Updates on W7-X diagnostics:

ITPA October 2019

- CXRS vs XICS ion temperature measurements.
  O.P.Ford[1], N.Pablant[2], R.McDermott[1]

- Dispersion interferometer drift mitigation.
  J. Brunner[1] et. al.

- Thomson scattering dual laser wavelength.
  E. Pasch[1] et. al.

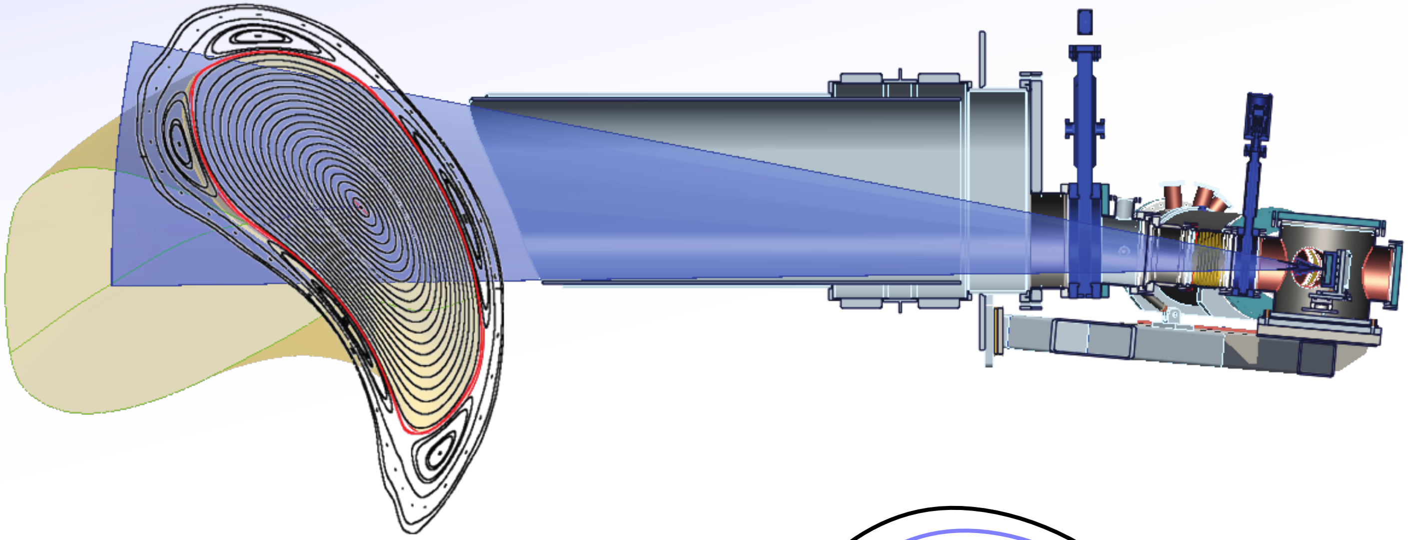
1: Max-Planck Institut für Plasmaphysik, Greifswald, Germany
2: PPPL, NJ, US

Charge exchange vs X-Ray crystal spectroscopy

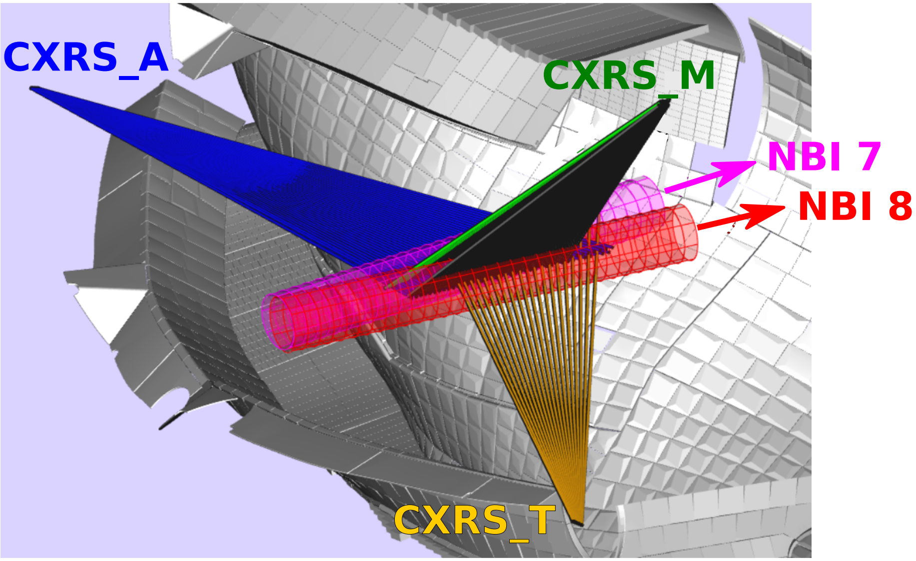
W7-X has two principle ion temperature diagnostics:

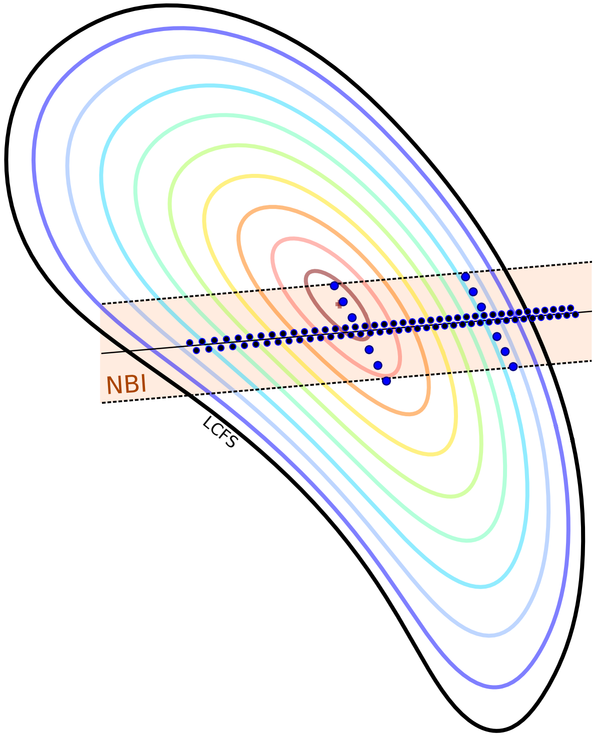
1) X-Ray Imaging Crystal Spectrometer (XICS)

High-resolution X-ray Crystal Spectrometer (HR-XCS)



