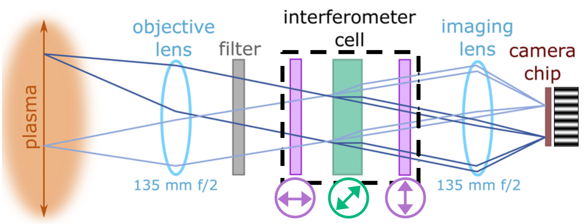
Coherence imaging spectroscopy

Coherence imaging spectroscopy (CIS) is an optical technique that uses a polarization interferometer to obtain 2D images of plasma parameters

Compared to dispersive spectroscopy, CIS has higher optical throughput and gives more spatial information, at the cost of reduced spectral information

CIS linear fringe configuration



Filter isolates light from a single spectral line

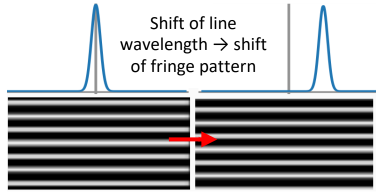
First polarizer linearly polarizes input light

Birefringent crystal imparts a wavelength-dependent phase delay

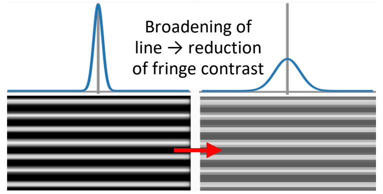
Second polarizer acts as an analyzer, converting the phase delay into an intensity modulation

Spectroscopic information is encoded into a fringe pattern having a linear spatial carrier (straight fringes)

Doppler shift: $\Delta\lambda/\lambda_0 = v_i/c$



Doppler broadening: $\sigma = k_B T_i/m_i$

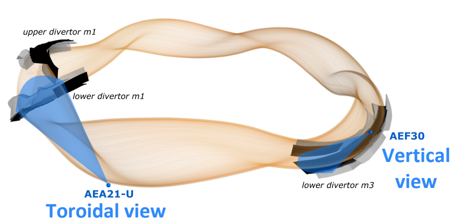


CIS diagnostic on W7-X

Two CIS diagnostics on W7-X, viewing plasma toroidally and vertically [V. Perseo et al, RSI **91** 013501 (2020)]:

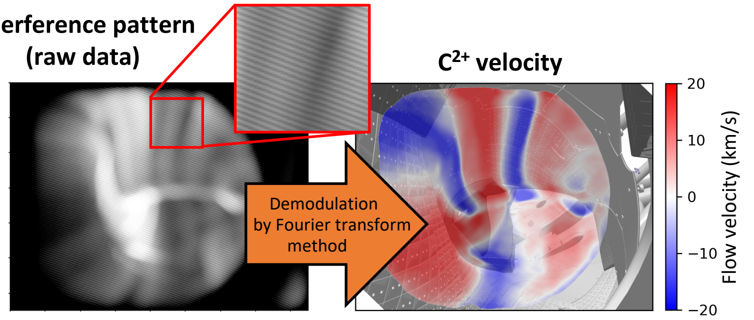
- ~1 cm spatial resolution
- ~50 ms time resolution
- Calibrated before/after every discharge using a tunable laser

CIS viewing geometry



Interference pattern (raw data)

C^{2+} velocity

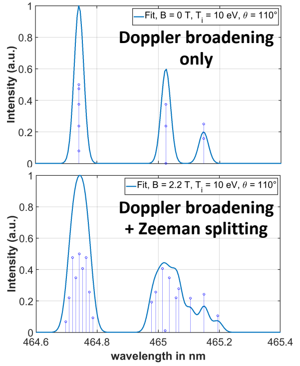


Accounting for Zeeman splitting in T_i analysis

Major challenge measuring scrape-off layer (SOL) T_i on W7-X: Zeeman splitting and Doppler broadening have comparable effect on linewidth

- SOL T_i in range of 10's of eV
- Magnetic field varies 2.2–2.9 T throughout plasma
- Measuring T_i requires Zeeman splitting to be modelled or independently measured

C III line at 465 nm



CIS contrast given by $\zeta = \zeta_I\zeta_D\zeta_{MZ}\zeta_B$

- ζ_I: instrument contrast (calibration factor)
- ζ_D: Doppler contrast, $\zeta_D = \exp[-T_i/T_C]$
- ζ_{MZ}: Contrast due to line splitting (multiplet and Zeeman effects)
- ζ_B: Contrast due to background light (e.g. bremsstrahlung or divertor thermal emission)

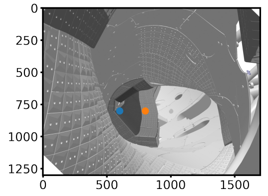
Zeeman contrast calculated along every CIS line of sight (LOS)

