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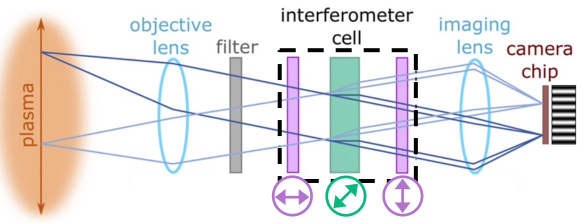
Scrape-off layer ion temperature measurements using coherence imaging spectroscopy on the W7-X stellarator

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

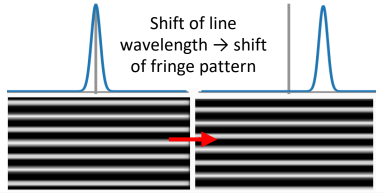
First polarizer linearly polarizes input light

Birefringent crystal (displacer plate) imparts a wavelength-dependent phase delay

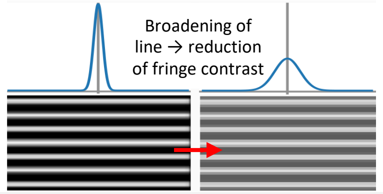
Second polarizer acts as an analyzer, converting the phase delay into an intensity modulation

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: $\sigma = k_B T_i/m_i$

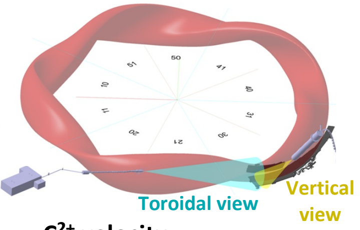


CIS diagnostic on W7-X

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

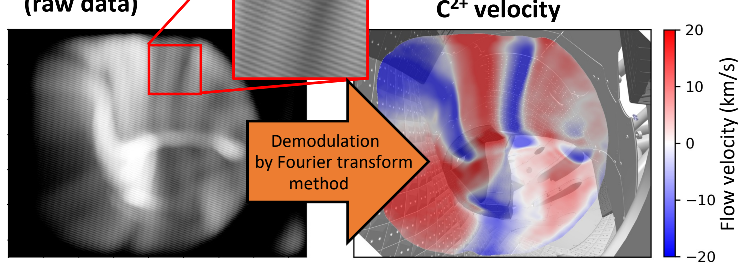
- ~1 cm spatial resolution
- ~50 ms time resolution
- Calibrated before/after every discharge using tunable laser

CIS viewing geometry



Interference pattern (raw data)

C^{2+} velocity

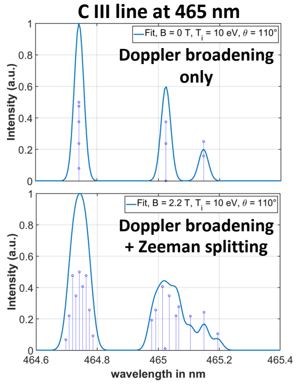


Accounting for Zeeman splitting in T_i analysis

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 electron-volts
- 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, ≈0.6–0.9)
- ζ_D: Doppler contrast,
  $$\zeta_D = \exp\left[-k_B T_i (2\pi\hat{N})^2/2m_i c^2\right]$$
- ζ_{MZ}: Contrast due to multiplet and Zeeman effects
- ζ_B: Contrast due to background light (e.g. bremsstrahlung or divertor thermal emission)

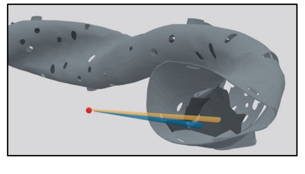
Zeeman contrast calculated along every CIS line of sight (LOS)

- 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

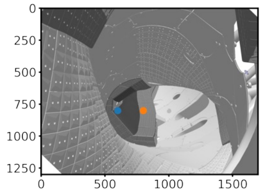
$$\zeta_{MZ} = \left| \sum_m \sum_z I_{m,z} e^{2\pi i \hat{N}(\nu_{m,z}-\nu_0)/\nu_0} \right|$$

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

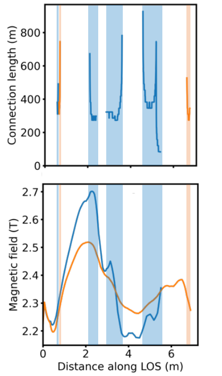
Example CIS lines of sight (3D scene)



Example CIS lines of sight (projected onto image)



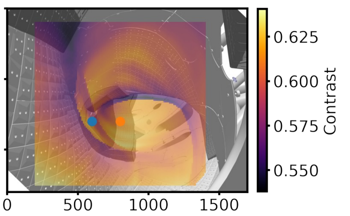
Magnetic quantities along lines of sight



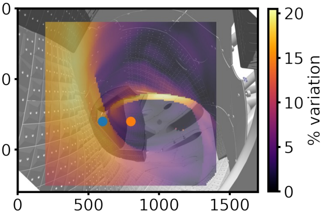
Connection length is used to determine regions along lines of sight where emission can come from

