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Insights of core density collapse event from MHD simulations

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IFERC-CSC Workshop on JFRS-1 projects for FY2024, June 4th 2025

State of the art

In Large Helical Device (LHD), super dense core (SDC) discharges can be achieved in "outward shifted" configurations, $R_{axV} \geqslant 3.75$ m, by means of consecutive pellet injection i[1].

The increase in axis beta is limited by an **MHD instability** where the central density and pressure are flushed out in the submillisecond timescale. This instability is referred to as the **core density collapse** (CDC) event [2].

A new 3D non-linear non-adiabatic MHD model has been extended in **MIPS code** [3]. The performance of the model is studied by the simulation of a typical discharge of LHD where CDC event is observed. The effect of an external heat source in the plasma MHD dynamics is studied.

[1] Ohyabu N, et al., 2006 Phys. Rev. Lett. **97**(5) 055002
[2] Yamada H, et al., 2007 Plasma Physics and Controlled Fusion **49** B487
[3] Todo Y, et al., 2010 Plasma and Fusion Research **5** S2062–S2062

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Introduction: CDC event observed in LHD

Super dense core discharges have been achieved in LHD after consecutive **pellet injection**. The SDC plasma is characterized by:

- Vacuum **R_{axV} ⩾ 3.75 m** (outward shifted configuration)
- **B_0 > 2.0 T**
- Peaked density and pressure profiles with **steep gradients**
- Relatively low temperature, **T_e < 1 keV**
- **High β** values with strong Shafranov shift

The **pressure increase is limited** by an **MHD instability,** the CDC. The main characteristic are:

- **Pressure and density** suffer a **drop** in the core, and the peak shifts inwards
- **Temperature** is practically **unaffected** in core
- **Pressure**, **density** and **temperature** grow in the edge, **flushing outwards**

In the **precursor phase**, oscillations at the outside edge of plasma were observed, which are consistent with the prediction of **ballooning modes** [4].

[4]Ohdachi S, et al., Contributions to Plasma Physics **50** 552–557

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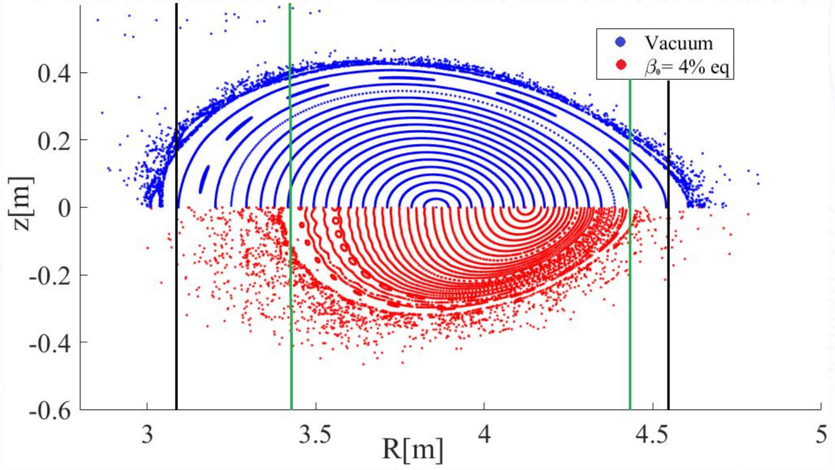
3D equilibrium by HINT code

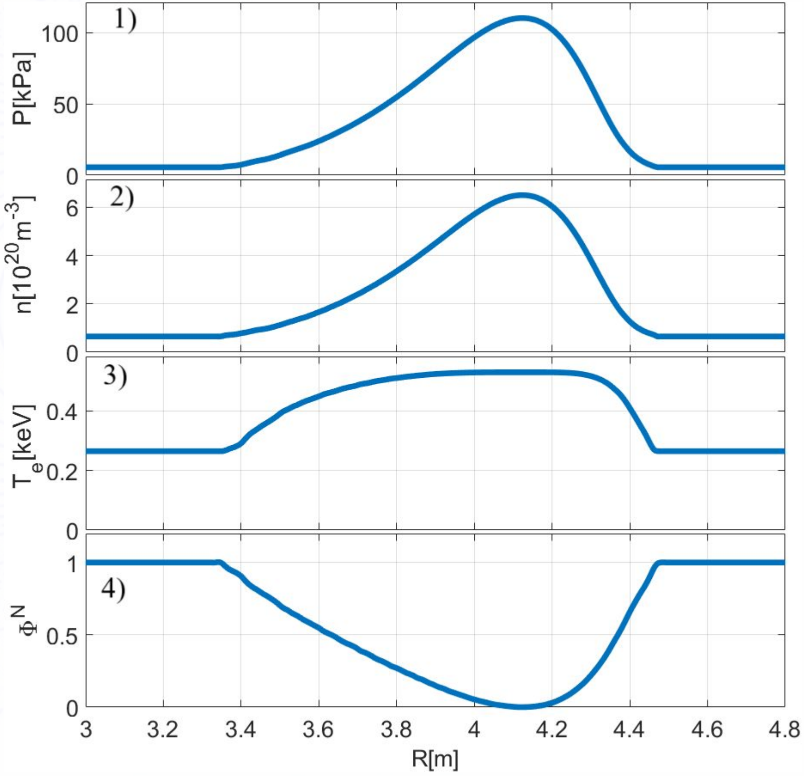
[5] Suzuki et al., 2006 Nuclear Fusion 46 L19

The 3D equilibrium of LHD discharge where CDC event is observed is built using HINT code [5].
The equilibrium configuration is:

- **R_{axV} = 3.85 m**
- **B_0 = 2.77 T**
- **β_0 = 4% ⟨β⟩ ~ 1%**
- **$T \propto T_0(1-\Phi^8)(1-\Phi^2)$, $p=nT=n(T_i+T_e) \cong 2nT_e$.**



Poincaré plot of vacuum (blue) and β_0 = 4% equilibrium. LCFS pointed by vertical lines.



