E-TASC General Meeting: TSVV Overview

Garching | Nov 11-15, 2024

Frank Jenko

Thanks to the TSVV PIs for providing input

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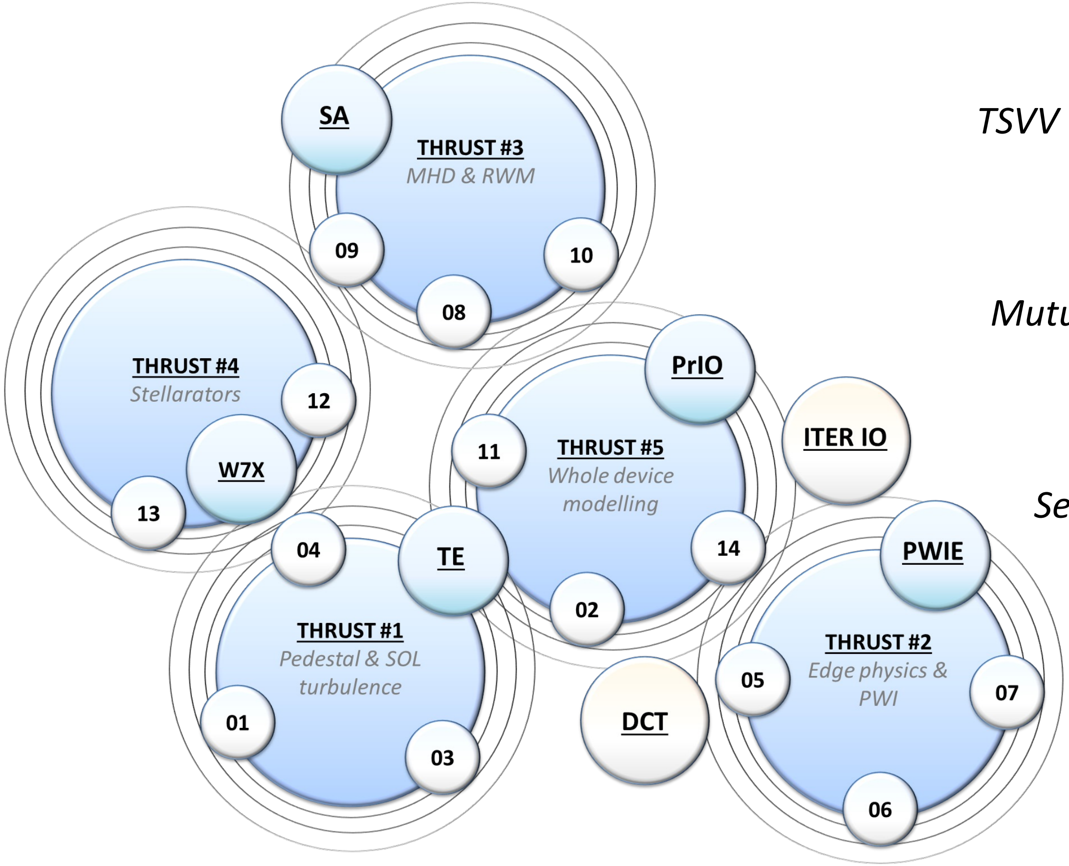
TSVV tasks: Top-down AND bottom-up

Dep.	WP	#	Title
FSD	TE	1	Physics of the L-H Transition and Pedestals
FSD	TE	2	Physics Properties of Strongly Shaped Configurations
FSD	TE	3	Plasma Particle/Heat Exhaust: Fluid/Gyrofluid Edge Codes
FSD	TE	4	Plasma Particle/Heat Exhaust: Gyrokinetic/Kinetic Edge Codes
FSD	PWIE	5	Neutral Gas Dynamics in the Edge
FSD	PWIE	6	Impurity Sources, Transport, and Screening
FSD	PWIE	7	Plasma-Wall Interaction in DEMO
FSD	TE	8	Integrated Modelling of Transient MHD Events
FSD	TE	9	Dynamics of Runaway Electrons in Tokamak Disruptions
FSD	TE	10	Physics of Burning Plasmas
FSD	PrIO	11	Validated Frameworks for the Reliable Prediction of Plasma Performance and Operational Limits in Tokamaks
FSD	W7X	12	Stellarator Optimization
FSD	W7X	13	Stellarator Turbulence Simulation
FTD	DES	14	Multi-Fidelity Systems Code for DEMO

The E-TASC ecosystem



TSVV teams working together in close collaboration

Related TSVVs in the "orbits" of Thrusts

Mutual interest between Thrusts on specific topics, emerging interactions between tokamak and stellarator efforts (turbulence, 3D, AI)

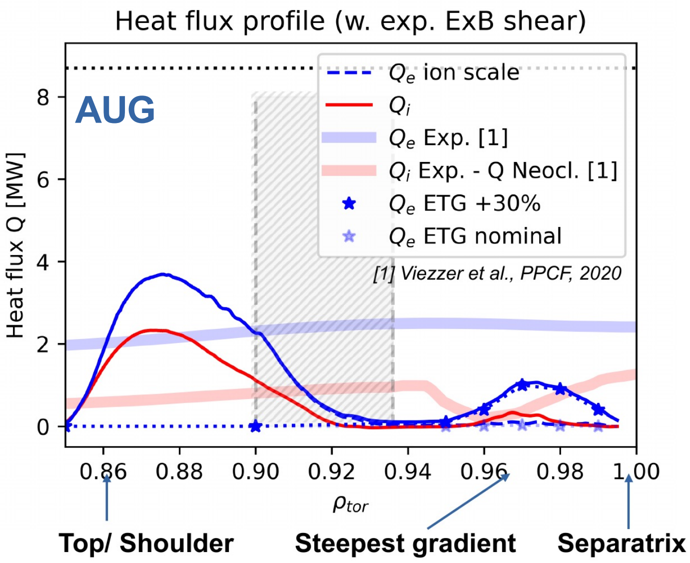
Several services provided (mostly through ACHs) for the benefit of the entire ecosystem

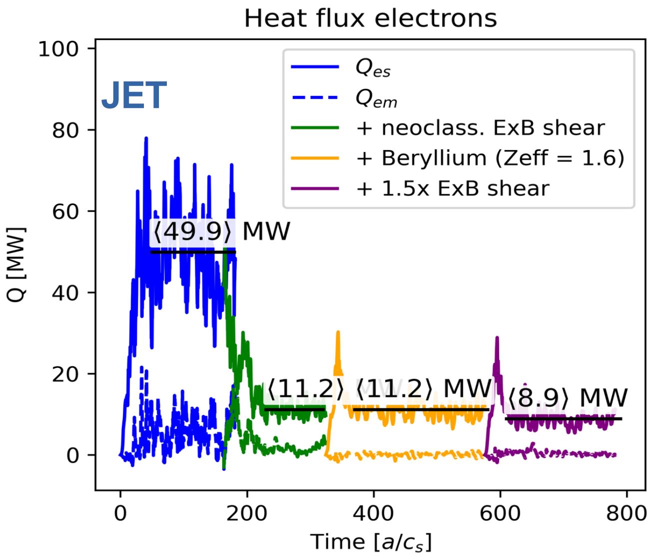
Close interactions with ITER IO

Interactions with the DCT

Thrust 1: Edge Turbulence

TSVV-01: Characterizing pedestal turbulence





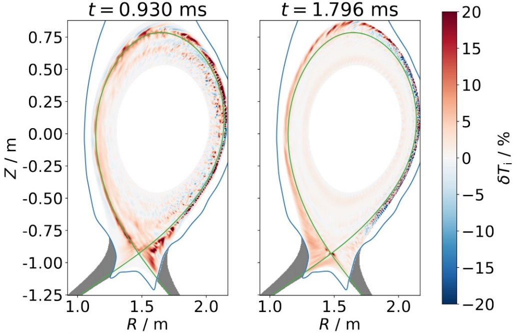
L. Leppin et al.

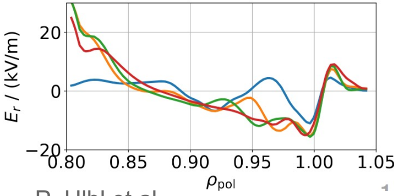
H-mode pedestals studies for ASDEX Upgrade and JET plasmas:

- **Pedestal top turbulence mainly ion scale (ITG/TEM/MTM)**
- **Pedestal often just below KBM thresholds**
- **Electron transport changes from ion-scale TEM to electron-scale ETG at pedestal foot**

TSVV-01: Creation of radial electric fields

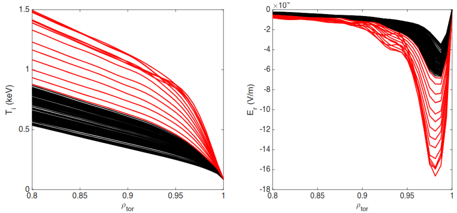
GENE-X





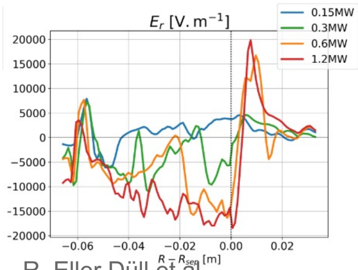
P. Ulbl et al.

ASTRA-TGLF



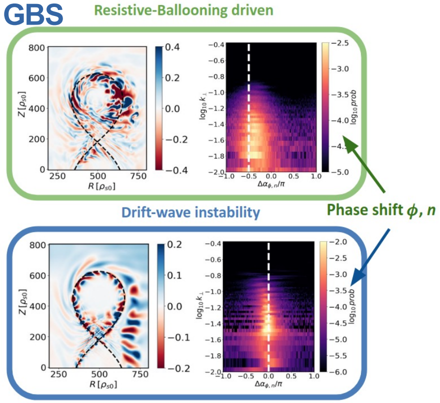
N. Bonanomi et al.

