Coherence Imaging Measurements of Impurity Ion Flow in the CTH and W7-X Experiments

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Fusion Energy Sciences Program

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Coherence Imaging Spectroscopy (CIS)

Abstract

Measurements of impurity ion emissivity and velocity in the Compact Toroidal Hybrid (CTH) experiment are achieved with a new optical coherence imaging diagnostic. The Coherence Imaging Spectroscopy (CIS) technique measures the spectral coherence of an emission line using an imaging interferometer of fixed delay[1]. CIS has a number of advantages when compared to dispersive Doppler spectroscopy, including higher throughput and the capability to provide 2D spectral images, making it ideal for investigating the non-axisymmetric geometry of CTH plasmas. Furthermore, detailed measurements of the ion flow structure provided by CIS combined with predictive computational models could also provide spatially resolved images of complex flow structures, such as those associated with an island divertor [2, 3]. Initial CIS measurements of CTH plasmas reveal strong signals for C III (465 nm), He II (468 nm) and C II (513 nm) emission. Preliminary analysis of C III interferograms indicates a net toroidal flow on the order of 10 km/s during the time of peak current. Additionally, bench tests using Zn and Cd light sources reveal that the temperature of the interferometer optical components must be actively controlled to within 0.01°C to limit phase drift of the interferogram resulting in artificially measured flow. Results from this diagnostic will aid in characterizing the ion flow in planned MHD mode-locking experiments.
A new collaboration has been established between Auburn University and the Max-Planck-Institute for Plasma Physics to construct and optimize two new coherence imaging instruments for installation on the W7-X experiment. The two instruments will measure ion impurity flows in both the toroidal and poloidal directions to investigate the physics of the W7-X island divertor beginning during OP1.2. A continuous wave laser tunable over most of the visible region will be incorporated to provide immediate and accurate calibrations of both CIS systems during plasma operations.

CIS Purpose

• Accurate measurement of fringe pattern parameters provides information about spectral emission (Doppler broadening & shift)

Advantages of CIS Compared to Dispersive Spectroscopy

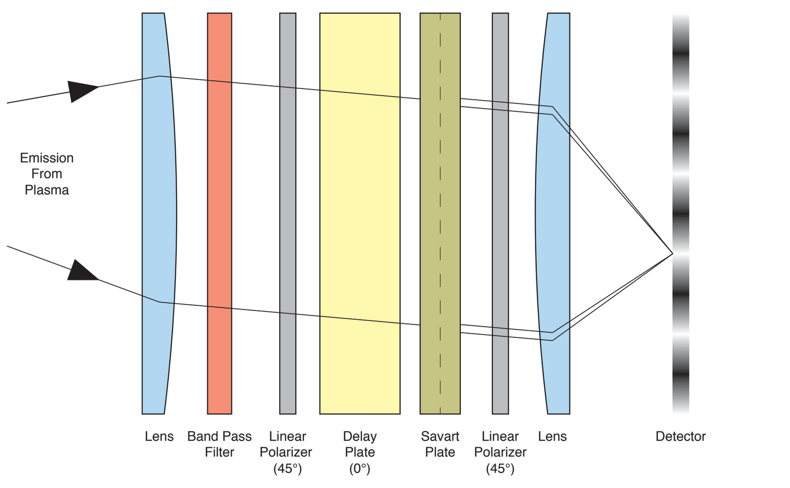
• High-throughput due to no requirements of apertures or slits

• Possible to capture an entire two-dimensional image of emission and extract spectral information at each point in the image

=> Important for fully 3D plasma geometries such as CTH & W7-X

• Possible extension to measure the spectral components of Zeeman splitting potentially yielding line-integrated magnitude and orientation of the magnetic field

Optical Schematic



Collection Lens: collimates plasma emission from a wide angle into the diagnostic

Band-Pass Filter: selects a particular spectral line corresponding to an ion charge state of interest

Linear Polarizer: assures that transmitted emission is equally comprised of orthogonal polarizations (needed for maximum fringe contrast of interferogram)

Delay Plate: delays components of emission with orthogonal polarizations relative to each other (birefringence) on the order of ~1000 wavelengths (needed to provided sufficient measurement sensitivity)

Savart Plate: composite of two birefringent plates with optical axes oriented 90° to each other. Effect is to slightly delay orthogonal polarizations of emission relative to each other as a function of incident angle (relative to the Savart plate). Therefore, emission from different vertical locations in the plasma have slightly different delays between orthogonally polarized components.