Radial profiles of β_0= 4% equilibrium

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MIPS model, methodology and benchmark

$$\frac{\partial n}{\partial t} = -\nabla\cdot(n\mathbf{v}) + \nabla\cdot(D_\perp \nabla n) + S_{\rm n}, \tag{5}$$

$$\begin{aligned}\frac{\partial \rho\mathbf{v}}{\partial t} =& -\nabla\cdot(\rho\mathbf{v}\mathbf{v}) - \nabla(nT) + \mathbf{J}\times\mathbf{B} \\ &+ \nabla\cdot\left(\rho\nu\left[\nabla\mathbf{v} + (\nabla\mathbf{v})^{\rm T} - \frac{2}{3}(\nabla\cdot\mathbf{v})\mathbb{I}\right]\right) \\ &+ \mathbf{S}_{\rho\mathbf{v}},\end{aligned} \tag{6}$$

$$\begin{aligned}\frac{\partial T}{\partial t} =& -\nabla\cdot(T\mathbf{v}) - (\gamma-2)T\nabla\cdot\mathbf{v} \\ &+ \frac{\gamma-1}{n}\left[\nabla\cdot\left(\kappa_\perp\nabla_\perp T + \kappa_\parallel \nabla_\parallel T\right)\right] \\ &+ \frac{\gamma-1}{n}\left[\frac{1}{2}m_i v^2\left(\nabla\cdot(D_\perp\nabla n) + S_{\rm n}\right)\right] \\ &+ \frac{\gamma-1}{n}\left[S_{\rm T} - \mathbf{v}\cdot\mathbf{S}_{\rho\mathbf{v}}\right] \\ &- \frac{T}{n}\left[\nabla\cdot(D_\perp\nabla n) + S_{\rm n}\right]\end{aligned} \tag{7}$$

$$\partial_t \mathbf{B} = -\nabla\times\mathbf{E}, \tag{8}$$

$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta\mathbf{J}, \tag{9}$$

$$\nabla\times\mathbf{B} = \mu_0\mathbf{J}, \tag{10}$$

New *3D non-linear non-adiabatic MHD* model has been extended in MIPS code. The extension modified:

- Solving evolution of ρ, ρ**v**, P → **n, ρv, T**
- Arbitral initial ρ plasma profile → **constructed initial n,T profile**
- Inclusion of **anisotropic** effects of **heat conductivity**
- Diffusion terms $\chi_\perp\nabla^2(P - P_{\rm eq})$,→ $\nabla\cdot(\kappa\nabla T)$
- **Viscous term:**

$$\nabla\cdot\mathbf{\Pi} \approx (4/3)\nabla(\rho\nu(\nabla\cdot\mathbf{v}) - \nabla\times(\rho\nu(\nabla\times\mathbf{v})$$

$$\nabla\cdot\mathbf{\Pi} = \nabla\cdot(\rho\nu[\nabla\mathbf{v} + (\nabla\mathbf{v})^{\rm T} - \frac{2}{3}(\nabla\cdot\mathbf{v})\mathbb{I}])$$

- Plasma parameters have dependence with T:

$$\nu(T) \propto \nu_0(T/T_0)^{-3/2}, \quad \eta(T) \propto \eta_0(T/T_0)^{-3/2}$$

$$\kappa_\parallel(T) \propto \kappa_{\parallel,0}(T/T_0)^{5/2},$$

- Consideration of **particle, momentum and heat sources: S_n, $S_{\rho v}$, S_T**

MIPS model, **methodology and benchmark**

Equispaced grid (R,ϕ,Z):

- R = [2.8, 5.0]
- ϕ = [0, 2π), (full torus)
- Z = [-1.1, 1.1]

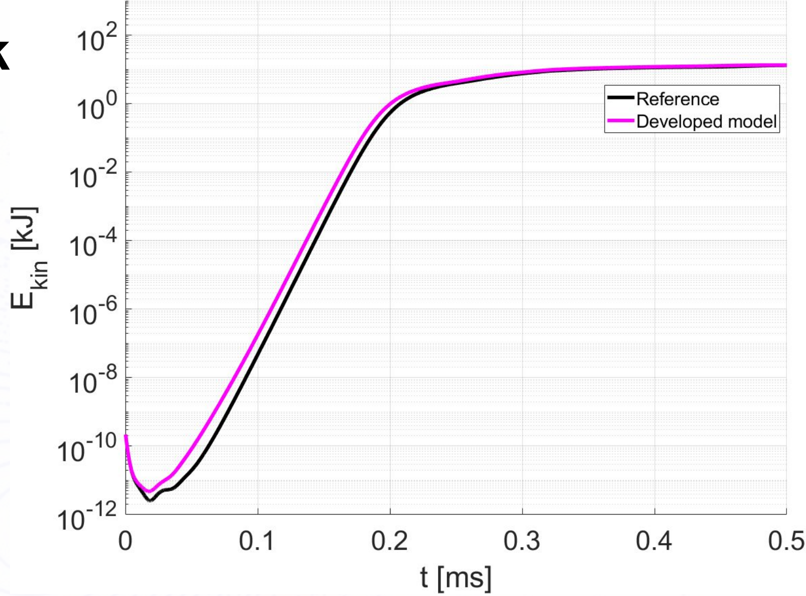
Spatial derivation: 4th order centered difference method

