TSVV3 project (Edge Fluid Modelling): update focused on WPTE applications

P. Tamain

In name of the TSVV3 team

ETASC Thrust 1 meeting | 03/05/2023

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Extended workplan 2024-2025

- **Extended workplan for 2024-2025** defined at end of 2023 following discussions started at annual workshop and feedback of gate review

- In brief:
  - All existing tasks renewed + 1 additional task on **electromagnetic turbulence** (high-beta plasmas)
  - **TCVX23** (WPTE RT-05 experiment) as key-stone + selected applications to other machines (AUG, WEST, W7-AS)
  - **Mutualize selected parts of models/codes**, starting with kinetic neutrals solvers

TSVV3 project workplan 2024-2025

P. Tamain and the TSVV3 team

The workplan of the TSVV3 project, as submitted in 2020 and validated in 2021 by the ETASC Scientific Board, defined a set of tasks and deliverables for the period 2021-2023. The project plan included a milestone for the second half of 2023 aiming at assessing the progress of the various tasks and defining the workplan for the period 2024-2025. This document is the output of this work. It is the result of discussions held in June 2023 at the general project workshop in Garching.

Overall orientation

The first 2.5 years of the project have allowed us to make significant progress in all the areas addressed by the project. Significant open questions however remain in each of the topics, so that the task structure defined for 2021-2023 remains relevant, with updated goals and deliverables.

Nevertheless, the progress made in the capabilities of the codes during the first years of the project (especially concerning the treatment of neutrals) unlocks new applications related to experiments. The proposed workplan reflects this inflection by putting stronger emphasis on comparison against experiments, using in particular a dedicated experiment on TCV (performed in the frame of the WPTE campaign) as a reference case for all codes.

An additional change is also the creation of a task dedicated to the inclusion and evaluation of electromagnetic effects in our edge plasma codes. The latter now appears as task 10 in replacement of the former task 10 that is not relevant anymore.

Task 0: project management

Unchanged with respect to 2021-2023.

Deliverables:

	Description	What?	Who?	When?
D0.1	Follow project advancement and promote communication between contributors and with related TSVV projects	• Organization and chairing of task advancement meetings (~3 per task per year) • Organization of inter-TSVV meetings (1 to 2 per year with TSVV4, 5 and 6)	CEA	Continuous
D0.2	Reporting	a) Presentations at SB meetings b) Project reports	CEA	Continuous

Task 1: gyro-fluid models

Situation at end of 2023:

- Method designed to derive systematically collisional closure for gyrofluid models
- Implementation of gyro-fluid model including collisional closure and interaction with neutrals on-going in FELTOR

https://wiki.euro-fusion.org/images/c/ca/TSVV3_workplan_2024-2025.pdf

Annual workshop 2024

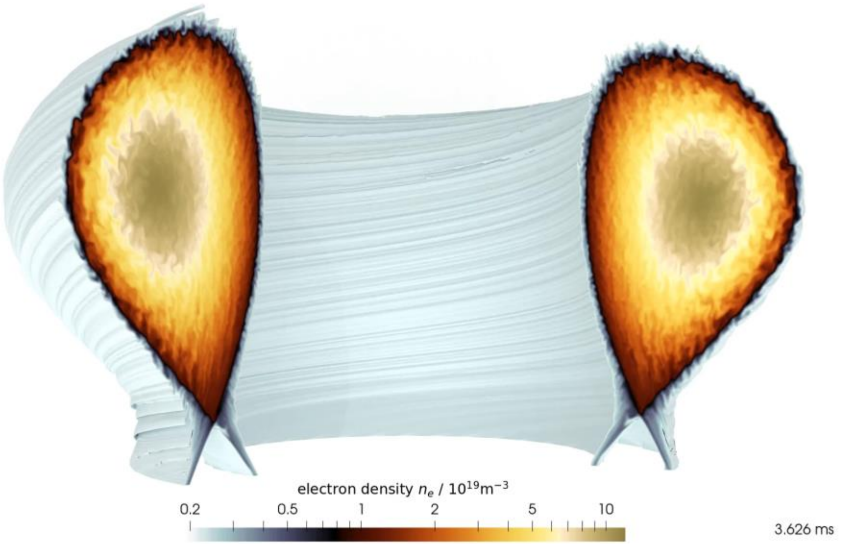
- **Annual workshop 2024** held last week (May 29th – 31st) at KU Leuven & on-line
  - 10 on-site participants
  - ~15 remote participants

- All presentations will be made available on INDICO: https://indico.euro-fusion.org/event/3165/ (page under construction)

- Objectives and **deliverables on track**

Gyrofluid turbulence reached critical milestone

- FELTOR = gyrofluid approach
  - Pros = FLR effects
  - Cons = no well established model, especially for collisions (closure!)
- Following theoretical and numerical effort, **FELTOR turbulent simulations can now run routinely**
  - Applied to resistivity scan and isothermal **TCVX21** simulation
- Next steps:
  - Implement **non-isothermal model with neutrals** => **TCVX23**
  - Develop high order model