Final Polarizer: detects total relative phase shift between the orthogonally polarized emission components (a rotation of the total polarization vector) due to both crystals (delay plate plus Savart plate).

=> Produces horizontal fringe pattern

Second Lens: focuses transmitted emission onto the image plane

Detector: captures emission with overlaid interference pattern in time (fast camera)

Interpreting the Interferogram

• Doppler shift of a spectral line (velocity) observed as a change in the fringe spacing

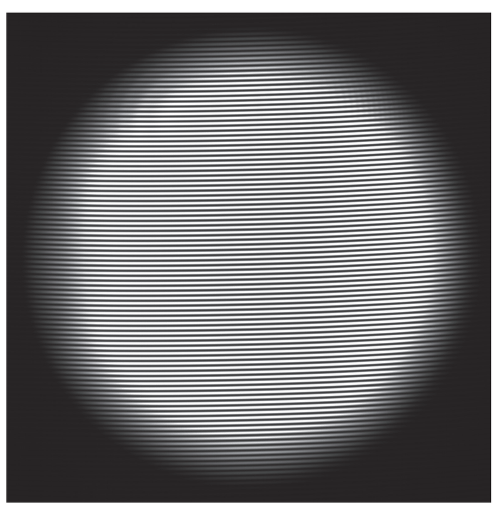
• Doppler broadening of a spectral line (temperature) observed as a modulation of the fringe contrast

• Measured fringe pattern from plasma compared to calibrated fringe pattern from known light source to determine Doppler shift and broadening

Calibrations

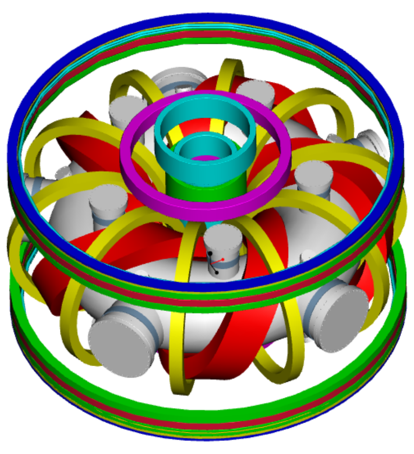
• Fringe pattern produced by instrument viewing integrating sphere illuminated by Zn I emission at 468.0 nm

• With proper accounting, the Zn I interferogram can be translated to the rest wavelength of He II emission at 468.6 nm and used as an absolute reference for He II plasma measurements



Compact Toroidal Hybrid (CTH)

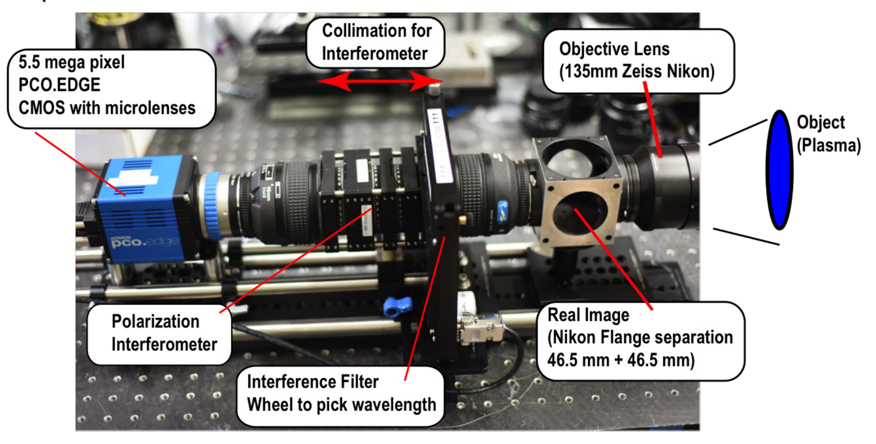
Parameter	Range
R_0	0.75 m
a_{vessel}	0.29 m
a_{plasma}	≤ 0.20 m
I_p	≤ 80 kA
$\lvert B \rvert$	≤ 0.7 T
t_{vac}	0.02 to 0.32
T_e	≤ 200 eV
n_e	≤ 5 × 10^{19} m^{-3}
P_{ECRH}	≤ 30 kW



