20th International Symposium on

Laser-Aided Plasma Diagnostics

九州 2023

Kyoto Garden Palace Hotel, Kyoto, Japan,
September 10–14, 2023

National Institute for Fusion Science
Faculty of Engineering, Hokkaido University

20th International Symposium on

LASER–AIDED PLASMA DIAGNOSTICS

Kyoto Garden Palace Hotel, Kyoto, Japan, September 10–14, 2023

The LAPD Symposium brings together scientists from laser physics, low-temperature plasma chemistry and physics, and nuclear fusion. The Symposium is an important, unique, and fruitful source for cross-fertilization between these fields. Major topics include laser-aided diagnostics for fusion plasmas, industrial process plasmas, and environmental plasmas. Instrumentation developments related to laser-aided plasma diagnostics also receive emphasis.

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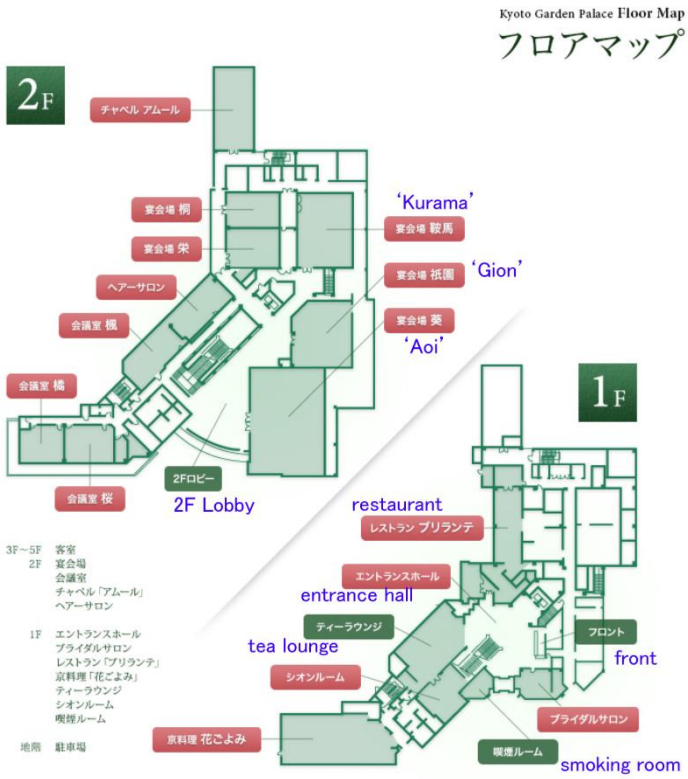

LAPD20 Web page

https://lapd20.nifs.ac.jp

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Sunday 10th September, 2023

17:30 - 19:00 Registration (Lobby on 2nd Floor)

19:00 - 20:30 Welcome Reception ('Kurama')

Monday 11th September, 2023

8:30 - 8:45 Welcome

8:45 - 9:35 Akazaki lecture (Chair: P. Bilkova)

8:45 - 9:35	**AK**	Laser and microwave diagnostics for ITER and beyond **G. Vayakis**

9:35 - 11:50 Incoherent Thomson scattering for fundamental plasma research (Chair: D.J. Den Hartog)

9:35 - 10:15	**G1**	Diagnostics of atmospheric pressure plasmas: recent progress and challenges **P. J. Bruggeman**
10:15 - 10:45		Coffee break
10:45 - 11:25	**G2**	DIAGNOSTICS OF PLASMA-LIQUID SYSTEMS: CHALLENGES AND THEIR MITIGATION **S. Yatom**
11:25 - 11:50	**T1**	Multi-Dimensional Incoherent Thomson Scattering System in PHAse Space MApping (PHASMA) Facility **E. Scime**

11:50 - 16:30 Laser spectroscopy I (Chair: K. Sasaki)

11:50 - 12:30	**G3**	Laser Spectroscopy on Low-Temperature Plasmas: Where are we going? **U. Czarnetzki**
12:30 - 14:00		Lunch (Lunch box will be provided.)
14:00 - 14:25	**T2**	1D Distribution Measurement of Electric Field in Streamer Discharge by E-FISH **Y. Inada**
14:25 - 14:50	**T3**	Ro-vibrational excitation of CO2 measured by quantum cascade laser absorption in a nanosecond pulsed discharge **D. Luggenhölscher**
14:50 - 15:15	**T4**	Cavity Ringdown Spectroscopy In Ns Pulsed Discharges **E.R. Jans**
15:15 - 15:45		Coffee break
15:45 - 16:00	**O1**	Electron density and electric field behavior of a plasma jet with pulse width closing to pulse duration **X. Li**
16:00 - 16:15	**O2**	Time-resolved electric field study of an impulse dielectric barrier discharge, in pure ammonia gas by means of induced second harmonic generation **R. Jean-Marie-Désirée**
16:15 - 16:30	**O3**	Single shot, non-resonant, four-wave mixing laser diagnostics for low temperature plasmas **A. Gerakis**

16:30 - 17:40 Poster Introduction #1 (Main room 'Aoi')

17:40 - 19:40 Poster Session #1 (Poster room 'Gion') Light meals are provided

Tuesday 12th September, 2023

8:30 - 10:00 Incoherent Thomson scattering for magnetic fusion plasma (Chair: L. Giudicotti)

8:30 - 9:10	**G4**	Overview of laser-aided plasma diagnostic developments at the Wendelstein 7-X stellarator **K.J. Brunner**
9:10 - 9:35	**T5**	Next steps in high-repetition-rate laser development for Thomson scattering **D.J. Den Hartog**
9:35 - 10:00	**T6**	Experimental study on in-situ calibration of spectral transmission of Thomson scattering in harsh environments **E. Yatsuka**
10:00 - 10:30		Coffee break

10:30 - 12:30 Laser-induced fluorescence spectroscopy (Chair: F. Skiff)

10:30 - 11:10	**G5**	Ultrafast Advanced Optical Diagnostics for Gases and Plasmas **A. Dogariu**
11:10 - 11:35	**T7**	Laser induced florescence spectroscopy for Hall thruster plasma diagnostics **W. Choe**
11:35 - 12:00	**T8**	Recent development of LIF diagnostics in ASIPP **C-S. Yip**
12:00 - 12:15	**O4**	Time-resolved laser-induced fluorescence spectroscopy with a continuouswave diode laser for the investigation of ion sheath dynamics **R. Takahashi**
12:15 - 12:30	**O5**	Atomic Oxygen Behavior in Sub-atmospheric Pressure Pulsed Corona Discharge **Y. Nakagawa**
12:30 - 14:00		Lunch break (Lunch box is provided.)

14:00 - 16:20 Phase contrsast imaging, interferometer/polarimeter, collective Thomson scattering high energy plasma diagnostics (Chair: H. Liu)

14:00 - 14:40	**G6**	Tangential viewing phase contrast imaging for turbulence measurements **S. Coda**
14:40 - 15:05	**T9**	Development of a Combined Polarimeter-interferometer system for Non-Inductive Plasma Position Measurement in Long Pulse discharges on EAST **H. Lian**
15:05 - 15:35		Coffee break
15:35 - 15:50	**O6**	Commissioning and first results of the 174 GHz collective Thomson scattering diagnostic at Wendelstein 7-X **D. Moseev**
15:50 - 16:05	**O7**	Laser-Plasma Instabilities of Frequency Doubled Pulses at the Extreme Light Infrastructure's L4 Beamline **M. Rivers**
16:05 - 16:20	**O8**	Prospective of multiple stages mJ energy level and ultrashort pulses OPA generation at Extreme Light Infrastructure-Nuclear Physics (ELI-NP) **L. Neagu**

16:30 - 17:40 Pre-Poster #2 (Main room 'Aoi')

17:40 - 19:40 Poster Session #2 (Poster room 'Gion') Light meals are provided

Wednesday 13th September, 2023

8:30 - 9:10 Microwave diagnostics for magnetic fusion plasma (Chair: M. Nishiura)

8:30 - 9:10	**G7**	The Latest Developments of Microwave Diagnostics for High Temperature Plasma in ELVA-1 Company **D. Korneev**

9:35 - 11:50 Diagnostics of EUV light source plasma (Chair: Y-C. Ghim)

9:10 - 9:50	**G8**	Plasma Dynamics and Future of LPP-EUV Source for Semiconductor Manufacturing **H. Mizoguchi**
9:50 - 10:05	**O9**	Collective Thomson scattering measurements of electron temperature and electron density in laser-driven EUV plasmas during the laser irradiation **Y. Pan**
10:05 - 10:35		Coffee break

10:35 - 11:35 LAPD 20th anniversary honorary talks (Chair: K. Tanaka)

10:35 - 11:05	**H1**	Forty years (1983-2023) with LAPD and for its future evolution **K. Muraoka**
11:05 - 11:35	**H2**	40 Years of high-temperature laser-aided plasma diagnostics (Honorary) **A.J.H. Donné**
11:35 - 12:15		Group Photo/Break

12:15 - 18:30 Excursion

19:00 - 21:00 Banquet ('Aoi')

Thursday 14th September, 2023

8:30 - 9:50 Laser-induced spectroscopy II (Chair: U. Czarnetzki)

8:30 - 9:10	**G9**	Electric-Field-Induced Coherent Anti-Stokes Raman Scattering in Visible Region for Sensitive Measurements in Near-Atmospheric-Pressure Environments **T. Ito**
9:10 - 9:35	**T10**	Mid-infrared frequency comb spectroscopy of plasmas **I. Sadiek**
9:35 - 9:50	**O10**	Coherent anti-Stokes Raman scattering on N2 and CO2 in a (sub-)atmospheric pressure plasma **J. Kuhfeld**
9:50 - 10:20		Coffee break

9:35 - 11:50 Incoherent Thomson scattering and plasma control using laser diagnostic for magnetic fusion plasma (Chair: P. Bilkova)

10:20 - 10:45	**T11**	First Measurements of Electron Temperature and Density Profiles Using Thomson Scattering on the ST40 Spherical Tokamak **H.F. Lowe**
10:45 - 11:00	**O11**	Development of Event-triggered Thomson Scattering System for Measurement of Electron Temperature/Density Profiles during Abrupt Phenomena **R. Matsutani**
11:00 - 11:15	**O12**	Double-pass Thomson scattering measurements in TST-2 Ohmic heated tokamak plasmas **Y. Peng**
11:15 - 11:30	**O13**	Real-time capabilities of laser aided plasma diagnostics at TCV **B. Vincent**
11:30 - 11:45	**O14**	Development of a multifunctional real-time data processing system for interferometers on EAST **Y. Yao**
11:45 - 12:00		Closing

Monday 11th September, 2023

Poster Session #1

17:40 - 19:40	Poster Session #1	(Poster room 'Gion')
	pre-poster start time	
P1-1	16:30	Development of a Collective Thomson Scattering Diagnostic System on SNU X-pinch device **J. Lee**
P1-2	16:32	Quantifying Uncertainties for a Coherent Thomson Scattering System with Bayesian Sensitivity Analyses on the Synthetic Data on X-pinch Plasmas **Y.S. You**
P1-3	16:34	Development of correlation ECE system for electron temperature fluctuation measurement in LHD **M. Gong**
P1-4	16:36	The Co-located arrangement of microwave imaging diagnostics on EAST tokamak **J.L. Xie**
P1-5	16:38	Physical design, fabrication and output power optimization of a 2.5 thz CH3OH laser **X. Li**
P1-6	16:40	Preliminary Results Of A Combined Interferometer Using 340 GHz Solid State Source And A HCN Laser On ENN's XuanLong-50 (EXL-50) **J. Xie**
P1-7	16:42	Simulation of fringe normalization for analyzing phase shift in plasma diagnostic using laser interferometry **S. Lee**
P1-8	16:44	Operation of the upgraded single crystal dispersion interferometer (SCDI-U) and its measurements in KSTAR during abrupt and large density changes **D.-G. Lee**
P1-9	16:46	Progress Of CO2 Dispersion Interferometer on EAST **Y.Y. Liu**
P1-10	16:48	Application of Multichannel Doppler Reflectometer for Fluctuation Measurements in GAMMA 10/PDX Anchor Heating Experiment **J. Kohagura**
P1-11	16:50	Highlighted studies of turbulence, flow shear and mode structure in MAST-U using UCLA Doppler Back-scattering system **C. Michael**
P1-12	16:52	First Data and Preliminary Experimental Results From a New Doppler Backscattering System on the MAST-U Spherical Tokamak **P. Shi**
P1-13	16:54	Stray light suppression for Thomson scattering diagnostic on linear magnetized plasma device **Z. Lin**
P1-14	16:56	The optical design of a vertical Thomson scattering system on SUNIST-2 **C. Liu**
P1-15	16:58	Performance of JT-60SA Thomson scattering data analysis system **M. Akimitsu**
P1-16	17:00	Twin synthetic diagnostic for the design and exploitation of the WEST high-resolution Thomson Scattering diagnostic. **M. Carole**
P1-17	17:02	THE WEST THOMSON SCATTERING DIAGNOSTICS **G. Colledani**
P1-18	17:04	Polarimetric Thomson scattering to reduce Te and ne measurement uncertainty in high performance ITER operating regimes **D.J. Den Hartog**
P1-19	17:06	Analysis of Dual Laser Thomson scattering signals on W7-X **F.A. D'Isa**
P1-20	17:08	Improvement of signal-to-noise ratio in Thomson scattering diagnostics by an accumulation of 100 laser pulses within 5 milliseconds **H. Funaba**

P1-21 17:10 Development of a LIDAR Thomson Scattering Diagnostic For DTT

L. Giudicotti

P1-22 17:12 Development and first results of the edge Thomson scattering diagnostic with compact polychromators on the HL-2M Tokamak

S.B. Gong

P1-23 17:14 Cavity Ringdown Lamb Dip Spectroscopy at Balmer Alpha Line of Atomic Hydrogen for Measuring Electric Field in Plasma

K. Sasaki

P1-24 17:16 Development of Ghost Imaging Absorption Spectroscopy

M. Aramaki

P1-25 17:18 Nonlinear Effect of Gas Flow on Helium Metastable Atoms in Weakly Ionized Gas Jet

H. Cho

P1-26 17:20 Design and Functional Testing of Cesium Atomic Concentration Detection System Based on TDLAS

LZ. Liang

P1-27 17:22 Comparative study of detached H/D plasmas using laser Thomson scattering and spectroscopy in the linear plasma divertor simulator NAGDIS-II

J. Shi

P1-28 17:24 Studies of Laser-produced Multi-ionized Plasmas for Soft X-ray and EUV Light Sources using Collective Thomson Scattering

K. Tomita

P1-29 17:26 Development of the Thomson scattering measurement system for cascade arc device with indirectly heated hollow cathode

K. Yamasaki

P1-30 17:28 cancelled

P1-31 17:30 Electric Field Measurements in N2:CO2 Ns-APPJ by E-FISH Technique

N.D. Lepikhin

Tuesday 12th September, 2023

Poster Session #2

17:40 - 19:40 Poster Session #2 (Poster room 'Gion')

pre-poster start time

P2-1 16:30 Interferogram Analysis of X-pinch Plasmas Using Lens-pair Configuration and Synthetic Dark-field Schlieren Image

S. Bong

P2-2 16:32 Dense Plasma Diagnostics with a Nomarski Interferometer Using a Frequency-tripled Ti:sapphire Laser

H. Lee

P2-3 16:34 Exploring high energy density plasmas sustained over inertia time by the interaction between high intensity laser and structured medium

Y. Kishimoto

P2-4 16:36 Diagnostics of a Laser-Produced Plasma With High Density-Gradient Using a Double-Grating Differential Interferometer

K. Roh

P2-5 16:38 Measurement of the Voltage Evolution on a Load of X-pinch Plasma System Using the Pockels Effect

S. Choi

P2-6 16:40 Development of 2D Thomson Scattering Measurement System Using Multiple Reflections and Time-of-Flight of Laser Light

S. Kamiya

P2-7 16:42 Design and Analysis of Divertor Thomson Laser Beam Dump for KSTAR

H. Kim

P2-8 16:44 Investigation of Thomson Scattering Measurement System for Long-Duration Discharges with a hot wall on the QUEST Spherical Tokamak
K. Kono

P2-9 16:46 cancelled

P2-10 16:48 New Polychromator System Design For KSTAR Thomson Scattering
J.-h. Lee

P2-11 16:50 Electron Cyclotron Heating/Diagnostics via Microwave Optical Vortex
S. Kubo

P2-12 16:52 Topological Charge and Phase Gradient Measurement for Optical Vortex Beams by Modifying Peripheral Region of Forked Grating on Spatial Light Modulator
S. Yoshimura

P2-13 16:54 Optimization of the Collection Optics System for KSTAR Divertor Thomson Scattering Diagnostic
G.H. Park

P2-14 16:56 Development of dual-path multi-pass Thomson scattering system in GAMMA 10/PDX
M. Yoshikawa

P2-15 16:58 Absolute value measurement of ion-scale turbulence by 2D-PCI in LHD
T. Kinoshita

P2-16 17:00 Development of Sweeping Detector Phase Contrast Imaging in LHD
H. Sakai

P2-17 17:02 Design Of An Ultrahigh-bandwidth Phase Contrast Imaging System For Fusion Grade Devices
A. Marinoni

P2-18 17:04 Optimization of HCN laser interferometer power automatic control system on EAST Tokamak
J.B. Zhang

P2-19 17:06 DEVELOPMENT OF AN HCN DUAL LASER FOR THE INTERFEROMETER ON A SMALL TOKAMAK DEVICE
N. Zhang

P2-20 17:08 Cotton-Mouton Effect Polarimetry on EAST Tokamak
M.Y. Shen

P2-21 17:10 Active Correction of Window Faraday Effects for ITER Laser Diagnostics
C. Watts

P2-22 17:12 Design Scheme of Line Array Detection for Polarimeter-interferometer System on EAST
H.H. Yan

P2-23 17:14 cancelled

P2-24 17:16 Improvement Of Time Resolution In Optical Vortex Laser Absorption Spectroscopy Using Quadrant Photodiodes
H. Minagawa

P2-25 17:18 High-Sensitivity Lamp Dip Spectroscopy with Frequency Modulation Technique
S. Nishiyama

P2-26 17:20 Investigation of Molecular-Impurity Decomposition in High-Pressure Low-Temperature Plasmas Using Laser Absorption Spectroscopy
K. Urabe

P2-27 17:22 Simulation of Doppler-Free Spectra Using the Collisional Radiative Model
J.J. Simons

P2-28 17:24 Magnetic field stabilized atmospheric pressure plasma: Diagnosis of gas temperature and its effect on nitrogen fixation
Z. Li

P2-29 17:26 Laser Thomson Scattering Measurements around Magnetized Model in Rarefied Argon Arc-jet Plume
H. Katsurayama

P2-30 17:28 Laser Thomson Scattering System for Anisotropic Electron Temperature Measurement in NUMBER
A. Okamoto

P2-31 17:30 Improving Pulsed Laser Induced Fluorescence Signal-to-Noise Through Matched Filter Signal Processing
T.J. Gilbert

P2-32 17:32 TALIF and CARS Diagnostics for Measuring Atomic and Molecular Hydrogen Densities in Divertor-relevant Plasmas
K. Schutjes

Abstracts of
The 20th International Symposium on
Laser-Aided Plasma Diagnostics

The proceedings of the LAPD20 Symposium will be published in the Proceedings Section of the Journal of Instrumentation (JINST).

Laser and microwave diagnostics for ITER and beyond

G. Vayakis* for the ITER diagnostics team

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ITER diagnostics include an extensive set of laser and microwave diagnostics to give access to a wealth of information on the core and edge plasma and to support high performance operation of ITER [1]. For example, Core and Edge Thomson scattering systems build detailed density and temperature profiles on time scales much faster than τ_E to follow transient events; ECE and reflectometry add time resolution to follow MHD events. Implementing these diagnostics is challenging, needing a panoply of technologies to keep them functioning reliably for thousands of hours despite extreme events such as disruptions and wall conditioning cycles. Shielding, shutters and cleaning systems protect the forward elements of most optical systems from the build-up of deposits and damage. Still, plasma-facing mirrors must survive laser loads and endure erosion, deposition and in-situ RF cleaning. Calibration and monitoring systems ensure accurate and drift-free operation. These support systems are also not straightforward and required specific R&D. Access also drive the design: To deal with the neutron and gamma sources yet allow maintenance of activated components, ITER uses large, multi-purpose ports that couple otherwise distinct systems into modules for maintenance. Machine movement requires provisions to maintain alignment and calibration, from these port plugs, shown in Fig. 1, to the accessible areas 10 – 50 m away. A final complication comes from the difficulty of employing electronics near the plugs. Extensive qualification for radiation resistance is needed. We will examine design adaptations that ITER adopted for its near-reactor environment, consider the lessons learnt from the ITER design activity specifically for laser and active (oscillator driven) microwave systems and lay out some possible evolution paths for the reactor diagnostician that must follow a more industrial approach.

[1] ITER Organization, 'ITER research plan within the staged approach (Level III – Provisional version' report ITR-18-03 (2018) Appendix H, online at: https://www.iter.org/technical-reports

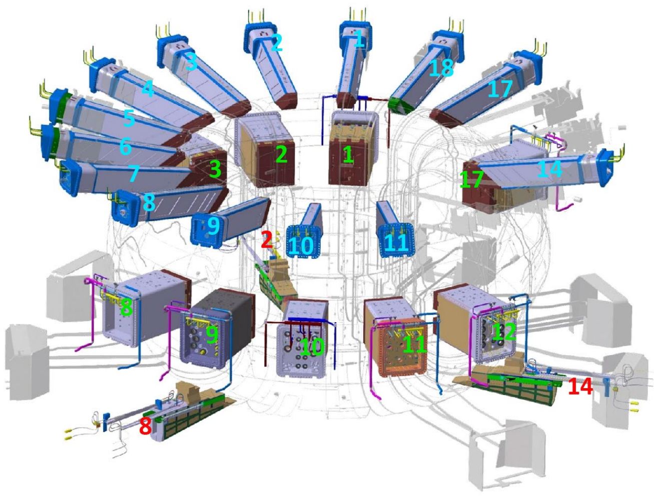

Figure 1. The ITER diagnostic port plus, divertor (3 ports, red numbers), Equatorial (9 ports, green numbers) and upper (14 ports of which 10 have significant payload, cyan numbers). For scale, the flanges of the ports are approximately 15 m from the machine vertical centerline.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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Forty years (1983-2023) with LAPD and for its future evolution

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"How about having a meeting in the laser diagnostics of plasmas?" was a remark of a man. Then another man replied "It sounds interesting". This was one of those casual conversations between myself (KM) and David Evans (DE) at the counter of Chikae live-fish restaurant in the central Fukuoka in September 1983, and it has turned out to have become the beginning of the by now prestigious LAPD symposia! DE was then a visiting fellow from UKAEA Culham Laboratory in England to KM's lab at Kyushu University for three months. Both KM and DE had subsequently contacted active researchers in the field, and Hans-Joachim Kunze (Bochum Univ) and Frieder Döbele (Essen Univ) from Germany, and Alan DeSilva (Univ Maryland, USA) agreed to come, along with about 30 participants from inside Japan. As one sees, the meeting modestly started, with the title of 'Kyushu International Symposium on Laser-Aided Plasma Diagnostics'. The meeting produced much interactions, resulting in the unanimous proposal at the end of the meeting to hold a similar one every other year, and DE volunteered to host it at a college in Oxford Univ in 1985. Naturally, many experienced plasma diagnosticians from around the world, in particular from UK such as Nick Peacock from Culham, came to this meeting, which was subsequently called as '2nd International Symposium on Laser-Aided Plasma Diagnostics'. Among the participants at the 2nd meeting, Neville Luhmann from UCLA agreed to organize the 3rd meeting around his vicinity in California. There, it was decided to hold the 4th meeting again in Kyushu. After around the world, the 4th meeting attracted about 80 participants from around the globe, and everybody agreed that this might be a good rotation from Japan, Europe and USA in every other year, with the optimum size of around 80 participants due to face-to-face interactions with sufficient times for discussion. All subsequent LAPDs have been carried out in these formats, except for special cases, such as the recent postponements due to the COVID pandemic.

From the outset of the meeting, it has been a tacit understanding among the LAPD proponents that "cross-fertilizations" (CF) with other fields of physics and chemistry have to be cultivated for the LAPD meetings to have any impact/*raison d'etre* in the scientific community, because various phenomena associated with LAPD, such as transmission, refraction, reflection and scattering of lasers have been established for a long time via theories of electromagnetic radiations in plasmas and no further expansion of science looked to be foreseen. Therefore, it was thought as essential to have good contacts with other fields of science to yield very essential outputs from LAPD, without which good progresses in the respective areas would not be possible. The present speaker hopes to show such examples from results of his group in <u>low-temperature plasmas</u>. These include laser Thomson scattering in discharge plasmas (CF with electrical engineering, laser science and semiconductor fabrication) and laser induced fluorescence to detect the temporal evolution of surface modification (CF with surface science). In addition, more recent on-going work of laser Thomson scattering is touched upon with respect to the laser-produced plasma for the EUVL (extreme ultra-violet lithography) light source (CF with semiconductor fabrication). It is the speaker's sincere hope that completely new CFs may be heard at the present and future LAPD meetings, such that both LAPD and related fields both flourish by LAPD's providing otherwise unobtainable information.

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40 Years of high-temperature laser-aided plasma diagnostics (Honorary)

A.J.H. Donné[1]

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The field of high-temperature laser-aided plasma diagnostics started already in the 1960-ies with first applications of incoherent Thomson scattering. Noteworthy are the measurements of a British team from UKAEA on the Russian T3 tokamak in the early days of fusion research has led to a worldwide focus of magnetic fusion research on the tokamak. Despite these early applications of high-temperature laser-aided plasma diagnostics, this talk will mainly focus on developments that have taken place since the first Symposium on Laser-Aided Diagnostics in Fukuoka, Japan in 1983. The emphasis will be on diagnostics in magnetic confinement fusion.

Already back in 1983 laser-aided plasma diagnostics were routinely used at many experiments:

- Incoherent Thomson scattering for measuring the electron density and temperature.
- Collective Thomson scattering and Phase-Contrast Imaging for measuring electron density fluctuations.
- Laser-induced fluorescence for diagnosing parameters of ions and neutral atoms.
- Interferometry/polarimetry for measuring electron density and internal magnetic fields.

Many of these diagnostics had a limited number of viewing chords as well as spatial and temporal resolutions that were constrained by the available technology at that time.

Ever since 1983 there has been a continuous improvement of lasers, detectors, and control hard- and software, making the diagnostics more sophisticated. Also new diagnostics have joined the scene like ion Thomson scattering for diagnosing fast ions, microwave reflectometry to measure the electron density and fluctuations in this quantity as well as zonal flows, laser-induced breakdown and desorption spectroscopy for studying the wall composition and fuel retention. Some of these diagnostics have been developed from earlier applications in the field of low-temperature plasma physics, and the LAPD Symposium has played an important role in this cross-fertilisation.

This talk will go one by one through the various known high-temperature laser-aided plasma diagnostics and will sketch the situation around the time of the first LAPD Symposium in 1983, followed by several developments that have taken place during the last 40 years and a description of the present status of the various diagnostics. The talk will be sketchy (using a limited number of examples) and is by no means intended to be an exhaustive overview of the developments during the last 40 years.

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Diagnostics of atmospheric pressure plasmas: recent progress and challenges

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Low temperature atmospheric pressure plasmas (APPs) interfacing with solid and liquid substrates have been extensively investigated in the context of material processing and synthesis, pollution control, decontamination, new medical treatment procedures and sustainable energy processes. These applications are enabled by the ability of APPs to deliver highly reactive plasma species to surfaces at near ambient temperatures. The plasma-produced reactive species and resulting fluxes to the interfacing substrate can in principle be controlled by voltage waveforms and feed gas composition. However, plasmas are self-organizing systems and the strong non-linear coupling between the plasma and substrate leads to complex plasma-surface interactions which remain not well understood to date and have a major, and sometimes unknown, impact on the plasma properties and species fluxes impinging on the substrate.

To gain a better understanding of the underlying plasma processes in complex APPs, a requirement to fully exploit the advantages of plasmas for many applications, there is a strong need for improved diagnostics or extension of the current boundaries of available diagnostics. The properties and species density distributions of APPs can have spatial gradients at micrometer length scales and exhibit transient behavior down to nanosecond timescales. This transient nature of APPs is further enhanced due to ubiquitous plasma instabilities at atmospheric pressure posing enormous challenges on diagnostics and their interpretation.

In this presentation, we will discuss these unique diagnostic challenges in probing plasma kinetics and chemistry, species flux measurements to substrates including boundary layer effects, and the measurement of highly dynamic plasma instabilities. This will include time and spatially resolved Thomson scattering measurements performed during the development of plasma instabilities in pulsed discharges which allowed us to describe the underpinning mechanisms that can trigger or prevent the formation of such plasma instabilities in the presence of a liquid electrode. We will also report on microscopic laser induced fluorescence measurements and how such measurements allow us to deduce sticking coefficients of radicals on substrates under realistic plasma conditions, critical input data for plasma models, and deduce species fluxes to solutions that allow us to quantitatively explain plasma-induced redox reactions with probe molecules in the liquid phase.

Acknowledgement: This work was partially supported by the US Department of Energy under Award Number DE-SC-0016053 and DE-SC-0020232, and the Army Research Office under Grant Number W911NF-20-1-0105.

References

[1] Y. Yue, V. S. S. K. Kondeti, N. Sadeghi, P. J. Bruggeman 2022 Plasma Sources Sci. Technol. **31** 025008
[2] Y. Yue, P. Bruggeman 2022 Plasma Sources Sci. Technol. **31** 124004
[3] Y. Yue, S. Exarhos, J. Nam, D. Lee, S. Linic, and P. J. Bruggeman 2022 Plasma Sources Sci. Technol. **31** 125008

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DIAGNOSTICS OF PLASMA-LIQUID SYSTEMS: CHALLENGES AND THEIR MITIGATION

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Abstract

Non-equilibrium, low-temperature plasma is gaining a very steady and dedicated following in the bustling, inter-disciplinary community interested in plasma science and technology. Small scale, uncomplicated ways of plasma generation in the ambient atmosphere and high plasma-induced chemical reactivity make low-temperature plasma very attractive for a wide variety of applications in biomedicine, environmental remediation, and agriculture. These applications prompt new avenues for studying plasma in rich chemical environments and plasma interaction with liquids. Often, these environments pose new challenges for plasma investigation, application of diagnostic methods and interpretation of results.

In this talk I will review two popular methods of laser diagnostics in plasma-liquid systems and generally in low-temperature plasmas. These are Thomson scattering and laser-induced fluorescence. Setting up the plasma-liquid interaction experiment will be described, while stressing the important points for laser diagnostics and maintaining conditions for correct and repeatable measurements. I will discuss the caveats that are encountered when measuring inherently unstable and collisional systems such as plasma interacting with liquid and how these challenges impact data analysis and calibration efforts for these two-diagnostic approaches.

Acknowledgements

The author is very grateful to the colleagues within Princeton Collaborative Research Facility (PCRF): Yevgeny Raitses, Sophia Gershman, Santosh Kondeti, Arthur Dogariu and Michael Shneider, who continually contribute to author's work through brainstorming, advice, and direct help in lab work.

The OH measurement in open air DBD discharge is supported by the U.S. Department of Energy (DOE) under Contract No. DE-AC02-09CH11466.

The work on plasma characterization in RF plasma jet in contact with liquid and humid He DBD discharge is supported by the Princeton Collaborative Research Facility (PCRF), which is supported by the U.S. Department of Energy (DOE) under Contract No. DE-AC02-09CH11466.

Laser Spectroscopy on Low-Temperature Plasmas: Where are we going?

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The history of the LAPD meeting has always mirrored well the evolvement of laser spectroscopy in plasma physics. Particularly, in the field of low-temperature plasmas, an amazing number of techniques has been developed over the past decades. However, the development of new laser spectroscopic techniques cannot be separated from the trends and the related needs in the field. Over the past decade, a strong shift of topic from low-pressure plasmas to atmospheric pressure plasmas can be observed. These plasmas are very small (typically 0.1 to 1 mm size) and often transient on a ns-scale. Further, collisionality of electrons with neutrals is in the THz range and often population transfer between excited states atoms and molecules plays a significant role. On the other hand, population densities are notably higher than in low-pressure discharges and naturally, the high collisionality leads to strong electric fields even in the quasi-neutral bulk of the plasma. Due to the small size, limited access and the highly transient time scale, optical techniques are often the only diagnostics applicable (plus current and voltage measurements and possibly mass spectroscopy in the effluent). The particular plasma features at high pressures have enabled some new spectroscopic techniques, like e.g. ps-resolved electric field induced second harmonic generation (EFISH) for electric field measurements, frequency-comb spectroscopy on molecules, or a re-vitalization of coherent anti-Stokes Raman spectroscopy (CARS). For the later, exciting developments show enhanced performance on the fs time-scale. The talk will give an overview of some of the most recent techniques and will provide also a personal perspective of possible near future developments.

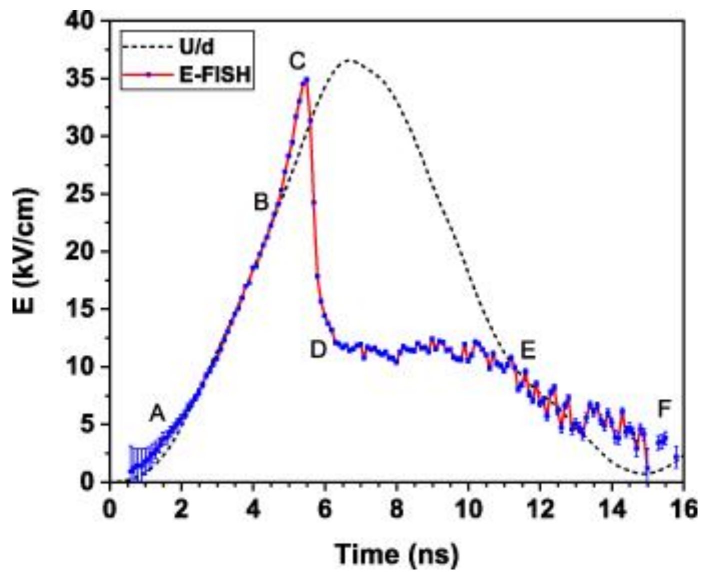

Figure 1. Example of a 100 ps time resolved electric field measurement in a ns-pulsed, near-atmospheric pressure micro-discharge in nitrogen/helium by EFISH [1].

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Overview of laser-aided plasma diagnostic developments at the Wendelstein 7-X stellarator

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Wendelstein 7-X (W7-X) situated in Greifswald, Germany, is the largest stellarator-type fusion experiment operating today. It aims to demonstrate the quasi-isodynamic stellarator concept as a viable option for a future fusion power plant. With its plasma volume of 30 m^3, W7-X reached plasma densities beyond $2.4 \cdot 10^{20}$ m^{-3}, as well as electron temperatures in excess of 5 keV. W7-X has recently finished its first experimental campaign with the new fully water cooled divertor, in which several record programs were conducted including an 8 min plasma with 1.3 GJ of injected energy. As such, W7-X has proven to be an exciting experiment to develop steady-state diagnostics for high-performance plasmas.

