

EP transport induced by core density collapses in LHD plasma

authors:

J. Varela, Y. Takemura, K.Y. Watanabe, K. Nagaoka, M. Matsuoka, B. Breizman, F. Waelbroeck, D. Spong, L. Garcia, Y. Ghai and D. del-Castillo-Negrete

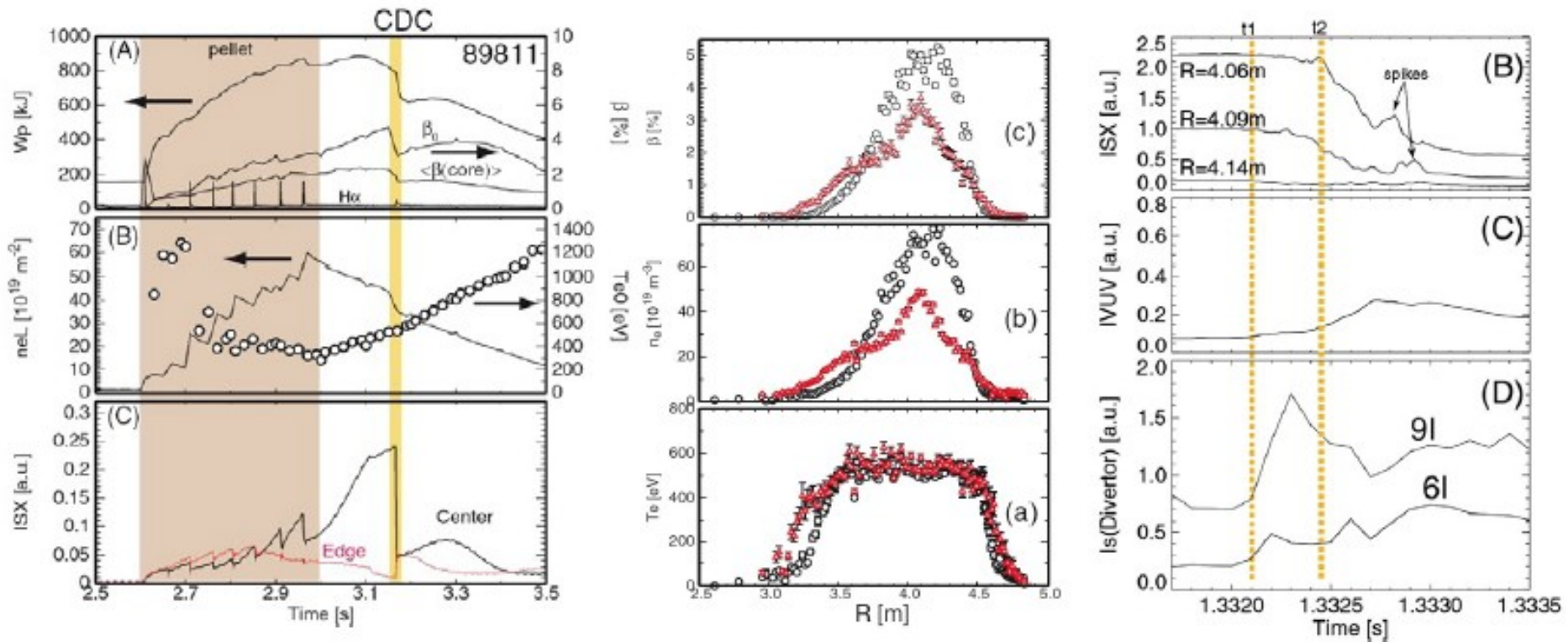


INDEX

- 1- Motivation: Core Density Collapse in LHD.
- 2- Nonlinear simulations: CDC collapse.
- 3- Nonlinear simulations including EPs
 - 3a- Tangential NBI: passing EP
 - 3b- Perpendicular NBI: helically trapped EP
 - 3c- alpha particles: theoretical reactor-relevant case
- 4- Summary and future analysis.

Motivation: unstable outwards configuration

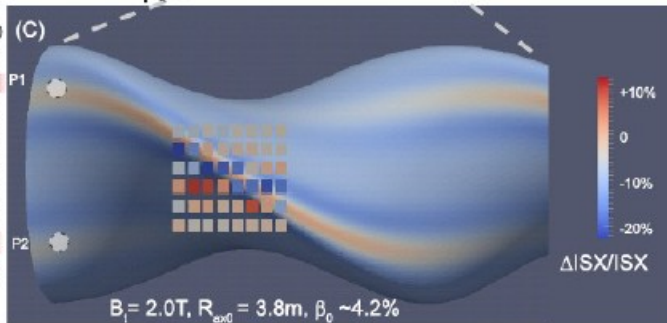
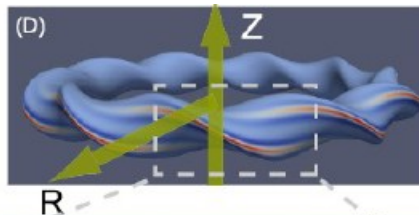
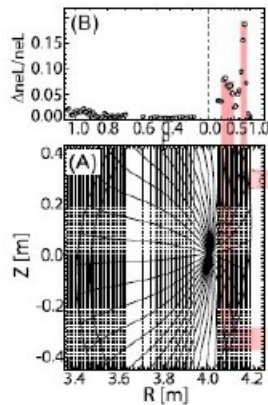
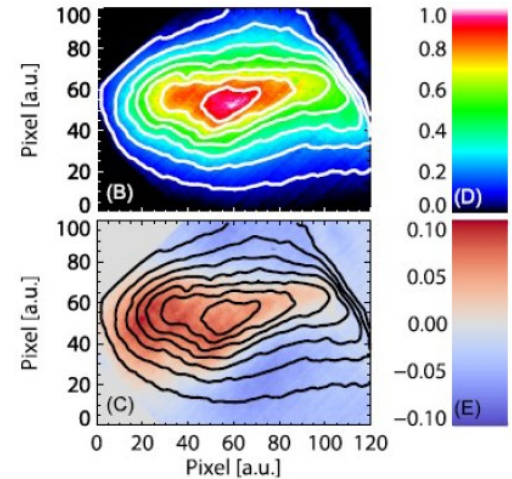
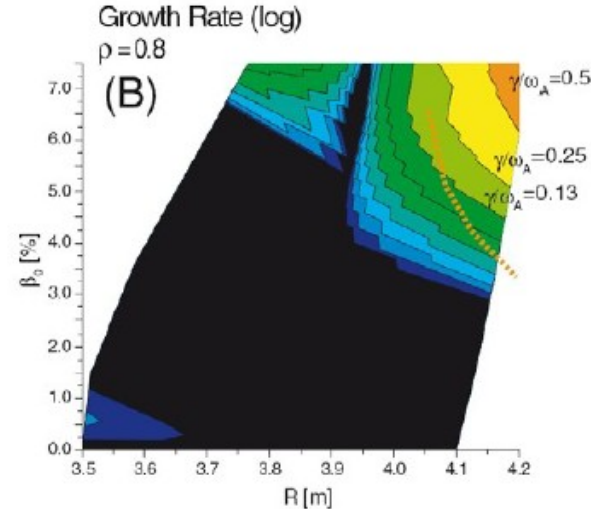
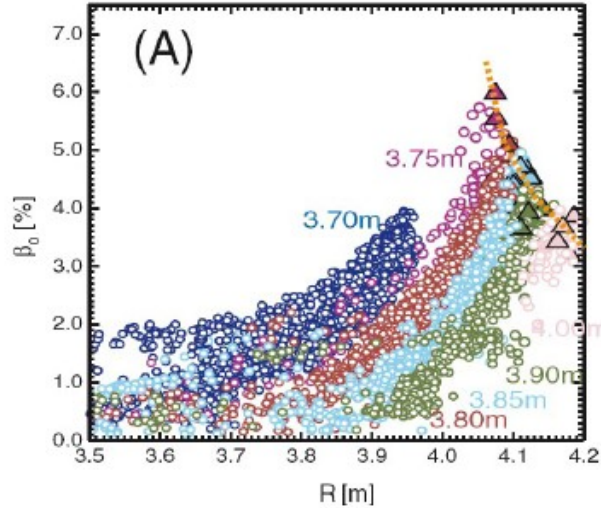
- LHD outward shifted configurations show a sharp decrease of the plasma energy during intense plasma pellet fueling and a collapse of the core density (CDC):



S. Ohdachi et al, Contrib. Plasma Phys., 50, 552 (2010)

- CDC: decrease of thermal β linked to a drop of the thermal plasma density.
- Plasma collapse last 0.5 ms

Motivation: Core Density Collapse in LHD plasma



- CDC observed in Mercier stable configuration (magnetic well).
- High n ballooning modes strongly unstable at the plasma edge ($r/a \approx 0.75$).
- SXR Tomography shows an $m=1$ perturbation nearby the magnetic axis.

