Density collapse events observed in IDB/SDC plasmas on LHD

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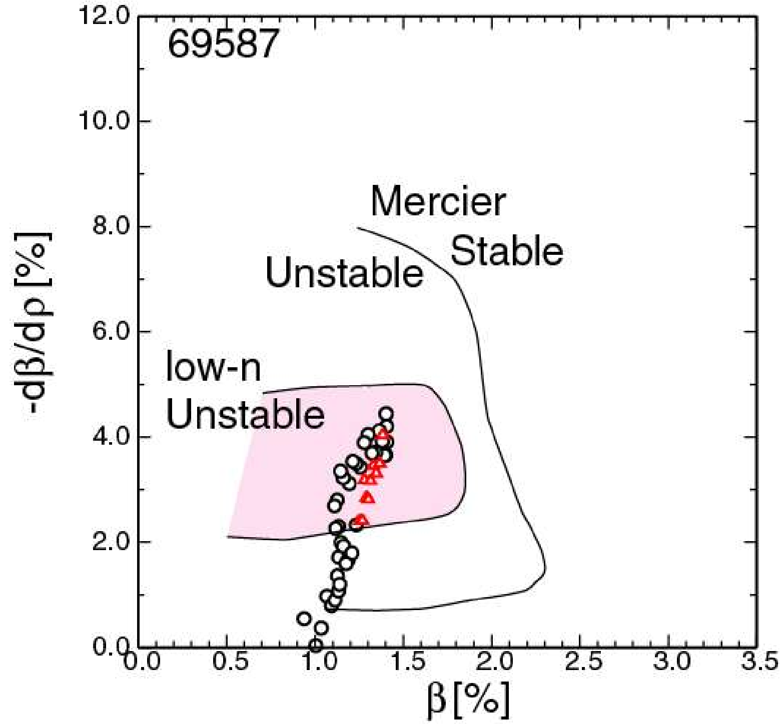
Outline of my talk

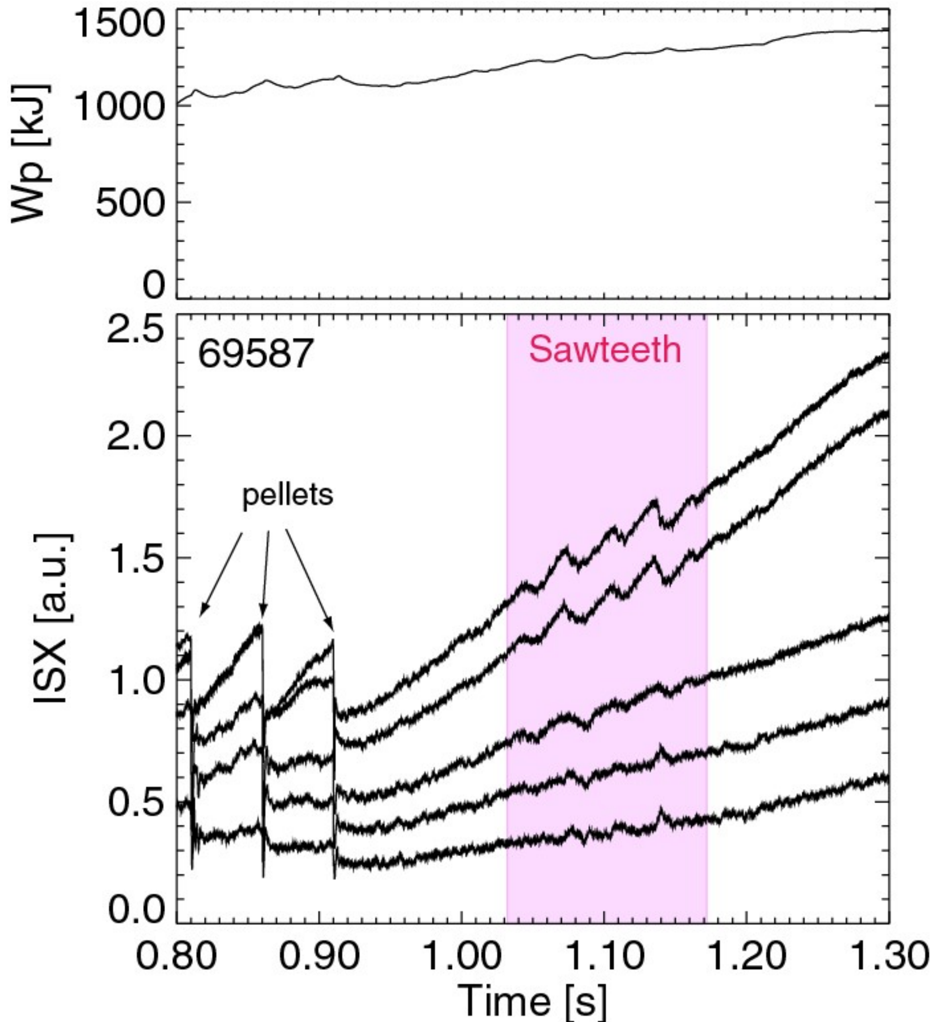
- There various kinds of MHD instabilities observed in LHD
  - Plasma can be sustained safely with Mercier-unstable region with magnetic fluctuations. Effect on confinement is small in normal operations.
  - Pressure profile is peaked / magnetic shear is reduced ...
    - Sawtooth-like phenomena with low-n unstable region
    - m/n=1/1 island formation.

- Core density collapse(CDC) in IDB/SDC plasma.
    - Different in scale and in speed.
    - Detailed observation of CDC event.
    - Condition for the appearance.
    - m=1 oscillation with low-collisionality condition.