To fulfill its mission and measure its plasma's parameters W7-X is equipped with over 45 diagnostics and uses 69 lasers. Of these, 37 lasers are connected to measuring plasma parameters with 8 lasers in 4 laser-based diagnostics currently employed directly at the W7-X plasma. This includes laser blow-off in combination with spectroscopic diagnostics for impurity transport estimation, phase contrast imaging for characterization of poloidally resolved density fluctuations, Thomson scattering for core electron density and temperature profile measurement as well as dispersion interferometry for real-time density measurement and control.

In this presentation, we give an overview of the diagnostic developments conducted at W7-X in recent years as well as the work envisaged for the future. This includes developments towards real-time steady-state operation, in-situ or remote absolute calibration, high temporal resolution and even plasma actuation. We will go over the aforementioned laser-based diagnostics and their contribution to the broader plasma diagnostics community as well as some diagnostic techniques employing lasers for calibration purposes.

Ultrafast Advanced Optical Diagnostics for Gases and Plasmas

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Recent developments in advanced optical diagnostics based on ultrafast lasers enable non-intrusive high sensitivity measurements in gases and plasmas with high temporal and spatial resolution. These diagnostics rely on nonlinear optical effects to enable measurements such as electron and gas densities, species concentration [1], temperature, flow velocity [2] and electric fields [3] in low temperature plasma devices and other gaseous applications. The talk focuses on non-equilibrium temperature measurements using a hybrid femtosecond/picosecond Coherent Anti-Stokes Raman Scattering (CARS) spectroscopy technique [4], and on measurements of neutral atomic species such as O, N, and H using femtosecond Two-Photon Laser Induced Florescence (fs-TALIF). We present results obtained plasmas ranging from atmospheric discharge and arc jet plasmas, to low density plasmas found in magnetized RF heated devices, and in discharges at parameters relevant to tokamak divertors. Measurements of neutrals (H) in mTorr plasmas show densities as low as 10^{10} cm^{-3} with sub-mm spatial resolution, and the dynamics of the atomic species with nanosecond temporal resolution.

The work has been performed in collaboration with the Princeton Plasma Physics Laboratory (PPPL) and the Princeton Collaborative Research Facility (PCRF) under Contract No. DE-AC02-09CH11466 by the U.S. Department of Energy (DOE).

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Tangential viewing phase contrast imaging for turbulence measurements

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Phase contrast imaging (PCI) is an established and powerful technique for measuring density fluctuations in plasmas [1] and has been successfully applied to several fusion devices [2-4]. Rooted in a concept first developed for microscopy [5], PCI belongs to the category of internal-reference interferometers and has been shown to possess superior qualities among such techniques, particularly in terms of spatial linearity. In essence, it produces a true image of fluctuations in the plane perpendicular to the propagation direction of the probing laser beam, provided their characteristic spatial scale is smaller than the beam width. The measurement in itself is line-integrated and thus not spatially resolved longitudinally to the beam. However, the properties of the turbulence itself can be exploited to achieve longitudinal resolution, particularly when the beam propagates nearly tangentially to the magnetic field. As micro-fluctuations are known to propagate perpendicularly to the magnetic field (**B**), and line integration naturally selects wave vectors perpendicular to the direction of beam propagation ($\mathbf{k_0}$), only wave vectors aligned along the local $\mathbf{B}\text{x}\mathbf{k_0}$ direction contribute to the signal. Selecting the measured wave vector through spatial filtering thus localizes the measurement to a segment along the beam path.
This intiuitive picture has been recently rigorously tested through numerical modeling, which has revealed significant additional complexity while confirming the general principle [6].
Tangential PCI has been employed extensively in the TCV tokamak and has resulted in a rich body of work on broadband microturbulence in the TEM/ITG range [7], on geodesic acoustic modes (GAMs) [8], and on macroscopic MHD modes; this work will be reviewed in this contribution. A similar diagnostic arrangement is also at an advanced planning stage for the new superconducting tokamak JT-60SA [9] and will be presented here.

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The Latest Developments of Microwave Diagnostics for High Temperature Plasma in ELVA-1 Company

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For nearly 30 years, we have been designing and supplying instruments for microwave diagnostics of high temperature plasma. This report provides a description of the mm-wave components we utilize to make diagnostics within the frequency range of 26-330 GHz. While most of these components are standard and readily available on the market, we have also developed a few specific devices that simplify the architecture of our instruments. The article includes descriptions of these devices: Backward Wave Oscillators (BWO), IMPATT sources, IMPATT Active Frequency Multipliers, Noise Sources, and Electronically Controlled Attenuators. Furthermore, we offer an overview of the microwave plasma diagnostics we have supplied, including ECE radiometers operating at 50-220 GHz, as well as heterodyne interferometers operating at fixed frequency 94 GHz, 140 GHz, or 300 GHz. We also discuss methods employed to ensure measurement stability and present the achieved results. The advent of the new era of modern MMIC-based devices has brought forth exciting possibilities. As an example, we discuss the upgrade of the low noise receiver for the Collective Thomson Scattering (CTS) diagnostic at Wendelstein 7-X, which enables ion temperature measurements in the plasma core [1]. Lastly, we provide a list of MMIC-based devices that are currently available and have garnered the attention of the plasma diagnostics community.

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Plasma Dynamics and Future of LPP-EUV Source for Semiconductor Manufacturing

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Recently progress of LPP EUV light source is remarkable. Ten years ago, power level is only several 10 W level. At present 250W power level is realized in semiconductor mass production factories[1)] by ASML. On the other hand, pioneer of this Unique technologies including; combination of pul sed CO2 laser and Sn droplets, dual wavelength pico second laser pulses for shooting and de bris mitigation by magnetic field have been applied by Gigaphoton[2).]
They have demonstrated high average power >300W EUV power with CO_2 laser more than 27kW at o utput power in cooperation with Gigaphoton and Mitsubishi Electric[3)]. In near future more higher p ower (>800W) EUV source is required to fit High NA (>0.55) lithography of semiconductor indu stry.In this paper we will discuss about the Sn plasma dynamics which dominate the EUV emis sion by using Tomson scattering (TS) measurement[4)] (FIG.1). Recent TS results have revealed whole profiles of electron temperature and ion density in the EUV sources. These results menti on that there is still sufficient potential to increase EUV output in the future.

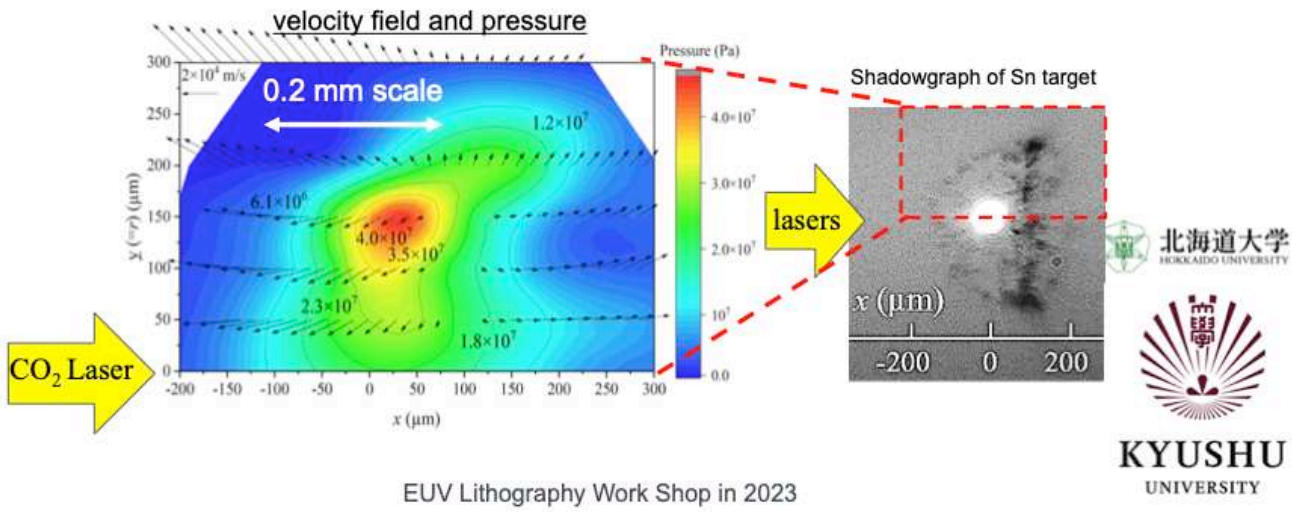

FIG.1 EUV PLASMA PARAMETER DISTRIBUTION

REFERENCE

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Electric-Field-Induced Coherent Anti-Stokes Raman Scattering in Visible Region for Sensitive Measurements in Near-Atmospheric-Pressure Environments

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Electric field is one of the most important parameters for understanding/controlling plasma. While various methods are available for the field measurements in low-pressure environments, limited methods are readily available in high-pressure environments, such as near-atmospheric-pressure environments. Especially in the area without electrically-excited species, the currently available choices seem to be non-linear laser spectroscopies.

Here, I am presenting our recent development of electric-field-induced coherent anti-Stokes Raman scattering (E-CARS) in the visible region (E-CARSv) for sensitive electric-field measurements in high-pressure environments [1,2]. While this method is essentially same as E-CARS in the infrared region [3], the signal can be initiated in the visible region with infrared-laser and visible-laser irradiations. When the energy of the infrared laser is tuned to the Raman transition energy of the probe molecules (examples are shown in Table 1), the signal, which has an energy equal to the sum of the energies of two incident lasers, is generated in the presence of an electric field. So far, we have successfully demonstrated the E-CARSv generations from hydrogen [1] and nitrogen [2] molecules. The results indicated that this method can allow us to detect a week electric field of 0.5 V/mm in atmospheric-pressure hydrogen environment. Further details will be presented at the symposium.

The presenting author would like to thank the co-authors of the related works, especially Mr. Koike for his excellent work in the measurements [1,2].

Table 1. Raman transition energies of several gaseous molecules.

Gas	Wavenumber (cm^{-1})
H_2	4155 [4]
N_2	2330 [5]
O_2	1556 [5]
CH_4	2916 [4]
CO_2	1388, 1286 [5]

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Multi-Dimensional Incoherent Thomson Scattering System in PHAse Space MApping (PHASMA) Facility

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A multi-dimensional incoherent Thomson scattering diagnostic system capable of measuring electron temperature anisotropies at the level of the electron velocity distribution function (EVDF) is implemented on the PHAse Space MAppgin (PHASMA) facility to investigate electron energization mechanisms during magnetic reconnection. This system incorporates two injection paths (perpendicular and parallel to the axial magnetic field) and two collection paths, providing four independent EVDF measurements along four velocity space directions. For strongly magnetized electrons, a three-dimensional EVDF comprised of two characteristic electron temperatures perpendicular and parallel to the local magnetic field line is reconstructed from the four measured EVDFs. Validation measurements of isotropic electrons were performed in a single magnetic flux rope and a steady-state helicon plasma. Measurements in merging flux rope experiments show spatial gradients of anisotropic electron heating (perpendicular greater than parallel) in the region around the magnetic X-point.

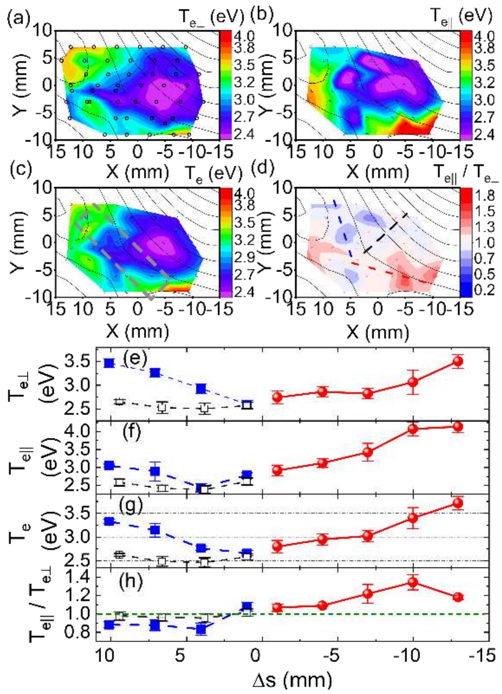

Figure 1. 2D spatial profile of (a) perpendicular electron temperature $T_{e\perp}$ (b) parallel electron temperature $T_{e\parallel}$ (c) effective electron temperature T_e and (d) anisotropy $T_{e\perp}/T_{e\parallel}$. Black lines are in-plane magnetic field projections and 43 gray dots show the measurement locations. The dashed rectangle in (c), half of the electron diffusion region, is used to calculate energy fluxes. The corresponding 1D profiles along separatrix I (red points for the red dashed line in (d)), II (blue solid squares for the blue dashed line in (d)) and the inflow direction (black open squares for the black dashed line in (d)): (e) $T_{e\perp}$ (f) $T_{e\parallel}$ (g) T_e and (h) $T_{e\perp}/T_{e\parallel}$. Δs is the distance from the X-point.

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1D Distribution Measurement of Electric Field in Streamer Discharge by E-FISH

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The electric field measurement of atmospheric-pressure nonthermal plasmas is essential for the fundamental understanding of the production mechanisms of the chemically reactive species utilized in wide ranging application fields. Recently, electric field induced second harmonic generation (E-FISH) has been reported as a promising method due to its technological superiority, e.g. versatility, setup simplicity, measurement sensitivity of ~ 0.1 kV/cm, temporal resolution of ~ 100 fs and spatial resolution of ~ 50 μm in the measurement plane vertical to the line of sight. However, the measurement accuracy of the E-FISH technique has not been accurately quantified. The measurement accuracy quantification requires the knowledge of the focused probe laser properties; such investigations have been conducted only for the spherically focused laser beam (0D measurement) and not for the cylindrically focused beam (1D measurement).

Here, the E-FISH method involving the cylindrically focused laser beam is demonstrated. The E-FISH signal generation is initially formulated and based on that, the spatial evolution of the E-FISH signal is analyzed along the laser propagation direction. Subsequently, the E-FISH signal analysis is conducted using model electric field profiles both with and without plasma. Comparison between the analysis data and the measured 1D E-FISH signal yields the 1D electric field distribution and the associated measurement accuracy. The measurement-accuracy-quantified E-FISH methodology captures the dynamic evolution of a single-filament streamer discharge in a primary-to-secondary transition phase generated in atmospheric-pressure air with spatiotemporal scales of ~ 1 ns and 100 μm. The precision of the experimental data in the transition regime is crucial to the development of a comprehensive numerical simulation model that links the primary and secondary phases.

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Ro-vibrational excitation of CO_2 measured by quantum cascade laser absorption in a nanosecond pulsed discharge

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Conversion of CO_2 is of growing interest in the context of greenhouse gas abatement and renewable energy exploration. Non-thermal plasmas are promising for an efficient conversion since their unique electron, vibrational, rotational, and gas temperatures allow to focus the discharge energy to the desired channels instead of heating the gas. Specifically, the vibrational excitation of states close to the dissociation threshold level is a more efficient dissociation pathway. In order to gain insight into the excitation and relaxation processes and to validate detailed kinetic models of CO_2 dissociation, temporally resolved measurement of the ro-vibrational excitation is of great importance in non-thermal and transient discharges.
A continuous wave quantum cascade laser tunable between 2276 and 2290 cm^{-1} and a fast detector (65 MHz) is used for measuring the absorption with high temporal resolution (8 ns) [1]. The chosen wavelength range allows for simultaneous measurement of rotational and vibrational populations and CO_2 concentration. Measurements are performed in a nanosecond pulsed discharge ignited between two parallel electrodes of 20 mm length, 1 mm wide and 1 mm apart. The discharge pressure is around 150 mbar with different N_2:CO_2 mixtures. The voltage pulses (V = 2-3 kV, f = 1 kHz) are about 200 ns long with discharge currents of 10 A. In these types of discharges there is a distinct separation of the timescales of electron heating and afterglow. The different phases can be studied in detail due to the high temporal resolution of the method here. The measurements show that the temperatures determined by the population density of the different states depend on the levels used and that the thermalization to a Boltzmann distribution takes much longer than the discharge duration (fig. 1).

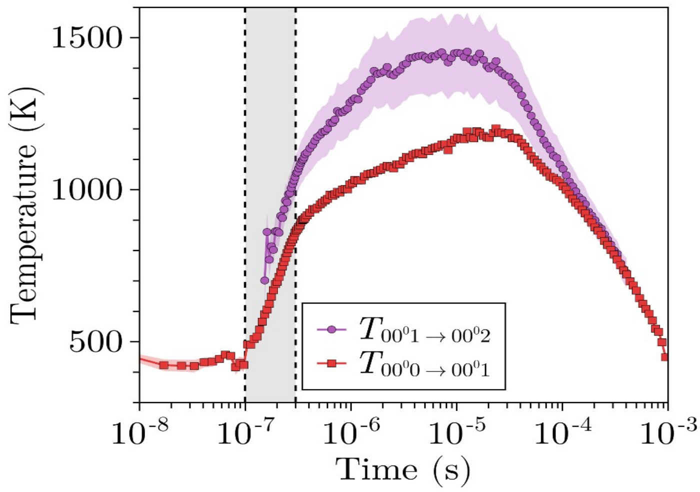

Figure 1. Different vibrational temperature T_3 due to a non-Boltzmann population, the discharge phase is marked in grey.

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Cavity Ringdown Spectroscopy In Ns Pulsed Discharges

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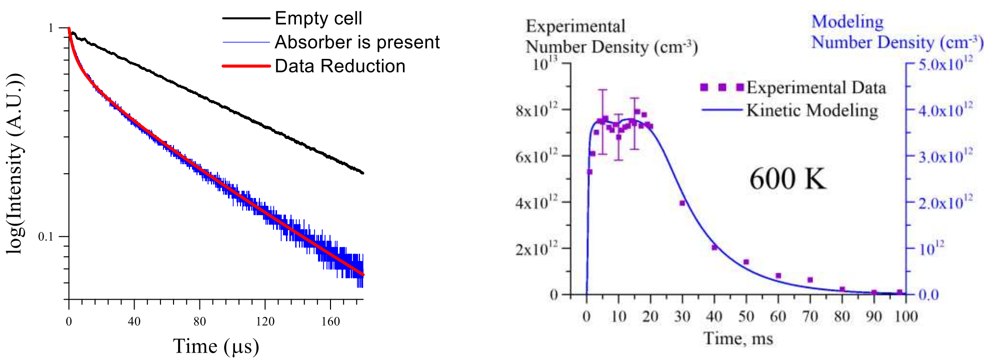
In recent years, ns pulsed discharges have become the subject of numerous studies for biomedical applications, fuel reforming, plasma-assisted combustion, nitrogen fixation, and beyond [1]. Although remarkable progress has been made in understanding the fundamental physics that occur in these low temperature nonequilibrium plasmas, many challenges still persist such as the chemical kinetics and reaction pathways of the plasma radicals [2]. In order to understand the driving mechanisms and key parameters of these plasmas, time-resolved absolute concentrations of the generated radicals must be measured. The most direct and reliable measurement of obtaining absolute radical concentrations is with absorption spectroscopy. With the lowest detection limit for absorption spectroscopy, cavity ringdown spectroscopy (CRDS) is a promising technique for measuring radicals in ns plasma discharges.

This talk will discuss the fundamentals of CRDS, the pros and cons of implementation in ns pulsed discharges, and recent CRDS measurements in a variety of different ns plasma systems [3-5]. The presentation will discuss implementation of pulsed CRDS and the effect of laser linewidth on the ringdown decay signal as shown in Fig. 1(a). The discussion will also include measurements taken in a repetitive, ns pulse, double dielectric barrier discharge plasmas of the excited metastable state of molecular nitrogen, $N_2(A^3\Sigma^+_u)$ and the low-temperature hydroperoxyl radical, HO_2, generated in a preheated plasma flow reactor as shown in Fig. 1(b).



(a) (b)

Figure 1. (a) Typical cavity ringdown traces for: (1) an empty cell, (2) when an absorber is present in the cell with an absorption lineshape on the order of the laser linewidth, and (3) obtained from data reduction. (b) Comparison of experimental CRDS HO_2 number density obtained in a 2% H_2 – 2% O_2 – 96% Ar plasma and afterglow, initially at T = 600 K to modeling predictions.

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Next steps in high-repetition-rate laser development for Thomson scattering

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We are beginning design of a next generation pulse-burst laser system, aiming for a maximum rep rate of 100 kHz for 1 ms. Pulse-burst laser systems with "fast burst" rep rates in the range of 10 – 20 kHz have been built for the Thomson scattering diagnostics on MST [1], NSTX-U [2], and LHD [3]. Recent measurements on LHD illustrate the new diagnostic capability to capture fast dynamics in the plasma [4, 5].

Pulse-burst laser programming is a type of heat-capacity laser operation. Heat-capacity laser operation is characterized by a burst of pulses is of limited duration, with burst length ≤100 ms and pulse rep rate ≥1 kHz. Waste heat accumulates in the laser rod during the burst. This heat is deposited evenly throughout the rod volume, with very little heat removed during the burst, such that temperature rises evenly across the rod radius. Thus beam distortion due to thermal gradients is small. Heat is removed from rod after the burst, with typically tens of seconds between bursts. Pulse-burst operation of flashlamp pumped Nd:YAG lasers is a cost-effective route to high-rep-rate capability. For Thomson scattering diagnostic application, the typical requirements are 1064 nm, 1-2 J/pulse, ≤30 ns FWHM pulse, with a top-hat beam profile. A major requirement for this next generation laser system is flexibility in burst sequence programs, ranging from 1 kHz for 100 ms to 100 kHz for 1 ms, and a variety of scenarios in between so that operation can be tailored to plasma experiment requirements.

Flashlamp pumping will be used for this next generation laser because it is inexpensive and flexible. We have tested a prototype of a new switch-regulated flashlamp driver that will provide improved flashlamp control at lower cost. We plan to scale up this prototype while additional design issues are addressed:

- Best layout of oscillator and amplifier stages
- Operation of KD*P Pockels at 100 kHz, or selection of alternative
- Optimum pumping chamber for 16 mm final amplifier rod
- Optimum flashlamp pumping spectrum and optimum Nd doping
- Feasibility of ceramic composite Cr-doped Nd:YAG to increase efficiency of flashlamp pumping

We aim to maximize the use of commercial components in this laser system, and are working with InnoLas on development and construction. Our hope is that the design and approach can be adapted to laser systems suitable for a variety of applications, including fusion research and plasma physics, fluid and combustion dynamics, and laser-plasma interactions.

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Experimental study on in-situ calibration of spectral transmission of Thomson scattering in harsh environments

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Incoherent Thomson scattering system determines electron temperature and density from the spectrum of light scattered by electrons. Calibrating the spectral transmittance of the optical system is essential for electron temperature and density measurements. The spectral transmittance of the Thomson scattering system at ITER changes due to various factors. The main factors are the deposition of impurities on the plasma-facing mirror, and the irradiation of the vacuum window, lenses, and optical fibers. Implementation of a mirror cleaning system is also planned to remove impurities and restore the reflectivity of the plasma-facing mirror. The spectral transmittance, which decreases and increases, must be calibrated frequently. Smith proposed an *in-situ* calibration method of the spectral transmittance during the plasma discharge using two lasers with different wavelengths [1]. Yatsuka considered applying this method to the ITER edge Thomson scattering system (ETS) [2]. In ITER, an edge pedestal of several keV is expected to form. As the main probing laser, it was assumed to use the Nd:YAG laser (wavelength 1064 nm), and a suitable second laser was examined. In general, it is important that the Thomson scattering spectra generated by the two lasers overlap and that the two spectra span the entire measured wavelength range. A ruby laser is promising as the second laser. The core plasma of Large Helical Device (LHD) has an electron temperature of 1-10 keV. Therefore, the LHD Thomson scattering system was used to demonstrate the applicability of the *in-situ* calibration technique using Nd:YAG and ruby lasers to the ITER ETS. In the first trial, the Nd:YAG laser and the ruby laser were coaxially injected with a time difference of 11 ms. The electron temperature obtained from the Thomson scattering spectra of Nd:YAG laser and ruby laser alone with known spectral transmittance and the electron temperature obtained by analyzing the two Thomson scattering spectra together with unknown spectral transmittance were in good agreement. At this time, five wavelength channels were used for measurement, one of which was unavailable due to stray light from the Nd:YAG laser, so 9 signals were used for analysis. On the other hand, there were seven unknowns: electron temperature, density, and spectral transmittance of each wavelength channel. After this trial, the time difference between the two lasers was shortened to 0.5 ms, and the filters of the polychromator were improved, including cut-off of stray light. Data were accumulated using 6 wavelength channels (12 data). The presentation will explain the usefulness of the calibration method using two lasers.

This work was performed with the support and under the auspices of the NIFS Collaborative Research Program (NIFS19KLEH083). The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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Laser induced florescence spectroscopy for Hall thruster plasma diagnostics

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Ion-propelled space propulsion is gaining increasing popularity due to its ability to drastically reduce spacecraft propellant mass, with Hall thrusters standing out as one of the most extensively utilized types. In a Hall thruster, plasma is generated and sustained by utilizing crossed electric and magnetic fields, and ions are accelerated outward along a hollow discharge channel by the axial electric field. Due to the fact that thrust is generated by ions, studying ion dynamics holds significant importance in investigating not only physics but also performance of Hall thrusters. Laser-induced fluorescence (LIF) spectroscopy is a highly effective ion diagnostic technique that allows for local measurements of ion velocity distribution functions (IVDFs) with minimal disturbance to the plasma. This presentation focuses on the two-dimensional measurement of ionization and ion acceleration in Hall thruster plasmas using time-averaged LIF spectroscopy as the primary diagnostic tool. The axial and radial IVDFs were measured in two different xenon-fueled Hall thrusters that exhibit distinct magnetic field configurations. In the cylindrical Hall thruster, the magnetic field strength was found to have no correlation with ionization and ion acceleration in the region dominated by an axial magnetic field. The ionization region was located approximately 2/3 of the discharge channel length upstream from the channel exit, while the ion acceleration region extended over a length approximately 3.5 times that of the discharge channel. However, as the radial component of the magnetic field increased to a level comparable to the axial component, both the ionization region and the location of maximum electric field shifted toward the position of maximum radial magnetic field. Simultaneously, the length of the ion acceleration region decreased. Within the region dominated by the axial magnetic field, a notable population of high-speed ions was observed.

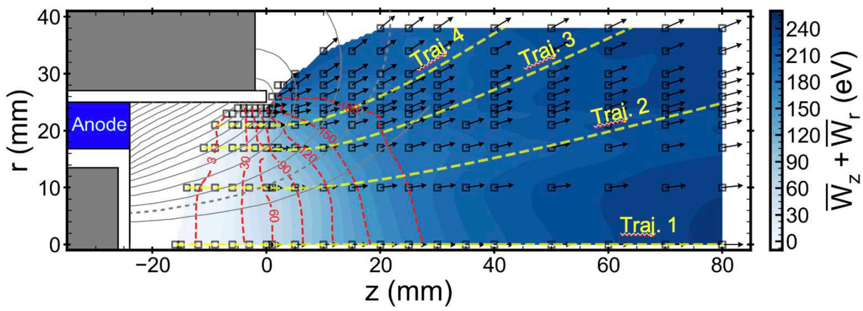

Figure 1. Mean energy (W) and velocity vector of xenon ions measured by time-averaged LIF spectroscopy in a cylindrical Hall thruster. Gray solid lines indicate magnetic field lines.

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Recent development of LIF diagnostics in ASIPP

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In this talk, recent work on laser induced fluorescence (LIF) diagnostics for ion and neutral VDF measurements performed in ASIPP will be presented.

To validate preliminary design of tokamak-relevant LIF diagnostics for edge and divertor helium ash VDF, signal evaluation has been on a diagnostics-test device (LTS) [1], and the obtained signal strength has been extrapolated to tokamak edge and divertor relevant environment with favorable results. These extrapolations only considered the available solid angle and the plasma density between test device and the design scenario with which the LIF diagnostics will be implemented in a tokamak device. With the higher abundance of energetic electrons in the edge and divertor regions, such estimation is considered conservative.

Automated post-DAQ processing of LIF signal via both "conventional" methods and AI-augmented method has been explored for the purpose of online monitoring of the helium ash VDF in a tokamak environment. Both conventional methods and AI-augmented method produced usable results, however trained AI seemed to provide a faster response which is favorable for the purpose of a real-time plasma diagnostics.

Basic mechanisms of the LIF diagnostics, in particular, the limitation of lock-in modulation of the LIF diagnostics was also investigated [2]. De-modulation and thus degradation of LIF signal was observed as the modulation frequency exceed 1/10th of the fluorescence frequency, giving a typical limit to how much we can benefit from lock-in amplification with increasing modulation frequency.

These works, along with other efforts in the ASIPP, are supposed to serve for future the implementation of LIF diagnostics in a future tokamak device, as well as to promote the LIF diagnostics in LTP fields. These other efforts will also be briefly discussed in this presentation.

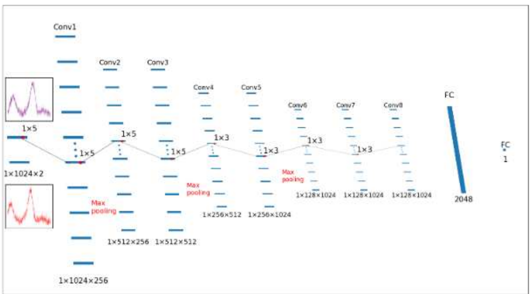

Figure 1. AI augmented online data processing

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Development of a Combined Polarimeter-interferometer system for Non-Inductive Plasma Position Measurement in Long Pulse discharges on EAST

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Vertical position stability plays a crucial role in maintaining safe and reliable plasma operation, vertical displacement events arising from the vertical displacement instability could lead to plasma disruption and even bring damage to the devices. Generally, the vertical position is measured with inductive magnetic coils installed inside the vacuum vessel, but the integration drift effect may exist in steady state or long-pulse plasma operation. Using polarimeter/interferometer to measure plasma vertical position has been tested on EAST [1]. The comparison between non-inductive measurement and inductive flux loops shows a consistent result in a short pulse discharge. In this paper we have compared the non-inductive vertical position measurement by polarimeter/interferometer to that by inductive flux loop in 1056 seconds discharge achieved on EAST in recent campaign. It shows that non-inductive measurement is more robust than flux loop after 200 seconds if integrator is not reset to suppress integrator drift. Real-time vertical position control using non-inductive POINT system is proposed on EAST for following experiment campaign.

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Mid-infrared frequency comb spectroscopy of plasmas

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The development of optical frequency combs has severely revolutionized many fields of physical sciences, including the field of molecular spectroscopy. The combination of wide bandwidth and high spectral resolution offered by frequency combs makes them ideal for sensitive detection of multiple species simultaneously [1], as well as precise line position measurements [2].

In this contribution, recent research activities focused on the development and application of detection methods based on frequency combs in the 3.2 µm spectral region are presented. This includes: (i) The development of a dispersive-type spectrometer known as a virtually imaged phased array (VIPA) spectrometer [3]. Such spectrometers utilize a VIPA etalon to vertically disperse light, while a grating is used for horizontal dispersion of the comb light. An infrared camera captures the resulting two-dimensional images. (ii) The utilization of a home-built fast-scanning Fourier transform spectrometer (FTS) to simultaneously measure the complete rovibrational bands of several species. Both techniques are extensively employed in the investigation of N_2-H_2-CH_4 plasmas at low pressures (a few millibars) typical for plasma based nitrocarburizing processes. Additionally, recent measurements on ammonia formation in N_2-H_2 plasmas using a dual comb spectrometer operating at 9.4 µm are introduced and discussed.

The measurements of highly resolved spectra of complete rovibrational bands employing comb-based techniques provide accurate information about the population and energy distribution along the vibrational ladders of the targeted molecules. The findings and outcomes of these experiments will be thoroughly discussed.

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First Measurements of Electron Temperature and Density Profiles Using Thomson Scattering on the ST40 Spherical Tokamak

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ST40 is a high field low-aspect ratio spherical tokamak built and operated by Tokamak Energy Ltd in the UK [1] with typical operating parameters of $R_{geo} \approx 0.4$ - 0 .5 m, A ≈ 1.6 - 1.9, $I_p \approx 0.4$ -0.8 MA and $B_T = 1.5$ - 2.2 T and a suite of more than 30 plasma diagnostics. In this presentation, we focus on the recent deployment of Thomson scattering on ST40 for the first time, providing real-time electron temperature and density profiles. Cross-validation of preliminary electron temperature and density results with spectroscopic [2] and interferometric measurements is underway and early results show encouraging correlations between instruments. In the next experimental campaign, we will perform a dedicated I_p/B_t parameter scan and an elongation factor scan to further verify system performance.

The Thomson scattering system is based on a 1 J, 9 ns, 100 Hz diode pumped Nd:YAG laser that transits through the ST40 midplane on a chord passing close to the centre column on a common path with an NIR interferometer and adjacent to radial rf interferometer views. The collection optics are located on the same midplane port as the laser flight tube utilising an oblique scattering angle of nominally 160° with a high numerical aperture, up to 0.16 (f/3) on the low field side (LFS). 16 duplexed 15 m and 25 m fused silica fibre bundles transport the scattered signal with a total throughput of >40% to 5 spectral channel polychromators [3]. The data is acquired by an 80 channel 250 MSPS data acquisition system provided by PPPL [4] that outputs 30 individual real-time temperature and density values to the ST40 Plasma Control System per laser pulse. This geometry provides electron temperature and density profiles consisting of 30 spatial points with a resolution of <10 mm on the LFS and an analytical error of <5% in the temperature range of 1 – 10 keV. The measured temperature and density profiles provided by the Thomson scattering system on ST40 will be essential for studying non-inductive current drive and optimising the fusion triple product paving the way to a first of a kind fusion reactor based on the spherical tokamak geometry.

Acknowledgements: The authors would like to acknowledge the contribution of the whole team at Tokamak Energy. Contributions from Princeton Plasma Physics Laboratory (PPPL) were funded by US Department of Energy CRADA NFE-19-07769 between Tokamak Energy Ltd and PPPL.

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Electron density and electric field behavior of a plasma jet with pulse width closing to pulse duration

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Previously, the plasma plume appears with three regimes (dark area next to the nozzle, bright area in the middle, and dim area on the right) is observed when the pulse width of the applied voltage is close to the pulse duration [1]. Based on Thomson scattering and electric field-induced second harmonic (E-FISH) method, the spatial and temporal resolved electron density and electric field in the three regimes are measured to understand such observation [2-4]. It is found that, in the dark regime next to the nozzle, the electric field is relatively low, it has a peak value of about 10 kV/cm, but the electron density is high, it has a peak value of about 4.2×10^{20} m^{-3}. This indicates that the dark regime is like a conductive channel. On the other hand, for the bright regime, the electric field is much higher, which has a peak value of about 17 kV/cm. However, its electron density is significantly lower than that in the dark regime, its peak value is only about 10^{20} m^{-3}. Even in the dim regime, the electric field is higher than that in the dark regime, it has a peak value of about 13 kV/cm. The electron temperature is directly related to electric field, the results indicate that the brightness of the plasma plume at different regime is mainly decided by the electron temperature rather than the electron density.