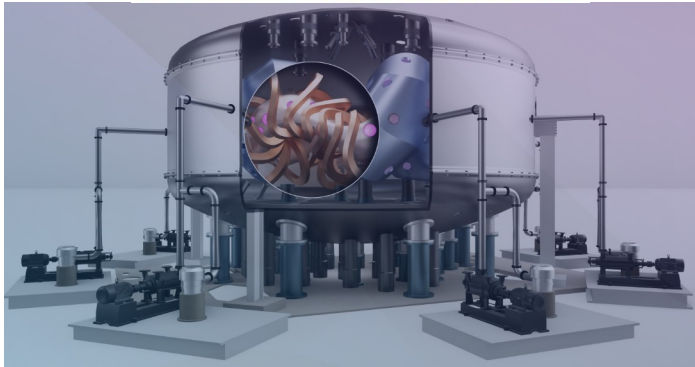
J. Varela et al, PFR, 6, 1403013 (2010)

S. Ohdachi et al, Nucl. Fusion 57 066042 (2017)

Motivation: Why this is important?

- Advance magnetic field traps in stellarator, based on different symmetries as:
 - Quasi-isodynamic: Infinity II (Type One Energy) or Stellaris (Proxima Fusion)
 - Quasi-axisymmetric: Helios (Thea)
 - Quasi-helical.

 TYPE ONE ENERGY



 Proxima Fusion



 THEA ENERGY



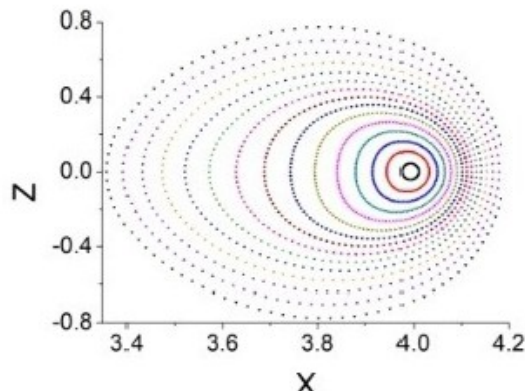
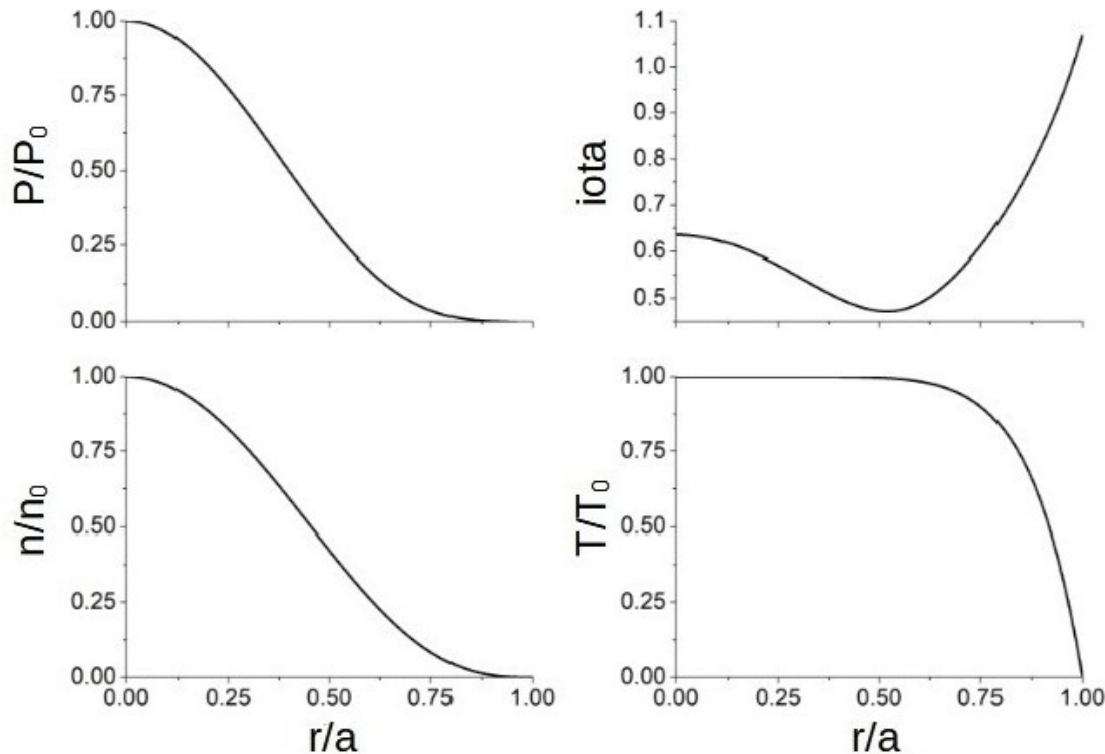
- These configurations have low magnetic shear and the ballooning modes destabilization threshold at the plasma edge is rather low.
- Stellarator fusion reactors **could be vulnerable to CDC**.

C. C. Hegna et al Journal of Plasma Physics, 91, E76 (2025)

J. Lion et al Fusion Engineering and Design, 214, 114868 (2025)

D.A. Gates et al, Nucl. Fusion, 65, 026052 (2025)

Model profiles: outwards shifted discharge 89811



- Plasma is Mercier stable.
- Reverse shear iota profile.
- Magnetic axis and magnetic surfaces displaced outwards.
- Numbers of modes in the simulation are 610:
Dynamic $n = 1 - 30$ toroidal mode families (including all rational surfaces).
- Evolving equilibrium modes $n = 0$ with $m = 0 - 63$.
- 1000 radial points for linear and 400 for nonlinear runs.
- Lundquist magnetic number $S = 10^7$.
- $\beta_{th} = 3.22 \%$

Parallel magnetic field perturbation in FAR3d

- Original FAR3d neglects the parallel magnetic field perturbation ($B'_{\parallel}$).
- $B'_{\parallel}$ is re introduced in the model imposing a radial equilibrium between the thermal plasma and magnetic pressure (B. Breizman et al PoP, 12, 112506, 2005)

$$0 = -\nabla \left(P_0 + \frac{1}{8\pi} B_0^2 \right) + \frac{1}{4\pi} (\mathbf{B}_0 \cdot \nabla) \mathbf{B}_0$$

- Neglecting the magnetic field bending, smaller compared to the other terms, the radial pressure balance can be written as:

