Towards Digital Twins of Fusion Systems

Achievements of the E-TASC Initiative

F. JENKO, IPP, Garching, Germany

J. BALL, EPFL, Lausanne, Switzerland
D. BORODIN, FZJ, Jülich, Germany
C. BOURDELLE, CEA, Saint-Paul-lez-Durance, France
G. CIRAOLO, CEA, Saint-Paul-lez-Durance, France
J. E. COOK, UKAEA, Oxford, United Kingdom
J. M. GARCÍA-REGAÑA, CIEMAT, Madrid, Spain
T. GÖRLER, IPP, Garching, Germany
M. HOELZL, IPP, Garching, Germany
F. IMBEAUX, CEA, Saint-Paul-lez-Durance, France
J. LOIZU, EPFL, Lausanne, Switzerland
D. MATVEEV, FZJ, Jülich, Germany
A. MISHCHENKO, IPP, Greifswald, Germany
E. NARDON, CEA, Saint-Paul-lez-Durance, France
P. TAMAIN, CEA, Saint-Paul-lez-Durance, France
D. TOLD, IPP, Garching, Germany

E-TASC = EUROfusion – Theory and Advanced Simulation Coordination

Coordinated EUROfusion effort (since 2021): 200+ researchers, 15 strategic projects

X. Litaudon, F. Jenko et al., PPCF 64, 034005 (2022)

Accelerating fusion research via supercomputing

nature reviews physics https://doi.org/10.1038/s42254-025-00837-1

F. Jenko, Nature Reviews Physics 7, 365 (2025)

https://rdcu.be/ex2Eb

Perspective

Check for updates

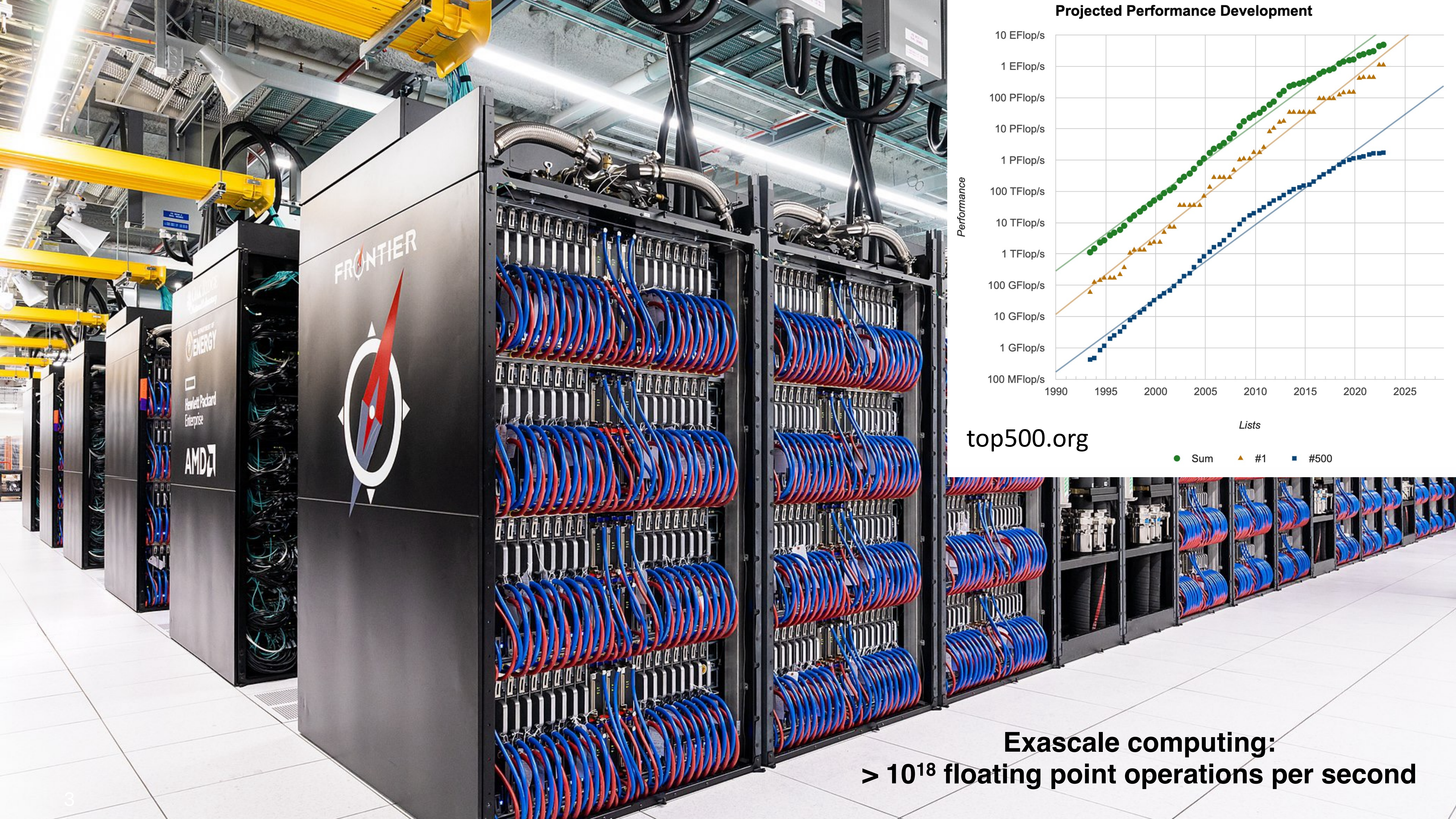
Accelerating fusion research via supercomputing

Frank Jenko [1,2]

Abstract

The pursuit of fusion energy is gaining momentum, driven by factors including advances in high-performance computing. As the need for sustainable energy solutions grows ever more urgent, supercomputing emerges as a key enabler, accelerating fusion power toward practical realization. Supercomputers empower researchers to simulate complex plasma dynamics with remarkable precision, aiding in the prediction and optimization of plasma confinement and stability – both essential for sustaining burning plasmas. They also have a critical role in assessing the resilience of materials exposed to the

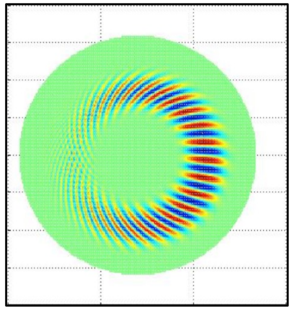
Sections

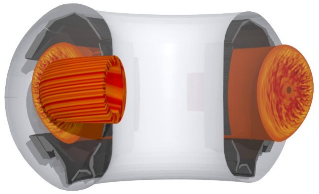


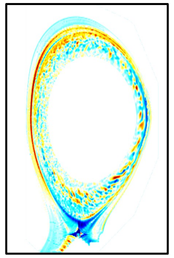
Exascale computing:
> 10^{18} floating point operations per second

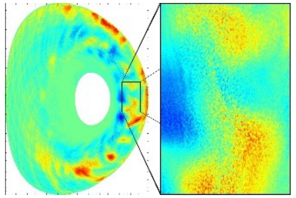
From highly idealized models towards digital twins

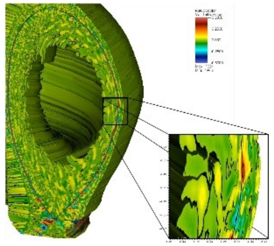
Increasing fidelity & modeling capability with increasing computing power

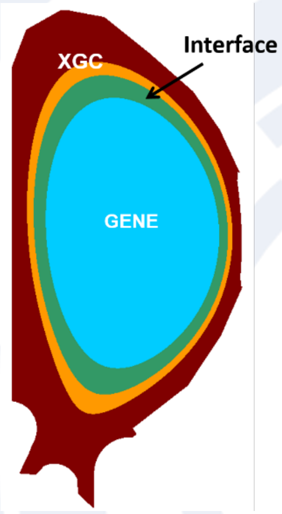


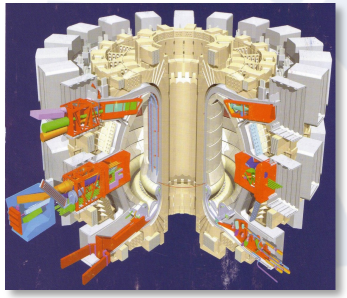












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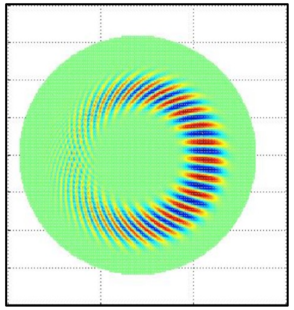
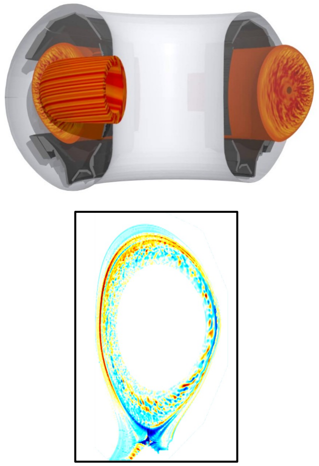
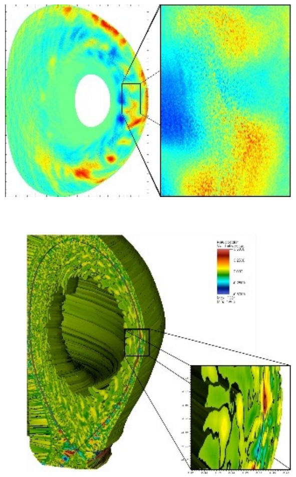
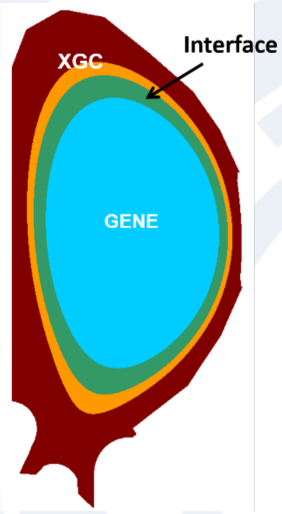
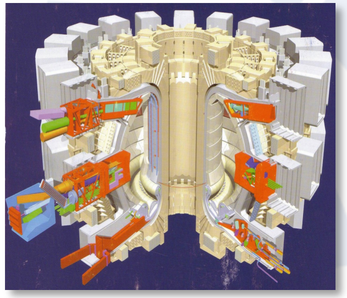
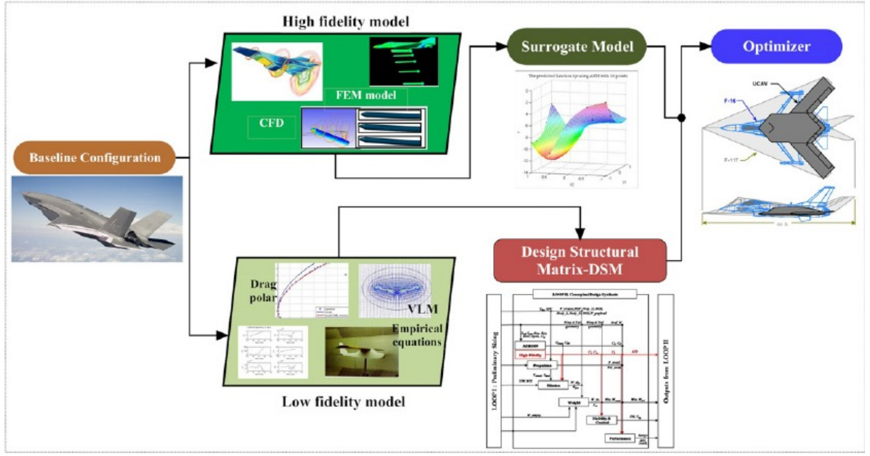












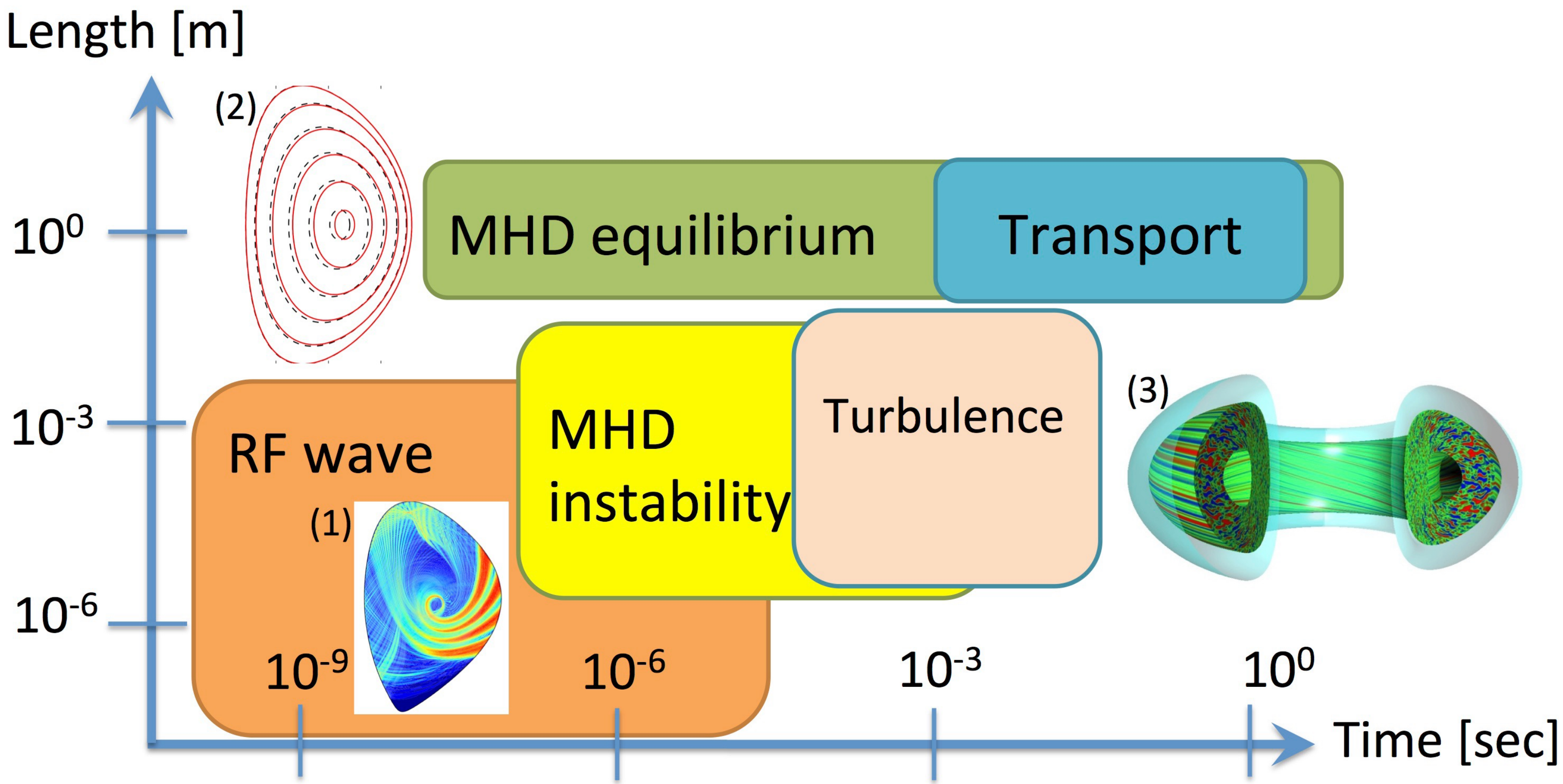
more complete physics

faster

Multi-fidelity approach:

- HiFi models for reliable extrapolation/prediction
- LoFi models (ideally based on HiFi models) for optimization, real-time control etc.

Digital twins: multi-scale, multi-physics challenges



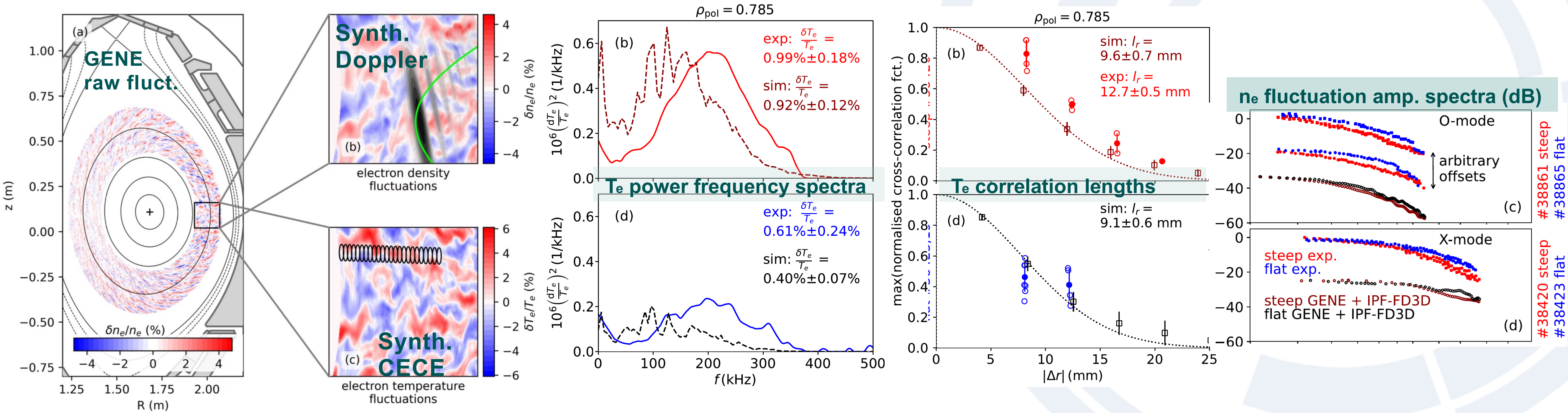
Many nonlinear interactions; we cannot use a simple "superposition principle"

Predicting Core Physics: Turbulence, Fast Particles, MHD

High realism of gyrokinetic (GK) core turbulence simulations

K. Höfler et al., Nature Communications 16, 2558 (2025)

GENE simulations compared to 8 (!) simultaneous fluctuation measurements in ASDEX Upgrade



Impact of fast particles on AUG plasma performance

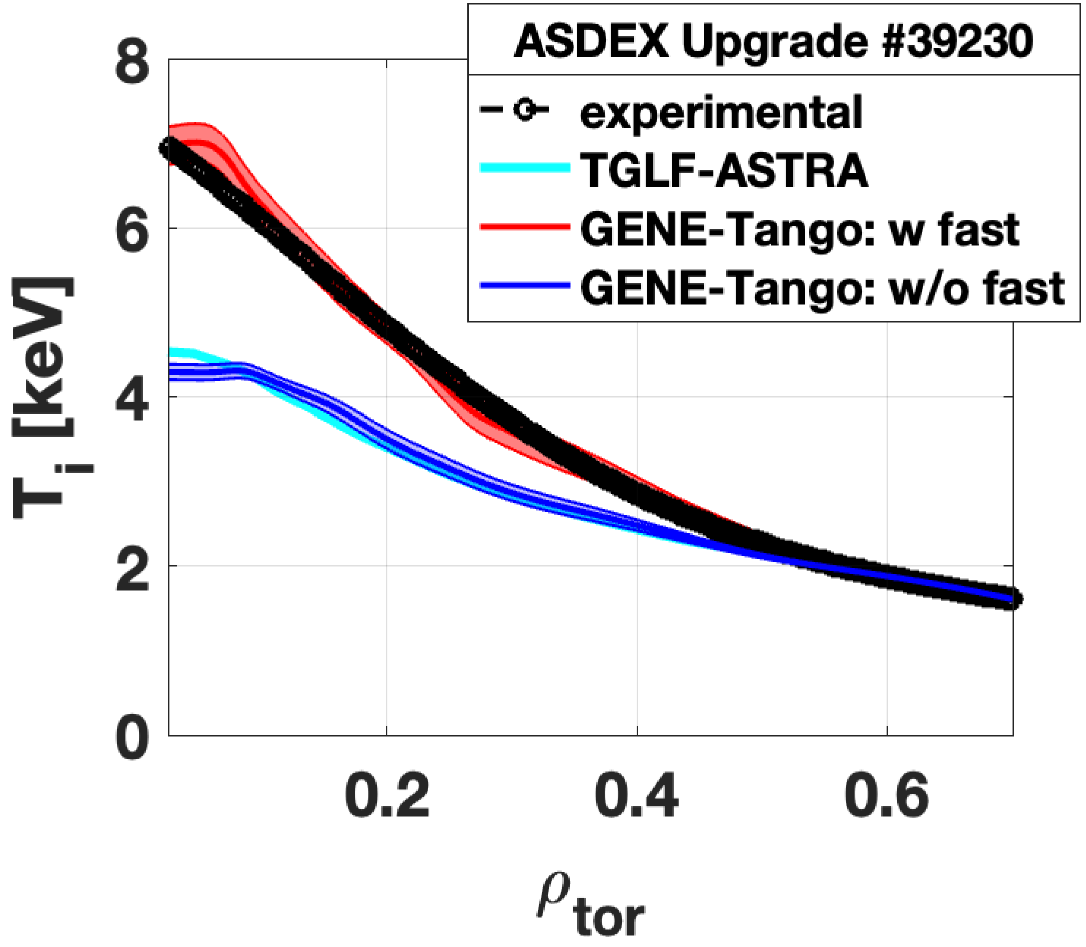
Di Siena NF 24

- Physically comprehensive GENE-Tango simulations for ASDEX Upgrade discharge #39230