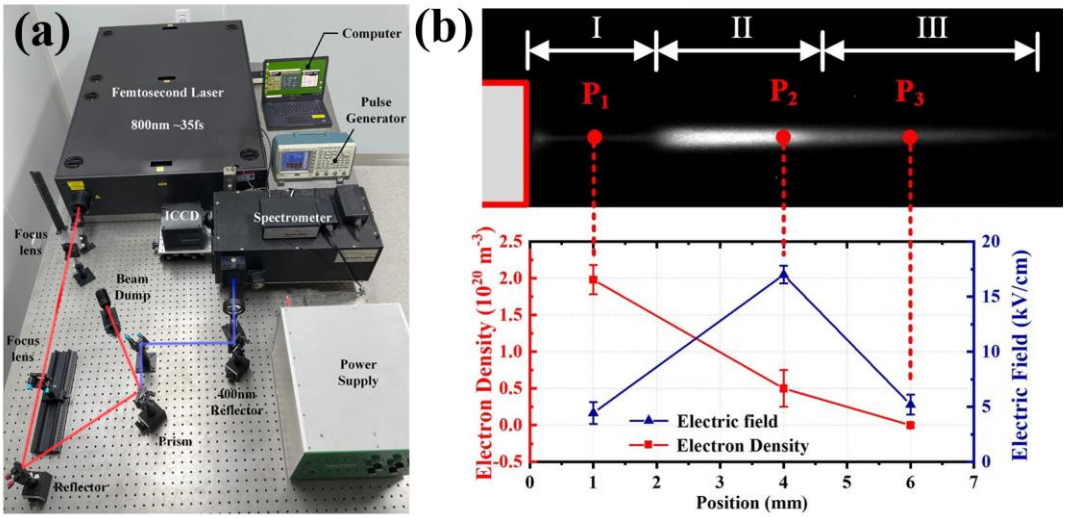

Figure 1. (a) Schematic of electric field induced second harmonic (E-FISH) system. (b)The electron density and electric field at different positions.

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Time-resolved electric field study of an impulse dielectric barrier discharge, in pure ammonia gas by means of induced second harmonic generation

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The aim of this study is to characterize the axial electric field strength that develops in an **impulse dielectric-barrier discharge (iDBD) in pure ammonia**, using the electric-field induced second harmonic generation (E-FISH) diagnostic. A fine management of a conventional Nd:YAG nanosecond laser allows a spatial resolution of **70 µm**, a time resolution of **2 ns** and a sensitivity of about **100 V.cm^{-1}**, matching the **millimetric and nanosecond scales** of the discharge. Indeed, the latter is driven by a 250 µs-periodic symmetrical applied voltage, inducing a discharge only during the transient regime (< 1µs) thanks to planar and symmetrical dielectrics. The time-evolution of the axial electric field in discharge has been studied over three sets of experimental parameters: the applied voltage, the gas pressure, and the gap where occurs the plasma discharges. On the one hand, compared to the E-FISH measurements in a non-breakdown condition (*i.e.* without discharge), those with plasma unveil a **counter-field (E_{cf})** whose variations oppose the electric field resulting from the applied voltage to the electrodes, **regardless of the experimental condition studied**. This counter-field results from **surface charged species accumulation** on the dielectric plate arising after the previous discharge. On the other hand, the axial electric-field measured in the gap midway depicts several trend according to the studied conditions. Finally, the next step would be to study the time-evolution of the axial electric field across the gap, since the issue of residual bulk charges remain [1]. Overall, these results are a first step of understanding the physics of such an iDBD, particularly in pure ammonia, throughout the E-FISH diagnostic.

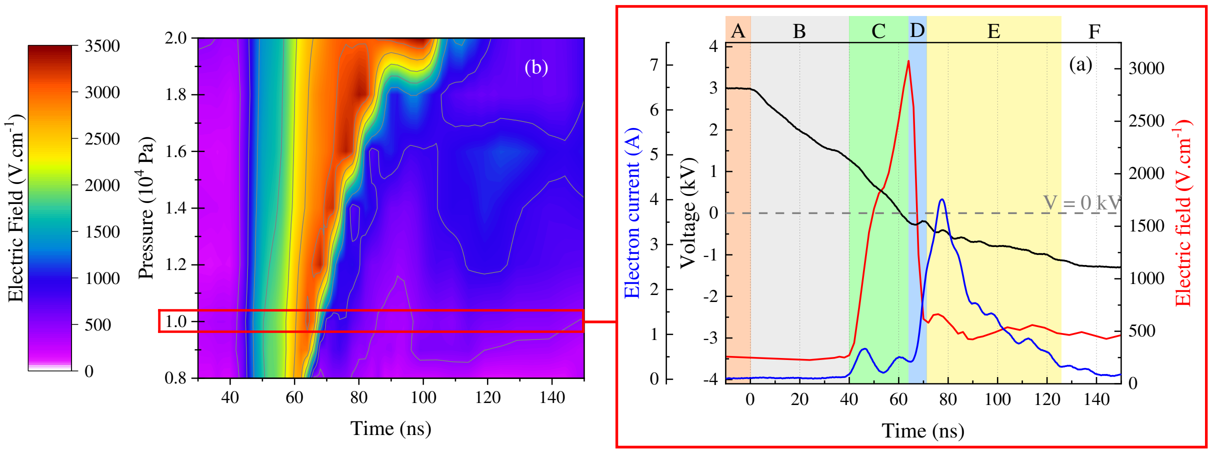

Figure 1. (a) Cartography over time and gas pressure, from 0.8 to 2.0 × 10^4 Pa, during the positive to the negative transient polarisation of upper electrode. (b) Focus of the electric field (red curve) and electrical (black and blue curves indicating respectively applied voltage and current variations) measurements for the 10^4 Pa gas pressure condition. Pure ammonia, applied voltage 6 kV_{pp} and gap 3 mm.

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Single shot, non-resonant, four-wave mixing laser diagnostics for low temperature plasmas

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We experimentally demonstrate the use of single shot coherent Rayleigh-Brilloui n scattering (CRBS) for the measurement of the velocity distribution function (VDF) o f neutral species in a glow discharge, from which macroscopic quantities, such as the flow velocity, density and translational temperature can be extracted. In CRBS, a four-wave mixing technique, a high energy optical lattice of precisely tailored chirped freq uency interacts with the medium, such as neutral or ionized gas. The variation of the CRBS signal intensity at different optical lattice phase velocities allows for the restor ation of the VDF and the resulting CRBS lineshape is a direct mapping of the mediu m's VDF. CRBS has already been demonstrated to be the coherent analogue of sponta neous Rayleigh-Brillouin scattering and has already been demonstrated in the measure ment of nanoparticles in an arc discharge[1].

Single-shot CRBS is applied to measure simultaneously the temperature and de nsity of neutral species in a weakly ionized DC glow discharge plasma. The DC glow discharge is generated at a pressure range of 15 Torr using xenon gas. For this appli cation, we employ a newly developed dual-color CRBS scheme[2,3] where the frequency doubled 532 nm beam serves as a probe beam to achieve a higher signal-to-noise rat io at the low-pressure environment versus the most employed single color CRBS appr oach. The temperature and density of neutral xenon particles inside the DC glow disc harge is evaluated simultaneously by analyzing the resolved single-shot CRBS lineshap es and is characterized as a function of the discharge current, successfully demonstrati ng the use of CRBS in a partially ionized plasma environment. A simulation model o f the glow discharge is also developed and there is good agreement between the simu lation and the experimental measurements in the glow discharge.

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Time-resolved laser-induced fluorescence spectroscopy with a continuous-wave diode laser for the investigation of ion sheath dynamics

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Laser-induced fluorescence spectroscopy (LIF) is an optical technique to measure the density and movement of target particles without disturbance. In low-temperature plasma studies, the LIF method has been utilized to measure ion velocity distribution functions (IVDFs) in and at the edge of plasmas [1]. To investigate the dynamic behaviors of ions in the ion sheath, where an AC bias voltage is applied to the electrode, the LIF system must possess a time resolution shorter than the AC-voltage period. In this study, we developed a time-resolved LIF system with a continuous-wave diode laser with a time resolution of less than 1 μs. The performance of the LIF system to measure the temporal evolution of IVDF is reported in the presentation.

In this study, we diagnosed an ECR plasma in Ar gas at 0.05 Pa. The LIF target species was metastable Ar ion (Ar^{+m}). An amplitude of the excitation laser at 668.6 nm ($3d^4F_{7/2} \rightarrow 4p^4D_{5/2}$) was modulated at 20 MHz by an EOM. A PMT detected the fluorescence through a bandpass filter at 442.6 nm ($4p^4D_{5/2} \rightarrow 4s^4P_{3/2}$) [2]. The temporal evolution of LIF signal intensity was recorded through a phase-sensitive detector (PSD) with an output bandwidth of 2 MHz (Fig. 1(a)). We applied an AC sinusoidal voltage at 100 kHz with an amplitude of 20 V and an offset of −11.23 V (= $V_f + V_{DC}$) to a bias plate placed in the ECR plasma. The excitation laser propagated perpendicular to the bias plate and passed its hole at the center. The detection optics was focused on the laser beam axis at 1 mm from the bias plate. Figure 1(b) shows the temporal evolution of IVDF plotted with a bias-voltage waveform. We found that the ion velocity does not follow the bias voltage (delay for ~1 μs) in t = 0~2 μs. This result suggests that the time-resolved LIF developed in this study can contribute to plasma science and technology by investigating the dynamic behavior of particle (ions, excited species, radicals…) in plasmas.

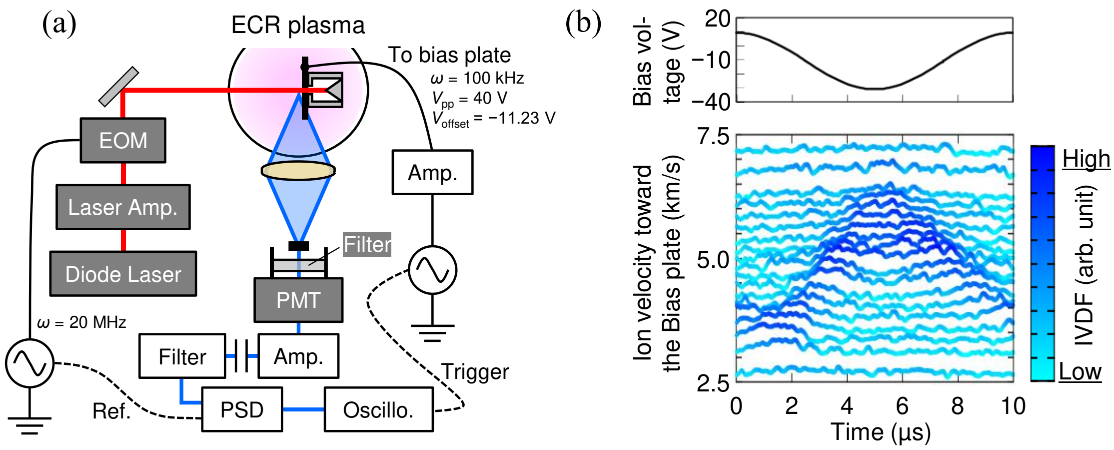

Figure 1. (a) Schematic diagram of time-resolved LIF system. (b) Temporal evolution of IVDF measured at 1 mm from the bias plate plotted with the bias-voltage waveform at 100 kHz.

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Atomic Oxygen Behavior in Sub-atmospheric Pressure Pulsed Corona Discharge

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Atmospheric pressure plasma can be applied to various fields. Plasmas in sub-atmospheric pressure, which is slightly reduced from the atmospheric pressure (namely 0.1-0.9 atm), can extend the radical lifetime with the radical production equivalent to atmospheric plasma. This leads to an increase in radical flux without compromising the diversity of the target[1]. In this study, we investigated the behavior of atomic oxygen, one of the most important oxidative radicals, in sub-atmospheric pressure pulsed discharges.

Ground state atomic oxygen O($2p^4\ ^3P$) in sub-atmospheric pressure pulsed O_2 discharge was measured using conventional TALIF technique. The electrodes consist of a stainless needle anode and a stainless sphere cathode covered by a glass hemisphere. Pure O_2 was flowed in the reactor at a pressure of 20–90 kPa. A 300-ns-duration pulsed high voltage was applied at 10 pulses/s to the needle. The discharge energy was adjusted to approximately 3 mJ. In the TALIF measurement, a 226-nm pulsed dye laser excites the atomic oxygen, and the 845 nm fluorescence was detected by a photomultiplier tube after passing optical filters. The observed volume was W5 × D6.25 × H0.005–0.01 mm^3, where the height was confined by the vertical height of the laser. The absolute amount of atomic oxygen was calibrated by Xe-TALIF[2].

Temporal profiles of atomic oxygen at 20–95 kPa near the cathode are represented in Fig. 1. Figure 1 exhibits the extension of the atomic-oxygen lifetime by decreasing pressure, whereas the peak O density was not proportional to the O_2 pressure. Figure 2 represents the peak O density at immediately after discharge. According to Fig. 2, there is a local maximum of peak O density near 50 kPa. The relative O yield was estimated by the time integral of O density; the estimated O yield resulted in a local maximum of O yield at 50 kPa, which was 6 times larger than that in atmospheric pressure. In the sub-atmospheric pressure range (20–70 kPa), the O density near the cathode was significantly larger than that near the anode. The experimental results suggest that the specific production of atomic oxygen near the cathode arises from low energy electrons which does not contribute to discharge emission.

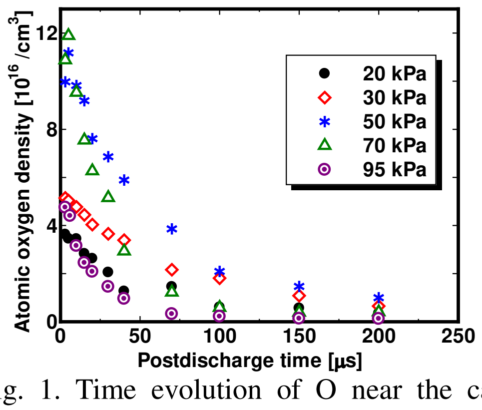

Fig. 1. Time evolution of O near the cathode.

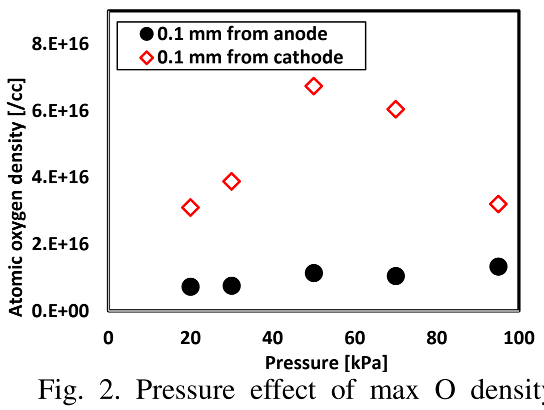

Fig. 2. Pressure effect of max O density.

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Commissioning and first results of the 174 GHz collective Thomson scattering diagnostic at Wendelstein 7-X

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Collective Thomson Scattering (CTS) diagnostics measure the scattering spectrum of monochromatic incident radiation off collective fluctuations in the plasma. In this contribution, we present the first results from the upgraded CTS diagnostic at Wendelstein 7-X (W7-X) operating in the frequency range between 172 and 176 GHz. This frequency range allows minimizing noise originating from the electron cyclotron emission in the plasma. Consequently, the good signal-to-noise ratio allows for fast ion measurements or bulk plasma parameters measurements with higher temporal resolution compared with the previously used 140 GHz system.

In this contribution, we present the first results from the CTS measurements in the W7-X plasma, as well as a characterization of the 174 GHz CTS receiver.

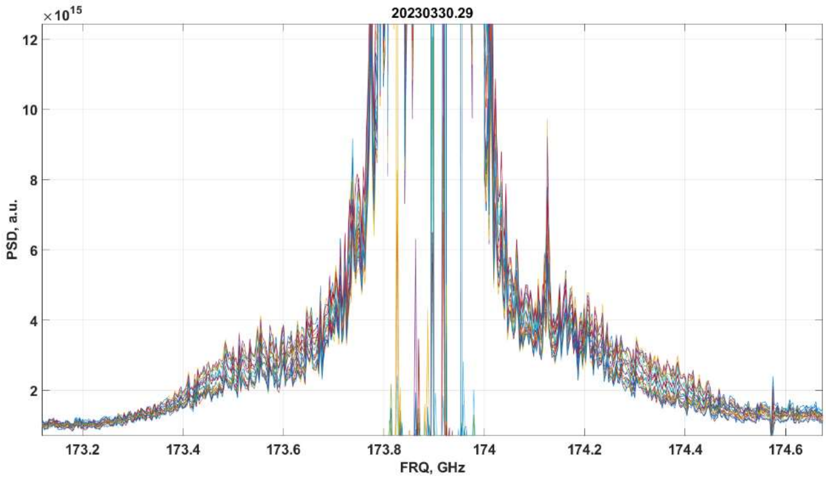

Figure 1. Example of thermal CTS spectra from W7-X discharge 20230330.29 with 3ms exposure time. Here a total of 22 thermal CTS spectra are presented, covering the plasma discharge phases with and without ICRF heating.

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Laser-Plasma Instabilities of Frequency Doubled Pulses at the Extreme Light Infrastructure's L4 Beamline

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Laser Plasma Instabilities (LPI) are one of the principal problems in laser-driven inertial confinement fusion (ICF) schemes. When these instabilities grow, plasma becomes turbulent, scattering laser energy and producing hot electrons that can pre-heat a compressing ICF target [1]. Thus, minimizing LPI effects is of significant concern when designing laser-based inertial fusion energy facilities. ICF systems generally employ short wavelength lasers, in the ultraviolet range, as LPI effects scale strongly with wavelength. As such, instabilities of particular concern, such as Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS), and Two Plasmon Decay (TPD), have been well characterized in the UV regime [2]. However, high frequency light comes with some significant drawbacks. First, converting to the higher frequencies (3ω of Nd:glass lasers) loses laser energy that can otherwise be irradiated on target. Second, it can inflict significant damage to the optics in the laser chain. Compared to optics for green light (2ω of Nd:glass lasers), developments in UV optics have been slow to achieve durability to the higher photon energies associated with UV light. Recent literature indicates that 2ω light has promise as an ICF driver but these LPI effects have a lower threshold compared to 3ω [3,4]. This calls for further study of LPI with green light. To this end, we have built a backscatter diagnostic to measure SRS, SBS, and TPD at the Extreme Light Infrastructure's L4n beamline. This work details measurements made with this diagnostic of laser-plasma instabilities of a 527 nm laser (intensities ranging from 0.5×10−13 W/cm^2 to 1.6×1015 W/cm^2) with a plane solid target during commissioning of the beamline.

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Prospective of multiple stages mJ energy level and ultrashort pulses OPA generation at Extreme Light Infrastructure-Nuclear Physics (ELI-NP)

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In the last decade, there was a significant progress in the femtosecond high power laser technology, which materialized in a couple of PW class laser systems that were worldwide installed. High Power Laser System (HPLS) of ELI-NP (Extreme Light Infrastructure - Nuclear Physics) research infrastructure delivers up to 10 PW laser pulses in two beamline arms. Output beams of 1 PW/1 Hz and 100 TW/10 Hz are available too [1].

Femtosecond laser pulses with more than 10 mJ energy at 1300 nm wavelength are necessary for experiments of dark matter search using four wave mixing, proposed at ELI-NP [2]. High-energy near-infrared (NIR) femtosecond laser pulses can be obtained in multi-stage optical parametric amplification (OPA) systems with nonlinear crystals pumped by femtosecond pulses at 800 nm. BBO crystals represent a good solution for NIR fs laser pulses OPA [3]. Because of intrinsic growth issues, the clear aperture of BBO crystals is restricted to 20 mm diameter. Due to limitations imposed to the LIDT fluence, the energy of amplified 1300 nm fs laser pulses in BBO crystals is restricted to few-mJ. For the generation of more than ten-mJ 1300 nm fs laser pulses, nonlinear crystals with larger than 50 mm clear aperture are necessary. 100-mm size YCOB crystals with good nonlinear optical properties can be grown [4]. The type I collinear OPA at 1300 nm in *xy* plane of YCOB crystals, has some significant features which contribute to a broad parametric gain bandwidth, an increased parametric interaction length and a high conversion efficiency, allowing an efficient amplification of 20-fs signal laser pulses.

A tiny fraction of the 100 TW Ti:sapphire femtosecond laser pulses is focused into a sapphire plate [5] to generate seed pulses by white-light generation in the NIR spectral range. The wavelength selection in the 1300 nm spectral range occurs in the first BBO OPA stage by adjusting the phase-matching angle in the crystal. The seed energy is boosted up to more than 10-mJ in the final OPA stage using a large diameter YCOB crystal, pumped by 800 nm femtosecond laser pulses of several-ten mJ – 100 mJ energy at ~100 GW/cm^2 intensity. The timing synchronization between seed and pump pulses play a critical role and must be achieved using precise delay lines with femtosecond temporal resolution.

In this contribution, the preparatory experimental set-up with multiple OPA stage configurations using different nonlinear crystals (BBO and YCOB) and the key experimental challenges will be discussed.

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Collective Thomson scattering measurements of electron temperature and electron density in laser-driven EUV plasmas during the laser irradiation

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Plasma temperature (T_e) and density (n_e) are the critical physical properties of laser produced plasma (LPP) to reveal the ablation dynamics, energy transport, and hydrodynamic evolution. In the time window during the drive laser irradiation, experimental data are very scarce so that the early-time LPP dynamics remain poorly understood, while such knowledge is of great importance for the extreme ultraviolet (EUV) lithography. In this talk, we demonstrate collective Thomson scattering (CTS) is a robust tool for characterizing T_e/n_e spatio-temporal evolutions in LPPs at this early stage, for low-Z to high-Z target materials. We investigated LPPs generated from planar solid targets of several metals using a 1.064 µm Nd:YAG laser with a power intensity ranging from 10^9 to 10^{10} W cm^{-2} and a spot size of approximately 550 µm. The study was focused on the dynamics of LPPs during the 7 ns pulse duration (FWHM) of the drive laser. The results demonstrate LPP undergoes a one-dimensional isothermal expansion during and immediately after the drive laser pulse. A comparison between experimental data and the radiative hydrodynamic code STAR shows good agreement. This enables the use of simulation results to predict and understand the dynamics of LPP and plasma-laser interactions in the region close to the target. The combined study of early-time LPP using both experimental and computational approaches provides novel insights into LPP behaviors and offers the potential for optimizing existing EUV-LPP sources.

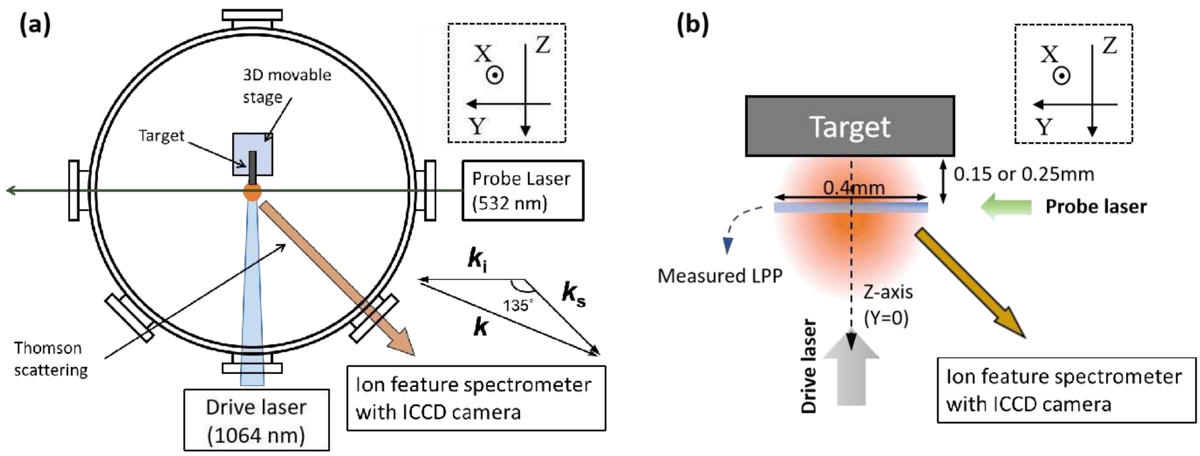

Figure 1. (a) Schematic illustration of the experimental arrangement. (b) Zoomed-in view of the region close to the target.

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Coherent anti-Stokes Raman scattering on N_2 and CO_2 in a (sub-)atmospheric pressure plasma

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In molecular plasmas at sub-atmospheric pressures (~100 to 1000 mbar), the vibrational degree of freedom of the electronic ground state molecules can contain a significant amount of energy. Therefore, detailed knowledge about the corresponding vibrational distribution functions is crucial to understand the dynamics of the system. While molecules with dipole allowed vibrational transitions can readily be measured by quantum cascade laser absorption spectroscopy, this is not possible for homo-nuclear molecules like nitrogen. To circumvent the apparent limitation, in this work coherent anti-Stokes Raman scattering is employed to measure the vibrational distributions of nitrogen and carbon dioxide. The method was previously demonstrated for pure nitrogen [1,2] and is now extended to carbon dioxide. By an appropriate choice of the pump and probe wavelength (see Figure 1), both molecules can be probed simultaneously, making it possible to investigate the interaction between them. Further, the use of pulsed Nd:YAG and dye lasers to produce the CARS input beams results in a time resolution in the order of 10 ns. The spatial resolution – determined by a folded BOXCARS phase matching geometry – is in the order of 100 µm in the direction perpendicular to the traveling direction and 5 mm along the beam paths. An important aspect in the analysis of CARS spectra obtained in transient plasmas is the non-equilibrium distribution of the vibrational modes. Its consequences for the data analysis are discussed.

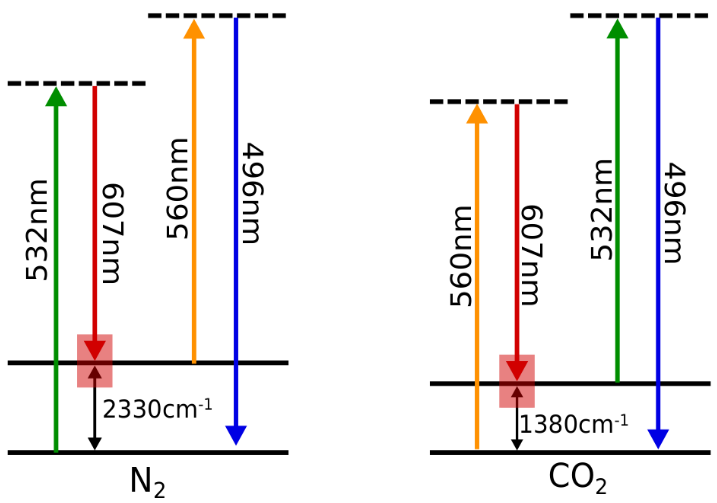

Figure 1. CARS scheme for the simultaneous measurement of vibrational excited nitrogen and carbon dioxide molecules.

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Development of Event-triggered Thomson Scattering System for Measurement of Electron Temperature/Density Profiles during Abrupt Phenomena

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A laser Thomson scattering system in Heliotron J has two Nd:YAG lasers with a repetition rate of 50 Hz, to make measurements at equal intervals of 10 msec with alternating injections[1]. Thus, it is difficult to observe abrupt phenomena in plasma e.g. pellet injection, L-H transition, MHD events. We cannot know in advance when that phenomena will occur. In order to make the Thomson scattering measurement during the abrupt phenomena, event-triggered Thomson scattering measurement system (Event trigger system) is strongly required, i.e. laser should be injected synchronously with the onset of the event. Here we report on newly developed Event-triggered Thomson scattering measurement system in Heliotron J. The event trigger system is applied to pellet injection experiments. A strong increase in the Hα-line signal due to pellet ablation is used to generate the event trigger by a DG535 digital delay/pulse generator. After trigger, a PIC18F2550 micro-controller makes two triggers to control the flashlamp and the Q-switch respectively. The delay time of the flash lamp trigger is ~70 μsec which is due to processing delays in the PIC18F2550 and it takes 250 μsec to reach the maximum intensity of the flash lamp, as shown in Fig. 1(A). Thus, the minimum delay time from the event trigger is ~320 μsec which is shorter than typical ablation time of 0.5 msec in the Heliotron J experiment. By using this system, the density profiles during the pellet ablation were successfully observed for the first time in the Heliotron J, as shown in Fig. 1(B). At 0.5 msec from the start of pellet ablation, symmetric increase in the density with respect to magnetic flux surfaces is observed in the region of r/a > 0.3. At 1.0 msec, the core density increase is observed, and the profile shape changed from a hollow to a peak.

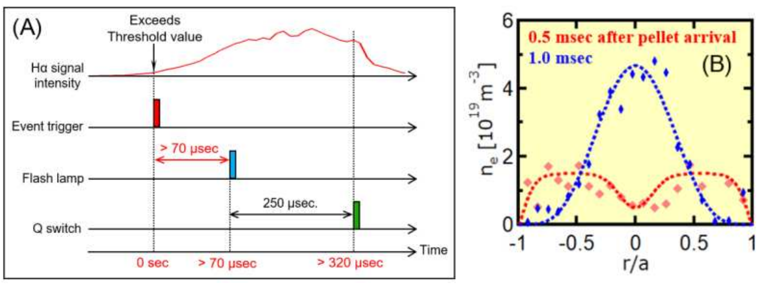

Figure 1 (A) Timing chart of control signal output by Event trigger system, (B) electron dens ity profile during pellet ablation.

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Double-pass Thomson scattering measurements in TST-2 Ohmic heated tokamak plasmas

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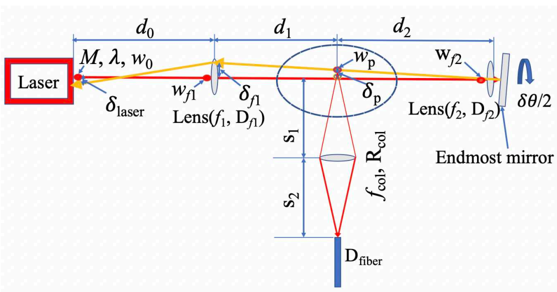
Most of electron heating mechanism can induce anisotropy in electron distribution in a specific condition, e.g. in early phase of ohmic heating, lower-hybrid wave heating, heating by electron cyclotron range of frequency wave, and so on. Therefore, measuring the electron temperature anisotropy can contribute to the understanding of the basic mechanism of electron heating. Double-pass Thomson scattering (TS) diagnostics offers the measurement of the anisotropy since the scattering angles are different between the forward and backward beam propagation. Here, a double-pass TS optical configuration was theoretically designed based on an optimization procedure [1], by tuning four parameters, d_0, d_1, d_2, and δ_p/a, where a is a plasma minor radius (Fig. 1) to a limitation from a TST-2 environment and available optical components. We experimentally confirmed the designed configuration by the measurement of forward and backward laser beam propagation (i.e., beam radius along the beam propagation). As a result, the safety requirement of the YAG laser device was satisfied, namely the residual backward power returning to the laser was less than about 0.2% (12 mW) of the laser output power. The double-pass TS configuration was applied to measure the temperature anisotropy in the Ohmic heated plasmas in TST-2 with various gas feeding amount and various loop voltages. The temperature anisotropy varies between (1.2 ± 0.5) and (-0.1 ± 0.2) in the edge region and between (0.01 ± 0.1) and (0.1 ± 0.08) in the central region under various gas feeding amount, as well as between (0.8 ± 0.4) and (0.4 ± 0.6) in the edge region and between (0.03 ± 0.04) and (-0.2 ± 0.05) under various loop voltage. It was found that the temperature anisotropy is qualitatively proportional to the ratio of electron temperature to electron density (T_e/n_e).



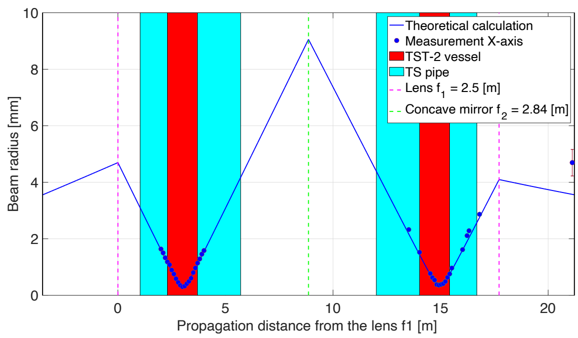


Figure 1. Schematic configuration of double-pass scheme (left), measurement and theoretical calculation of the beam radius along the double-pass optical path (right).

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Real-time capabilities of laser aided plasma diagnostics at TCV

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The Tokamak à Configuration Variable (TCV) employs a flexible digital control system for the exploration of multiple control solutions [1]. Accurate real-time measurements are crucial in identifying the plasma confinement state to better constrain real-time predictive models. Two real-time available laser-aided plasma diagnostics at TCV provide information on the electrons' properties: an incoherent Thomson Scattering (TS) diagnostic and the Far-InfraRed interferometer (FIR).

Incoherent Thomson Scattering diagnostics use the elastic scattering process of photons by free electrons. In the limit of probing length scale smaller than the Debye screening length scale, scattered photons are imprinted by the thermal properties of the electrons. At TCV, three Nd:YAG Q-switch lasers deliver 60Hz repetition rate pulses at 1064nm to induce TS. Scattered photons spectra is analyzed by 4 or 5-channel polychromators, the electron temperature is estimated by the ratios between spectral channels and assuming a Maxwell-Boltzmann (thermal) velocity distribution. The electron density is then obtained from the measured signal intensities. TCV's TS diagnostic has undergone several upgrades to improve spatial coverage [2] and extend sensitivity to electron temperatures down to ~1eV [3]. A recent upgrade introduced 10 low-temperature polychromators to complete the vertical spatial coverage within the TCV vacuum chamber. Additionally, a real-time acquisition system has been commissioned, and real-time TS analysis has been improved to provide electron temperature/density estimations in less than 1ms after data arrival. This real-time analysis was validated by the legacy post-shot analysis.

The FIR interferometry diagnostics estimate the line-integrated electron density from the phase shift induced by passage of electromagnetic light-waves through the plasma. At TCV, an optically pumped CH2F2 laser in a Mach-Zehnder heterodyne configuration probes the plasma along a radial array of 14 vertical chords. A real-time compatible acquisition system has been commissioned to acquire the sine-cosine decomposition of the phase shifts, enabling digital fringe counting algorithms. Digital fringe counting generally exhibits increased robustness to fringe jumps compared to legacy analog trigonometric function conversion.

By employing these laser-aided plasma diagnostics in real-time at TCV, accurate and timely measurements of plasma properties are now available, that are essential for plasma control and modeling advances.

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Development of a multifunctional real-time data processing system for interferometers on EAST

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Due to the disadvantages of the old interferometer with high voltage drive, such as instability during long-pulse discharge and unsafety of personnel operation, interferometers for electron density measurements are gradually being replaced by interferometers built with smaller, more stable sources.

In the latest campaign of EAST experiments, two new interferometers were installed, a dispersion interferometer (DI) based on a Carbon Dioxide laser and a solid source interferometer (SSI) based on microwave multiplier sources. In order to make them available for the Plasma Control System (PCS) system, each of them needs to be provided with a real-time processing system to extract the detector output signal and afterward obtain the electron density information through signal processing.

