INFUSE Workshop, February 27, 2024, PPPL

Hybrid simulation studies in support of FRC experiments at TAE Technologies

E. Belova (PPPL)
S. Dettrick, D. Barnes, S. Krashenninnikov, R. Groenewald,
S. Nicks, C. Lau, A. Necas and the TAE team

OUTLINE

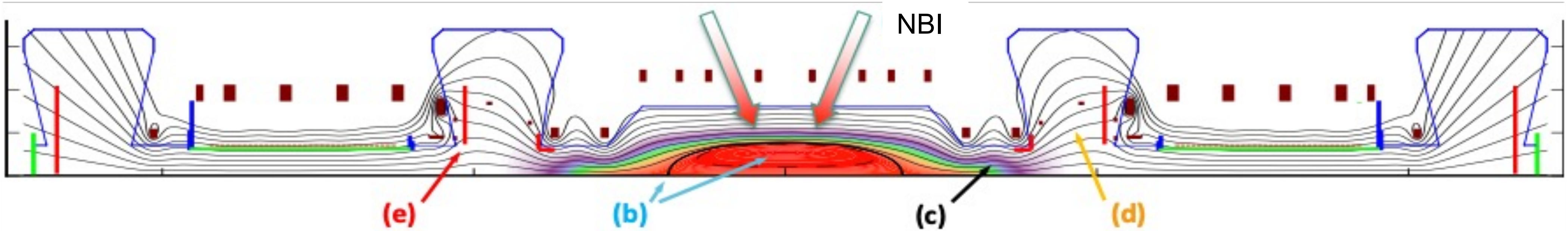
- Description of FRC experiments at TAE Technologies
- Simulation model, linear / nonlinear simulation results
- Linear dispersion relation for compressional modes
- Thermal ion heating
- Code benchmarking
- Summary

Advanced FRC concept at TAE

Steady state field-reversed configuration (FRC) confinement concept:

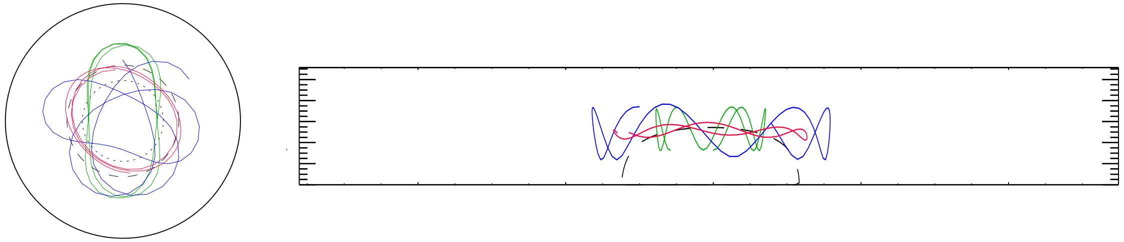
- High power neutral beam injection (stability, current drive and heating)
- Electrode biasing with plasma guns
- Expander divertors

Latest device, C-2W, has exceeded its major performance goals, achieving steady-state (30msec) FRC plasmas with high electron temperature (Te > 400eV).



Sketch of the C-2W device (aka Norman). (c) Magnetic mirror; (d) Magnetic field expander diverter; (e) Red lines indicate electrodes used for biasing.

Need for kinetic simulations for C-2U/C-2W



- Kinetic simulation tools are needed:
  - Large orbit thermal ions, S*≲10
  - Betatron orbit beam ions
- Operation / parameter regime different from conventional FRCs:
  - n=1 tilt mode is stabilized for small S*/E
  - n=2 rotational mode is stabilized due to rotation control by electrode biasing
  - Large fraction of the NBI current (~50%) is generally beneficial for stability in C-2W (reduction in NB power is correlated with uptick in low-n signals)
  - TAE's plasmas exhibit bursts of oscillations associated with fast particles
  - Evidence of (more than expected) transfer of energy from the fast ions to the background plasma
- Need to understand the FRC stability properties and NBI effects theoretically - <u>TAE aims to develop a comprehensive set of validated simulation tools - ***Numerical FRC***</u>