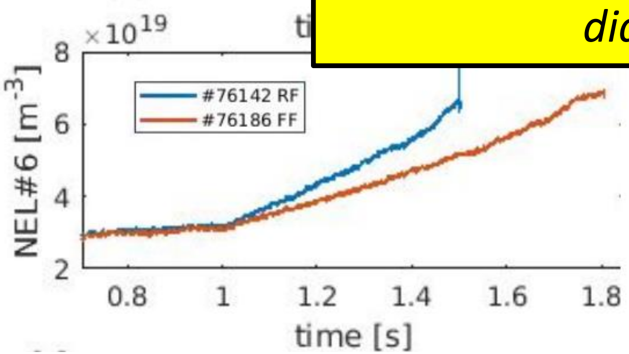


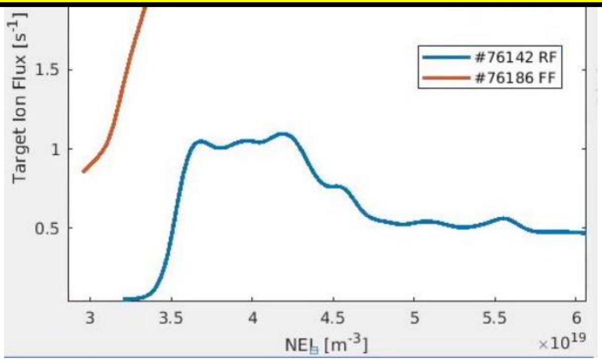
[Wiesenberger, PPCF 2024]

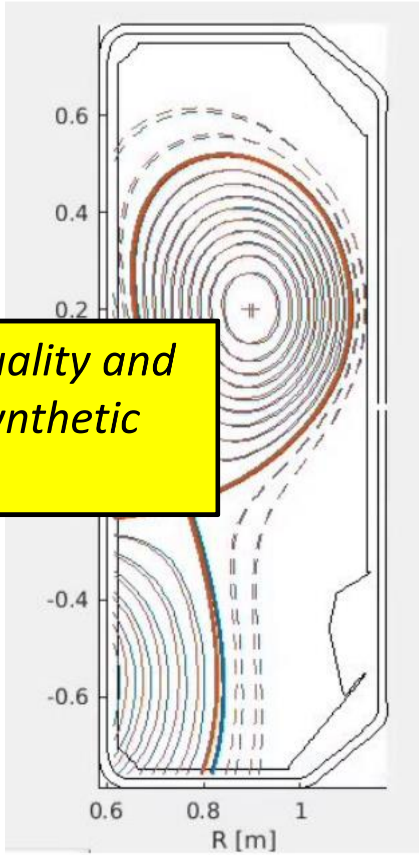
TCVX23 validation exercise

- Dedicated **TCV experiment** for turbulence through density regimes (**RT22-05**):
  - density scans in low field discharges adapted for modelling
  - max diagnostics coverage for turbulence and profiles
- Chosen as **reference case for all TSVV3** codes

Pulses to be re-run this year due to issues with data quality and to allow GPI measurements. Time used to prepare synthetic diagnostics in collaboration with TSSV3.





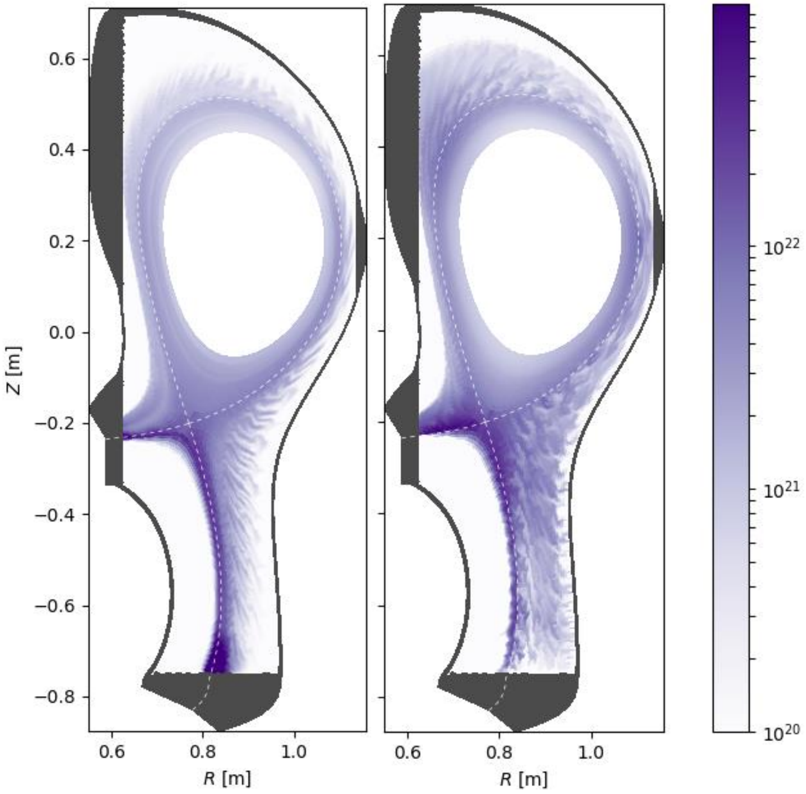


Turbulence in high density regimes

- First analysis of TCVX23 **simulations at low (attached) and high density (detached) achieved**
  [Mancini, PSI 2024; Quadri, PSI 2024]

- Key results:
  - Turbulence characteristics drastically change in high density regime

