EUROfusion

EUROfusion Science Meeting, 14/01/2026

TSVV11 EUROfusion “Validated Frameworks for the Reliable Prediction of Plasma Performance and Operational Limits in Tokamaks”

Clarisse Bourdelle

CEA

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Multiple goals for integrated modelling: steady-state, whole pulse modelling, tests of controllers, inform design of future device

Physics understanding		Prepare operation	Design future devices
1st principle codes	**High Fidelity Integrated Modeling**	**Pulse Design Tools** Full pulse, testing controllers	**System codes** in/out are engineering parameters only

Validation against tokamak experiments !

!

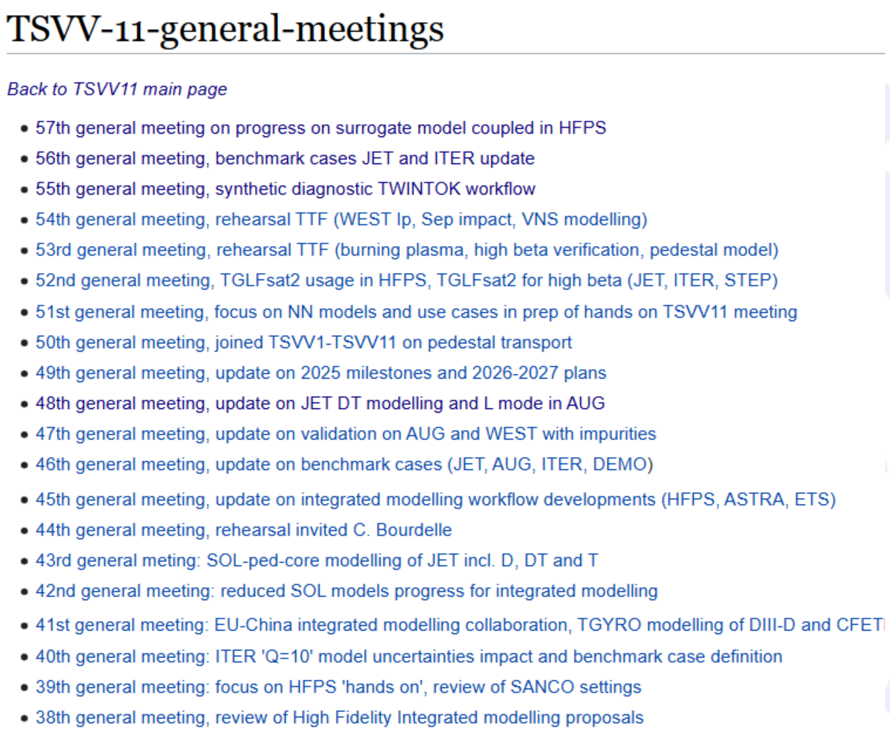
Various levels of non-linear couplings, predicted vs interp.: j+heat only, j+heat+particle, etc,

Various boundary conditions: pedestal top, separatrix, divertor targets

Various model fidelity: empirical scaling, reduced physics model etc

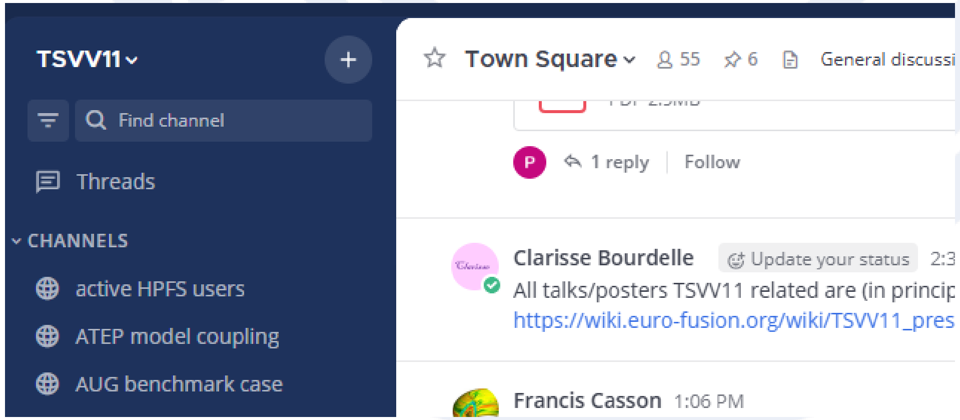
TSVV11: an active forum supporting integrated modelling challenges

- **Regular meetings**, 57 since May 2021, archived on TSVV11 wikipages
  - Surrogate models
  - Validation exercises reporting
  - Benchmark of workflows
  - Model reduction
    - Some joint with TSVV1 on L mode edge and pedestal physics
    - Some with TSVV10 on the interplay of Energetic Particle with transport
  - Hands on support
- **5 in person meetings** (Poznan, Eindhoven, ITER and twice in Culham), summary/slides on the wiki
- **Documentation**, useful links all maintained on the wiki as well: Gateway, HFPS, etc.
- **WP activities supported** by
  - Wiki updated documentation
  - Mattermost channels


TSVV-11-general-meetings

Back to TSVV11 main page

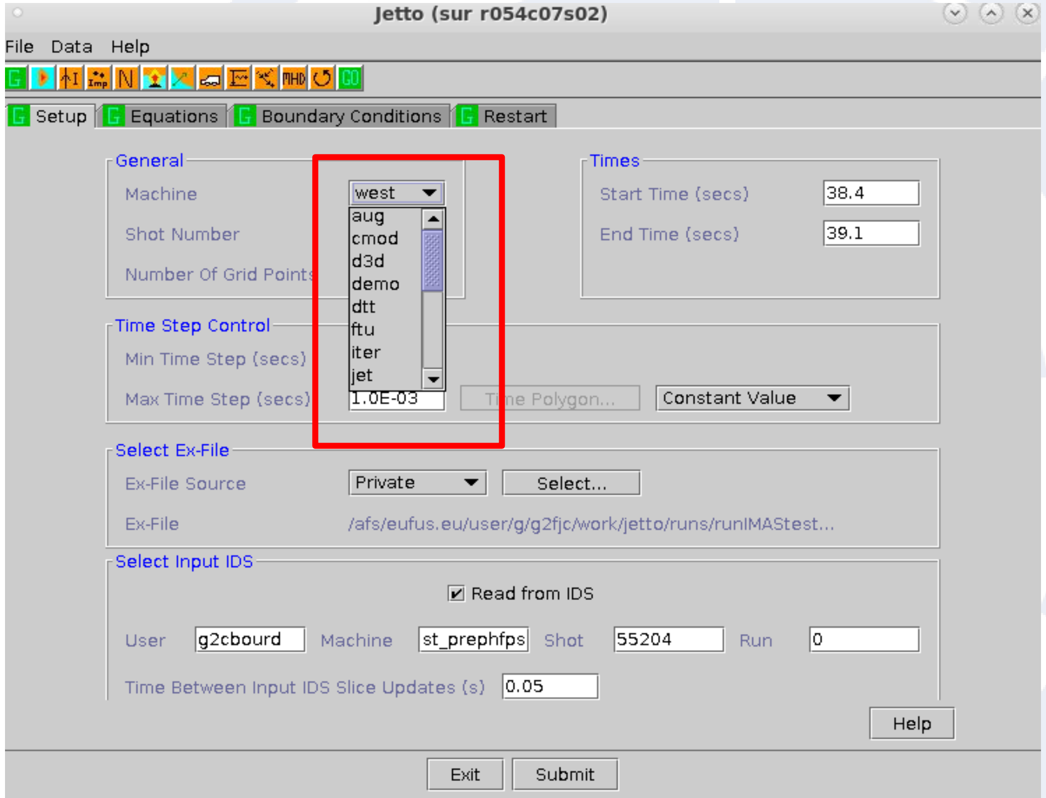
- 57th general meeting on progress on surrogate model coupled in HFPS
- 56th general meeting, benchmark cases JET and ITER update
- 55th general meeting, synthetic diagnostic TWINTOK workflow
- 54th general meeting, rehearsal TTF (WEST Ip, Sep impact, VNS modelling)
- 53rd general meeting, rehearsal TTF (burning plasma, high beta verification, pedestal model)
- 52nd general meeting, TGLFsat2 usage in HFPS, TGLFsat2 for high beta (JET, ITER, STEP)
- 51st general meeting, focus on NN models and use cases in prep of hands on TSVV11 meeting
- 50th general meeting, joined TSVV1-TSVV11 on pedestal transport
- 49th general meeting, update on 2025 milestones and 2026-2027 plans
- 48th general meeting, update on JET DT modelling and L mode in AUG
- 47th general meeting, update on validation on AUG and WEST with impurities
- 46th general meeting, update on benchmark cases (JET, AUG, ITER, DEMO)
- 45th general meeting, update on integrated modelling workflow developments (HFPS, ASTRA, ETS)
- 44th general meeting, rehearsal invited C. Bourdelle
- 43rd general meting: SOL-ped-core modelling of JET incl. D, DT and T
- 42nd general meeting: reduced SOL models progress for integrated modelling
- 41st general meeting: EU-China integrated modelling collaboration, TGYRO modelling of DIII-D and CFETR
- 40th general meeting: ITER 'Q=10' model uncertainties impact and benchmark case definition
- 39th general meeting: focus on HFPS 'hands on', review of SANCO settings
- 38th general meeting, review of High Fidelity Integrated modelling proposals



High Fidelity Pulse Simulator: allowing for machine agnostic validation

Coupled to experimental IMAS data from AUG, JET, TCV, WEST, **on the EUROfusion Gateway**