HYM code model / capabilities

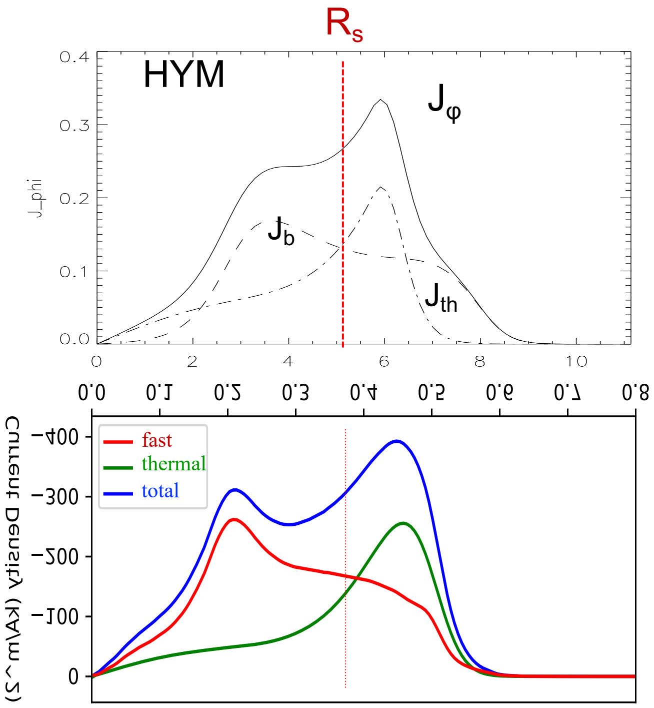
HYM code was developed to study FRC formation and stability properties; adapted to study beam-driven sub-cyclotron Alfven eigenmodes in NSTX(-U) and DIII-D

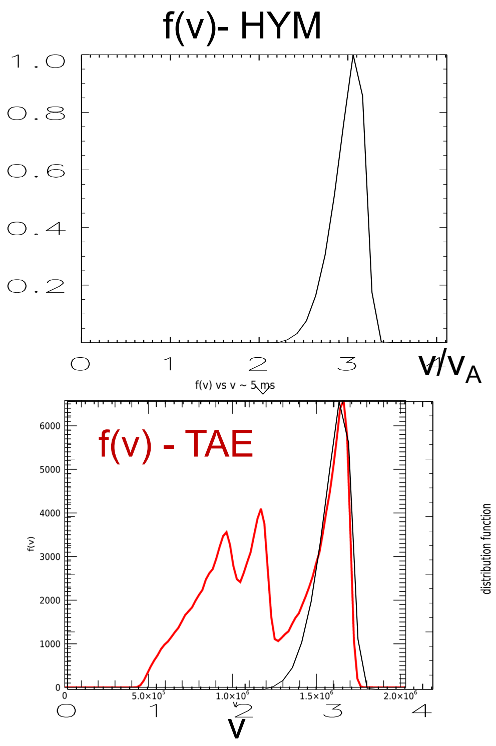
- 3-D nonlinear
- Three different physical models:
  - Resistive MHD & Hall-MHD
  - Hybrid (fluid electrons, particle ions)
  - MHD/particle (one fluid thermal plasma, + energetic particle ions)
- Full-orbit kinetic ions
- For particles: delta-f / full-f numerical scheme
- Parallel (3D domain decomposition, MPI)
- Self-consistent equilibria, including beam ion effects

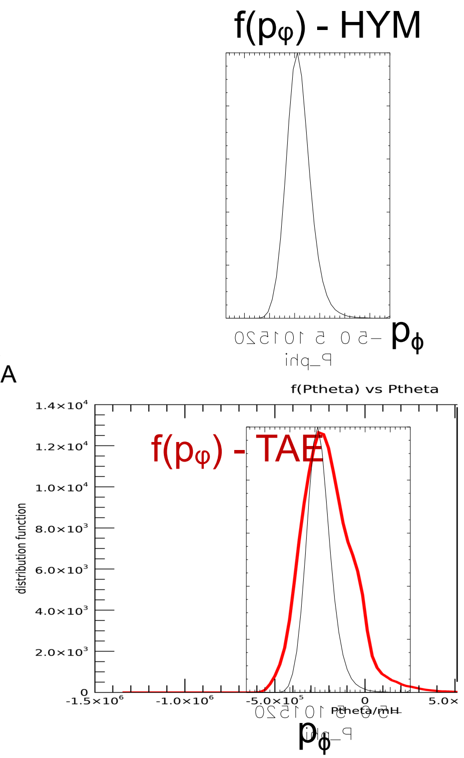
Why INFUSE:

- Numerical tools (HYM) suitable for FRC physics, many options
- PPPL had established collaboration with TAE before start of the INFUSE program
- Cross-code verification: HYM (PPPL) and WarpX, CLAUS (TAE)

Equilibrium fit to TAE profiles







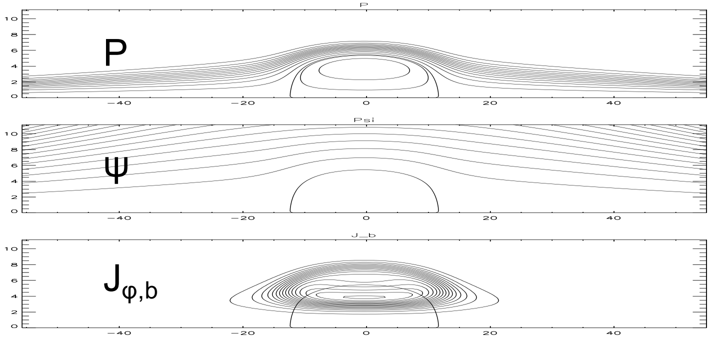
NBI - taking into account only the full energy component or full beam ion distribution

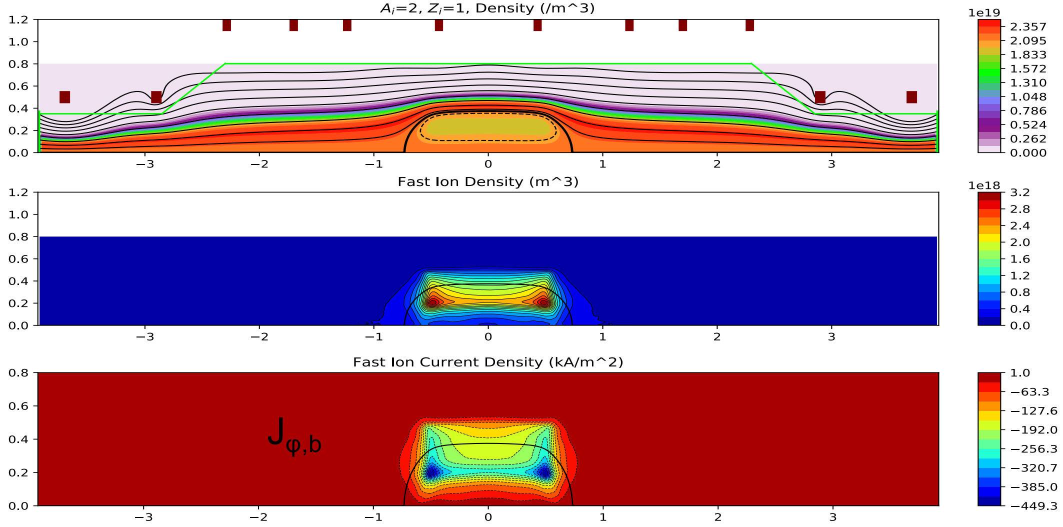
$n_b/n_e=0.08$,

$V_0=3.2V_a$, $\Delta V=V_0/7$

$S^*=5.1$, $I_b/I_{tot}=0.59$

TAE’s FRCs have different stability properties





Previous studies on fast ions: use beams to stabilize the n=1 tilt mode (internal)

