

EPFL

19th Technical Meeting on Energetic Particles in Magnetic Confinement Systems



**EPFL
Swiss
Plasma
Center**

**September 28 -
October 2, 2026**

**Beaulieu
Lausanne,
Switzerland**

Perspectives: From present experiments to future burning plasmas

Chair: W. W. Heidbrink

Non-linear amplitude and EP transport

- AE/zonal/microturbulence
- impact of other dangerous modes

H. Cai, L. Chen, M. Fitzgerald, R. Ma

TMEP2026Panel DiscussionsLiu CHEN(I) Effects of AEs on Microscopic Instabilities (μI)① AEs $\Rightarrow$ beat-driven zonal state (ZS)② ZS: { zonal fields ($\delta\phi_z, \delta A_z$), Phase Space zonal structure (δF_z) }③ ZS on μI : $\delta f = \delta f_\mu + \delta F_z$, $\delta\phi = \delta\phi_\mu + \delta\phi_z, \dots$

$$\Rightarrow \boxed{[\underbrace{L_{g0}}_{(i)} + \delta L_z] \delta f_\mu = - \delta L_\mu [\underbrace{F_0 + \delta F_z}_{(ii)}]}$$

 $\Rightarrow$ Mitigation/suppression of μI via (i) $\delta L_z = \langle \delta u_{gz} \rangle \cdot \nabla$ decorrelation / resonance detuningor (ii) δF_z : $\downarrow$ instability drive??(II) Roles of Kinetic Alfvén Waves (KAWs)① KAWs generated via (i) mode conversion (Radiative damping), (ii) scatterings of AEs by μ turbulence $\Rightarrow$ stimulated absorption (damping of AEs)② KAWs $\Rightarrow$ global radial propagation, enhanced $\delta\phi_\mu$ (acoustic) polarization, e-heating, transport, ..③ Identification/Investigation of KAW in simulation/experiments??

Important topics in nonlinear amplitude & EP transport

- Nonlinear physics is complicated and interesting if we allow ourselves to get carried away – **we must focus – spamming computers probably not tractable**
- Establishing the **(1) energy content available** to drive instability in current experiments and future experiments will clarify the **relevant nonlinear regimes**
 - Transient available energy γ_L – classically obtained “flat-top” gradient drive may well be unphysical **unstable equilibrium vs evolving self-consistently**
 - Long term balance and collisions ν – can we neglect transients and settle down to balancing energy in/out or do violent things burst on γ_L timescale? Do those bursts break things or do we limit-cycle?
- Scale invariance – **(2) does nonlinear saturation physics change when $\rho_\alpha^* \ll 1$ and alphas become “gyrokinetic” or is it still just the energy content?**
- Creating “three animal problem” (Alphas $\leftrightarrow$ Zonals $\leftrightarrow$ Thermals) predator prey systems could help nail down where to focus our efforts and establish the basic information to transport modelers **(3) Resonantly driven modes good/bad/boring?**

Nonlinear amplitude & EP transport

Research focus: Balance the ongoing study of energetic particle transport and microturbulence synergy with a shift toward developing active control mechanisms for these modes.

Plasma dynamics: Investigate how Alfvén eigenmode-induced phase space zonal structures affect microturbulence, evaluate the overall impact on plasma confinement, and understand multiple Alfvén eigenmode coupling alongside associated avalanching.

The community has studied EP transport for decades and more recently the synergy with microturbulence. Can the panel comment on the group's need to further study the impact/function of these modes, or should we put more focus into active control mechanisms for these modes?

How would the AE-induced phase space zonal structure (PSZS) affect microturbulence?

Nonlinear amplitude & EP transport

1. Stucchi. Future work: Build a reduced model to assess the impact of ZF on confinement. The role of resonant particles in ZF generation. Trapped particles, more general geometry. Benchmarking.
2. Bonfiglio. ST reactor needs to control ETG. RF more important than NBI.

-How does the suppression shot database compare to the critical-gradient EP database (Collins)? q , density, $\beta_{\text{thermal}}/\beta_{\text{beam}}$, beam distributions, RSAE-TAE growth rates/amplitudes, locations ...?

