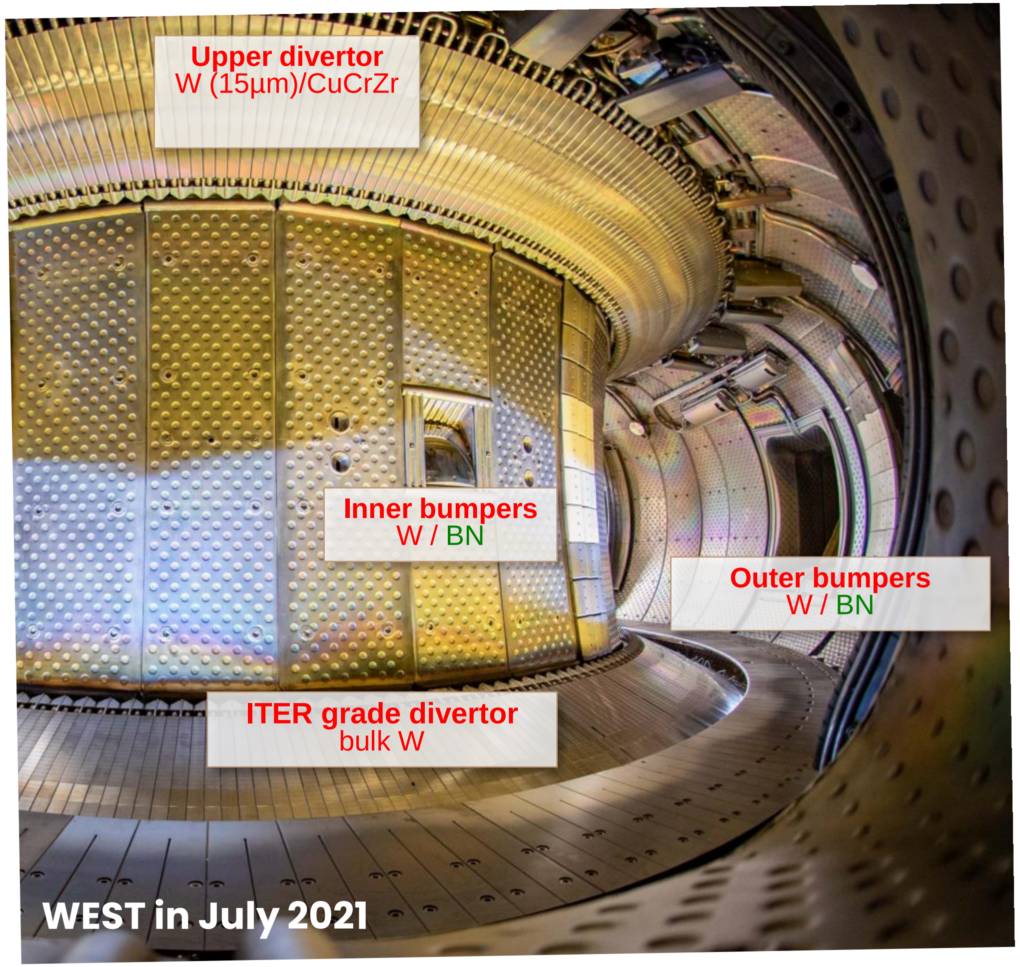
WEST operational domain predictions of L-mode non-inductive discharges with an integrated modeling approach

T. Fonghetti, P. Manas, R. Dumont, J-F. Artaud, C. Bourdelle, F.J. Casson, N. Cummings, L. F. Delgado, P. Maget, J. Morales, Y. Peysson, M. Schneider and the WEST team

17/10/2024

WEST Tokamak



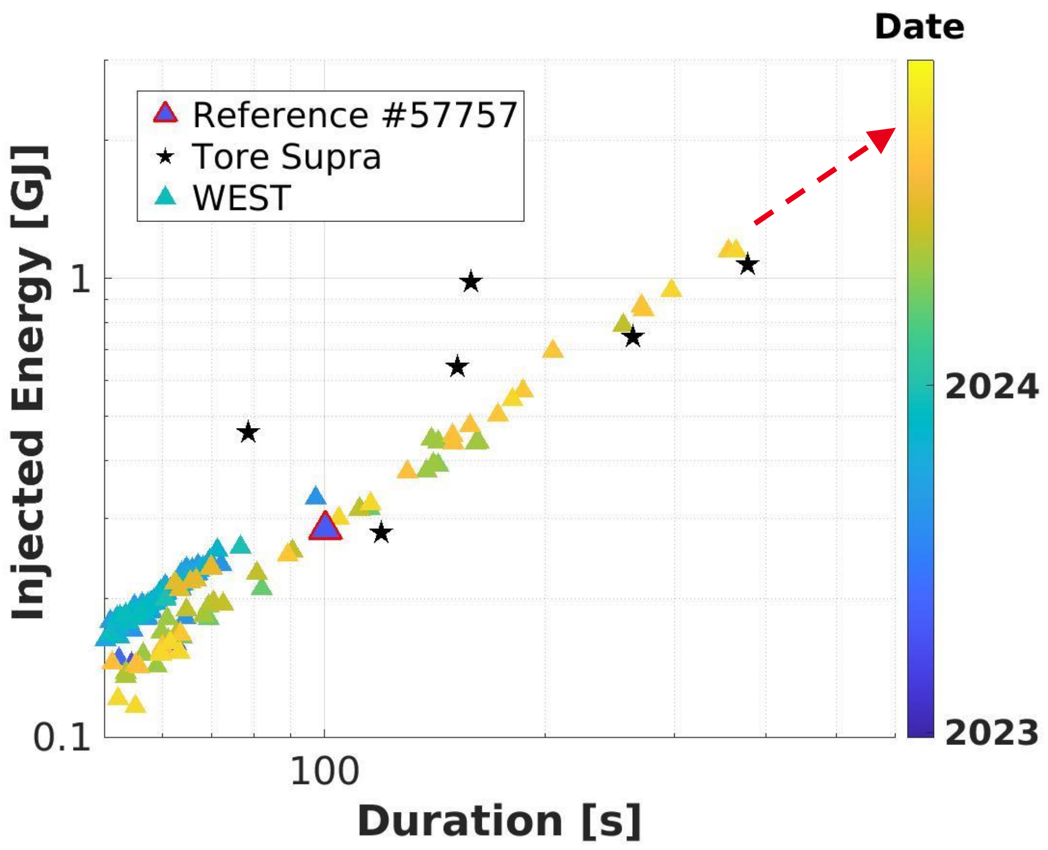
WEST is designed for long duration plasmas:

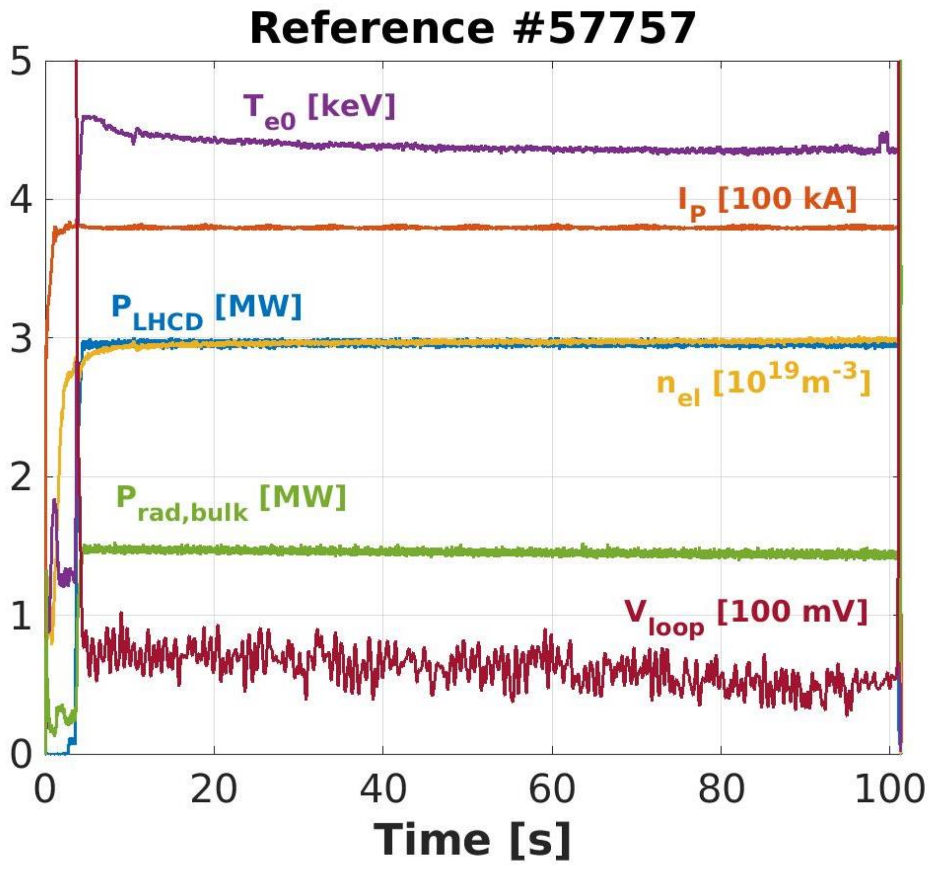
- ITER-relevant **W-environment**
- Up to **7 MW of LHCD** *[Regal-Mezin, this conference]*
- Superconducting magnets
- Actively-cooled plasma facing components
- Expecting up to **3 MW of ECRH** by 2025 *[Bernard, this conference]*

- **Explore steady-state regimes**
- **Characterize the ageing of plasma facing components**

WEST long pulse results

Record long duration discharges obtained **recently…**





… guided by **predictions** based on shot **#57757** using **integrated modeling**

Contents

1. WEST Database analysis
2. The integrated modeling workflow
3. Reference pulse and operational domain predictions
4. Comparison to post-prediction experiments
5. MHD stability improvement with ECCD

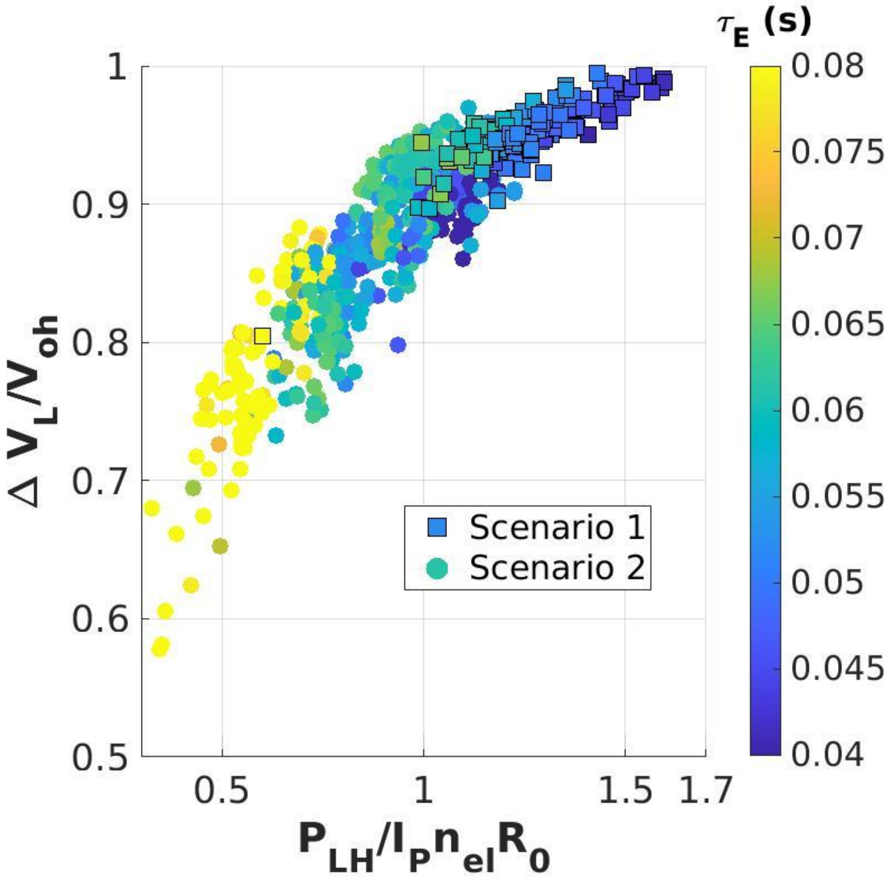
What are the main ingredients to reduce the loop voltage ?

