STRAHL modeling of impurity transport experiments with on- and off-axis heating during the first divertor campaign on Wendelstein 7-X

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Impurity transport characterization is an important topic in stellarator physics

- For high performance, high density discharges theory predicts that impurities will accumulate, potentially leading to radiative collapse. [1]
- However there is evidence from LHD's impurity hole to W7-AS's HDH mode that high energy confinement and avoidance of impurity accumulation are not mutually exclusive [1]
- For high performance steady state operation, both screening near the edge and core flushing of impurities will be important. Before possible advanced operational scenarios can be identified, **impurity transport needs to be characterized under various conditions**.
- Specifically an on- to off-axis ECRH scan alters the radial electric field and hence the neoclassical transport. Therefore comparisons with neoclassical predictions and the role of turbulent transport in the different heating scenarios can be evaluated.

Presentation Outline

- Transport diagnostics: XICS, HR-XIS, HEXOS, & LBO
- OP 1.2b: Impurity transport experiments
- STRAHL modeling of Fe LBO
- Synthetic sensitivity studies
- Fe transport during on- and off-axis ECRH
- Summary

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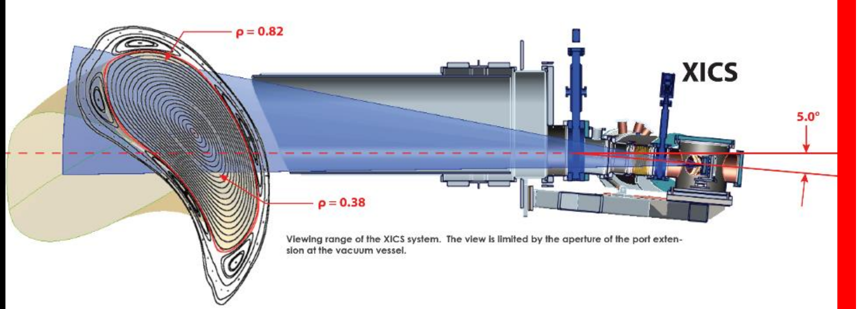
[1] R. Burhenn *et al* 2009 *Nucl. Fusion* **49** 065005

The spectral diagnostics used for the Fe impurity transport experiments provide the right balance of spatial resolution and spectral coverage

X-ray Imaging Crystal Spectrometers (XICS & HR-XIS)



- **Spatial resolution:** 2 cm
- **Temporal resolution:** 2 ms
- **Viewing:** 0.38 to 0.82 ρ
- **Impurities:** $Ar^{16+}, Ar^{17+}, Fe^{24+}, Mo^{32+}$

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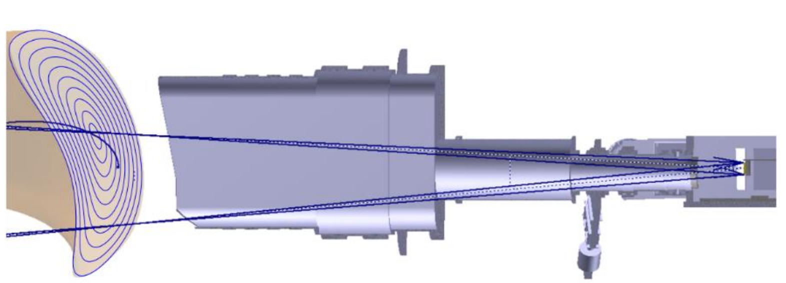

- **Spatial resolution:** 2 cm
- **Temporal resolution:** 2 ms
- **Viewing:** 0.05 to 0.6 ρ
- **Impurities:** $Si^{12+}, Ar^{16+}, Ti^{20+}, Fe^{24+}, Ni^{26+}, Cu^{27+}, W^{60+}$

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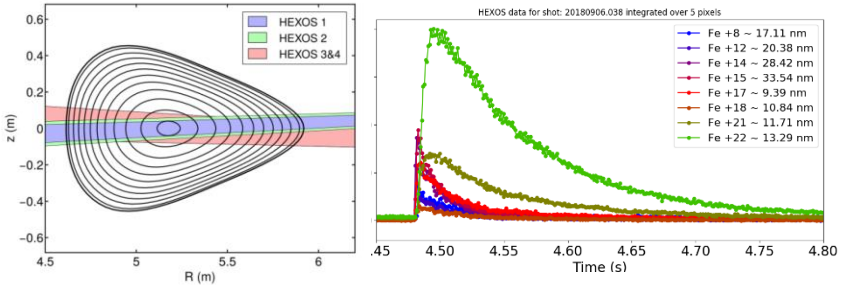
High-Efficiency eXtreme ultraviolet Overview Spectrometer (HEXOS)



- **Temporal resolution:** 1 ms
- **Viewing:** Single central sightline
- **Spectral coverage:** 2.4 to 161.1 nm
- **Iron chargestates:** Fe^{8+} to Fe^{22+}

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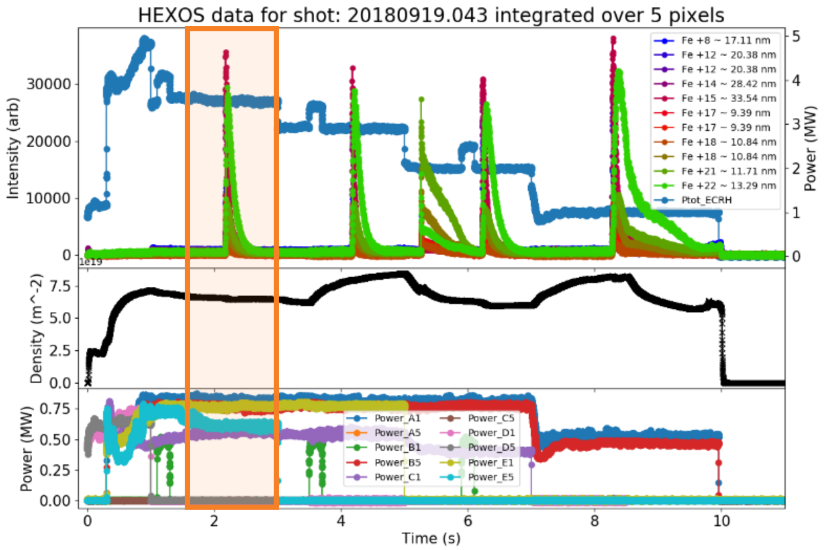
- Three XICS systems are installed on W7-X with one system having the flexibility to change between eight different crystals during a discharge
- Fast time resolution coupled with spatial information from 1-D image make this an ideal diagnostic for studying impurity transport

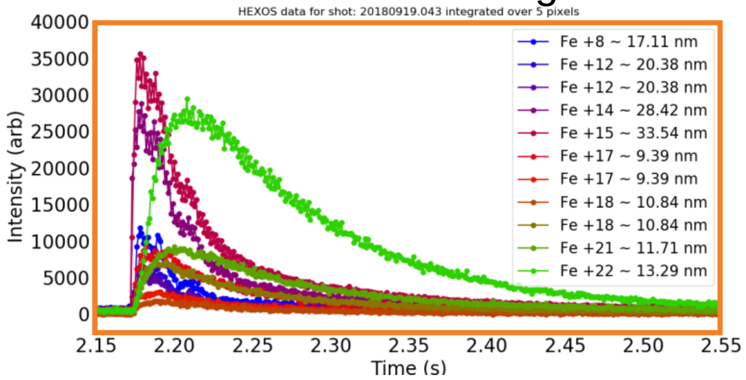
- Four detectors provide wide VUV spectral coverage to capture wide range of iron chargestates simultaneously
- Only provides single, central sightlines (i.e. no spatial resolution), but at high time resolution

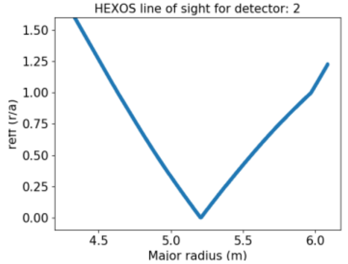
Example of an iron impurity transport experiment with corresponding measurements from HEXOS and XICS



- Keeping the line-integrated density constant, ECRH total power was stepped down by turning off specific gyrotrons
- 4 Fe LBO injections starting at $\sim 2.0\ s$ occurred at each total power level
- Similar discharges were performed with gyrotrons at various axial heating positions from completely on-axis to most off-axis heating

