EUROfusion

TSVV11

C. Bourdelle and the TSVV11 team

11-15/11/2024 Garching

Aix-Marseille université · IPP Max-Planck-Institut für Plasmaphysik · EPFL École Polytechnique Fédérale de Lausanne · Swiss Plasma Center · CEA De la recherche à l'industrie · DIFFER · UKAEA

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

TSVV11 team

- Team members

C. Angioni, J.-F. Artaud, M. Bergmann, N. Bonanomi, Y. Camenen, F.J. Casson, D. Coster, N. Cummings, E. Fable, D. Fajardo, T. Fonghetti, P. Fox, A. Ho, R. Lorenzini, P. Maget, P. Manas, M. Marin, A. Panera-Alvarez, Z. Stancar, G. Tardini, E. Tholerus, V.K. Zotta

- Regular participants to TSVV11 meetings

F. Koechl, J. Citrin, L. Garzotti, T. Luda, Th. Jonsson, S. Gabriellini, G. Snoep, R. Coelho, P. Strand, D. Yadykin, C. Giroud, L. Chôné, F. Imbeaux, R. Dumont, F. Auriemma, P. Vincenzi, M. Valisa, E. Militello-Asp, P. Mantica, J. Simpson, J. Citrin, F. Felici, J. Morales, K. van de Plassche, S. Wiesen, A. Kirjasuo, J. Lombardo, H. Dudding, S. Shi, F. Eriksson, A. Kit, A. Järvinen, E. Vergnaud, R. Bilato, B. Labit, Ph. Huynh

3 in person meetings, 1 ‘hands on’ meeting + regular results/challenges update incl. some joined with other TSVVs

Poznan April 2022

Eindhoven March 2023

ITER January 2024

September 2024, ‘hands on’ week at Culham

3 joined TSVV1 meetings: Er well, L and L-H

4 joined TSVV10 meetings

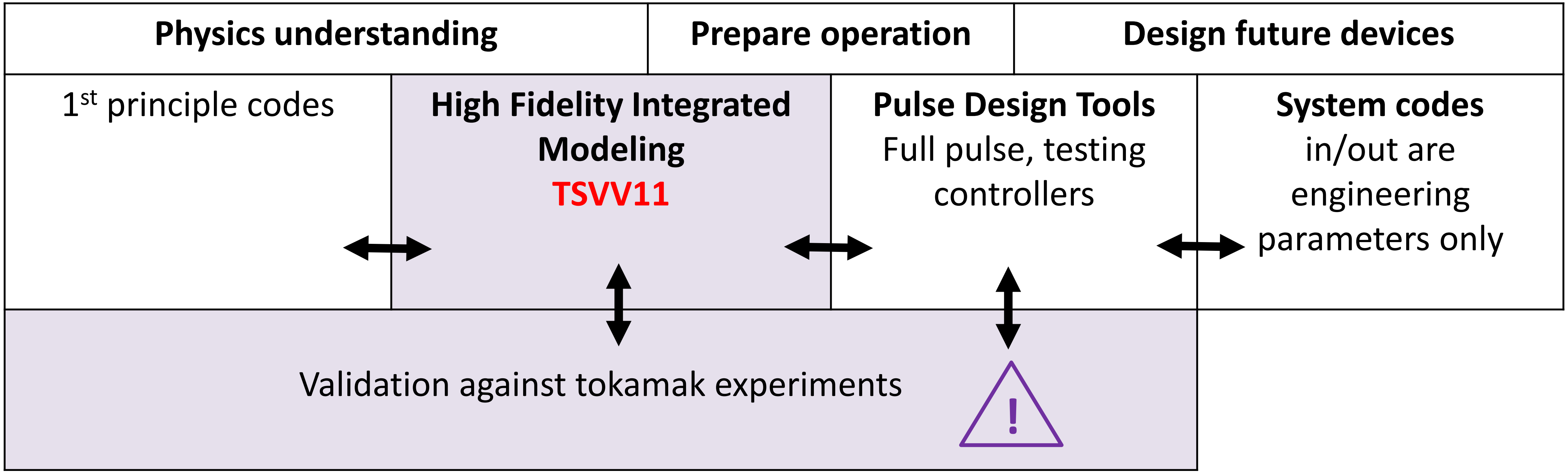
- a fundamental understanding oriented approach is carried out in strong synergy with the TSVV10
  - 4th joined meeting, October 2024, GENE-TAngo on ITER 15 MA w/o fast alpha interplay but with Pfus update, slides here
  - 3rd joined meeting April 2024, summary and slides here
  - 2nd joined meeting Nov 2023, summary and slides here
  - 1st joined meeting, Sept 18 2023, slides, summary and action plan here

Regular on-line meetings

TSVV-11-general-meetings

- 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
- 37th general meeting, large scale automated validation of JET data (A. Ho)
- 36th general meeting, joined with TSVV1, on L mode 1st rpinciple vs reduced models validation (G. Snoep)
- 35th general meeting, joined TSVV1-TSVV11, on Er profile formation
- 34th general meeting, JET EDGE2D+ERO+PED+NEO+W modelling (Henri Kumpulainen)
- 3rd in person TSVV11 meeting Jan 22-26 2024 at ITER
- 33rd general meeting, joined TSVV1-TSVV11, on L-H transition integrated modelling results and challenges (N. Bonanomi)
- 32nd general meeting, turbulent transport model settings within HFPS vs ASTRA/ETS
- 31st general meeting, workflow orchestration progresses
- 30th general meetiing, TTF rehearsals: TCV Ip ramp up (M Marin), impurity transport in AUG (D. Fajardo), Bayesian Optimization in WE
- 29th general meetiing, EPS poster rehearsals: large scale valdiation on JET database (A. Ho) and TCV Ip ramp up gyrokinetic modellin
- 28th general meeting, June 16th 2023: WEST ICRH impact on core heating with HFPS and JINTRAC ITER Q=10 modelling