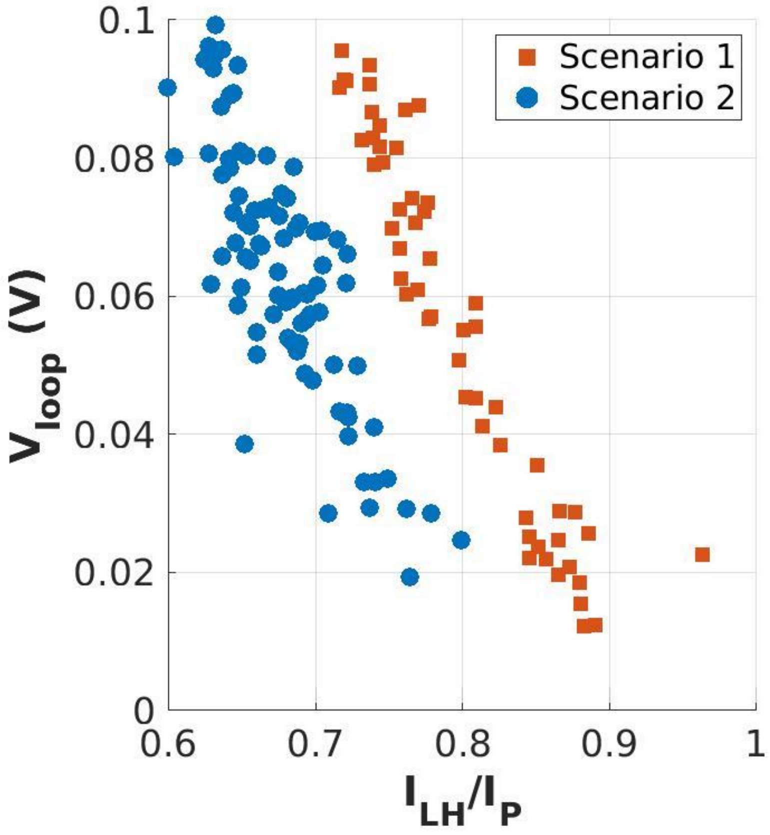
1. WEST database analysis

Identifying ingredients to decrease $V_L\sim0$

V_{loop} drops with LHCD current

$$\frac{\Delta V_L}{V_{OH}} \twoheadrightarrow \frac{I_{LH}}{I_P} = \frac{P_{LH}}{I_P n_{el} R_0}\eta_{LH}$$





$$\eta_{LH} \propto \tau_E^{0.4}$$

[Goniche, AIP, 2005]

$$\frac{I_{LH}}{I_P} \propto \frac{P_{LH}}{n_e R_0 I_P}\tau_E^{0.4}$$

How to accurately capture those ingredients ?

2. Integrated modeling workflow

Integrated modeling framework

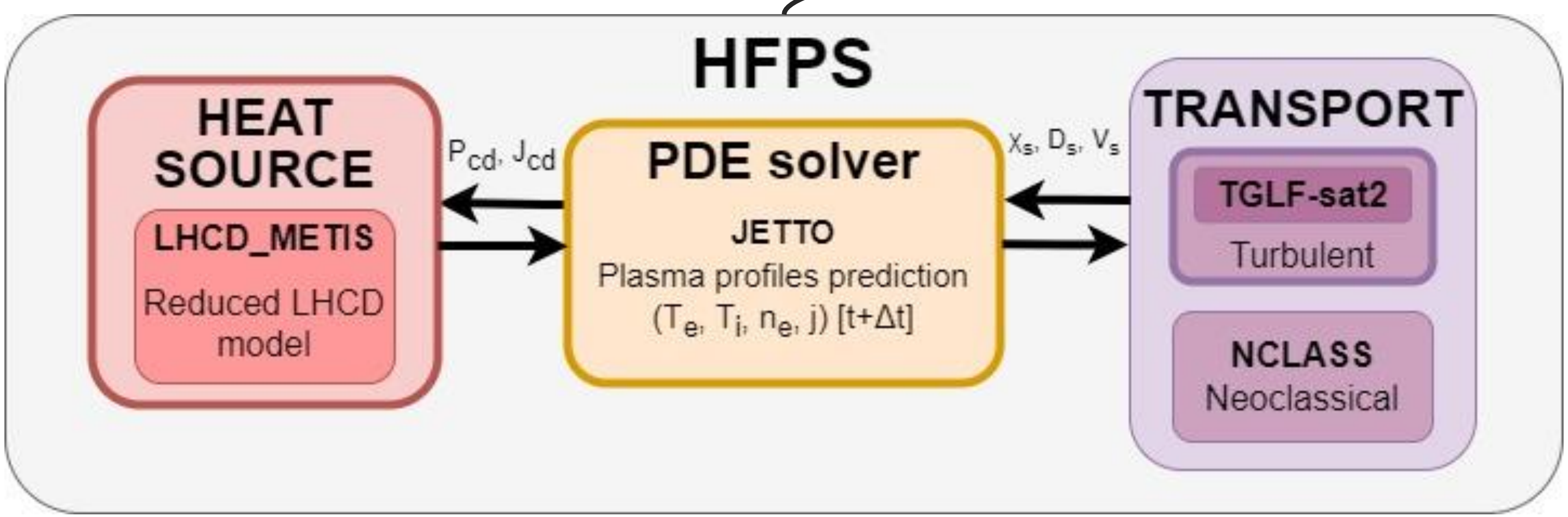
- Key physics ingredients is the coupling between HCD & transport predictions

[Goniche, AIP, 2005]

- In the reduced model, we use an experimental scaling law for predicting the **current drive efficiency from the energy confinement time**

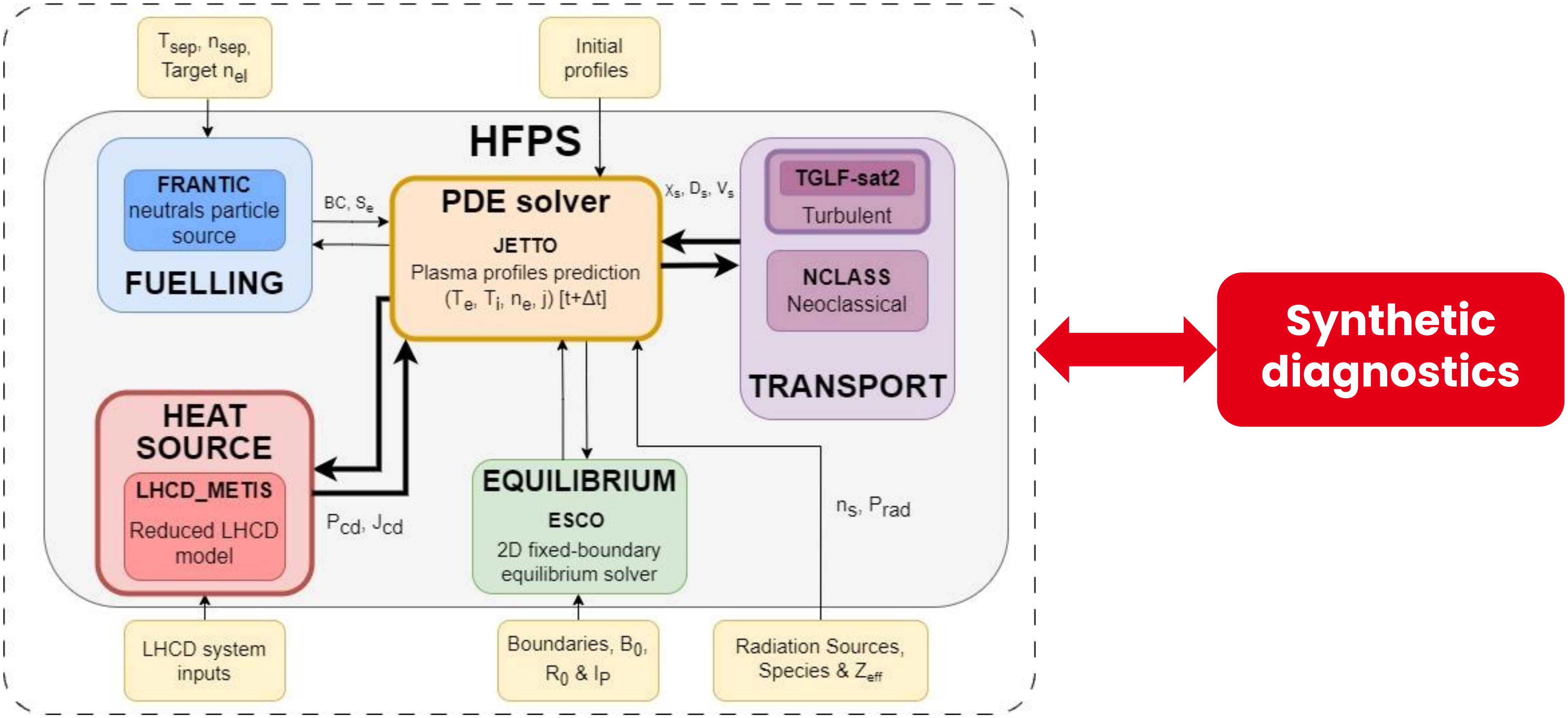
(JINTRAC – IMAS in/out)

[Romanelli, PFR, 2014]



