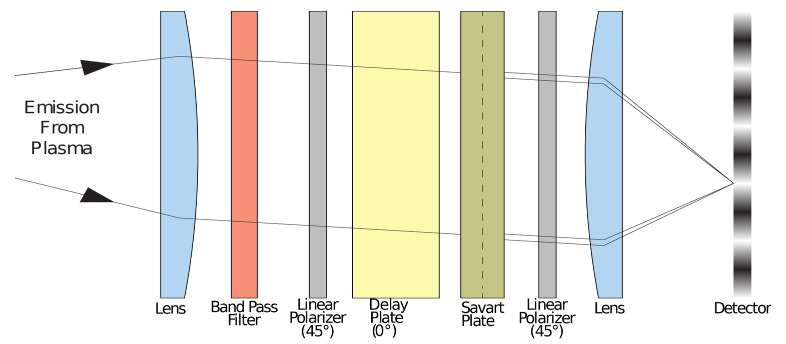
Abstract

Two dimensional profiles of line-integrated impurity emissivity and velocity in the Compact Toroidal Hybrid (CTH) experiment are obtained with Coherence Imaging Spectroscopy (CIS), a polarization interferometry technique with fixed delays. The 2D measurement output provided by a recently developed analysis routine, is necessary for the non-axisymmetric geometry of CTH plasmas. Bench tests of the CIS instrument demonstrate externally applied magnetic fields induce spurious flows of order $1\,\mathrm{km\,s^{-1}}$ for field strengths of up to 200 G irrespective of field direction. Additionally, two new CIS instruments designed to investigate the 3D physics of the W7-X island divertor by providing ion impurity flow measurements in orthogonal directions are fully operational. Further, a continuously tunable laser over most of the visible region now provides immediate and accurate calibrations of both CIS systems during W7-X plasma operations.

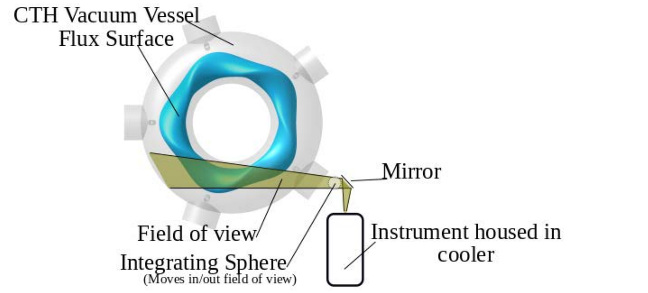
Coherence Imaging Spectroscopy

Coherence Imaging Spectroscopy (CIS) is a polarization interferometry technique that resolves the 2D ion flow of an image by using the spectral coherence of a single emission line.



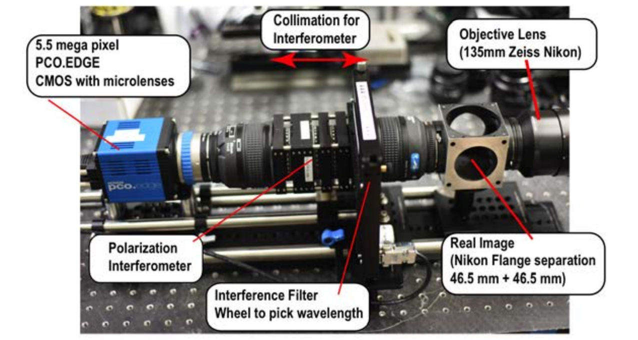
- Collection Lens - Collimates all rays from same object point through the interferometer optics
- Bandpass filter - Selects ion emission line of interest
- First Linear Polarizer - Ensures transmission of equally comprised orthogonal polarization vectors
- Delay/Savart Plate - Birefringent crystal that delays orthogonal polarizations relative to each other on the order of ∼1000 wavelengths
- Savart Plate has birefringence that is dependent on the angle of incidence. Therefore, emission from different positions on object plane have different delays between orthogonally polarized components.
- Second Linear Polarizer - Acts as an analyzer to the system for measuring relative phase delay between orthogonal polarizations through birefringent crystal