- Magnetic axis control in order to avoid CDC activity

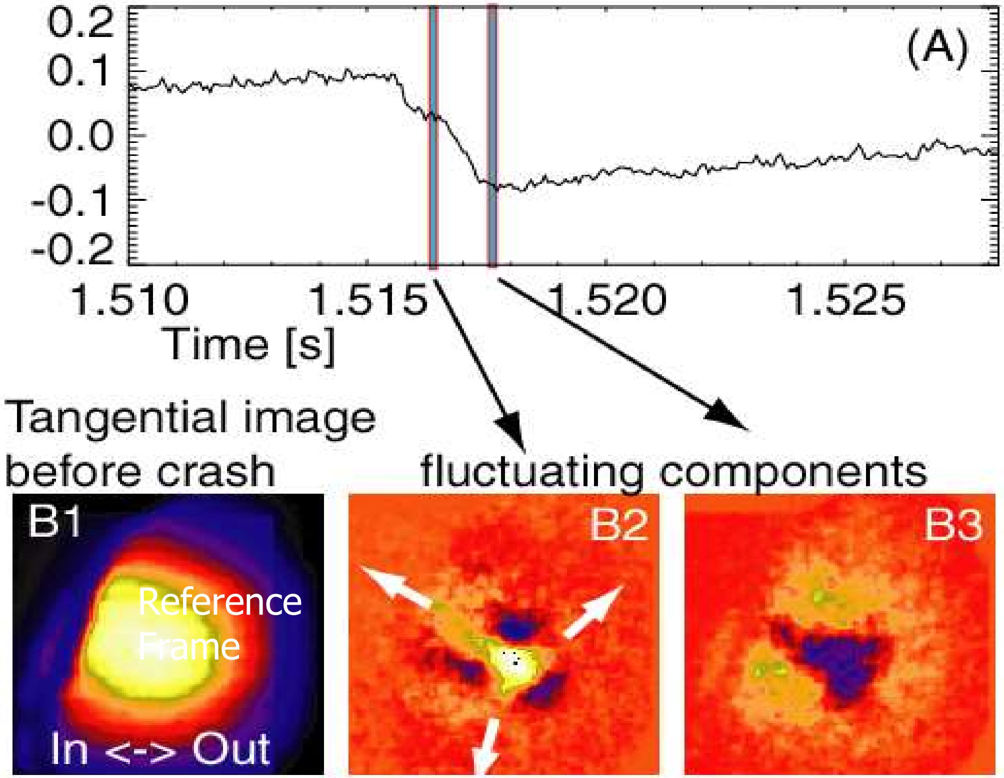
Sawtooth-like activities

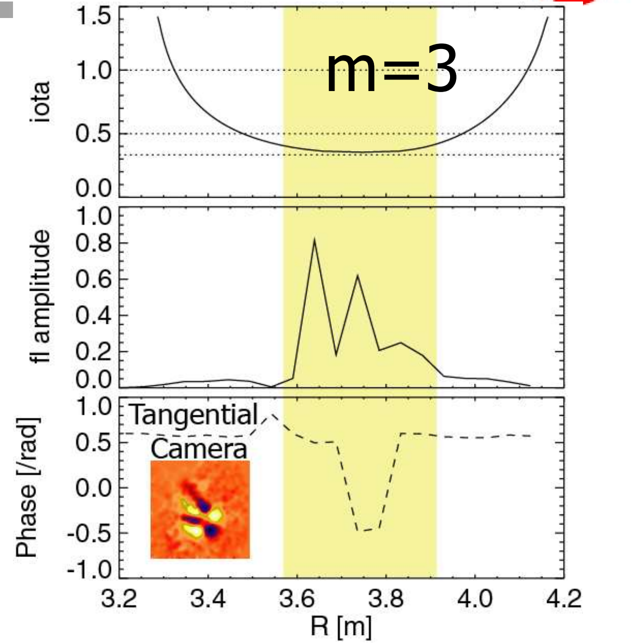


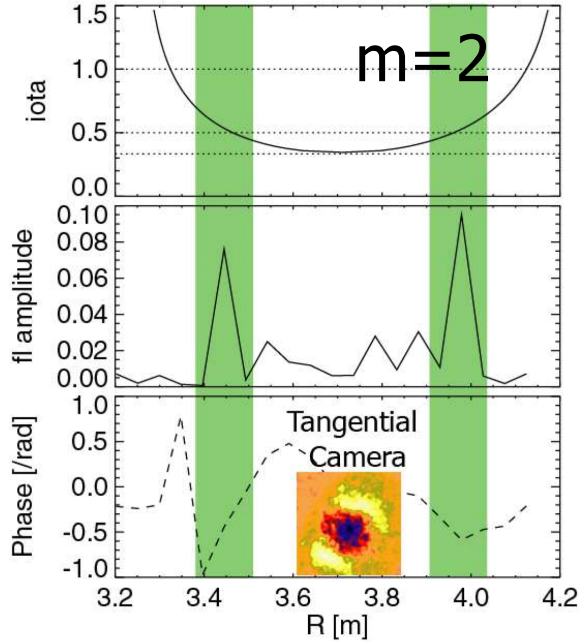


- After pellet injection, pressure profile is more peaked than gas-puffing discharges.
- When the pressure gradient exceeds the low-n unstable condition, sawtooth-like MHD activities are destabilized.

Sawtooth: m=3, m=2 ST-like events







- Several types of sawtooth are observed at different rational surface.
- Increase of the flow from the interchange mode deforms the flux surface (m=3) . Crash can be seen after the deformation.

Relaxation events observed in LHD

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

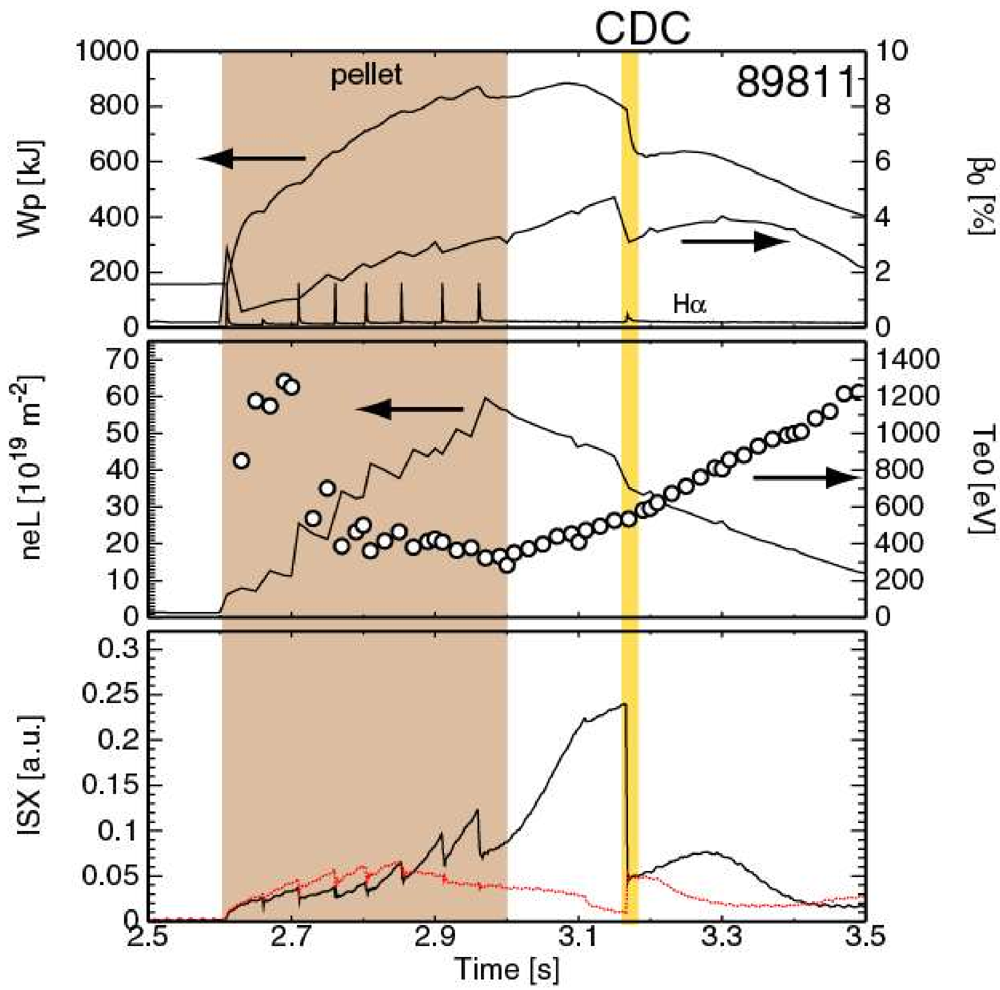
- MHD events has been observed only when the pressure gradient is fairy steep and/or the magnetic shear is very week.

