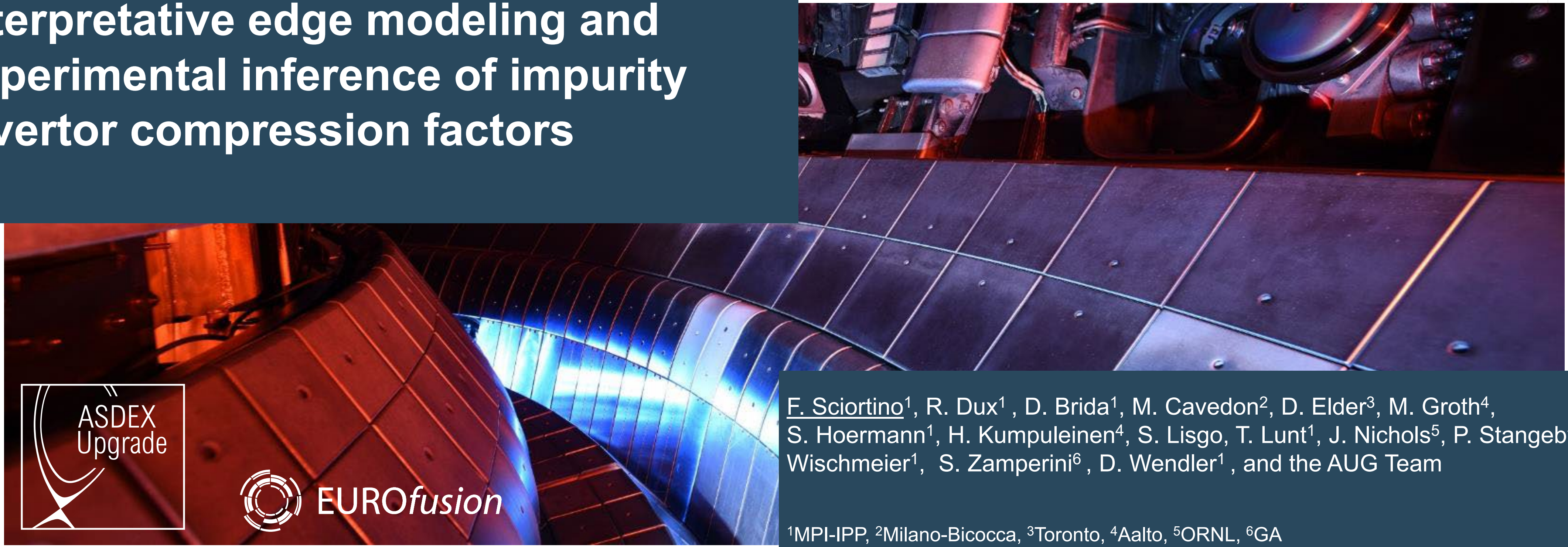
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Interpretative edge modeling and experimental inference of impurity divertor compression factors



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Wealth of edge measurements available on AUG

Significant investment has gone into expanding AUG divertor/SOL measurements

Langmuir probes

Divertor Thomson (…)

Divertor helium beam

Edge midplane Thomson

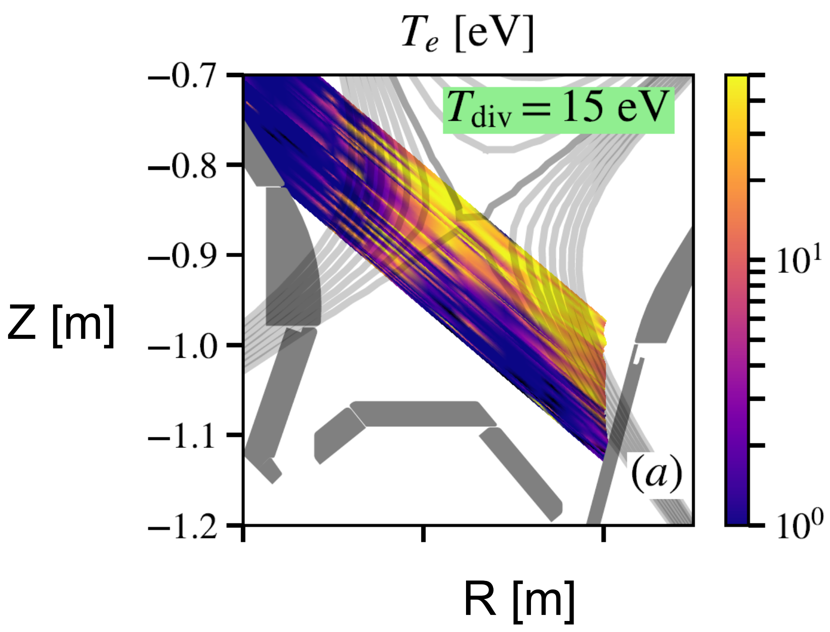
Midplane lithium beam

CXRS

2D camera data

Line ratio techniques from D (Balmer) or impurity spectroscopy

…



AUG divertor T_e based on DTS data
Cavedon et al., 2022, Nucl. Fusion

How can we build a coherent picture based on these scattered observations?

Divertor spectra are qualitatively rich, but hard to interpret

AUG divertor spectroscopy is well developed, but line-integration hinders interpretation

Opportunities particularly related to splitter setup

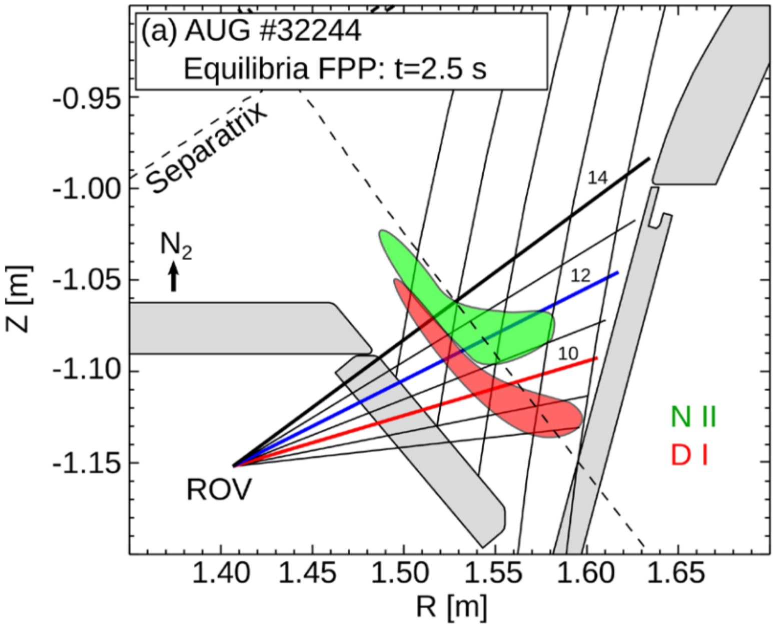
~15 Lines-Of-Sights (LOS) on 3 visible spectral windows of 10-20nm width each

allows coverage on Balmer series, or multiple impurity charge states

Approach by S. Henderson, using N II line ratios, allows simultaneous estimation of n_e, T_e and c_N

- Unfortunately, signal localization limits interpretation

Edge impurity transport commonly modeled with unrealistic assumptions – critically in need of validation