$S_n\ (m^{-3}.s^{-1})$ *[Quadri, PSI 2024]*



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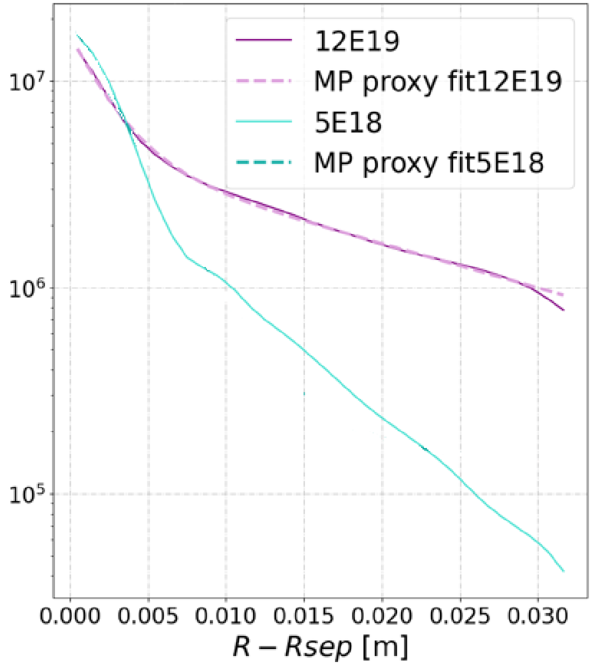
  [Mancini, PSI 2024; Quadri, PSI 2024]

- Key results:
  - Turbulence characteristics drastically change in high density regime
  - Leads to **significant SOL width increase**

$n_{sep}[m^{-3}]$	$\lambda_{q,NEAR}$ [mm]	$q_{peak,NEAR}[\frac{W}{m^2}]$	$\lambda_{q,FAR}$ [mm]	$q_{peak,FAR}[\frac{W}{m^2}]$
$0.5E19$	~ 1	$1{,}6E7$	~ 10	$2.1E5$
$1.2E19$	2.35	$1.24E7$	20.3	$4.4E6$
	x2.3	x0.77	x2	x20

[Quadri, PSI 2024]

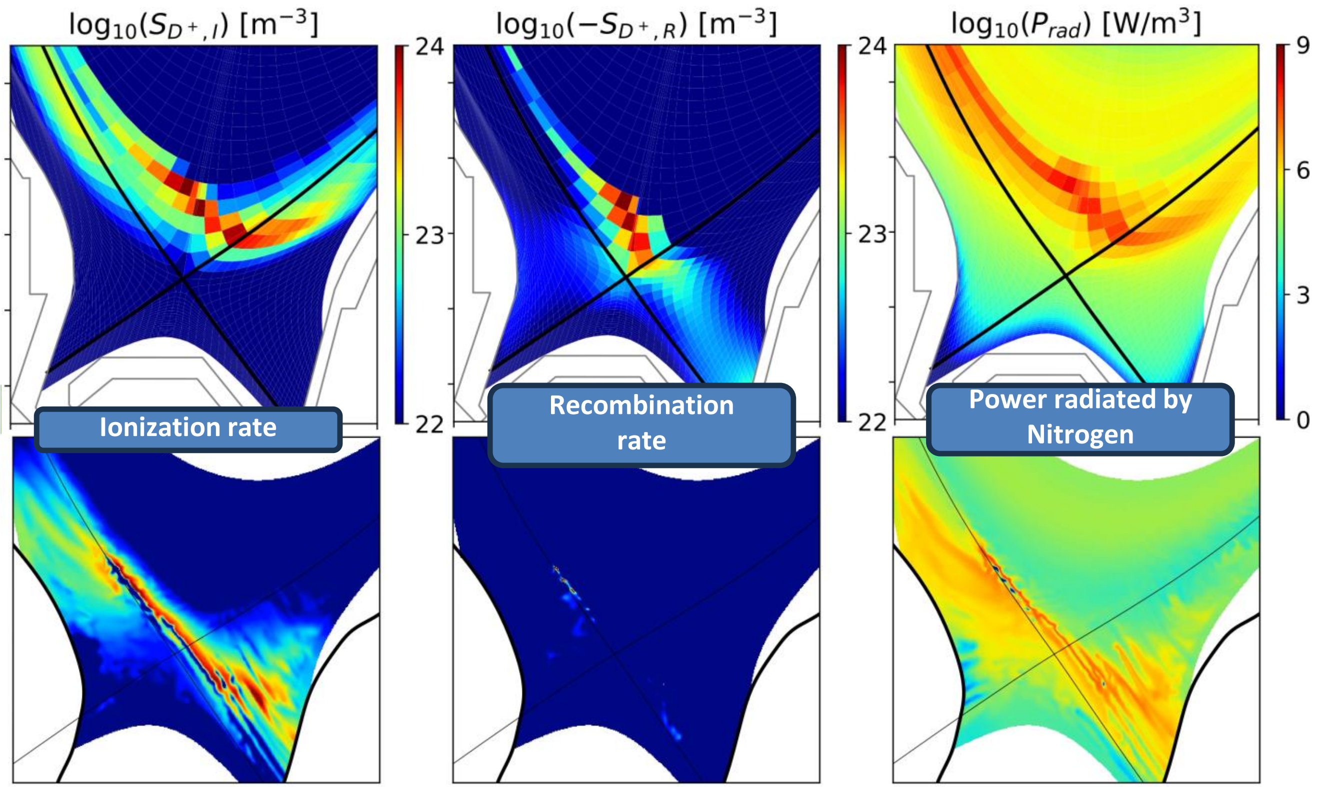


Turbulence in XPR!