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



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

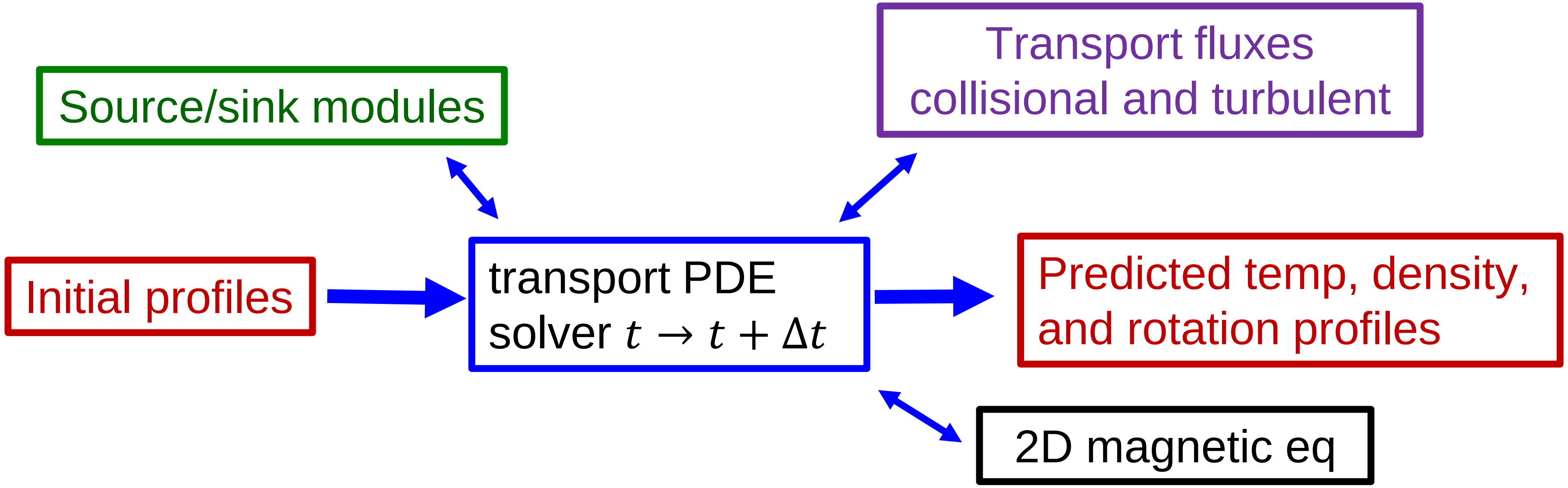
Various boundary conditions: pedestal top, separatrix, divertor targets

Various model fidelity: empirical scaling, reduced physics model etc

Integrated modelling framework
to orchestrate iterations btw physics modules

Integrate our physics understanding: radiation, heating, transport, MHD stability, equilibrium, neutrals in a time evolving framework

Multi-scale (spatial&temporal) and multi-physics problem



Particle flux — Particle sources/sinks

Particle density: $$\frac{\partial n_s}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_s) = S_s$$

Energy: $$\frac{3}{2}\frac{\partial P_s}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r q_s) = Q_s$$

Heat flux — heat sources/sinks

$$t_{integrated\ sim.} = t_{turb.fluxes} \times \frac{t_{discharge}}{\Delta t_{transp.\ solver}} \times N_{iterations}$$

($t_{discharge}$: 1-1000 s; $\Delta t_{transp.\ solver}$: 10^{-3} s; $N_{iterations}$: 1-10)

$$t_{integrated\ sim.} \approx 10^4 \times t_{turb.fluxes} < \sim 24\text{h}$$

($t_{turb.fluxes}$: ~<10s)

Multiple such modelling frameworks in use, JINTRAC, ASTRA, ETS, TOPICS, PTRANSP among others

High Fidelity Pulse Simulator Development Strategy

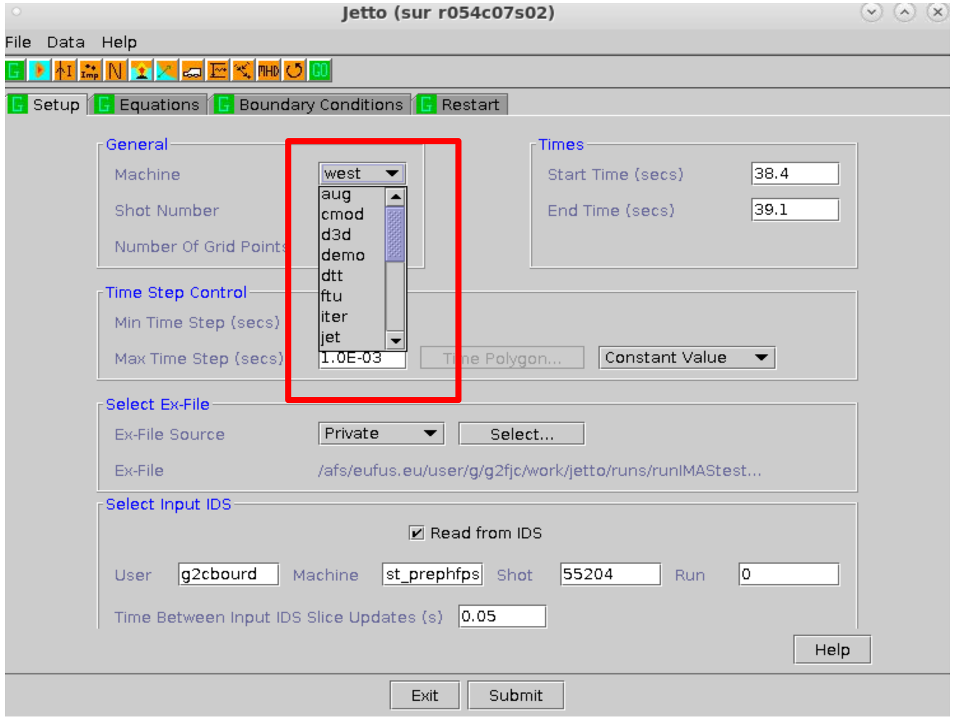
Guidelines for the High Fidelity Pulse Simulator in TSVV11

	High Fidelity Pulse Simulator
Infrastructure	Python-driven workflow based on IMASified JINTRAC **Ideally aligned with ITER but…** ASTRA (A. Polevoi) , ETS based (F. Poli), IMASified JINTRAC (SH Kim), JINTRAC (F. Koechl)
	IMAS data structure for inputs and outputs also at module level NB: Open-sourcing at ITER in the pipeline
On-going	**Validate advanced physics modules** in flux driven int. modelling Synergy with other physics activities within EUROfusion and elsewhere
	Benchmark cases: including W interplay, Burning plasma
	Large scale validation against EU operating tokamaks, incl. automated validation tools
upcoming	Planned devt: Open-sourcing the workflow and most modules, use of Muscle3 lib. in python workflow. Maximize synergy with Pulse Design Tools (TSVV15)

