



Core density collapse phenomena observed in high-beta Helical plasma and its relationship to high-n Ballooning modes

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Outline of my talk

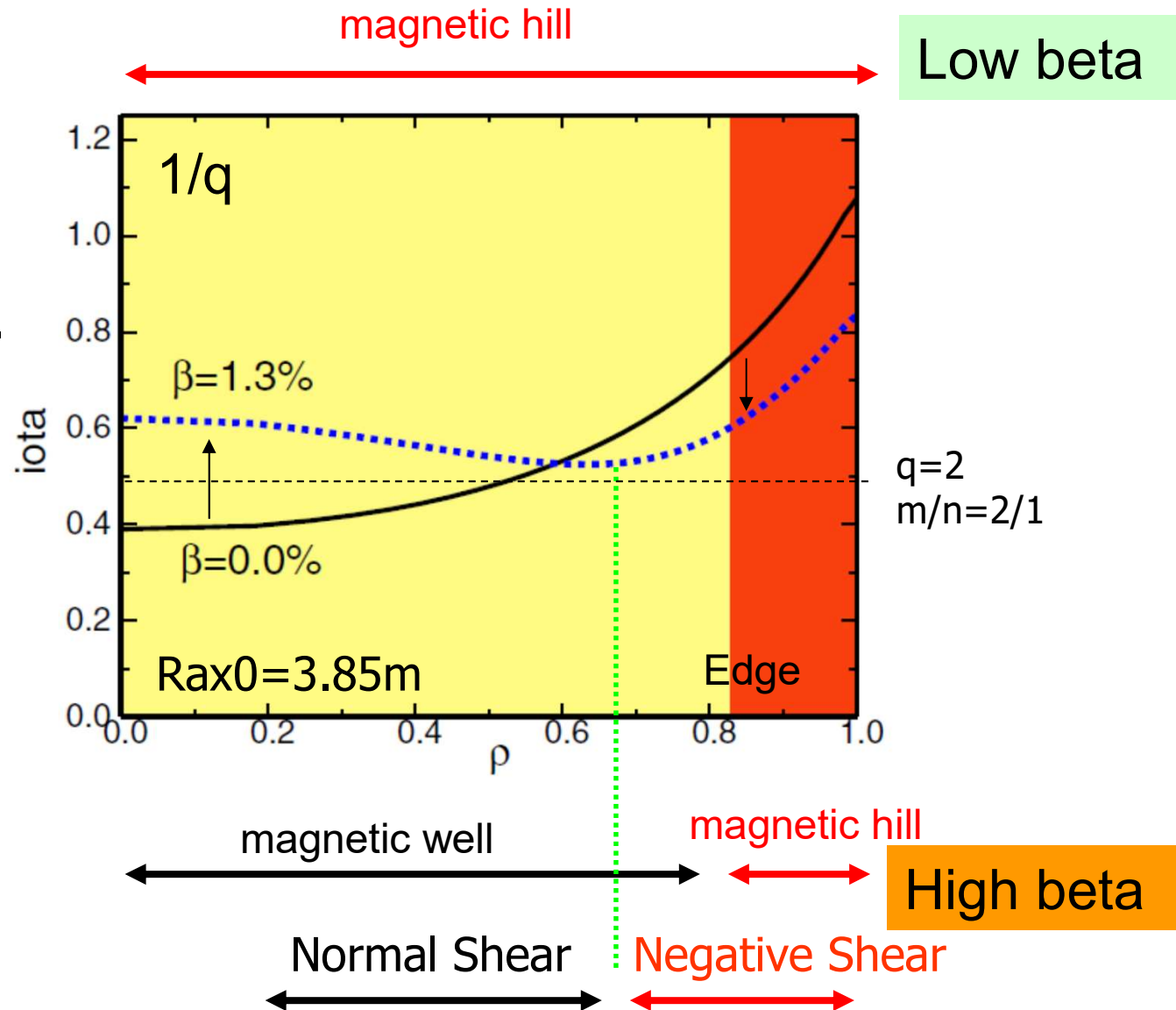


- Various kinds of MHD instabilities are observed in LHD
 - Plasma can be sustained safely in Mercier-unstable region with magnetic fluctuations. Effect on confinement is small in normal operations.
 - Pressure profile is peaked / magnetic shear is reduced ...
 - Sawtooth-like phenomena with low-n unstable region
- Core density collapse (CDC) in Internal Diffusion Barrier with super dense core (IDB/SDC) plasma is the first MHD phenomena where operational region is restricted by the appearance.
 - Characteristics of CDC. Impact on the confinement.
 - Condition for the appearance and its relation to ballooning unstable region.
 - Ballooning-mode like precursor.
- Profile control to avoid CDC phenomena.

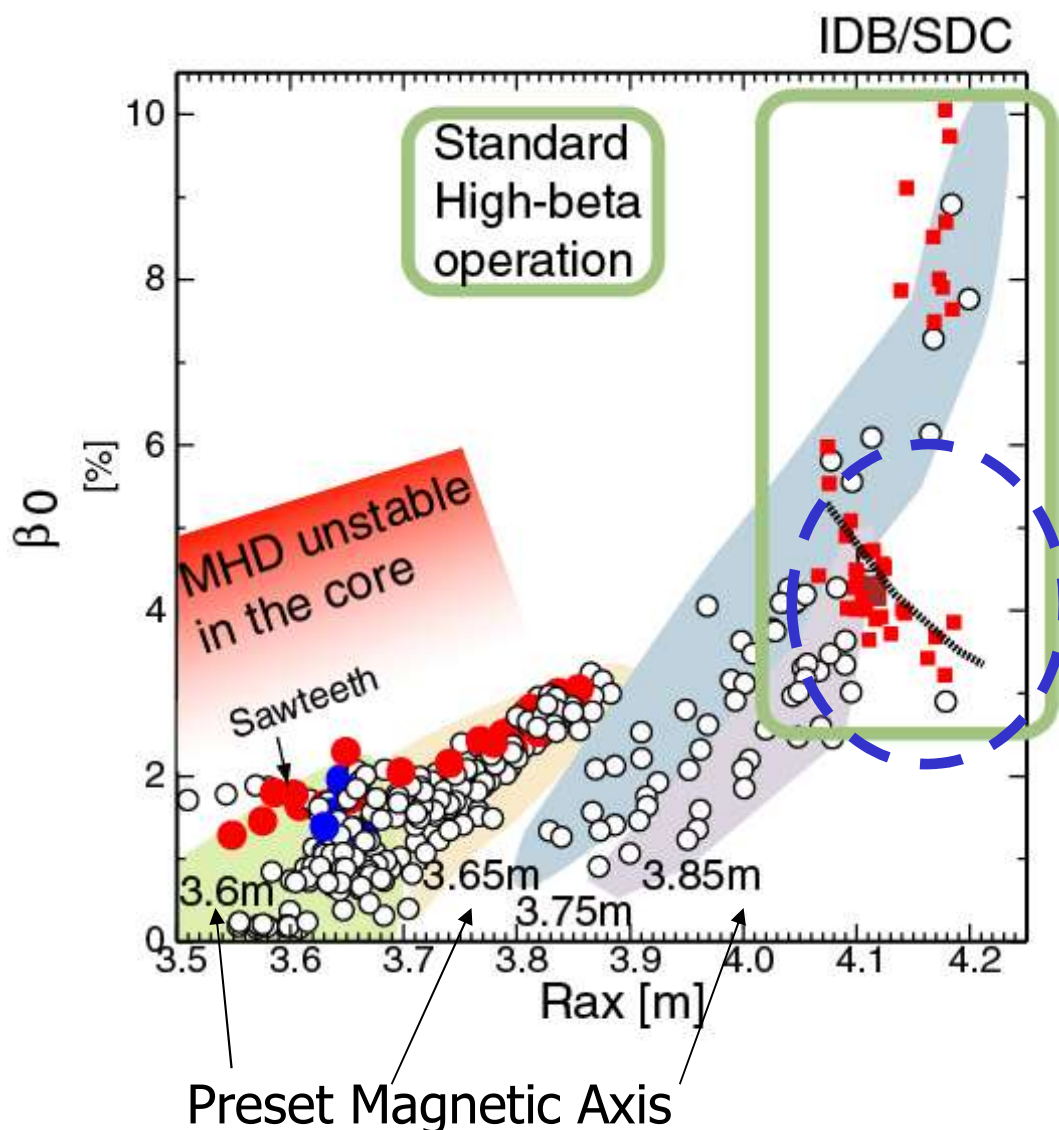
Typical Iota profile and well/Hill boundary



- In LHD, **pressure gradient driven modes** are important; stability depends on magnetic well depth.
- With increase of beta, the well region expands. (core instabilities vanish.)
- **Ballooning mode** both in Tokamak-like normal-shear region and negative-shear region is expected with steep pressure

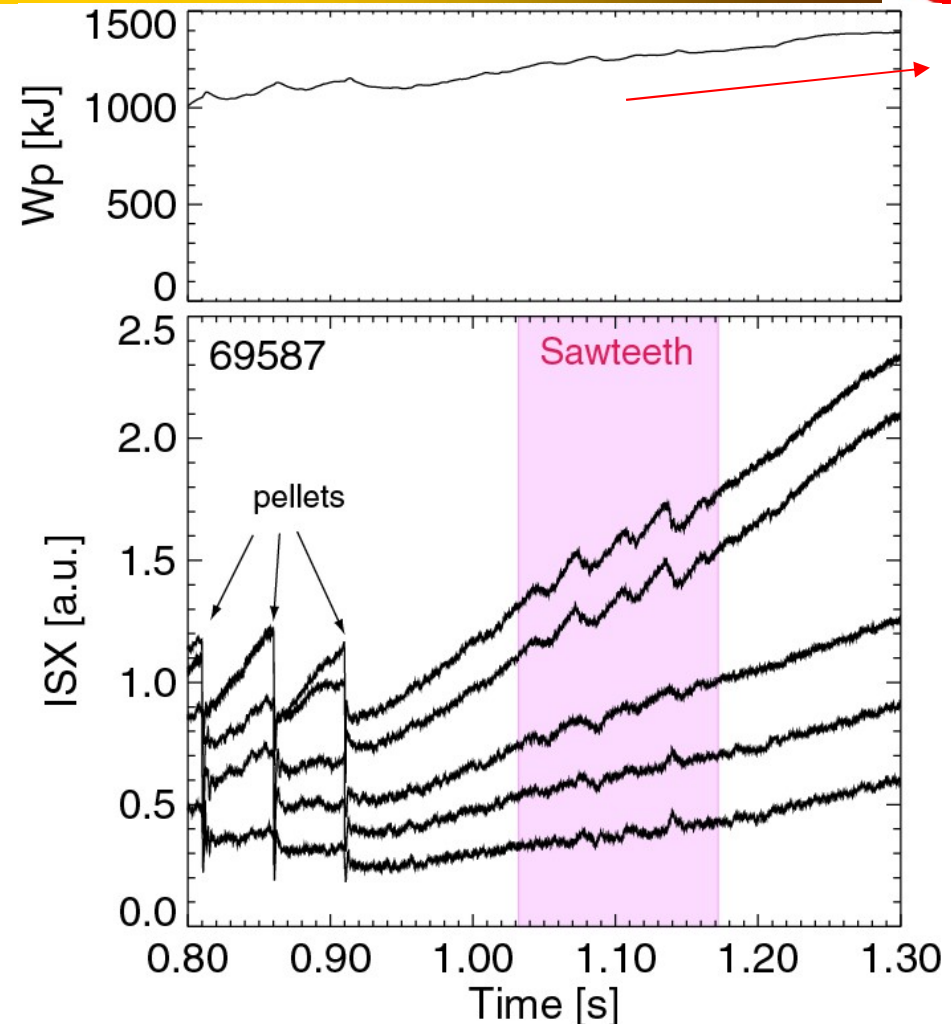
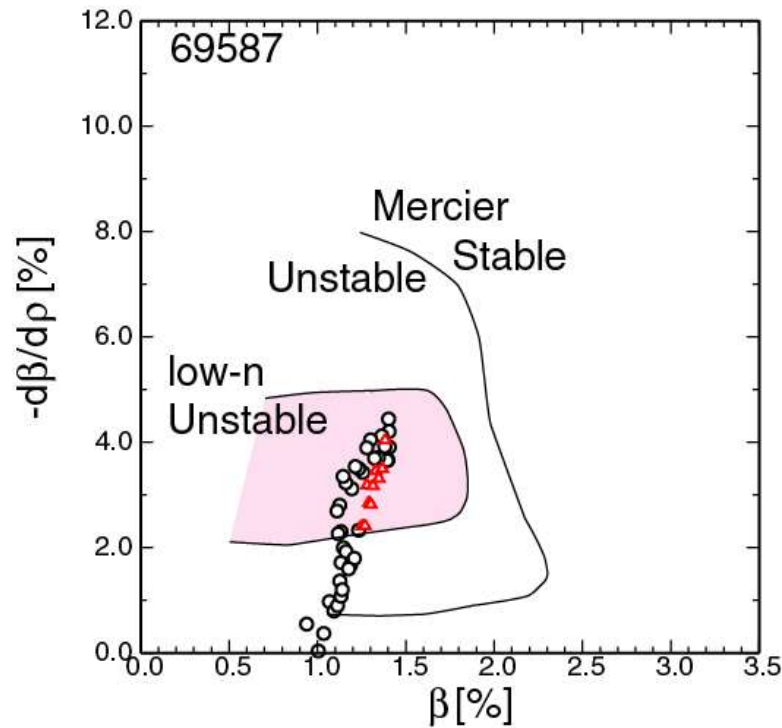


MHD instabilities and high- β operational regime



- When the magnetic axis is shifted inward, $m/n = 2/1$, $3/1$ sawtooth is unstable. (effects are smaller.)
- In outward shifted cases, fairly peaked profile is realized, which we call internal diffusion barrier with super dense core (IDB/SDC) plasmas. CDC is observed in such kind of operations.