Time integration: 4th order explicit Runge-Kutta

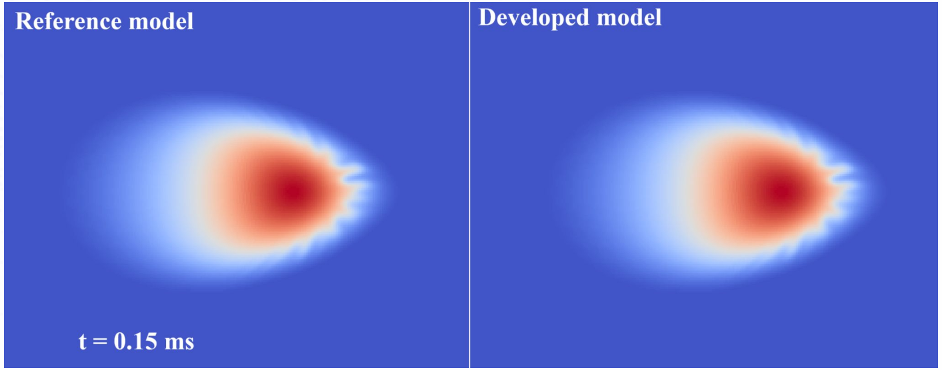
Convection terms: use 3rd order Upwind Scheme term for numerical stability

Benchmark with former version of the code used:

- Resolution (R,ϕ,Z) = (256,1232,256)
- dt = 1.62 ns
- $D_\perp = 100\ m^2s^{-1}$, $\nu_0 = 10\ m^2s^{-1}$, $\eta_0 = 1.0 \times 10^{-3}\ \Omega m$, $\chi_\perp = 100\ m^2s^{-1}$, $\chi_{//} = 1\times10^3\ m^2s^{-1}$
- Uniform plasma parameters
- Uniform density profile



Kinetic energy evolution of reference and developed model



Contour plot of pressure of models at same time

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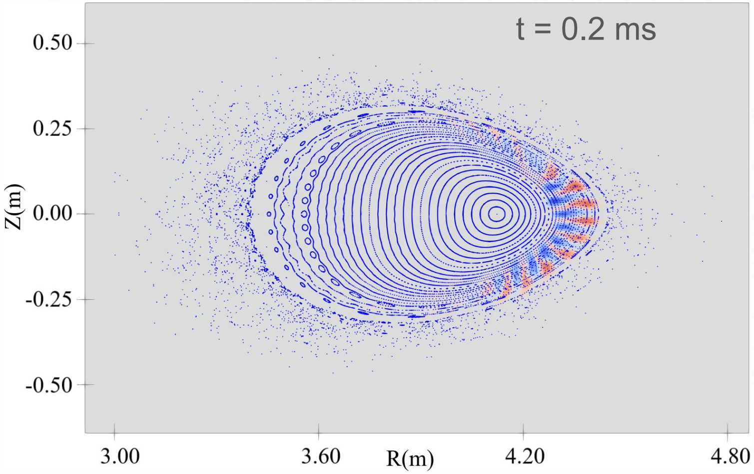
Simulation results: **spontaneous CDC event**

The study was performed using:

- Resolution (R,ϕ,Z) = (384,1792,384)
- dt = 1.62 ns
- $D_\perp$ = 1 m^2s^{-1}, ν_0 = 100 m^2s^{-1}, η_0 = 1.0 ×10^{-4} Ωm,
  $\chi_\perp$ = 1 m^2s^{-1}, $\chi_{//}$ = 1×10^5 m^2s^{-1} ($\chi_{//}/\chi_\perp=10^5$) ($\chi \propto \kappa/n$)

Plasma parameters are temperature dependent

$$\nu \propto \nu_0 T^{-3/2},\ \eta \propto \eta_0 T^{-3/2},\ \kappa_{\|} \propto \kappa_{\|,0} T^{5/2}$$

