Nonlinear simulations of core density collapses in Large Helical Device

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ABSTRACT

The stability of ballooning modes at the plasma edge of Stellarator fusion reactors is a major concern, considered a severe limiting factor of the device performance, particularly for low magnetic shear configurations based on quasi-isodynamic symmetry magnetic traps, restricting the maximum thermal β of the operation scenarios. The present analysis is dedicated to study the core density collapses (CDC) observed in Large Helical Device (LHD), a hard MHD limit relaxation caused by the destabilization of high n ballooning modes at the plasma edge, leading to the collapse of the plasma pressure and the LHD performance deterioration. A set of simulations are performed using the code FAR3d to reproduce the CDC [1].

BACKGROUND

-LHD outward shifted configurations are unfavorable with respect to the stability of ballooning modes at the plasma edge [2].

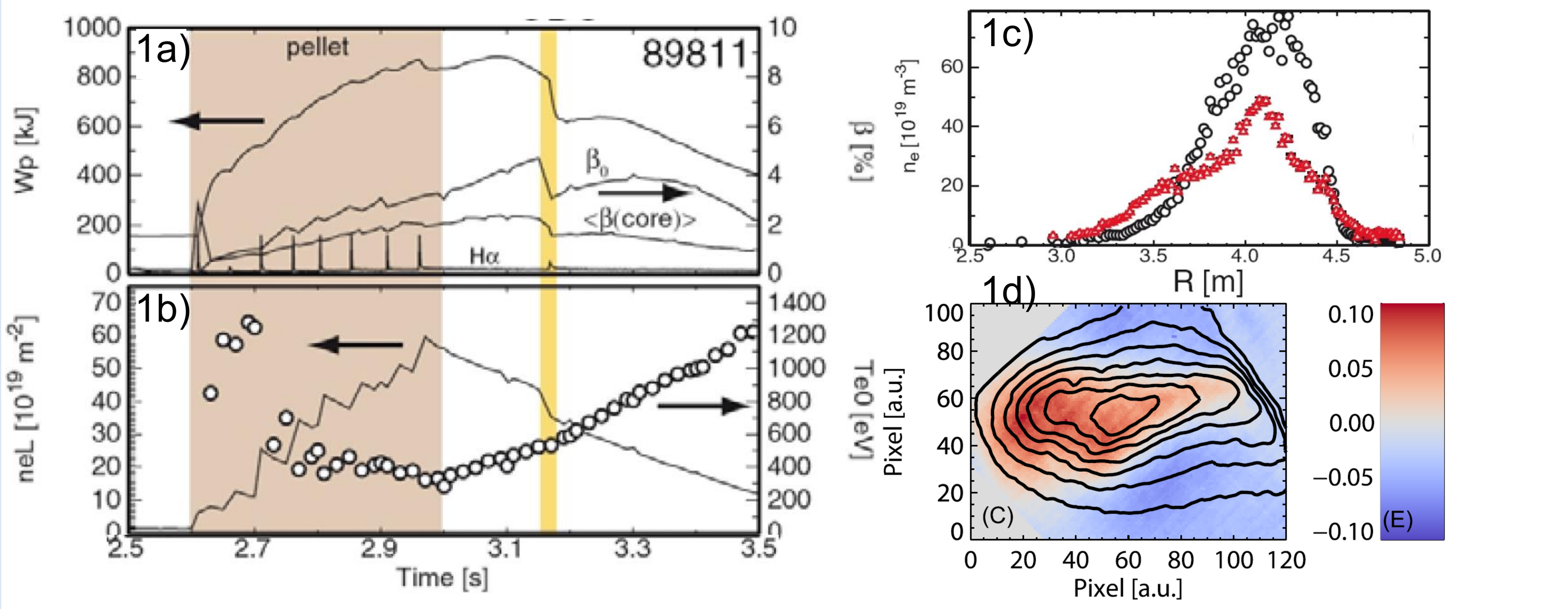
-Intense pressure gradients exist consequence of a strong fueling by pellets [3], destabilizing core density collapses (CDC), fig 1a and b [4].