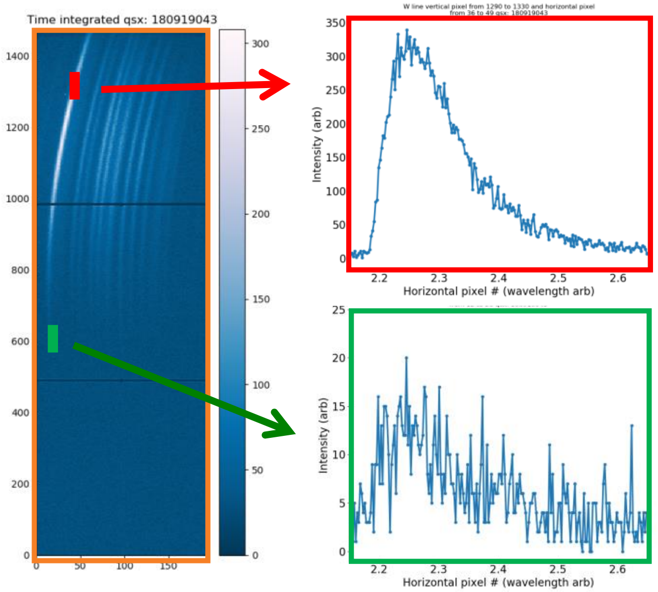
HEXOS signals and sightline

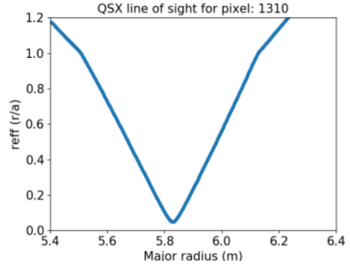


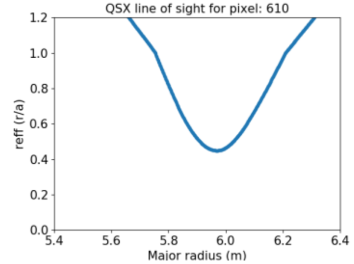


- From know diagnostic position, line integrated measurements can be properly matched in STRAHL model
- Seven different charge states are taken to then be matched within STRAHL.

XICS image, signals, and sightlines

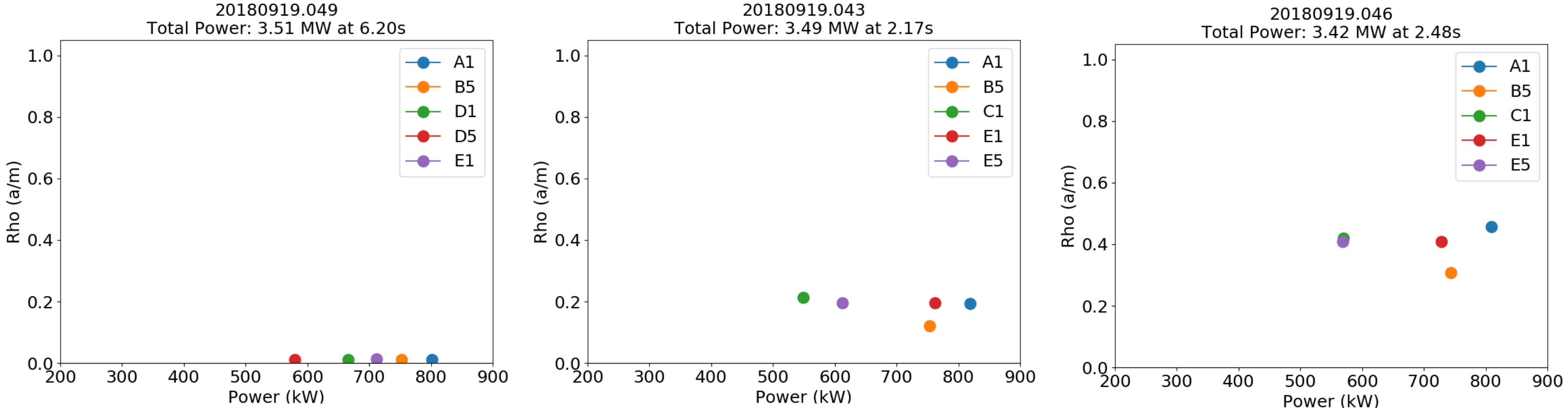




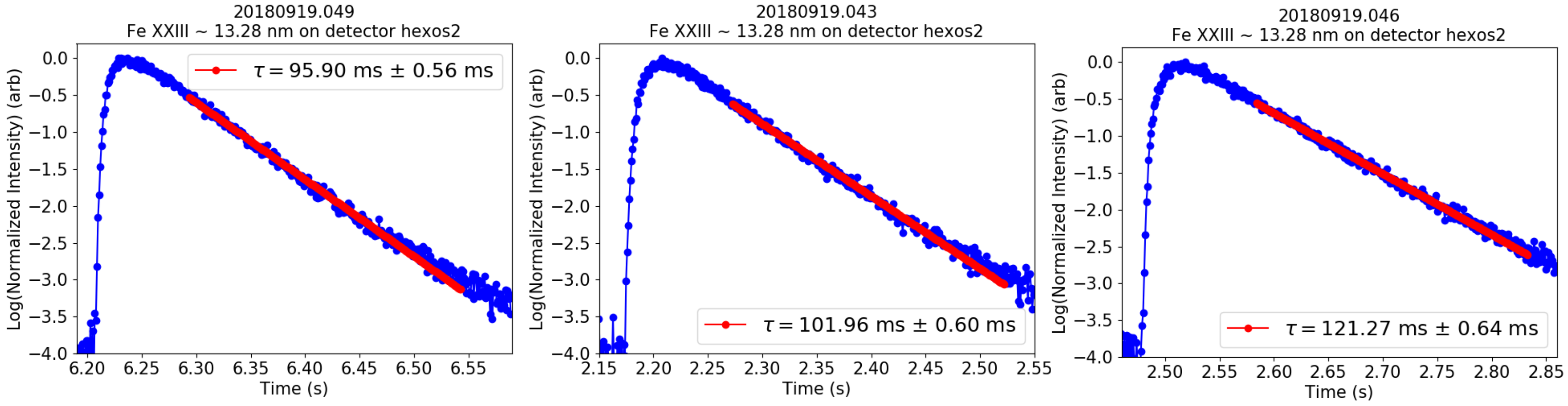


- Spatially resolved line radiation data is necessary for ensuring the inferred profiles are unique
- Eight evenly spaced line-of-sights are taken from the XICS w-line to then be modeled in STRAHL

At fixed input ECRH power of P_{total}~3.5 MW the ECRH position is placed further off-axis for each Fe LBO demonstrating an increased global transport time