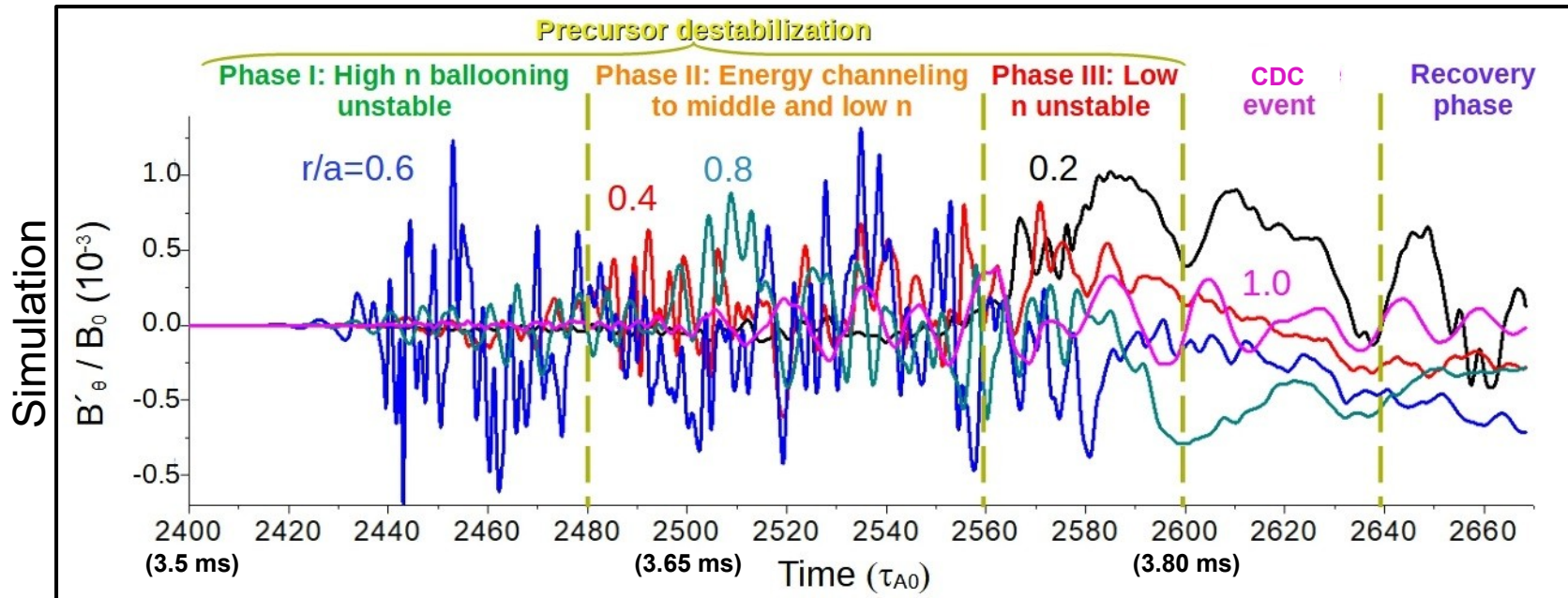
$$4\pi \delta P + (\mathbf{B}_0 \cdot \delta \mathbf{B}) = 0$$

- A self-consistent expression for $B'_{\parallel}$ is obtained:

$$\Rightarrow \partial B^{\zeta} = \frac{R_0}{J} \left(\frac{2\rho\beta_*}{a^2} \frac{1}{\sqrt{g}} \frac{1}{R_0} \frac{1}{\rho} \frac{\partial \psi}{\partial \theta} - \frac{I}{\rho} \frac{1}{\sqrt{g}} \frac{1}{R_0} \frac{\partial \psi}{\partial \rho} - 2\mu_0 \partial P \right)$$

- A new FAR3d linear and nonlinear version is developed including the new term coming from the $B'_{\parallel} \neq 0$.

Non linear simulations: different stability phases



- The non linear simulation show different phases with respect to the plasma stability:

Precursor phase:

Phase I: high n ballooning unstable in the plasma periphery .

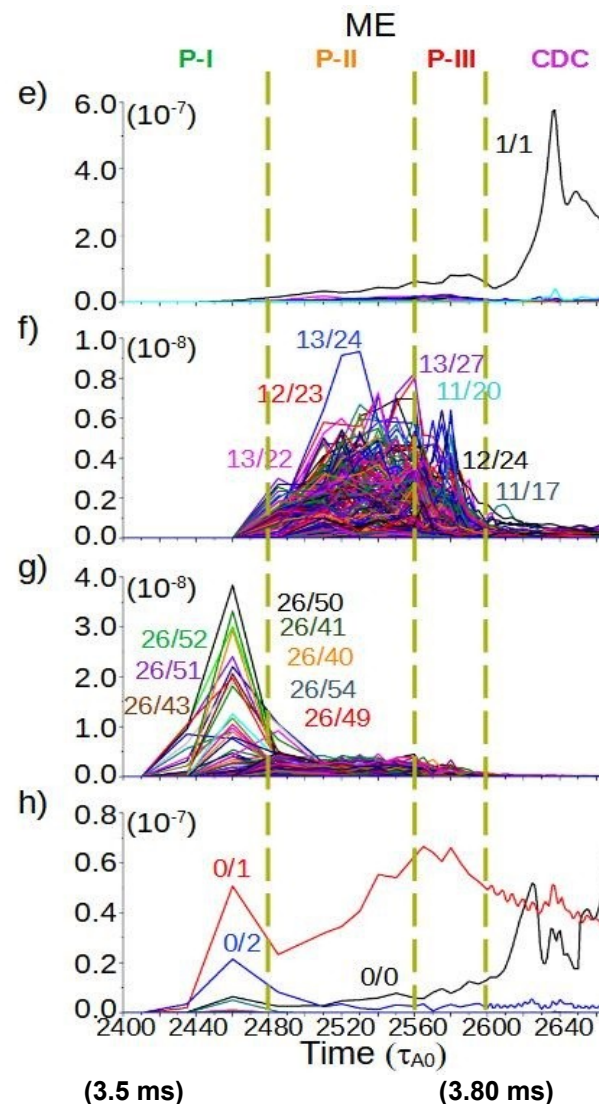
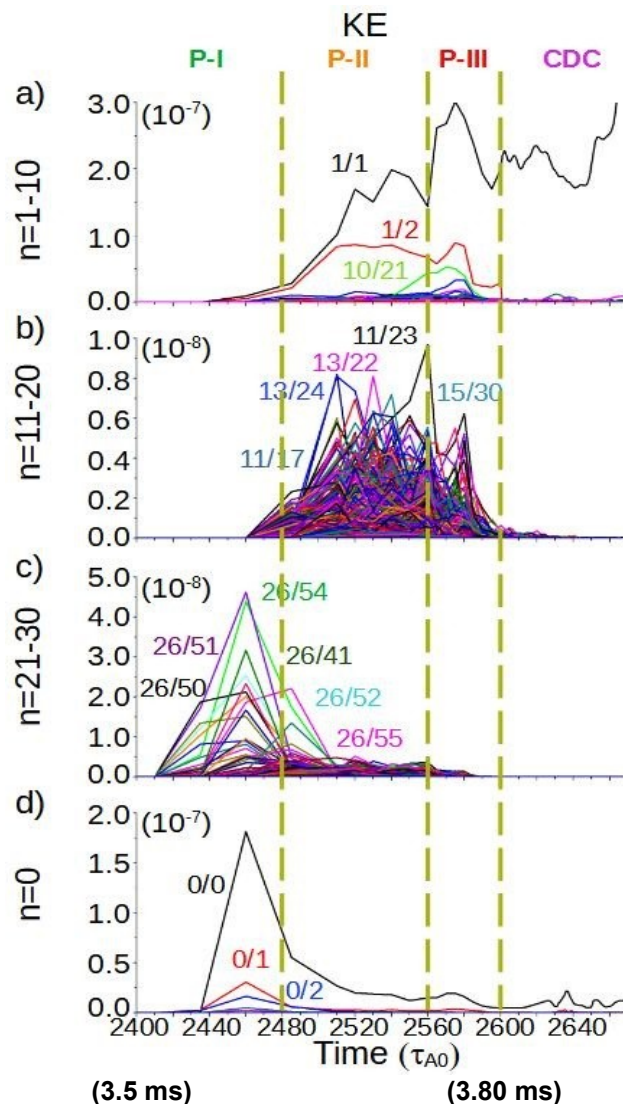
Phase II: energy cascade from high n ballooning to middle and low n modes.

Phase III: inner plasma destabilized and low n unstable.

CDC event: m=1 perturbation in the plasma core and partial pressure collapse.

Recovery phase: m=1 perturbation decays and magnetic / flux surfaces recover.

Non-linear destabilization of low n modes



PI:

- High n ballooning modes dominant instability.
- Energy transfer to the equilibrium and lower n modes.

PII:

- High n ballooning modes saturate.
- Middle and low n modes unstable.

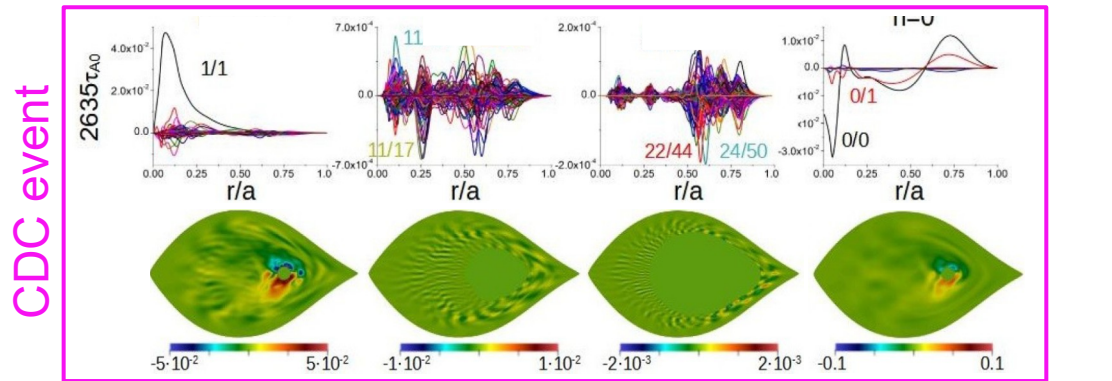
PIII:

- Low n modes dominant.
- Middle n ballooning saturates.