To obtain interferometer data quickly and reliably, a unified hardware template was applied to both interferometers. Three main parts are included in this hardware template - digitization, digital signal processing, and output modules. In particular, the digitization section uses a multi-channel Analog-to-Digital Convertor (ADC) to acquire the signals that need to be calculated. The digital signal processing part is implemented by an FPGA, which is the hardware basis of this multifunctional template that can be used for multiple interferometers. This section includes two main parts, wrapped density signal extraction and signal unwrapping. For DI it is a phase calculation based on the intensity ratio, while for SSI it is a phase calculation by means of FFT or phase demodulation. Both computational approaches form independent IP cores to build systems quickly, while these IP cores provide parameter interfaces to adapt to different application scenarios. The output module provides a variety of data transmission methods, including fiber optic transmission and Digital-Analog-Convertor based analog transmission, to interface with PCS or other subsequent systems.

This data processing system template has been applied to each of the above two interferometers and valid data were obtained in a recent EAST experiment campaign. It demonstrates the usefulness of the template and provides a reference for the design of data processing systems on future devices.

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Development of a Collective Thomson Scattering Diagnostic System on SNU X-pinch device

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The Collective Thomson Scattering (CTS) diagnostic system has been developed for the X-pinch device at Seoul National University [1]. The system is designed to measure various parameters of plasma jets, including ion temperature and plasma flow velocity. For the flow velocity measurement, the second harmonic Nd:YAG laser (1.0J, 8ns, 532nm) and the collection optics are oriented in order to ensure the scattering vector is aligned with the flow direction. The collection optics have been optimized to maximize photon efficiency. Due to the requirement of high spectral resolution for the diagnosis of CTS spectra, the spectrometer is designed with a resolution of 0.004 nm/pixel. In addition, rotational Raman scattering is measured for wavelength calibration of the spectrometer. The CTS diagnostic system will contribute to a deeper understanding of X-pinch plasma dynamics and the development of advanced High Energy Density Plasma (HEDP)-based technologies.

[1] Jonghyeon Ryu, *et al.,* Rev. Sci. Instrum **92** (2021) 053533.

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Quantifying uncertainties for a coherent Thomson scattering system with Bayesian sensitivity analyses on the synthetic data of X-pinch plasmas

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An X-pinch device has been developed to investigate dynamics of the high energy density plasmas during an X-pinch discharge [1]. Coherent Thomson scattering (CTS) systems have provided plasma properties such as electron density, ion and electron temperature as well as jet velocity in other similar devices [2, 3]. We perform sensitivity analyses on the density, temperature and velocity of the X-pinch plasma jet to determine uncertainty levels associated with the expected measurements from the to-be-built CTS system. By utilizing a forward model within the Bayesian analysis framework, synthetic data are generated to perform the sensitivity analyses. We further investigate effects of the instrumental broadening and the electrical noise on the uncertainty of the inferred parameters. With the sensitivity analyses on the model parameters, it is possible to identify required improvements for the CTS system such that the parameters can be reliably measured. [4]

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Development of correlation ECE system for electron temperature fluctuation measurement in LHD

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Correlation-ECE (C-ECE) is a standard method for investigating turbulence driven transport. This method allows electron temperature fluctuations that contain information on turbulent transport and independent thermal noise. The turbulence feature is extracted from a correlation analysis from two close locations. The A C-ECE system is utilized on the large helical device (LHD) to measure emission within the frequency range of 74-79.6 GHz. This system employs the spectral decorrelation method and serves as a collective Thomson scattering diagnostic receiver in the LHD [2]. The C-ECE receiver system is comprised of a filter bank system with 32 band-pass filters and a fast digitizer system operating at a sampling rate of 12.5 GHz in the intermediate frequency (IF) stage. This study presents initial experimental results on temperature fluctuation spectra in the LHD, obtained through the C-ECE system using a coherency-based analysis method [3]. An MHD mode at 5 kHz is excited from the onset of neutral beam injection in a magnetic probe, and coherence spectra are obtained from two C-ECE receiver systems. The temperature fluctuation results are derived from the coherence spectrum after bias removal and indicate a level of approximately 3% in the frequency range of 0 to 400 kHz. Further investigations will be conducted to explore drift wave turbulence activities and reconstruct the radial profile of temperature fluctuation in the LHD using the C-ECE receiver systems.

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The Co-located arrangement of microwave imaging diagnostics on EAST tokamak

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Electron Cyclotron Emission Imaging (ECEI) and Microwave Imaging Reflectometry (MIR) diagnostics systems have been applied on EAST for 2D temperature and density fluctuations imaging. Both of ECEI and MIR require large-aperture quasi-optical systems to obtain high spatial resolution. Here the details of ECEI/MIR co-located configuration are presented. This arrangement will not only help to save limited window resources but also benefit to the simultaneous measurements of density and electron temperature fluctuations at same toroidal position, which will provide advanced research opportunities for electron heat transport and other important issues. Here the details of the co-located ECEI/MIR configuration on EAST tokamak are presented, including the layout, imaging optics combination, beam-splitting arrangement and the preliminary results.

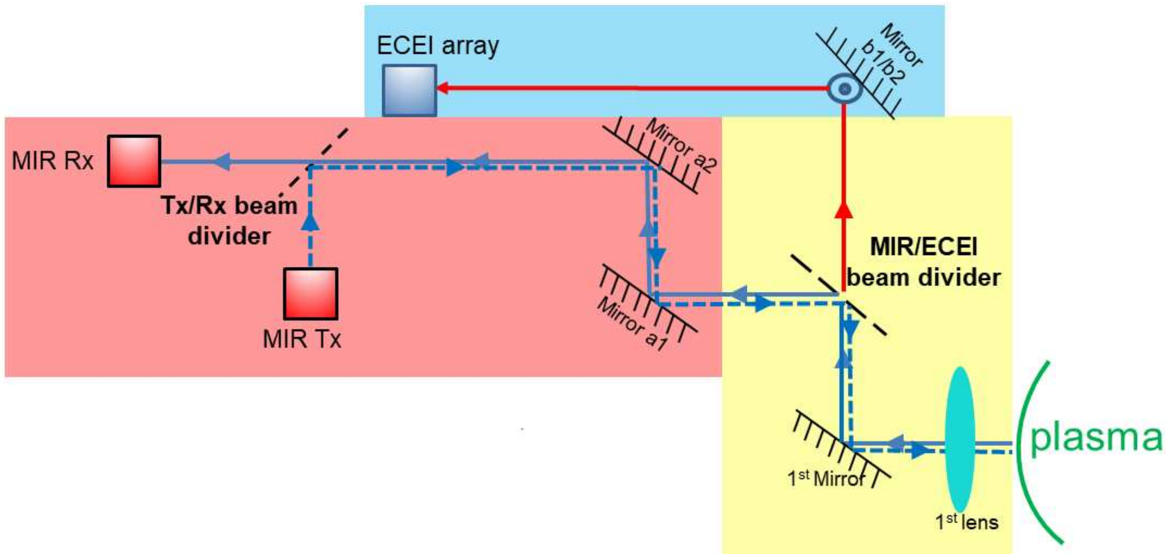

Figure 1. The optical scheme of MIR/ECEI combination.

[1] Y.L. Zhu, *et al.,* IEEE Transactions on Plasma Science **47** (2019) 2110–2130

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Physical design, fabrication and output power optimization of a 2.5 thz CH3OH laser

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A continuous and stable THz source is an important guarantee for plasma electron density and current density measurements by a polarimeter/interferometer. An 11-channel polarimeter/interferometer at 0.69THz has been operating on east for nearly a decade. A CW optically pumped high power 2.5THz CH3OH laser has been developed for future fusion plasma diagnostics. Its weaker refraction effect, smaller spot size and larger output power provide more possibilities for the arrangement of detection channels. Routine testing and optimization of the laser was done (including the gas pressure and flow rate, the wall temperature and the rate of buffer gas). In particular, the output coupling is optimized in detail to seek a balance between output power and beam quality. Qualified terahertz output was obtained, and this source will have applications in the immediately following countertop test of interferometer and polarimeter.

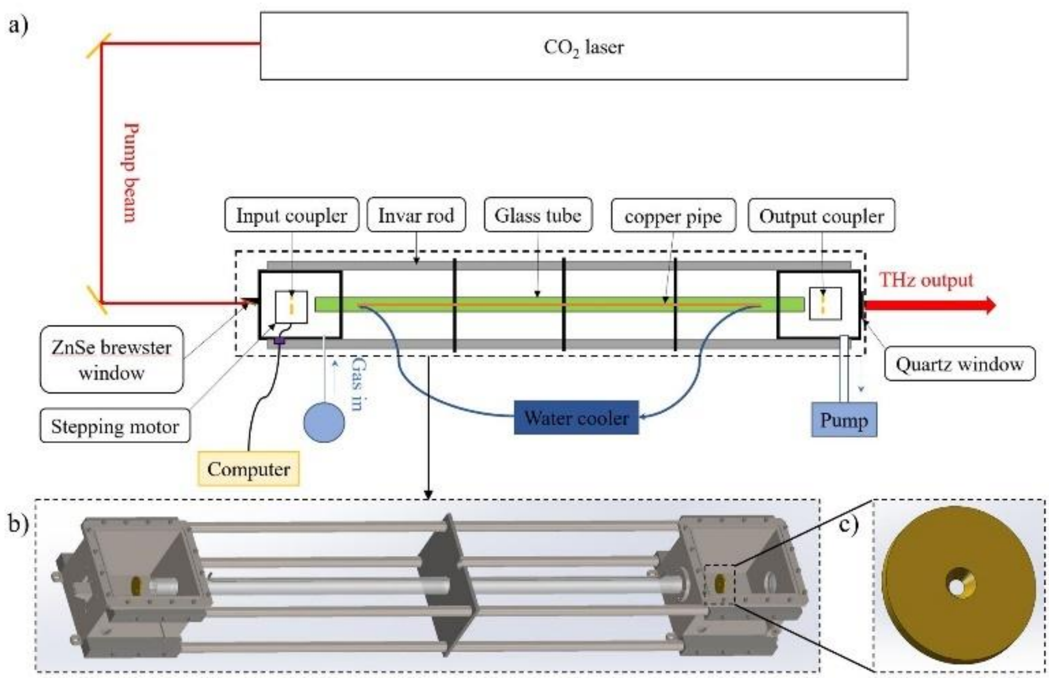

Figure 1. a) Diagram of CO_2 laser pumped methanol gas laser. b) Terahertz laser resonant cavity. c) Centric-hole gilded copper mirror.

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Preliminary results of a combined interferometer using 340 GHz solid state source and a HCN laser on ENN's XuanLong-50 (EXL-50)

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A millimeter wave solid state source - far infrared laser combined interferometer system (MFCI) consists of a three-channel 890 GHz hydrogen cyanide (HCN) laser interferometer and a three-channel 340 GHz solid state source interferometer (SSI) is developed for real-time line-integrated electron density feedback and electron density profile of the EXL-50 spherical tokamak device. The interferometer system is a Mach-Zehnder type, with all probe-channels measured vertically, covering the plasma magnetic axis to the outermost closed magnetic plane. The HCN laser interferometer uses an HCN laser with a frequency of 890 GHz as a light source and modulates a 100 kHz beat signal by a rotating grating, giving a temporal resolution of 10 μs. The SSI uses two independent 340 GHz solid-state diode source as the light source, the frequency of the two sources is adjustable, the temporal resolution of SSI can reach 1 μs by setting the frequency difference of the two sources at 1 MHz. The main optical path of the two interferometers is compactly installed on a set of double-layer optical platform directly below EXL-50. Dual optical path design using corner cube reflectors avoids the large support structures. At present, the phase noise of the HCN interferometer and SSI is 4.1 deg and 2.1 deg respectively，corresponding to a line-integrated electron density of 0.75×10^{17} m^{-2} and 1.5×10^{16} m^{-2} respectively, 6-channel measuring result was obtained by the MFCI system, and the highest density measured is about 1×10^{19} m^{-2} [1].

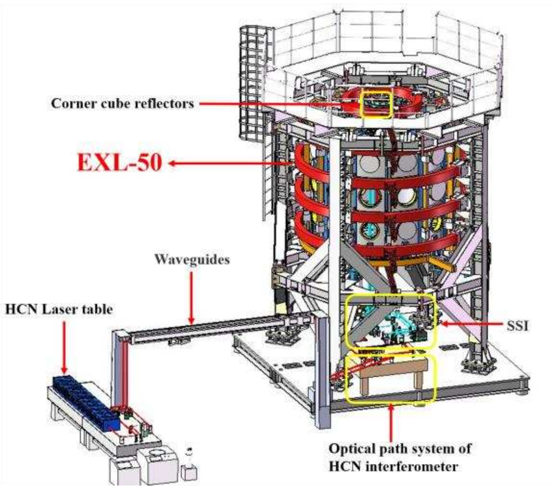

Figure 1. The MFCI system on EXL-50.

[1] Jiaxing XIE et al 2022 Plasma Sci. Technol. 24 064004

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Simulation of fringe normalization for analyzing phase shift in plasma diagnostic using laser interferometry

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In plasma diagnostics using interferometry, the phase shift caused by the plasma in the fringes is extracted to determine the plasma density. To extract the phase shift from the fringes, the commonly employed method is the Fast Fourier Transform (FFT). However, this technique encounters challenges when dealing with insufficient fringe numbers, spatially varying fringe frequencies, or extremely sharp phase changes. These challenges result in errors and hinder the acquisition of precise phase measurements. To tackle this issue, we have introduced the Fringe Normalization (FN). Through simulations, we have confirmed that the FN method accurately extracts phase information, surpassing the capabilities of the FFT method [1]. As a result, this advancement enables more precise plasma diagnostics by mitigating errors that arise during the phase data processing. We plan to apply this method in the field of laser-plasma acceleration to analyze the density distribution of a plasma source with a sharp density profile.

[1] K. Okada, E Yokoyama, and Hidetoshi. M. *Electronics and Communications in Japan*, Part 2, Vol. 90, No. 1, (2007)

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Operation of the upgraded single crystal dispersion interferometer (SCDI-U) and its measurements in KSTAR during abrupt and large density changes

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Disruption is one of the most critical phenomena that can happen in high performance fusion devices, and it must be mitigated. Since the shattered pellet injection (SPI) scheme has been selected in ITER as the basis of the disruption mitigation system [1], it is very important to understand how SPIs affect plasmas, such as electron densities. To measure abrupt and large density changes induced by the SPI, we have developed an upgraded single crystal dispersion interferometer (SCDI-U) system with the laser wavelength of 1064 nm. The SCDI-U system uses only one non-linear crystal (NLC), while other types of DI systems use two NLCs, allowing the SCDI to have a simpler optical setup. Furthermore, the SCDI-U has a completely overlapped beam paths between fundamental and second harmonics beams within the whole beam paths even if it uses an acousto-optic modulator (AOM) to secure large bandwidth of the system, which were not the case in other DI systems with an AOM [2]. In this work, we report its measurements in KSTAR during the SPIs and compare them with those from existing two-color interferometer (TCI) in KSTAR whose wavelength of the laser is 10.6um. The results show that the SCDI-U is more reliable in abrupt and large density changes compared to the TCI. We also discuss its possible application to ITER.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization. The KSTAR SPI experiments were performed in collaboration with the ITER DMS Task Force and the work reported here received funding by the ITER Organization under contract IO/CT/43-1918.

Also, this work is supported by Ministry of Science and ICT under KFE R&D Program of KSTAR Experimental Collaboration and Fusion Plasma Research (KFE-EN2101-12) and by the National R&D Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (Grant Nos. RS-2022-00155917 and NRF-2021R1A2C2005654).

[1] L.R. Baylor, *et al.,* Nucl. Fusion **59** (2019) 066008

[2] T. Akiyama, *et al.,* JINST **15** (2020) C01004

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Progress of CO_2 Dispersion Interferometer on EAST

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The dispersion interferometer (DI) system on the Experimental and Advanced Superconducting Tokamak (EAST) has been successfully operated, providing measurements of plasma electron density. The DI system utilizes a continuous-wave 9.3 μm CO_2 laser source to measure line-averaged electron densities [1]. It offers significant advantages, including the ability to overcome calculation errors caused by fringe jumps in the traditional far-infrared interferometer, and immune mechanical vibration. These characteristics make it well-suited for future high-density, long-pulse plasma discharges. The DI system on EAST had provided a real-time density feedback signal to plasma control system (PCS) for routinely density feedback control for long pulse operation. Experimental results on EAST have demonstrated a good agreement between the density obtained by the DI system and the preset values of density. The DI system also shows stability in long pulse discharges. Moreover, the DI system has shown stability during experimental measurements involving rapid density changes and highly dense pellet injections. In shot 120596, the DI system exhibited stable density feedback during continuous projectile injection lasting over 50 seconds, the electron density is around $4.1\times10^{19}m^{-3}$. Additionally, in contrast to the long wavelength source interferometer, which may deflect light away from the detector due to excessive refraction angles in larger density gradient discharges, the dispersion interferometer ensures accurate density measurements. In general, the DI system on EAST has demonstrated dependability in accurately measuring electron density. As shown in Figure 1, in three adjacent plasma discharges with a plasma current of 0.3 MA and discharges duration of about 65 seconds, the electron density is measured to be around $4\times10^{19}m^{-3}$.

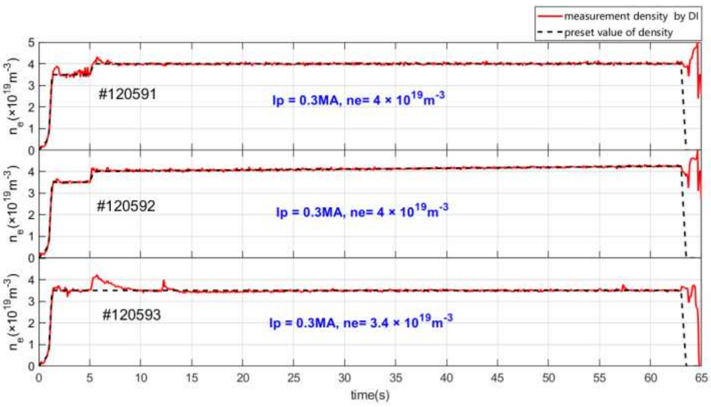

Figure 1. Good agreement between the density measurement results obtained by the DI system and the preset values of density.

[1] W. M. Li, H. Q. Liu, .et al 2019, Rev Sci Instrum **90** (2019), 026105.

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Application of multichannel Doppler reflectometer for fluctuation measurements in GAMMA 10/PDX anchor heating experiment

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A Ku-band (12–18 GHz) multichannel Doppler reflectometer (DR) [1] has been developed and installed in the central cell (the main confinement region) of GAMMA 10/PDX tandem mirror device to investigate electron density turbulent (or coherent) fluctuations including turbulent flows.

In GAMMA 10/PDX during discharges with additional RF heating in the anchor cells large increases have been observed in the space potential of the core region and the floating potential of the central-cell limiter, which indicates some changes in potential profile. By using the multichannel DR, Doppler frequency shifts were simultaneously observed in a single discharge at different cutoff layers during additional RF heating. Density fluctuation flow velocity V_p observed by DR is in the electron diamagnetic drift direction and the flow profile shows radially sheared structure in the peripheral region (r/a >0.5, a is the limiter radius 18 cm). Here, a ray tracing simulation is used to estimate density turbulent wavenumber and scattering positions. Space potentials in the edge region (r>10 cm) are estimated by floating potentials observed by a fast reciprocating probe and a gold neutral beam probe (GNBP) was used to measure potential in the core region. Potential profile shows well-type shape with negative E_r indicating V_{ExB} with the electron diamagnetic drift direction. Both V_p and V_{ExB} profiles show similar shape with flow peaks at edge region (16~18 cm), which represents the dominant influence of E_r on the edge plasma flow.

This work was supported by the NIFS bi-directional collaboration research programs (NIFS19KUGM137, NIFS19KUGM144).

[1] J. Kohagura, *et al.,* Rev. Sci. Instrum. **93** (2022) 123507.

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Highlighted studies of turbulence, flow shear and mode structure in MAST-U using UCLA Doppler Back-scattering system

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An eight channel Q-band (33-50GHz) Doppler back-scattering/reflectometry system, provided by the University of California Los Angeles is installed on MAST-U [1]. These channels can target the core plasma in low density plasmas, as well as probing the pedestal of H-mode plasmas. Wave-guide switches enable remote switching between O mode and X mode, giving the capability to do cross-polarization scattering [2], and a movable lens is used for poloidal & toroidal steering [3] to match the scattered wavenumber with the field line pitch.

The radial profile of turbulence intensity and phase velocity, are compared with profiles, and can probe the core of L mode plasmas and the pedestal of H-mode plasmas. Of particular importance is the role of on and off-axis beams to drive rotation and produce ExB shear. This data may help to explain why the off-axis beam is more favorable in order to avoid disruptions and deleterious MHD.

Also, when the beam is steered normal to the flux surfaces, i.e. acting as a reflectometer, the system shows clear signatures of modes can be observed including fishbones, Toroidal and Compressional Alfven eigenmodes, which using proper phase analysis model fitting [3] can deliver the displacement radial eigenfunctions of these modes.

1. T. Rhodes et al, Rev Sci Instrum 93, 113549 (2022)
2. R. Hong et al, Rev Sci Instrum 92, 063505 (2021)
3. V.H. Hall-Chen et al, Rev Sci Instrum 93, 103536 (2022)
4. N. A. Crocker *et al.,* Nucl. Fusion **58**, 016051 (2018).

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First data and preliminary experimental results from a new Doppler Backscattering system on the MAST-U spherical tokamak

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A new Doppler backscattering (DBS) system, consisting of Q- and V-bands, has been installed and achieved its first data on the MAST-U spherical tokamak. The Q- and V-bands have separate microwave source systems, but share the same optical front-end components. Both the Q- and V-band sources generate eight simultaneous fixed frequency probe beams, which are (34, 36, 38, 40, 42, 44, 46 and 48 GHz) and (52.5, 55, 57.5, 60, 62.5, 65, 67.5 and 70 GHz) respectively. These frequencies provide a large range of radial positions from the low-field-side edge plasma to the core, and possibly to the high-field-side edge, depending on the plasma conditions. The quasi-optical system consists of a remotely-tunable polarizer, a focusing lens and a remotely-steerable mirror. By steering the mirror, the system provides remote control of the probed density wavenumber, and the angle of the launched DBS to match the magnetic field pitch angle. The range of accessible density turbulence wavenumbers (k_θ) is reasonably large with normalized wavenumber $k_\theta\rho_s$ ranging from <0.5 to 15. Additionally, combining with the previously established DBS system by UCLA [1], the toroidal correlation of density turbulence has been studied.

[1] T.L. Rhodes, *et al.,* Rev. Sci. instrum. **93** (2022) 113549.

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Stray light suppression for Thomson scattering diagnostic on linear magnetized plasma device

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Abstract
In Thomson scattering (TS) diagnostic system, the stray light is a key factor affecting the measurement of electron velocity distribution function and density. The suppression issue is particularly severe for the low density and low temperature plasma due to very few scattered photons and narrow line broadening. The traditional methods, such as Brewster window, beam dump and transmission pipeline with black-coated internal surface, have been adopted in the stray light suppression system on our Linear Magnetized Plasma (LMP) device. Moreover, an assembly of apertures are placed in the optical path. Via numerical simulation, the optimal configuration of the adjustable aperture tube (size and location) that provide the best suppression has been found. Finally, the optimal aperture group with 6 mm and 8 mm tapered apertures can maintain over 97% transmission rate of the main laser energy while reducing stray light by 1-2 order of magnitude.

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The optical design of a vertical Thomson scattering system on SUNIST-2

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Thomson scattering (TS) is a key method to measure electron temperature (T_e) and density (n_e) profiles in fusion plasmas. A vertical Thomson scattering system with 900 mm field of view using a 5J/100 Hz laser as the light source is being developed for the upgraded Sino-UNIted Spherical Tokamak (SUNIST-2) to measure T_e and n_e in the ranges of 100 ~ 3000 eV and 5×10^{18}~10×10^{19} m^{-3}, respectively. The optical design, simulation and test results of the TS system mainly including the laser beam path, a special beam dump, a scattered light collection optics and fiber bundles will be presented.

Figure 1 shows the optimized optical design of the collection optics with ZEMAX software. The axis of the lens is tilted up by 16 degrees in order to cover the 900 mm field of view. The near-axis magnification and NA in the image plane are about -0.28 and 0.34, respectively. Solid angles of the view fields are in the range from 9.3 msr to 27 msr. The RMS radius of the whole field of view is from 89 μm to 270 μm. The Brewster windows, tube baffles, the beam dump and wire grid polarizers are designed to suppress the stray laser light [1]. The self-developed high performance 5-ch polychromator [2] will be employed to detect the scattered light, which has a trans-impedance gain of 22k Ohms and the noise level is below 5 mV. Considering the solid angles, scattering angles, scattering lengths, laser pulse width, detector quantum efficiency, laser pulse energy, and the transmissivity of the entire optical system, the estimated errors of T_e in the core and edge regions are about 10% and 20%, respectively.

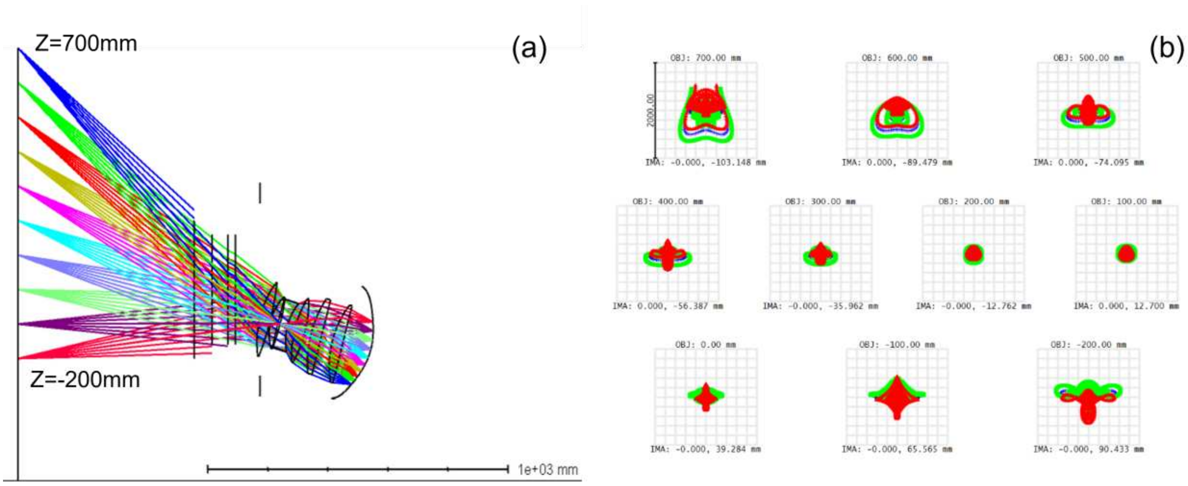

Figure 1. Optical design results of the collection optics. (a) Ray traces from the fields of view to the image plane, and (b) Spot diagrams in the image plane with wavelengths of 850 nm, 950 nm and 1050 nm indicated by colors.

[1] H. Y. Li, *et al.*, Rev. Sci. Instrum. **93** (2022) 053504.
[2] Gong S B, *et al.,* Plasma Science and Technology **25** (2023) 075601.

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Performance of JT-60SA Thomson scattering data analysis system

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A data analysis system has been developed for high spatial resolution and high-precision electron temperature and density Thomson scattering measurements in the JT-60SA project [1]. The performance of the system, including the noise from 1 GS/s digitizer and high efficiency polychromator [2], has been analyzed. In JT-60SA, various discharges with different electron temperatures, electron densities, and discharge durations are planned (T_e = 0.1–30 [keV], $n_e < 1 \times 10^{20} [\mathrm{m}^{-3}]$). Currently, our data analysis system can analyze data taken from the polychromators for the core (46 spatial channels at 50 Hz) and the edge (49 spatial channels at 100 Hz) plasma in one system. The requirement for the density and temperature calculation is to be finished within a nominal repetition time, which is 3000[s] for 100[s] flattop of the plasma current. Hence, evaluations of the time from the beginning of data acquisition to the end of calculation of T_e and n_e must be investigated. Each polychrometer (6 spectral channels) data is required to be calculated within 4.2ms assuming sequential computation.

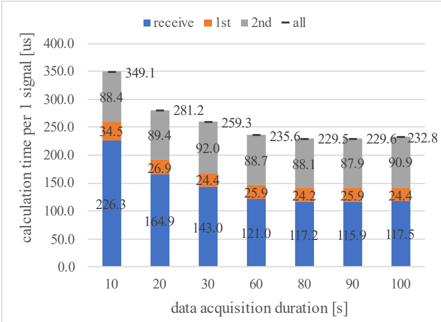

Fig. 1 processing time per a signal

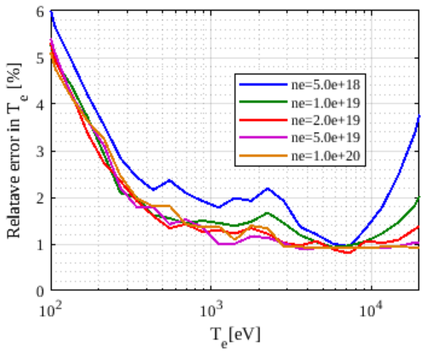

Fig. 2 result of phantom test

We applied the simple summation method to JT-60SA discharge conditions with the parameters of the Thomson scattering measurements and investigated their performance. Figure 1 shows the averaged computation time per a signal data including receiving raw data and writing processed data file (1^{st} : raw data, 2^{nd} : scattered intensity). Figure 2 shows the relative error from the phantom test. The computational performance was evaluated in terms of computation time and error. Using simple summation, the determination of the scatted intensity finishes with 233 μs x 6 [ch] ~ 1.4 [ms] at 100 [s] of the data acquisition duration and within the limitation duration (4.2[ms]). The relative error in T_e < 6% at $n_e > 5 \times 10^{18} [\mathrm{m}^{-3}]$. Evaluations of curve fitting method to obtain the scattered intensity [3] in low signal-to-noise ratio conditions and calculation method of density and temperature determination will be presented.

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[2] F.A. D'Isa *et al.,* Fusion Engineering and Design 192, 113591 (2023)

[3] H. Funaba, *et al.,* Plasma and Fusion Res. 17, 2402032 (2022)

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Twin synthetic diagnostic for the design and exploitation of the WEST high-resolution Thomson Scattering diagnostic.

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WEST is a medium-size tokamak which is relevant for the ITER project. One purpose is to test and assess the behavior and ageing of components ahead of ITER divertor installation [1,2].
Detailed characterisation of edge kinetic profiles is important to understand the physics of power load distribution, coupling of Radio-frequency heating systems and confinement properties of the plasma.
Precise measurement of the density and temperature profiles are required in the pedestal and scrape of layer regions (SOL) to evaluate and investigate the heat flux (HF) deposited on the divertor target. Precise temperature and density profiles are also needed in the plasma core to characterize the confinement regime and evaluate the upstream fluxes.
For this purpose, a new High Resolution Thomson scattering (HRTS) diagnostic is being developed for determining the electron density n_e and temperature T_e.

In the plasma edge, the HRTS will probe 18 cm at the plasma top with 6 mm vertical resolution, corresponding to 3.5 mm resolution once remapped to midplane (corresponding to approximately 10 radial positions across the pedestal). To achieve such resolution a water cooled in-vessel endoscope will be implemented [3].

In the plasma core, the resolution requirement is less stringent. The optical system is thus outside the vacuum vessel 20 vertical positions will be probed with a 25 mm spatial resolution from the equatorial plane. Owing to an overlap with the edge system, the HRTS will offer a full coverage of the plasma upper half.

To prepare the operation of the HRTS and evaluate its performance, a synthetic diagnostic has been developed to model the complete transmission function of the system from the laser up to the polychromators signal in order to validate the system.
More specifically, the model includes Thomson scattering processes, laser characteristics and system geometry, Monte Carlo rendering of photon statistics through optics of the telescopes, optical fibres, and finally the instrument transfer functions of the detector, i.e the polychromators channels.
Thanks to this synthetic diagnostic, one verify that the photonic budget of the final optical design fulfils the requirements for precise measurements of electron temperature and density. Namely, for standard plasma parameters of $n_e = 10^{19}\ m^{-3}$ and $T_e = 1\ KeV$, about 5000 photo-electrons are generated by polychromators with an error of 2 % on the electron temperature estimate. We have also verified that SOL measurements were possible :
for SOL parameters $n_e = 10^{18}\ m^{-3}$ and $T_e = 10\ eV$, about 500 photo-electrons are generated by polychromators leading to an error of 15 % on the electron temperature.

Note that the background signal is also evaluated using a Bremsstrahlung emission model and experimental conditions from previous WEST experiments.
Twofold objectives are followed :
1) quantifying the impact on temperature and density estimates through sensitivity analysis of the signal to noise ratio,
2) addressing the possibility to measure the effective charge (Z_{eff}) of the background plasma through Bremsstrahlung inversion.

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[2] Bucalossi J and al, 2022, Operating a full tungsten actively cooled tokamak :overview of WEST first phase of operation, doi 10.1088/1741-4326/ac2525
[3] Colledani G, 2023, this conference

THE WEST THOMSON SCATTERING DIAGNOSTICS

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The IRFM has designed an innovative Thomson scattering diagnostic for WEST in order to obtain measurements of the density and temperature profiles with a centimetric spatial resolution in the plasma core area and a millimetric resolution in the pedestal region.

Due to the different plasma configurations possible in the WEST Tokamak, 50 viewing lines will be installed: 20 in the core with 25 mm resolution and 30 for the pedestal measurement with 6 mm resolution.

Although the optomechanical design for the core views is classic, the one for the edge is much more challenging. Indeed, to avoid reflections from the divertor, the measurement of the pedestal can only be done by introducing an endoscope inside the vacuum chamber, so all internal optical components are protected from the plasma radiation with a water-cooled thermal shield and the first mirror will be actively cooled.

The former inner wall has been replaced by one with a viewing dump to reduce the light coming from the lower divertor.

Two lasers of 2J at 30Hz repetition frequency have been installed. The characteristics as well as the displacement of their beams are controlled all along the path by cameras, pyrometers, photodiodes and motorized mounts.

For both diagnostics, single and duplexed optical fiber bundles have been designed to carry the scattered light towards the polychromators placed in thermoregulated cubicles located in the Torus Hall. The swift nanosecond electrical pulse waveforms generated by the APDs inside the polychromators are acquired using Nectar fast analog sampler chips. A custom electronic board was designed to provide, for each polychromator, six Nectar input channels, six slower channels for background measurements and the necessary programmable resources for data readout and possible local real time processing. Downstream a local gigabit network, the data acquisition system includes back-end PCs to gather and further process the acquired waveforms.