- large S*, MHD-like FRC
- large E, for reduced n=1 tilt growth rate

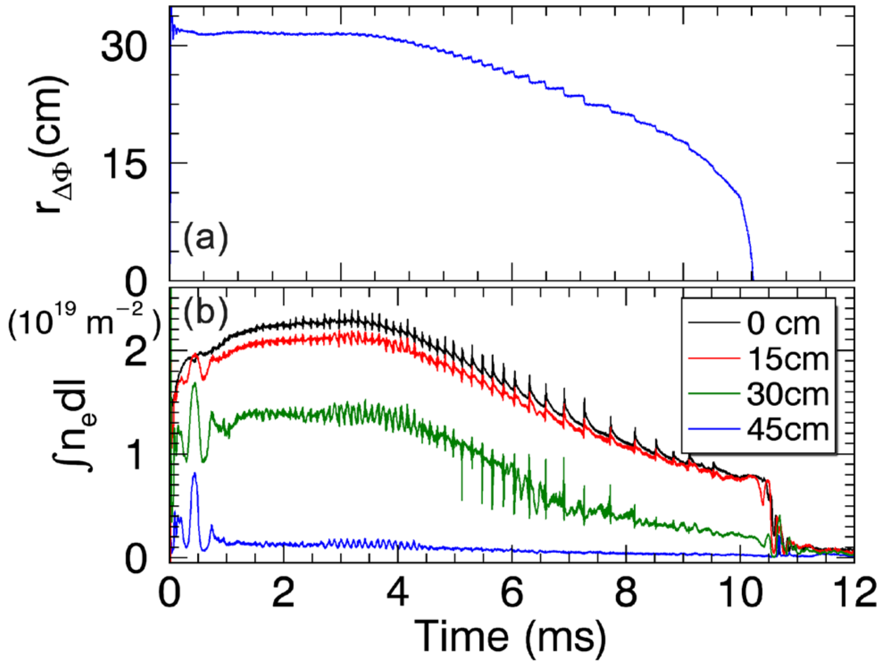
- Generalized energy principle [Lovelace’75, Finn and Sudan’93]:
  - The beam ion contribution is stabilizing provided: $n\Omega > \omega_Z$
- Considered incompressible modes!

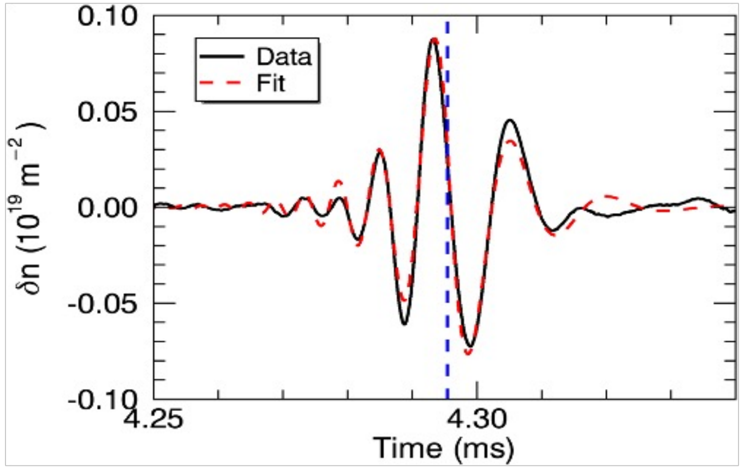
TAE FRC configurations: $n\Omega \sim \omega_R >> \omega_Z$

- n=1 tilt and n=2 rotational modes are stabilized
- Fast ions can interact with low-*n* compressional modes

n=2 microbursts observed in experiments

- n=2 mode with $\omega \approx 0.1\omega_{ci}$ was first observed on the C-2U experiment as a brief, small amplitude “microburst”, accompanied by a minor “staircase” drop in diamagnetic pressure.
- In the C-2W experiment, the same mode is still observed, but at smaller amplitude and with no measurable change in plasma pressure.





(a-b) In C-2U the excluded flux radius shows step drops, correlated with periodic micro-bursts in the FIR interferometer data; (c) Line-integrated density in C-2U showing microburst.

Dispersion relation for 1D FRC

- No significant difference in the properties of these modes in a simplified case of 1D (radial) equilibrium.
- An analytic dispersion relation for 1D cylindrical FRC has been derived.