- Experimental T_i profile matched only if *fast particles* and *electromagnetic effects* are *simultaneously* retained

- TGLF-ASTRA simulations fail to accurately reproduce the experimental profiles

- Shear-flow turbulence suppression triggered by global MHD modes

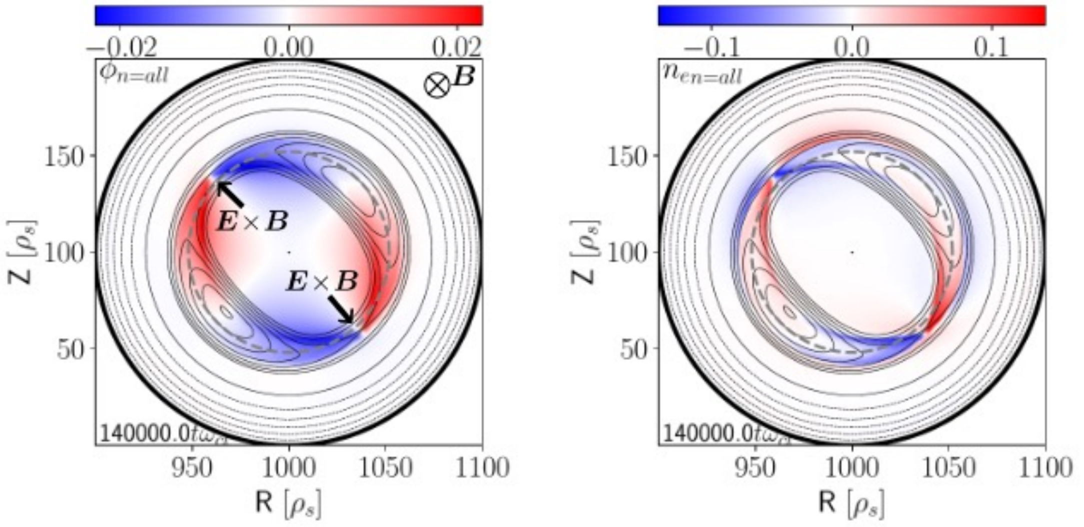


Nonlinear GK simulations of tearing modes

Tokamaks (ORB5)

Tearing modes and turbulence coexist and interact

tearing instability > islands > flows > island saturation



(a) Electrostatic potential ϕ.

(b) Electron density n_e.

Widmer PoP 24

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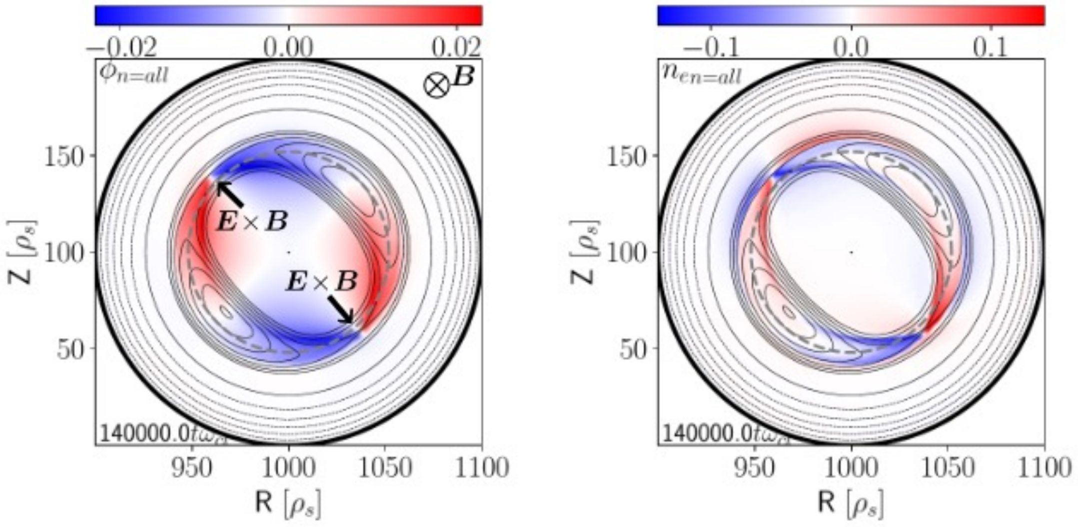


(a) Electrostatic potential ϕ. (b) Electron density n_e.

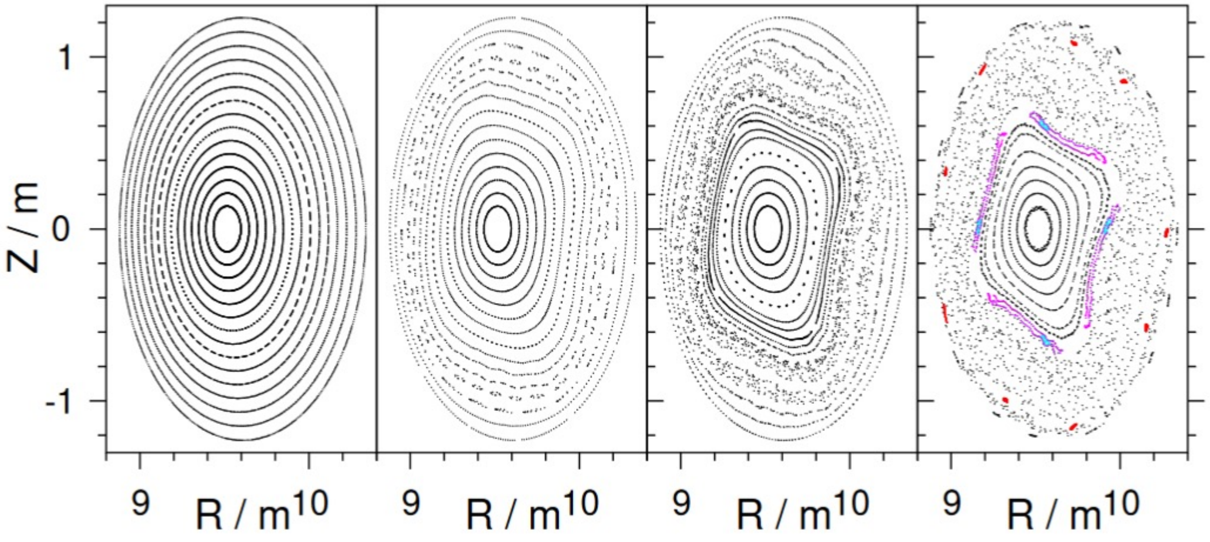
Widmer PoP 24

Stellarators (EUTERPE)

Tearing modes destroy flux surfaces

nonlinear growth of magnetic islands > ergodization

First-ever GK simulations of NL MHD in stellarators

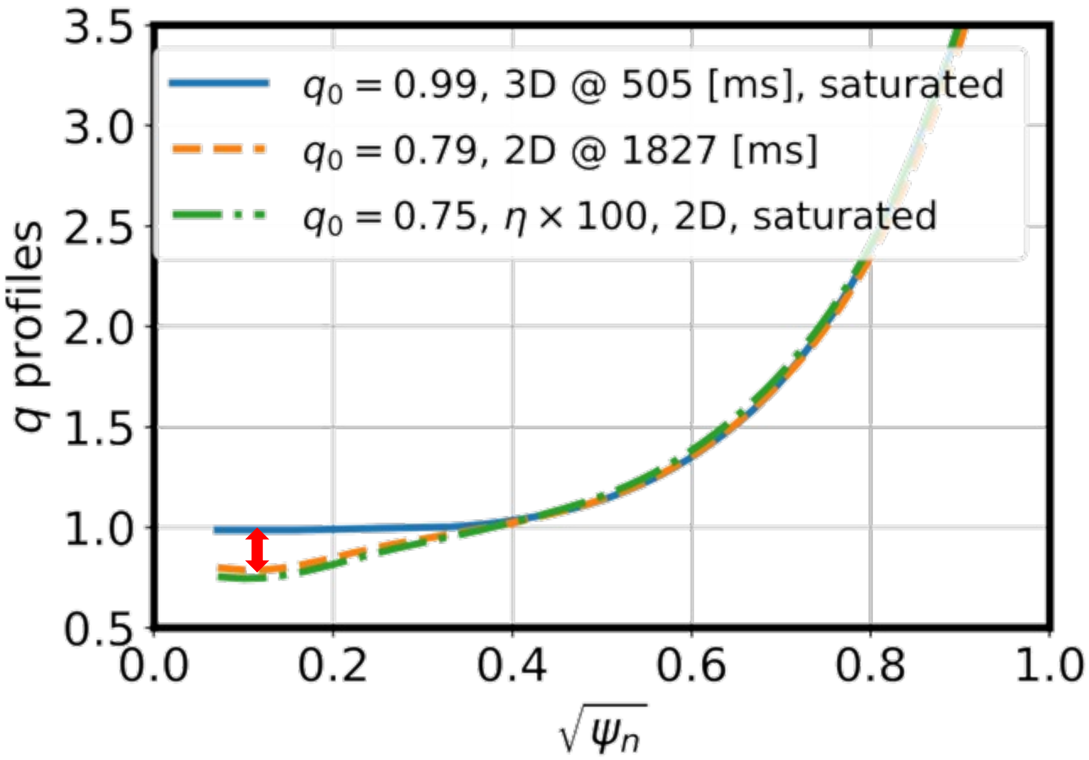


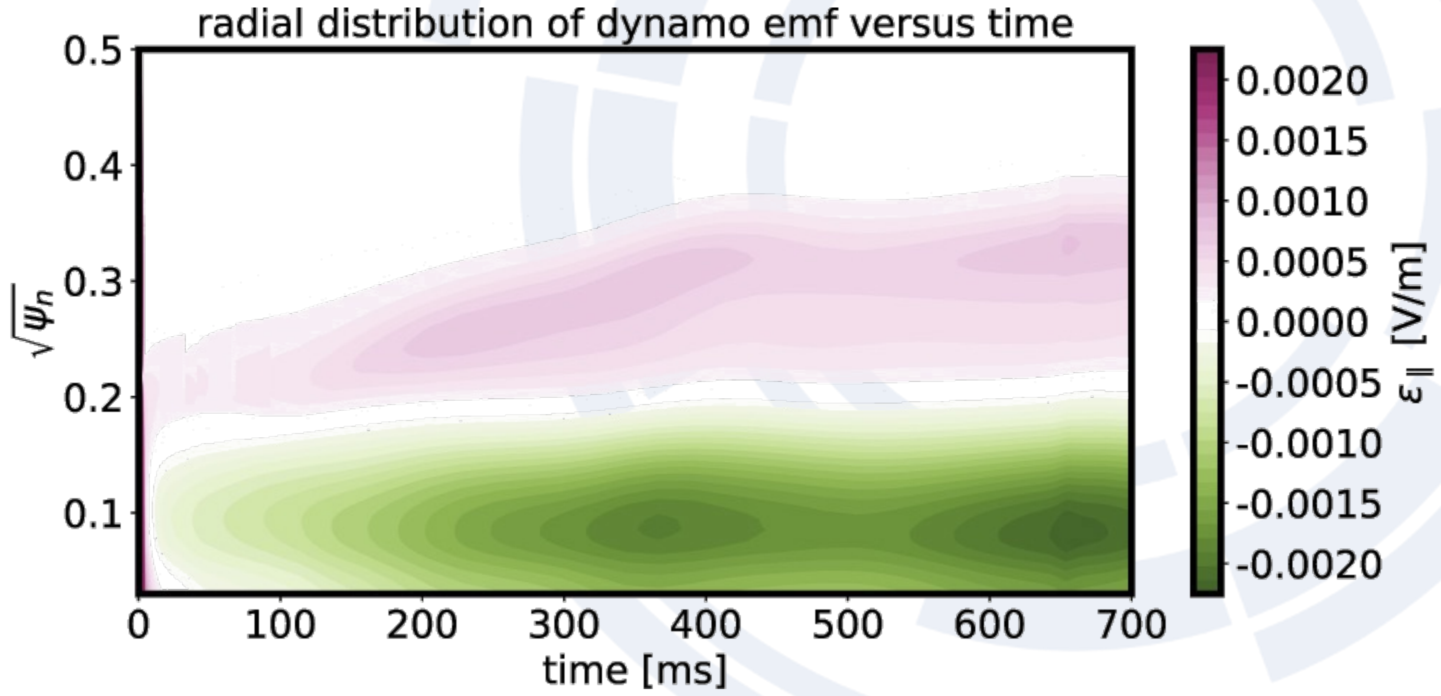
Nührenberg JPP 25

MHD modeling of flux pumping for sawtooth prevention

Zhang NF 25

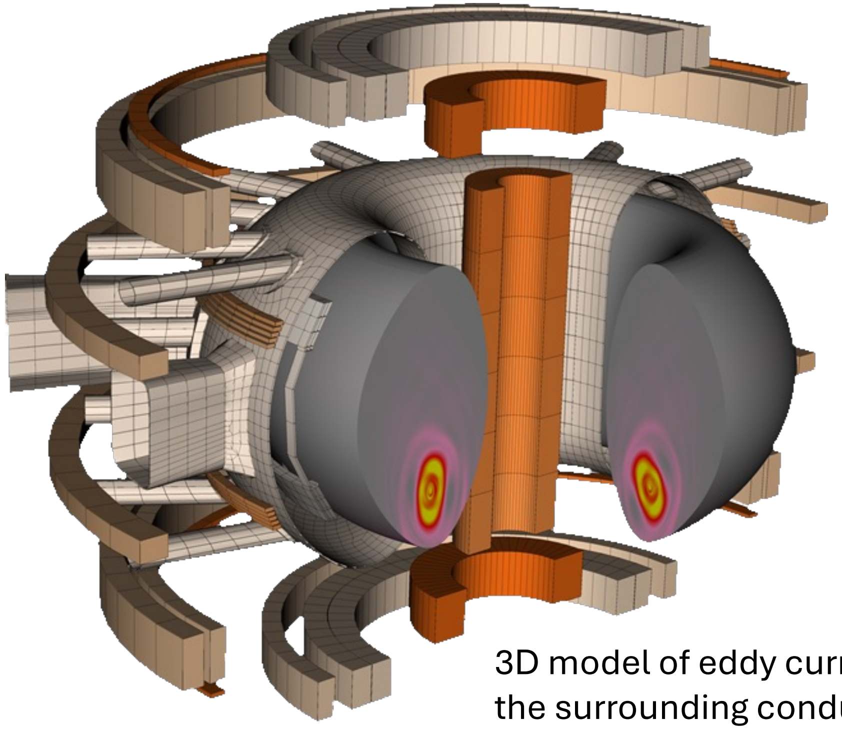
- **Sawtooth crashes** can seed **neoclassical tearing modes (NTMs)**, potentially triggering **disruptions**
- **Flux pumping (via anomalous current redistribution) can prevent this by keeping q_0 close to unity**
- **JOREK simulations of ASDEX Upgrade hybrid scenarios**





MHD modeling of vertical forces during mitigated disruptions

Mechanism of vertical force reduction in disruptions mitigated by massive impurity injection



3D model of eddy currents in the surrounding conductors

3D VDE simulation for AUG with the coupled JOREK-CARIDDI code suite
Isernia PoP 23

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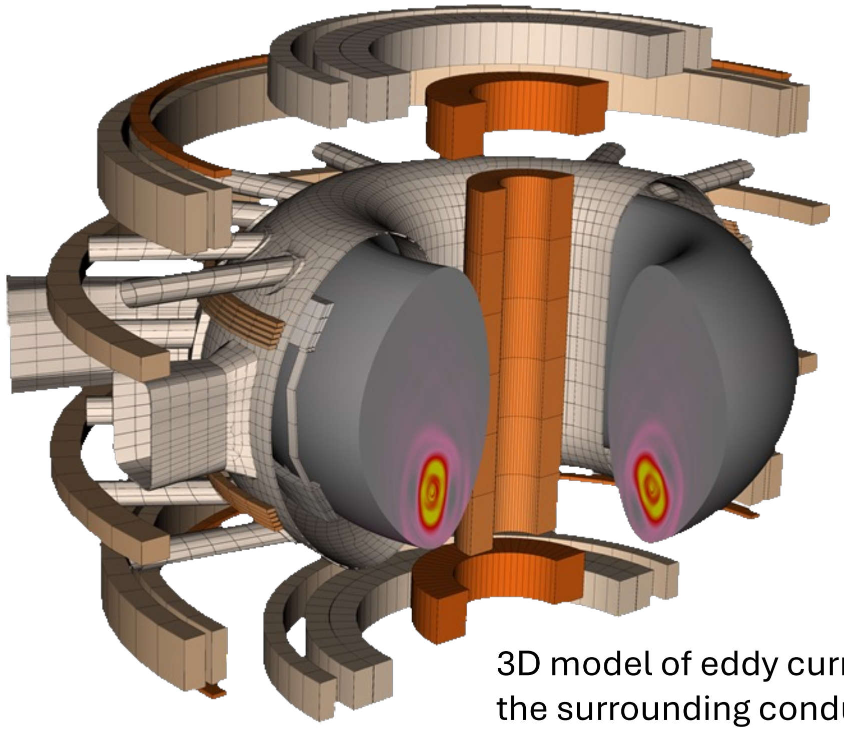

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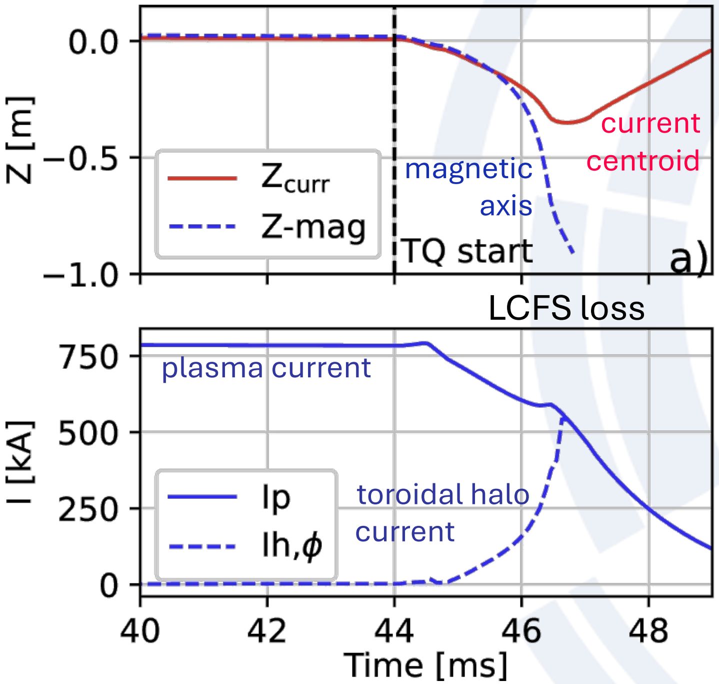

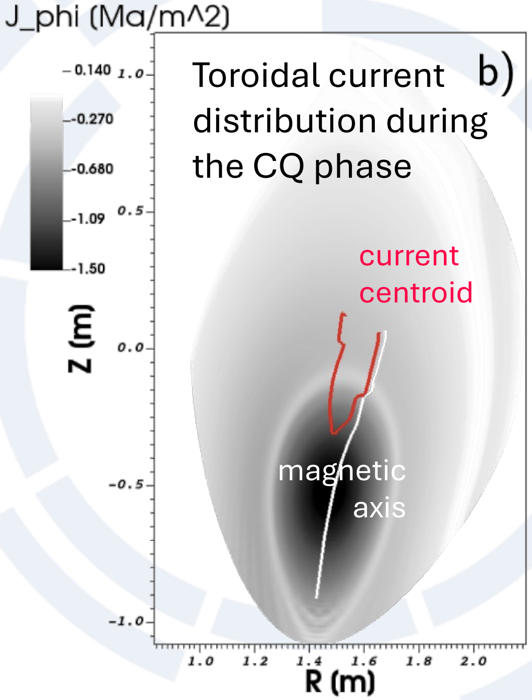

3D VDE simulation for AUG with the coupled JOREK-CARIDDI code suite
Isernia PoP 23

Large toroidal halo currents cause a decoupling of the vertical motion of the magnetic axis from the current centroid
Schwarz NF 23

New insights on RE avalanches in mitigated ITER disruptions

Shattered Pellet Injection (SPI) simulations
with DREAM for 15 MA ITER L- and H-modes:

I_{RE} > 4 MA (!)