SOLPS-ITER simulation of H-mode XPR, taken from O. Pan et al., Nucl. Fusion (2022)

Model:

- Fluid neutrals
- No impurities, only radiation



GRILLIX simulation of L-mode XPR

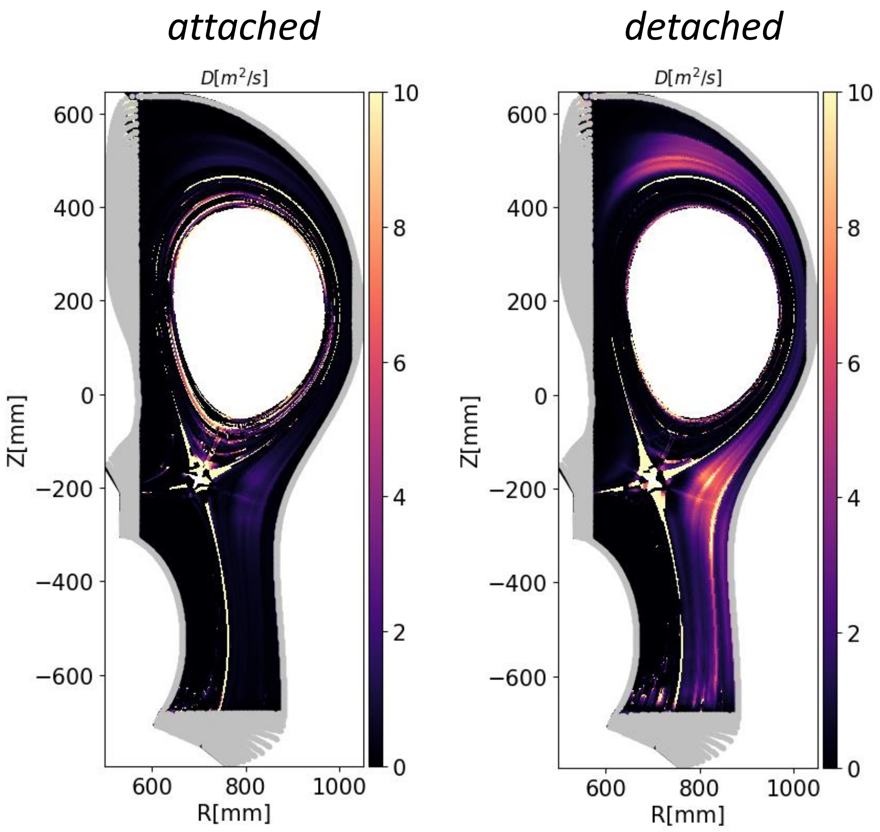
[Eder, PSI 2024]

Guiding the mean-field community? (1)

- Feedback to mean-field community for transport coefficients = high priority

- Some clear trends observable
  - E.g.: increase of D_{turb} at detachment

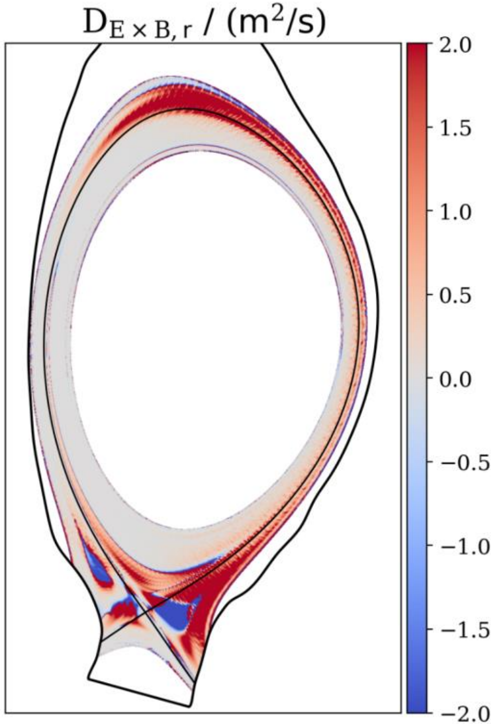
- …



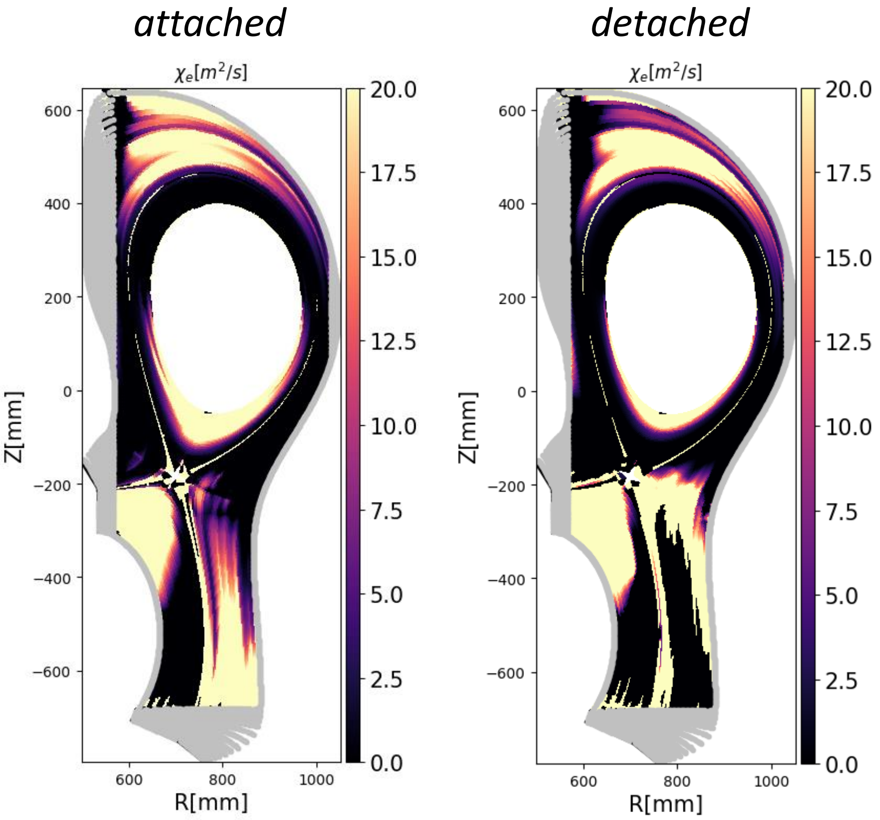
[V. Quadri, SOLEDGE3X]

