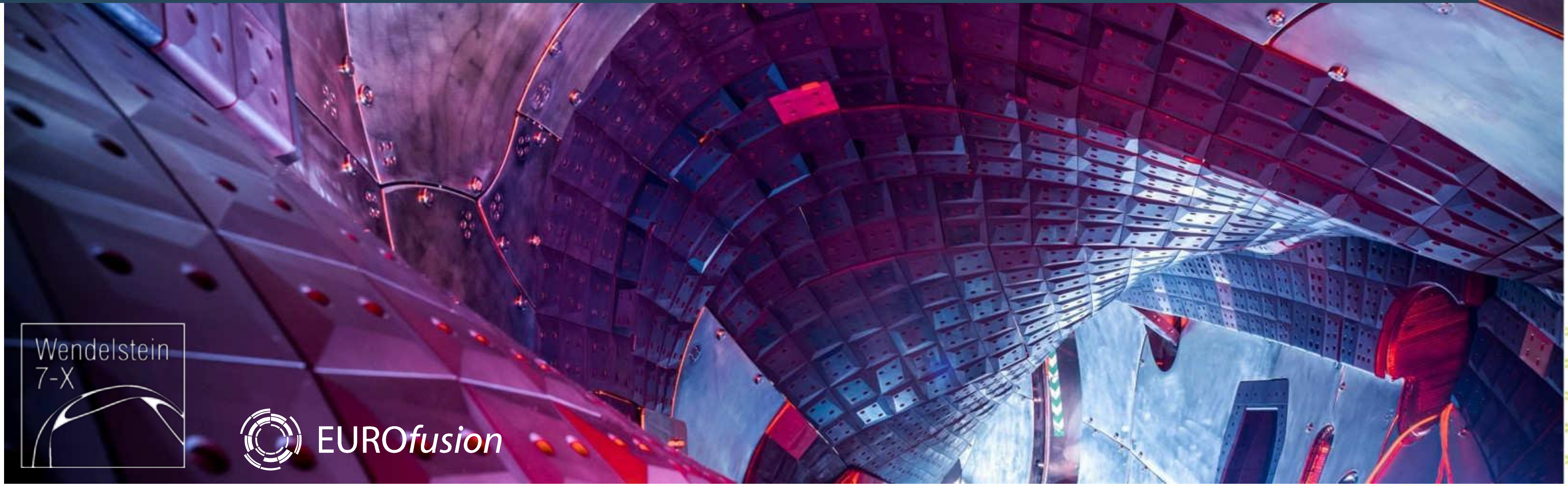
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Forward models and Bayesian analysis results at W7-X

Oliver P. Ford, S. Kwak
including work by: S. Bannmann, E. Flom, U. Höfel, M. Krychowiak, A. Langenberg, J. Schilling, J. Svensson and the W7-X Team

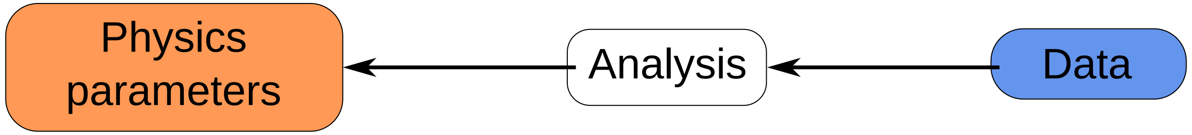


ITPA TG Diagnostics. April 2024

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.

Introduction

First a clarification of terms....



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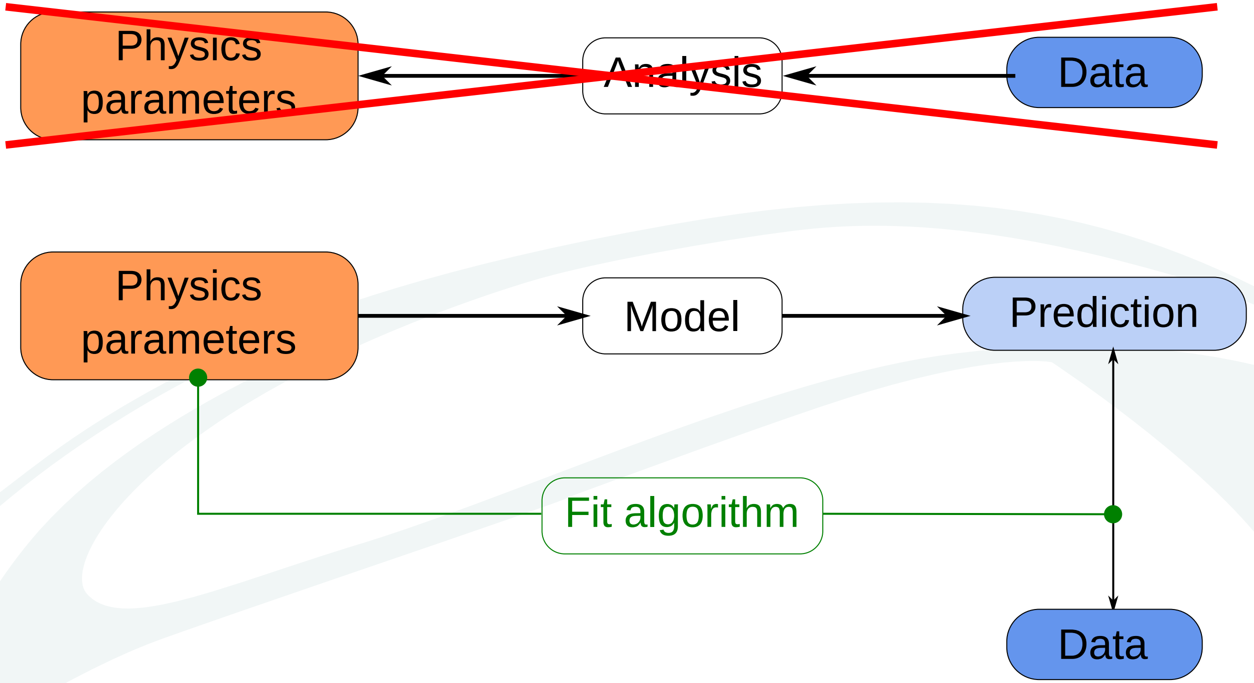
Develop models of what diagnostics measure given the physical parameters.

'Fit' modelled data to measured data and determine desired parameters.



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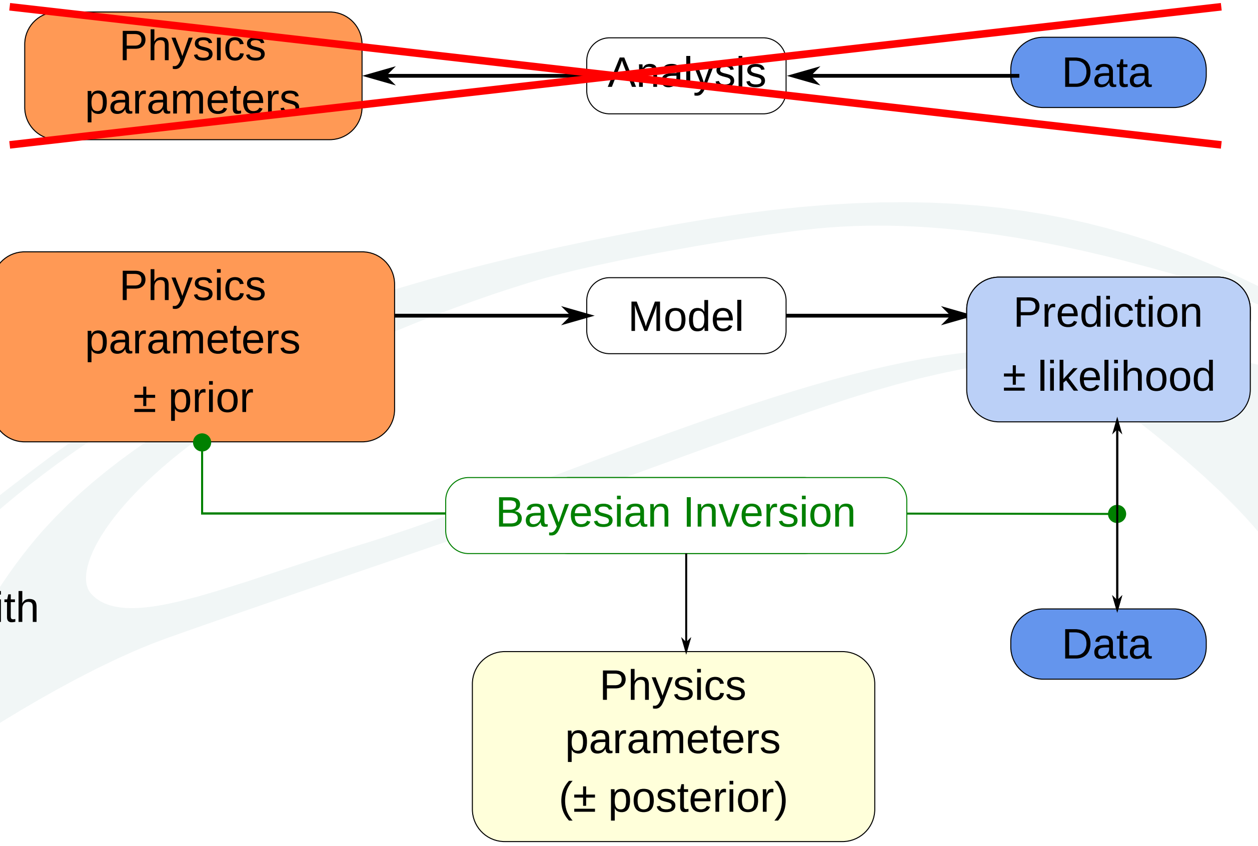
Rigorous probabilistic comparison of data with prediction.

--> Uncertainties



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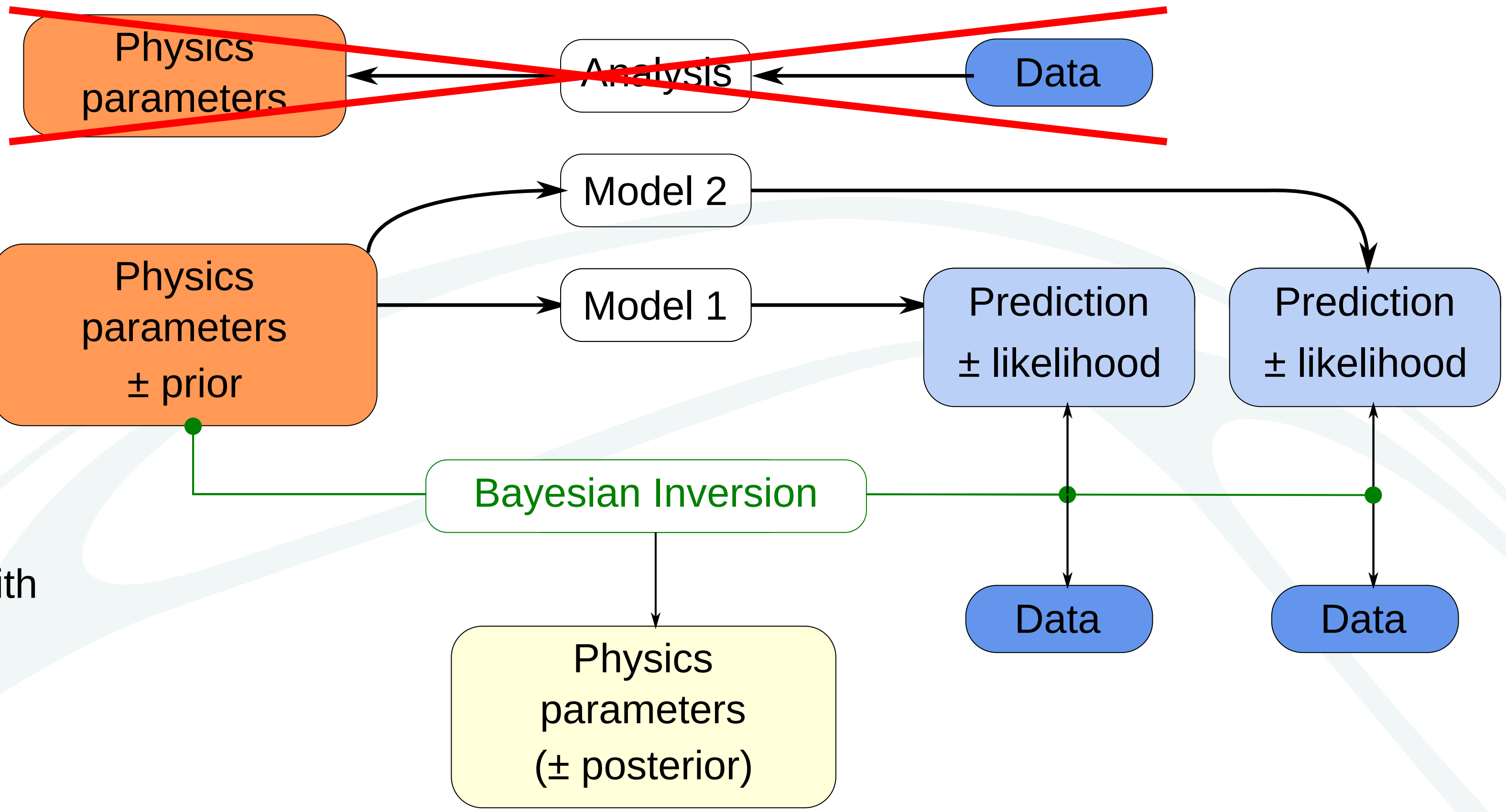
Integrated Analysis:

Combination of multiple systems to a single 'posterior' (result).



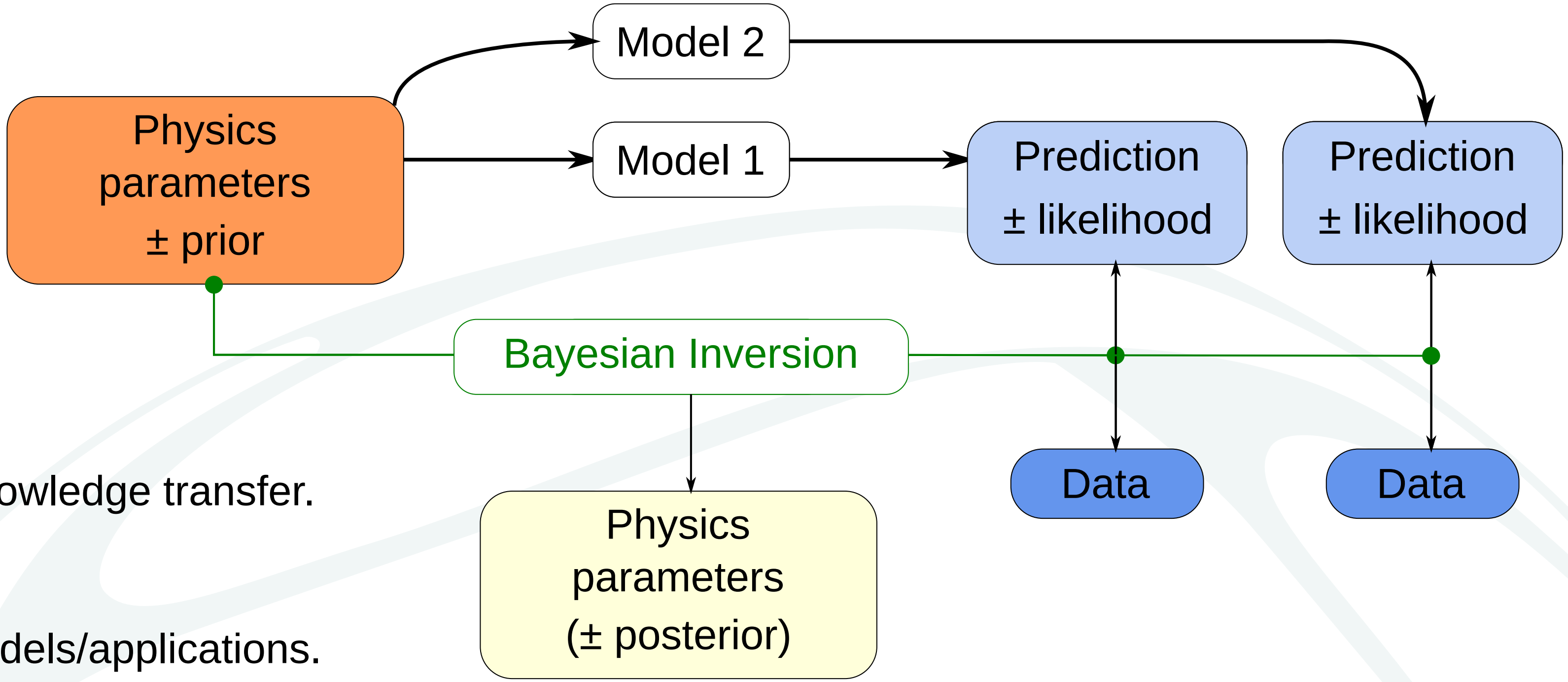
Integrated Data Analysis (IDA): Sometimes general but usually name of code by R. Fischer for integrated analysis at AUG/ITER.

Minerva

First a clarification of terms....

Minerva:

Minerva is a general software framework for complex forward modelling and Bayesian inversions.



+ Highly modular, good code re-use and knowledge transfer.
+ Born in fusion (W7-X + JET + ...)
+ Now quite widespread.
+ Very large collection of existing fusion models/applications.

± Java - Good object orientated language but less popular than python.

- Relatively steep learning curve - hard for simple things but easy for complex things.
- Framework purchased from Seed eScience Ltd.
  (physics/diagnostic modules open to community)

Data analysis at W7-X

Plan was a unified model-based Bayesian analysis.
All diagnosticians would provide data-sources and models to common effort.

- Many really good projects have been completed, with impressive results
  and many models and specific applications were made.

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  - Directing physicists is hard...

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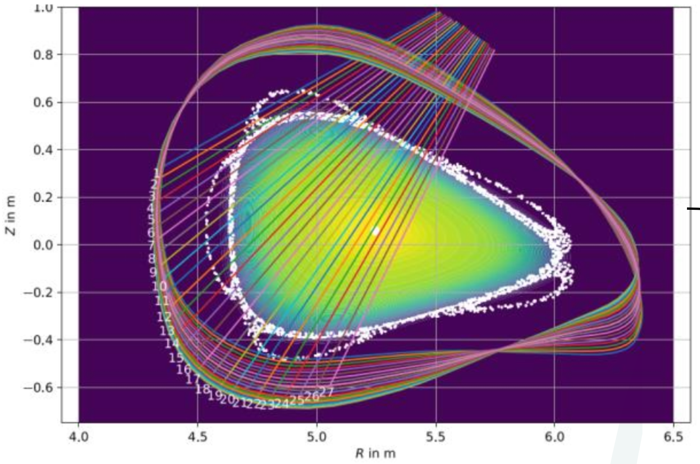
Particular notes:
- Many diagnostic disagreements are due to 'unknown unknowns' and are not automatically solved by integrated analysis.
- Uncertainties are either:
  1) Random noise: We can simply average over long time window.
  2) Known systematic uncertainties: Modelling helps to assess and *sometimes* to correct,
     e.g. Soft X-ray (see later) but they should really be fixed at the hardware level.

  3) **unknown systematic uncertainties**: Not in the model, so not correctly represented by a posterior!