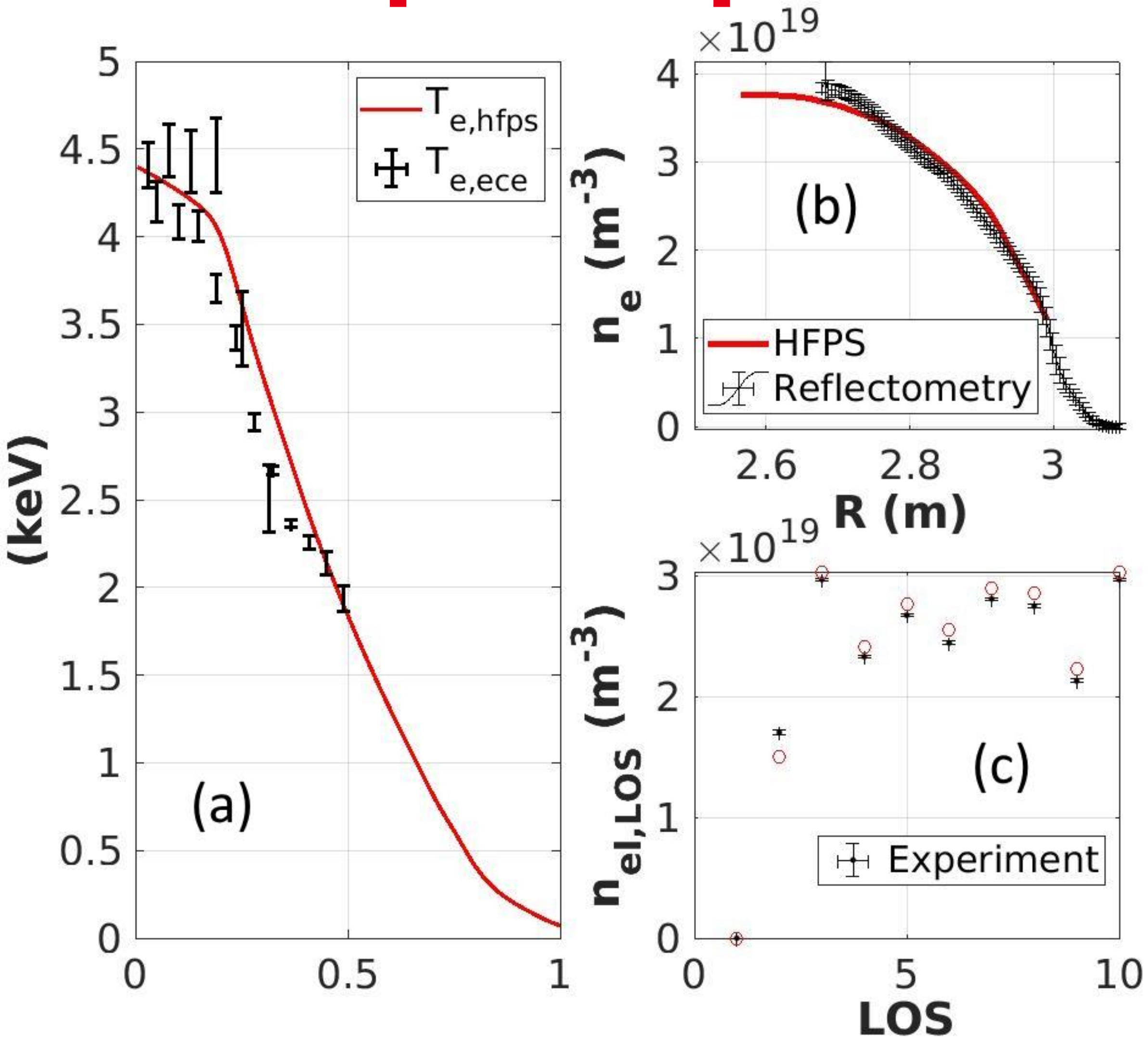
$$\frac{I_{LH}}{I_P} \propto \frac{P_{LH}}{R_0 n_e I_P} \tau_E^{0.4}$$

Integrated modeling framework



3. Reference pulse and operational domain predictions

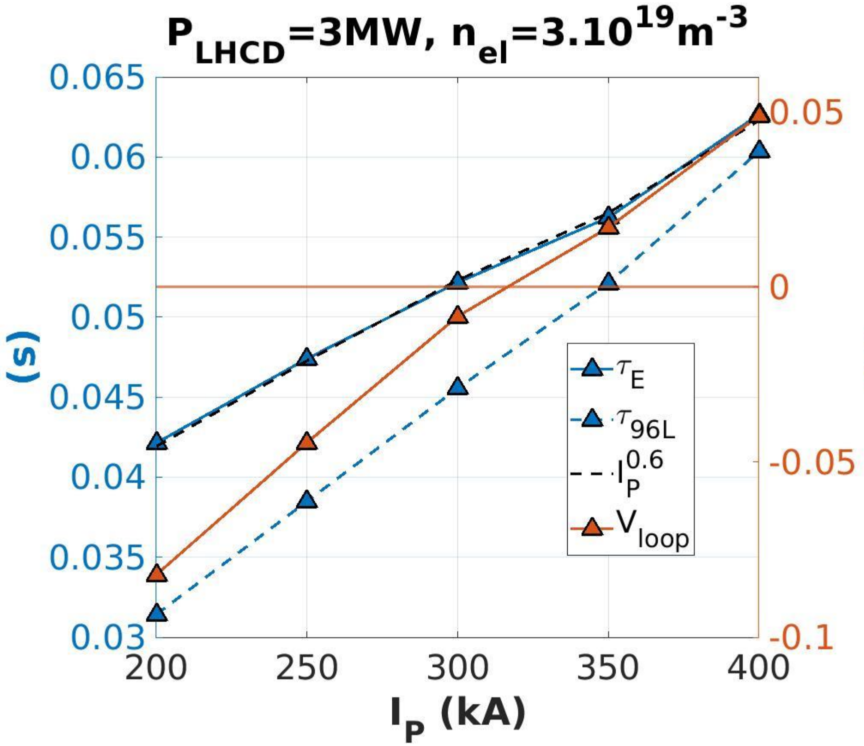
Integrated modeling predictions are validated against reference pulse experiment



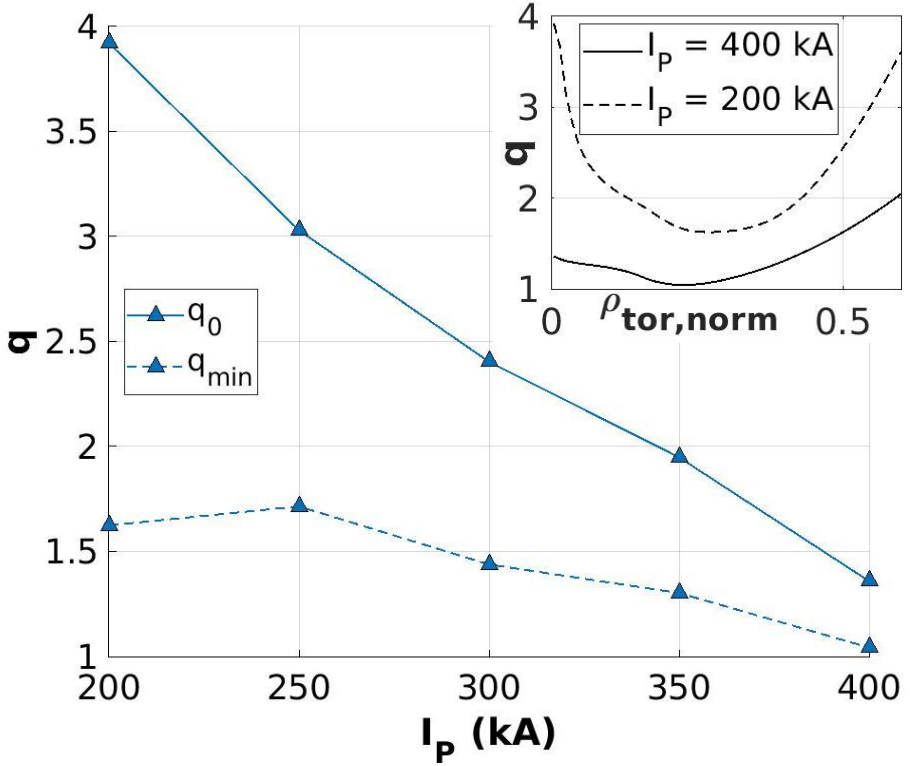
- Electron temperature and density profiles are validated ►global **energy content** is well predicted

- Loop voltage is predicted within a **10 mV error range** ► **few kA** discrepancy of LHCD current generated

Decreasing Ip for reaching lower loop voltages



$$\frac{I_{LH}}{I_P} \alpha \frac{P_{LH}}{n_e R_0} \frac{\tau_E^{0.4}}{I_P}$$



Energy confinement time **dependency** with I_P **retrieved**

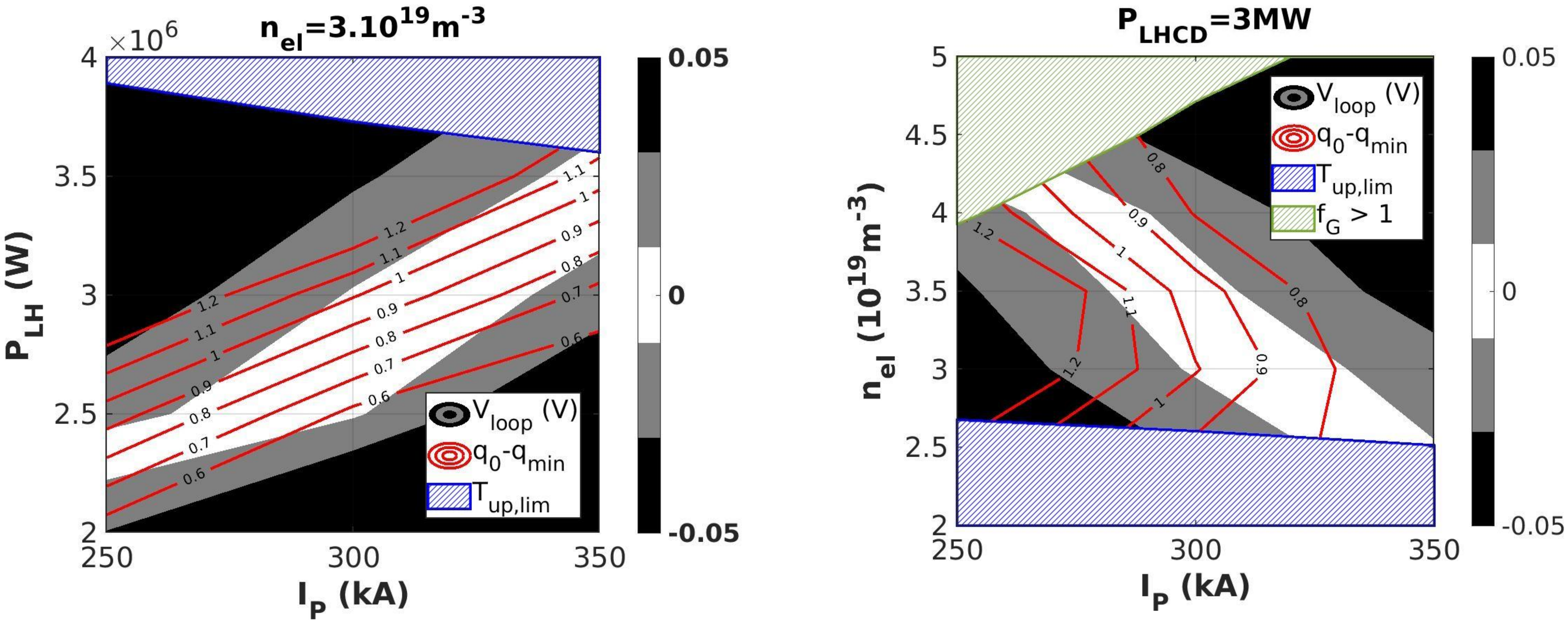
Non-inductive discharge is predicted for **I_P=320kA…**