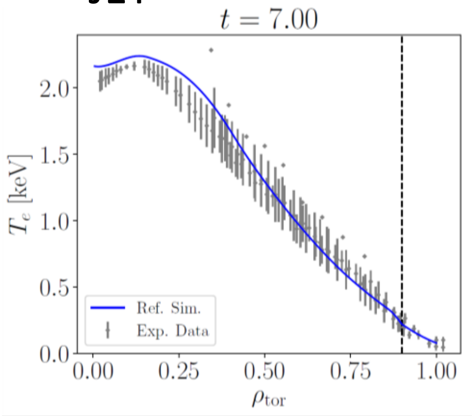
High Fidelity Pulse Simulator

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

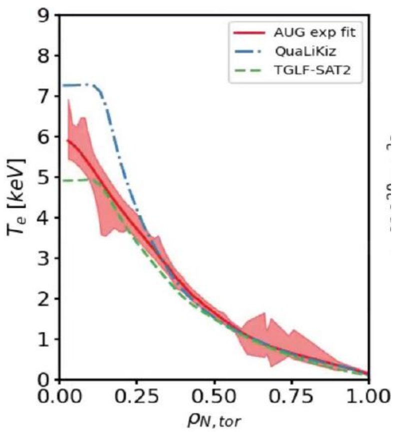
Looking forward for systematic access to JET IMASified data, as well as AUG and TCV (Data Management Plan)



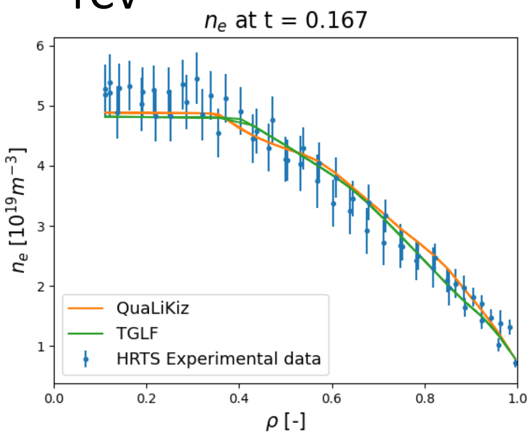
JET



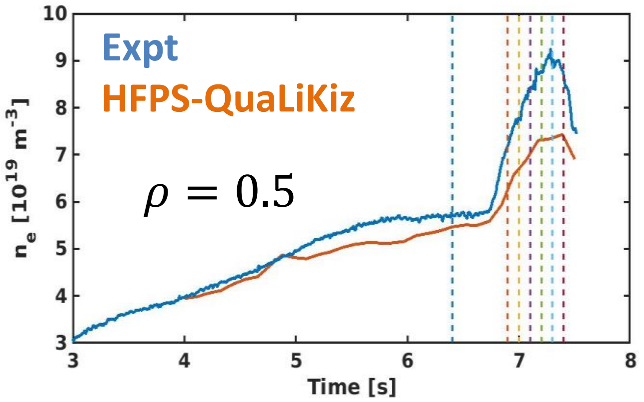
AUG



TCV



WEST



High Fidelity Pulse Simulator

The HFPS is a collection of IMAS actors used together in a python workflow

- Combines ETS components (HCD) and all JINTRAC components
- Coupling *framework* prototypical but functional: we hope it will grow further

All actors take physics input / output from IMAS Data Structure via argument

- Actors wrapped via FC2K -> **migrating to Persistent Actor Framework MUSCLE3**
- Each actor handles code specific params in it's own way
- GUI collects *all* input files in one folder, launches workflow.
- Non JINTRAC actors provide their own GUI
- MDS+ and HDF5 backends supported
- Most JINTRAC components containerized, deployed to cloud resources

netherlands eScience center

IGNITIONCOMPUTING

ACH PSNC

How it could evolve

- Agree standards for IMAS python workflows, converge on common methodology / tools with ETS, ASTRA and TSVV15 Pulse Design Simulator
- Add new actors as they are adapted to python
- A common GUI

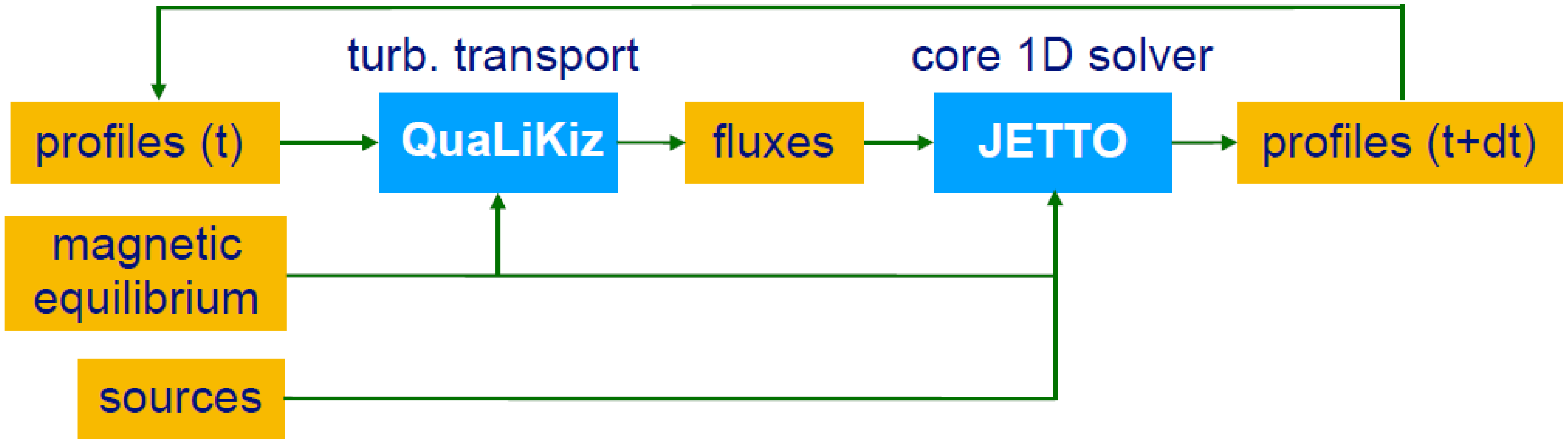
- Twice / year: ASTRA, ETS, HFPS meeting on workflow/module coupling framework
- To be extended to PDT and TSVV15 in 2025