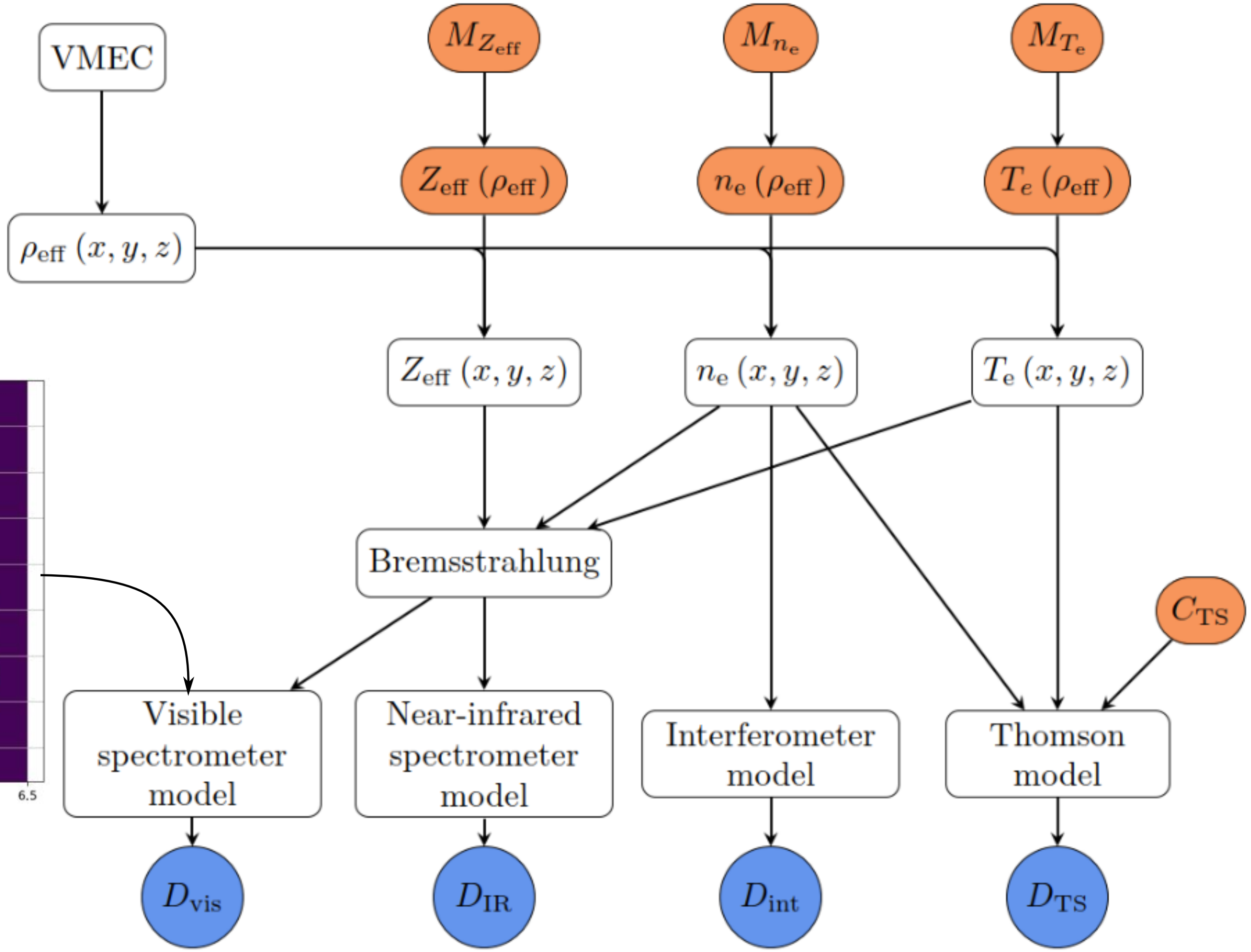
Examples: Bremsstrahlung

Bremsstrahlung model developed for Z_{eff} inference.

[S Kwak RSI **92**, 043505 2021
A Pavone JINST **14** C10003 2019]



Lines of sight + calibration



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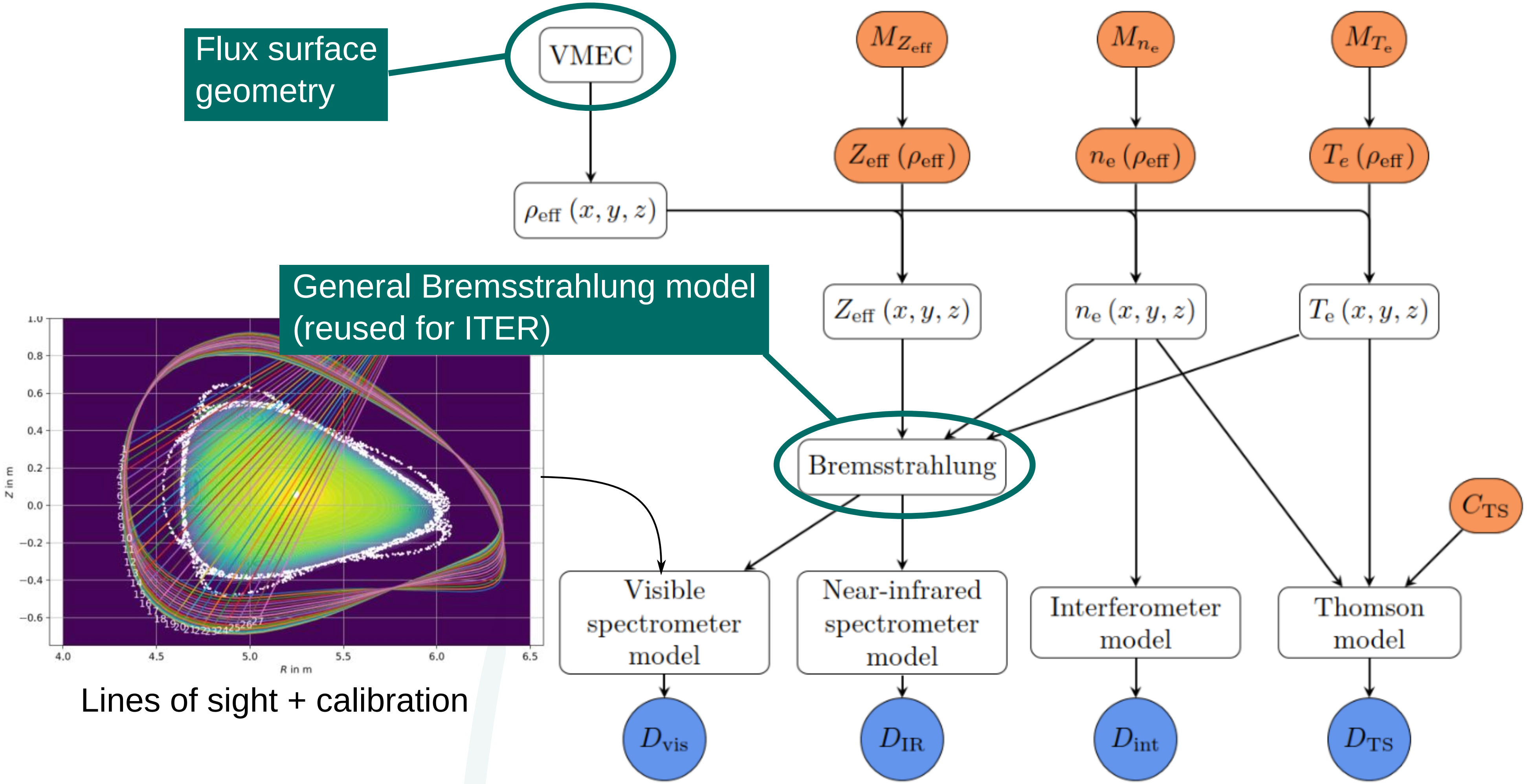

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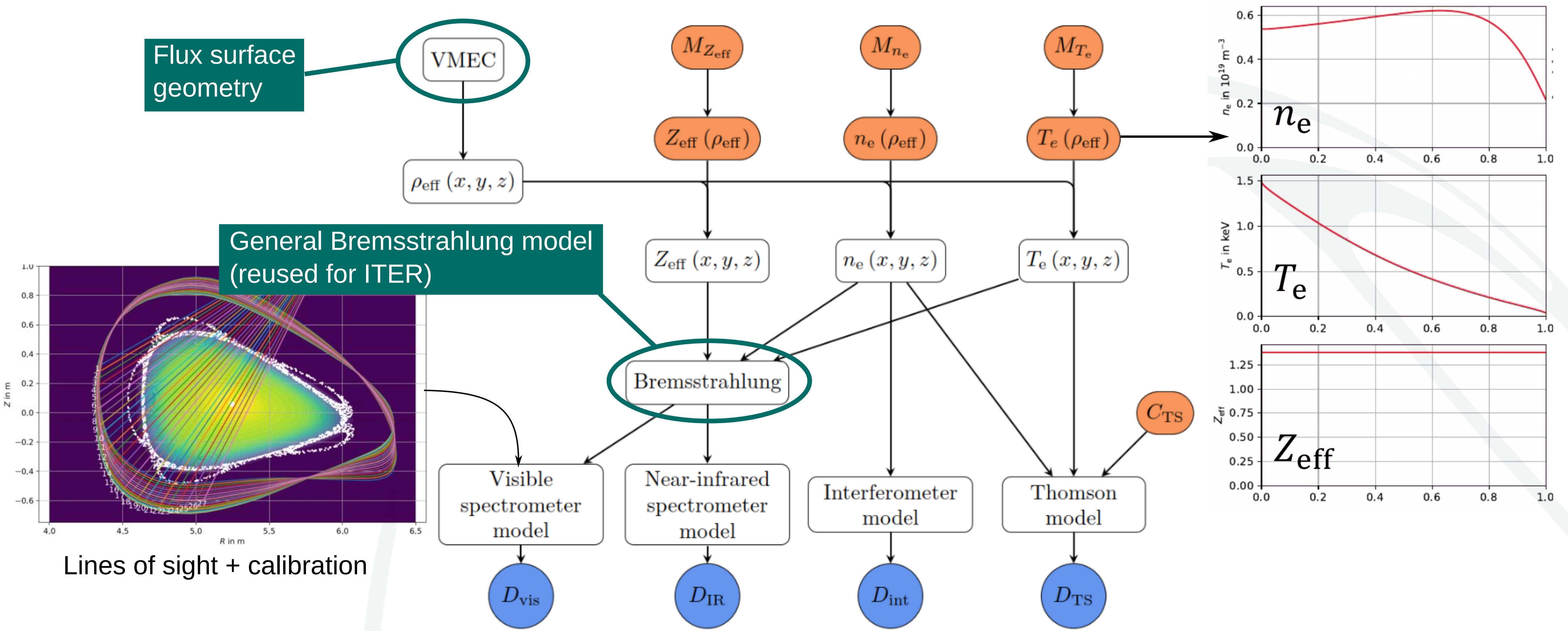

Examples: Bremsstrahlung

Bremsstrahlung model developed for Z_{eff} inference. Can be integrated with Thomsons Scattering model or run based on existing n_e, T_e profiles:

[S Kwak RSI **92**, 043505 2021
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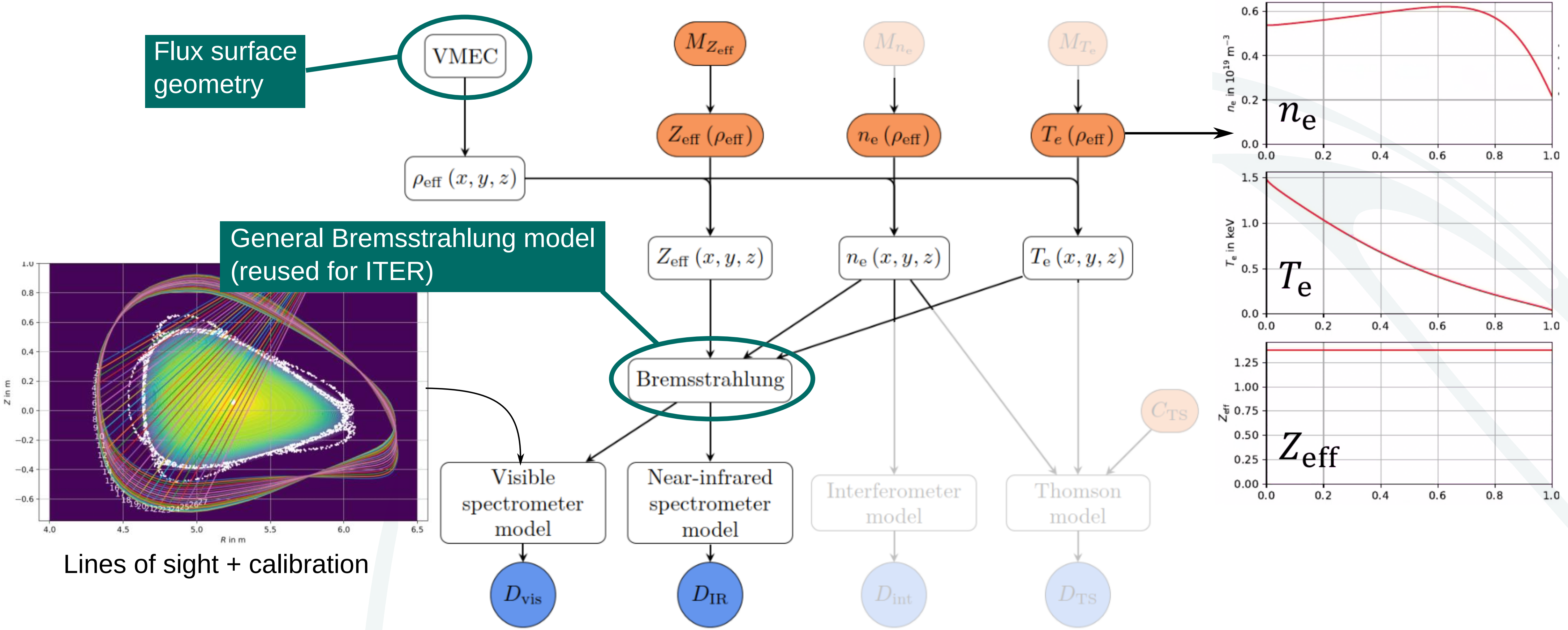

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Some validation exercises completed:

1) Change of Z_{eff} ~ 1 to Z_{eff} ~ 2 when puffing helium into H plasma:

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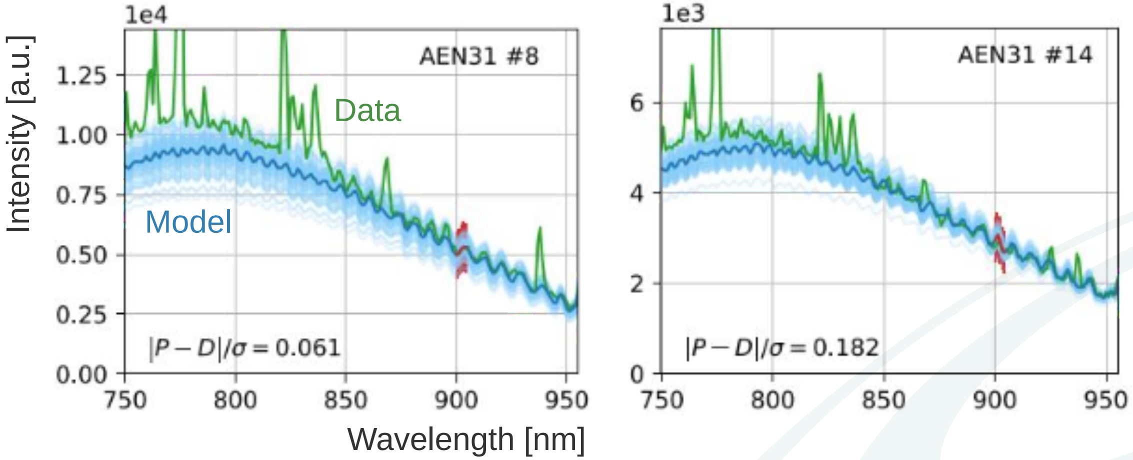

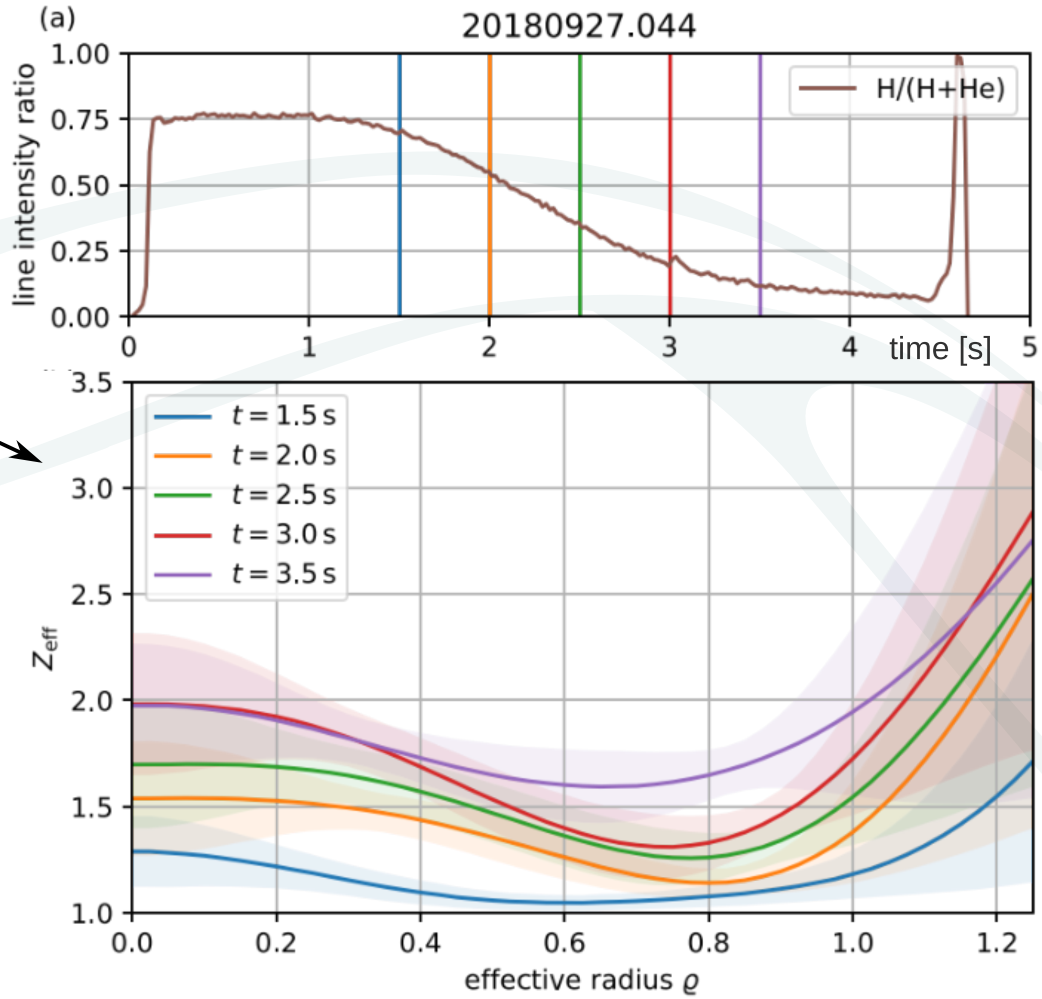

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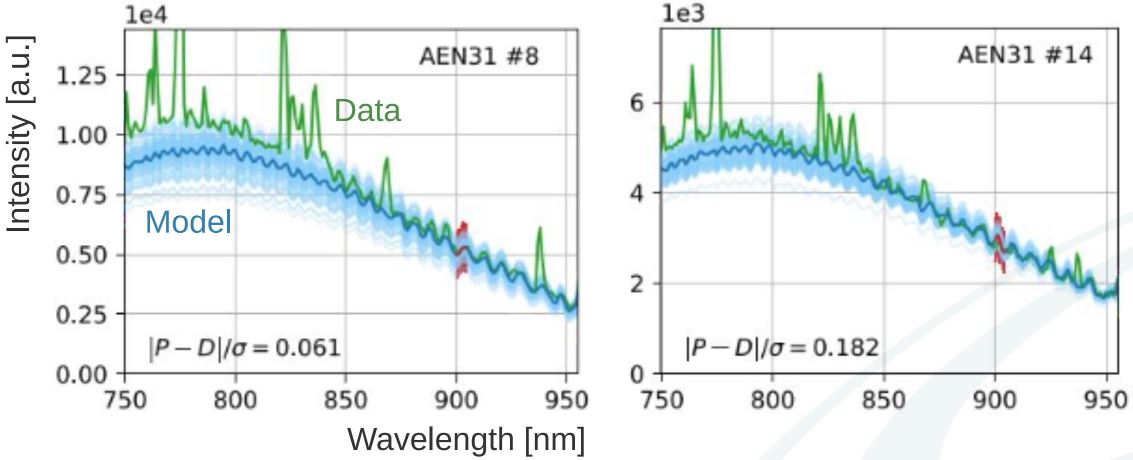