Synergy with Data Management Plan, ready to use more IMAS data



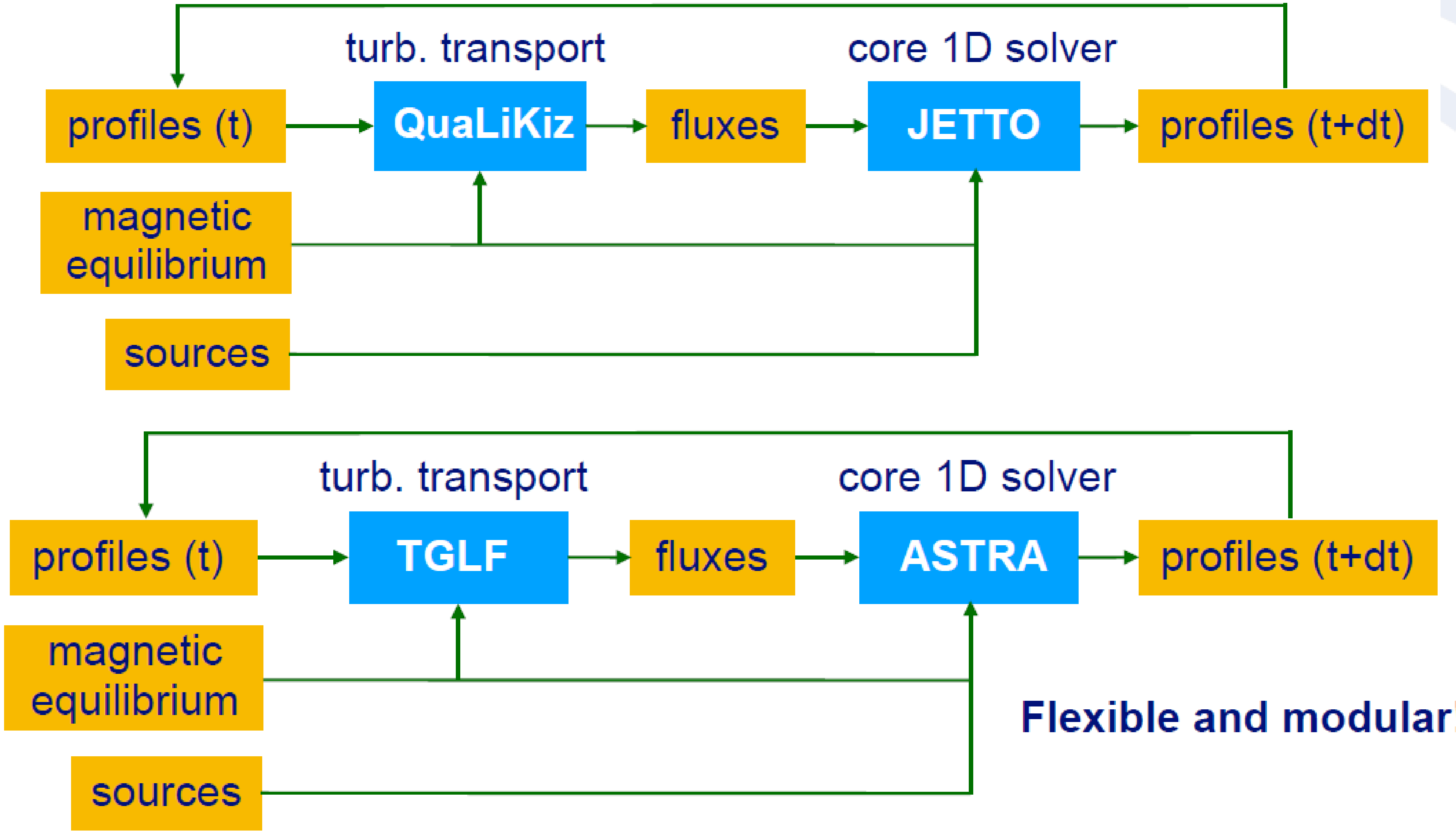
A flexible and modular integrated modelling framework

Towards more interoperability and an increased flexibility
16 HFPS releases on the Gateway since 2020

+
Python

+
Muscle 3

multiscale / **muscle3**



Flexible and modular!

Outline

- **High Fidelity Integrated Modelling guiding operation**
- Can integrated modelling do better than scaling laws?
- Disentangling the causality chain thanks to integrated modelling
- Extrapolating towards burning plasmas
- Benchmark cases
- Perspectives

More complete overview: [Bourdelle PPCF2025]

Full radius ohmic ramp-up : better prediction if density self-consistently evolved

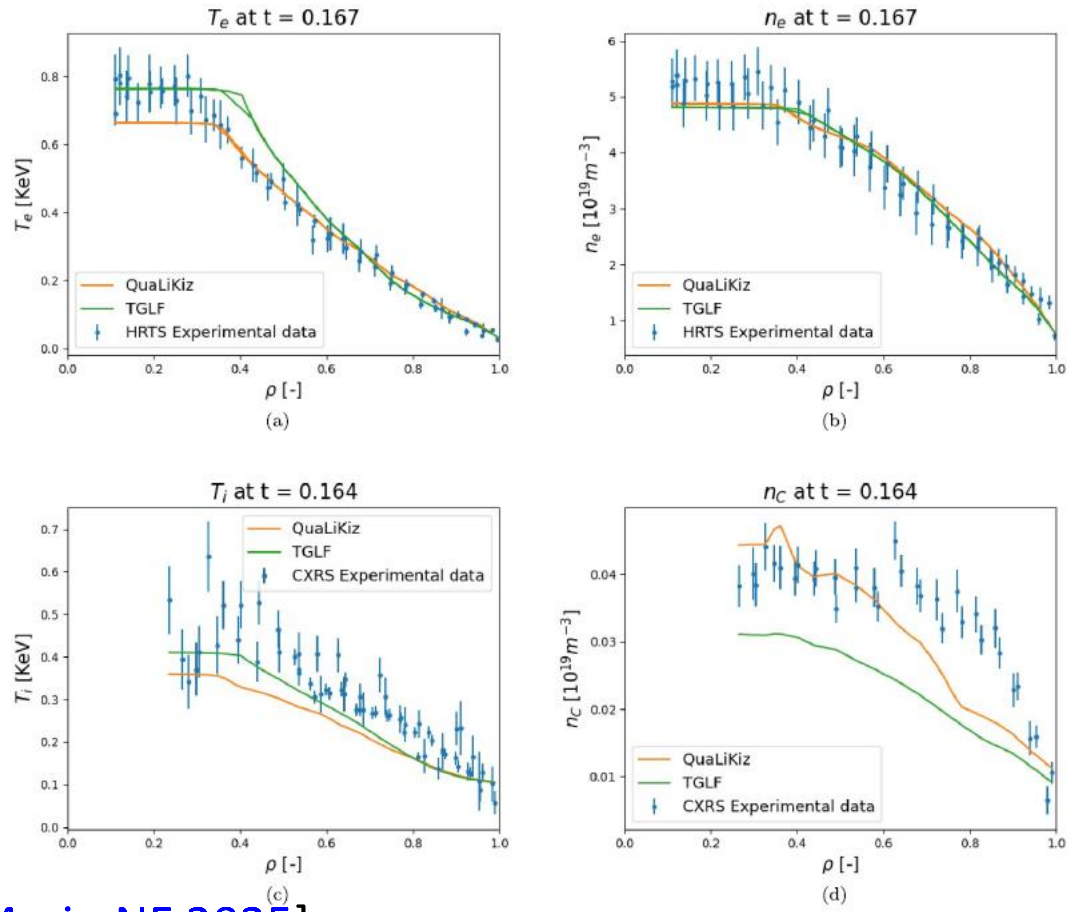
TCV

- **Non-linear couplings:**
  j, T_e T_i **& n_D n_C** QuaLiKiz / TGLFsat2, equip., ohmic, neutrals feedback on nl
  up to ρ=1 I_p ramps 70 to 300 kA
- fixed quantities: sep. values

Question: validity of reduced turbulent models up to LCFS in ramp up? Crucial to prepare operation

Understanding: in C envt, reliable I_p ramp modelling up to ρ=1, predictions better with self-consistent n_D and n_C

Good agreement across the whole radius



[M. Marin NF 2025]

HFPS

Full radius ohmic ramp-up : better prediction if density self-consistently evolved

- **Non-linear couplings:**
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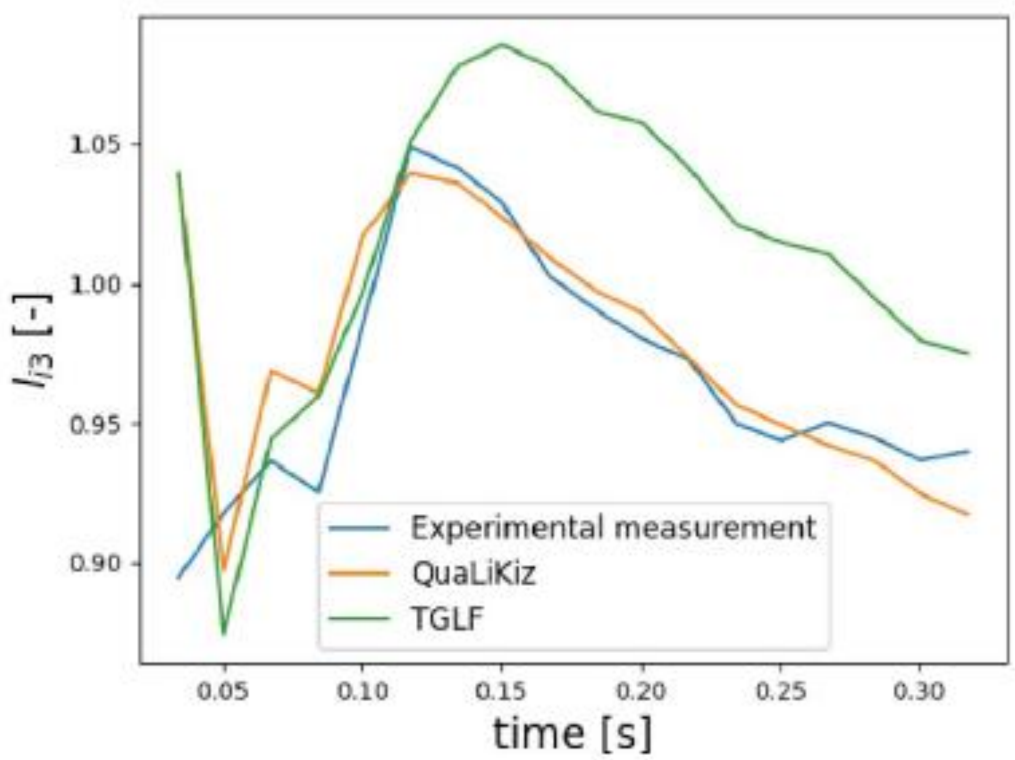