Vallhagen NF 24

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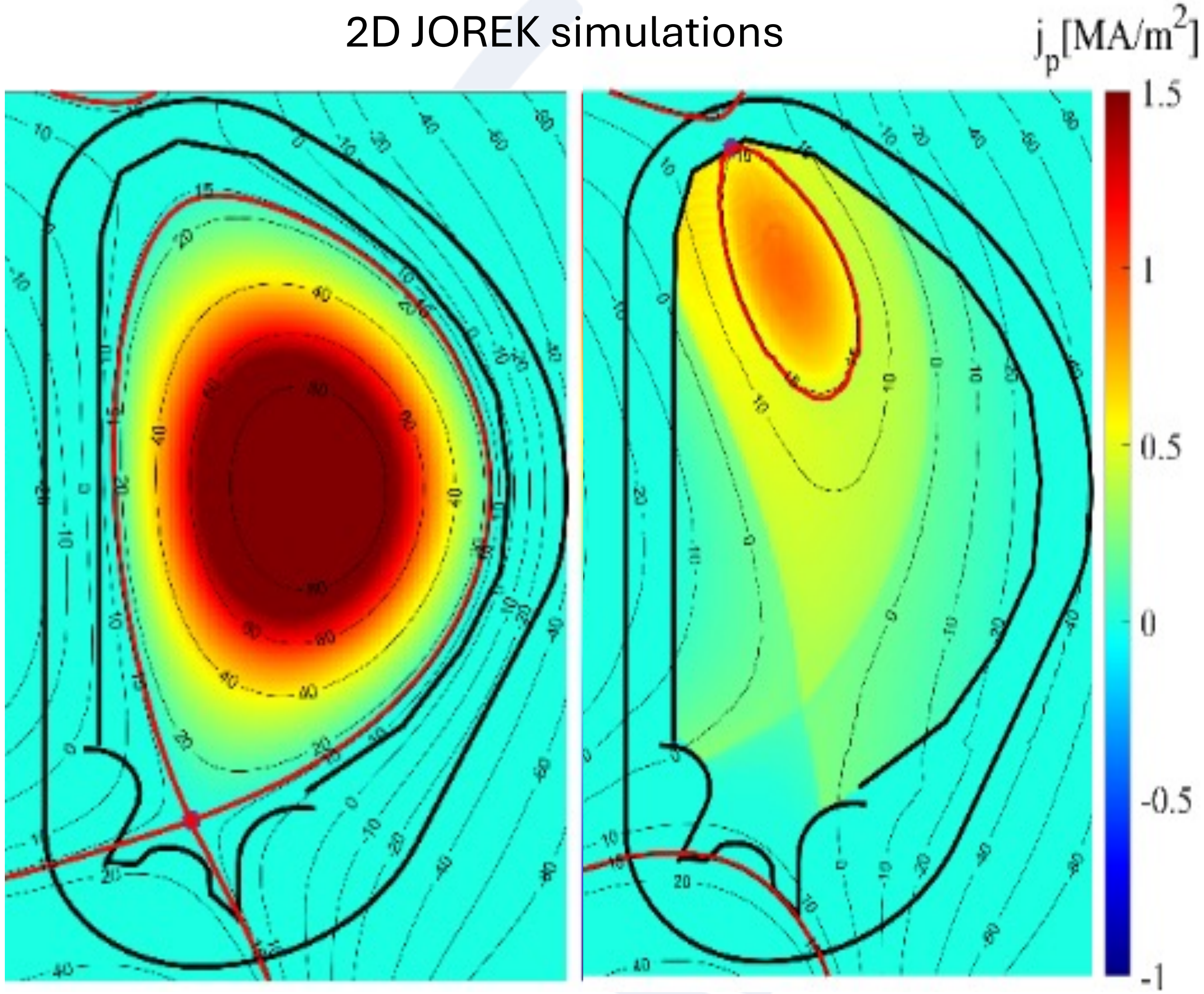
Vallhagen NF 24

Vertical motion of the plasma during the disruption reduces the RE avalanche gain by many orders of magnitude!

Wang NF 25

2D JOREK simulations



New insights on RE avalanches in mitigated ITER disruptions

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Vallhagen NF 24

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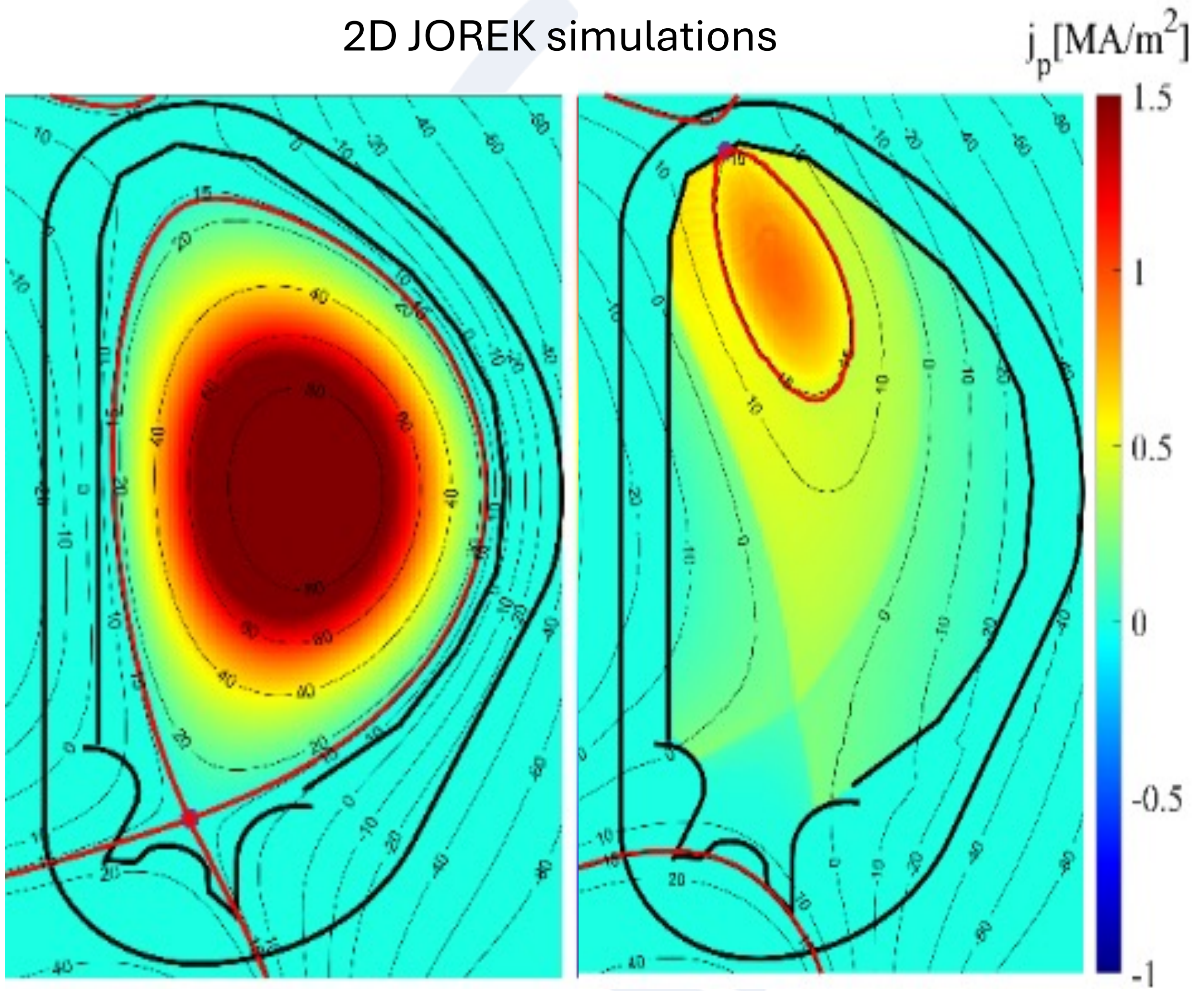
Wang NF 25

RE avoidance in ITER is predicted to be very challenging, but remains within reach!

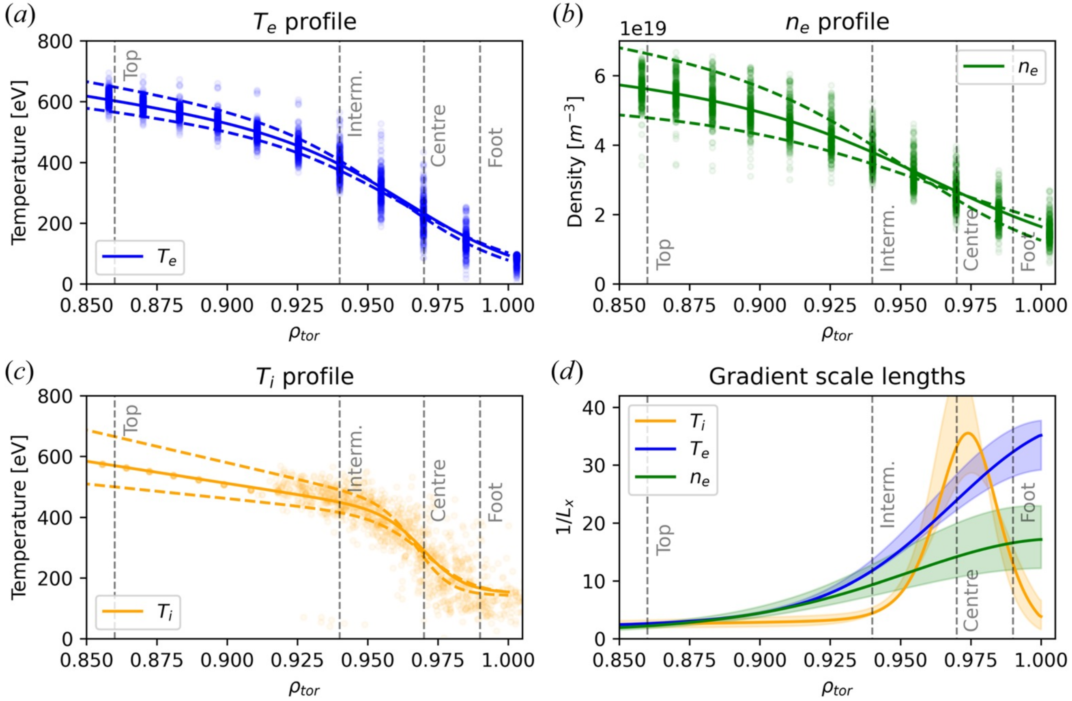
2D JOREK simulations

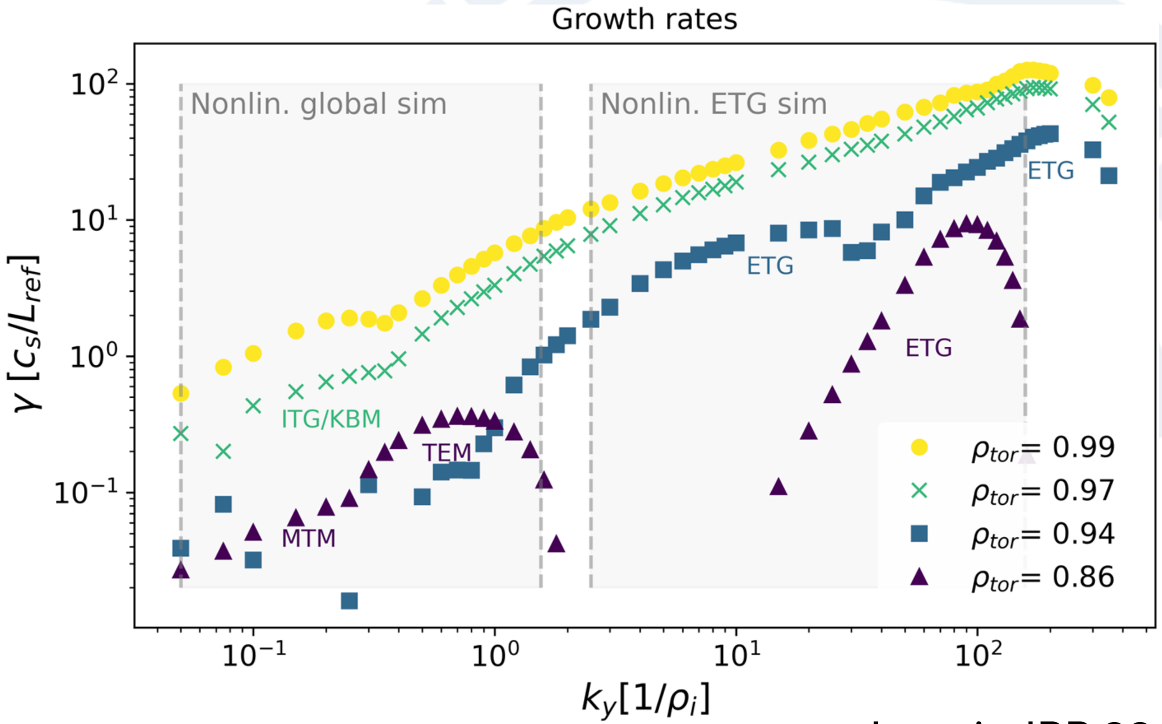


Predicting L-H Transitions

Edge and pedestal turbulence characterization

AUG #31529



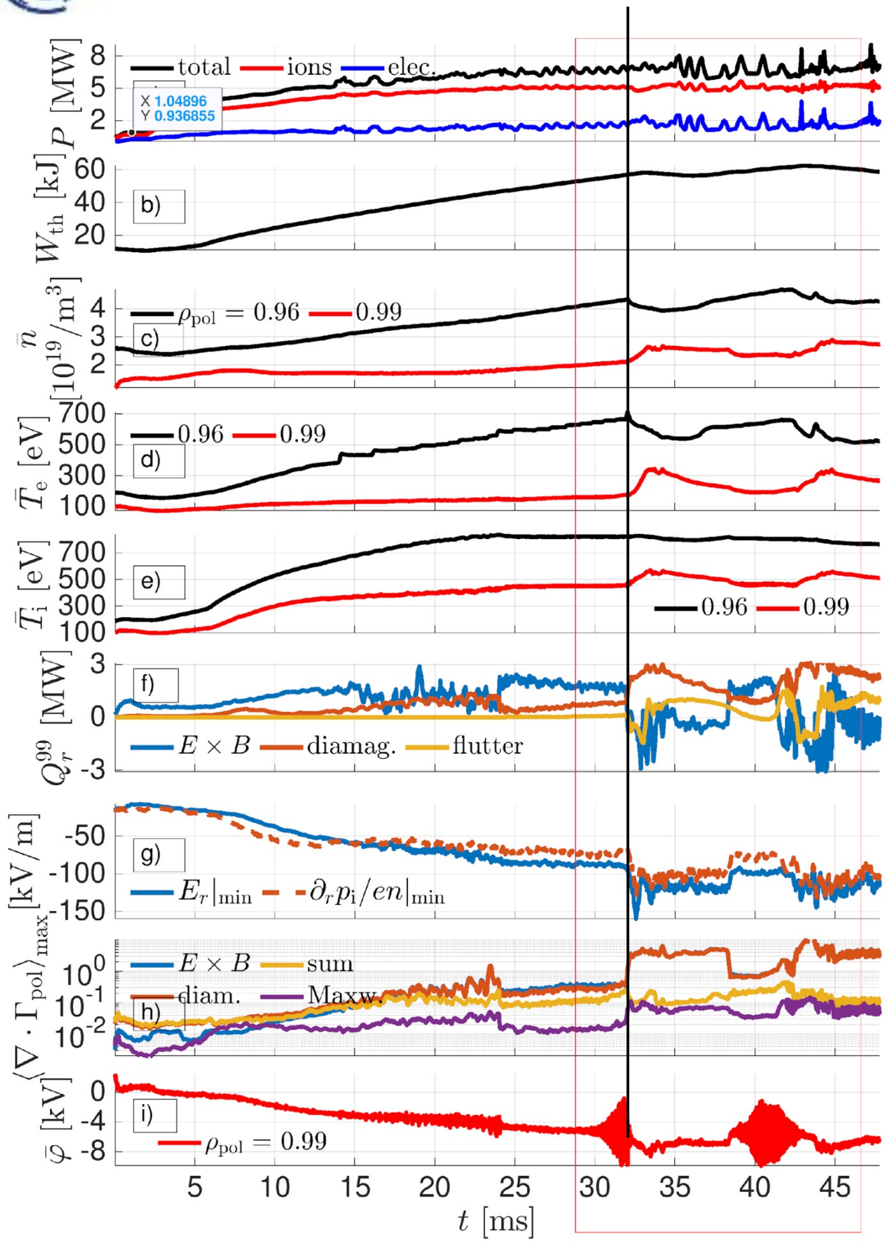


Leppin JPP 23

Extensive AUG / JET H-mode pedestals studies reveal complex physics:

- **Pedestal top turbulence mainly ion-scale** (ITG/TEM/MTM)
- **Pedestal foot turbulence mainly electron-scale** (ETG)
- **Pedestal often just below KBM thresholds**

Fast transition in a power ramp simulation with GRILLIX



- Extremely long (~50 ms), flux-driven GRILLIX simulation of a power ramp from L-mode
- **Fast (~100 μs) transition at ~32 ms**

