Nonlinear MHD simulation of core plasma collapse events in stellarators

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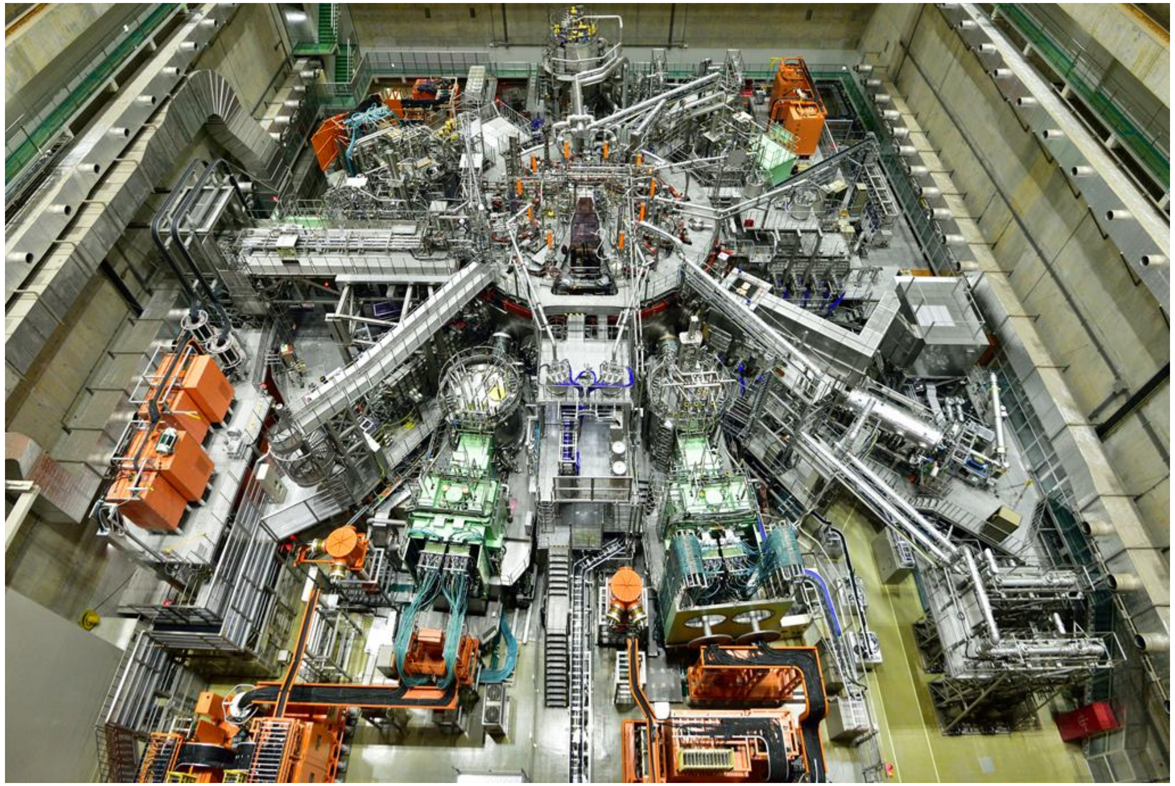
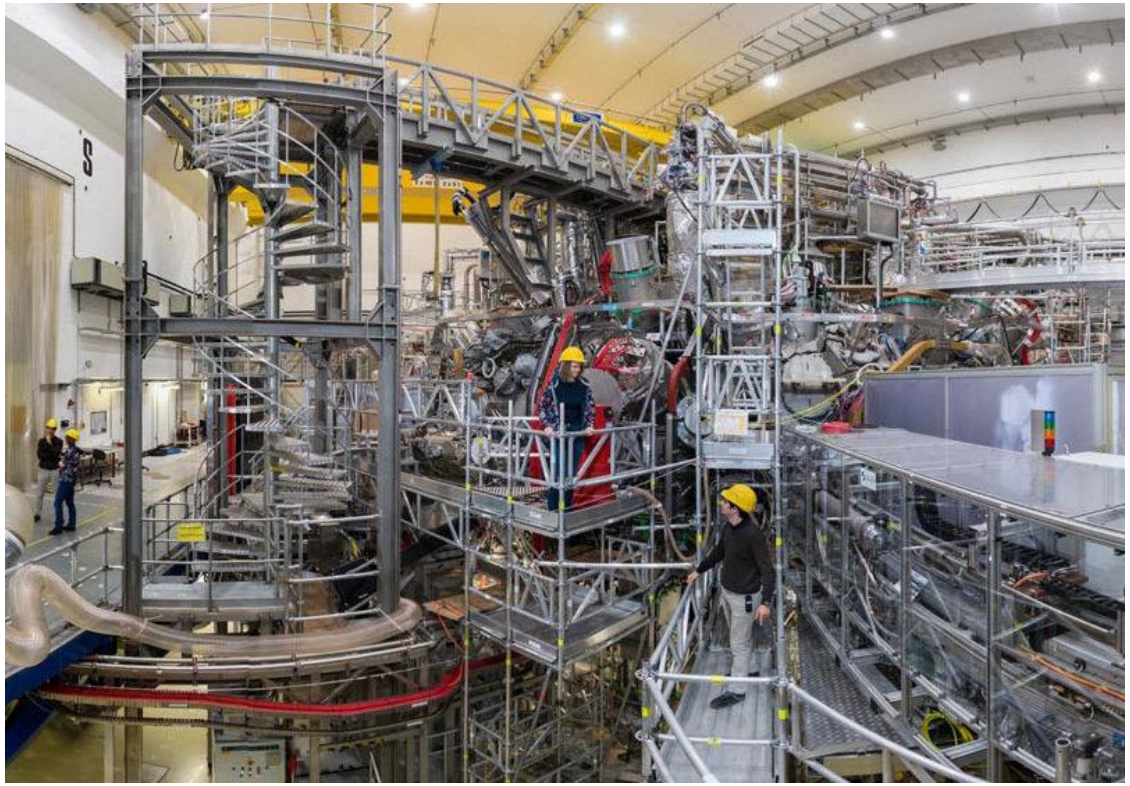
Stellarators are alternatives for steady-state fusion reactor…

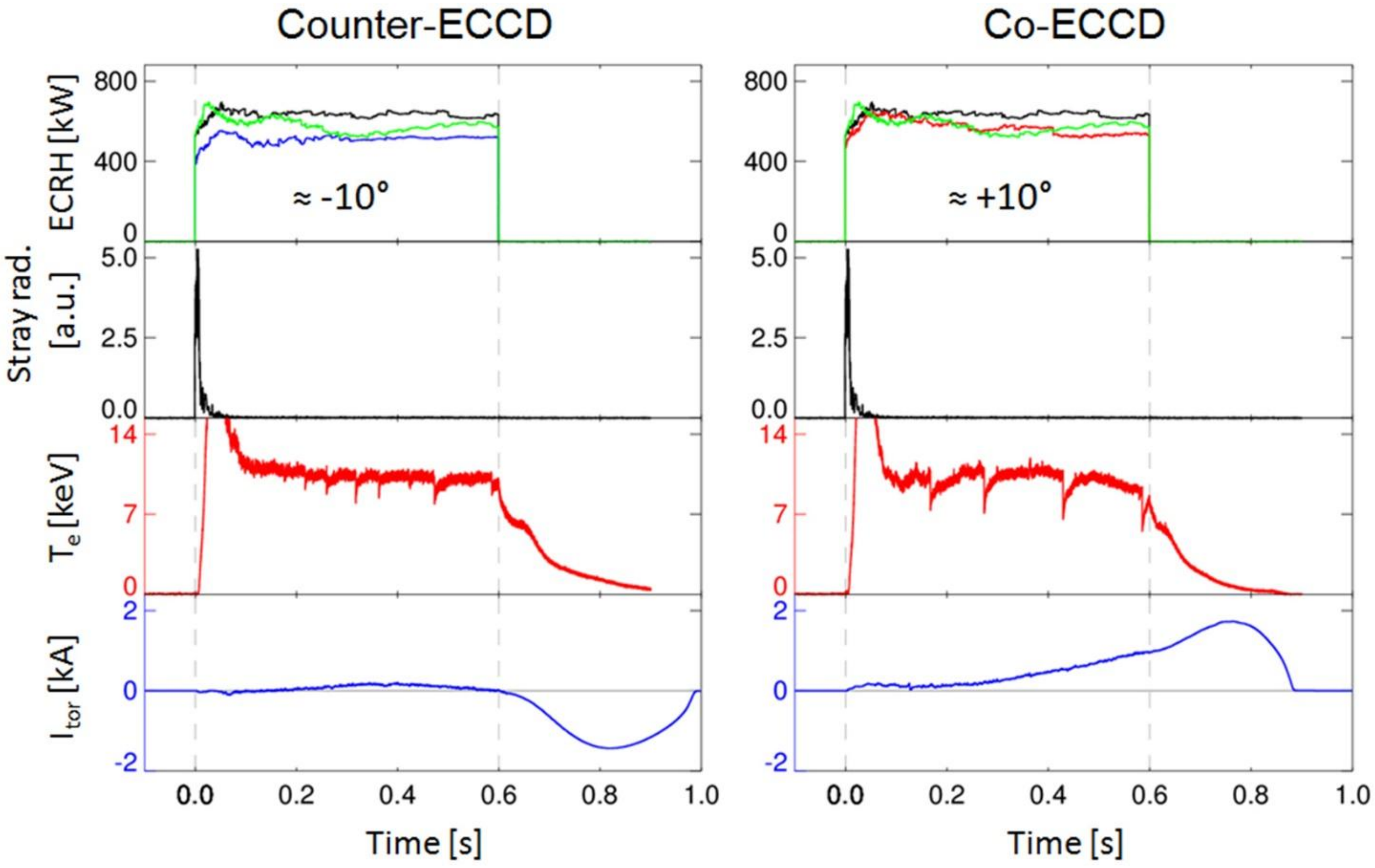
LHD: Large Helical Device (Toki, Japan)