[M. Marin NF 2025]

HFPS

Full radius ohmic ramp-up : better prediction if density self-consistently evolved

TCV

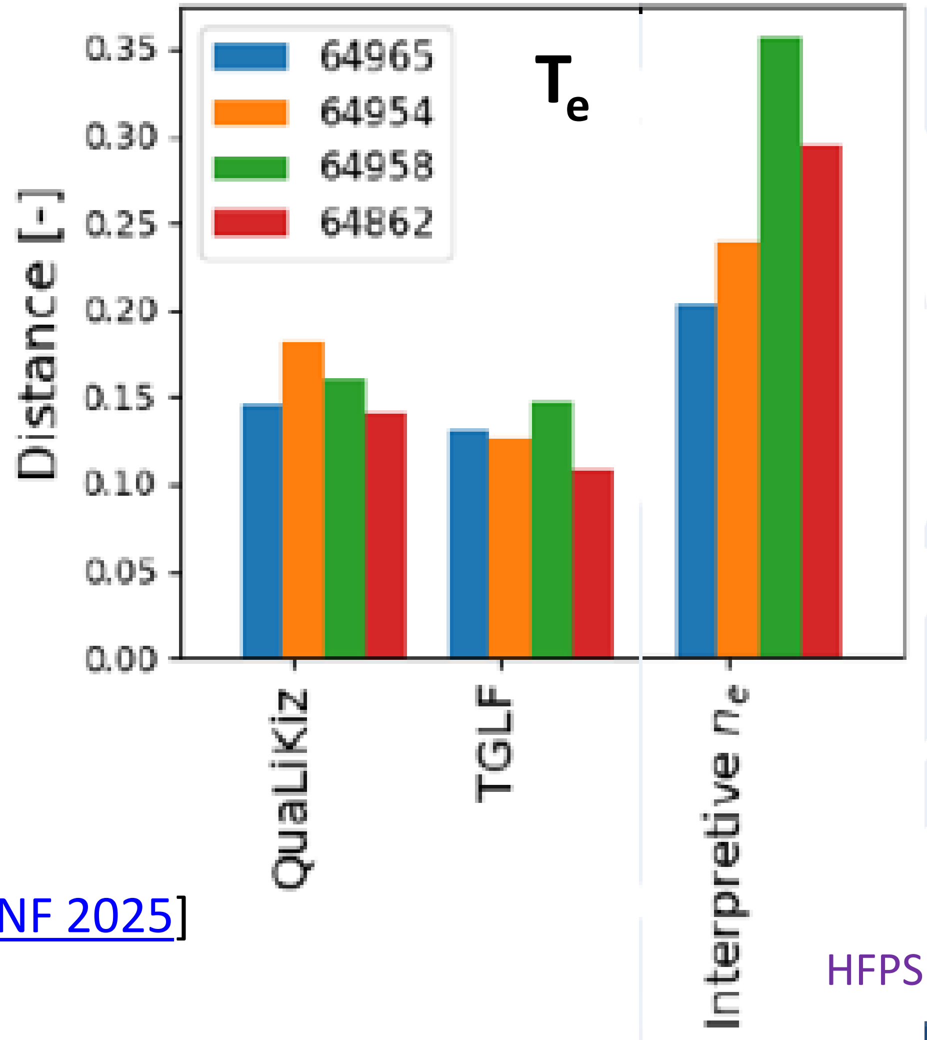
Metrics averaged over multiple radii/times $d = \sum_{\rho=sep}^{axis} 2 \left|\frac{d_{fit}^{\rho} - d_{model}^{\rho}}{d_{fit}^{\rho} + d_{model}^{\rho}}\right|$

- **Non-linear couplings:**

j, T_e T_i **&** n_D n_C QuaLiKiz / TGLFsat2, equip., ohmic, neutrals feedback on nl

up to ρ=1 I_p ramps 70 to 300 kA

- fixed quantities: sep. values



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Understanding: in C envt, reliable I_p ramp modelling up to ρ=1, predictions better with self-consistent n_D and n_C

[M. Marin NF 2025]

HFPS

Preparing WEST 22 min pulse thanks to integrated modelling

WEST

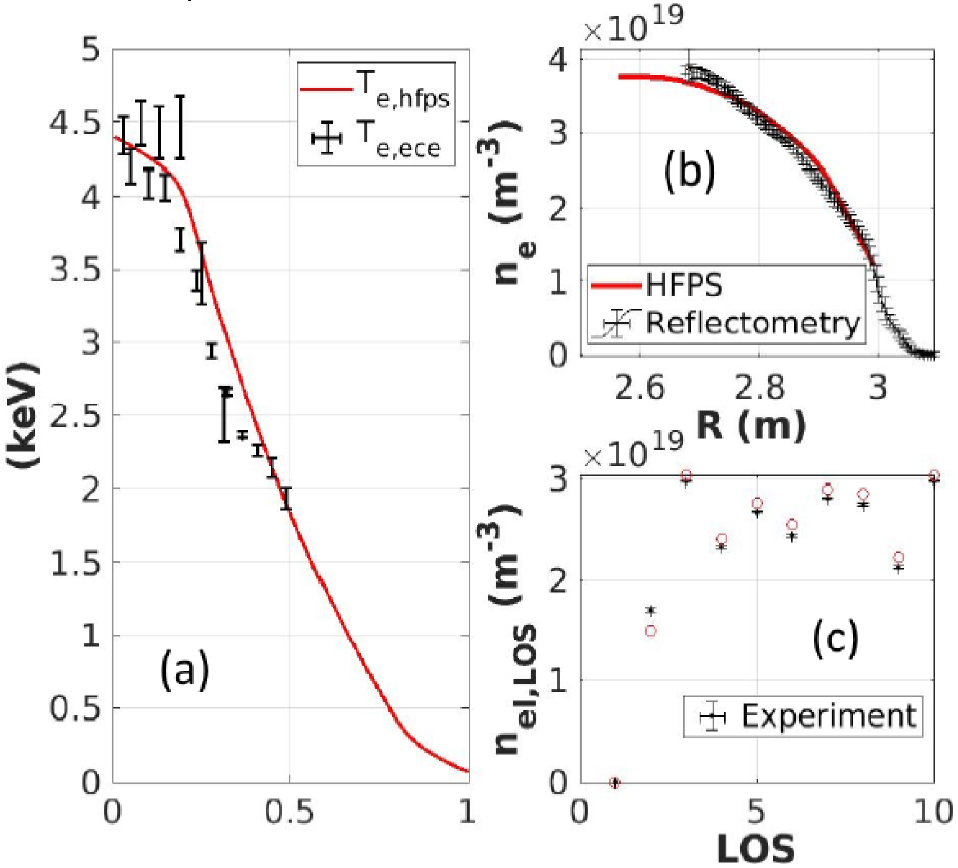
Reference case validation

V_{loop}=47 mV

- **Non-linear couplings**: j, T_e T_i n_D, LHCD (HCD) TGLFsat2, equip., ohmic, neutrals feedback on nl **up to ρ=1**
- Fixed: neutral energy, separatrix values, Z_{eff} and P_{rad}

Question: in which direction to go to reduce the loop voltage?

Understanding: The Ip and LHCD power range 2D map has been provided to guide long pulse experiments



[Fonghetti NF2025]

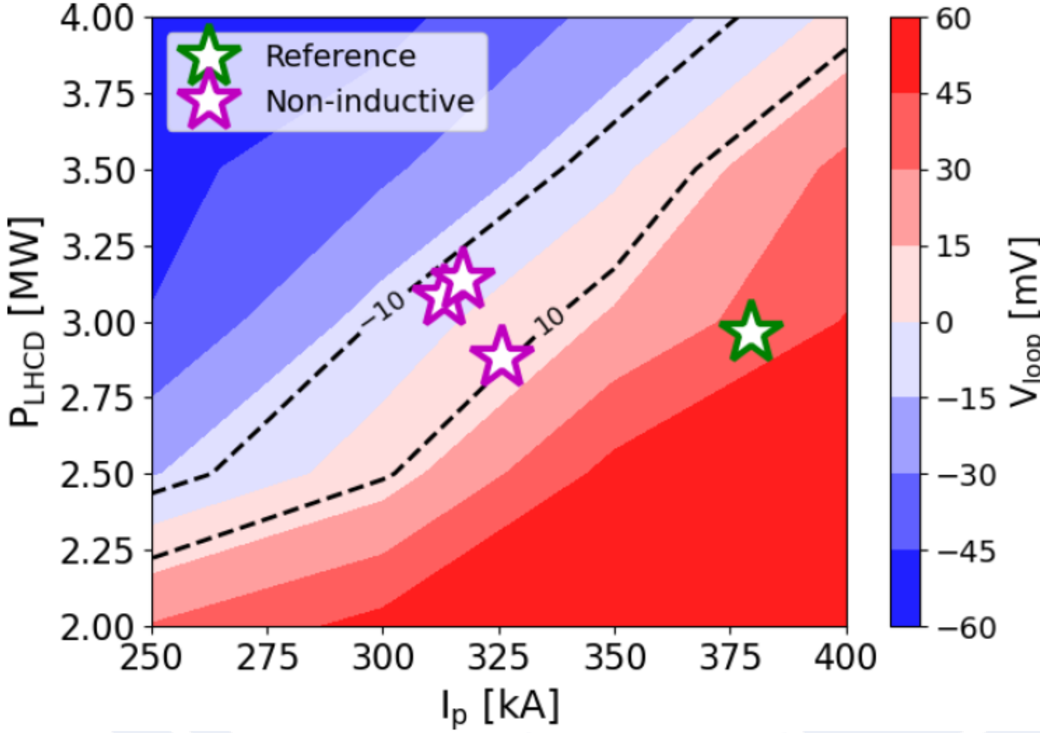
HFPS

Preparing WEST 22 min pulse thanks to integrated modelling

- **Non-linear couplings**: j, T_e T_i n_D, LHCD (HCD) TGLFsat2, equip., ohmic, neutrals feedback on nl **up to ρ=1**
- Fixed: separatrix values, Z_{eff} and P_{rad}

Question: in which direction to go to reduce the loop voltage?