Increasingly off-axis

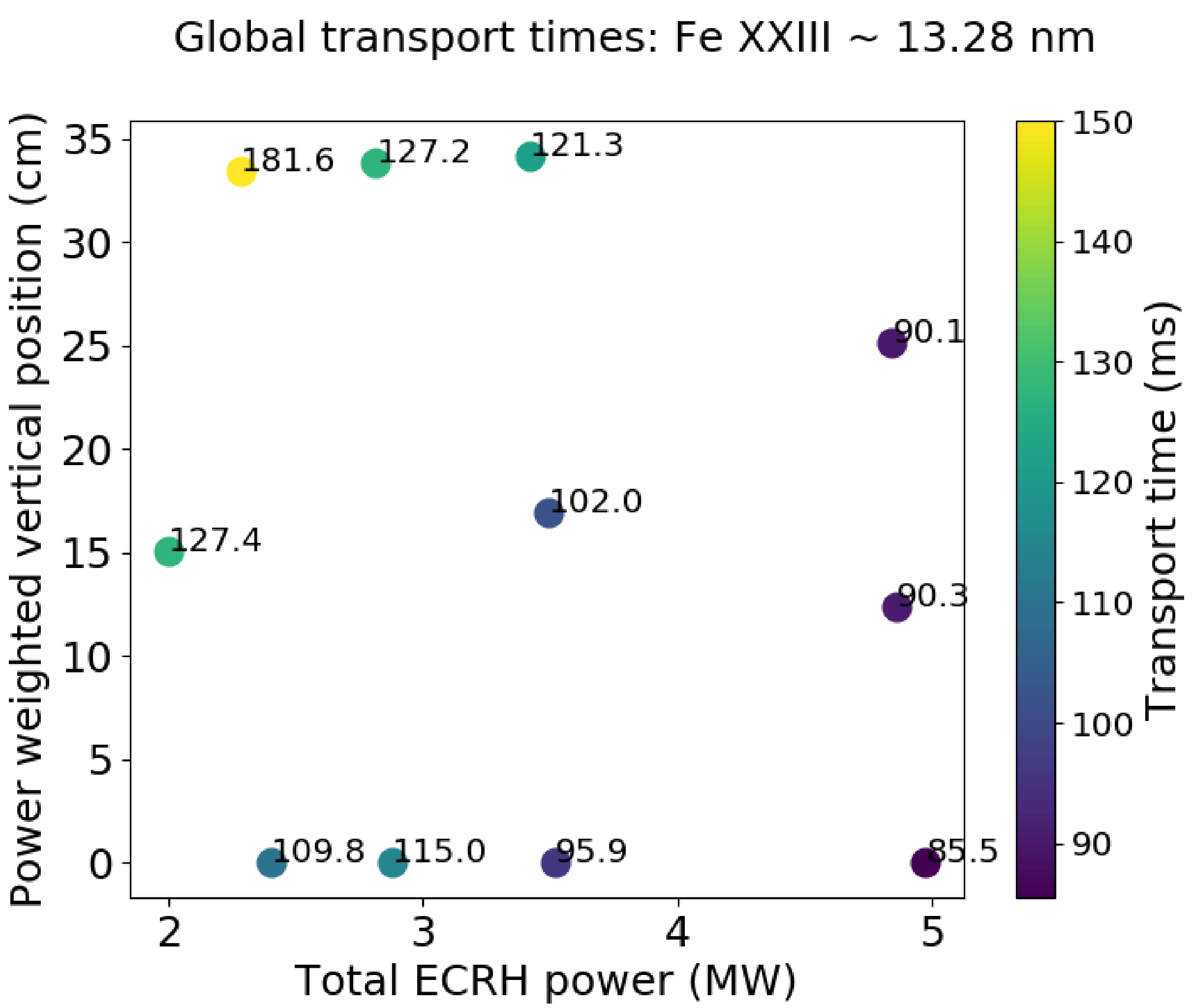


[3] A. Langenberg et al Plasma Phys. Control. Fusion 61 014030 (2019)

Motivation for least squares inference of diffusion profile

- In agreement with the OP 1.2a experiments in Helium there is an increase in global impurity transport time as ECRH is moved off-axis [3]
- The ~ 30% increase in global impurity transport time are corroborated by the fits to the Fe^{24+} w-line signals
- Transport times are derived from fitting the exponential decay after the Fe impurity profiles have relaxed

Scaling of impurity global transport times shows known power degradation



- At roughly the same line-integrated density, Fe impurity transport experiments were performed with ECRH axial scans at various constant ECRH power levels.
- As more ECRH power is deposited into the plasma the shorter the transport time
- In previous W7-X experiments in Helium [3], **the off-axis ECRH scenario shows a significant increase in impurity iron transport time** as compared to fully on-axis case

[3] A. Langenberg et al Plasma Phys. Control. Fusion 61 014030 (2019)

Utilizing the 1D transport code STRAHL, anomalous transport profiles can be inferred and further utilized to estimate the inherent uncertainties and systematics

Impurity emissivity

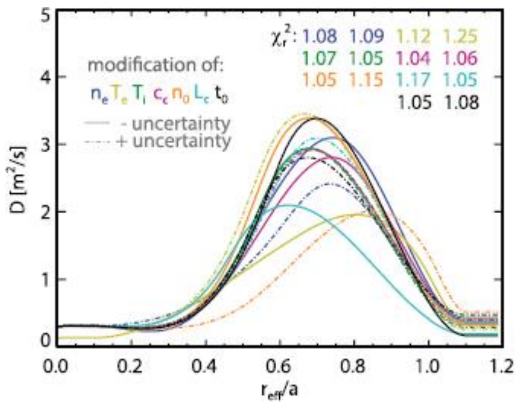
Least squares minimization on signal: $D_{I,Z}$, $\boldsymbol{v_{I,Z}}$

STRAHL

$$\frac{\partial n_{I,Z}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r\left(D_{I,Z}\frac{\partial n_{I,Z}}{\partial r} - \boldsymbol{v_{I,Z}} n_{I,Z}\right) + Q_{I,Z}$$

- STRAHL calculates the radial transport and emission of impurity ions with input of kinetic profiles and atomic data
- One dimensional means that transport and plasma parameters are at best calculated in a flux surface averaged sense
- To match the measured emissivities, a least squares minimization is done by varying STRAHL's input anomalous diffusion and/or convective velocity profiles until a minimum is found

Previous impurity transport work [2] demonstrated



- The observed anomalous diffusion was roughly two orders of magnitude larger than the calculated neoclassical levels
- The inferred anomalous diffusion profiles were most sensitive to changes in **electron temperature, neutral density, and connection length**

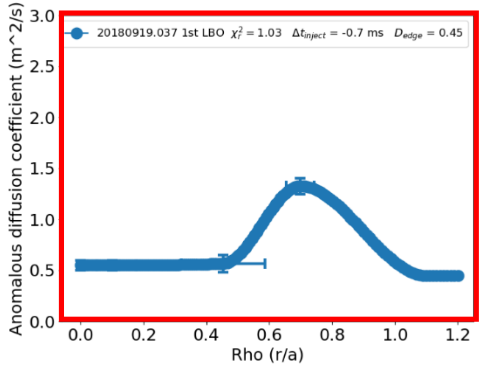
[2] B. Geiger *et al* 2019 *Nucl. Fusion* 59 046009

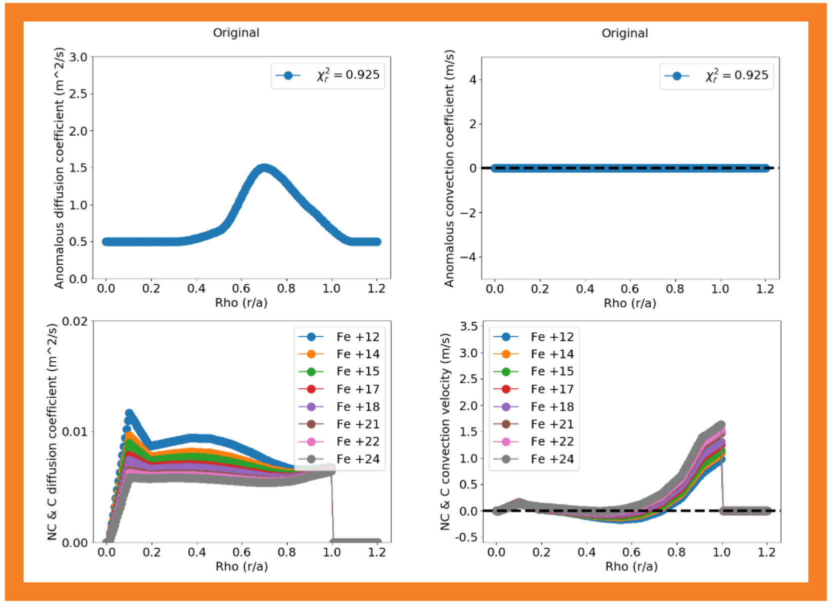
Motivation for synthetic data generation and sensitivity testing

- Determine which model inputs, within their uncertainty levels, limit the least squares minimization from recovering the accurate transport profiles
- Understand any potential coupling between model input parameters and where possible isolate their effect on the recovery of the accurate transport profiles
- Construct a best-practices procedure for performing the least squares minimization with particular inputs as free fit parameters.
- Establish whether the W7-X impurity transport diagnostic set is well suited to accurately infer the transport profiles.