Top down view of CIS diagnostic

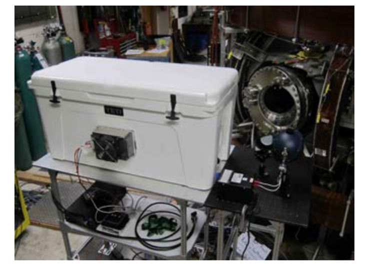


- Sampling across the object plane sweeps the angle of incidence on the Savart Plate leading to a changing crystal response and a subsequent fringe pattern on the detector
- *Crystal's degree of birefringence is sensitive to temperature and wavelength*
- Integrating sphere is used to measure a calibration fringe pattern corresponding to a known zero-flow measurement
- Find, via indirect measurement, a relationship for wavelength and corresponding changes in fringe pattern
- The difference in fringe patterns between plasma and calibration images is related to the change in wavelength then the flow velocity via Doppler shift

Instrument Specifications



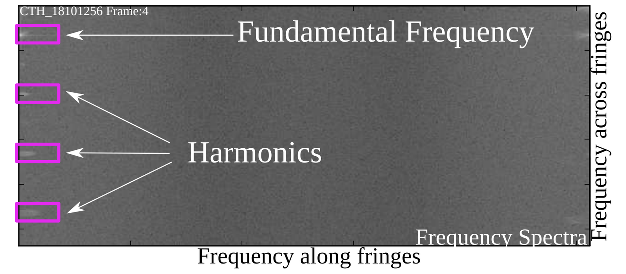
- Reversed F-mount lenses collect emission from a wide angle and pass it through the polarization interferometer in parallel. Image of first collection lens is placed at the detector plane the second lens
- Polarization interferometer assembled from 2” optical components
- Delay plate and Savart plate integrated into a single birefringent αBBO crystal (6 mm thick)



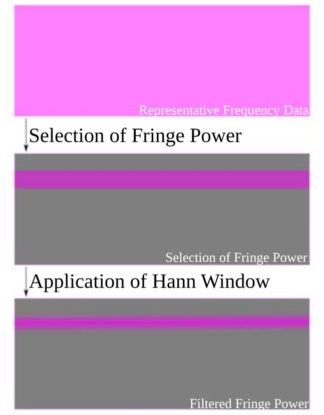
- Entire instrument now housed in a marine style cooler to further reduce temperature fluctuations of the interferometer crystal better than ∼ 0.01 °C
- Dedicated support structure allows for in-situ calibrations using a flip mirror to view the integrating sphere and lead shielding of x-rays

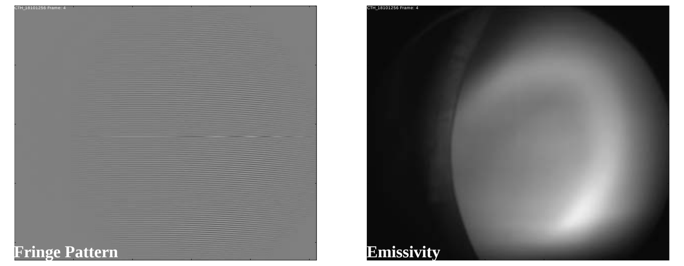
CIS Data Analysis

- Raw data taken of CTH toroidal view at the mid-plane
- 10 ms exposure with a 50 Hz duty cycle (∼20 ms)
- 3 point boxcar smooth is applied to smooth X-rays

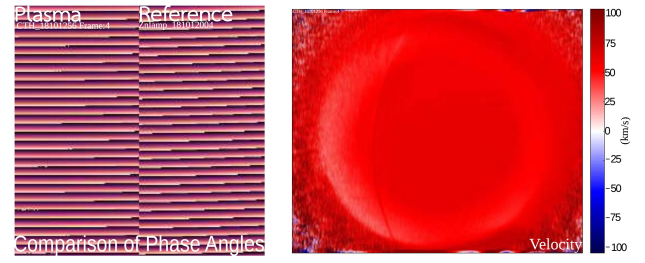


- The Fourier spectra is calculated via real 2D Fourier transform, first across then along fringes
- Hann window applied along fringe frequency, centered at peak power, to only select fringe power
- Fringe power is subtracted from raw image power to obtain plasma emissivity