Henderson et al 2018 Nucl. Fusion 58 016047

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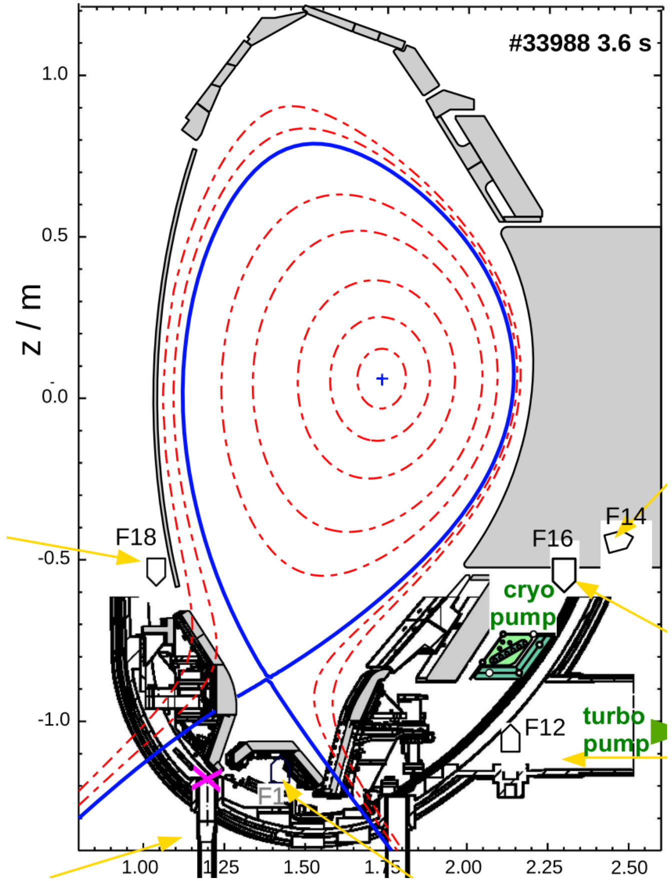
Matching edge diagnostic constraints at AUG

Quasi Monte Carlo inference

Divertor impurity compression factors

Summary & conclusions



Kallenbach et al. PPCF 60 (2018) 045006

Physical models to constrain plasma/neutral 2D distributions

Several objectives:

Obtain a description of 2D plasma/neutral background-- better than 2PM, not as detailed as SOLPS

Onion-Skin Modeling (OSM)

Infer unobserved quantities, such as neutral atomic and molecular densities, also for pedestal studies

EIRENE

Enable interpretation of impurity spectroscopy using 2D background estimates

DIVIMP

Python interfaces to these codes now included in the Aurora package for particle transport & radiation modeling
https://aurora-fusion.readthedocs.io/en/latest/

1D fluid equations for each edge flux tube

Particle flux

$$\nabla \cdot \Gamma = \frac{d}{ds}\big(n(s)v(s)\big) = S_p(s)$$

Static pressure **Dynamic pressure**

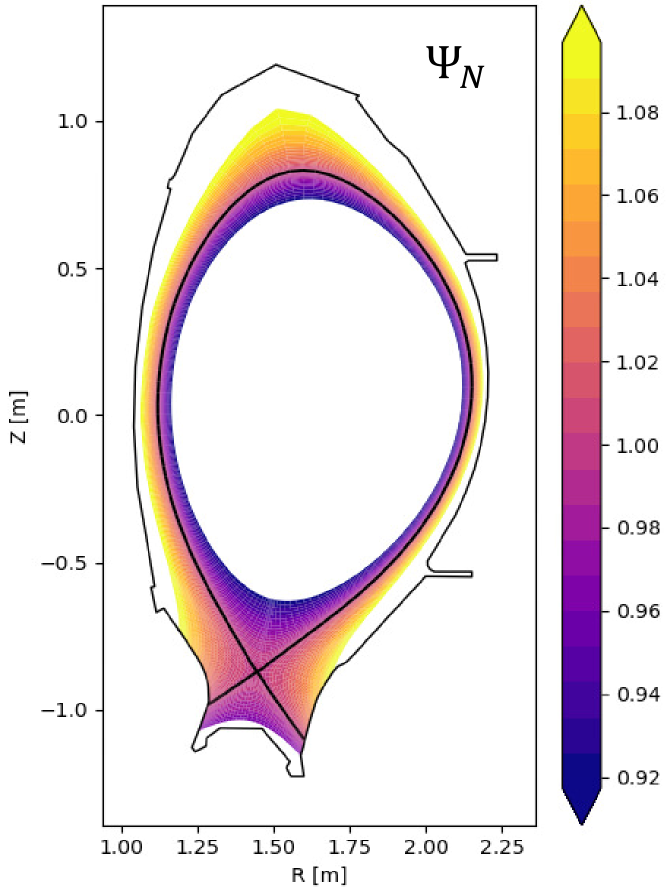
$$\nabla \cdot p = \frac{d}{ds}\Big(n(s)\big(kT_e(s) + kT_i(s)\big) + n(s)m_i v(s)^2\Big) = S_m(s)$$

Convected heat **Conducted heat**

$$\nabla \cdot Q_e = \frac{d}{ds}\left(\frac{5}{2}n(s)v(s)kT_e(s) - \kappa_{0e}kT_e(s)^{\frac{5}{2}}\frac{dkT_e(s)}{ds}\right) = S_{e,e}(s)$$

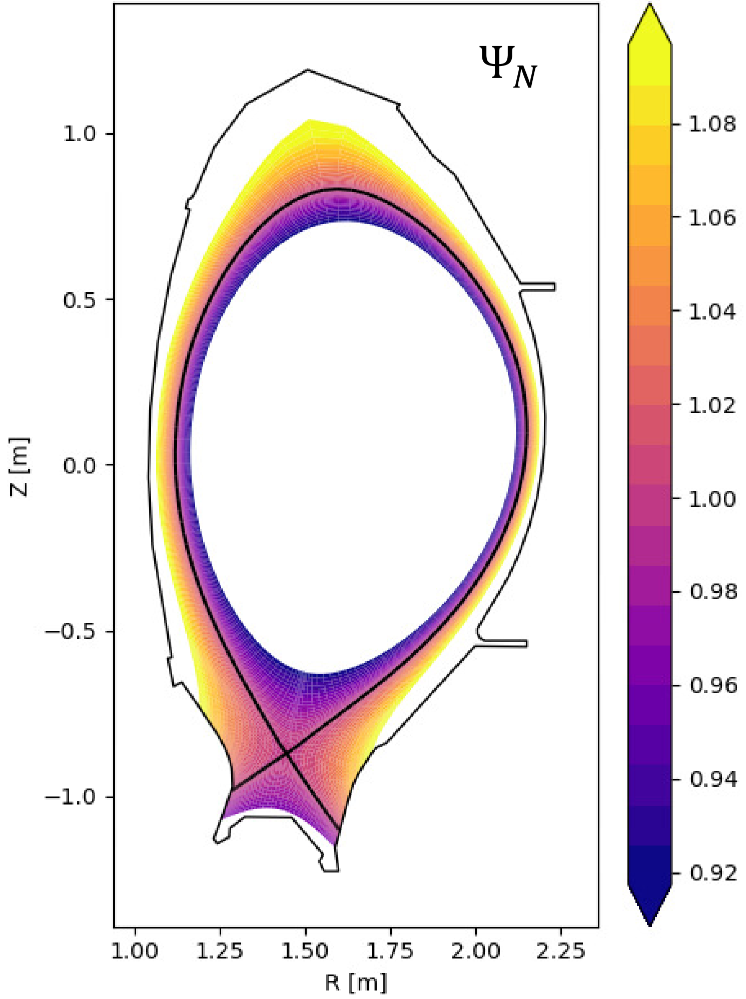
Convected heat **Higher-order convected heat** **Conducted heat**

$$\nabla \cdot Q_i = \frac{d}{ds}\left(\frac{5}{2}n(s)v(s)kT_i(s) + \frac{1}{2}m_i n(s)v(s)^3 - \kappa_{0i}kT_i(s)^{\frac{5}{2}}\frac{dkT_i(s)}{ds}\right) = S_{e,i}(s)$$