-Experimental indicate the precursor of the CDC are high n ballooning modes destabilized at the plasma edge [5].

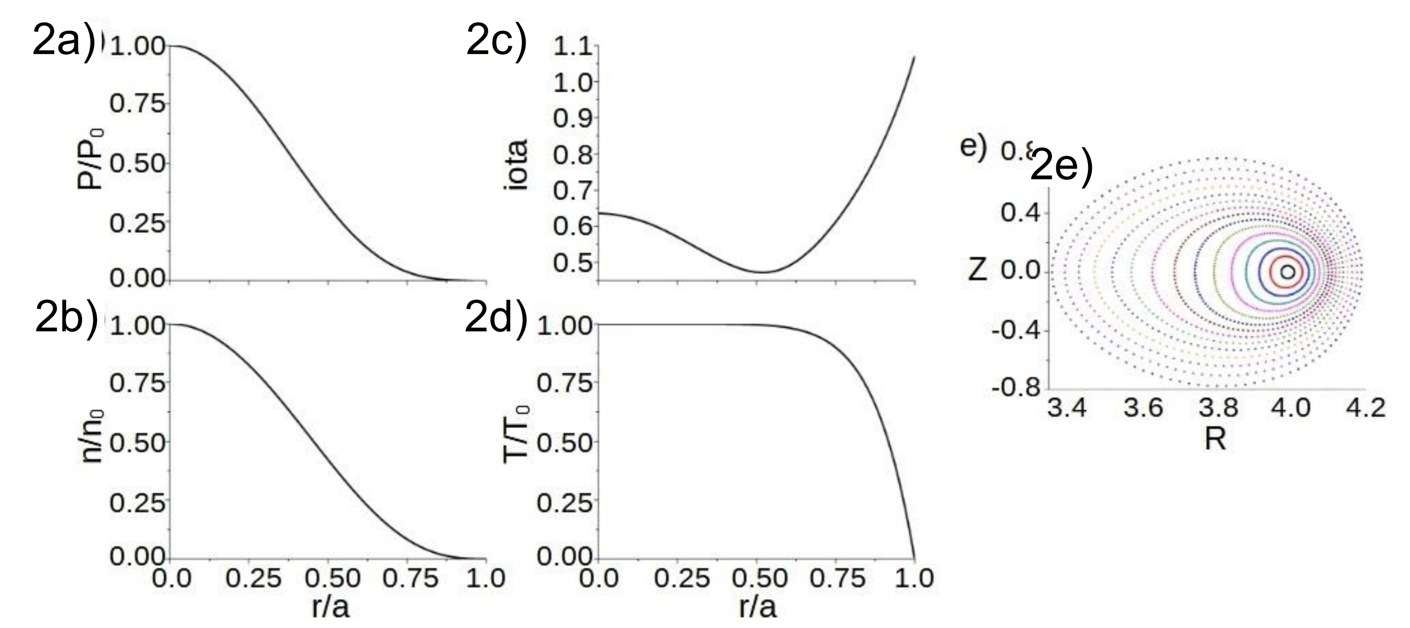
-The CDC causes a significant decrease of the thermal β and energy contained in the plasma linked to a drop of the plasma density, fig. 1c.

-The collapse in the core that takes place in around 0.5 ms linked to an m=1 instability triggered at r/a = 0.1 – 0.15, fig. 1d.

-During the collapse, a perturbation from the plasma periphery propagates towards the inner plasma (from low to high field side).