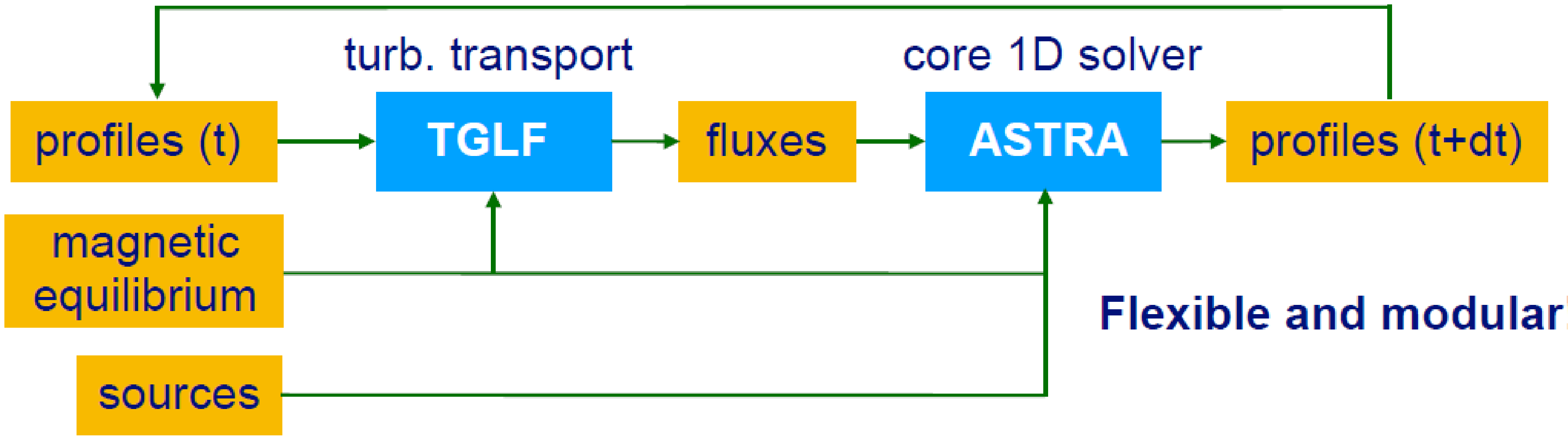
Aiming at flexible and modular integrated modelling framework

+
Python

+
Muscle 3

multiscale / muscle3

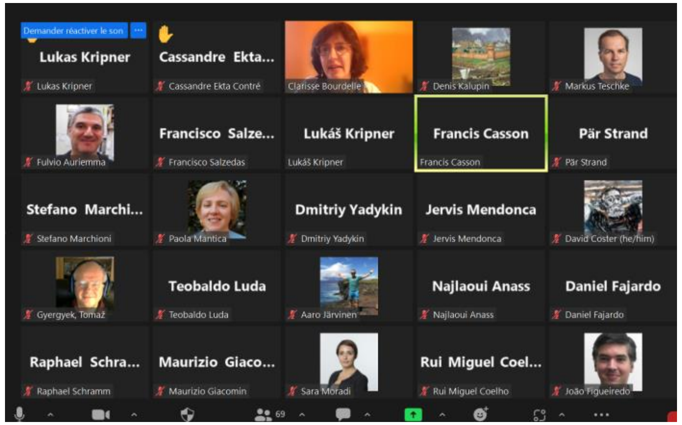




Flexible and modular!

1st HFPS training open to all EUROfusion (Jan. 2023)

Wed. Jan. 25th 10.30-12.30 CET	**General introduction and overview (open to all, no registration needed)**: · Recent achievements of integrated modelling · What is the High Fidelity Pulse Simulator?
Wed. Jan. 25th 14.30-17.30 CET	**2.30 CET: all, Intro/demo interpretative case: F. Casson Breakout rooms as needed (ref. supervisor see table below) 5 pm CET: all, update on progresses/issues**
Thur. Jan. 26th 9.30-12.30 CET	**9.30 CET: all, intro/demo predictive case with QLKNN Breakout rooms as needed (ref. supervisor see table below) 12.00 CET: all, update on progresses/issues**