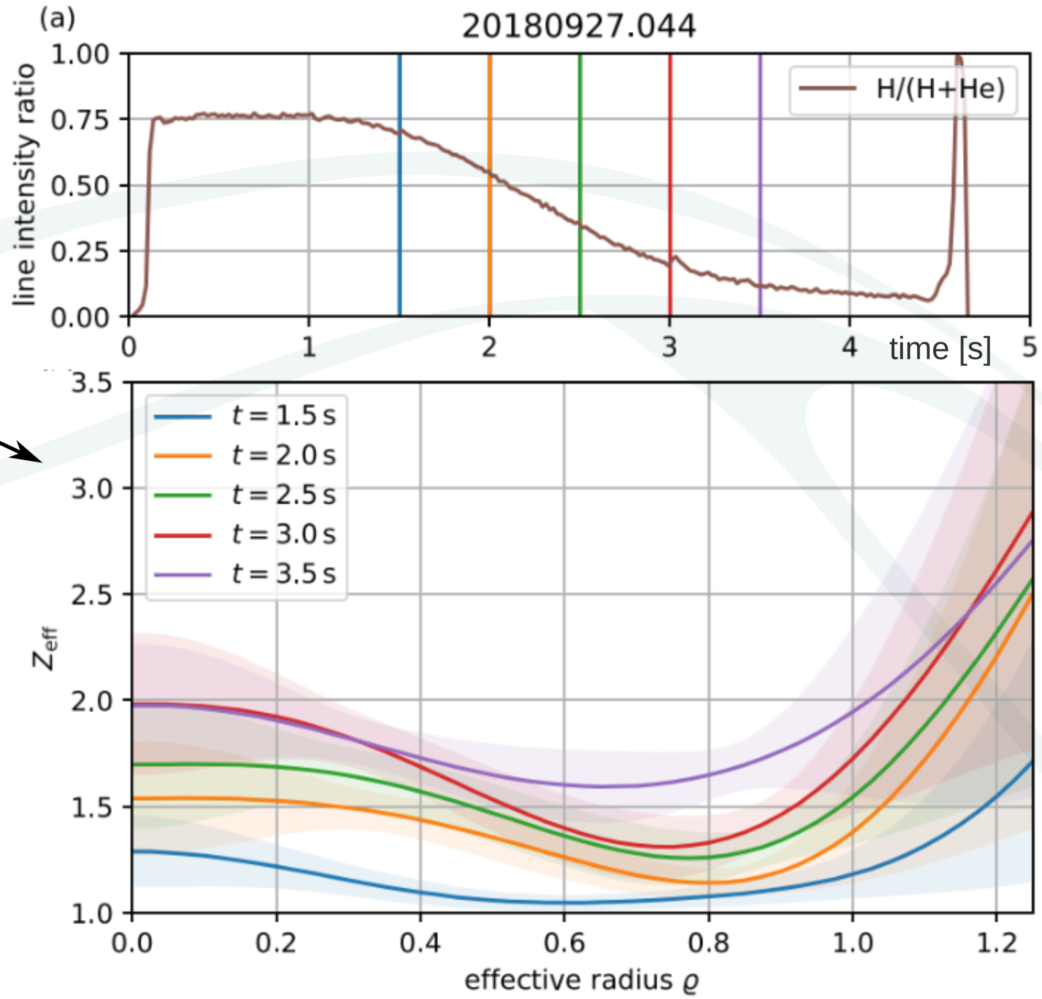

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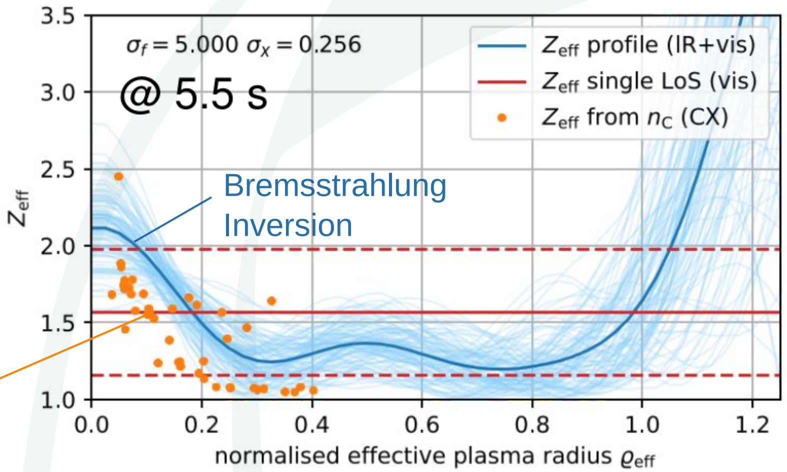

From n_C
(assuming only C)

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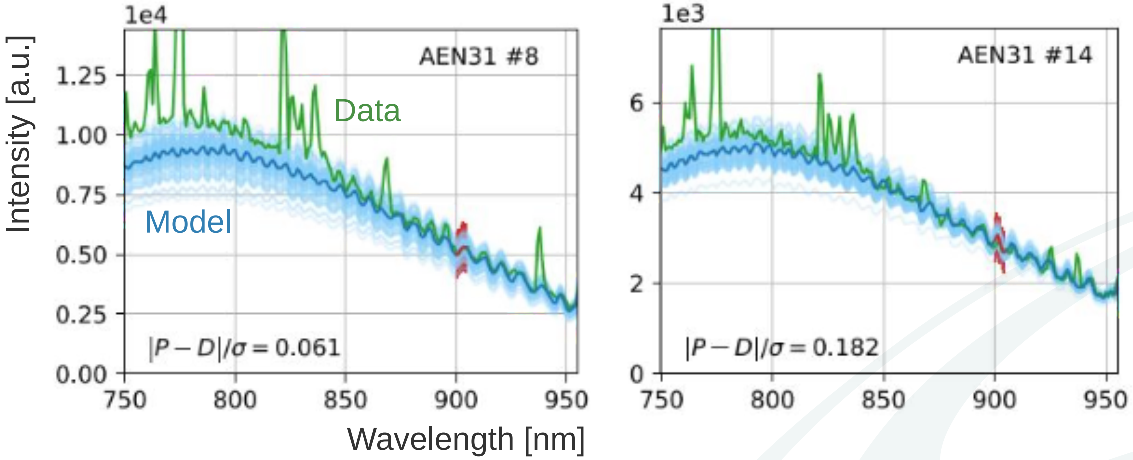

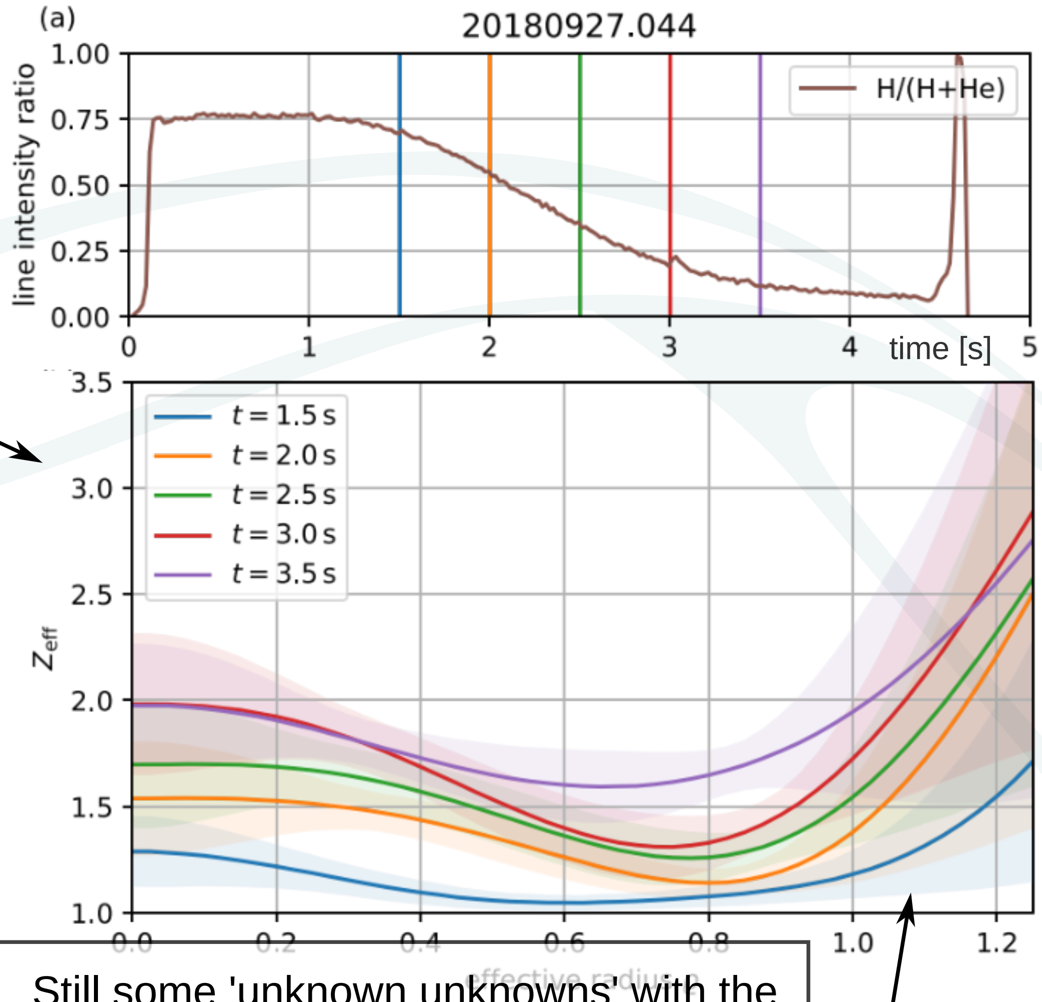

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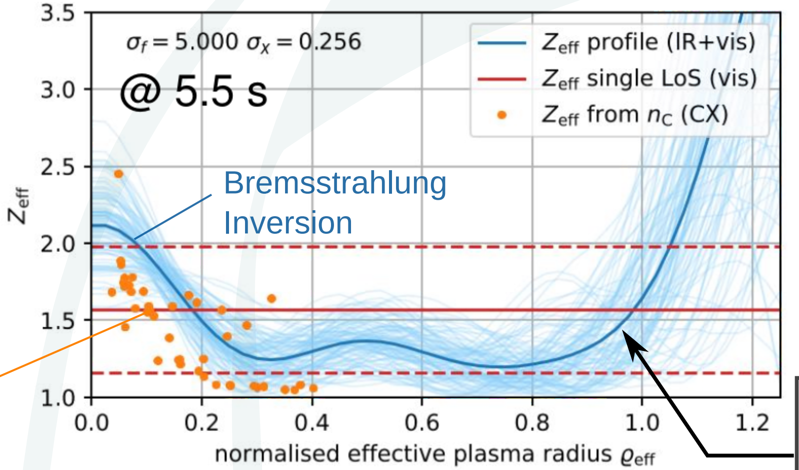

From n_C
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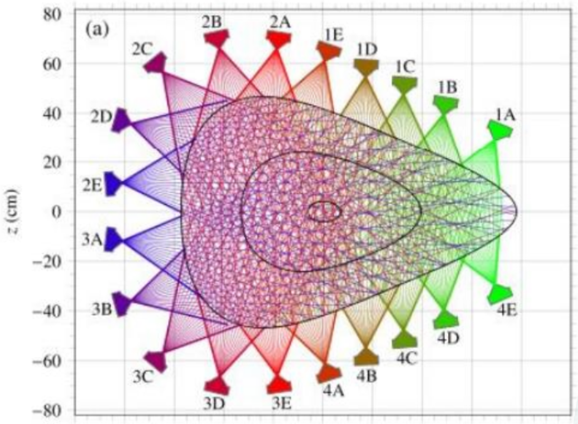
Still some 'unknown unknowns' with the Bremsstrahlung radiation at the edge.

Examples: Soft X-ray

XMCTS: Soft X-ray diagnostic with 20 cameras.

[J. Schiling et al. PPCF **63** 055010
S. Kwak ECPD 2023]



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- Resulting tomograms unphysical.

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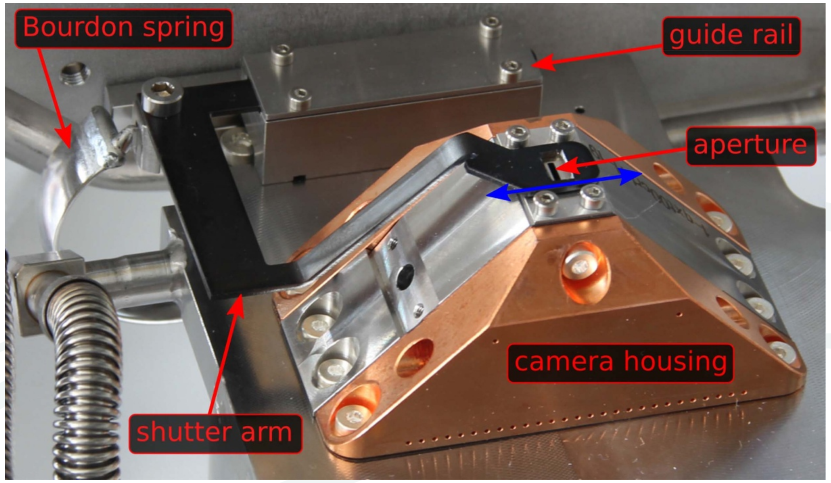

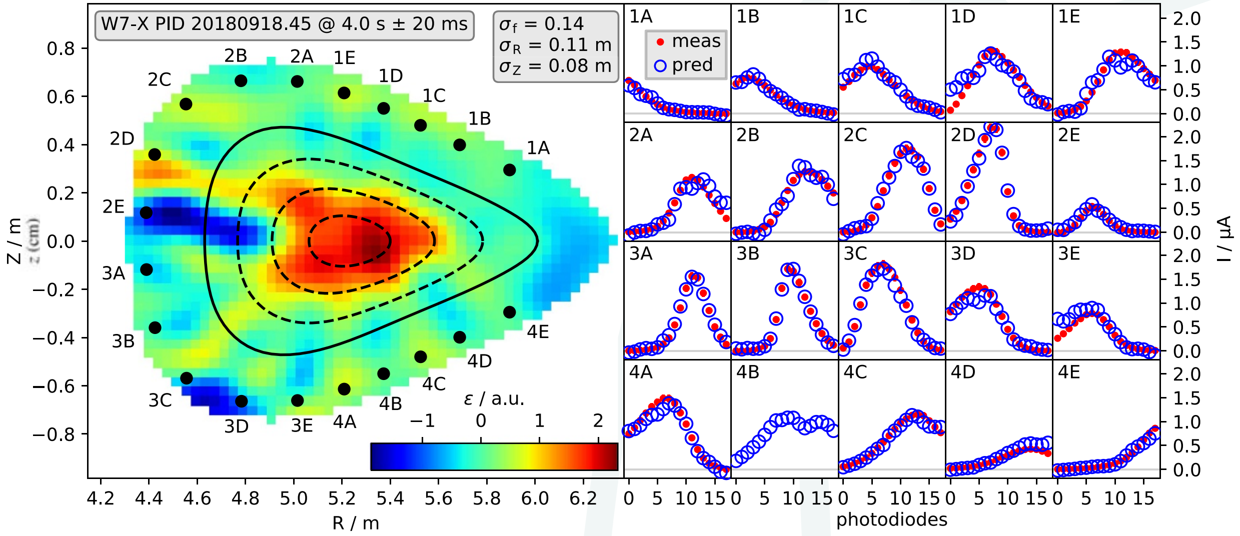

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- Faulty shutters open to unknown position.
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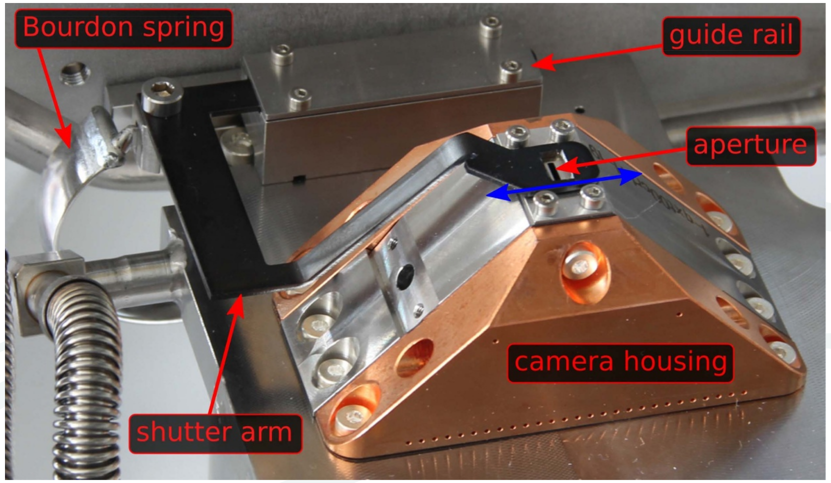
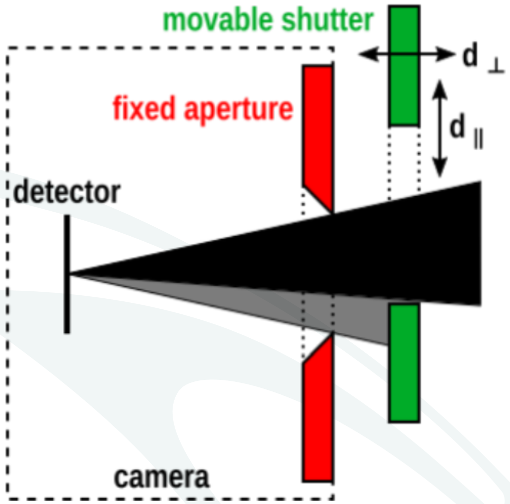
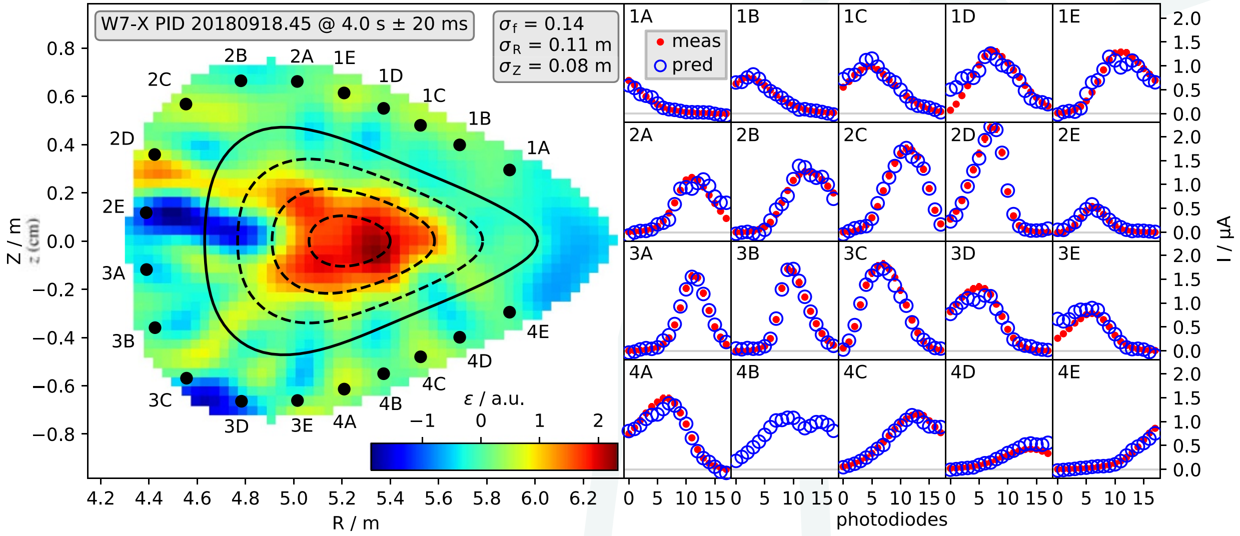
Solution:

- Include shutter positions as free parameters in model.
- Use Bayesian model selection to find 'simplest' model with a consistent with flux-surfaces and a matching set of shutter positions.
- Perform 2D inversion using these shutter positions.