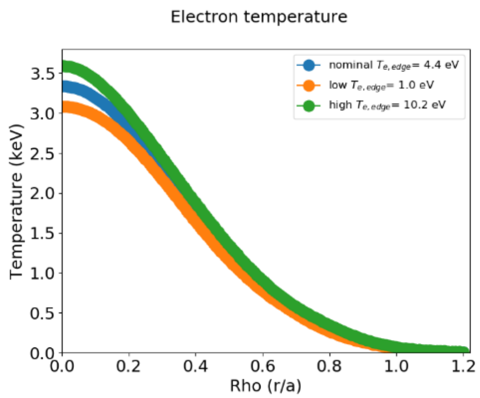
Synthetic sensitivity studies based on realistic W7-X profiles were used to estimate the uncertainties and systematic errors on the inferred transport profiles

Realistic transport profiles utilized to generate noisy synthetic data based on best experimental inference

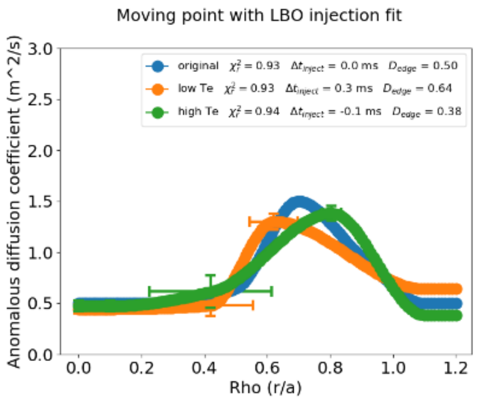


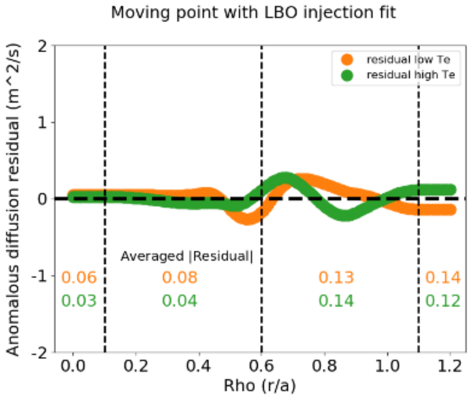


Individual input parameters were held at the experimentally-derived max and min values



- E.G. the incorrect high and low electron temperature profiles were used within the model to recover differences in the inferred diffusion profile
- The residual between the true and inferred diffusion profile can be used to estimate the average error level in 4 regions





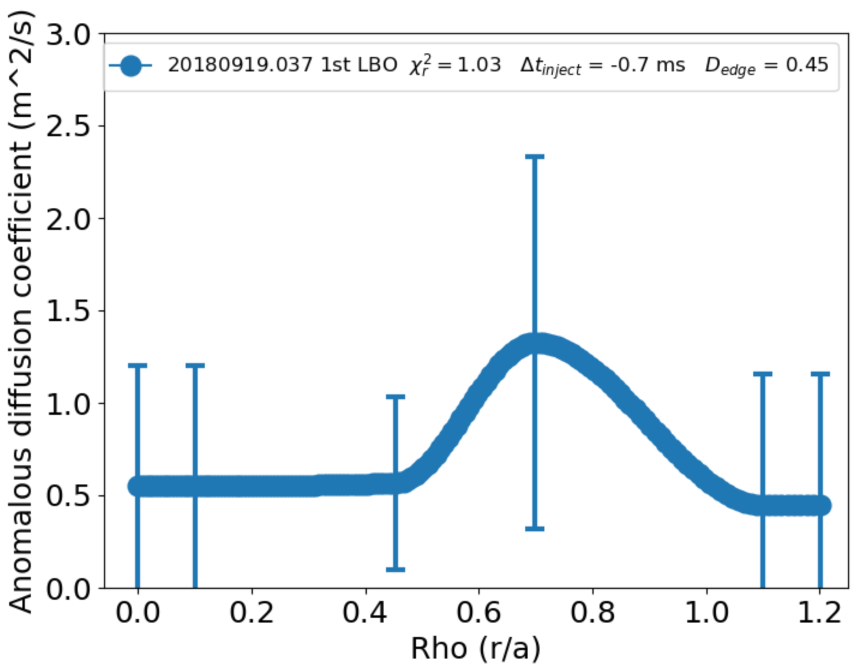
Initial conclusions from synthetic sensitivity studies

- The spatial information provided by Fe^{24+} w-line was a necessity for the accurate and unique inference of the anomalous transport profiles.
- The synthetic data demonstrated that the spectral signals could not be reproduced without the anomalous diffusive channel.
- The synthetic signals based on the W7-X diagnostic coverage were dramatically less sensitive to the anomalous convection velocity, indicating the inclusion of this transport channel as a free parameter could easily lead to inaccurate inferences

The total averaged error on the inferred anomalous diffusion profile from the synthetic sensitivity variations are at least $\sim 0.5\,\frac{m^2}{s}$

		Average of |Residual| $\left(\frac{m^2}{s}\right)$ in region ρ			
Uncertainty source	Parameter variations	0 to .1	.1 to .6	.6 to 1.1	1.1 to 1.2
Procedural method	N.A.	0.07	0.04	0.09	0.01
Neoclassical & classical transport	50% to 200%	0.03	0.05	0.13	0.01
X-ray to VUV timing offset	±2.5 ms	0.30	0.15	0.13	0.02
LBO injection timing	±3.5 ms	5.02	2.29	2.1	0.35
LBO temporal shape	Outside a 2.5 ms window	0.04	0.04	0.14	0.19
Limiter connection length	0.5 to 25 m	0.05	0.05	0.12	0.13
Divertor connection length	200 to 300 m	0.06	0.03	0.09	0.05
T_e far SOL	1 to 16 eV	0.08	0.04	0.10	0.02
T_e core	±250 eV	0.08	0.05	0.12	0.06
T_e entire profile	(see above)	0.04	0.06	0.14	0.13
Neutral hydrogen profile	edge from 10^{14} to $10^{16}\ m^{-3}$	0.04	0.04	0.17	0.16
Total errors summed**	N.A.	**0.65**	**0.47**	**1.01**	**0.71**

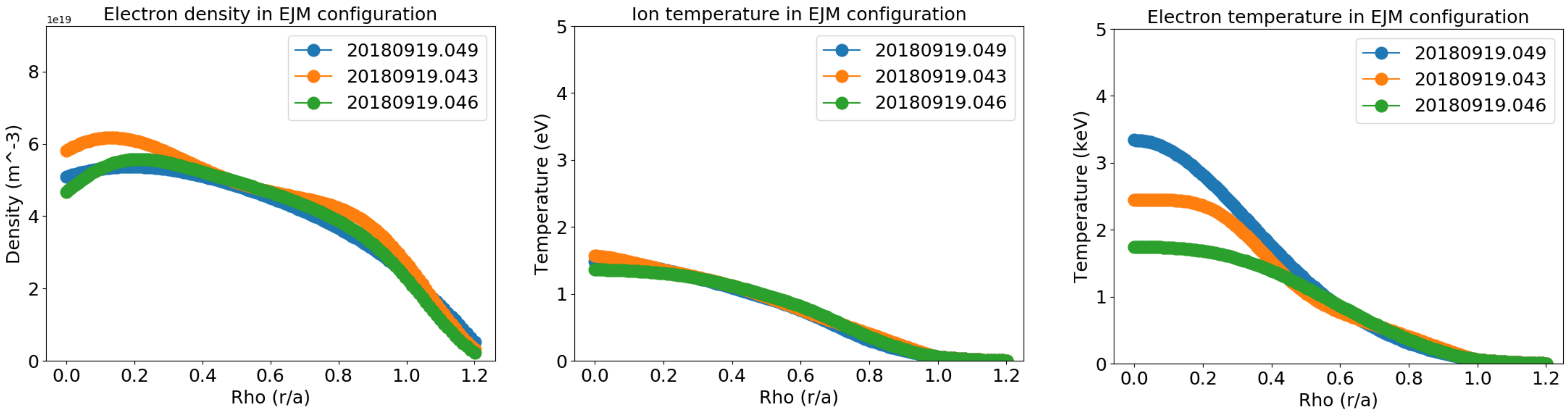
Applying the averaged error derived for each radial region to the experimentally inferred diffusion profile that was used as a basis for the synthetic data