… BUT the q-profile gets more **reversed with low V_{loop}**

MHD stability is expected to be **degraded** (cf ECCD)

2D operational domain predictions

- Upper pipes temperature **constrains low n_{el} & high P_{LHCD} operation**
- **Reversed q-profile** always observed at V_{loop}~0 ► minimised at low P_{LHCD}



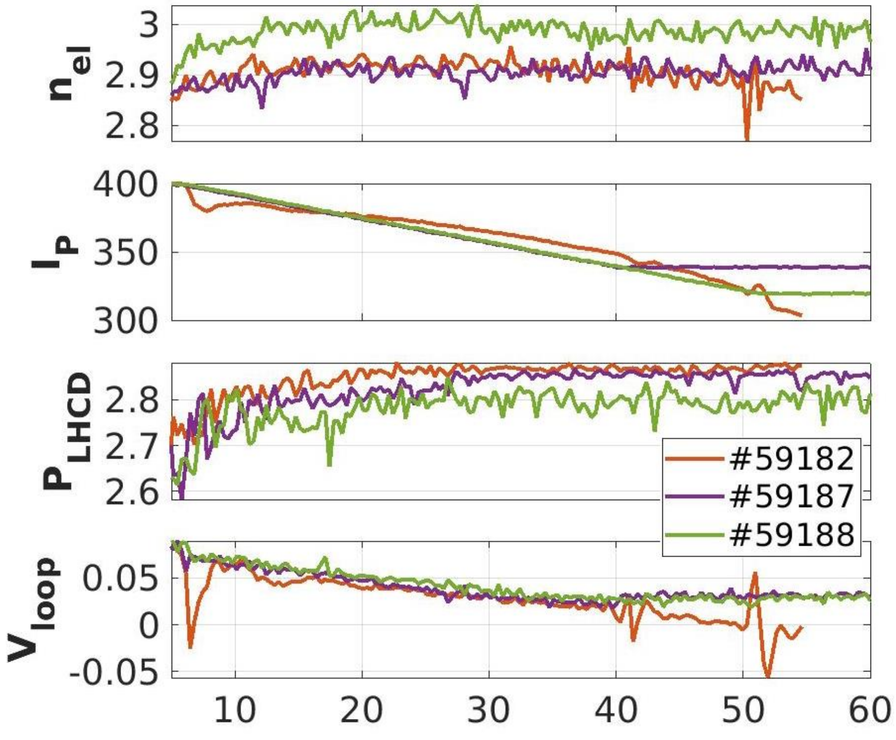
4. Comparison to post-prediction experiments

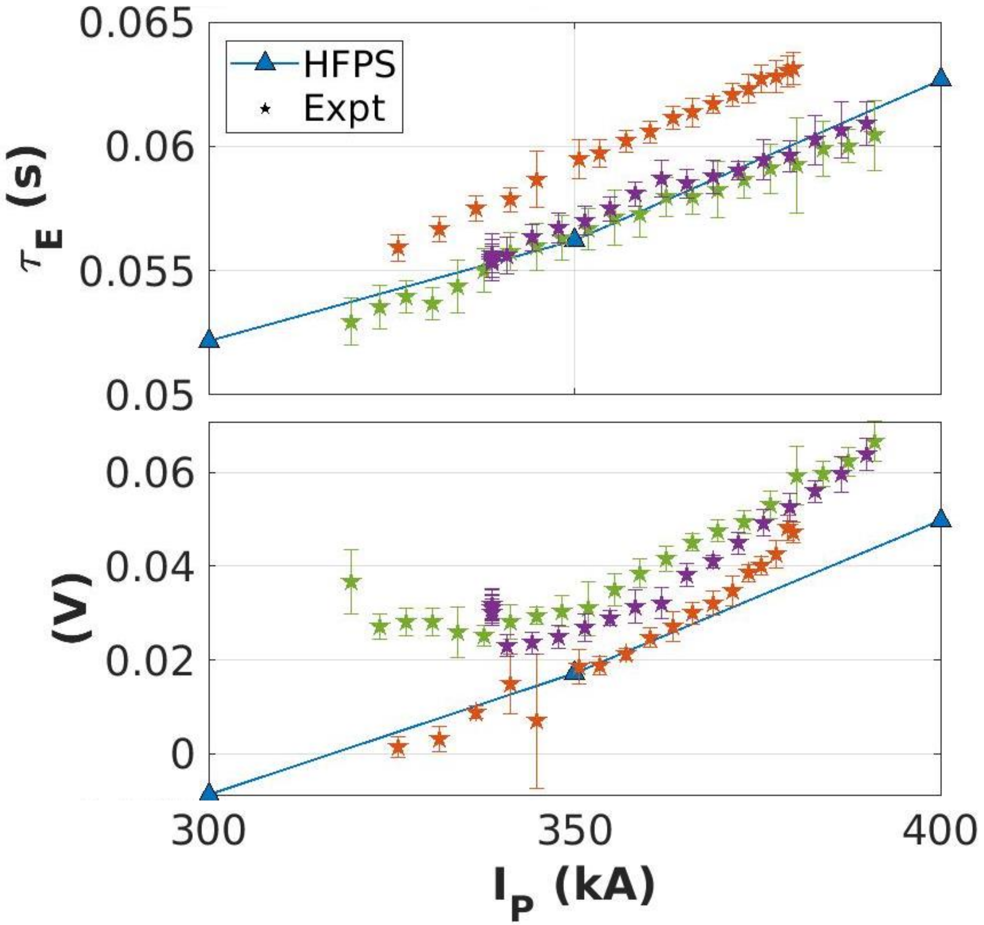
Quantitative agreement with Experiments

In the experiments, V_{loop} **was feedback-controlled** with I_P …

I_P ramp-down

[Nouailletas, this conference]





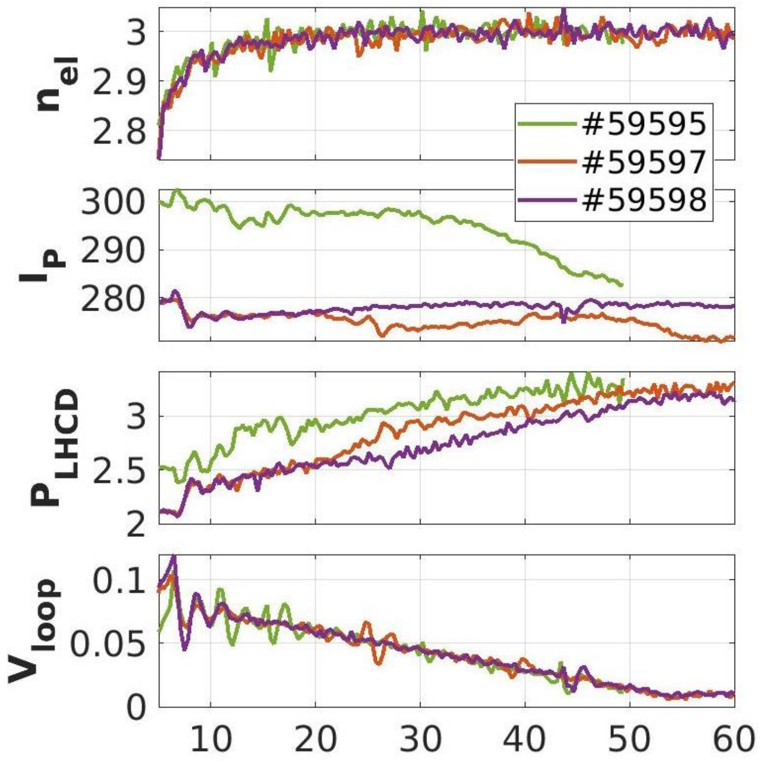
… and was shown to be in **good agreement with predictions**

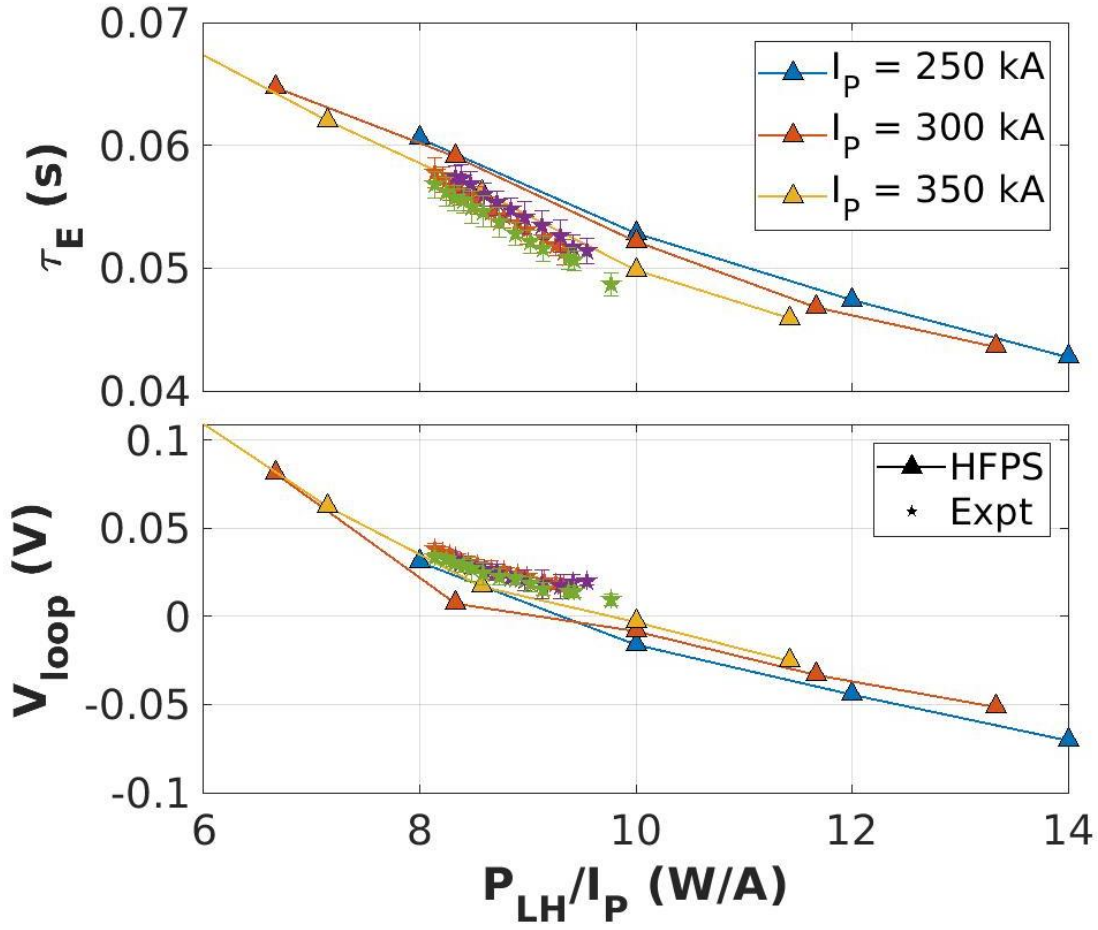
Quantitative agreement with Experiments

Later on, V_{loop} **was feedback-controlled** with P_{LHCD} …

P_{LHCD} ramp-up

[Nouailletas, this conference]