- Core density collapse is the first events in LHD where the plasma confinement is largely affected by MHD instabilities.

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.

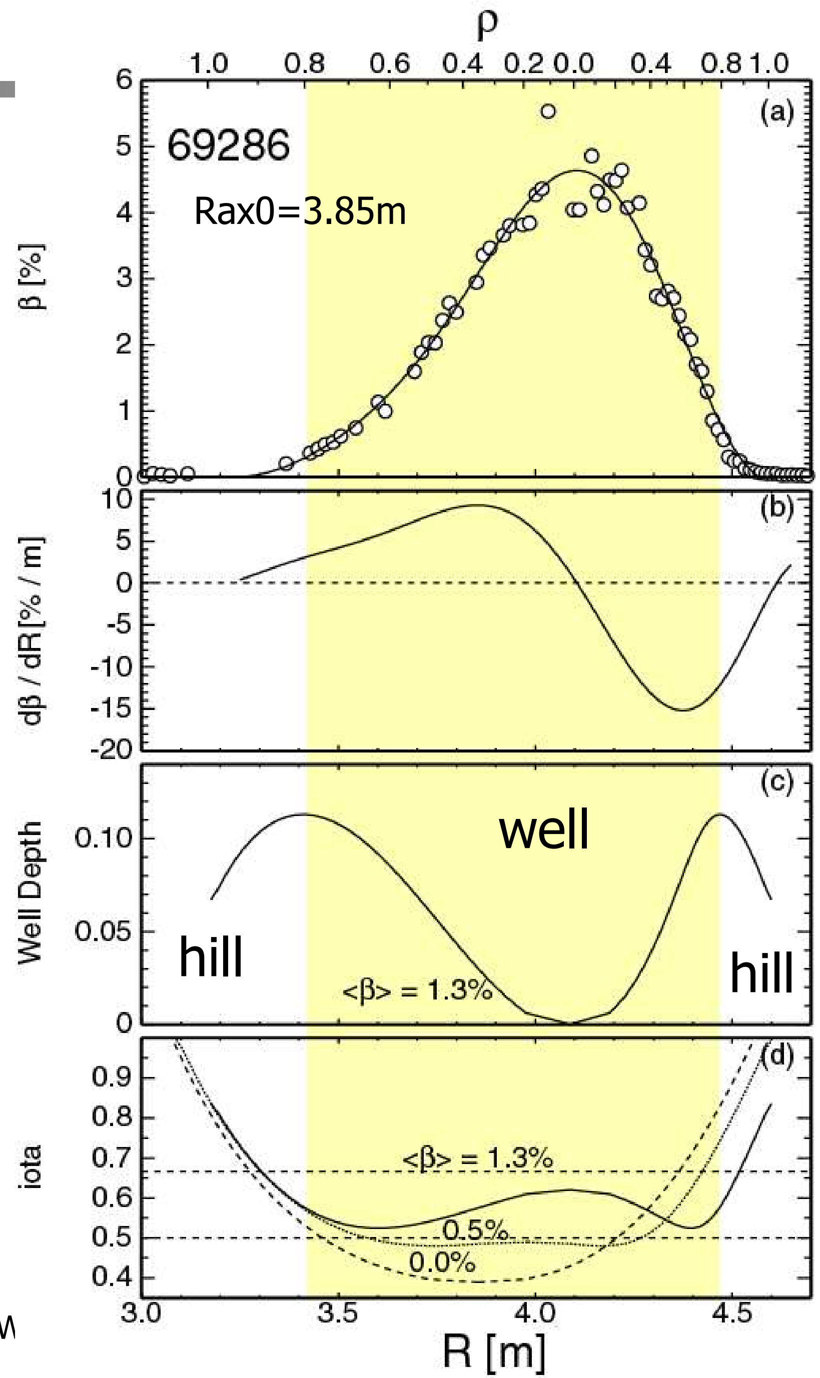
- Increase of the β_0 is disturbed by so-called core density collapse(CDC) events. CDC is an abrupt event where the core density is collapsed within 1 ms. (much faster than other MHD relaxation events in the LHD)