- Magnetic field B is generated by coils → known with high accuracy throughout plasma
- Zeeman splitting calculated along CIS lines of sight → gives ζ_{MZ} along lines of sight

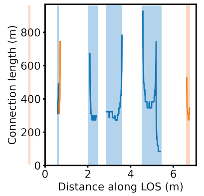
$$\zeta_{MZ} = \left|\sum_m \sum_z I_{m,z} e^{2\pi i \hat{N}(\nu_{m,z}-\nu_0)/\nu_0}\right|$$

$I_{m,z}$: intensity of multiplet/Zeeman component
$\nu_{m,z}$: frequency of multiplet/Zeeman component
ν_0: line center frequency
$\hat{N}$: interferometer group delay

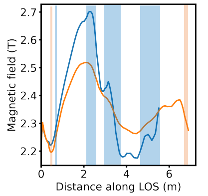
Example CIS lines of sight (projected onto image)



Connection length along lines of sight



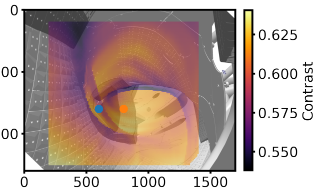
Magnetic field along lines of sight



Connection length used to determine emitting volume:

- L_c is infinite → confined plasma → no emission
- L_c is finite → scrape-off layer plasma → emission possible
- Most lines of sight pass through two SOL regions (orange example), some pass through many (blue example)

SOL-averaged ζ_{MZ}



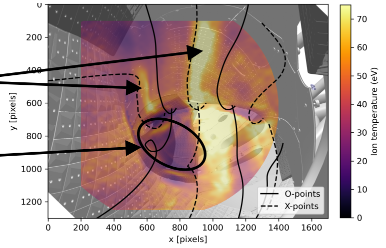
Initial scrape-off layer T_i measurements

T_i using Zeeman contrast averaged over the scrape-off layer islands

Bands of high T_i aligned with islands

Low T_i near divertor, in agreement with spectrometer measurements [D. Gradic et al, NF **61** 106041 (2021)]

C^{2+} impurity ion temperature

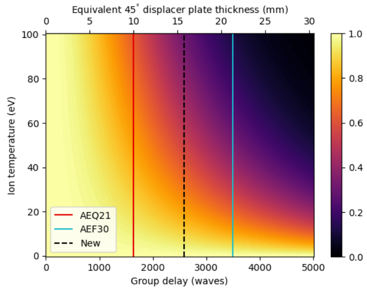


C^{2+} temperature measurements are spuriously large: $T_i = 30$–100 eV, while other measurements show $T_e = 10$–40 eV
→ possibly error due to Zeeman contrast variation or unaccounted for line-broadening mechanisms (bremsstrahlung, line-of-sight integration effects, spectral contamination)

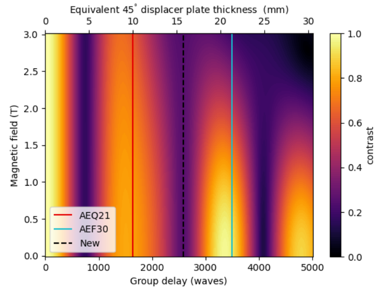
Interferometer crystals optimized for measuring T_i

Birefringent crystals in **two CIS instruments during OP1.2b were optimized for maximum contrast**, i.e., optimized for velocity measurements, not T_i
→ **Goal**: optimize crystals for C^{2+} T_i measurements using C III line at 465 nm

Doppler contrast



Multiplet + Zeeman contrast

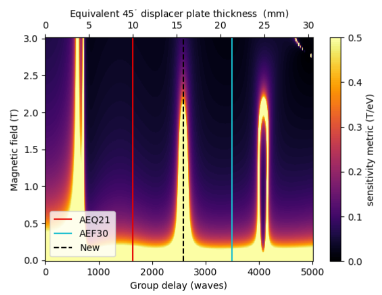


CIS sensitivity to physics parameters is determined solely by the **interferometer group delay** (proportional to crystal thickness)

Objective: maximize sensitivity to T_i and minimize sensitivity to B

- Normalized sensitivity to T_i: $S_{T_i} = \frac{1}{\zeta_D}\frac{\partial\zeta_D}{\partial T_i} = -\frac{1}{T_C}$ (depends only on group delay)
- Normalized sensitivity to B: $S_B = \frac{1}{\zeta_{MZ}}\frac{\partial\zeta_{MZ}}{\partial B}$