Understanding: The Ip and LHCD power range 2D map has guided long pulse experiments, reaching 22 min



[Dumont IAEA2025, to be sub.]

HFPS

Outline

- High Fidelity Integrated Modelling guiding operation
- **Can integrated modelling do better than scaling laws?**
- Disentangling the causality chain thanks to integrated modelling
- Extrapolating towards burning plasmas
- Benchmark cases
- Perspectives

More complete overview: [Bourdelle PPCF2025]

Integrated modelling based on engineering parameters: better than τ_E scaling laws (L mode)

Non-linear couplings:

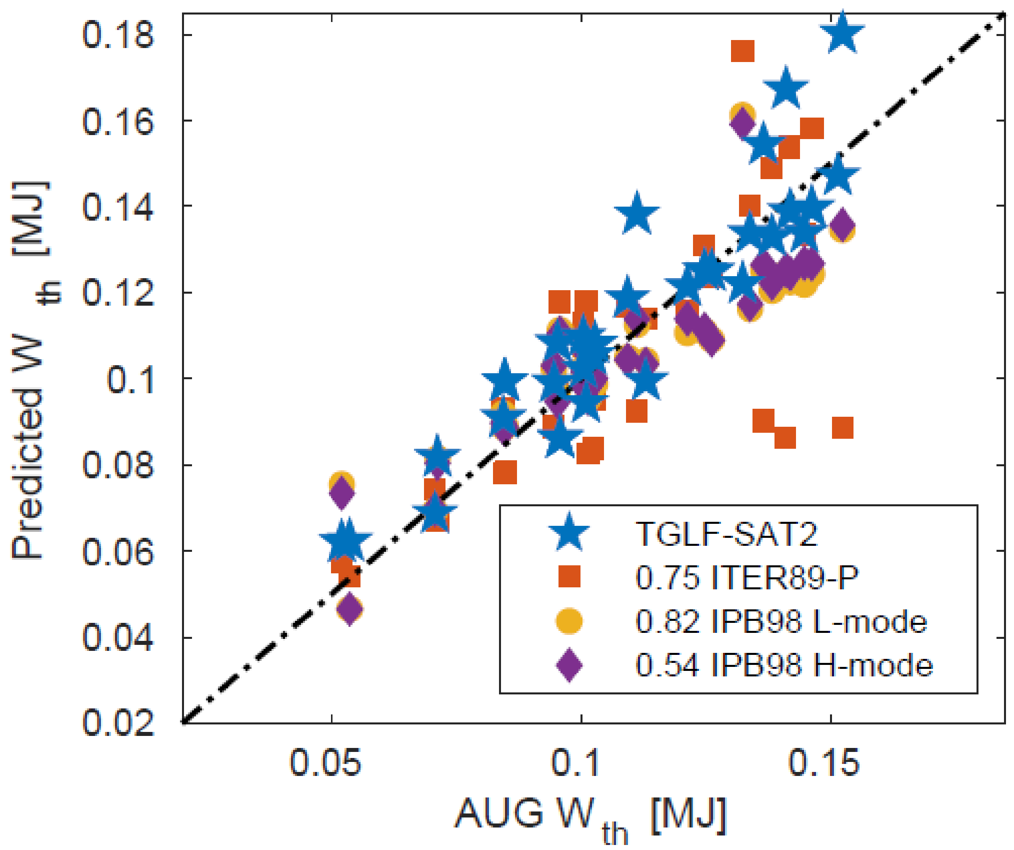
- **up to ρ=1**. T_e T_i n_D, NBI, ECRH, TGLFsat2
- **At sep:** T_{sep} from 2 point model using λ_q scaling [Goldston], n_{sep} =0.3<n> with feedback on <n> frozen current profile

Fixed: j, separatrix Z_{eff} , neutrals energy and P_{rad} = $0.25 \times (P_{heat} - 2)$

Question: can integrated modelling informed by engineering parameters do better than τ_E scaling laws?

Understanding: quantitatively <u>and</u> qualitatively: can investigate causality of I_p, B, R dependences, etc.[Angioni NF2023]. Better than τ_E scaling laws

In H mode : [Luda NF 2020 Luda NF 2021]



[Angioni NF 2022]

ASTRA

Integrated modelling based on engineering parameters: better than τ_E scaling laws (L mode)

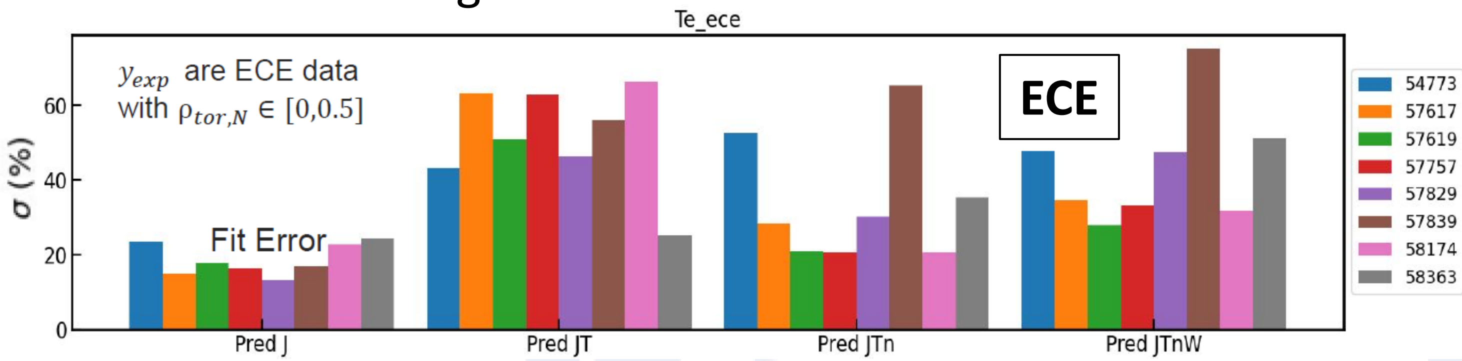
WEST

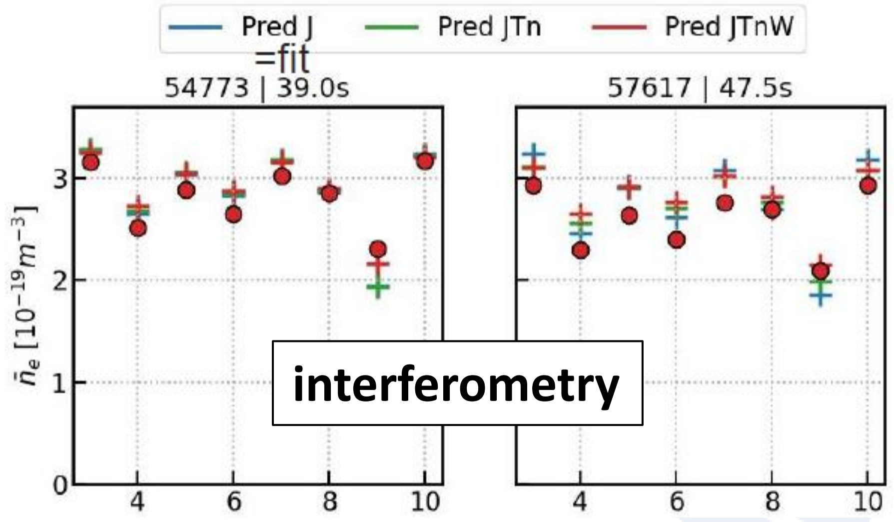
- **Non-linear couplings**: j, T_e T_i n_D, n_W, n_N, LHCD, TGLFsat2. feedback on nvol
- Fixed: neutrals energy, separatrix : Z_{eff} , density, Temp.

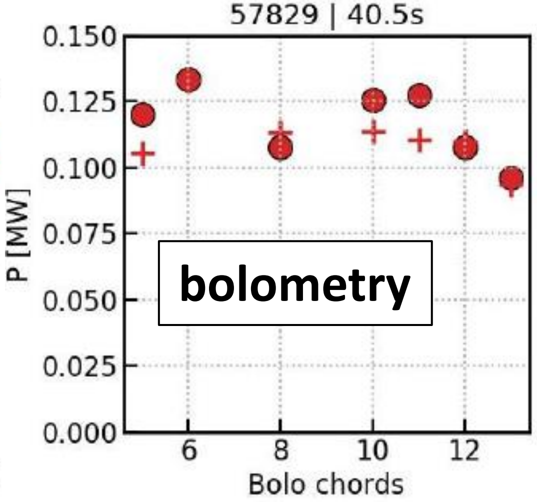
Question: can integrated modelling informed by engineering parameters do better than τ_E scaling laws?