-any idea why stabilisation does not work for $q < 2$ (ITER relevant)?

What is the feedback loop that solidifies the strong suppression regime? What causes the back transition?

Predictive capability

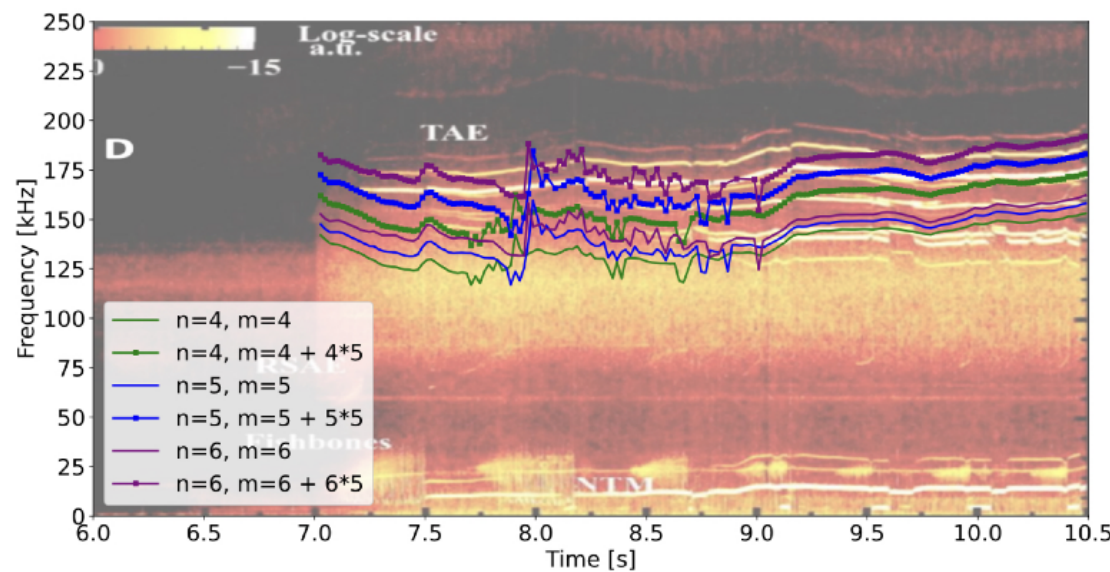
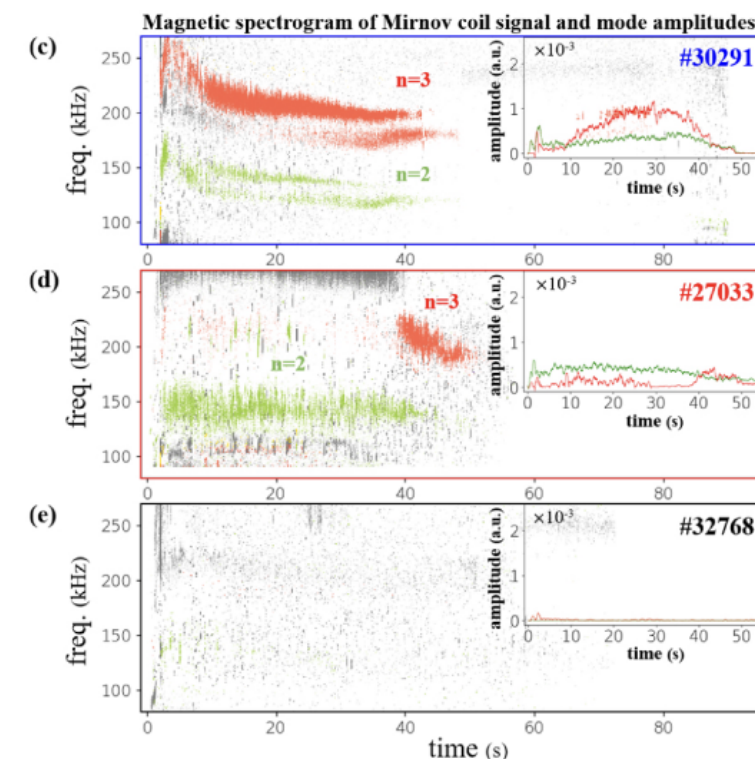
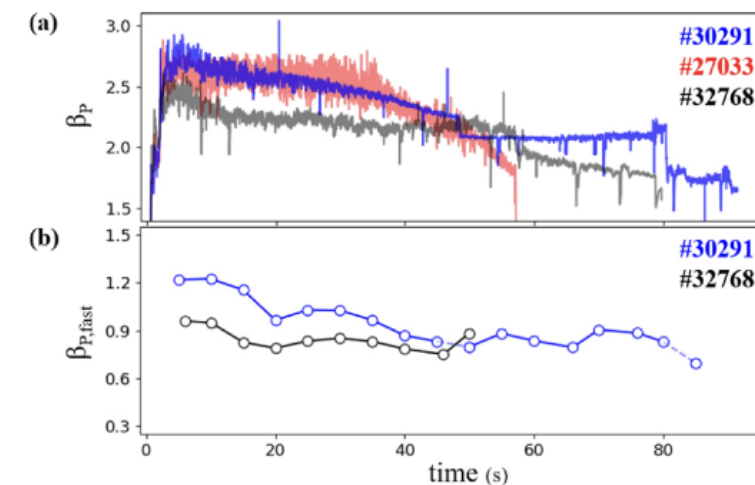
- needed simulation advances, including reduced models
- validation