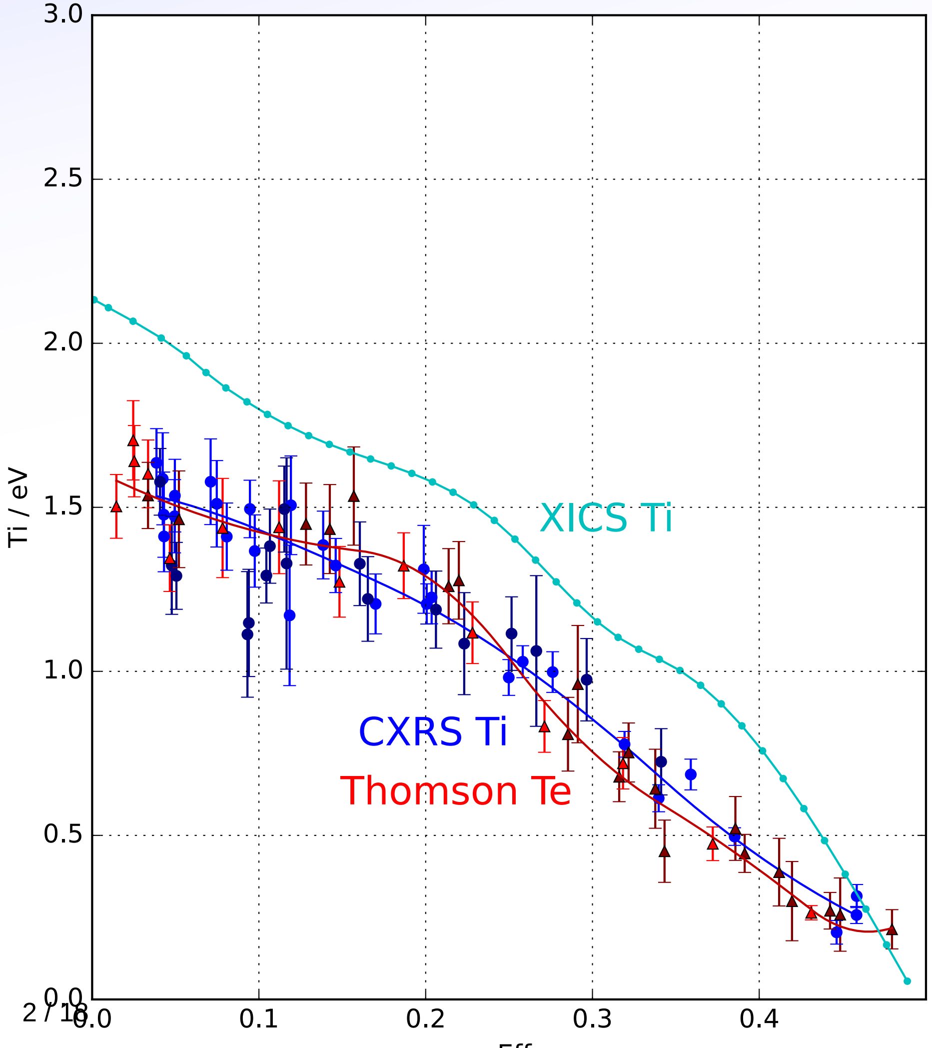
2) Charge Exchange Recombination Spectroscopy (CXRS) on the NBI heating beams

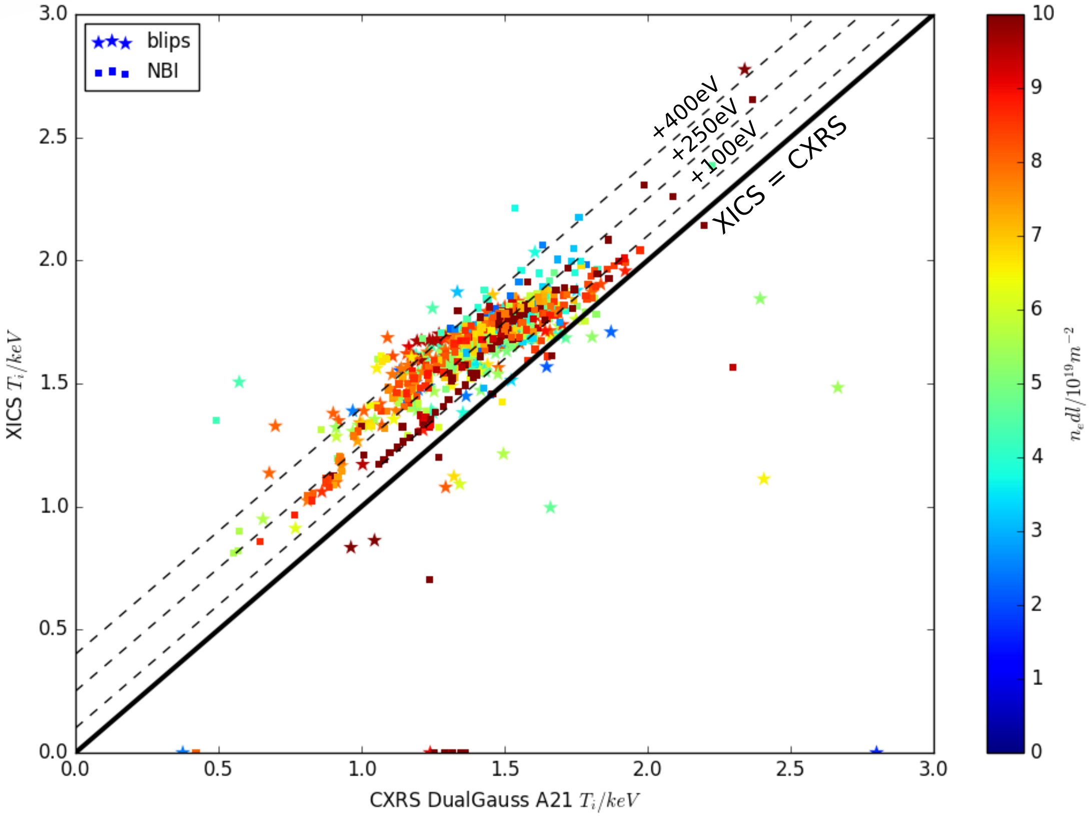




XICS vs CXRS - Ion temperature

Initially 100 - 400eV difference observed between XICS and CXRS
(reported TGD April 2019)





XICS corrections

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SOURCES OF TI OVERESTIMATION

1. Spherical aberration

The XICS system uses a very large crystal (focusing optic) to provide high light throughput (good signal to noise. This leads to significant spherical aberrations that were were not previously considered. Ti error of ~ 100 eV.