• CTH is a stellarator/tokamak hybrid device with an array of magnetic coils (helical, toroidal, poloidal, ohmic) providing access to a broad range of magnetic configurations

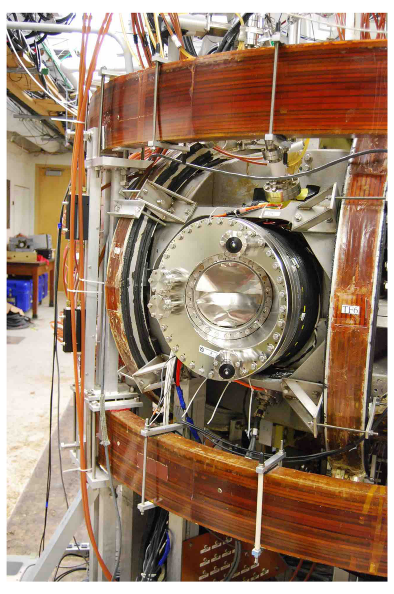
• A primary objective of the CTH program is to investigate the plasma stability when applying significant 3D magnetic shaping to current-carrying plasmas

• Measurements of ion parameters in both the edge and the core of CTH plasmas beneficial for island divertor and MHD mode-locking experiments



• Reversed F-mount lenses used collect emission from a wide angle and pass it through the polarization interferometer parallel. Image of first collection lens placed at detector plane the second lens.

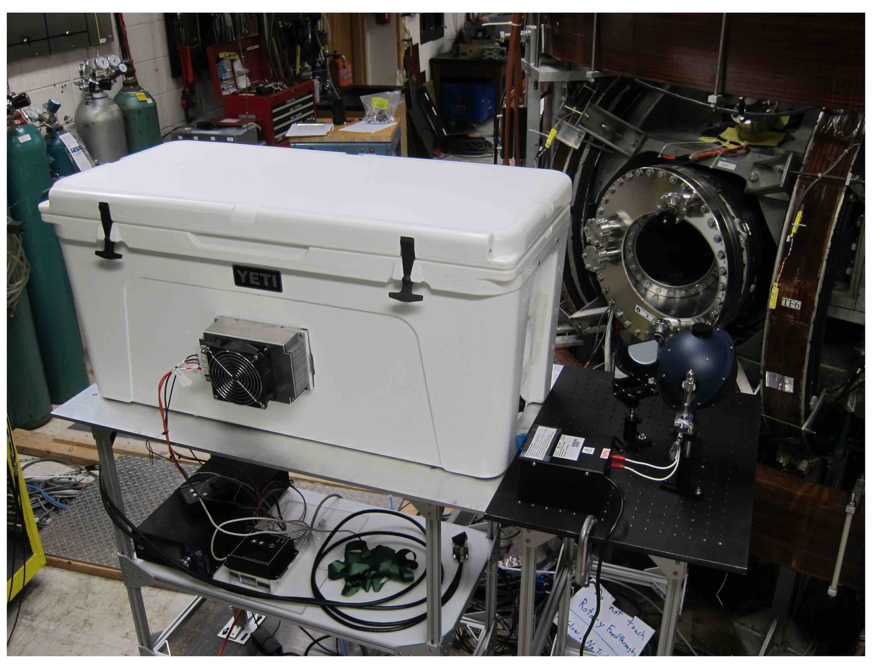
Upgrades



• A number of upgrades completed to the instrument & set up to improve measurements

• New toroidal viewport installed on the midplane (~7.75" clear aperture) to be shared w/ Thomson Scattering

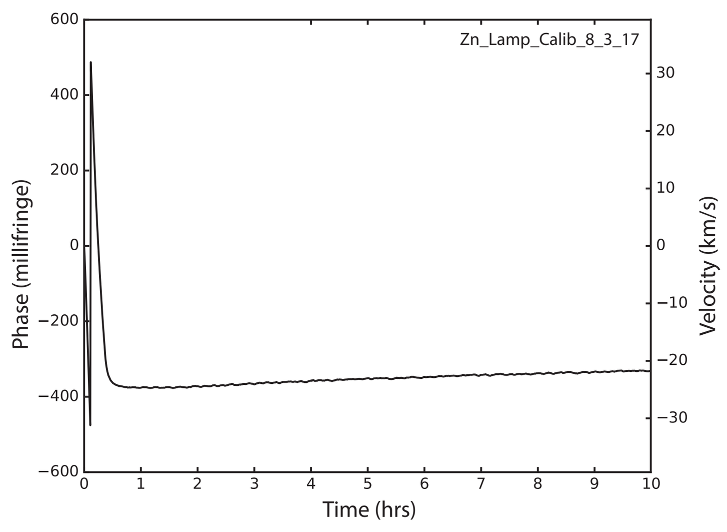
• New support structure allows for in situ calibrations using a flip mirror to view the integrating sphere and lead shielding of x-rays