P. Lauber, M. Mantsinen, S. Pinches, Y. Todo

- **Target**
 - Predict EP-driven instabilities and alpha/fast-ion distributions for future operation scenarios
- **Present capability of kinetic-MHD hybrid simulation (MEGA)**
 - Kinetic alphas / fast & thermal ions + MHD, NBI/ICRF, collisions, full-orbit dynamics
- **Reduced / data-informed models**
 - Experimental database + ML $\rightarrow$ predictive effective dissipation coefficients (ν_{eff} , η_{eff} , ...)
 - Represent unresolved physics: radiative damping, effects of microturbulence, etc.
 - Incorporate the predicted coefficients into MEGA
- **Validation: from reproduction to prediction**
 - Systematic validation: many discharges $\rightarrow$ multiple devices
 - **Predictive validation: calibrate on some discharges $\rightarrow$ predict unseen discharges**
 - First step: systematic validation using the LHD database
- **Goal: from reproducing experiments to predicting future experiments**

- long time scales for long-pulse/steady state operation requires taking into account effects that are often neglected, e.g. current diffusion: importance of accurate description of non-linear equilibria including phase space structures; even more crucial in self-organising plasmas
- need for theoretical guardrails + reduced models for different regimes describing cross-scale coupling
- high fidelity codes need to deliver fundamental insights into physics mechanisms
- validation: automated application of workflows on entire discharges is possible: EP-WF on JET [\[V.A. Popa, PhD\]](#)
- well curated/shared databases are key (in particular q profile), also for the results!

[\[Kim, NF 24\]](#): power degradation due to TAEs in long-pulse high power discharges at KSTAR observed