Sawtooth-like activities

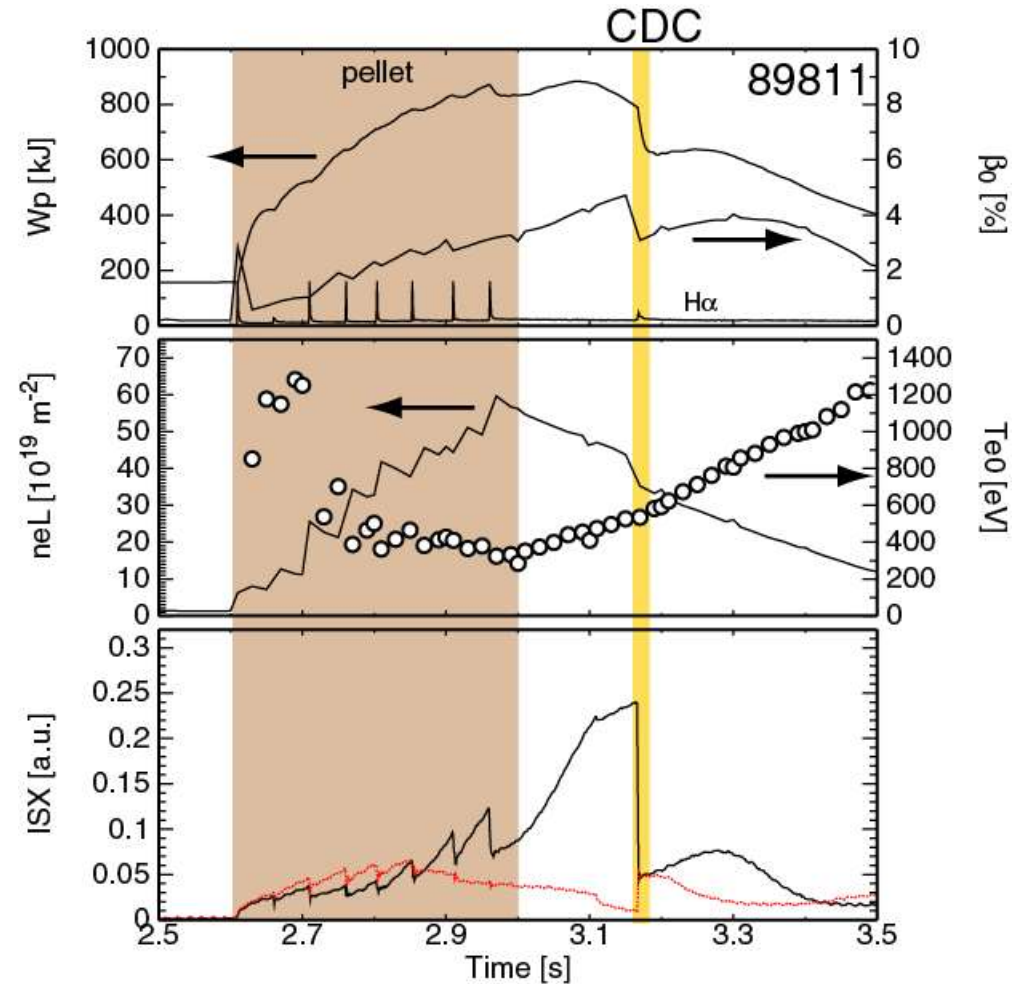


- After pellet injection, pressure profile is more peaked than gas-puffing discharges.
- When the pressure gradient exceeds the low-n unstable condition, sawtooth-like MHD activities are destabilized. **The effect on the confinement is very small.**

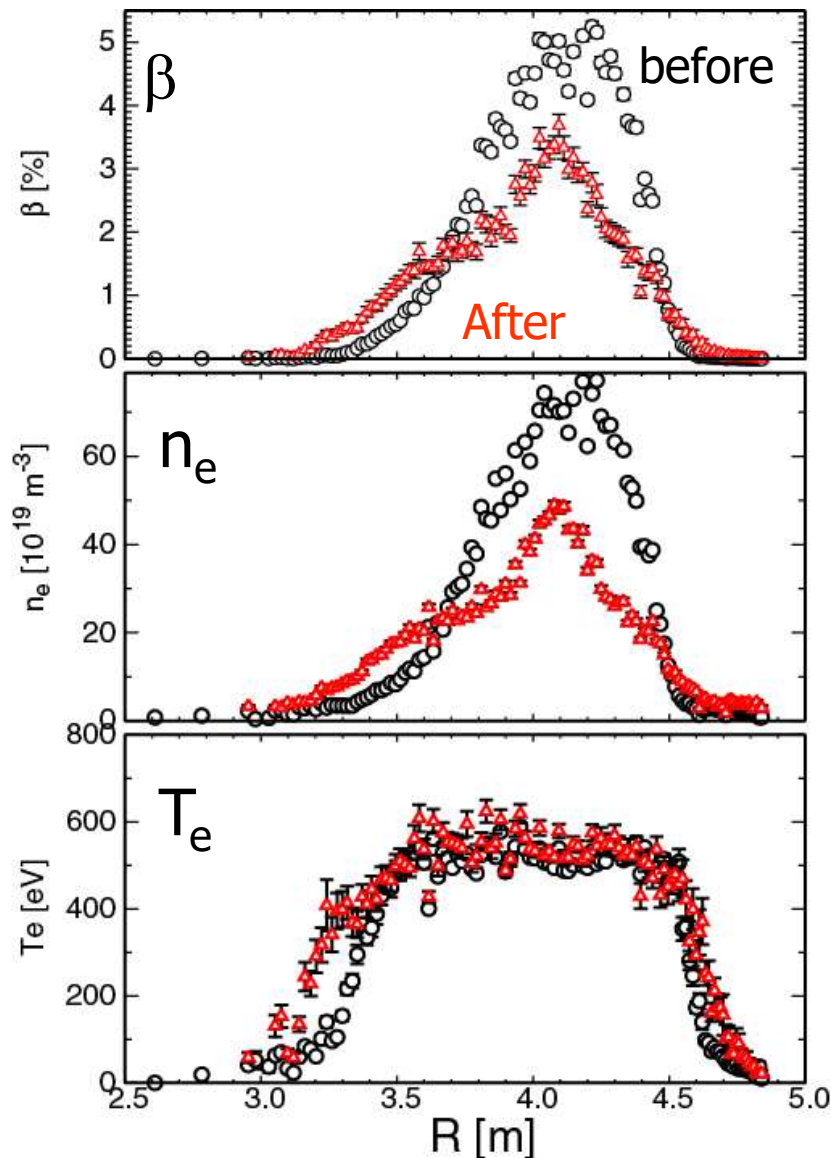
IDB/SDC discharge with CDC



- 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.

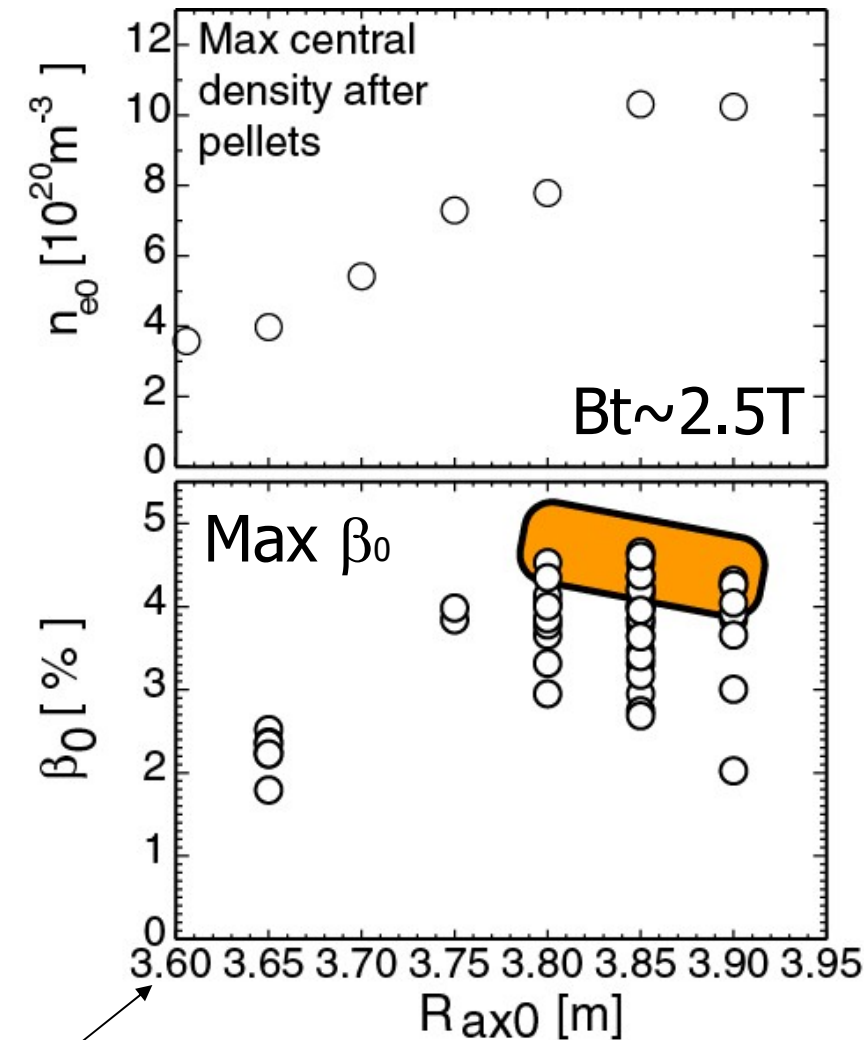


Profile changes with CDC events



- Central beta/density decreases by up to 50%.
- Whole plasma is affected; rapid increase in I_{is} at divertor probes is observed with CDC.
- The drop of the electron density in the core is obvious. Though we have named this event '**Core Density Collapse**' due to this characteristic, it does not mean that the electron temperature is not affected.
- \Rightarrow Core plasma is transferred to the edge region by a convective manner.