Registered participants
13 persons

JET, AUG and TCV

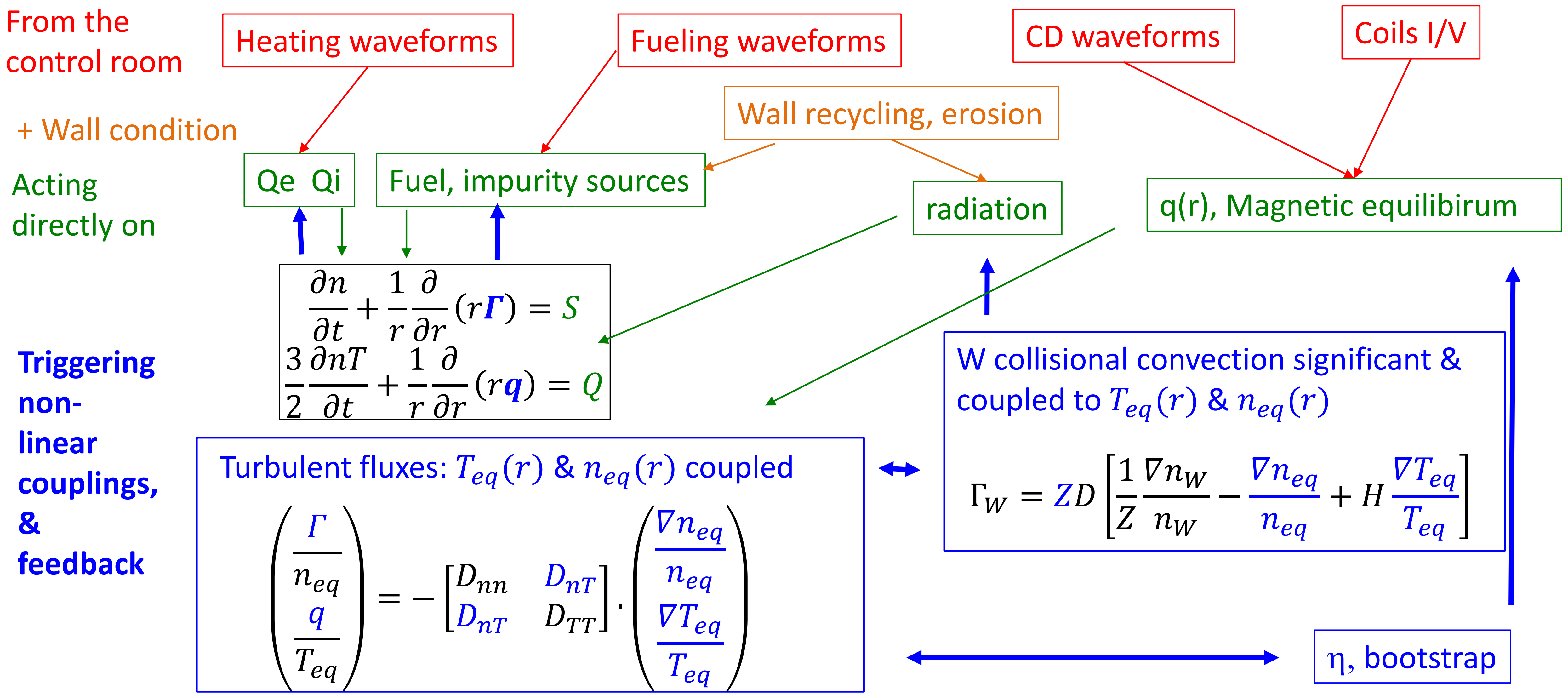
Using zoom and breakout rooms.
+ dedicated TSVV11 meetings to support new users, focused on physics module: past FRANTIC neutral source, coming turbulent transport codes QuaLiKiz/TGLF and impurity SANCO

High fidelity Integrated Modelling validation and challenges

Time-dependent flux driven integrated modelling over multiple confinement times: highly nonlinear coupling

- Level 1: **j, T_i, T_e**
  - Forgiving: transport driven by temp. gradients and is "stiff"
  - Always predict T_i and T_e profiles otherwise turbulence amplitude wrong
- Level 2: **j, T_i, T_e, n_e**
  - Non-trivial: particle transport not stiff (off-diagonal transport)
  - Depends sensitively on turb. spectra, collisions, kinetic resonances
- Level 3: **j, T_i, T_e, n_e, V_{tor}**
  - Challenging: momentum transport from symmetry breaking
  - Feedback potential for barrier formation (ExB shear)
- Level 4 : **j, T_i, T_e, n_e, n_i multi-ion (isotopes, impurities), V_{tor}**
  - Exciting territory, complex non-linear interplays
  - Heavy Impurity transport needs all L3 channels (sets neoclassical transport and poloidal asymmetries), and provides radiation feedback
- Level ++ : **j, T_i, T_e, n_e, n_i multi-ion (isotopes, impurities), V_{tor} in burning plasmas** where P_{alpha} > P_{aux} (Q>5), background profiles impact P_{alpha} accounting for EP-MHD, Alpha redistribution and impact EP/β on turbulent transport

From control room actuators to plasma response: highly non-linear physics coupling, a (not-exhaustive) illustration



Maximizing the ion temperature in an electron heated plasma

WEST

- Non-linear couplings:

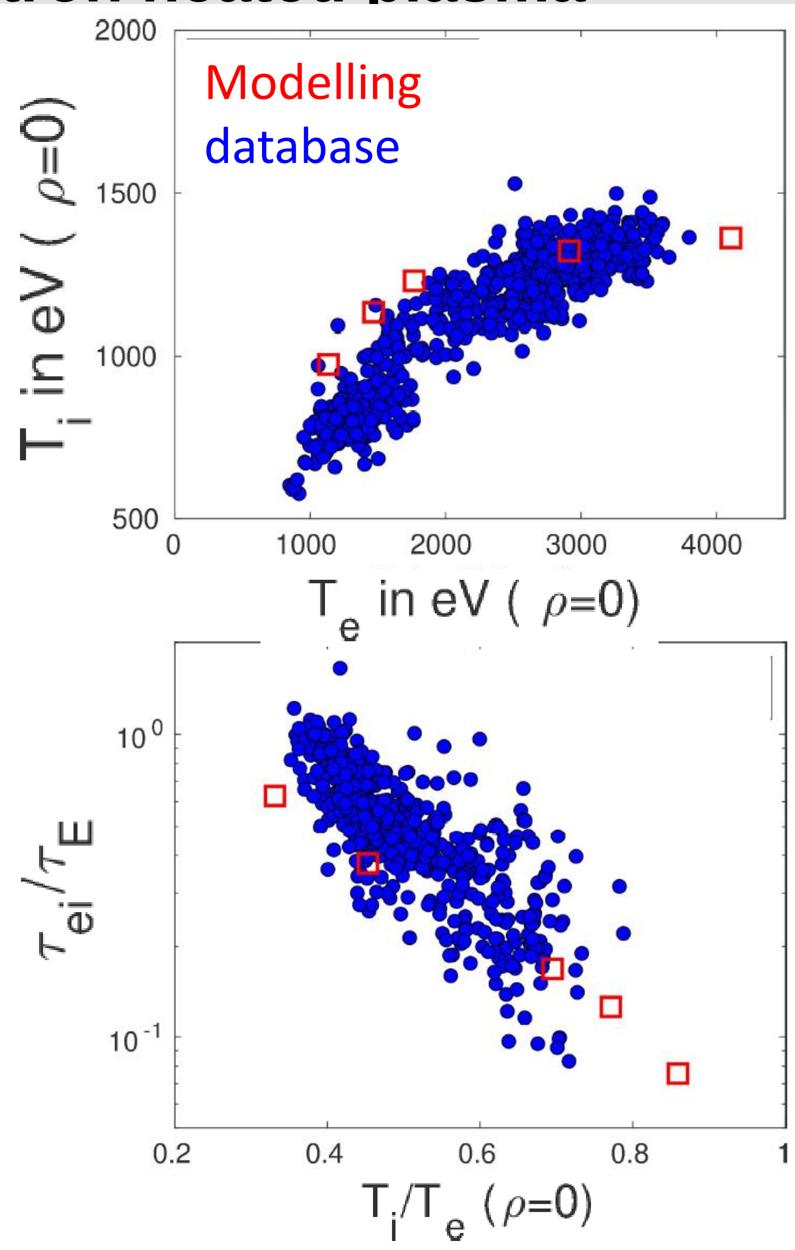
j, T_e & T_i : NN-QuaLiKiz, equipartition, ohmic, P_{rad} **up to ρ=1** (L mode)

- Fixed quantities:

n_e and plasma compo., LHCD source profile shape, separatrix values

Question: how T_i saturation observed in electron heated W7X, AUG, WEST extrapolates towards ITER?