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Polarimetric Thomson scattering to reduce T_e and n_e measurement uncertainty in high performance ITER operating regimes

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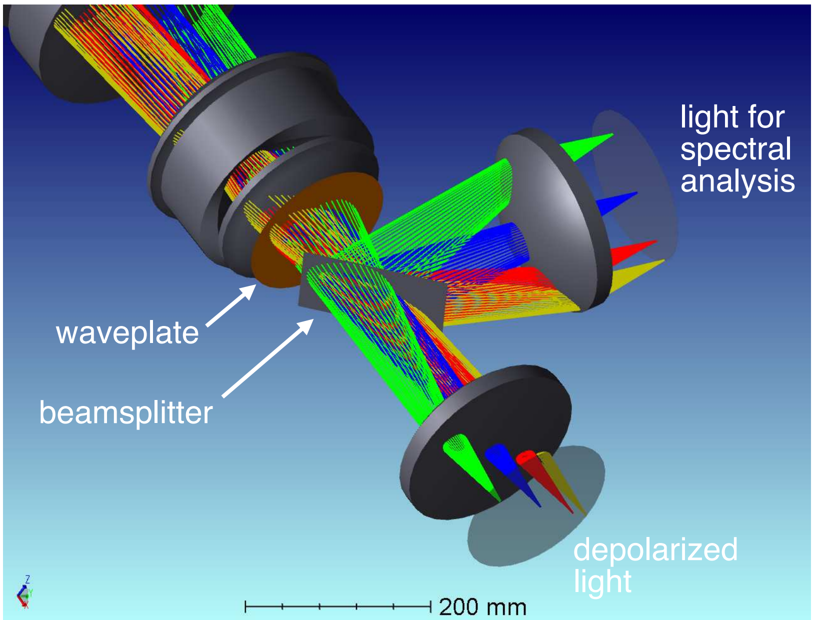
The ITER Core Plasma Thomson Scattering (CPTS) system is the primary diagnostic for the electron temperature (T_e) and electron density (n_e) profiles. For high performance ITER operating scenarios in which core T_e > 20 keV, the conventional spectral CPTS will not provide measurement accuracy sufficient for advanced machine control. Addition of polarimetric measurement capability to the CPTS diagnostic is projected to increase measurement accuracy in high temperature / low density plasmas to required levels. The need to develop Polarimetric TS is Issue A.17 in the 2020 ITER Technical Report on Required R&D [1]. Polarimetric TS measurements have been made in JET high T_e plasmas [2]; further tests of Polarimetric TS could also be made in other high T_e plasmas such as JT60-SA or W7-X. To determine the feasibility of Polarimetric TS implementation on ITER, the polarization characteristics of the CPTS scattered light collection system have been modeled as part of a conceptual design study [3]. When linearly polarized light is propagated through the CPTS collections optics, polarization is rotated and ellipticized. This characteristic of the ITER collection optical system complicates separation and analysis of the depolarized component of the Thomson scattered light that is produced at high T_e. To address this challenge, a custom waveplate and polarizing beamsplitter should be mounted before the final lens in the CPTS collection optical system (see figure below). Additionally, polarization performance should be one of the criteria by which materials and coatings are selected for the CPTS collection optical system.



[1] A. Loarte *et al.*, *Required R&D in Existing Fusion Facilities to Support the ITER Research Plan* (2020) ITER Technical Report **ITR-20-008**.
[2] R. Scannell *et al.*, *Rev. Sci. Instrum.* **94** (2023) 013506.
[3] D. J. Den Hartog and M. A. Thomas, *Final Report for Task Agreement IO/21/TA/4700000231 - Pre-Conceptual Design for Polarization Thomson Scattering Diagnostics 55.C8* (2022) IDM UID **8ANU2R**.

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Analysis of Dual Laser Thomson scattering signals on W7-X

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Dual-laser Thomson scattering (DLTS) is an advanced diagnostic technique in which two laser pulses of different wavelengths are sent to the plasma with a very short time delay and the two scattered signals are separately and independently measured with the same set of polychromators [1,2]. Owing to the dependence of the TS spectrum on the input laser wavelength, the two sets of signals correspond to two different spectra, both related to the same T_e and n_e. The pair of scattering signals collected in this way from each spectral channel was initially intended to correct systematic errors in the calibration of spectral channels, but it is now also aimed to extending the accuracy of the T_e and n_e measurements in the high T_e range. These features are of interest for the next generation of fusion experiments where the electron temperature in the core reaches values that are difficult to precisely measure with a single laser Thomson scattering, and where inaccessible optical elements are subject to deterioration of their spectral characteristics. Recently, a dual laser Thomson scattering has been developed at W7-X [3]: a unique system employing, in combination with a 1064 nm laser, a 1319 nm Nd:YAG laser. For the first time during OP2.1, a dual laser Thomson scattering system was operated stably during the entire experimental campaign. In this work, the dual-wavelength signals recorded in several W7-X discharges are analyzed and the electron temperature profiles and the experimental errors are discussed, with the aim of identifying the capabilities of this diagnostics.

[1] O. R. P. Smith et al., *Rev. Sci. Instrum*. 68 725-7 (1997).
[2] O. McCormack, et al., *Plasma Phys. Control. Fusion* 59, 055021 (2017)
[3] E. Pasch, et al, *Rev Sci Instrum* 89, 10C115 (2018)

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Improvement of signal-to-noise ratio in Thomson scattering diagnostics by an accumulation of 100 laser pulses within 5 milliseconds

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The signal-to-noise ratio (SNR) of the Thomson scattering diagnostics usually becomes small in high electron temperature, T_e, plasmas because of the low electron density, n_e. In order to derive precise T_e, averaging of signals in time or spatial positions are made [1]. Recently, operation with an Nd:YAG laser with high repetition rate up to 20 kHz started in the Thomson scattering system on the Large Helical Device (LHD) in order for the high temporal resolution [2]. In the 20 kHz operation, 100 laser pulses, each of which has almost 1 J of the pulse energy, are irradiated in 5 ms with the interval of 50 μs. Therefore, assuming that T_e does not change in 5 ms, it is possible to add up all signals by the 100 laser pulses.

Figure 1 shows signals which were detected by a polychromator (Poly#57) in the Thomson scattering system on LHD. The closest channel to the laser wavelength is Ch. 1. Raw data by one laser pulse are shown in Fig. 1 (a). The SNR may be small because of the small signal intensity, except Ch. 5. The observed position by Poly#57 is near the plasma center. High T_e is expected since this plasma was heated by the electron cyclotron heating (ECH) with the injection power of 3.2 MW and n_e was almost 2 x10^{18} m^{-3}. Figure 1 (b) and (c) show averaged signals of 10 signals in almost 0.5 ms and 100 signals in 5 ms, respectively. The signal components become clear in Fig. (b) and (c). The blue horizontal dashed line shows the background level which determined by averaging the data in the first 50 ns. This background level is important for the integration of the signals in time. It is still affected by noise in Fig. 1 (b), while the effect of noise seems to disappear in Fig. 1 (c). The value of T_e and the error of T_e will be evaluated for each case.

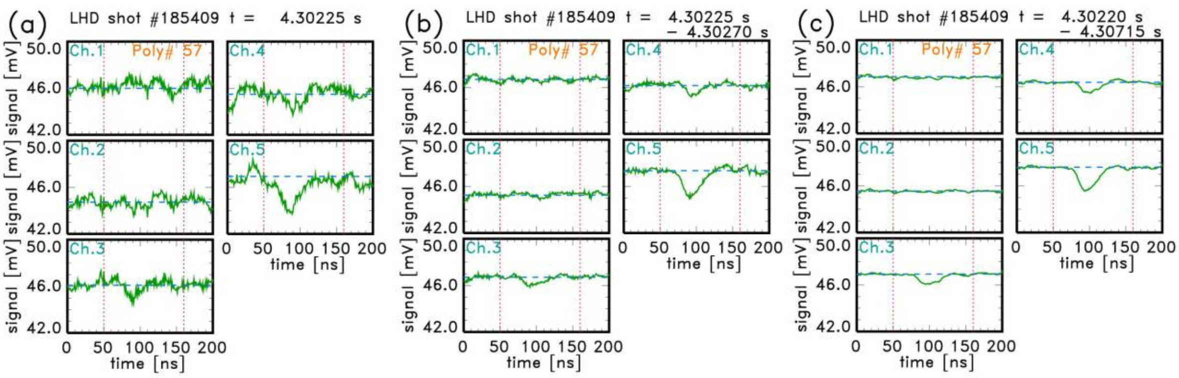

Figure 1. Thomson scattering signals in a polychromator on LHD. (a) Raw signals by one laser pulse. (b) 10 signals in almost 0.5 ms are averaged. (c) 100 signals in 5 ms are averaged.

[1] I. Yamada, *et al.*, JINST, **7** (2012) C05007.
[2] H. Funaba, *et al.,* Sci. Rep. **12** (2022) 15112.

*Presenting author: funaba.hisamichi@nifs.ac.jp

Development of a LIDAR Thomson Scattering Diagnostic for DTT

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A LIDAR TS diagnostic is being developed for the measurement of the spatial profiles of electron temperature T_e and density n_e in the DTT (Divertor Tokamak Test) experiment under construction in Italy. The system will use a line of sight tangential to the central column in the equatorial plane, a layout that offers the possibility to diagnose the edge profiles on the high field side in addition to the plasma core. Possible detrimental effects of stray light pulses and mitigation countermeasures are discussed both for the core and edge measurements. The performances expected with two types of detectors, microchannel photomultipliers (MCP PMTs) or digital single-photon-avalanche-diode (SPAD) arrays type are compared for this layout. SPAD arrays show superior properties for many aspects such as spatial resolution, resilience against intense stray light pulses, and possible high repetition rate of the diagnostic. Last, but not least, their use can reduce the cost of the diagnostic by doing away with the need of a two-wavelength laser system and of very high bandwidth transient digitisers.

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Development and first results of the edge Thomson scattering diagnostic with compact polychromators on the HL-2M Tokamak

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An edge Thomson scattering (ETS) diagnostic system on the HL-2M tokamak has been developed recently. A Nd: YAG laser (1064 nm, 2 J, 30 Hz, 15 ns) is used as the probe beam. The laser beam propagates vertically through the plasma region and the scattered light is observed horizontally. The combination of a half-wave plate and a polarizing beam splitter is used for stray light suppression. Characteristics of the non-ideal Gaussian laser beam is studied in detail. The laser beam waist and vertical spatial resolution are 2 mm and 10 mm, respectively. A set of collection lens is designed to image the 400 mm scattering region onto the rectangular fiber arrays. Scattered light is focused onto the 2.20 × 2.86 mm (10 × 13) fiber optic bundle. The collection optics is installed inside the vacuum chamber and the solid angle at central field of view is 0.018 sr. The 5-channel compact polychromator (Width 482 cm × Height 8.8 cm) is developed to measure the scattered light. The noise level of each channel is less than 5 mV. The designed electron temperature measurement range is from 5 to 1000 eV and electron density measurement range is from 5×10^{18} to 1×10^{20} m^{-3}. Measurements results of electron temperature and electron density by ETS are compared with that from the electron cyclotron emission (ECE) radiometer, the microwave interferometer, and the CO_2 dispersion interferometer. Combined with the data from the core Thomson scattering diagnostic system, the HL-2M plasma electron temperature profile is presented for the first time.

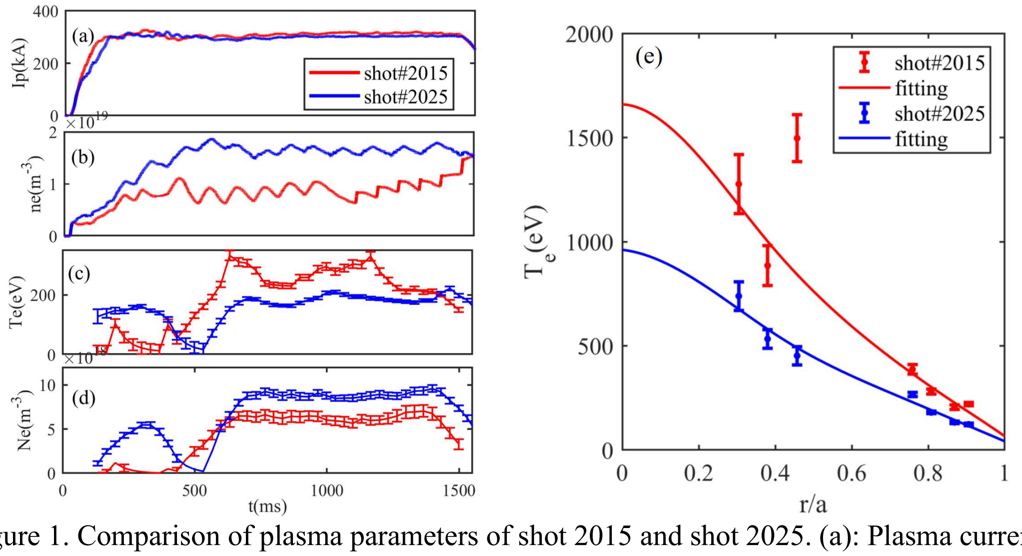

Figure 1. Comparison of plasma parameters of shot 2015 and shot 2025. (a): Plasma current. (b) Averaged electron density. (c) Electron temperature by EST. (d) Electron density by EST. (e) Plasma electron temperature profile.

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Cavity ringdown Lamb dip spectroscopy at Balmer α line of atomic hydrogen for measuring electric field in plasma

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We have reported in a previous work that the sheath electric field can be determined by the Stark spectrum of the Balmer-α line of atomic hydrogen if saturation spectroscopy with a Doppler-free resolution is adopted for measuring the Lamb dip spectrum [1]. However, we needed the pulse modulation of the plasma production to amplify the absorption signal using a lock-in amplifier even in the case that we employed a high-power (1 kW) inductively coupled plasma. The difficulty was caused by the weak absorbance of the Balmer-α line. In this work, we combined saturation spectroscopy with cavity ringdown to measure Lamb dip spectra in low-density cw plasmas.

An inductively coupled hydrogen plasma was generated inside an optical cavity consisting of two mirrors with high reflectivities. A single-mode cw diode laser beam was injected into the cavity. The laser beam was truncated using an acousto-optic modulator when the cavity length was resonant with the laser wavelength. The laser beam transmitted through the cavity was detected using a photodiode, and the temporal decay of the laser intensity after the truncation (the ringdown curve) was recorded using an oscilloscope. As shown in Fig. 1, the ringdown curve was deviated from an exponential curve. The deviation was attributed to the saturation in the initial phase after the truncation because of the high laser intensity inside the cavity. We fitted the experimental ringdown curve with the theory reported by Cancio and coworkers [2]. Based on the fitting shown in Fig. 1, we estimated the ringdown frequency of the empty cavity, the ringdown frequency due to absorption, and the saturation parameter. We obtained the absorption spectrum by repeating the measurement with scanning the laser wavelength. Although the spectrum was seriously noisy, we identified the Lamb dip corresponding to the $2p^2P^o_{3/2}$-$3d^2D_{5/2}$ transition of atomic hydrogen. We observed the Stark splitting of the Lam dip spectrum when we measured it at a distance of 1.8 mm from a planar electrode which was biased at -200 V. We estimated the strength of the sheath electric field from the Lamb dip spectrum with Stark splitting.

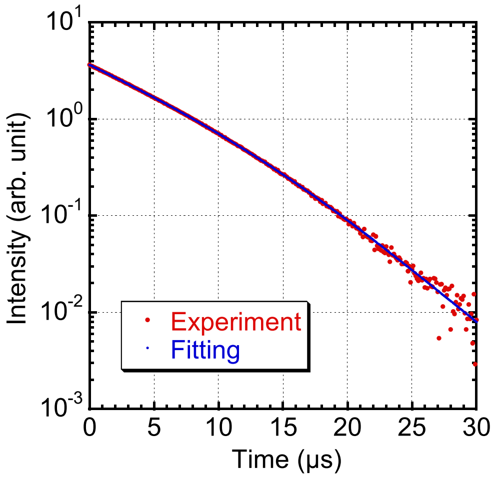

Fig. 1 An example of ringdown curve and its fitting with theory reported by Cancio et al.

[1] S. Nishiyama, H. Nakano, M. Goto, and K. Sasaki, J. Phys. D: Appl. Phys. **50**, 234003 (2017).
[2] P. Cancio, et al., "*Saturated-Absorption Cavity Ring-Down (SCAR) for High-Sensitivity and High-Resolution Molecular Spectroscopy in the Mid IR*" (in *Cavity-Enhanced Spectroscopy and Sensing*, Ed., G. Gagliardi and H.-P. Loock, Springer, 2014, Chap. 4).

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Development of Ghost Imaging Absorption Spectroscopy

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We are developing ghost imaging absorption spectroscopy by integrating computational ghost imaging (CGI) with plasma absorption spectroscopy [1]. Ghost imaging is a method that employs a single-pixel detector such as a photodiode to capture an image of an object. Structured light with a random intensity distribution, $I_{\mathrm{r}}(x, y)$, as depicted in Fig. 1, is absorbed by plasma with a density distribution, $T(x, y)$. A photodiode measures the integrated value, b_r, of the transmitted light. The value of $T(x, y)$ is subsequently computed as follows:

$$T(x,y) = \frac{\langle b_r I_r(x,y)\rangle - \langle I_r(x,y)\rangle\langle b_r\rangle}{|\langle I_r(x,y)\rangle|^2} \quad (1)$$

By switching and averaging tens of thousands of $I_{\mathrm{r}}(x, y)$ patterns, the contrast of the resultant $T(x, y)$ is progressively improved. As this imaging method is predicated on the correlation between b_r and $I_{\mathrm{r}}(x, y)$, it exhibits a noise tolerance analogous to lock-in detection. Moreover, by restricting the area of correlated absorption with $I_{\mathrm{r}}(x, y)$ through the focusing of structured light, as illustrated in Fig. 2, spatial resolution in the line-of-sight can be attained even in absorption spectroscopy. Figure 3 presents an image procured using our ghost imaging system, with the letter "P" printed on an acrylic plate serving as a test target. In this presentation, we will exhibit the outcomes of a proof-of-principle experiment, demonstrating that our imaging technique retains spatial resolution in the line-of-sight direction. We will also detail the application of this method to the measurement of metastable helium atoms in a helicon wave plasma."

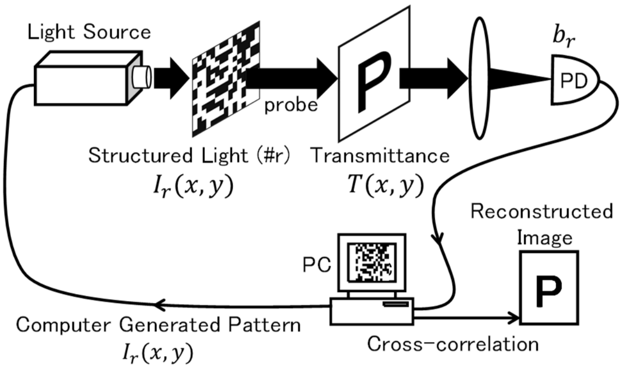

Figure 1. Schematics of ghost imaging absorption spectroscopy system.

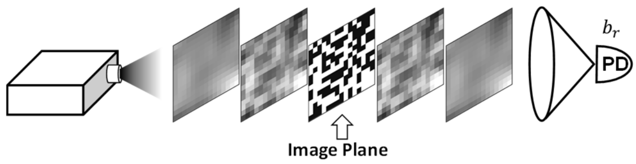

Figure 2. Restriction of the correlated area by foc using of structured light.

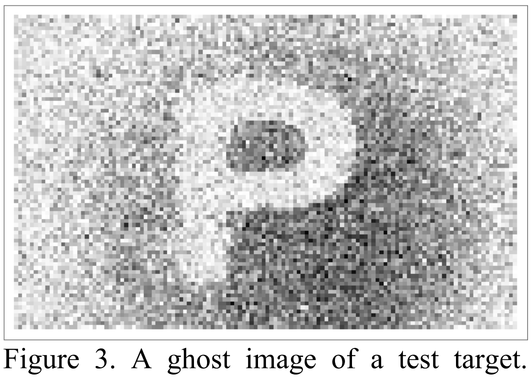

Figure 3. A ghost image of a test target.

[1] J. H. Shapiro, Phys. Rev. A **78**, 061802(R) (2008).

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Nonlinear Effect of Gas Flow on Helium Metastable Atoms in Weakly Ionized Gas Jet

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Metastable atoms play a crucial role in low-temperature plasmas, particularly in weakly ionized gas jets (known as plasma jets). Nonetheless, experimental data regarding helium metastable atoms (He*) in plasma jets have been scarce thus far, thereby limiting our knowledge of plasma characteristics and its applied research. The aim of this study is to investigate the nonlinear effect of gas flow on the He* dynamics in a plasma jet. A pin-type plasma jet source operating with a 50 kHz bipolar square voltage waveform was utilized, and the spatiotemporal distribution of He*(2^3S_1) was obtained using tunable diode laser absorption spectroscopy. By varying the gas flow rate within a range of 1 to 5 standard liters per minute (slpm), we first observed a wave-like pattern of He* formation preceding the main ionization wave, which was not detected by a conventional intensified CMOS camera. To better understand this phenomenon, optical emission spectroscopy and flow simulation using Comsol were conducted. We conclude that the high penetration of ambient N_2 into the plasma channel somehow induces this phenomenon. Thus, this study provides valuable insights into the complexities of plasma jet in relation to Penning ionization of ambient N_2. Furthermore, our findings demonstrate that certain effects are sensitive to specific ranges of the flow rate, emphasizing the importance of understanding and controlling gas flow dynamics in plasma jet applications.

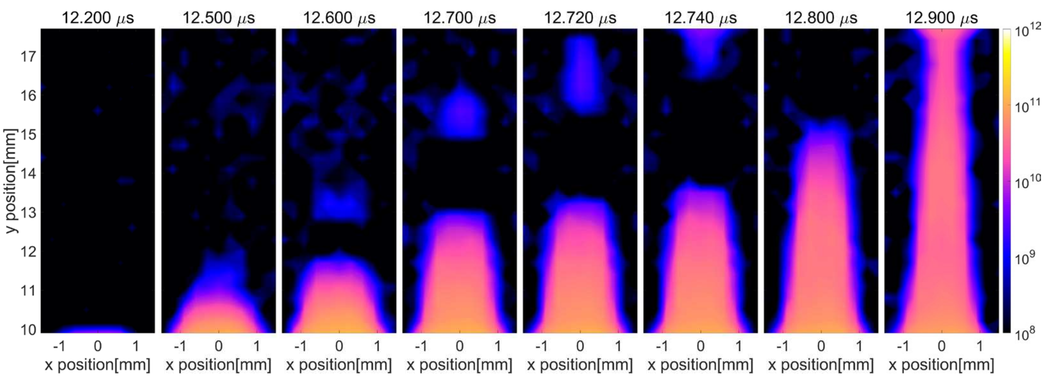

Figure 1. The wave-like pattern of He* observed in the plasma jet with a gas flow rate of 1 slpm.

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Design and Functional Testing of Cesium Atomic Concentration Detection System Based on TDLAS

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In order to better build the Neutral Beam Injector with Negative Ion Source (NNBI), the pre-research on key technologies has been carried out for the Comprehensive Research Facility for Fusion Technology (CRAFT). Cesium seeding into negative-ion sources is a prerequisite to obtain the required negative hydrogen ion. The performance of ion source largely depends on the cesium conditions in the source. It is very necessary to quantitatively measure the amount of cesium in the source during the plasma on and off periods (vacuum stage). This article uses the absorption peak of cesium atoms near 852.1nm to build a cesium atom concentration detection system based on Tunable Diode Laser Absorption Spectroscopy (TDLAS) technology. The test experiment based on the cesium cell is carried out, obtained the variation curve of cesium concentration at different temperatures. The experimental results indicate that: the system detection range is within 5×10^6-2.5×10^7 pieces/cm^3 and the system resolution better than 1×10^6 pieces/cm^3.

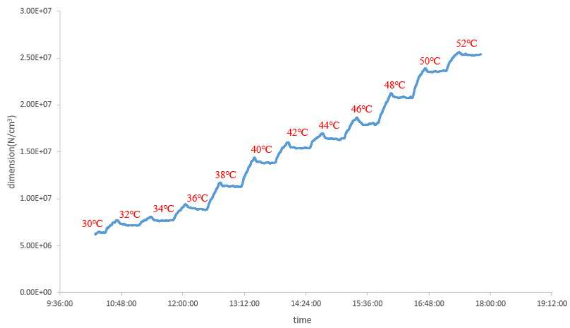

Figure 1. Trend chart of cesium concentration changing with cesium cell temperature.

Acknowledge

This work was supported by the HFIPS Director's Fund (YZJJQY202204 and 2021YZGH02), Comprehensive Research Facility for Fusion Technology Program of China under Contract No. 2018-000052-73-01-001228 and National Key R&D Program of China(2017YFE300103, 2017YFE300503)

[1] U. Fantz, *et al.,* J. Appl. Phys. 2011,**44** (33).

[2] U. Fantz, et al., AIP Conf. Proc.2011,**1930**(1)

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Comparative study of detached H/D plasmas using laser Thomson scattering and spectroscopy in the linear plasma divertor simulator NAGDIS-II

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Plasma detachment is a necessary condition for fusion device operation and hydrogen isotopes are the main component of fusion plasmas. To investigate the isotope effect on the plasma detachment in hydrogen (H) and deuterium (D) plasmas, the stable H and D plasmas were generated in the linear plasma device NAGDIS-II [1], and different detachment degree were achieved by controlling the neutral pressure. The radial distributions of the electron temperature (T_e) and the electron density (n_e) were measured by upstream and downstream laser Thomson scattering (LTS) systems [2] and the spectrum of Balmer series and Fulcher-α band were measured by optical emission spectroscopy (OES) [3]. In the plasma recombination region (downstream), T_e decreases from several eV to 0.1eV, and n_e is about 10^{18} m^{-3}. A distinct variation in the distribution of the atomic state population densities was observed. The results indicated that the dominant mechanism of the plasma recombination transitions from molecule activated recombination (MAR) to electron ion recombination (EIR) with increasing neutral pressure. Exhaustive plasma parameters of the recombination process are measured in both H and D plasma, from the MAR phase to the EIR phase. Analysis of isotope effects and mechanisms will be presented.

[1] N. Ohno, *et al.,* Phys. Rev. Lett. **81**, (1998) 818–821.

[2] S. Kajita, *et al.,* Phys Plasmas **24**, (2017) 073301.

[3] H. Tanaka, *et al.,* Nucl. Mater. Energy **19**, (2019) 378.

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Studies of Laser-produced Multi-ionized Plasmas for Soft X-ray and EUV Light Sources using Collective Thomson Scattering

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Observations of electron and ion dynamics are essential to diagnose multi-ionized light source plasmas, which are characterized by interactions among atomic physics, radiation hydrodynamics, and plasma physics. However, it is highly challenging to observe local plasma parameters, such as electron temperature (T_e), electron density (n_e), and averaged ionic charge (Z) due to their short (<50 ns) lifetime and small (< 0.5 mm) scale. Under such background, we have measured time-resolved two-dimensional profiles of T_e, n_e, and Z of laser-produced multi-ionized plasmas using collective Thomson scattering technique. In this presentation, we will report two types of plasmas. First one is carbon plasmas produced with a solid-plain target and a Nd:YAG laser (wavelength of 1064 nm, 10 ns pulse width) as a driving laser. Second one is tin (Sn) plasmas produced with droplet-type target and a CO_2 laser (wavelength 10.6 μm, 20 ns pulse width) as a driving laser. For both cases, we measured T_e, n_e, and Z during the laser irradiation timing. For the carbon plasmas, the Thomson scattering results were compared with 2D hydro-dynamic simulations [1]. For the Sn plasmas, the Thomson scattering results were discussed with self-emission image of 13.5 nm (±1%) wavelength width (in-band EUV) and absolute values of in-band EUV measurements [2].

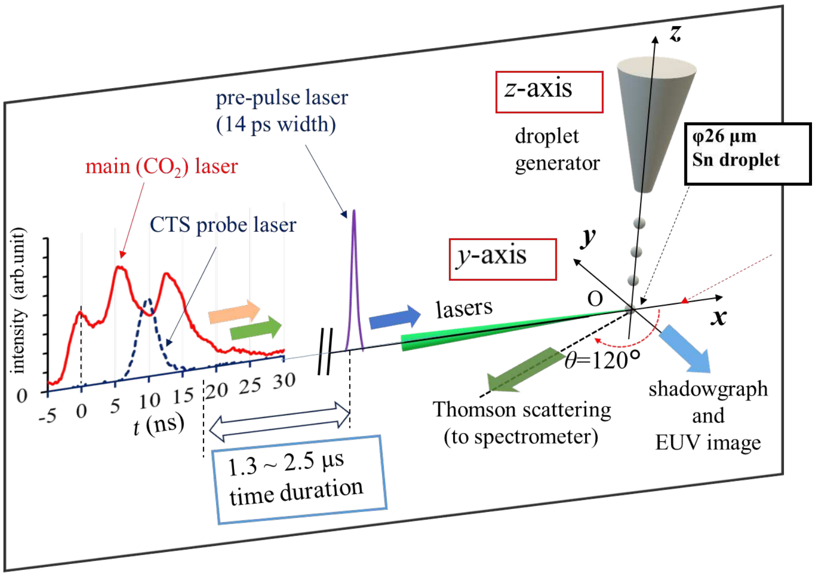

Figure 1. Schematics of collective Thomson scattering (CTS) setup for laser-produced Sn plasmas.

[1] Y. Pan, *et al.,* J. Phys. D: Appl. Phys. **56**, 025201 (2022).

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Development of the Thomson scattering measurement system for cascade arc device with indirectly heated hollow cathode

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We have developed a Thomson scattering measurement system for the cascade arc discharge device designed for the plasma window (PW) application study. PW is a plasma application technique that separates a high-pressure (10-100 kPa) and vacuum (~1 Pa) environment using plasma [1,2]. The plasma inside the channel of the PW heats the neutral gas to reduce the flow conductance. The flow inside the channel is considerably suppressed due to the decrease in the conductance, resulting in the high-pressure difference between the gas inlet and outlet of the PW. These features enable the PW to transmit the soft-X rays, electron, and ion beams into the atmospheric pressure side without drastic beam attenuation/scattering. Since the plasma thermal energy is the essential parameter for the pressure separation capability of PW, we installed the Thomson scattering measurement system to observe the electron density and temperature within the anode and cathode of the PW. A schematic diagram of the cascade arc device (PW) and the Thomson scattering measurement system is shown in Figure **1**. Frequency-doubled Nd:YAG laser (532 nm, 200 mJ, 8 ns) was employed for the probe laser. The scattered light was fed to the triple grating spectrometer. The notch filter between the first and second grating eliminated the stray light, realizing a sufficiently high signal-to-noise ratio. The Thomson scattering measurement system successfully obtained the electron density and temperature of the cascade arc plasma at 2 cm downstream from the tip of the cathode. We will discuss the detail of the measurement system and the analysis result on the obtained data.

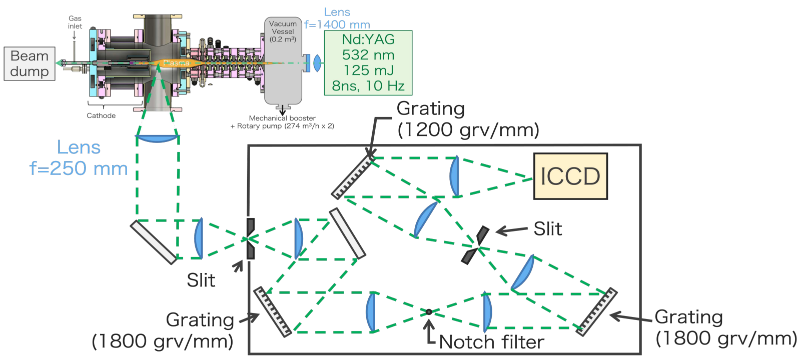

Figure 1 Schematic diagram of the cascade arc device and the Thomson scattering measurement system with a triple grating spectrometer.

[1] K. Yamasaki, *et al.*, RSI **93**(5) (2022) [2] K. Yamasaki, *et al.*, JJAP **62** (2023)

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Electric field measurements in N_2:CO_2 ns-APPJ by E-FISH technique

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The electric field in the nanosecond (near) Atmospheric Pressure Plasma Jet (ns-APPJ) is measured by the Electric Field Induced Second Harmonic generation (E-FISH) technique. The optical system used for the E-FISH measurements is similar to the one described in [1, 2], but has been optimized: the laser beam bypasses the amplifiers of the ps-laser in order to suppress an astigmatism of the beam caused by the non-uniform pumping of Nd:YAG rods in the amplifiers. With this modification the maximum possible energy of the laser pulse is much lower (~1 mJ), but nevertheless is still sufficient for generation of the second harmonic at 532 nm. At the same time, elimination of the amplifiers from the laser path leads to higher quality and better stability of the beam, which allows to achieve reliable E-FISH signals even at the relatively low pressure of 150 mbar. The electric field measured in different N_2:CO_2 mixtures is shown in Fig. 1: its value ($E/N \approx 100$ Td) is steady after the breakdown, moreover it weakly depends on the CO_2 content. It was shown already [1, 3] that electron density, pulse duration and volume of the plasma bulk can be controlled independently of *E/N*. Fig. 1 demonstrates that an exact gas mixture composition can be considered as an independent control parameter for applications, e.g. vibrational excitation, too. Influence of the electrical circuit characteristics on *E/N* value is investigated in order to optimize the vibration excitation in the jet studied by QCLAS in a similar discharge cell in the framework of SFB1316 project.

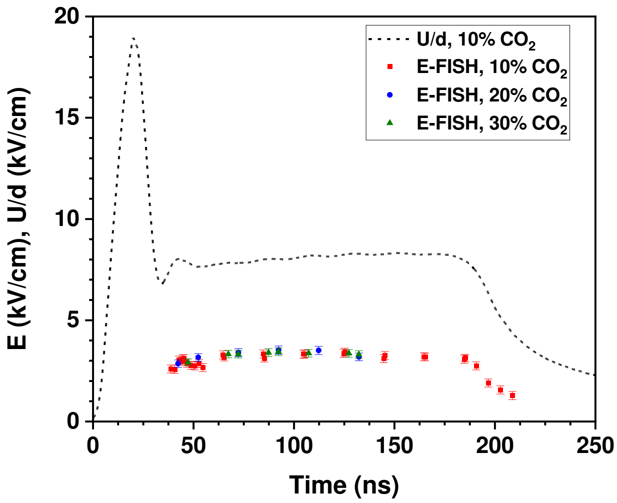

Figure 1. Electric field in ns-APPJ measured by E-FISH technique together with voltage over gap (1 mm) ratio for different N_2:CO_2 mixtures at pressure of 150 mbar and gas temperature of 340 K.

[1] J. Kuhfeld *et al.*, J. Phys. D: Appl. Phys. **54** (2021) 305204.

[2] N. D. Lepikhin *et al.*, J. Phys. D: Appl. Phys. **54** (2021) 055201.

[3] N. D. Lepikhin *et al.*, PSST (2023) accepted manuscript, DOI 10.1088/1361-6595/acde09

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Interferogram analysis of X-pinch plasmas using lens-pair configuration and synthetic dark-field Schlieren image

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The wire core region of X-pinch plasmas has very high electron densities even comparable to solid density within a few millimeter scales [1]. Although a Mach-Zehnder interferometer imaging system is developed to diagnose the two-dimensional line-integrated electron density of X-pinch plasmas, Its analysis is quite challenging because of the stiff electron density gradient. There are mainly two factors that make interferometer analysis difficult. One is significant refraction losses and the other is complex fringe patterns may lead to misjudgment of fringe numbering. To obtain electron density information in such high electron density gradient regions, lens-pair configuration is adopted to increase the acceptance angle of the imaging systems. Synthetic dark-field Schlieren images are qualitatively compared to simultaneously taken actual dark-field Schlieren images to detect misjudgment of fringe numbering. We present the experimental results of lens-pair configuration and a method to generate synthetic dark-field Schlieren images from interferograms. The practicality and limitations of lens-pair configuration and synthetic dark-field Schlieren comparison are also discussed.