SOLEDGE-3X



R. Eller Düll et al.

GBS



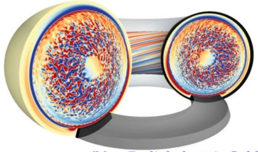
▸ B-field config : Single-null Biot-Savart (vacuum), $\epsilon \simeq 0.3$, $q_a \simeq 4$, $\hat{s}_a \simeq 3/2$

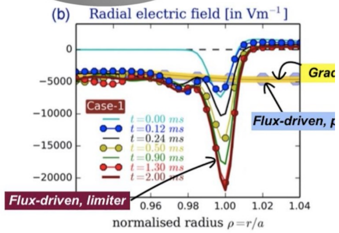
$$P_{th}^{phys} \sim n^{0.83} B_T^{0.65} a R_0^{0.72} A^{-0.49} q^{-0.34}$$

$$T_c^{th} \sim n^{-0.73} B_t^{1.30} A^{-0.064} q^{-1.46} R_0^{-0.34}$$

B. De Lucca et al.

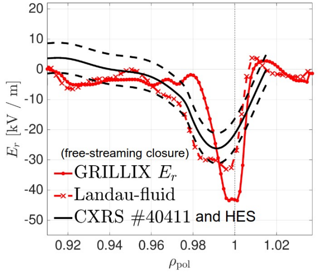
GYSELA





Dif-Pradalier, Comm. Phys, 2022

GRILLIX



W. Zholobenko et al.

GK models (TSVV-04)

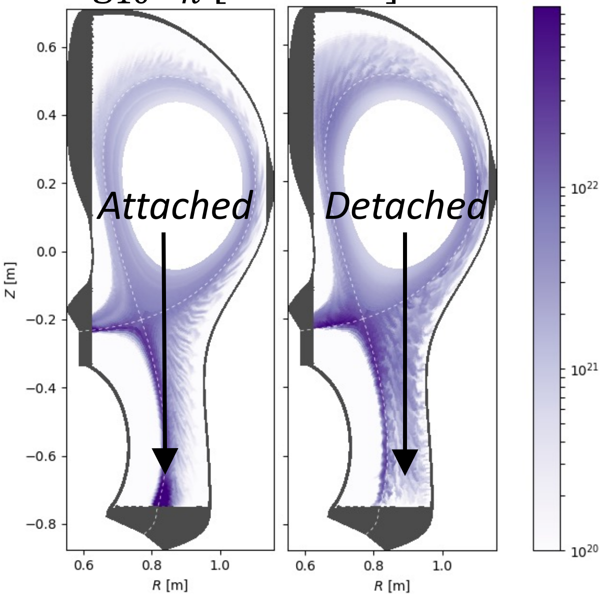
First flux-driven GK simulations in diverted/limited configurations

TSVV-03: Tackling dissipative divertor regimes

- First **turbulent simulations of highly dissipative divertor regimes** in support to **WPTE** experiments demonstrate impact on turbulence

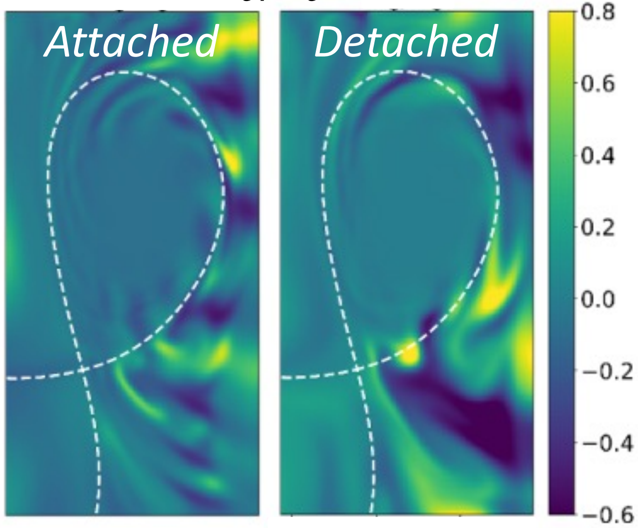
Detached divertor (TCV)

$\log_{10} S_n\ [m^{-3}.s^{-1}]$



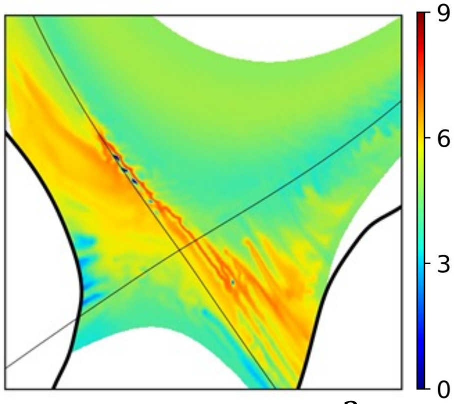
[Quadri, PSI conf. 2024; submitted to NME]

$\tilde{n}_e/n_e$



[Mancini, PSI conf. 2024; Mancini, NF 2023]

X-point radiator



$\log_{10}(P_{rad}\ [W.m^{-3}])$

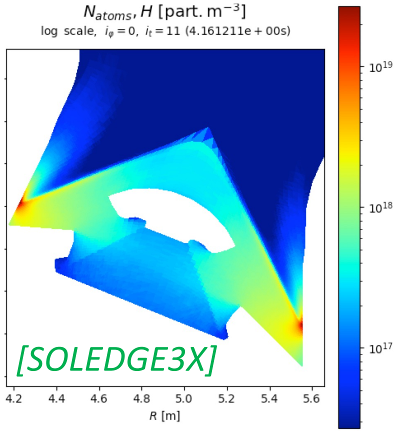
[Eder, PSI conf. 2024; Eder, submitted to PPCF, pinboard #38797]

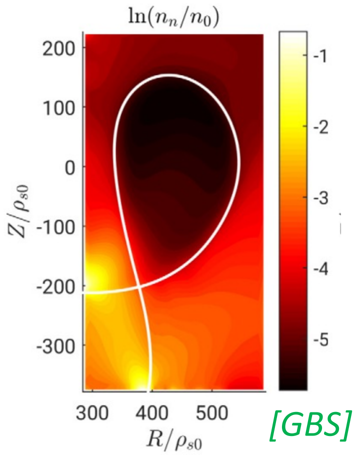
TSVV-03: Modularization of tools

- **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**
  - TSVV-03 codes are a priority, but this could be extended to other codes

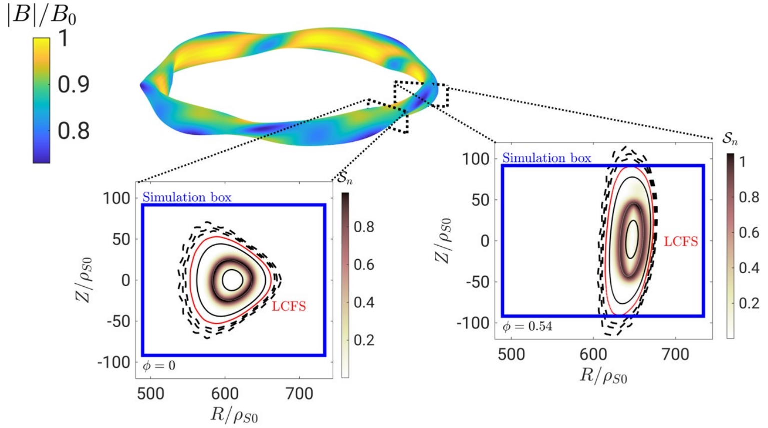
- Working also on memory limit issue of coupling to EIRENE





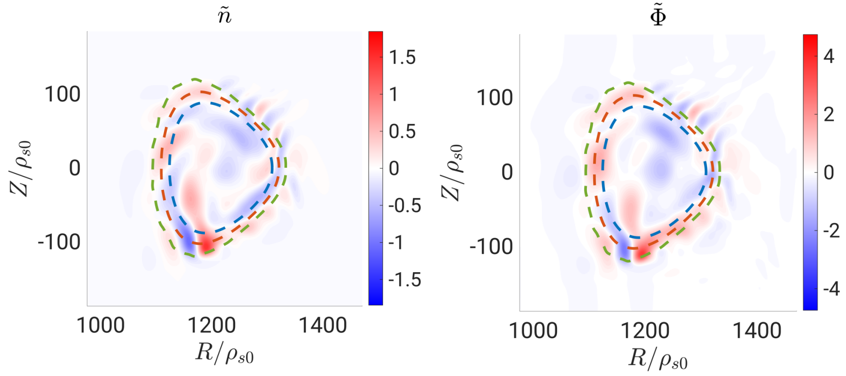
TSVV-03: Stellarator turbulence towards exp's

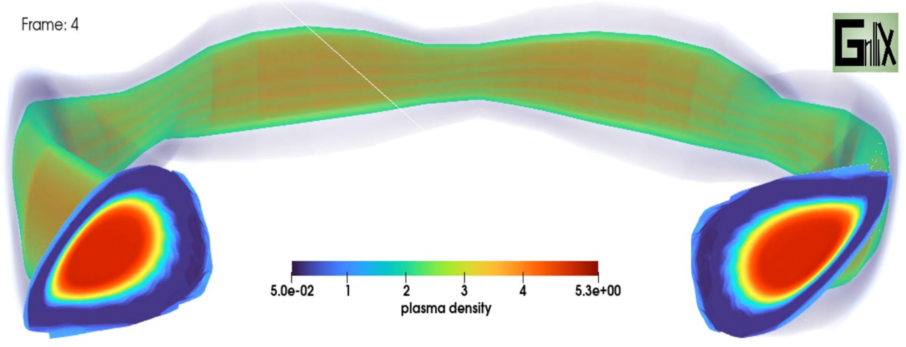
- After proof of principle demonstrations in 2023, **stellarator turbulence** modelling moving towards large machines
  - **W7-AS** as intermediate step towards W7X
  - Both GBS and GRILLIX are enabled
  - Note: GK code GENE-X is also enabled



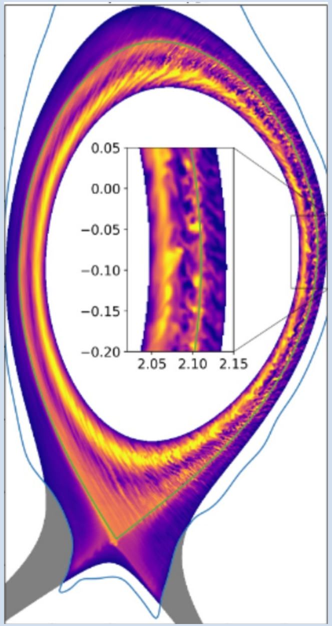
[courtesy Z. Tecchiolli]