2. Detector focus

The system was focused for the edge of the crystal, rather than the center, leading to larger than optimal spherical aberrations.

3. Sub-pixel intensity distribution

The analysis of the XICS spectrum makes an implicit assumption that the distribution of intensity within a single pixel is **linear** (no second derivative). Ti error of ~ 40eV.

4. Decurving

Decurving of the spectra is needed to allowing binning of multiple rows on the detector (for better S/N). The decurving procedure makes the implicit assumption that the distribution of intensity within a single pixel is **constant** (no first derivative). Ti error of ~ 0-100 eV.

XICS corrections

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CORRECTION FOUND THROUGH X-RAY RAY-TRACING

Correction was determined through x-ray ray tracing

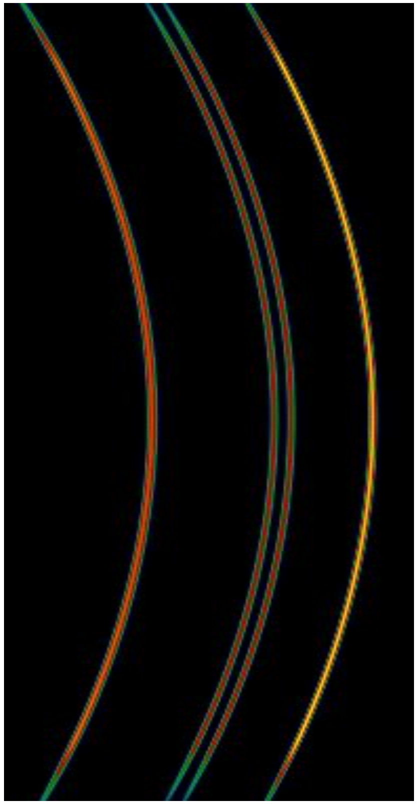
- **Using the XICSRT code [J. Kring, RSI, 2018]**

Raytracing uses best known system calibration (geometry calibration).

- **A slab plasma is modeled with a single temperature.**
- **A single Ar16+ line is modeled based on Doppler broadening and natural line with.**
  (line shape modeled as a Voigt profile).
- **Crystal rocking curve estimated from x0h (poor estimate).**

Raytracing generates an image in the same format as the actual system that can then be analyzed using the standard XICS analysis suite.

Difference between the input Ti in the ray-tracing model and the measured Ti after analysis is then the correction.



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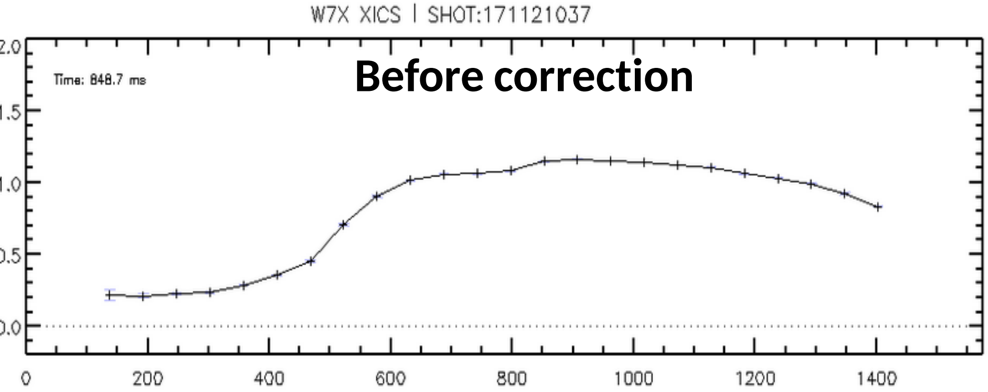
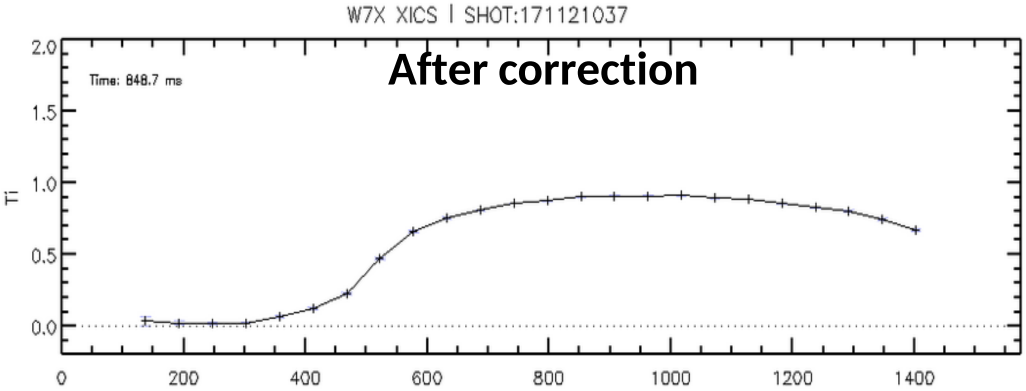
CORRECTION IS CONSISTENT WITH LOWEST TEMPERATURES MEASURED BY XICS

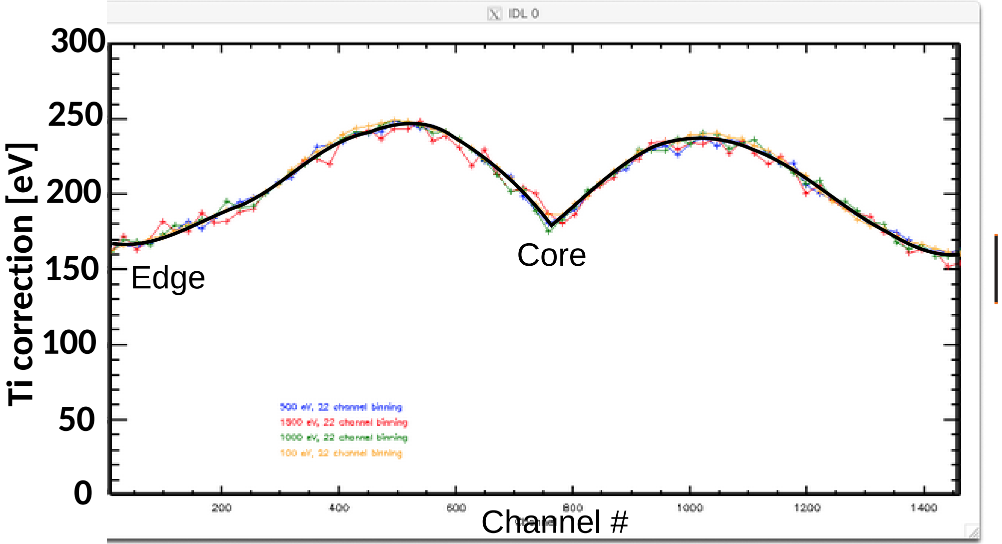
The lowest temperatures ever measured by XICS (from Ar16+ charge exchange spectra) were around 180 eV before correction.