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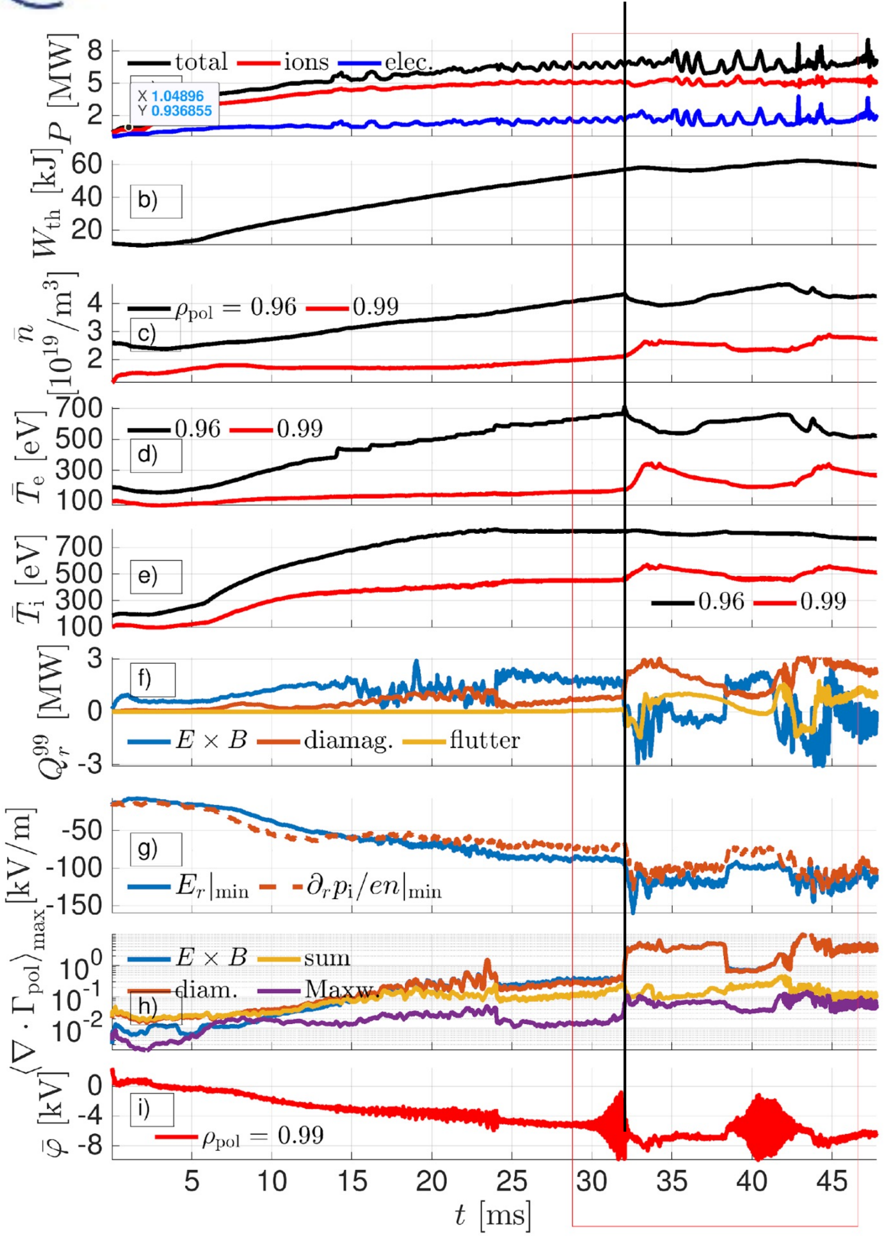
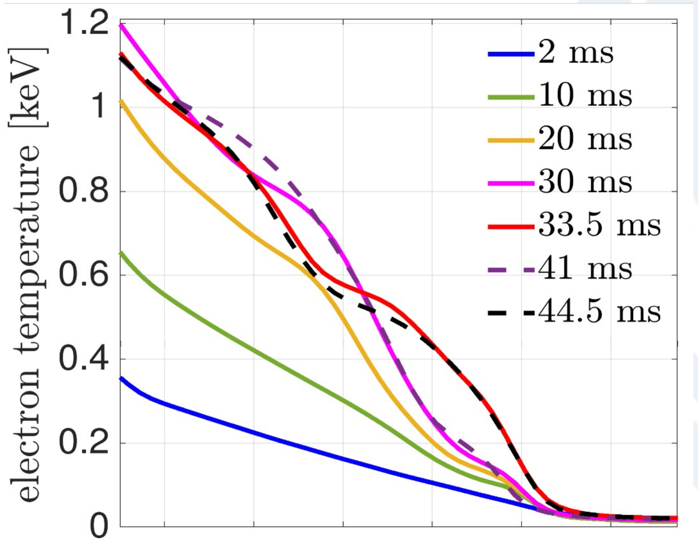
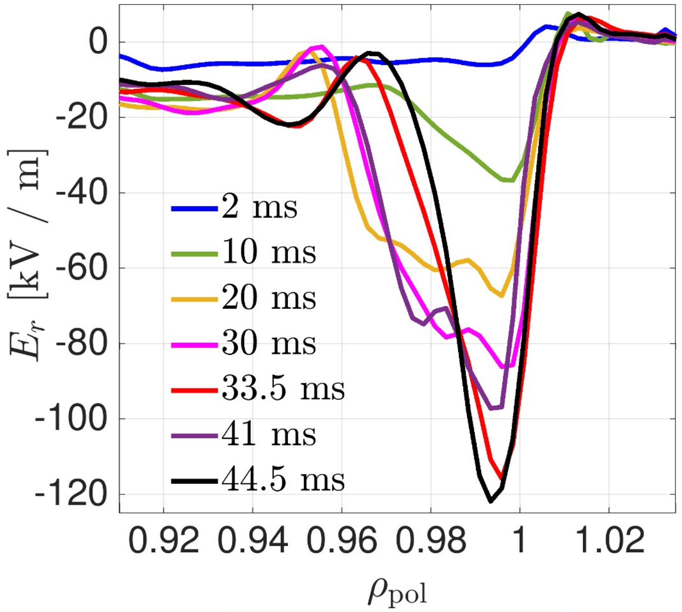


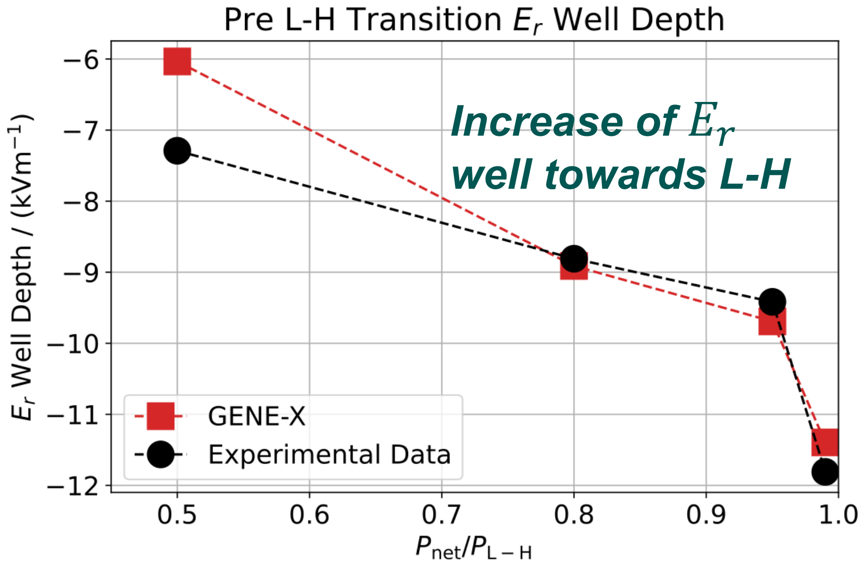
- Extremely long (~50 ms), flux-driven GRILLIX simulation of a power ramp from L-mode
- **Fast (~100 μs) transition at ~32 ms**
- Pedestal not (yet) stationary: I-phase
- E_r well is too deep, pedestal is too steep: limits of fluid approach; **need to resort to gyrokinetics…**





Towards GK simulations of a dynamical L-H transition with GENE-X

Pre L-H transition validation of E_r in AUG



Good agreement of GENE-X simulations with experiments

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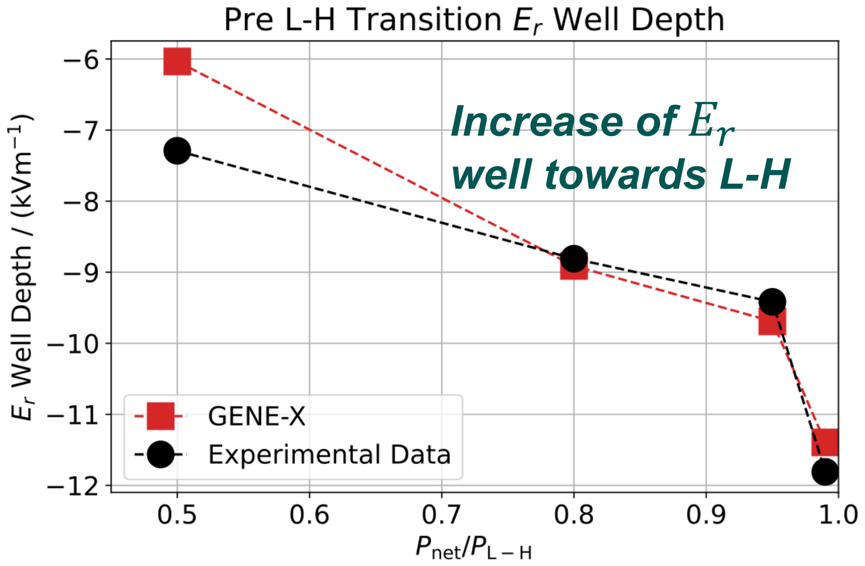

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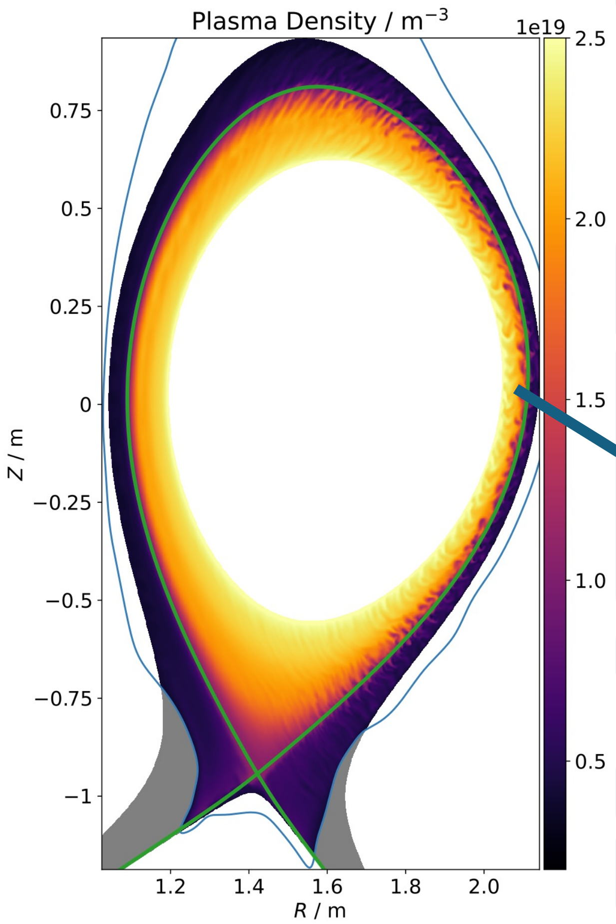
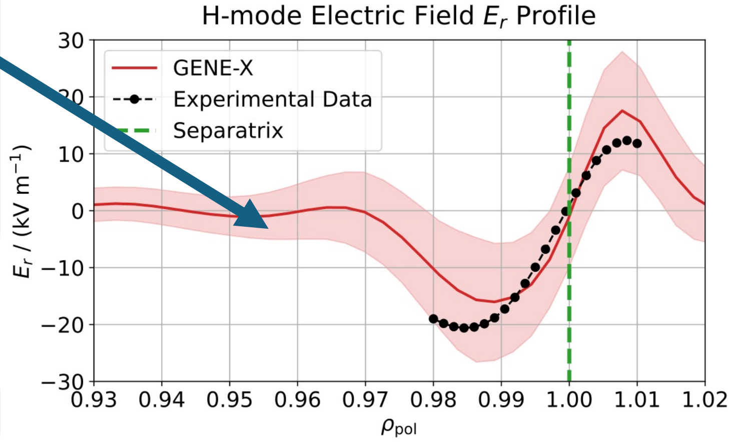


First validation of E_r in H-mode plasmas



Formation of E_r well and ***strong shear layer*** near the separatrix

Predicting SOL Physics

Edge turbulence in dissipative divertor regimes

Efforts to enable edge fluid turbulence codes for dissipative regimes

- Realistic magnetic and wall geometries
- Self-consistent neutrals recycling and plasma-neutrals interactions

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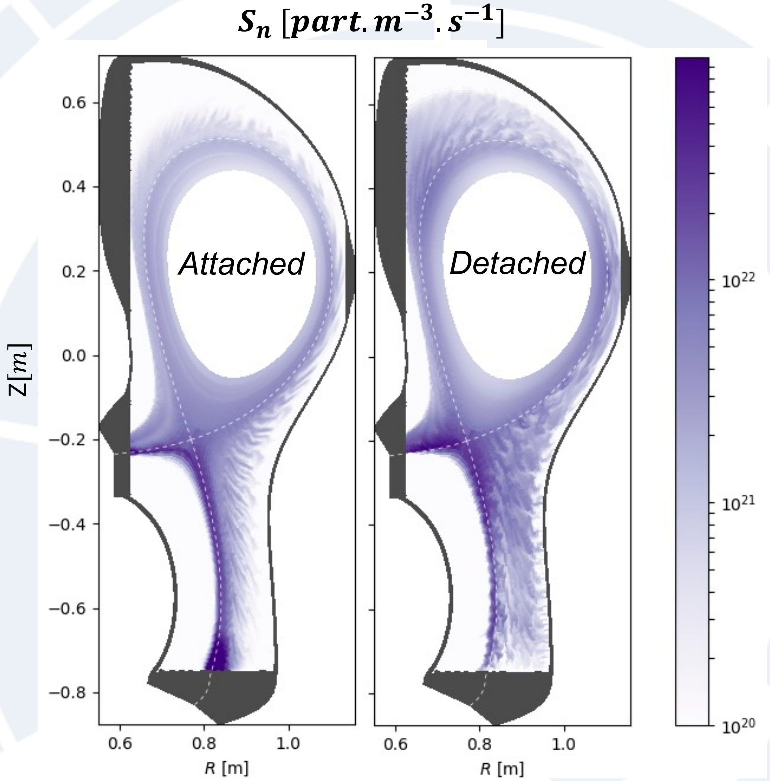
First-ever turbulence simulations in detached regimes have been carried out with GBS [Mancini NF 24] **and SOLEDGE3X** [Quadri NME 24]

- Strong impact on turbulent transport
- **Widening of λ_q: 1.7 x (near SOL) to 2.7 x (far SOL)**



TCV detached plasma simulation with ***SOLEDGE3X***

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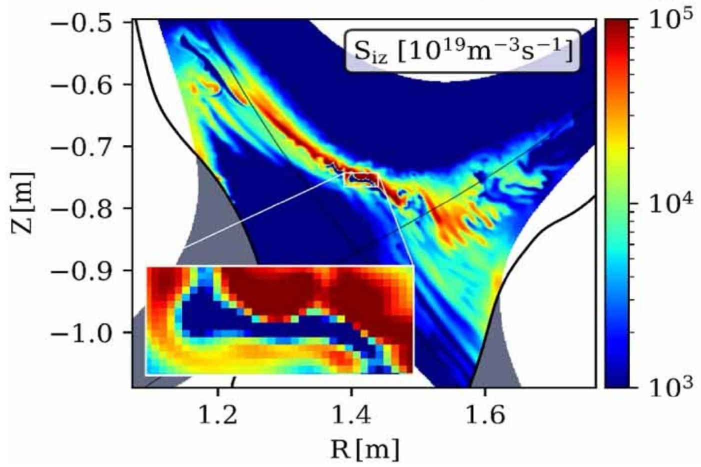
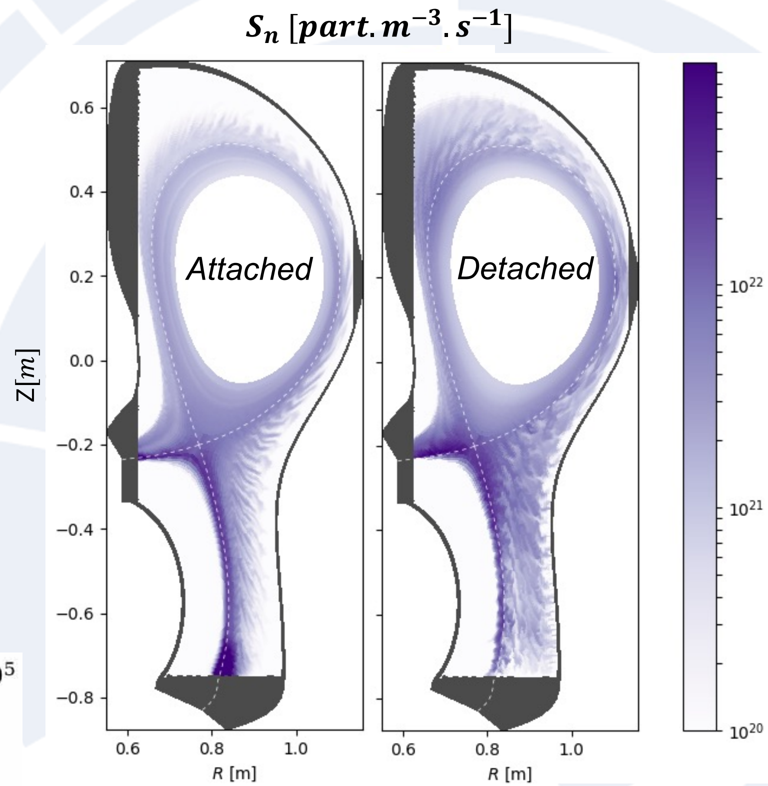
Turbulence in an X-Point Radiator (XPR) performed with GRILLIX [Eder NF 25]