Guiding the mean-field community? (2)

- … but complex to reduce info in most cases



[K. Eder, GRILLIX]

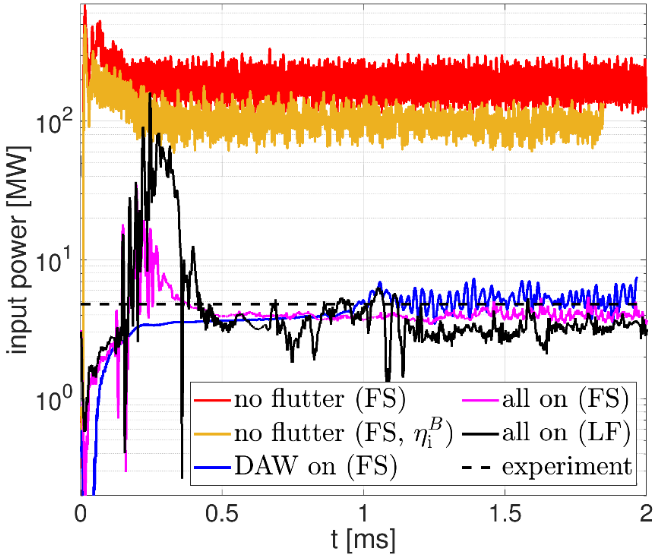


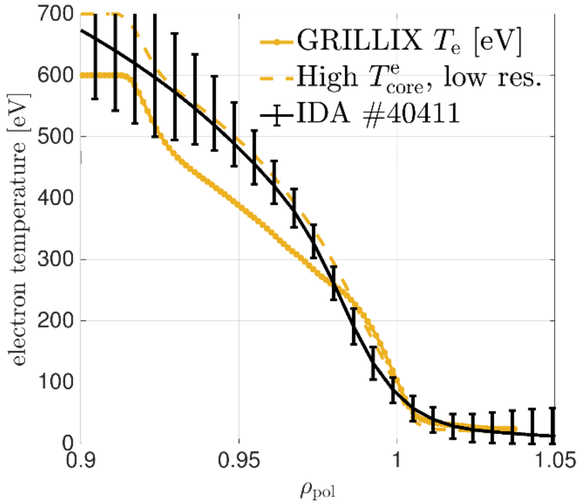
[V. Quadri, SOLEDGE3X]

Tackling high-performance regimes

- 2 key implementations in GRILLIX unlock high-performance regimes
  - electromagnetic fluctuations => **high β**
  - Landau fluid closure => **low $\nu^\star$**

[Zhang, NF 2024]





- Demonstrated on modelling of **AUG H-mode**
  - **Flutter is fundamental** contributor to transport (reduction!)

[Zholobenko et al, arXiv:2403.10113]

The issue of time scales

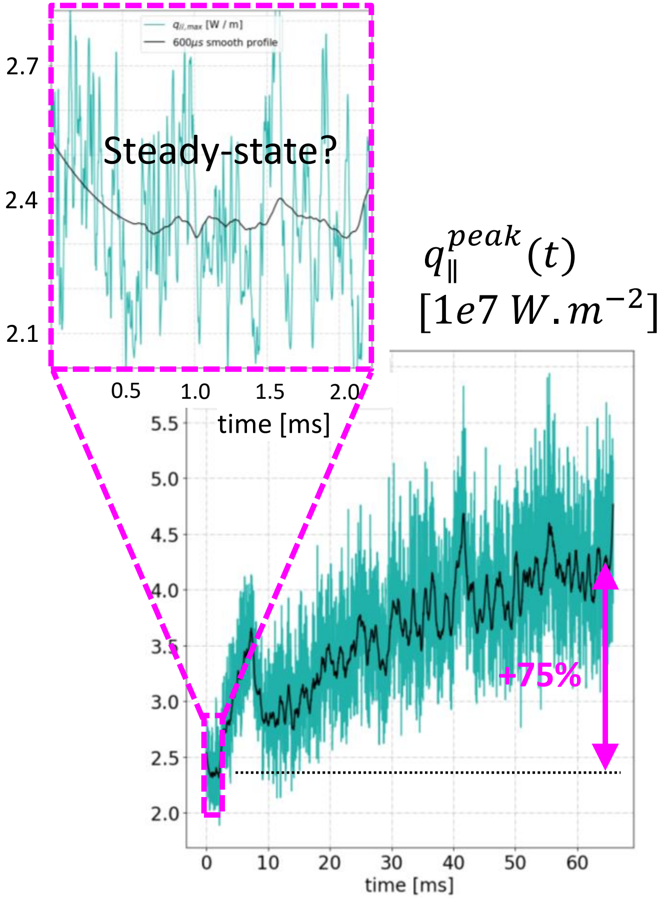
- Global flux-driven simulations require long plasma time to meaning-full steady state
  - Ex: ITER mean field high-power case > 1s of plasma time
  - 2 key factors: confinement time + recycling

$$\tau_{ss} = \frac{\tau_{conf}}{1 - R}$$

$R > 0.99$ for particles in metallic machine!