Understanding: quantitatively <u>and</u> qualitatively: can investigate causality of I_p, B, R dependences, etc.Better than τ_E scaling laws

8 pulses at different I_p, identical HFPS settings,
Validation against measurements







[Vergnaud TTF2025, to be sub.]

HFPS

Integrated modelling based on engineering parameters: better than τ_E scaling laws (L mode)

- **Non-linear couplings**: j, T_e T_i n_D, n_W, $n_{N,}$ LHCD, TGLFsat2. feedback on nvol
- Fixed: neutrals energy, separatrix : Z_{eff} , density, Temp.

Question: can integrated modelling informed by engineering parameters do better than τ_E scaling laws?

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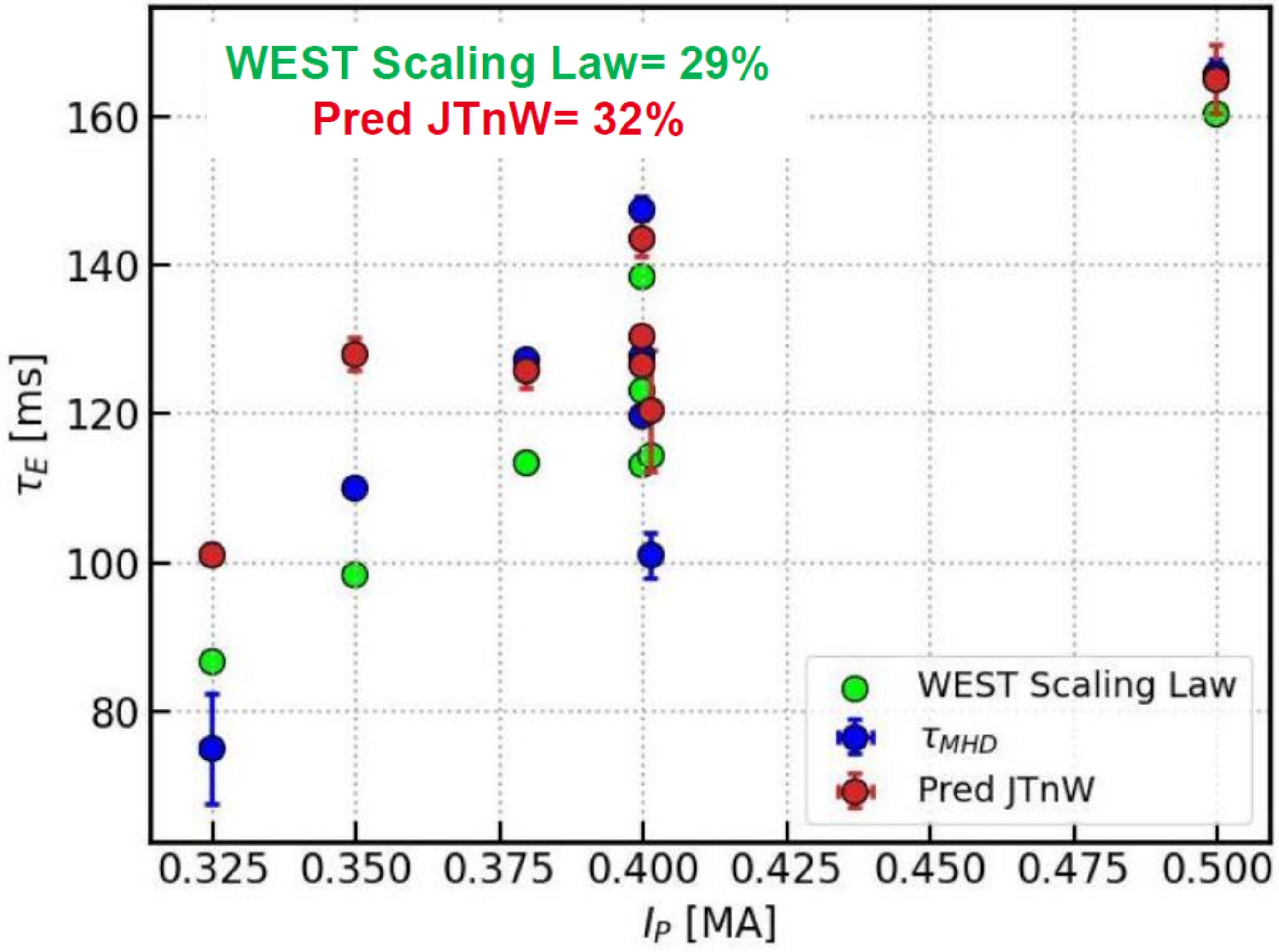


[Vergnaud TTF2025, to be sub.]

HFPS

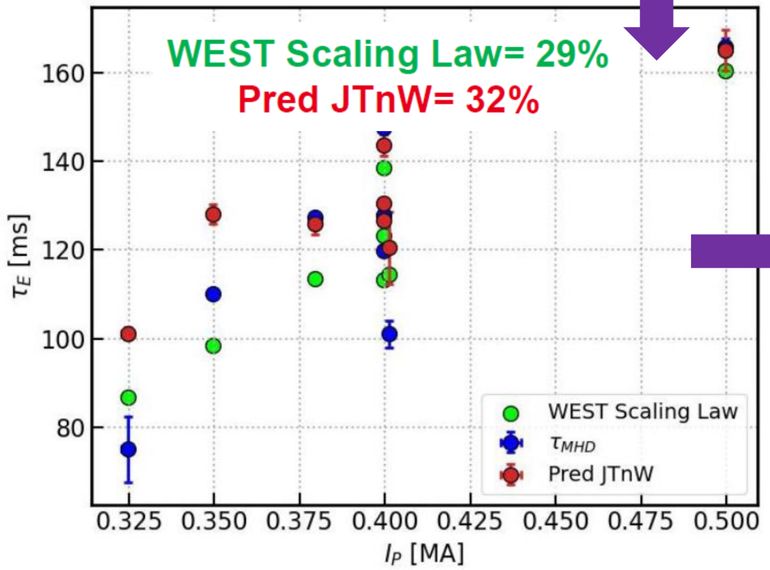
Verificiation of turbulent transport model eased by IMAS gyrokinetics

WEST

Question: HFPS-TGLFsat2 agreement with experiment: for good or bad reasons?

Understanding: for good reasons, we can explore causality & extrapolate

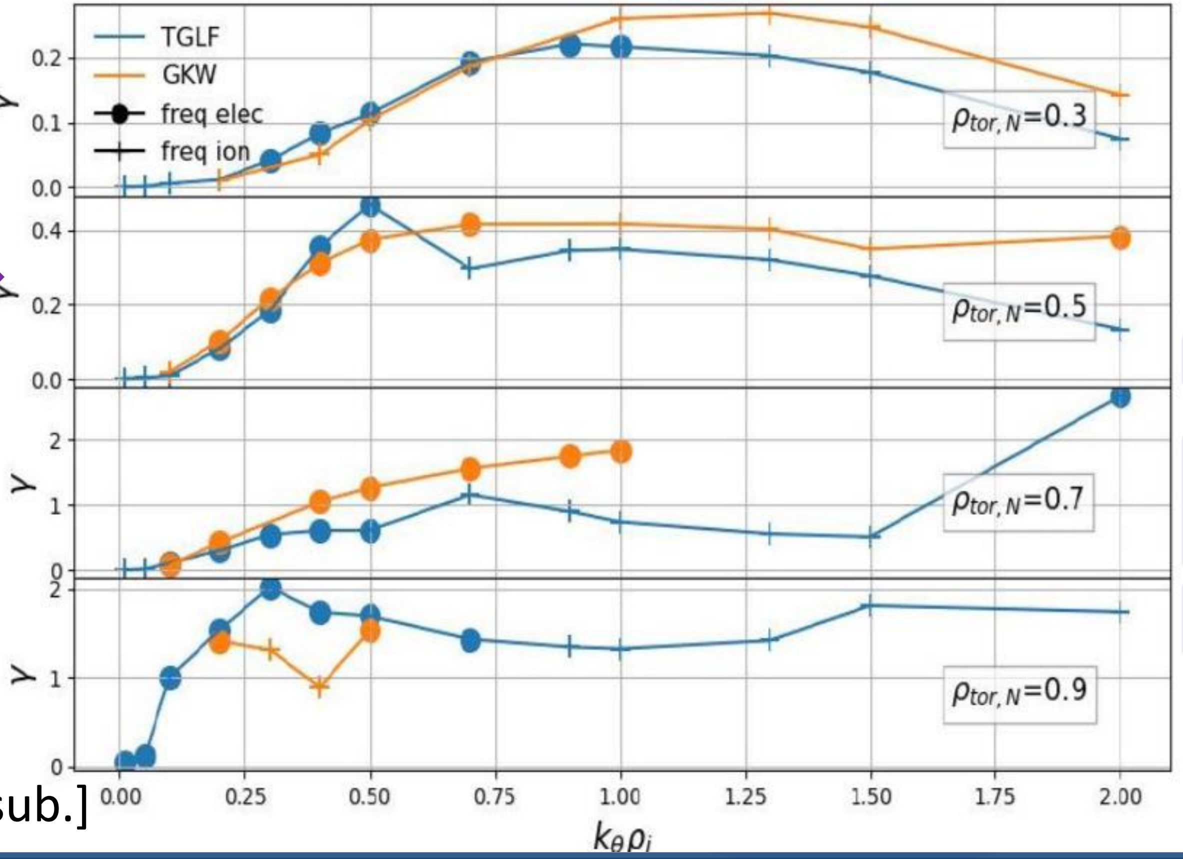
TGLFsat2 used in HFPS here is verified stand-alone against GKW at 4 radii



HFPS

core profiles and equilibrium IDS used to create **gyrokinetic local IDS**

Python scripts
https://gitlab.com/gkdb/imas-gk



[Vergnaud TTF2025, to be sub.]