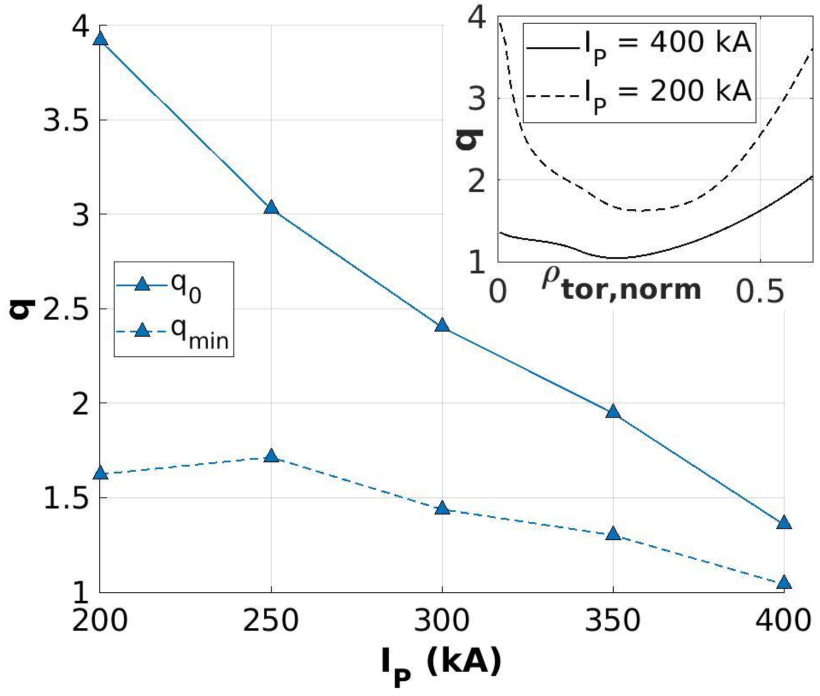


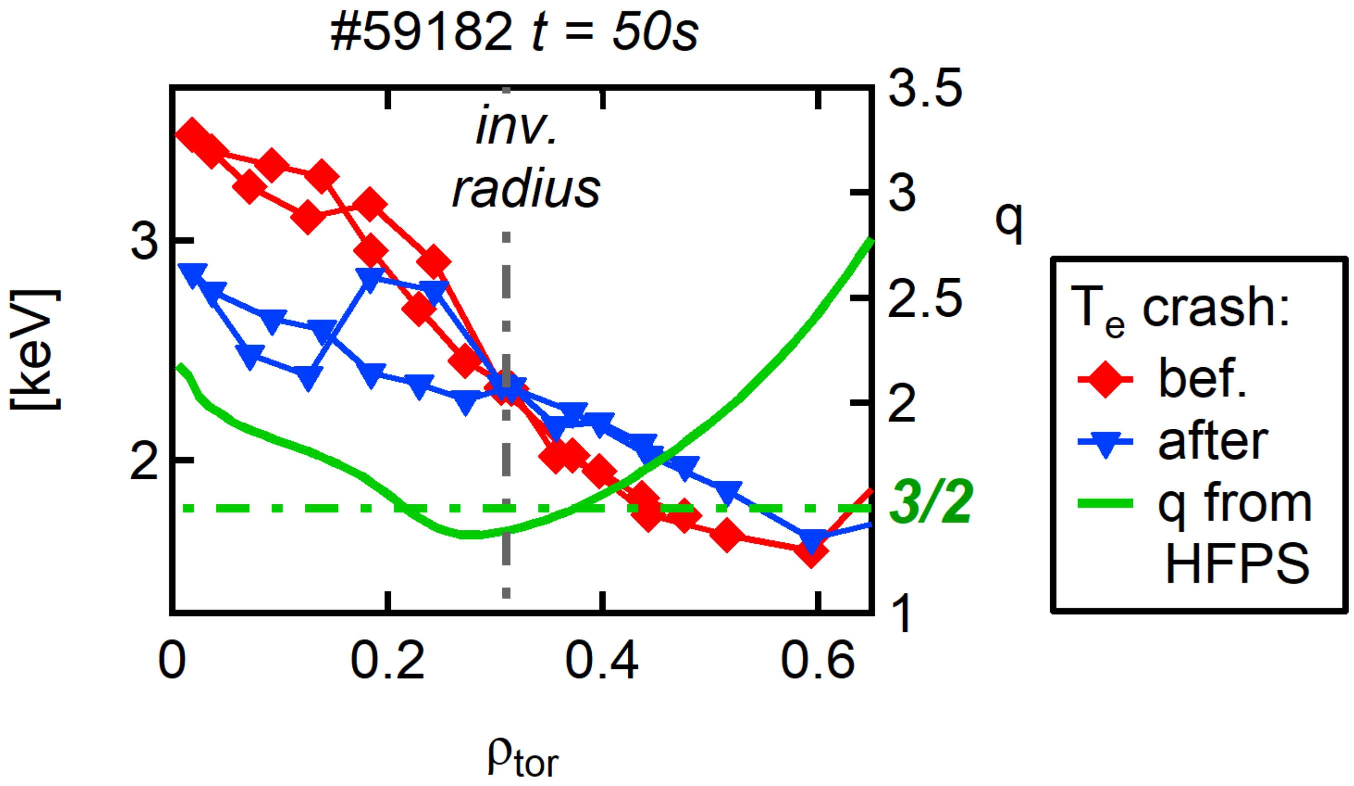
… and again was shown to be in **good agreement with predictions**

5. MHD avoidance with ECCD

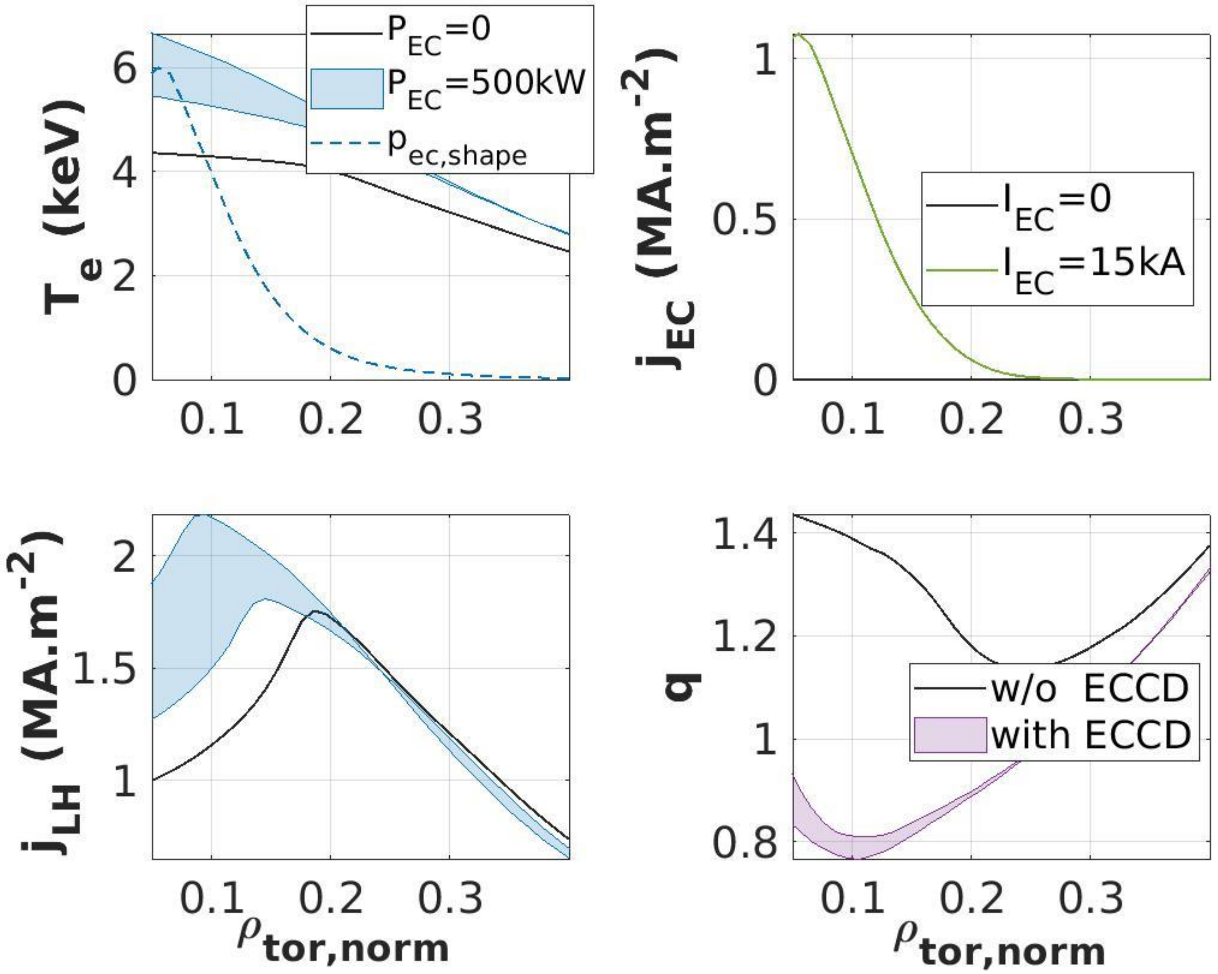
MHD triggering ⇒ ECCD ?