PREDICTIVE CAPABILITY FOR ENERGETIC PARTICLES

M.J. Mantsinen, ICREA and Barcelona Supercomputing Center

GOAL: Ensure energetic particle physics informs reactor design from the outset

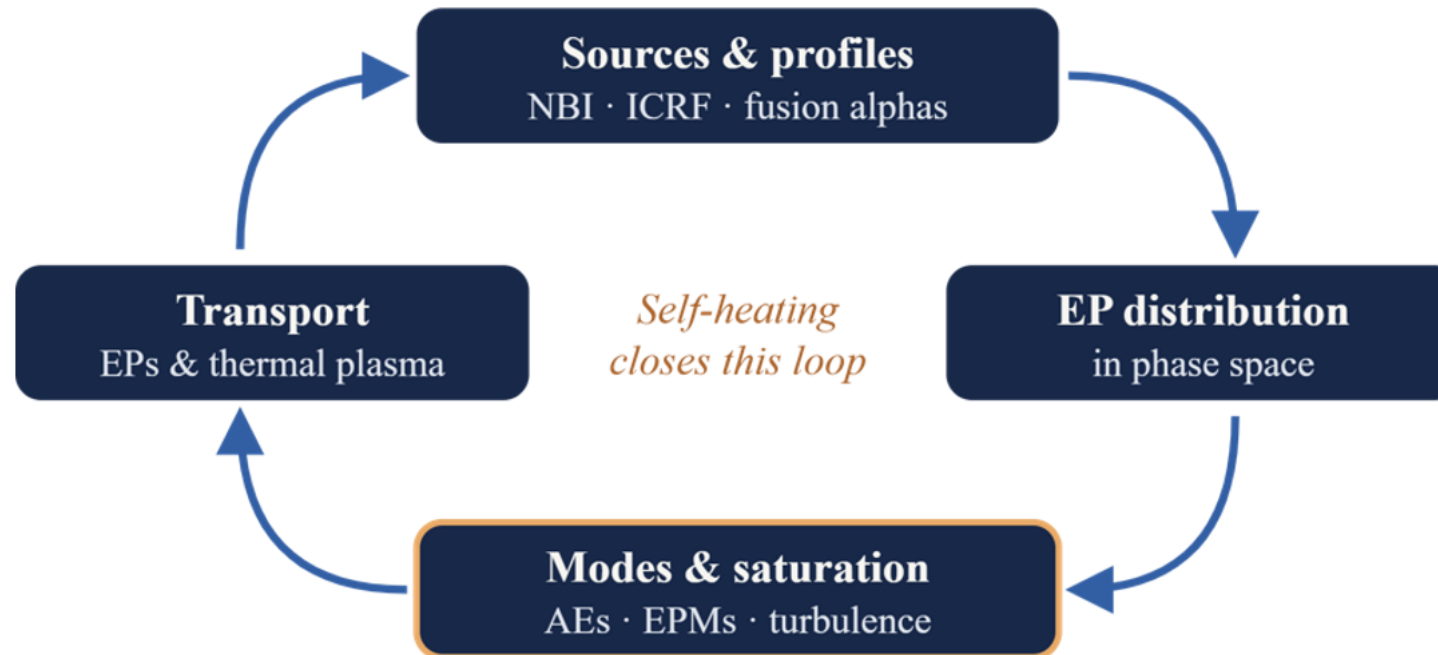
ACTIONS:

DEVELOP A SCALABLE HIERARCHY OF
MODELS, INCLUDING REDUCED AND
AI MODELS

ESTABLISH PREDICTIVE CAPABILITY
WITH QUANTIFIED UNCERTAINTY

TRANSLATE VALIDATED PHYSICS INTO
DESIGN INPUTS
Constraints • Margins • Sensitivities

Closing the loop: How well can we predict?



Goal: Close this loop for the whole plasma in time-dependent integrated modelling, with reduced models calibrated on first-principles runs

PROPOSAL

An open prediction challenge

- 1 Share or agree on experimental data**
Participants contribute experiments, mapped to common representation (IMAS)
- 2 Any model can enter**
First-principles, reduced or AI/ML, compared via synthetic diagnostics
- 3 Define success together**
Agreeing metrics and target accuracy is part of the challenge, e.g., neutron rate, rotation profile, etc.

Build on progress at this meeting: Database validation of reduced models (Lestz); Validating EP transport models (Podestà); Phase-space engineering to control AE (J. Wang); Low- p^* AE self-saturation (Bass); etc.

Predictive capability

What reduced models and advances do we need to better incorporate the more recent analysis of EP/zonal/microturbulence affects?

Stellarators

→ distinct challenges (relative to tokamaks)

Future stellarator research topics

- **Improved reduced dimensionality models**

- Traditionally, reduced models have been derived by physics intuition – leads to high degrees of freedom, spurious modes, computational fragility
- New approaches for methodically reducing dimensionality
 - SVD (Singular Value Decomposition), POD (Proper orthogonal decomposition)
 - Neural networks => latent spaces

- **A broader approach to stellarator optimization (3D => 5D)**

(a) Currently 3D magnetic field structure is optimized (Source: coils, permanent magnets, Sink: non-symmetries, ferritic materials, etc.)

(b) But plasma phenomena also depend on phase space (Source: ECCD, bootstrap, ICRH, NBI, alphas, Sink: loss regions, transport, charge exchange, fusion reactions, runaways, etc.)