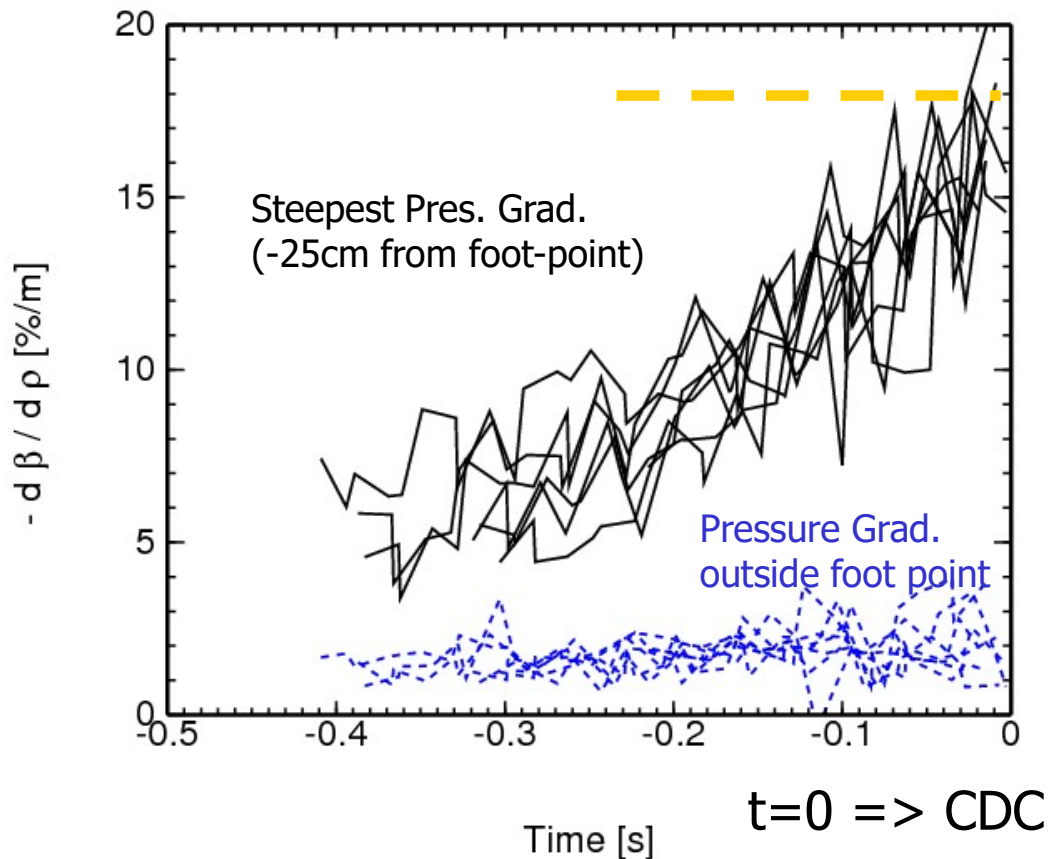
CDC limit the increase of the central beta



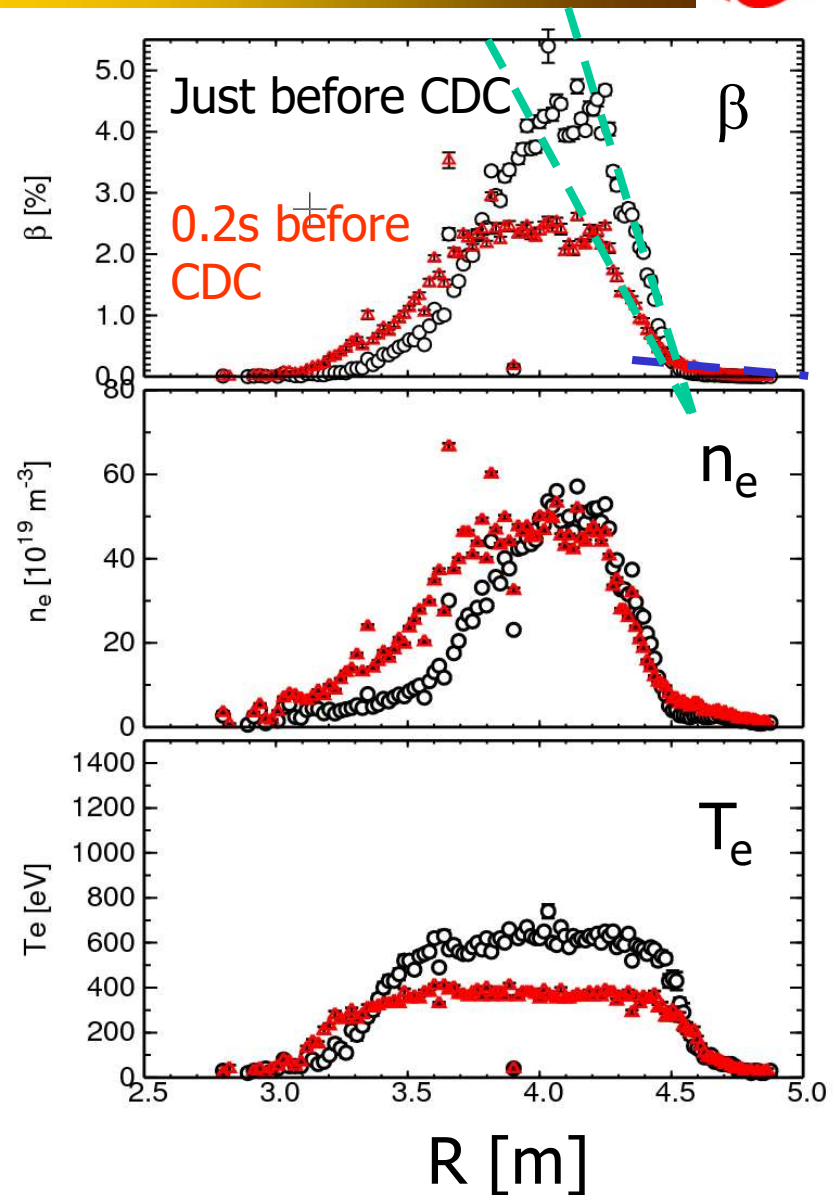
Standard Preset magnetic Axis

- Achievable density is higher, when preset magnetic axis is located outward.
- $R_{ax0} > 3.75\text{m}$, increase of the central beta is **limited by CDC**.
- **Understanding/controlling of the CDC is required.**

Pressure Profile is being peaked until CDC



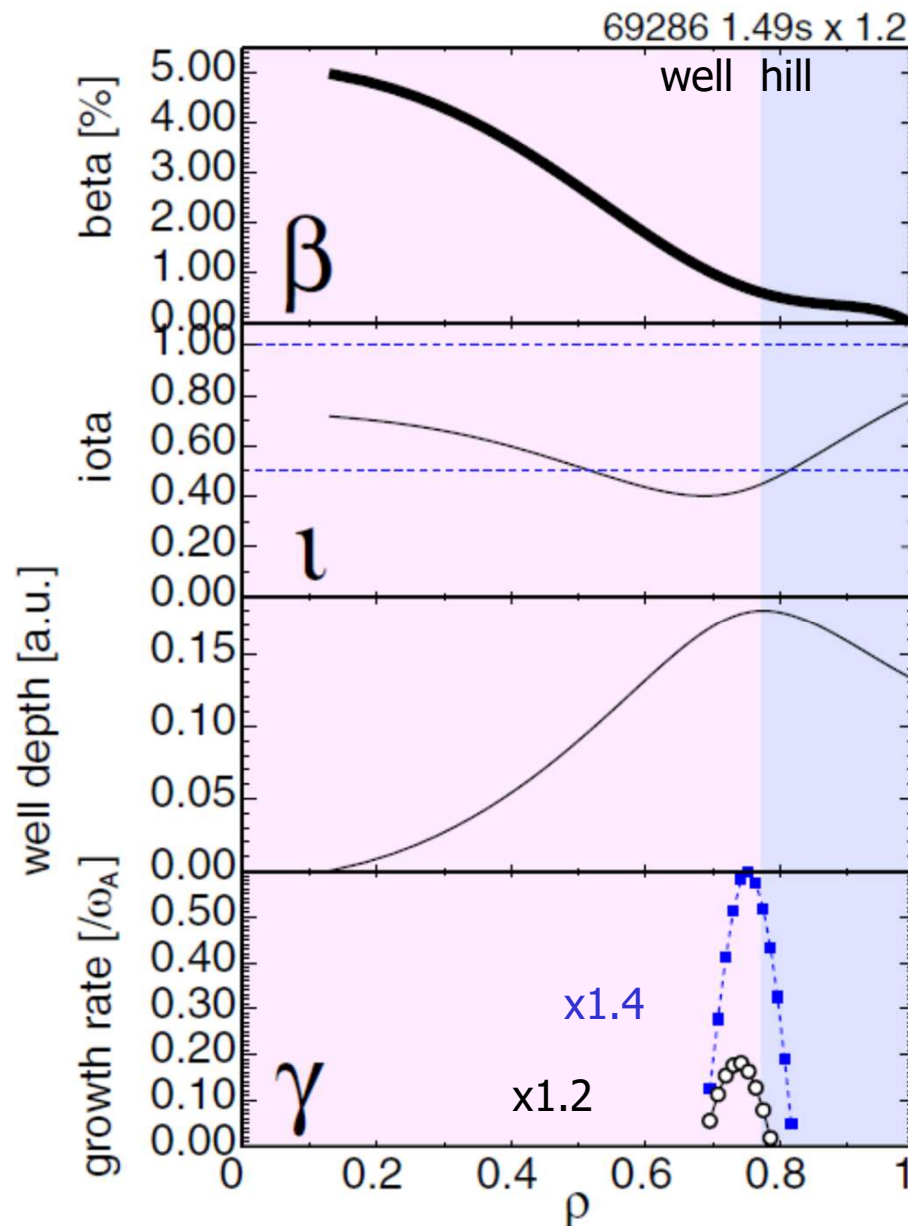
- There is a limit in the pressure gradient before CDC.



Growth-rate is calculated by Hn-Bal code

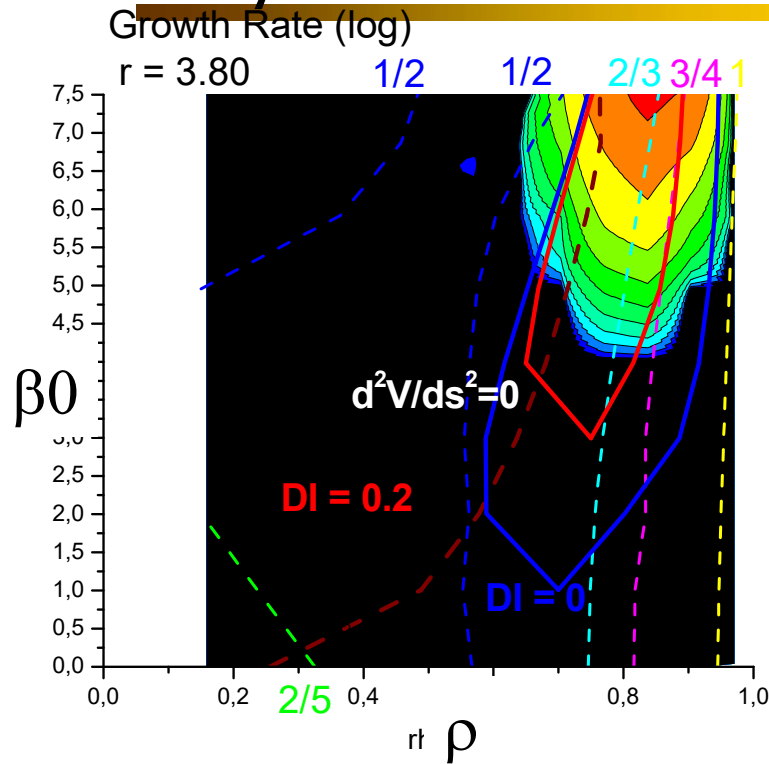


N. Nakajima, et.al., Fusion Science and Technology 51(2007)79

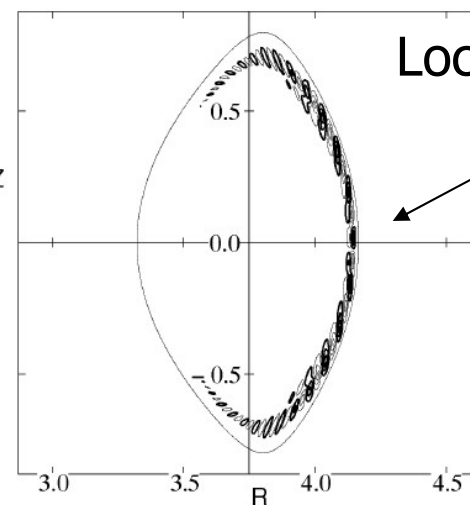
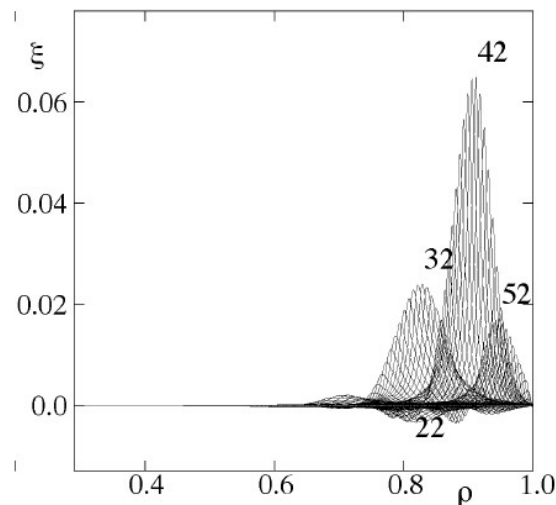