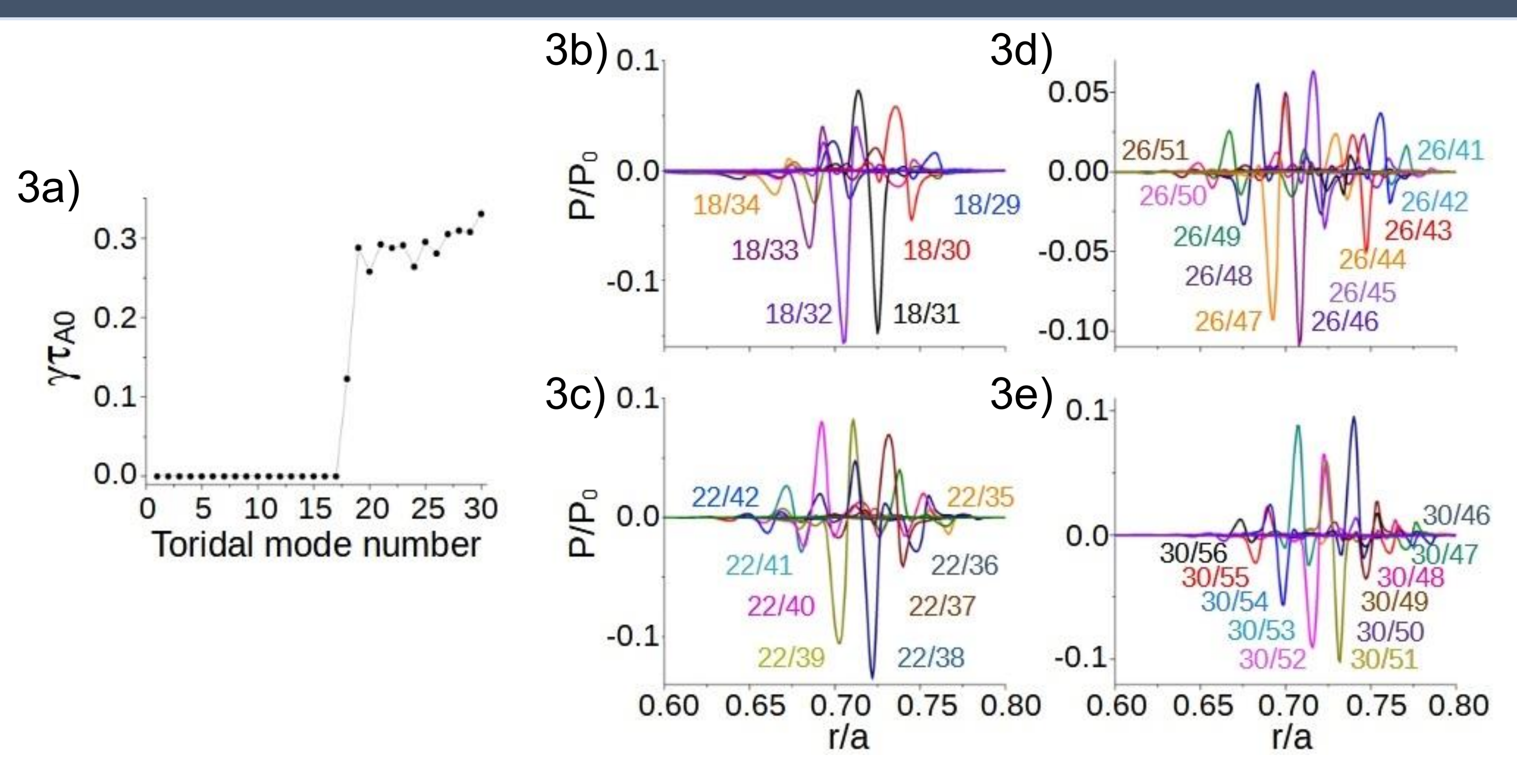


NUMERICAL SCHEME AND MODEL PARAMETER



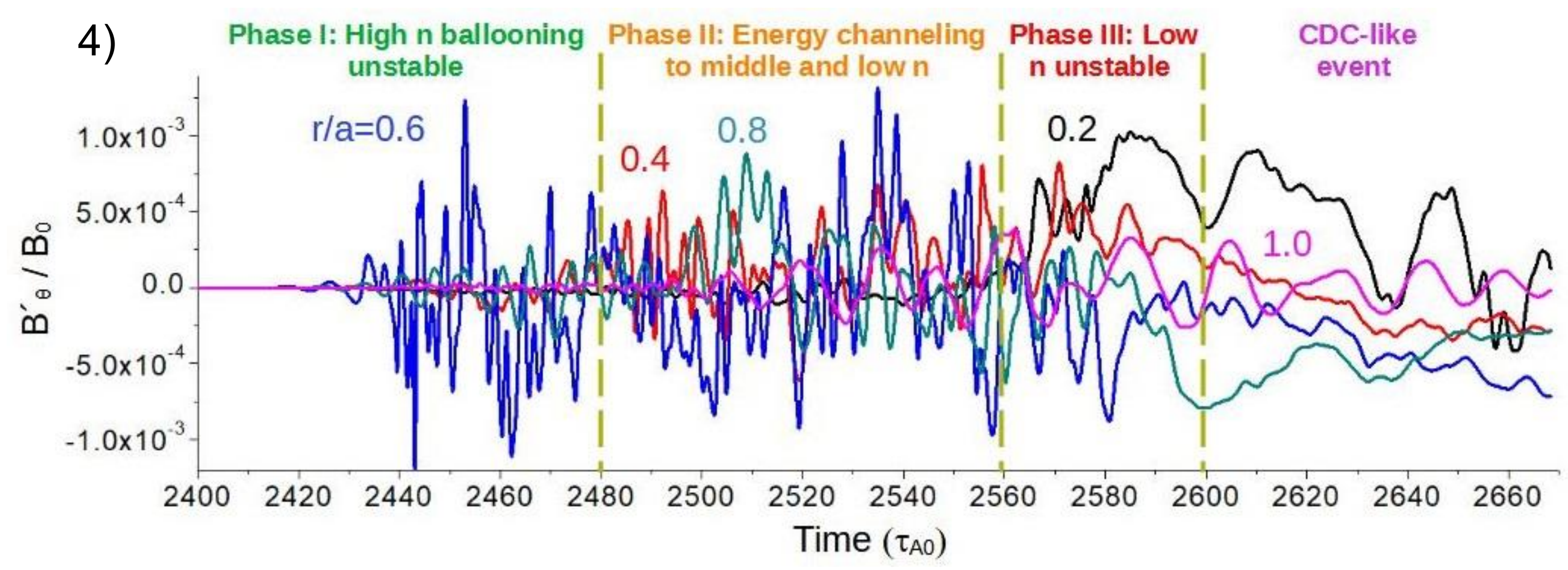
- A free boundary equilibrium (VMEC) of the discharge 69268 is calculated before the CDC event, fig. 2c and e. The magnetic field intensity is 2.539 T and the vacuum magnetic axis is 3.85 m.
- Thomson scattering diagnostics data is used to identify the function form of the plasma synthetic profiles, fig. 2a, b and d.
- Toroidal mode families n=0 to 30 including all resonant modes (610 modes). The radial grid has 1000 points linear (400 nonlinear) simulations. The magnetic Lundquist number is 10. Normalized diffusivity is D = 5x10^{-5}.