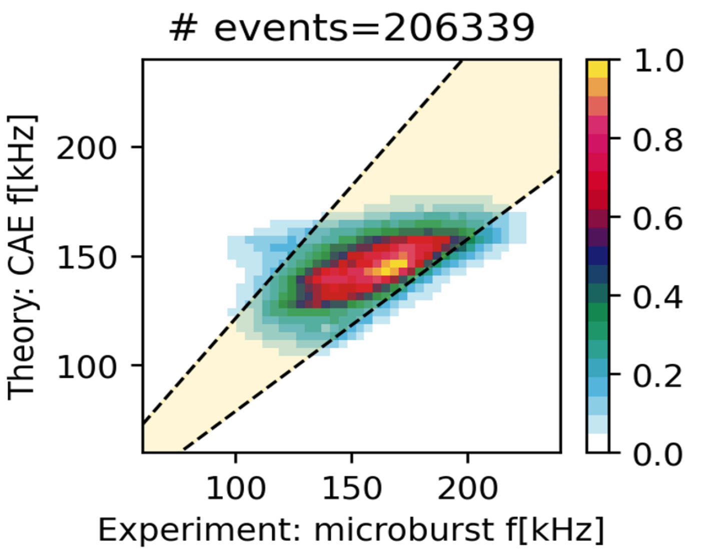
Condition for instability can be derived for 1D equilibrium case as:

$\omega^2 = k^2 v_A^2 \left(1 - \alpha \frac{\bar{\Omega}}{(1-\bar{\Omega}^2)}\right)$, where $\bar{\Omega} = \frac{n\Omega-\omega}{\omega_R}$, and $\alpha = \omega_{ci}/(k_\phi v_A)\, J_b$

For instability $\bar{\Omega} = \frac{n\Omega-\omega}{\omega_R} < 1$ needed

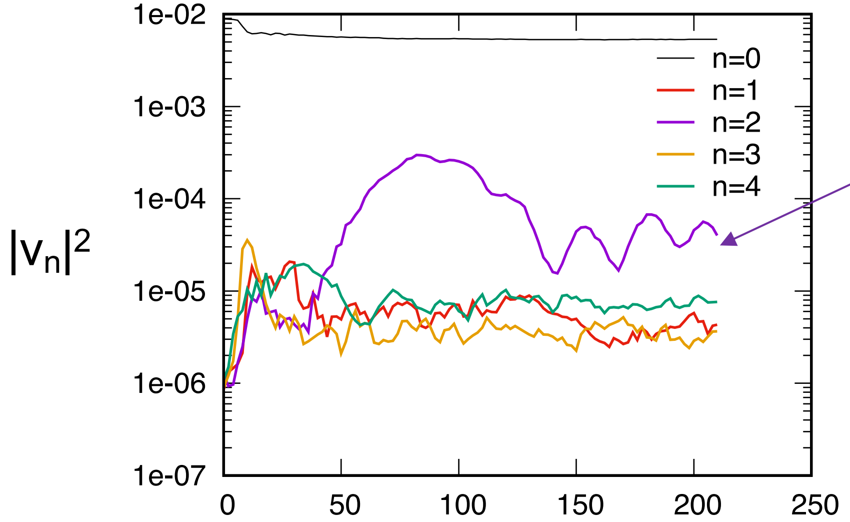
Sufficient condition for stability is $\frac{n\Omega-\omega}{\omega_R} > 1$.

- For TAE parameters, $\Omega/\omega_R \sim 1/2$ and improved stability is predicted for n > 2 modes in agreement with simulations.
- Dispersion relation also predicts stabilization of all low-n compressional modes in larger FRCs due to $\Omega/\omega_R \sim 1/S^*$ scaling