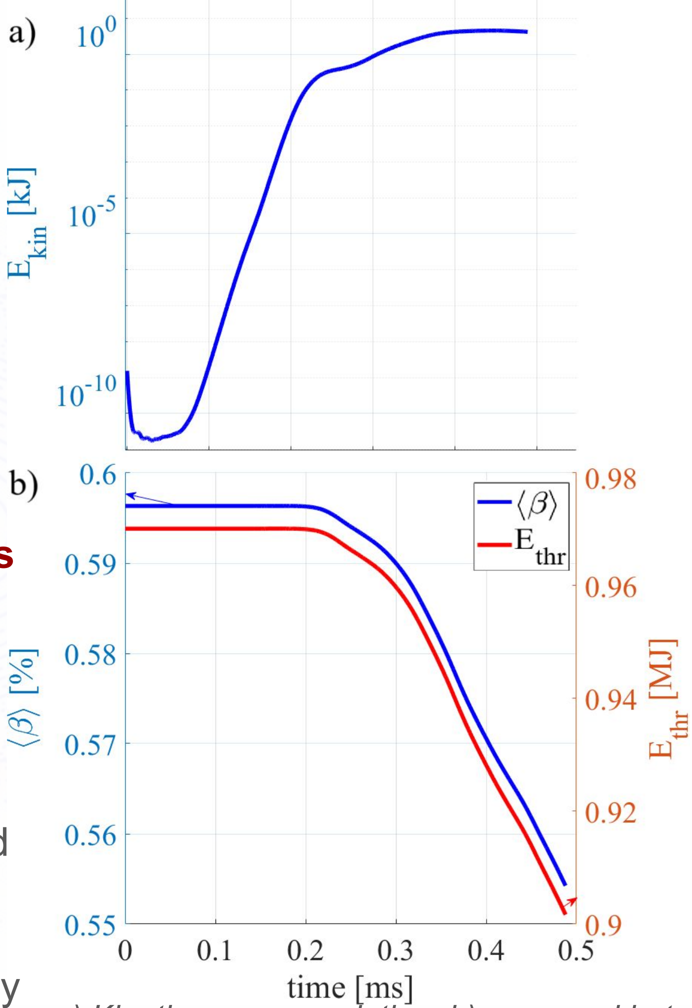


Mode structure of density perturbation

"Crash time" t~0.22ms

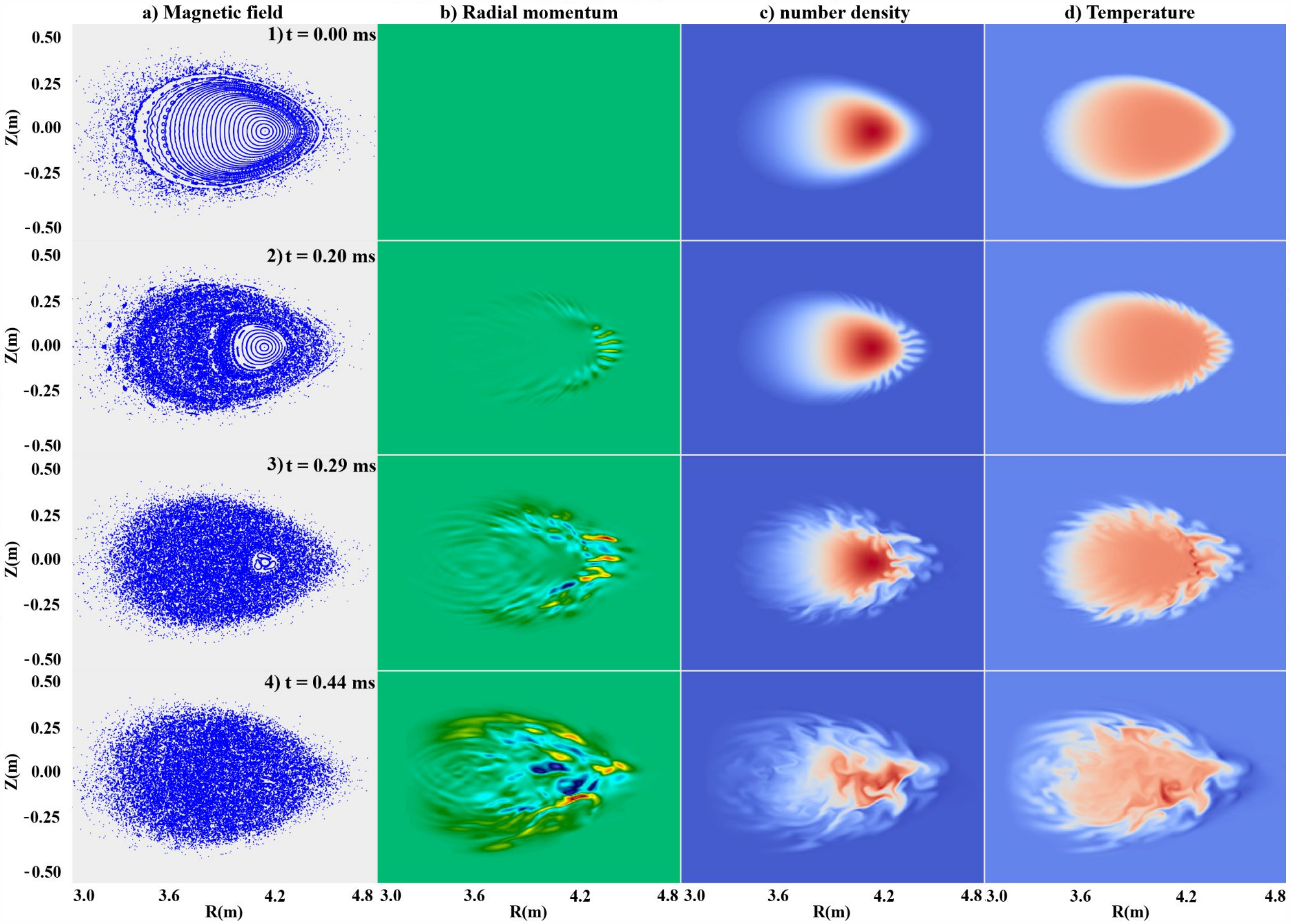
Linear growth corresponds to development of **ballooning modes.** Perturbation is localized in outer edge region.