BALLOONING MODES LINEAR STABILITY

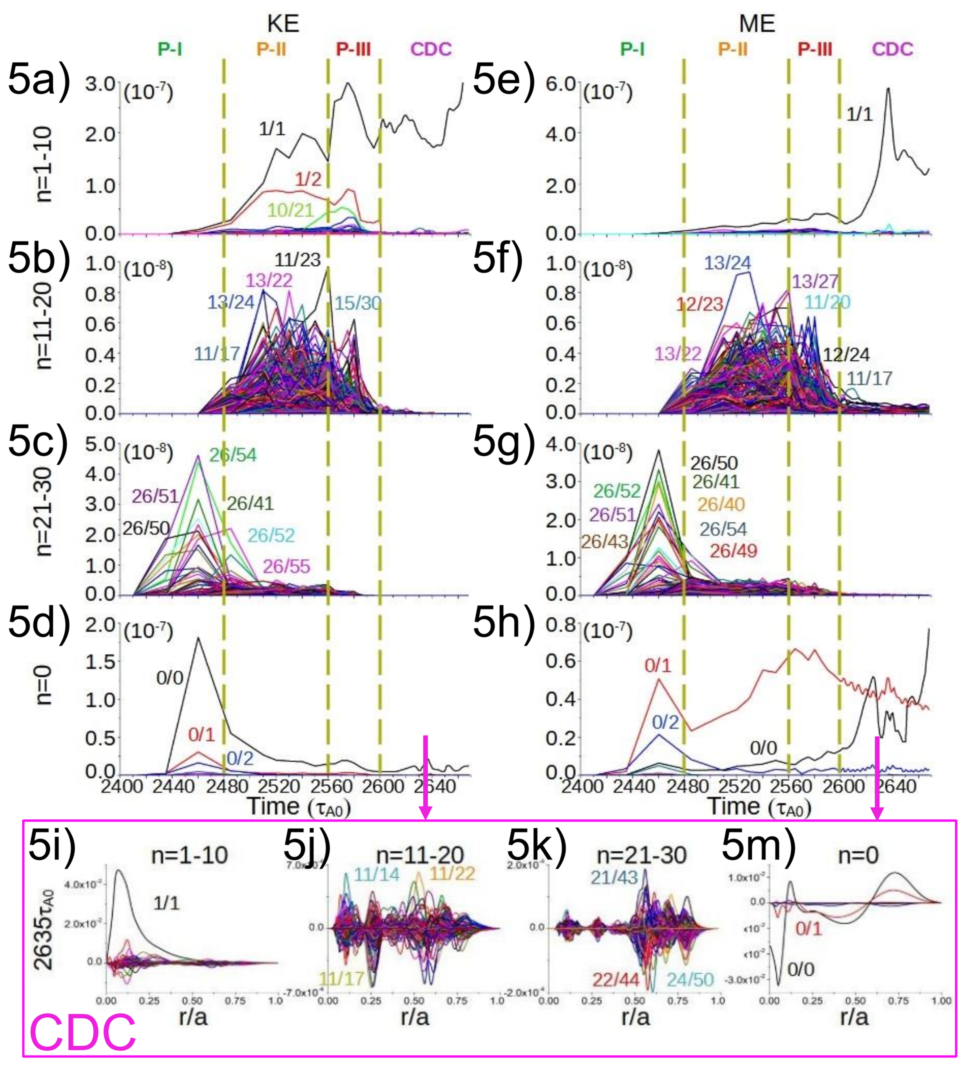


- Unstable pressure gradient driven modes if n > 17, fig 3a.
- Perturbations located at r/a = 0.65 – 0.8 (maximum amplitude at 0.7-0.75).
- Large poloidal mode coupling indicates the destabilization of ballooning modes (BM) at plasma outer region with local bad curvature, fig 3b-e.