W7-X: Wendelstein 7-X (Greifswald, Germany)



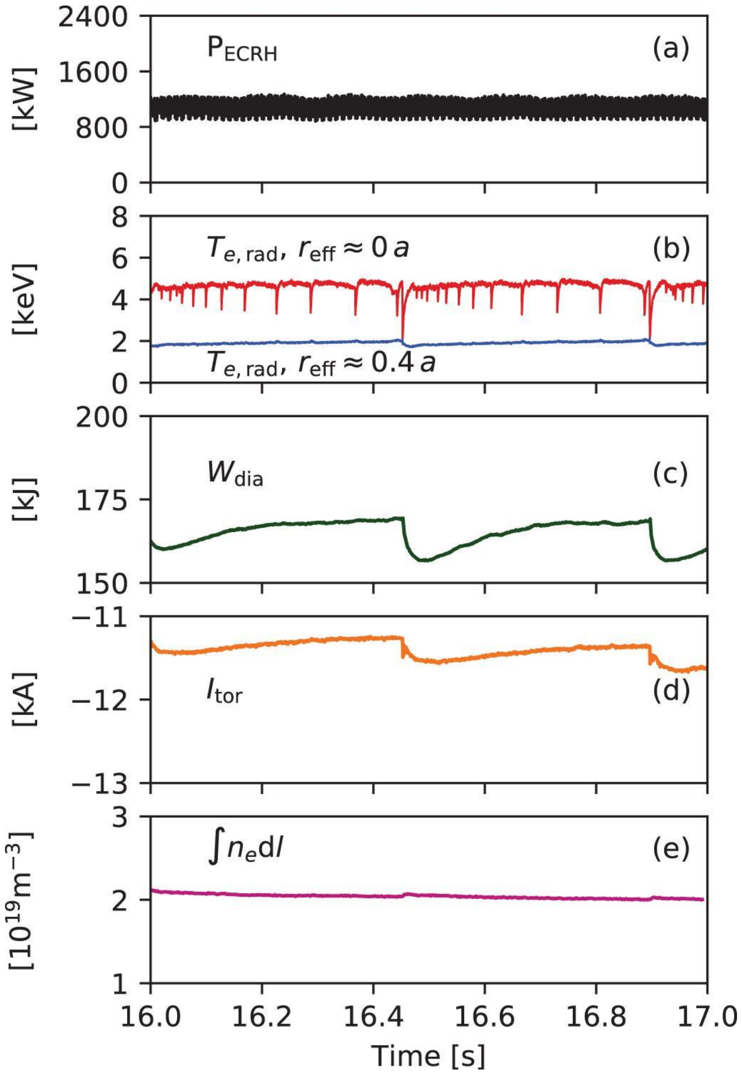
Core temperature crashes were observed in OP1.1 of W7-X experiments

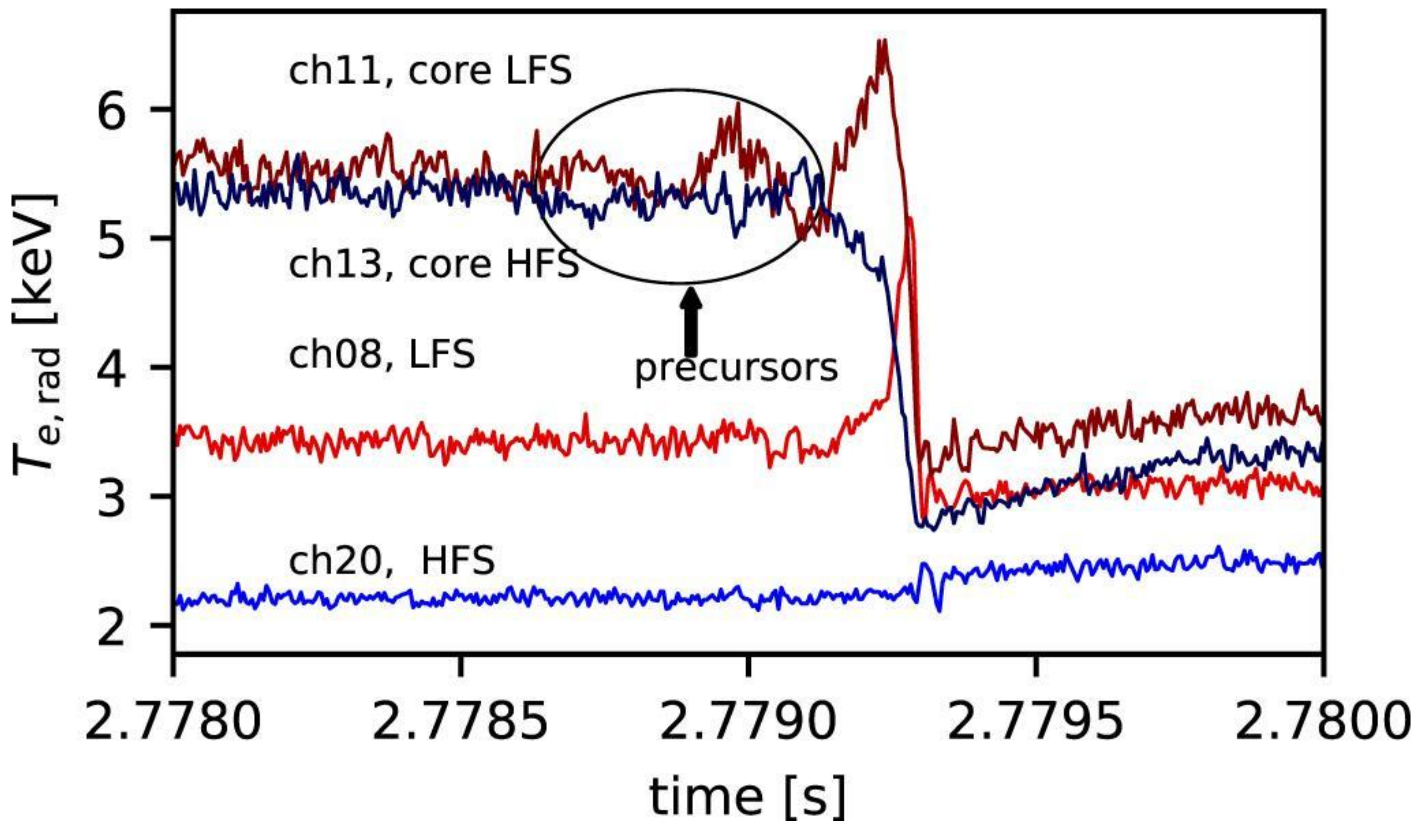


- ECCD current drive are applied.
- For a case of co-ECCD current, crash of core temperature is frequently observed.
- That might be related to the iota profile change in the core by co-ECCD.
- The iota will be crossing the unity.

R.C. Wolf, *et al*., 2017 Nucl. Fusion **57** 102020

ECCD-induced sawtooth-like crashes studied systematically





The temperature does not change in the plasma edge, but the Te in the core sharply drops after the crash.