- Inversion radius matches **reversed rational q=3/2** surface ► **DTM ?**
- Central ECCD can overcome the central reversion of the q-profile
  ► **improve the MHD stability**





Adding ECCD in previous simulation



- Central heating **increases T_e,** displacing **LHCD on-axis**
- **Increased Bootstrap current** in the center
- Central ECCD adds on top of current sources and **increases total current in the center**

No more reversed q-profile

6. Conclusion

Conclusion

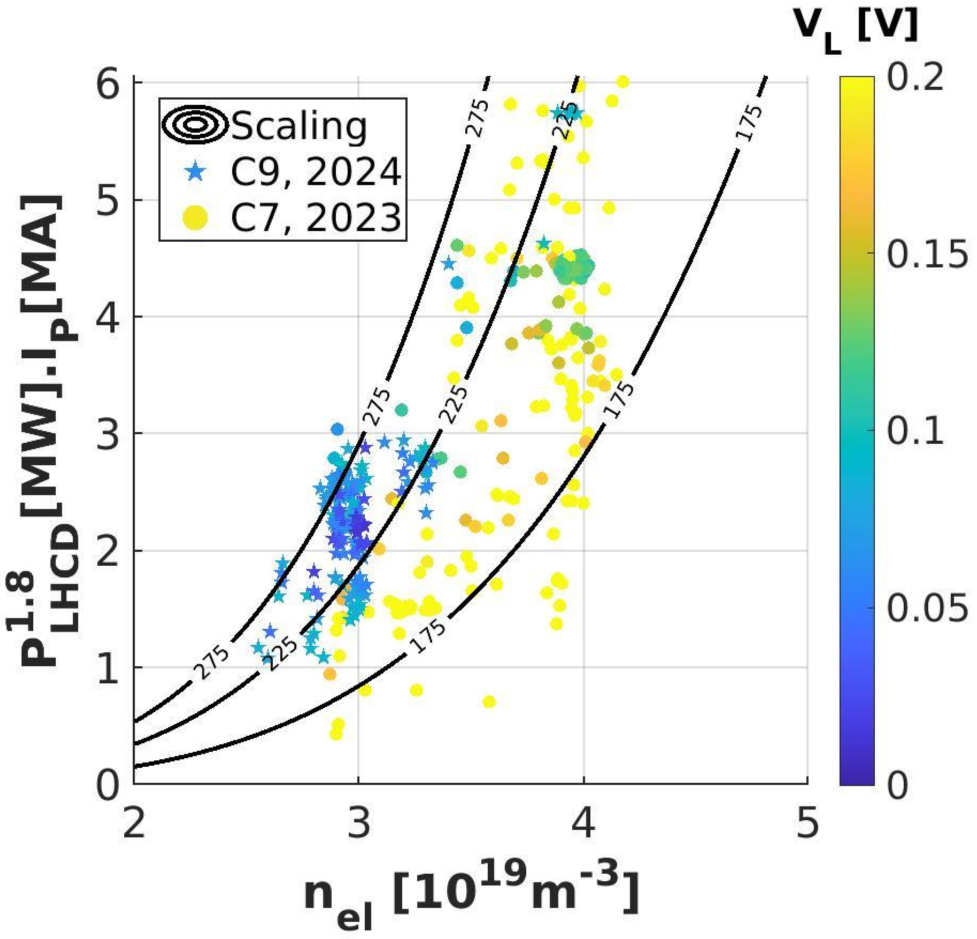
- **Experimental strategy motivated integrated modeling predictions**
- Successful coupling of **LHCD & Transport** self-consistent predictions
- **Pre-campaign simulations** are in **good agreement** with **experimental results**
- **Long duration plasmas** up to a **364 s / 1.15 GJ** obtained
- **ECCD** for controling current profile ► **improve MHD stability**

Perspectives: Explore actuators to increase performances ► low-Z impurity seeding, additional heating (up to 3 MW of ECRH)

X. Backup

Machine limitations

Upper pipes heating from LHCD-induced **ripple losses constrains** the **operational domain**



Several other limitations:

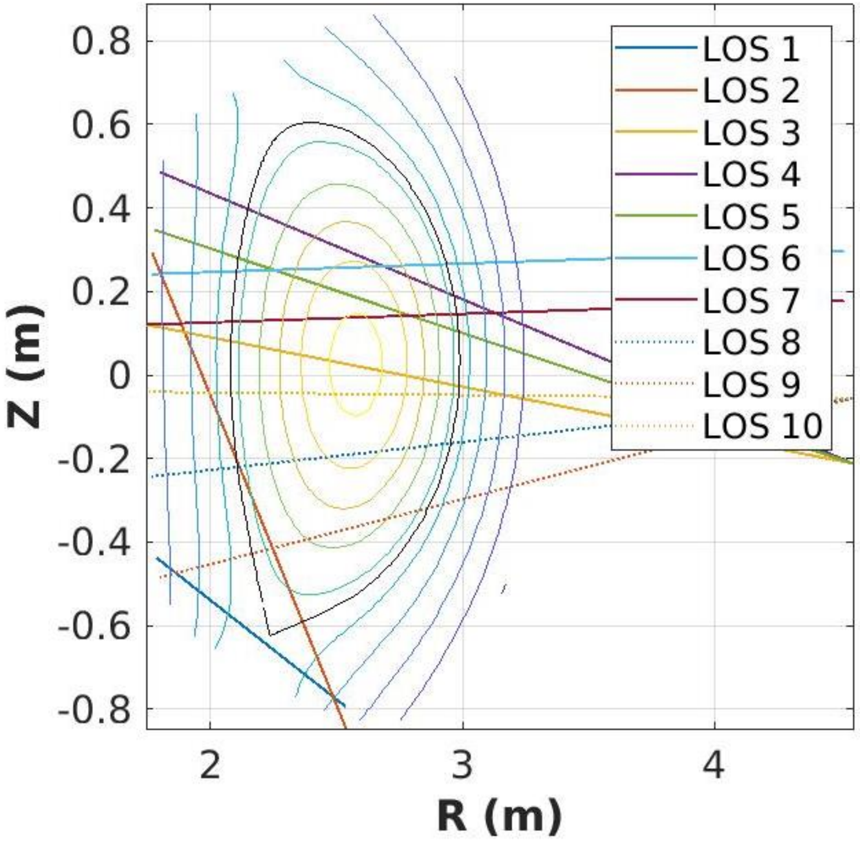
- **Greenwald** limit :

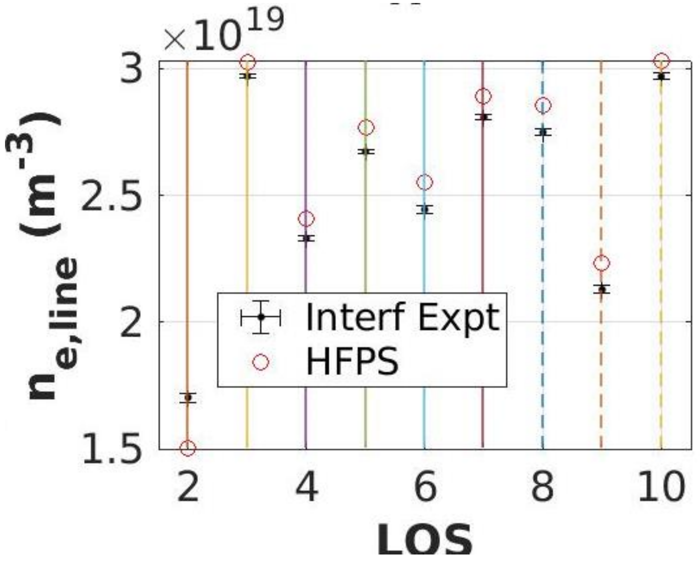
$$n < n_G \propto \frac{I_P}{a^2}$$

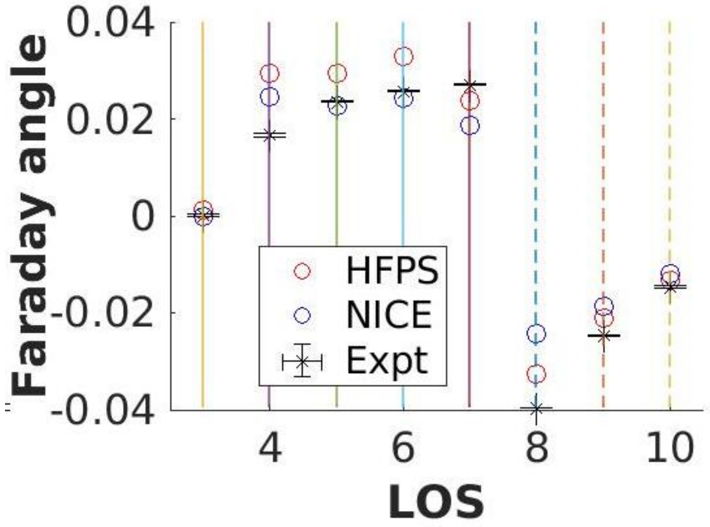
[Greenwald, PPCF, 2002]

- MHD stability comes with q-profile verification *[Maget, NF, 2005]*
- Radiative collapses limiting the operation at high density *[Ostuni, NF, 2021]*
- …