- First results agree qualitatively with exp's

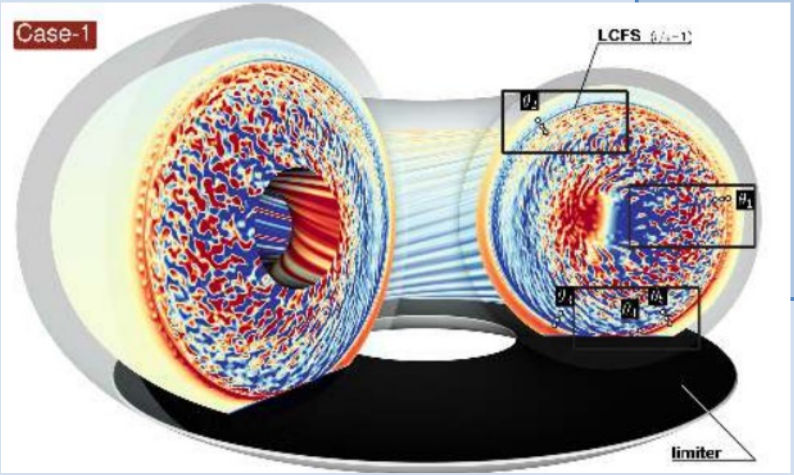




TSVV-04: Gyrokinetic codes for the edge/SOL

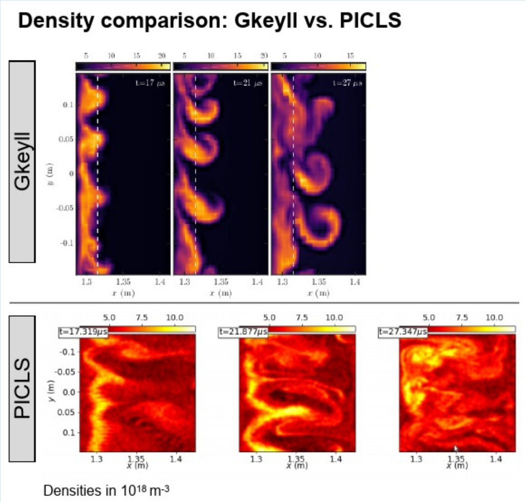


GENE-X /
D. Michels et al.,
Phys. Plasmas 2022



GyselaX /
G. Dif-Pradalier et al.,
Commun. Phys. 2022

PICLS /
A. Bottino
2021



TSVV-04: Key achievements so far

GyselaX

Full-f limiter plasma simulations

Immersed boundary condition studies using VOICE (1D1V kinetic)

Recovered major fluid/kinetic properties of sheath (Bohm criterion, space charge)

2D field solver for **arbitrary geometry**

G. Dif-Pradalier, Comm. Phys. 2022
Y. Munschy, NF 2024
Y. Munschy, NF 2024

GENE-X

Arbitrary geometry (open/closed field lines)

Dirichlet boundaries (Maxwellian BC)

Collision operators: BGK, LBD

Electromagnetics ($A_{\parallel}$)

Nonlinear quasineutrality equation

Validation on TCV-X21

D. Michels CPC 2021
D. Michels PoP 2022
P. Ulbl CPP 2022
P. Ulbl PoP 2023

PICLS

Moment-based **full-f nonlinear collisions**

Second-order particle Lagrangian terms (prep. for nonlinear polarization)

Delta-f model using Maxwellian control variate

Delta-f/full-f transition scheme for noise control in core/edge transition (to be used with limiters in ORB5)

M. Murugappan PoP 2022
M. Murugappan, submitted
A. Stier CPC 2024

Thrust 2: Edge Physics & PWI

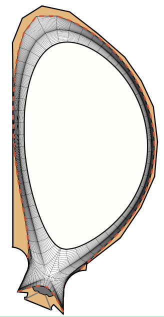
TSVV-05: A hierarchy of neutral models

Advanced Fluid Neutral (AFN) models

- Efficient (direct) coupling to plasma equations, no MC noise
- Basis for hybrid methods
- Good accuracy in highly collisional regimes

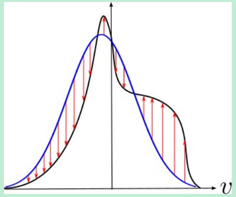
Hybrid fluid-kinetic models

Spatially (SpH)



- F-K transition based on location
- User-defined transition criteria

micro-Macro (mMH)



$$f_{\mathrm{n}}(v) = f_{\mathrm{n,f}}(v) + f_{\mathrm{n,k}}(v)$$

- Decomposition in velocity space
- Can be made **fully equivalent** to kinetic model

Kinetic model

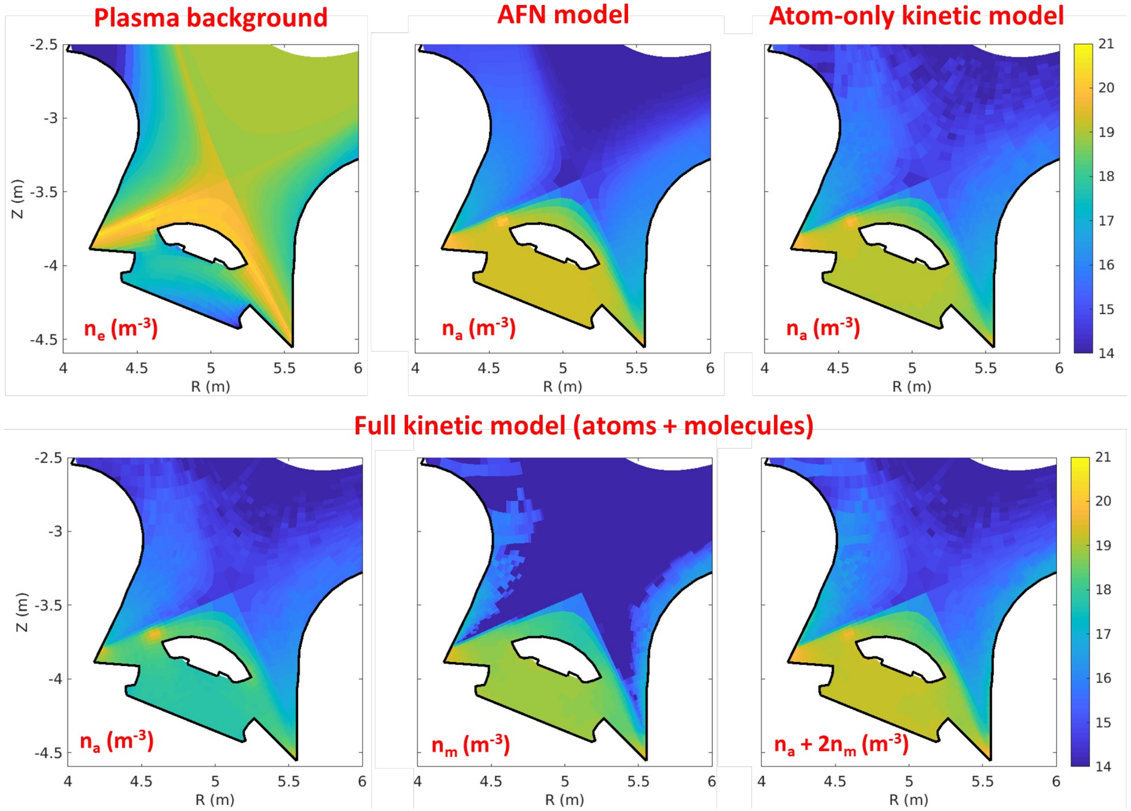
- Most complete physical description
- Flexibility w.r.t. geometry, collisional processes, sources, boundary conditions,…
- Very expensive in highly collisional regimes

Model accuracy →

← Computational efficiency

CPU × 1/10?

TSVV-05: Applying AFN model to ITER

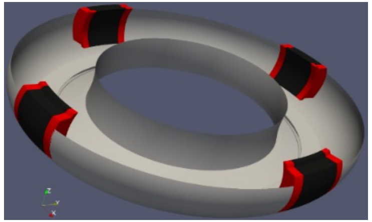


- AFN transport coefficients adapted to account for *n-n* collisions
- First application to ITER plasmas using grids extended to the wall
  - Fixed plasma background
  - Comparison to fully kinetic simulations: AFN solution qualitatively resembles *effective* neutral density (atoms + molecules)
- AFN models also applied to DEMO modeling (WP8-DES)

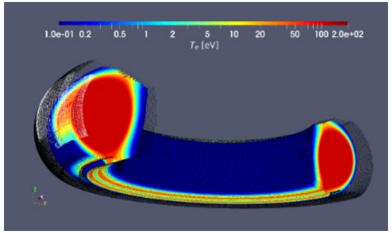
TSVV-06: SOLEDGE3X-ERO2.0 for WEST

INVESTIGATION OF **W CORE CONTAMINATION IN WEST GEOMETRY DUE TO ANTENNA LIMITER** WITH 3D TRANSPORT **SOLEDGE3X-ERO2.0 SIMULATIONS**

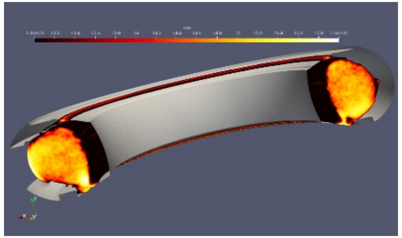
3D non-axsymmetric wall :
Radial Outer Gap: 1.5 cm

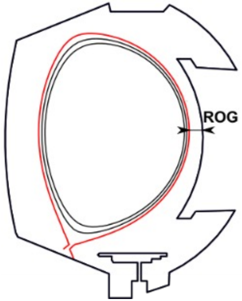


SOLEDGE3X plasma background

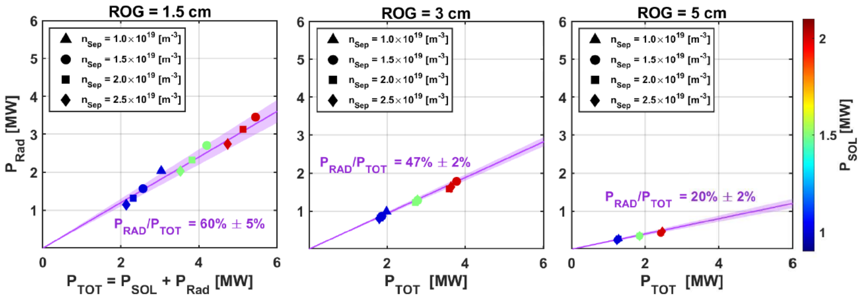


3D density map of W obtained with ERO2.0 using SOLEDGE3X backrgound





Simulations results indicate the role of the antenna limiter in the tungsten contamination of core plasma depending on the distance from the plasma (ROG parameter)