CDC AND BALLOONING MODE SATURATION

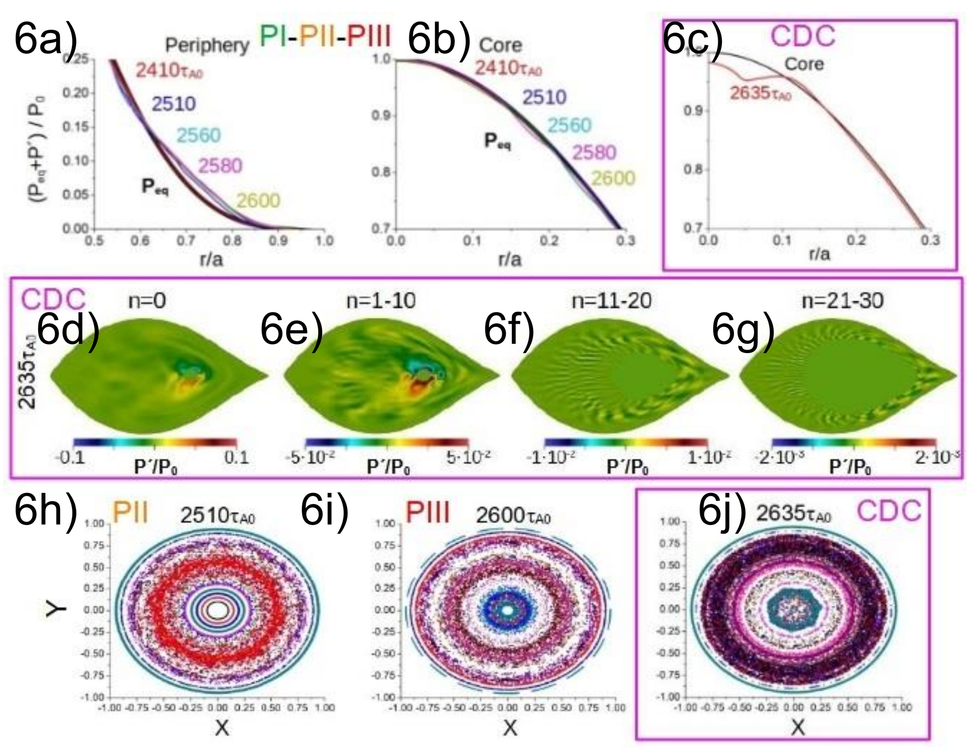


- Nonlinear simulation is divided into 4 phases (B_θ field perturbation, fig 4):
1. PI (t = 2400 – 2480τ): High n BM destabilization.
2. PII (t = 2480 – 2560τ): High n BM saturation and inverse energy cascade to middle n=11-20 and low n≤10 modes.
3. PIII (t = 2560 – 2600τ): Inner plasma and low n mode unstable
4. CDC (t > 2600τ): Low n modes cause the core pressure profile collapse.



- Kinetic (KE) and magnetic energy (ME) analysis, fig 5a-h:
PI: High n BM dominant.
PII: High n BM saturate, middle - low modes unstable.
PIII: Low n modes dominant, middle n modes saturate.
CDC: m=1 perturbation dominant, 0/0 ME maximum, torn core magnetic surfaces.

- Eigen-functions during CDC, fig. 5i-m: Core 1/1 perturbation, middle - high n perturbation decay, large 0/0 amplitude at the core.



- Pressure prof. evolution (6a-c):
PI-PII-PIII: High n BM saturate, edge pressure gradient reduces, perturbation propagates inwards.
CDC: Core pressure collapses linked to the m=1 perturbation.

- Poloidal pressure contour (6d-g):
CDC: Core localized m=1 perturbation and strong distortion of the magnetic surfaces.

- Poincare plot of B field (6h-j):
PII-PIII: BM cause stochastic regions in middle-outer plasma.
CDC: core stochastic region caused by m=1 perturbation.

CONCLUSION

- **Linear analysis shows n>17 BM at r/a=0.65-0.8. CO2 laser imaging interferometer data measure BM at the outer plasma region, identified as the precursors of the CDC event.**
- **Nonlinear simulations reproduce several experimental observations:**
  1. Instability propagation from the periphery towards the core.
  2. m=1 perturbation triggered nearby the magnetic axis.
  3. Time scale of the CDC relaxation: approximately 0.5 ms.
- **High n BM destabilized at the plasma edge cause an inverse energy cascade leading to the low n modes destabilization at the core.**
- **Saturating BM distort the flux surfaces at the middle-outer plasma flattening the pressure profile, although enhancing inner plasma pressure gradients and promoting low n modes destabilization.**
- **Energy channeling from m=1 perturbation towards the thermal plasma strongly perturbs the core magnetic surfaces, generating wide stochastic regions by reconnection process, leading to the pressure profile collapse and the deterioration of the plasma confinement.**

ACKNOWLEDGEMENTS / REFERENCES

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