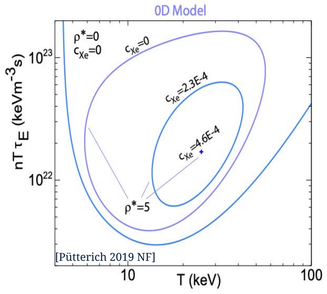
Introduction

A future fusion power plant must simultaneously confine bulk ions and remove impurity ions, otherwise radiative cooling can dominate.

1. High-Z impurities like Tungsten (W) are especially detrimental
2. Currently W is a plasma facing material (PFM) expected to be utilised by ITER and W7-X
3. PFMs will be eroded and sputtered during operation

Understanding and exerting some control of how impurities move in the plasma is a critical component of achieving Q > 1.



Theory

The transport of ions is dependent on the diffusive/convective flux and the ionization distribution

Ionizations from charge state below | Recombinations from charge state above | Electrons ionized or recombined from current charge state

$$\frac{\partial n_Z}{\partial t} = -\nabla \cdot \mathbf{\Gamma} + n_e S_{Z-1} n_{Z-1} + n_e \alpha_{Z+1} n_{Z+1} - (n_e S_Z + n_e \alpha_Z) n_Z$$

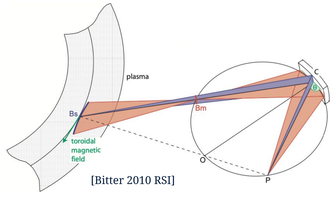
Γ = Diffusion & Convection S = Ionization α = Recombination

- Ionization/recombination rates from atomic data calculations and **collisional radiative (CR)** modelling
- In a 1-D radial model **particle flux Γ** is modeled as a diffusive and convective process:
  - Diffusion coefficient **D(r)** scales **impurity density gradient**
  - Convection coefficient **V(r)** scales **impurity density**
- Diffusion occurs through 3 channels: $\Gamma_I(r) = -D(r)\nabla n_I(r) + V(r) n_I(r)$
  - **Classical** diffusion - particle collisions
  - **Neoclassical** diffusion - drifts from toroidal geometry
  - **Turbulent** diffusion - gradient driven turbulence

Impurity transport measurements aim to characterise the diffusion and convection coefficients that determine the particle flux

X-Ray Imaging Crystal Spectroscopy (XICS) Diagnostic

- Known impurity emissions can be imaged using XICS
  - Specific crystals view specific wavelengths according to Bragg condition
  - Spherically bent crystals give spatial resolution in the meridional plane (~ 2 cm)
  - Used for ion temperatures and observing high charge state emissions of transport interest
- Pilatus X 300K-W single photon counting detector provides high efficiency and 5 ms temporal resolution

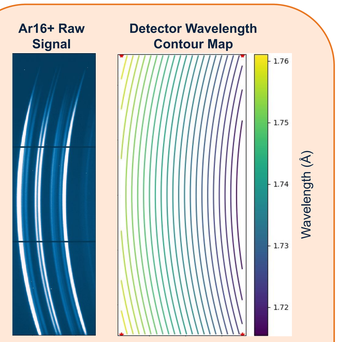


[Bitter 2010 RSI]

Commissioning and Modeling of the HR-XIS

The High Resolution X-Ray Imaging Spectrometer (HR-XIS) is equipped with 8 different crystals installed on a translating and rotating table, capable of viewing many regions between 0.5 - 7 Å

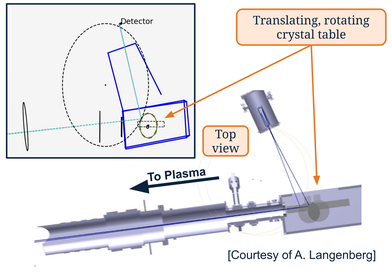
Fully 3D model of HR-XIS system being constructed:
- Use coordinate system of W7-X
- Predict and identify spectral lines
- Save system calibration sets between campaigns



A 2D view of the detector in the 3D model replicates the geometric curvature of the spectral lines according to the Bragg condition