After correction these values are now close to 0 eV.





Final correction curve for XICS:



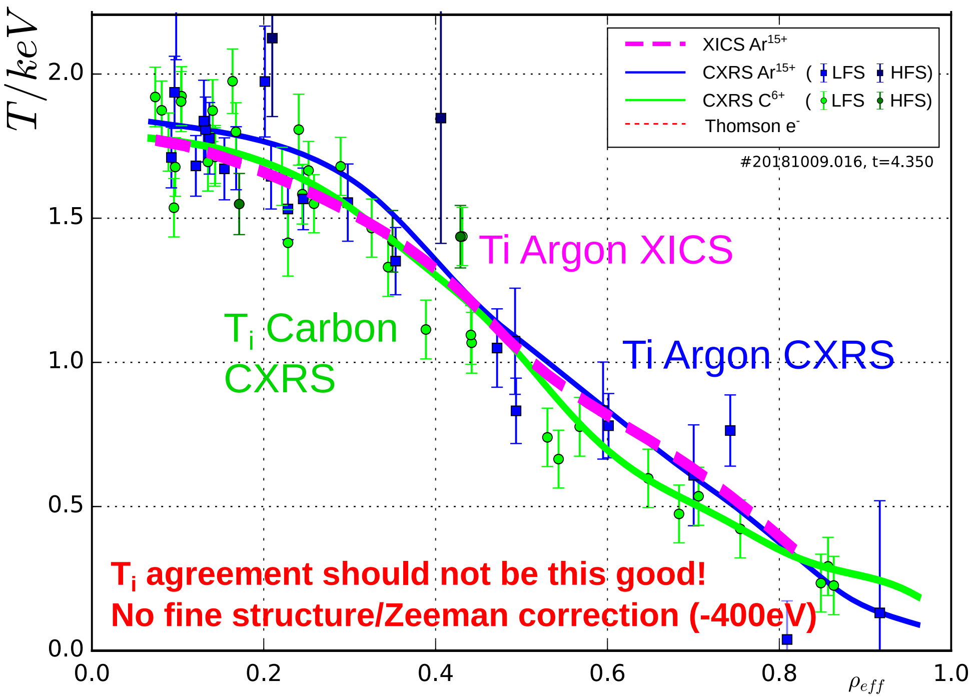
CXRS corrections

For CXRS, there are many corrections that need to be checked:

Correction (at W7-X)	**C VI 529.1nm**	**Argon XVI 436.5nm**
Instrument function correction	-40eV	~1.2keV (non-gaussian --> +200eV)
CX cross-section effects	~0	~0
Finite lifetime effects	~0	~0
Fine-structure effects + Zeeman broadening	-100eV	-400eV
Line integration effects	±50eV	±50eV
Passive subtraction error	±50eV	~0
Total unaccounted	±150eV	±400eV

(Included)

(not yet Included)



T_i agreement should not be this good!
No fine structure/Zeeman correction (-400eV)

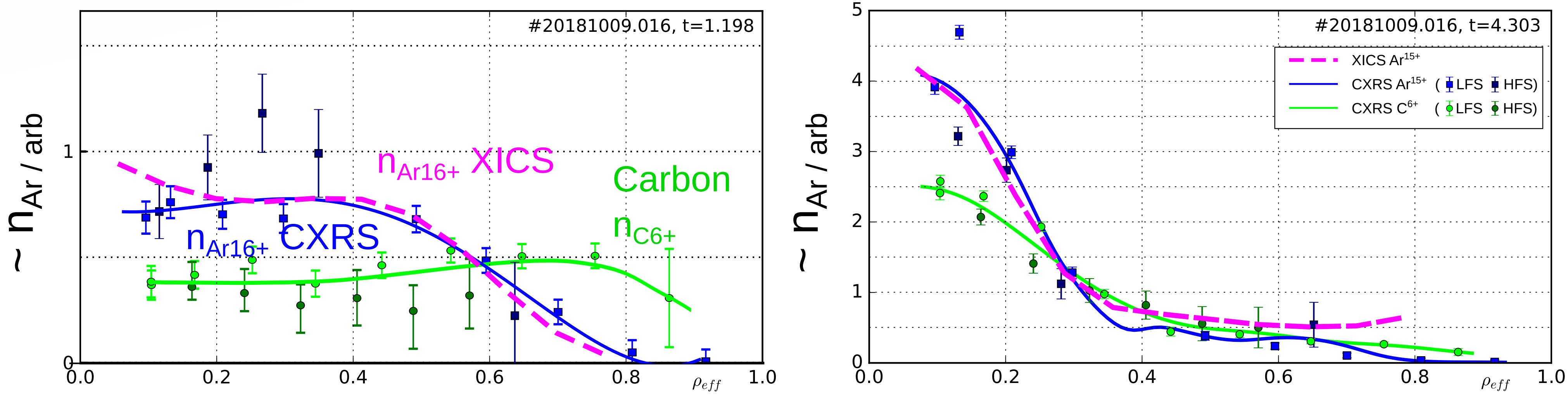
Argon density / CX cross-section improvement

Significant discrepancies in available Ar CX-cross sections.

- Work at ASDEX Upgrade to investigate E_b dependence. [R. McDermott]

- At W7-X we can measure Ar 16+, 17+ with CXRS and relative absolute levels on XCS.
  --> Experimentally check relative CX cross-sections --> Uncertainties in ADAS
  Use for CX/XCS calibration cross-check at ITER?