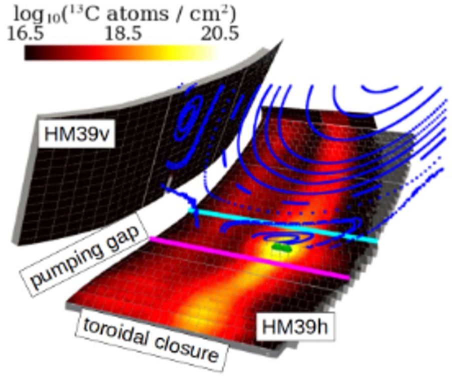


Collaboration with WP TE, WP PWIE

S. Di Genova et al NME 2023, G. Ciraolo et al PSI 2024

TSVV-06: W7-X modelling using ERO/ERO2.0

- ❑ **Modeling of impurity transport and validation w.r.t. experimental measurements**
  - Finalized OP1.2 **intrinsic carbon erosion and transport studies** + validation using spectroscopy (presented at IAEA-FEC 2023, publication NF 2024)
  - Finalized OP1.2 ^{13}C **tracer studies + validation using post-mortem data** (presented at PSI 2024, publication ready for submission in NF)
  - Ongoing: **tungsten in W7-X**
- ❑ analysis of W tiles exposed in OP1.2
- ❑ predictions for W7-X with full-W wall in Ne-seeded plasma



courtesy j.romazanov@fz-juelich.de

<u>Interactions with other WPs: PWIE</u>

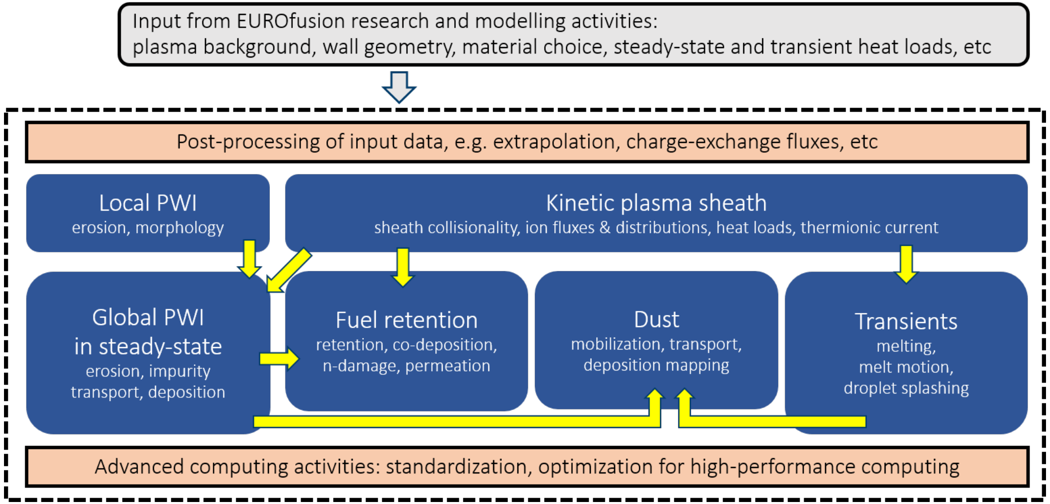
PWIE-SP D.3.T-T003-D003	Modelling of 13C injection experiments (local and global) in comparison to post-mortem data in W7-X and steady-state simulations. First plasma in full W environment in W7-X. Erosion, impurity migration and deposition modelling for JET-ILW: (FZJ)	Andreas Kirschner(FZJ)
PWIE-SP D.3.T-T003-D004	Predictive material migration in W7-X with 3D-shaped wall. Beryllium/tungsten migration with realistic 3D ITER first wall with high density case, comparison to ERO2.0. (MPG)	Klaus Schmid(MPG)

TSVV-07: PWI in DEMO (1/2)

Objectives

Assessment of

- Steady-state W erosion rates
- Preferential W re-/co-deposition locations
- Dust mobilization, survival and accumulation
- PFC response to transients: melting, splashing
- W erosion for locations affected by transients
- Tritium inventory: co-deposition, bulk retention



Teams

Jülich Forschungszentrum, KTH, cea, Université Sorbonne Paris Nord, IPP, IPP ASCR, University of Helsinki, JSI

Project overview paper published:
D. Matveev et al, Nucl. Fusion 64 (2024) 106043

Codes and model development

ERO2.0
→ PWI & impurity tracing
MIGRAINe
→ dust transport
MEMENTO
→ transient melting

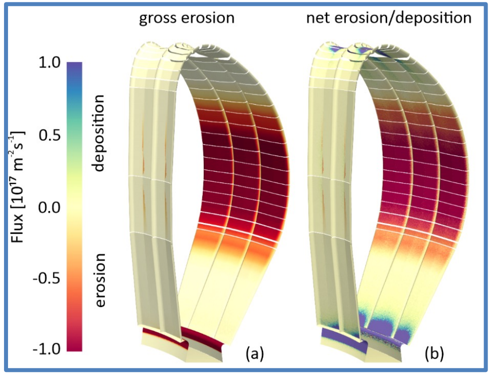
- **BIT-1:** high density divertor sheath for ERO2.0
- **SPICE:** thermionic emission for MEMENTO
  heat & particle fluxes to shaped PFC
- **FESTIM & TESSIM:** - T retention & permeation
- **SDTrimSP, MD:** erosion yields, surface effects

\+ Uncertainty quantification

TSVV-07: PWI in DEMO (2/2)

Erosion-deposition maps with ERO2.0

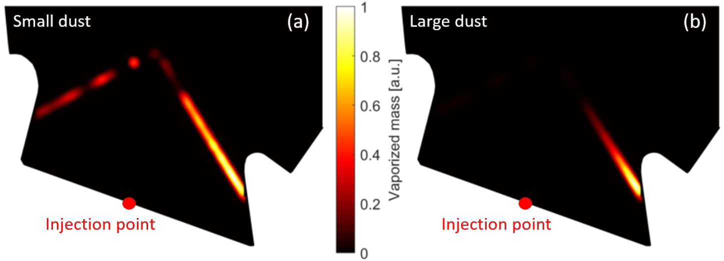
- Using baseline 2017 equilibrium with SOLPS-ITER plasma background (DCT)
- Extrapolation of plasma solution to the wall – major source of uncertainties
- Charge-state resolved background impurities fluxes and energy-resolved charge-exchange (CX) D fluxes implemented in ERO2.0
- Main wall erosion dominated by CX fluxes and divertor by seeding species
- **Work in progress:** high density divertor sheath, improved sputtering data
- *Paper in preparation, to be submitted to Nuclear Fusion by end of October*



Gross W erosion (a) and net erosion-deposition (b)

Dust remobilization and transport with MIGRAINe

- Using baseline 2017 equilibrium with SOLPS-ITER plasma background (DCT)
- Tracing dust with pre-defined grain size distributions and starting speeds
- Injection sites at the bottom of the divertor in the private flux region
- Vaporization dominant for small grains (<25 µm), localized along separatrix
- **Work in progress:** other injection sites according to ERO2.0 deposition maps, iteration of single-discharge results to predict long-term inventory evolution



W dust evaporation maps for indicated injection point (a) Small dust (5-20 µm) and (b) large dust (30-50 µm)

TSVV-07: Interactions with WPs

- WP-PWIE
  - W sputtering data from lab experiments and modelling (incl. supersaturated W)
  - Experiments in support of development and parameterization of models of tritium (deuterium) transport in materials
- WP-TE
  - Experimental programs at tokamaks (AUG, WEST) for validation of modelling tools (e.g. ERO2.0, MEMENTO)
- DEMO Central Team (DCT)
  - Plasma background(s) for wall lifetime (ERO2.0) and dust inventory (MIGRAINe) simulations
  - Transient heat loads for melting simulations (TQ, CQ) – in progress
  - Transient plasma profiles for start-up and VDEs for dust mobilization and transport – currently not available
- TSVVs & Thrust 2
  - TSVV-05 – EIRENE as part of SOLPS-ITER for consistent plasma backgrounds and CX neutrals distributions
  - TSVV-06 – W impurity sources, screening, coupling to core plasma
  - Potential links to other TSVVs mainly via the need/interest in plasma backgrounds and/or impurity sources

Thrust 3: MHD & Energetic Particles

TSVV-08: MHD transients - Overview

JOREK (3D extended MHD & hybrid) ↔ **CARIDDI/STARWALL** (resistive walls)

Disruptions incl. natural disruptions, SPI, VDEs, consequences, REs (↔ TSVV 9)
↔ **core physics** incl. sawtooth control, NTMs, EPs

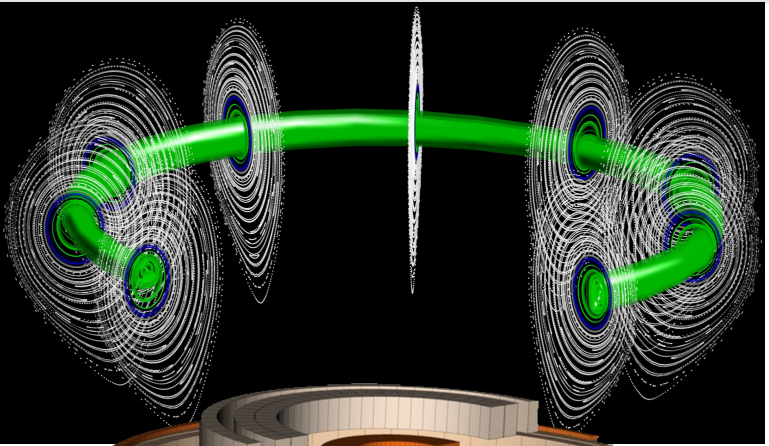
Pedestal incl. small-ELM, no-ELM, RMPs, pellets
↔ **SOL/divertor** incl. detachment/burn-through, XPR, HFSHD, tungsten migration

Selected key results on the next two slides

↔ **WPs TE** (various RTs) **DES, DTT, SA** & **ITER** & **TSVV 9/10**

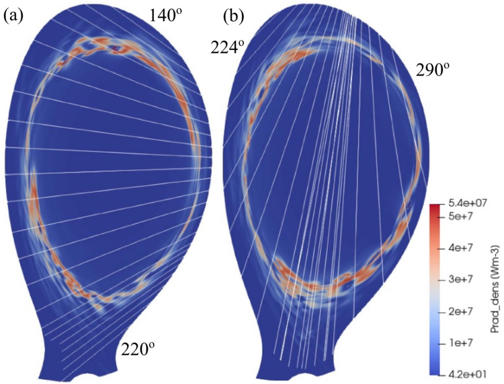
→ Nuclear Fusion 61, 065001 (2021) & Nuclear Fusion 64, 112016 (2024)

TSVV-08: Core MHD and disruptions



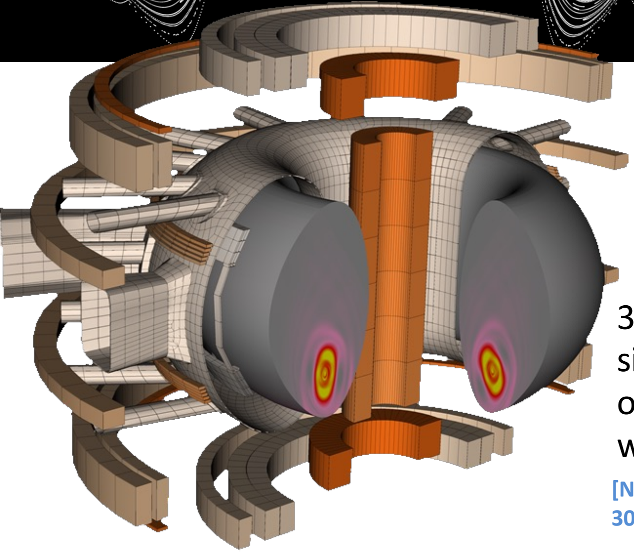
Helical core formed by interchange modes driving a dynamo that prevents sawtooth instabilities; surrogate model in development

