MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Energetic Particle Physics in stellarators

A. Könies, R. Kleiber, A. Mishchenko,
C. Nührenberg, J. Riemann, C. Slaby

Stellarator Properties

EUTERPE development strategy

EUTERPE application examples

- LHD benchmark with GTC and MEGA
- Three- dimensional full- torus electromagnetic simulations
- Alfvénic Modes and Electromagnetic Turbulence in Wendelstein 7-X

Ongoing activities

Conclusions

Introduction

Energetic particle stability and transport in stellarators

special consideration: EUTERPE code suite
outline of strategic approach and application examples

Introduction

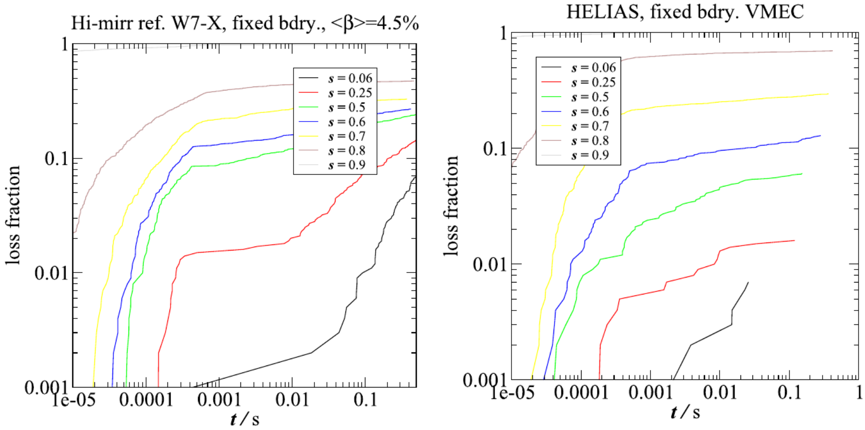
objectives of EUTERPE development

provide theoretical basis for

- understanding the experimental results of W7-X
- design and optimization of a stellarator reactor
- (...with the equilibrium particle confinement problem spared out)

Stellarator optimization

one of the goals: reach better α- particle confinement



M. Drevlak et al. Nucl. Fusion 59 (2019) 016010

Hot spots to appear . . .

one of the goals: reach better α- particle confinement

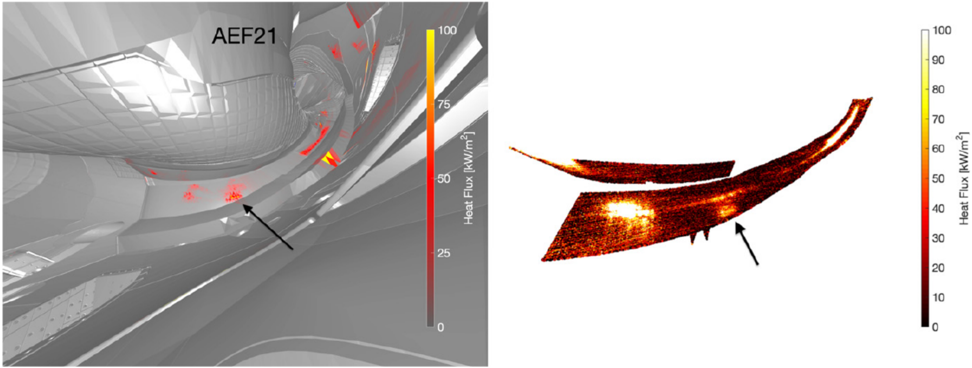


Figure 4. Simulated fast ion wall loads (left) and measured heat flux in the divertor of W7-X (right). The arrow highlights the hot stop which is correlated with NBI injection. (Discharge 20180822.12, AEF21 camera).