- Qualitative profile shows good shape agreement for Ar 16+:



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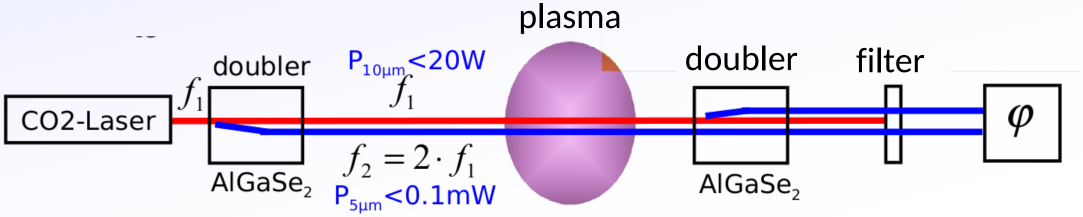
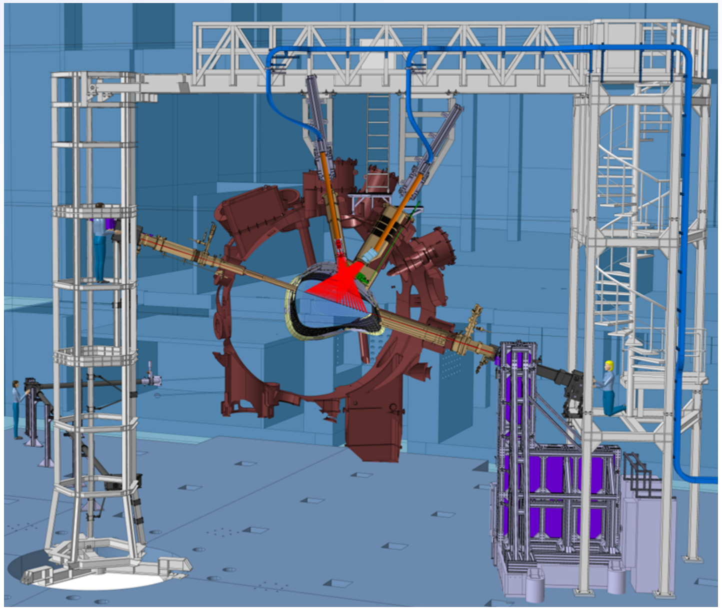
Dispersion Interferometer

- Single channel core interferometer provides average density in real-time

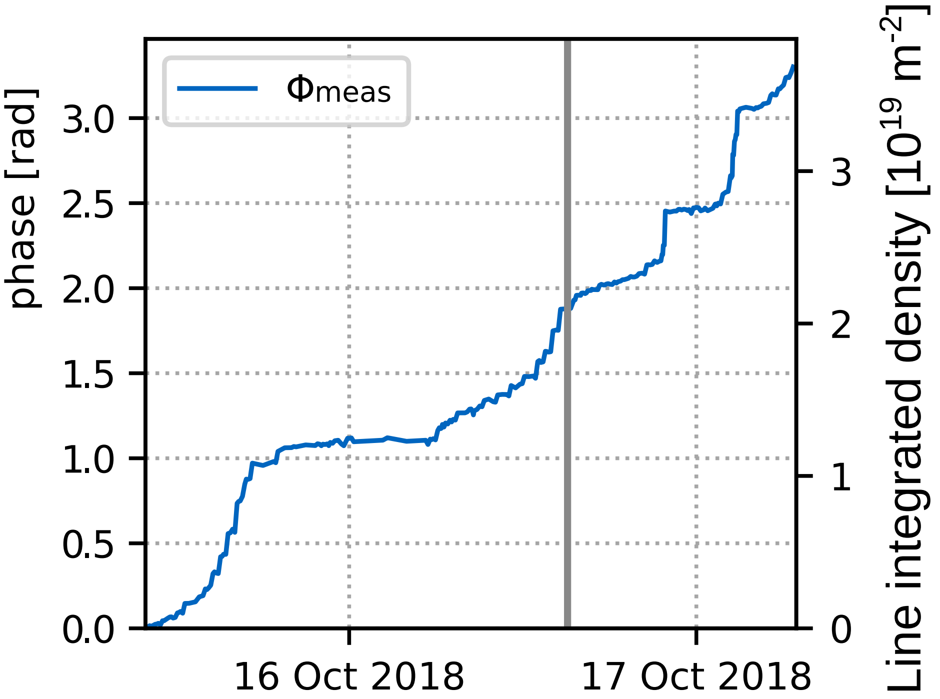
- Dispersion-interferometer type, (as 'DIP' on ITER)





- Inherent vibration insensitivity
- Generally running very well for short discharges.
- Real time FPGA analysis
  --> Density feedback controller.
- Some issues with unexplained non-ideal behaviour ('non-circularity')

Issue for future W7-X discharges up to 30 min:
- Significant phase drifts over day due environmental changes (temperature, pressure, humidity).



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Dispersion Interferometer

- Path length changes (movement/vibration) dealt with by dual-wavelength (dispersion).

- Model air and optical components as function of :
  λ - Wavelength
  T - Ambient temperature
  p - Ambient pressure
  H - Humidity

- Path length <LN> in air can be expressed as polynomial series in T, p, H
  - 2nd order sufficient to reduce drifts significantly: *[K. J. Brunner et al.2018 JINST 13 P09002]*

- All dispersive elements can be combined as an average optical path length: *<LN>(λ, T, p, H)*

- Assume all components equilibriate to the same temperature *T*.

- Use simple hardware (Arduino + sensors) to measure environmental *T, p, H*.

- Measurements of phase with varying p, T, H and no plasma allow determination of series approximation - this should remain fixed when diagnostic is not modified.

- Measurements of *T, p, H* can then be used to correct drifts during plasma.