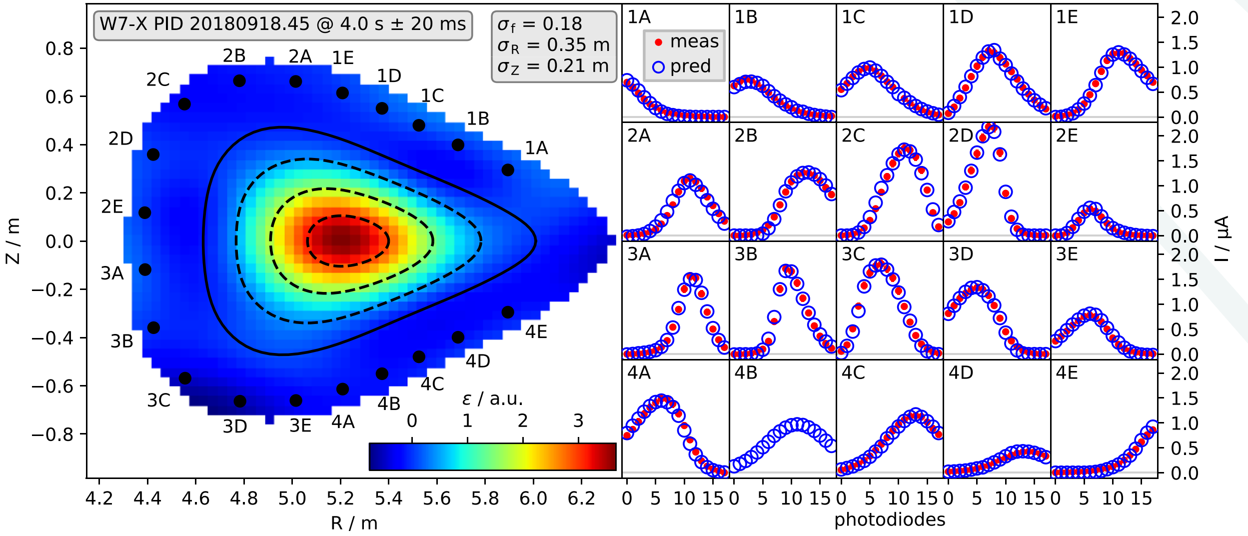




Ignoring shutter:



With shutter model:



X-Ray spectroscopy

- Minerva forward model developed for X-Ray spectroscopy, used for two independant systems at W7-X:
  - Different field of view, hardware, instrument function, spectra etc but many common forward model modules.

[A. Langenberg
Nucl. Fus. **61** 116018,
Fus. Sci. Tech. **69** 560,
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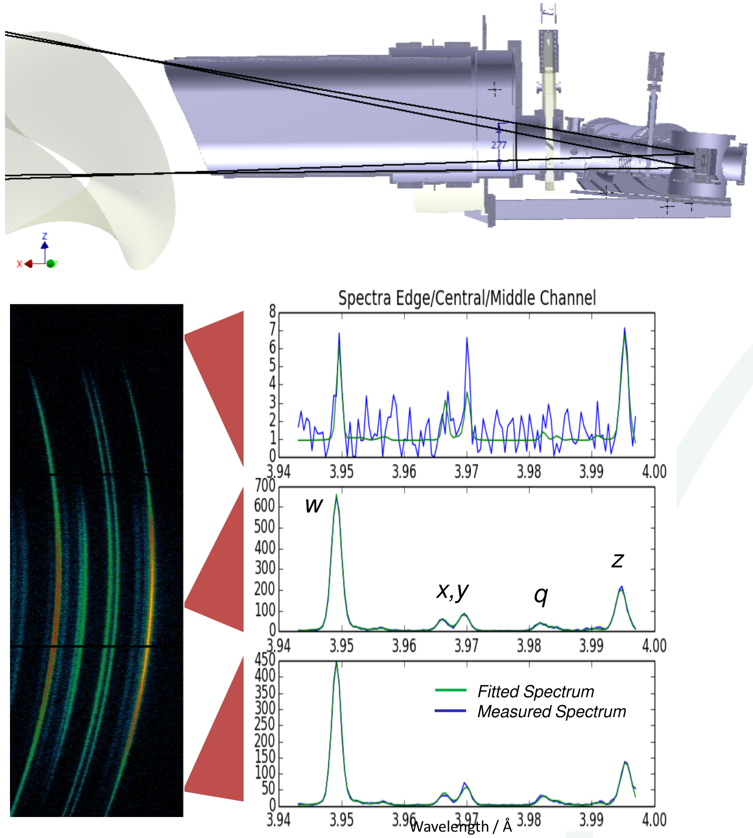
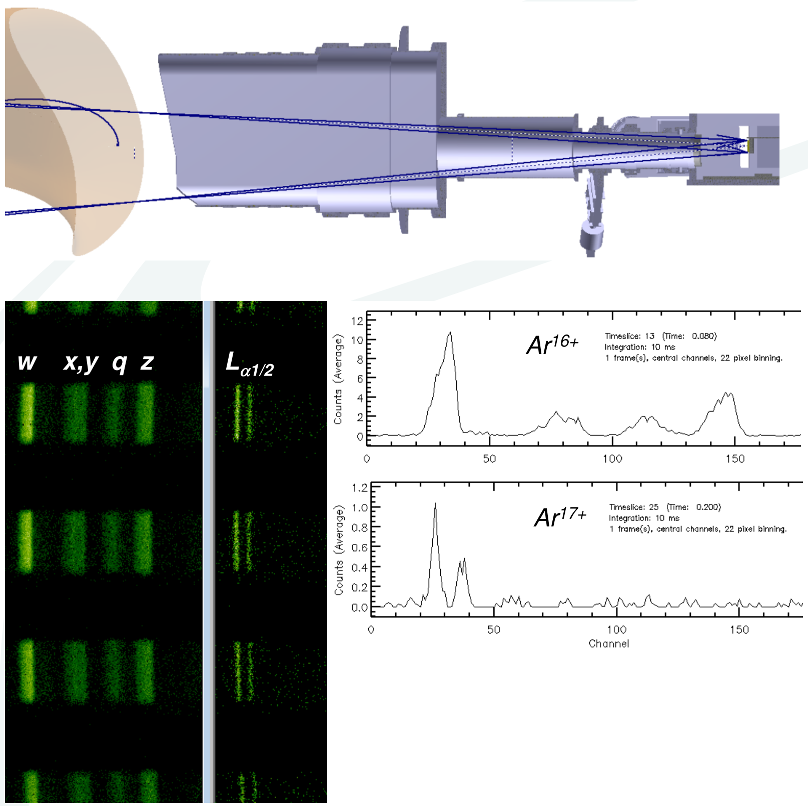
XICS He-like Ar Spectra (PPPL)



HR-XIS He- and H-like Ar Spectra (FZ Jülich)



160310.016 @ 200 ms 160310.007 @ 80 ms

X-Ray spectroscopy

- Minerva forward model developed for X-Ray spectroscopy, used for two independant systems at W7-X:
  - Different field of view, hardware, instrument function, spectra etc but many common forward model modules.
  - Regular Ti, Te and nZ profile inversions, compare well with faster PPPL code.
  - Used in multiple transport analyses and publications.

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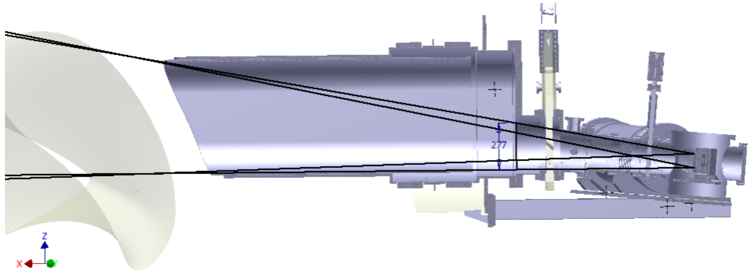

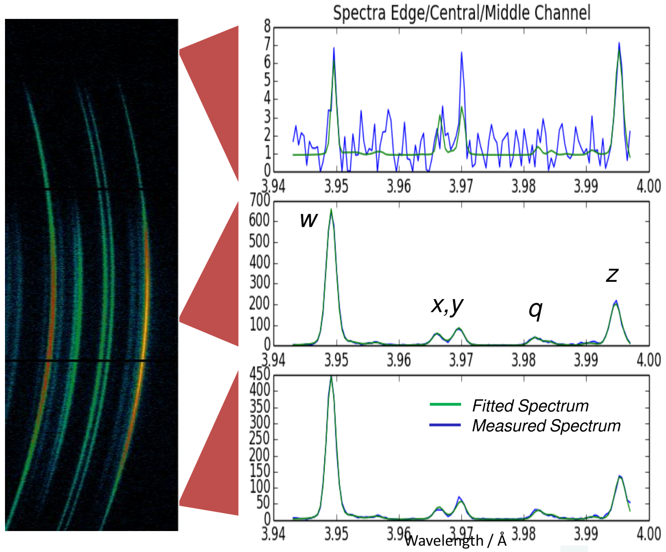

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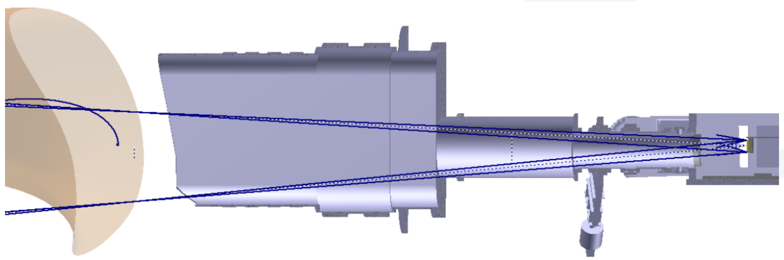

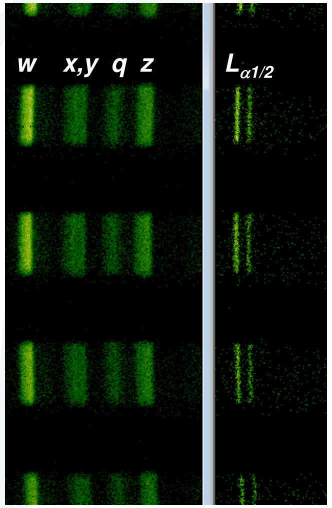

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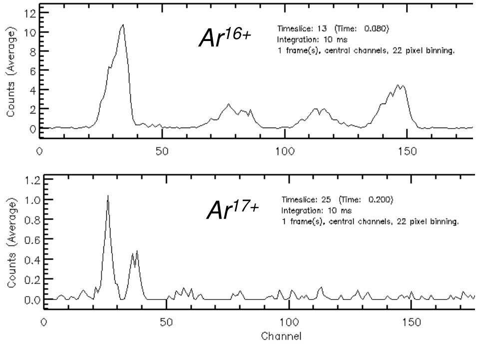
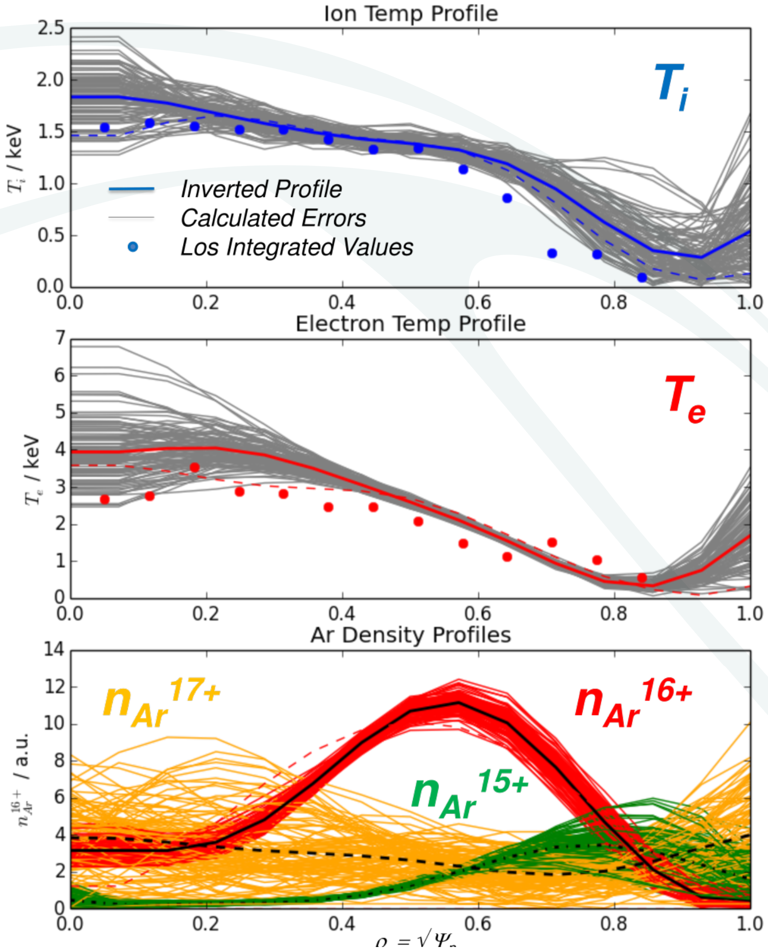
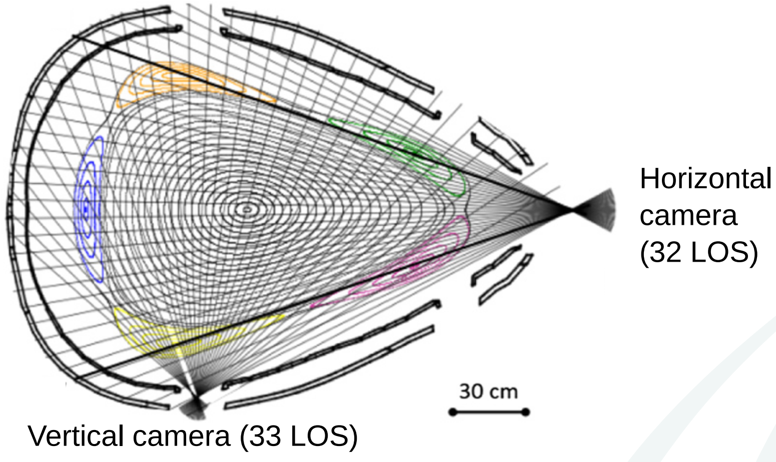


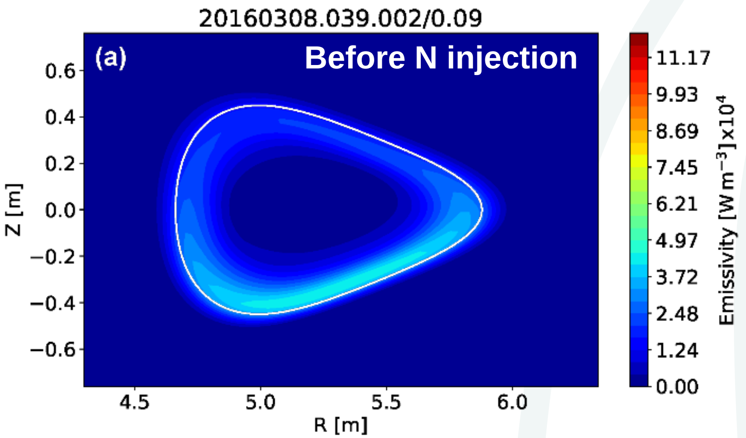


Bolometry

[Contact J. Svensson, Seed e-Science,,
M. Krychowiak et al. RSI **87**, 11D304 (2016),
T. Barbui et al 2019 Nucl. Fus. **59** 076008]

- Model for W7-X bolometers
- Gaussian-process tomography.
- Example: N-injection in limiter plasma.