4 equations, 4 unknowns: $n(s), v(s), T_e(s), T_i(s)$

OSM-EIRENE: iterative coupling

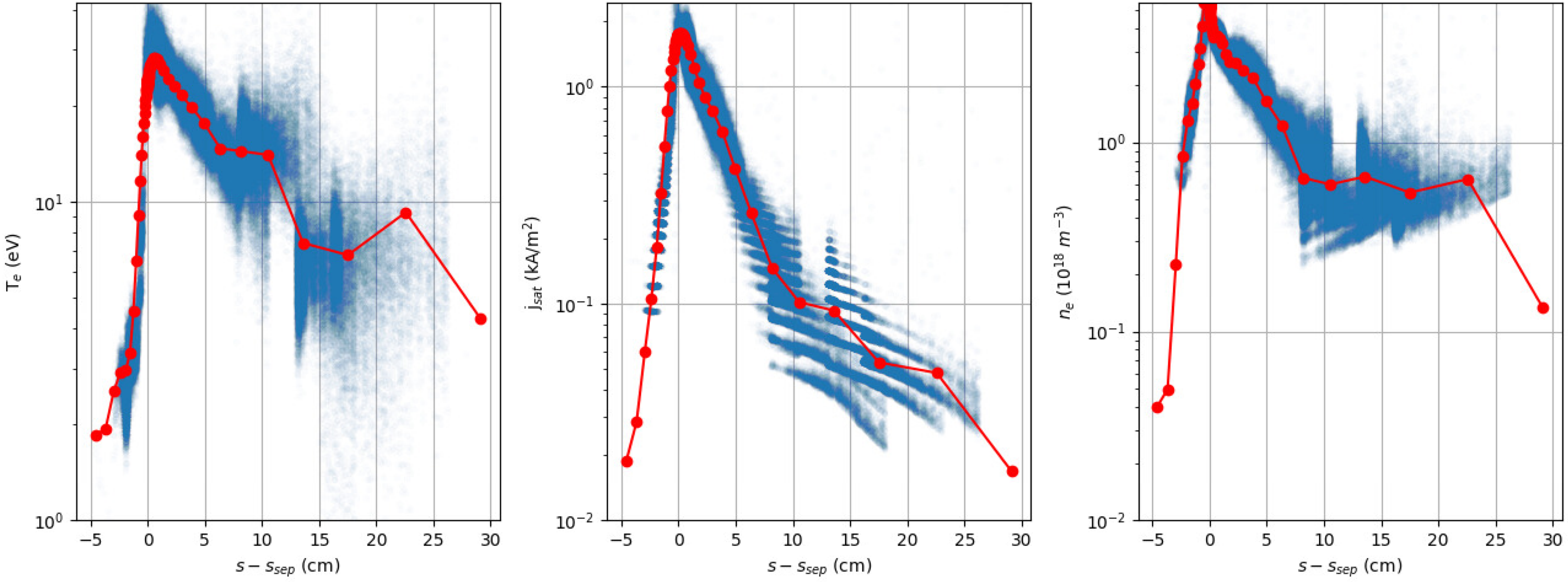


Iterate ~5 times

Approx. 10 mins in total

It all starts from the target (*not* the midplane)

- Set B.C. based on target measurements (Langmuir probes) *rather than trying to match target a-posteriori*
- Gaussian Process Regression (GPR) used to fit arbitrary experimentally-measured profiles



No background transport coefficients need to be prescribed

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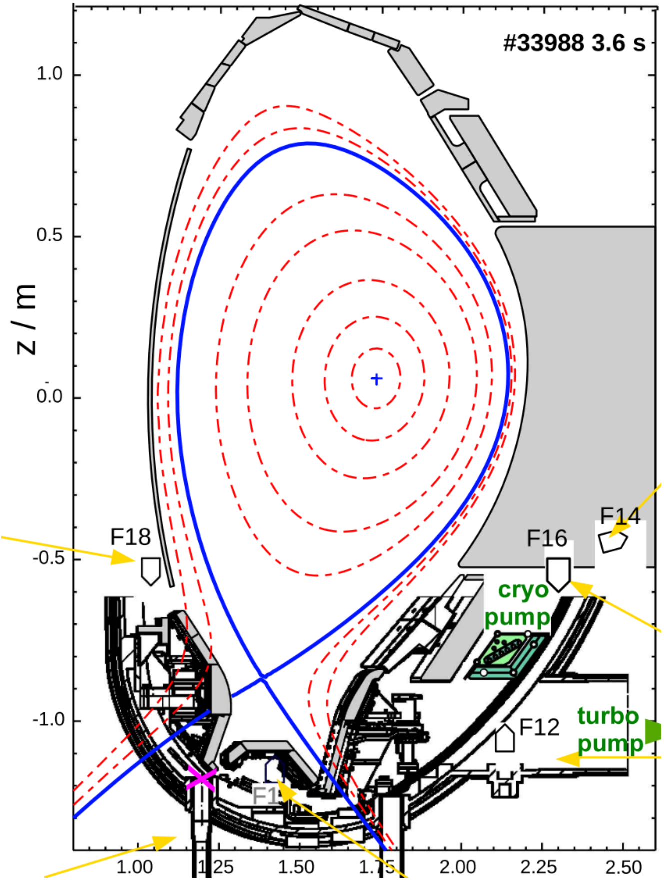

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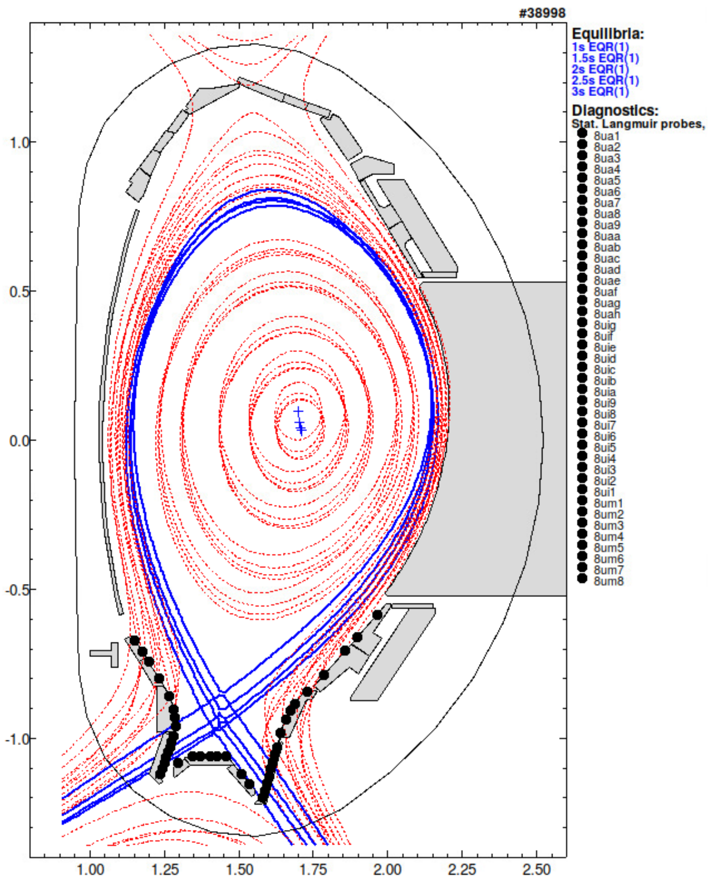
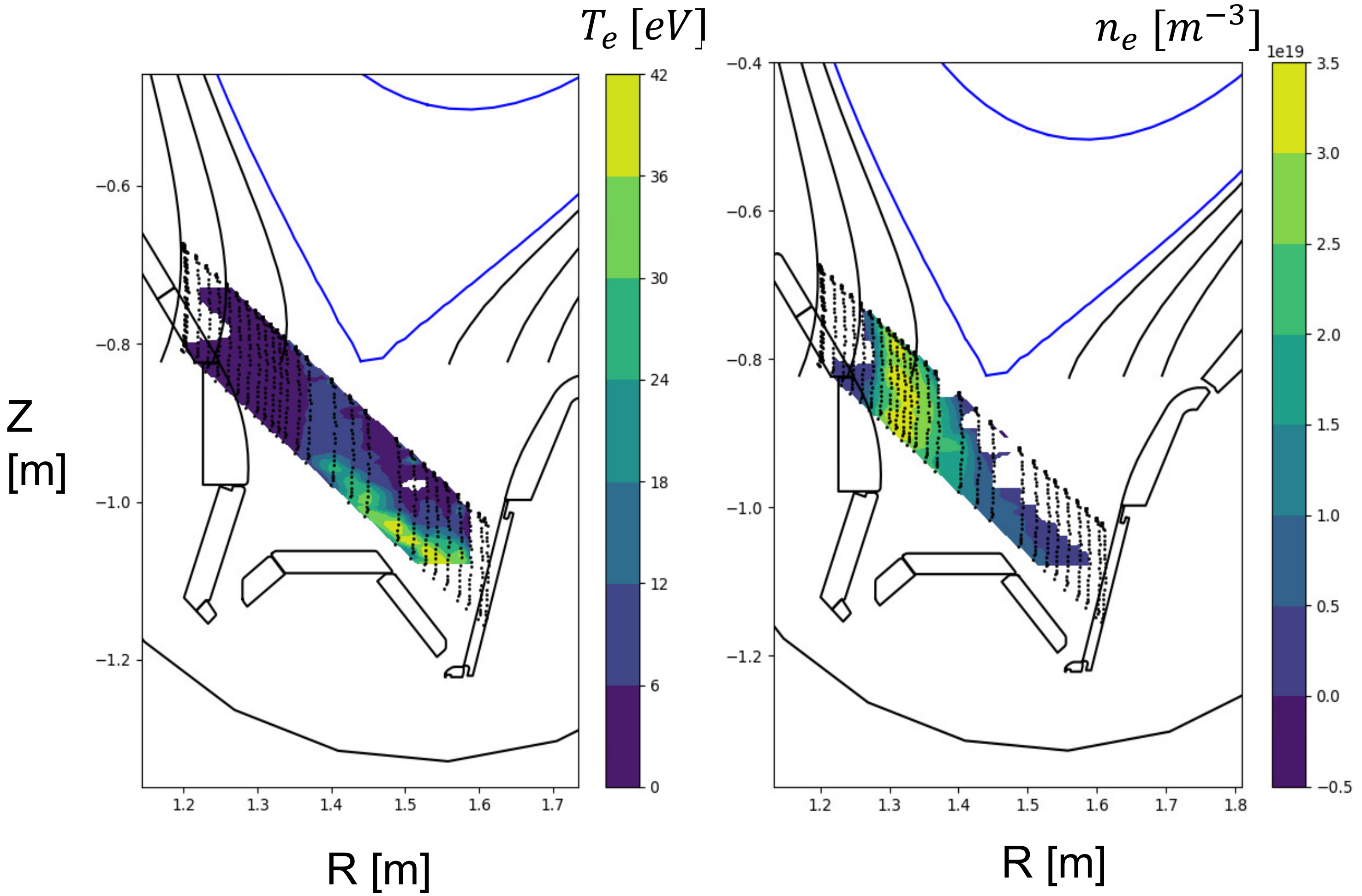
2D coverage via Divertor Thomson offers strong constraints