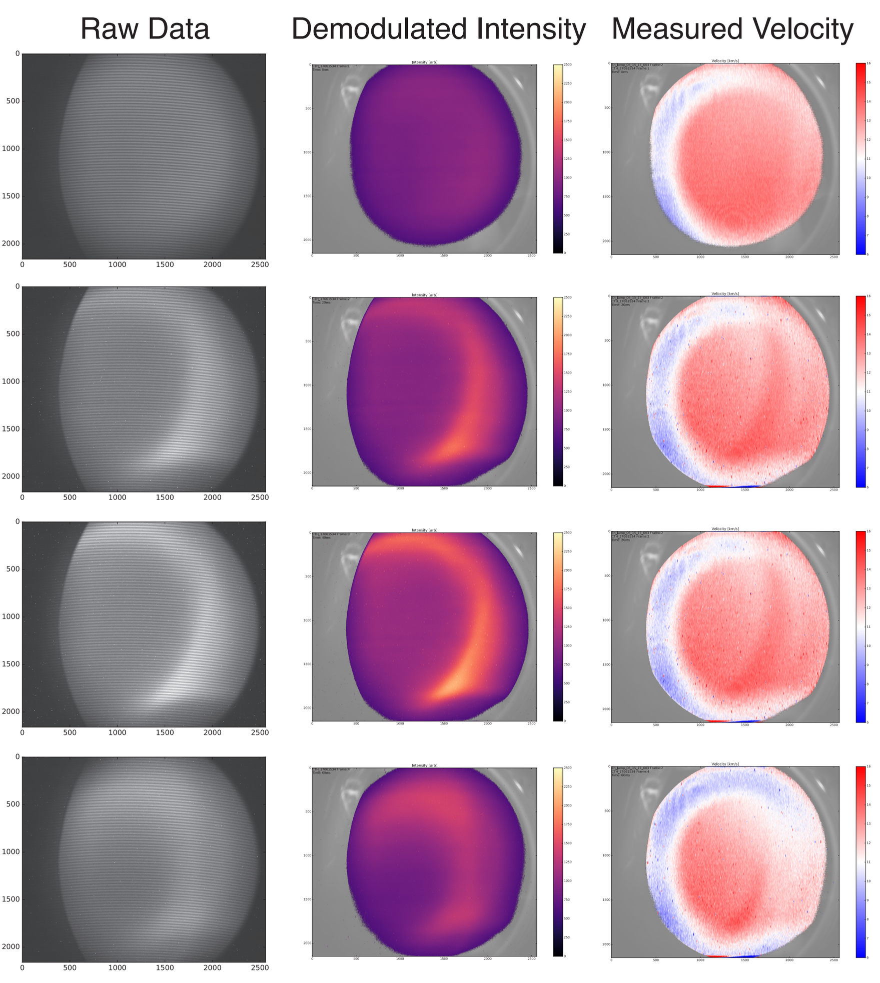
• Entire instrument now housed in a marine cooler to further reduce temperature fluctuations of the interferometer crystal

• Peltier cooler mounted onto the cooler to feedback control the ambient temperature (~23 °C) inside the cooler

• Result of two temperature control systems is constant crystal temperature to better than ~0.01 °C



Measurements



• Initially, mostly uniform toroidal flow (10 to 14 km/s) followed by slow down of flow near the edge