- Growth-rate of ideal ballooning modes using a profile just before CDC is calculated.
- The profile is marginally unstable. When we use pressure profile multiplied by 1.2, unstable region appears localized in the foot of the IDB/SDC profile. (Mercier stable region.)
- The magnetic shear there is negative. \Rightarrow **Helical type ballooning modes.**

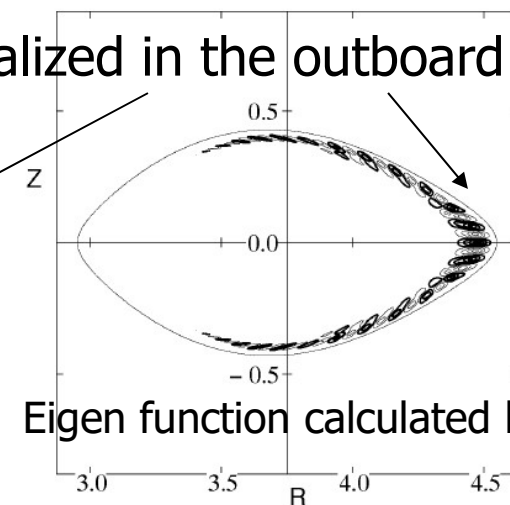
Systematic survey of High-n ballooning mode



- Growth rate are calculated increasing the central beta value.
- High-n ballooning mode is destabilized in Magnetic hill region when central beta is increased.
- Growth rate is estimated in the outboard side of horizontally elongated section. We expect mode structure even in the vertically elongated section.

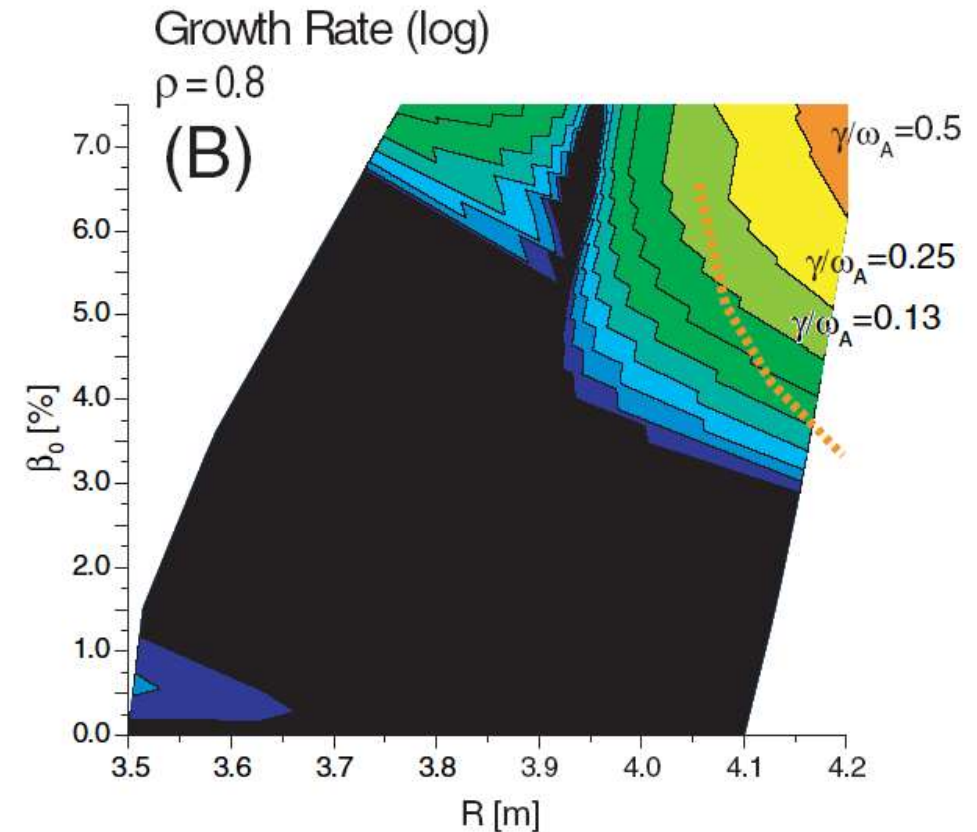
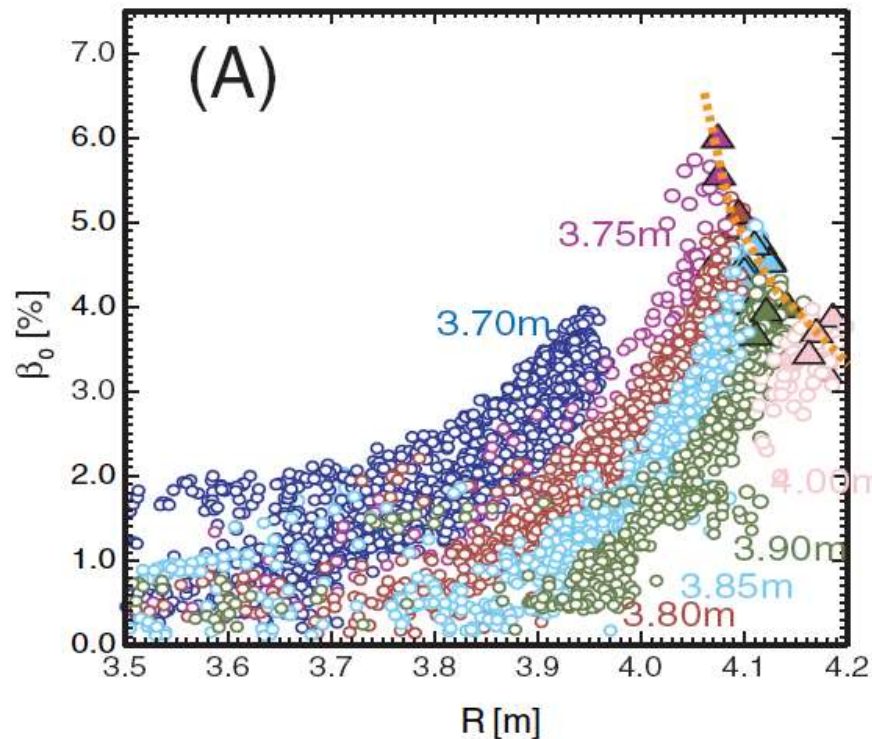