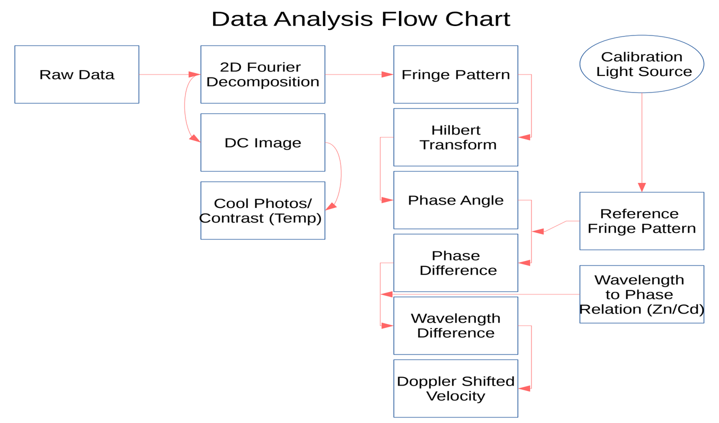




- Fringe and emissivity image are obtained by taking the inverse Fourier transform
- Emissivity is useful for masking low signal data as well as determining the contrast of the image
- Fringe pattern contains information about flow profile of the plasma by comparison to a reference fringe pattern
- The fringe pattern is mapped to complex space by Hilbert transform and the complex angle of each point is calculated



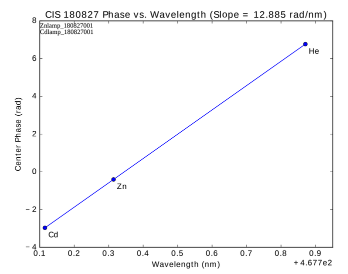
- The difference in phase angle between the calibration fringe pattern and plasma fringe pattern is calculated for each pixel
- The phase difference is directly related to the flow velocity (depending on wavelength) by various instrument parameters
- **Measured flows from CIS instrument have been systematically larger than expected ∼ 60 km/s**



Instrument Calibration

- Plasma measurements calibrated using a reference fringe pattern produced by illuminating an integrating sphere with a Zn spectral lamp

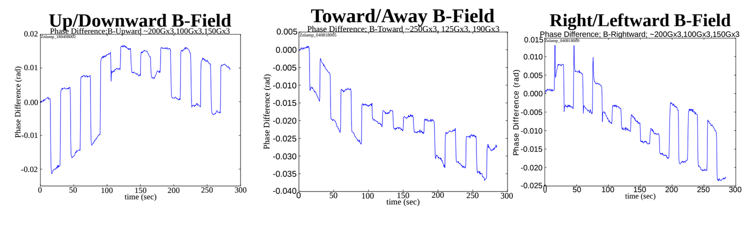
- The wavelength dependence of the instrument phase is determined by using two spectral lamps, Zn and Cd.
- This phase-wavelength relationship is used to extrapolate the Zn fringe pattern to the He II line corresponding to a true zero-flow calibration image



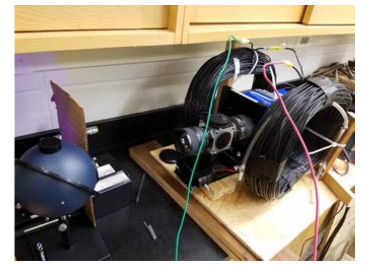
Instrument Characterization

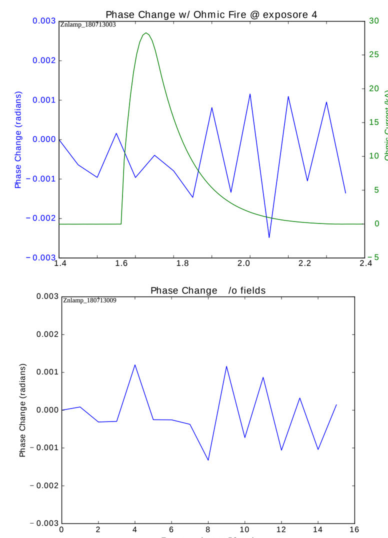
Instrument Response to Background Magnetic Fields

- Expected stray magnetic fields from CTH are ∼ 55 G



- Crystal response to magnetic fields tested with Helmholtz-like setup in multiple orientations
- Measured instrument response is upwards of 20 mrad phase change, ∼ $1\,\mathrm{km\,s^{-1}}$ calculated spurious flow