(a) and (b) can be tightly coupled, so why not optimize them together?

Stellarators

1. jk

Diagnostics and inference

→ needed advances in measurement & interpretation

Diagnostics & inference

Main statement

Fusion reactors (e.g. ITER) allow limited set of EP diagnostics due to complexity, difficult (unlikely?) to study unknown regimes for the first time. Diagnostics unlikely to be modifiable.

Recommendations

- Ensure extended set of diagnostics at auxiliary flexible devices (D and DT) where we have higher flexibility to explore unknown regimes.
- Test reactor compliant diagnostics at flexible devices together with more informative (but not necessarily reactor compliant) EP diagnostics
- Identify minimal set of EP diagnostics needed to measure essential physics at larger devices. Test what we can/cannot tell if we had limited set of diagnostics at flexible devices.
- Complement measurements with theory prior when needed to fill gaps: see next slide

Inference of the EP distribution function – What's next?

- **Goal:** Integrated data analysis of whatever sparse EP diagnostic data we have at any machine, in the end automatic inference within minutes or seconds, perhaps for plasma control
- **Frameworks** for integrated data analysis of any EP diagnostic at any machine: Tikhonov, Bayesian, machine learning, 1D to 5D phase-space inversions, uncertainty quantification, physics-informed prior information, automatic
- **Use physics-informed prior information, e.g.**
 - Gryro orbits, drift orbits
 - Collision physics (Gaffey (1976) type slowing-down distributions)
 - Neoclassical collision physics: e.g. ASCOT simulations
 - Wave-particle interaction physics (Streamlines in CoM space)
 - More sophisticated codes: 'Kick model' also strength of the kicks
 - Other prior information: e.g. NBI geometry, numerical simulations

Diagnostics & inference

As we transition to machines that use purely RF or negative ion neutral beams, how will our EP diagnostics and inference shift and adapt? Not all of our current diagnostics can easily measure in these regimes.

Runaway electrons and EP control

→ including machine protection & real-time control

Runaway electron & EP control

SOME THOUGHTS ON FUTURE DEVELOPMENT:

- Many burning plasma machines plan using ECRH/ ECCD, so the use of ECRH/ ECCD for AE control looks inevitable. And the most effective
- RMP effects do exist, but may affect fast ions too much. More work is needed for identifying the boundaries of the usefulness for AE control
- The NBI energy and geometry effects on AEs were demonstrated, but may require too much effort in future machine (e.g. the beam position changes)

WHAT DO WE WANT OF AE?

- Control of thermal plasma turbulence via AEs may be of great interest
- Use of numerous low amplitude AEs as MHD markers has demonstrated an excellent tool for MHD spectroscopy. We want such MHD spectroscopy, with AE amplitudes low enough
- ECRH/ ECCD on TJ-II (maybe more?) was affecting not only AE existence, but also type of nonlinear AE evolution: bursting versus steady state in amplitude, sweeping vs. constant in frequency. A control of nonlinear AE evolution may be more useful than suppression of AEs

Hot topics for RE studies

☐ What causes fast cooling of the bulk electrons?

(Impurity penetration, magnetic surface breaking or both? We still lack a satisfactory understanding of the thermal quench.)

☐ Can magnetic energy of the toroidal current ensure bulk electron reheating?

☐ Can RF current drive prevent RE production?

(The current carrying electrons are much faster than thermal electrons in case of RF current drive. This should preclude high inductive field when bulk electrons cool down.)

Post-disruption runaway kinetic stability: marginal regulation versus violent relaxation

Limiting runaway energy through marginal stability is important. A violent fan-like instability that depletes a substantial fraction of the post-disruption runaway population would be especially interesting.

Impact on fusion strategic developments

→ impact of EP physics and technology on reactor
concepts and design

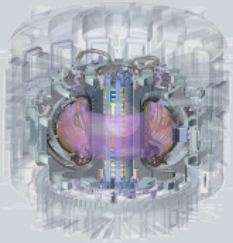
A. Fasoli, A. LeViness, K. McClements

Impact of EP physics and technology on reactor concepts and design

Ambrogio Fasoli (ackn. Justin Ball)



EP issues must be design drivers and high-priority targets for diagnostic & actuators developments – in DT good α confinement supports high fusion gain and reduces recirculating power; α losses must be $< \text{few}\%$; α profiles affect equilibrium, stability, and burn control. EP protection and observability must be built into design before the magnetic configuration is frozen.