- High level of intermittency



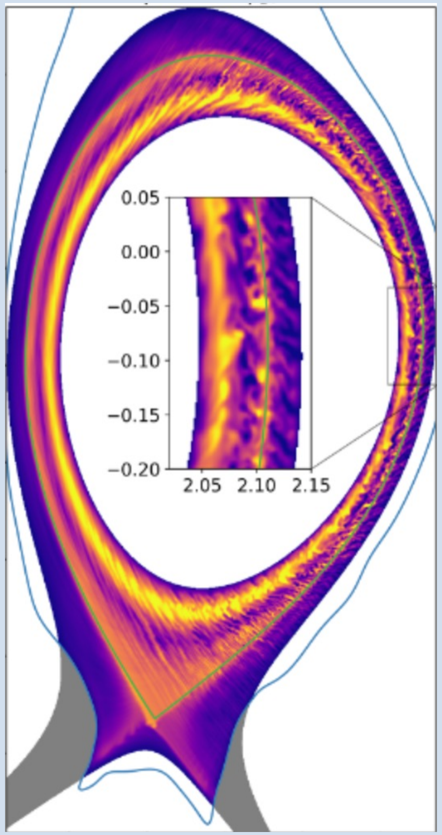
XPR simulation with ***GRILLIX***



TCV detached plasma simulation with ***SOLEDGE3X***

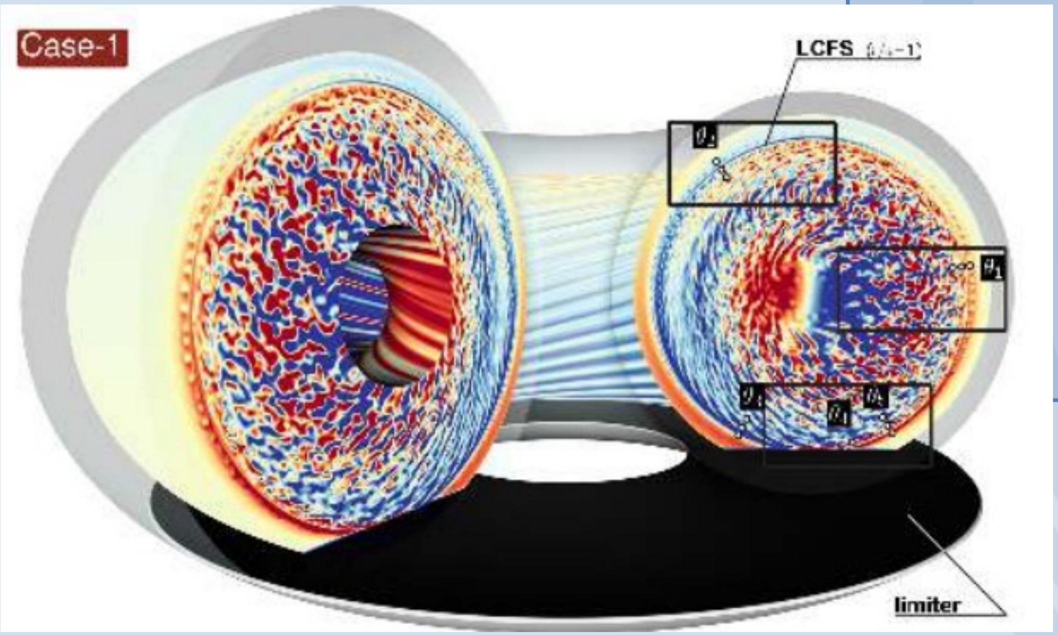
GK simulations for the edge and SOL

Eulerian



GENE-X
Michels CPC 21

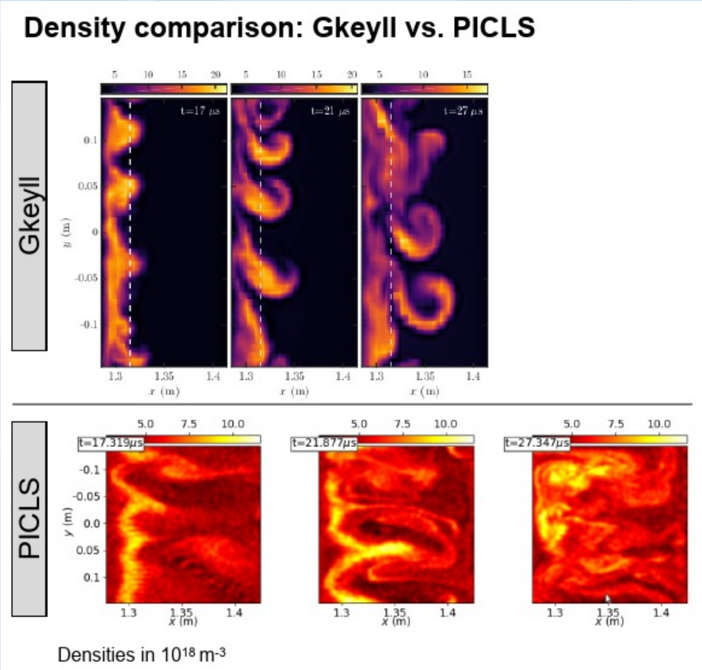
Semi-Lagrangian



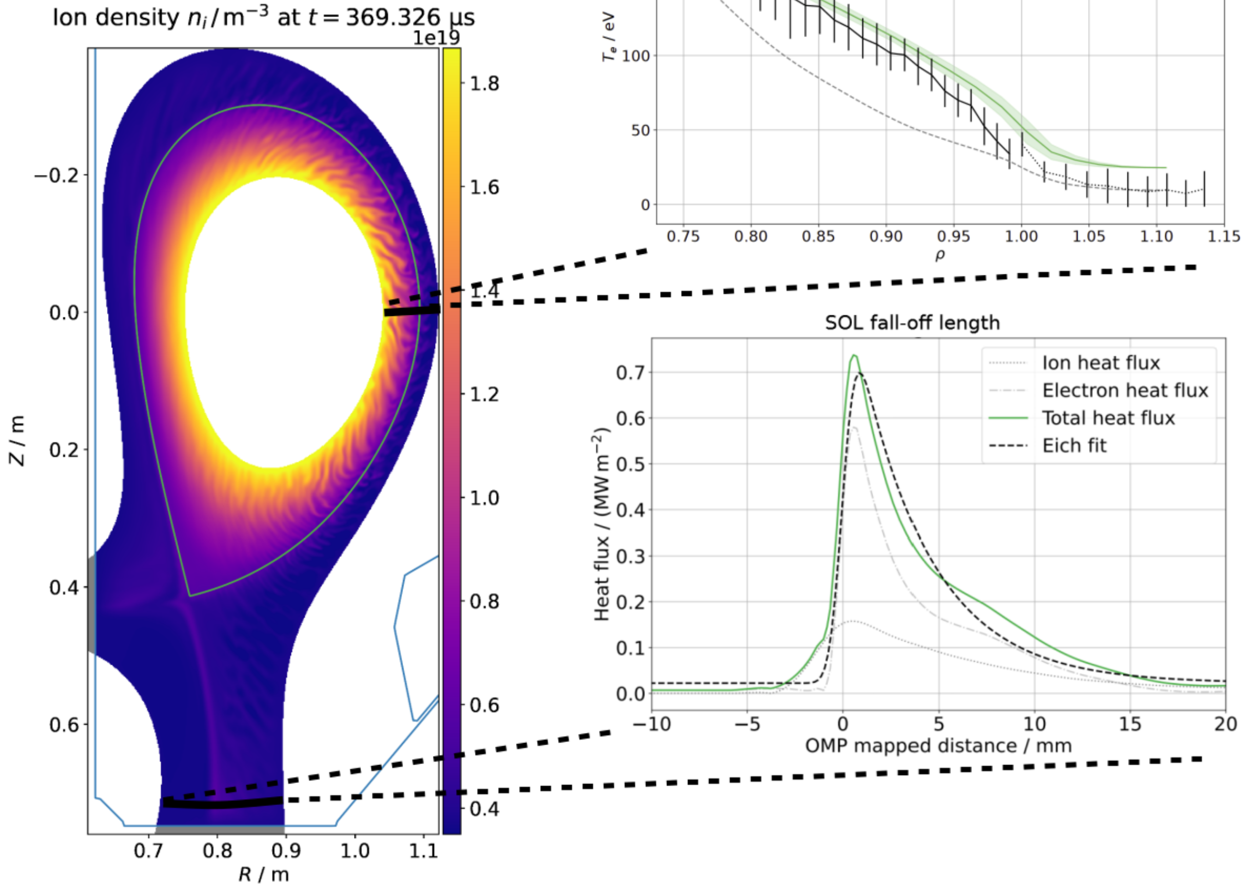
Gysela-X
Dif-Pradalier Commun. Phys. 22

Lagrangian

PICLS
Stier
CPC 24



GENE-X accurately reproduces key SOL observables in TCV



- Simulations reproduce key aspects of the experimental observations
- Divertor heat flux fall-off follows Eich-fit function

SOL fall-off length λ_q : Exp. **5.5 mm***

Fluid Models*		GENE-X (Gyrokinetic)	
GRILLIX	1.1 mm	No Coll	1.34 mm
GBS	11.6 mm	Coll BGK	**4.68 mm**
TOKAM3X	0.1 mm	Coll LBD	**3.75 mm**

*Olivera NF 22

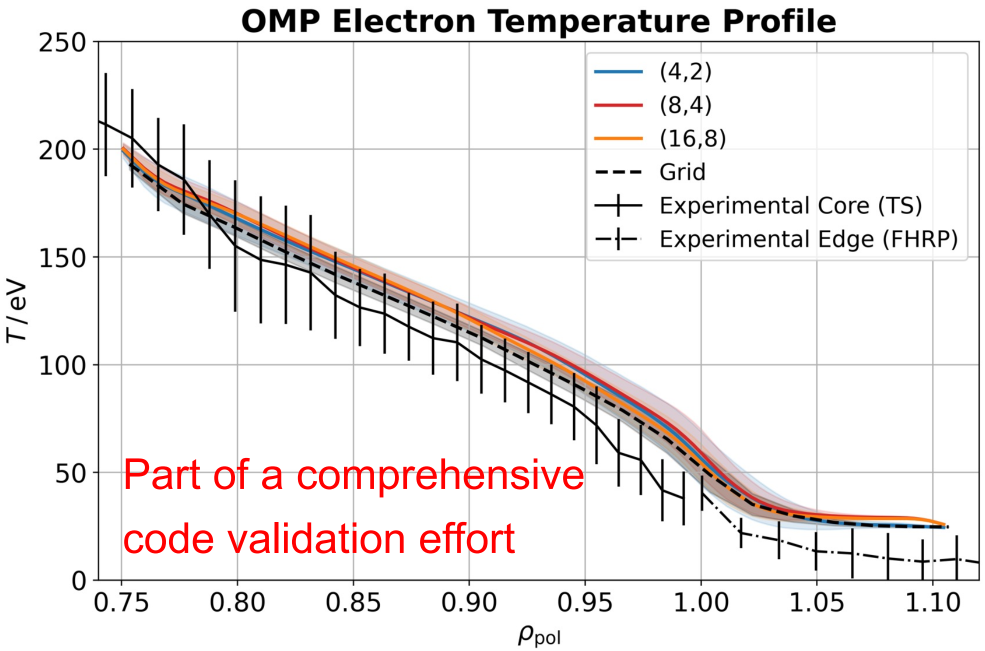
- Results published open access Ulbl PoP 23
- Data published open access DOI: 10.5281/zenodo.7894731

GK edge and SOL simulations with GENE-X: 50x speedup

Frei CPC 25

Spectral approach in 2D velocity space, using Hermite and Laguerre polynomials

TCV-X21 L-mode dominated by ***TEM turbulence***



Excellent agreement (profiles and turbulence) between fast ***spectral*** and slow ***grid*** simulations

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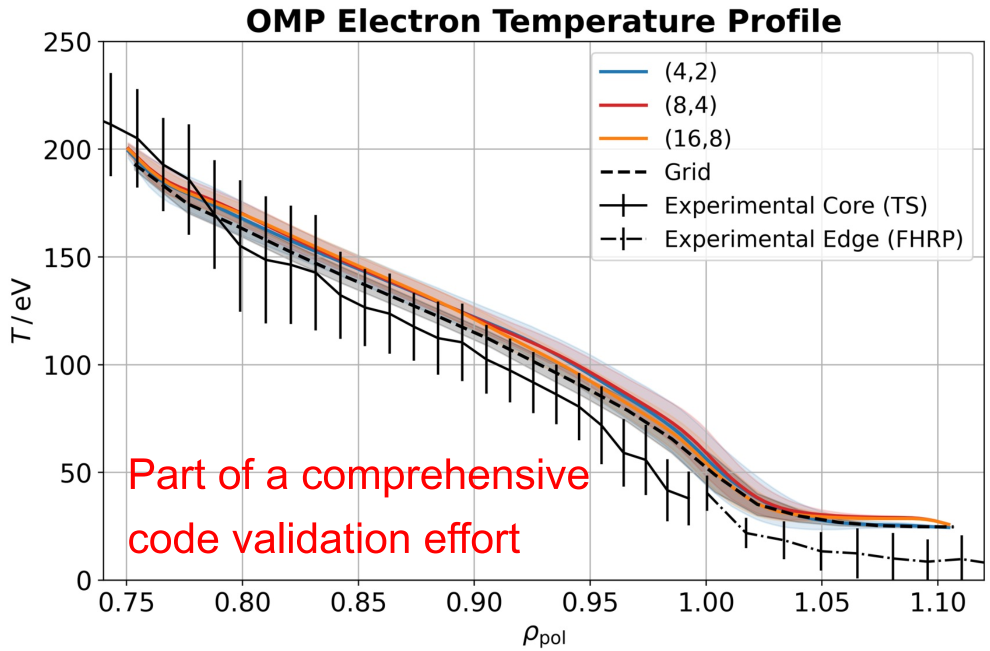

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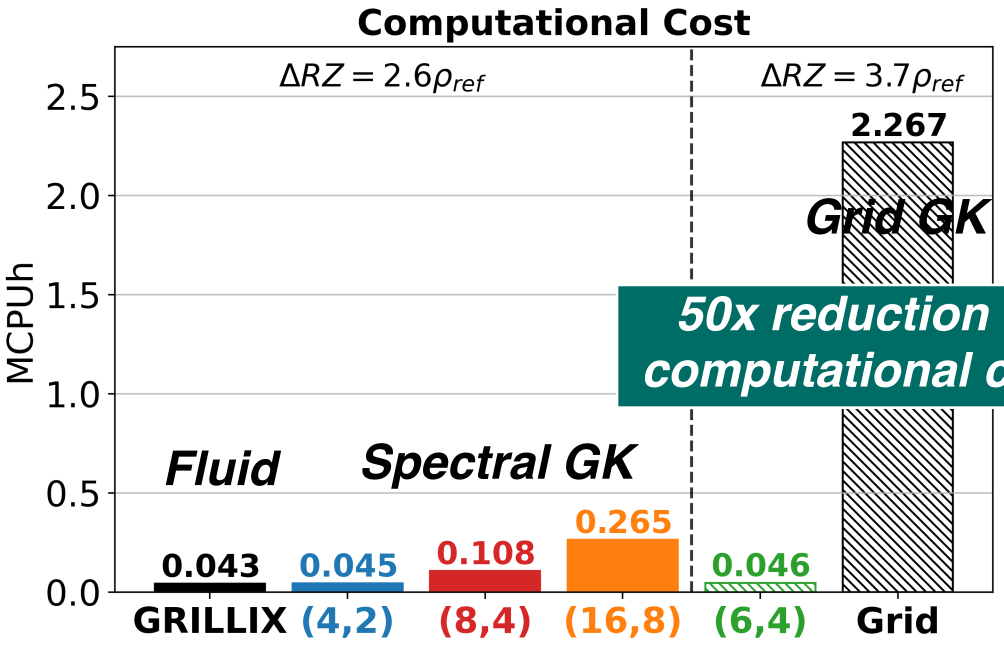
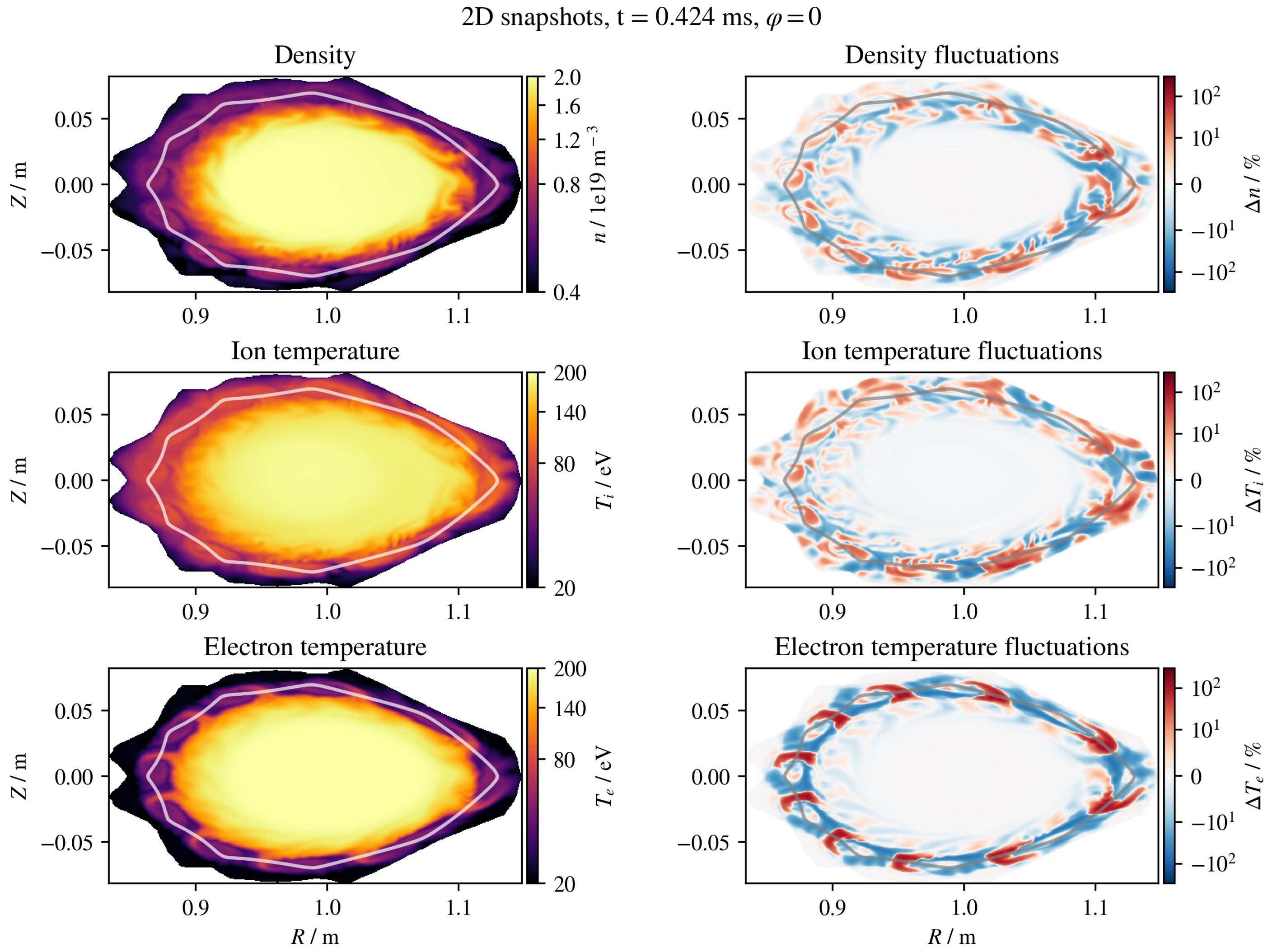


GENE-X competes with fluid code GRILLIX

Remarkable reduction of computational cost enabling efficient simulations towards reactor-relevant conditions

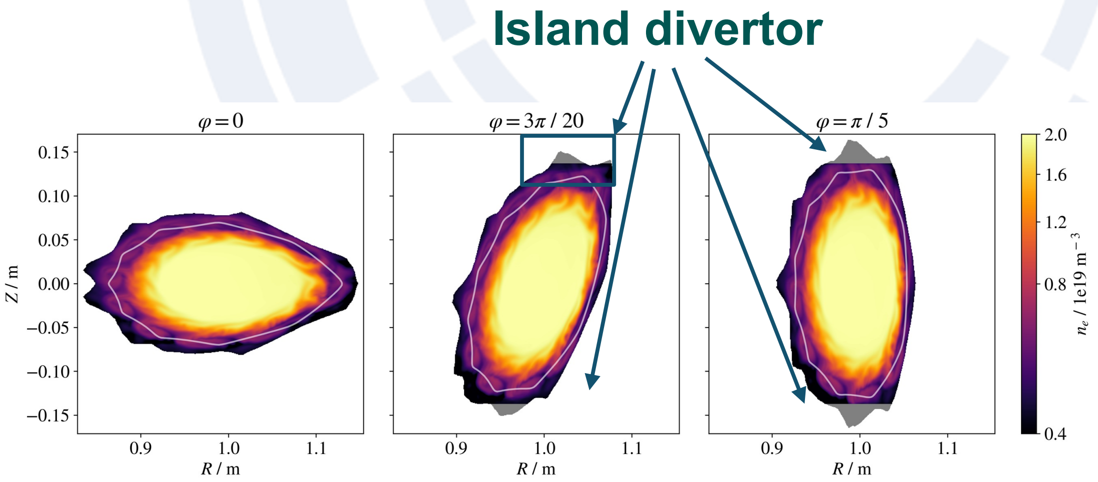
First GK edge turbulence simulations in stellarator geometry

Basis: Extension of GENE-X to non-axisymmetric geometries



Magnetic island chain located at outer radial simulation boundary; island divertor localized around φ=π/5

W7-AS-like equilibrium with realistic plasma parameters



Designing Optimized Stellarators

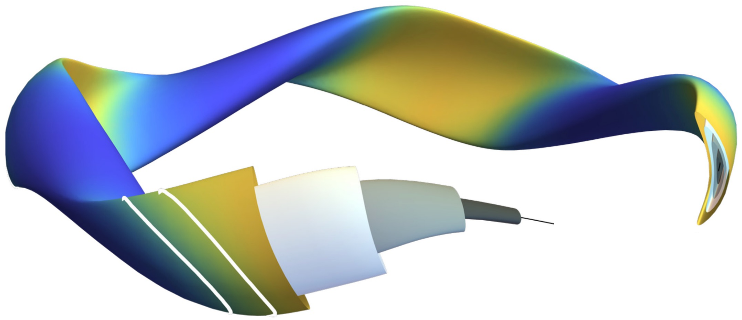
A new ecosystem of optimized stellarator configurations

Beyond W7-X: Plasma performance, fast particle confinement, coil complexity etc.

A new ecosystem of optimized stellarator configurations

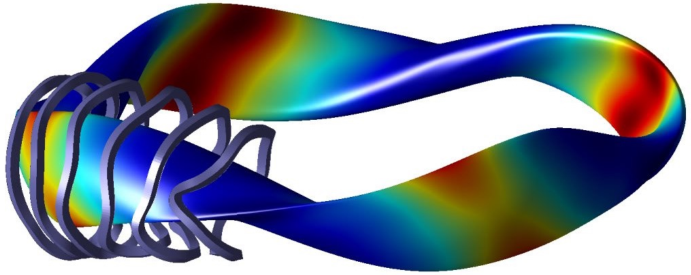
Beyond W7-X: Plasma performance, fast particle confinement, coil complexity etc.

<u>Quasi-Isodynamic</u> (minimal bootstrap current, MHD stability, turbulence optimization)



SQUIDS

Goodman PRX 24



CIEMAT-QI

Sanchez NF 23

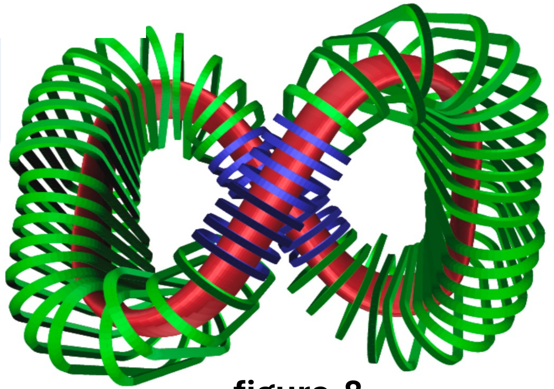


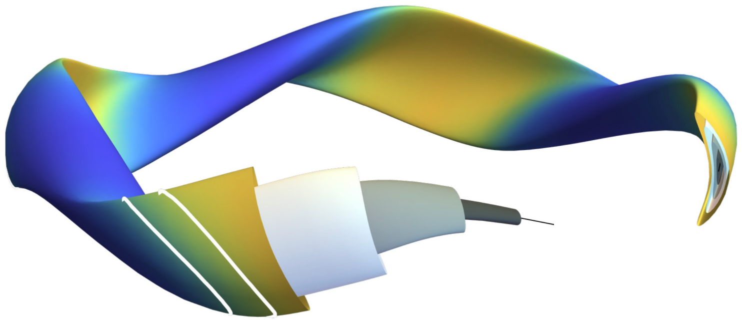
figure-8

Plunk PPCF 25

A new ecosystem of optimized stellarator configurations

Beyond W7-X: Plasma performance, fast particle confinement, coil complexity etc.