CDC event:

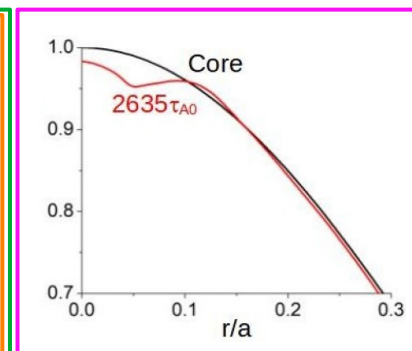
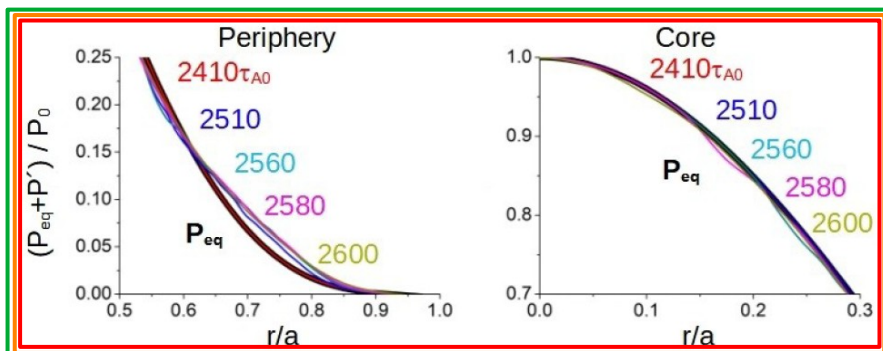
- 0/0 ME maximum:
- Strong distortion of core magnetic field surfaces.

Plasma collapse linked to magnetic field stochastization



P - I & II & III

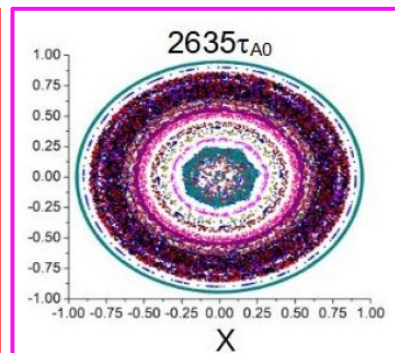
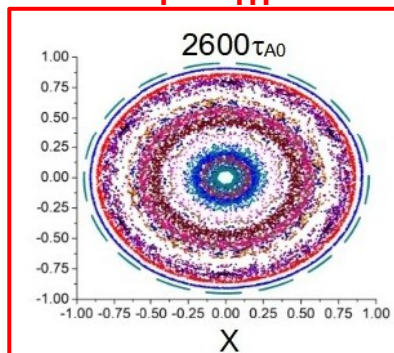
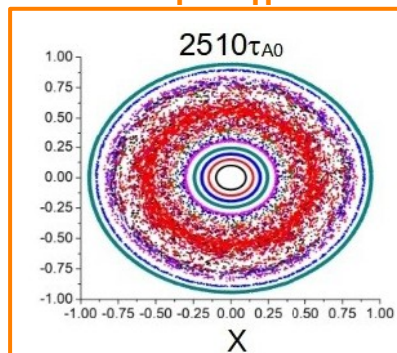
CDC event



P - II

P - III

CDC event



PII: High n ballooning saturate and pressure gradient reduces at the edge.

PII & III: Perturbation and pressure flattening propagates inwards.

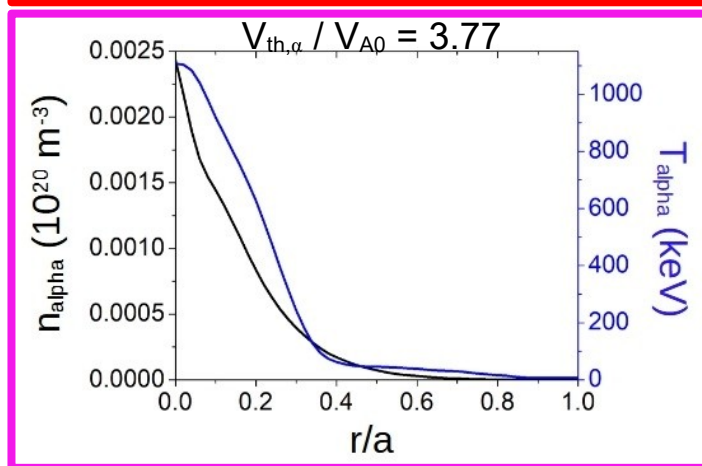
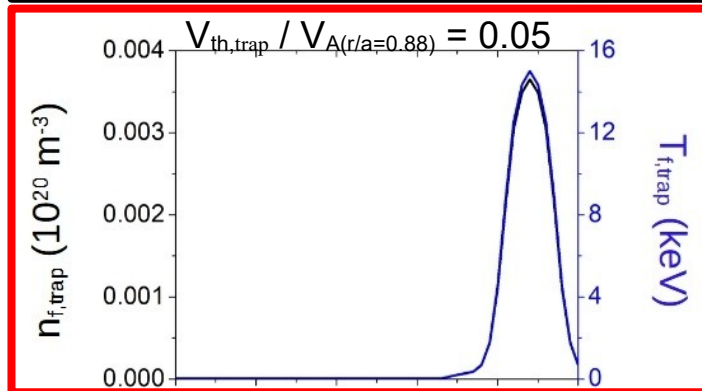
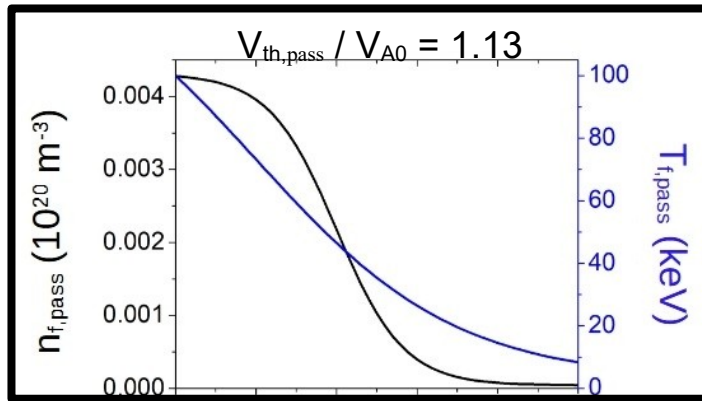
CDC: Partial collapse of the core pressure by m=1 perturbation

PII: high/middle n ballooning induce B field stochastization of middle-outer plasma region.

PIII: wider stochastic region in the middle plasma caused by middle-low n modes.

CDC: strong m=1 pert. extends the stochastic region to the magnetic axis.

EP populations added in the model



- Two different EP populations generated by neutral beam injector in LHD:

1- Tangential NBI:

- Passing EP
- On axis injection.
- Averaged $T_f=100$ keV

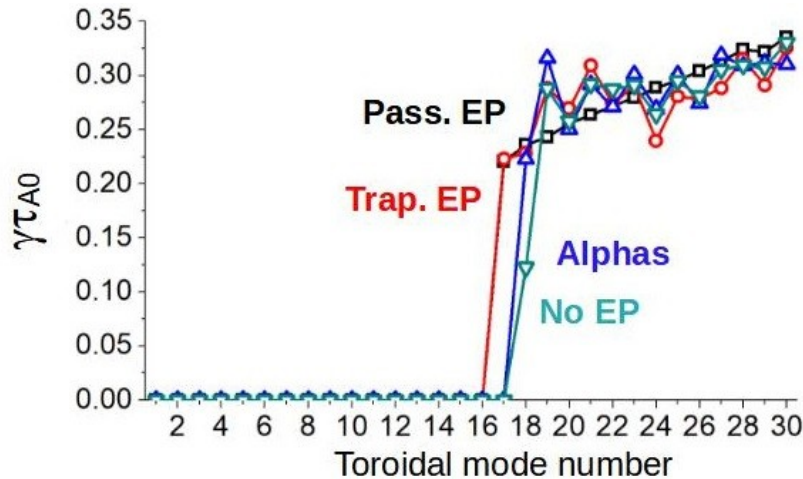
2- Perpendicular NBI: helically trapped EP

- Helically trapped EP
- Off axis injection, plasma edge
- Averaged $T_f=15$ keV

- Theoretical reactor relevant configuration:
Alpha particle population.