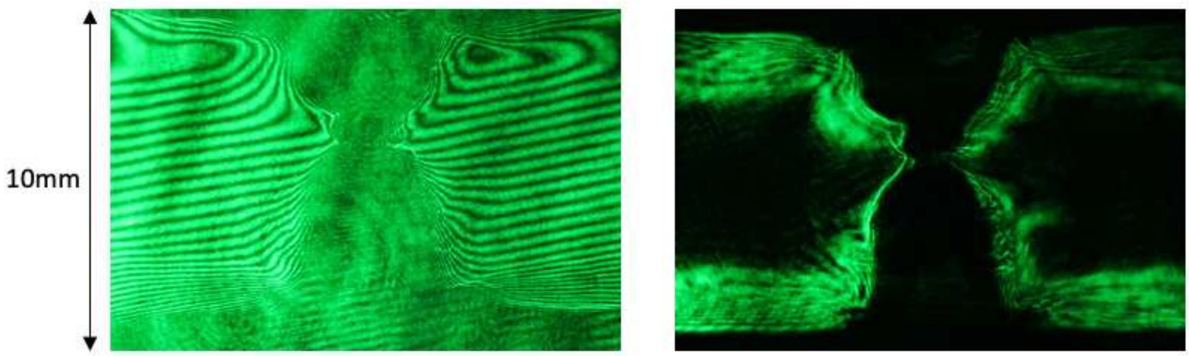

Figure 1. An example of simultaneously taken Interferogram (left) and dark-field Schlieren image (right) of the 25 um Cu from an X-pinch plasma.

Acknowledgments
This work was supported by the Defense Research Laboratory Program of the Defense Acquisition Program Administration and the Agency for Defense Development of Republic of Korea.

[1] Pikuz, S. A., Shelkovenko, T. A., & Hammer, D. A. (2015). X-pinch. part i. Plasma physics reports, 41, 291-342.

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Dense Plasma Diagnostics with a Nomarski Interferometer Using a Frequency-tripled Ti:sapphire Laser

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The peak power output of femtosecond lasers is inherently limited by the size and damage threshold of the final grating in the chirped pulse amplification compressor which presents a significant bottleneck. To overcome this limitation, some research has been conducted to explore materials with higher damage tolerance, and one promising method is using the dispersion characteristics of plasma for laser pulse compression. In order to effectively utilize plasma for the pulse compression, it is crucial to diagnose the expansion dynamics of the plasma over time. In that reason, we employed a time-resolved Nomarski interferometer to measure side-view density profiles of a laser-induced aluminum plasma. Our experimental setup utilized a frequency tripled Ti:sapphire laser system, generating a probe pulse with a central wavelength of 266 nm. This measurement system will be employed for studying laser-aluminum target interactions in experiments exploring plasma-based laser pulse compression.

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Exploring high energy density plasmas sustained over inertia time by the interaction between high intensity laser and structured medium

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By irradiating a matter with a high-power laser with the peak intensity of $I > 10^{18}$ W/cm^2, a high energy density (HED) plasma with the pressure of several G bar is produced. Such plasmas open-up a variety of applications. However, the plasma is spatially localized in a limited region of the laser focal spot and then expands within the inertia time defined by L/C_s with L the typical plasma scale length and C_s the sound speed. This indicates that if the plasma is maintained (confined) on a longer timescale as a bulk plasma beyond the inertia time, we can extend the range of applications. An example is the proton-boron thermonuclear fusion, where the confinement time is of specific importance.

In order to study such a state, we developed the silicon rod assembly having high aspect ratio of 10~50 (height/diameter) by using semiconductor manufacturing technology [1,2]. Also, we used the assembly of aligned carbon nanotube (CNT) with the height of 300 μm. As a first step, we performed interaction experiments using T^6 laser at ICR, Kyoto University and measured the electron energy distribution using two sets of the electron spectrometer (ESM) from two directions, one is side (~22.5 degree) and the other is normal (90 degree) to that of rod. In the case of the CNT, a clear anisotropic feature is observed that the average electron temperature for the side case is approximately double compared to that of the normal case. Moreover, the spectra from the side show a flat pedestal region which connects lower energy part and that of high energy. These features are not seen for the slab geometry, indicating that the laser sensitively reacts the nm-ordered surface structure of the CNT. We present a possible mechanism to explain the measured ESM data from the PIC simulation, which results from the potential structure produced near the target surface.

We are now planning to experiments using silicon rod assembly targets to study the anisotropy nature as the first step for generating HED bulk plasmas beyond the inertia time incorporating with a back-light system as well as interferometry system for the density distribution measurement, which directly investigate the dynamics and structure of produced plasmas. We also planning to the scheme to generate plasmoid and high-speed ejection for the approach to make an FRC type plasma.

[1] Y. Kishimoto et al., IFSA 2017, St Malo France and IFSA2019, Osaka, Japan.
[2] R. Matsui et al., HEDS2022, April 21th, 2022, R. Matsui et al., JSPS conference, September 9th, 2022.

Diagnostics of a laser-produced plasma with high density-gradient using a double-grating differential interferometer

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We used a high peak power of 1 TW to tightly focus the laser beam onto a gas jet with a nozzle orifice size of 100 μm. Due to the tightly-focused laser pulse, a high density-gradient plasma is generated, which is not easy to measure accurately. For this purpose, we developed a new differential interferometry method using a pair of gratings. It was found that our method can mitigate the detrimental impact of all kinds of noises arising from phase measurement, recovery, unwrapping, and Abel inversion processes. As a result, this technique showed enhanced precision and better reliability in plasma density diagnostics, compared with other conventional interferometry methods. In this presentation, we will show the comparison results.

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Measurement of the voltage evolution on a load of X-pinch plasma system using the Pockels effect

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A measurement system using the Pockels effect (linear electro-optic effect) is developed to measure a voltage on a load of the SNU X-pinch device [1]. The sensor part of the measurement system consists of an EO(electro-optic) crystal, whose refractive indices are effectively changed due to the Pockels effect when an external electric field is applied to the crystal, and its mount. As the EO crystal is small in physical size and can withstand high electric fields, the sensor can be located close to the load of the X-pinch system to measure the voltage evolution on the load. The sensor part is completely isolated from all the other components of the measurement system, and it induces a change of the polarization state of the incident laser beam. This allows all the electronic devices to be separated and shielded from the high electric pulses generated by the X-pinch system. We present the configuration of the voltage measurement system that uses Lithium niobate crystals as one of the EO crystals and the measurement results from the different types of the loads such as single wire and X wire cases. Also, we discuss the temporal evolution of the voltage especially during the wire expansion and pinching stage of the X-pinch plasmas.

[1] Jonghyeon Ryu, *et al.,* Rev. Sci. Instrum, **92** 053533 (2021).

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Development of 2D Thomson Scattering Measurement System Using Multiple Reflections and Time-of-Flight of Laser Light

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We are developing a cost-effective two-dimensional (2D) Thomson scattering measurement system using multiple reflections and time-of-flight of a single Nd:YAG laser [1, 2] for 2D elucidation of electron heating/acceleration of magnetic reconnection. Its key ideas are to cover the 2D measurement area by the multiple reflections of laser light and to save the number of polychromators using the time of flight of laser light.

Figure 1 shows our experimental setup. When the Nd:YAG laser light is reciprocated between $\phi 25$ concave mirrors, its backscattered light collected by a concave mirror is guided to polychromators through optical fibers. The scattered lights from 2D (20 x 7) measurement points are detected by 1D (20) polychromators. Since the distance between mirrors is about 3.485m, time of the round trip flight: $(3.485\times2)/(3.0\times10^8)$ s = 23 ns is almost equal to intervals of pulses. However, the measured pulse duration of Raman scattering light was longer than expected. Figure 2 (a) implies signals from adjacent return paths are difficult to be separated. On the other hand, Figure 2 (b) shows numerical sums of signals from the first and the third return paths, indicating signals from every other return path can be separated. As we succeeded 1D measurement and the noise was not too large to separate signals, we will be able to introduce our 2D data.

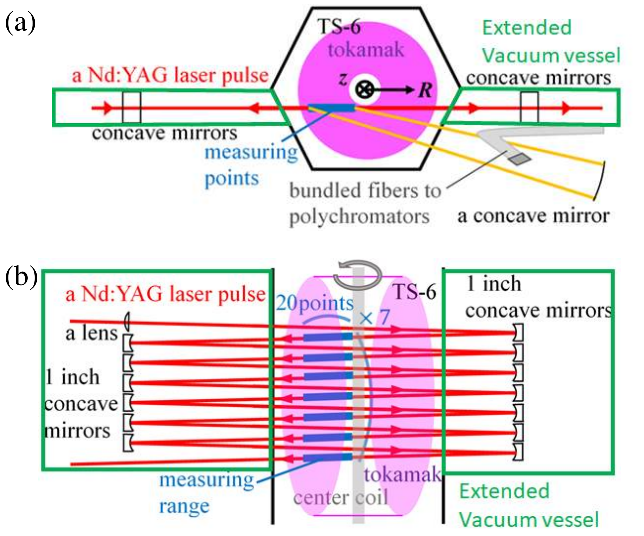

Figure 1. (a) The vertical and (b) the horizontal cross section of the experimental setup.

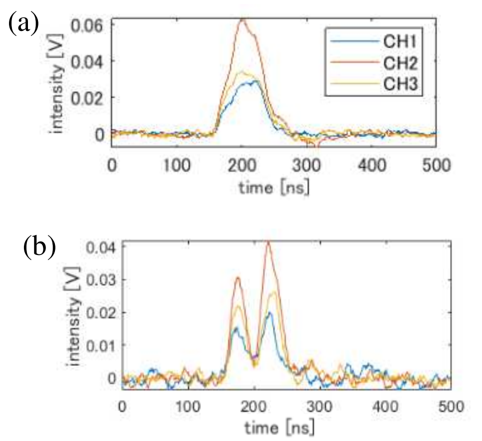

Figure 2. (a) Measured Raman scattering signals from return paths 1st, 2nd, and 3rd. (b) Numerical sums of Raman scattering signals from return paths 1st and 3rd without 2nd.

[1] S. Ito et al., IEEJ Trans. FM, 2, 132, 574 (2012).
[2] S. Kamiya et al., 35th annual meeting of JSPF, Osaka (2018).

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Design and Analysis of Divertor Thomson Laser Beam Dump for KSTAR

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Thomson scattering (TS) is a standard diagnostic device for measuring an electron temperature and density profiles in the most of Tokamaks. For this reason, TS is one of the most important diagnostic system in KSTAR (Korea Superconducting Tokamak Advanced Research). In KSTAR, a tangential type TS system has been developed few years ago and measure the electron temperature and density profile at the plasma.
Recently, the divertor region has been replaced with tungsten (W) tiles to improve the performance of KSTAR plasma. Thus, we need to measure the electron temperature and density porfile near the divertor region using TS. To install the divertor TS system, we have to design a laser guiding system, a collection optic system and a laser dump system which inside the KSTAR vacuum vessel.
In this poster, we will introduce the new beam dump system of the divertor TS in KSTAR. Already installed tangential TS system have a knife edge type beam dump which made of SUS316L inside the KSTAR[1]. Design of the divertor TS beam dump referred to the material and shape of tangential TS beam dump. TS signal is very week, and difficult to analysis because of a stray light inside the KSTAR vacuum vessel. So in order to properly measure a divertor TS signal, reducing the stray light is one of the most important issues[2], and the beam dump plays a key role in this case[3]. Thus, we designed the beam dump considering its installation location and incident angle of the TS laser beam. And then stray light sources of the beam dump system were simulated and analyzed.
We will show the design of KSTAR divertor Thomson beam dump system and discuss about the simulation and test result of divertor Thomson beam dump system.

[1] J.H.Lee et al., RSI. **81** (2010) 10D528.

[2] Shumei Xiao et al., RSI. **87** (2016) 073506.

[3] E. Yatsuka et al., RSI. **84** (2013) 103503.

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Investigation of Thomson Scattering Measurement System for Long-Duration Discharges with a hot wall on the QUEST Spherical Tokamak

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The QUEST spherical tokamak is equipped with temperature-controllable plasma-facing metal walls (called hot walls) for studies of particle recycling during long-duration discharges [1]. The temperature of the hot walls can be controlled from room temperature to 673K. In the future, long-duration discharges for about six hours at the wall temperatures from 573 to 673 K is planned. The Thomson scattering (TS) measurement system for long-duration discharges in QUEST was introduced in 2022, and electron density and temperature profiles can be measured at 10 Hz for 15 seconds, which is repeated every minute, using oscilloscopes under the wall temperature of 473K [2]. For the accurate and continuous TS measurement during several-hour discharges, the following two developments are in progress. The first is the automatic alignment system for the YAG laser path. The laser spots are constantly monitored at the final mirror of the injection beamline and at the mirror positioned after passing through the plasma by three cameras as shown in Figure 1, and the misalignment is automatically corrected by motor-driven mirrors. The second is the development of a data acquisition system for long-duration discharges. Switched capacitor ADCs capable of continuous data acquisition is in preparation. In addition, it was found that the temperature control of the glass vacuum window is necessary for applying the TS system to long-duration discharges at the wall temperature of 573 K. The temperature of the window surface rises due to the radiant heat from the hot walls and plasma, while the surrounding flange is water-cooled. The temperature difference between the window and the flange may cause damage to the glass windows. One of the solutions is to install a remotely controllable light-shielding shutter. The above development will allow us to measure the electron density and temperature in the long-duration discharges with high-temperature plasma-facing walls, only during the periods when the shutter is open.

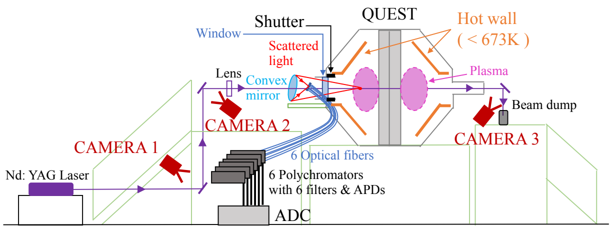

Figure 1. Conceptual diagram of TS measurement in long-duration discharges with a hot wall.

[1] M. Hasegawa, *et al.,* Plasma Fusion Res. **16** (2021) 2402034.

[2] K. Kono, *et al.,* Plasma Fusion Res. **18** (2023) 1405012.

*Presenting author: kono@triam.kyushu-u.ac.jp

New Polychromator System Design For KSTAR Thomson Scattering

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The polychromator is a crucial component in Thomson scattering diagnostics used for estimating electron temperature and density profiles. Its optimization plays a significant role in accurately measuring these parameters. Researchers have conducted extensive studies to design the most optimized polychromator, and KSTAR (Korea Superconducting Tokamak Advanced Research) has also developed an optimized design for this purpose [1]. In a recent development, the KSTAR Thomson polychromator incorporated a special function that allowed for the simultaneous measurement of Zeff (effective ionic charge) and Thomson signals by including a bremsstrahlung measurement part [2]. However, modifying the structure of the existing polychromator to add this function proved to be challenging. Therefore, a new polychromator was designed, taking into account the inclusion of the bremsstrahlung measurement part right from the beginning of the design process. In addition to the bremsstrahlung measurement part, a white LED was installed inside the new polychromator to serve as an alignment backlight. By providing visual assistance, the LED aids in achieving accurate alignment of the collection optics in the KSTAR vacuum vessel. Another notable feature of the new polychromator design is the inclusion of an Avalanche Photodiode (APD) temperature error correction. APDs are sensitive to temperature variations, which can introduce measurement errors. To address this issue, a temperature compensation circuit was incorporated into the design. This circuit helps mitigate the impact of temperature changes on the APD, enhancing the accuracy of the measurements. Overall, the new polychromator design integrates the bremsstrahlung measurement part, a white LED for alignment backlight, and a temperature compensation circuit for the APD. These additions aim to improve the functionality and performance of the polychromator in measuring electron temperature and electron density distribution using Thomson scattering.

[1] J. H. Lee *et al.*, RSI. **81** (2010) 10D528.

[2] Jong-ha Lee *et al.*, FED. **123** (2017) 838.

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This work was supported by Ministry of Science and ICT under KFE R&D Program of "KSTAR Experimental Collaboration and Fusion Plasma Research (KFE-EN2301)".

Electron Cyclotron Heating/Diagnostics via Microwave Optical Vortex

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[2]*Kyoto Fusioneering Ltd., Chiyoda-ku, Tokyo, 100-0004, Japan*

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Optical Vortex (OV) has been interested in a wide range of wavelength and interaction with various materials in particular in the context of the interaction of the topological charge of photon and material. Magnetized plasma is one of these materials. The dispersion properties and the propagation and absorption of the OV is not well investigated so far. The optical vortex in the vacuum is well expressed by the para-axial approximation of the wave equation as Laguerre-Gauss beam. A theory of quasi-geometrical optics [1] is developed introducing the complex eikonal with an azimuthal mode number (topological charge). This theory predicts a strange property of the propagation, that seems OV-O mode injected from low field side is transformed to the OV-X and might further excite electron OV-Bernstein mode. In order to check this property, high power OV injection systems using spiral mirror plate [2] are installed on LHD and Heliotron-J and preliminary experiment were performed in Heliotron-J. Another experimental plan is to investigate a basic property of the OV propagation in HYPER-I device. In parallel, numerical code to describe OV propagation / scattering absorption in an inhomogeneous magnetized plasma is underdevelopment extending the quasi-optical code. This OV propagation /scattering /absorption might open a new feature to plasma diagnostics such as electron cyclotron emission, (collective) Thomson scattering. The experimental /numerical trials to investigate OV heating/propagation in the magnetized plasma and applications to the heating/diagnostics are discussed.

[1] T. I. Tsujimura and S. Kubo, Physics of Plasmas **28**, 012502 (2021).

[2] T. I. Tsujimura *et al.,* Review of Scientific Instruments **93**, 043507 (2022).

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Topological charge and phase gradient measurement for optical vortex beams by modifying peripheral region of forked grating on spatial light modulator

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Recently, laser measurements of plasma flow using azimuthal Doppler shift associated with the phase structure of optical vortex (OV) beams have shown steady progress, where the topological charge (TC) that determines the azimuthal phase gradient plays a crucial role [1]. Various methods have been proposed to measure the topological charge of optical vortices using interference or diffraction, but most require dedicated optical paths and additional optical elements. Here we propose a new method of topological charge determination by only replacing the peripheral region of the hologram grating used for generating OV with blazed grating.

In our experimental setup, a Gaussian beam was converted into an optical vortex beam using a fork-shaped hologram grating depicted on the spatial light modulator (SLM). Figures 1 (a) and (b) show the hologram pattern for generating TC = 20 OV beam and the resulting diffracted beam image taken by a beam profiler, respectively. A narrow donut-shaped intensity distribution, which is characteristic of higher-order optical vortex (Laguerre-Gaussian) beams, is seen. In order to visualize the phase structure of this beam, it is necessary to measure the interference pattern with a plane wave traveling through another optical path. We instead replaced the hologram pattern on the SLM from Fig. 1 (a) to (c), where the forked diffraction grating in the central part is retained, and the other parts are replaced with blazed diffraction gratings. The resulting diffraction pattern is shown in Fig. 1 (d). The bright and dark patterns are repeated 20 times in the azimuthal direction, indicating that an interference pattern between the TC = 20 OV beam and a plane wave has been obtained.

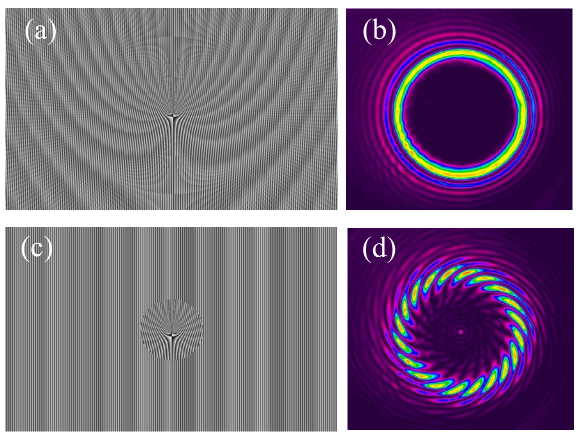

Fig. 1 (a) fork grating on SLM (b) OV with TC = 20 (c) modified fork grating on SLM (d) diffraction pattern (interference).

Details of this measurement method will be reported at the symposium, including the determination of phase gradients and the application to OV beams with asymmetric intensity distributions.

[1] S. Yoshimura *et al.*, Jpn. J. Appl. Phys. **59** (2020) SHHB04.

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Optimization of the Collection Optics System for KSTAR Divertor Thomson Scattering Diagnostic

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Thomson scattering (TS) diagnosis is one of plasma diagnostic methods that measures a density and temperature of electrons by using laser and optical system that collects a light emitted through the interaction of free electrons and laser beams in plasma. In Korea Superconducting Tokamak Advanced Research (KSTAR), a tangential TS diagnosis has been installed and measured the electron temperature and density profile every KSTAR campaign [1][2][3].

Recently, KSTAR is in the process of replacing a divertor with tungsten (W) tile to increase a performance of KSTAR plasma. So we are planning to install a divertor TS diagnosis on the divertor X point area to measure the electron temperature and density profile [4].

In this study, we would like to describe the collection lens design for the divertor TS diagnosis of the KSTAR tokamak. Since the divertor material is replaced with tungsten, it is important to minimize the optical noise such as stray light entering into the divertor collection optic system.

In this research, an optimum collection optic design for the KSTAR divertor Thomson scattering diagnostic was derived under various conditions which based on the Cooke triplet lens system [5]. And the optimized divertor collection optic design is introduced and discussed with simulation analysis result.

This work was supported by Ministry of Science and ICT under KFE R&D Program of "KSTAR Experimental Collaboration and Fusion Plasma Research (KFE-EN2301)".

[1] J.H. Lee, *et al.,* Review of scientific instruments. **81** (2010) 10D528.
[2] S. Oh, *et al.,* Review of scientific instruments. **81** (2010) 10D504.
[3] J.H. Lee and H.J. Kim, Journal of Instrumentation. **14** (2019) C11015.
[4] S. Kajita, *et al.,* Fusion engineering and design. **89** (2014) 69-76.
[5] https://en.wikipedia.org/wiki/Cooke_triplet

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Development of dual-path multi-pass Thomson scattering system in GAMMA 10/PDX

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Plasma detachment formation in fusion plasma devices is one of the most useful methods for handling heat and particle fluxes to the plasma facing components. In the tandem mirror GAMMA 10/PDX, the divertor simulation experimental module (D-module) is set in the end-cell (EC) for studying the underlying mechanisms for reducing heat and particle fluxes to the divertor plate under plasma detached conditions relevant for ITER SOL and divertor plasma. GAMMA 10/PDX confines the main plasma in the central-cell (CC), and the escaping plasma is led to the D-module to perform divertor simulation plasma experiments. In the D-module, the electron temperature and density are normally measured using the electrostatic probes on the V-shaped target plate. In the previous studies, we have developed the dual-path Thomson scattering system (DPTS) for simultaneously observing electron temperature and densities both in the core and end plasmas [1]. The DPTS contains CC Thomson scattering system (CC-TS) and the end-cell Thomson scattering system (EC-TS). In the CC-TS, we have been developing multi-pass system to improve the signal intensities and time resolution. In the EC-TS, double-pass system has been developed as a preliminary step of developing the multi-pass system. In the previous EC-TS, optical components for double-pass configuration were set in the vacuum vessel. To reduce the influence of stray light and facilitate alignment, a hole for double-pass laser path was made on the partition wall in the vacuum chamber so that the probe laser could be extracted to the atmosphere and the double path configuration could be easily adjusted. We applied the DPTS to detached plasma experiments and successfully measured core and edge electron temperatures and densities, simultaneously.

This study was conducted with the support and under the auspices of the NIFS Collaborative Research Program (NIFS11KUGM056) and the Bidirectional Collaboration Research Programs (NIFS14KUGM086, NIFS14KUGM088).

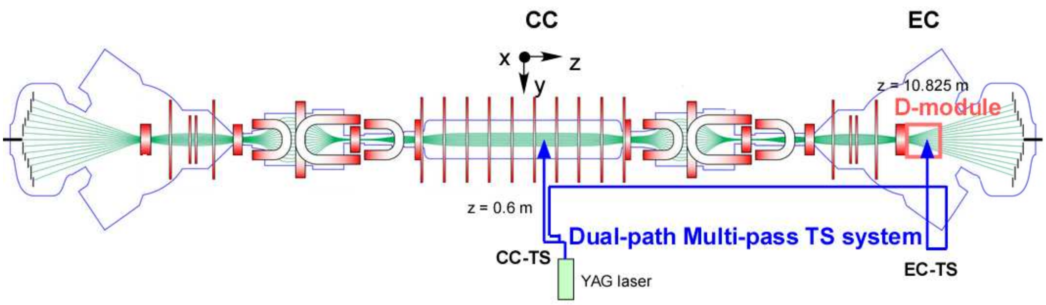

Figure 1. Schematic of GAMMA 10/PDX and DPTS.

[1] M. Yoshikawa, *et al.,* AIP Advance. **11** (2021)125231-1-6.

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Absolute value measurement of ion-scale turbulence by 2D-PCI in LHD

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Ion-scale turbulences in magnetically confined plasmas play a significant role in a plasma confinement. Phase contrast imaging (PCI) is one of the promising techniques to measure density fluctuations caused by ion-scale turbulence in high-temperature plasmas[1]. In the Large Helical Devise (LHD), a PCI using a CO_2 laser as a light source and a 6×8 two-dimensional photoconductive mercury tellurium cadmium (MCT) detector shown in Figure 1 for detection is in operation and is called a two-dimensional PCI (2D-PCI). The advantage of PCI is that it can theoretically determine the absolute value of the turbulence amplitude which is less than 1% of the electron density from $I_{AC}/(2\times I_{DC})$. Here, I_{AC} and I_{DC} are AC and DC components of a detected intensity signal. In addition, 2D-PCI can measure the time evolution of the spatial profile of the turbulence by applying the magnetic shear technique[1]. However, in practice, the MCT detector has nonlinear response characteristics of the incident laser power[2], making the absolute measurement difficult. In the previous work, an absolute value evaluation method was established by simultaneously performing sound wave measurements with HeNe laser interferometer [2]. In this study, the turbulence profile in LHD is evaluated in absolute value according to the process shown in Figure 2. First, the line-integrated turbulence amplitudes are evaluated for each channel and their average and standard deviation are obtained, as shown in Fig. 2(a). Then the turbulence profile is evaluated in arbitrary units as shown in Fig. 2(b). Finally, the integrated value of the turbulence profile in the line-of-sight direction and the average value of the line-integrated turbulence amplitude are determined to coincide, and errors were evaluated from standard deviations, as shown in Fig. 2(c). In this study, in addition to the above, we report the results compared with other diagnostics and nonlinear gyrokinetic simulations.

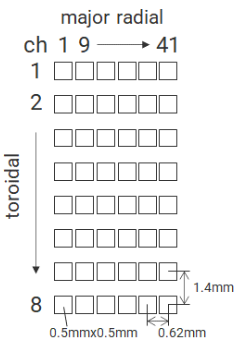

Figure 1. Layout of MCT detector for 2D-PCI

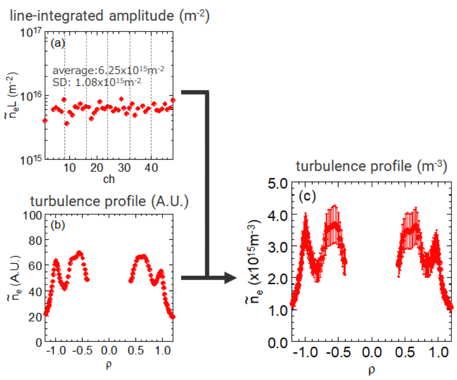

Figure 2. Process for evaluating the absolute value of fluctuation distribution.

[1] K. Tanaka *et al.*, Rev. Sci. Instrum. **79** (2008) 10E702

[2] T. Kinoshita *et al.*, JINST **15** (2020) C01045

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Development of Sweeping Detector Phase Contrast Imaging in LHD

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Phase contrast imaging (PCI) is one of the powerful techniques to measure turbulences in magnetically confined plasma. PCI can measure electron density fluctuation with excellent sensitivity by converting small phase variation to small intensity variation giving $\pi/2$ phase shift between scattered and non-scattered component. 10.6μm CO_2 laser and liquid nitrogen cooled HgCdTe multi-channel detector array are usually used. In order to get spatial resolution along the beam axis, the magnetic shear technique is applied. The magnetic shear technique makes use of turbulence characteristics and magnetic shear. The former has a strong asymmetry in the parallel and perpendicular directions of the magnetic field. This results in turbulence propagation to perpendicular direction to the magnetic field. The latter is spatial change of the magnetic field direction. Since the magnetic field direction is known from the equilibrium calculation, the location of the turbulence can be obtained from the propagation direction of the turbulence. In two-dimensional phase contrast imaging (2D-PCI), line integrated two-dimensional pictures of turbulence are measured by two-dimensional detector array. Spatial Fourier transform of a turbulence picture decomposes the turbulences in the direction of propagation. Then, a location of a turbulence is determined from the location of magnetic field which is perpendicular to the turbulence propagation.

In 2D-PCI for LHD utilizes 6x8=48 channels 2D-detector. However, spatial and wavenumber resolutions are not excellent in the present 2D system due to the limit of the channel number. In order to improve spatial and wavenumber resolutions, sweeping detector PCI (SD-PCI) was developed. For SD-PCI, the laser beam was separated into two, and one is aligned into a 1D detector which has a lot of channels, and a single channel detector into another detector as reference. Then, one of them is swept to a perpendicular direction to the 1D detector array with constant velocity and by dividing the swept area. Through this way, high-resolution 2D image of turbulence is obtained for steady state plasmas. In this study, 16-channels 1D detector was used as swept detector, and a center channel of 2D-detector for 2D-PCI as reference detector. As a result, 2D picture with 16x16=256 elements was obtained separating the swept area into 16. By using this technique, higher spatial and wavenumber resolution was realized compared with present 48ch 2D-PCI. In this conference, the detail method of SD-PCI and a profile of turbulence will be reported.

[1] K.Tanaka et al., Rev. Sci. Instrum. 79, 10E702 (2008)

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Design of an ultrahigh-bandwidth Phase Contrast Imaging system for fusion grade devices

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A preliminary design of a novel Phase Contrast Imaging (PCI) system that uses probing light in the Near-Infrared region is presented with application to fusion grade devices. The PCI diagnostic is an internal reference interferometer that creates an image of electron density fluctuations integrated along the line of sight of the probing laser beam. Conventional PCI diagnostics installed on worldwide fusion experiments employ laser light of wavelength equal to 10.6 um. A prototype PCI system using light at 1.55 um wavelength was developed on a bench-top to extend the spectral response in wave-number and frequency by factors of seven and over one hundred, respectively [1]. When absolutely calibrated using piezoelectric transducers and imaged onto properly sized arrays of detectors, such a system can potentially provide quantitative measurements of the internal structure of density perturbations induced by either turbulent or radio-frequency waves, simultaneously covering ion to electron gyro-radius scales up to the GHz frequency region. Being an internal reference interferometer, the PCI signal is insensitive to mechanical vibrations as long as proper alignment is maintained. The performance requirements for active feed-back systems stabilizing the position of a 1.55 um laser beam are evaluated and compared to those of conventional systems. Exploratory designs for such a diagnostic in fusion grade devices are presented, covering a variety of options in terms of system complexity, beam path lengths, spectral response, expected signal to noise ratio and corresponding overall costs for a given performance.

[1] A. Marinoni, *et al.,* JINST **17** (2022) C06011

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Optimization of HCN laser interferometer power automatic control system on EAST Tokamak

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The HCN laser interferometer is one of the necessary diagnostics for the operation of EAST Tokamak device, which can provide the necessary density feedback signal for the operation of EAST. Previously, an electric platform was used as an actuator to automatically adjust the HCN laser power[1], but the actuator adjustment precision is not very well. In addition, the control algorithm of the control system moves the actuator from a wave to next wave, so the power will be zero, which can affect EAST operation. At present, a new actuator is developed, using a piezoelectric ceramic and a stepper motor. The stepper motor is for coarse adjustment, the piezoelectric ceramic is for precise adjustment, so the precision of the new actuator is improved, accuracy up to nanometers. In addition, PID control method and slope judgment algorithm are used to optimize the power control system algorithm, which can make the output power of the laser stable at a peak and avoid the state of zero power. This is important for EAST operation.

[1] J.B. Zhang, *et al.* 2015 *JINST* 10 C11004

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Development of an HCN dual laser for the interferometer on a small tokamak device

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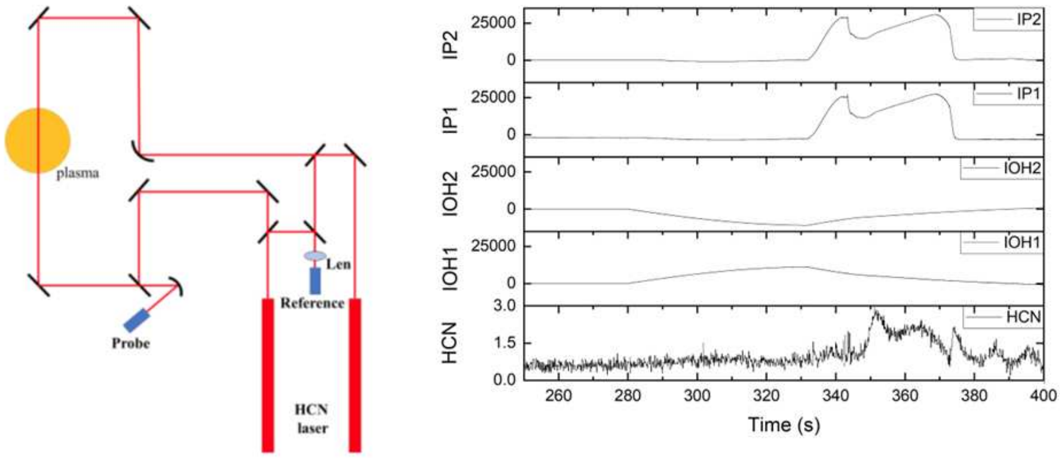
A dual hydrogen cyanide (HCN) laser interferometer has been designed and developed for measuring plasma electron density in a small tokamak device (R=0.65m, a=0.20m, BT≥15kG, and IP≥150kA). The dual HCN laser system comprises two terahertz continuous wave (CW) discharge pumped HCN lasers with an output frequency of 0.89 THz and an output power up to 100 mW. Different from the conventional method of modulating the intermediate frequency (IF) with a rotating grating, the dual laser's difference of cavity length is modified and maintained to generate the IF. The IF can reach up to 1 MHz, and the temporal resolution is 1 μs. We describe the detailed optical design for the dual HCN laser interferometer, and we verify the feasibility of the dual HCN laser interferometer system by simulating the plasma using a wedge, after which preliminary experimental results were obtained from the small tokamak device.



(a) (b)

Figure 1. (a) Schematic of the interferometer system, (b) Line-integrated electron density.