Quasi-Isodynamic (minimal bootstrap current, MHD stability, turbulence optimization)



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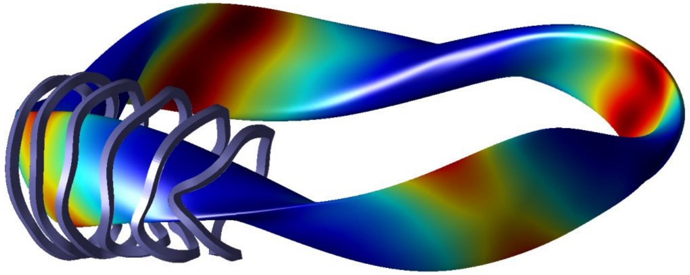


CIEMAT-QI

Sanchez NF 23

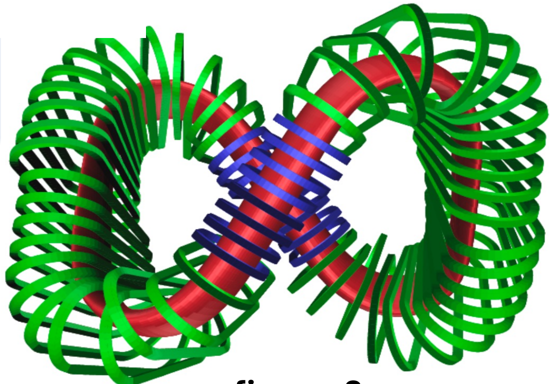
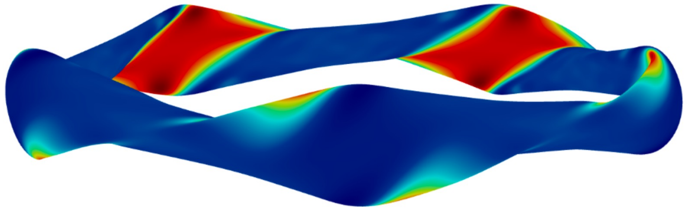


figure-8

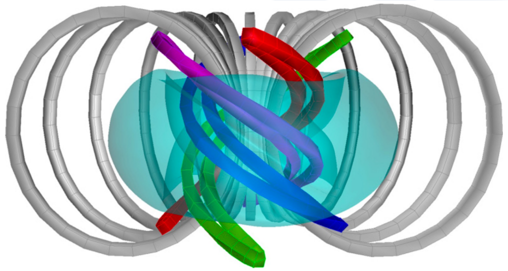
Plunk PPCF 25

Piecewise Omnigenous (keeping QI properties)



Velasco PRL 24

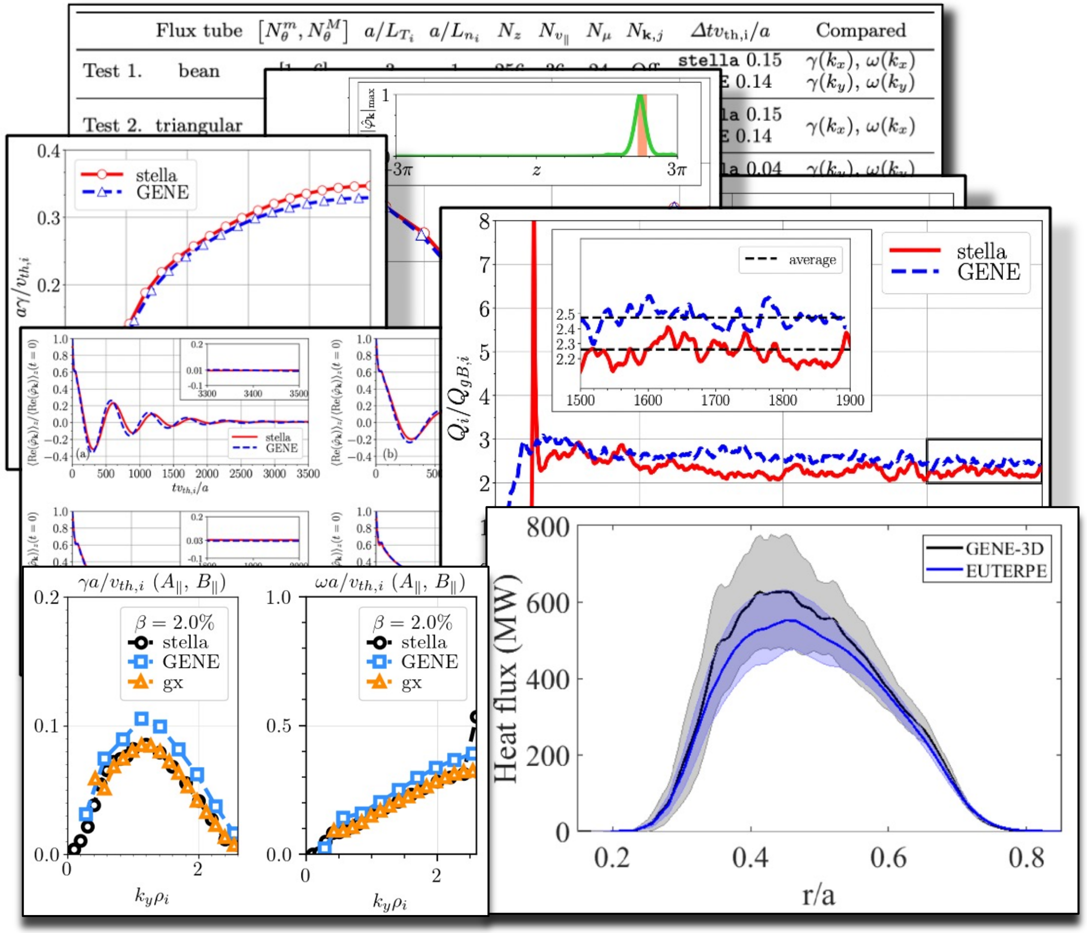
Quasi-Axisymmetric Hybrids (close to a tokamak!)



Henneberg PRR 24

State-of-the-art stellarator core turbulence simulations

Extensive verification of GK turbulence codes
[González-Jerez JPP 22, Sánchez NF 21, NF 22]



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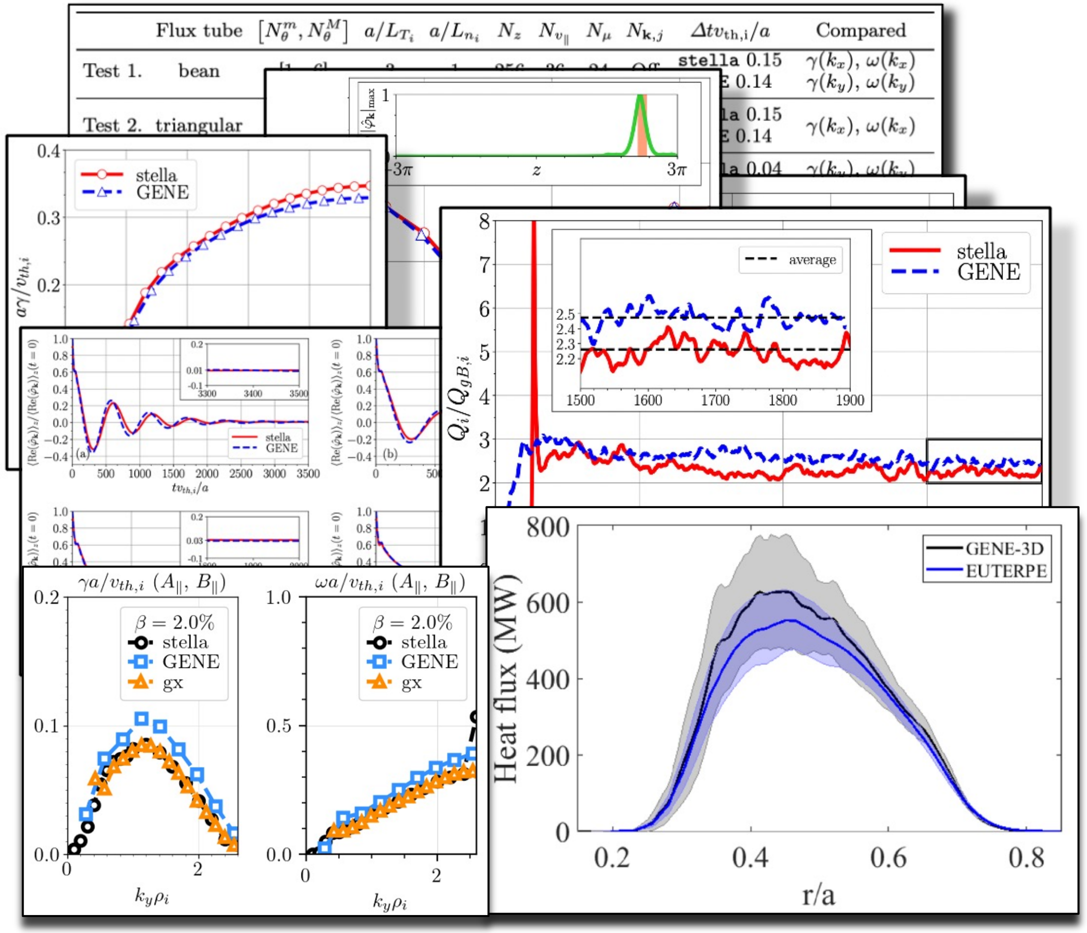
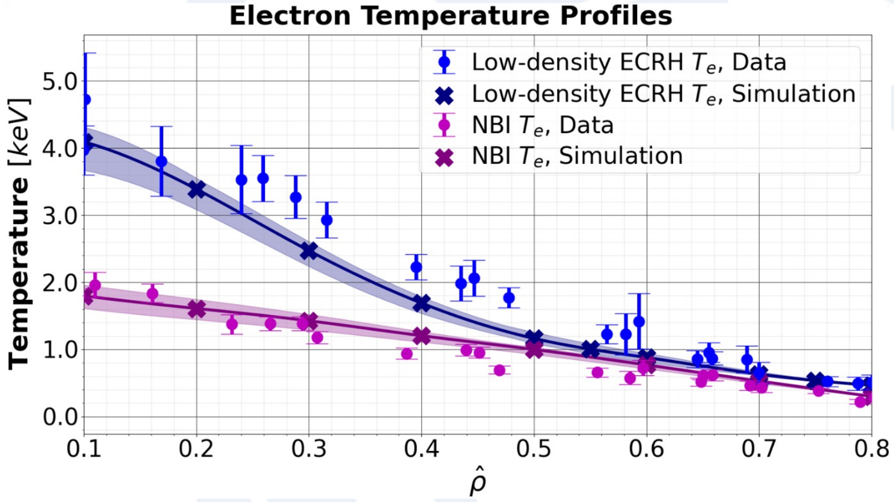
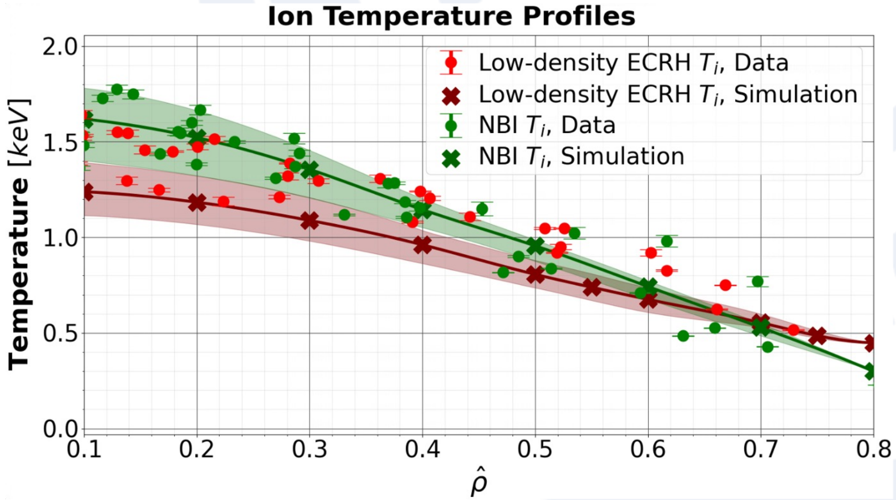


Successful code validation across multiple W7-X scenarios



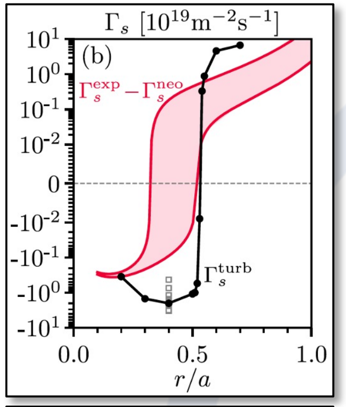


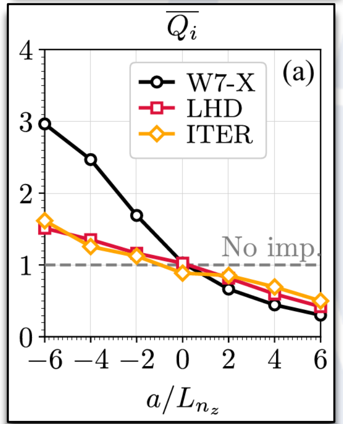
Agapito Fernando PoP 25

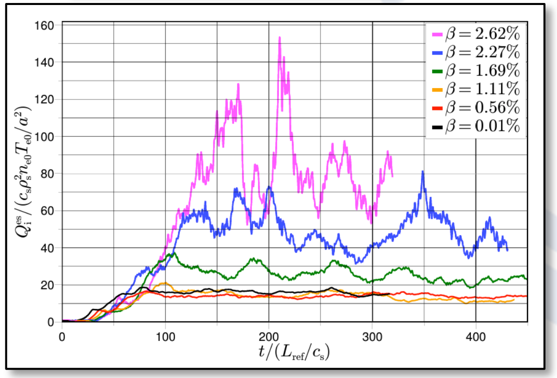
Growing understanding of core turbulence in W7-X

Selected highlights:

- **GK-based profile predictions**
  [Bañón Navarro NF 23, Agapito Fernando PoP 25]
- **Electromagnetic turbulence at high β**
  [Mulholland PRL 23]
- **Turbulent particle transport**
  [Thienpondt PRR 23]
- **Turbulent impurity transport**
  [García-Regaña JPP 21]







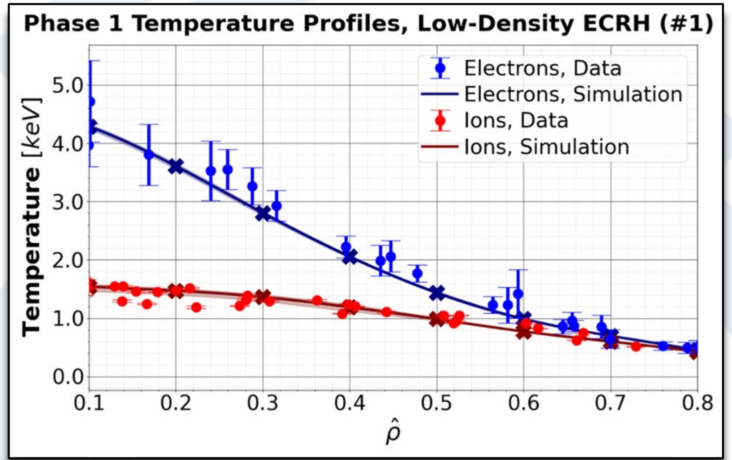
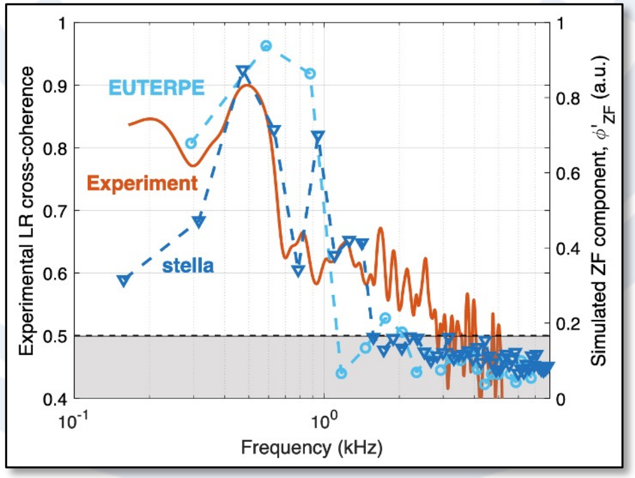


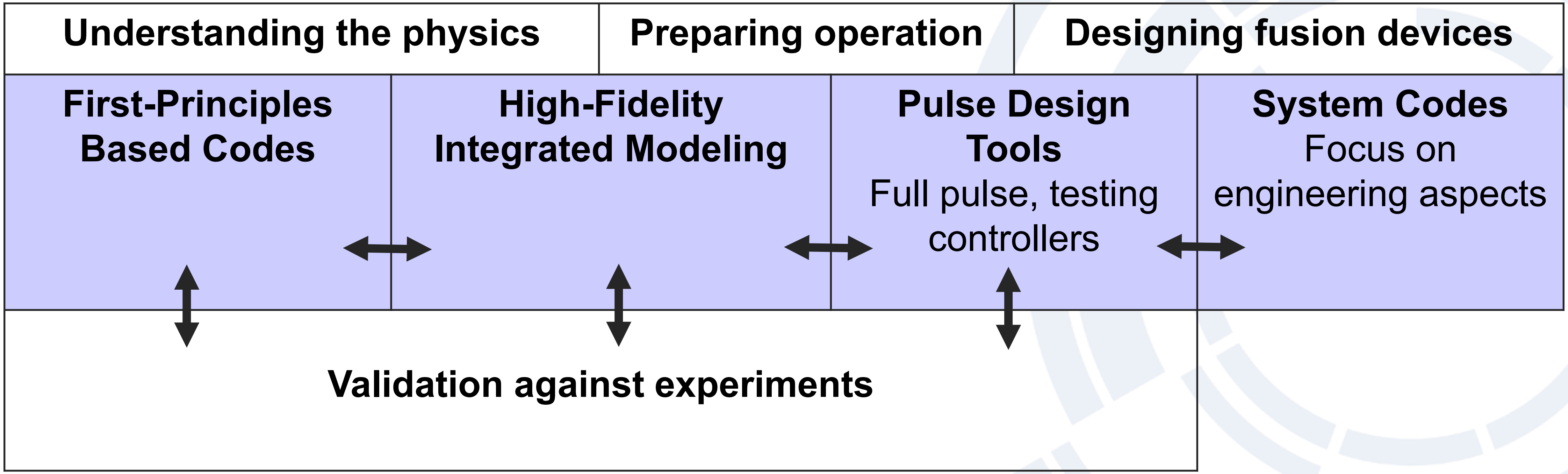
TABLE II. Turbulent thermal diffusivities from STELLA in S.I. units.