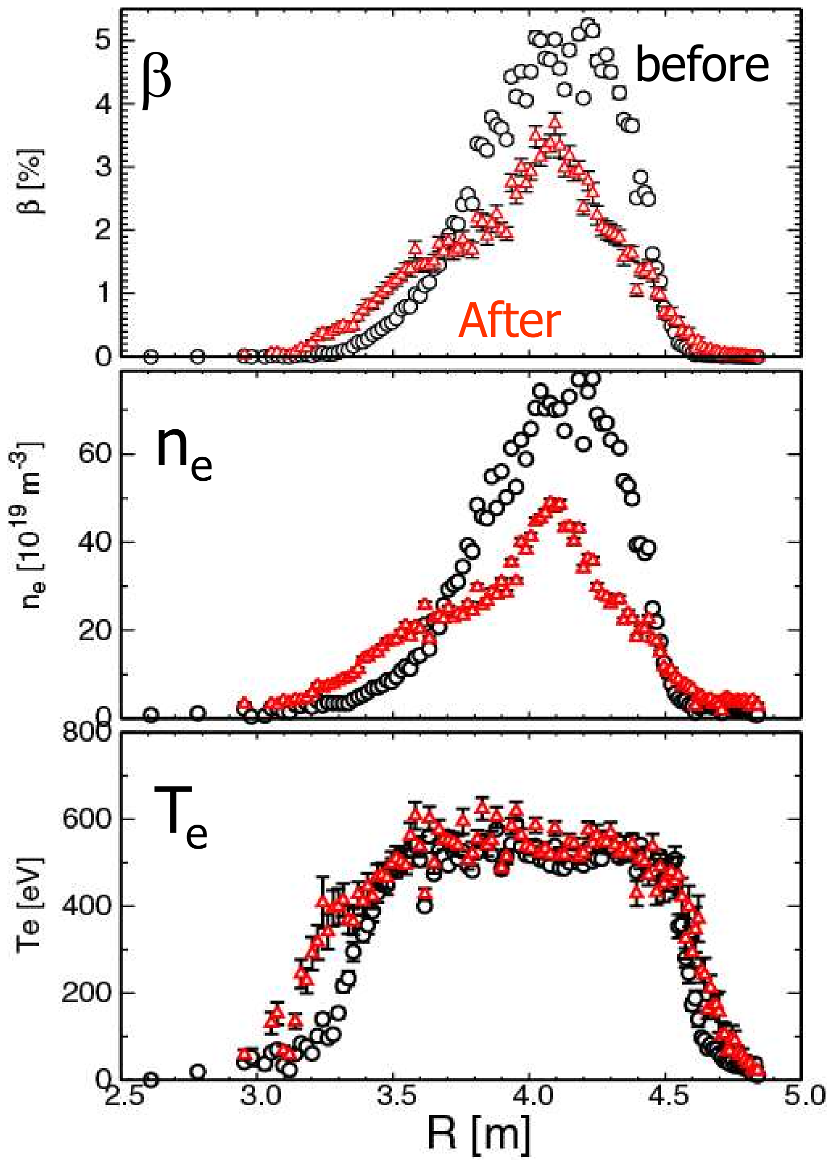
MHD property of IDB/SDC

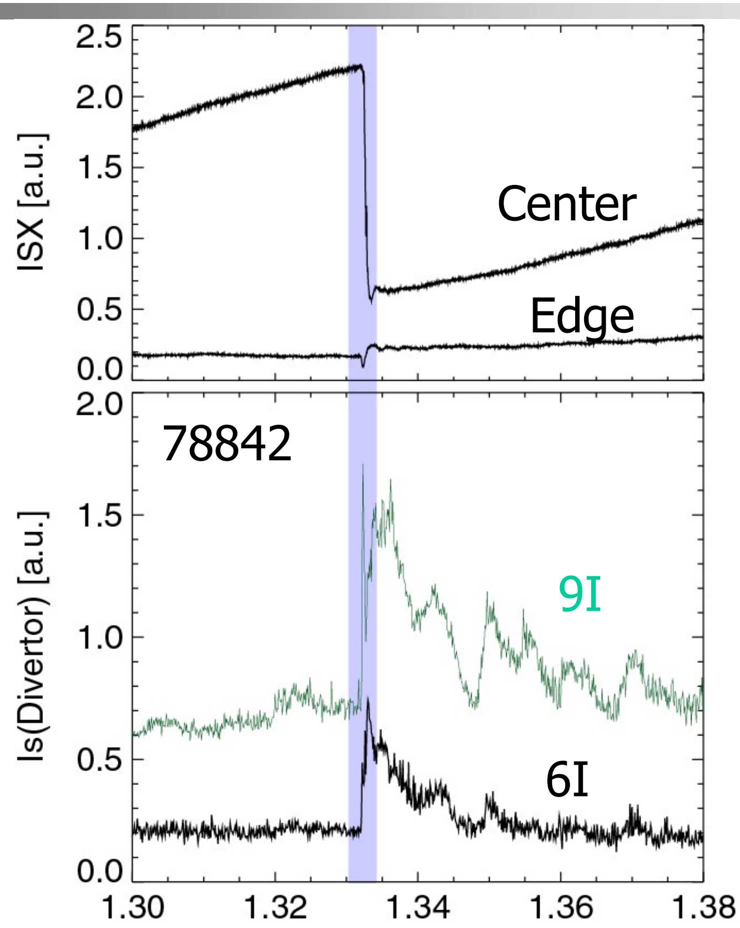
- Pressure profile just before CDC is shown. It is peaked at ρ = 0.4~0.6. It is within the magnetic well region.

- Rotational transform profile is reversed in the core region (tokamak-like shear.) With the increase of the beta, the magnetic shear in the edge region is increased.