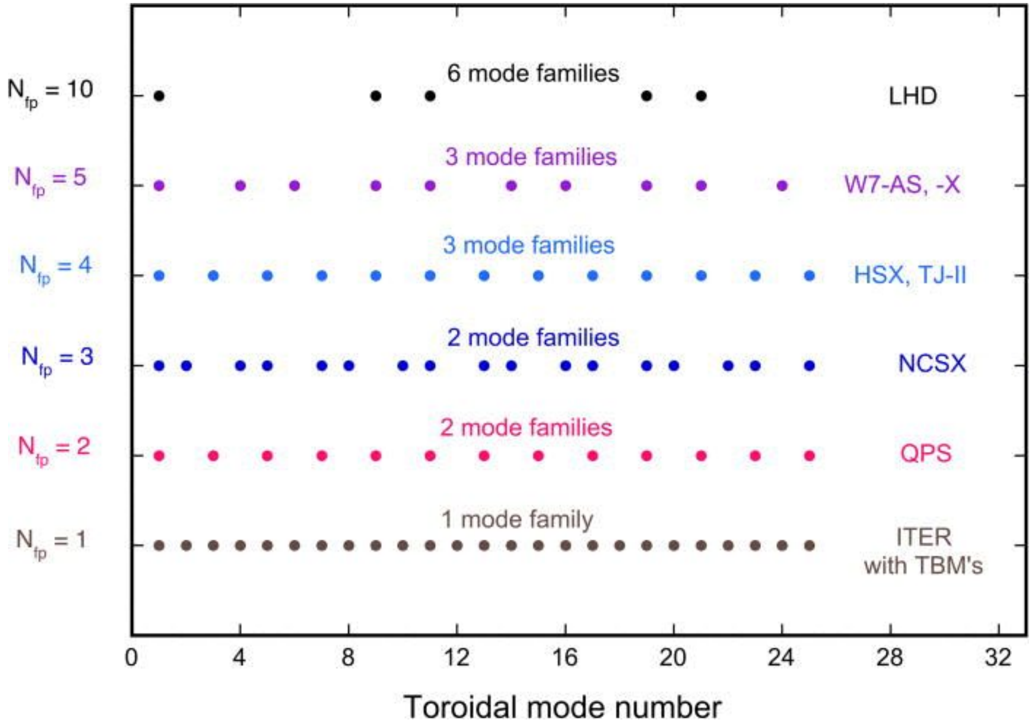
M. Zanini, *et al.*, 2020 Nucl. Fusion **60** 106021

Stellarator study needs "true" 3D code

3D (perturbed) tokamak ≠ stellarator

Toroidal mode coupling with "3D" equilibrium is important for stellarator: $n = \pm k N_{fp}$. N_{fp} is toroidal field periodicity.

Ex: $N_{fp} = 1$ mode family



- Usual tokamak codes are initialized by 2D equilibrium $(n = 0)$.
- Equilibrium and instability decouple. This allows "independent" mode analysis, in particular, linear mode analysis.
- Also, for tokamak (2D system), flux surface function, ψ, can be defined. This allows the "reduced model" can be used.

In many tokamak codes, 2D FEM + Fourier expansion method is widely adopted.

- **However, for stellarator (general 3D configuration), the full 3D equations must be solved.**

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Extended MHD model in MIPS code: Hazeltine-Meiss

Hazeltine (1992)

$$\begin{cases} \mathbf{v} = \mathbf{v}_E + \mathbf{v}_{\|,i} \\ \mathbf{v}_i = \mathbf{v} + \mathbf{v}_i^\star \end{cases}$$

$$\begin{cases} \partial_t \rho + \nabla\cdot(\rho\mathbf{v} + \cancel{\rho\mathbf{v}_i^\star}) = \cancel{S_\rho} + \nabla\cdot(D\nabla\rho) \\ \rho\left(\partial_t\mathbf{v} + \mathbf{v}\cdot\nabla\mathbf{v} + \cancel{\mathbf{v}_i^\star\cdot\nabla\mathbf{v}_\perp}\right) = \mathbf{J}\times\mathbf{B} - \nabla p + \nu\nabla^2\mathbf{v} \\ \partial_t p_s + \mathbf{v}\cdot\nabla p + \Gamma p\nabla\cdot\mathbf{v} = \cancel{S_p} + \nabla\cdot(\chi_\perp\nabla p) \\ \partial_t\mathbf{B} = -\nabla\times\mathbf{E} \\ \mathbf{E} + \mathbf{v}\times\mathbf{B} = \eta\mathbf{J} \end{cases}$$

$$\mathbf{v}_i^\star = d_i\frac{\mathbf{B}\times\nabla p_i}{\rho B^2}$$

$$d_i = K/\sqrt{n_0}$$

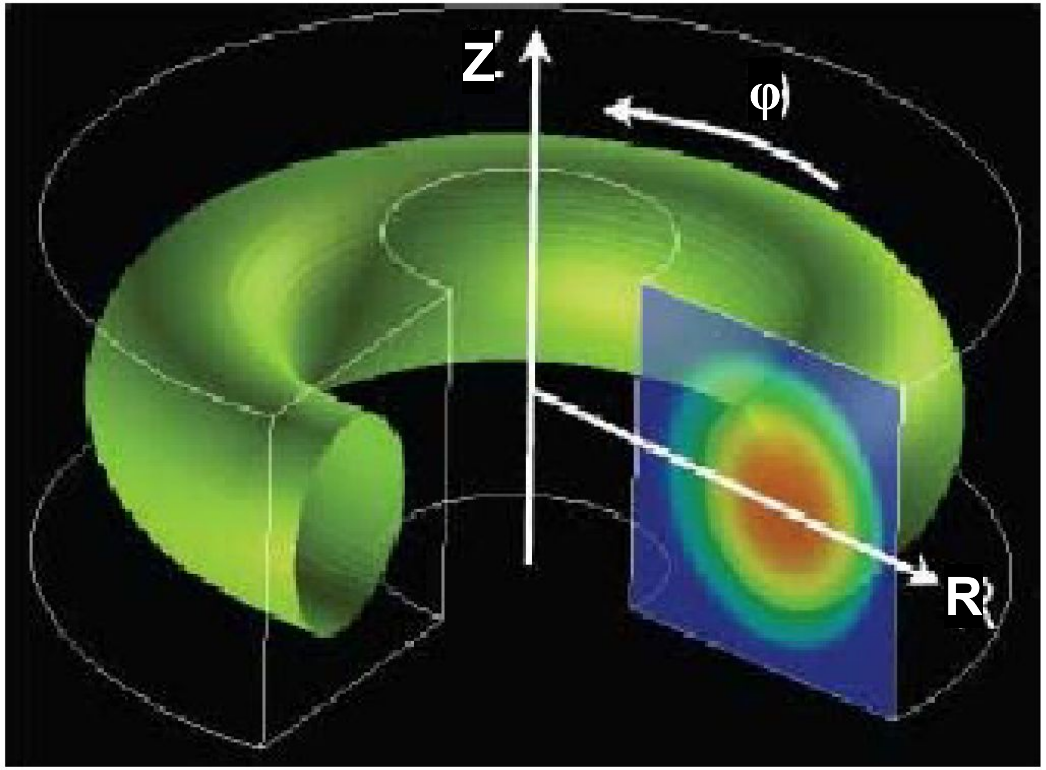
- d_i is the normalized ion skin depth

In this study, followings were assumed;

1. No source terms
2. No extended terms
3. Dissipations are fixed in time and space
4. Fixe boundary condition
5. Initialized by 3D equilibrium from HINT code

3D nonlinear extended MHD code: MIPS

MIPS: MHD Infrastructure for Plasma Simulation



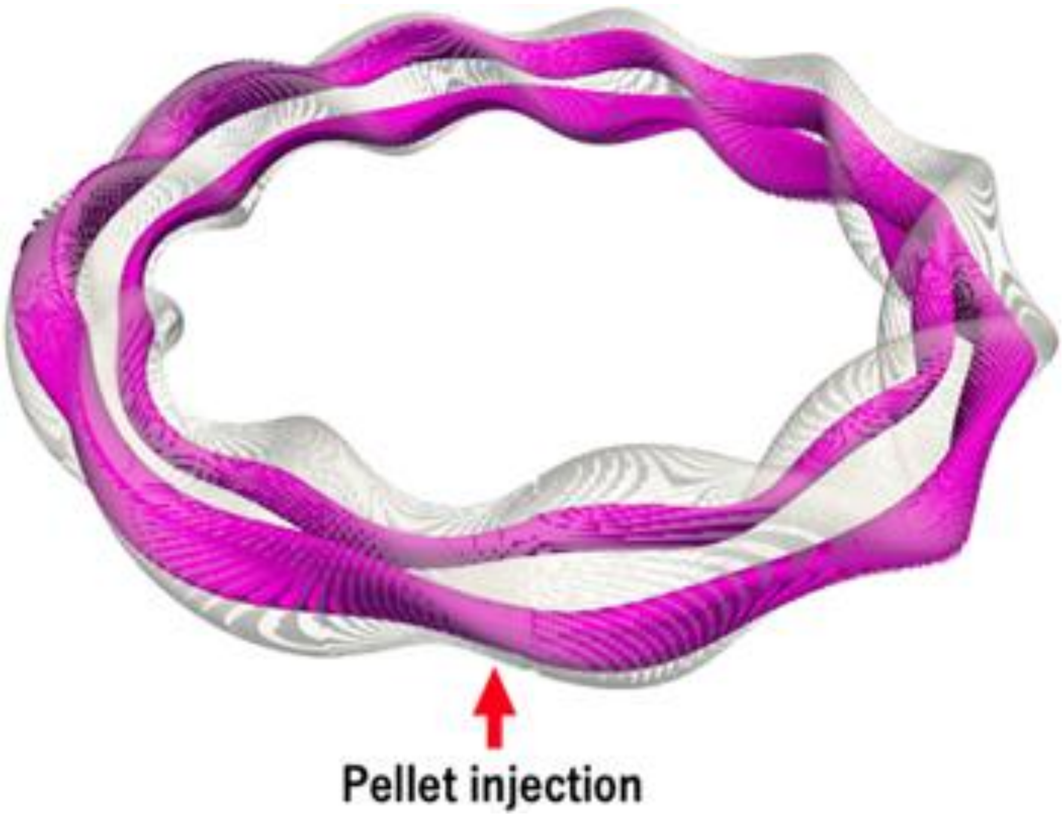
[Mizuguchi 2012]

- 4^{th} order finite difference
- 4^{th} order Runge-Kutta method for time integration
- Grid points on the cylindrical coordinates (R, ϕ, Z).