Key results from synthetic sensitivity studies

- Incorrect diagnostic timing offsets have large effects, i.e. $> 0.5\,\frac{m^2}{s}$, on the accuracy of the inferred diffusion profile. However the LBO timing offset can be determined though the least squares minimization, while unfortunately the x-ray to VUV timing offset cannot
- The accurate inference of the anomalous diffusion profile is minimally effected, i.e. $\sim 0.2\,\frac{m^2}{s}$, by the electron temperature profile variations within its 1-sigma uncertainties.
- **The LBO injection temporal shape is critically important for accurate inference of the anomalous diffusion profile.**

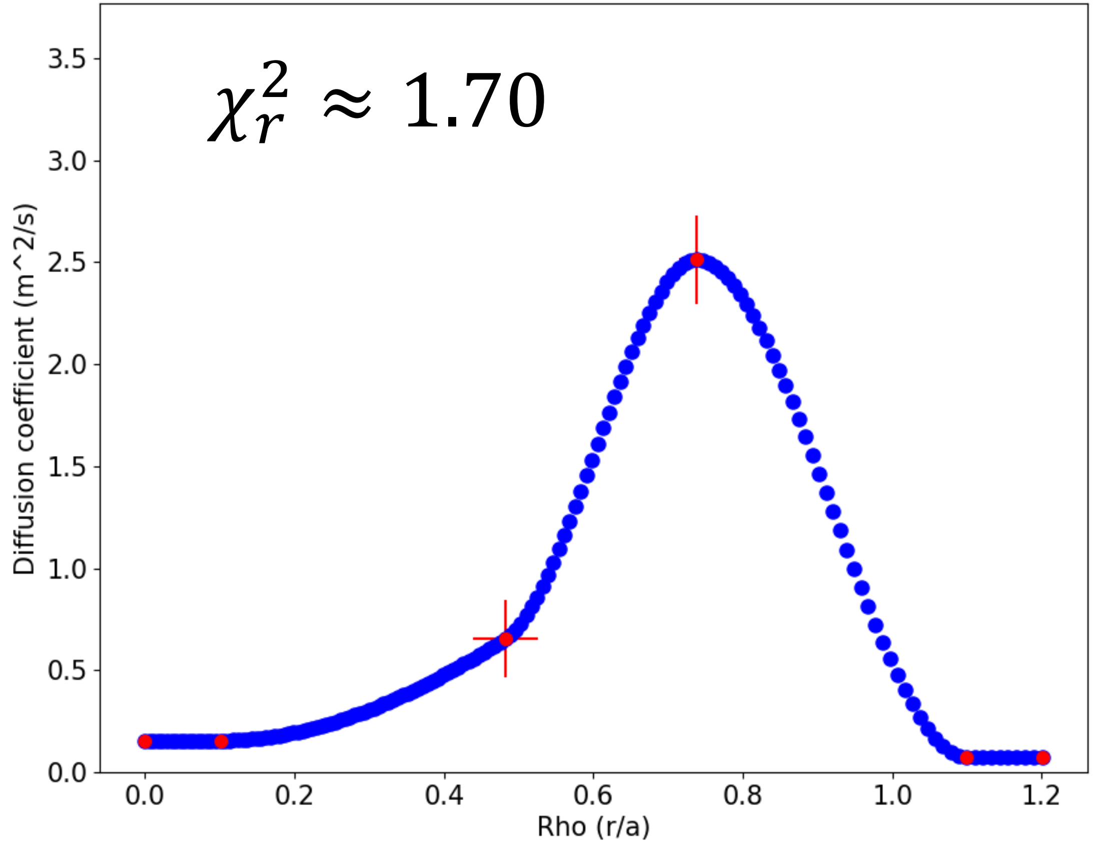
At fixed input ECRH power of P_{total}~3.5 MW, the kinetic profiles are well matched except for T_e as ECRH position is varied

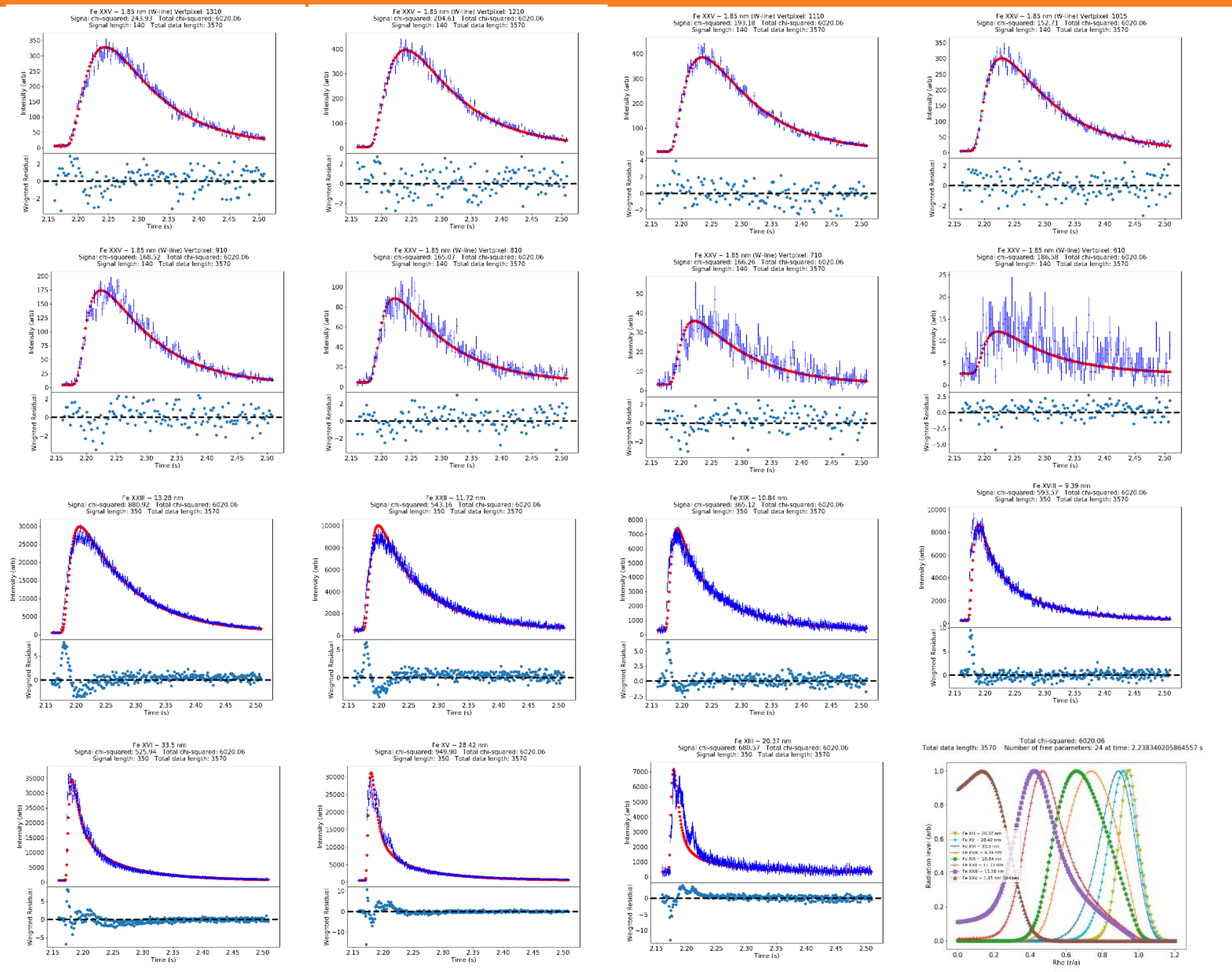


- As ECRH power is placed more off-axis, core electron temperature peaking is decreased
- Edge gas fueling with feedback control ensured similar density profiles
- Ion temperature profiles were consistently stiff