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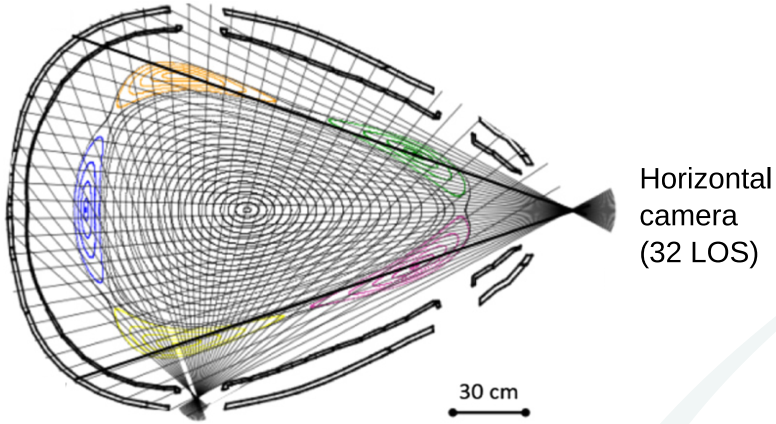
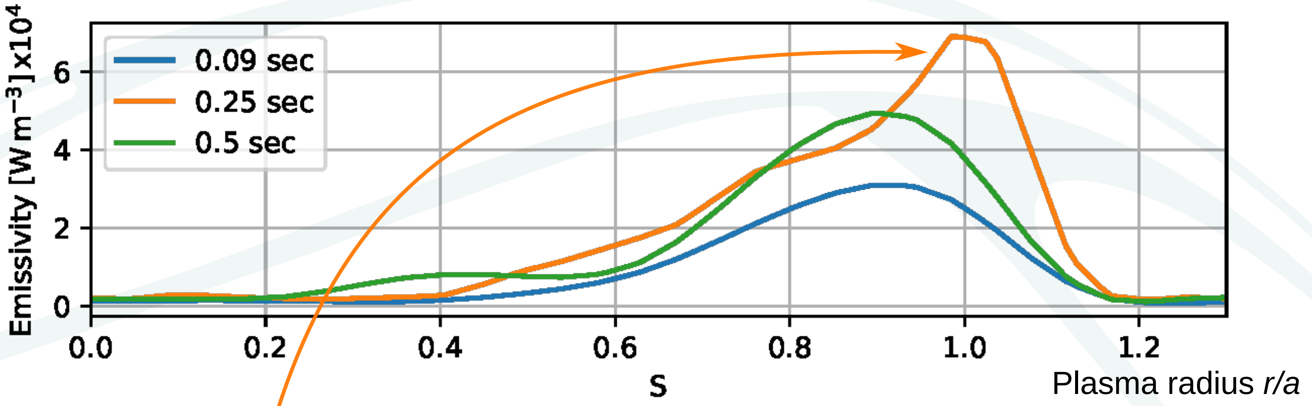
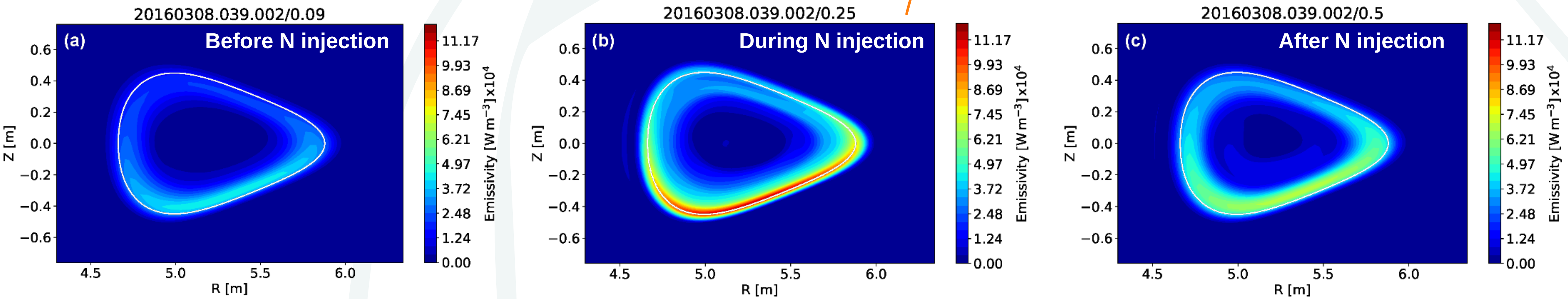
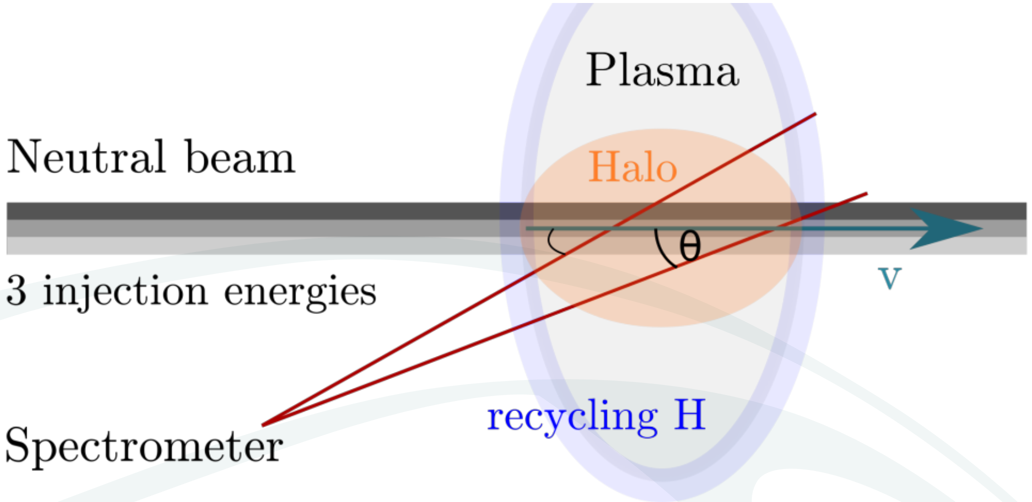






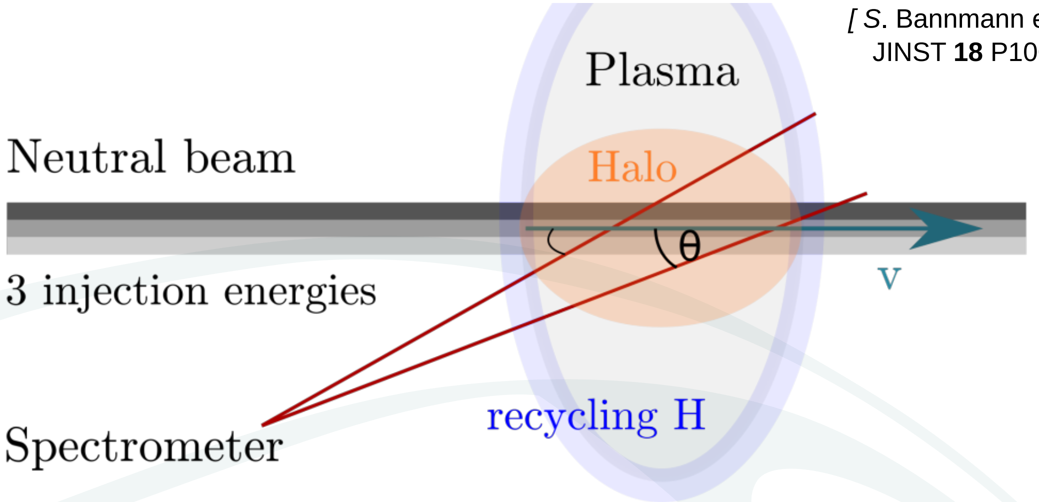
Beam Emission Spectroscopy

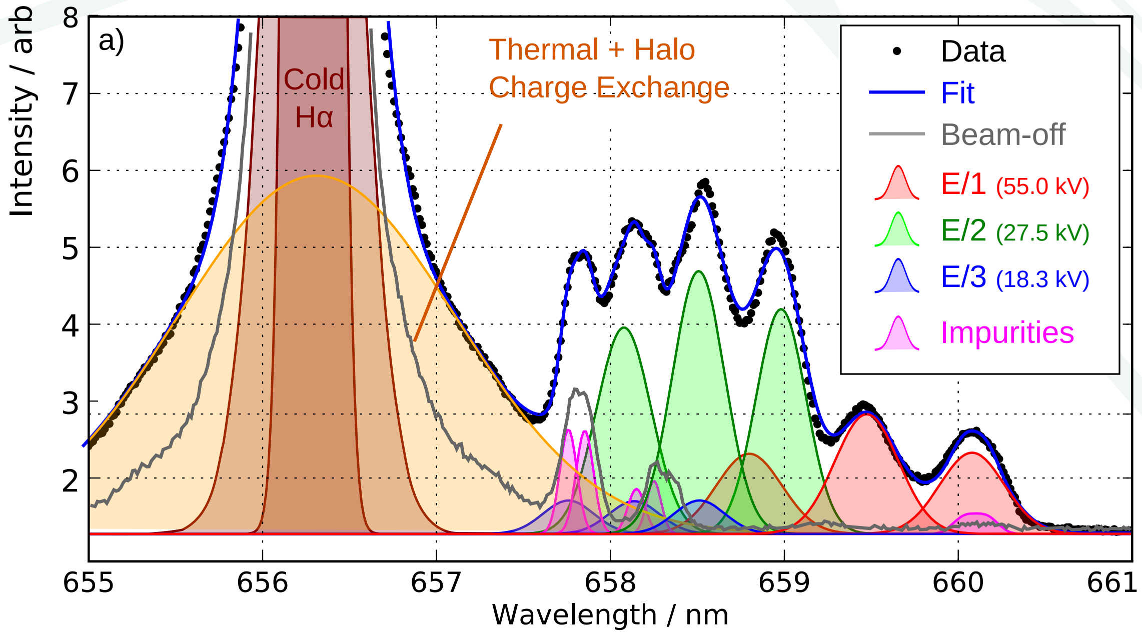


Beam Emission Spectroscopy

- Very complex spectra containing lots of information:
- Analyse with multi-Gaussian fit.... No! Too much freedom.
  Disagreements at edge. Too crude using only ADAS beam-stopping.

[*S.* Bannmann et al.
JINST **18** P10029]





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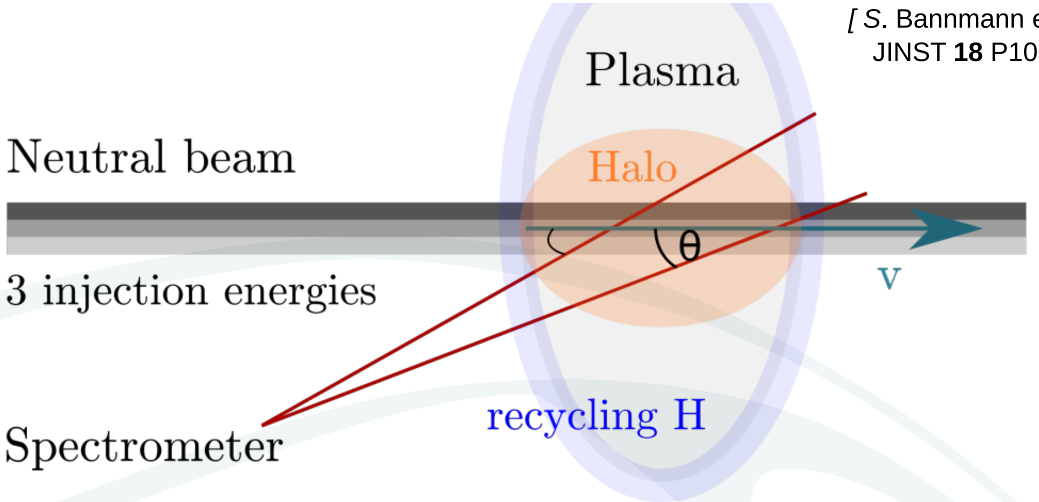
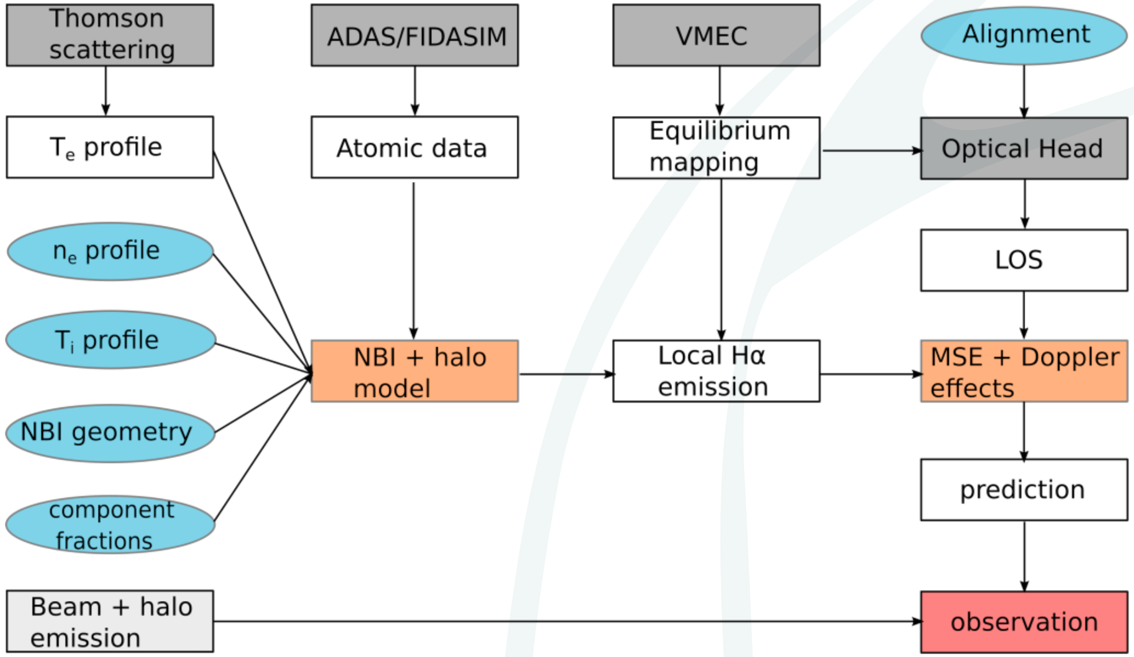
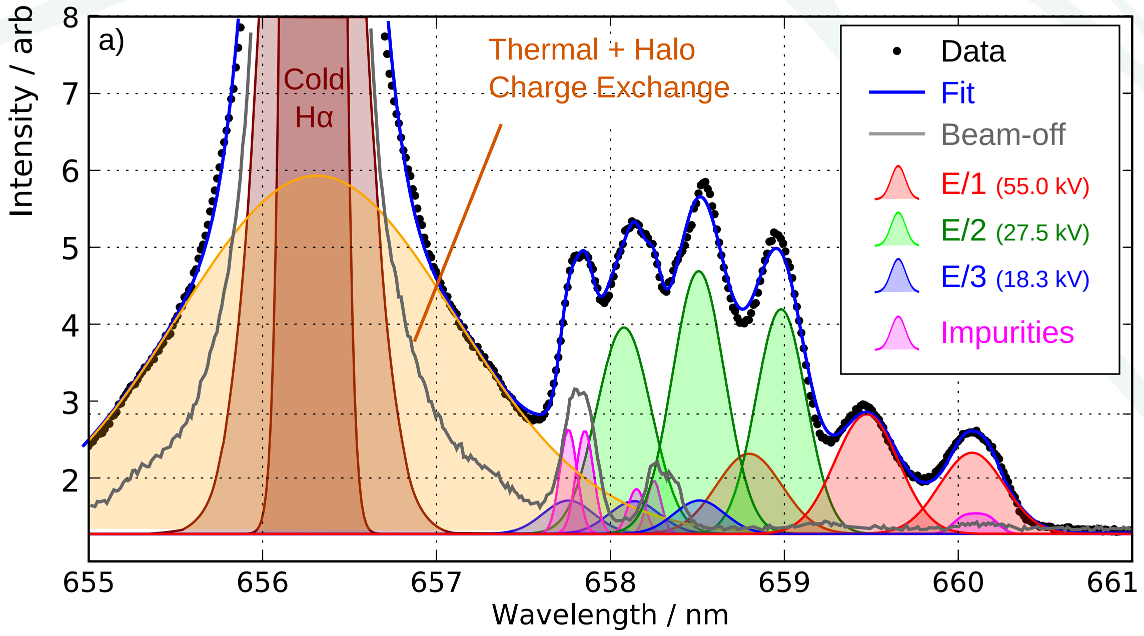
- PhD project to build Minerva complete model.
    - Simple model, data sources, calibration etc already present.
    - 3 months getting used to Minerva, Java etc.
    - 4 months developing model.
    - 3 months applying, debugging etc.

[S. Bannmann et al. JINST **18** P10029]







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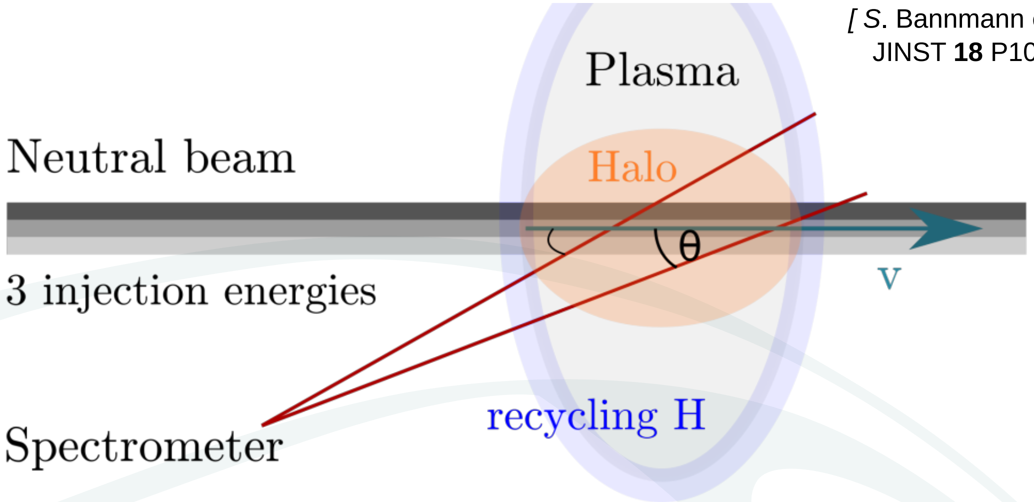
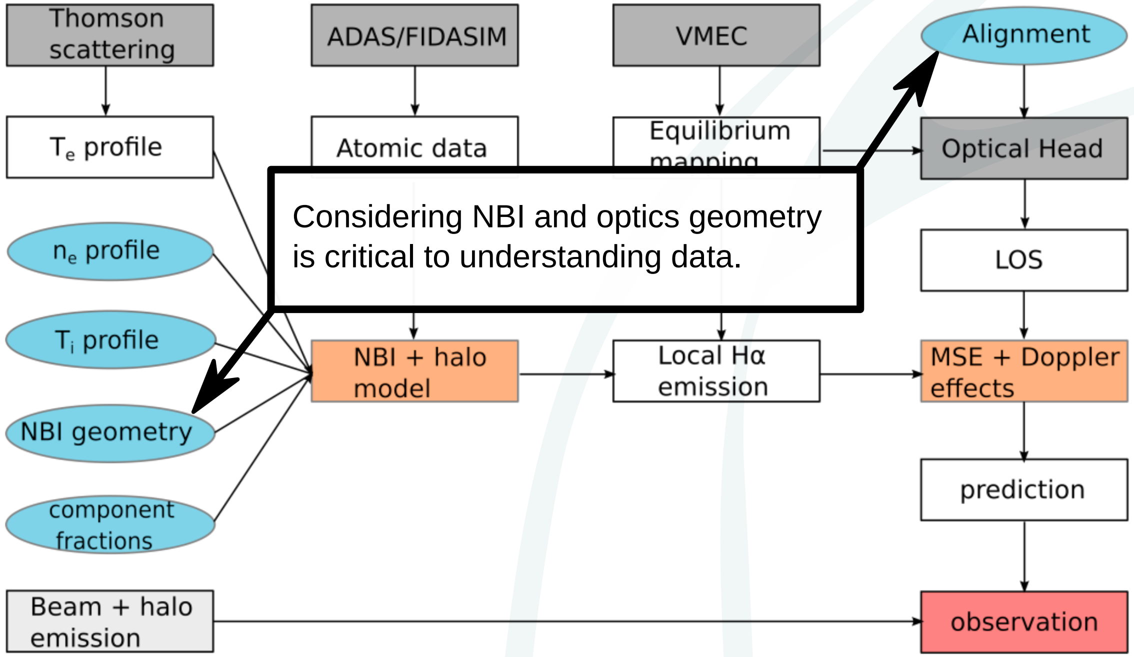
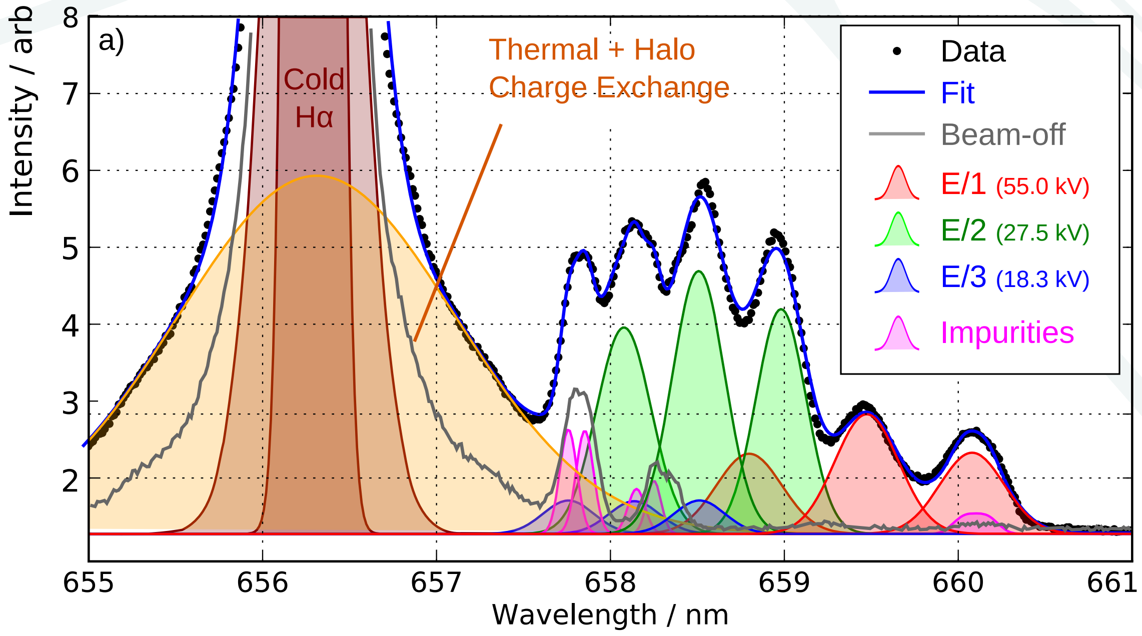
[S. Bannmann et al. JINST **18** P10029]







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[S. Bannmann et al. JINST **18** P10029 2024,
S. Bannmann et al. PPCF **66** 065001 2024]

- Complex physical model for beam+halo diffusion + ionisation + excitation + emission:
- Added to minerva model:
    - Collisional-radiative model for beam ionisation/excitation.