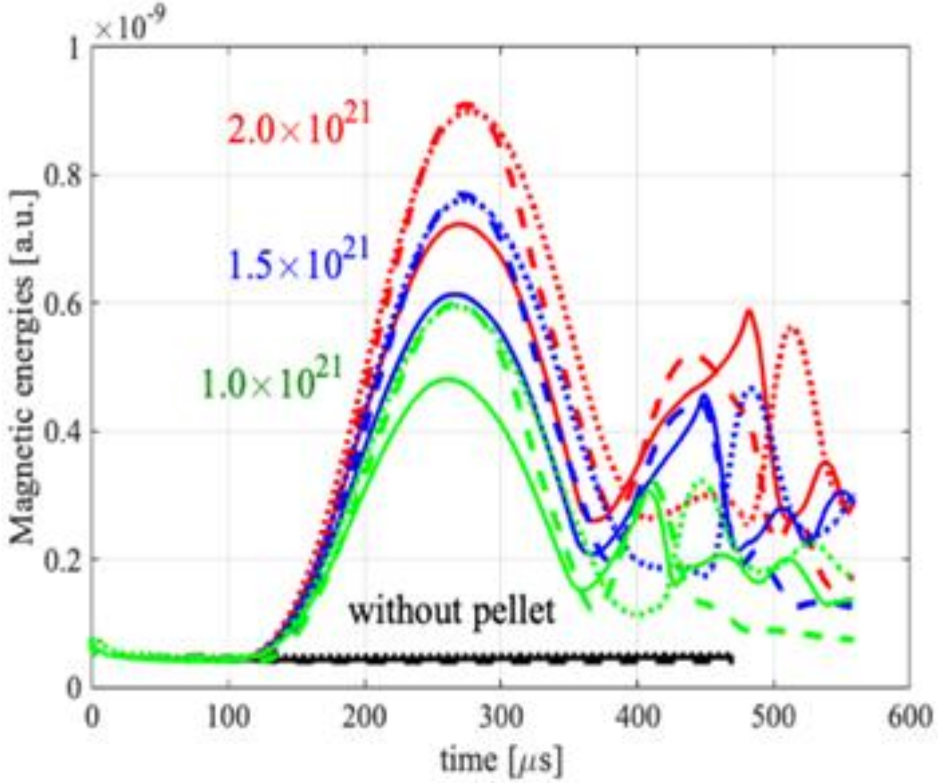
Small time steps and fine grid spacing are necessary, but the code is very robust and fast.

MIPS code successful applied nonlinear MHD studies for LHD plasmas

Pellet cloud in LHD plasma



Nonlinear evolution of magnetic energy

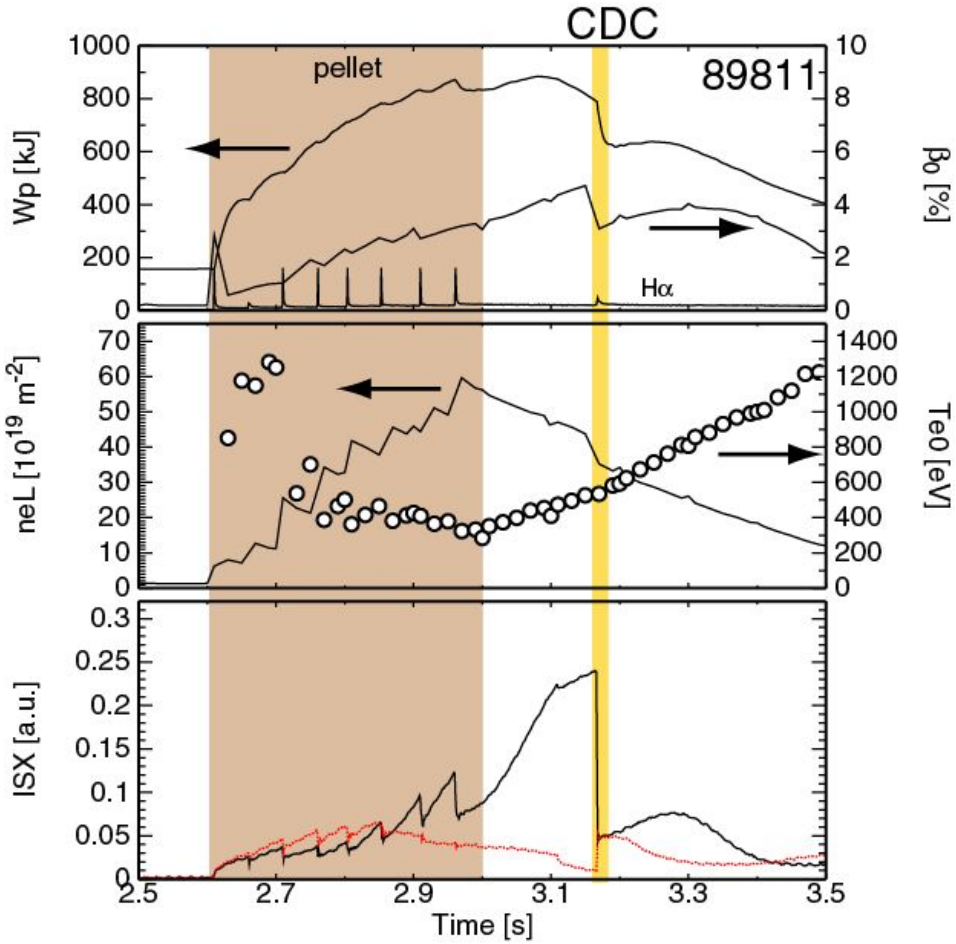


Ice pellets excite nonlinear MHD

Shimpei Futatani and Yasuhiro Suzuki 2019 Plasma Phys. Control. Fusion **61** 095014