[H Zhang et al, AAPPS-DPP 2024, invited]



JET Deuterium SPI simulation with virtual bolometry lines for direct experiment comparison

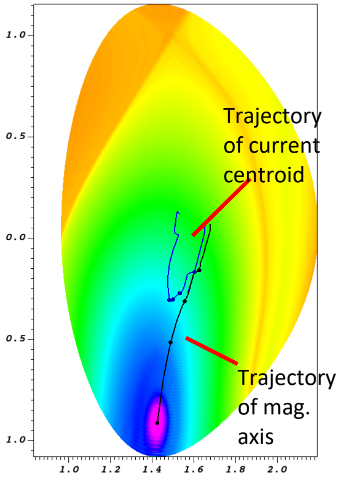
[M Kong et al, Nucl Fusion 64, 066004 (2024)]



3D thermal quench AUG simulation in the course of a hot VDE simulated with JOREK-CARIDDI

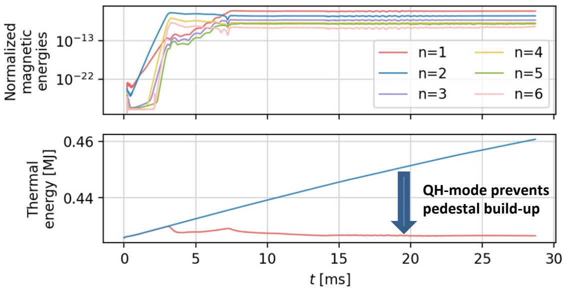
[N Isernia et al, Phys Plasmas 30, 113901 (2023)]

Mechanism of vertical force mitigation by massive impurity injection identified as decoupling current centroid from axis



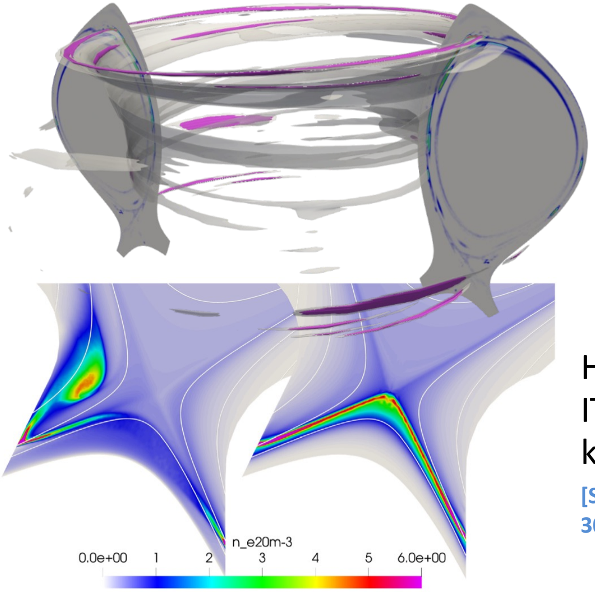
[N Schwarz et al, Nucl Fusion 63, 12606 (2023)]

TSVV-08: Edge MHD



QH-mode simulation for AUG with stationary modes preventing ELMs; incl. q_{95} windows and density limit

[L Meier et al, Nucl Fusion 63, 086026 (2023)]



Kinetic 3D tungsten transport in ITER pedestal and SOL with applied RMPs

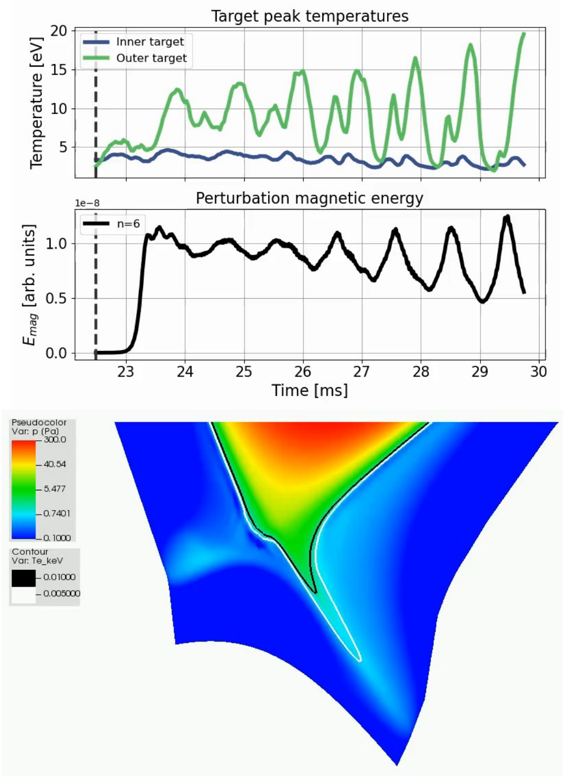
[S Korving et al, Phys Plasmas 31, 052504 (2024)]

HFSHD formation in ITER with a full-f kinetic neutrals model

[S Korving et al, Phys Plasmas 30, 042509 (2023)]

3D detachment and burn-through in an AUG small-ELM scenario with kinetic neutrals and impurities

[M Szucs et al, in preparation]



TSVV-09: REs during disruptions

- 2 main workhorses: **DREAM** & **JOREK** (↔ TSVV 8)

- Main focus: **RE avoidance & mitigation in ITER**
  - Ekmark JPP 2024, Vallhagen NF 2024, Wang NF 2024 subm., Nardon IAEA FEC 2023, Hoppe REM 2024, Bergström PPCF 2024

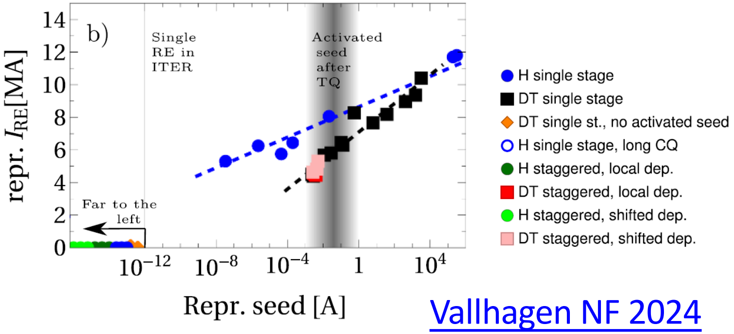
- **Validation** on present devices: ASDEX Upgrade, JET
  - Halldestam REM 2024, Nardon REM 2024, Järvinen JPP 2022 & REM 2024
  - Regular meetings with RT-03 coordinators + TSVV 8 organized by Umar Sheikh

- **Model development**
  - JOREK: self-consistent kinetic treatment of REs (Bergström invited talk @ EPS 2024)
  - DREAM: ablation plasmoid drifts, scrape-off RE losses (Vallhagen REM 2024 & invited talk @ EPS 2024)
  - Unified atomic description for high-Z impurities (Savoye-Peysson NF 2023)

- **Collaborations** with colleagues working on…
  - EU-DEMO with DREAM (Pokol REM 2024) and JOREK (Vannini 2024 subm.)
  - DTT (Emmanuelli SOFT 2024)
  - JT60-SA (Olasz FED 2023 & REM 2024)

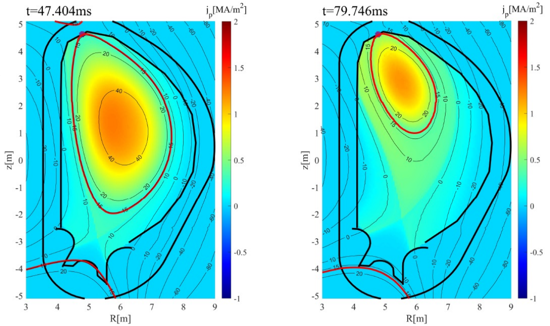
TSVV-09: Recent highlights

- **ITER RE avoidance** prospects **not looking good** according to DREAM simulations, at least in presence of activated seeds



Vallhagen NF 2024

- However, JOREK sims. suggest **RE scraping-off effect** from vertical motion may help significantly

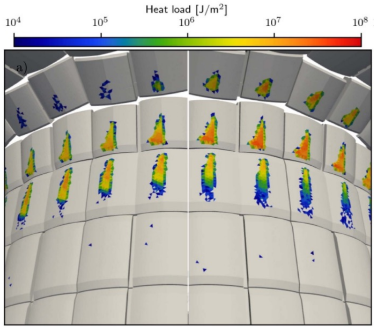


Wang NF 2024 subm.

- DREAM study being revisited → **RE avoidance now found in some cases** with activated seeds (Vallhagen to be subm.)

- JOREK is **progressing towards a self-consistent prediction of RE impacts** in ITER and other machines