Col-Rad:

$$\frac{\mathrm{d}\mathbf{\Phi}(z)}{\mathrm{d}z} = \frac{1}{v_b}\mathbf{T}_{\mathrm{CR}}\mathbf{\Phi}(z)$$

$$T_{\mathrm{CR}} = T_{\mathrm{CR}}(T_e, T_i, n_e) = \begin{bmatrix} -L_1 & A_{21} & A_{31} & . & A_{k1} \\ E_{12} & -L_2 & A_{32} & . & A_{k2} \\ E_{13} & E_{23} & -L_3 & . & . \\ . & . & . & . & A_{ki} \\ E_{1k} & E_{2k} & . & E_{jk} & -L_k \end{bmatrix}.$$

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    - Coupled diffusion + col. rad. model for halo processes.

Halo diffusion:

$$\frac{\partial \mathbf{n}}{\partial t} - (\nabla(\mathbf{D}\nabla)) \odot \mathbf{n} = \mathbf{T}_{\mathrm{CR}} \cdot \mathbf{n} + \mathbf{S}_{\mathrm{DCX}}$$

Col-Rad:

$$\frac{\mathrm{d}\mathbf{\Phi}(z)}{\mathrm{d}z} = \frac{1}{v_b}\mathbf{T}_{\mathrm{CR}}\mathbf{\Phi}(z)$$

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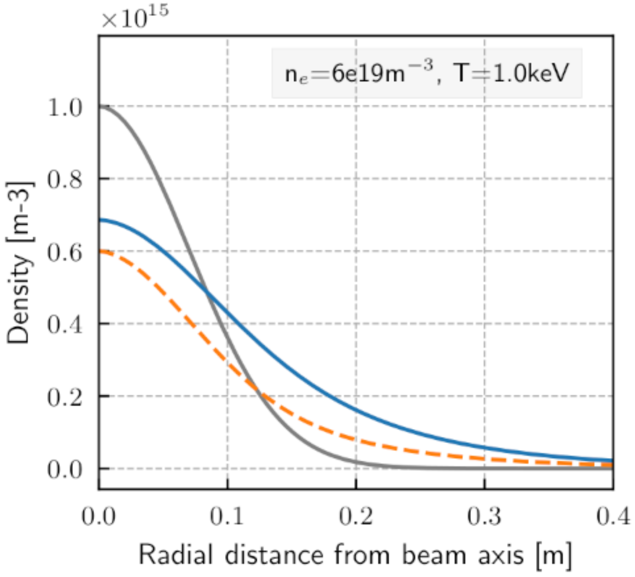
Important for localisation at medium density:



Beam Emission Spectroscopy

[S. Bannmann et al. JINST **18** P10029 2024,
S. Bannmann et al. PPCF **66** 065001 2024]

- Complex physical model for beam+halo diffusion + ionisation + excitation + emission:
- Added to minerva model:
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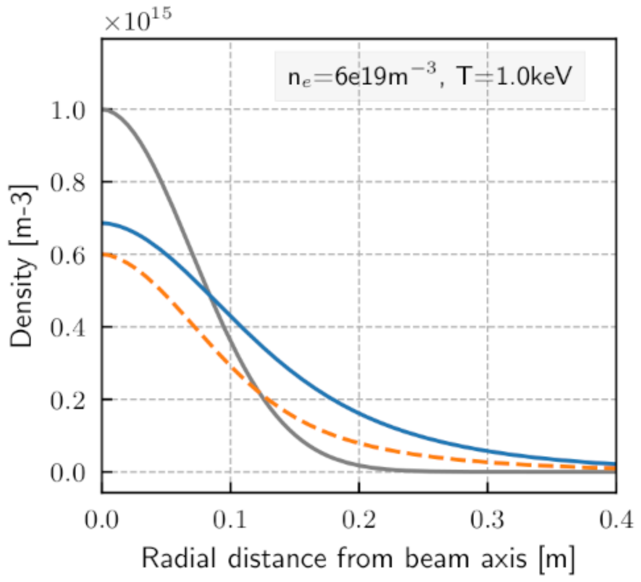
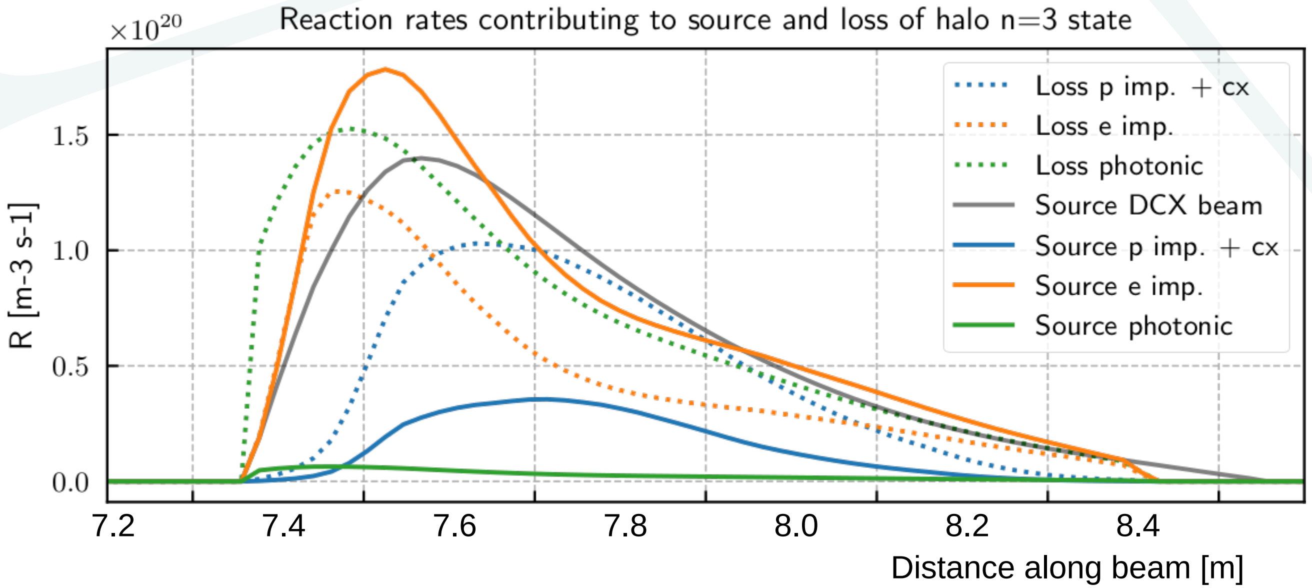


Many atomic processes important for halo population:



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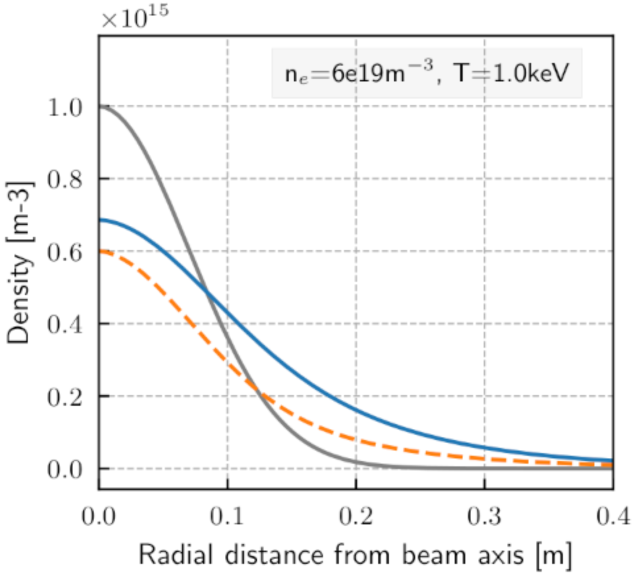

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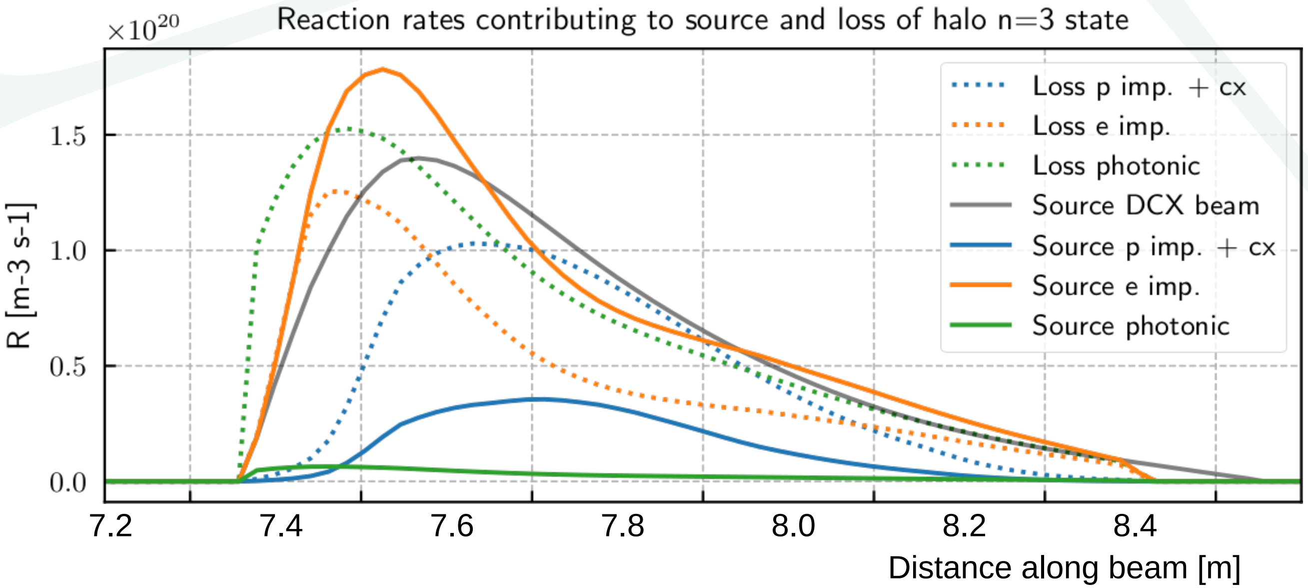
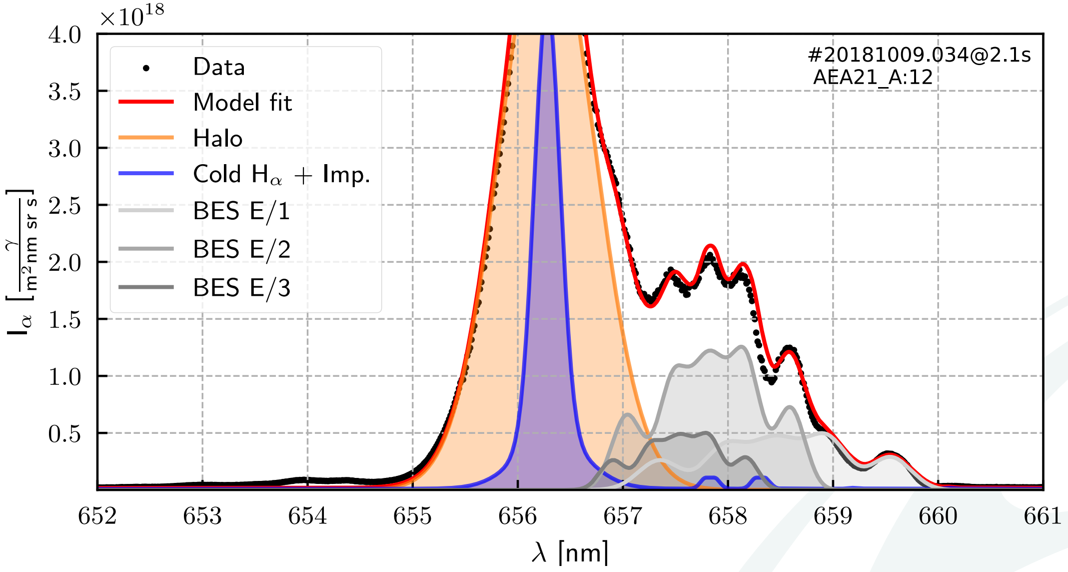


Beam Emission Spectroscopy

[S. Bannmann et al. JINST **18** P10029 2024,
S. Bannmann et al. PPCF **66** 065001 2024,
S. Bannmann et al. (in preparation) 2024]

- Final model fits well to spectrum and produces a wealth of information:



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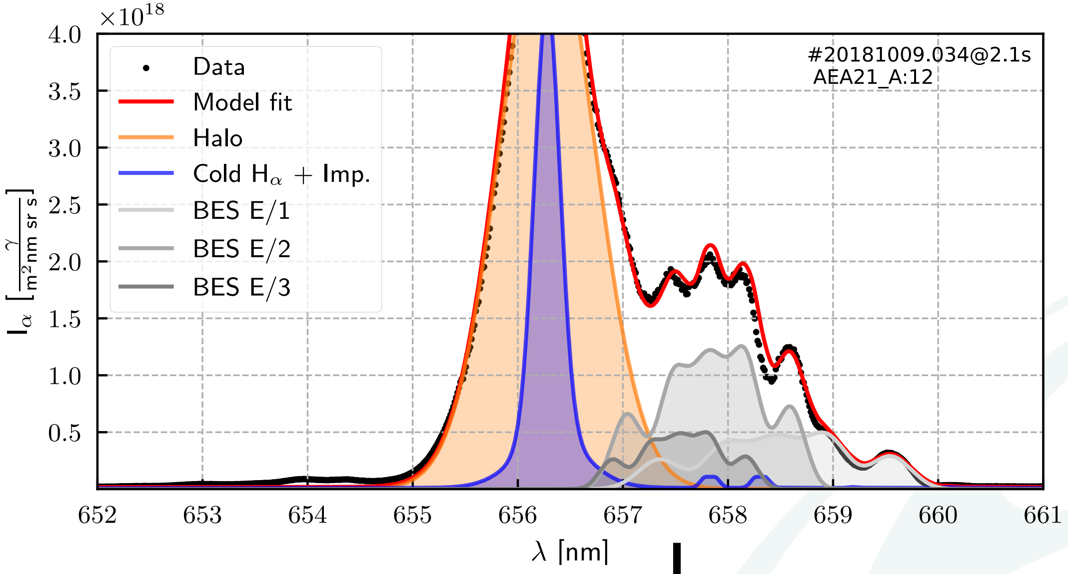

Beam + optics parameters:

	Nominal value	MAP fit
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Total power S8 (into torus) [MW]	1.7	1.8
Beamlet divergence [°]	0.8	0.75
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Upward shift (S7+S8 traversing the plasma)	-	5 cm

(fixing systematic errors)

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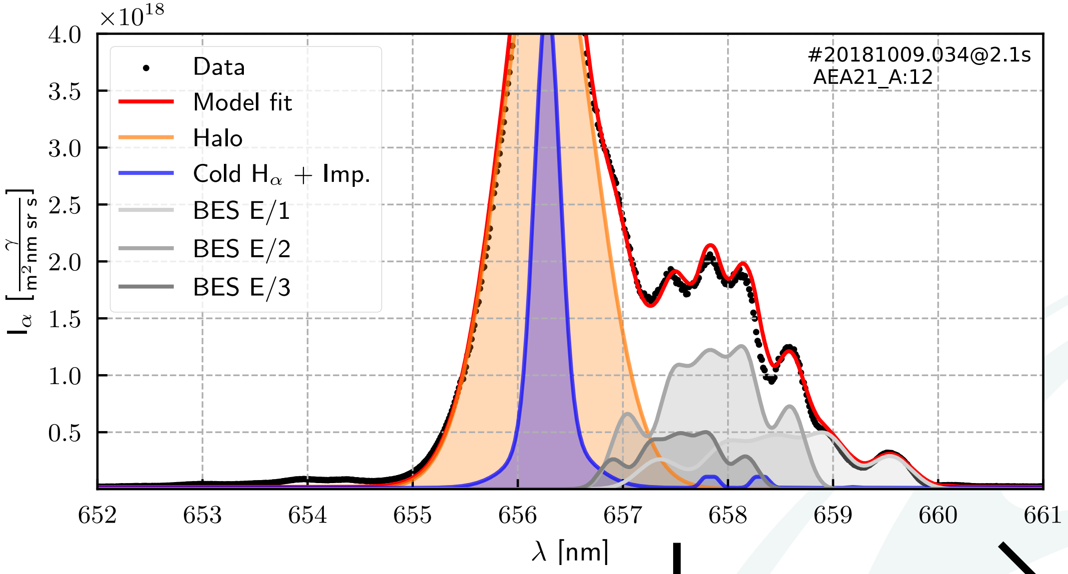

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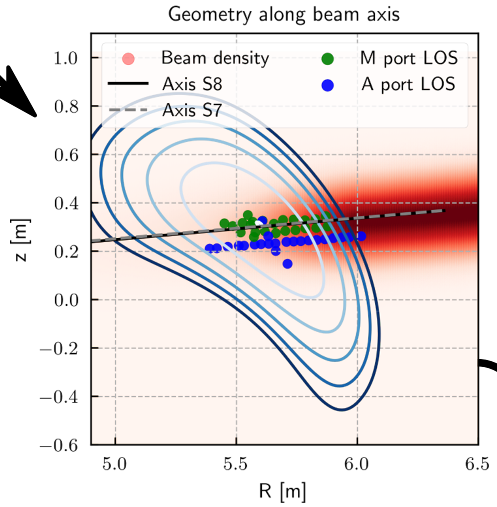

CXRS Impurity density

Beam Emission Spectroscopy

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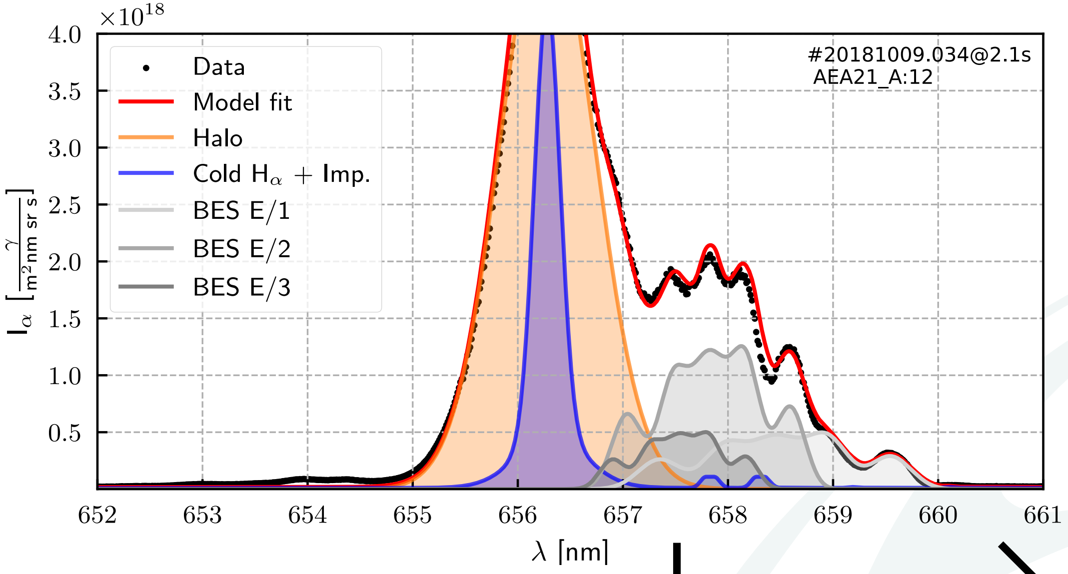