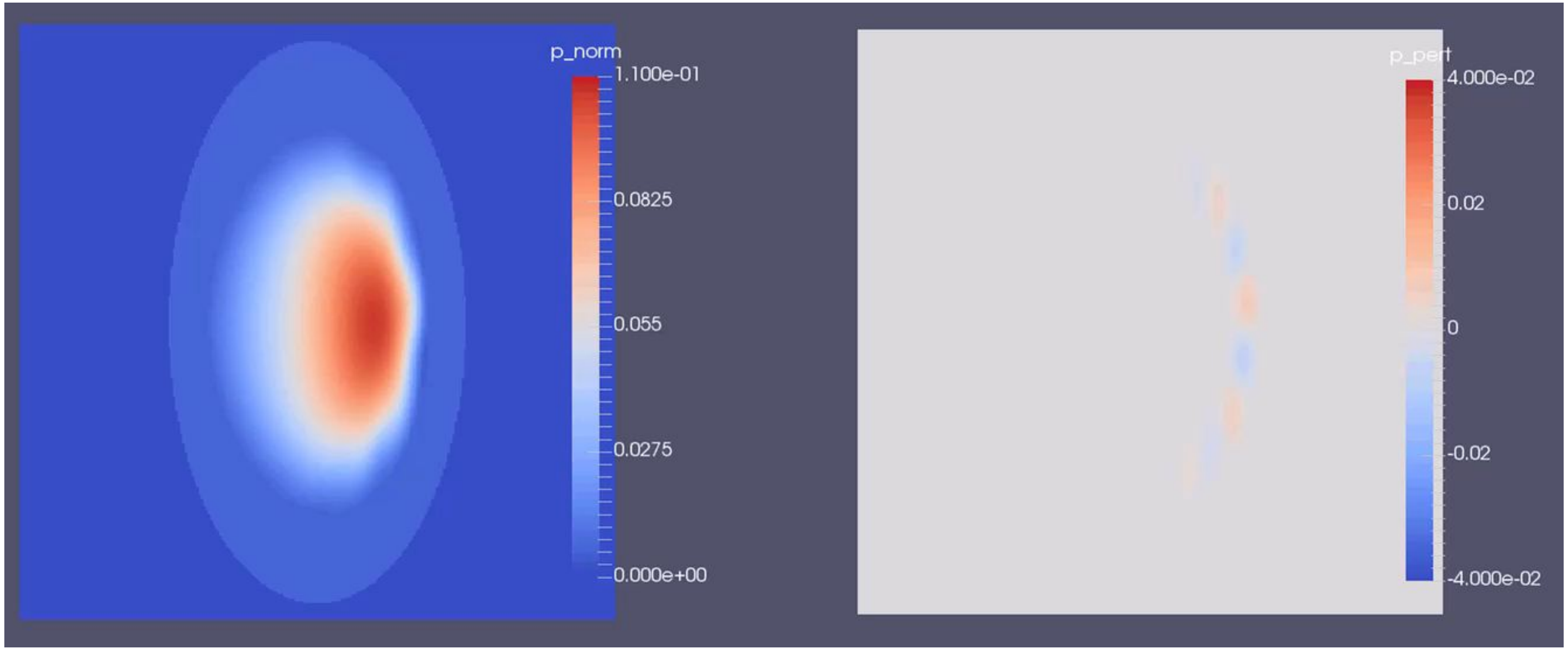
IDB/SDC discharge with CDC

- A peaked profile is formed in the recovery phase after sequentially injected hydrogen pellets. In this recovery phase, the pressure profile becomes peaked; **IDB/SDC** plasma is formed.
- Increase of the β_0 is disturbed by so-called core density collapse(**CDC**) events. CDC is an abrupt event where the core density is collapsed within **1 ms**. (much faster than other MHD relaxation events in the LHD)
- CDC is the first phenomenon that MHD activities are so large that operation is restricted by them.



Nonlinear simulation results

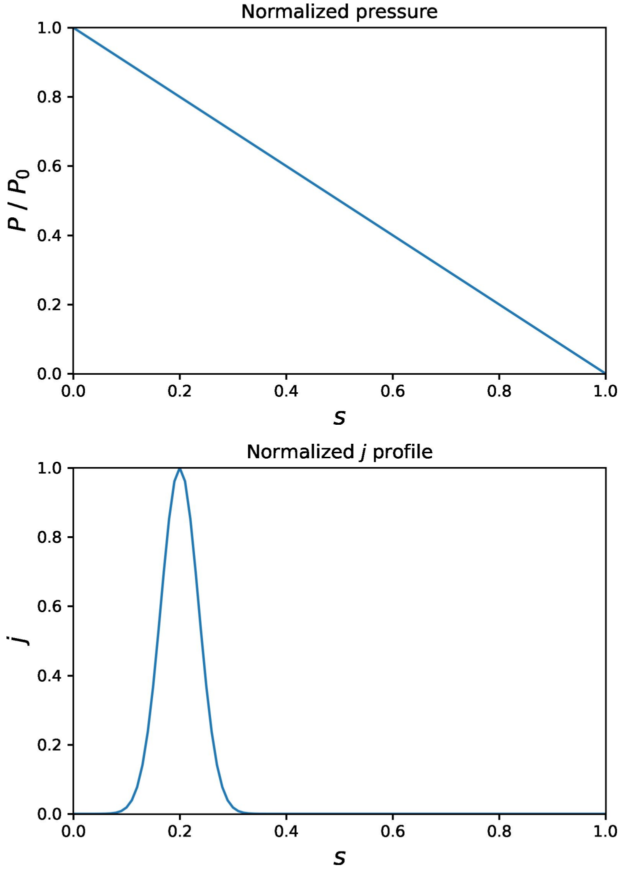
Pressure **Perturbed pressure**



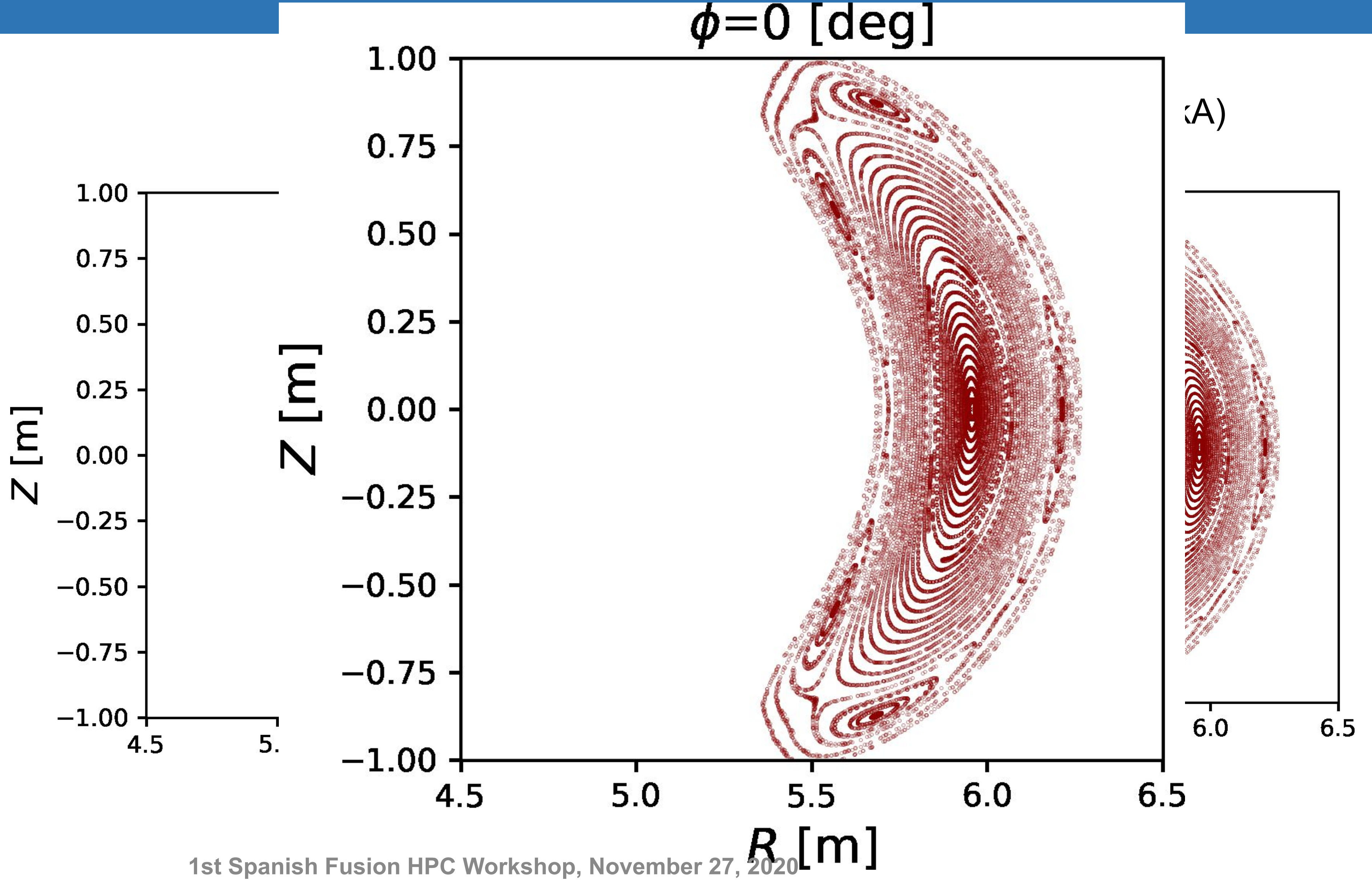
Nonlinear simulation well reproduce collapse event.