- Passing EP
- Inner plasma
- Averaged $T_f=1200$ keV

Ballooning mode stability with EPs



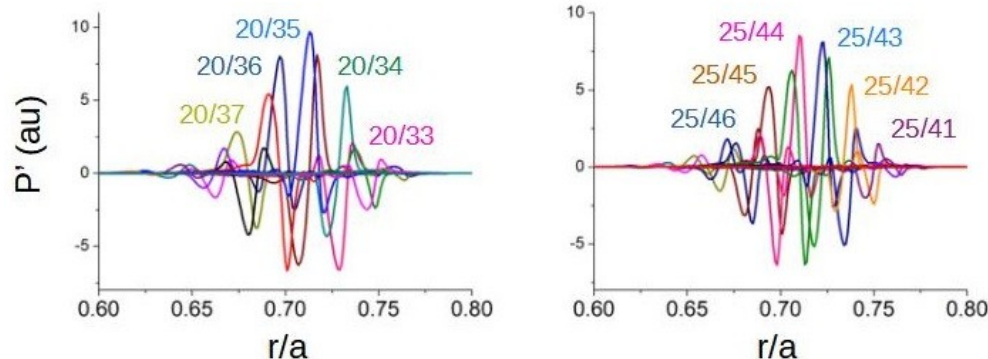
- Ballooning modes growth rate is similar to the reference case (without EPs).

- Simulations EP $\beta = 0.1\%$: AEs are stable and cause negligible effects on the ballooning modes (BM) stability.

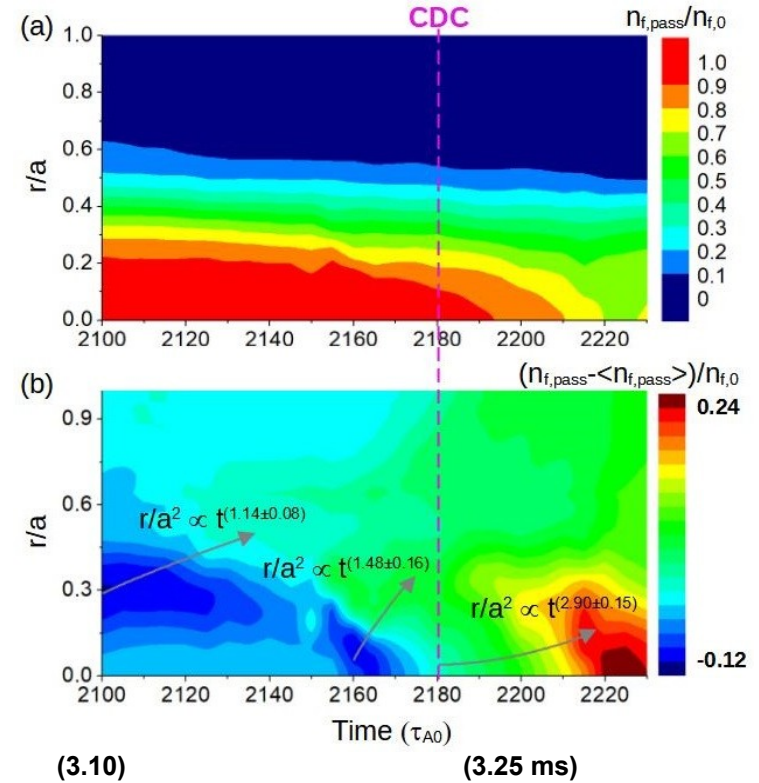
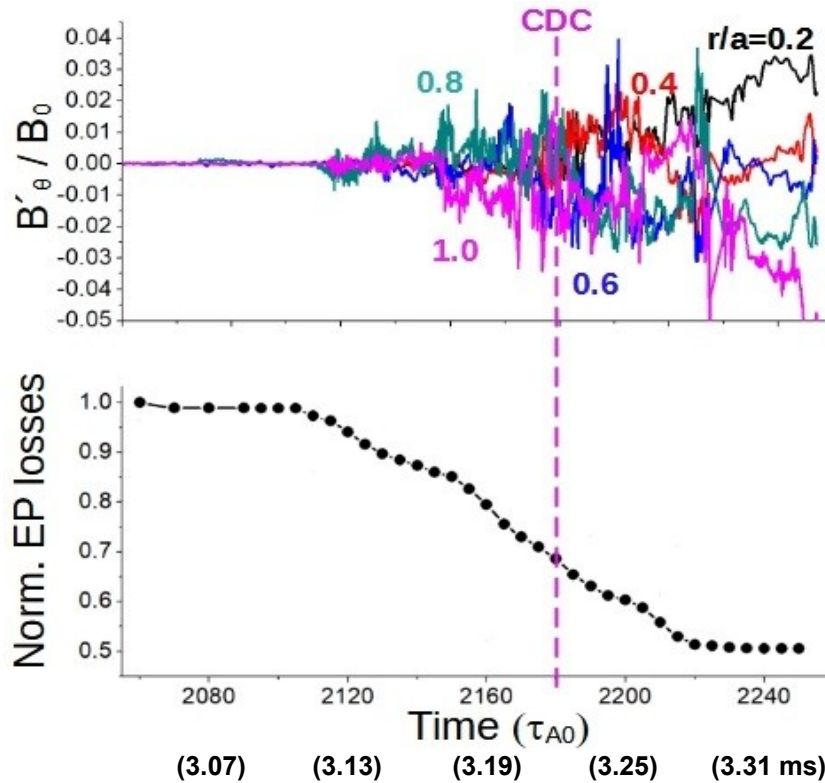
→ EPs behave as passive tracers.

- EP $\beta / \beta_{th} = 0.031$

- Ballooning modes structure similar to the reference case.

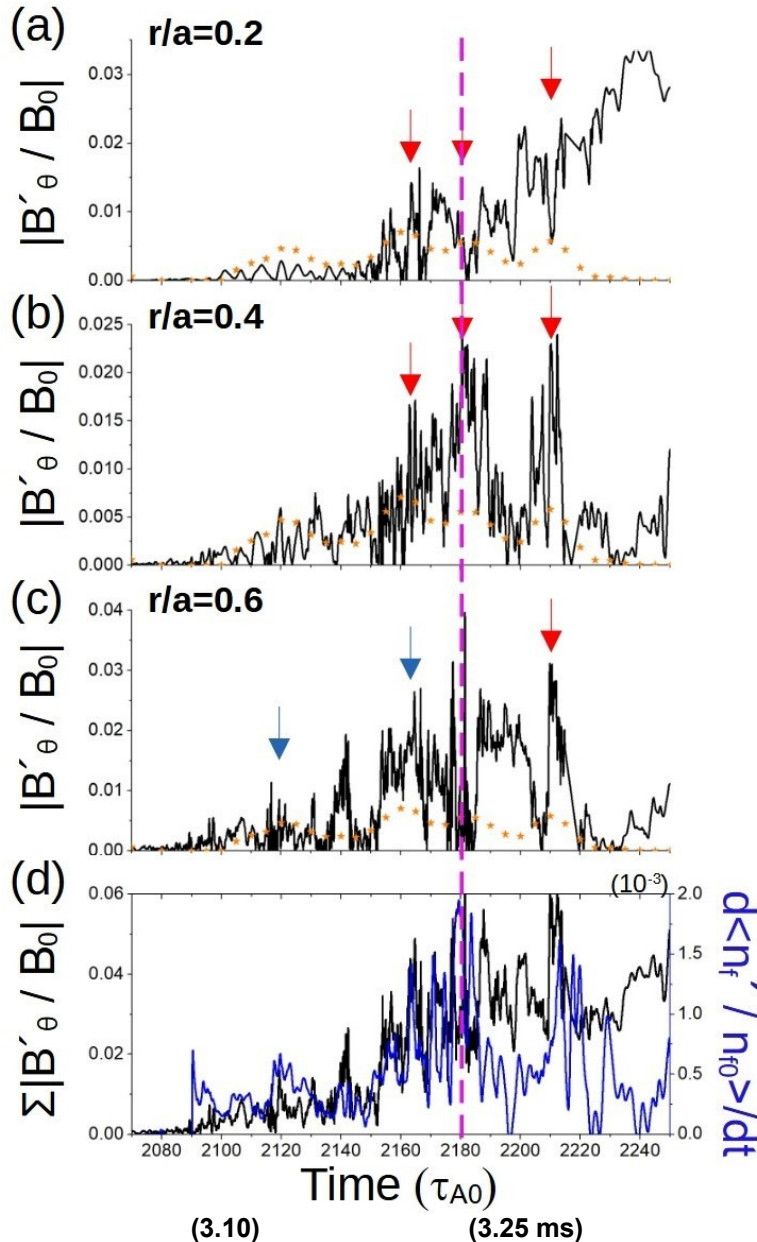


CDC effect on tangential NBI EP transport



- Magnetic field perturbation evolution reproduce the CDC event pattern.
- CDC precursors induce 30% of passing EP losses. The CDC event causes around 50% of passing EP losses.
- Large passing EP losses at the inner-middle plasma region.
- Quasi-ballistic EP transport before the CDC although intense ballistic transport once the CDC is triggered: intense stochastization of the magnetic field at the plasma core.