• Analysis completed by N. R. Allen

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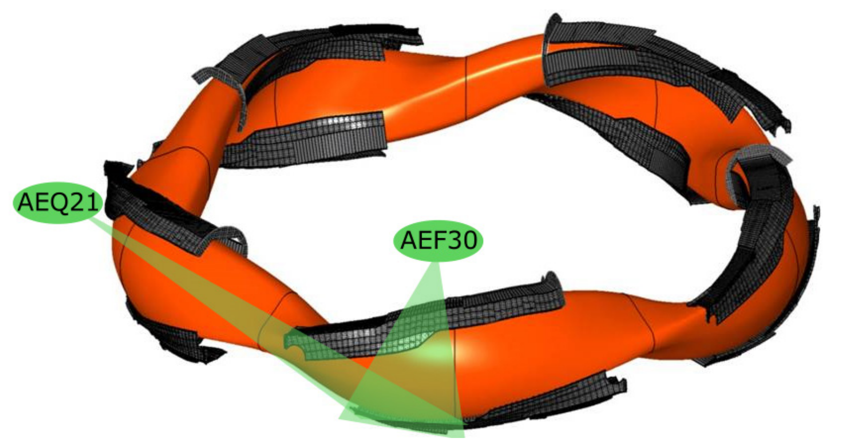
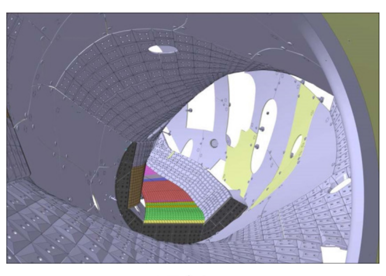
• *New collaboration established between Auburn University and Max-Planck-Institute for Plasma Physics to construct and optimize two coherence imaging instruments to investigate the physics of the W7-X island divertor*

• Two new CIS instruments are being installed on W7-X providing approximately perpendicular views of the divertor target region [4]





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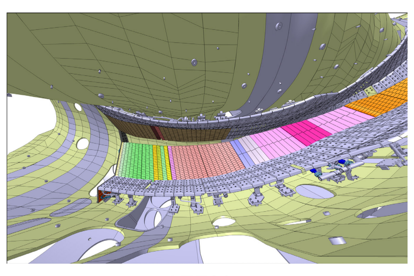

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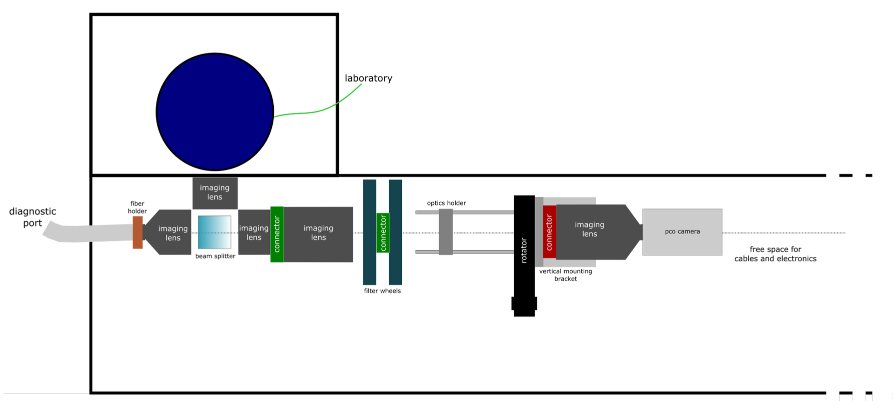
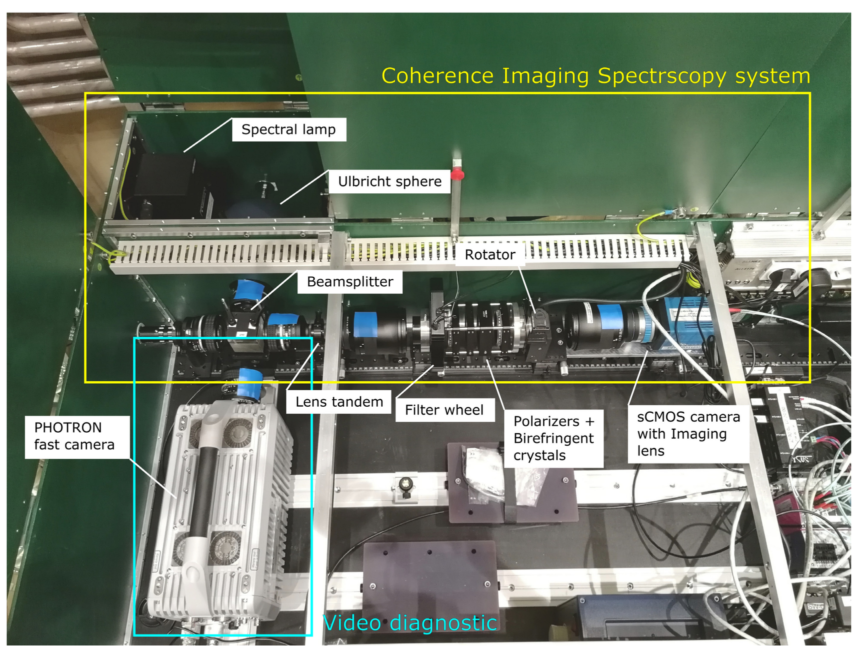
• Divertor target contains five nozzles for introducing impurity gases allowing for possible measurements of a range of impurities

