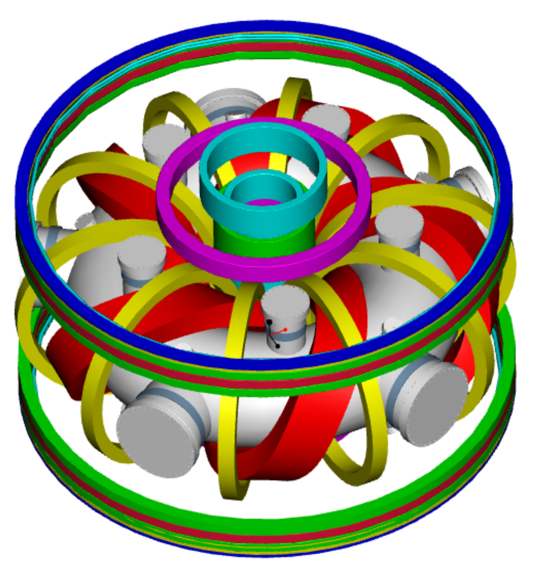
Introduction

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 with an imaging interferometer of fixed delay. 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. First 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 indicate a net toroidal flow on the order of 10 km/s during the time of peak current. Bench tests using Zn and Cd light sources reveal that the temperature of the instrument must be actively controlled to within 0.01°C to limit phase drift of the interferometer resulting in artificially measured flow. Results from this diagnostic will aid in characterizing the ion flow in planned island divertor and MHD mode-locking experiments.

Compact Toroidal Hybrid (CTH)



- 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
- CTH serves as an excellent platform for the development of 3D equilibrium reconstruction, yielding enhanced understanding and predictive capability

Parameter	Range
R_0	0.75 m
a_{vessel}	0.29 m
a_{plasma}	$\leq$ 0.20 m
I_p	$\leq$ 80 kA
$\lvert B \rvert$	$\leq$ 0.7 T
t_{vac}	0.02 to 0.32
T_e	$\leq$ 200 eV
n_e	$\leq 5\times10^{19}$ m^{-3}
P_{ECRH}	$\leq$ 30 kW

- Internal equilibrium measurements needed to understand MHD stability in 3D geometry
- Many core plasma parameters are reconstructed from edge measurements using the V3FIT[2] equilibrium solver
- Measurements of ion parameters in both the edge and the core of CTH plasmas beneficial for island divertor and MHD mode-locking experiments

Coherence Imaging

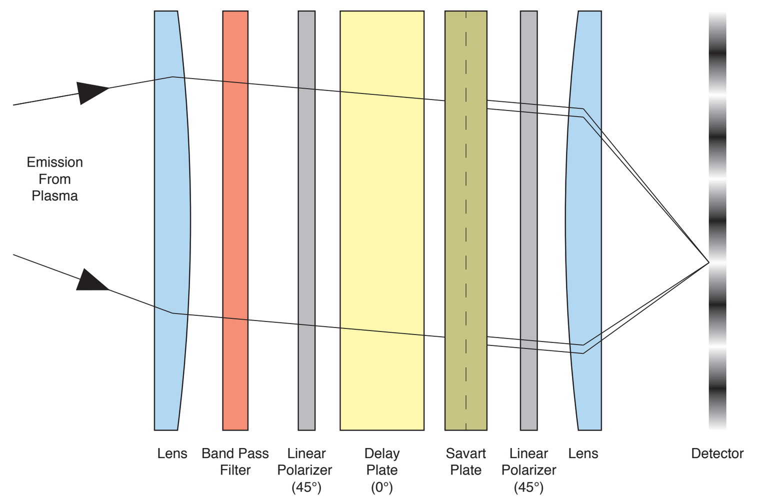
- Accurate measurement of interference pattern parameters provides information about the spectral emission (Doppler broadening and shift)

Advantages 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
- 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 interferogram*