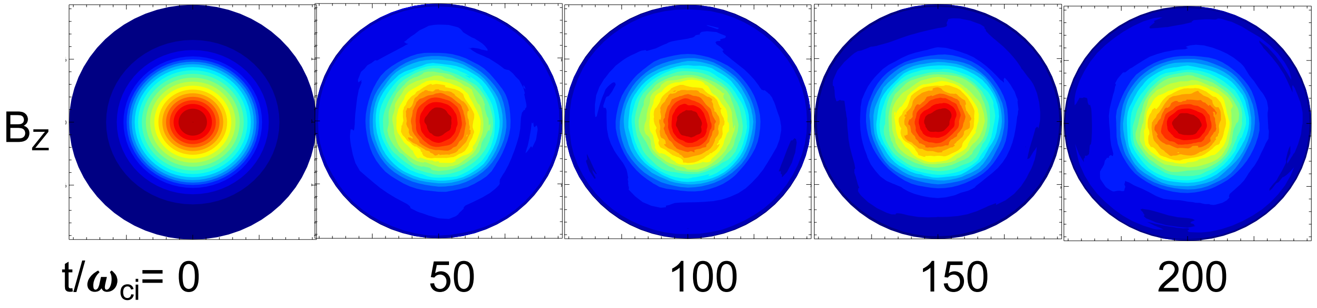
Comparison of experimentally measured microburst frequencies with compressional Alfven eigenmode frequencies calculated using TAE-developed linear eigenvalue solver, CLAUS.

Kinetic thermal ions have stabilizing effect



Nonlinear simulations with kinetic thermal ions, for R_s=3.6, v_0=3.64, n_b=0.12n_e

n=2 saturates at small amplitude for small S* case

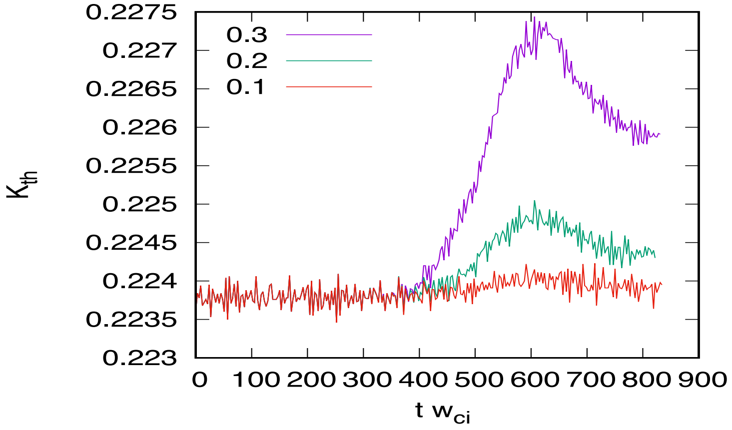


For assumed experimental parameters, profiles and NBI distribution, the nonlinear simulations show strong n=2 instability that either not saturate or saturate via significant beam redistribution – not consistent with experiments.

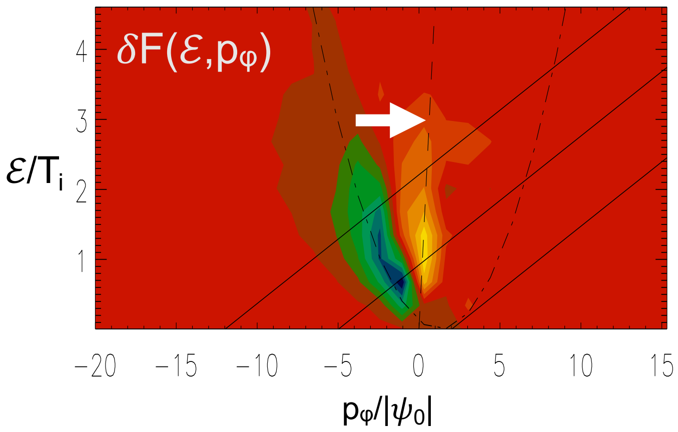
- Uncertainties in equilibrium reconstructions and NBI distribution or approximations in the electrode biasing model may affect stability.