• Plasma emission collected by optics housed in an immersion tube & coupled to the CIS instrument by an imaging fiber bundle

• Flexible design allows for remotely switching between spectral lines, rotation of interferometer relative to plasma geometry



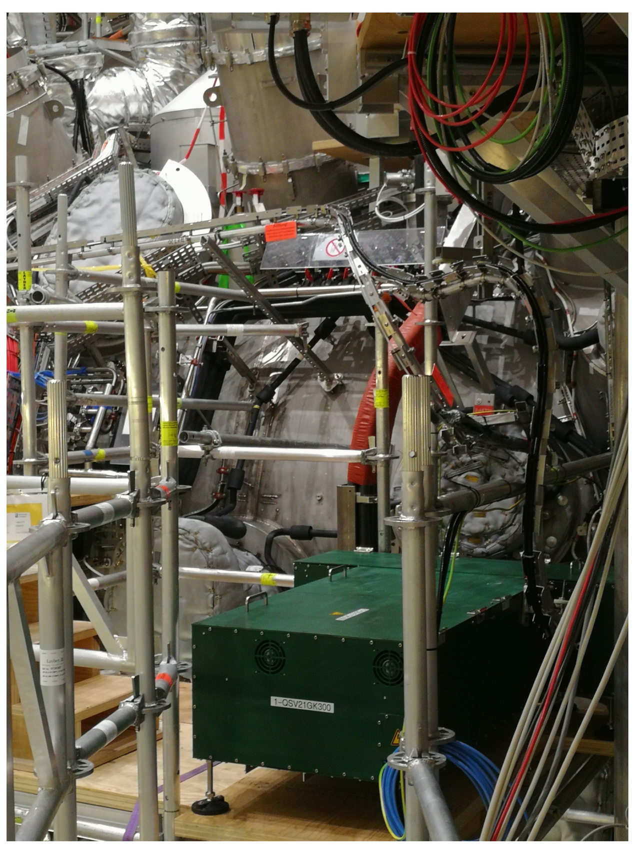


• Real time calibration provided by fully tunable continuous wave laser in combination with a wavemeter provides:

  • Zero flow reference needed for absolute flow measurements

  • Frequent calibrations reduce the effects of temperature variation of the birefringent crystal

  • Calibration measurements account all for differences between crystal manufacturing and published values



• Tunable laser scheduled to arrive at the end of OP1.2a but will mostly likely go into service for OP1.2b. In the meantime calibrations will be conducted with a Zn lamp & He II filter.

• Installation of both CIS systems in the Torus Hall nearing completion with first measurements expected in the beginning of OP1.2a

References

[1]J. Howard, J. Phys. B: At. Mol. Opt. Phys. **43**, 144010 (2010).

[2]J. Howard, A. Diallo, M. Creese, S.L. Allen, R.M. Ellis, W. Meyer, M.E. Fenstermacher, G.D. Porter, N.H. Brooks, M.E. VanZeeland, and R.L. Boivin, Contrib. Plasma Phys. **51**, 194 (2011).

[3]S.A. Silburn, J.R. Harrison, J. Howard, K.J. Gibson, H. Meyer, C.A. Michael, and R.M. Sharples. Rev. Sci. Instr. **85**, 11D703 (2014).

[4]V. Perseo, R. König, C. Biedermann, O. Ford, D. Gradic, M. Krychowiak, G. Kocsis, D. Ennis, D. Maurer, T.S. Pedersen and the W7-X Team, Proceedings of the 44th EPS Conference on Plasma Physics (2017).

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