MIPS code is initialized by HINT 3D equilibrium code

Assumed profiles



$$s = \rho^2$$



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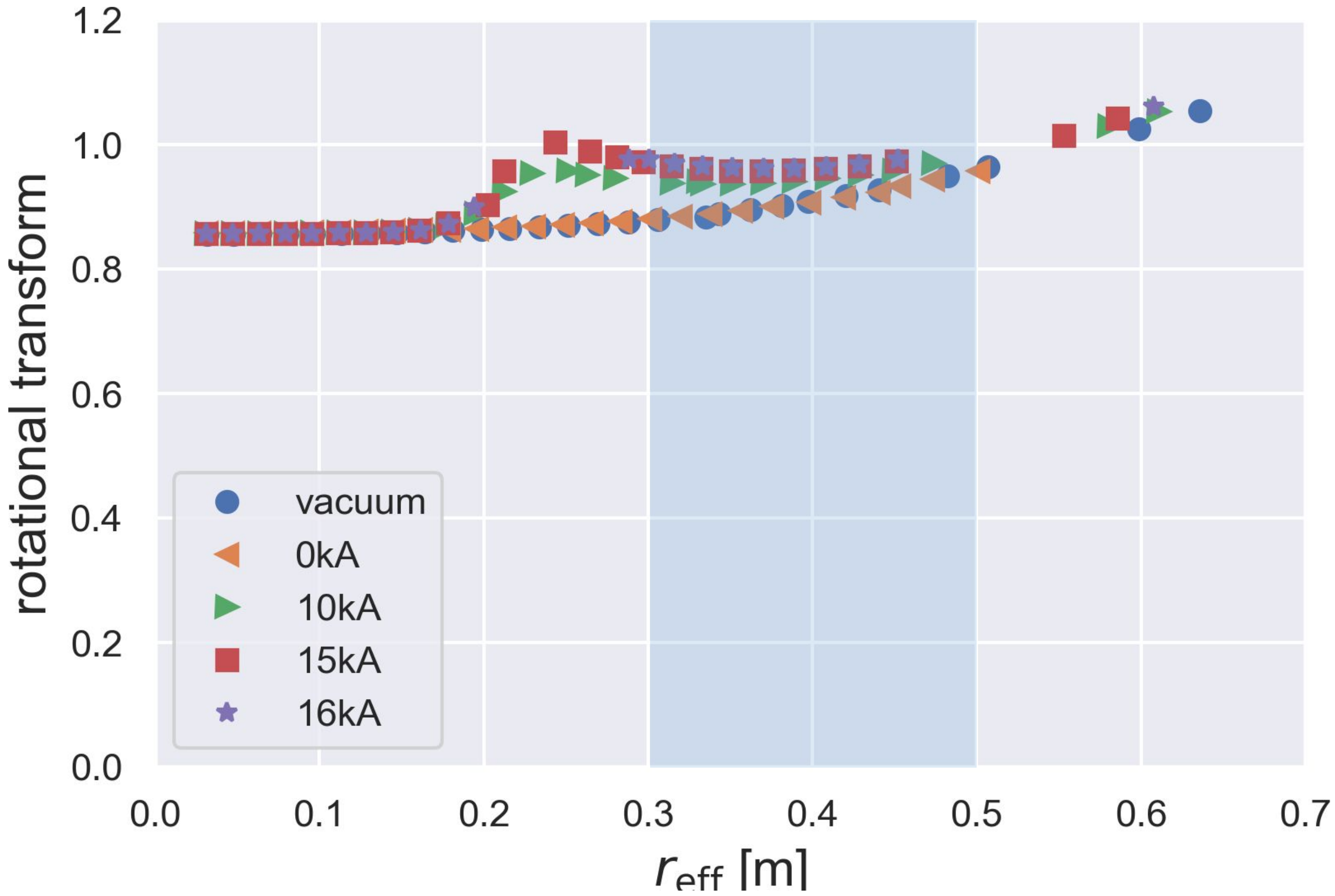
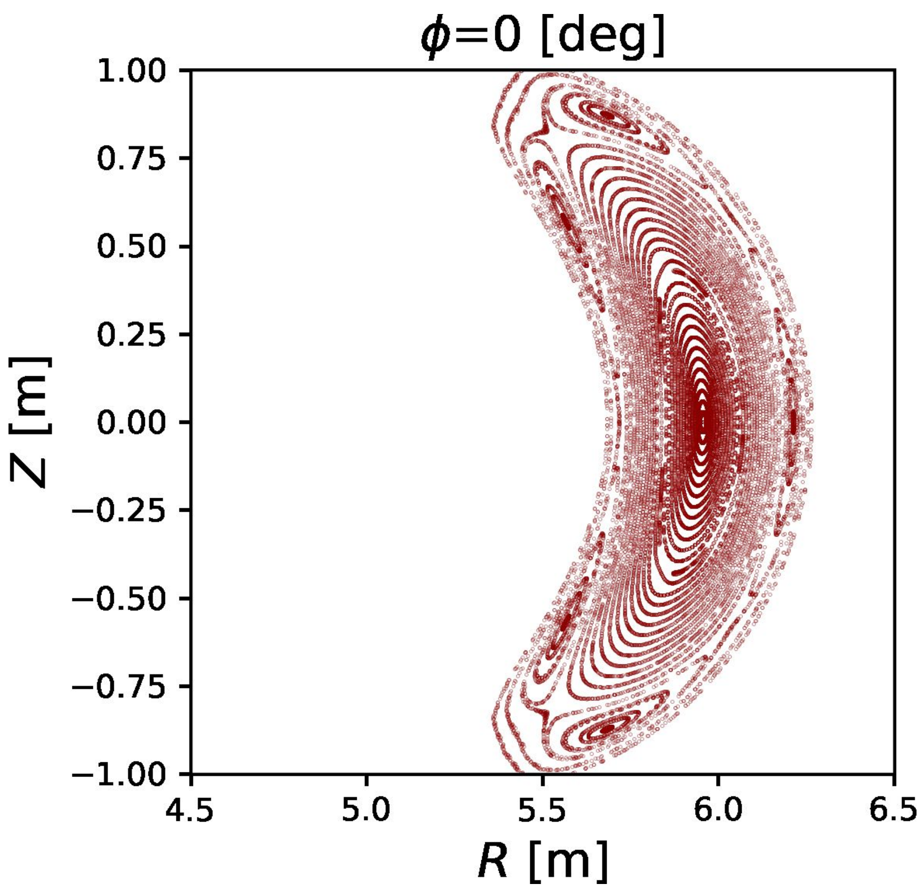
Localize ECCD significantly affects rotational transform profile