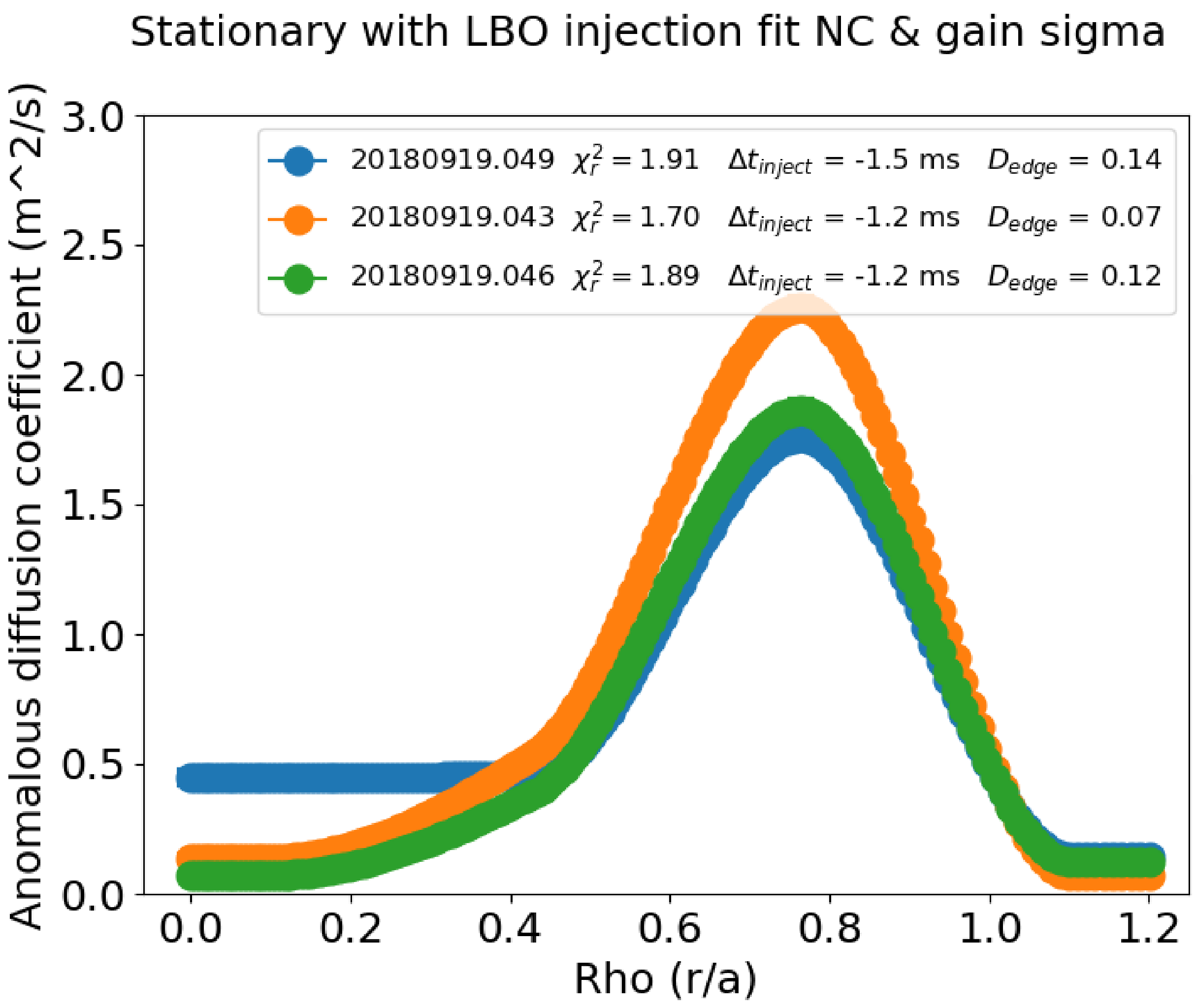
Utilizing **only anomalous diffusive transport** within STRAHL yields good reproduction ($\chi_r^2 < 2$ & minimal residual structure) of observed Iron emissivity

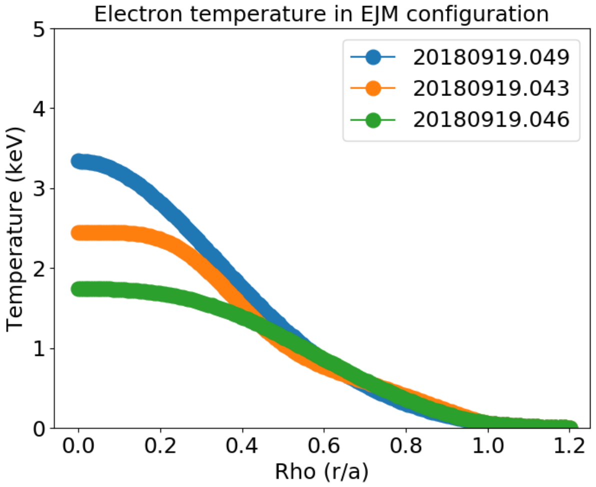
Inference of anomalous diffusion by the least squares optimization for the **mid off-axis case**

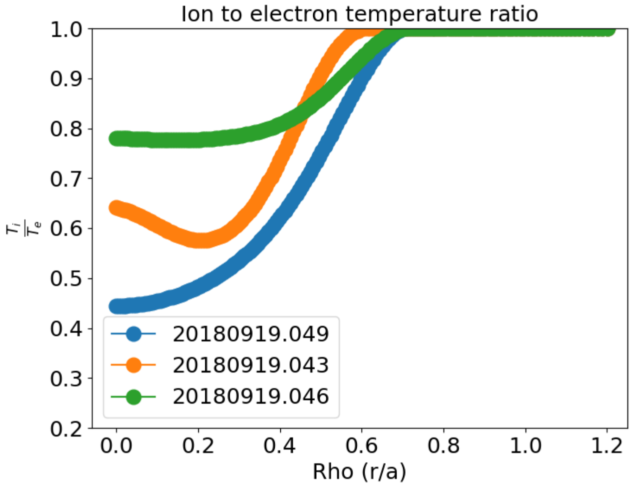




When only utilizing anomalous diffusion not only are accurate fits achieved, but also the inferred anomalous diffusion profiles outside of mid-radius, $\rho > 0.4$, match for all three ECRH positions



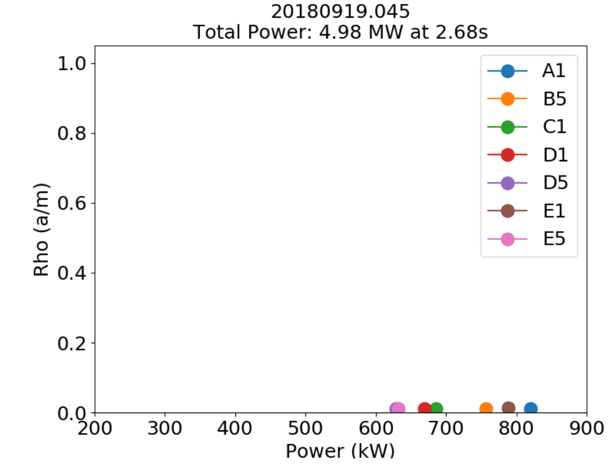


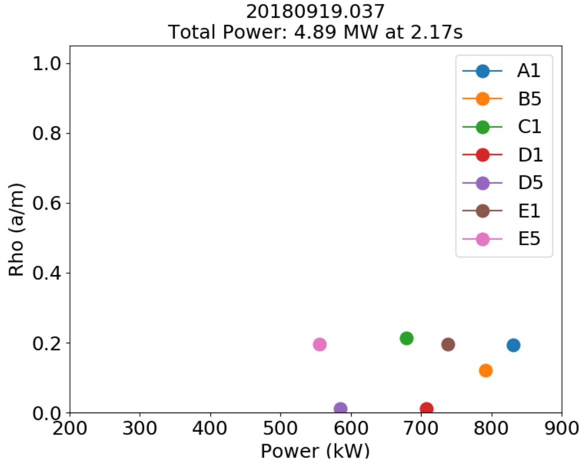


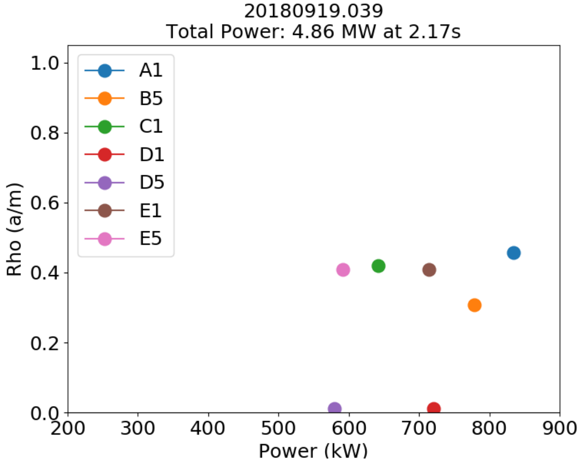
- As reported in [4], the increase in global transport time following the increase in $\frac{T_i}{T_e}$ ratio was verified to be the suppression of turbulence driven by the ion temperature gradient (observed experimentally by decreased density fluctuations and shown numerically through gyro-kinetic simulations)
- **However in this ECRH positional scan, all the inferred anomalous diffusion profiles roughly match especially considering the uncertainty analysis from the synthetic simulations, i.e. uncertainty levels of at least $\sim 0.5\,\frac{m^2}{s}$ (not plotted)**