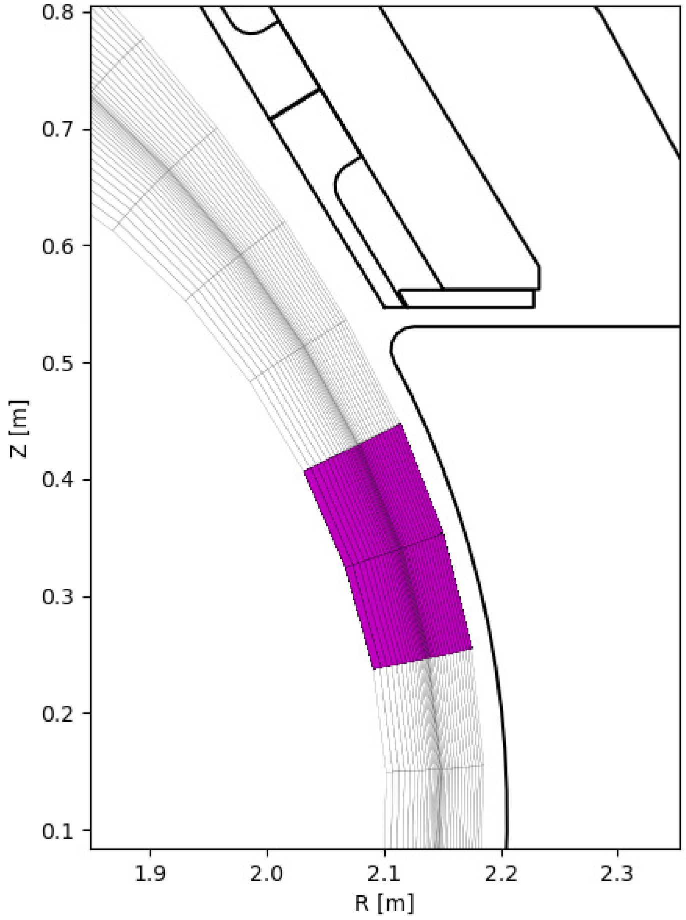
Good coverage during Z-scans



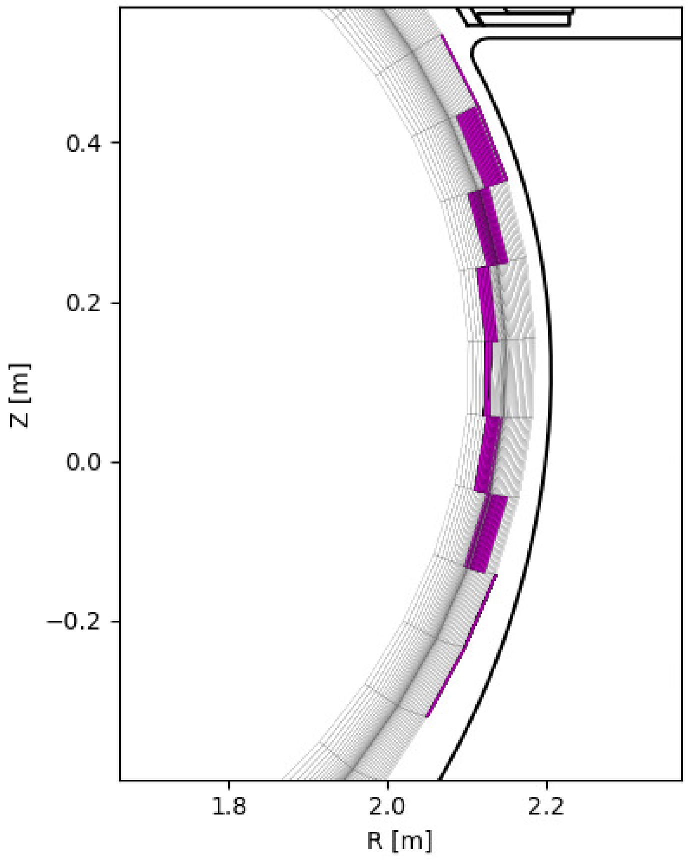


Compare to multiple local measurements

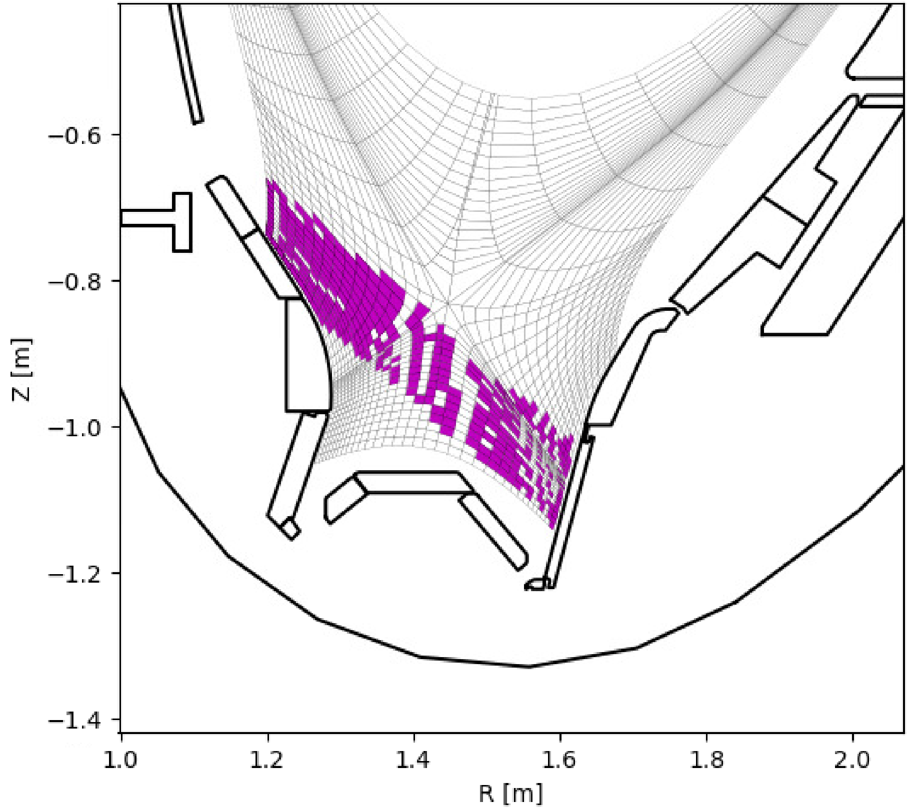
Lithium beam



Midplane Thomson Scattering



Divertor Thomson Scattering

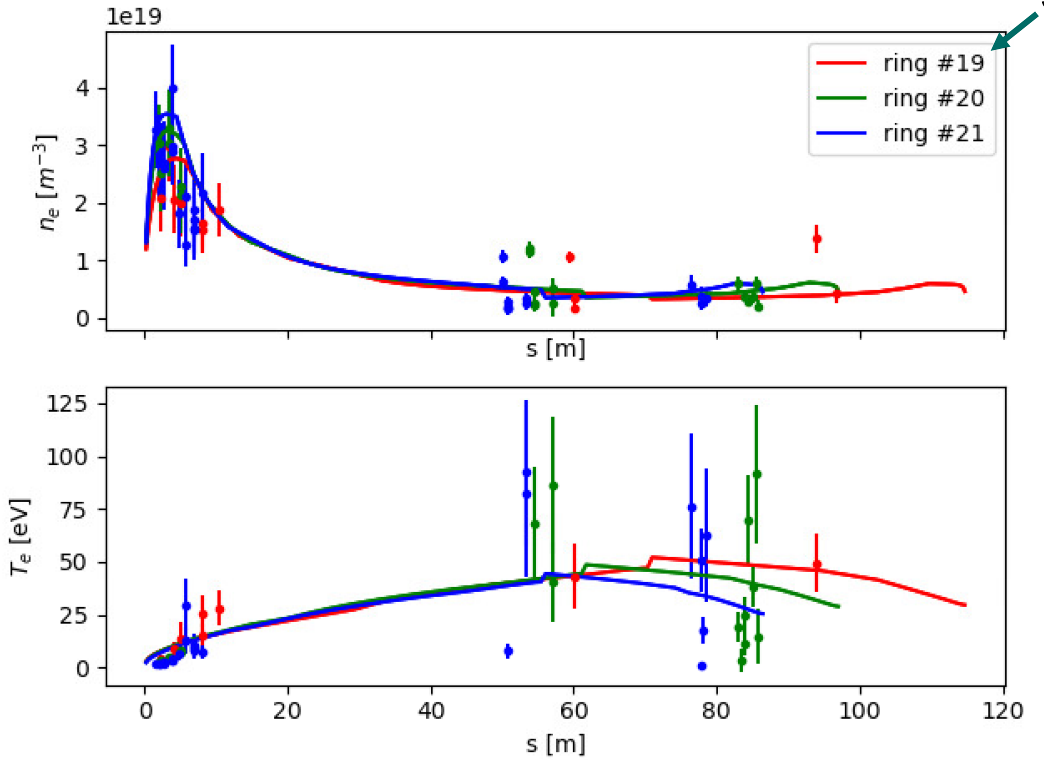


Comparison with local ring-by-ring measurements