Understanding: ITER vs AUG-W7X-WEST: both shorter τ_{ei} and longer τ_E, hence higher $T_i(0)/T_e(0)$~0.75



[Manas NF 2024]

METIS

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

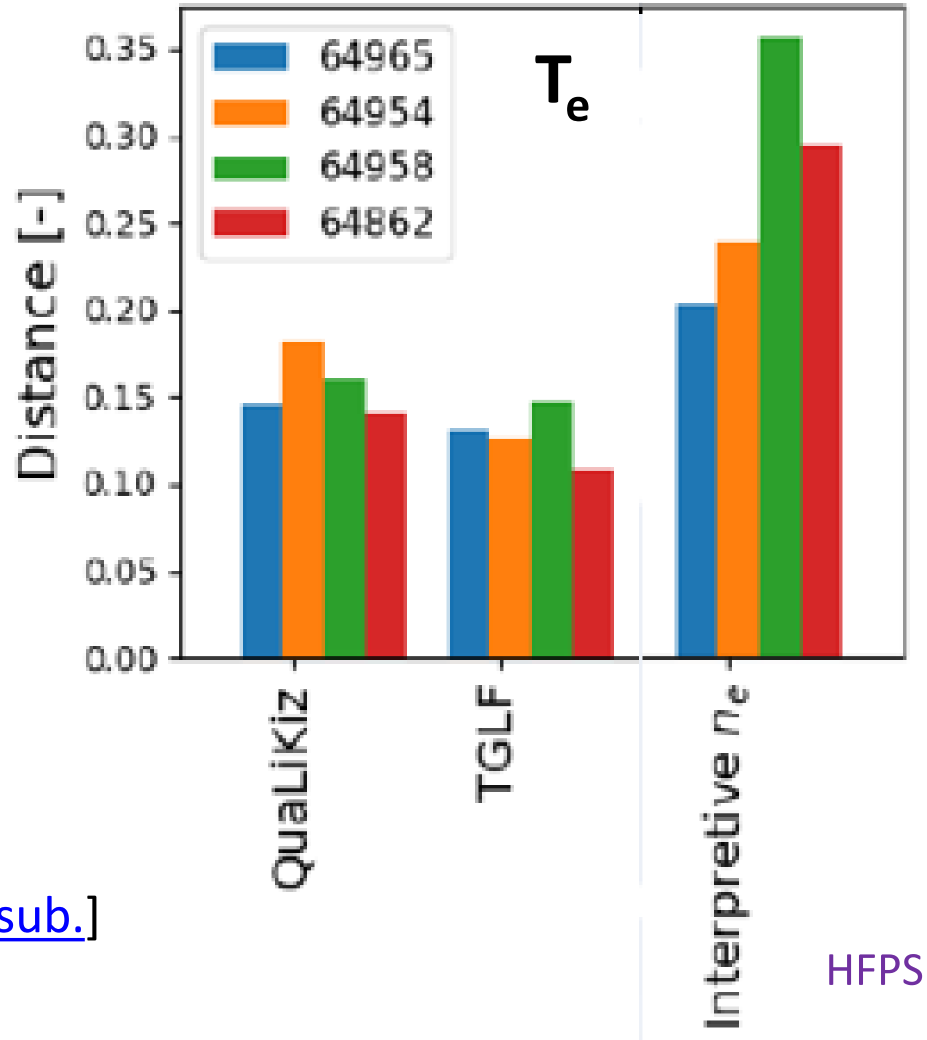
- fixed quantities: sep. values

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

Metrics averaged over multiple radii/times

$$d = \sum_{\rho=sep}^{axis} 2 \left| \frac{d^{\rho}_{fit} - d^{\rho}_{model}}{d^{\rho}_{fit} + d^{\rho}_{model}} \right|$$



[M. Marin sub.]

HFPS

Integrated modeling a key tool for Knowledge Management

Slide borrowed to W. Morris

Flight simulat… CF at least)

UK Atomic Energy Authority

Pro (may affect FS design and implementation)

- **Integrates** the elements in space and time over the whole evolution
  - does integration of many moving parts reveal multiple solutions, or over-constrained?
- Design **exploration**, and eventually **substantiation** (if high fidelity)
- **Focus for R&D** – how does an R&D activity help the FS?
- Explore **control**, effect of disturbances, bifurcations – handle “failure modes”
- Organised **interface with engineering** design
- **Track progress** in integration and fidelity, assumption removal
- Powerful **communication** tool: “fly” a plasma on a real journey, take-off, cruise, air turbulence, evasive action, land, system or even engine/structure failures etc
- **Knowledge repository** – important given staff changes

Con/caution

- **Inaccurate initially**: simplified, assumptions, approximations. Scaling multipliers: e.g. increased H-factor as design driver is formally invalid? Can also block innovation (H>1 outcome rejected?)
- Possible **faux-fidelity**, misleading confidence– increases with exposure.
- Can **conceal issues**, even from experts, esp. when incomplete

Integrated modelling: as complex as experiments

- **Need the equivalent of the control room** integration where MHD experts work with turbulent transport experts, SOL experts, with control engineers and Heating and current drive systems

- Else each integrated modeler will switch on advanced physics modules only in his/her field of expertise…