[4] Th. Wegner et al 2020 Nucl. Fusion 60 124004

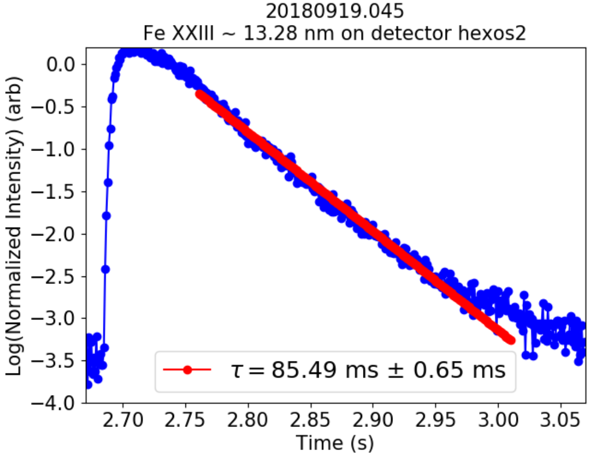
At fixed input ECRH power of P_{total}~4.9 MW the ECRH position is placed further off-axis for each Fe LBO demonstrating no increased global transport time

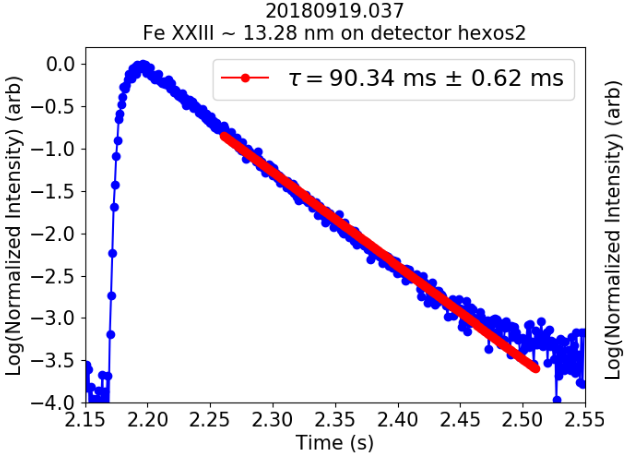


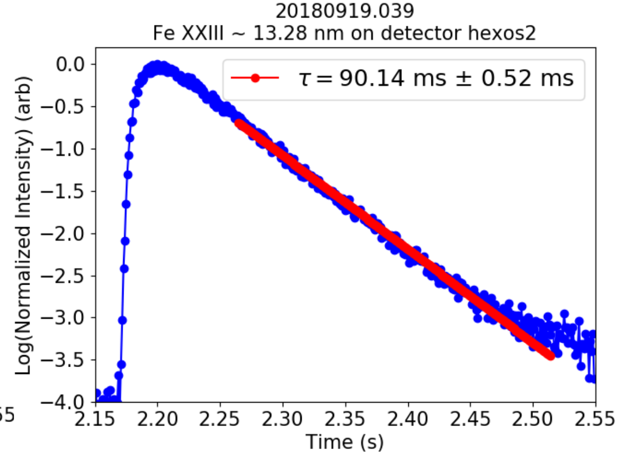




Increasingly off-axis

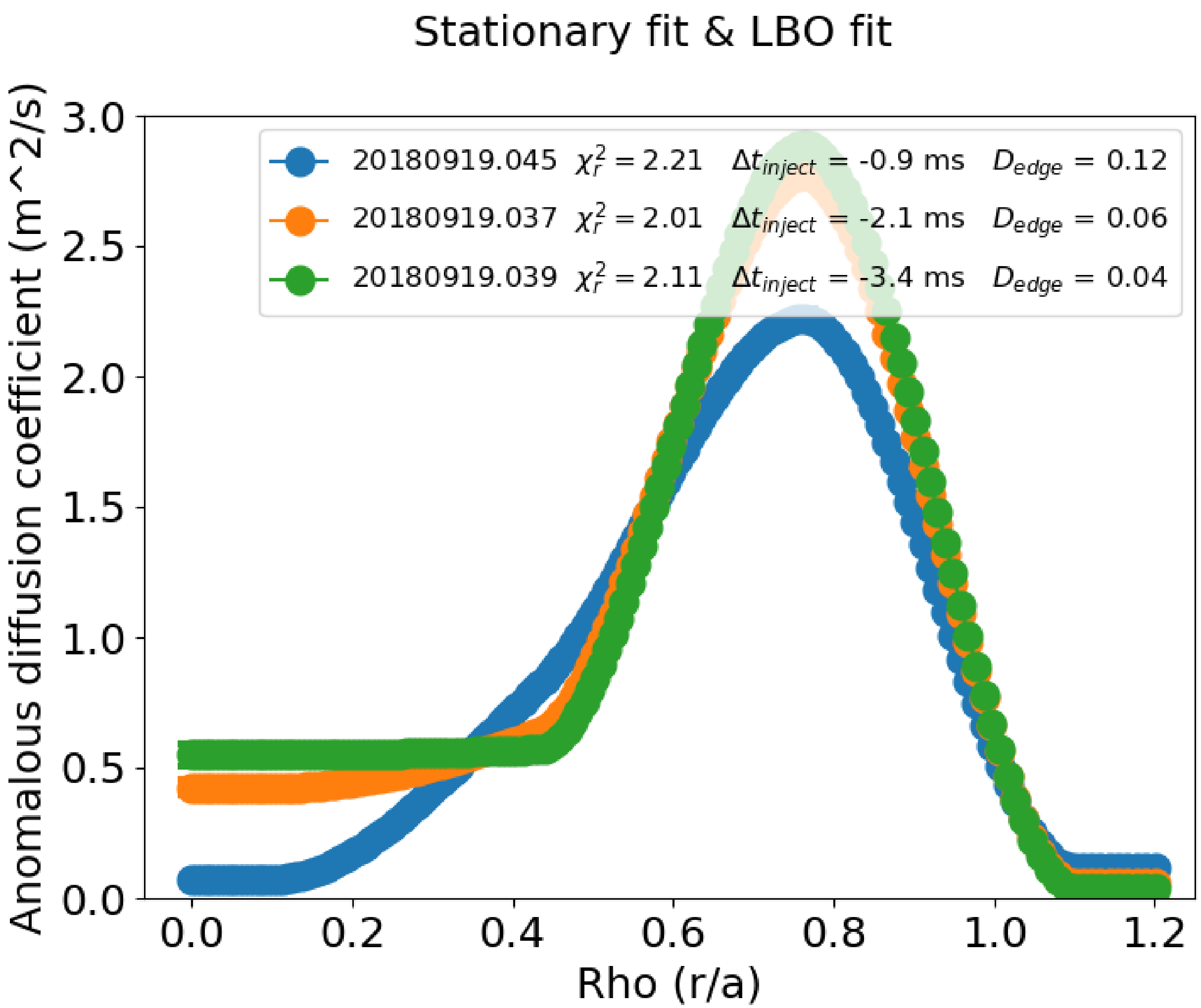


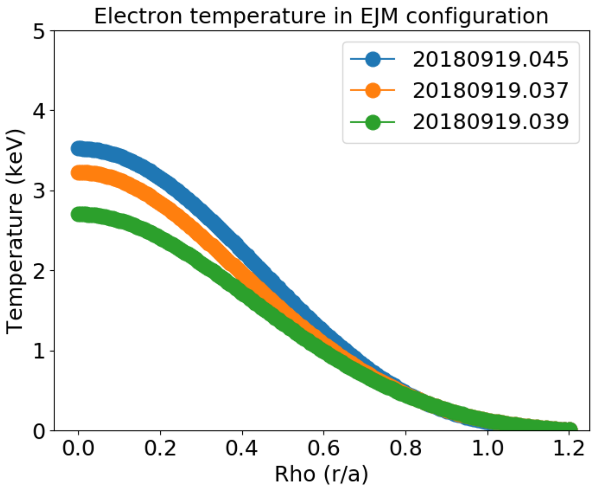


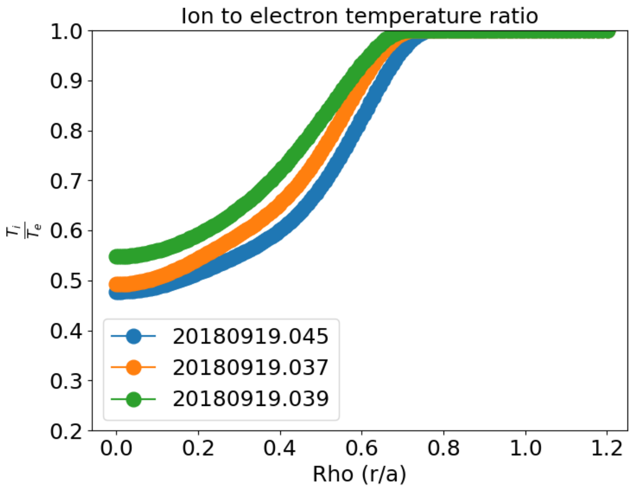


- Two gyrotrons were always kept on-axis for a minimum of ~1.2 MW ECRH going to the core plasma
- There is a small increase the in global transport time as the ECRH position is changed to further off-axis.

At fixed input ECRH power of P_{total}~4.9 MW, the kinetic profiles are well matched as ECRH position is varied leading to similar inferred anomalous diffusion profiles







- All the inferred anomalous diffusion profiles match for all three ECRH heating positions when considering the uncertainty analysis from the synthetic simulations**, i.e. uncertainty levels of at least $\sim$ 0.5 $\frac{m^2}{s}$ (not plotted)**
- Although an Increased average inferred anomalous diffusion is observed for ~4.9 MW scenarios as compared to the ~3.5 MW scenarios, the differences are well inside the uncertainty levels and can't be firmly concluded.

Note the fully on-axis case has significant LBO injection temporal shape errors

Summary

- **Spatially resolved line radiation data is necessary for ensuring the inferred profiles are unique.**