Example of comparison for a few rings, starting from the separatrix

- Analogous to *Stangeby et al. Nuclear Materials and Energy 12 (2017) 876–881*

separatrix



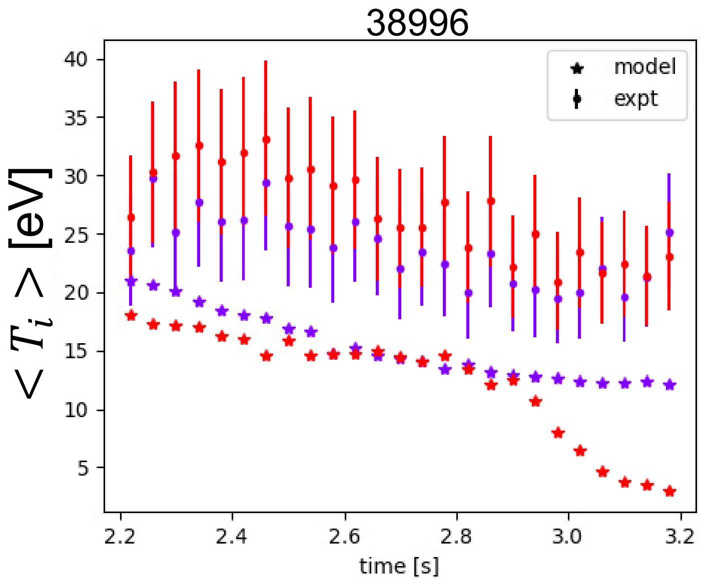
More experimental constraints from line-integrated signals

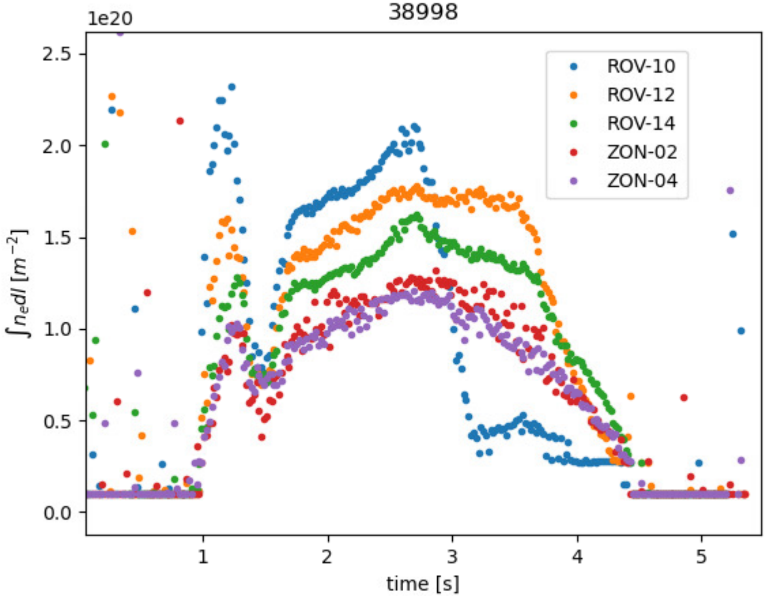
High-resolution divertor spectroscopy, ~3 LOS --> $\int T_i \, dl/\Delta l$