S. A. Lazerson et al. Nucl. Fusion 61 (2021) 096008

Stellarator Properties

Theory:

- fast particle confinement is an issue
- apart from μ, E no constant of motion
  (may change somewhat for new generation of quasi-symmetric stellarators)
- additional wave particle resonances

3D analytical theory

(see Kolesnichenko et al. 2002)

- proportionality to equilibrium quantities

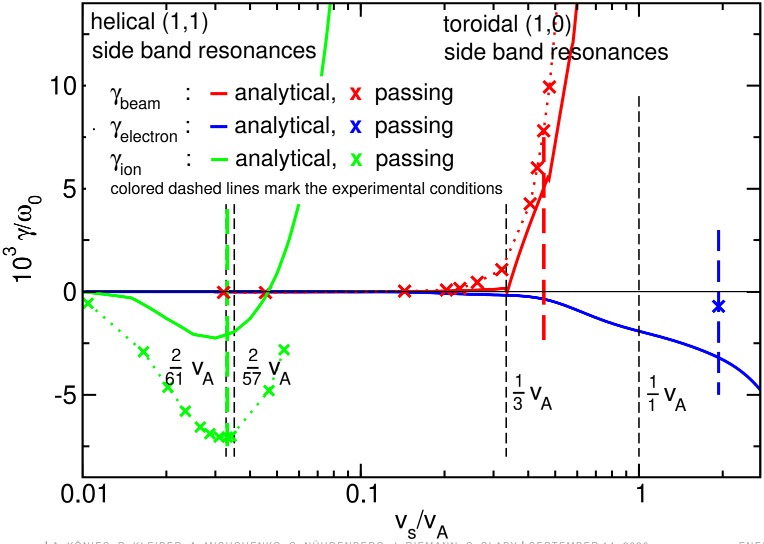
$$\frac{\gamma}{\omega_0} \propto A^2 \sum_{m'n'} |\epsilon^{\kappa}_{m'n'}|^2 \approx A^2 \sum_{m'n'} |\epsilon^{B}_{m'n'}|^2$$

- coupling is approximately given by the structure of B
  $\Rightarrow$ investigate spectrum of B
- note, that for a TAE in a large aspect ratio tokamak: $\frac{\gamma}{\omega_0}$ is independent of the equilibrium
- the resonance condition $\omega - k_{||} v_{th} = 0$ determines

$$v^{\mathrm{res}}_{m'n'} = v_A \left| 1 \pm \frac{m'\iota^* + n'N_p}{m\iota^* + n} \right|^{-1}$$

i.e. well known resonances at $v_0 = v_A$ and $v_0 = v_A/3$ for a Tokamak

growth and damping rates for TAE in #39042



growth/ damping rates of Alfvénic modes in stellarators

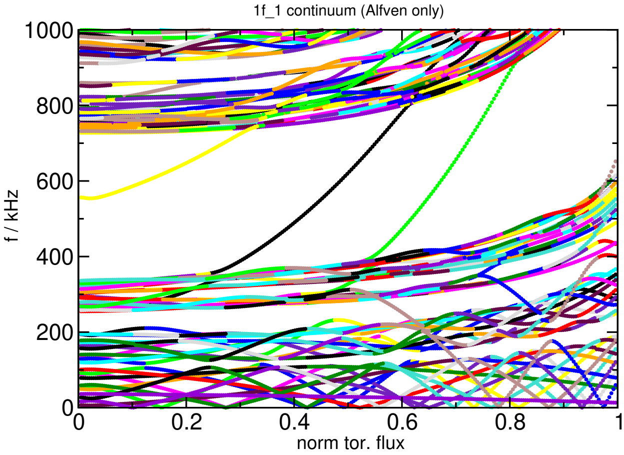
- additional resonances may lead to interaction with bulk ions
- likely to cause additional damping
- may cause drive of Alfvénic modes by bulk ions

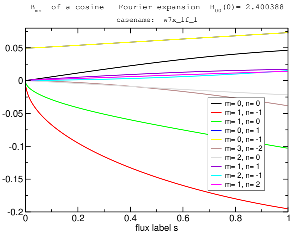
Stellarator Properties - Theory

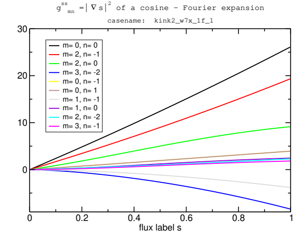
Theory:

- fast particle confinement is an issue
- apart from μ, E no constant of motion
  (may change somewhat for new generation of quasi-symmetric stellarators)
- N_p periods, $0 \dots N-1$ mode families ($n_1 - n_2 \equiv N \pmod{N_p}$) for linear coupling
- additional wave particle resonances
- strong mode coupling (MHD)
- small shear $\rightarrow$ radially extended modes

example of MHD coupling (W7-X)







Stellarator Properties - Theory

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- small shear $\rightarrow$ radially extended modes
- soft MHD stability limits

Stellarator Properties - Theory

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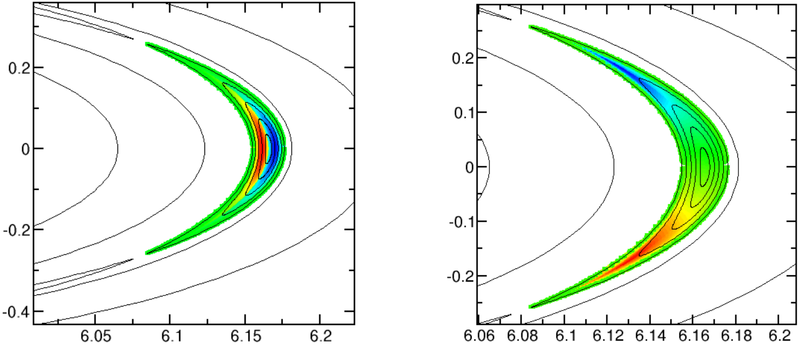
- small shear $\rightarrow$ radially extended modes
  (low mode number GAE)
- soft MHD stability limits
- equilibrium islands inside the plasma

digressing: modes in magnetic islands



Global even and odd EAE-like $\text{MiAE}_{2,0}$ inside the island W7-X FLM configuration
[A. Könies et al. Nucl. Fusion 2024]

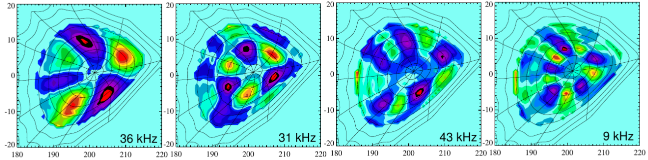
Stellarator Properties - Experiment

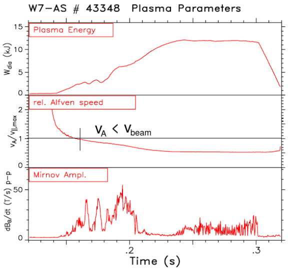
W7-X

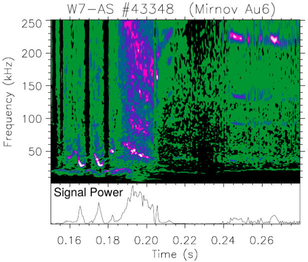
- relatively low fast particle energy and density
  $\Rightarrow$ few observations of fast partice driven modes
- broad band Alfvén mode activity without fast particles is common
- island related mode activity

fast particle driven GAE in W7-AS

#39029

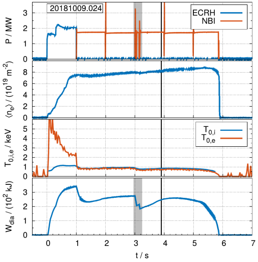






[A. Weller et al. 12th ISHW, Madison 1999]

fast particle driven modes in W7-X

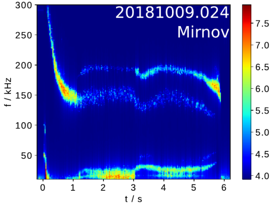


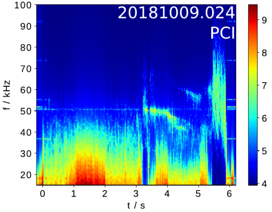
W7-X OP1.2b:

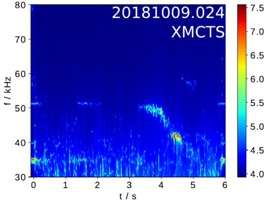
$P = 1.75$MW

NBI driven modes observed

discharge 20181009.024

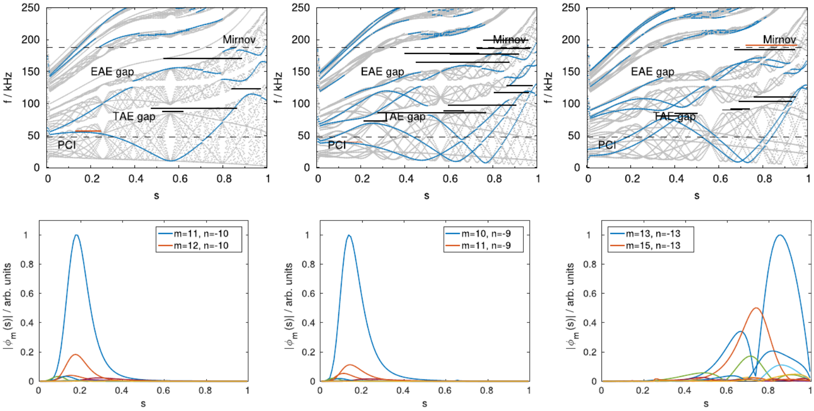






C. Slaby et al. Nucl. Fusion 60, 112004 (2020)

fast particle driven modes in W7-X



fast-ion drive is insufficient to overcome the background-plasma damping (CKA- hybrid model)

C. Slaby et al. Nucl. Fusion 60, 112004 (2020)

EUTERPE development strategy

code development to account for

- MHD stability
- radially extended modes (low mode number GAE)
  $\rightarrow$ allow stable calculation on full radius
- strong bulk damping $\rightarrow$ long time stability

Stellarator Properties

EUTERPE development strategy

EUTERPE application examples

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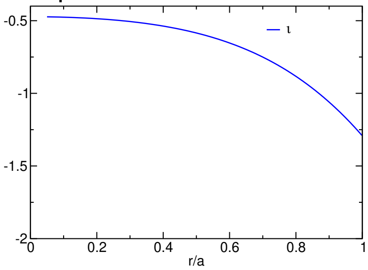
LHD benchmark with GTC and MEGA

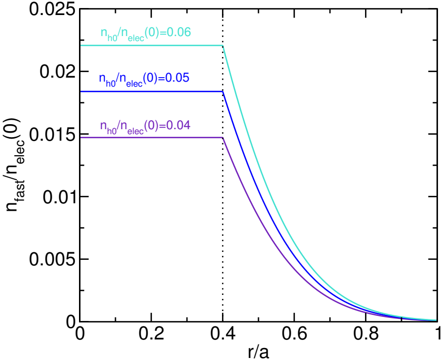
LHD case with $B_0 = 0.619\mathrm{T}$

$T_\mathrm{i} = T_\mathrm{e} = 1\mathrm{keV}, \quad T_\mathrm{fast} = 100\mathrm{keV}, \quad R_0 \approx 3.7\mathrm{m}, \quad N_p = 10$

$< \beta > \approx 3\%, \; \beta_\mathrm{fast}(0) \approx 1.3\%$

iota profile:





comparison GTC vs. MEGA

D. A. Spong et al.,
Nucl. Fusion **57** 086018 (2017)

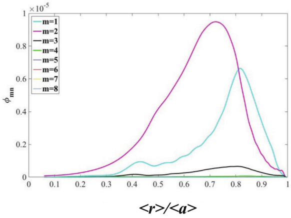
- GTC: 3D EM GK turbulence code
- fluid electron model with $E_{||}$ to lowest order in
- markers are not re-inserted: about 40% fast and 7% of thermal ion markers lost
- Gaussian drop-off the fields for the edge and axis boundary condition
- Fourier mode window $m = 1 \ldots 8$, $n = 1$

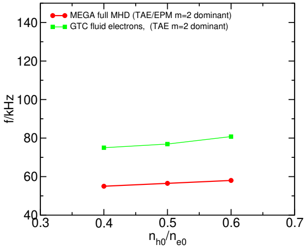
Y. Todo, et al.,
Phys. Plasmas **24**, 081203 (2017)