Large-scale validation thanks to automated extraction, fitting, setup & execution

Metrics on T_e, Ti and n_e

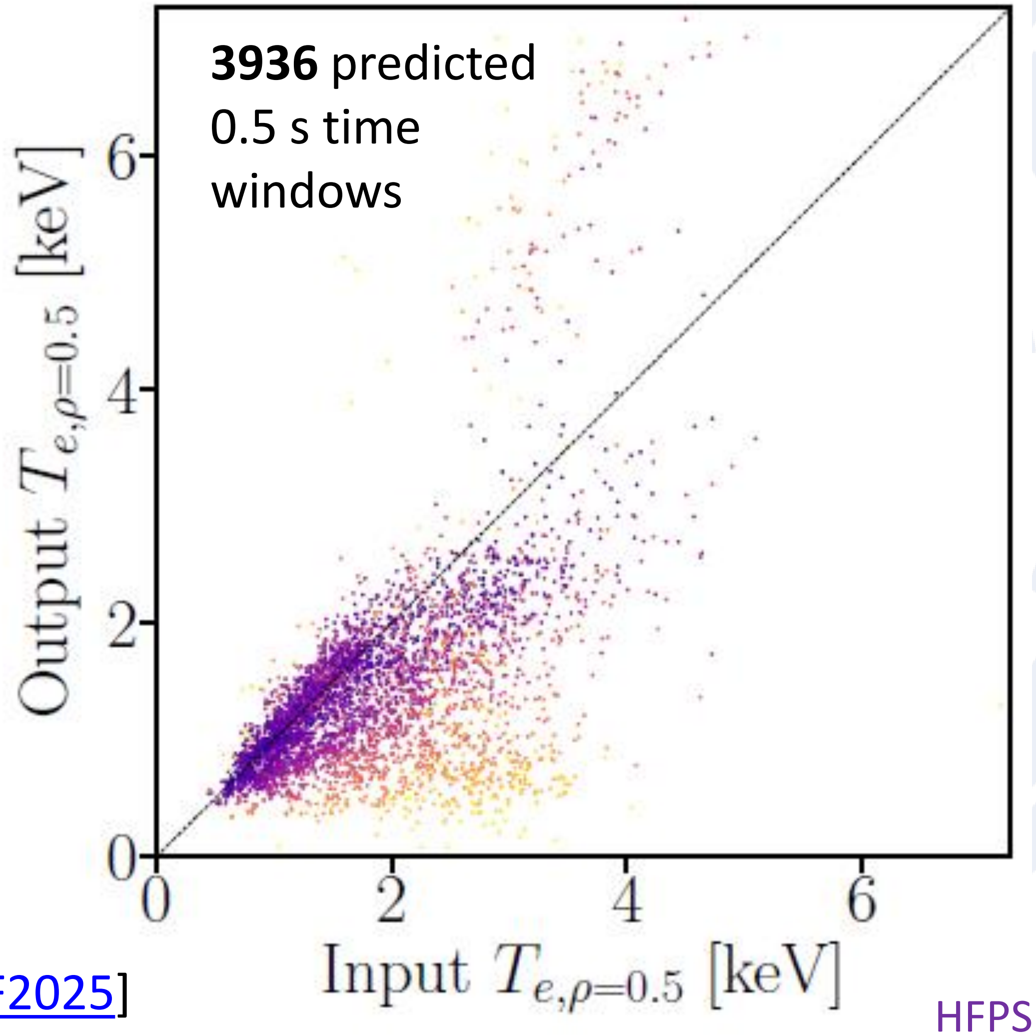
JET

$$M = \sqrt{\frac{1}{6}\left(M^2_{T_e,3} + M^2_{T_i,3} + 4M^2_{n_e,3}\right)}$$

- **Non-linear couplings**: j, T_e T_i n_D NN-QuaLiKiz
- Fixed: from database NBI, Z_{eff}, P_{rad}, exptal measurements at **ρ=0.9**

Questions: 1/ for which range of parameters model prediction best/worse (NN, QuaLiKiz, TGLF), to **guide future model devt needs?**
2/ can we do better than scaling laws **2.0**?

Understanding: on-going, will add 100s of plasmas from WEST, TCV in TSVV-H 2026-2027



[A. Ho EPS/TTF 2023, Bourdelle PPCF2025]

HFPS

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More complete overview: [Bourdelle PPCF2025]

Better than scaling laws: if causality leading to I_p, B, R dependencies revealed

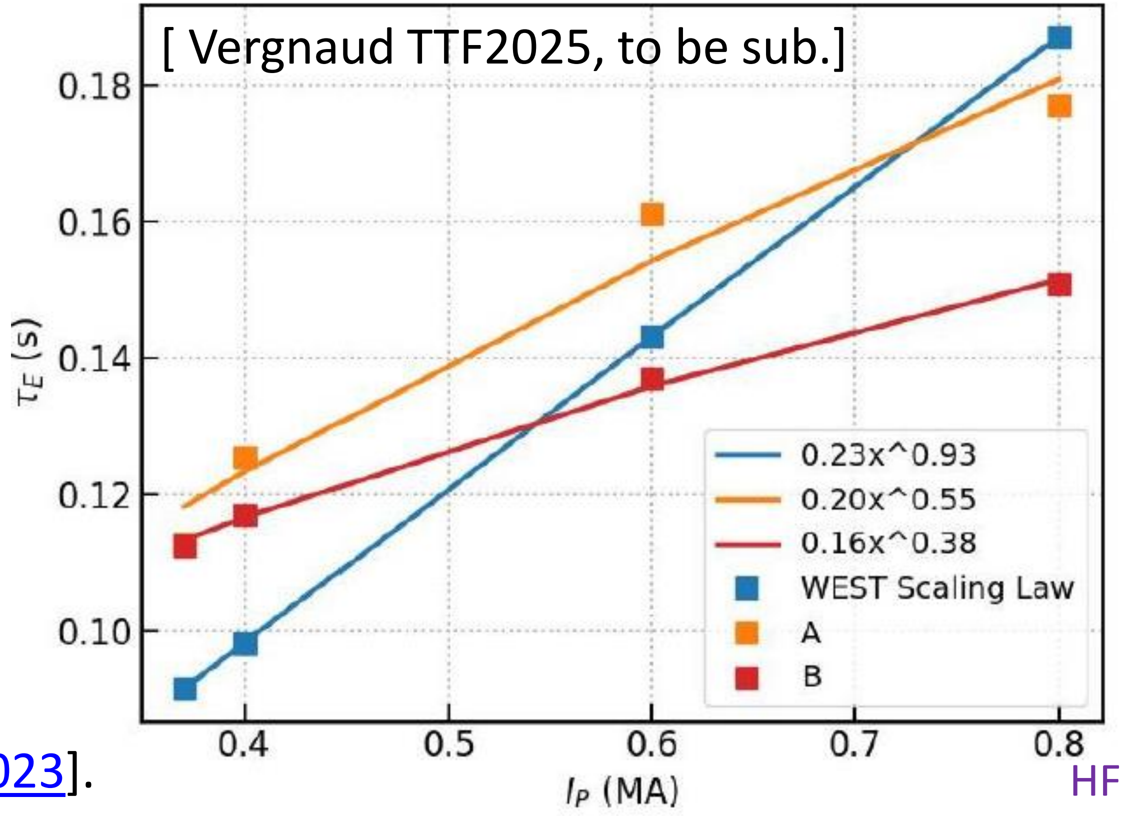
WEST-like

- **Non-linear couplings**: j, T_e T_i n_D, TGLFsat2. Feedback on nl on/off
- Fixed: neutrals energy, separatrix : Z_{eff} , density, Temp. no feedback on Prad, LHCD

Question: what is the physics responsible for I_p impact on τ_E?

Understanding: stronger increase of τ_E with I_p impact when turbulent transport only, weaker when adding feedback on nl. so q impact on turbulence not the only player. On-going

Run Name	J Diffu -sion	Heat Transp.	Particle Transp.	Particle source feedback	LHCD reduced model	Impurity Transp.	T_{sep}, n_{sep}
A	✓	✓	✓	✗	✗	✗	fixed
B	✓	✓	✓	✓	✗	✗	fixed



NB: More causality of I_p, B, R dependences in [Angioni NF2023].