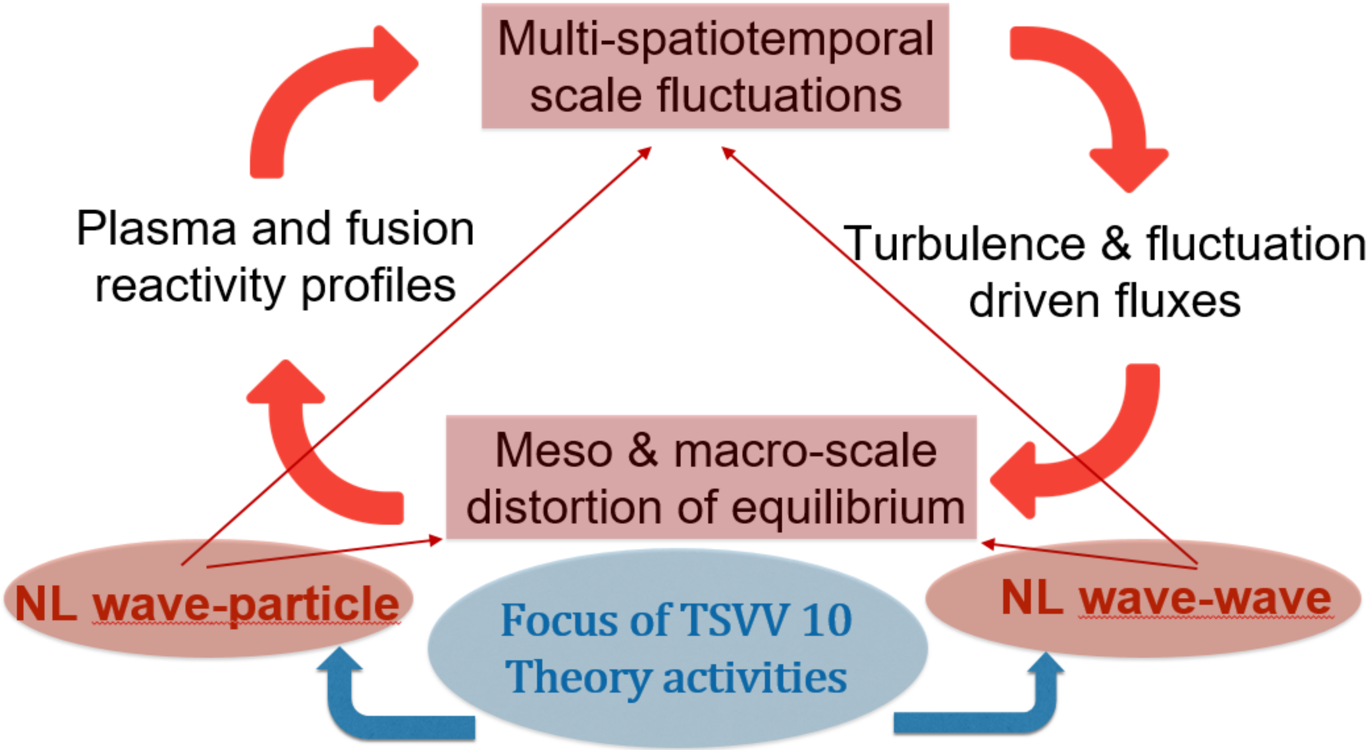
  KTH collaboration on predicting resulting damage



Bergström PPCF 2024

TSVV-10: Physics of burning plasmas

❑ Burning plasmas as complex self-organized systems:



Requires a comprehensive theoretical framework for the self-consistent description of drift Alfvén wave excitation and phase space energetic particle transport in fusion plasmas [Chen&Zonca RMP16].

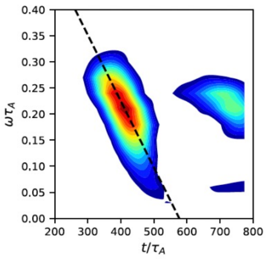
General theory is based on nonlinear gyrokinetic formulation of fluctuation spectrum evolution and energetic particle transport, treated on the same footing.

Evolution of fluctuation spectrum and EP transport suggest two possible routes to nonlinear physics: nonlinear wave-wave interactions and nonlinear wave-particle interactions.

TSVV-10: GK simulations of chirping inst‘s

1. Theory compared to simulations (verification):
chirping modes in presence of energetic particles.
Chirping rate from simulations is proportional to saturation amplitude (as predicted theoretically, [Zonca et al., Varenna Conf. 2024])
Plasma Phys. Control. Fusion **65** 074001

- Comprehensive studies on the nonlinear frequency chirping of energetic particle driven Alfvén modes with the fully gyrokinetic code **ORB5**.
- Aim to understand the likelihood of a mode to oscillate at a constant frequency or to evolve to nonlinear chirping oscillations, as well as its consequences on the type of energetic particle induced transport.

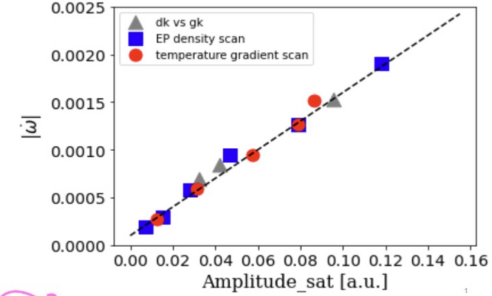


Time evolution of the mode frequency

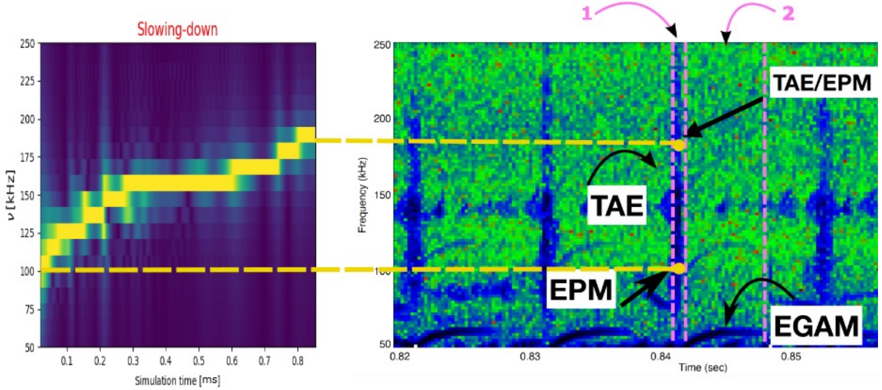
various parameter scans to map chirping rate vs saturation amplitude

Energetic particle density, energy, …

$(\Delta\omega/\Delta t)_{sat} \sim (\omega_{res}')\ A_{sat}$

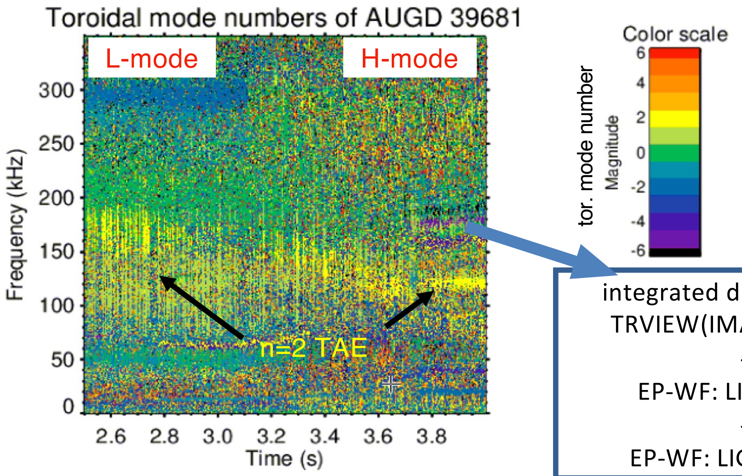


2. Simulations compared to experiment (validation):
ASDEX Upgrade discharge #312213@0.84s
Same chirping range in simulations as in experiment
Nucl. Fusion **62** 126042



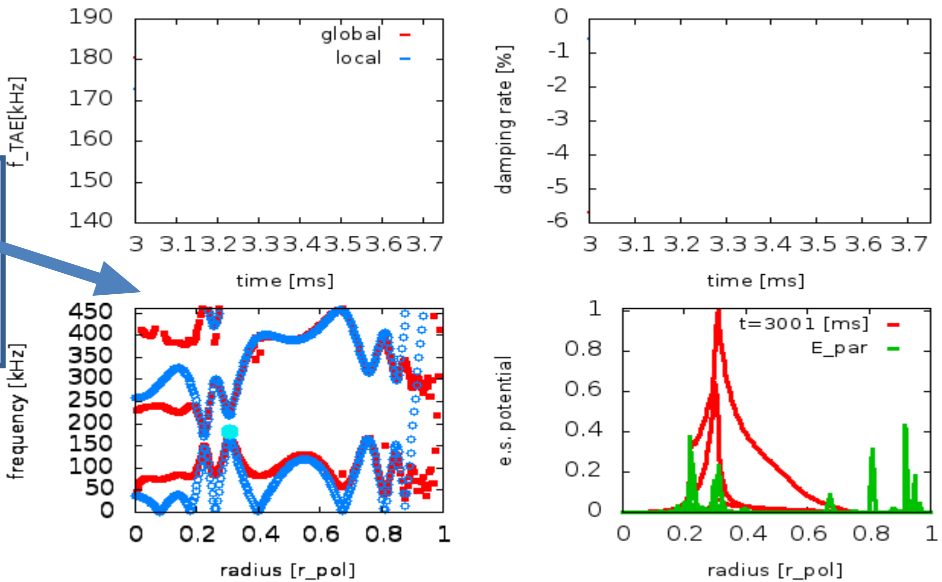
1) Further gyrokinetic applications in JET, TCV, ITER, MAST-U, W7-X plasmas using ORB5&EUTERPE codes.
2) Hybrid particle-MHD simulations with HYMAGYC and XTOR-K codes (kink, AEs).

TSVV-10: Integrated modeling of EP inst‘s



•automated processing of 160 time slices based on IDA equilibria and profiles
•fully implemented in IMAS, ensuring reproducibility [Lauber, EPS 2022, Popa 2020-2023]

integrated data analysis +
TRVIEW(IMAS interface)
+
EP-WF: LIGKA local
+
EP-WF: LIGKA global



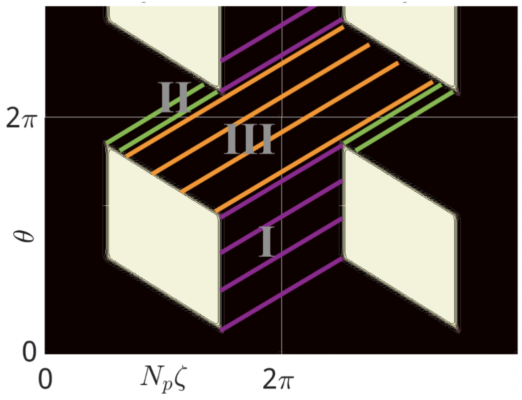
•analyse L-mode,H-mode and transition phases: beat infamous problem of AE stability sensitivity to profiles - compare trends instead of single time slices
•compare local and global models
•systematic uncertainty quantification feasible
•applied also to TCV, JET, JT-60SA, ITER, DEMO

- stable version available on ITER and Gateway
- training course and documentation available (July 2023)
- continued development and speed up of various components
- embedded in emerging reduced EP transport model ATEP capabilities:
- analyse AE stability in transient phases - local/global
- physics results for ITER case: low TAE damping rates in ramp-up phase ; flat top very stable with respect to TAEs

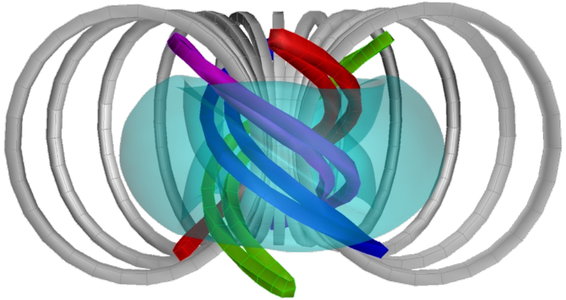
Thrust 4: Stellarator physics

TSVV-12 : Highlights and plans for 2025

- **Quasi-isodynamic stellarators** with few field periods, good fast-ion confinement, low bootstrap current and also with reduced turbulent transport. **[Goodman, PRX-Energy 2024]**
- **Piecewise-omnigeneous fields:** Finding explanation for good confinement outside the standard pictures. [Velasco, PRL 2024]