- 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}



Variation of ζ_{MZ} throughout SOL



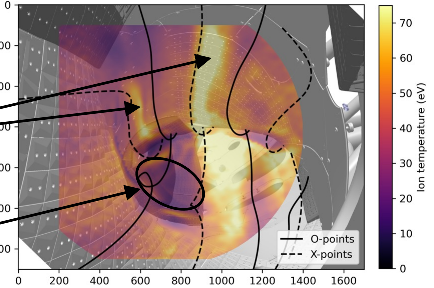
Initial scrape-off layer T_i measurements

T_i calculated using average value of Zeeman contrast 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

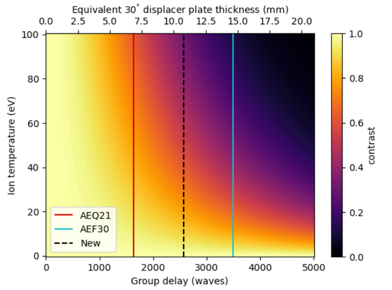


C^{2+} temperature measurements are spuriously large: $T_i = 30\text{–}100$ eV, while other measurements show $T_e = 10\text{–}40$ eV
→ possibly error due to Zeeman contrast variation or unaccounted for line-broadening mechanisms (bremsstrahlung, line-of-sight integration effects, spectral contamination)

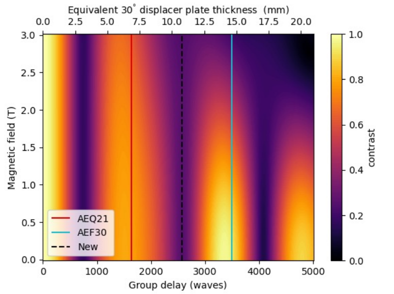
Interferometer crystals optimized for measuring T_i

Birefringent crystals in **existing two CIS instruments 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

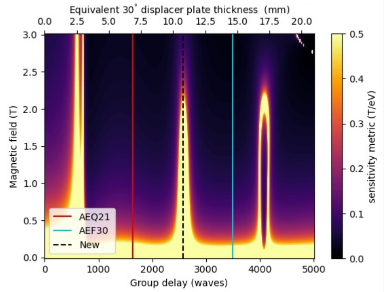


CIS sensitivity to physics parameters is determined solely by the **interferometer group delay** (proportional to crystal thickness)

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

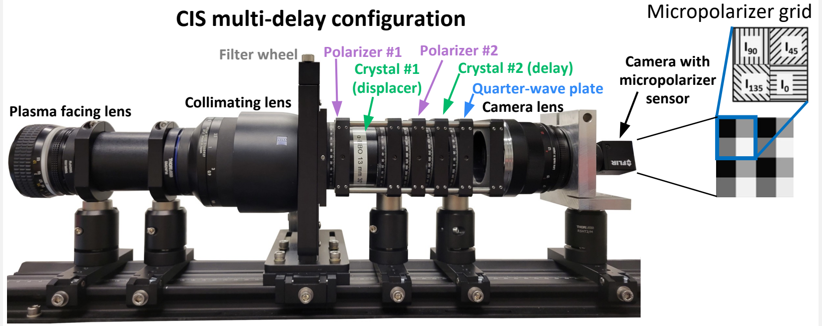


Multi-delay CIS design

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



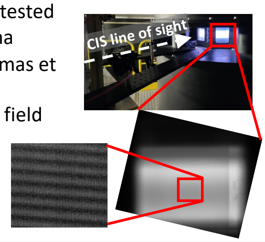
Polarizers and **crystal #1** form a linear fringe pattern, encoding coherence at delay $\hat{N}_1$

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

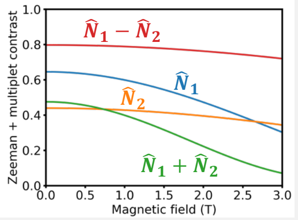
Two fringe patterns are multiplied together, resulting in combined linear + pixelated fringe patterns encoding coherence at delays $\hat{N}_1 + \hat{N}_2$ and $\hat{N}_1 - \hat{N}_2$

Multi-delay CIS instrument tested on Magnetized Dusty Plasma Experiment (MDPX) [E. Thomas et al, JPP **81** (2015)]

- Low-temperature, high field (>3 T) plasma source to test ability to measure B via Zeeman contrast
- Analysis ongoing



Predicted contrast for each delay



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 show quite 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 configuration is being pursued for T_i-optimized CIS diagnostic
  - Tested on MDPX and will be used for next W7-X run campaign

We would like to thank Saikat Thakur, Cameron Royer, and Ed Thomas for their help planning and executing the MDPX experiment. Work supported by US Department of Energy grant DE-SC0014529. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.