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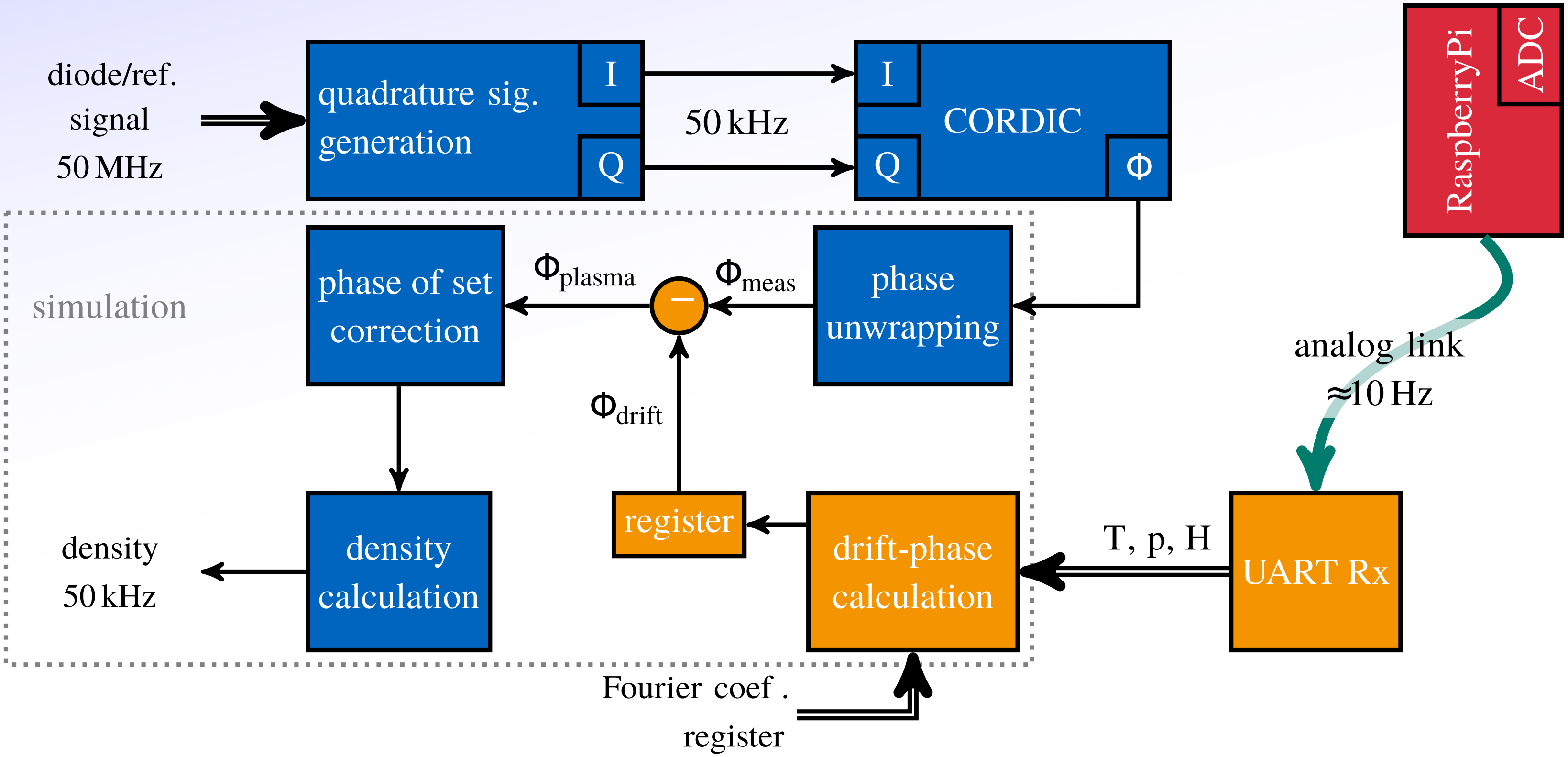
Dispersion Interferometer

- *T,p,H* measurements fed to evaluation FPGA via a UART link to allow real-time correction:



The structure of the firmware's DSP core. The original implementation is indicated in blue and has been detailed previously[K. J. Brunner *et al.* 2018 *JINST* **13** P09002]. The external environmental sensor is indicated in red. The logic applying the phase drift model to the real-time phase is indicated in orange.

- SImple hardware (~100€) that can be retro-fitted to existing DI systems.

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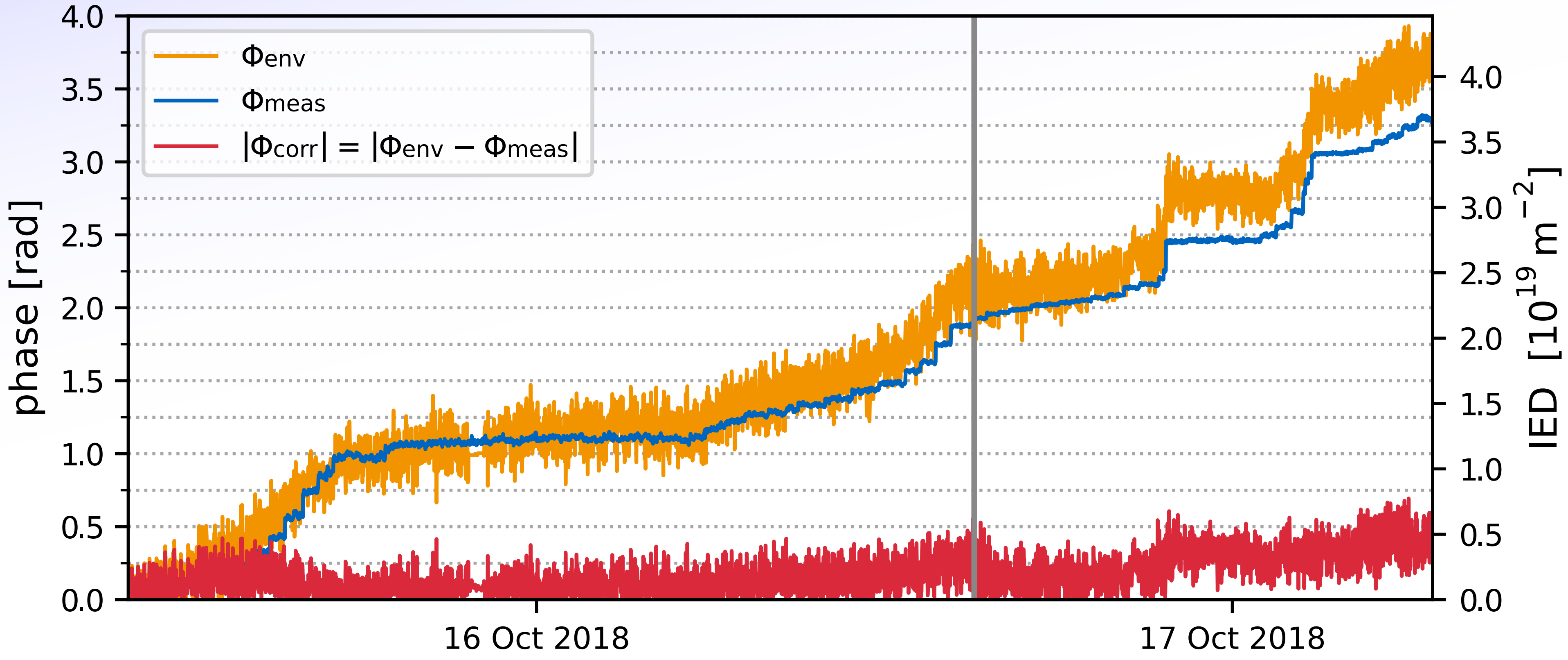
Dispersion Interferometer

Tested on simulated FPGA using real raw data collected during last campaign (no-plasma):



Demonstration of phase drift stabilization using a GHDL simulation. The simulation input data is real data from Oct 16 & 17, 2018. The left ordinate indicates the phase, the right one the equivalent density error. Abscissa not to scale. Gray line is midnight.