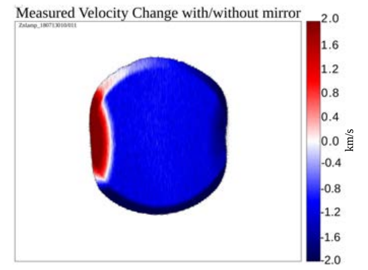


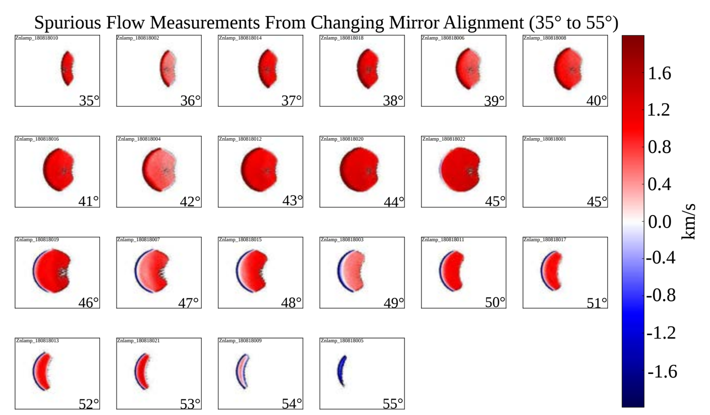


- Instrument's magnetic field response tested in-situ on CTH by firing field coils
- In both maximum fields case and partial coil firings, any instrument response was below or on par with normal noise levels
- Unlikely any spurious flows measured on CTH are due to magnetic field effects

Effect of Mirror Orientation on Calculated Flows

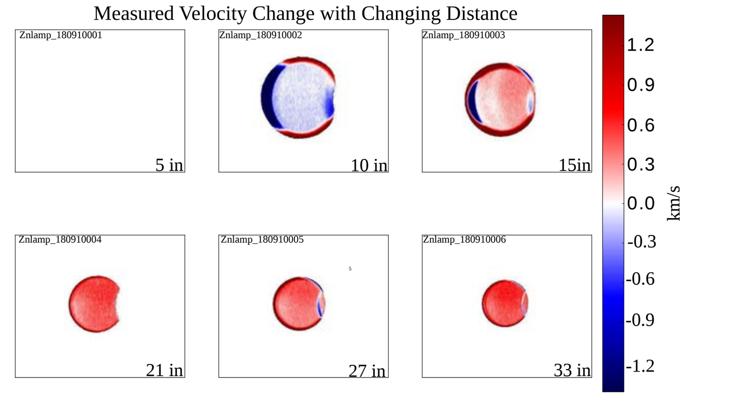
- Spurious flow measurements due to the reference image being taken in front of mirror or with no mirror show small effect ($< 1\,\mathrm{km\,s^{-1}}$)





- Spurious flow calculations due to changing mirror alignments. All measurements with respect to initial 45 degree mirror orientation show spurious flows ($\le 1\,\mathrm{km\,s^{-1}}$)
- Any large spurious flows in CTH are likely not due to a changing mirror orientation

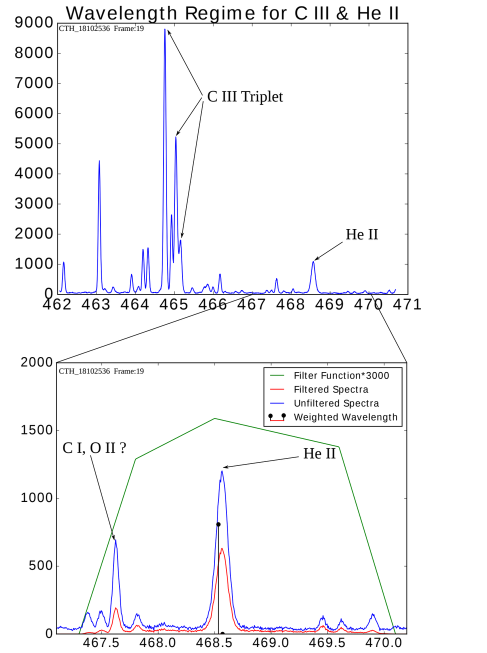
Measured Velocity Changes with Increasing Distance to Calibration Source



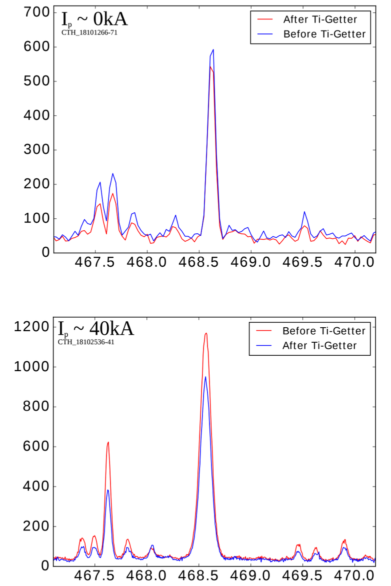
- Increasing distance from the camera does not significantly affect the calculated velocity (shift $< 1\,\mathrm{km\,s^{-1}}$) from a range of 6 in to 33 in (∼ halfway to the object plane)