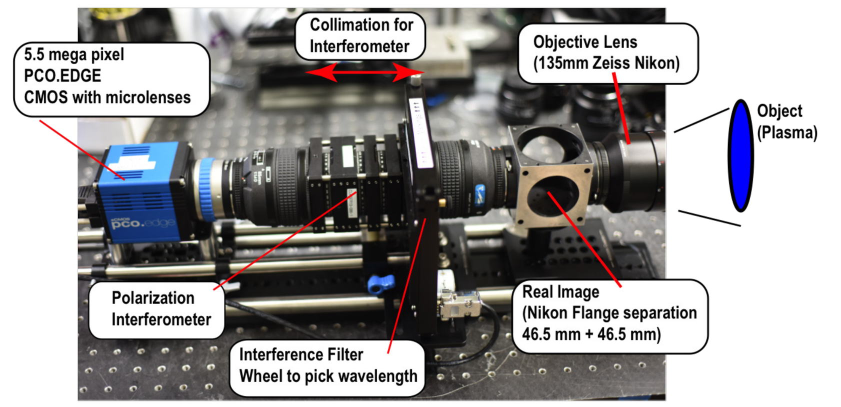
Second Lens: focuses transmitted emission onto the image plane

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

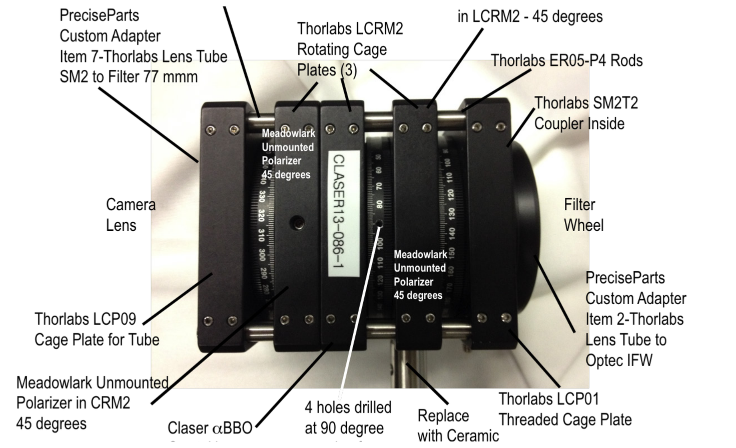
Interpreting the Interferogram

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

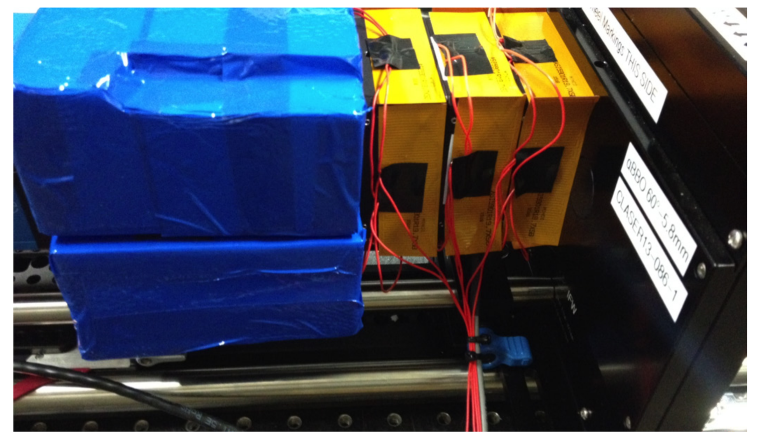
Instrument Specifications



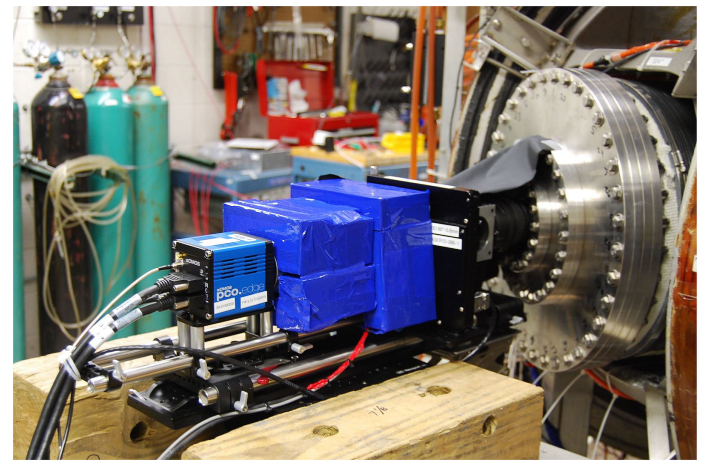
- Reversed F-mount lenses used collect emission from a wide angle and pass it through the polarization interferometer parallel. Image of first collection lens placed at detector plane the second lens.
- Polarization interferometer assembled from 2" optical components



- Delay plate and Savart plate integrated into a single birefringent αBBO crystal (6 mm thick)
- Phase delay provide by αBBO crystal is sensitive to temperature variations. Therefore, interferometer surrounded by low power heaters and insulation for temperature feedback control to better than ~0.01 °C