Integrated modeling predictions are validated against experiments

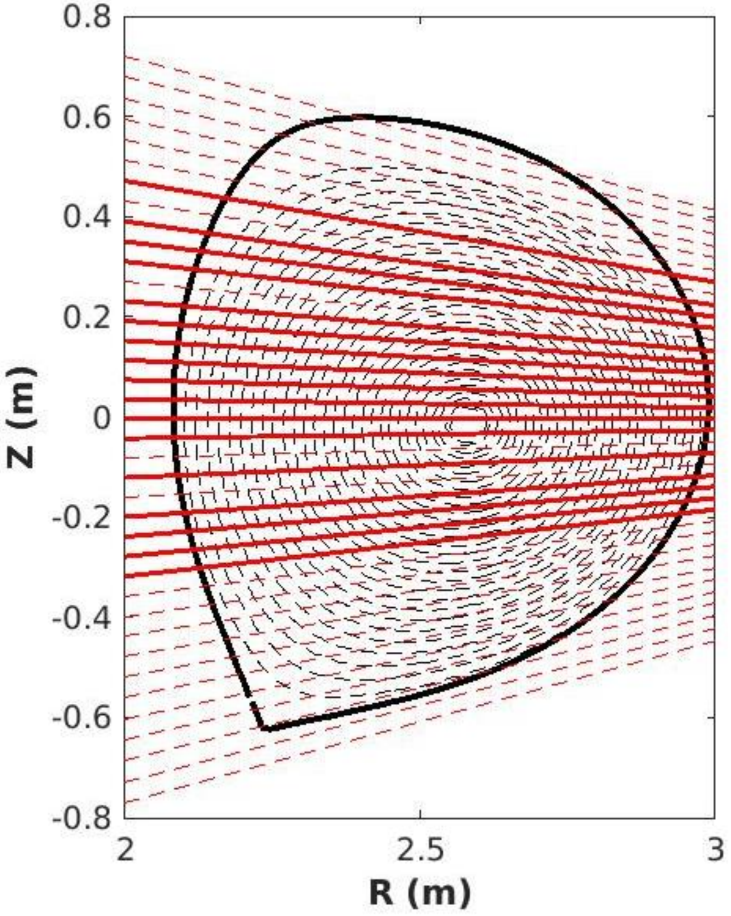


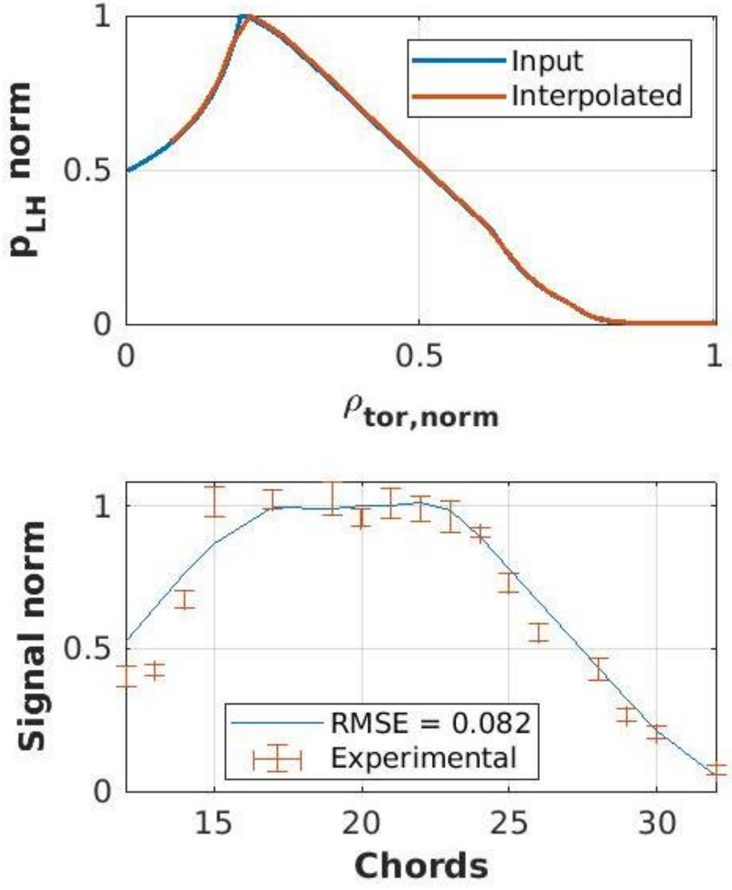




- Interferometry profile is validated as the discrepancy with different chords is similar
- Faraday angle comparison is harder to validate but the overall agreement lies within the NICE reconstruction error bar

Plh validation

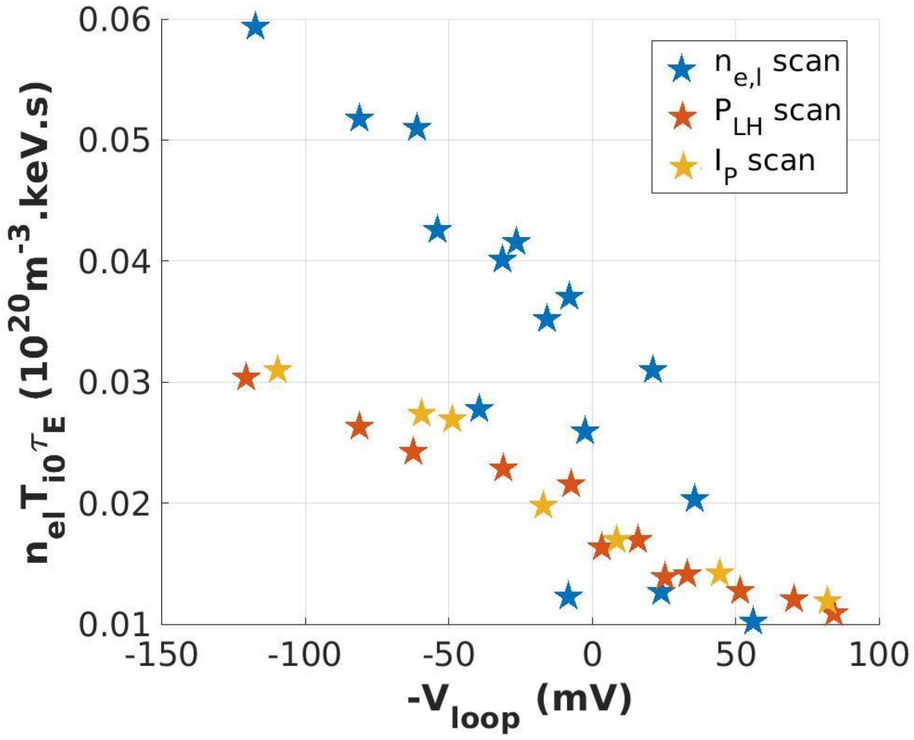


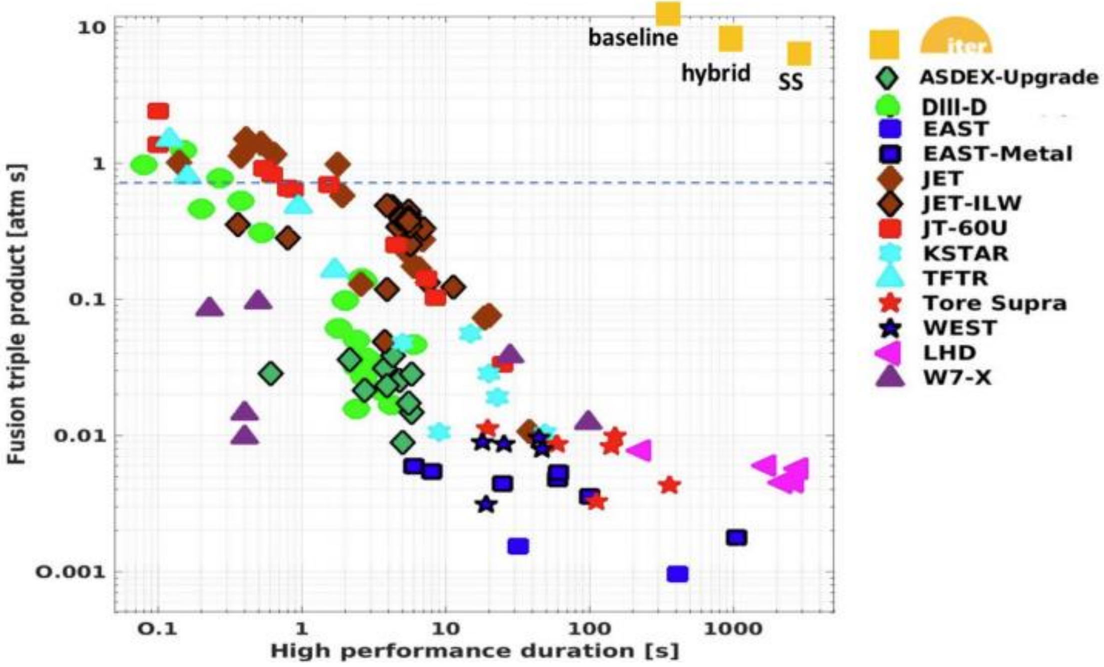


- HXR in the 60 to 80 keV is a proxy of fast electrons LHCD-induced populations (neglecting effect of high-Z impurity)
- Simple approximation emissivity proportional to power deposition allows to compare experience and simulation
- Validation of the reduced model

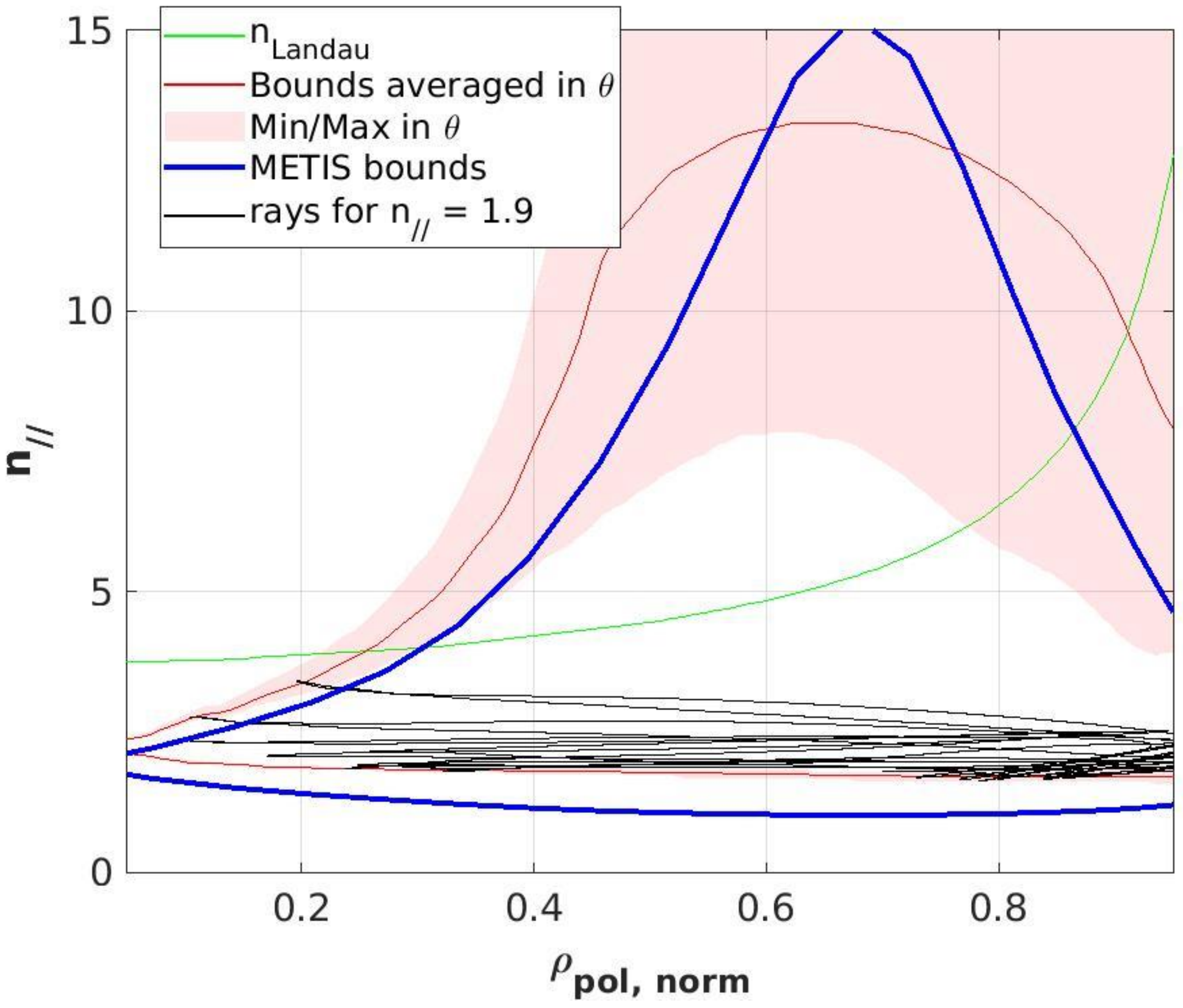
Overall performance

- Same degradation of the performances with longer durations as CICLOP database
- Electron heated machines like WEST are limited as Ti is saturated
- High electron density scenarios are limited with CD efficiency and Greenwald limit