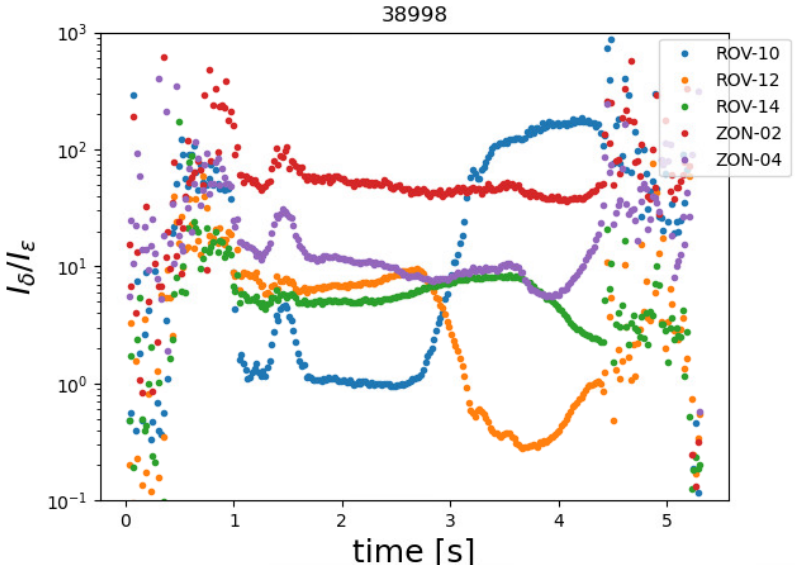
Balmer spectroscopy (D_α, D_β, D_γ, D_δ, D_ϵ), variable LOS (both inner and outer divertor)

Constraints on n_e, T_e, n_n (n_m)

n_e via Stark broadening







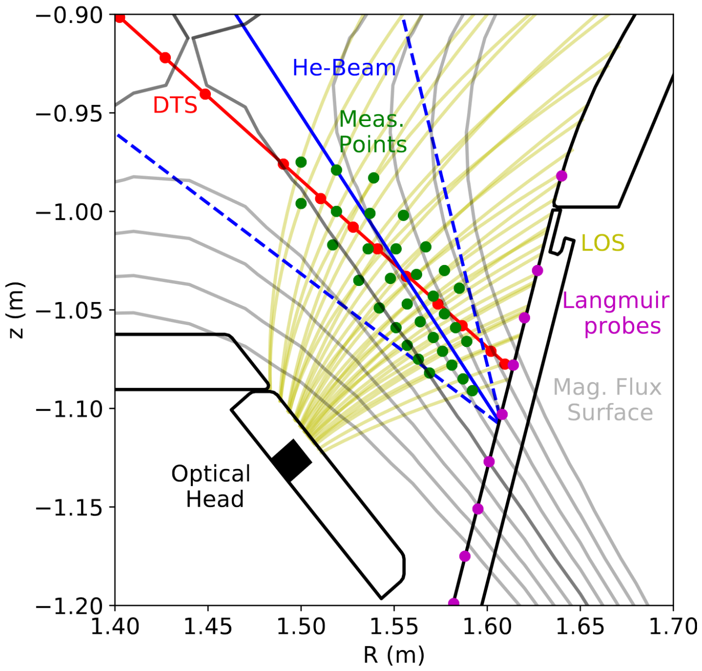
Exploitation of the new Divertor Helium Beam (DHB)

Novel DHB diagnostic at AUG complements DTS measurements of n_e and T_e, but requires He forward model for interpretation

- **Leverages work by M. Griener, D. Wendler, R. Dux et al. with midplane He beam**
- **Divertor system (M. Cavedon) allows us to explore detachment physics**

Two approaches being pursued for DHB analysis:

- S. Hoermann: inference of parametrized (physics-free) n_e and T_e distributions, iterating over forward model
- This work: tuning of OSM-EIRENE parameters for integrated interpretative divertor modeling



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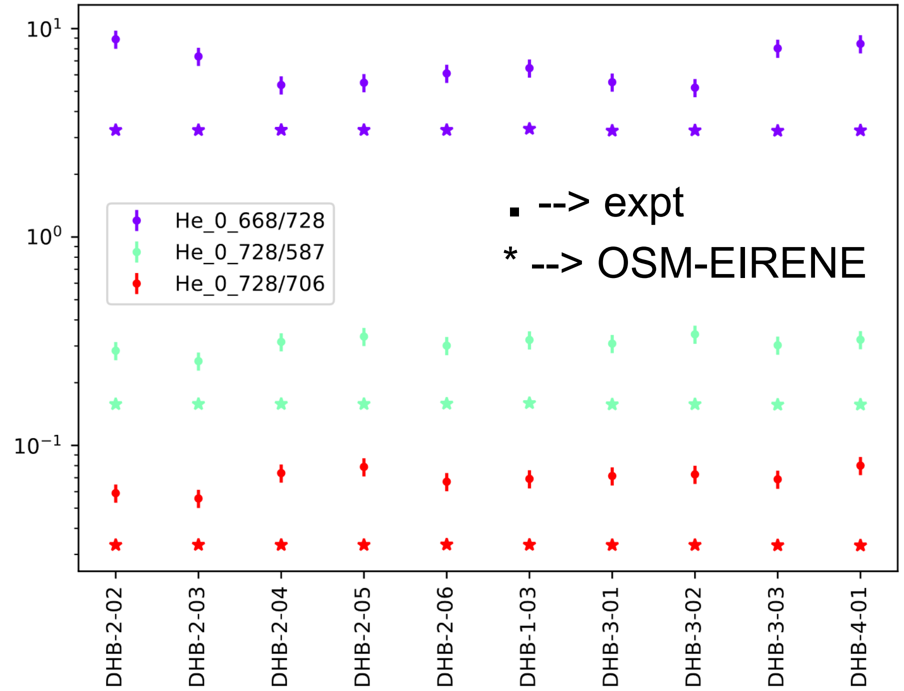
Preliminary



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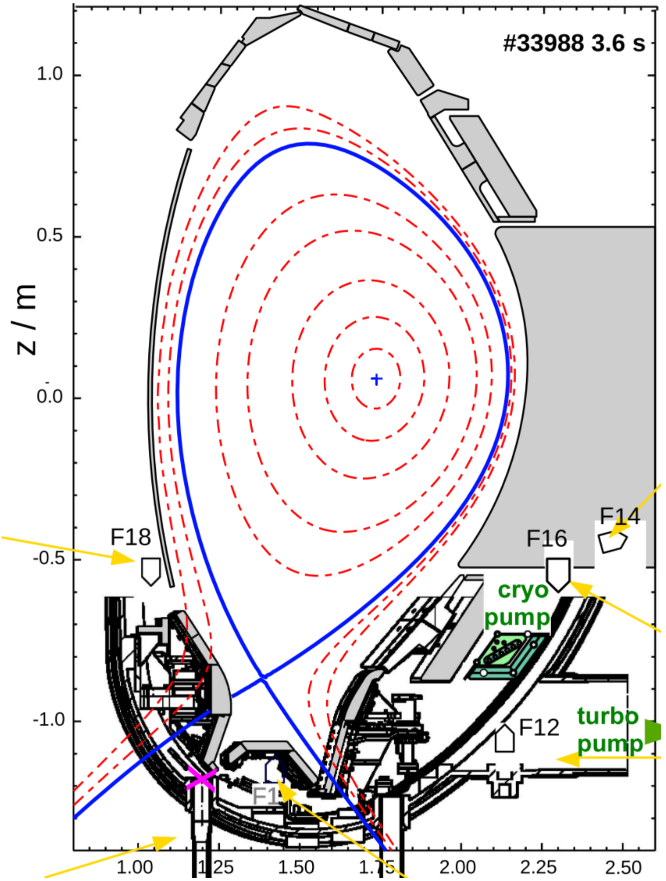

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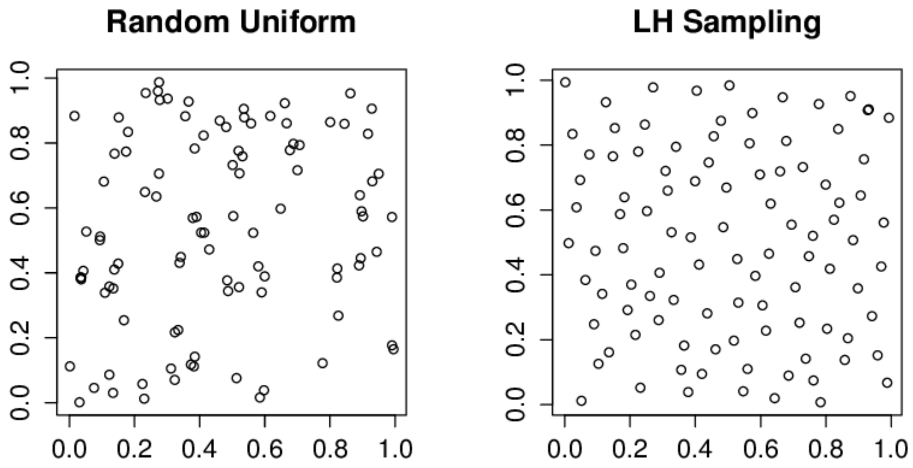
Strategy to efficiently explore parameter space

Use simple free parameters: target multipliers of n_e and T_e, uniform f_{mom} factors, etc.