Simulation of CDC study used ~ 193 536 cpuh



a) Kinetic energy evolution, b) averaged beta and thermal energy evolution

Simulation results: **spontaneous CDC event**



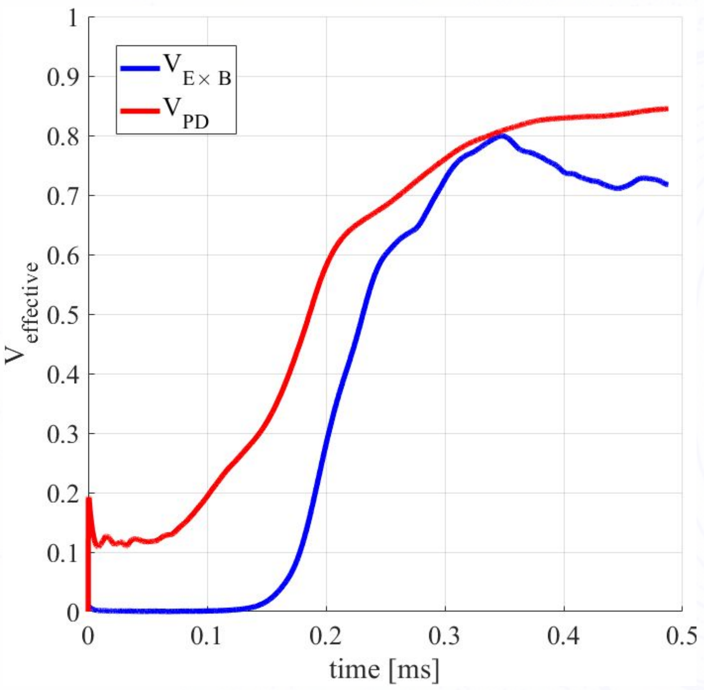
At **t~0.20 ms perturbation** is localized in **edge region**, following ballooning mode structures. Ballooning modes are accompanied by **stochastization of magnetic field**.

Ballooning mode saturates and the **plasma profile breaks**.

Magnetic field becomes more stochastic and plasma profile is further lost.

2D profile evolution of a) ***B****, b)* ρ**v**, c) n , d) T

Simulation results: **spontaneous CDC event**



Evolution of V_{PD} and V_{EXB}

Effective volume of **parallel diffusion** [6] has been computed during the simulation:

$$V_{\mathrm{PD}} = V^{-1} \int \mathcal{H}(\kappa_{\|} |\nabla_{\|} T|^2 - \kappa_{\perp} |\nabla_{\perp} T|^2) \, \mathrm{dV},$$

Similarly, the effective volume of ExB convection has been introduced:

$$P_{\mathrm{E}} = vL/\chi, \quad L = T/\nabla T, \quad \mathbf{v}_{\mathrm{E}\times\mathrm{B}} = \mathbf{E} \times \mathbf{B}/B^2$$

$$V_{\mathrm{E}\times\mathrm{B}} = V^{-1} \int \mathcal{H}(|V_{\mathrm{E}\times\mathrm{B}}| T - |\chi_{\|} \nabla_{\|} T + \chi_{\perp} \nabla_{\perp} T|) \, \mathrm{dV}$$

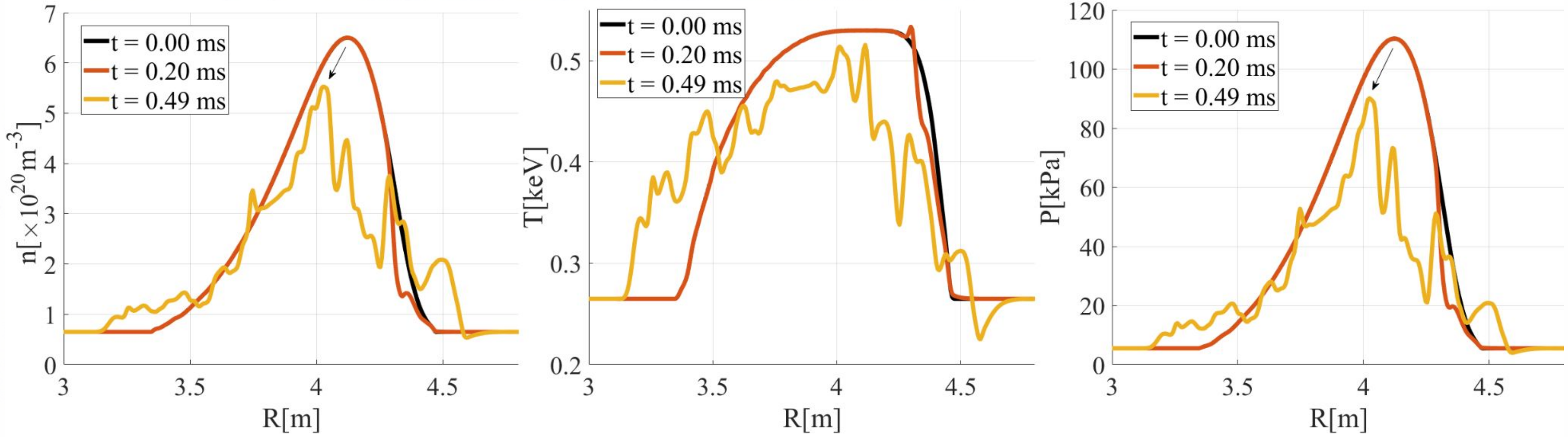
Effective volumes range [0,1] and give an idea of which fraction of volume is dominated by

- parallel diffusion over perpendicular (V_{PD}).
- ExB convection over heat diffusion (V_{ExB}).

During linear regime, **t~0.08 - 0.22ms**, V_{PD} and V_{ExB} grow. Near crash, **t~0.22 ms**, **V_{ExB} > 0.5: ExB fluctuations dominate** over heat diffusion when crash occur.