CDC effect on tangential NBI EP transport



- Perturbation characterization:

- ➔ High n ballooning mode
- ➔ Middle n ballooning mode
- ➔ Low n mode

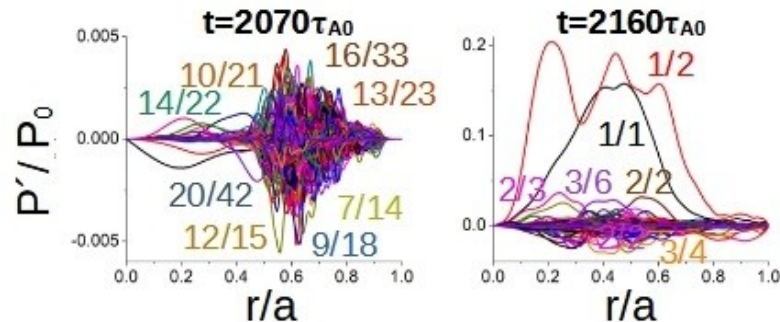
- Definition of the EP fluxes:

$$\langle F_{EP} \rangle(t) = \frac{1}{n_{EP,eq}} \frac{d \langle n'_{EP}(t) \rangle}{dt}$$

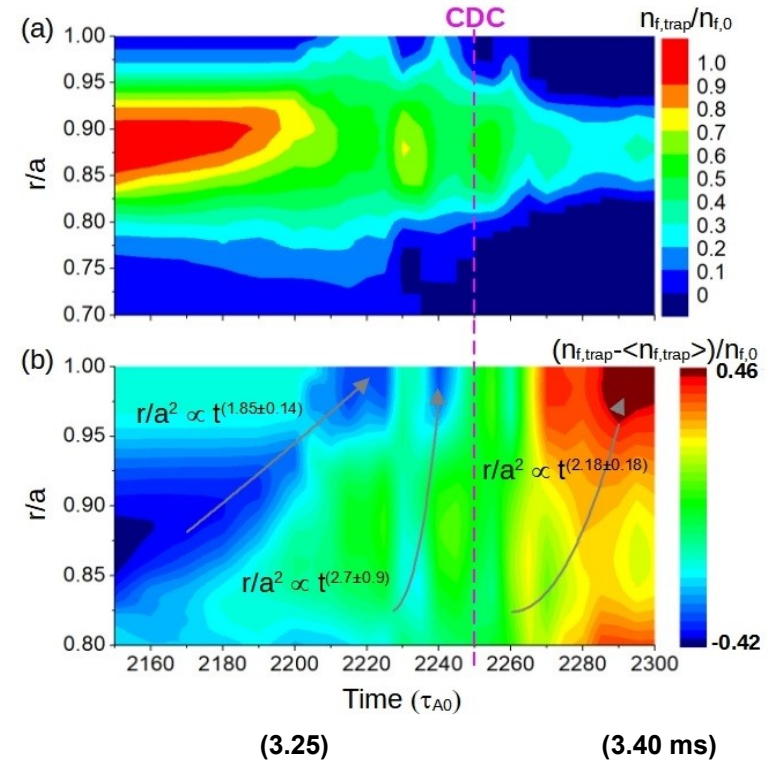
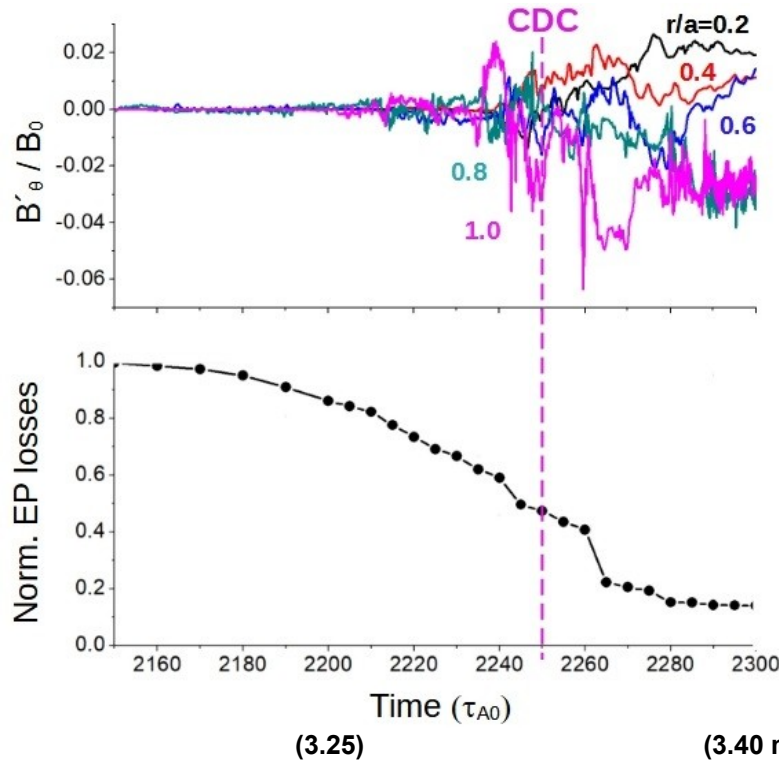
- Fluxes maxima at $t = 2090$ and $2120\tau_{A0}$ are induced by middle n BM at $r/a=0.6$.

- Destabilization of low n modes at $r/a=0.2-0.4$ from $t = 2165\tau_{A0}$ lead to enhanced fluxes.

- The largest fluxes are observed once the collapse is triggered at $t = 2180\tau_{A0}$.