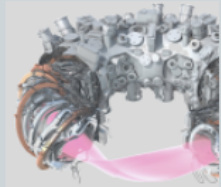


EP in tokamaks

Conventional configurations - coordinate equilibrium, stability, and current-profile control; investigate non-active phases in BP expts (ITER, BEST, SPARC) to derisk and maximise output of DT ops

Negative Triangularity - complete studies, so far no clear showstoppers

Spherical - orbit widths and losses can be important (also see Ken's slide)



EP in stellarators

Magnetic geometries (QI, QA) now optimized for neoclassical EP transport as well as thermal, but EP confinement still to be demonstrated experimentally, and no 'optimization' for instability-driven redistribution and losses



EP in other magnetic fusion concepts

Often overlooked but must be considered in depth, as could be critical; e.g. NBI-driven FRCs ($\sim 40\%$ of pressure from EPs to improve confinement requires large p_{NBI} and may drive AEs), tandem mirrors (intense high-energy NBI required into mirror plug cells to create e.s. potential can lead to instabilities), levitated dipoles (so far, plasma pressure primarily from >1 keV ECRH-driven electrons, no info on thermal plasma)



Impact of EP physics and technology on power plant concepts and design – Alexandra LeViness

Two overriding questions for a power plant:

1. Does it work? (i.e. consistently produce net fusion power without breaking)
2. How much does the electricity cost? (\$/kWh)

Physics concerns should be justified by their impact on the answers to these questions.

For EP physics, the impact boils down to **plasma performance** and **PFC damage**.

Performance: Does P_{net} go up or down? & Can we stay within operational limits?

- Alphas main source of heating ($Q \gg 5$) + limited diagnostic coverage → need to understand alpha physics to predict and control plasma!
 - Strongly coupled burning plasma, potential for feedback & control loops
- Understanding impact of EPs on fusion power/gain, both good and bad
 - EP-driven modes may reduce performance, but can also potentially suppress turbulence

PFC damage: Can stop operations or require costly replacements

- Alpha losses to the wall: steady-state & transient heat loads, localized erosion
- Runaway electrons: prevention and mitigation

Impact of EP physics & technology on reactor concepts & design: Ken McClements

- All fusion reactor concepts (including ICF ones) rely on self-heating of plasma by charged fusion products & for essentially all credible designs that means 3.5 MeV α -particles
- NBI & ICRF waves will NOT be used as external current drive actuators in some MCF reactor concepts:
 - NB injectors capable of driving current deep inside reactor-grade tokamak plasmas need to be enormous & are exposed to neutrons, creating performance & maintenance challenges; also wall-plug efficiency is poor (~25-30%)
 - due to fast wave evanescence, ICRF antennae need to be very close to plasma, hence in reactors are vulnerable to radiation damage & impact on breeding, particularly in ST reactors in which most / all breeding is on low field side
- So fusion α -particles in many MCF reactor concepts (e.g. STEP) will be sole important energetic ion species
- Impacts of α -particles on reactor design include:
 - unlike neutrons, footprint of α -particle losses on 1st wall can be extremely localised & main chamber armour needs to be thin to minimise attenuation of neutron flux needed for breeding, hence especially vulnerable to α -particle damage
 - consequences of α -particle impacts on 1st wall include surface fuzz growth, increasing erosion rates, impurity contamination of plasma & disruption risk
 - ramp-up scenarios may require early introduction of tritium to provide α -particle heating & bootstrap current – if so, need to consider α -particle-driven instabilities during this phase when current is low and bulk ions are relatively cold, hence do not provide strong Landau damping

Impact on fusion strategic developments

It appears that groups tend to prioritize other issues (e.g. thermal confinement, disruptions, heat exhaust, etc.) rather than EP physics. What is the largest issue in EP physics to address toward reactor designs?