Localized in the outboard region



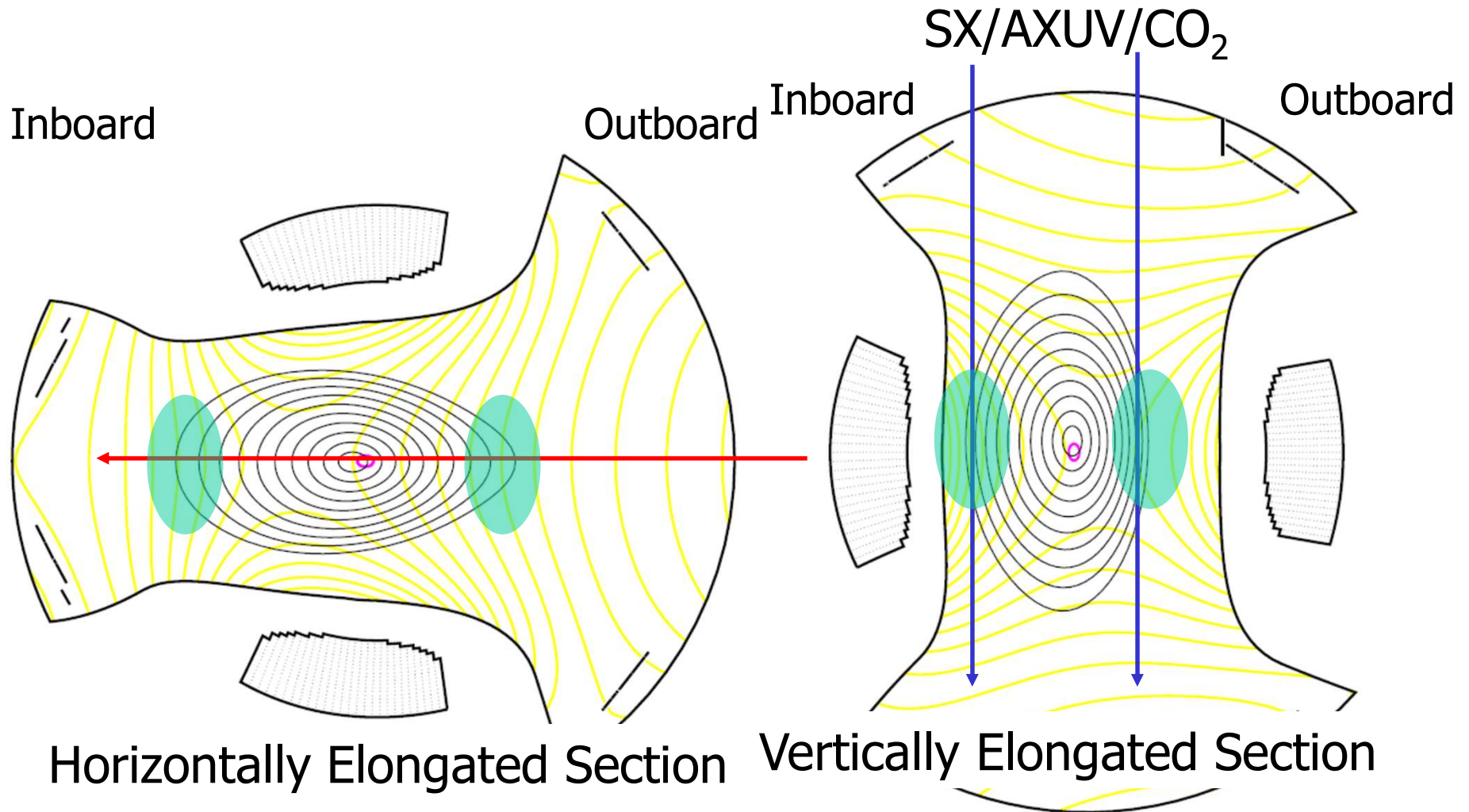
Eigen function calculated by CAS3D

CDC region and Ballooning unstable region



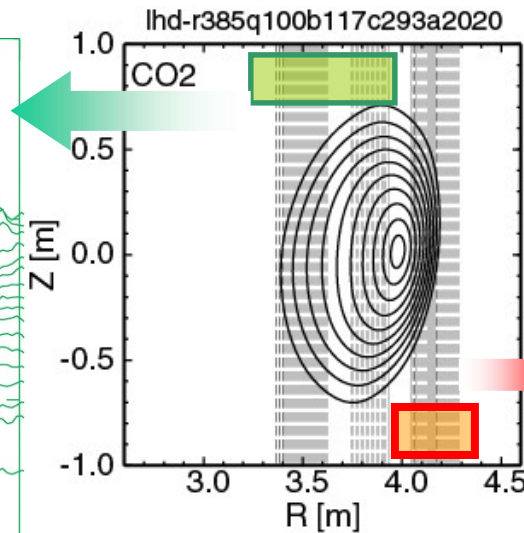
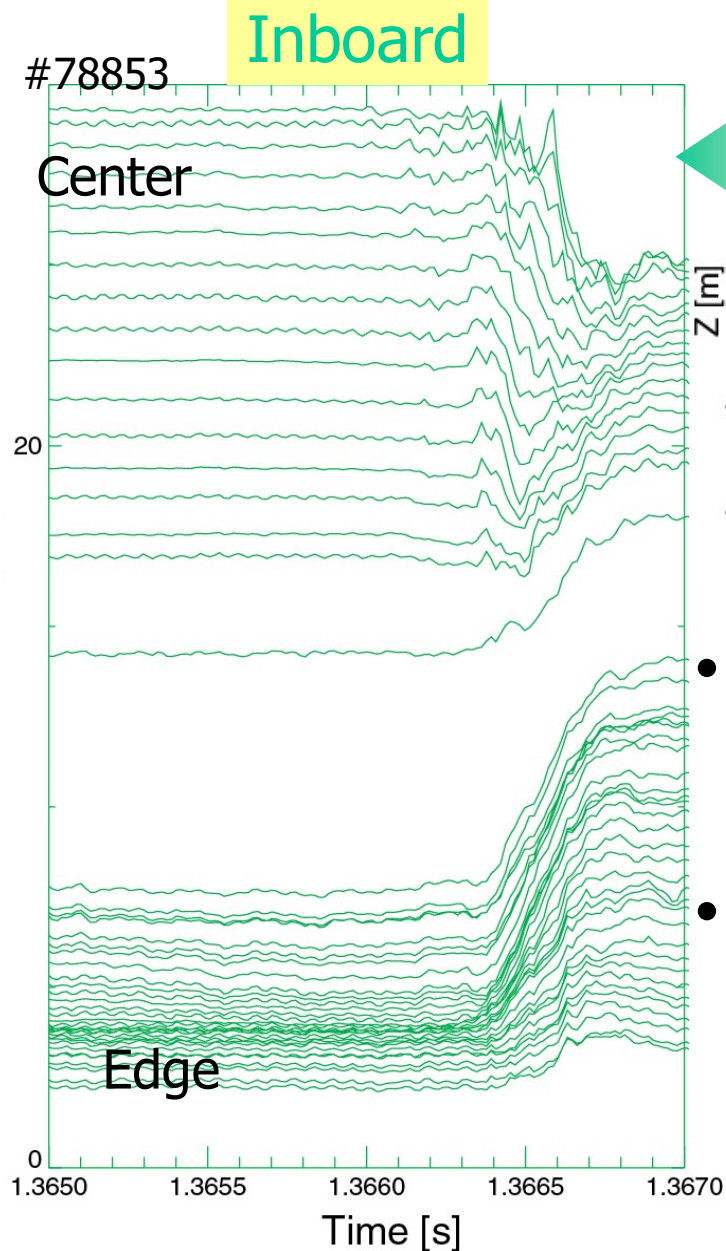
- Experimental data(A) is organized by magnetic axis position and the central beta.
- CDC appears where growth rate is rapidly increasing.

Magnetic field and diagnostics in LHD

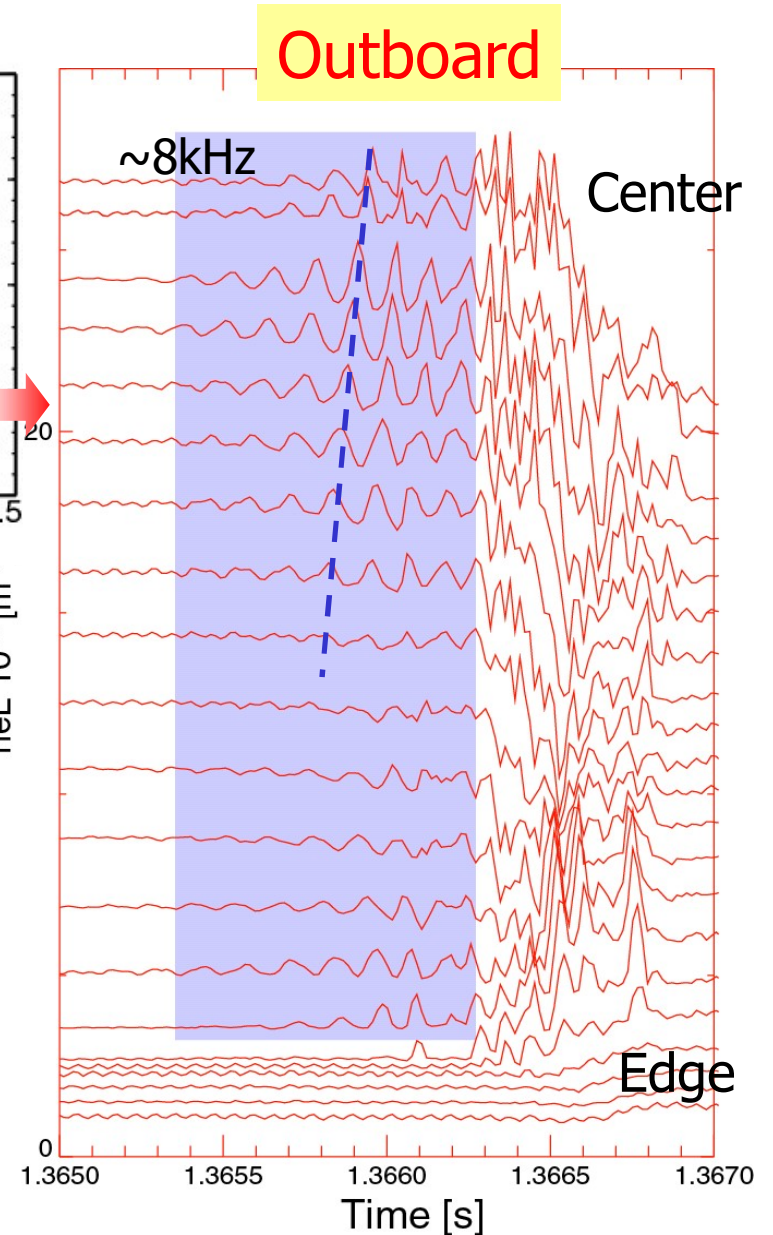


- Most of the fluctuation diagnostics in LHD is **line-integrated** ones.
- We use vertically elongated section to compare **in/out asymmetry**.

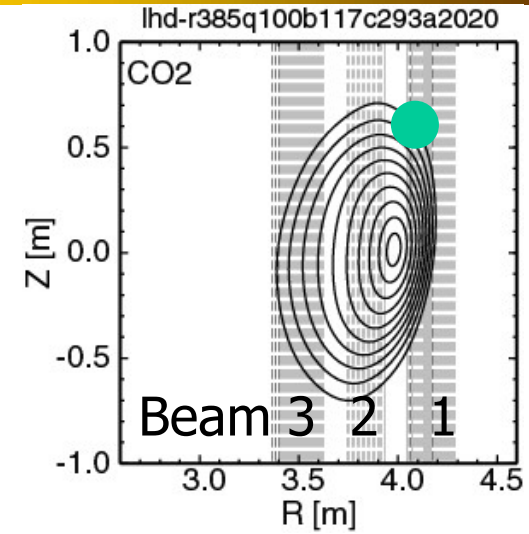
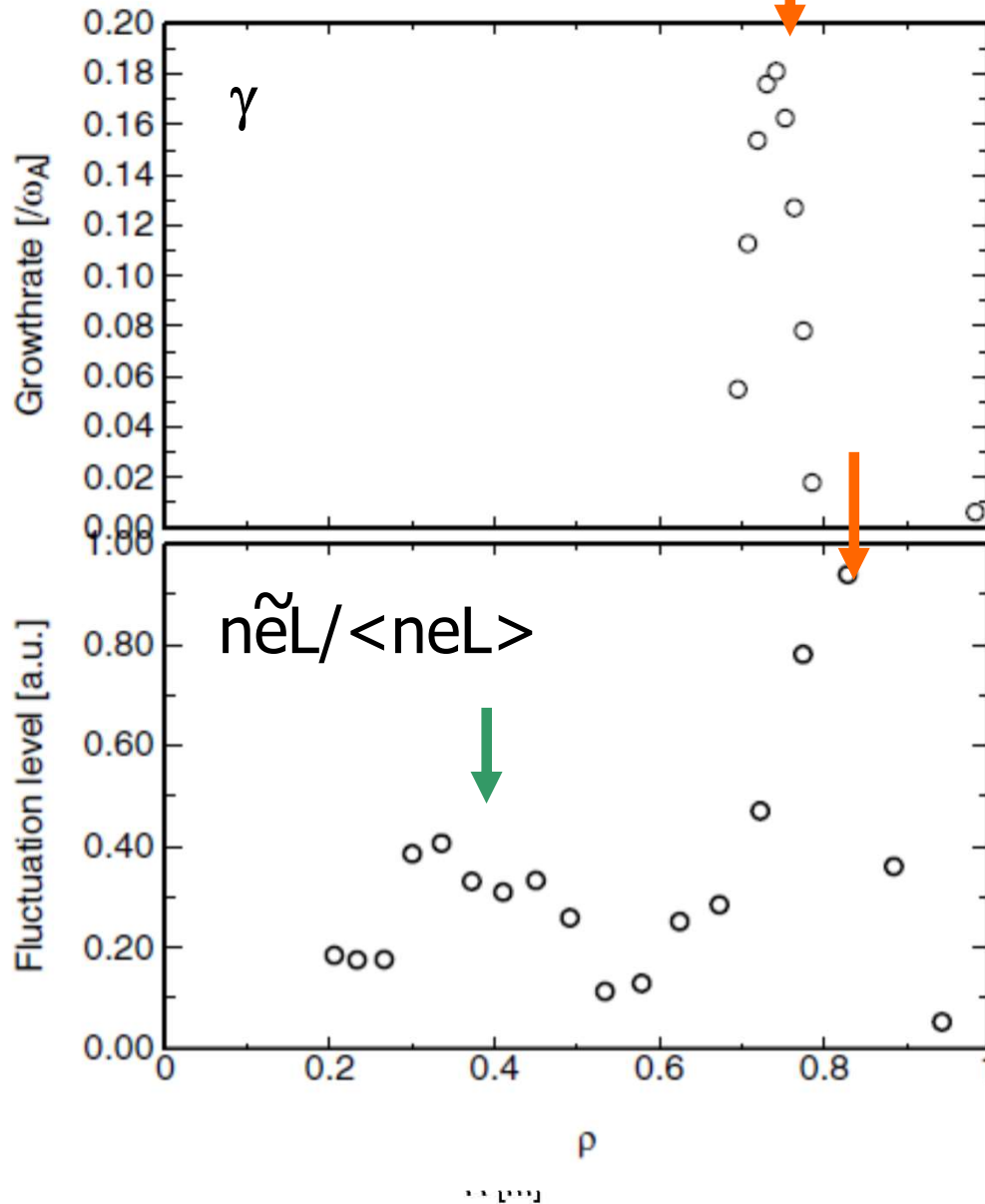
Pre-cursor observed in CO2 interferometer



- Oscillations just before CDC is observed only in **outboard** side.
- Pre-cursor is distinguished in relatively low Bt (2.0T) experiments.



Profile of pre-cursor like oscillations

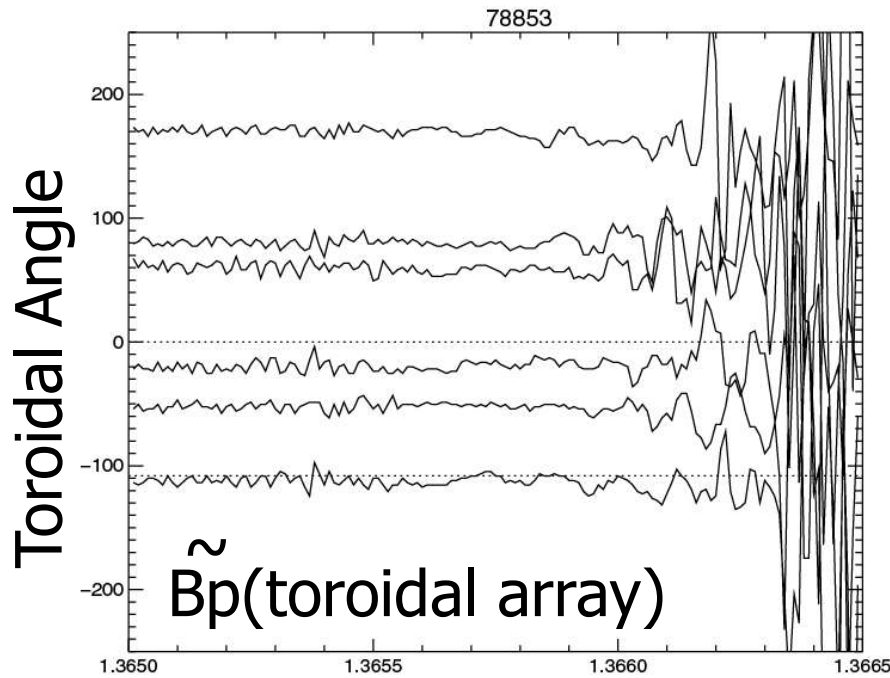


Location of the fluctuations are consistent with the calculation of Hn-bal code.

