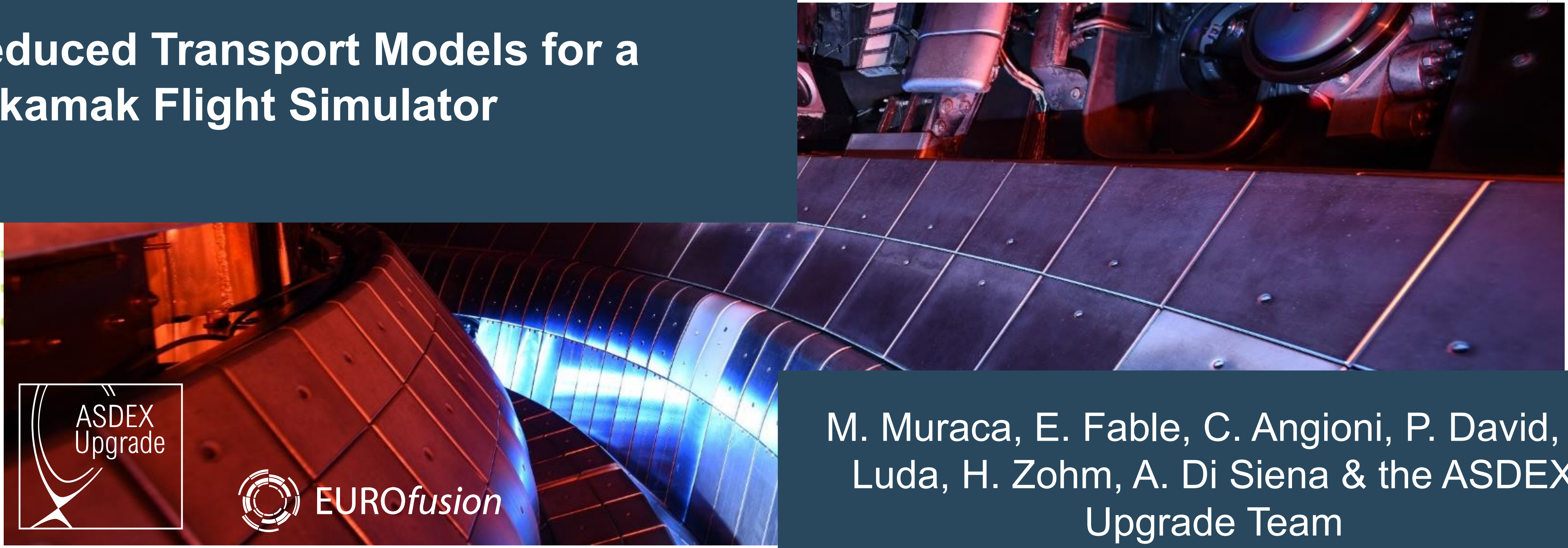
Reduced Transport Models for a Tokamak Flight Simulator



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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.

Goal/Motivation of the study

Prediction of a plasma discharge evolution

Check bad discharge evolutions

Avoid disruptions

Which cause delays and costs

Match physics goals

Develop control and physics models

- *To achieve this:*

Tokamak Flight Simulator (Fenix [1],[2])

Suite of codes which predicts the evolution of a plasma discharge by matching the actuator trajectories of the discharge plan

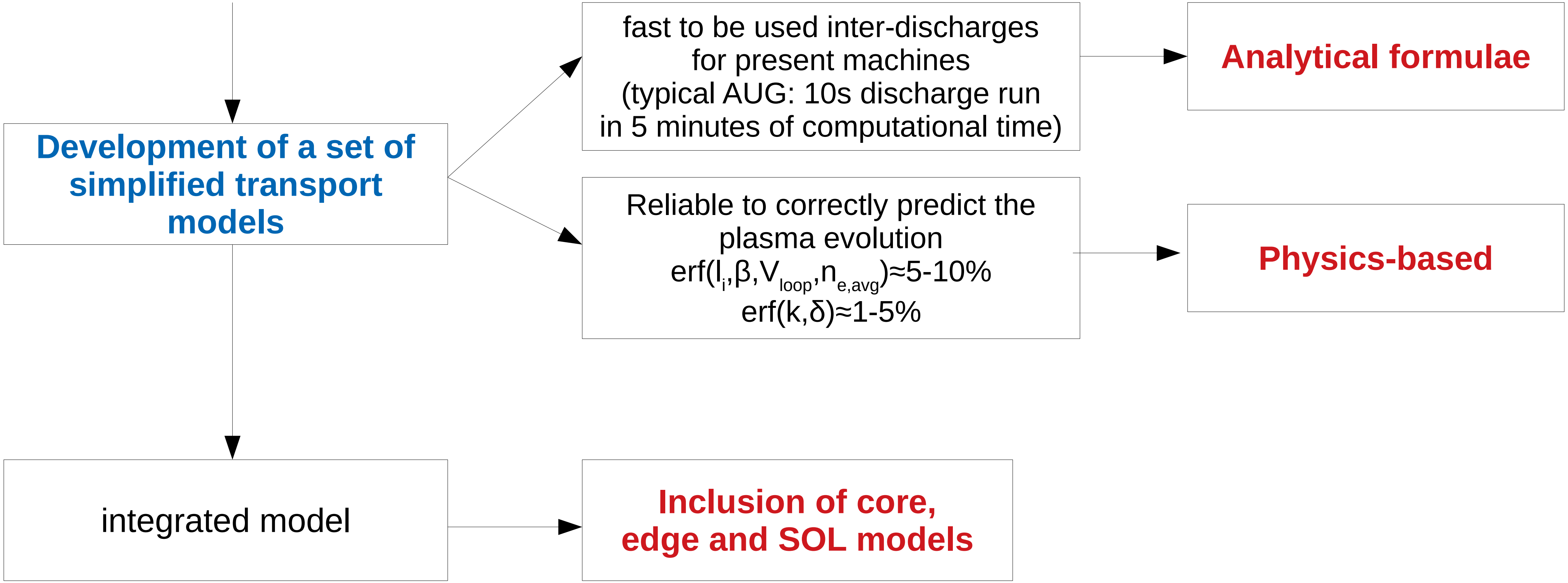
Interaction between control system, equilibrium and **transport**

[1] Janky F et al., Fusion Eng. Des. 163 112126 (2021)

[2] E. Fable et al., PPCF 64 044002 (2022)

Simplified Plasma Transport Models

- The Asdex Upgrade (AUG) control system is represented in Simulink, the equilibrium is calculated with SPIDER [3], but the plasma physics models are not fully developed.



[3] Ivanov A A et al. 32nd Conf. on Plasma Physics vol 29C (ECA)

Structure of the plasma model

Development of simplified physics-based models for:

- CORE transport, based on analytical coefficients obtained by fitting a TGLF [4] database;
- EDGE pedestal, with L-H transition and simple ELMs average model;
- SOL multispecies density, based on 0-D particle balance between 6 different zones;
- Power exhaust ($T_{e,sep}$), based on a 2-point model.

[4] Staebler G M et al., Nucl. Fusion 57 066046 (2017)

Core heat transport model

- 15 stationary phases of AUG discharges simulated with TGLF (L-mode, H-mode, I-mode and negative triangularity).
- For every discharge a scan in pedestal height (+-10%) for n_e, T_e and T_i.
- 6 different ρ toroidal coordinates between 0 and 0.9 (around 12600 points). For 1 L-mode discharge points up to ρ_t=1 are included.
- Fitting over gyroBohm normalized TGLF database to match χ_e and χ_i.
- Thresholds are taken from literature [5], [6].

ELECTRONS

$$\hat{\chi}_{e,TEM} = C \cdot H_{TEM} \left(\frac{R}{L_{Te}} - \frac{R}{L_{Te,TEM}} \right)^{\epsilon_{30}} e^{-\gamma_{nu} \nu} e^{-\gamma_s s} e^{-\gamma_{\delta,e} \delta}$$

$$\hat{\chi}_{e,ETG} = C \cdot H_{ETG} \left(\frac{R}{L_{Te}} - \frac{R}{L_{Te,ETG}} \right)^{\epsilon_{20}} q^{\gamma_{q,e}} k^{-\gamma_{k,e}}$$

$$\hat{\chi}_{e,ITG} = max \left\{ 1 ; f_t D_3 \frac{L_{Te}}{L_{Ti}} \right\} \hat{\chi}_{i,ITG}$$

$$\hat{\chi}_e = (1 - f_t) \hat{\chi}_{e,ETG} + f_t \hat{\chi}_{e,TEM} + \hat{\chi}_{e,ITG}$$

IONS

$$\hat{\chi}_{i,ITG} = C \cdot H_{ITG} \left(\frac{R}{L_{Ti}} - \frac{R}{L_{Ti,ITG}} \right)^{\epsilon_{10}} q^{\gamma_q} e^{-\gamma_{\beta_e} \beta_e} k^{-\gamma_k} e^{-\gamma_{imp} (1 - c_I)}$$

[5] A. G. Peeters et al., Phys. Plasmas 12, 022505 (2005)

[6] F. Jenko et al., Physics of Plasmas 8, 4096 (2001)

Core heat transport model

- Thresholds formulae for micro-instabilities

$$\frac{R}{L_{T_{i,ITG}}} = max\left\{A_{10}\left(1+B_{10}Z_{eff}\frac{T_i}{T_e}\right)\left(1+B_{20}\frac{s}{q}\right)\left(1-1.5f_t^2\right)\left[1+0.3(k-1)\right]; A_{20}\frac{R}{L_{ne}}\right\}$$