- MEGA: 3D non-linear resistive MHD code
- +gyro-kinetic fast particles (pressure coupling)
- finite differences, full radius
- numerical resistivity much larger than physical, leads to mode damping

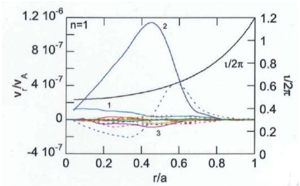
GTC and MEGA results

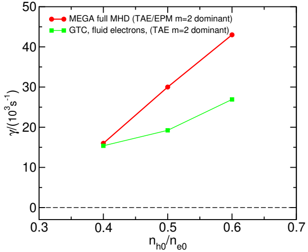
GTC (Spong et al. 2017):



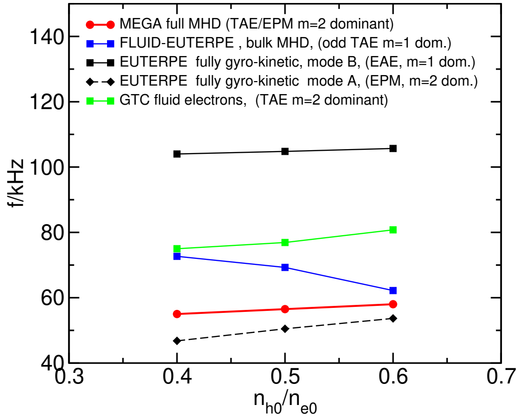


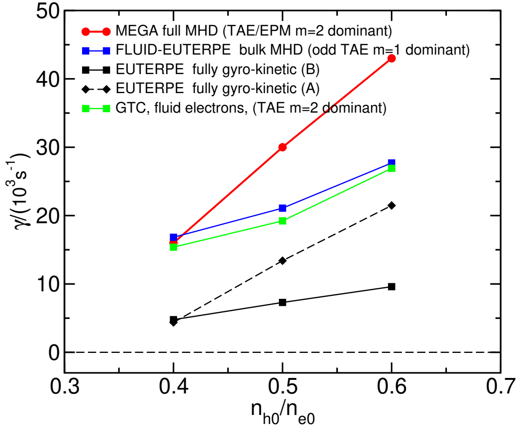
MEGA (Todo et al. 2017):