Profile changes with CDC events

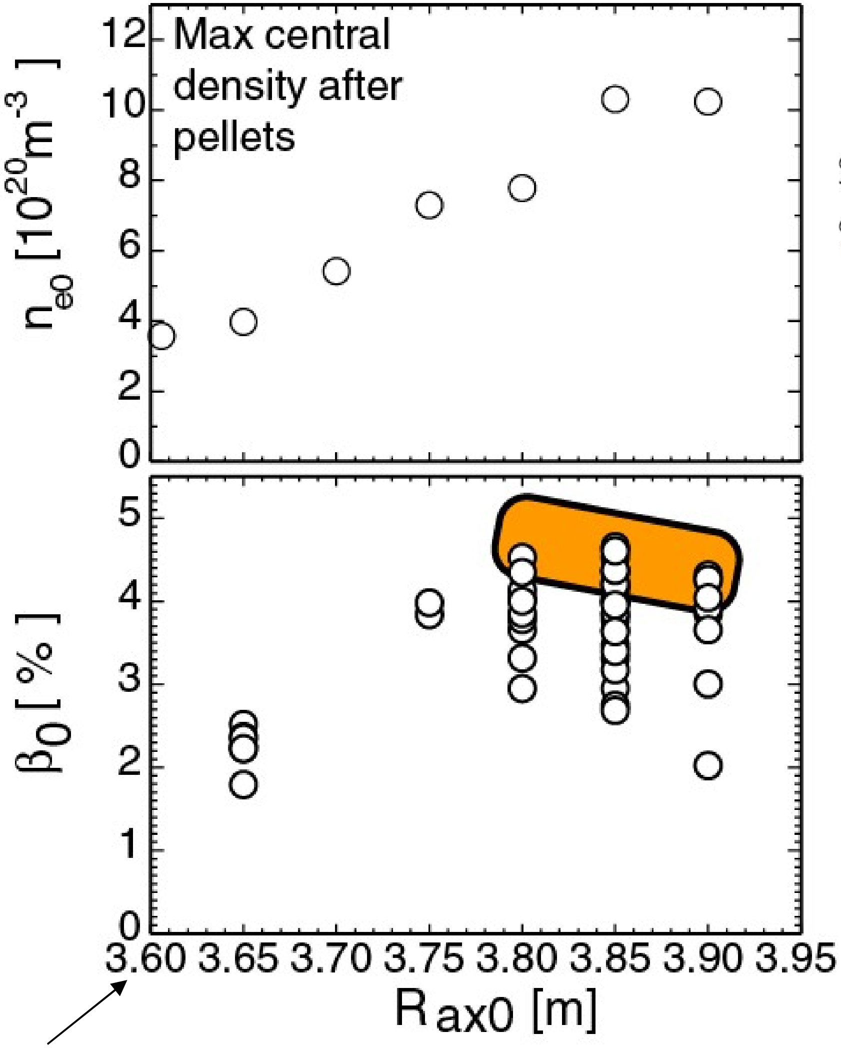




Density collaps

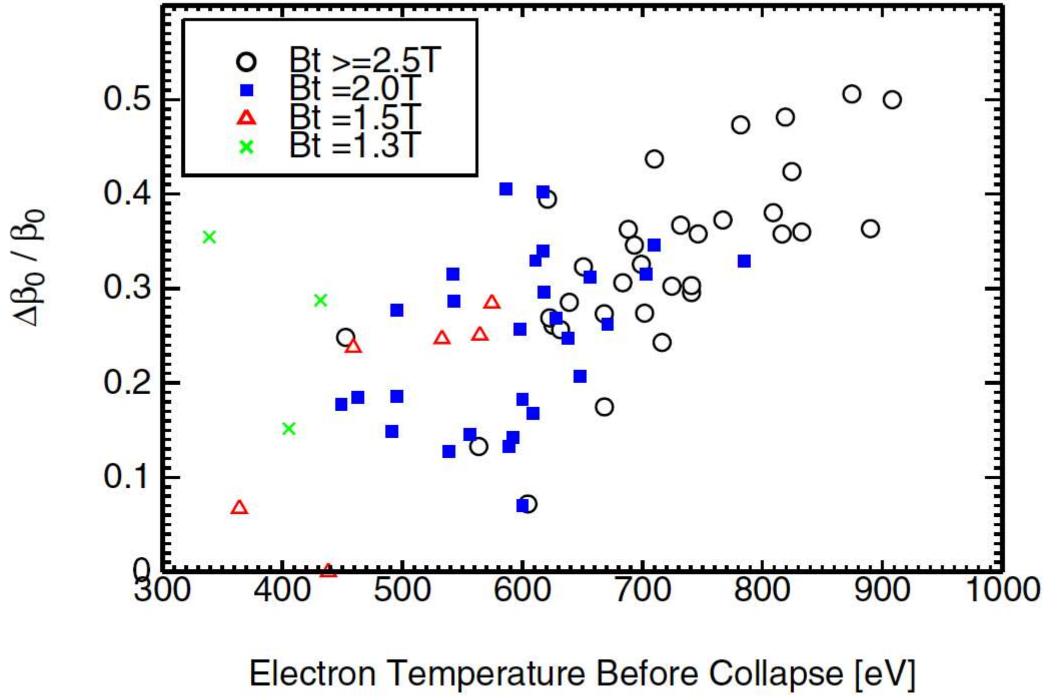
- Central beta/density decreases by up to 50%.
- Whole plasma is affected; rapid increase in I_{is} at divertor probes is observed with CDC.