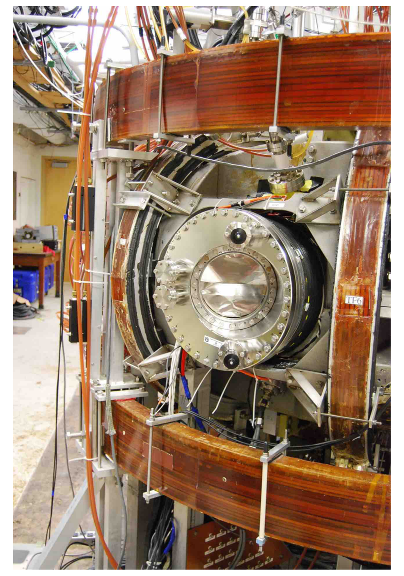


- Coherence imaging instrument installed on the CTH midplane

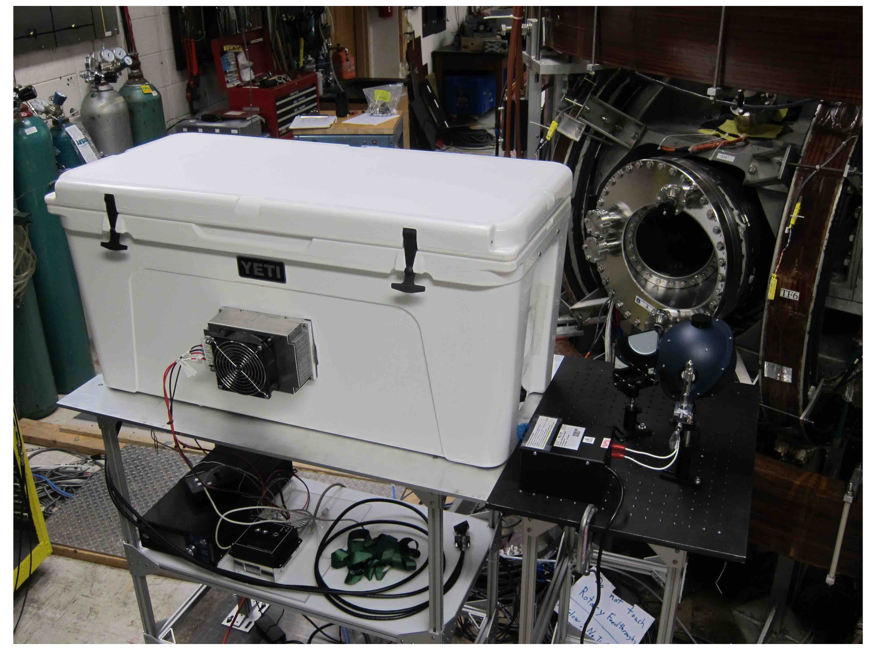


Instrument Upgrade

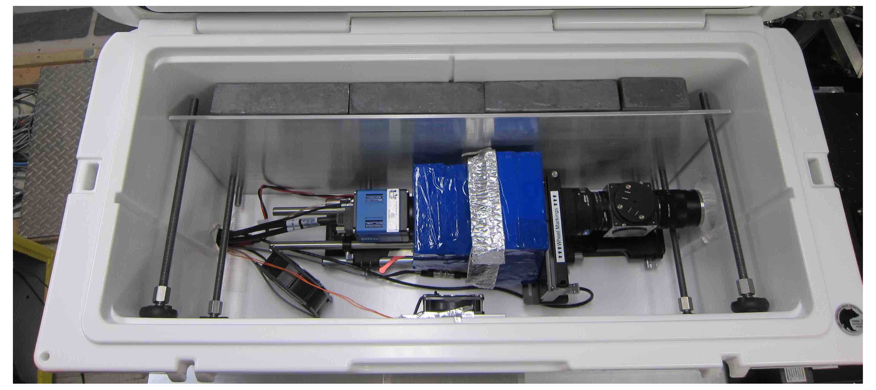
- Over the last year a number of upgrades have been completed to the instrument and set up on the CTH experiment to improve the measurement



- New toroidal viewport installed on the CTH midplane (~7.75" clear aperture) to be shared between the Thomson scattering and coherence imaging diagnostics
- New support structure allows for in situ calibrations using a flip mirror to view the integrating sphere and lead shielding of x-rays

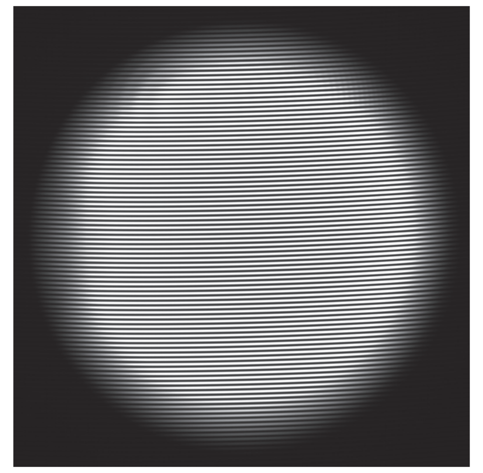


- Entire instrument now housed in a marine style cooler to further reduce temperature fluctuations of the interferometer crystal