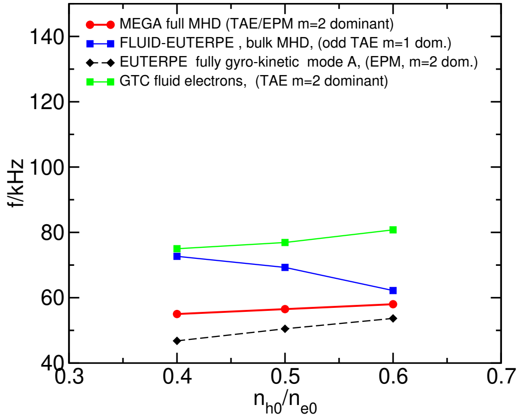


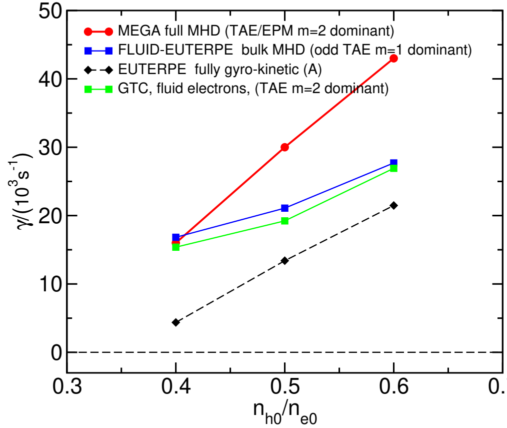
EUTERPE gyro-kinetic results



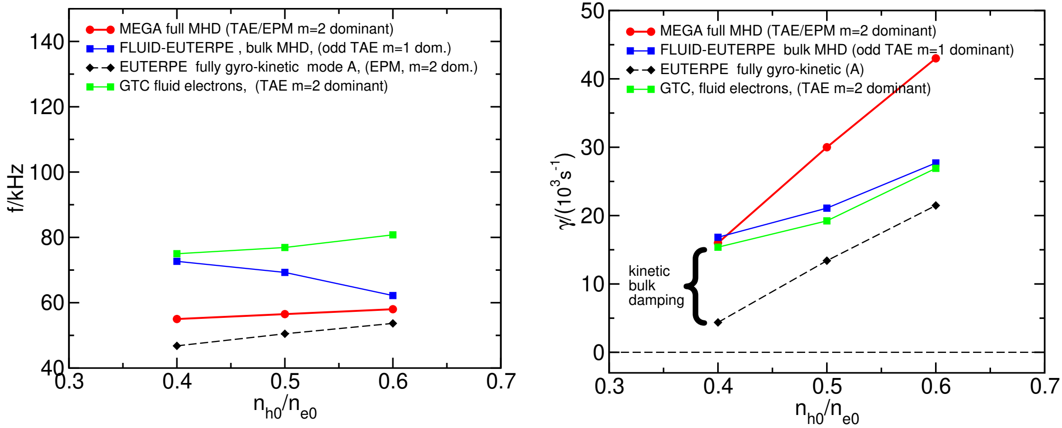


EUTERPE gyro-kinetic results





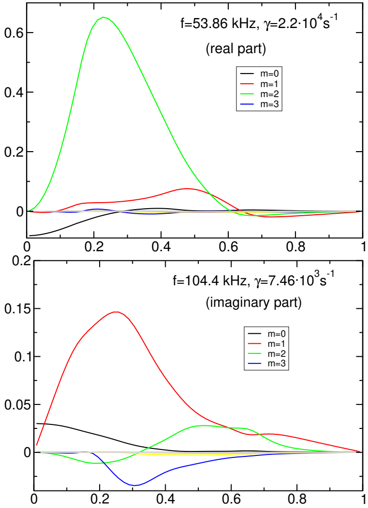
EUTERPE gyro-kinetic results



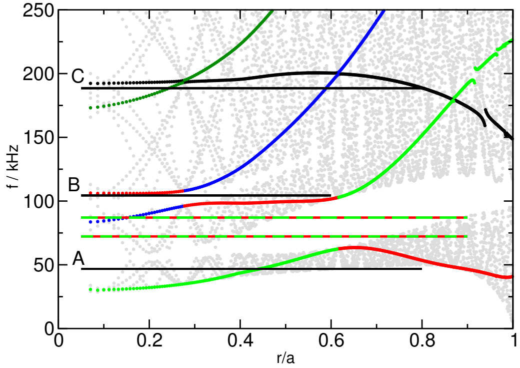
EUTERPE: mode structure gyro-kinetic

EPM

EAE



Continuuos spectra and mode location



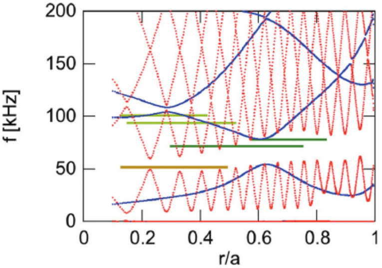


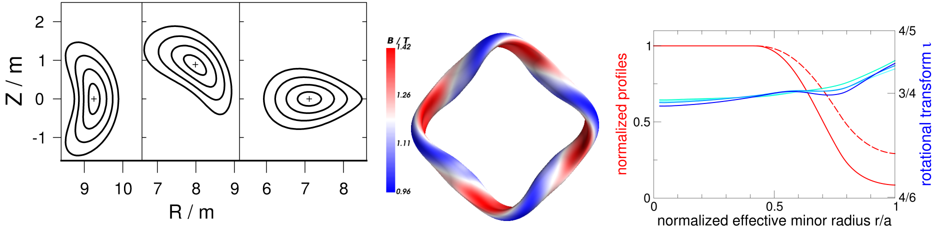
FIG. 5. Alfvén continuous spectra of the toroidal mode number (a) $n=1$ (blue) and (b) $n=11$ (red). The frequency and the spatial location of each AE with frequency $f=52$, 72, 78, 94, 101 kHz are shown with a horizontal line.