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



Towards Digital Twins of Fusion Systems

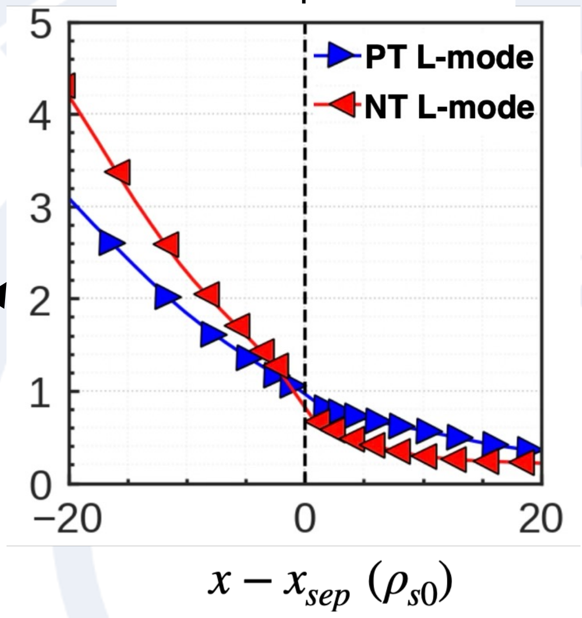
Digital twins: different fidelity levels and goals



Extrapolating to negative triangularity (NT) power plants

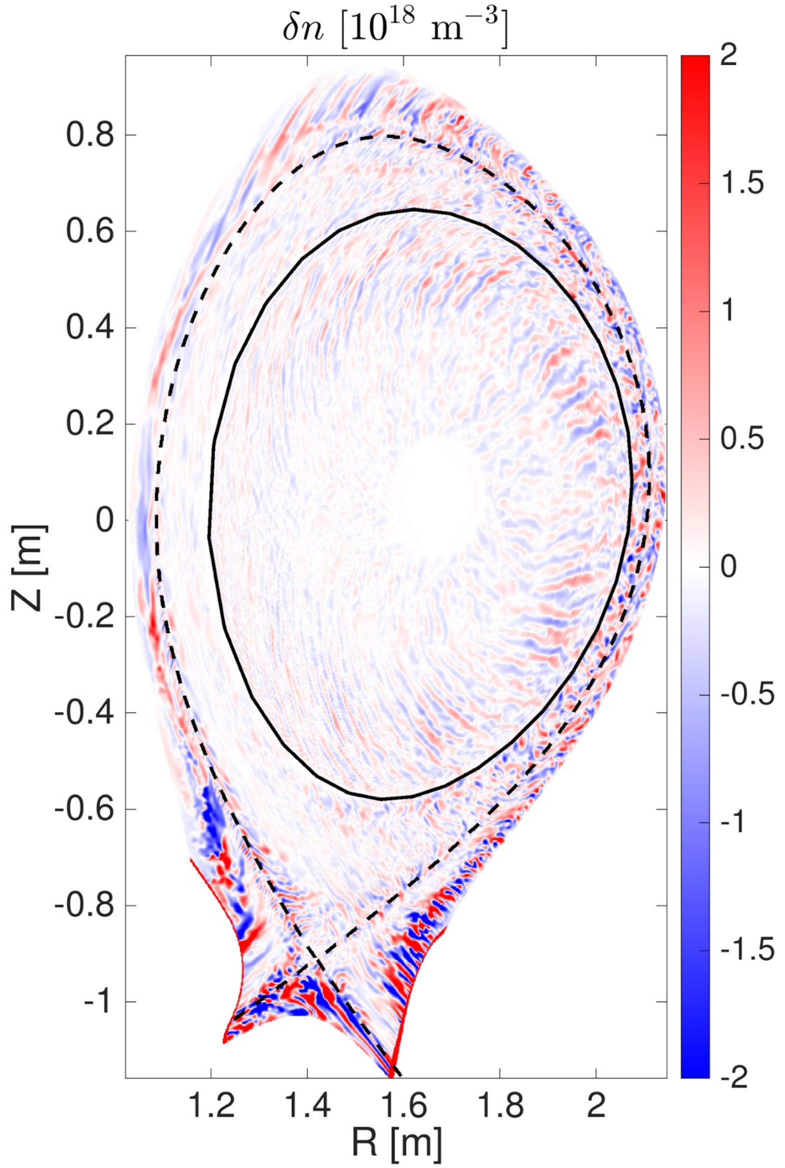
- GK simulations indicate that **confinement improvement** observed in existing NT plasmas **should scale to (A~3) power plants**[1−4]
- Integrated modeling with ASTRA−TGLF indicates **high core pressures** can be achieved **in DTT NT scenarios**[5]
- Lack of L−H heating threshold enables **attractive low−heating-power (Ohmic) reactor scenarios**[6]
- λ_q in NT will be in between PT L-mode and PT H-mode[7,8]
- **Fast-ion dynamics appear similar in NT and PT**[9]
- **NT is less vertically stable**[10], which may necessitate passive stabilizing plates

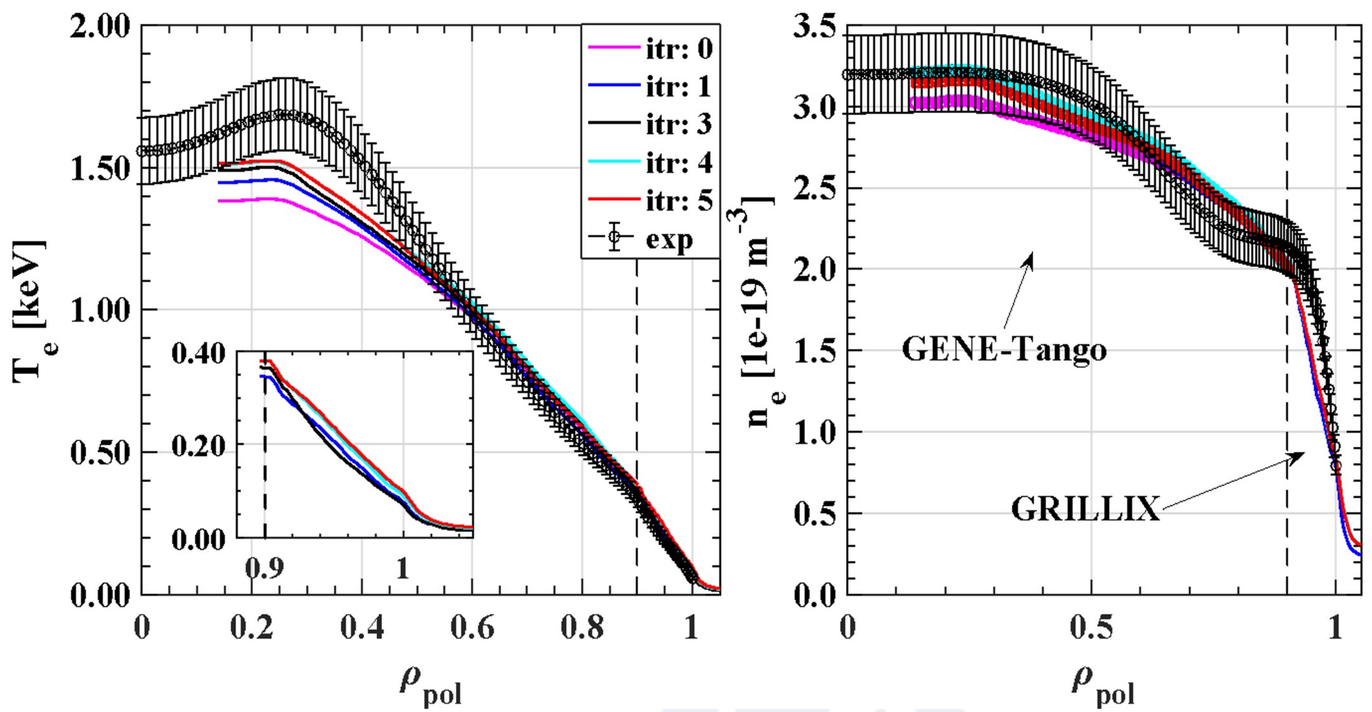
Electron pressure[8]



[1] Di Giannatale PPCF 24
[2] Pueschel PoP 25
[3] Balestri PPCF 24
[4] Balestri PPCF 25
[5] Mariani NF 24
[6] Balestri NF 25
[7] Muscente NME 23
[8] Lim PPCF 23
[9] Poley NF 25
[10] Marchioni, EPFL PhD Thesis (2024)

Whole-device modeling with GENE-Tango-GRILLIX





- **ASDEX Upgrade L-mode**
- **GENE-Tango for the core** (ρ_{pol} = 0.1 to 0.9)
- **GRILLIX for the edge** (ρ_{pol} = 0.9 to 1.05)
- Iterative process

Goal: Parameter-free performance predictions for tokamaks & stellarators

High-fidelity integrated modeling: conceptual overview

Control room actuators…

- Heating waveforms
- Fueling waveforms
- CD waveforms
- Coils I/V

Wall recycling, erosion

…acting directly on…

- Qe Qi
- Fuel, impurity sources
- radiation
- q(r), magnetic equilibrium

$$\frac{\partial n}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\boldsymbol{\Gamma}) = S$$

$$\frac{3}{2}\frac{\partial nT}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\boldsymbol{q}) = Q$$

…triggering NL couplings

Turbulent fluxes: $T_{eq}(r)$ & $n_{eq}(r)$ coupled

$$\begin{pmatrix} \frac{\Gamma}{n_{eq}} \\ \frac{q}{T_{eq}} \end{pmatrix} = -\begin{bmatrix} D_{nn} & D_{nT} \\ D_{nT} & D_{TT} \end{bmatrix} \cdot \begin{pmatrix} \frac{\nabla n_{eq}}{n_{eq}} \\ \frac{\nabla T_{eq}}{T_{eq}} \end{pmatrix}$$

W collisional convection significant & coupled to $T_{eq}(r)$ & $n_{eq}(r)$

$$\Gamma_W = ZD\left[\frac{1}{Z}\frac{\nabla n_W}{n_W} - \frac{\nabla n_{eq}}{n_{eq}} + H\frac{\nabla T_{eq}}{T_{eq}}\right]$$

η, bootstrap

Automated large-scale code validation

Automated extraction, fitting, setup, and execution

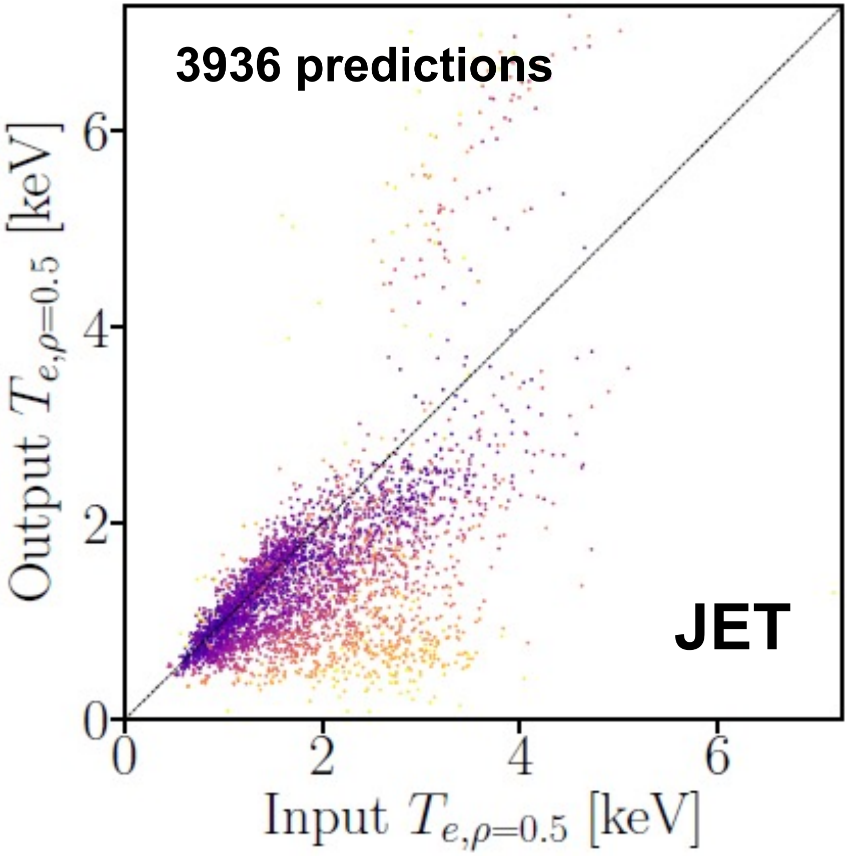
Comparison of kinetic quantities (averaged over time windows of 0.5 s) across a JET database of 3936 data points

Key questions:

- How good are our models?
- How can we improve them?
- Can we do better than empirical scaling laws?

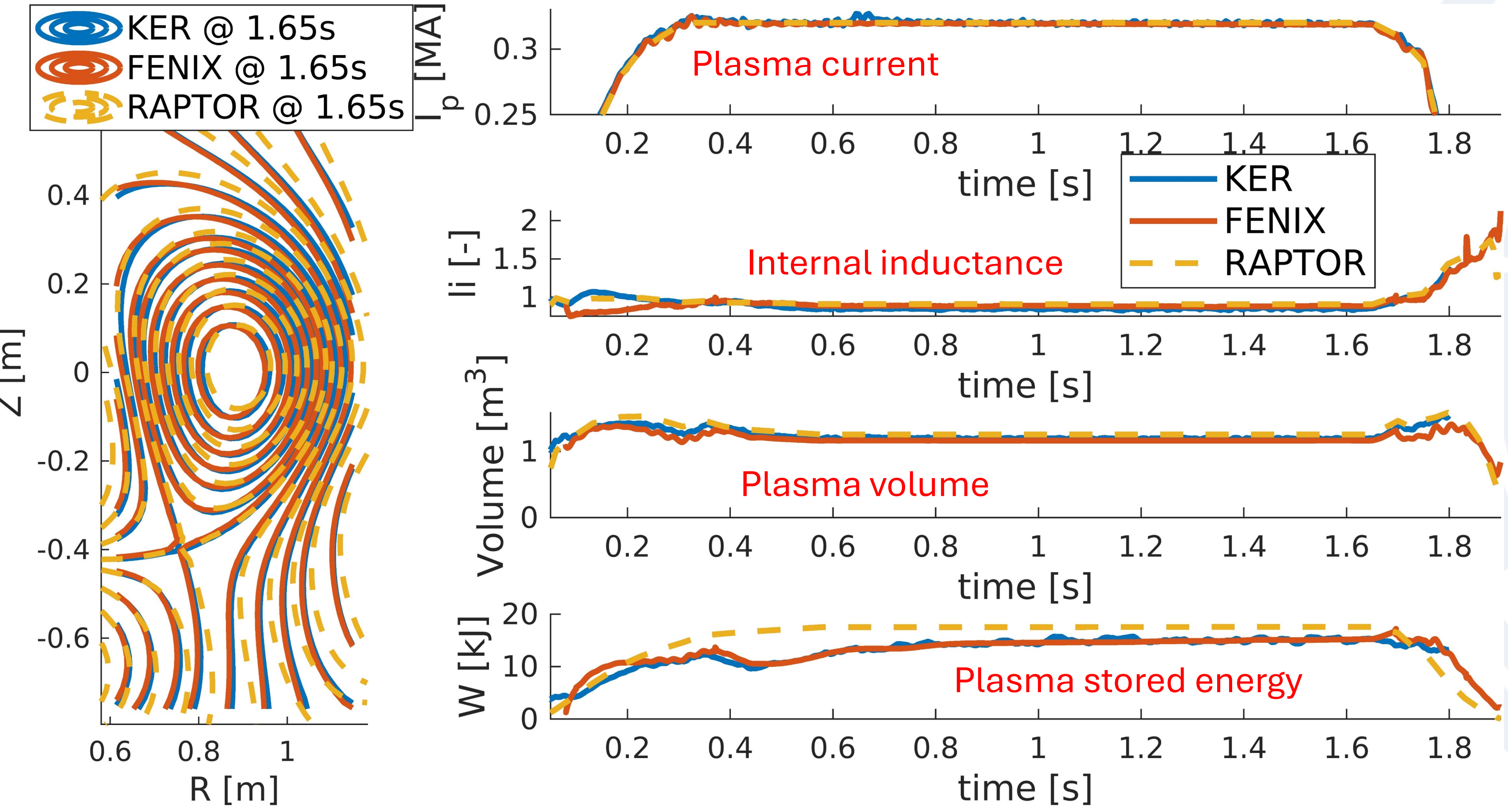
Bourdelle PPCF 25

Predicted vs. measured T_e at half radius



Pulse Design Tools applied to TCV

Kinetic Equilibrium Reconstruction (KER) for TCV #64965 (Ohmic L-mode discharge)



RAPTOR-FBT

Fast transport code RAPTOR [1]

Inverse equilibrium code FBT from MEQ suite [2]

FENIX

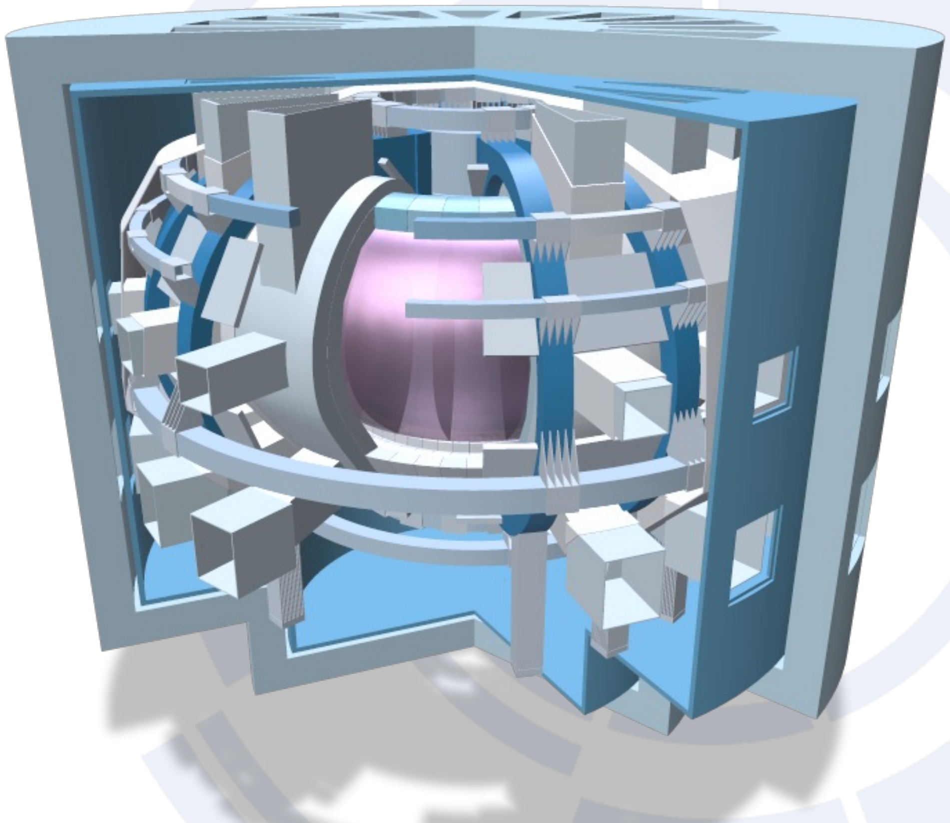
Originally developed for AUG [3,4]

Coupled to forward equilibrium code FGE from MEQ suite and TCV controller

[1] Felici NF 11 [2] Carpanese, EPFL PhD Thesis (2021) [3] Fable PPCF 22 [4] David OPS 25

System codes: solving the integration problem

- **Integration of disparate subsystems** is critically important for designing any complex device
- A typical systems code like **PROCESS is a collection of integrated 0D/1D models**
- **BLUEMIRA** takes typical systems code outputs and **extends the modelling to 2D/3D**, producing "space reservation" CAD in a matter of minutes
- This provides a **great starting point for detailed design studies**



"Space Reservation" CAD generated by BLUEMIRA

https://github.com/Fusion-Power-Plant-Framework/bluemira

Summary

HPC and AI allow researchers to simulate complex, multi-scale, multi-physics plasma dynamics with unprecedented realism and reliability.

The ultimate goal is to create digital twins of fusion systems, thereby saving cost and time.

To be effective, the fidelity level of a digital twin must match its intended purpose.

New research areas include multi-fidelity techniques and uncertainty quantification (UQ).