- **MONKES:** a fast (< minute/point) and accurate NC code for the evaluation of the bootstrap current. [Escoto, NF 2023]
- **Inventing fast metrics for alpha particle losses.** [Albert, JPP 2023]
- **Global fluid turbulence simulations** have been performed in the edge and scrape-off-layer of stellarators using the BOUT++ framework. [Shanahan, JPP 2024]
- **Semi-automated divertor plate design algorithm for low target heat loads.** [Davies, NF 2024]
- **A new compact quasi-axisymmetric stellarator-tokamak hybrid concept.**



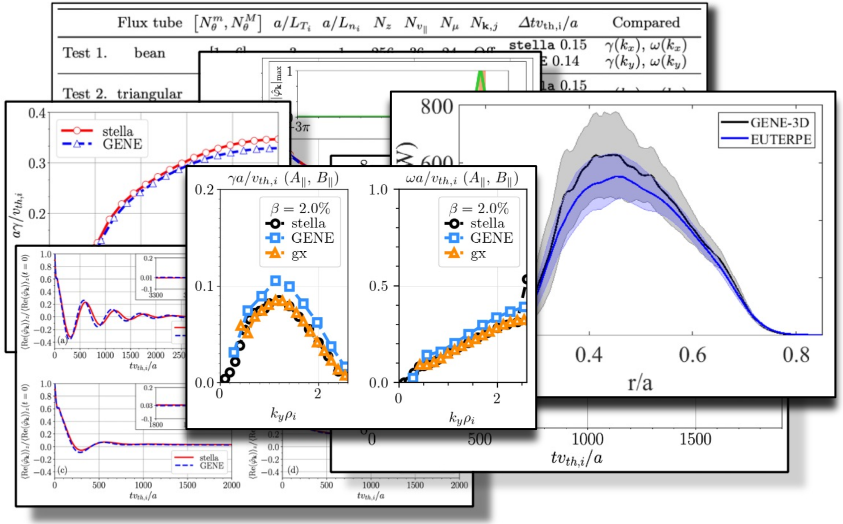
[Henneberg, PRR 2024]
[Schuett, PRR 2024]

2025

- **Divertor optimisation.**
- **Free-boundary version of GVEC.**
- **Comparison of stellarators of different topological classes.**

TSVV-13: Code verification & exploitation

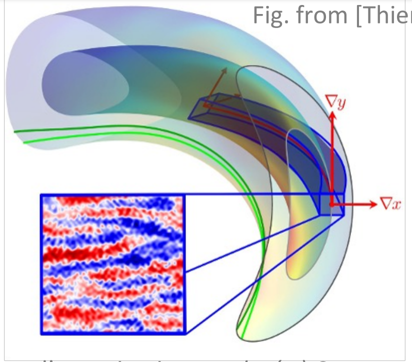
- TSVV-13 has advanced **stellarator gyrokinetic code development**, including electromagnetic (EM) and full flux surface versions of `stella` and EM version of `GENE-3D`.
- **Verifying** new and existing code features has been a **continuous effort** within TSVV-13, see e.g., [González-Jerez JPP´22], [Sánchez NF´21] and [Sánchez NF´22]



⇒ Set of European stellarator-specific gyrokinetic codes that are benchmarked and being validated against experiments.

⇒ **Code exploitation to support W7-X campaigns,** following certain priority lines*, is central to TSVV-13 and strengthens its **connection with WPW7X**.

Fig. from [Thienpondt subm.´24]



*TSVV#13 proposal's motivation *reads: (…) Some aspects of turbulence remain **practically unexplored** (**impurity transport, bulk particle transport, electromagnetic turbulence**, interplay between neoclassical (NC) and gyrokinetic (GK) physics (…)* []

TSVV-13: W7-X related physics issues

- First approach to the particle transport problem in W7-X. Turbulent pinch proven to prevent core density depletion [Thienpondt PRR´23]
- High fidelity transport model with `TANGO+GENE-3D-KNOSOS`, successfully applied to scenarios with T_i clamping [Bañón Navarro NF´23]
- First assessment of impurity transport in W7-X [García-Regaña JPP´21] and evaluation of impact of impurity on turbulence [García-Regaña PRL´24]
- Revisiting pellet-enhanced plasmas [Zocco PRR ´24] to confirm that previous works overestimated heat flux reduction
- Indications of confinement degradation with β in W7-X based on electromagnetic simulations [Mulholland PRL´23]
- First measurements of zonal activity in W7-X accurately reproduced with `EUTERPE` and `stella` [Carralero subm.´24]
- (...)

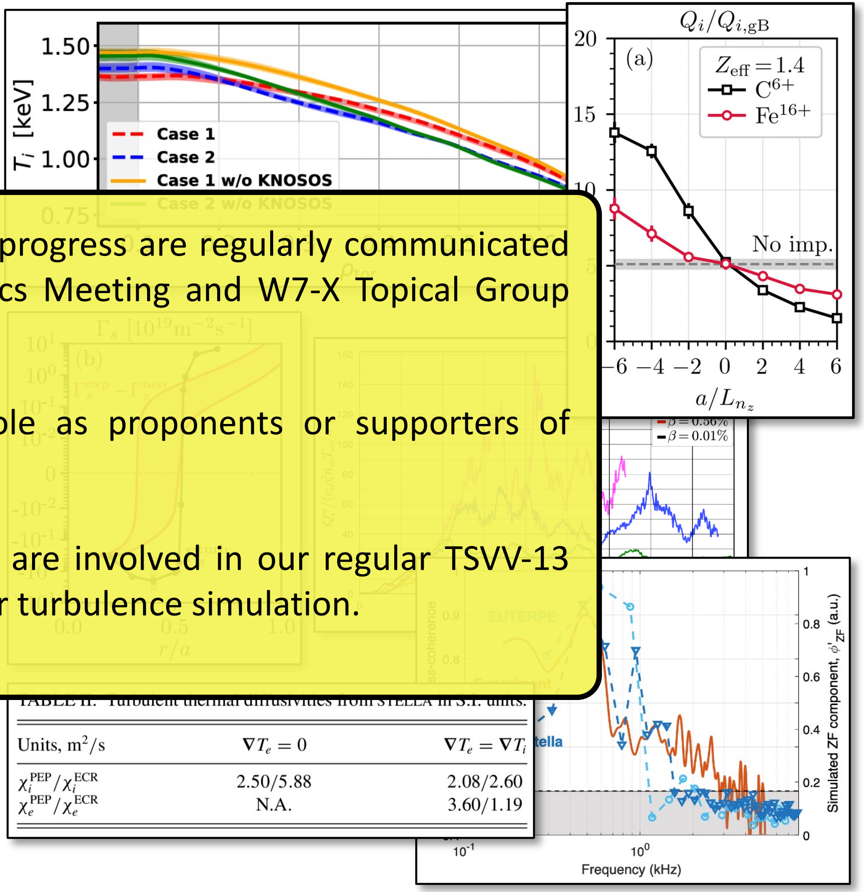


TABLE II. Turbulent thermal diffusivities from STELLA in S.I. units.

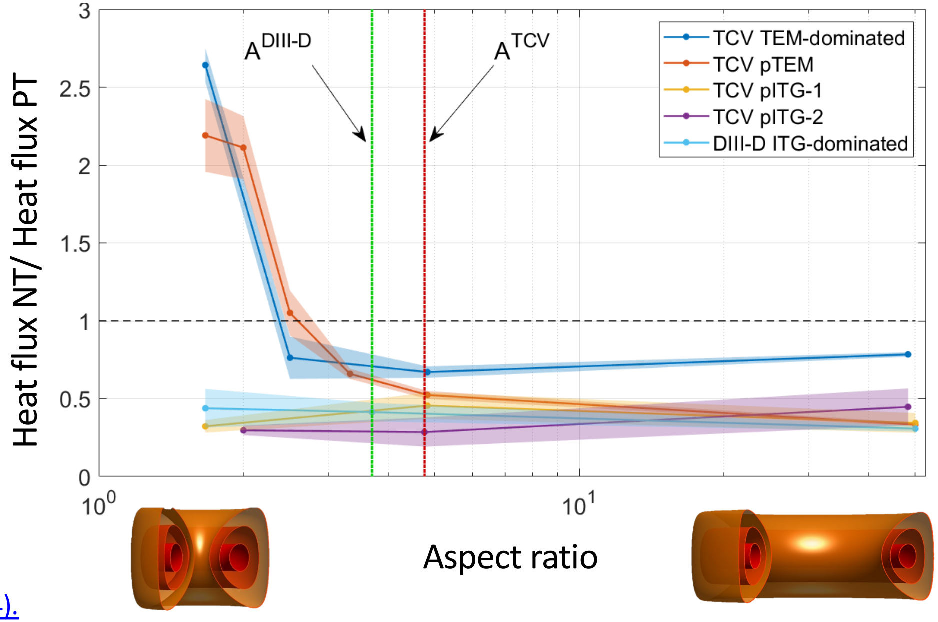
Units, m^2/s	$\nabla T_e = 0$	$\nabla T_e = \nabla T_i$
$\chi_i^{PEP}/\chi_i^{ECR}$	2.50/5.88	2.08/2.60
$\chi_e^{PEP}/\chi_e^{ECR}$	N.A.	3.60/1.19

- All these achievements and preliminary progress are regularly communicated in common forums like the W7-X Physics Meeting and W7-X Topical Group meetings.
- TSVV-13 members play a significant role as proponents or supporters of upcoming experiments.
- External members from the W7-X team are involved in our regular TSVV-13 meeting as external experts on stellarator turbulence simulation.

Thrust 5: Whole-device modeling

TSVV-02: Negative triangularity tokamaks (1/2)

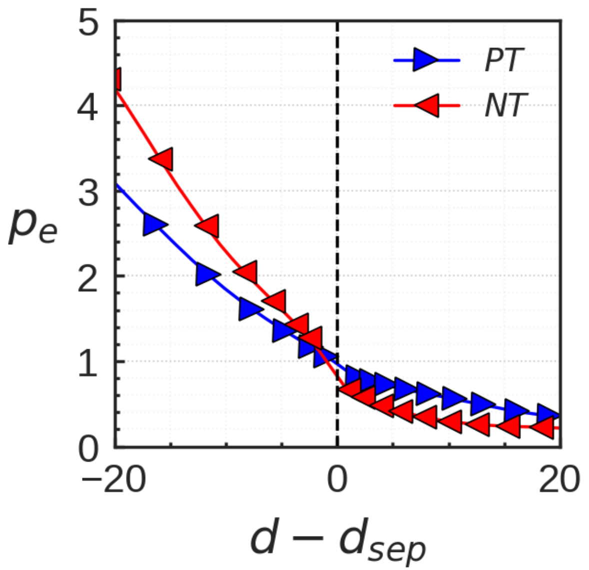
Simulations indicate that NT will still benefit confinement at reactor scales in standard tokamaks (but perhaps not in spherical tokamaks)[1,2]



[1] A. Balestri, et al. *PPCF* (2024).
[2] G. Di Giannatale, et al. PPCF (2024).