- Proposal: **Modelling campaigns** focusing on some reference benchmark cases

Tools developed for automated HFPS launching

Tools developed for automated HFPS (or any IMAS I/O integrated modelling framework) launching:
https://github.com/duqtools/duqtools
open-source
[Azizi et al ArXiv 2024]
Supported now through ACH-VTT

netherlands eScience center

Automated run creation

- Template-based run creation
- Set up variable dimensions
  - Generate new IMAS data
  - Smart hypercube sampling
  - Support for coupled variables


```
create:
  dimensions:
    - variable: t_e
      operator: multiply
      values: [0.8, 1.0, 1.2]
    - variable: zeff
      operator: multiply
      values: [0.8, 1.0, 1.2]
  sampler:
    method: latin-hypercube
    n_samples: 4
```

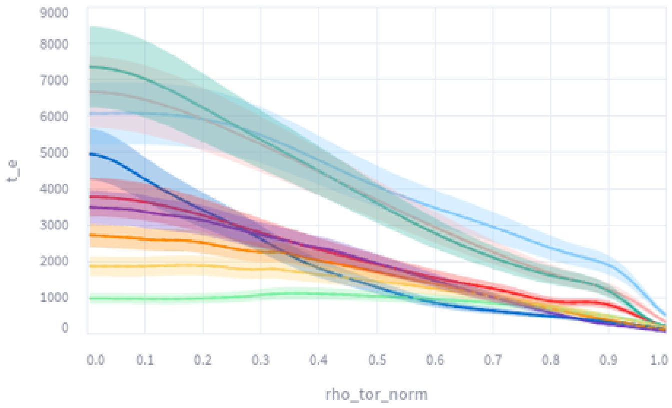
List of IMAS data

```
g2aho/aug/36982/2
g2aho/jet/75225/2
g2aho/jet/90350/2
g2aho/jet/92432/2
g2aho/jet/94875/1
g2aho/tcv/64958/2
g2aho/west/54568/1
g2aho/west/54728/1
g2aho/west/55181/1
g2aho/west/55525/1
...
```

Canonical UQ template

```
create:
  runs_dir: ./duqduq/{{ run.name }}
  template: ./path/to/template/
  template_data:
    user: {{ handle.user }}
    db: {{ handle.db }}
    shot: {{ handle.shot }}
    run: {{ handle.run }}
  sampler:
    ...
  dimensions:
    ...
system: jetto-v220922
```

duqduq



1st example of automated HFPS launching and validation on > 5000 pleateaus of JET

Metrics on T_e, Ti and n_e

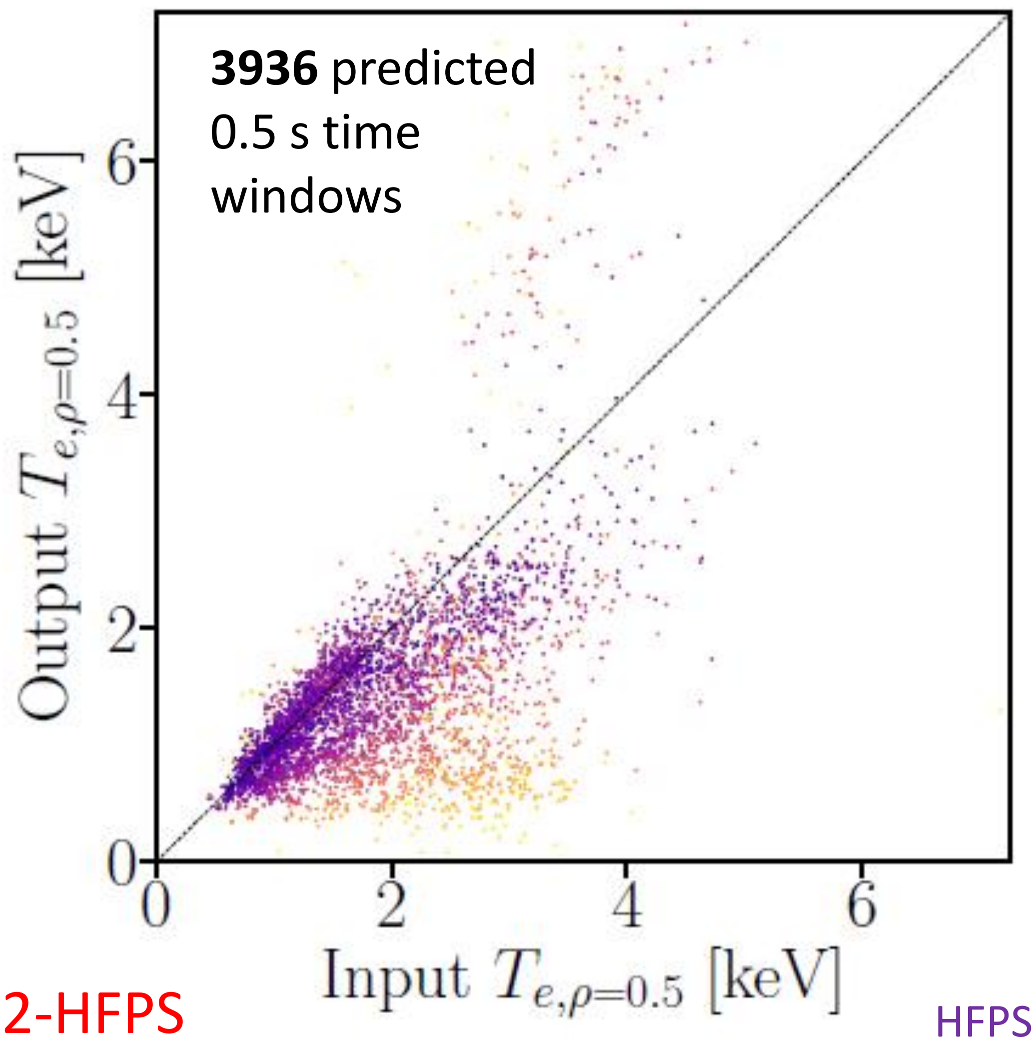
$$M = \sqrt{\frac{1}{6}\left(M^2_{T_e,3} + M^2_{T_i,3} + 4M^2_{n_e,3}\right)}$$

- **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**

Question: for which range of parameters model prediction best/worse (NN, QuaLiKiz, TGLF), to guide future model devt needs

Understanding: on-going

[A. Ho EPS/TTF 2023, publi. in prep.]