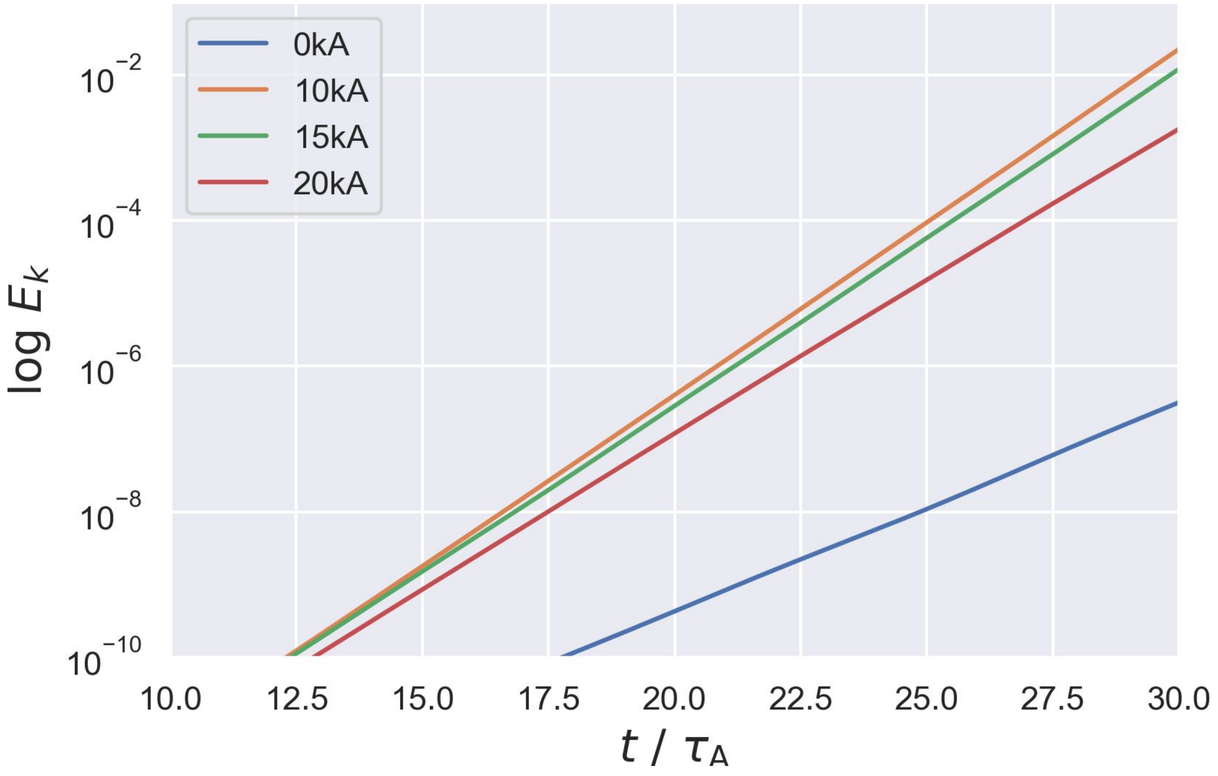
$\beta_0 = 1\%$

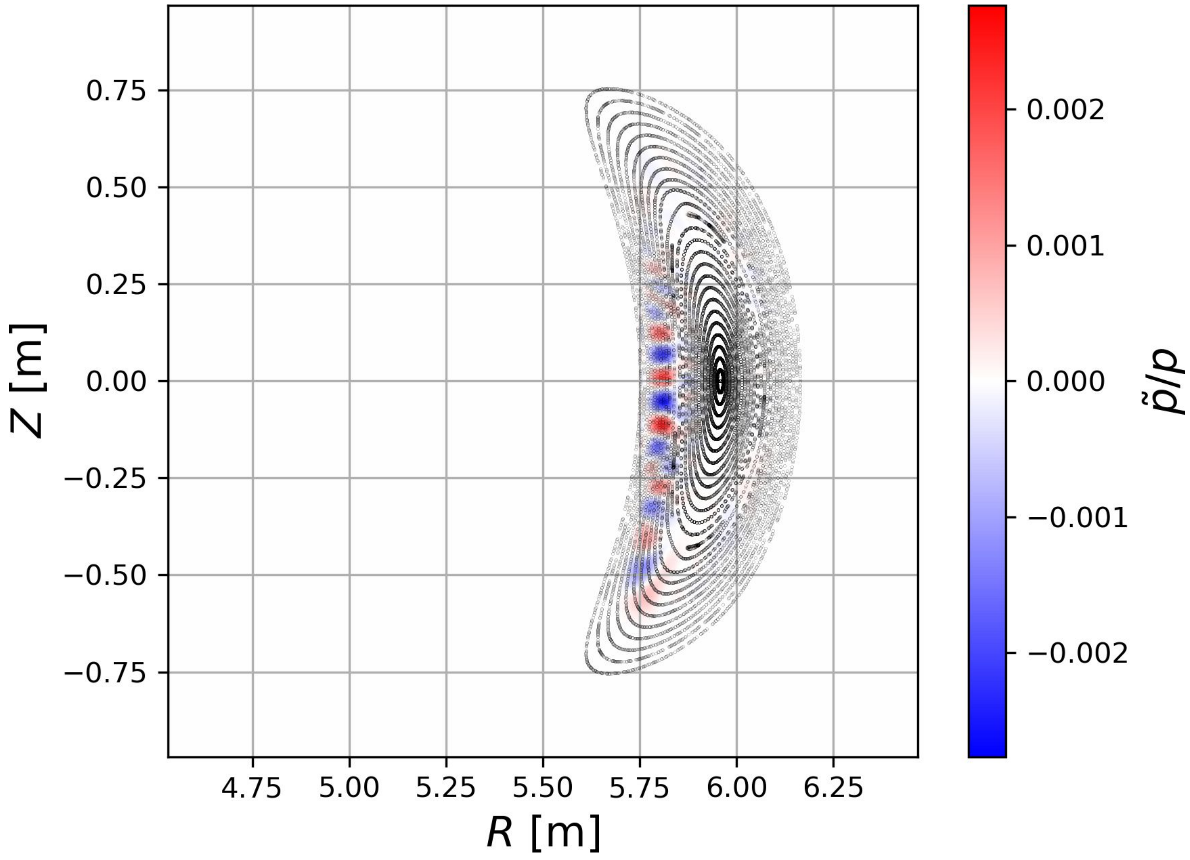
with ECCD (15kA)



- The iota is crossing 5/5 rational surface.
- Zero shear region appears.

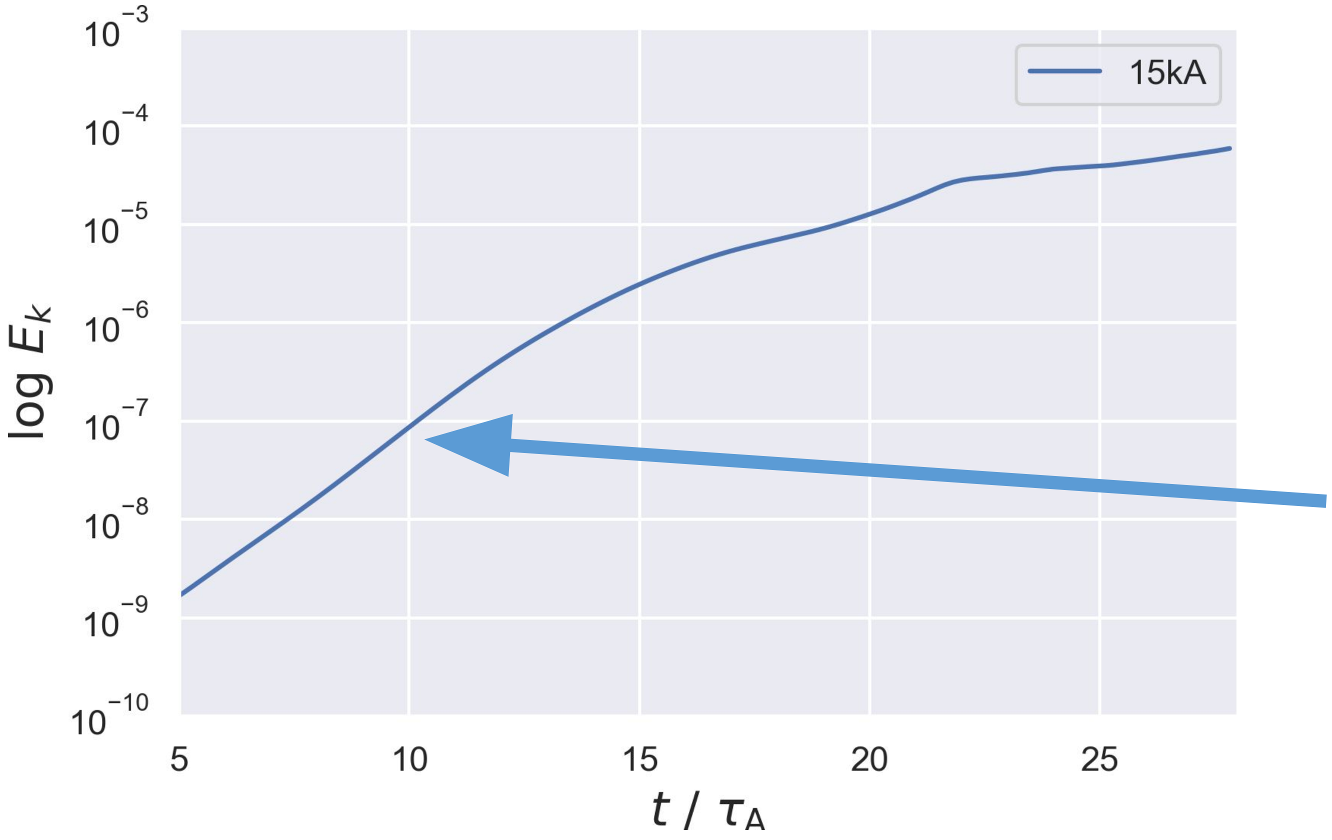
Linear growth and mode structure





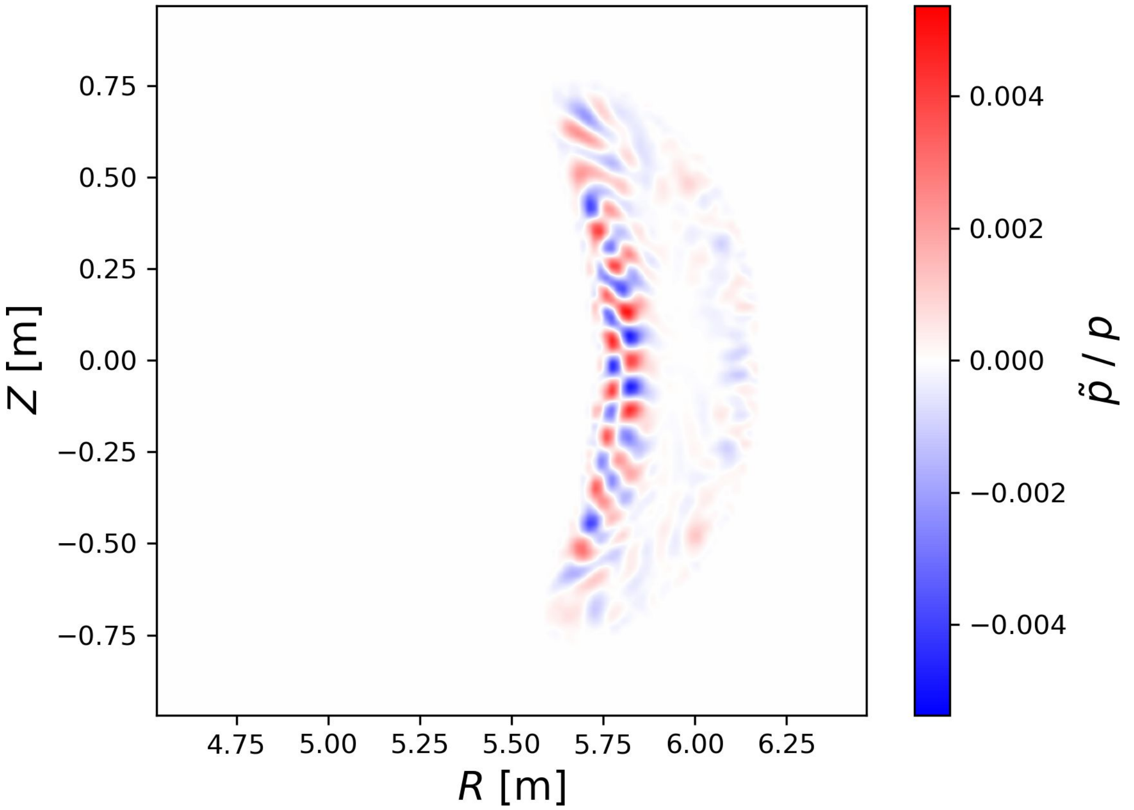
Kinetic energy evolution in linear phase and mode structure