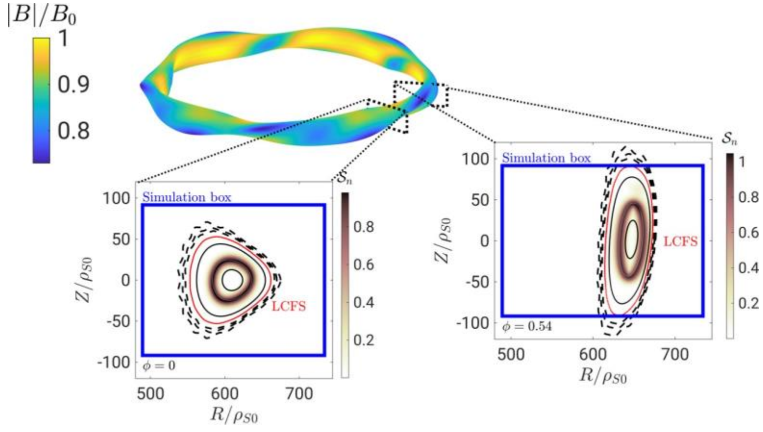
- Investigated solutions:
  - Accelerate codes (GPU porting on-going)
  - Develop **acceleration methods** is crucial

[Kaveeva et al, NF 2018; Rivals, PhD 2023]



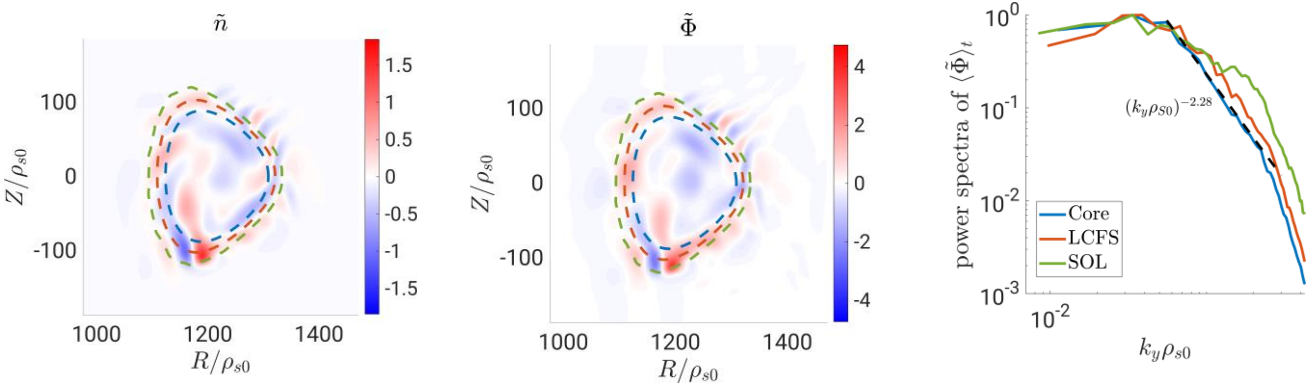
Stellarator turbulence towards experiments

- After proof of principle demonstrations in 2023, **stellarator turbulence** modelling moving towards large machines
  - **W7-AS** as intermediate step towards W7X
  - Here with GBS, GRILLIX joining soon



[courtesy Z. Tecchiolli]

- First results in line qualitatively with experiments. WIP…

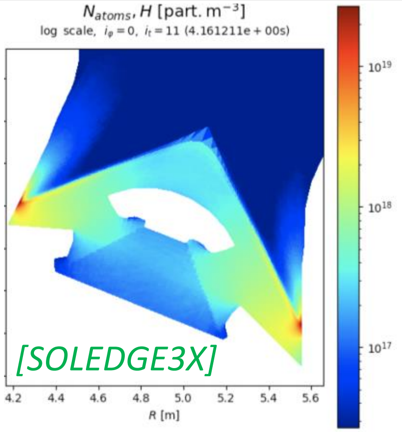


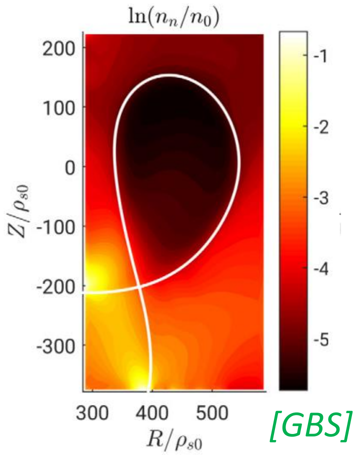
Mutualization of tools

- **GBS** and **SOLEDGE3X** already feature **kinetic neutrals solvers**
  - GBS = home-made, method of charateristics
  - SOLEDGE3X = EIRENE