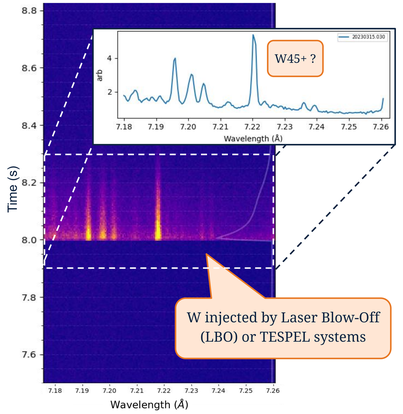
During the OP2.1 scientific campaign at W7-X the HR-XIS was commissioned with added variability as a result of modeling the diagnostic:

- The viewable spectral range was doubled, and if second-order diffraction is considered, quadrupled
- New W emissions, previously unavailable, were observed using settings from the model



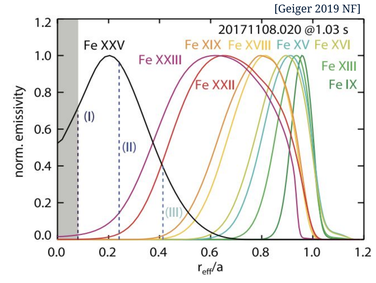
[Courtesy of A. Langenberg]

20230315.030 New HR-XIS W Observation

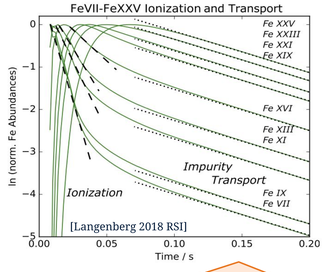


Making a Transport Measurement

Transport modeling codes like Aurora and STRAHL calculate a radial ionization fraction profile



Injected impurities initially come to an ionization equilibrium following the T, n profiles

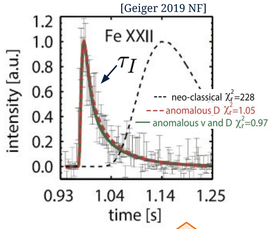


Measuring spectral intensity over time can experimentally inform **impurity density** and **ionization fraction**

The ionization fraction stabilizes and the impurity transport, determined by the flux coefficients, dominates

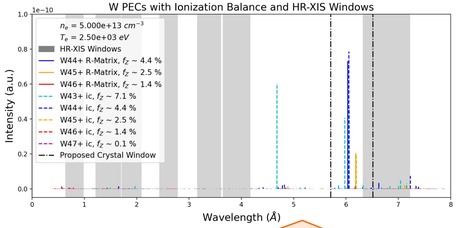
$$I_{i->j}(T_e, n_e) = PEC_{i->j}(T_e, n_e) n_e n_I f_Z$$

$I_{i->j}$ = Spectral Intensity $PEC_{i->j}$ = Photon Emissivity Coefficient f_Z = Ionization Fraction



Fit the spectrally observed injection and **decay time** of impurities to transport code calculations, iteratively improving diffusion/convection coefficients

Using reasonable plasma parameters for W7-X, the strength of W emissions can be predicted from collisional radiative modeling of atomic calculations



A new crystal is being considered to allow for observation in this area, where W PECs predict greater emission

Future Work

The W7-X OP2.2 scientific campaign is slated to begin in Sept. 2024, in preparation for the experiments:
- Complete HR-XIS 3D model and make identifications of observed W emissions, predict where, if any, new high-charge state W emissions may be observable
  - A new crystal, selected to diffract in a region where strong W emissions are predicted, may be added
- Develop and validate spectral analysis suite of codes
  - Compatible with transport codes pySTRAHL and AURORA and atomic modeling code ColRadPy
  - HR-XIS has observed Fe from LBO or TESPEL injections more commonly than W, may allow for analysis

During and following the OP2.2/OP2.3 campaigns:
- Observe W emissions in standard W7-X operating conditions for W transport analysis
- Publish spectral analysis codes for use with established transport codes as an application

Conclusions

- HR-XIS modeling allowed for observation of previously unavailable W emissions in the 0.5 - 7 Å range
- Spectral analysis software is being developed to use HR-XIS observations with transport codes
- New W observations still must be identified and other potential W emissions must be accounted for to optimize W transport measurements during next W7-X scientific campaign

Acknowledgements

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