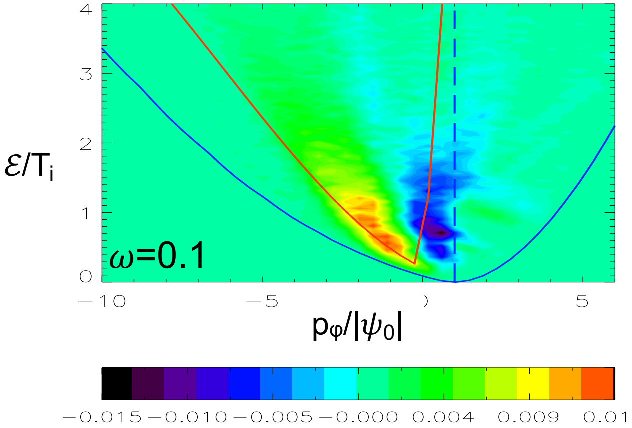
Thermal ion heating by low-n MHD modes

- HYM code was used to study the thermal ion heating by the low-n magnetic perturbations, including the n=0 (magnetic pumping).
- Possibility of the thermal ion heating by the NBI driven modes was investigated, as well as the scaling with the mode frequency and FRC parameters for different thermal ion orbit types.
- Significant thermal ion heating predicted for $\omega > 0.2\text{-}0.3\omega_{ci}$ for typical C-2W parameters.
- Stronger heating, including the lower required perturbation frequencies, was obtained for larger-S* FRCs.



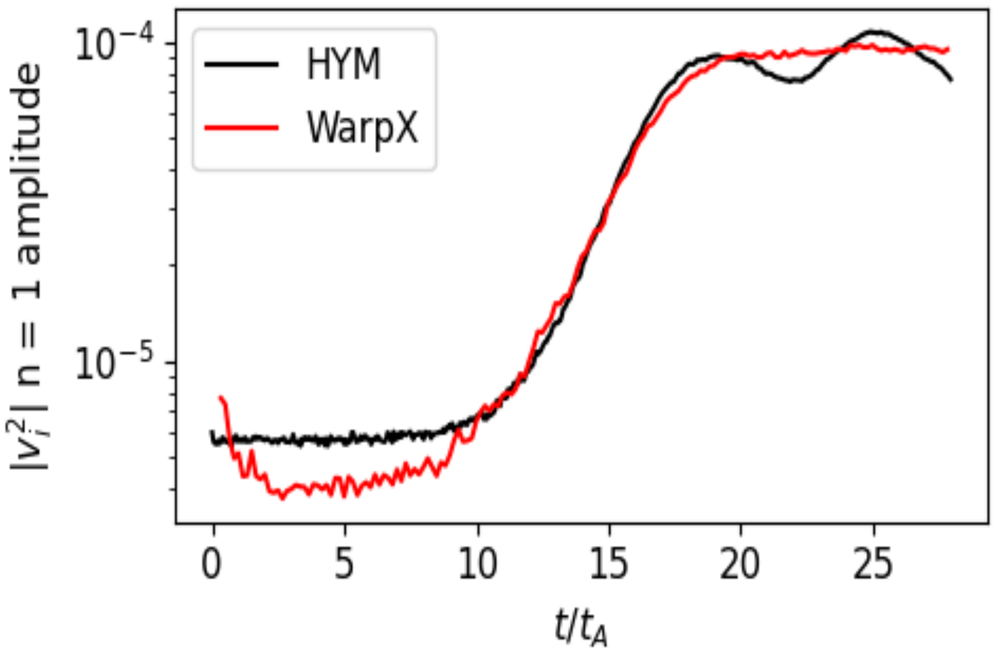
Higher frequencies n=2 modes are more efficient in heating thermal ions





Most effective energy exchange (heating) for figure-8 orbits

Codes benchmarking / verification



Comparison of tilt-mode growth and saturation amplitude as calculated with WarpX and HYM when starting from the same equilibrium (case with no NBI, large S* FRC).

Summary

- HYM (now also WarpX, CLAUS) simulations show that for large beam ion toroidal rotation frequencies low-n compressional modes can be destabilized.
  - Linear dispersion relation for compressional modes explains the linear stability results.
- Additional simulations show that low-n compressional modes can heat thermal ions – can explain higher than expected energy transfer from the fast ions to the background plasma.
- INFUSE project contributed to code verification between 3D nonlinear HYM, WarpX codes and CLAUS – a step towards the TAE goal of *Numerical FRC* development
- INFUSE project contributed to understanding stability properties of FRCs with high NBI power but need to continue validation against experiments: improve equilibrium reconstruction, NBI distribution and / or model improvements.