- Actions started to **modularize these solvers and make them available to other codes**
  - TSVV3 codes in priority, but could extend to other codes

- Working also on memory limit issue of coupling to EIRENE





Report on interaction with ACH

- TSVV3 in interaction with ACH: EPFL (code optimization), CIEMAT (code opitmization), IPPLM (IMASification), and VTK (CICD setup)

- Key outcome:
  - **Globally happy** with support received and progress it allowed, especially for HPC hubs
  - **Overheads due to project start, staff turn-over, low ppy commitment are issues**

    => continuity of manpower on a given project is essential

    => much more effective not to sprinkle resources and to have a dedicated contact person at significant proportion of their time
  - **Resources sometimes not fully in adequacy with needs**:

    Not enough HPC experts, sometimes available expertise not high priority

    Led to paradox: high priority tasks less served than low priority ones

Additional slides

Reminder of project structure

TSVV1
TSVV4

Improve models

- Task 1: gyrofluid models
- Task 2: sheat BCs
- Task 3: reduced turbulence models

TSVV2
TSVV5
TSVV6

ACHs

Improve codes capabilities

- Task 4: codes optimization
- Task 5: neutrals physics
- Task 6: multi-species plasmas
- Task 7: complex geometry
-Task 10: EM turbulence

Coordinate and rationalize effort

- Task 0: project coordination

Disseminate

- Task 9: make verified codes available to WPs

ACHs

WPs

Validate

- Task 8: IMAS-ification and synthetic diagnostics
- All tasks: test new capabilities against experiments

WPs

ACHs

Old slides

Facilitating comparison with experiments

- Action started to **port I/O of codes to IMAS**
  - Decision to do it via wrappers (e.g, Python) not internally
  - Step 1: **commonly agreed definition of needs** in terms of data input / output - done
  - Step 2: identify need or not for new IDSs (existing incomplete “edge turbulence” IDS) – on-going

- Progress on **synthetic diagnostics**
  - Standard for embedded **Langmuir probes** synthetic diagnostics defined and being implemented
  - Coupling to standard libraries (e.g. **CHERAB**) through IMAS

Langmuir probes in FELTOR (illustration)

A first application: WEST visible camera

[Courtesy A. Medvedeva, M2P2 laboratory]

Revised model for BC tested in SOLPS

- Analytical model fits well PIC data:

$$M_{\parallel} = 1 + \chi - \sqrt{\chi^2 + 2\chi}$$

$$\chi = \frac{(\nu_{mt}(1-\alpha) + \nu_{ei})x_0}{2c_s \sin\theta}$$

$\alpha = V_{\parallel}^{D}/V_{\parallel}^{D+}$

Dist. of demag.: $x_0 \approx 20\rho_i$

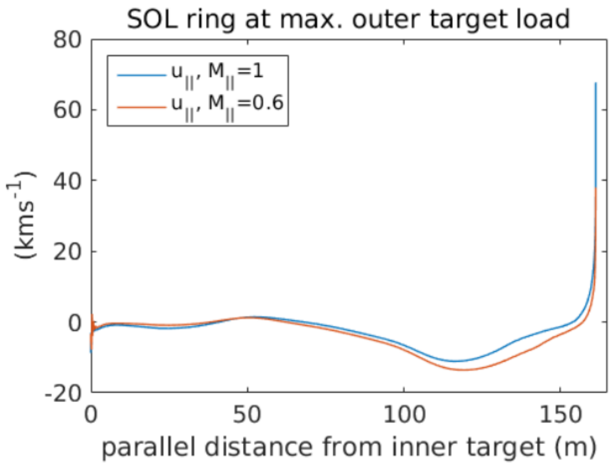
Ion-atom momentum transfer frequency

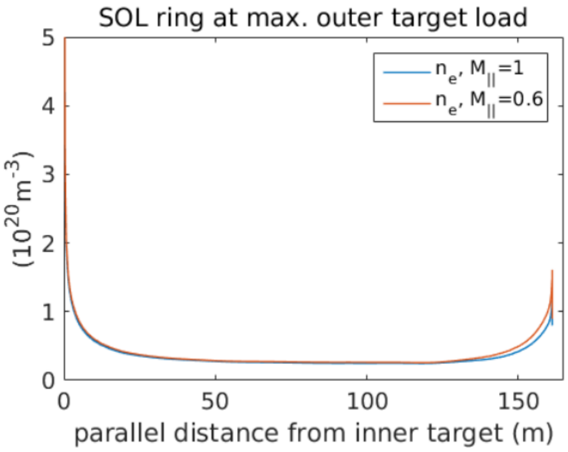
Incidence angle

[Tskhakaya, EPS 2021; D. Moulton, ISFN 09/2021]

- First **application in SOLPS** => **60% difference in target density**, likely to impact divertor regimes