CONTI

STELLGAP

with slow sound approximation

Three- dimensional full- torus electromagnetic simulations

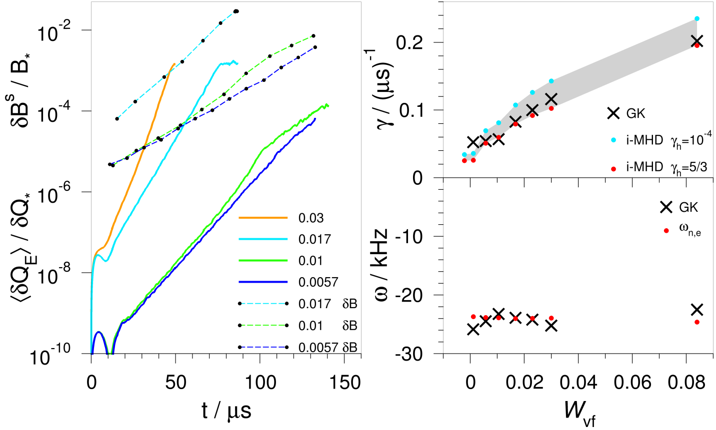


4-period HELIAS [Nuehrenberg1986] stellarator, *B* on plasma boundary, temperature and density (red dashed), pressure (red solid), rotational transform (blueish).

- non-linear, electromagnetic simulations using EUTERPE, shifted electron equilibrium Maxwellian
- markers: 150 (300) mio. ions (electrons); physical mass ratio
- device-periodicity-breaking perturbations on the full torus
- full plasma radius;
- equilibrium on 128x128x512 grid (radial, poloidal, toroidal)

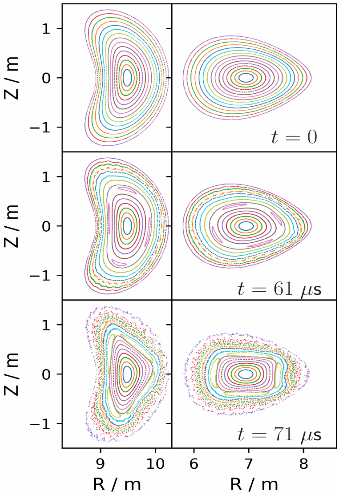
[C. Nührenberg et al., JPP 2025]

Gyrokinetic simulations – Agreement with ideal MHD



Sequence of HELIAS equilibria with variation of the vacuum-field magnetic anti-well, $\mathcal{W}_{vf}$, at fixed $\langle\beta\rangle = 0.02$. [C. Nührenberg et al., JPP 2025]

Three- dimensional full- torus electromagnetic simulations



Field-line tracing in GK perturbed magnetic field of HELIAS stellarator with vacuum-field magnetic anti-well 0.017 and $\langle\beta\rangle = 0.02$.

growth rate in linear phase

$\gamma = 0.09/\mu$s

$\omega = -24.4$ kHz

fully developed linear phase

$\delta B/B_0 \approx 3.4 \cdot 10^{-3}$

evolution of $m = 4$ island

early non-linear phase

$\delta B/B_0 \approx 1.1 \cdot 10^{-2}$

island and ergodization

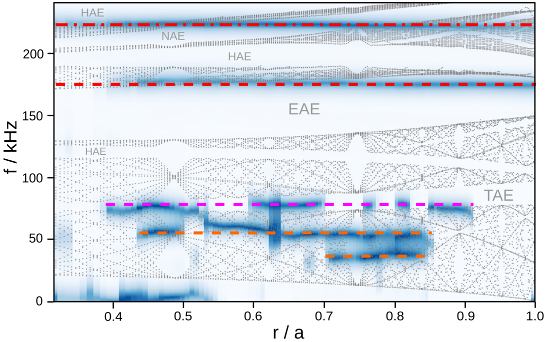
[C. Nührenberg et al., JPP 2025

]