Nonlinear evolution of kinetic energy



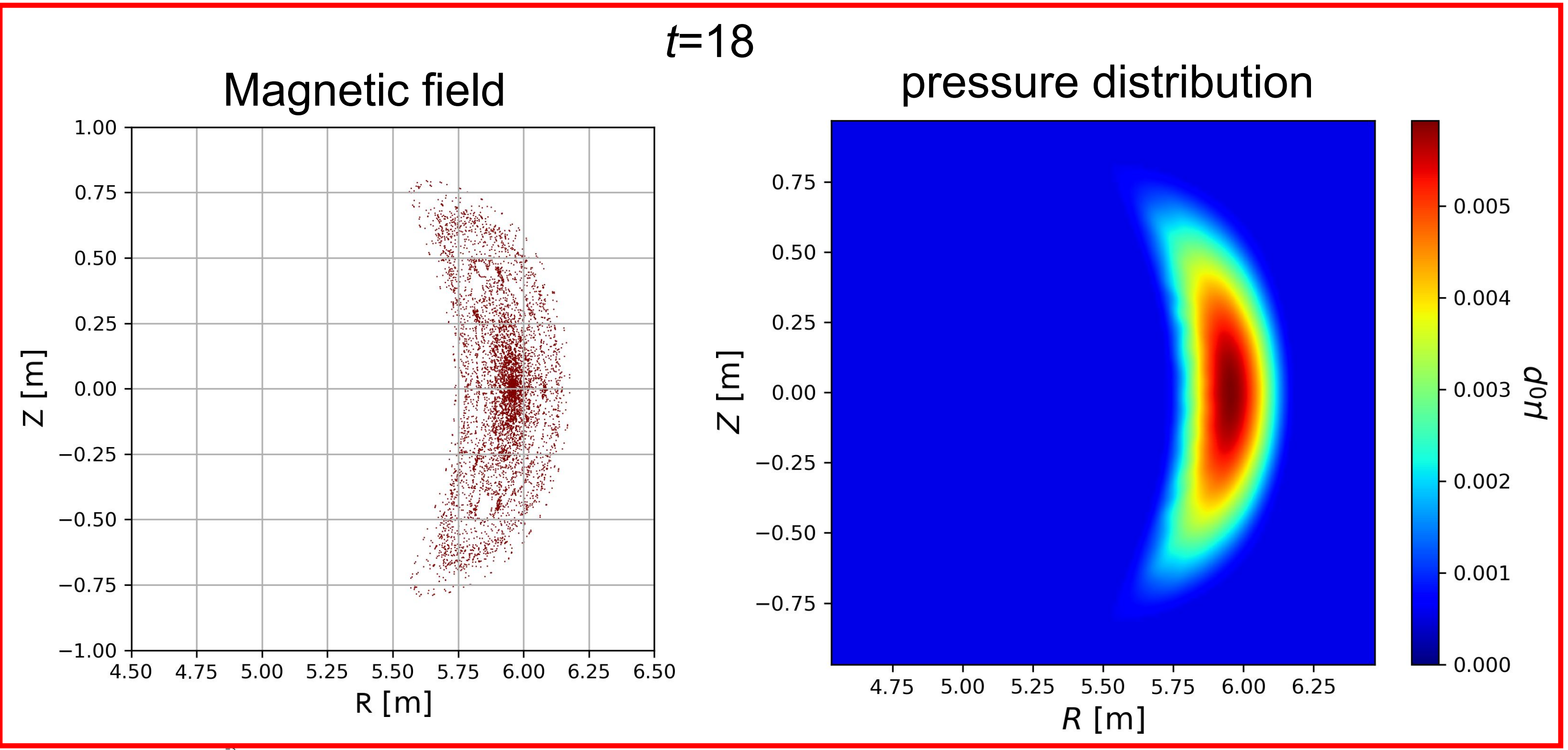
After linear evolution, nonlinearly saturates.

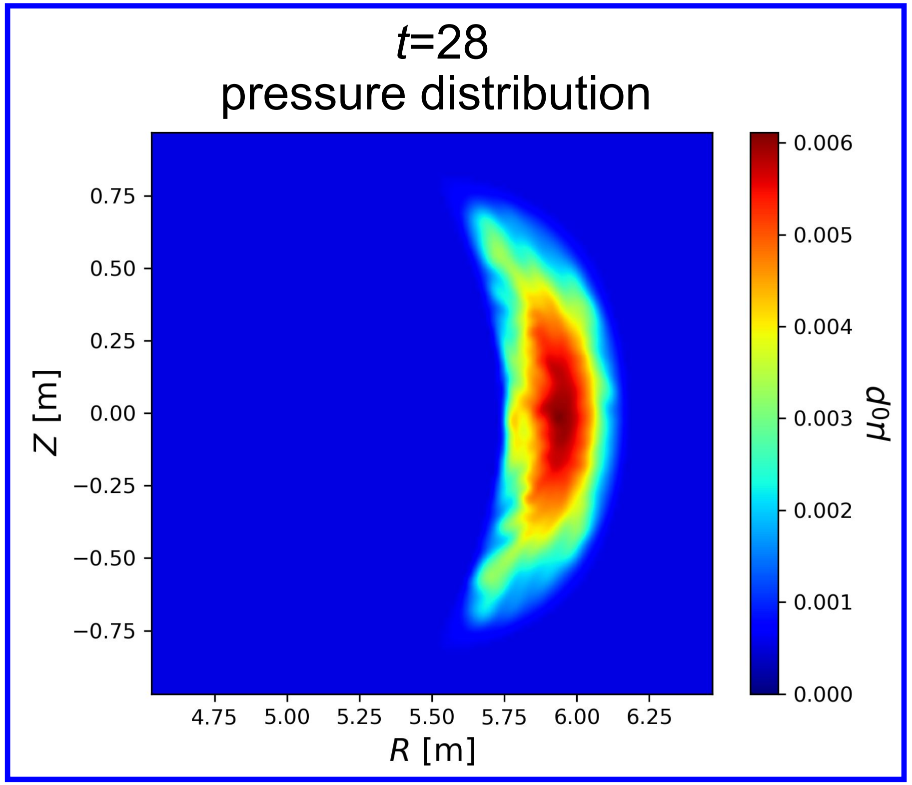
Linear mode structure

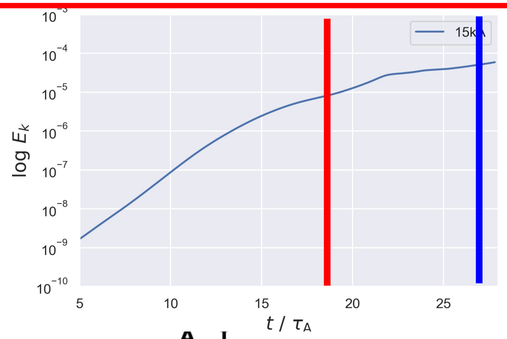


- Modes appear in low magnetic shear region.
- Mode structure deforms by 5/5 rational surface.

Nonlinear coupling destroys magnetic field topology







- At t=18, nested flux surfaces are broken. Also, deformation of plasma pressure begins.
- At t=28, pressure diffuses along stochastic field lines. This diffusion leads drop of core temperature.

Brief summary and outlook

1. 3D equilibrium with ECCD is studied by HINT.
2. Localized current density significantly changes the iota profile.
3. For I_{ECCD} = 15kA, the iota crosses the unity.
4. Linear growth rate with ECCD is larger than the case without ECCD.
5. In nonlinear phase, the pressure diffuses by modes.
6. Magnetic topology should be studied.
7. Mode analysis should be examined.