- Generalization to **multi-species plasmas** on-going

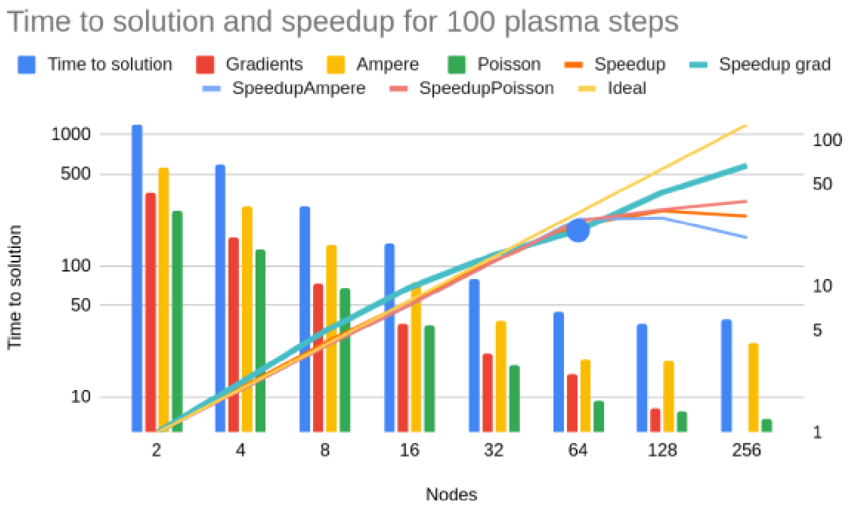




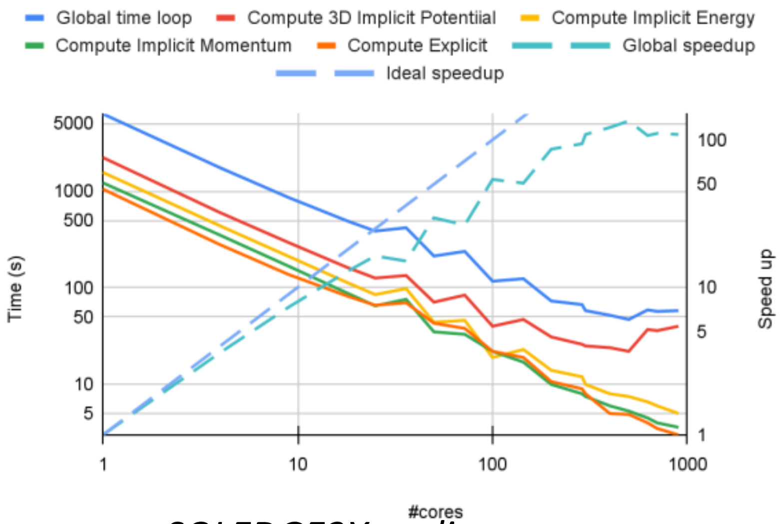
Codes performance optimization

- Strong **collaboration with ACH** focusing on:
  1. **Implicit solvers optimization** (common botteleneck) => HYPRE as attractive option (good perf., hybrid paralleization, GPU version (AMGX))
  2. **Codes profiling** completed, started implementing recommendations => essentially porting to GPU, but also load balance optimizations…

[*https://wiki.euro-fusion.org/images/9/9f/Report_2021_TSVV3_ACH_EPFL_Task4_code_optimization.pdf*]



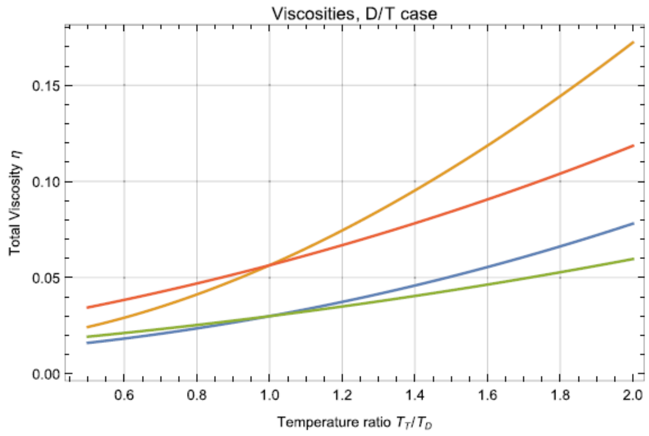
GBS scaling report

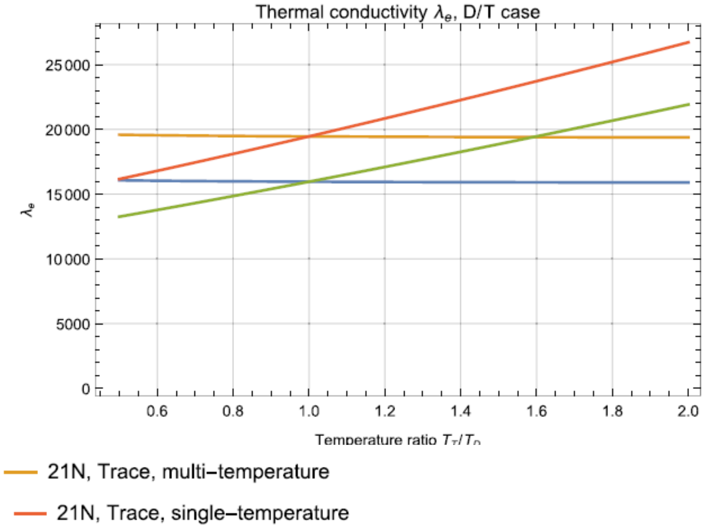


SOLEDGE3X scaling report

Beyond the Zhdanov closure

- ❖ Several limitations to Zhdanov's closure: single ion temperature, small departure from mass-average flow velocity
- ❖ On-going **theoretical developments** to go beyond these limitations
  - ➢ Practically implementable **generalization of Zhdanov's closure**
  - ➢ **On-going implementation** in FELTOR, GRILLIX and SOLEDGE3X





[Raghunathan, PPCF 2022]