To be extended on TCV and WEST in 2025 using TGLFsat2-HFPS

Need Long Term Storage Facility mandatory to pursue this route

HFPS

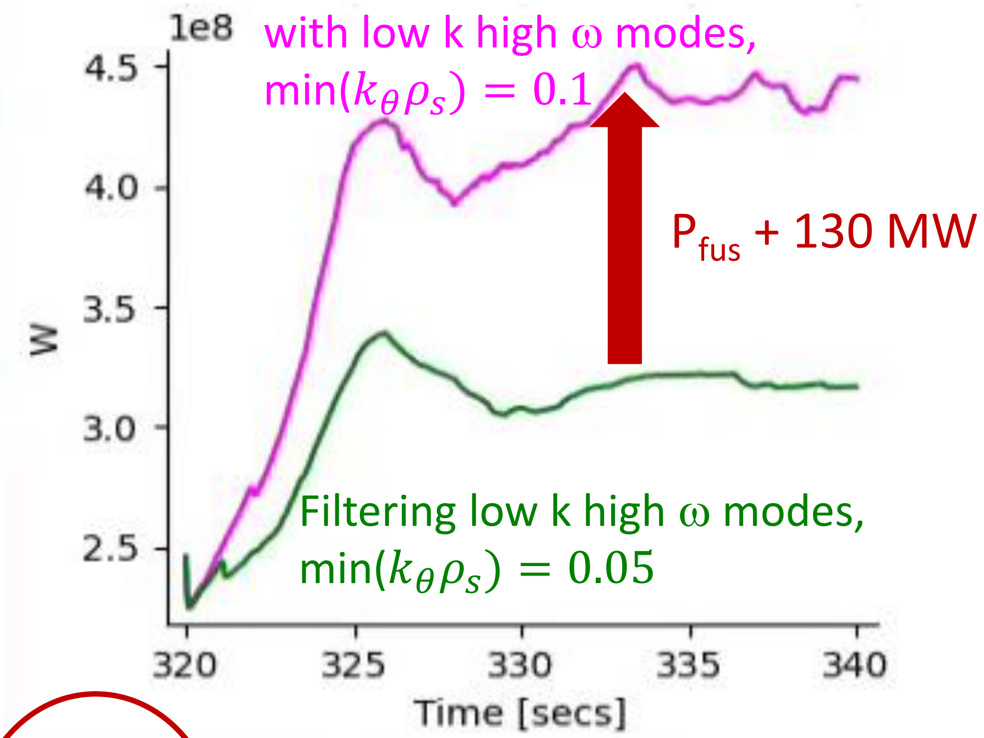
Illustration of importance of physics based understanding in burning plasma: impact of β on turbulence (w/o fast particles)

ITER 15 MA case

- **Non-linear couplings:**

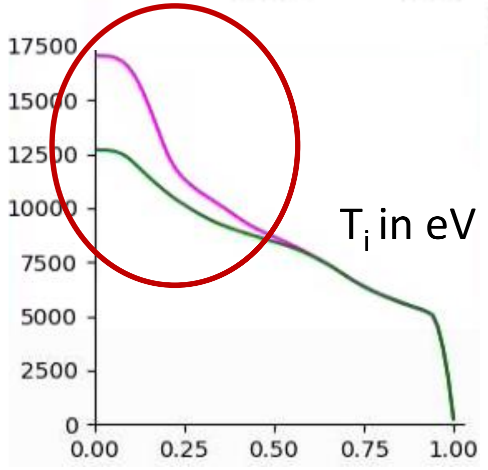
j, $\mathbf{T_e}$ $\mathbf{T_i}$ **&** $\mathbf{n_T}$ $\mathbf{n_D}$, equip., ohmic, P_{rad} , NBI , $\mathbf{P_{fus}}$

- 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} = 0



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 (on-going) [Howard ArXiv2024] and GENE-Tango A. Di Siena et al



*[A. Najlaoui et al sub. PPCF 2024, see EUROfusion pinboard]

How to close the gaps?
go up the hierarchy of models and improve model reduction

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

↕ ↕

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

* Thursday 5-6pm session

Session: Core transport reduced model towards burning plasmas
Horaire et Lieu: R3.054 (16:00 - 18:00)
Président de session: Colin Roach

Benchmark cases: essential meeting point between ML based Pulse Design Tools and High Fidelity Integrated Modelling

- **For heat and particle coupling**, the cold pulse challenge up to the LCFS [Angioni NF 2019].
  - With reduced cases heat only

- **The complex interplay with W** radiation based on AUG [Fajardo NF 2024]
  - With reduced cases, heat only with prescribed W and radiation etc

- **Fueling impact on H mode performances**, based on AUG case [Luda NF 2021]

- A case with **light impurity seeding** should be included as it is a challenge for core-exhaust integration, it could be based on JET Ne seeded case [Gabriellini NF 2023]

- **A burning plasma reference case,** to this aim, within the ITPA transport and Confinement, a benchmark ITER 15 MA baseline scenario is presently being defined.

2025 and beyond perspectives

Perspectives 2025 and beyond

- **HFPS workflow and module coupling enhancing modularity and interoperability** with other EF tools such as ETS, ASTRA and Pulse Design Tools (TSVV15), using the toolbox: IMAS, Python, Muscle3. *Alignment btw EF tools mandatory. With ITER tools tbc*

- **High fidelity Integrated Modelling validation** on high β scenarios, seeded impurities, in I_p ramp. WPTE and ITER/DEMO priorities welcome. *Need IMAS data from all EU machines: JET, TCV, AUG asap (see Data Management plan)*

- **Large scale validation extended** to WEST and TCV. *Need Long Term Storage facility*

- **Physics driven Benchmark cases** for *HFPS/ETS/ASTRA and Pulse Design Tools* defined. AUG ECRH-NBI and W is one, ITER 15 MA another one. More possible, to be discussed.

- Reduced model missing: for the separatrix parameters, for high b in presence of Alpha in bruning plasma (*see Thursday 5 pm proposal for a new activity*)

- **Integrated modelling is a ‘Knowledge Repository’.** Need to enforce the maximization of the non-linear physic coupling (SOL, MHD, HCD etc) as on tokamak exploitation. *Need to think of ‘modelling campaigns’*