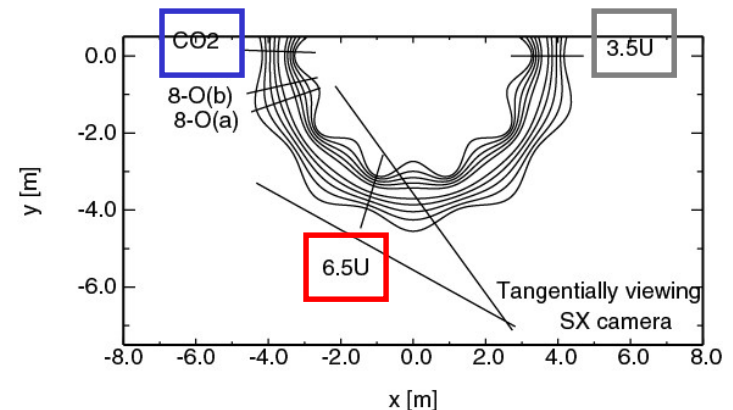
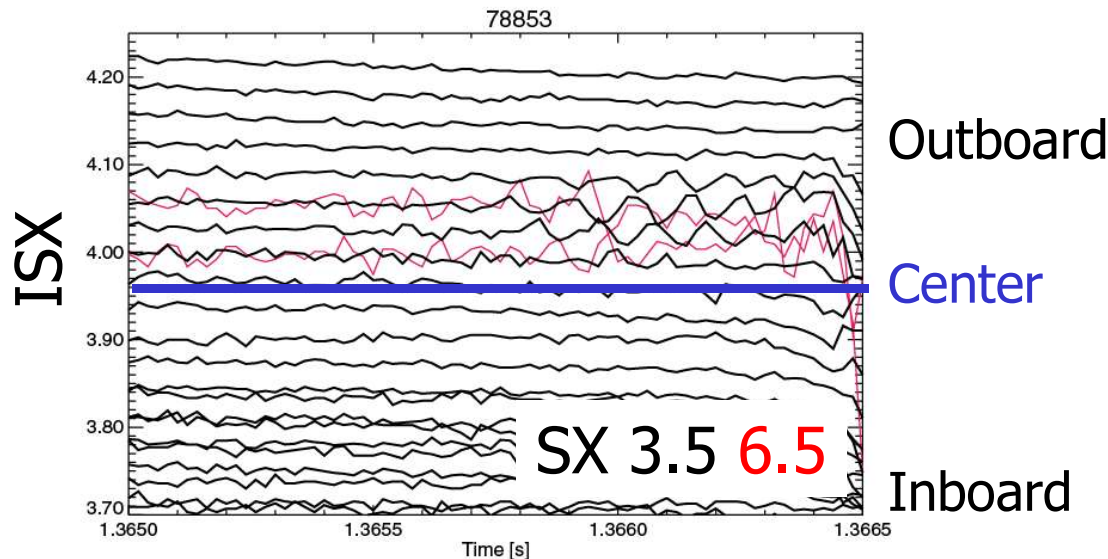
Error in the estimation of ρ is not small ($\Delta\rho \sim 0.2$) since the distance of the flux surfaces are quite small in the outboard side.

Inner peak ($\rho \sim 0.3-0.5$) might be caused by the line-integration effect.

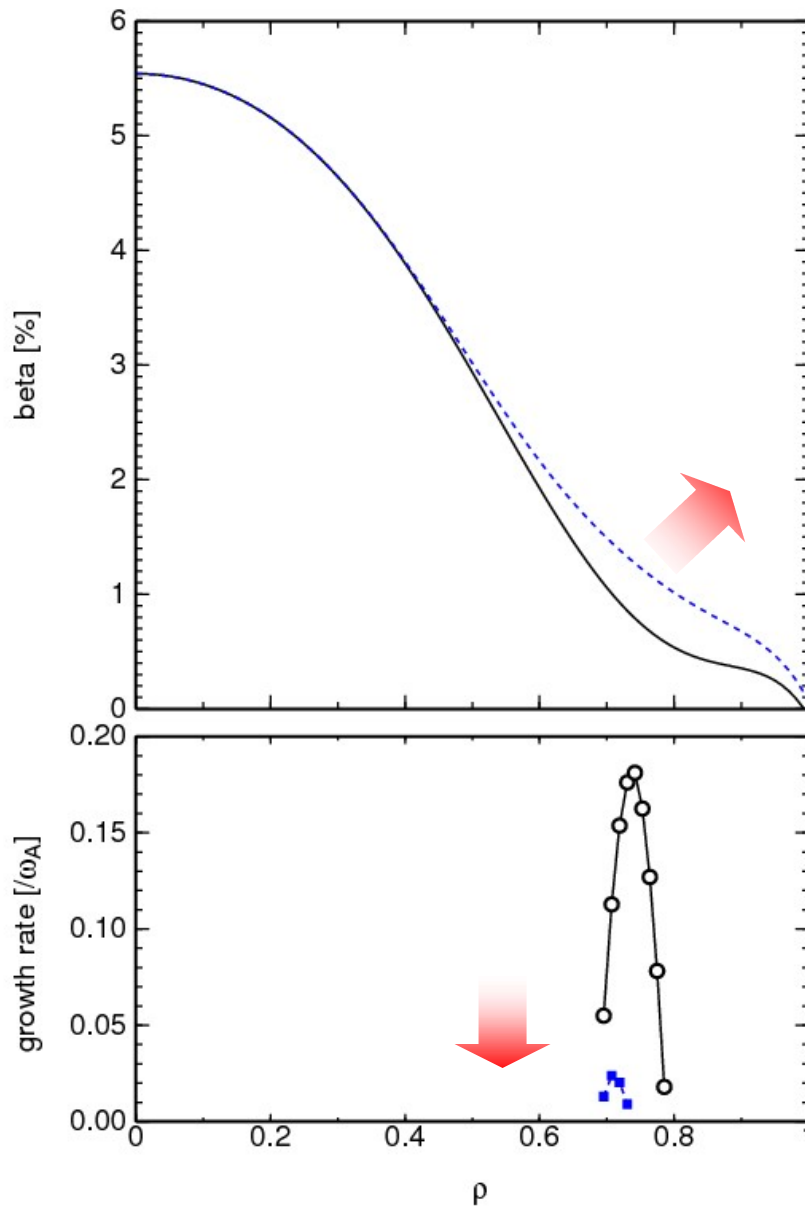
pre-cursors are observed at many sections.



- Precursors, localized at outboard side are observed in different toroidal sections, by SX array and Magnetic probes?
- Toroidal mode number is not clear.(n=2?)

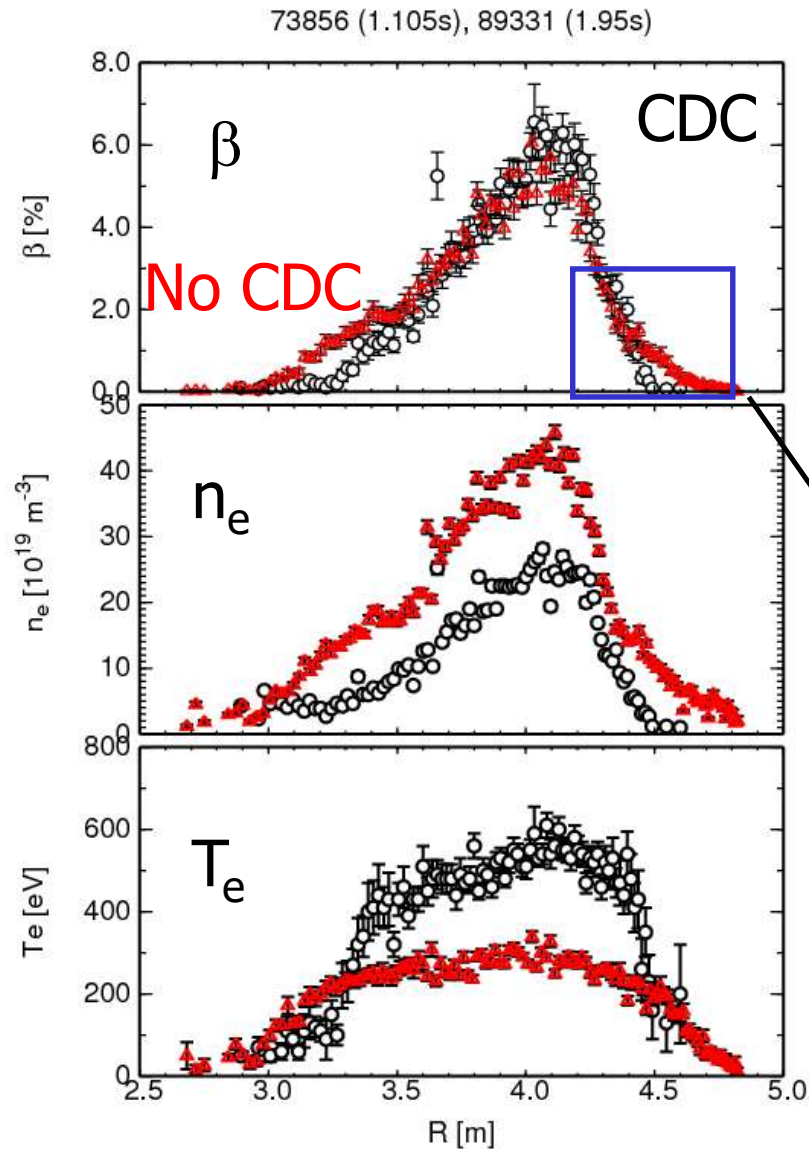


Growth rate with different profile

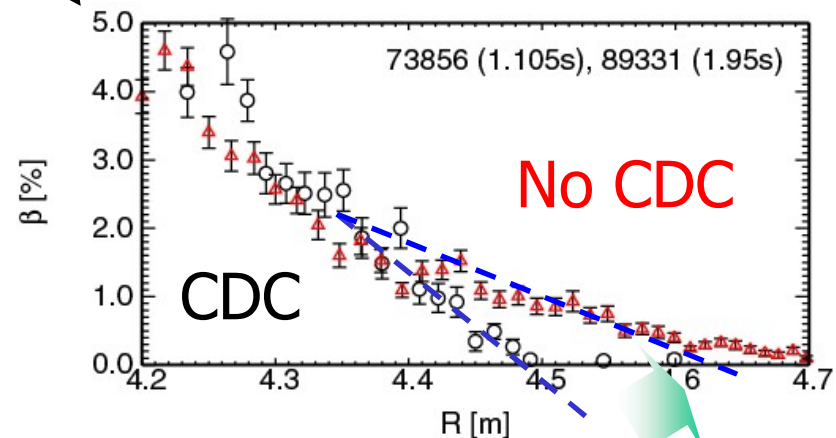


- If we assume a reduced pressure gradient near the foot point in the beta profile, growth rate of the ballooning mode decreases.
- Can CDC be suppressed by the profile control?