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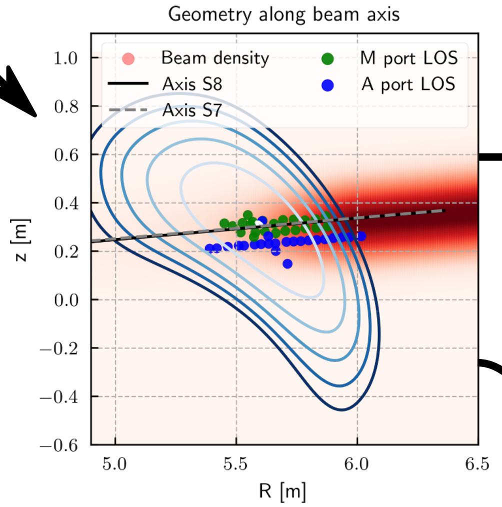
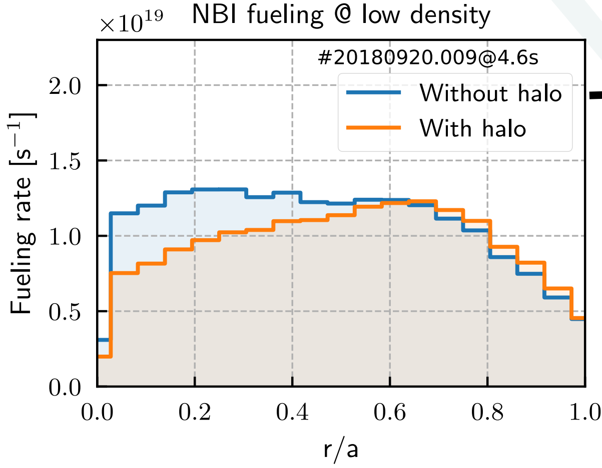


Particle source:



Particle transport

CXRS Impurity density

Beam Emission Spectroscopy

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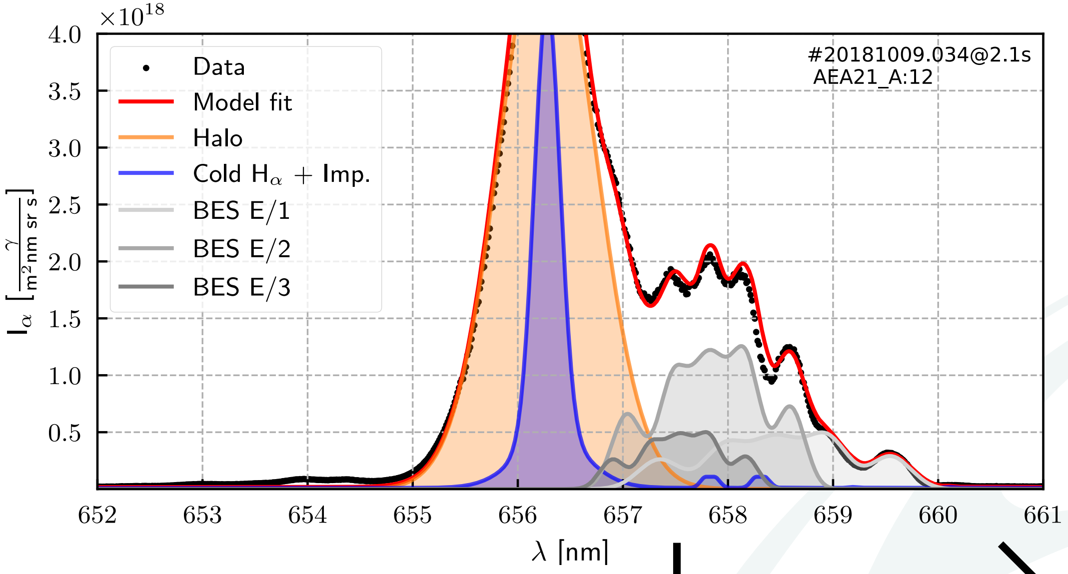
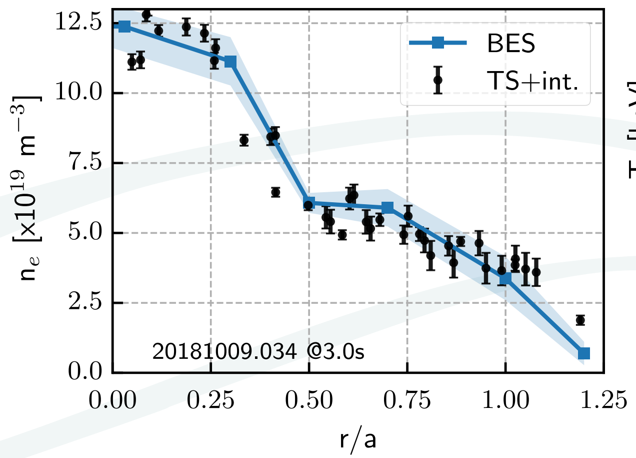
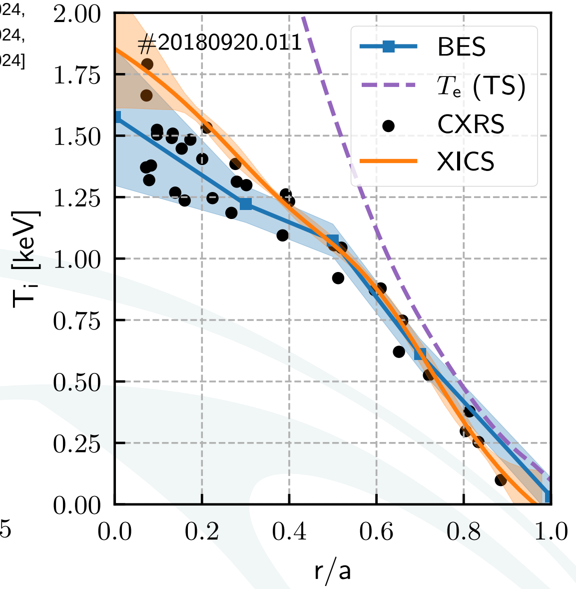


[S. Bannmann et al. JINST **18** P10029 2024,
S. Bannmann et al. PPCF **66** 065001 2024,
S. Bannmann et al. (in preparation) 2024]

Inferred n_e / T_i profiles:





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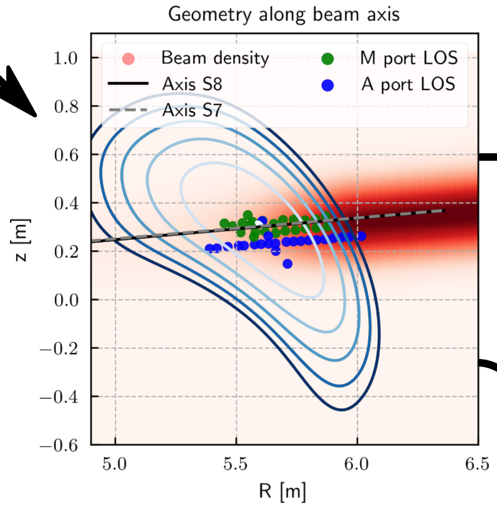

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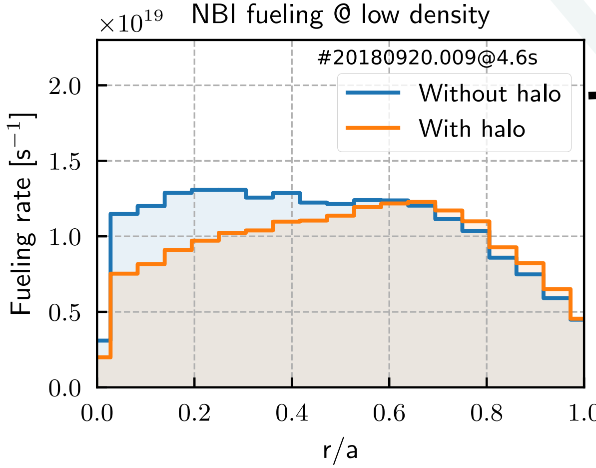

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(fixing systematic errors)

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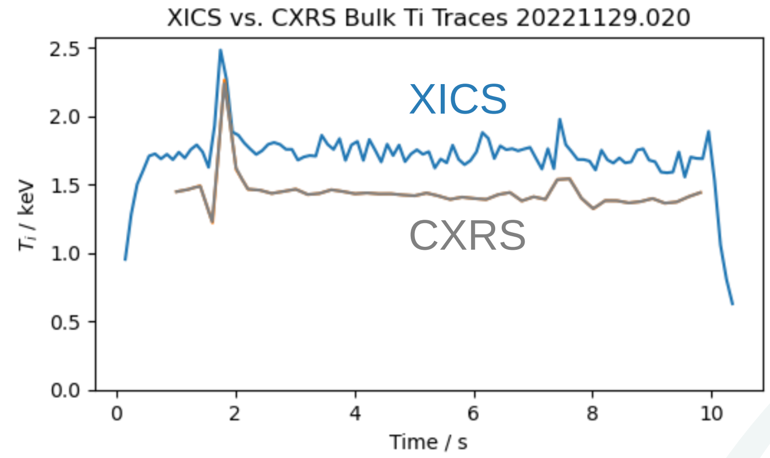
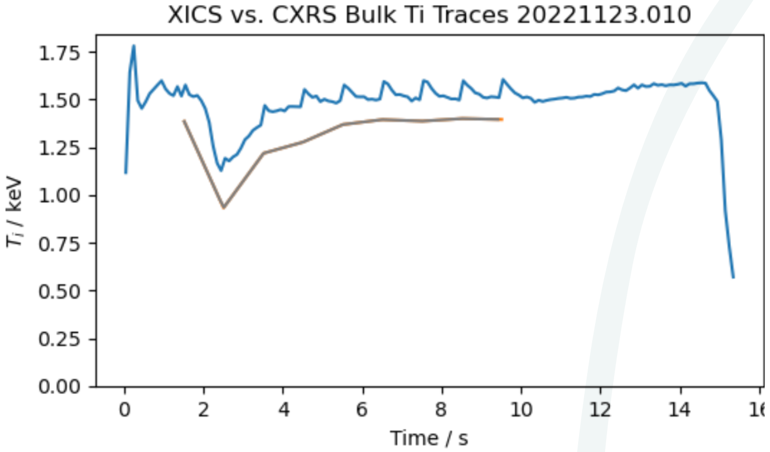
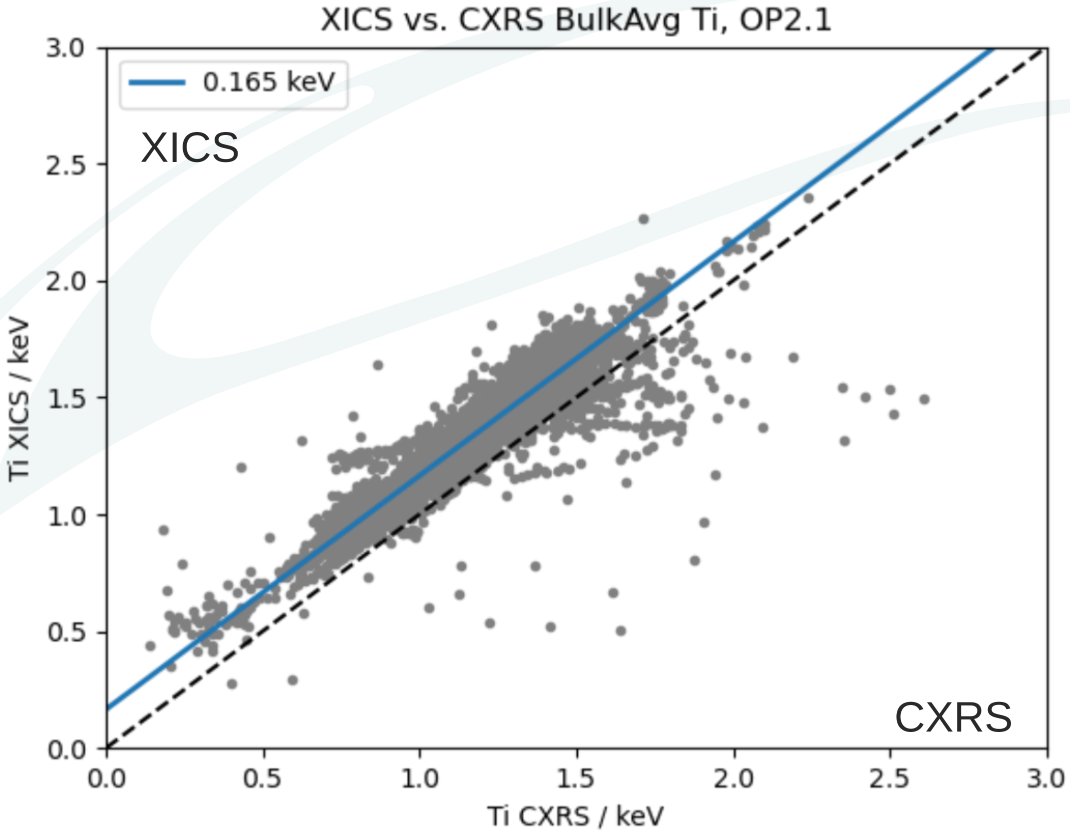
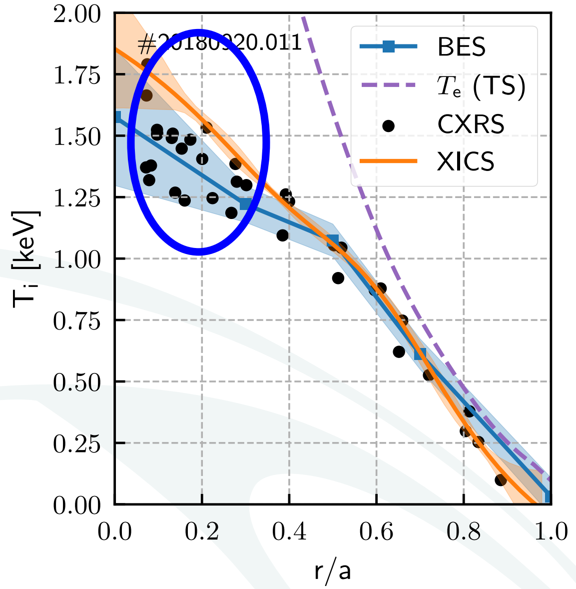
CXRS vs X-Ray T_i

- Halo T_i agrees well with standard C^{VI} measurement and also Ne^{X}, Ar^{XXVI} etc.
- X-Ray spectroscopy (XICS) still shows systematically 100 - 300eV higher in core, varies shot to shot - expected additional broadening mechanism in XICS.





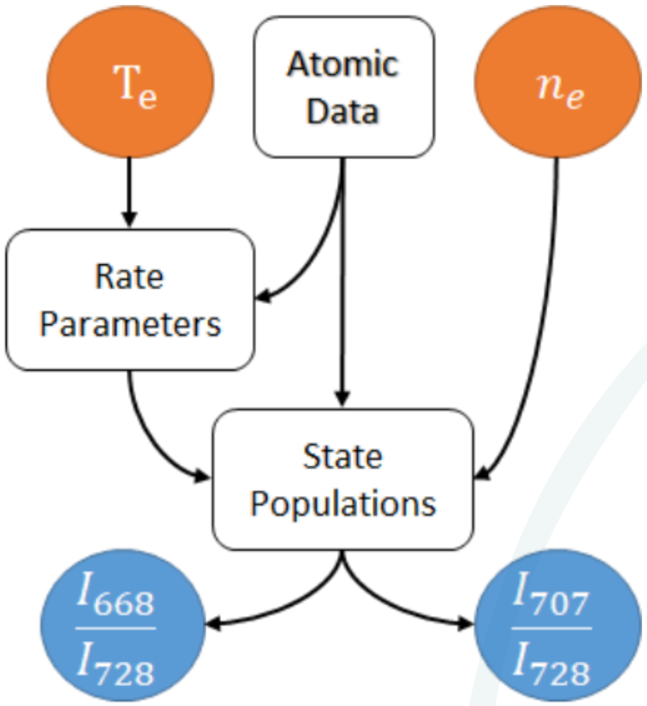




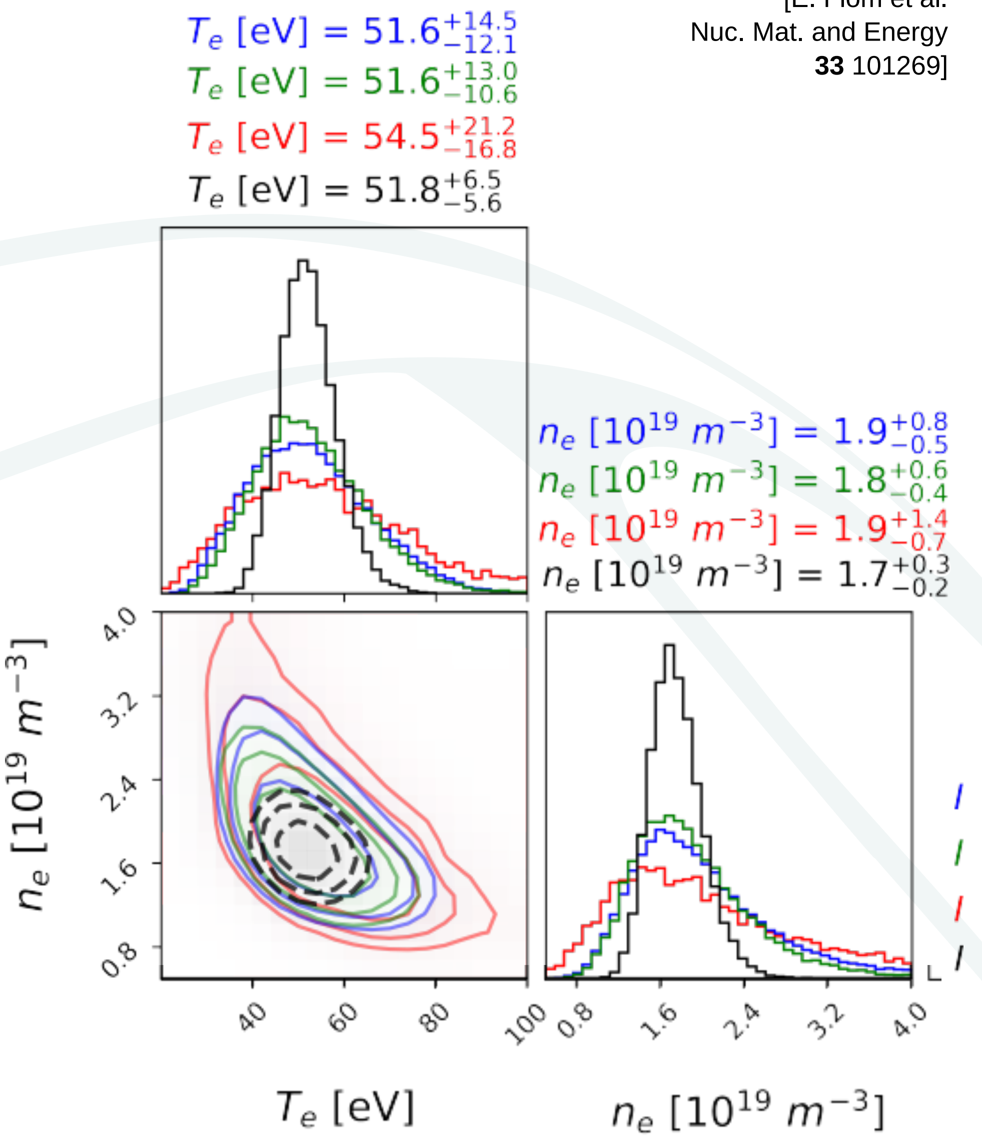
Thermal helium beam

[E. Flom et al.
Nuc. Mat. and Energy
33 101269]

- Thermal helium beam delivers:
  - (n_e, T_e) with uncertainties
  - Guidance for improvment of atomic data.