[6] Paul E J,et al., 2022 Journal of Plasma Physics **88** 905880107

Simulation results: **spontaneous CDC event**



Radial profile vs major radius of n (left), T (center) and p (right), over three time slices.

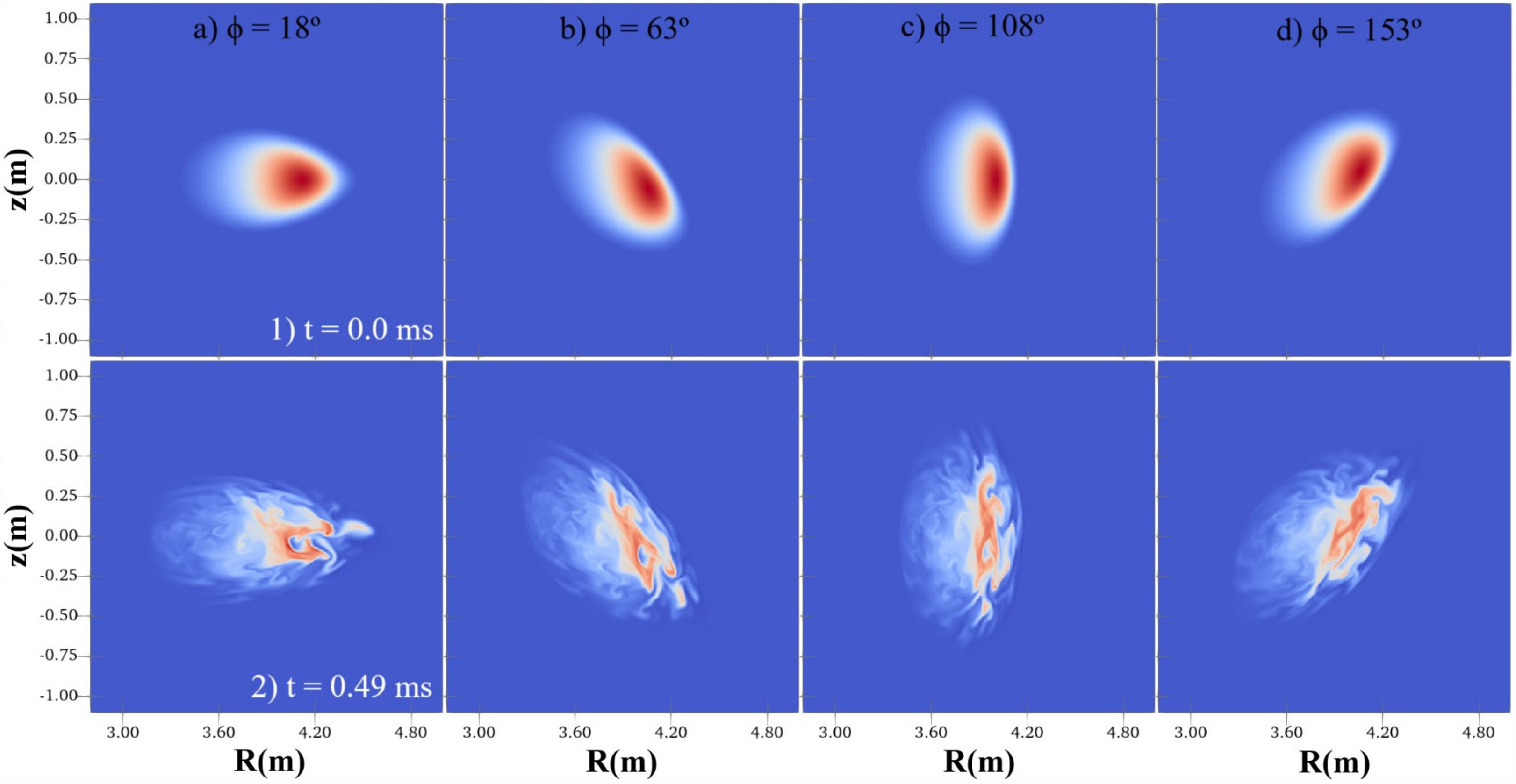
After plasma has reached the saturation regime, t > 0.22 ms, at t=0.49 ms, the radial profiles of density and pressure at the core have **collapsed**, and peak shifts inwards.

T profile in the core **decreases** by numerical simulation, which is not observed experimentally,

At the **edges**, n, T and p profiles **grow** in accordance with the rapid **outward flushing of plasma**.

Simulation results: **spontaneous CDC event**

The collapse of pressure is observed to occur **throughout the torus**.



2D poloidal pressure profile along different toroidal angles of reactor at equilibrium (top) and at t=0.49 ms (bottom)

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Simulation results: **effect of an external heat source**

External particle, momentum and heat sources have been considered in the extension of the MHD model in MIPS code.

The effect of **heat source** on the **CDC** event has been studied.