TSVV-02: Negative triangularity tokamaks (2/2)

- SOL widths and ease of detachment in NT appears between PT L-mode and PT H-mode[1,2]
- Lack of H-mode transition can be understood from ballooning stability[3]
- Vertical stability may be worse in NT [4]
- Currently studying how a NT reactor might optimize differently than PT[5]



[1] K. Lim, et al. *PPCF* (2023).
[2] P. Muscente, et al. Nucl. Mater. Energy (2022).
[3] O. Sauter, et al. IAEA (2023).
[4] S. Marchioni. EPFL PhD Thesis (2024).
[5] A. Balestri, et al. arXiv:2407.06439.

TSVV-02: Interaction with Work Packages

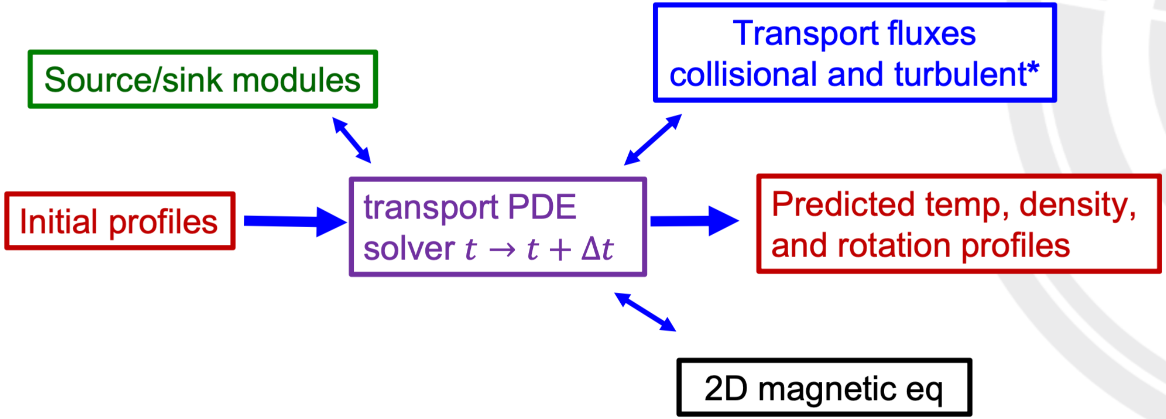
Key interactions with Work Packages regarding experimental data:

- Collaborated with WPTE RT-07 (which focused on NT)
- Results from WPTE NT campaigns on TCV and AUG, facilitated by the EPFL ACH, have been used in our analysis[1-7]
- Plan to analyze recent results from JET and MAST-U
- Looking forward, additional experiments on AUG appear crucial for evaluating potential disparity between carbon machines (TCV, DIII-D) and metal machines (AUG, JET) using reduced modeling

[1] A. Mariani, et al. *Nucl. Fusion* (2024).
[2] M.J. Pueschel, et al. Nucl. Fusion (2024).
[3] A. Balestri, et al. *PPCF* (2024).
[4] A. Balestri, et al. *PPCF* (2024).
[5] K. Lim, et al. *PPCF* (2023).
[6] M. Vallar, et al. *Nucl. Fusion* (2022).
[7] P. Muscente, et al. Nucl. Mater. Energy (2022).

Integrated modelling framework to orchestrate iterations btw physics modules

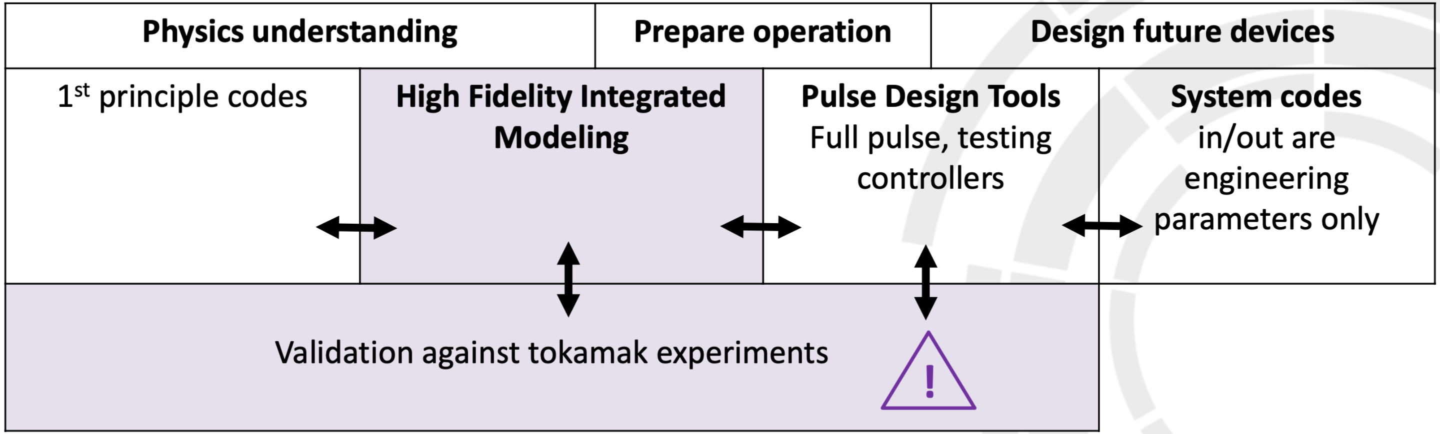
Multi-scale: spatial & temporal, multi-physics problem
Long standing know-how
JETTO Cennacchi G., Taroni A. 1988
ASTRA Pereverzev G.V. et al 1991
CRONOS/METIS Artaud J.F. et al NF 2010 NF 2018
Etc [F.M. Poli PoP 2018]



*** Using reduced but physics based turbulent transport models**: TGLF/ QuaLiKiz [Mantica NF 2020]

TSVV-11

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

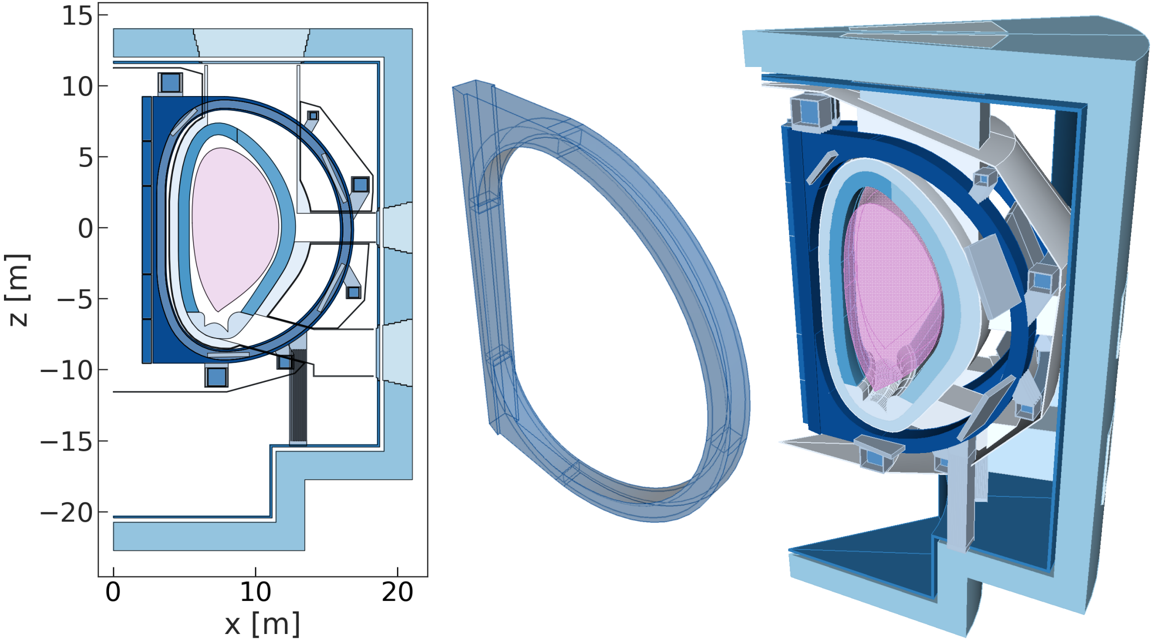
TSVV-14: Overview

- Majority of outstanding tasks have minimal viable examples
- Progress being made to integrate new models into Bluemira while keeping software quality high
- On track for completion of existing tasks for end of 2025

Deliverables – Completion level		
Software architecture review and merge of BLUEPRINT and MIRA		2-D magnet winding pack design module
Integration with existing 0-D/1-D systems codes (e.g. PROCESS)		Vertical stability model incorporated into equilibrium solver
Coupled 1.5-D transport solver and free-boundary equilibrium solver		Coupling to open-source 3-D multi-physics FEA tools for “post run” workflow
Automatic 3-D CAD generation		Plant power balance
2-D deterministic radiation transport		First wall design module taking advantage of integrated tools
3-D radiation transport model integration (e.g. OpenMC)		Implementation of global optimisation solver in BLUEMIRA

TSVV-14: Integration into EU-DEMO workflow

- PROCESS run
  - PSD-PSDD iteration
- BLUEMIRA run
  - PSD-PSDD iteration
  - TF coil shape algorithm modified (cross-check with 3-D FEA, L. Giannini)
  - FW shape algorithm adjusted (F. Maviglia)
  - Breakdown magnetostatic optimisation modified
  - Several subtly different configurations investigated
- BLUEMIRA outputs then "re-done" and ownership is transferred
  - FW shape redone by F. Maviglia
  - The equilibria and PF coil positions are improved by CREATE
  - 2-D and 3-D CAD converted into CATIA by the CAD office...
- PSD-PSDD workflow continues as normal



TSVV-14: Remote maintenance integration

- Specification of constraints on remote maintenance
  - Space availability and with optimisation constraints
  - Manipulator constraints (eg. mass)

- Early concept stage integration of RM considerations
  - Integrated with all other systems
  - 2D Keep out zones for ports part of automated PF coil positioning and blanket segmentation
  - Access restrictions respected
- Immediate generation of space claim CAD expedites further analysis
- Ongoing work to expand included constraints and considerations