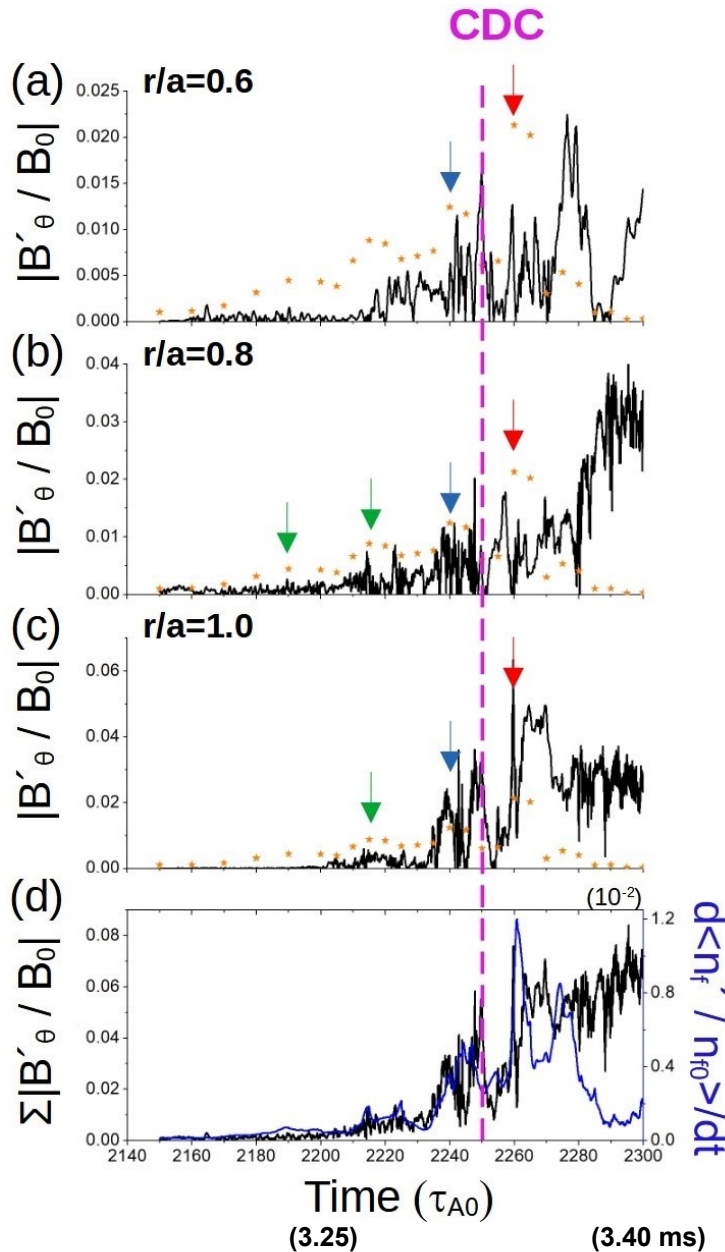


CDC effect on perpendicular NBI EP transport



- Precursors induce 50% trapped EP losses at the plasma edge.
- The collapse increases the trapped EP losses to 85%.
- EP population is mainly evacuated at the plasma edge.
- The EP transport is strongly ballistic due to the magnetic field stochastization caused by the saturating ballooning modes.

CDC effect on perpendicular NBI EP transport



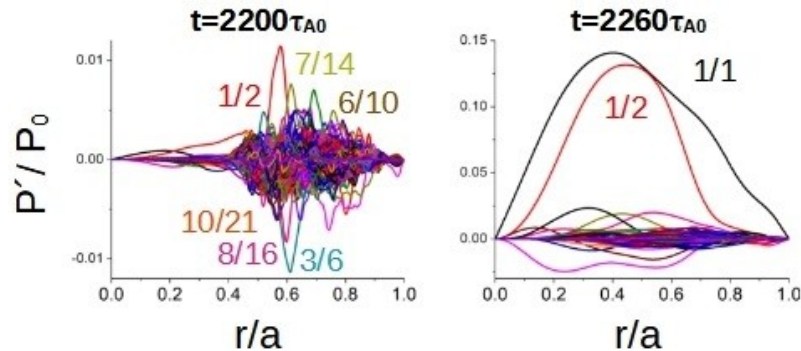
- Perturbation characterization:

- ➔ High n ballooning mode
- ➔ Middle n ballooning mode
- ➔ Low n mode

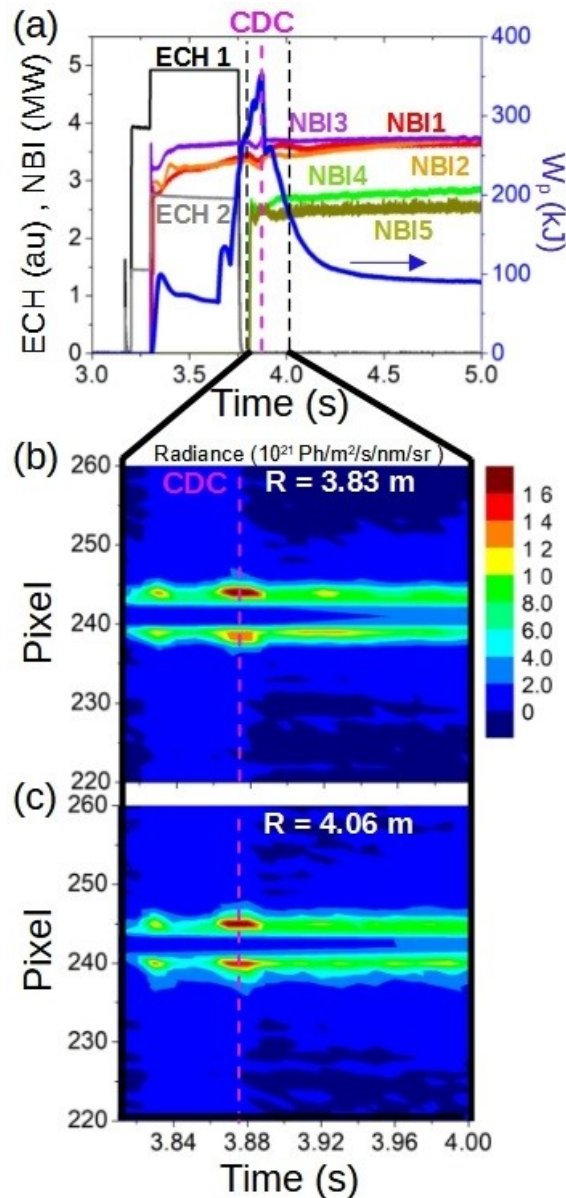
- Fluxes maxima at $t = 2190$ and $2220\tau_{A0}$ are induced by high n BM at $r/a=0.8-1.0$.

- The flux enhancement at $t = 2240\tau_{A0}$ is induced by middle n BM triggered at $r/a=0.6-1.0$.

- Further intensification of the fluxes after the collapse is triggered, once the low n perturbation reaches $r/a \geq 0.6$.

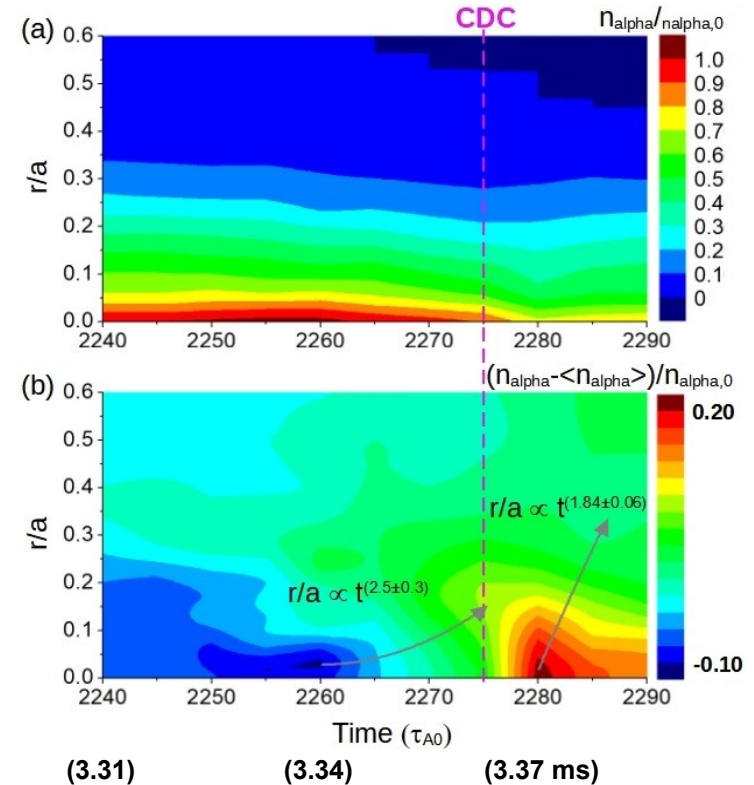
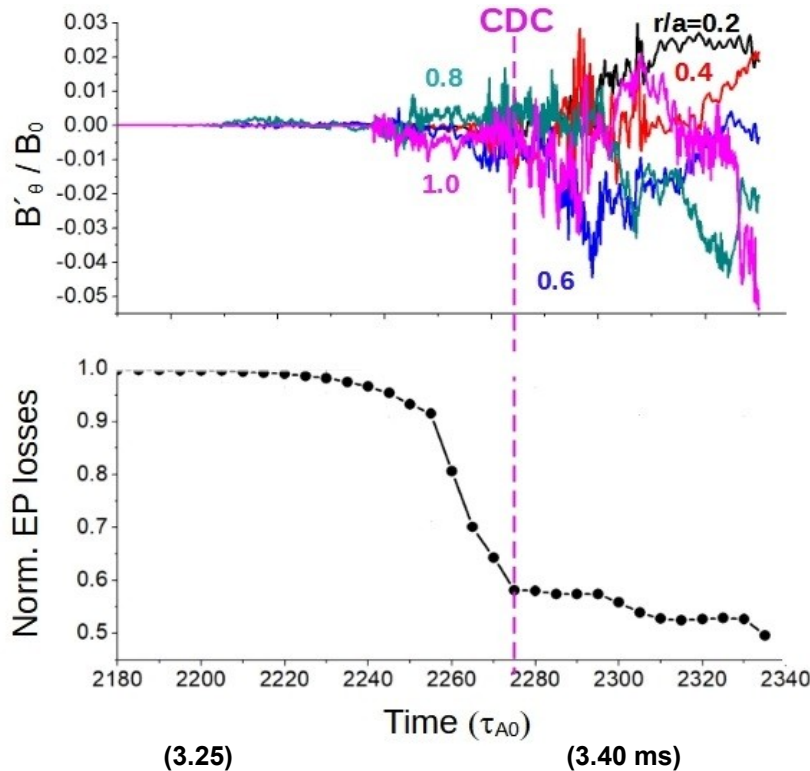