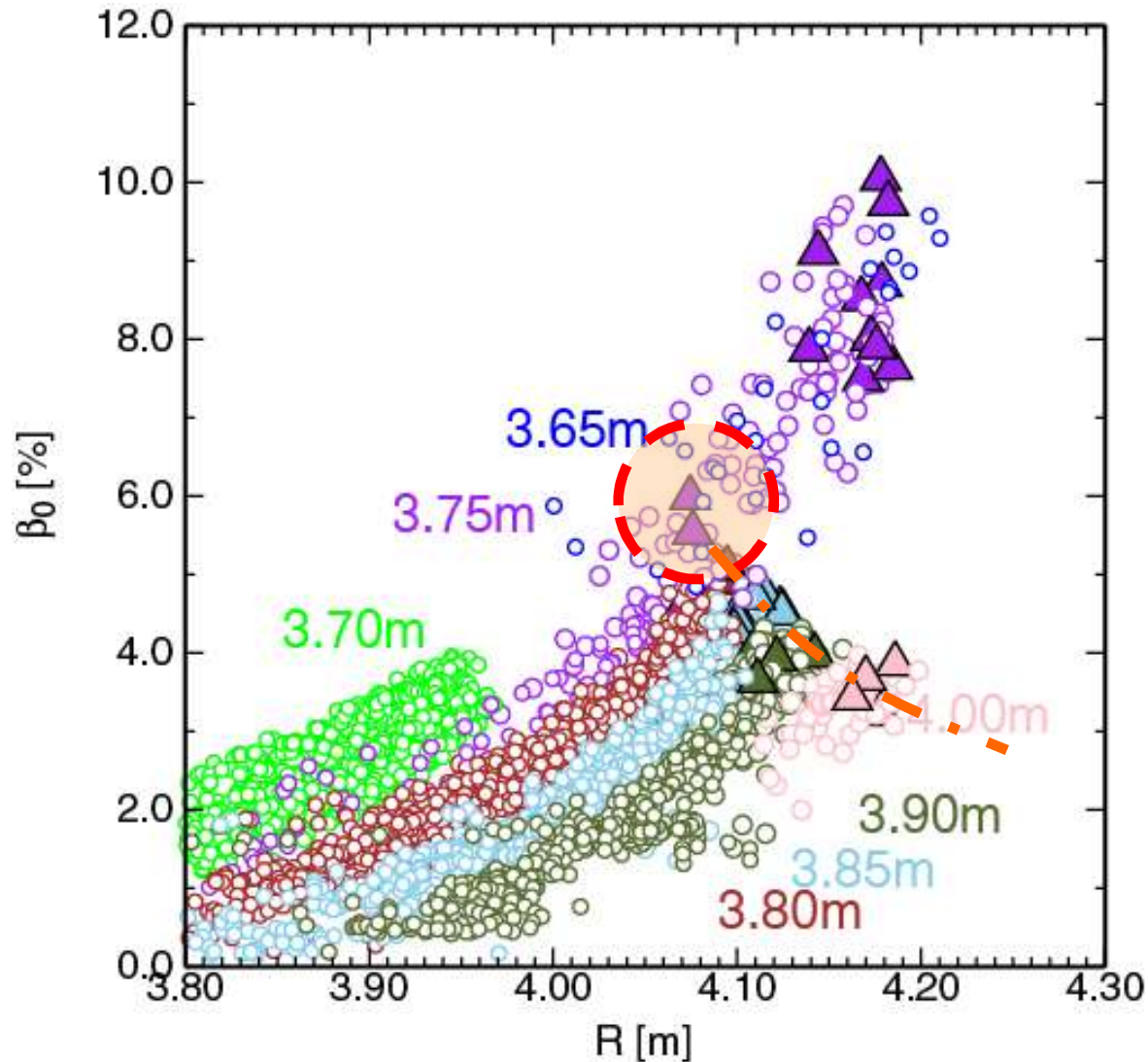
Profile w CDC and w/o CDC



- We observe CDC with steep pressure gradient around the foot point, and **no CDC is observed with broader profile** with similar central beta and similar magnetic axis locations.



Profile control and operational region



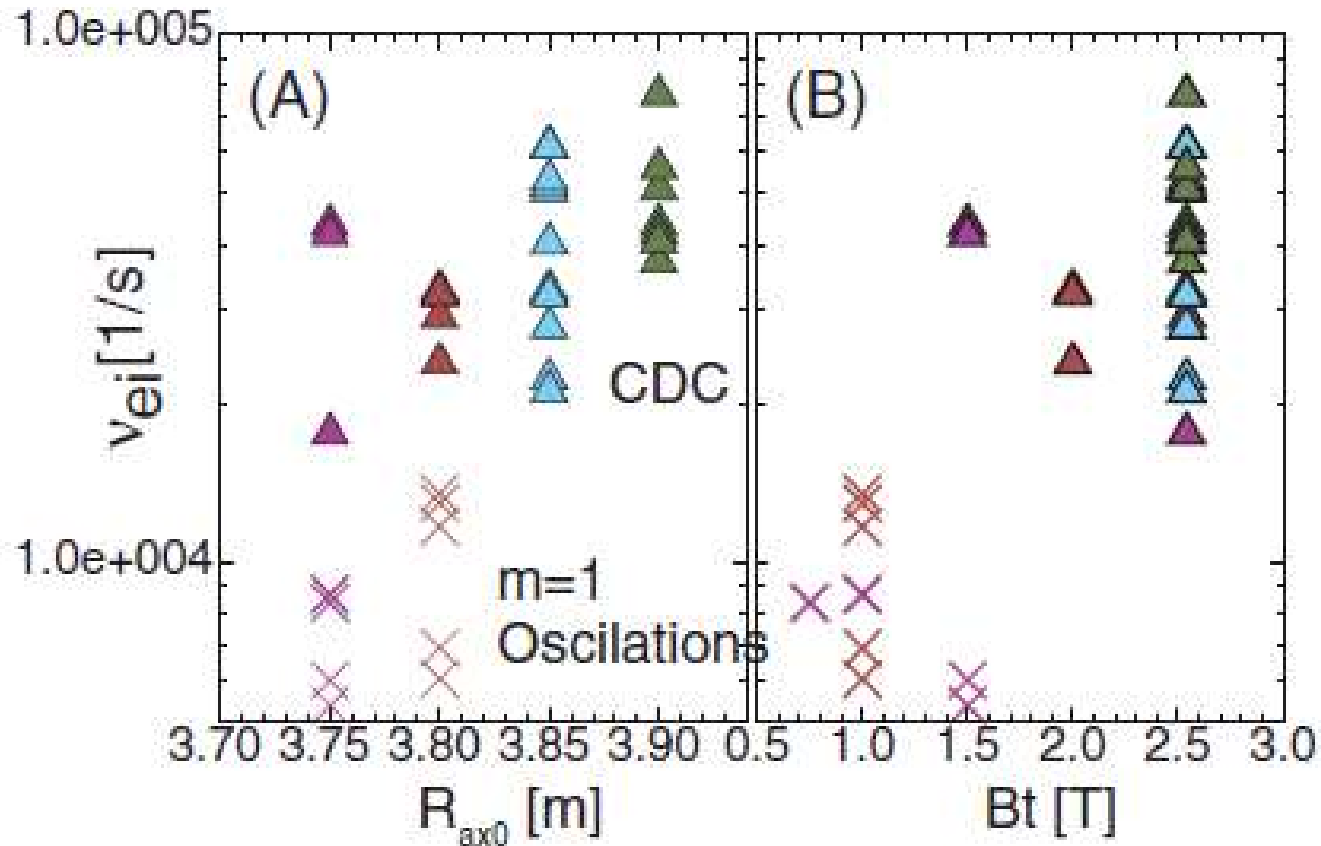
- With broader profile, we can access higher central-beta region.
- Operational limit by CDC is extended to higher beta region.
- This observation also supports that CDC is caused by the ballooning mode.

Summary



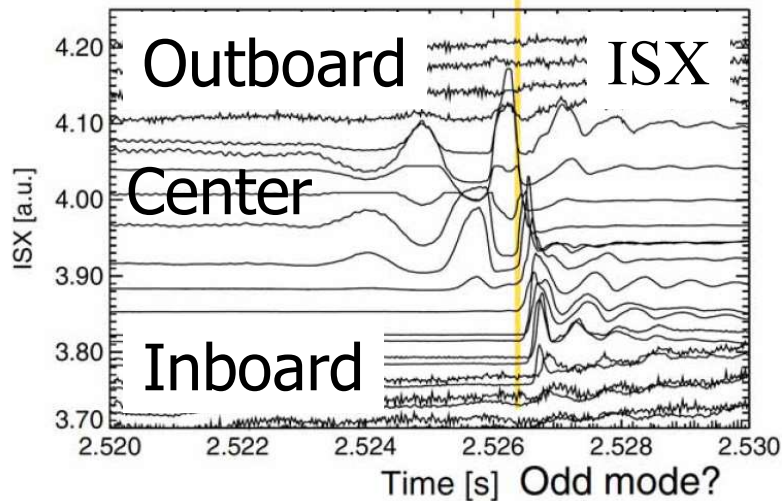
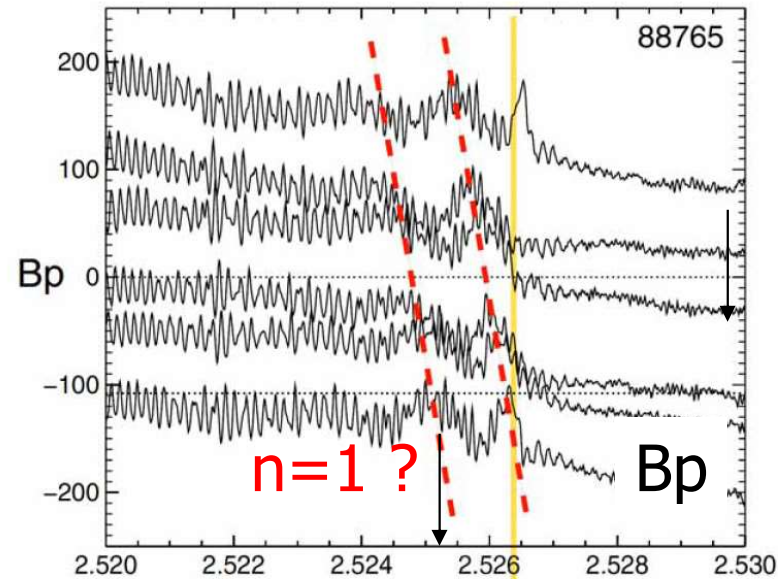
- Increase of the central beta is limited by the CDC events. By CDC, core plasma is collapsed within 1ms. Maximum decrease in the central beta is about 50%
- The characteristics of the activities before CDC is consistent with that of Ballooning mode.
 - Pre-cursor activities in density fluctuations is observed. Profile of the amplitude is quite asymmetric; **localized in the outboard side.**
 - **Unstable region of ideal ballooning modes agrees with the operational limit.**
- Hn-Ballooning mode in IDB/SDC configuration is quite sensitive to the pressure gradient near foot point. Reduction of the pressure gradient in the edge region increase the limit of the CDC.
- 2D imaging diagnostics, which can be observe outboard region of horizontally elongated section is being developed.

In low-Bt / low Collisionality case



- We observe CDC with $Bt \geq 1.5T$. The scale of the CDC becomes small and the time scale is longer with lower magnetic field.
- The difference in plasma parameter seems to be collisionality.
- With lower collisionarity, we observe $m=1$ oscillations rather than CDC with similar beta profile.

Precursors before CDC in low Bt case

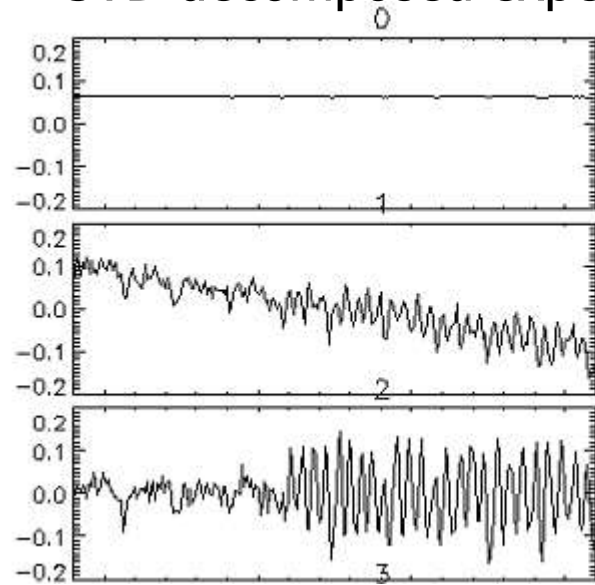


- With low magnetic field, we observe pre-cursor oscillations with a mode numbers $m=1$.
- Amplitude is not uniform; larger in the outward region.
- In many discharges, $m=1$ oscillations are just saturated. No CDC is observed.