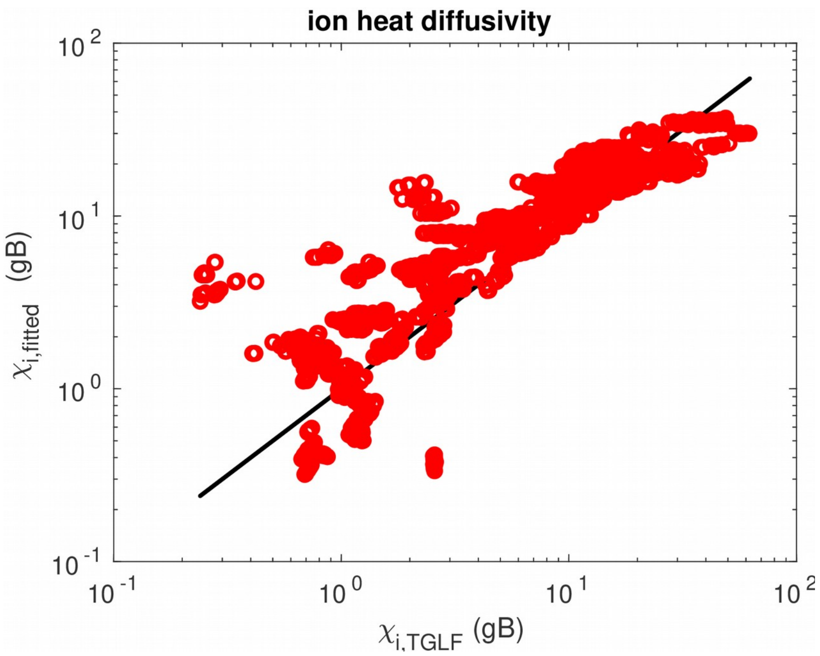
$$\frac{R}{L_{T_{e,ETG}}} = max\left\{F_{10}\left(1+G_{10}Z_{eff}\frac{T_e}{T_i}\right)\left(1+G_{20}\frac{s}{q}\right)\left(1-1.5f_t^2\right)\left[1+0.3(k-1)\right]; F_{20}\frac{R}{L_{ne}}\right\} \qquad [6]$$

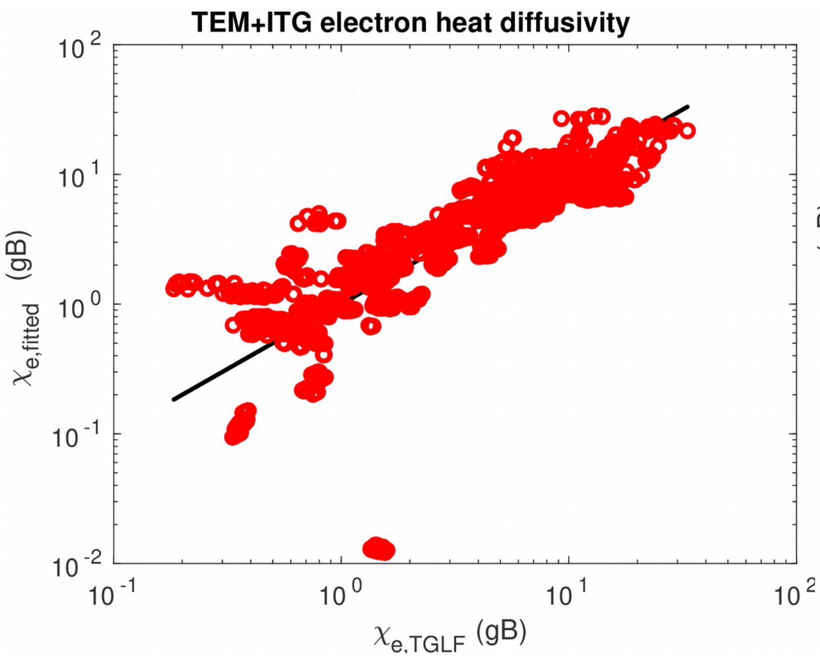
$$\frac{R}{L_{T_{e,TEM}}} = 0.357\frac{f_t+0.271}{f_t}\left[4.9-1.31\frac{R}{L_{ne}}+2.68s+\log(1+20\nu)\right] \qquad [5]$$

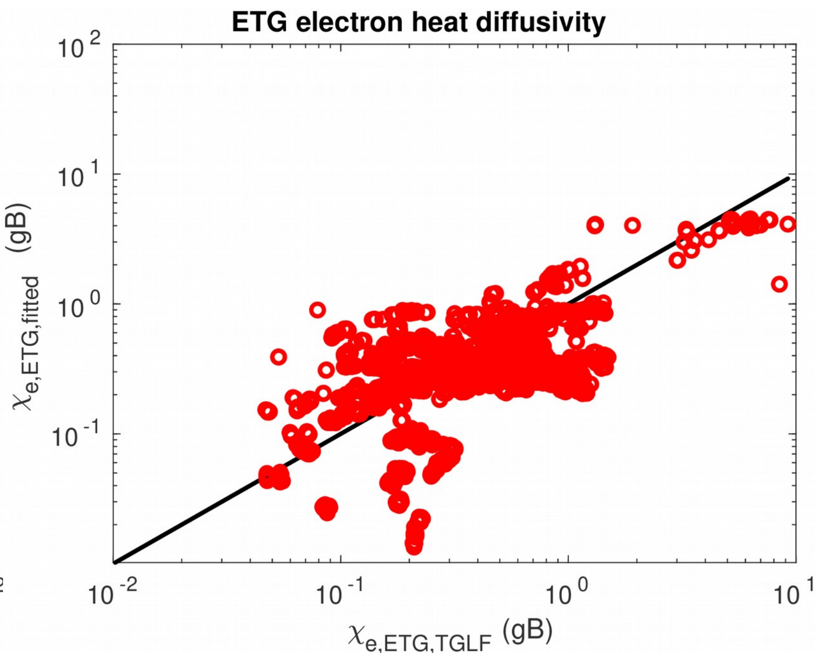
[5] A. G. Peeters et al., Phys. Plasmas 12, 022505 (2005)
[6] F. Jenko et al., Physics of Plasmas 8, 4096 (2001)

Core heat transport model

- TEM+ITG and ETG contributions to χ_e fitted separately to improve fitting procedure.







- Scattering of fitted coefficients respect to TGLF due to
  - Lack of some parameters
  - Smearing of coefficients profiles
  - Low χ, proximity to the thresholds

Core particle transport

- D=0.96*χ_e has been assumed to match an experimental case.
- Particle pinch is calculated with a heuristic formula:

$$v_p = -D_n \frac{max\left\{0\,;0.2\,R_{tor}\left|\frac{\partial_r T_e}{T_e}\right| + 0.15\,s - \frac{\nu_{ei}}{15}\right\}}{R_{tor}}$$

EDGE model

PEDESTAL

- Schmidtmayr scaling [7] for L-H transition.
- ELM averaged model, using a critical normalized pressure gradient (Ballooning model) from top of pedestal (ρ_t=0.9) outwards:

$$\chi_e = C\left(\frac{\beta_{p,top}}{\beta_{p,MHD}}\right)^4 \qquad \beta_{p,MHD} = 0.686\sqrt{k}(1+\delta)^{1.68} q^{1.61} \beta_{p,top}^{\;0.33} \hat{n}_e^{\;0.06} w_p^{\;1.29} \quad [8] \qquad \chi_i = \chi_e + \chi_{i,nc} \quad [9]$$

Particle diffusivity has been assumed equal to 0.03*χ_e in H-mode [9].

L-MODE

- Edge in L-mode has been modeled by extending the core model to separatrix.
- During L-mode particle diffusivity is C*χ_e, where C was calibrated to 0.1 to match an L-mode phase.

[7] Schimdtmayr M et al., Nuclear Fusion 58 056003 (2018) *[8] J. Puchmayr, Optimization of Pedestal Stability on ASDEX Upgrade, IPP report 2020-11*
[9] T. Luda et al., Nucl. Fusion 60 036023 (2020)

SOL models

1) For the exhaust **($T_{e,sep}$)** an analytical formula derived from 2-point model [10] is used:

$$T_{e,sep} = \left(\frac{7}{2} \frac{q_{\parallel} l_{\parallel}^{*} \pi q_{cyl} R}{k_z k_0} \right)^{\frac{2}{7}}$$

2) To give density at the separatrix **(n_{sep})** a multispecies SOL particle balance between 6 confining regions has been developed:

- Diffusion is modeled by diffusivities (D_{jk}) and enrichment factors (ε_{jk}) are used to simulate compression factors between confining regions.