CDC dependencies



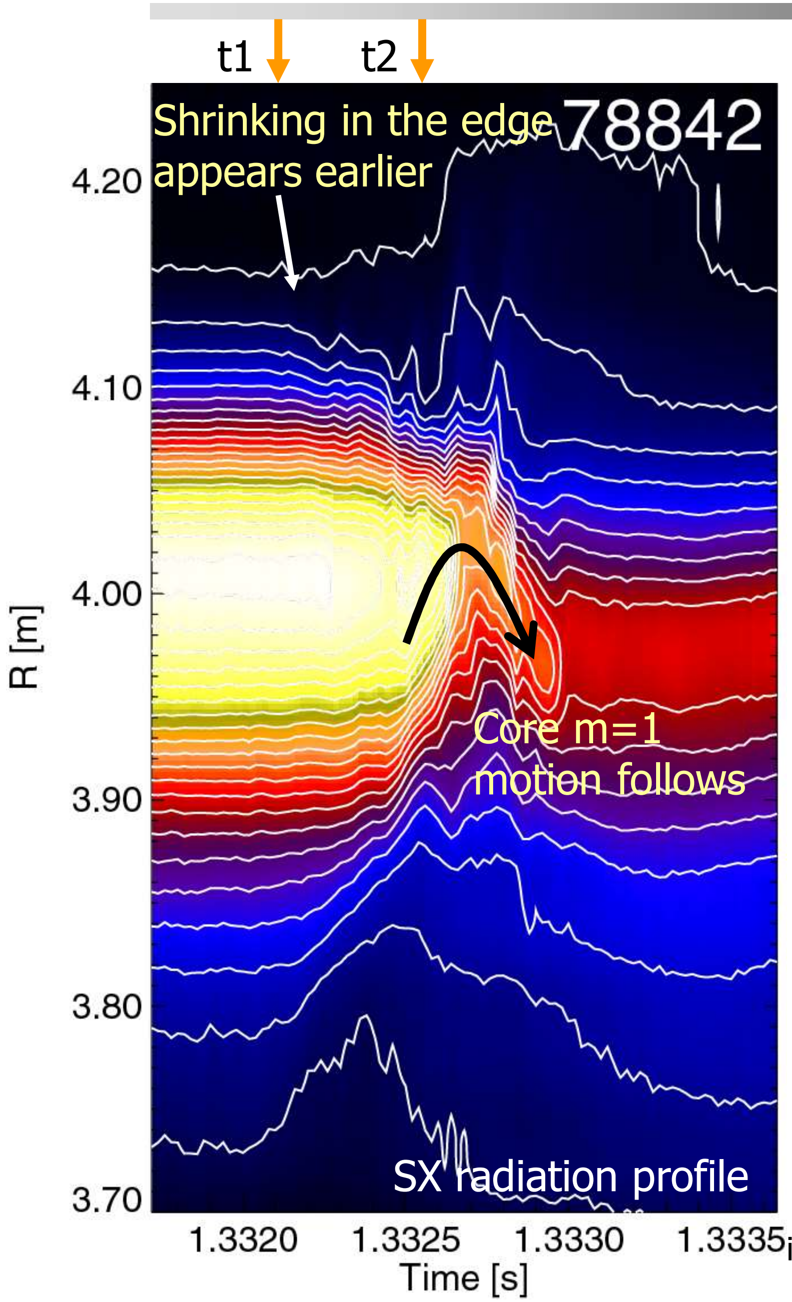
Standard   Preset magnetic Axis

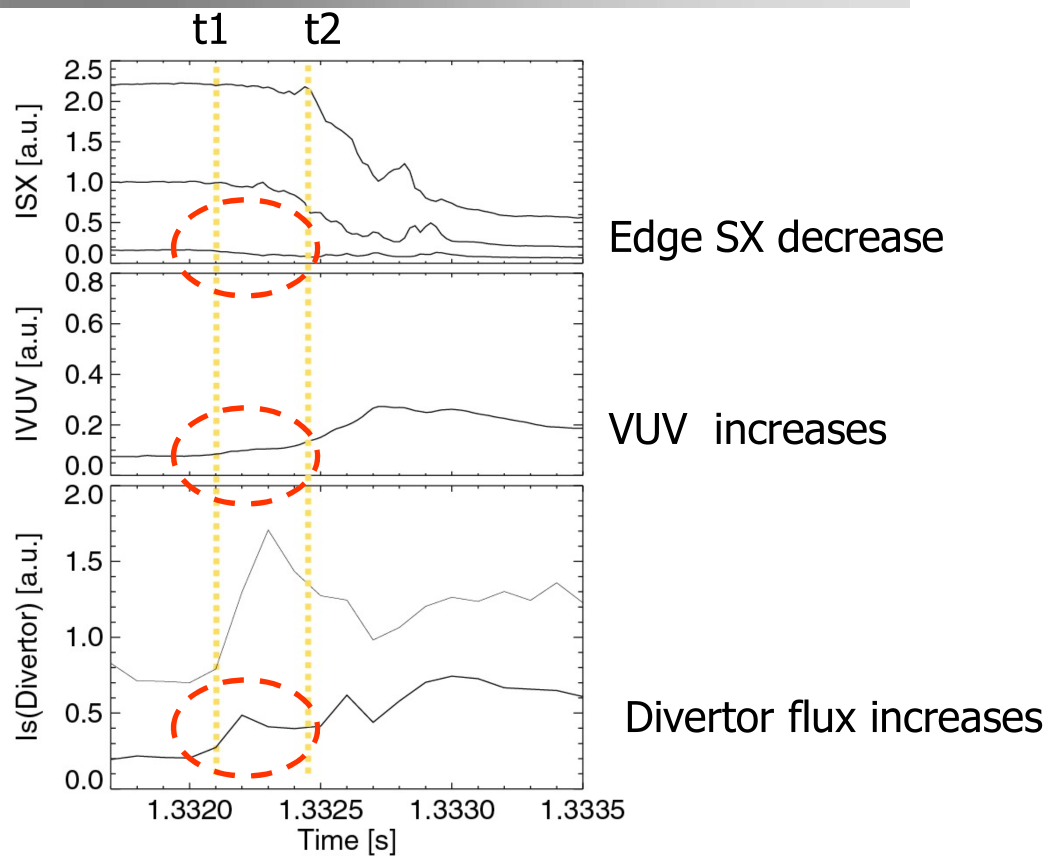
Density collapse



- Achievable density is higher, when preset magnetic axis is located outward.
- R_{ax0} > 3.75m, increase of the central beta is limited by CDC.
- Change of the central beta is up to 50% in higher magnetic field.

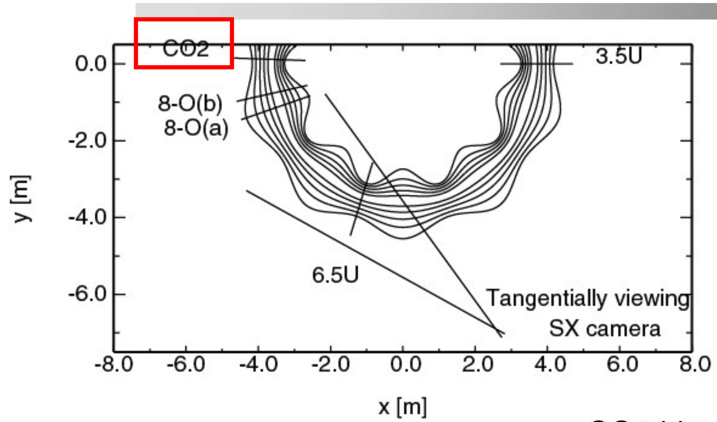
A CDC starts from the edge region



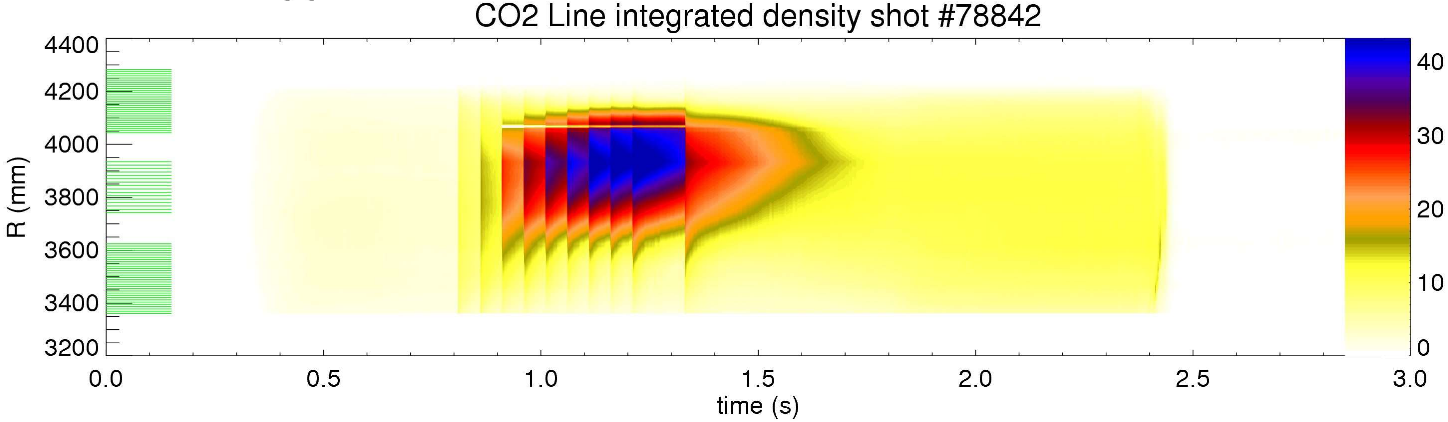


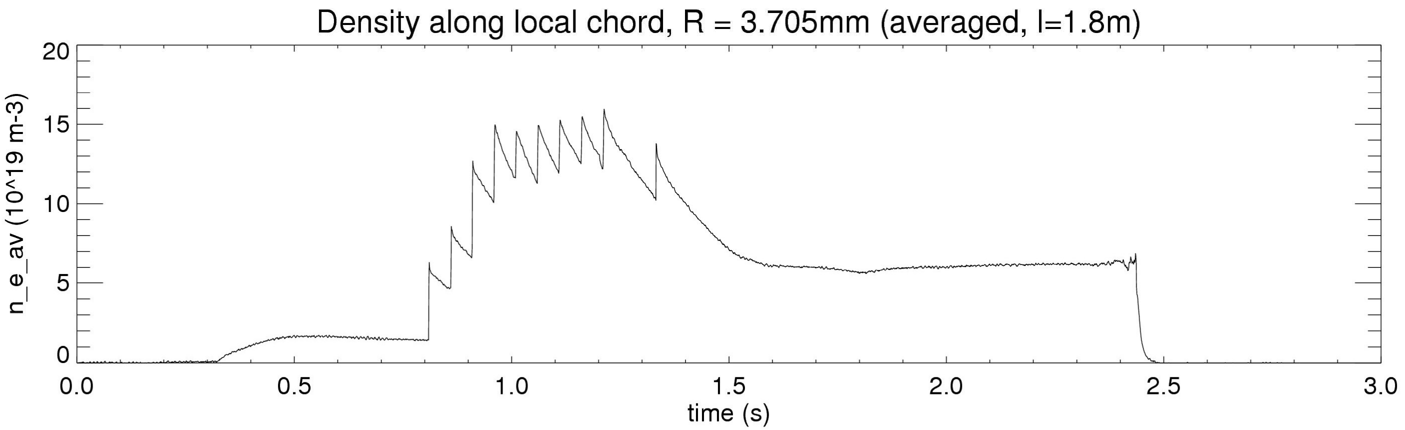
- A CDC events starts from the shrinking in the edge plasma
- After steepening of the profile, core plasma moves outward/inwards. Then a rapid core crash occurs.