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Cotton-Mouton Effect Polarimetry on EAST Tokamak

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The feasibility of electron density measurement using the Cotton-Mouton (CM) effect is systematically investigated through a combination of theoretical derivation and simulations. For laser wavelength of 432.6 μm, fringe jumps due to phase shift over 2π can be avoided to provide reliable density measurement for machine operation. The study clarifies that elliptical modulation enables the direct measurement of the phase variation of the second component s_2 of the Stokes parameters, providing information about $\delta_{CM} = C_{CM}\lambda^3 \int B_{\perp}^2 n_e dl$. The measurement principle for heterodyne detection in the case of small CM effects is presented, along with the design of an optical setup. In a real laboratory environment, the power density of the two orthogonal light beams received by the detector may not be strictly equal. It is shown that non-equal power emission only affects the DC offset of the light intensity, and does not affect the phase variation of measured signals. It is further confirmed that the higher-order term errors introduced by the Faraday rotation effect on CM effect are small (1%) for current parameters of EAST.

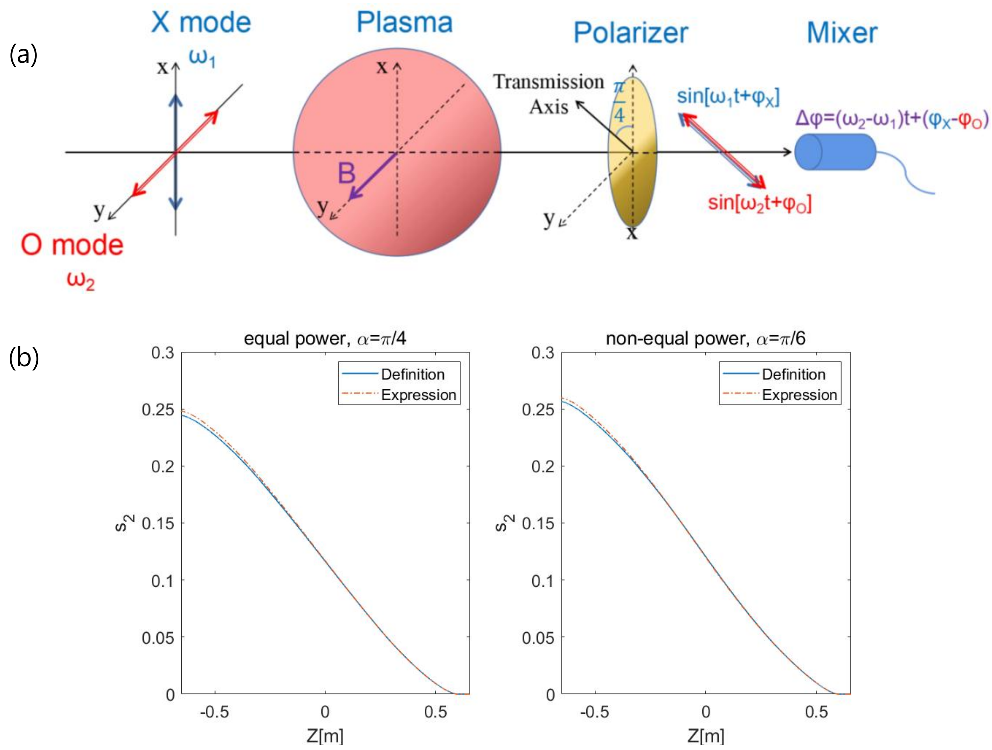

Figure 1. (a) Schematics of the optical arrangement of the CM polarimeter; (b) The comparative analysis of the simulated results for time modulation of s_2.

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Active Correction of Window Faraday Effects for ITER Laser Diagnostics

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Measurement of the change in polarization of a laser beam traversing a magnetized plasma is a standard diagnostic technique for extracting key plasma parameters, including density and current profile. Depending on the polarization orientation of the incident laser beam relative to the plasm magnetic field the polarization change is denoted either Faraday or Cotton-Mouton effect. On ITER three laser diagnostics will make use of this effect to make their measurements. Unfortunately, this effect is also evident when the laser beam passes through the vacuum window. The large magnetic field and finite Verdet constant of the window material mean that on ITER this effect – in particular Faraday rotation – are non-negligible, and needs to be disentangled from the desired measurement parameter. The Toroidal Interferometer-Polarimeter and Density Interferometer-Polarimeter, in particular, are affected. Both diagnostics use lasers in the 5-10 µm range, and will use zinc-selenide (ZnSe) as the vacuum window material.

In order to compensate for this a sensor is being developed to monitor the magnetic field perpendicular to the window and actively compensate for the Faraday rotation in real time. The sensor consists of an inductive coil closely fitting just in front of the window disc. It comprises several turns of fine wire in center-tap configuration. Both the raw voltage signal, as well as the integrated signal, will be monitored to estimate the magnetic field through the window disk. The system is designed to measure fields up to B<1T with an accuracy of 0.01T, at frequencies of D.C. to 1kHz. Alternatively, the raw signal specifications are dB/dt <0.5 T/s with a sensitivity of 0.001 T/s. The backend will use standard integrators developed for other ITER magnetics systems. Using the real-time magnetic field information, in conjunction with published and/or measured data on the Verdet constant of the ZnSe window material, in-house developed software will estimate the Faraday rotation induced on passing through the window

Initial prototypes of the sensor and results from preliminary characterization trials of the system will be presented. Detailed testing is planned for the future using the DIP system prototype currently under development.

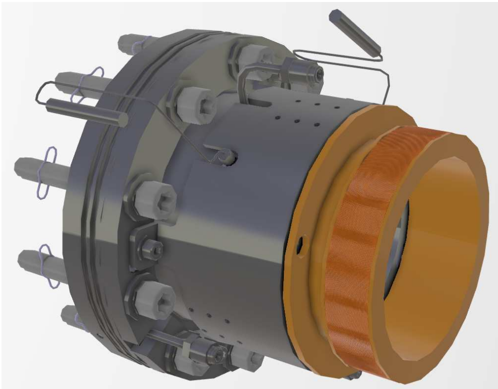

Figure 1. CAD model of magnetic sensor (orange) mounted on ITER window assembly.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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Design scheme of line array detection for Polarimeter-interferometer System on EAST

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Abstract—A multi-channel POlarimeter-INTerferometer (POINT) system has been constructed on the core region of Experimental Advanced Superconducting Tokamak (EAST) plasmas for electron density profile and current density profile measurements, with a spatial resolution of 8.5cm. Aiming to explore the small spatial scale density phenomena in the core plasma induced by MHD instabilities effects, a higher spatial resolution measurement is required. A novel line array detection scheme of POINT is proposed. By replacing the original single Schottky mixer with a line array HEMT detector at the central channel position, the original single channel can be extended to 5 channels for spatial continuous measurement, which has a significantly simplified structure design compared with the discrete upgrade scheme. Related optical design, components selection and bench test have been carried out to validate the feasibility and reliability of the novel scheme. The high responsivity and low noise of the detector can meeting the essential requirements of coherent signal measurement. Additionally, a circular plano cylindrical lens is designed as a beam-shaping component to compress the Gaussian beam into stripe. Bench test results obviously displayed the well performance of the cylindrical lens designed to convert the shape of laser beam. Furthermore, the coupling effect between the cylindrical lens and the line array HEMT detector in signal detection is optimized to verify the reliability of the scheme.

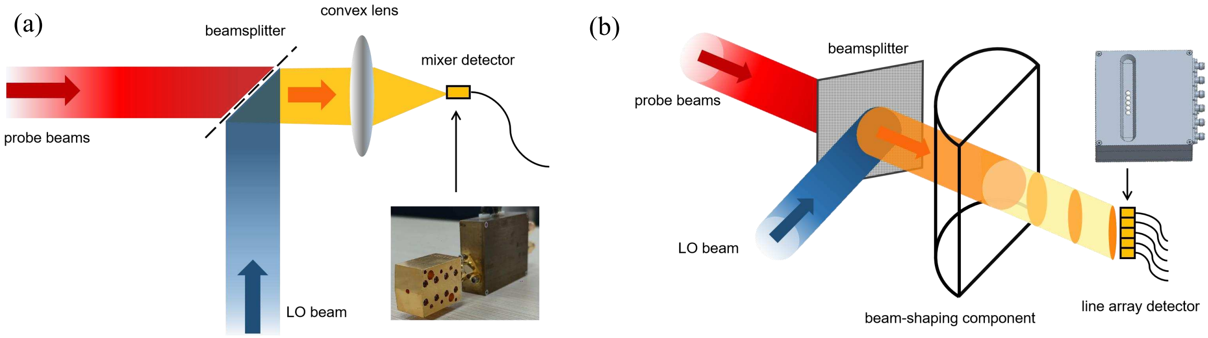

Figure 1. (a) original detection system , (b) a novel line array detection scheme .

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[4] Hillger P, *et al.,* IEEE Transactions on Terahertz Science and Technology, Vol. 9, pp.1-19, Jan 2019.

[5] Y.F.Sun, *et al*., Micronanoelectronic Technology, Vol. 54, pp.69-73, Nov 2017.

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Improvement of time resolution in optical vortex laser absorption spectroscopy using quadrant photodiodes

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We are developing optical vortex laser absorption spectroscopy (OVLAS) [1], which substitutes the probe beam of tunable diode laser absorption spectroscopy (TDLAS) with an optical vortex. OVLAS can measure the velocity component across the beam axis, which is undetectable with conventional TDLAS. Azimuthal Doppler shift in the optical vortex varies by each position, assuming uniform flow across the optical vortex beam. Therefore, using a camera as the detection system, the observed absorption spectrum indicates different Doppler shift for each pixel. Current OVLAS has successfully measured transverse flow velocity using a camera to accurately observe azimuthal Doppler shift distribution. However, the time resolution of the OVLAS, which is limited by data transfer and exposure times, needs to be improved for real-time measurement of time evolving velocity distribution function in plasma. To improve this, we employ a quadrant photodiode (QPD), a device that, unlike single-element conventional photodiodes, divides the photosensitive area into four sections. Furthermore, by using a lock-in amplifier, the azimuthal Doppler shift is measured at high speed.

Fig. 1 shows a schematic of the OVLAS using a QPD and a lock-in amplifier. The frequency of the ECDL is modulated, and the absorption signal from the QPD is input to the lock-in amplifier. Since the lock-in amplifier detects variations in absorption within the modulation frequency range as a DC component, a derivative waveform signal of the absorption spectrum can be observed by performing a frequency sweep of the laser. The Doppler shift corresponds to the point where the derivative value becomes zero. Therefore, the azimuthal Doppler shift can be conveniently measured with high time resolution by simply sweeping the frequency near the resonant absorption frequency. The details of the attempt at real-time OVLAS will be reported in this presentation.

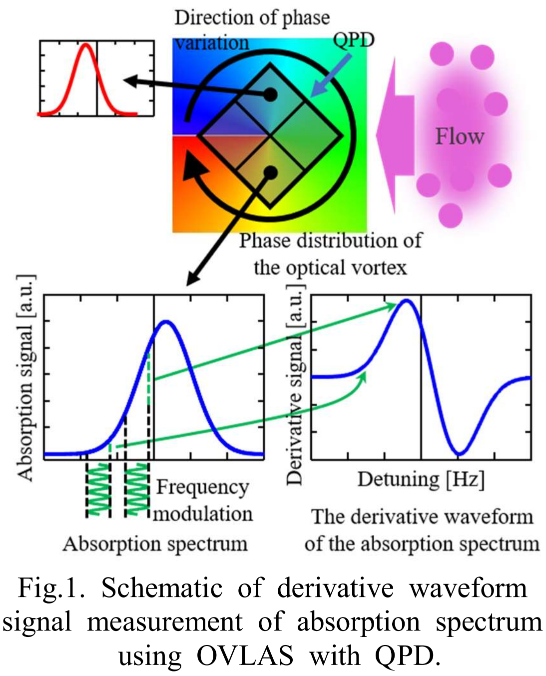

Fig.1. Schematic of derivative waveform signal measurement of absorption spectrum using OVLAS with QPD.

[1] H. Minagawa *et al.*, Plasma Fusion Res.**17**, 1401099 (2022)
[2] L. Allen *et al.*, Opt. Commun. **112**, 141 (1994).

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High-sensitivity Lamb dip spectroscopy with frequency modulation technique

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The Balmer-alpha line of atomic hydrogen is useful for sheath electric field measurements because of its accessibility by diode lasers and its high-sensitivity to electric field due to the linear Stark effect. The Balmer-alpha line of atomic hydrogen has fine structure components and a large Doppler broadening. Therefore, the Doppler-free spectroscopy is required for highly sensitive electric field measurements. However, it is difficult to apply a simple Doppler-free absorption spectroscopy because the hydrogen plasma is optically thin for the Balmer-alpha line of atomic hydrogen. In our previous work, a high-power and pulse modulated hydrogen plasma was used to demonstrate sheath electric field measurement [1]. The modulation technique limits the applicability of electric field measurement for other plasmas.

In this work, we applied the frequency modulation (phase modulation) technique [2] to enhance the sensitivity of absorption spectroscopy for low-power cw plasmas. In the frequency modulation technique, the laser light frequency is modulated by a high-frequency sinusoidal wave. The laser light of frequency f_0 modulated by frequency f has sideband components at $f_0 + f$ and $f_0 - f$ with antiphase. The modulated laser light is transmitted through a plasma and detected by a photodiode. When the two sideband components have different intensity at the detector, a beat signal with a frequency of f is generated. For Lamb dip spectroscopy, the modulation frequency is chosen to be equal to the Lamb dip width, typically tens MHz, and the RF signal is detected with high sensitivity by an RF lock-in amplifier or narrow band RF rectifier. We confirmed this technique with the argon $4s[3/2]^o_2$-$4p[3/2]_2$ transition in a low-density plasma. The laser light oscillated by a tunable diode laser was phase modulated by an electro-optic modulator with a 50 MHz RF signal. The modulated laser light was split into two beams, an intense pump beam and a weak probe beam, and then injected into the plasma from counter directions. Two beams were crossed in the plasma at a small angle. The transmitted probe beam was led to an avalanche photodiode detector. The detected RF signal was amplified, rectified and the signal intensity was recorded on an oscilloscope. The Lamb dip of 2.5×10^{-3} depth was clearly detected. The results applied to the Balmer-alpha line of atomic hydrogen will be discussed at the conference.

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[2] G. C. Bjorklund, Opt. Lett. **5**, 15-17 (1980)

*Presenting author: s-nishiyama@jhu.ac.jp

Investigation of Molecular-Impurity Decomposition in High-Pressure Low-Temperature Plasmas Using Laser Absorption Spectroscopy

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In experimental studies of plasmas, it is challenging to completely eliminate impurities incorporated into the gas flow between the gas cylinder and the discharge space. The small-fraction impurities impact the discharge behaviors in high-pressure low-temperature plasmas because of the frequent collision between electrons/ions/excited species and the impurities. When the impurity includes molecular species, they are decomposed in the plasma. The molecular-impurity decomposition changes the total fraction and reaction rates of the impurity, and spatiotemporal characteristics of plasma parameters. To precisely control reaction kinetics (e.g., selective generation of critical reactive species for applications) in high-pressure low-temperature plasmas, molecular-impurity decomposition is one of the key phenomena which must be quantitively evaluated.

This study investigates the molecular-impurity decomposition in a high-pressure dielectric barrier discharge (DBD) in high-purity helium (He) gas flow. We have revealed by optical emission spectroscopy (OES) that a major impurity species in our He-DBD system is water (H_2O) vapor [1], and the H_2O decomposition depends on the original impurity fraction and the discharge conditions [2]. To quantify the impurity fraction and analyze the decomposition, time-resolved laser absorption spectroscopy (LAS) of the He metastable 2^3S_1 (He^m) atom is installed in the system. (Fig. 1(a)) The dependence of He^m quenching frequency on the applied-voltage frequency (Fig. 1(b)) is analyzed in detail to achieve the quantitative investigation of H_2O decomposition in the He-DBD.

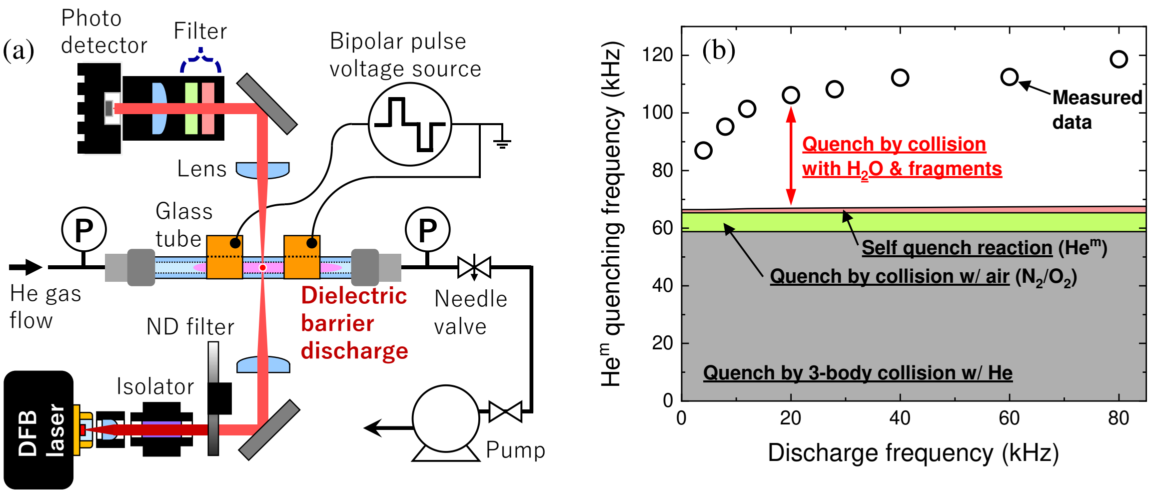

Figure 1. (a) Experimental setup of He-DBD and LAS used in this study. (b) Dependence of He^m quenching frequency on the discharge frequency measured by the LAS method. The contribution of gas species to the He^m quench is shown to investigate the influence of H_2O decomposition.

[1] K. Urabe *et al.,* Proc. 75th GEC / 11th ICRP, HW6.00048 (Sendai, Japan, 2022).
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Simulation of Doppler-free Spectra using the Collisional Radiative Model

J. J. Simons[A] and M. Goto[A,B]

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Saturated absorption spectroscopy is a tool that can be used to suppress the Doppler broadening of observed atomic and molecular transition lines in order to measure their precise wavelengths. Obtaining a saturated absorption condition by laser excitation is an essential technique for use in saturated absorption spectroscopy. We are introducing the laser excitation process into the collisional-radiative model of hydrogen atoms to uncover how much saturation can be achieved under realistic plasma conditions and laser power density. Results show that the simulated spectra were able to successfully model Lamb dips and peaks utilising this method, with the simulated plasma and laser parameters showing good agreement with the ones used in the experiment. This model has additionally helped to give further insight into how plasma parameters can affect the spectral characteristics of Lamb dips and peaks by noting the dependence of the simulated spectral saturation on these parameters.

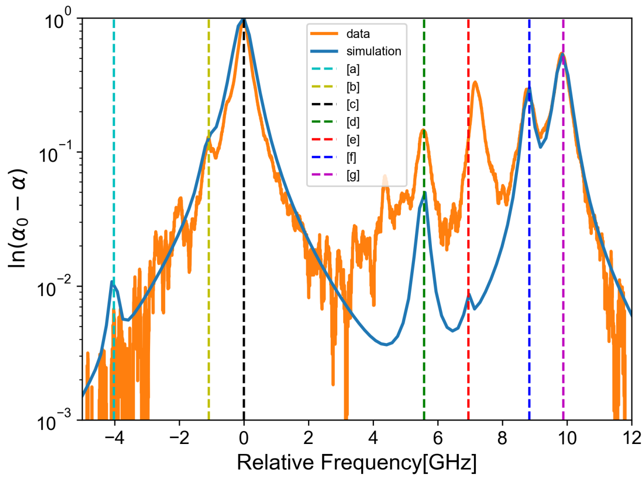

Fig. 1: Log plot of direct comparison between experimentally obtained Doppler-free Lamb peak spectra [data] with simulated model Lamb peak spectra [simulation], showcasing the 7 fine structure hydrogen Balmer-α transition lines [a-g].

Magnetic field stabilized atmospheric pressure plasma: Diagnosis of gas temperature and its effect on nitrogen fixation

Z. Li [1*], X. Li [1], L. Nie [1], D Liu [1], and X. Lu[1]

[1] *State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, HuBei, 430074, People's Republic of China*

In this work a magnetic field stabilized atmospheric pressure plasma is reported. The plasma is fixed at a position when the direction of the Lorentz force and the air flow is opposite. Under such condition, a stable glow discharge can be achieved, the plasma characteristics, such as gas temperature and electric field [1], don't vary with time and can be independently adjusted by controlling the discharge current, the gas flow rate and the external magnetic field. Laser-induced Rayleigh scattering method [2] is used to measure the plasma gas temperature, which plays an important role in chemical reactions [3, 4]. The results show that the gas temperature of the inverted U-shaped plasma channel is almost the same and it decreases from 2637 K to 1474 K with the increase of the gas flow rate, which is beneficial for the production of NO_x, and the energy cost is reduced by about 15 %. In addition, the increase of the discharge current only leads to the decrease of the average electric field of plasma channel from 0.75 $kV \cdot cm^{-1}$ to 0.55 $kV \cdot cm^{-1}$, while the gas temperature varies little. The best energy cost is obtained at a discharge current of 55 mA, a gas flow rate of 6 $L \cdot min^{-1}$, and an O_2 fraction of 40 %. The lowest recorded energy cost of 2.29 $MJ \cdot mol^{-1}$ and a NO_x concentration of approximately 15925 ppm are achieved.

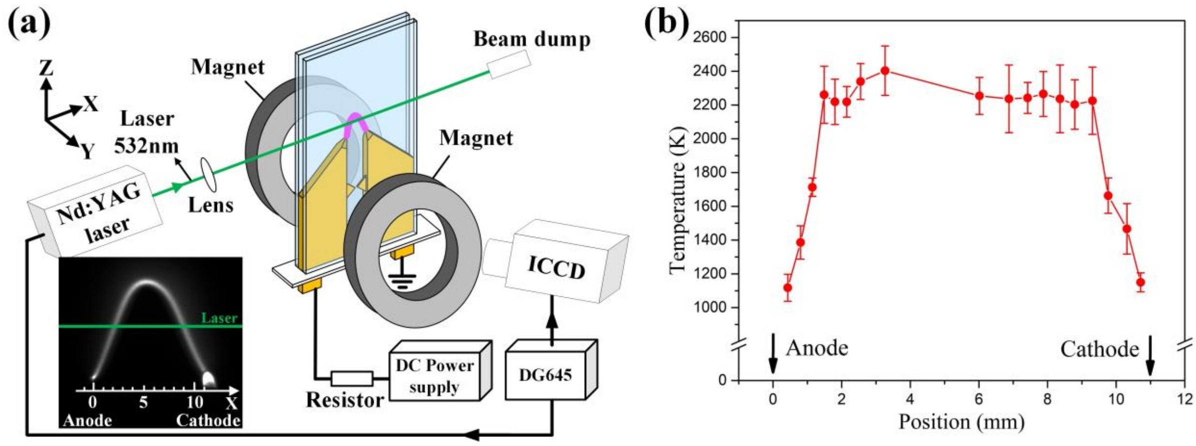

Figure 1. (a) Schematic of the plasma gas temperature measurement system. (b) Spatial distribution of gas temperature in the plasma channel.

[1] W. Wang, *et al.*, ChemSusChem, **10** (2017) 2145

[2] J. Li, *et al.*, Curr. Appl. Phys. **34** (2022) 41–49

[3] S. Alphen, *et al.*, Sustain. Energy Fuels, **5** (2021) 1786

[4] S. Alphen, *et al.*, Chem. Eng. J. **443** (2022) 136529

*Presenting author: zhiyuli@hust.edu.cn

Laser Thomson Scattering Measurements around Magnetized Model in Rarefied Argon Arc-jet Plume

H. Katsurayama[1*], R. Wada[1], K. Moriyama[1], and K. Tomita[2]

[1]*Mechanical and Aerospace Engineering Course, Tottori University, Tottori, Tottori 680-8552, Japan*
[2]*Division of Applied Quantum Science and Engineering, Hokkaido University, Sapporo, Hokkaido 060-8628, Japan*

Magnetohydrodynamic aerobraking [1] is attracting attention as a thermal protection system for atmospheric entry vehicles. This system uses the Lorentz force to control the weakly ionized plasma generated around the vehicle during atmospheric entry. To investigate the mechanism of the Lorentz force generation at high altitudes, where the Hall effect is dominant, we measured the electron temperature and density around a magnetized model with 0.35 T in a rarefied supersonic argon plasma using the non-collective laser Thomson scattering (LTS) method, which uses a triple-grating spectrometer with a Rayleigh block [2]. We compared the measurements with a detailed computational fluid dynamics (CFD) analysis [3]. Figure 1 compares the radial distributions of the electron temperature and density in the LTS and CFD. Without the magnetic field, the CFD overestimated the electron temperature of the LTS by only about 500 K and reproduced its radial distribution well. With the magnetic field, the LTS measurements showed an increase in electron temperature only at r=0 mm and a sharp decrease with radial direction. On the other hand, the CFD values showed an overall increase in electron temperature. The radial distribution of the electron density showed a negligible effect on the magnetic field, and the LTS and CFD values were in excellent agreement.

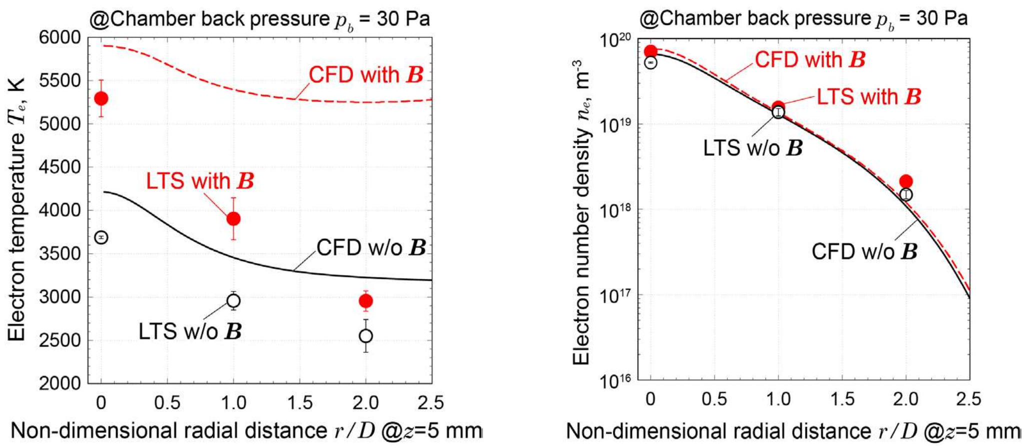

Figure 1. Comparison of radial distributions of electron temperature and density in LTS and CFD.

[1] A. R. Kantrowitz, Proc. Conf. High-Speed Aeronaut. (1995) 335.

[2] K. Tomita, *et al.,* Plasma Fusion Res. **12** (2017) 1401018.

[3] H. Katsurayama and T. Abe, J. Appl. Phys. **113** (2013) 053304.

[*]Presenting author: katsurayama@tottori-u.ac.jp

Laser Thomson scattering system for anisotropic electron temperature measurement in NUMBER

A. Okamoto*, S. Higuchi, K. Sato, Y. Yamada, M. Koike, M. Sugimoto, and T. Fujita

[1]*Nagoya University,*
Nagoya, 464-8603, Japan

The laser Thomson scattering is a powerful measurement tool for electron energy distribution. Injecting a laser with an oblique angle to the external magnetic field and detecting scattering photon from a line of sight along another oblique angle enable us to obtain parallel and perpendicular components of electron temperature [1]. In order to clarify the effect of electron temperature anisotropy on volumetric recombination process [2] and intermittent bursting events [3], we have developed a laser Thomson scattering system in the Nagoya University Magnetoplasma Basic Experiment (NUMBER) device. Optics layout is shown in Fig. 1. A 2nd harmonics of Nd:YAG laser is injected into an observation volume, which is located in 0.2 m downstream from the electron cyclotron resonance (ECR) point in a diverging magnetic field configuration. Backward (165°) scattering spectrum corresponds to quasi perpendicular velocity distribution, while that for forward (15°) scattering; quasi parallel. Collecting lenses are set in vacuum to maximize solid angle in a limited space of port, where the laser path and collecting optics share an ICF152 flange. A standard imaging spectrometer is used to evaluate stray light level. Rayleigh scattering intensity is measured as a function of argon gas pressure. An initial result on residual stray light intensity is equivalent to the argon Rayleigh scattering intensity under ≤ 1 kPa of filled pressure. In order to obtain Thomson scattering spectra, a notch filter type stray light rejection optics is proposed. Collected light transferred through an optical fiber is collimated and passes a reflective type volume holographic grating. Then the stray light is reflected, while Doppler shifted Thomson spectrum passes through the grating.

This work was supported by JSPS KAKENHI Grant Nos. JP19H01869, JP20H01883, and JP23H01148.

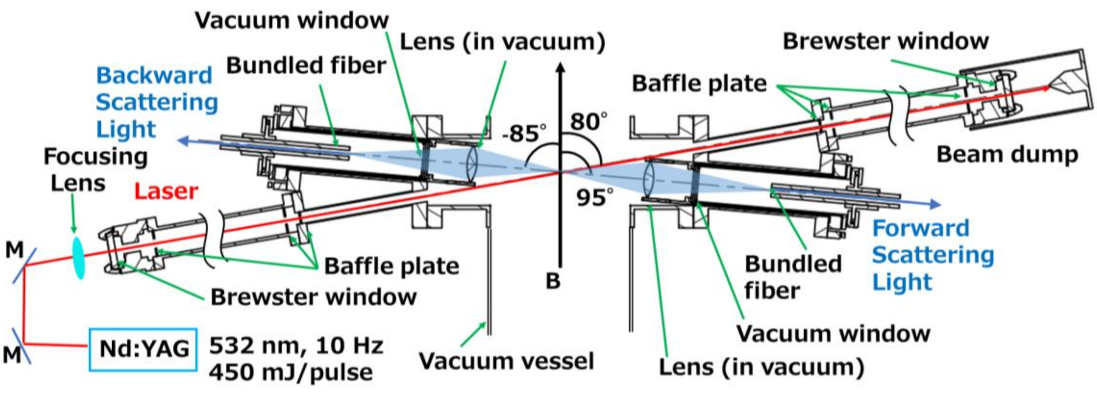

Figure 1. Schematic of Thomson scattering optics installed in NUMBER.

[1] M.D. Bowden, *et al.,* J. Appl. Phys. **73** (1993) 2732.
[2] K. Yagasaki, *et al.,* Plasma Fusion Res. **18** (2023) *in press.*
[3] A. Okamoto, *et al.,* Jpn. J. Appl. Phys. **62** (2023) *in press.*

*Presenting author: a-okamoto@energy.nagoya-u.ac.jp

Improving pulsed laser induced fluorescence signal-to-noise through matched filter signal processing

T.J. Gilbert[1*], K.J. Stevenson[1], T.E. Steinberger[1], E.E. Scime[1]

[1] *Department of Physics and Astronomy, West Virginia University, Morgantown, WV, USA*

The PHAse Space MApping (PHASMA) facility was constructed to facilitate laboratory electron-only magnetic reconnection studies at kinetic scale lengths using dual plasma gun discharges. Electron velocity distribution functions (VDF) have been measured during electron-only magnetic reconnection with a Thompson scattering diagnostic [1-3]. No effect is expected on ions or neutrals in the reconnection event in PHASMA, but this has yet to be successfully measured. A discrete pulsed laser induced fluorescence (LIF) diagnostic is being developed for PHASMA to measure both ion and neutral VDFs during magnetic reconnection. LIF is a non-perturbative laser spectroscopic technique that uses the Doppler motion of a species and a narrow linewidth laser to measure the VDF of ions or neutral atoms. It has also been shown that LIF measurements of Zeeman split spectra offer a method to measure magnetic fields in laboratory plasmas [4,5]. Using neutral LIF schemes that exhibit strong Zeeman splitting, we can non-perturbatively measure the magnetic field throughout the reconnection event without the use of probes. Performing LIF during a plasma gun discharge presents unique challenges. A pulsed dye laser is necessary to produce sufficient fluorescent signal, but to avoid laser saturation, measurements must be made at relatively low laser energies at which reliable signal is only recovered by averaging over many plasma discharge events. We have implemented a matched filter signal processing technique to greatly improve the signal-to-noise ratio of our measurements. This allows us to reduce the number of discharges needed to measure a VDF or to achieve signal at lower laser energies.

[1] P. Shi, *et al.*, "Incoherent Thomson scattering system for PHAse space MApping (PHASMA) experiment," Review of Scientific Instruments **92**, 033102 (2021) https://doi.org/10.1063/5.0040606

[2] P. Shi, *et al.*, “Laboratory Observations of Electron Heating and Non-Maxwellian Distributions at the Kinetic Scale during Electron-Only Magnetic Reconnection,” Physical Review Letters **128**:2, 025002 (2022)

[3] P. Shi, *et al.*, "Electron-only reconnection and associated electron heating and acceleration in PHASMA," Physics of Plasmas **29**, 032101 (2022) https://doi.org/10.1063/5.0082633

[4] D.S. Thompson, *et al.*, “Laser induced fluorescence of Ar-I metastables in the presence of a magnetic field,” Plasma Sources Science and Technology, **27**, 065007 (2018)

[5] T.J. Gilbert, *et al.*, "Magnetic field imaging in a laboratory plasma", AIP Advances **11**, 055314 (2021) https://doi.org/10.1063/5.0052957

*Presenting author: tjg0030@mix.wvu.edu

TALIF and CARS Diagnostics for Measuring Atomic and Molecular Hydrogen Densities in Divertor-relevant Plasmas

K. Schutjes[1*], K.J. Loring[1,2], I.G.J. Classen[1], J. Vernimmen[1], H.J. van der Meiden[1], C.J.D. Robben[1] and the Magnum-PSI team[1]

[1]*Dutch Institute For Fundamental Energy Sources (DIFFER), Eindhoven, The Netherlands*
[2]*Stanford University, Palo Alto, California, United States of America*

One of the biggest challenges of a reliable fusion reactor is the handling of large heat and particle loads on the divertor wall. Key to reducing these loads is by plasma detachment, in which a large range of processes occur between the plasma and the neutral background [1,2]. Atomic and molecular processes largely determine the plasma dynamics, which is why these particles are often studied in divertor research [1,2]. However, measurements on electronic ground state densities for atoms and molecules are lacking for divertor-relevant plasmas. We will use active laser spectroscopy, using TALIF and CARS, to measure these densities.

To measure the atomic hydrogen ground state density, a TALIF setup has been developed to allow measurements in the linear plasma device UPP. UPP is able to create divertor-relevant plasma conditions ($n_e \approx 10^{20}$ m^{-3}, $T_e < 5$ eV). Nanosecond laser pulses in the 204-206 nm range are used to excite hydrogen from the ground state, and fluorescence was monitored with a gated ICCD camera. The first spatially-resolved measurements in UPP were performed and the results are shown in Figure 1. In the centre of the plasma column, closest to the target, the density is measured to be highest at $2.3 \cdot 10^{19}$ m^{-3}. Increasing the target distance seems to yield a hollow density profile, until reaching a constant value around $1 \cdot 10^{19}$ m^{-3} for larger distances.

A CARS setup is currently under construction to determine the rovibrational distribution of hydrogen molecules in the electronic ground state, and is expected to measure populations up to the second vibrational state. The plans for incorporating this setup in UPP will be discussed.