HFPS

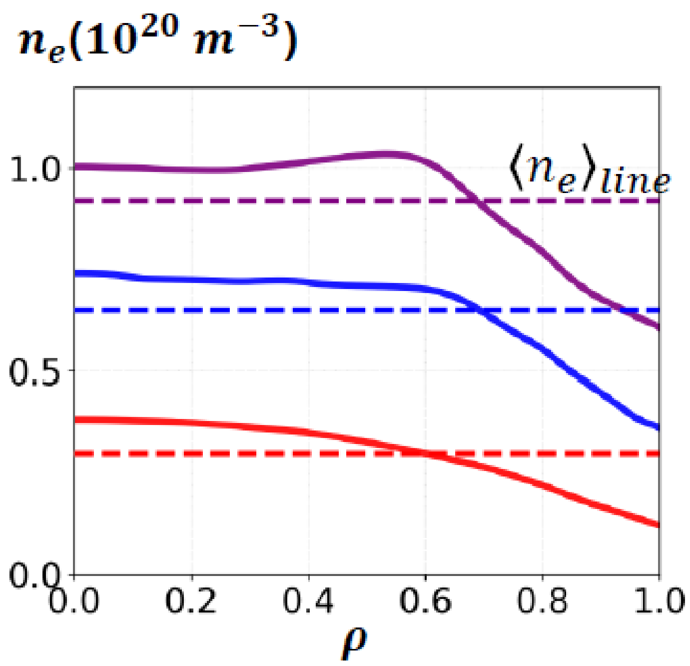
Separatrix T and n impact on core performances : higher energy content at larger n_{sep}

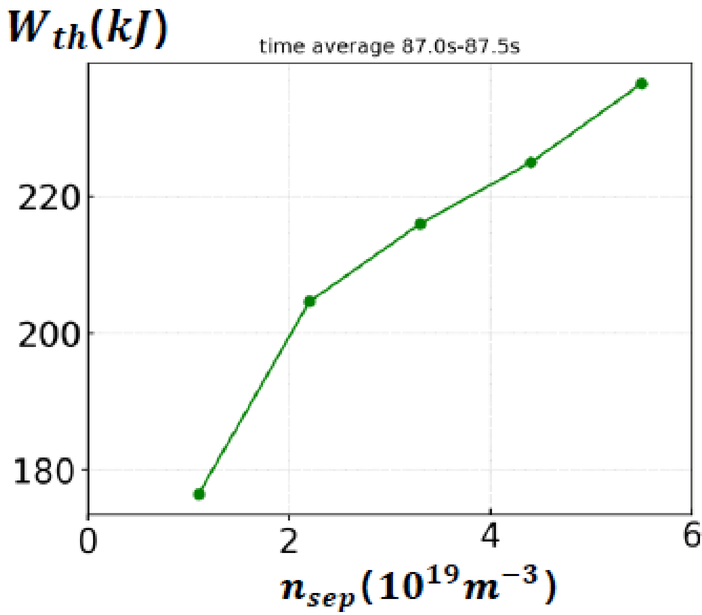
WEST-like

- **Non-linear couplings**: j, T_e T_i n_D, TGLFsat2.
- Fixed: neutrals energy, separatrix : Z_{eff} , density, Temp. no feedback on nvol, Prad, LHCD

Question: do the separatrix T and n impact core performances? Why?

Understanding: strong impact of n_{sep} up to ρ=0.6. Likely due to collisionality impact on turbulence nature, leading to inward particle flux.





[Bing Liu TTF2025, to be sub.]

HFPS

Separatrix T and n impact on core performances : verification TGLFsat2 vs higher fidelity GENE

Verification TGLFsat2 vs GENE

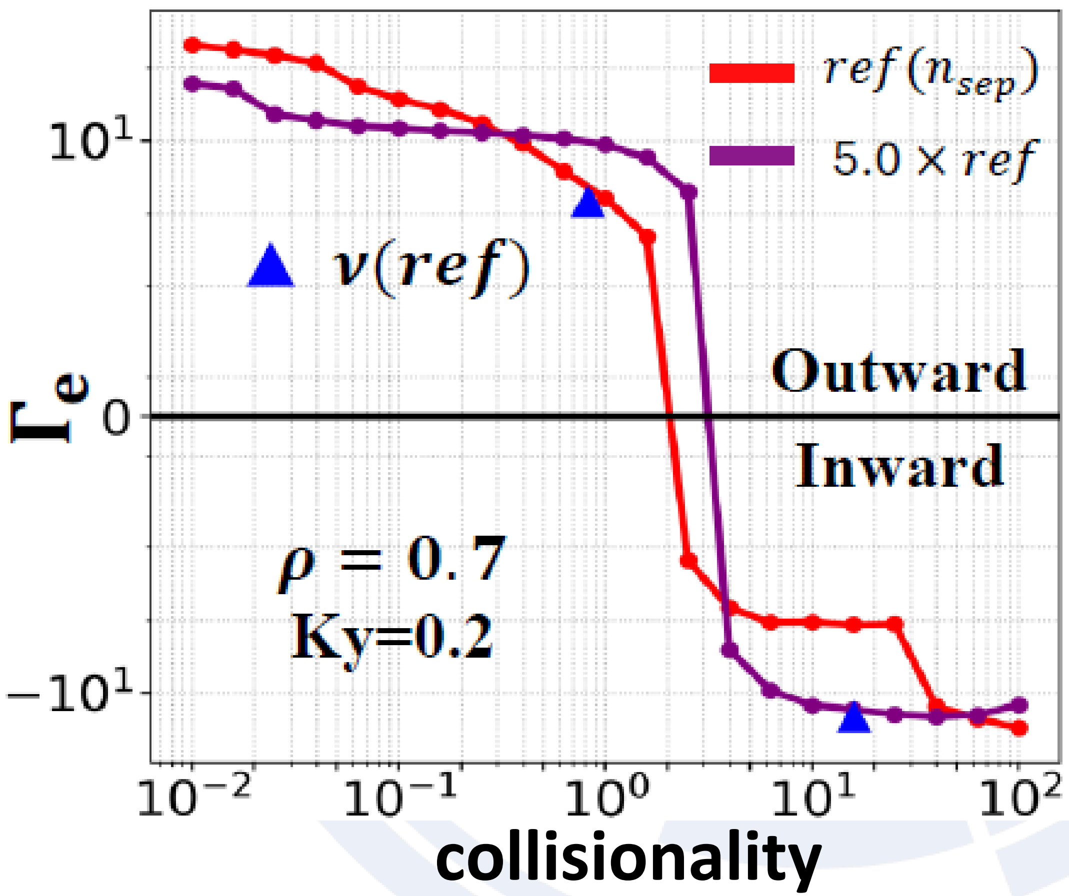
- IDS from HFPS used to produce gyrokinetic local IDS directly input in TGLFsat2 and GENE for stand alone verification
- Hence we can trust validity of TGLFsat2 stand alone exploration

Question: do the separatrix T and n impact core performances? Why ?

Understanding: strong impact of n_{sep} up to ρ=0.6. Likely due to **collisionality impact on turbulence nature, leading to inward particle flux.**

See also [Snoep ArXix 2025, Bonanomi PPCF 2025]

TGLFsat2 particle flux



[Bing Liu TTF2025, to be sub.]

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More complete overview: [Bourdelle PPCF2025]

Illustration of importance of physics based understanding in burning plasma: impact of β on turbulence (w/o fast particles)

- **Non-linear couplings:**

j, **T_e T_i & n_T n_D**, equip., ohmic, P_{rad} , NBI **, P_{fus}**
- Core, ρ<0.93 **TGLFsat2, different low $k_\theta \rho_s$ settings**
- Ped: n_{ped} pellet feedback P_{ped}: ITER-EPED scaling
- n_{sep} T_{sep}, SOLPS-ITER scaling

- Fixed: plasma composition, ECRH, V_{tor}

For the 1st time, a reference IDS is shared within ITPA T&C for the ITER 15 MA scenario. It is on ITER cluster and includes initial conditions, plasma composition, heat/particle sources, V_{tor} and q profiles

ITPA TC-33 joint activity

ITER Ip=15 MA reference cases: sources and profiles in IMAS Data Structure

C. Bourdelle, F. Koechl, E. Tholerus, M. Schneider, F. Casson, C. De Piccoli, F. Eriksson, D. Fajardo, S-H Kim, L. Garzotti, E. Militello-Asp, S. Pinches, A. Polevoi

**

Reference ITER 15 MA case to be used for:
- Integrated modeling framework benchmark (HFPS, ASTRA, ETS, PTRANSP etc. But also Portals, Tango, etc).
- Comparing/verifying turbulent transport codes while keeping fixed to this reference case identical pedestal, plasma composition, toroidal velocity and sources.
- Isolating the impact of a particular parameter around a case familiar to all, such as impurity content, rotation, the q profile, the pedestal height etc.

**

- **Starting point** : Florian Koechl's JETTO case published in [Mantica PPCF 2020] and used in [Citrin PoP 2023].
- **Time frame** lasting 130 s (from 320 to 450 s)

Question: can we predict turbulent transport at high β using physics based reduced el-mag model ?

Understanding: Small changes on lowest k modes at high β (KBM) impact profiles ρ>0.6, hence P_{fus} need higher fidelity code verification at high β

Illustration of importance of physics based understanding in burning plasma: impact of β on turbulence (w/o fast particles)

- **Non-linear couplings:**

T_e T_i & n_T n_D, equip., ohmic, P_{rad}, NBI, P_{fus}

- Core, ρ<0.93 **TGLFsat2, different low $k_\theta \rho_s$ settings**
- Ped: n_{ped} pellet feedback P_{ped}: ITER-EPED scaling
- n_{sep} T_{sep}, SOLPS-ITER scaling

- Fixed: q (flat inside q=1), plasma composition, ECRH, V_{tor}

Question: can we predict fusion power in a burning plasma?