Measurements at different toroidal position

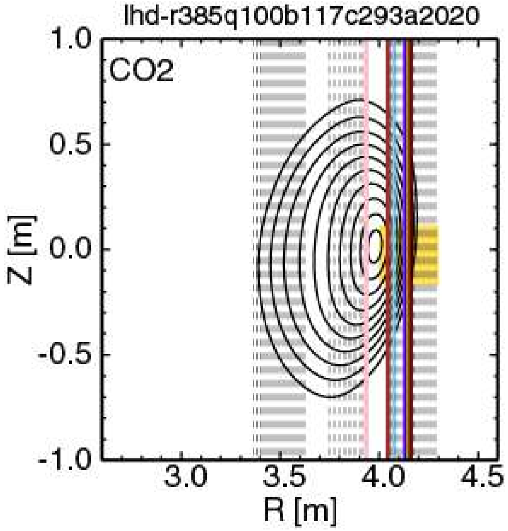


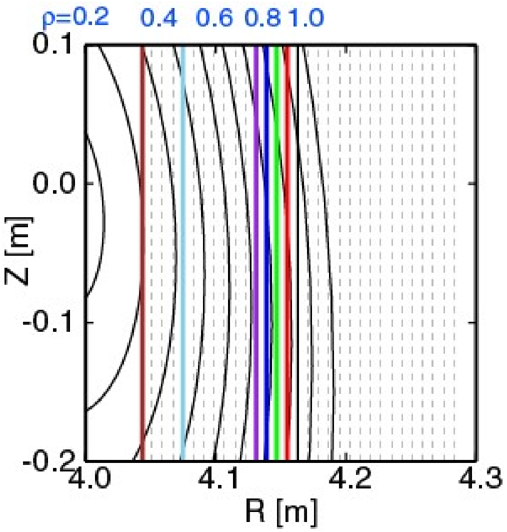
- Same behavior can be seen toroidally separated port.
- Sampling freq~133kHz, dx = 7.5mm.

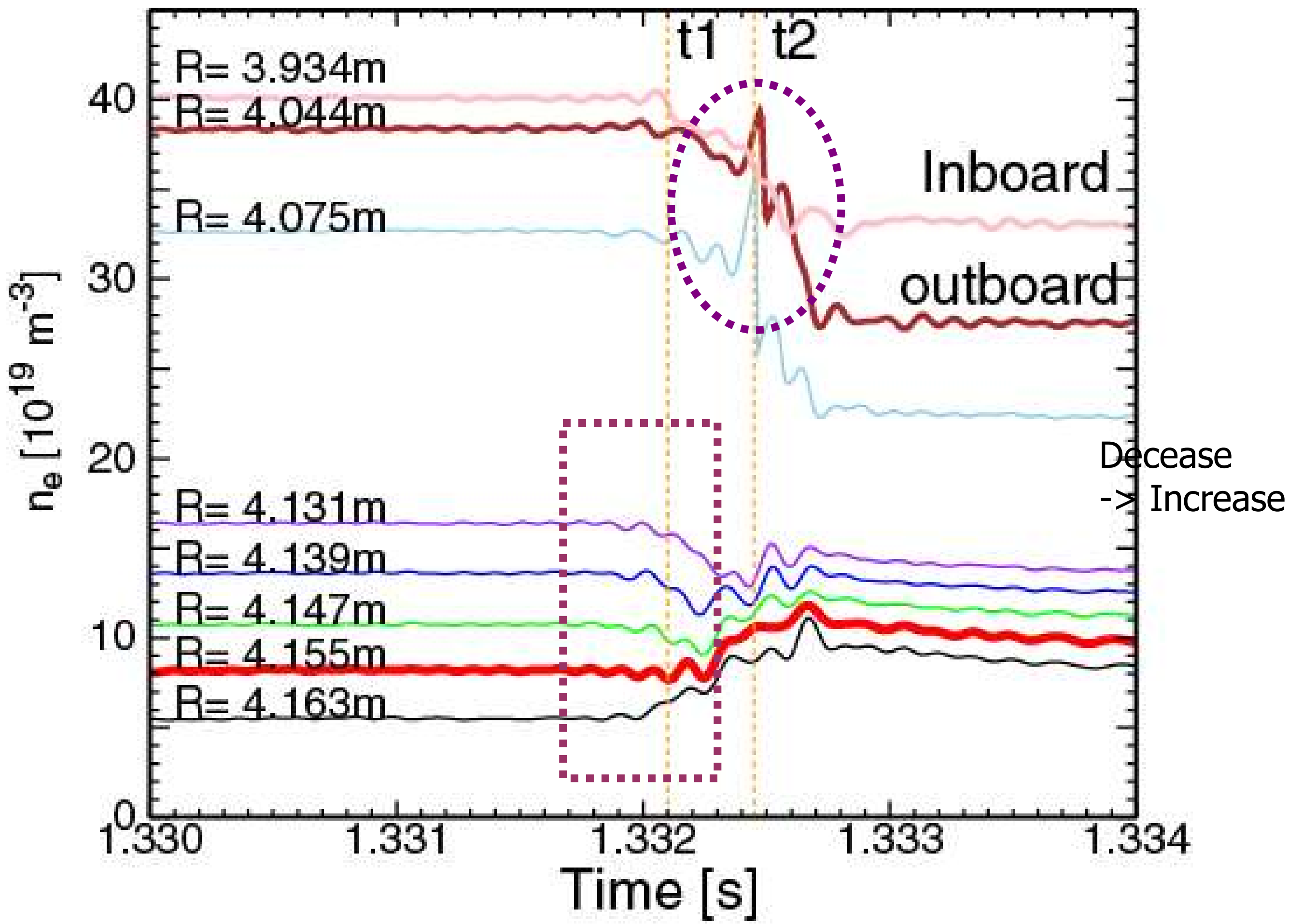




Density evolution by CO2 interferometer







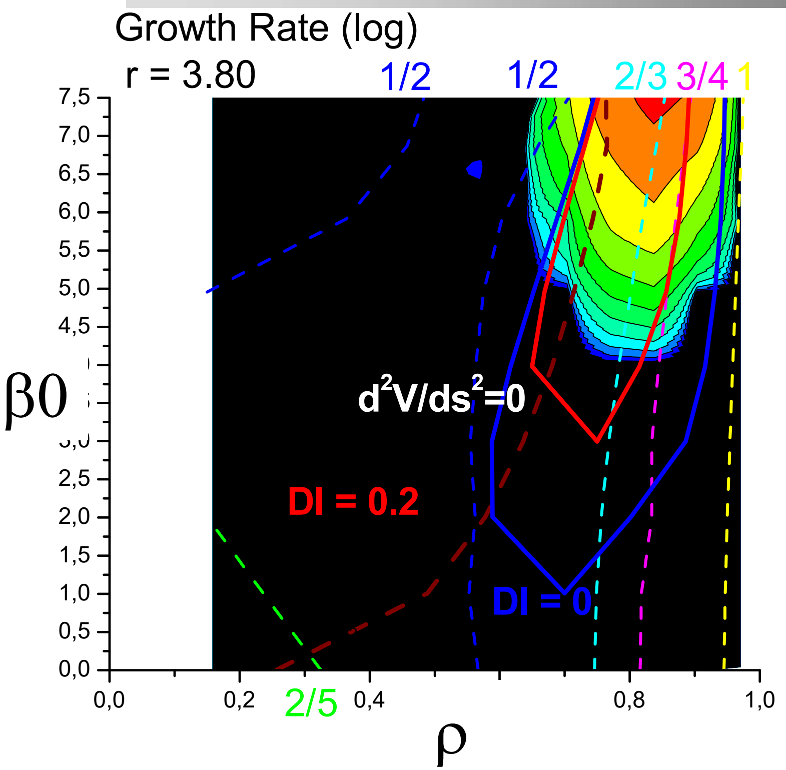
- Small crash in the outboard edge appears first. Inversion surface is about $\rho = 0.8$.
- Spikes with main collapse can be seen only in outboard side.