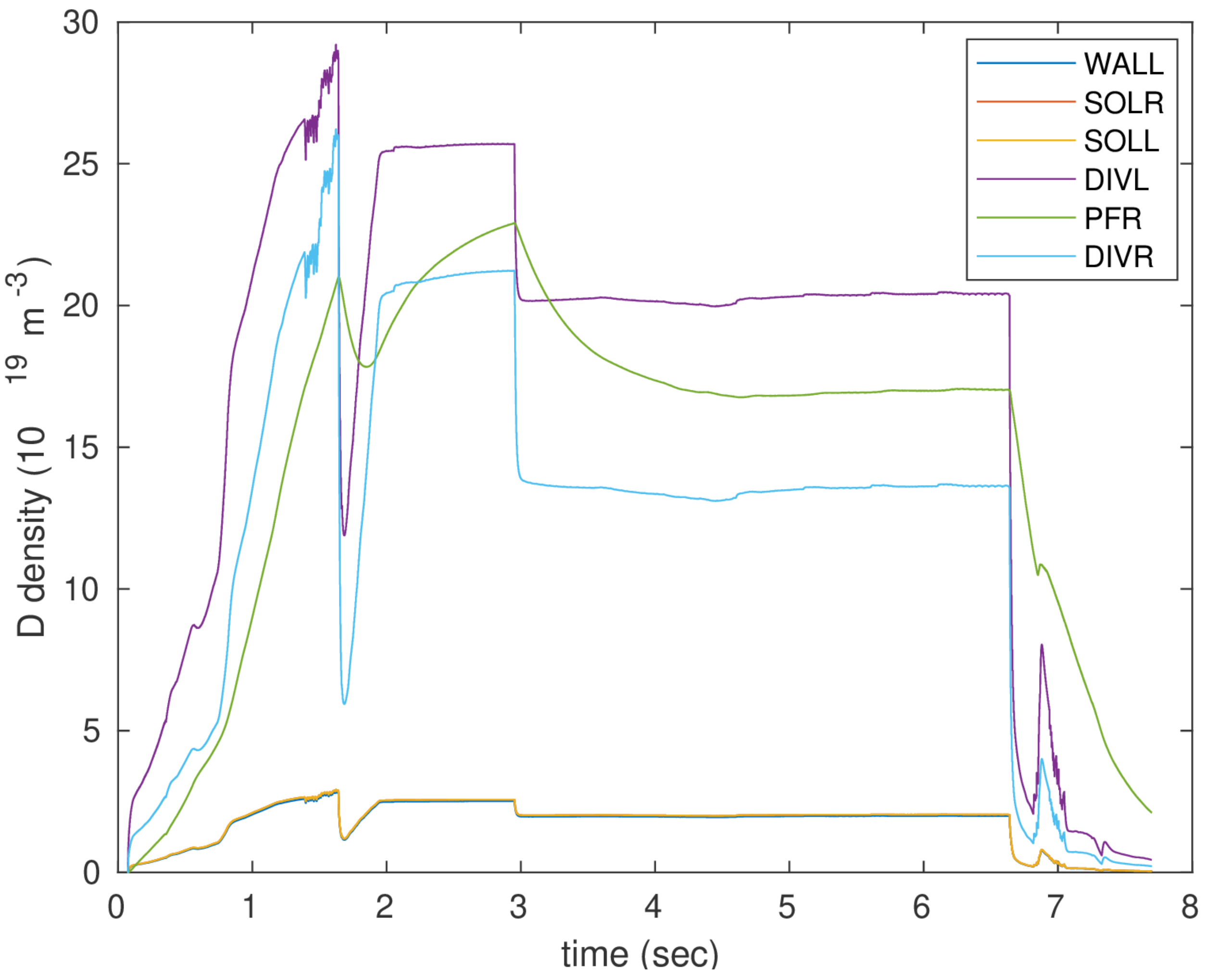
- Vacuum pump, gas puffs and plasma from the confined region are treated as local sinks and sources.

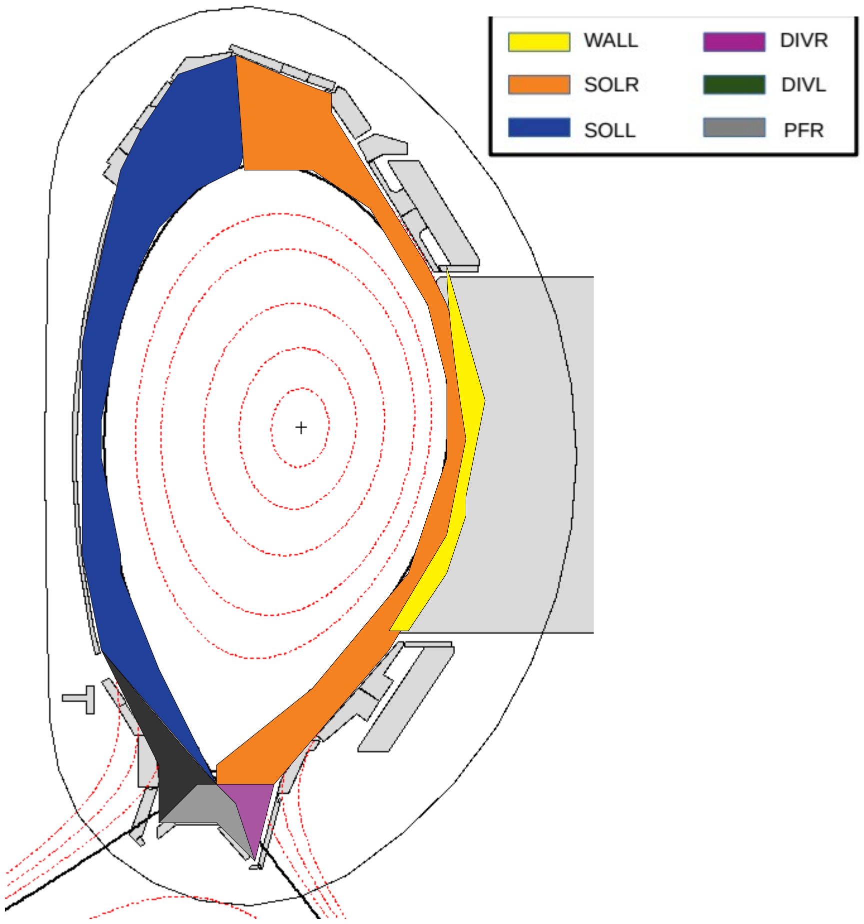
$$\frac{\partial N_k}{\partial t} = S_k + P_k + \sum_{j=1, j \neq k}^{6} D_{jk} \left(\epsilon_{jk} \frac{N_j}{V_j} - \frac{N_k}{V_k} \right)$$

[10] R. J. Goldston et al., PPCF 59 055015 (2017)

SOL particle balance

Temporal evolution of D density in the 6 regions of the SOL for discharge #40446 in Fenix:

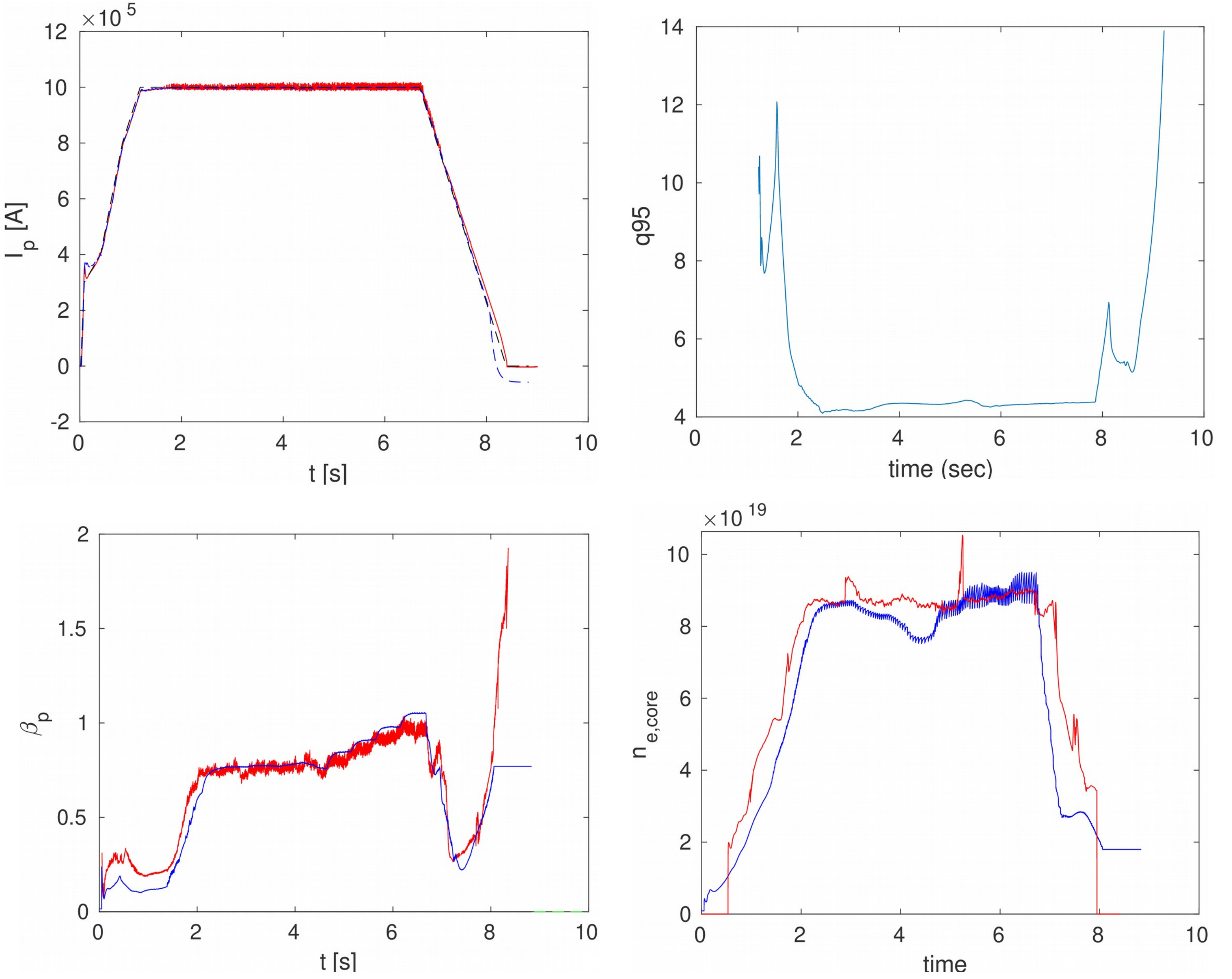




Integrated simulation of discharge #40446 in Fenix

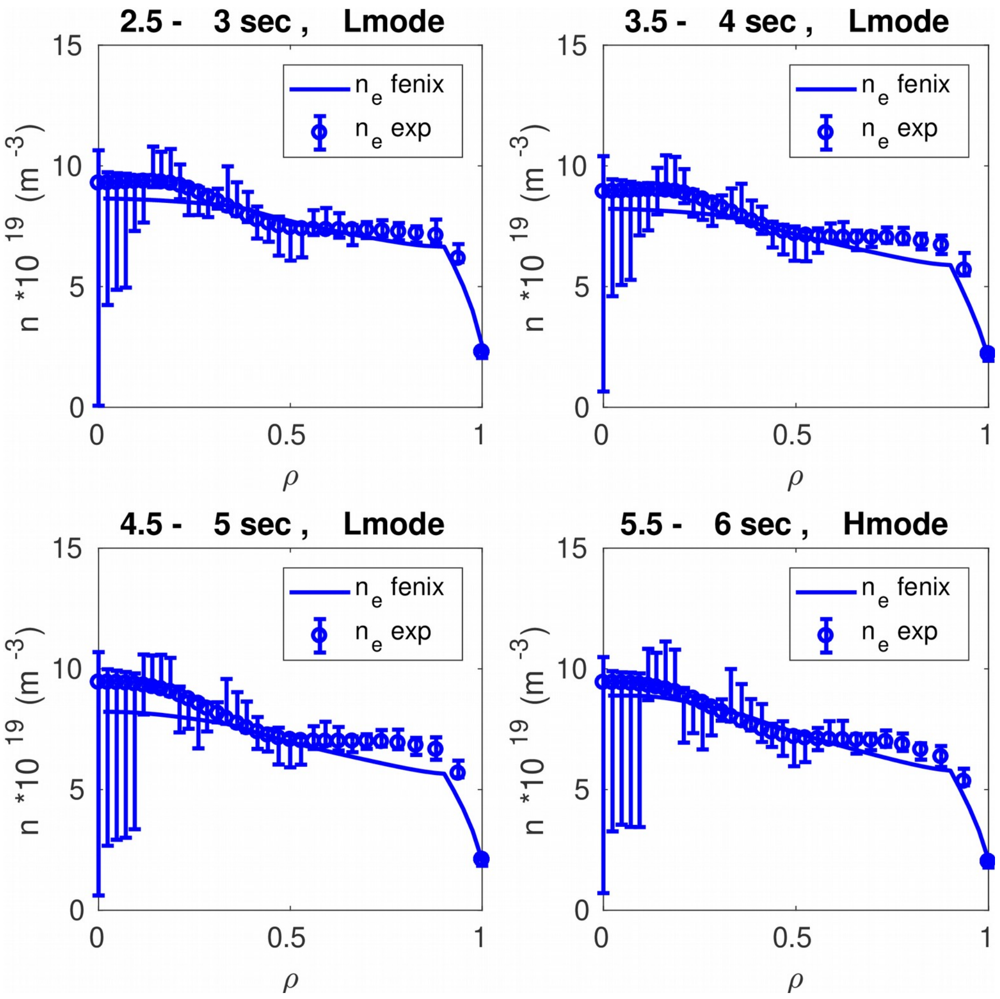
A match of the experimental time traces and profiles for a standard H-mode (#40446) in a Fenix simulation with the fully integrated model has been reached during flattop and ramp-down:

Experiment
Fenix

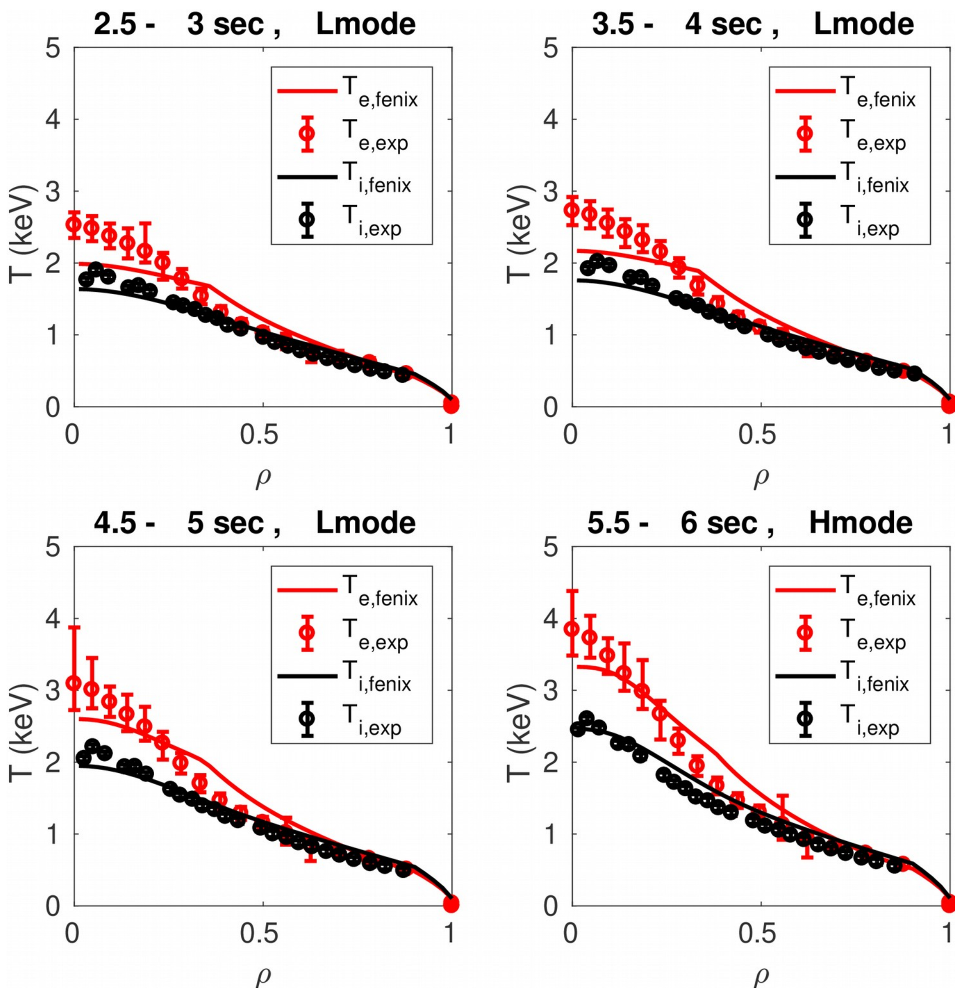


Integrated simulation of discharge #40446 in Fenix

ELECTRON DENSITY

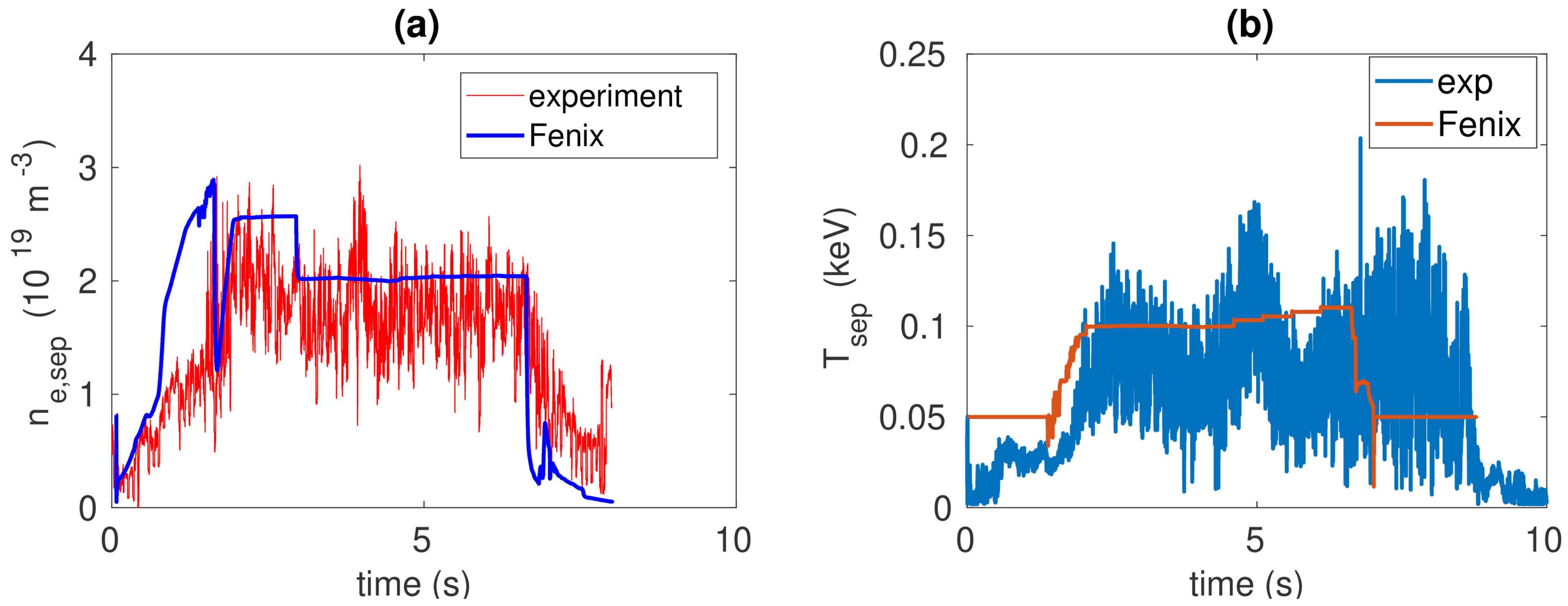


ELECTRON AND IONS TEMPERATURE



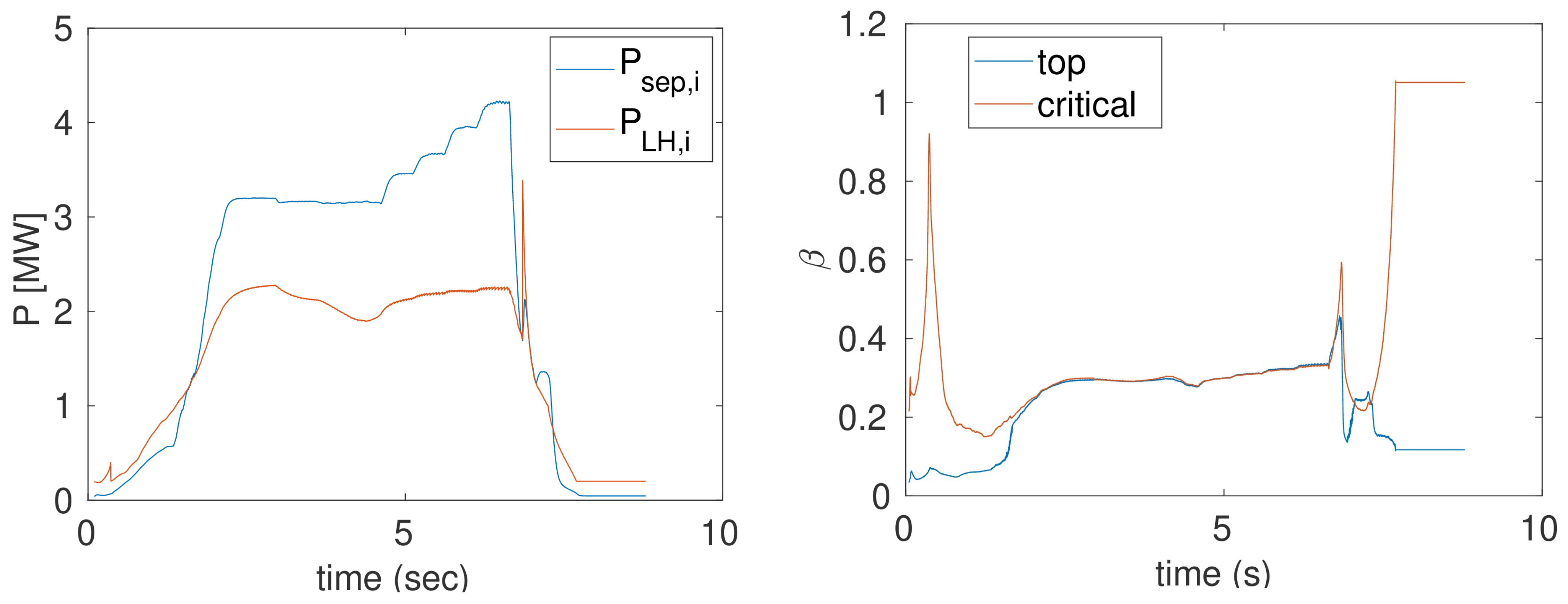
Boundary condition evolution of discharge #40446

Temporal evolution of $n_{e,sep}$ and $Te_{,sep}$ for discharge #40446 of AUG (std Hmode):



Integrated modeling parameters of discharge #40446

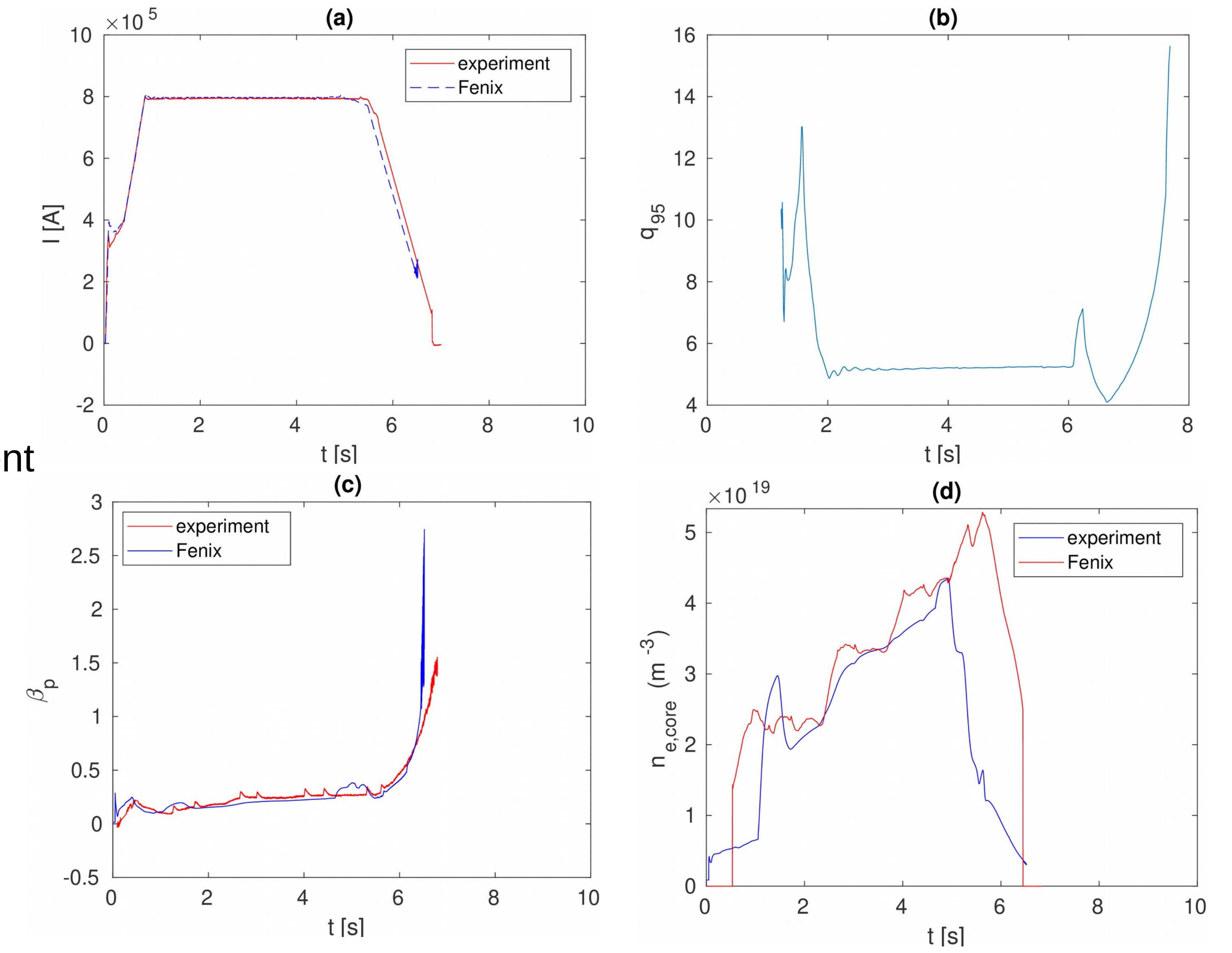
- Ion power at the separatrix and beta time traces for discharge #40446



Integrated simulation of discharge #38898 in Fenix

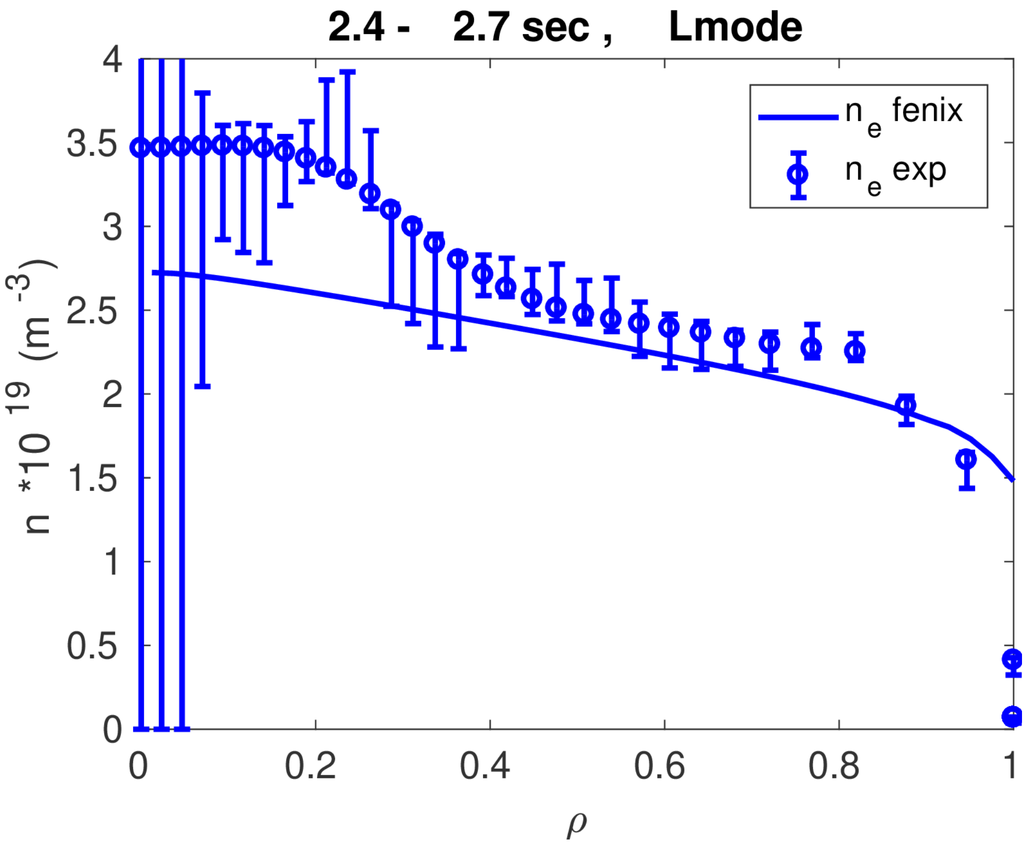
A match of the experimental time traces and profiles for an L-mode (#38898) in a Fenix simulation with the fully integrated model has been reached during flattop and ramp-down:

Experiment
Fenix

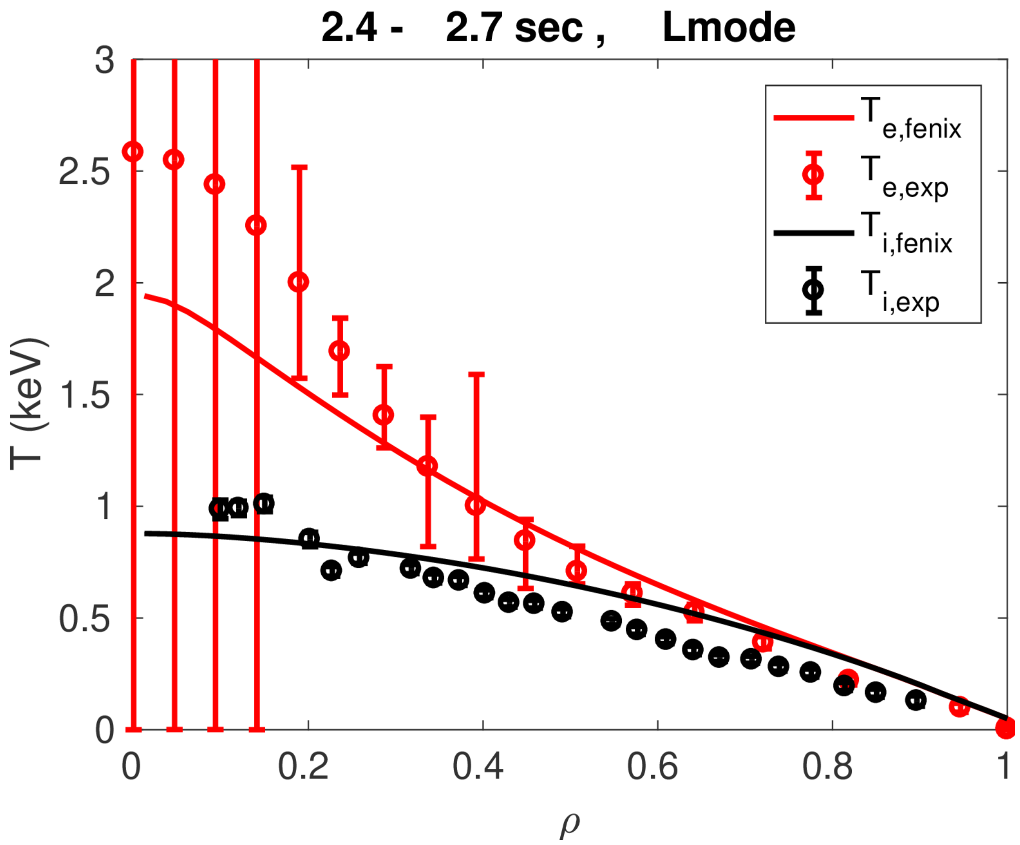


Integrated simulation of discharge #38898 in Fenix

ELECTRON DENSITY

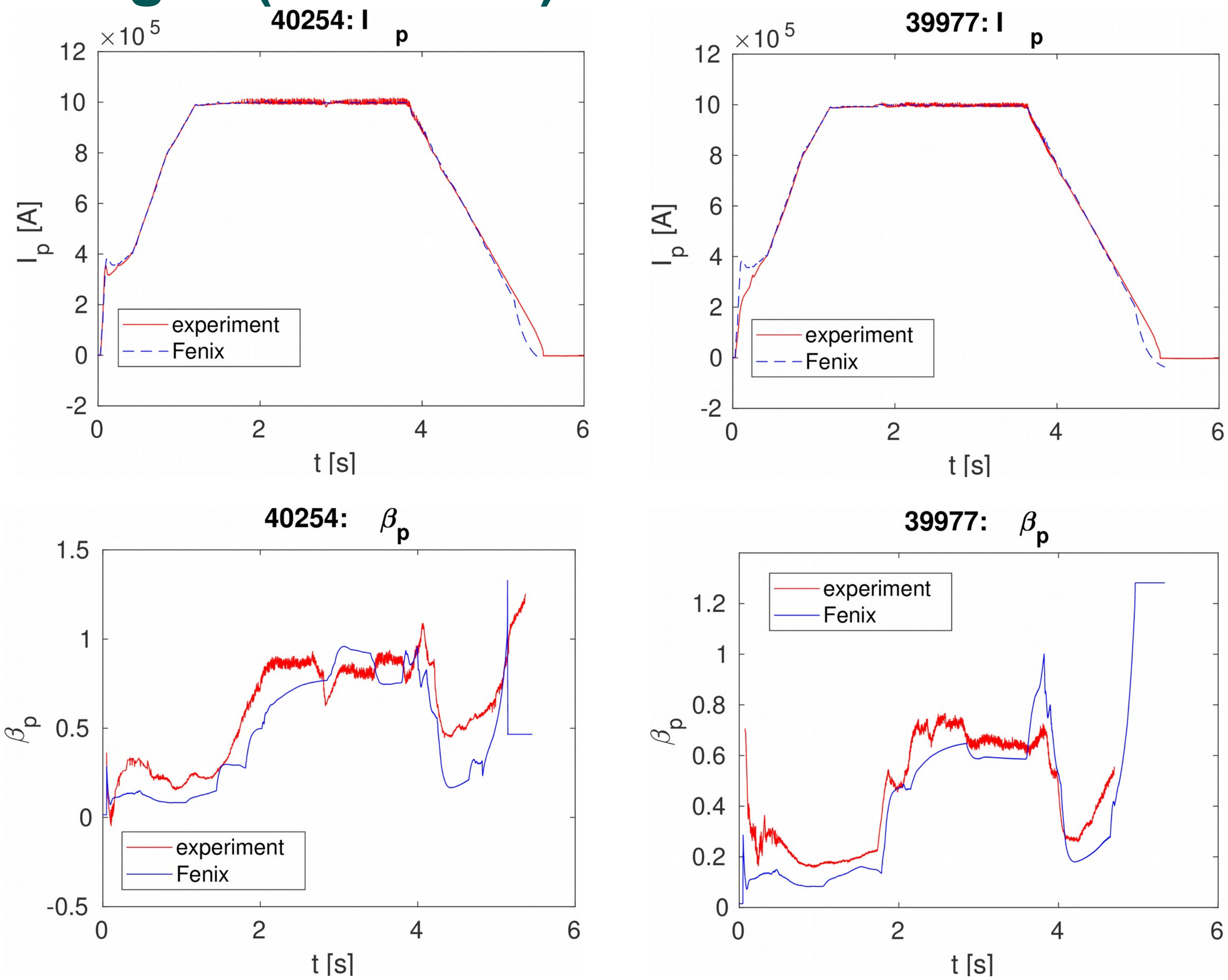


ELECTRON AND IONS TEMPERATURE



Validation of other discharges (H-modes)

Some other discharges with different densities and heating powers have been validated



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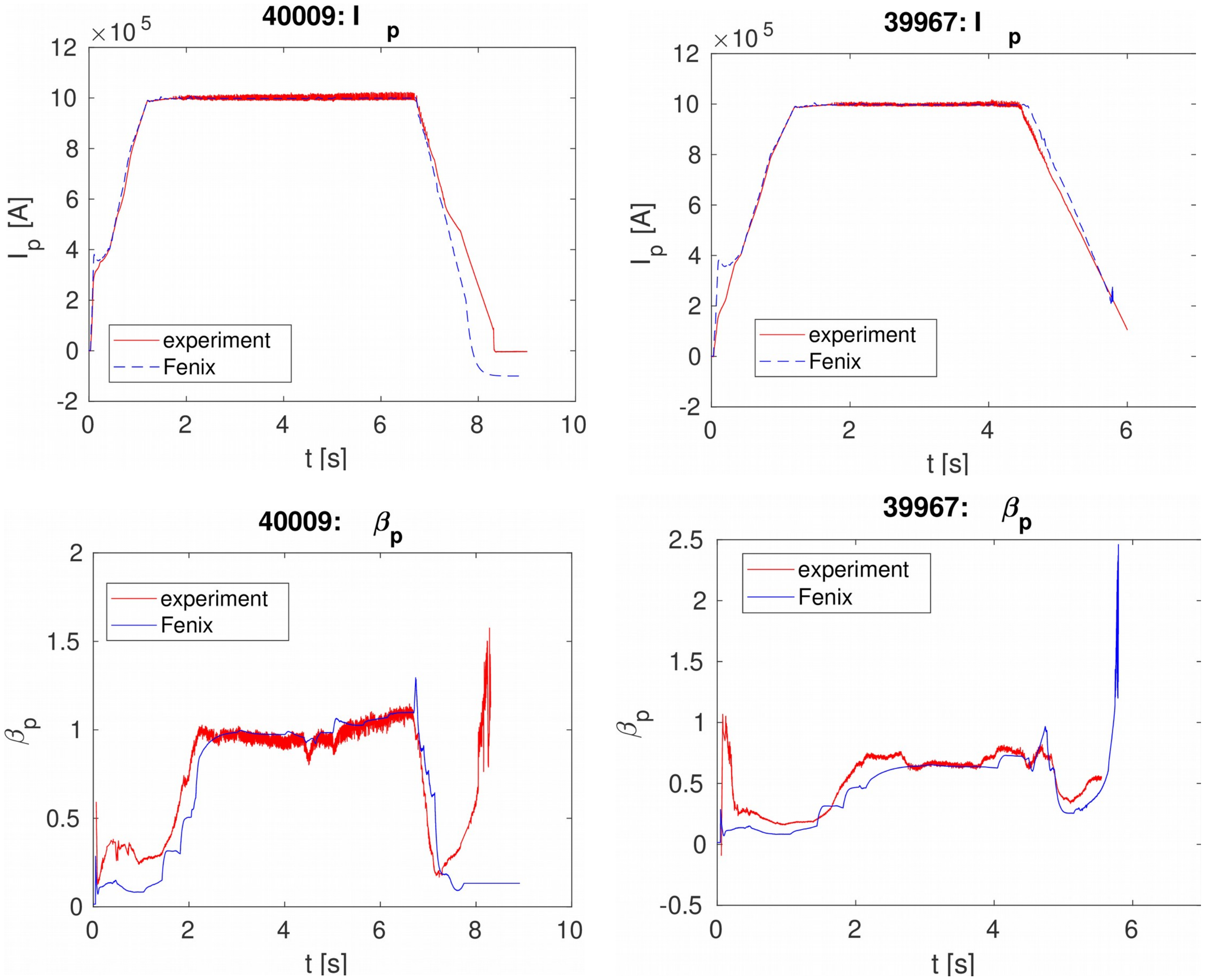