NBI EP transport measured in CDC experiments



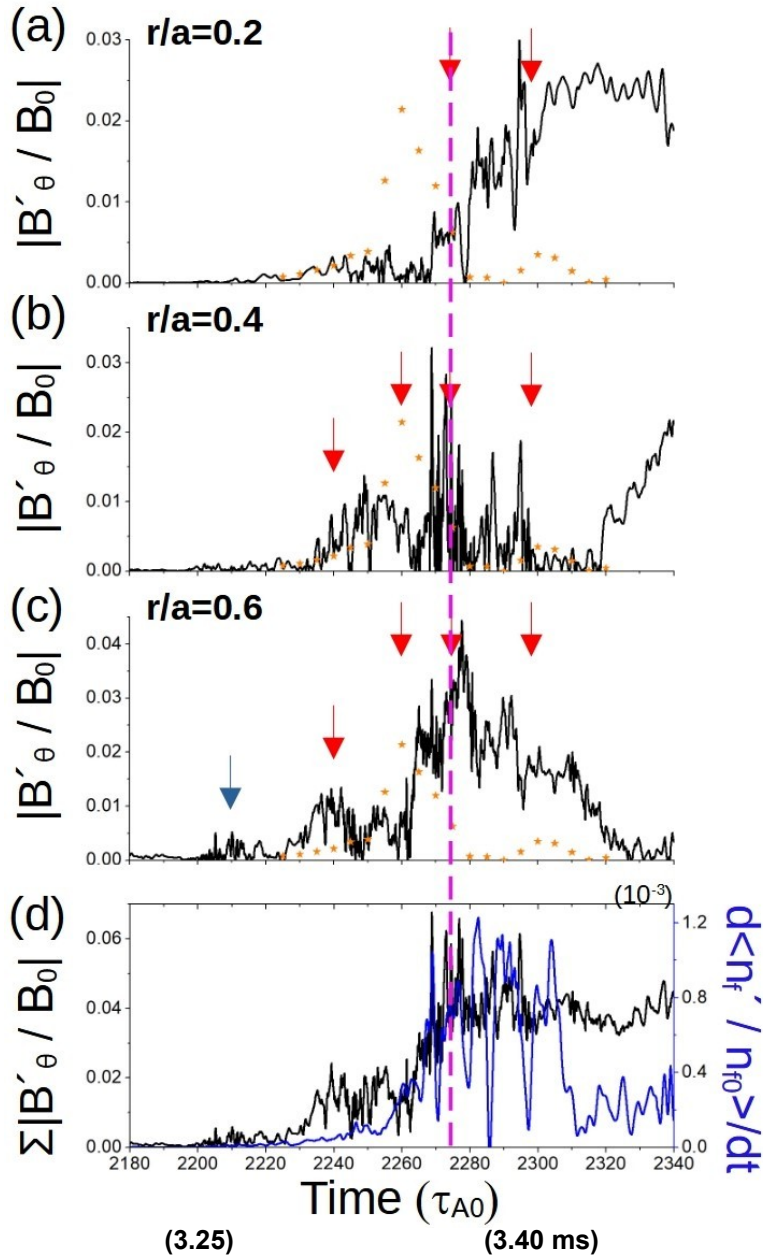
- FICXS diagnostic measures the content of EPs in the plasma.
- Discharge 195257: collapse at $t = 3.874$ s.
- EP content at the plasma core decreases around 50% after the collapse.
- Consistent result comparing to the passing particles losses in the experiment and the nonlinear simulation.
- No information of the trapped EP: outwards measurement location at $R = 4.06$ m, nearby the magnetic axis.

CDC effect on alpha particle transport



- Precursors cause 40% of alpha particle losses.
- Once the collapse is triggered, alpha particle losses reach 50%.
- Precursors remove part of the alpha particle population at $r/a \geq 0.2$ and the CDC destabilization extends the losses to the magnetic axis.
- Ballistic transport linked to the B field stochastization in the middle-inner plasma due to the saturation of middle n and low n modes. Quasi-ballistic once the collapse is triggered.

CDC effect on alpha particle transport



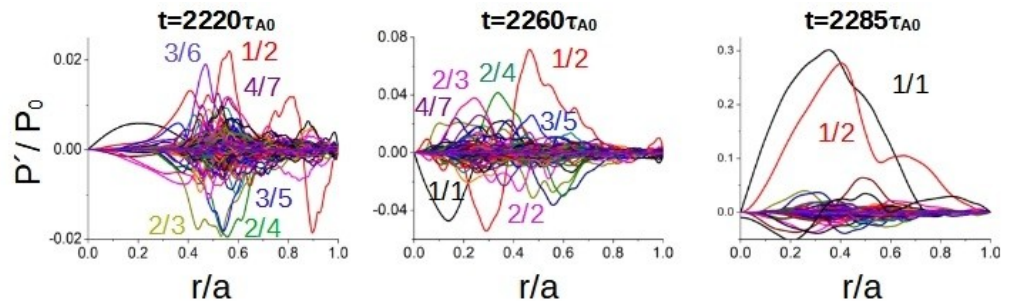
- Perturbation characterization:

- ➔ High n ballooning mode
- ➔ Middle n ballooning mode
- ➔ Low n mode

- Negligible alpha particle fluxes induced by high and middle n BM.

- At $t = 2230-2260\tau_{A0}$ low n modes are triggered at $r/a=0.4-0.6$ leading to enhanced fluxes.

- The most intense fluxes are observed from $t = 2270\tau_{A0}$ once the low n modes extend towards the magnetic axis and the collapse is triggered.



Summary

- $B_{\parallel}$ perturbation is essential to destabilize high n ballooning modes in the simulations.
- Nonlinear simulation reproduce several measured features of CDC events:
 - Saturating high n ballooning modes at the plasma edge can non-linearly destabilize the middle plasma and core (energy cascade from high to low n modes).
 - Inward perturbation propagation observed in the experiment could be linked to unstable middle n ballooning and interchange modes in the inner-middle plasma.
 - An $m=1$ perturbation and partial collapse of the pressure profile at the plasma core.
 - The magnetic field stochastization at the plasma core induced by the $m=1$ perturbation can cause the plasma collapse.
- Future analysis
 - Analysis of edge magnetic field shaping on ballooning mode stability.
 - CDC avoidance strategies: plasma fueling and heating pattern.
 - Extend the analysis to different magnetic field configurations: quasi-axisymmetric, quasy-isodynamic, etc ... (TODAY EXPERIMENT AT W7-X)

Summary

- Tangential NBI EPs:
 - 50% passing EP losses caused by saturating middle n ballooning modes in the middle plasma region and low n modes at the inner plasma.
 - Ballistic EP transport linked to the stochastization of the magnetic field. CDC precursors and low n perturbation after the CDC induce intense EP losses.
- Perpendicular NBI EPs:
 - 80% trapped EP losses caused by saturating high and middle n ballooning modes at the plasma edge, leading to the magnetic field stochastization.
 - Precursors induce a ballistic transport before the CDC destabilization.
- Alpha particles:
 - 50% losses caused by the combination of saturating middle n ballooning modes in the middle plasma region and low n modes at the inner plasma.
 - Ballistic transport linked to the stochastization of the magnetic field. The largest losses and fluxes induced by the precursors.
- FICXS measurement indicates a decrease of the EP content at the plasma core, mainly passing EPs generated by the tangential NBI once the CDC is triggered.
- CDCs does not only reduce the confinement capability of the device, it also significantly decreases the heating performance: must be avoided in Fusion reactors !!