- 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

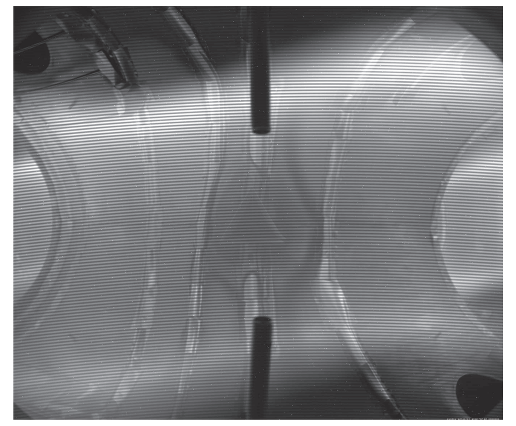
Calibrations



- Interferogram 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

Measurements

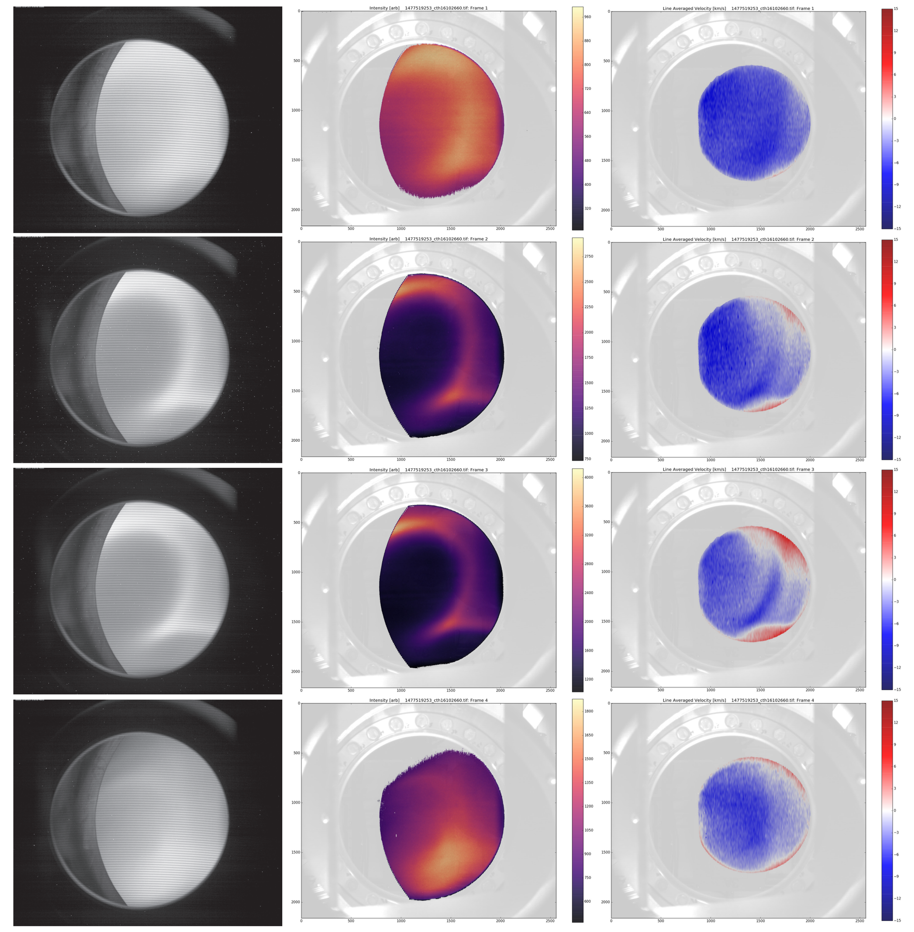
- Previous measurements with coherence imaging instrument produced strong fringes (high signal levels) for various impurity species He II (468 nm), C II (513 nm), & C III (465 nm)



- Interferogram of C III emission at 465 nm during peak current with a 10 ms exposure

- New measurement of He II emission sequence using toroidal viewport
- 10 ms exposures acquired every 20 ms (50 Hz) during ~ 50 kA CTH discharge with significant He doping
- Incorporated Zn I absolute calibration to determine He ion flow along instrument line of sight

Raw Image | Demodulated Intensity (fringes removed) | Measured Velocity



- Analysis completed by C. M. Samuell
- Evolution of He line-integrated toroidal velocity during CTH discharge indicates:

  - Initially, uniform toroidal flow (~ 6 km/s) during plasma current ramp

  - Followed by non-uniform flow structures as plasma current peaks and decays

  - Direction of net ion flow is consistent with direction of driven current in CTH
- See C. M. Samuell poster on Wednesday afternoon (PP10.00078) for further details of analysis methods

Conclusions

- Upgrades to coherence imaging diagnostic completed for improved measurements of CTH ion flows
- Enclosing entire instrument in a marine style cooler with feedback controlled Peltier cooler further improved temperature stability providing increase flow measurement sensitivity
- Incorporating in situ calibrations using Zn I light source provides absolute reference for He II ion flow
- Preliminary analysis of He ion flows in CTH indicates net toroidal flows on the order of ~ 5 km/s with non-uniform flows appearing as the discharge evolves

Future Work

- Optimize arrangement of collection optics to increase measurement field of view
- Conduct perturbative experiments in CTH using bias probe and error correction coils to assess impact on ion flows
- Expand calibration light sources for absolute measurements of other impurity ions (C III) in CTH
- Test different interferometer crystals for greater sensitive (larger delay) to detect smaller scale flows in CTH

References

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Work supported by USDoE grant DE-FG02-00ER54610