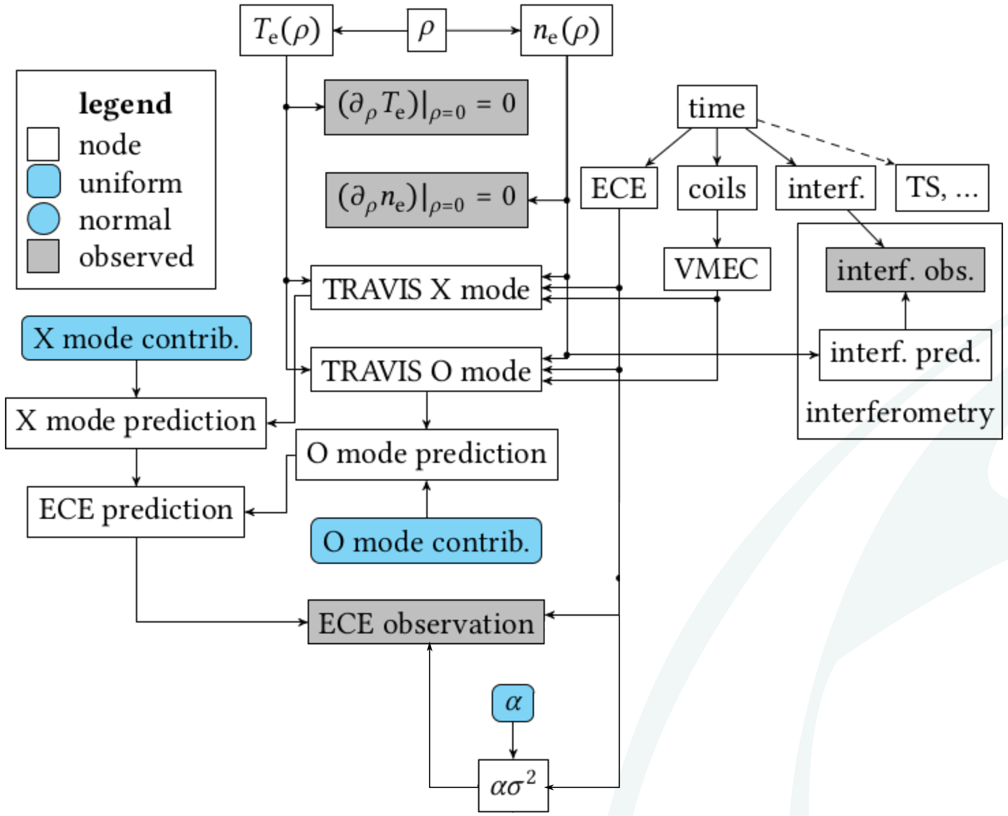


(n_e, T_e) with uncertainties including different levels of atomic data uncertainties



- Foward model of W7-X ECE diagnostic including TRAVIS coupled into model for radiation transport.

[U. Höfel, PhD Thesis https://depositonce.tu-berlin.de /items/1000194b-7825-4e4e-acec-7415665d7708]



ECE

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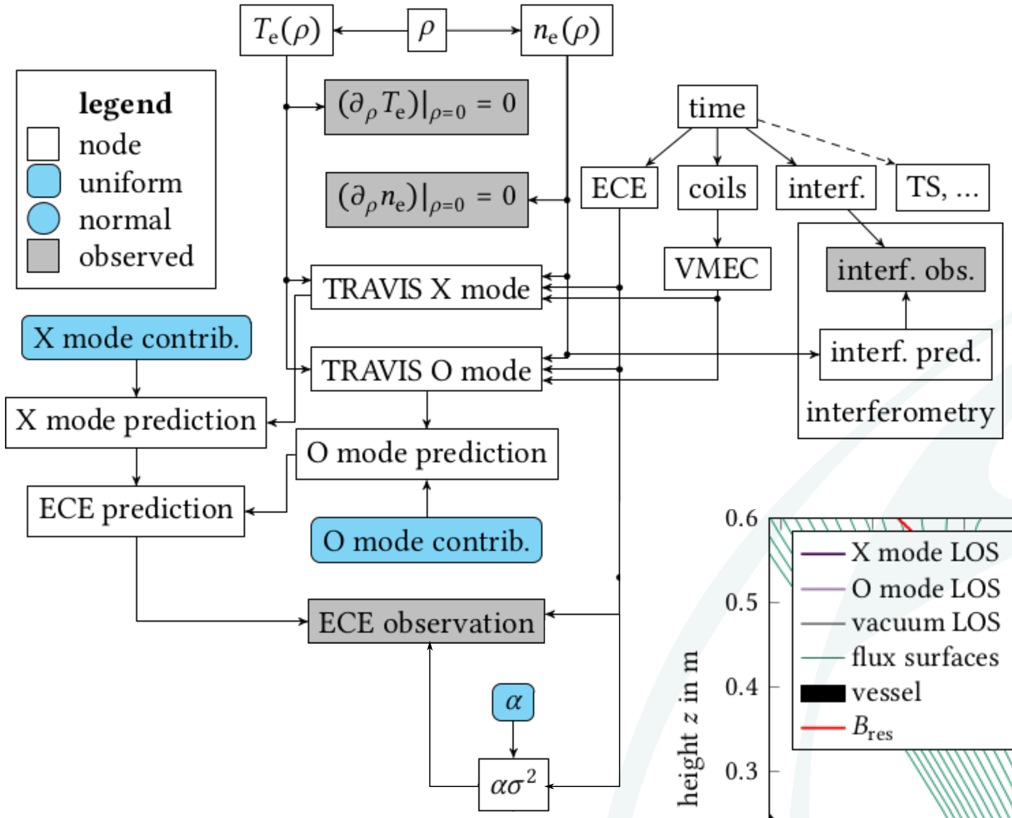
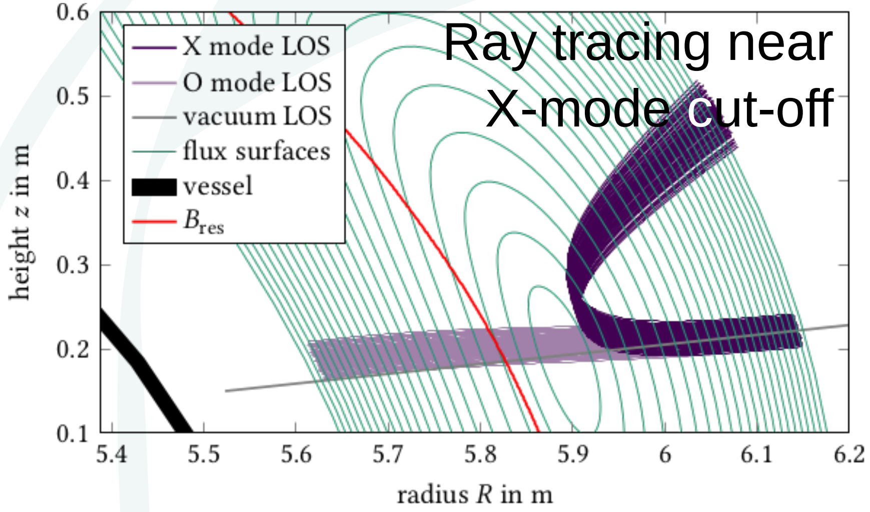
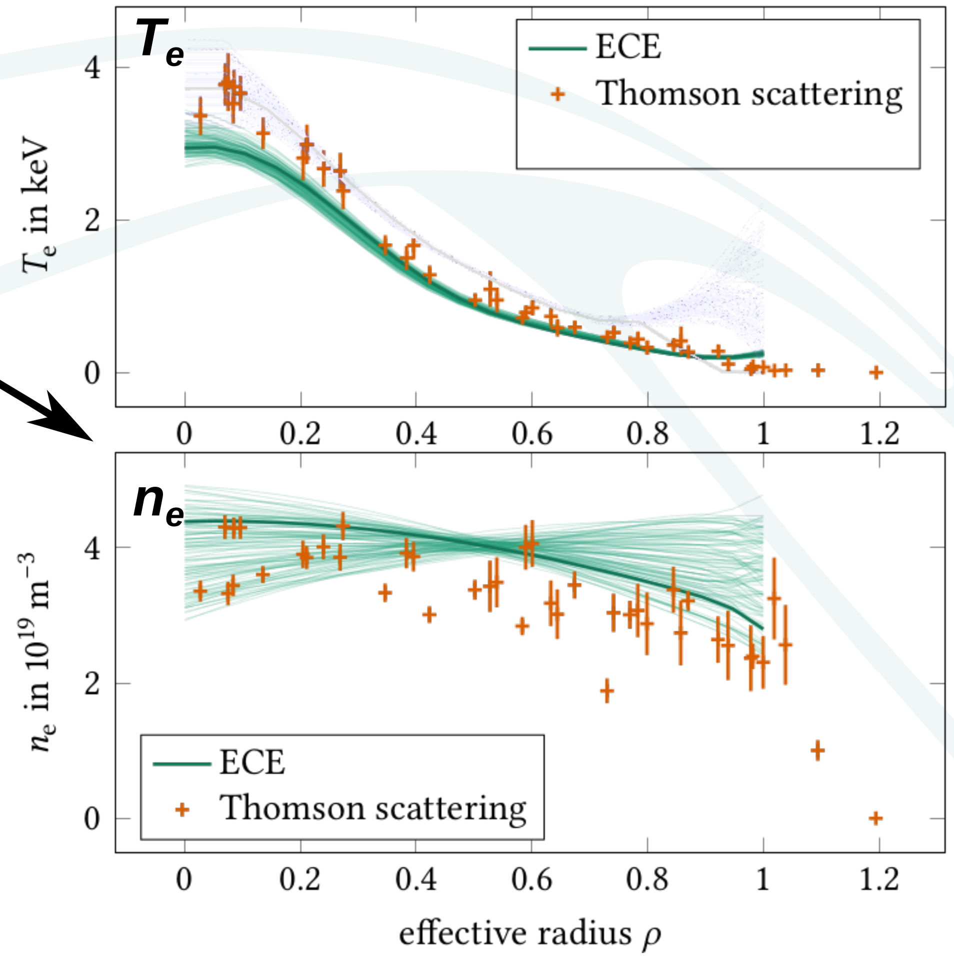


Ray tracing near X-mode cut-off

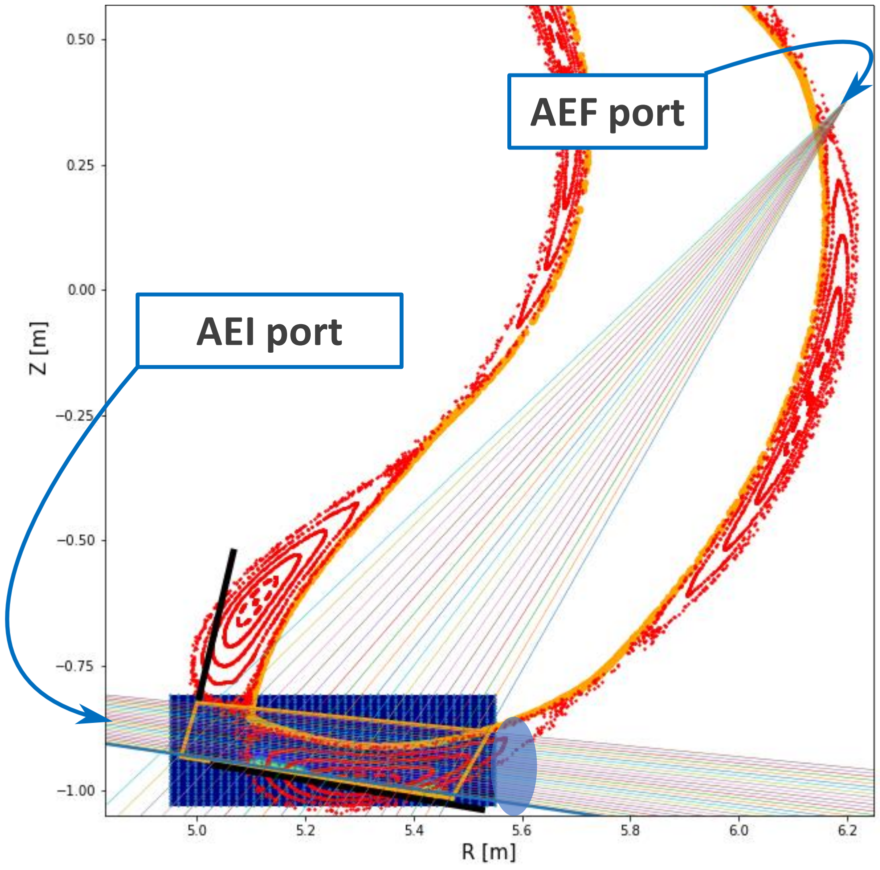


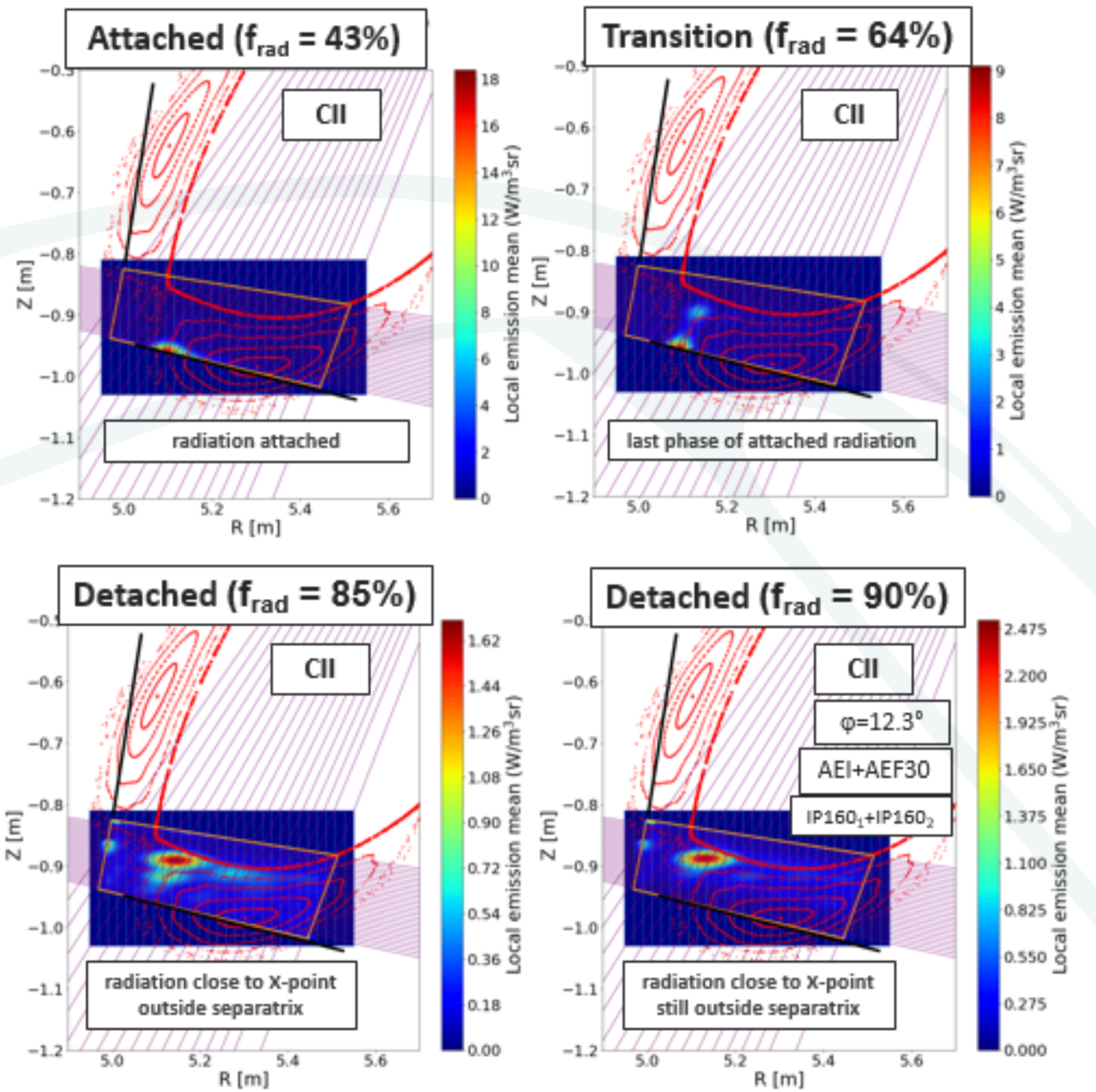


Divertor Spectroscopy

[M. Krychowiak et al. EPS 2022]

- Two fans of visible spectroscopy sight lines across W7-X divertor.
- Gaussian-process tomography of impurity emission.
- Length scales determined by method --> simplest model given by data.
- Observes transition to detachment in e.g. C^{II} radiation.





Summary

- Many models and applications for diagnostic analysis developed at W7-X in the Minerva Bayesian analysis framework:
  - Visible Bremsstrahlung [S Kwak RSI 92, 043505 2021] + Neural network fast surrogate [A. Pavone et. al. PPCF **62** 045019]
  - Soft X-ray cameras [J. Schiling et al. PPCF 63 055010]
  - X-Ray spectroscopy [A. Langenberg Nucl. Fus. 61 116018]
  - Bolometry [Contact Seed eScience Ltd]
  - Beam emission spectroscopy (not fluctuations) [S. Bannmann et al. JINST 18 P10029 2024]
  - ECE [U. Höfel, PhD Thesis https://depositonce.tu-berlin.de/items/1000194b-7825-4e4e-acec-7415665d7708]
  - Thomson Scattering / Interferometry
  - Thermal helium beam [E. Flom et al. Nuc. Mat. and Energy 33 101269]
  - Divertor visible spectroscopy [M. Krychowiak et al. EPS 2022]
  - Langmuir probes [L. Rudischhauser RSI. 91, 063505]
  - 3D Equilibrium magnetics [J. Schilling et. al. MSc Thesis Kiel University 2018] + Neural network fast surrogate [A. Merlot Nucl. Fus. **61** 096039]
  - Heavy-ion beam probe [H. Trimino Mora et al. HTPD 2024]
  - Ellipsometry (Stand-alone) [M. Krychowiak et al, HTPD 2024]

- Generally:
  - Forward modelling, Bayesian analysis and 'integrated analysis' have proven very powerful in many projects.
  - Supports understanding and design of diagnostics but does not replace good understanding or calibration!
  - Supplements (not replaces) the simple analysis.

Seed eScience now offer more services: Jupyter integration, cloud computing, contracts for complete analysis.