Create a latin-hypercube grid in space of free parameter priors

Produce samples from low-discrepancy (quasi-random) sequences



Run baseline OSM-EIRENE case on all samples (~ 2^N)

Quasi Monte Carlo (QMC) approach, entirely parallel (SLURM)

Quantify likelihood (~χ^2) and prior probability density

combine for Bayesian posterior probability of each sample

Sample with highest posterior probability is best "interpretative experimental solution"

Scheme can be similarly applied to OSM-EIRENE and DIVIMP

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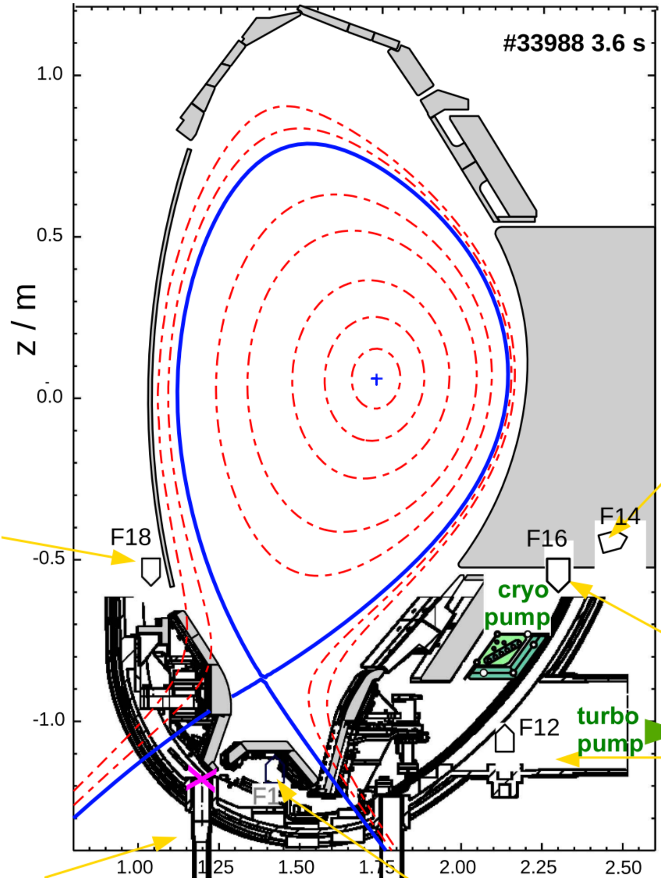

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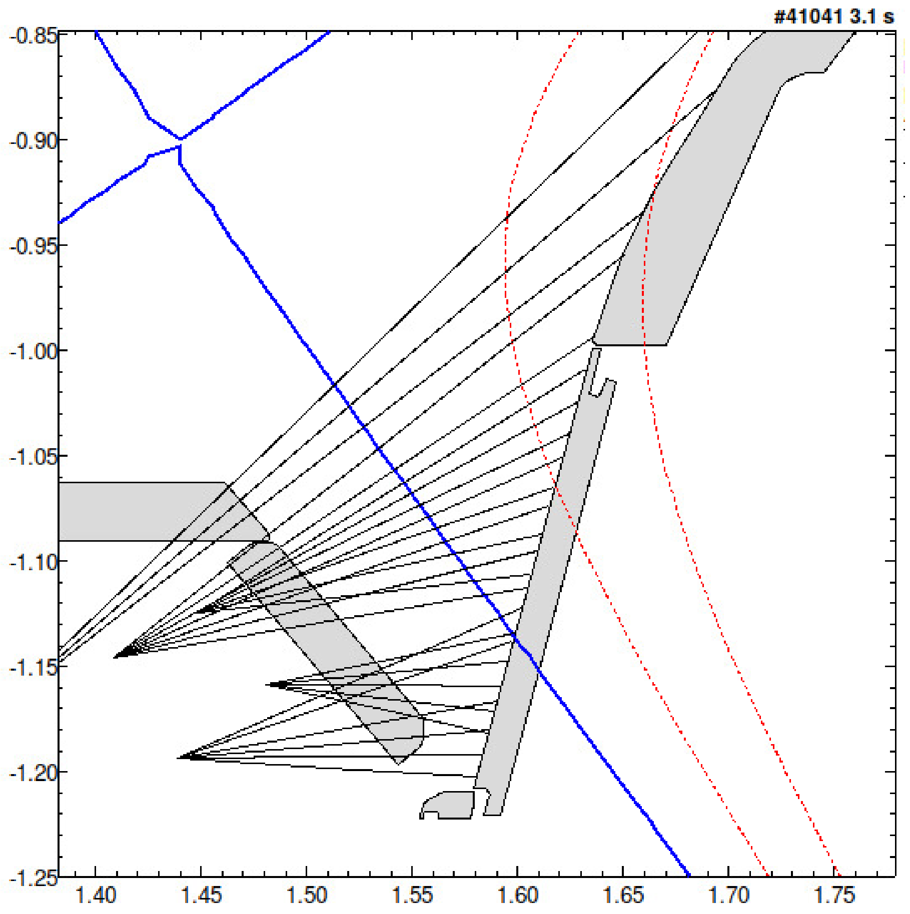
Focus on outer divertor for new boron spectroscopy setup



Emitting CS	Wavelength [Å]	Transition
B II	4121.93	1s2 2s 4f ^3F - 1s2 2s 3d ^3D
B II	3452.32	1s2 2p2 ^1D - 1s2 2s1 2p1 ^1P
B III	7840.06	1s2 3p1 ^2P - 1s2 3s1 ^2S
B IV	2823.3	1s2s ^3S - 1s2p ^3P
B V (B VI density)	4944.60	6h ^2H - 7i ^2I (CX-populated)

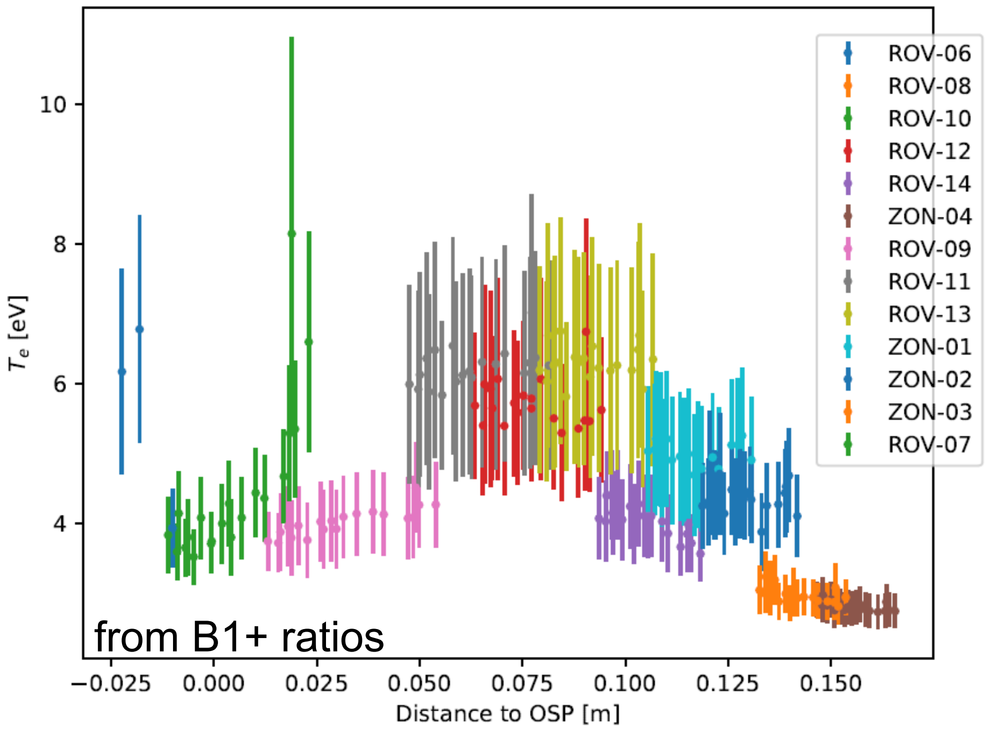
Emitting CS	Wavelength [Å]	Transition
B II	3324.36	1s2 2s1 4d1 ^3D - 1s2 2s1 3p1 ^3P
B II	3452.32	1s2 2p2 ^1D - 1s2 2s1 2p1 ^1P
B II	4121.93	1s2 2s 4f ^3F - 1s2 2s 3d ^3D
B II	4196.04	1s2 2s1 4s1 ^1S - 1s2 2s1 3p1 ^1P
B II	6080.44	1s2 2p2 ^1S - 1s2 2s 3p ^1P
B II	7032.84	1s2 2s1 3p1 ^3P - 1s2 2s1 3s1 ^3S