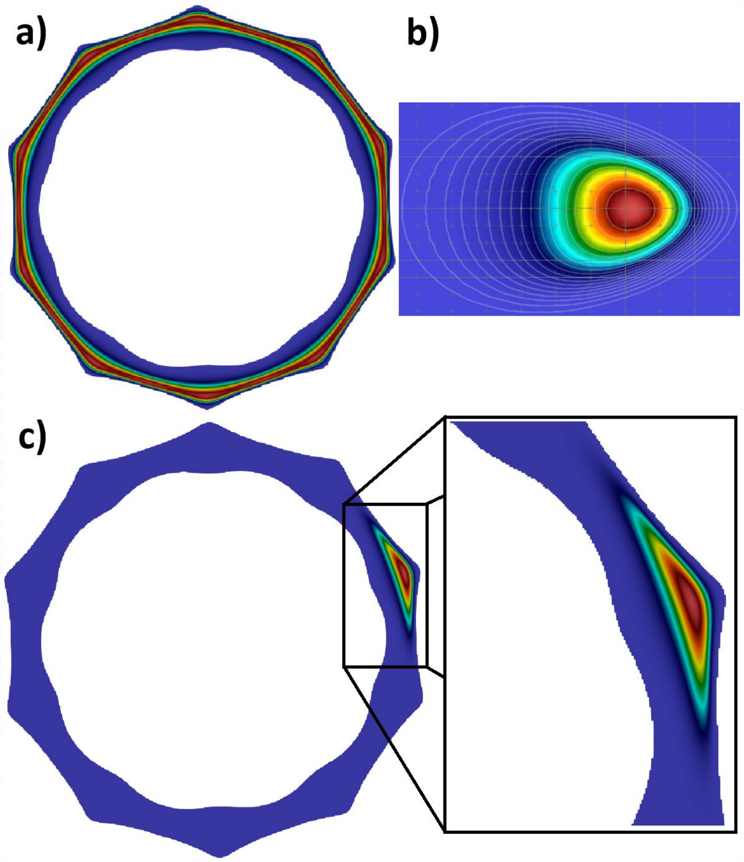
Easy gaussian profiles have been used as preliminary study. Two heat source geometries have been investigated.

1. Toroidally uniform $\mathbf{S_{T,uni}}$
2. Toroidally localized $\mathbf{S_{T,loc}}$

$$S_{\mathrm{T,uni}}(\Phi_{\mathrm{N}}) = h_0 \exp\left(-\frac{(\sqrt{\Phi_{\mathrm{N}}} - \mu_{\Phi_{\mathrm{N}}})^2}{\sigma_{\Phi_{\mathrm{N}}}}\right), \qquad (13a)$$

$$S_{\mathrm{T,loc}}(\Phi_{\mathrm{N}}, \phi) = S_{\mathrm{T,uni}}(\Phi_{\mathrm{N}}) \exp\left(-\frac{(\phi - \mu_\phi)^2}{\sigma_\phi}\right), \qquad (13b)$$

Two heat source amplitudes have been studied for each case, H.S = **1MW** and **10 MW**, with $H.S = \int_{\mathrm{V}} S_{\mathrm{T}}\,\mathrm{dV}.$

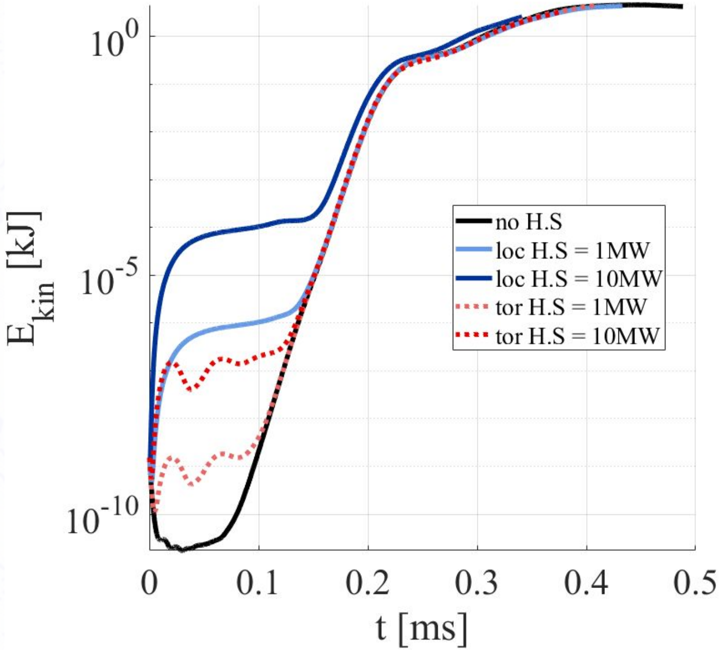


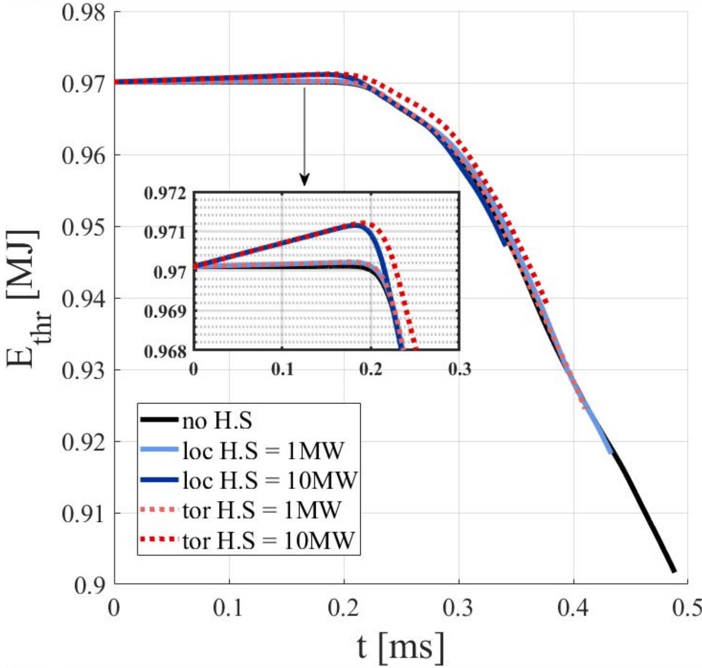
a) toroidal profile of $S_{T,uni}$ b) poloidal profile of $S_{T,uni}$, $S_{T,loc}$, c) toroidal profile of $S_{T,loc}$

Simulation results: **effect of an external heat source**

The heat source is expected to **increase pressure** in the core, making the profile more peaked and shifting outwards slightly, which would **accelerate the CDC** event.