Ratio of T_i sensitivity to B sensitivity



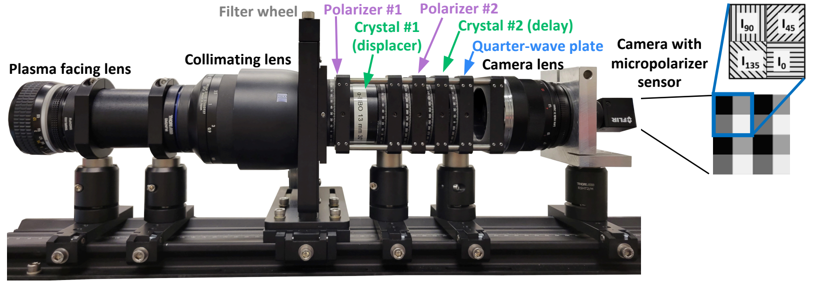
Multi-delay CIS design

Multi-delay CIS configuration [J.S. Allcock et al, RSI **92** 073506 (2021)] promises to improve T_i measurements by independently measuring B

- Standard CIS: coherence measured at one interferometer delay → limited spectral information → suitable for simple line shapes
- Multi-delay CIS: coherence measured at four interferometer delays simultaneously → more spectral information → can resolve more complex line shapes

CIS multi-delay configuration

Micropolarizer grid



Polarizers and **crystal #1** form a linear fringe pattern, encoding coherence at delay $\hat{N}_1$

Crystal #2, **quarter-wave plate**, and **polarization camera** form a pixelated fringe pattern, encoding coherence at delay $\hat{N}_2$

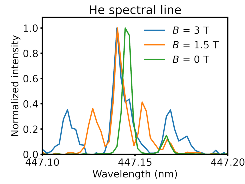
Two fringe patterns are multiplied together, resulting in combined linear + pixelated fringe patterns encoding coherence at delays $\hat{N}_1 + \hat{N}_2$ and $\hat{N}_1 - \hat{N}_2$

Initial multi-delay CIS measurements

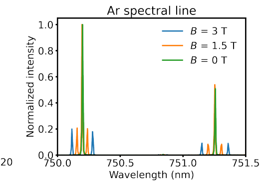
Multi-delay CIS instrument tested on the Magnetized Dusty Plasma Experiment (MDPX) [E. Thomas et al, IEEE **41** 811 (2013)]

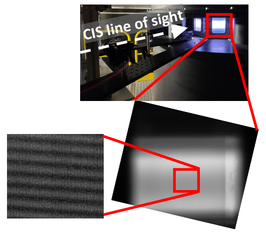
- Low-temperature (~2-4 eV), high field (>3 T) plasma source
- Excellent test bed of instrument response to Zeeman contrast with minimal Doppler broadening

He spectral line



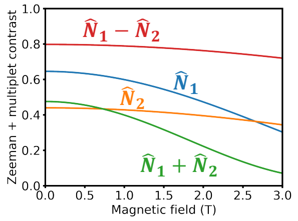
Ar spectral line



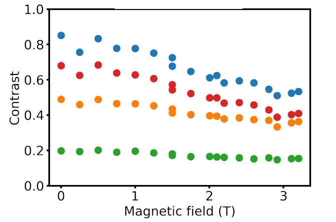


Observed CIS contrast decreases with increasing magnetic field (as predicted)

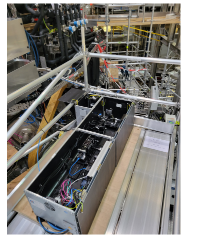
Predicted contrast for each delay

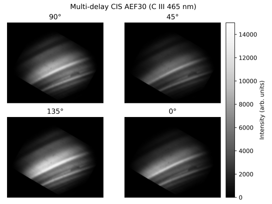


Observed He spectral line contrast



Contrast reduction (w/B-field) lower than predicted and likely due to overall low contrast levels resulting from imprecise rotational alignment of optical components





Multi-delay CIS instrument recently installed on W7-X for OP2 experimental campaign and first images were captured; commissioning in progress

Conclusions

- Analysis procedure developed to account for the effect of Zeeman splitting on CIS T_i measurements in the 3D island scrape-off layer magnetic topology of W7-X
- Initial SOL T_i measurements with flow-optimized CIS diagnostic yield high T_i bands that may be unphysical, motivating development of a new T_i-optimized instrument
- Crystals optimized for maximum ratio of T_i sensitivity to magnetic field sensitivity have been designed and procured
- Multi-delay CIS configuration developed for T_i-optimized CIS diagnostic:
  - New instrument tested on MDPX to assess effect of Zeeman splitting
  - Installed on W7-X for OP2 run campaign

EUROfusion

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