Conclusions and Outlook

Conclusions

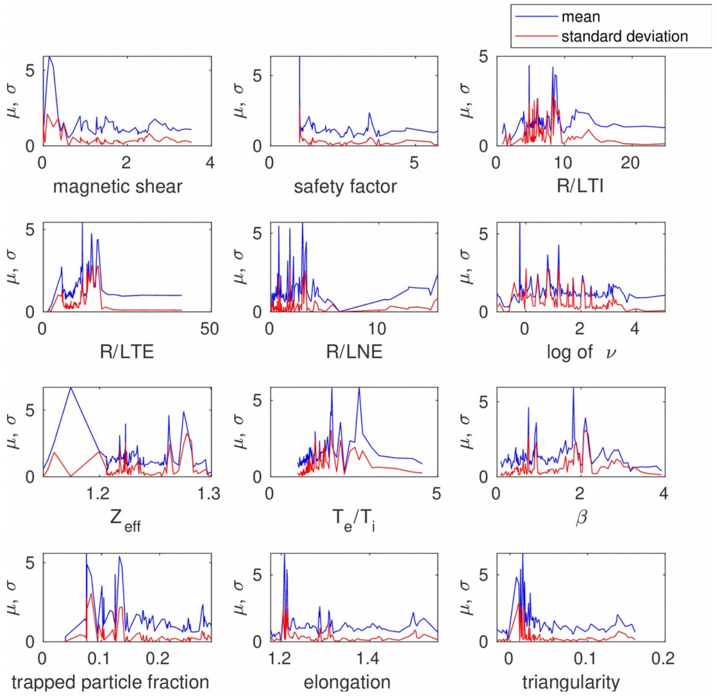
- A set of simplified transport models for the tokamak flight simulator Fenix has been derived.
- The CORE model consists of analytical formulae which fit a TGLF database.
- The EDGE pedestal model is based on an L-H transition and an ELMs averaged transport.
- SOL models give the boundary conditions of temperature and density at the separatrix respectively through a 2-point model and a particle balance.
- Using these models, the experimental trajectories of 5 AUG standard H-mode and 1 L-mode have been matched in Fenix during the flat top and the ramp-down.

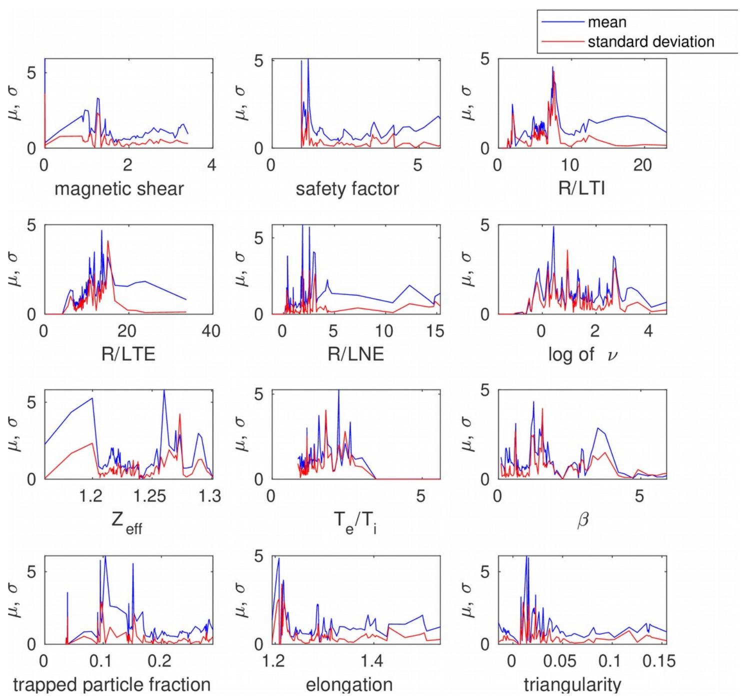
Future Work

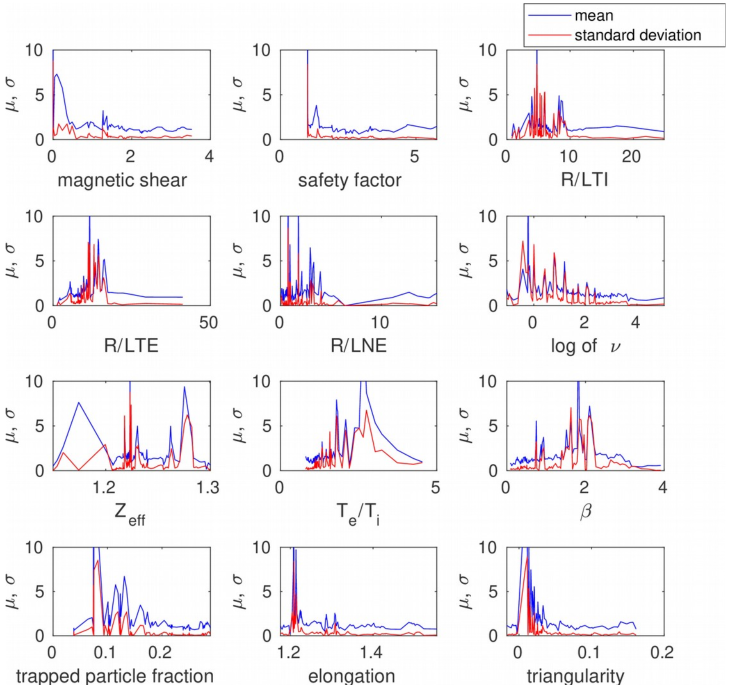
- Expansion of physics models (detachment, core particle transport, MHD).
- Validation of Fenix over a wide range of experimental scenarios.
- Generalization of physics models for different machines.

BACKUP SLIDES

- Standard deviations of transport coefficients depending on different fitting parameters







BACKUP SLIDES

- Diffusion coefficients in the SOL model

$$D_{\parallel} = 0.1 \frac{Ma}{L_{par,sep}}$$

$$D_{12} = 0.5\, D_{\perp} \qquad D_{10} = 0.03\, D_{\perp} \qquad D_{23} = D_{34} = D_{26} = 1000\, D_{\parallel}$$

$$D_{\perp} = \frac{0.05\, v_{sep}}{\left(R_w - R_{omp}\right)^2}$$

$$D_{45} = D_{56} = 0.1 \qquad D_{16} = 0$$

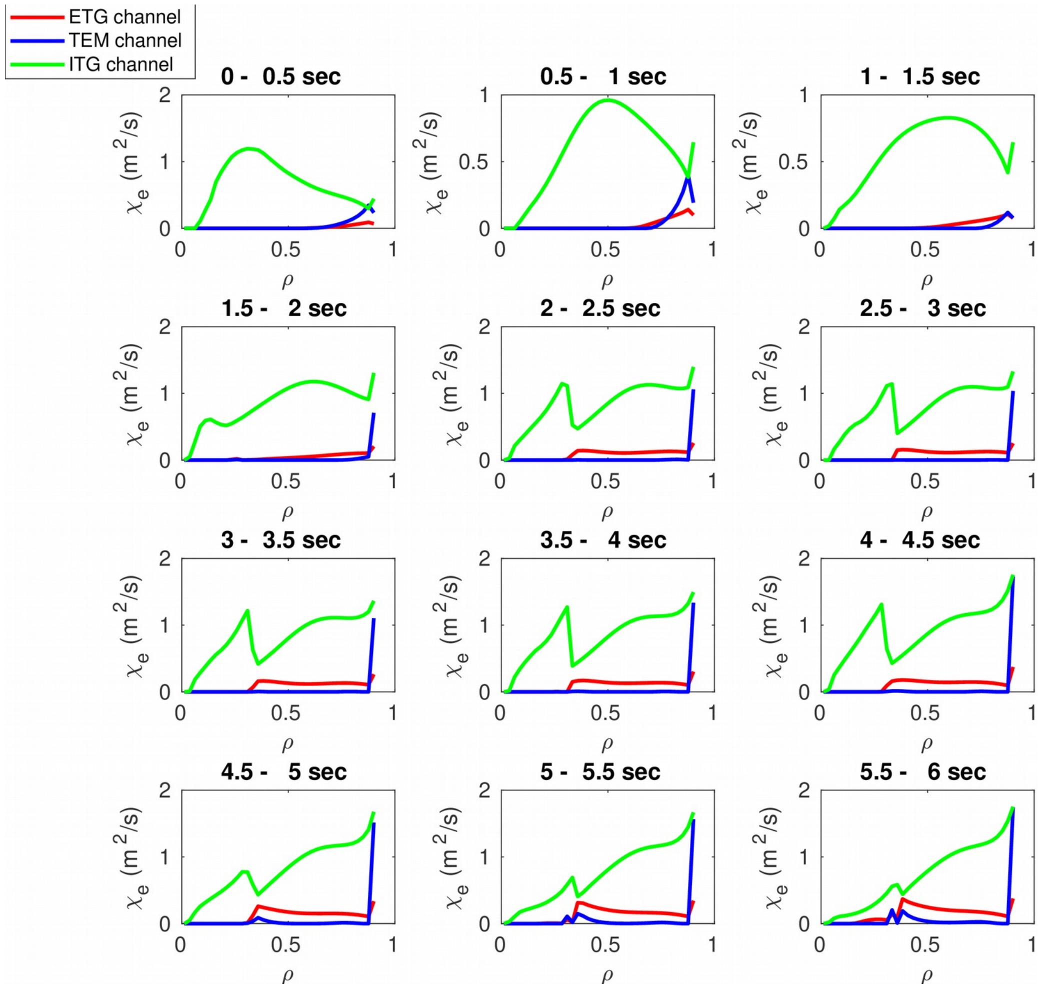
- Enrichment factors in the SOL

$$\epsilon_{12} = \epsilon_{23} = \epsilon_{45} = \epsilon_{16} = \epsilon_{56} = 1 \qquad \epsilon_{34} = 10$$

$$\epsilon_{26} = 5\, max\left\{1 ; min\left\{20 ; 0.2\, n_d^{0.67}\right\}\right\}$$