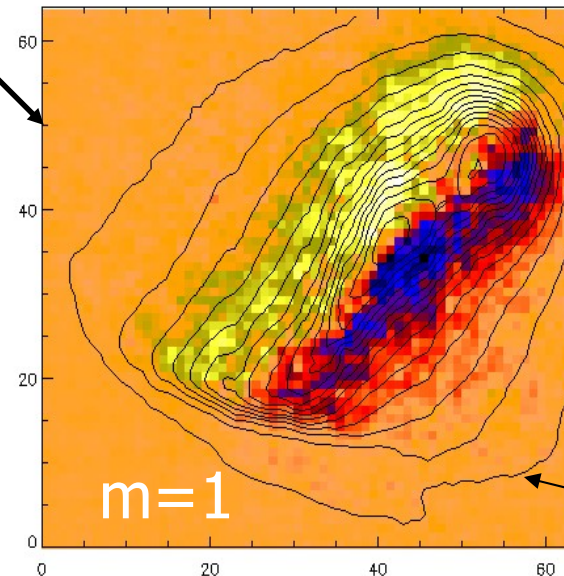
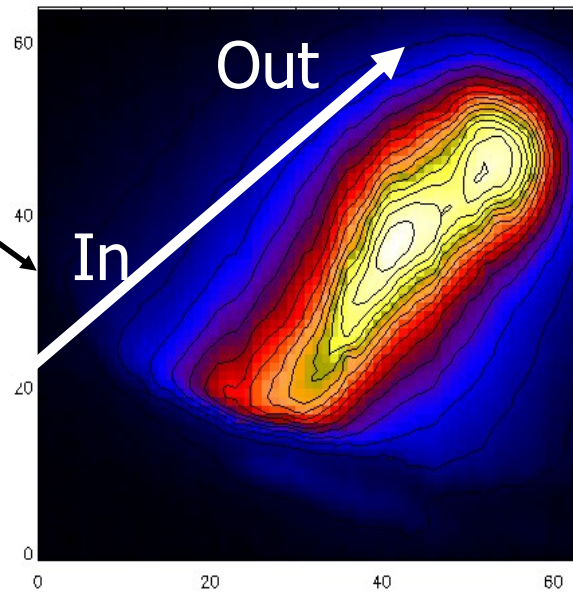
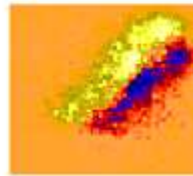
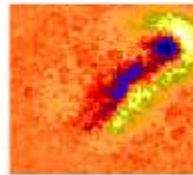
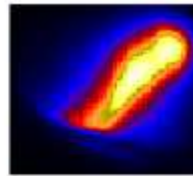
m= 1 structure can be seen 2D fast SX camera



SVD decomposed experimental image

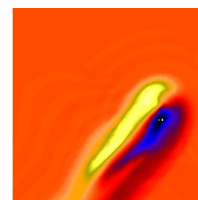
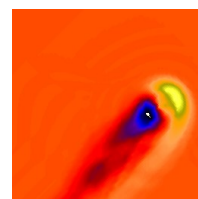


Time [s]

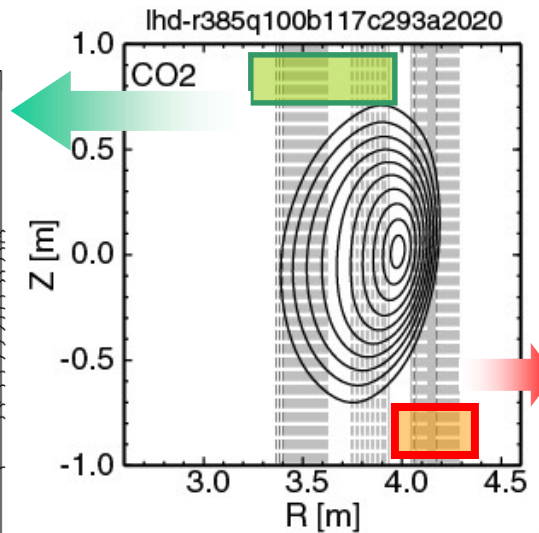
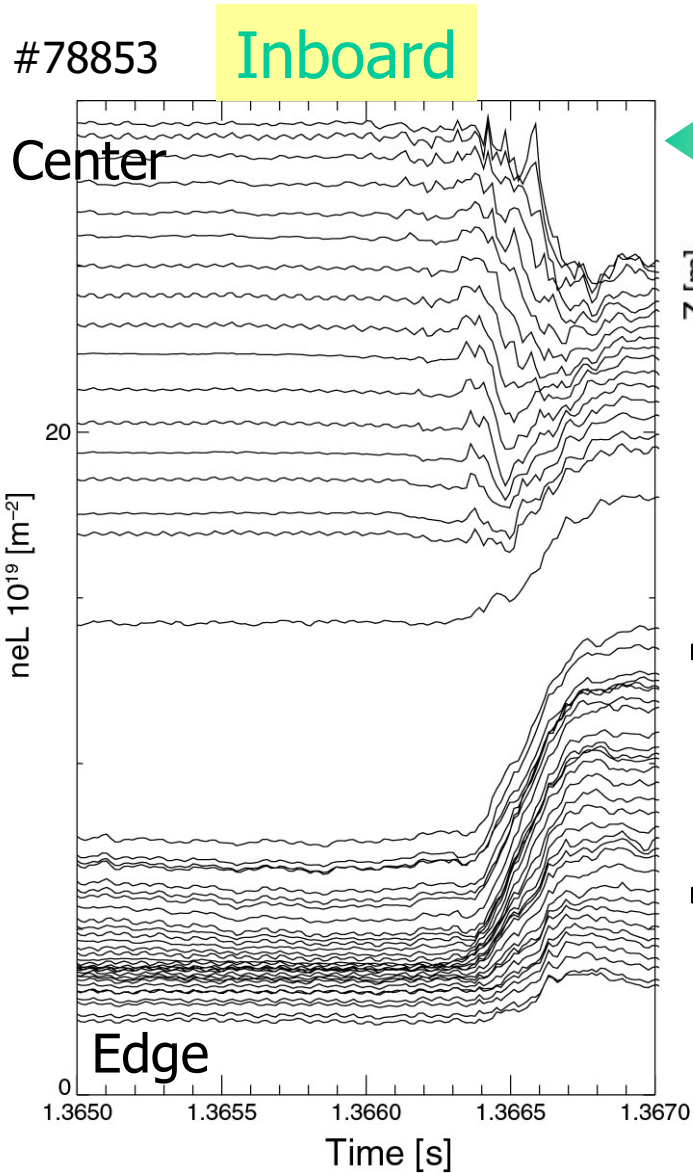


Contour line is from stationary image above.

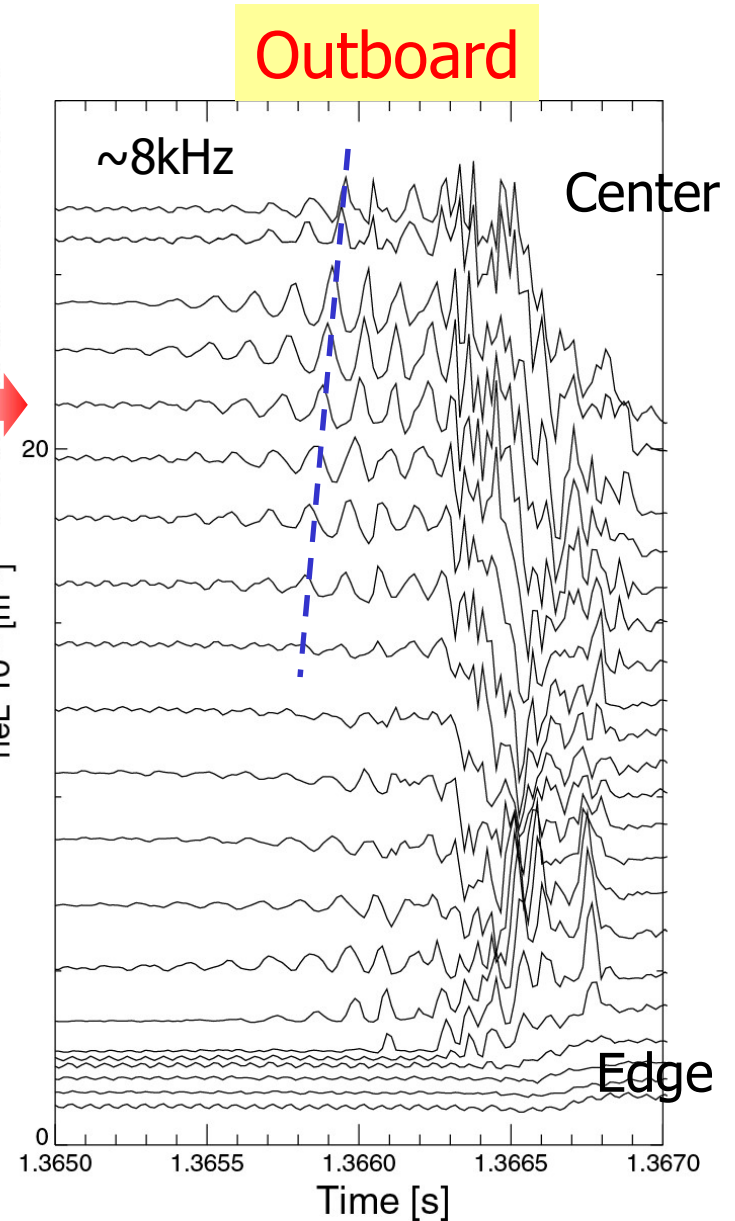
Data is consistent with the simulated image assuming core localized m= 1 mode. Radial profile is assumed by $\text{Exp}(-((\rho-0.15)/0.1)^2)$.



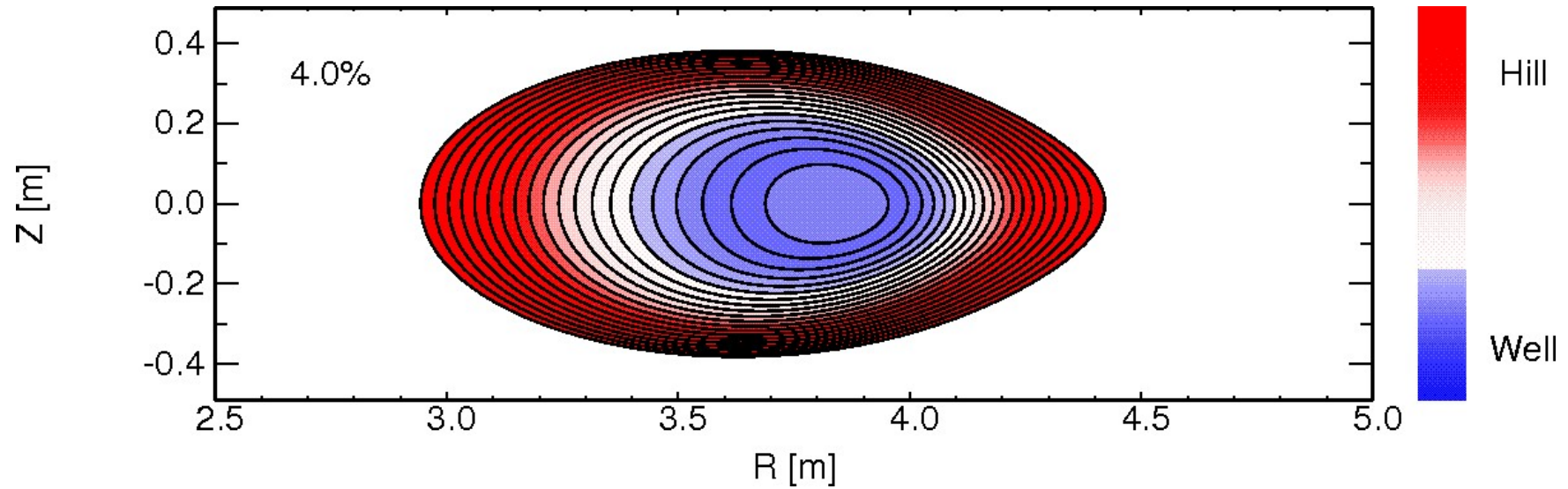
Pre-cursor observed in CO2 interferometer



- Oscillations just before CDC is observed only in **outboard** side.
- Pre-cursor is distinguished in relatively low Bt(2.0T) experiments.



Well/Hill boundary with increase of Beta



Relaxation events observed in LHD



	Location/Rational surface	Time scale	Cause
Sawtooth-like activities	Core $\iota=1/2, 1/3$	2~5ms	Interchange modes
Low shear collapse	Edge $\iota=1/1$	~50ms	Low magnetic shear in magnetic hill region
Core Density Collapse	Core-Edge independent to ι ?	< 1ms	Ballooning mode?

- MHD events has been observed only when the pressure gradient is fairly steep and/or the magnetic shear is very week.
- Core density collapse is the first events in LHD where the plasma confinement is largely affected by MHD instabilities.