Spectroscopy

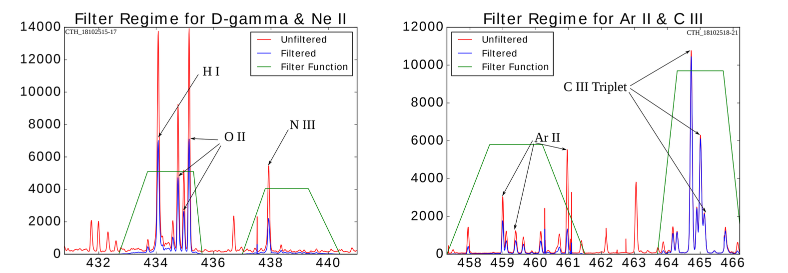
- Multiple spectral lines generate multiple overlapping fringe patterns; any extra spectral lines will result in phase offsets and spurious flow measurements
- The filter regime for a He II emission line; there are multiple lines within the filter window, particularly a relatively large line at 467.6 nm



- The appearance of an additional line in the filter window causes a shift of the weighted wavelength, which if interpreted as a Doppler shift 1 Å would be ∼ $64\,\mathrm{km\,s^{-1}}$. This accounts for a significant portion of the measured high flows. (25-30 $\mathrm{km\,s^{-1}}$)



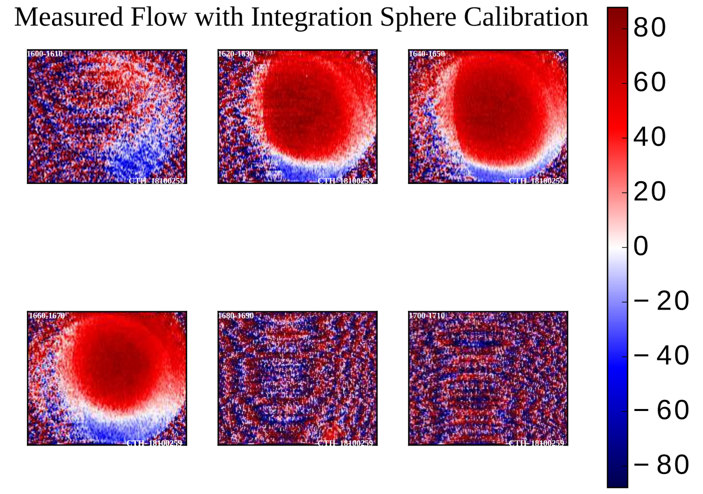
- In an attempt to remove the impurities from the spectra, titanium was gettered onto the vacuum vessel surface
- While there is a decrease in the size of the impurity line, it is insufficient to neglect the contaminating lines in the analysis
- Since both lines drop by the same relative amount, no significant change to the weighted wavelength is observed

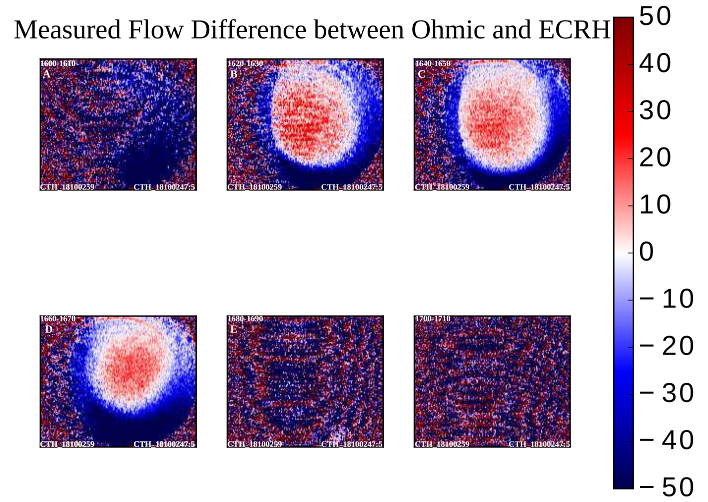


- The wavelength region of other filters also includes impurity lines. Many of these lines appear to be oxygen lines, though some carbon and nitrogen lines may also be present.