In this study, the plasma configuration and parameter set is largely unstable. The **MHD dynamics** is **too quick** to let the heat sources have significant effects on the evolution.

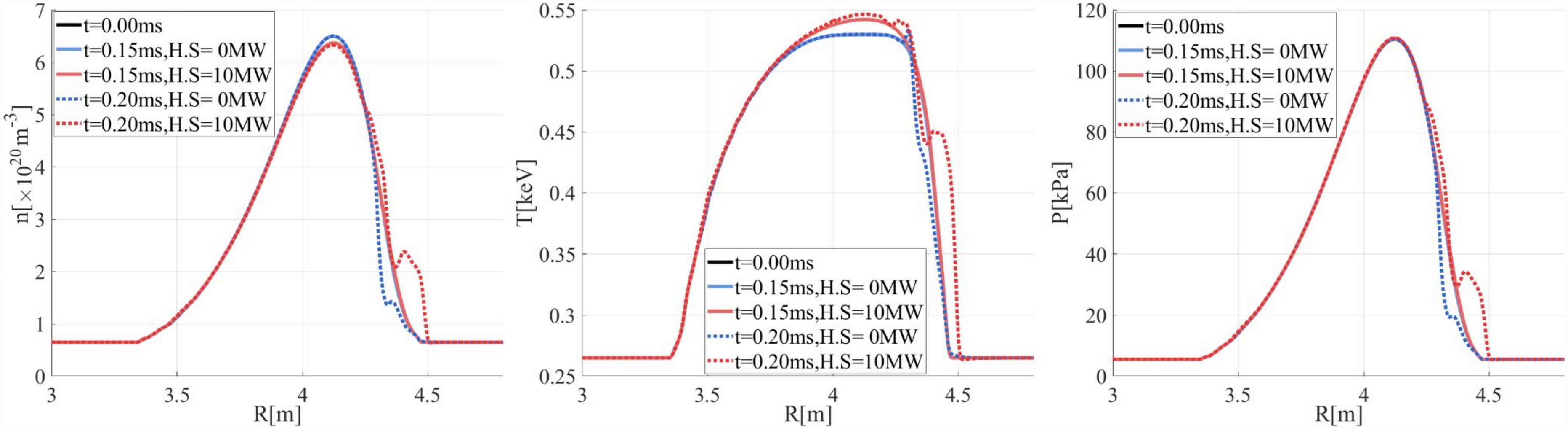




Evolution of kinetic energy (left) and thermal energy (right) for the spontaneous CDC and cases with different sources

Geometry and **amplitude** of source are observed to have an effect on plasma evolution.

Simulation results: **effect of an external heat source**



Radial profiles evolution of density (left), temperature (center) and pressure (right) for case of spontaneous CDC event, and case with localized HS=10 MW.

The case of localized H.S = 10 MW has the largest effect. In t~0.2 ms, temperature and pressure profiles grow, ΔT ~ 3% and Δp ~ 0.4%. The density profile decreases Δn ~ -2%

The slight **pressure increase** steepens the gradient moderately, and plasma shifts outwards. Both effects cause the **CDC event to be triggered sooner** in time.

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Conclusions and future perspectives

- The developed 3D non-linear non-adiabatic MHD model allows to calculate the **anisotropic** heat conductivity and external **particle, momentum** and **heat source.** The model has been **benchmarked and validated** against the former model in MIPS code.
- The model shows preliminary results of the CDC event observed experimentally:
    - Plasma is unstable to **ballooning modes**, localized in the outer edge. Ballooning modes lead to **collapse** of **density** and **pressure** core profiles, accompanied by a shift inwards.
    - Density, temperature and pressure increase in the edge, **outwards flushing** of plasma
    - Magnetic field is **stochastized** by ballooning modes.
- The **geometry** and **amplitude** of the heat source has been observed to have an effect on the plasma evolution. A large heat source accelerates the CDC event.
- The studied plasma configuration and parameter set is **too unstable** to let the external heat source have significant effects on the evolution.
- Future studies are expected to extend the physics model and numerical model to allow performing with more realistic plasma parameters. Particle, momentum and heat sources will be extended to scenarios where MHD activity is slower.

Acknowledgements

The authors gratefully acknowledge the computer resources through EUROfusion HPC project from Marconi-Fusion and Leonardo, the High Performance Computers at the CINECA headquarters in Bologna (Italy) and JFRS-1 provided under the EU-JA Broader Approach collaboration in the Computational Simulation Centre of International Fusion Energy Research Centre (IFERC-CSC).

One of the authors (Civit. A) has the support of the Joan Oró predoctoral grants program AGAUR-FI (2023 FI-3 00065) from the Secretary of Universities and Research from the Research and Universities Department from the Government of Catalonia and from European Social Fund Plus.