Dual-wavelength Thomson Scattering

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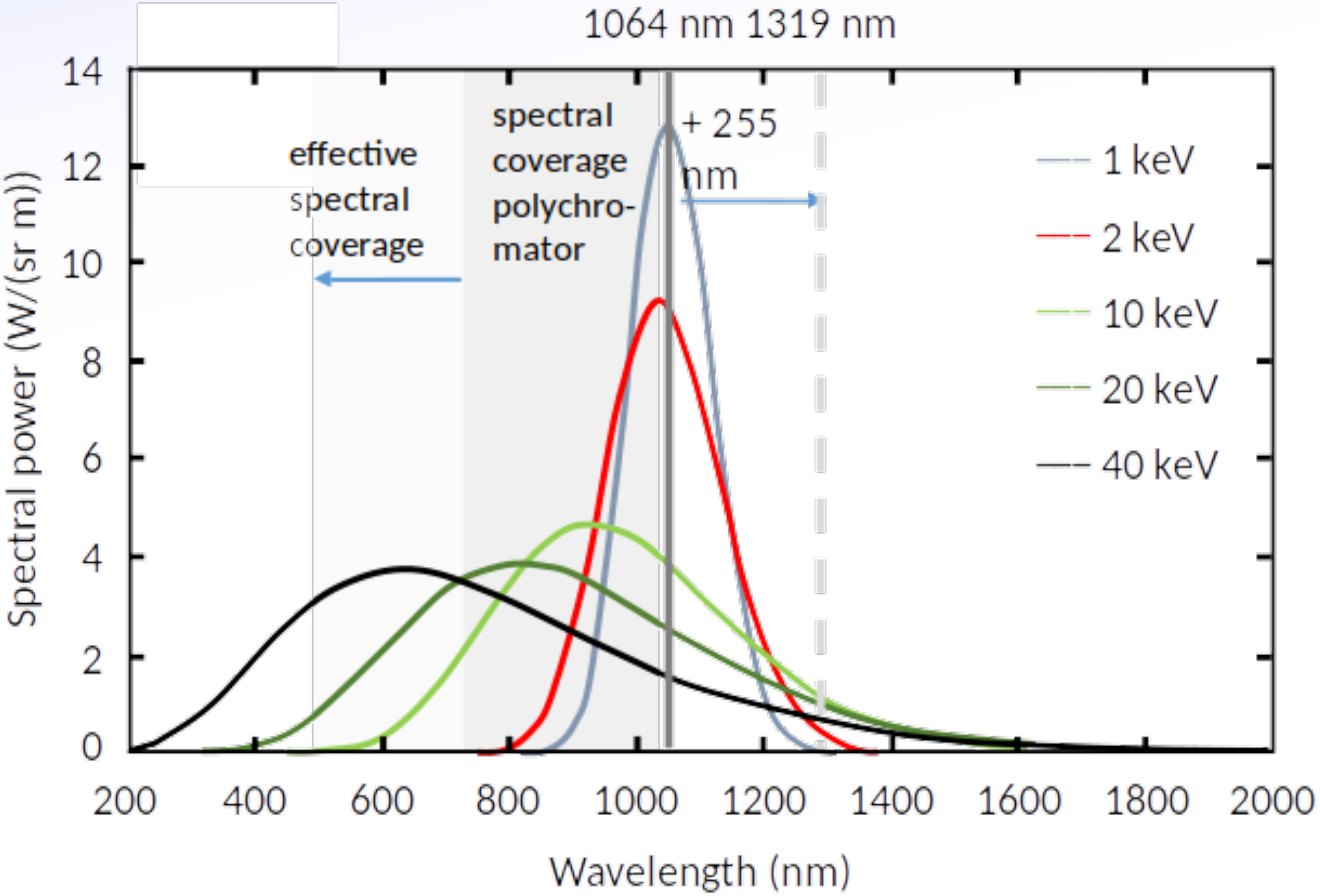
- Add 1319nm laser along same path as standard 1064nm laser to effectively increase T_e range of existing polychromator channels:
  (Reported in detail ITPA TGD October 2018)



Dual-wavelength Thomson Scattering

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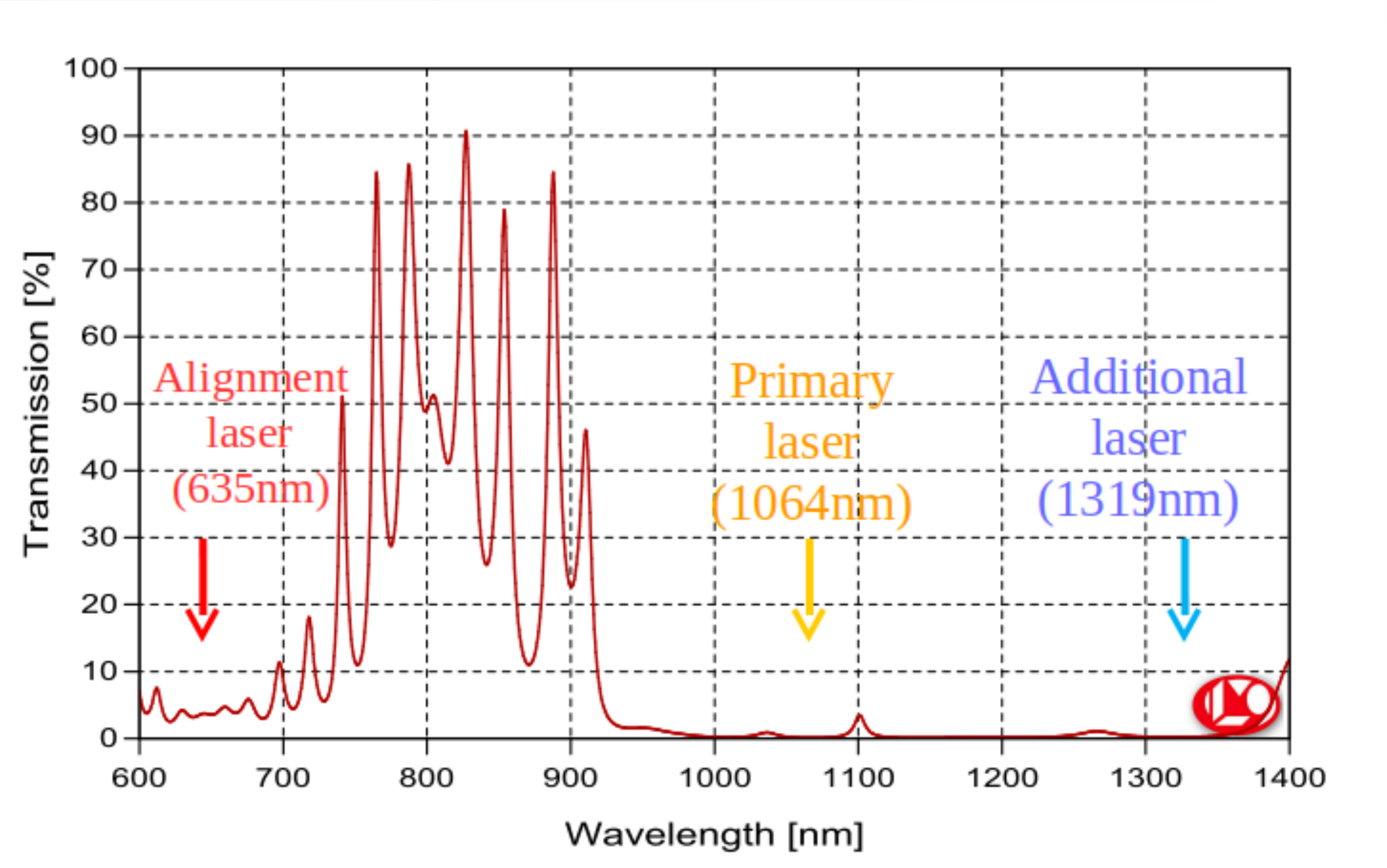
- Requires mirrors with high reflectivity at both wavelengths:



B-14475: HR635-658nm+1064nm+1319nm/27.5°s

Dual-wavelength Thomson Scattering

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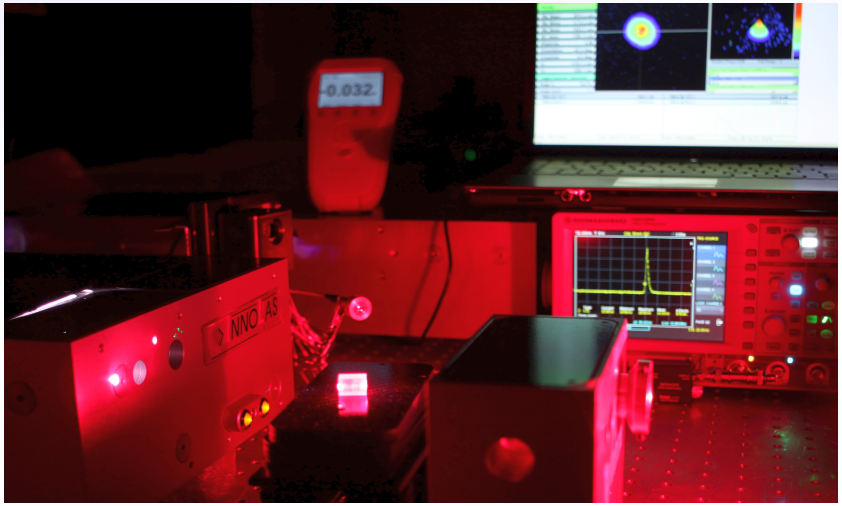
- Tested laser induced damage threshold (LIDT) for mirrors using 1064 and 1319nm lasers.

Nd:YAG, 1319 nm, E <= 820 mJ, t = 15 ns, f = 10 Hz

Nd:YAG, 1064 nm, E = 2000 mJ, t = 10 ns; f=10 Hz, d=12 mm, A=1.1 cm^2 „spot“ size > d=5 mm



Typical results show much lower LIDT than quoted by manufacturers, also for 1064nm laser:

Specification under ISO 21254-2:
1064 nm
Angle of incidence: 0°
Polarization: linear
Minimum time between shots: 5 s
Effective beam diameter in target plane: 0.34 mm
Pulse duration: 12 ns
Exposure duration: 200 shots/sites
Test prep: N2 gas blow

Typical mirrors for 1064nm give guarantee
LiDT < 20 - 70 J/cm^2

Dual-wavelength Thomson Scattering

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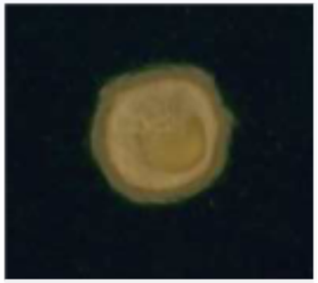
Determination of beam diameter:

e

Beam diameter:

„Burning“ paper



d=7 mm

TS

Plastic bag

d=5 mm

AlO_2 plate

d=5 mm

Specification under ISO 21254-2:

Minimum time between shots: 5 s

Effective beam diameter in target plane: 0.34 mm

Test prep: N2 gas blow

TS Test:

A=1.1 cm^2 „spot“ size > d=5 mm, in air, without N2 gas cooling, exposure time 5 min

Dual-wavelength Thomson Scattering

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Tested mirrors with different manufacturing processes.
- LIDT usually much lower under real TS conditions than under ISO standard test.

Single wavelength mirrors:

Nd:YAG 1064 nm, E=2000 mJ, f=10 Hz

Electron beam evaporated: **6 J/cm^2**
Magnetron Sputtered (MS): **7.5 J/cm^2** (Al2O3), **7 J/cm^2** (ZrO2), **6.5 J/cm^2** (HfO2)

Dual wavelength mirrors:

Nd:YAG 1064 nm, E=2000 mJ, f=10 Hz
Nd:YAG 1319 nm, E=800 mJ, f=10 Hz

Ion assisted deposition: **1.0 J/cm^2**
Ion beam sputtering: **1.5 J/cm^2**
Electron beam evaporation: **2.0 J/cm^2**
Magnetron sputtering: T.B.D. (ZrO2, 60-80 layer)

↔ Specified to **10 J/cm^2** under ISO standard.

- Dual wavelength mirrors have lower specification --> ISO vs TS conditions critical.
- EBE mirror sufficient for W7-X, but challenging for ITER

W7-X Updates

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- CXRS vs XICS ion temperature measurements.
  - Identified most major discrepancy. Agreement now < ±150eV.
  - Intention to work on resolving argon CX cross section issues (W7-X and AUG).

- Dispersion interferometer drift mitigation.
  - Model developed and tested in simulation. Online test in next campaign (end 2021)

- Thomson scattering dual laser wavelength.
  - Dual wavelength mirrors have lower specification --> ISO vs TS conditions critical.
  - Identified suitable mirrors for W7-X, careful consideration required for ITER.

Other W7-X updates:

- *High-repetition rate Thomson scattering - H. Damm (tomorrow morning)*

- Investigation of tungsten divertor possibilities started (2030+)