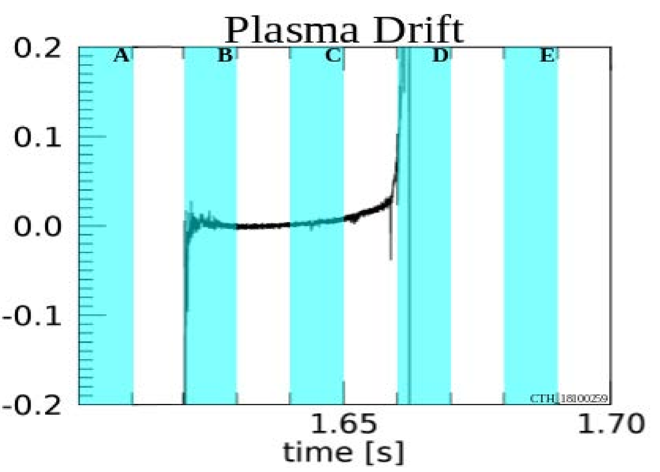
Plasma Measurements

- CTH is a 5 field period torsatron used to investigate disruption events over a wide range of plasma parameters
- Disrupting plasmas in CTH are frequently vertically unstable and tend to drift upwards





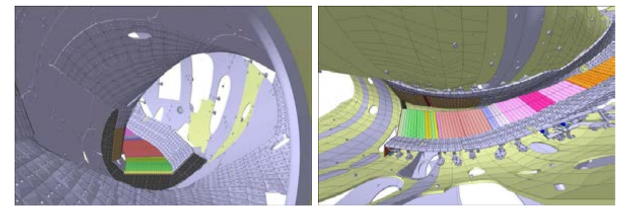
- CIS observes an upward plasma drift shortly before a disruption event



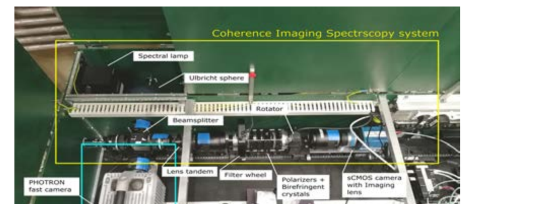
- Poloidal magnetic probe data appear to corroborate vertical drift measured with CIS

Wendelstein 7-X

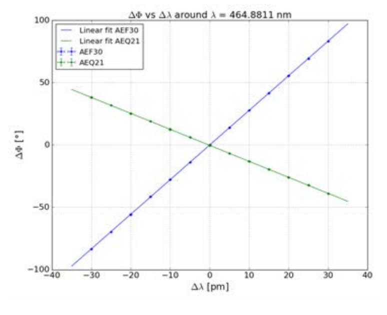
- An existing collaboration between Auburn University and the Max-Planck-Institute for Plasma Physics formed to construct and optimize two coherence imaging instruments to investigate the physics of the W7-X island divertor
- Two CIS instruments commissioned on W7-X providing approximately perpendicular views of the divertor target region



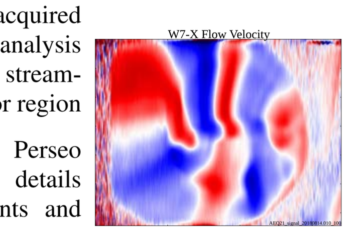
- Divertor target contains five nozzles for introducing impurity gases allowing for possible measurements of a range of impurities
- Flexible design allows for remotely switching between spectral lines, rotation of interferometer relative to plasma geometry



- Real time calibration using a fully tunable continuous wave laser in combination with a wavemeter:
  - Zero flow reference needed for absolute measurements
  - Frequent calibrations reduce the effects of temperature variation of the birefringent crystal
  - Calibration measurements account for all differences between crystal manufacturing and published values
- Tunable laser went into service for OP1.2b (July-October, 2018)
- The phase to wavelength relationship of the CIS instruments is measured by scanning the tunable laser on picometer scales around the target wavelengths



- C III CIS measurements acquired throughout OP1.2b - initial analysis reveals ∼ $30\,\mathrm{km\,s^{-1}}$ counter streaming flows in the island divertor region
- See poster by V. Perseo (BP11.00064) for more details about W7-X CIS instruments and OP1.2b experiment results)



Conclusions

- CIS flow measurements on CTH are consistently higher than expected
- In an attempt to explain large flow measurements, investigations of the CIS instrument sensitivity to background magnetic fields, mirror alignments, and distance to the calibration source account for small errors in measured flow (∼ $1\,\mathrm{km\,s^{-1}}$)
- Multiple lines, identified within various CIS filter windows, result in spurious flows
- The acquisition of narrower filters will make for more pure measurements of a single emission line
- Preliminary data from CIS suggests a vertical drift of the plasma volume during disrupting plasmas
- Two new CIS instruments commissioned for W7-X in combination with a tunable calibration laser acquired measurements during the entire OP1.2b run campaign

References

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

Acknowledgements

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