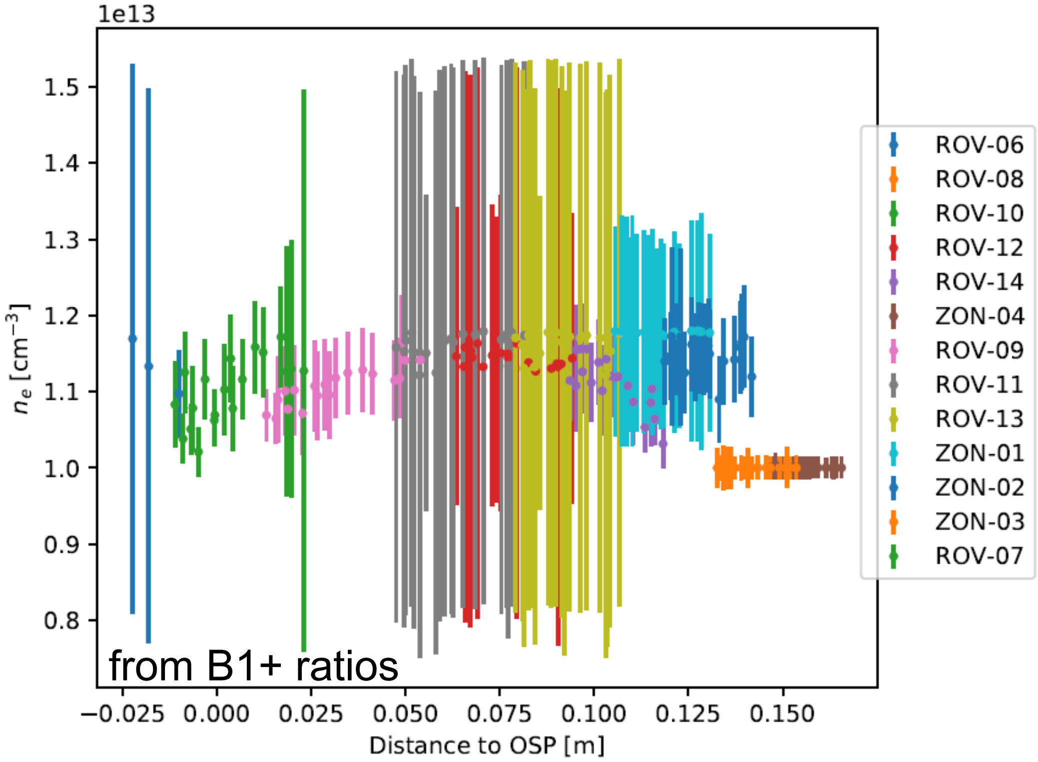
Boron spectroscopy offers opportunities to study impurity transport + constrain background plasma

Measurement of line-averaged T_e weighed by B1+ density

Spectral lines at 4122A and 3451A can be measured simultaneously with N2 spectra

- Measurement available in many N2 seeding experiments
- New ADAS data allows inference of T_e from line ratio, weak dependence on n_e (extra slide)

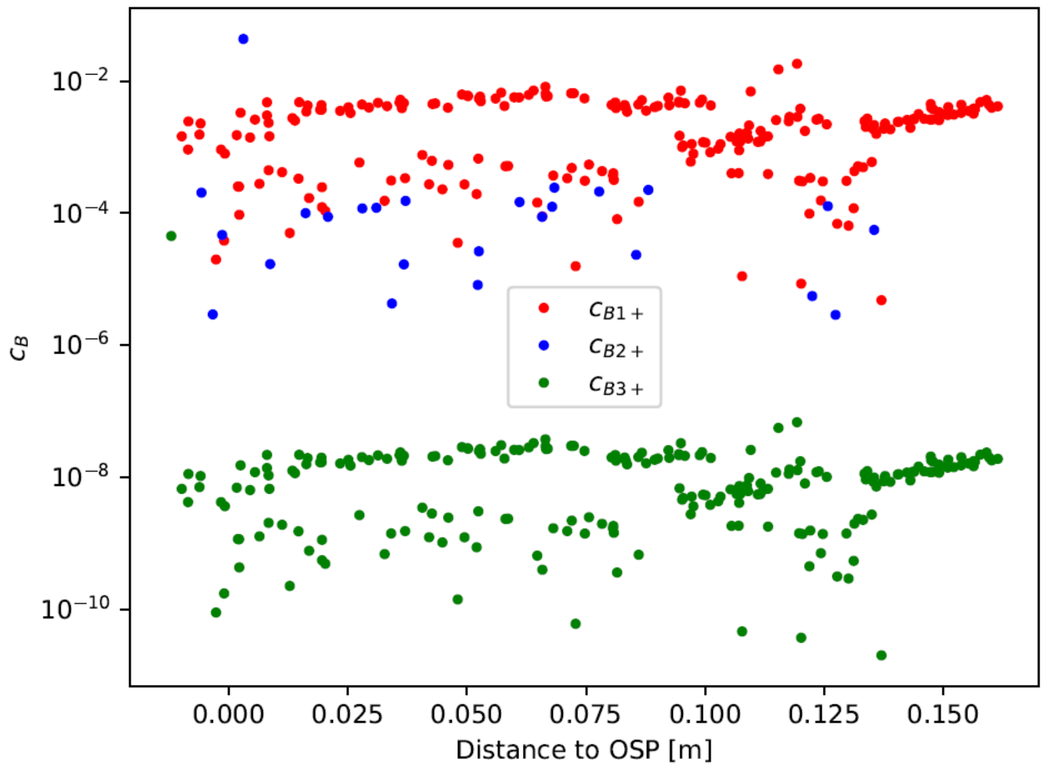




PRELIMINARY quantification of B charge state concentrations

Complex measurement, to be compared to midplane CXRS

- Uncertainties dominated by n_e from B1+ line ratios
  - ✓ Can be improved using Stark broadening and/or N1+ line ratios



Summary & Conclusions

1. **Integrated interpretative modeling of divertor/SOL plasma complements standard 2D modeling (SOLPS, EMC3, SOLEDGE2D, UEDGE…)**

   Reconstruction of plasma/neutral conditions based on experimental measurements

2. **Bayesian inference workflow for integrated *edge* data analysis at AUG**

   Objective: transform *qualitative* observations into *quantitative* insights

3. **AUG divertor and midplane spectroscopy leveraged to determine impurity compression factors in closed divertor**

   Leads to better validation of impurity transport & detachment in predictive modeling of future devices