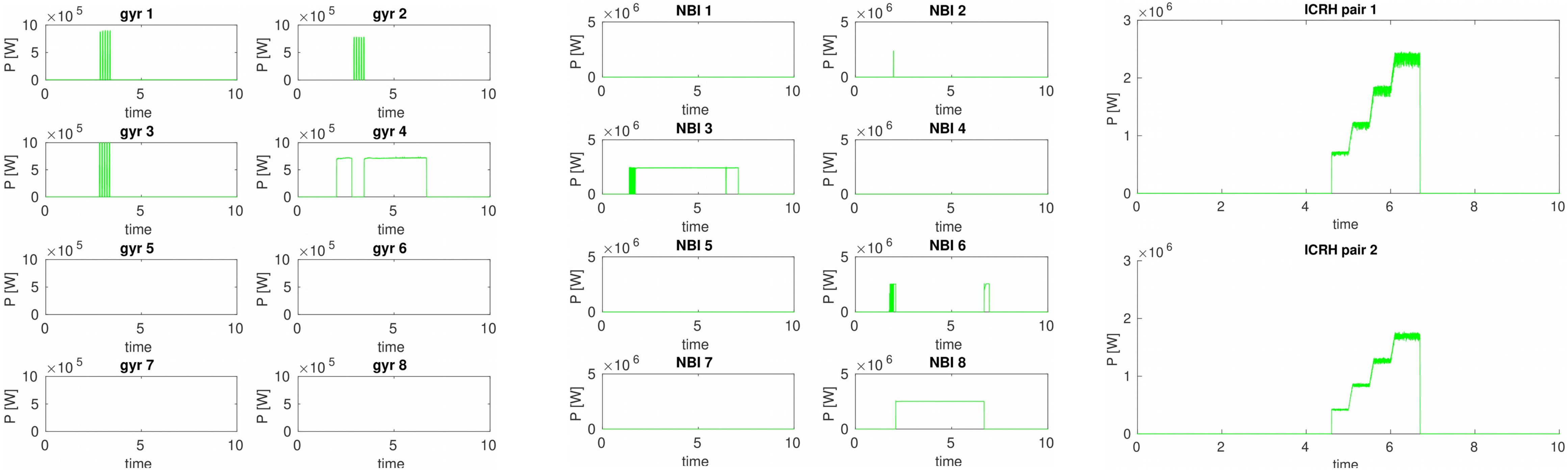
BACKUP SLIDES

- Contribution of different micro-instabilities to transport and time traces of discharge #40446



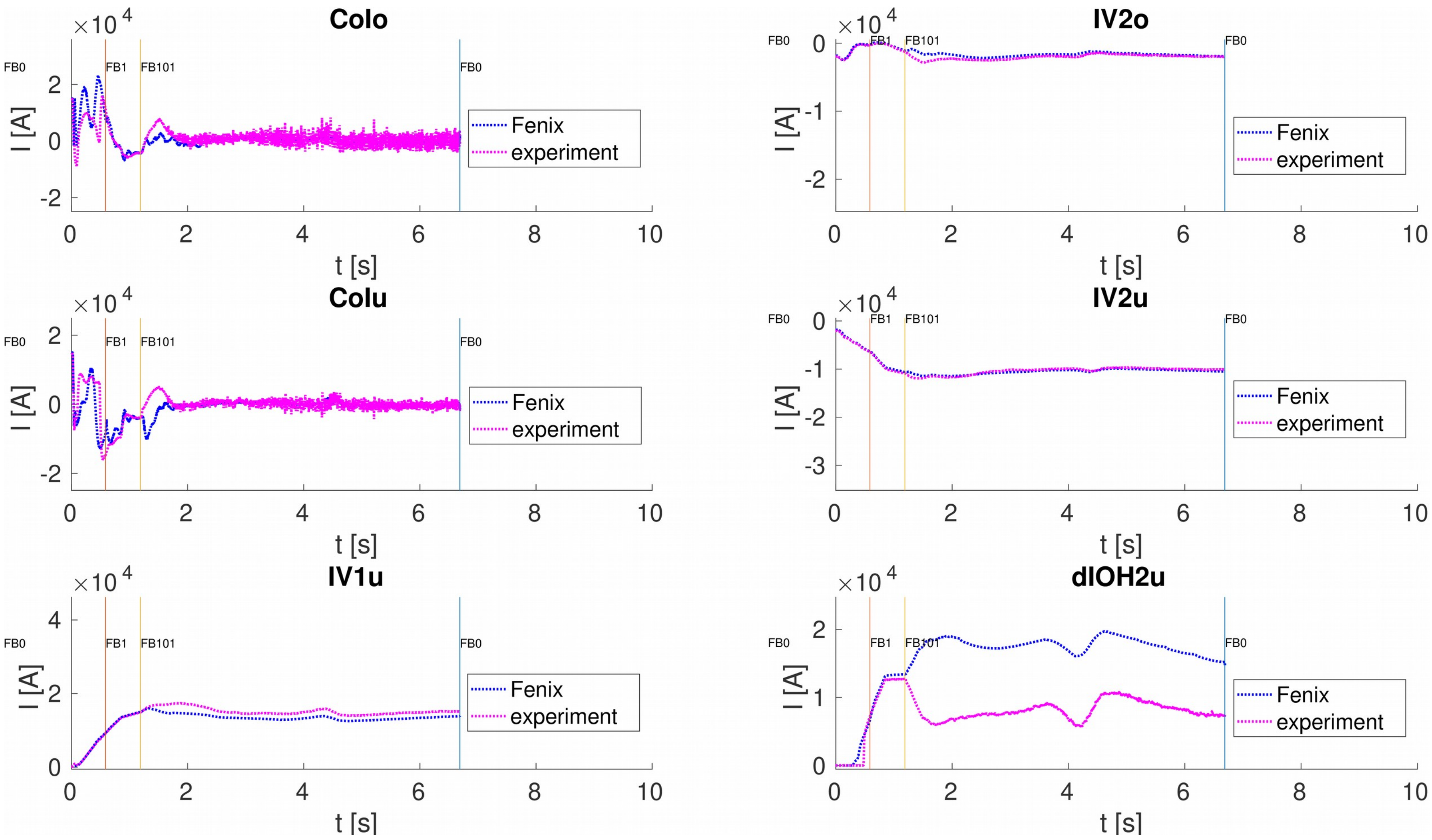
BACKUP SLIDES

- Heating powers of discharge #40446



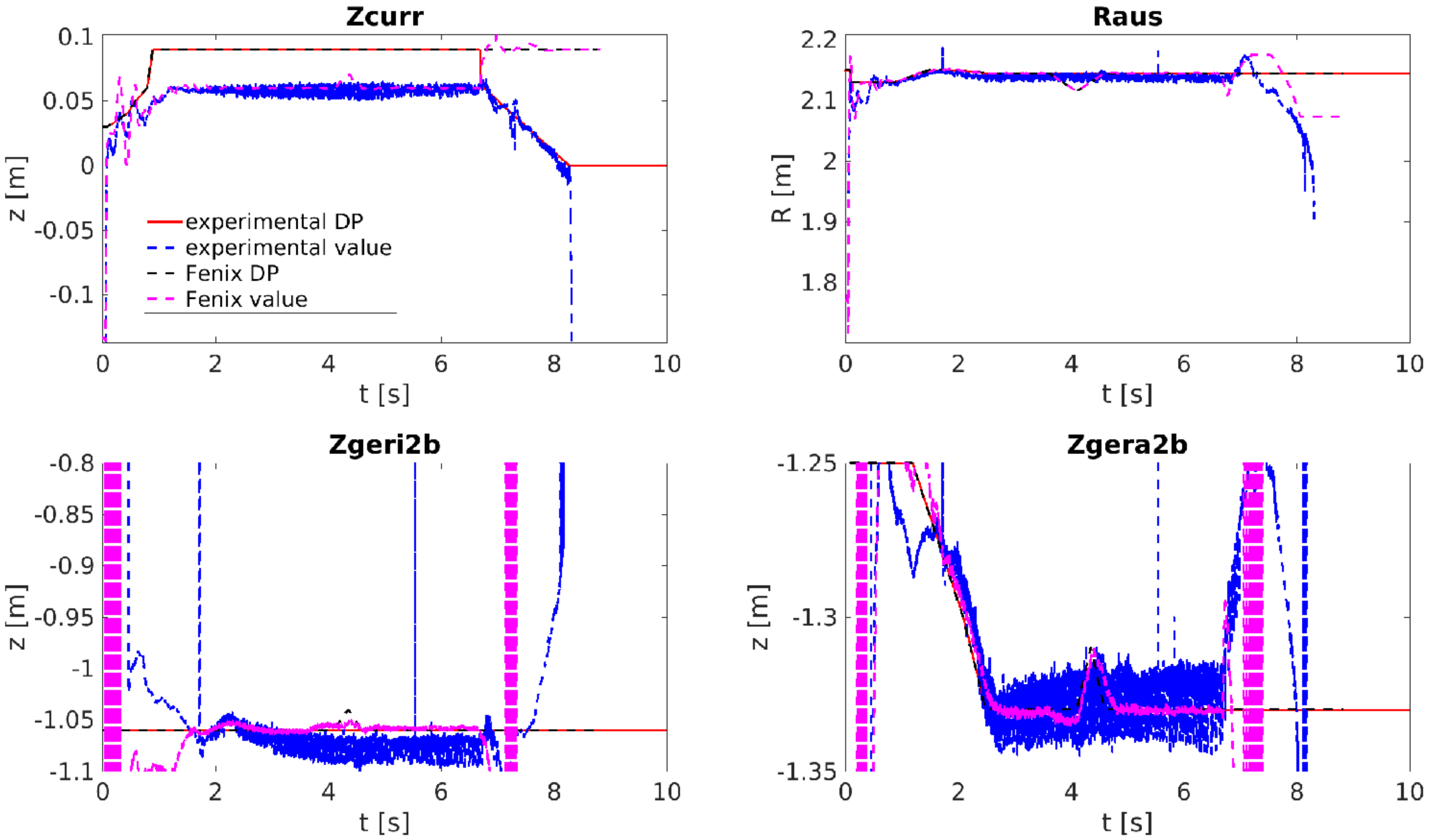
BACKUP SLIDES

- Actuators (stabilizing coil currents) of discharge #40446



BACKUP SLIDES

- Position and shape feedback of discharge #40446



BACKUP SLIDES

- Average density feedback of discharge #40446