Related presentations at this meeting (selection)

Regular Oral

- H. Bergström — Hybrid kinetic-MHD studies of runaway electron beam termination events
- H. Bufferand — Hierarchy of turbulent transport models with the SOLEDGE3X code
- D. Matveev — Analysis of fuel retention and recovery in JET with Be-W wall
- F. Warmer — Towards a Stellarator Fusion Reactor: Achievements of the European Stellarator Program
- W. Zholobenko — Validated, global edge-SOL turbulence simulations in various ELM-free regimes

Overview Poster

- J. M. García-Regaña — Transport in high-performance plasmas of the TJ-II stellarator
- M. Hoelzl — JOREK contributions to the predictive understanding of transient phenomena in future tokamaks and stellarators

Additional Slides

Fluid-kinetic hybrid neutral models

Borodin NF 22

Accuracy

Code performance

Fluid, AFN

Hybrid Fluid-Kinetic approach (FKH)

kinetic, MC

Asymptotic-Preserving MC (APMC)

Not fully rigorous, speedup >100

Spatial FKH

Firm domain allocation

Spatial by source

Flexible domain border - tested

Evapor./condens.

micro-Macro FKH (mMH)

- **Cancellation error** (can be suppressed by enforcing positivity)

Typical speedup ~10 (or less)

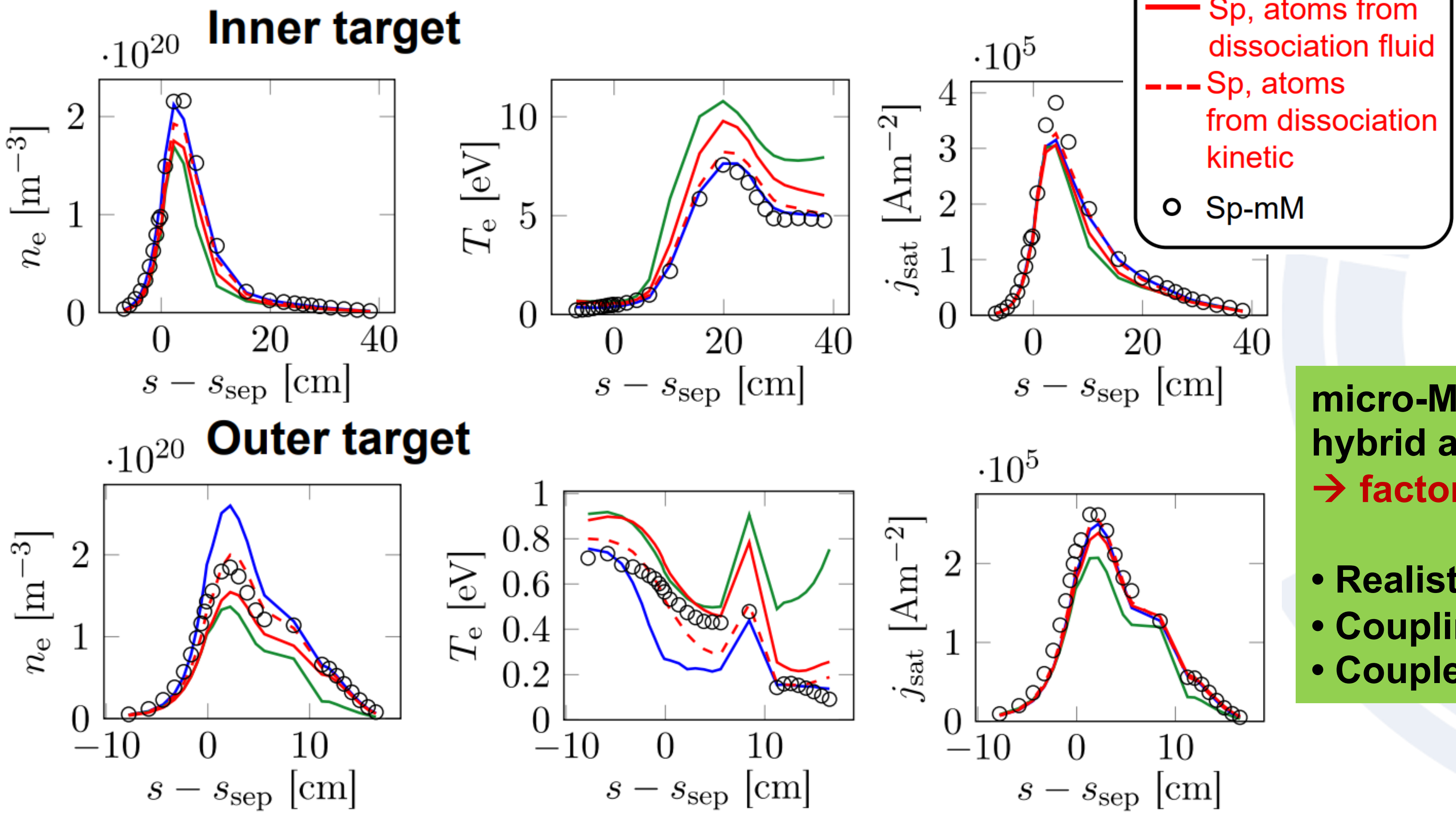
micro-Macro kinetic diffusion (KDMC)

- **Bias error** (can be suppressed via multi-level)
- No coupling with CFD needed

Seamless in volume

Recent progress with micro-Macro (JET L-mode case)

Horsten PET 21



Purely micro-Macro (mM) approach for rectangular slab geometry with fixed background plasma

2021

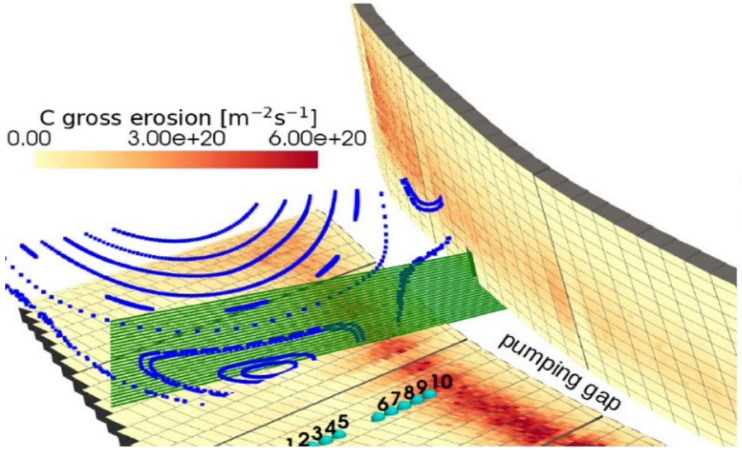
micro-Macro combined with spatially hybrid approach (Sp-mM)
→ factor 5-10 faster than full kinetic!

- **Realistic geometry, void regions**
- **Coupling to kinetic molecules**
- **Coupled plasma-neutral simulations**

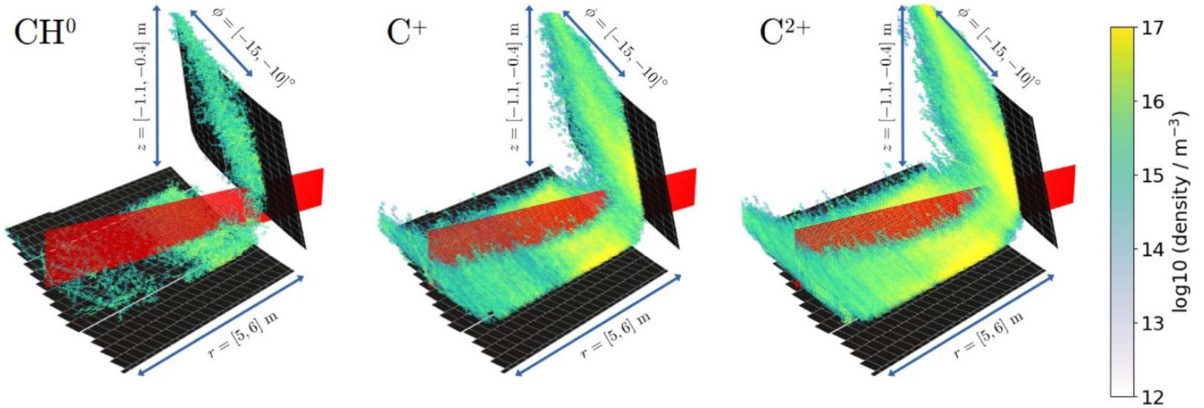
Erosion and migration of impurities in W7-X

3D EMC3-EIRENE + ERO2.0 modeling

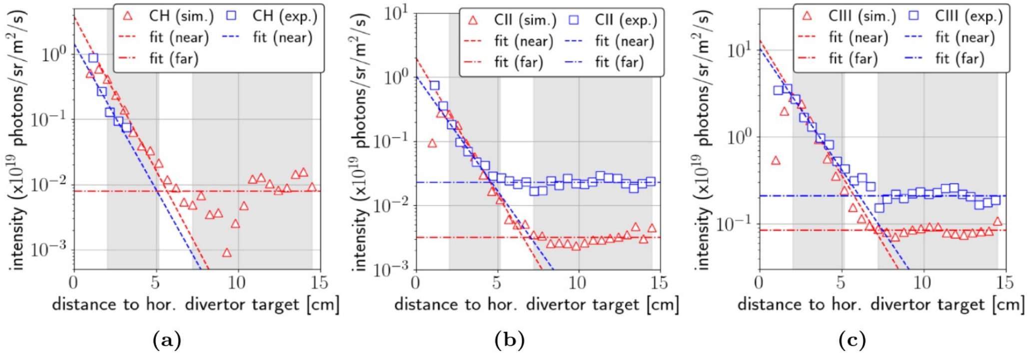
Romazanov NF 24
Romazanov EPS 2025



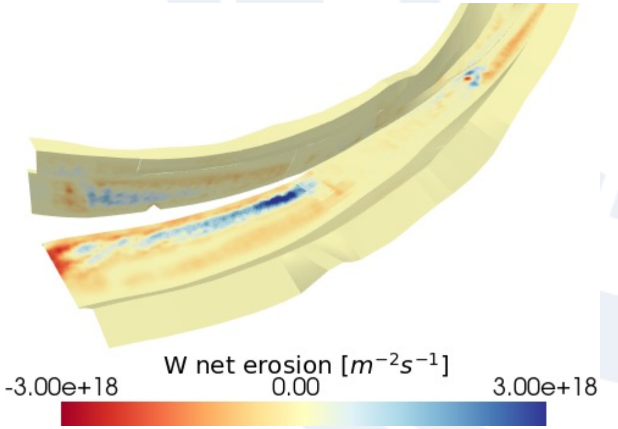
Carbon erosion simulations for benchmark with spectroscopy



(Hydro-)Carbon densities in 3D for synthetic diagnostics



CH molecular band and C line emission: experiment vs. simulation



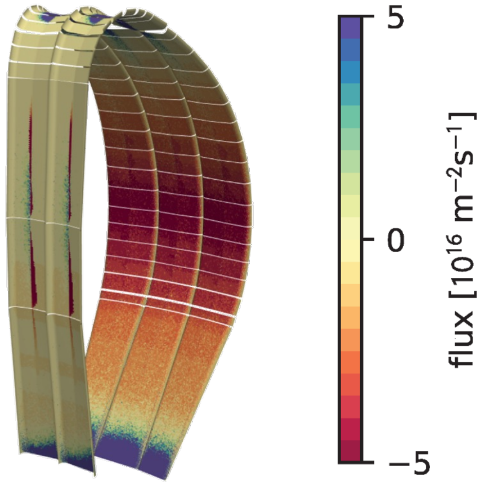
First predictions for W divertor upgrade

Plasma-wall interactions in future fusion devices

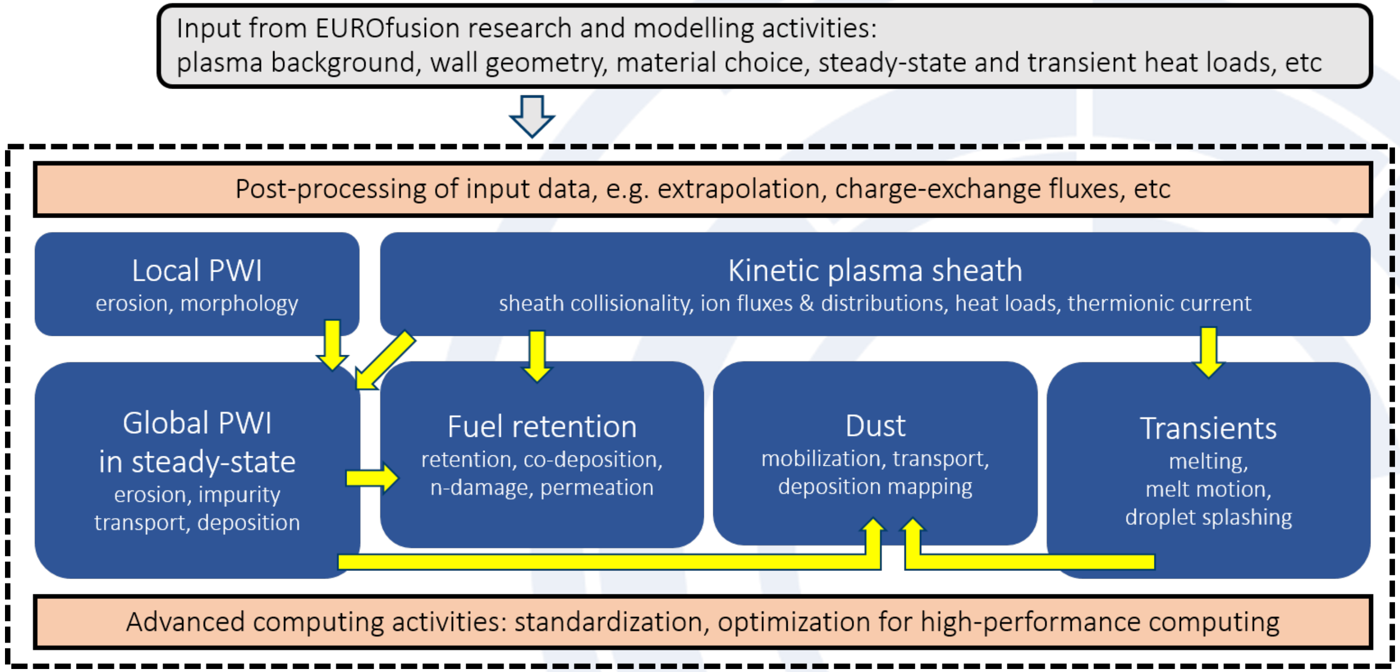
Matveev NF 24

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



ERO2.0: erosion-deposition rate map for W



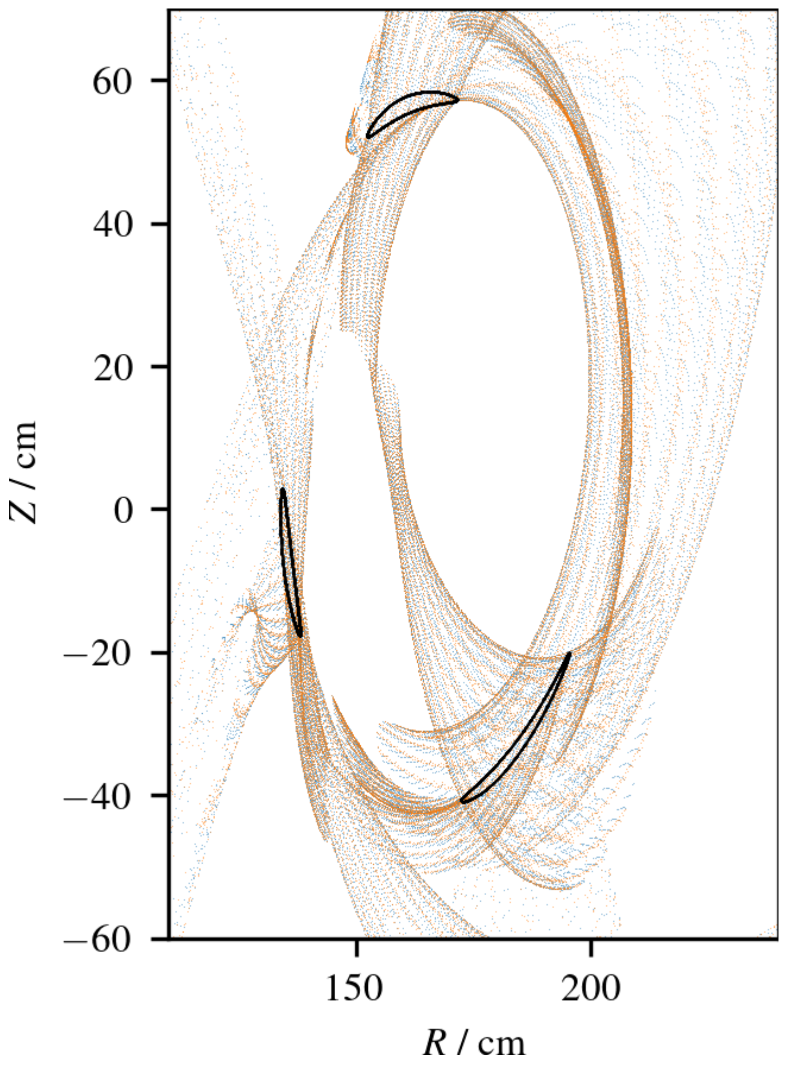
Code and model development

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

Estimating alpha particle losses in stellarators became SIMPLE



Alpha particle loss estimation is expensive in optimization loop

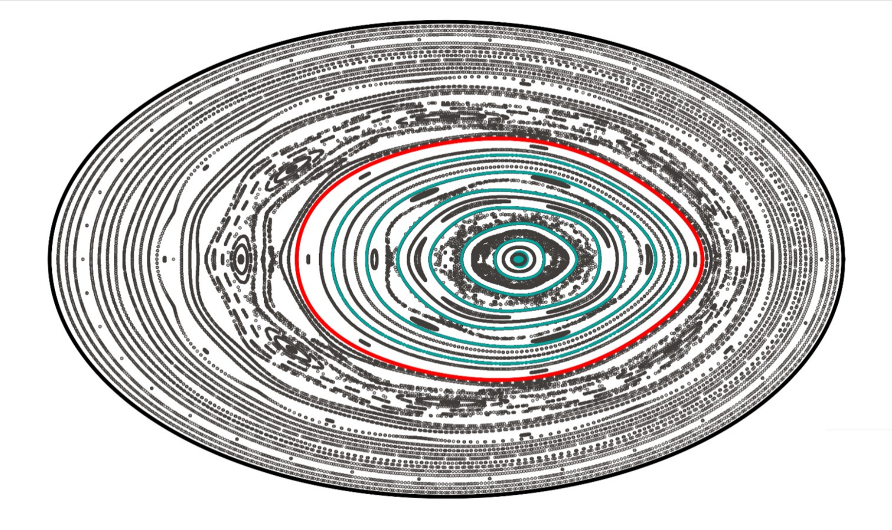
SIMPLE code uses symplectic integrators: long-term stability with large time-steps

— SIMPLE accelerates alpha particle loss estimation by orders of magnitude —

https://github.com/itpplasma/SIMPLE

Albert JCP 20

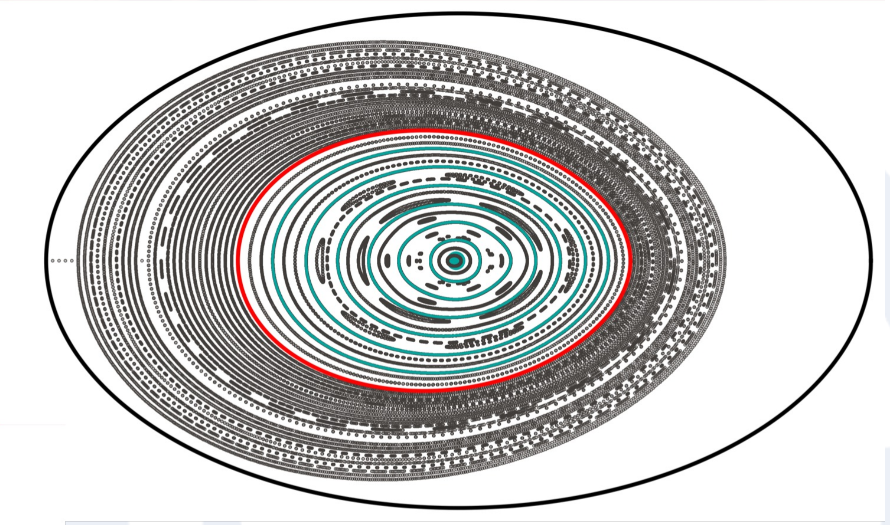
Direct-from-coils optimization of magnetic islands



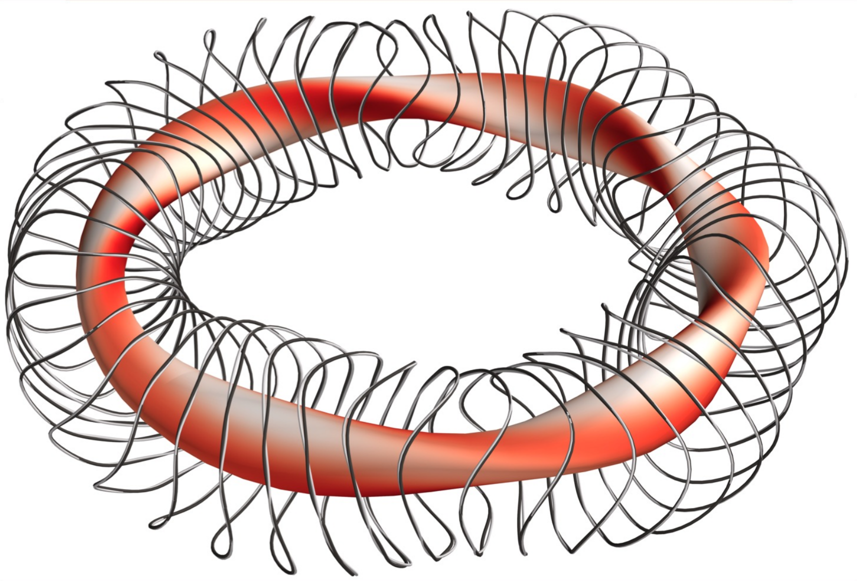
initial
(β~1.5%)

coupling SIMSOPT + SPEC

80-dimensional coil optimization space



optimized
(β~1.5%)



Smiet PoP 25