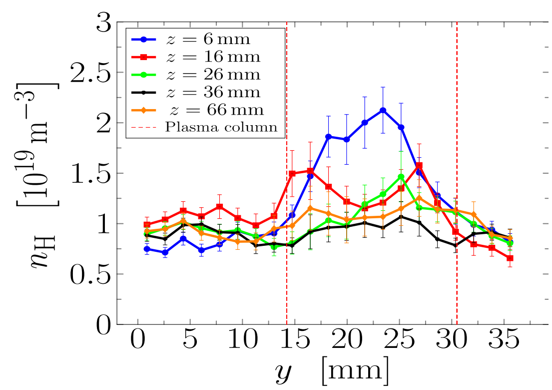

Fig. 1: spatially-resolved measured atomic ground state hydrogen densities, at varying radial positions *y* for a given distance to a tungsten target *z*.

[1] A. Loarte, *et al.,* Nucl. Fusion 47 S203 (2007). DOI: 10.1088/0029-5515/47/6/S0
[2] S.I. Krasheninnikov and A.S. Kukushkin, J. Plasma Phys. 83 (2017). DOI:10.6100/IR58304

*Presenting author: k.schutjes@differ.nl

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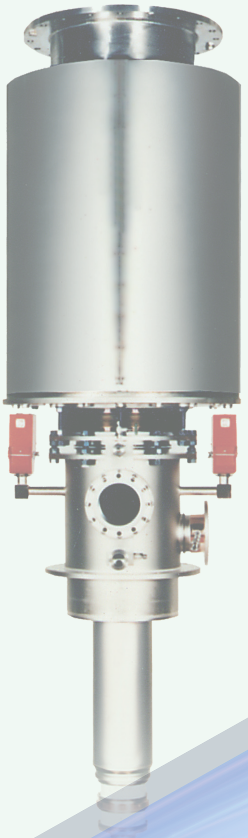

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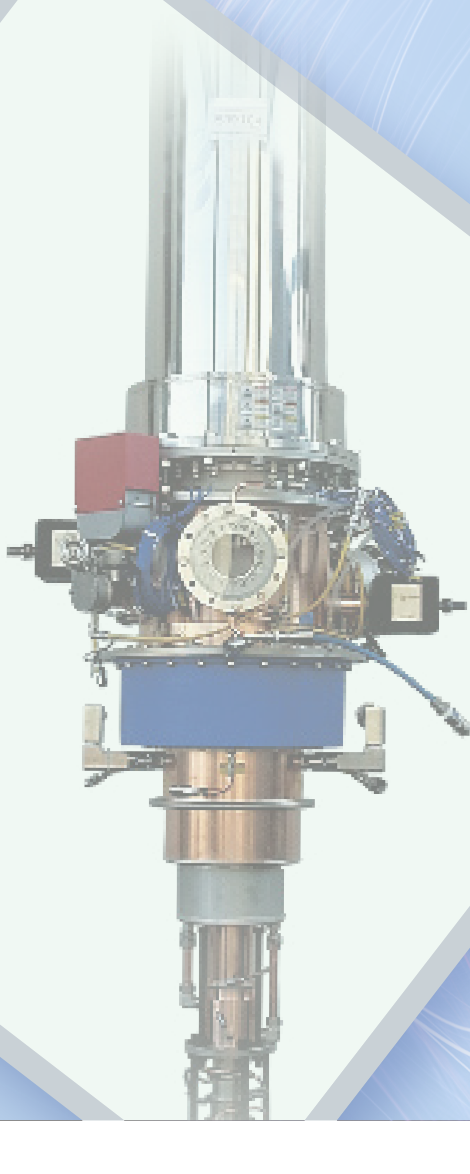

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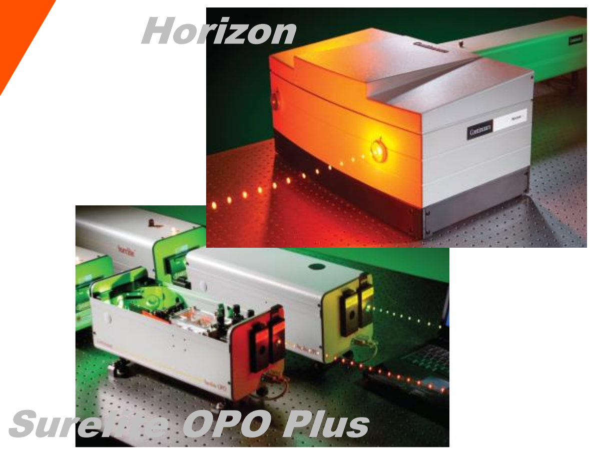

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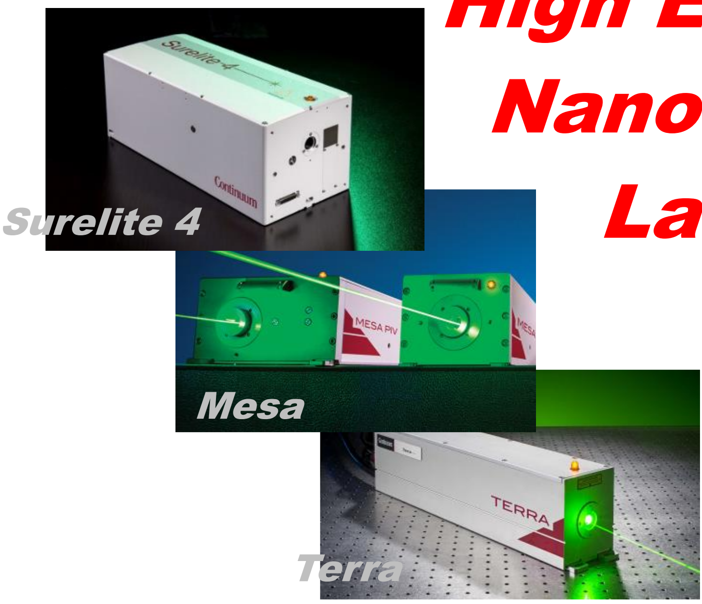

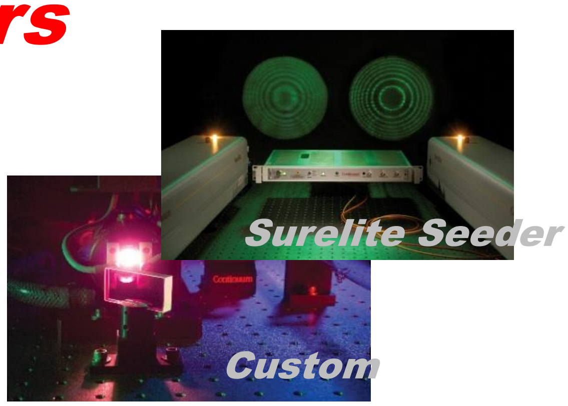

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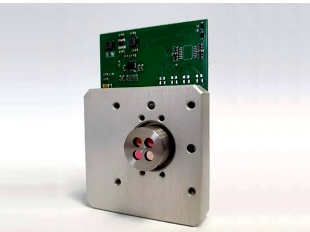

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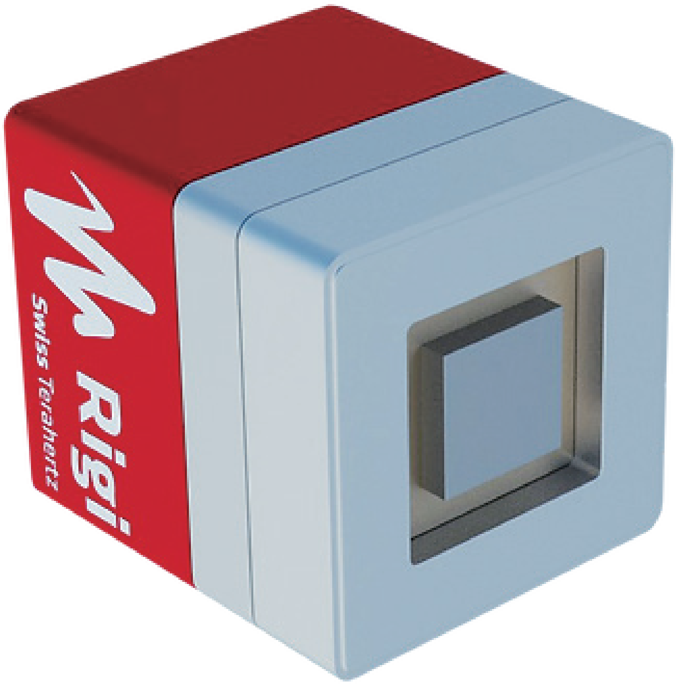

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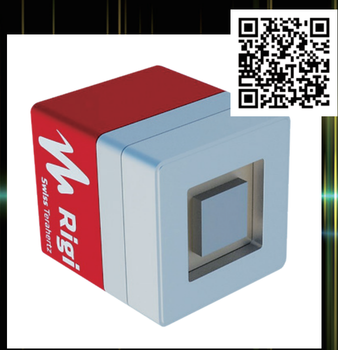

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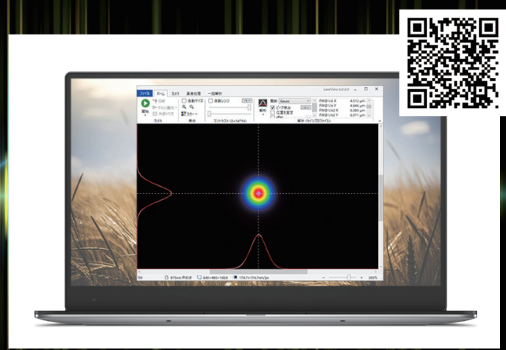

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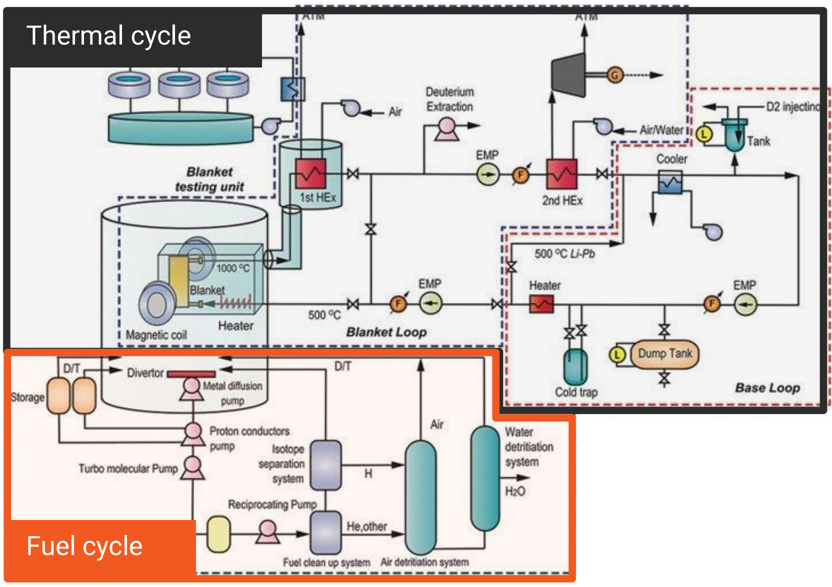

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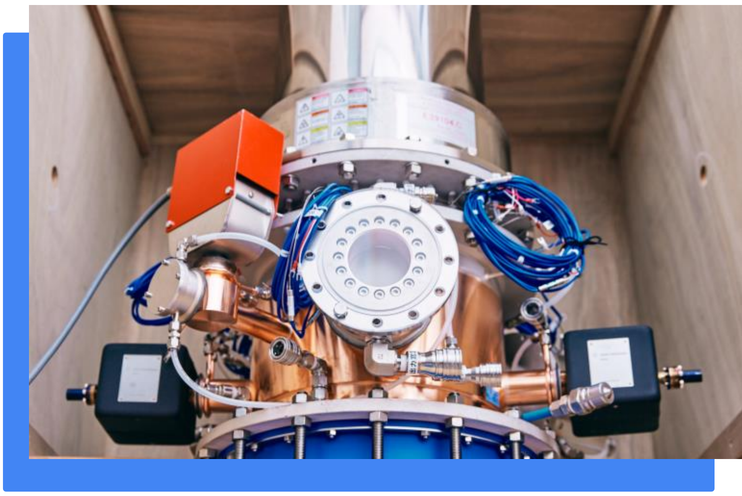

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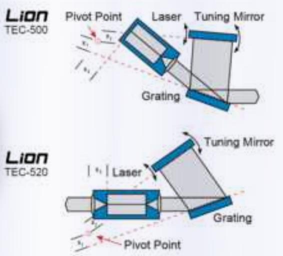

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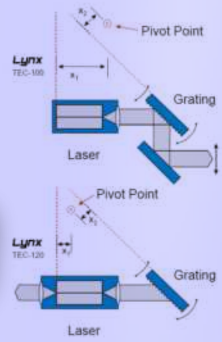

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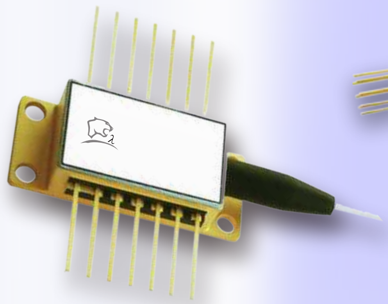
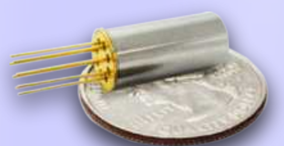
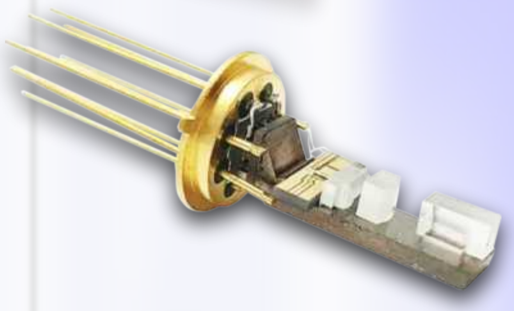
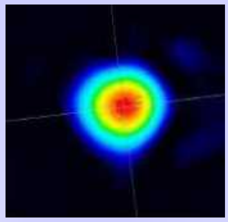




波 長 ラインアップ	**633 ～ 1908 nm** 633, 638, 671, 674, 679, 689, 698, 707, 729, 767, 770, 780, 785, 795, 830, 843, 845, 852, 866, 895, 995, 1064, 1397, 1908 nm
パワー	**～ 500 mW**
パッケージ	**TO39 or バタフライ**
線幅	**100 kHz @ 1ms**





- モノリシックキャビティデザイン・可動部品なし
- サイドモード抑圧比 ＞40 dB
- 高速波長チューニング ＞10 kHz
- 非点収差フリーのビーム
- シングルモードファイバ出力オプション

ナノ秒パルスレーザーシステム

Nanosecond Pulsed Laser System

Cat series

TEC-045
レーザーヘッドシステム

TEC-047
バタフライパッケージシステム

コンパクトなナノ秒ダイオードレーザーシステムです。パルス幅は PC より可変できます。時間分解蛍光分光などに最適です。

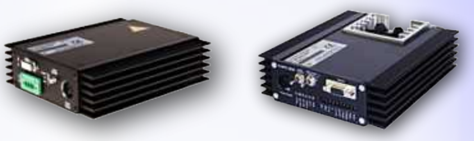
波長		**375 to 1650 nm**
ピークパワー	TEC-045	**up to 300 mW / 30 nJ**
	TEC-047	**up to 20 mW**
パルス幅		**5 ns to 100 ns** (CW モードあり)
繰り返し	TEC-045	**16 kHz to 67 MHz**
	TEC-047	**up to 133 MHz**

レーザーコントローラー
PilotPC series

Pilot PC シリーズは、ベンチトップ型で超精密・低ノイズのマイクロプロセッサー制御によるコントローラーです。LD 電流または光出力、LD 温度を正確に制御することができます。GPIB/IEEE488.2、RS232・USB を装備し、遠隔プログラミングと読み込みができます。

レーザーコントローラー
PioltOEM/BFY series

PilotOEM・BFY シリーズは産業用品質、超精密・低ノイズのマイクロプロセッサー制御によるコントローラーで、過酷な環境に対応できるよう設計されています。LD 電流または光出力、LD 温度を正確に制御することができます。GPIB/IEEE488.2、RS232・USB を装備し、遠隔プログラミングと読み込みができます。スロースタート機能、インターロック、コンプライアンス電圧保護、受動極性保護など、安全対策機能も充実しています。



Thorlabs Solutions

フェムト秒パルスレーザ
Femtosecond Lasers

当社では、さまざまな用途のフェムト秒(fs)レーザをご用意しています。

▶ Ti:サファイアレーザ
OCTAVIUS-85M-HP オクターブ帯域にわたる広い出力スペクトル幅


OCTAVIUS-85M-HPの出力スペクトル

OCTAVIUS-85M-HP

パルス幅	< 8 fs
平均出力	> 600 mW

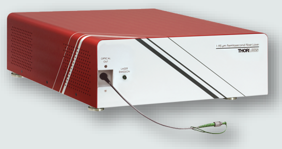
▶ 中赤外域SC光源
SC4500 低い強度ノイズ

波長帯	1.3～4.5 µm
平均出力	> 300 mW

▶ ER添加 偏波保持ファイバ設計
FSL1550
1.56 µmファイバーレーザ

パルス幅	< 40 fs
平均出力	> 500 mW

▶ 高ピーク出力 2 µmレーザ
FSL1950F
1.95 µmファイバーレーザ



パルス幅	< 80 fs
ピーク出力	>100 kW

▶ 繰り返し周波数可変Ybレーザ
FSL1030X1/-X2
1030/1035 nm レーザ

パルス幅(fs)	< 220(-X1), <130(-X2)
エネルギー	> 2～3 µJ
繰り返し	1～11 MHz

▶ 分散測定システム 超短パルス用光学素子の特性を測定するのに適した分散測定システムです。測定ごとに、位相、群遅延、群遅延分散(GDD)、3次分散、4次分散を評価できます。

- 分散測定システム **CHROMATIS** (500～1100 nm)
- InGaAsディテクターモジュール CHROMATIS用アドオン **CHRDETN** (1000～1650 nm)

・標準測定モード
入射角0°、反射光測定
入射角0°～70°、透過光測定
入射角5°～70°、反射光測定

・S偏光およびP偏光を同時に測定

※仕様は予告なく変更される場合があります。予めご了承ください。

www.thorlabs.co.jp E-mail: sales@thorlabs.jp

THORLABS ソーラボジャパン株式会社・〒179-0081 東京都練馬区北町3-6-3・TEL：03-6915-7701

軟X線、EUVを100fpsで直接撮像可能！
リソグラフィ、タイコグラフィ用途などに最適

軟X線/EUV用高速sCMOSカメラ Marana-X

OXFORD INSTRUMENTS ANDOR

お問い合わせNo：**AD18**

特長

- 背面照射型sCMOSセンサー搭載
- VUV、EUV、軟X線検出用
- 高画素：4.2メガピクセル（2048×2048）
- 高感度：最大量子効率99%
- 高速：74 fps（フルフレーム），108 fps（1400×1400画素）
- ハイダイナミックレンジ：最大16bit

用途・アプリケーション

- *in situ* X線計測
- トモグラフィー
- X線分光法
- ハイパースペクトルイメージング
- EUV リソグラフィー
- EUV タイコグラフィー

ウェイクフィールド粒子加速、X線・高次高調波発生など

フェムト秒OPCPAレーザー UltraFlux シリーズ

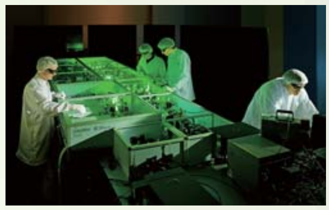
EKSPLA

お問い合わせNo：**EP51 / EP46 / EP25**

光パラメトリックチャープパルス増幅（OPCPA）は、従来の Ti：サファイアよりも、
高い出力が得られ、優れた時間コントラスト、広帯域バンド幅を実現します。

特長

- 波長可変：750 ～ 960 nm, 375 ～ 480 nm, 250 ～ 320 nm, 210 ～ 230 nm
- パルス幅：最小 10 fs
- 高エネルギーモデル：最大 1 J　>50 mJ@100Hz
- 高繰り返しモデル：最大 14 mJ@1kHz
- カスタムモデル：>15 TW、sub-8 fs、>120 mJ、>120 W



プラズマ研究、OPCPAやTWシステムの励起に最適

高エネルギーピコ秒/ナノ秒レーザー

EKSPLA

お問い合わせNo：**EP69 / EP71 / EP40**

高度なビーム整形技術により、ホットスポットのない滑らかなビーム空間プロファイルを実現しています。
高エネルギーモデル、高繰り返し高出力モデル、パルス時間波形を任意に制御可能なモデルと多様なラインナップがございます。

モデルごとの特長

- APL HE　最大 2.2 J、20 ～ 300 ps、10 Hz
- APL HP　最大 >150 mJ、20 ～ 300 ps、最大 2 kHz
- ANL AWG　最大 10 J、10 Hz、ナノ秒パルス任意時間波形
- ANL HP　最大 3.7 J、1 kHz、2 ～ 500 ns

その他ナノ秒・ピコ秒波長可変レーザーもございます、お気軽にお問い合わせ下さい。

TII 東京インスツルメンツ TOKYO INSTRUMENTS

本　　社：〒134-0088 東京都江戸川区西葛西6-18-14 T. I.ビル　03-3686-4711
大阪営業所：〒532-0003 大阪府大阪市淀川区宮原4-1-46 新大阪北ビル　06-6393-7411
https://www.tokyoinst.co.jp　sales@tokyoinst.co.jp

TII Group Company ー グローバルにネットワークを広げ、最先端の科学をお客様に提供 ー

UNISOKU TII Group
超高真空・極低温走査型プローブ顕微鏡
高速分光測定装置、クライオスタット

LOTIS TII
Nd:YAGレーザー、Ti:Sレーザー
OPOレーザー

SPECS™ - TII
Enviro ESCA（準大気圧XPS）
ARPESなど

液体窒素ジェネレーター
Liquid Nitrogen Generator

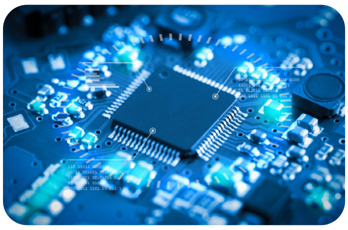
フロン不使用

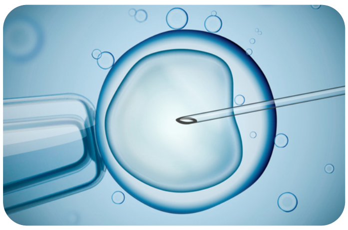
空気から液体窒素を作れます

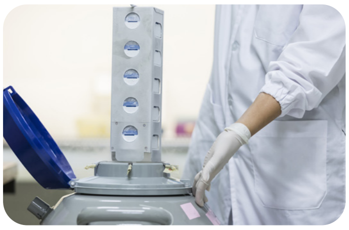
詳細はwebへ
VOC動画も公開中

液体窒素をOne Pushで取出し可能

液体窒素を様々な場面で活用







- 電源さえあれば、空気から液体窒素が作れます。
- 電子顕微鏡、フーリエ変換赤外分光光度計、ゲルマニウム検出器など様々な分析機器への液体窒素自動供給の実績も御座います。
- 液体窒素にまつわる発注業務・管理・補充・運搬などの煩雑さから解放されます。

型式	EMP-07W/A	EMP-14W/A	EMP-20W	MP-300K
冷却方式	水冷式/空冷式	水冷式/空冷式	水冷式	水冷式
液化量	8L/day	14L/day	20L/day	30L/day

ULVAC CRYOGENICS INC.
www.ulvac-cryo.com　TEL：0467-85-8884（営業）

List of Participants

presentation	name	country	affiliation
P1-15	Akimitsu, Moe	Japan	National Institutes for Quantum Science and Technology (QST)
P1-24	Aramaki, Mitsutoshi	Japan	Nihon University
	Bilkova, Petra	Czech Republic	Institute of Plasma Physics ASCR, v.v.i.
P2-1	Bong, Seungmin	Korea	Korea Advanced Institute of Science and Technology (KAIST)
G1	Bruggeman, Peter	USA	University of Minnesota
G4	Brunner, Kai J.	Germany	Max-Planck-Institut für Plasmaphysik
P1-16	Carole, Mathieu M.	France	The French Alternative Energies and Atomic Energy Commission (CEA)
P1-25	Cho, Hyeondo	Korea	Korea Advanced Institute of Science and Technology (KAIST)
T7	Choe, Wonho	Korea	Korea Advanced Institute of Science and Technology (KAIST)
P2-5	Choi, Seongmin	Korea	Korea Advanced Institute of Science and Technology (KAIST)
G6	Coda, Stefano	Switzerland	EPFL - SPC
P1-17	Colledani, Gilles	France	CEA Cadarache
G3	Czarnetzki, Uwe R.	Germany	Ruhr University Bochum
T5, P1-18	Den Hartog, Daniel J.	USA	University of Wisconsin - Madison
	Diallo, Ahmed	USA	Princeton Plasma Physics Laboratory (PPPL)
P1-19	D'Isa, Federico A.	Italy	Consorzio RFX
G5	Dogariu, Arthur	USA	Texas A&M University
H2	Donné, Antonius J.H.	Germany	EUROfusion
P1-20	Funaba, Hisamichi	Japan	National Institute for Fusion Science (NIFS)
O3	Gerakis, Alexandros	Luxembourg	Luxembourg Institute of Science & Technology
	Ghim, Young-chul	Korea	Korea Advanced Institute of Science and Technology (KAIST)
P2-31	Gilbert, Tyler J.	USA	West Virginia University (WVU)
P1-21	Giudicotti, Leonardo	Italy	Padova University
P1-3	Gong, Mingzheng	Japan	National Institute for Fusion Science (NIFS)
P1-22	Gong, Shaobo	China	Southwestern Institute of Physics (SWIP)
T2	Inada, Yuki	Japan	Saitama University
G9	Ito, Tsuyohito	Japan	The University of Tokyo
T4	Jans, Elijah R.	USA	Sandia National Laboratories (SNL)
O2	Jean-Marie-Désirée, Ronny	France	Institut Jean Lamour, CNRS
P2-6	Kamiya, Shun	Japan	The University of Tokyo
P2-29	Katsurayama, Hiroshi	Japan	Tottori University
	Kawaguchi, Haruki	Japan	National Institute for Fusion Science (NIFS)
P2-7	Kim, Hajin	Korea	Korea Institute of Fusion Energy (KFE)
	Kim, Jung-Hwa	Korea	Seoul National University (SNU)
P2-15	Kinoshita, Toshiki	Japan	Kyushu University

presentation	name	country	affiliation
P2-3	Kishimoto, Yasuaki	Japan	Kyoto University
P1-10	Kohagura, Junko	Japan	University of Tsukuba
	Koike, Takeru	Japan	The University of Tokyo
P2-8	Kono, Kaori	Japan	Kyushu University
G7	Korneev, Daniil	Estonia	ELVA-1 OU company
P2-11	Kubo, Shin	Japan	Chubu University
O10	Kuhfeld, Jan	Germany	Ruhr University Bochum
P1-8	Lee, Dong-Geun	Korea	Korea Advanced Institute of Science and Technology (KAIST)
P2-2	Lee, Hyojeong	Korea	Gwangju Institute of Science and Technology
P2-10	Lee, Jong-ha	Korea	Korea Institute of Fusion Energy (KFE)
	Lee, Jongmin	Korea	Seoul National University (SNU)
P1-7	Lee, Sihyeon	Korea	Gwangju Institute of Science and Technology
P1-31	Lepikhin, Nikita D.	Germany	Ruhr University Bochum
O1	Li, Xu	China	Huazhong University of Science and Technology
P1-5	Li, Xuan	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
P2-28	Li, Zhiyu	China	Huazhong University of Science and Technology
T9	Lian, Hui	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
P1-26	Liang, Zhen li	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
P1-13	Lin, Zhiyi	China	University of Science and Technology of China
P1-14	Liu, Chunhua	China	Southwestern institute of physics (SWIP)
	Liu, Haiqing	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
P1-9	Liu, Yuyang	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
T11	Lowe, Hazel F.	UK	Tokamak Energy (TE)
T3	Luggenhölscher, Dirk	Germany	Ruhr University Bochum
P2-17	Marinoni, Alessandro	USA	Massachusetts Institute of Technology (MIT)
	Matsui, Ryutaro	Japan	Kyoto University
O11	Matsutani, Ryo	Japan	Kyoto University
P1-11	Michael, Clive A.	USA	University of California, Los Angeles (UCLA)
P2-24	Minagawa, Hiroki	Japan	Nihon University
G8	Mizoguchi, Hakaru	Japan	Kyushu University
O6	Moseev, Dmitry	Germany	Max-Planck-Institut für Plasmaphysik
H1	Muraoka, Katsunori	Japan	Kyushu University (Emeritus)
O5	Nakagawa, Yusuke	Japan	Tokyo Metropolitan University
O8	Neagu, Liviu	Romania	IFIN-HH / ELI-NP
	Nishiura, Masaki	Japan	National Institute for Fusion Science (NIFS)
P2-25	Nishiyama, Shusuke	Japan	Japan Healthcare University
P2-30	Okamoto, Atsushi	Japan	Nagoya University
	Ota, Masato	Japan	National Institute for Fusion Science (NIFS)

presentation	name	country	affiliation
O9	Pan, Yiming	Japan	Hokkaido University
P2-13	Park, GeunHyeong	Korea	University of Science and Technology, Korea Institute of Fusion Energy (KFE)
O12	Peng, Yi	Japan	The University of Tokyo
O7	Rivers, Margarita	USA	The University of Texas at Austin
P2-4	Roh, Kyungmin	Korea	Gwangju Institute of Science and Technology
T10	Sadiek, Ibrahim	Germany	Leibniz Institute for Plasma Science and Technology (INP)
P2-16	Sakai, Hikona	Japan	Kyushu University IGSES
P1-23	Sasaki, Koichi	Japan	Hokkaido University
P2-31	Schutjes, Kay	Netherlands	Dutch Institute for Fundamental Energy Research (DIFFER)
T1	Scime, Earl	USA	West Virginia University (WVU)
P2-20	Shen, Minyong	China	University of Science and Technology of China
P1-27	Shi, Jielin	Japan	Nagoya University
P1-12	Shi, Peng	UK	United Kingdom Atomic Energy Authority (UKAEA)
P2-27	Simons, Joseph John	Japan	The Graduate University for Advanced Studies (SOKENDAI)
	Skiff, Frederick N.	USA	University of Iowa
O4	Takahashi, Ryosuke	Japan	Kyoto University
	Takemura, Yuki	Japan	National Institute for Fusion Science (NIFS)
	Tanaka, Kenji	Japan	National Institute for Fusion Science (NIFS)
P1-28	Tomita, Kentaro	Japan	Hokkaido University
P2-26	Urabe, Keiichiro	Japan	Kyoto University
AK	Vayakis, George	France	ITER Organization
O13	Vincent, Benjamin	Switzerland	EPFL - SPC
P2-21	Watts, Christopher	France	ITER Organization
P1-6	Xie, Jiaxing	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
P1-4	Xie, Jinlin	China	University of Science and Technology of China
P1-29	Yamasaki, Kotaro	Japan	Hiroshima University
P2-22	Yan, Huihui	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
O14	Yao, Yuan	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
	Yasuhara, Ryo	Japan	National Institute for Fusion Science (NIFS)
G2	Yatom, Shurik	USA	Princeton Plasma Physics Laboratory (PPPL)
T6	Yatsuka, Eiichi	Japan	National Institutes for Quantum Science and Technology (QST)
T8	Yip, Chi-Shung	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
P2-14	Yoshikawa, Masayuki	Japan	University of Tsukuba
P2-12	Yoshimura, Shinji	Japan	National Institute for Fusion Science (NIFS)
P1-2	You, Yong Sung	Korea	Korea Advanced Institute of Science and Technology (KAIST)
P2-18	Zhang, Jibo	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
P2-19	Zhang, Nu	China	Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)

Time	Sep. 10 (Sun.)	Sep. 11 (Mon.)	Sep. 12 (Tue.)	Sep. 13 (Wed.)	Sep. 14 (Thu.)
		Main room 'Aoi'	Main room 'Aoi'	Main room 'Aoi'	Main room 'Aoi'
8:30		Welcome (8:30-8:45)	General 4 (8:30-9:10) K. J. Brunner	General 7 (8:30-9:10) D. Korneev	General 9 (8:30-9:10) T. Ito
8:45		Akazaki lecture (8:45-9:35) G. Vayakis			
9:00			Topical 5 (9:10-9:35) D.J. Den Hartog	General 8 (9:10-9:50) H. Mizoguchi	Topical 10 (9:10-9:35) I. Sadiek
9:30		General 1 (9:35-10:15) P.J. Bruggeman	Topical 6 (9:35-10:00) E. Yatsuka		Oral 10 (9:35-9:10) J. Kuhfeld
9:45				Oral 9 (9:50-10:05) Y. Pan	Coffee break (9:50-10:20)
10:00			Coffee break (10:00-10:30)	Coffee break (10:05-10:35)	
10:15		Coffee break (10:15-10:45)			Topical 11 (10:20-10:45) H.F. Lowe
10:30			General 5 (10:30-11:00) A. Dogariu	Honorary 1 (10:35-11:05) K. Muraoka	
10:45		General 2 (10:45-11:25) S. Yatom			Oral 11 (10:45-11:00) R. Matsutani
11:00			Topical 7 (11:10-11:35) W. Choe	Honorary 2 (11:05-11:35) A.J.H. Donné	Oral 12 (11:00-11:15) Y. Peng
11:15		Topical 1 (11:25-11:50) E. Scime			Oral 13 (11:15-11:30) B. Vincent
11:30			Topical 8 (11:35-12:00) C-S. Yip	Group photo/Break (11:35-12:15)	Oral 14 (11:30-11:45) Y. Yao
11:45		General 3 (11:50-12:30) U. Czarnetzki			Closing
12:00			Oral 4 (12:00-12:15) R. Takahashi		
12:15			Oral 5 (12:15-12:30) Y. Nakagawa	Excursion (with lunch box) (12:15-18:30)	
12:30		Lunch (12:30-14:00) Lunch box will be provided.	Lunch (12:30-14:00) Lunch box will be provided.		
14:00		Topical 2 (14:00-14:25) Y. Inada	General 6 (14:00-14:40) S. Coda		
14:15		Topical 3 (14:25-14:50) D. Luggenhölscher			
14:30			Topical 9 (14:40-15:05) H. Lian		
14:45		Topical 4 (14:50-15:15) E.R. Jans			
15:00			Coffee break (15:05-15:35)		
15:15		Coffee break (15:15-15:45)			
15:30			Oral 6 (15:35-15:50) D. Moseev		
15:45		Oral 1 (15:45-16:00) X. Li	Oral 7 (15:50-16:05) M. Rivers		
16:00		Oral 2 (16:00-16:15) Jean-Marie-Désirée	Oral 8 (16:05-16:20) L. Neagu		
16:15		Oral 3 (16:15-16:30) A. Gerakis			
16:30		Pre-Poster #1 (16:30-17:40)	Pre-Poster #2 (16:30-17:40)		
17:30	Registration (17:30-19:00)	Poster session #1 (17:40-19:40) Light meals available	Poster session #2 (17:40-19:40) Light meals available		
18:30				Break (18:30-19:00)	
19:00	Welcome Reception (19:00-20:30)			Banquet (19:00-21:00)	
21:00					