Alfvénic Modes and Electromagnetic Turbulence in Wendelstein 7-X

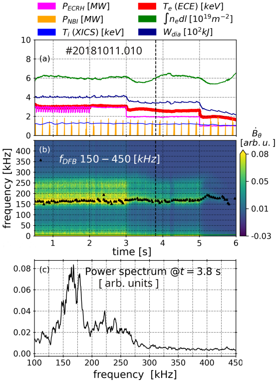
- global electromagnetic gyrokinetic simulation using particle-in-cell code EUTERPE [Kleiber et al. JPC 2024, Riemann et al. PRL 2025]
- W7-X high-mirror magnetic configuration, equilibrium pressure closely matching experimental conditions
- up-scaling of the temperatures to shift the ITG mode activity to lower Fourier mode numbers
  (along with down-scaling of density to maintain pressure)
- radial annulus ($0.32 \leq r/a \leq 1.0$) with $128 \times 768 \times 128$ grid points (radial, poloidal and toroidal direction) modelling one of five field periods of W7-X
- Fourier diagonal filter aligned with the rotational transform, with 92 poloidal and 75 toroidal modes (resolving scales up to $k_\perp \rho_i \approx 0.67$)
- $5 \cdot 10^8$ hydrogen and $7.5 \cdot 10^8$ electron markers

Alfvénic Modes and Electromagnetic Turbulence contd.



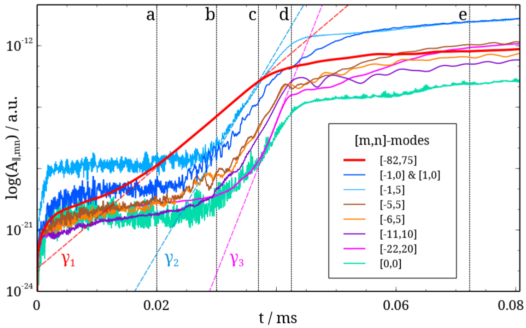
Spectrogram (blue) taking into account modes with $|m| = 1, 5, 6, 11,$

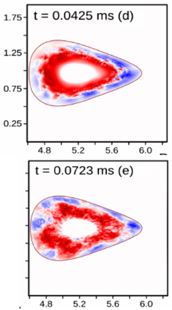
[Riemann et al. PRL 2025]



(a) Plasma parameters for the W7-X experimental discharge #20181011.010.
(b) Spectrogram of $\dot{B}_\theta$ signal from Mirnov coil central frequency $f_{\mathrm{DFB}}(t)$ of the DFB (black triangles)
(c) The power spectrum for the Mirnov coil signal in (b) at $t = 3.8 - 3.803$ s (courtesy S. Mendes [Vaz Mendes et al. PoP 2023]).

Alfvénic Modes and Electromagnetic Turbulence contd.





- no drive if ITG are filtered out
- distinct ratio of $\gamma_1 : \gamma_2 : \gamma_3 = 1 : 2 : 3$
- seems to resemble mechanism of "forced-driven" zonal flows [Qiu 2016]

[Riemann et al. PRL 2025]

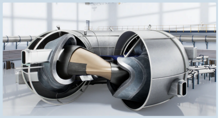
Ongoing activities – W7-X

small fast particle drive

- small (detached) plasmas
- start-up plasmas with very low density
- low-field, high-performance discharges (NBI drive only)

Ongoing activities – Reactor related

- cooperation mit Proxima Fusion on their "Alpha" ($Q = 1$) project



- own reactor stability study in preparation, concept not yet decided
  rather SQuID [Goodman et al. PRXEnergy 2024] than Helias [Nührenberg and Zille, Phys. Lett. A. 1986, Beidler et al. Fus. Technol. 1990]

Conclusions

- code and theory development determined by stellarator properties
  - strong (MHD) mode coupling
  - low shear $\Rightarrow$ radially extended modes
  - almost marginal drive conditions
- successful description of MHD limit and non-linear Alfvén mode drive
- emphasis on reduced models (talk by Christoph Slaby)
- new numerical developments (talk by Ralf Kleiber) allow progress for long-time full radius calculations