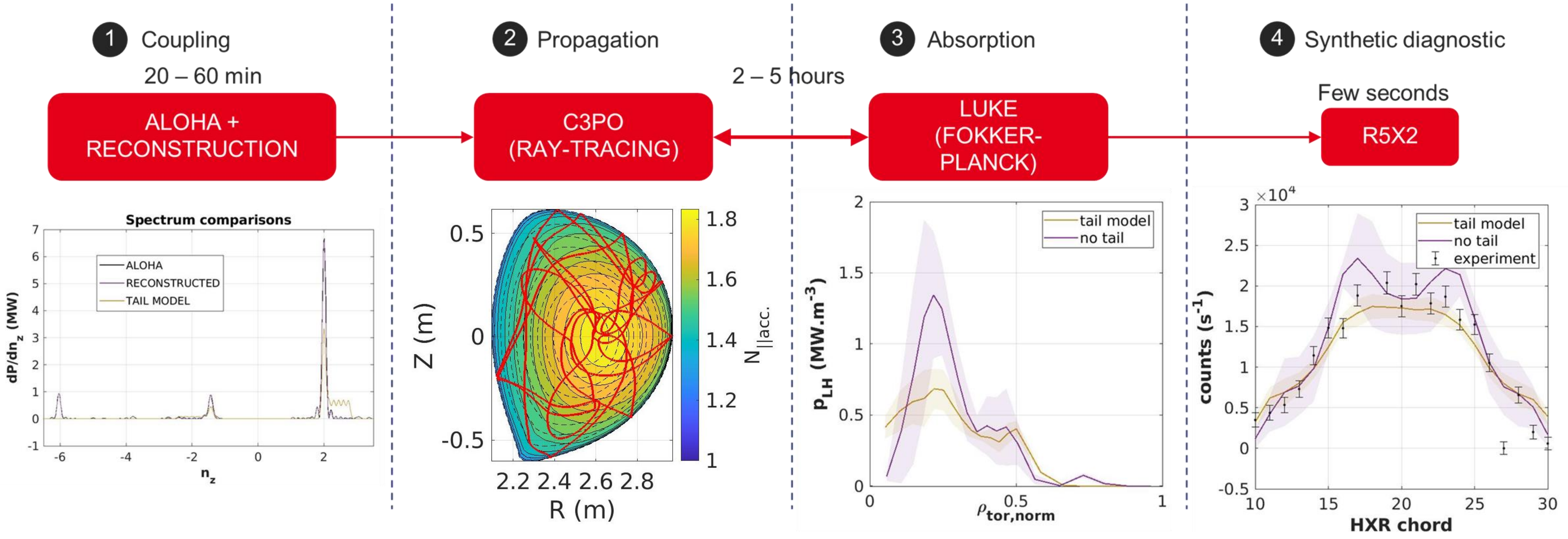


SLUKE vs REDUCED MODEL



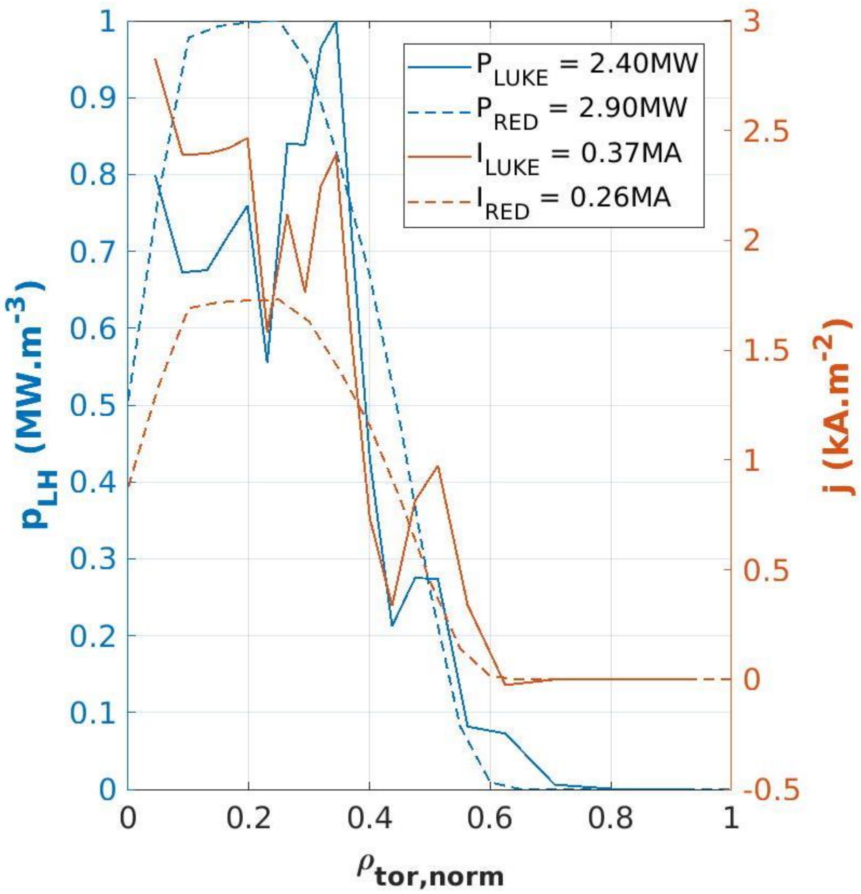
- Propagation domains are similar even if cylindrical approximation with the reduced model
- SLUKE describes ray propagation => lots of reflection for low n// lobes leading to sensitive deposition
- Reduced model heuristically captures the main ingredients evolution

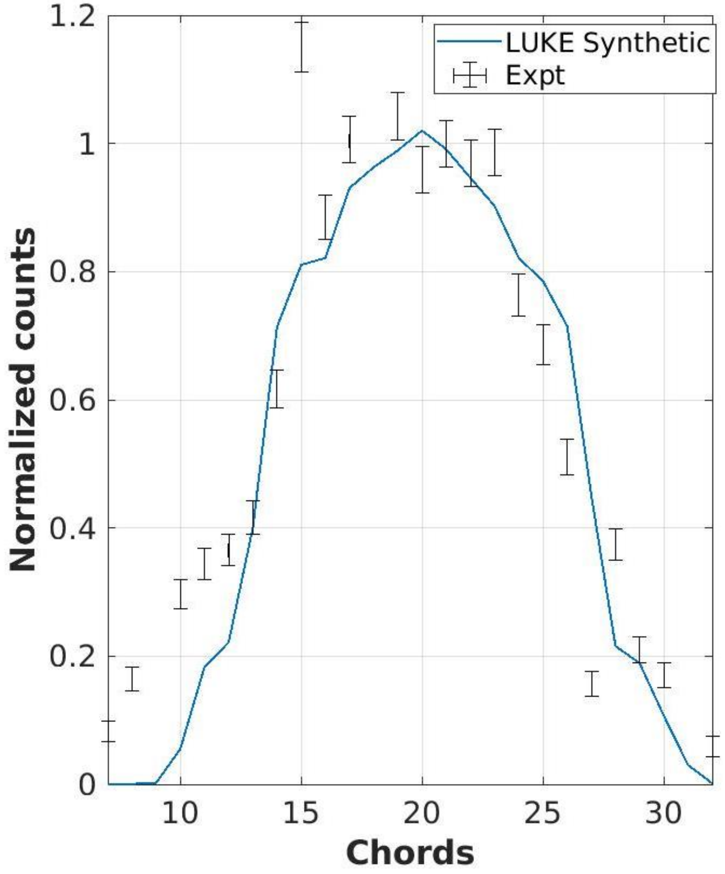
Modélisation LUKE



Le signal des x-durs (60-80 keV) est retrouvé à partir de modélisations premiers principes pour la branche chaude.

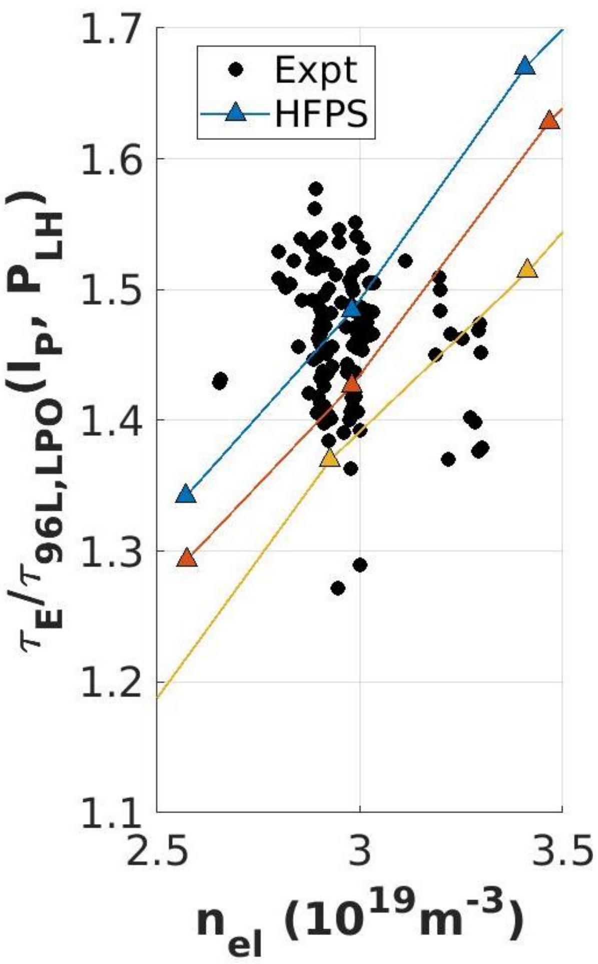
Reduced model vs SLUKE





- Agreement is ok ; the deposition location is similar and validated against HXR profiles.
- Huge difference between LUKE current prediction (overestimation even higher than Ip) and reduced model (vloop is matched with reduced model).

Electron density scan agreement



$$\tau_{E,norm}(n_{el}) = \frac{\tau_{E,HFPS}(I_P, P_{LHCD}, n_{el})}{\tau_{E,96L}(I_P, P_{LHCD})}$$

- Agreement around the reference electron density
- The **predicted** high dependency of the energy confinement time with $n_{el}^{0.8}$ **does not match experimental** trends meaning the extrapolation is not straight-forward