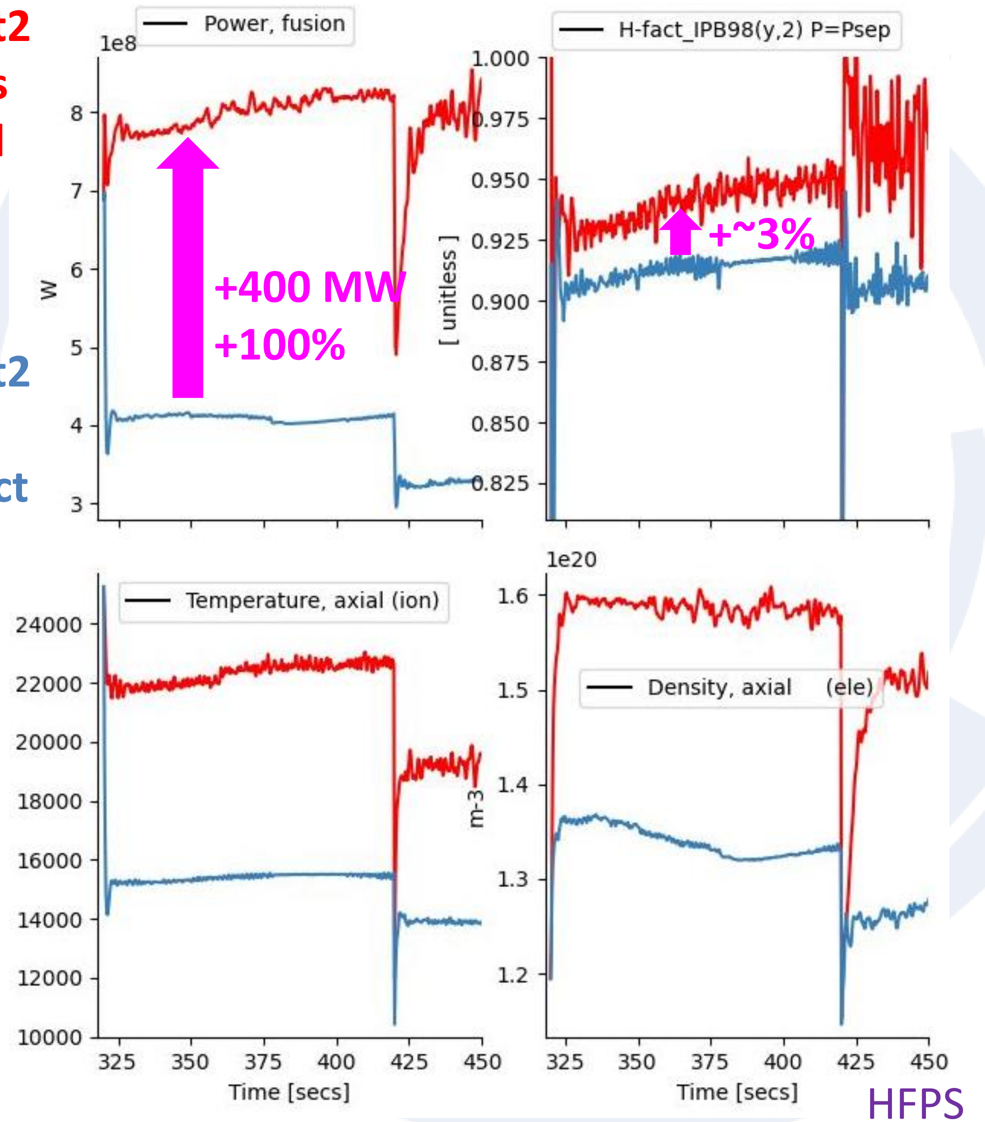
Understanding:

- **No linear link btw H factor and P_{fus}. Here H factor + 3% = $P_{fus} \propto n_{fuel}(0)^2 T_i(0)^2$ + 100%**
- Small changes on lowest k modes at high β (KBM) impact profiles ρ<0.6, hence P_{fus} need higher fidelity code verification at high β [A. Di Siena sub. NF] GENE-Tango vs TGLFsat2-HFPS

IDS of **ITER 15 MA ref** as input

TGLFsat2 settings verified against GENE-Tango

TGLFsat2 default electrostatic



HFPS

Outline

- High Fidelity Integrated Modelling guiding operation
- Can integrated modelling do better than scaling laws?
- Disentangling the causality chain thanks to integrated modelling
- Extrapolating towards burning plasmas
- **Benchmark cases**
- Perspectives

Benchmark cases: what for?

Aiming at interoperability among High Fidelity Integrated Modeling Frameworks and Pulse Design Tools Need to be able to verify various fidelity levels on integrated modelling

IMAS

+
Python

+
Muscle 3

multiscale / muscle3

4 cases proposed:

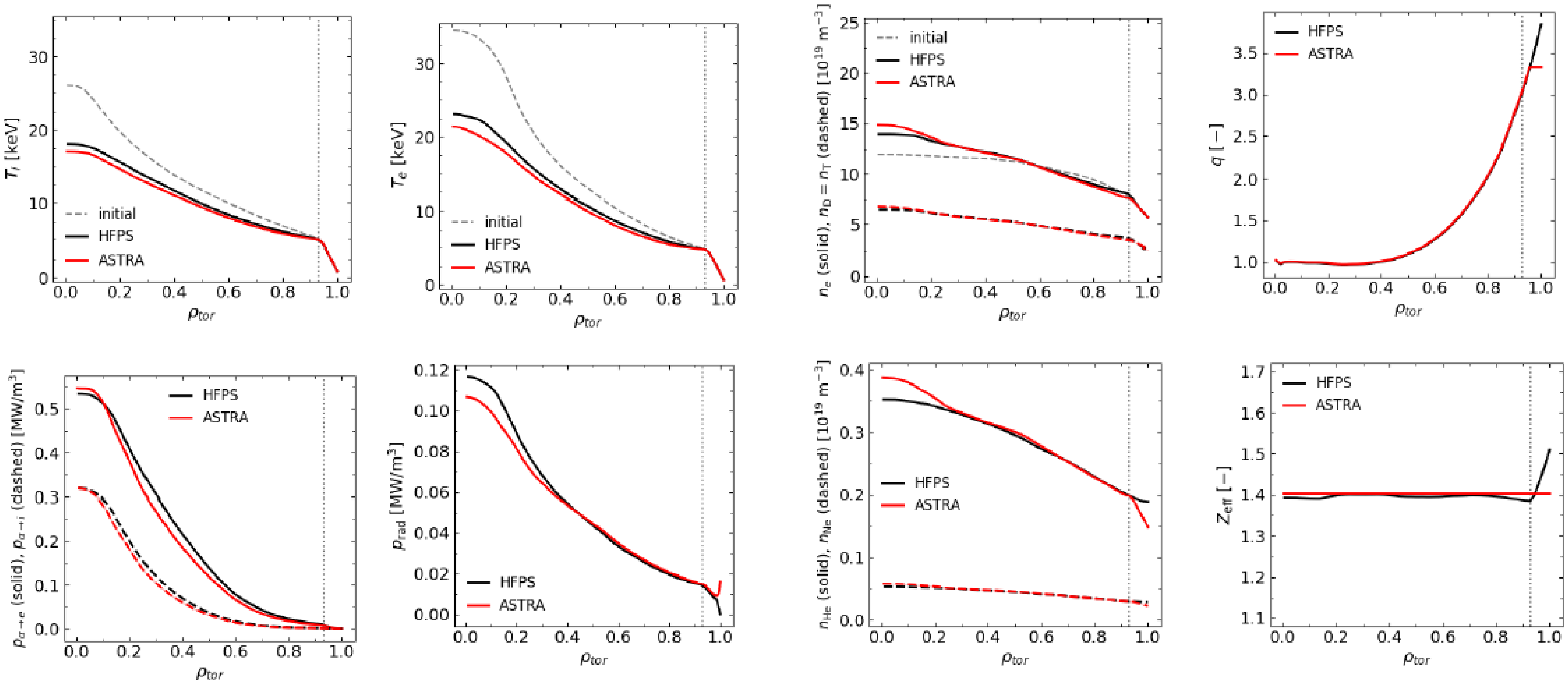
- Turbulent heat+particle transport on JET case DT vs D
- + Self-consistent W neoclassical and turbulent transport: AUG case
- + HCD: WEST long pulse case
- Burning plasma: ITER 15 MA benchmark ITPA case

IDS for each cases: available on the EUROfusion Gateway and on ITER simdb for the ITER case

On-going high fidelity integrated modelling: HFPS, ASTRA, ETS
Pulse design tools: TORAX, METIS.
Open to more.

ITER 15 MA benchmark ASTRA/HFPS

- Both running TGLF-SAT2 with the same (new) settings and flat, fixed *q*-profile



MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK | D. FAJARDO | 25.11.2025

ITER 15MA REFERENCE SCENARIO: PARAMETER SCANS WITH ASTRA AND BENCHMARK WITH HFPS

Perspectives

- High Fidelity Integrated Modelling guiding operation: need to maximize synergy with Pulse Design Tools, to maximize physics model exchange, flexibility to go up/down fidelity levels of various models. Adding MHD module in HFPS

- Can integrated modelling do better than scaling laws? Yes! Need more automated large scale validation, planned in 2026-2027 TSVV-H (continuing TSVV-11) adding more surrogates FACIT, TGLFNN, MISHKANN, HPI2NN

- Disentangling the causality chain thanks to integrated modelling: more to be done to understand engineering parameters impact, boundary condition impact adding SOLPSNN

- Extrapolating towards burning plasmas: turbulent transport model verification mandatory! Core profile prediction essential $\boldsymbol{P_{fus}} \propto n_{fuel}(0)^2 T_i(0)^2$ +10% on $T_i(0)$ and $n_{fuel}(0)$ means +40% on P_{fus} adding ATEP

2026-2027 : From TSVV-11 to TSVV-H

TSVV-H: Reliable Prediction of Plasma Performance and Operational Limits in Tokamaks

WP1: Integrating Modelling Workflow orchestration and module coupling framework

WP2: key physics modules validation

WP3: Physics driven benchmarks

WP4: Large scale validation

Welcome to Michele Marin from SPC as our new TSVV-H PI!

Poznan 2022

Eindhoven 2023

ITER 2024

Culham 2025

Validation, verification before extrapolation!

EXTRAPOLATION

VALIDATION

Physics understanding	Prepare (ITER) operation	Design future devices (DEMO)

1st principle codes Turbulent transport SOL Pedestal Core: High β, fast ion	**High Fidelity Integrated Modeling**	**Pulse Design Tools** Full pulse, testing controllers	**System codes** in/out are engineering parameters only

VERIFICATION

Validation against tokamak experiments,
including high β (JT60-SA), $P_{alpha}>P_{aux}$ hence **Q>5 experiments (ITER)**

Whole device modelling, **different fidelity levels need synergy/verification.**
To prepare ITER operation and design future devices
2020-2025: TSVV11-TSVV15, TSVV14 →2026-2027: TSVVH **+ ?**