- Utilizing **only anomalous diffusive transport** within STRAHL yields good reproduction ($\chi_r^2 < 2$ & minimal residual structure) of observed Iron emissivity.

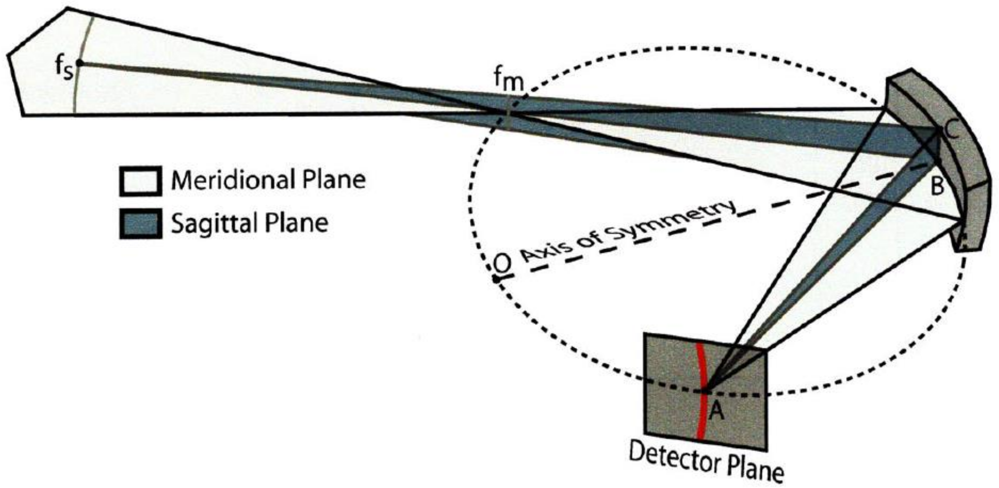
- The Fe impurity transport is **dominated by anomalous diffusive flux**, at levels at least an order of magnitude larger than neoclassical & classical flux.

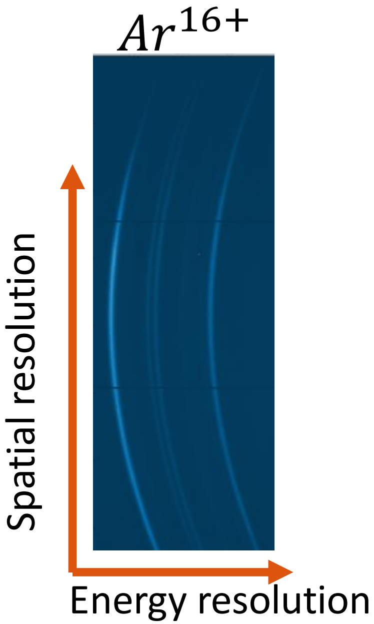
- Although the **global transport time demonstrated a distinguishable increase as more ECRH power was placed off-axis**, the inferred **anomalous diffusion profiles were indistinguishable** when model uncertainties were considered.

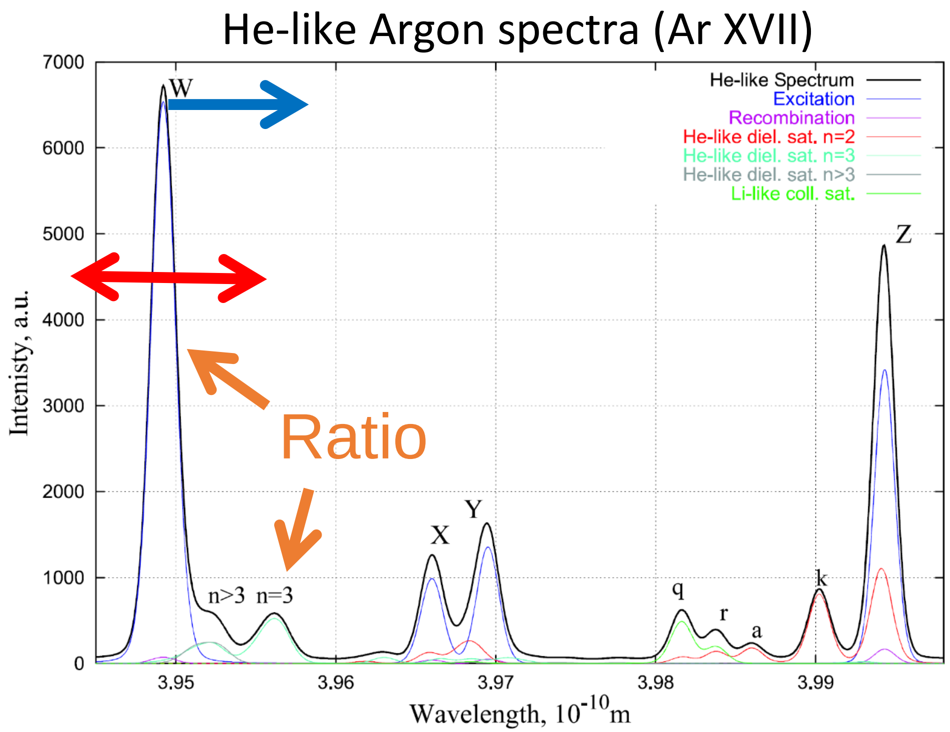
- Unfortunately the total uncertainties stemming from the input parameters and systematics on the least squares inference are on the order of $\sim 1\ \frac{m^2}{s}$ making conclusions based off the on- to off-axis profiles difficult

EXTRAS

X-ray Imaging Crystal Spectrometer (XICS) provides spatially resolved emission from medium Z impurities







- Measures impurity line radiation from the highly charged states of medium and high Z materials
- Bragg reflection used in conjunction with the crystal astigmatism yields a 1-D image of the plasma
- Amounts of medium Z materials required for a measurement are non-perturbative

- Ion temperature (T_i) : line width
- Electron temperature (T_e) : ratio of specific lines
- Ion Flow velocity $(v_\perp)$: line shift
- Impurity density $(n_{impurity})$: line intensity