Why is two steps collapse considered?

- Edge profile modification
  - The high-n ballooning modes is one of the candidate for the CDC. Interchange modes are stable in highly Shafranov-shifted plasmas.
  - The region where CDC appears is consistent with unstable region of ideal ballooning modes.
  - This kind of high mode number instabilities is not easy to be detected by line-integrated diagnostics.

- Core m=1 activities
  - In standard experimental condition (Bt > 2.5T), the phenomena is too fast; we could not catch the MHD activities before the events.
  - However, we observe large amplitude m=1 oscillations in low Bt (0.75-1.5T) experiments with similar beta profile. In some cases, m=1 activity finally make the plasma crashed.

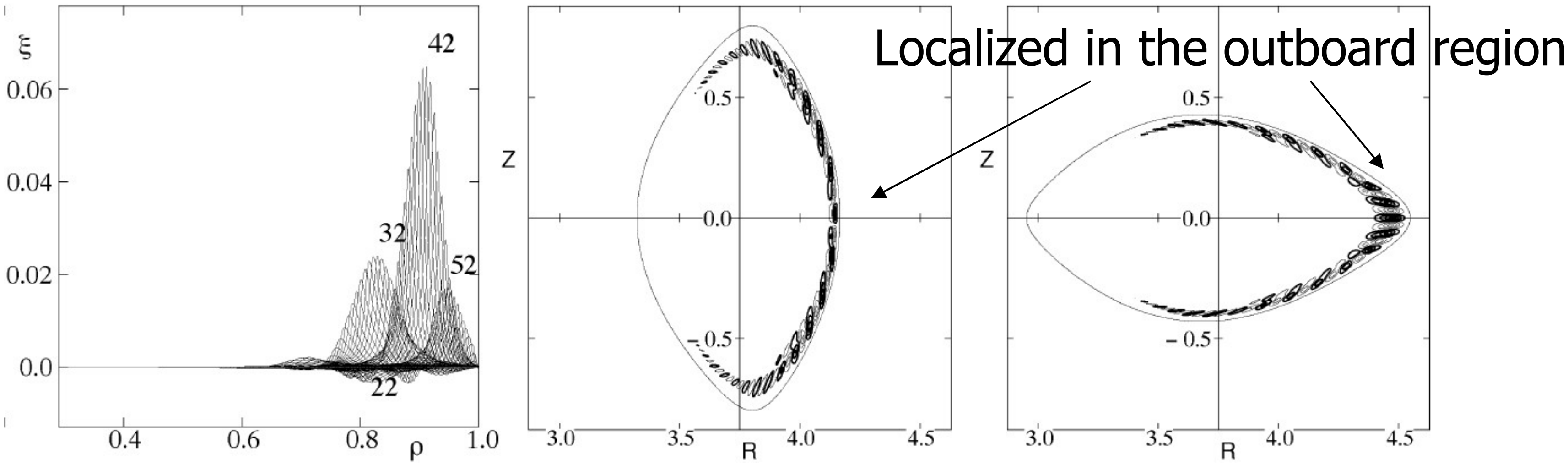
High-n ballooning mode



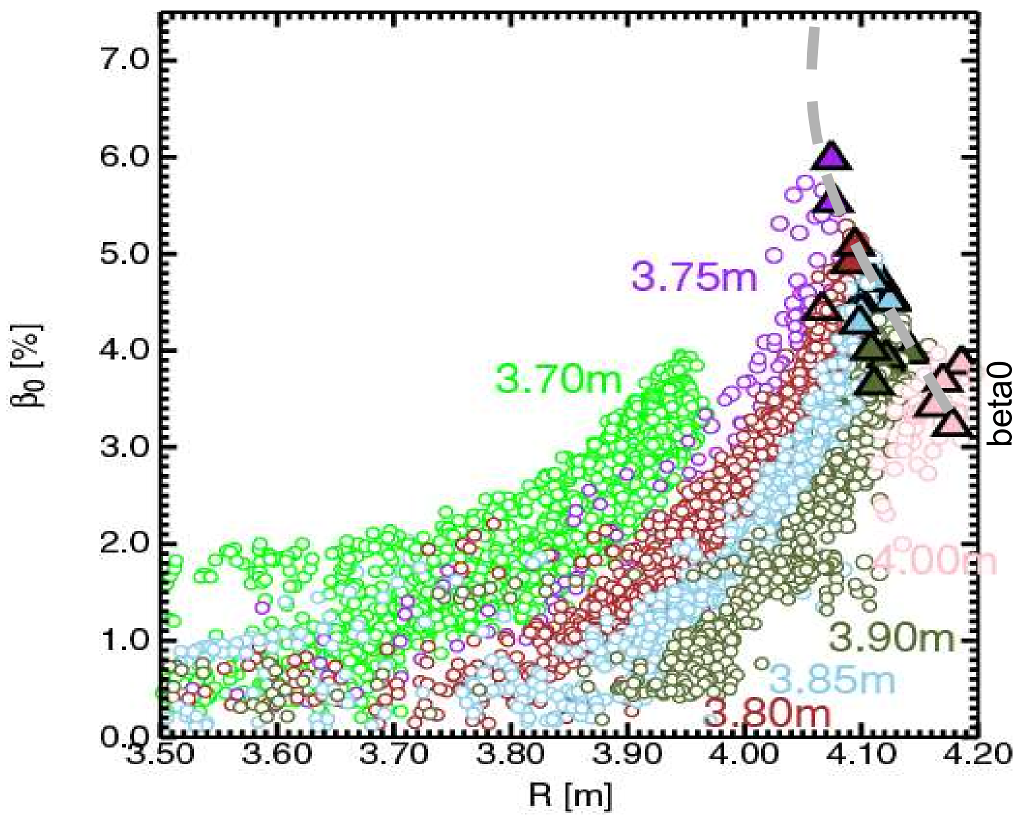
- High-n ballooning mode is destabilized in Mercier unstable region when pressure gradient is increased.
- Though the pressure gradient is larger in the core region, it is stable by the magnetic well due to the large Shafranov shift

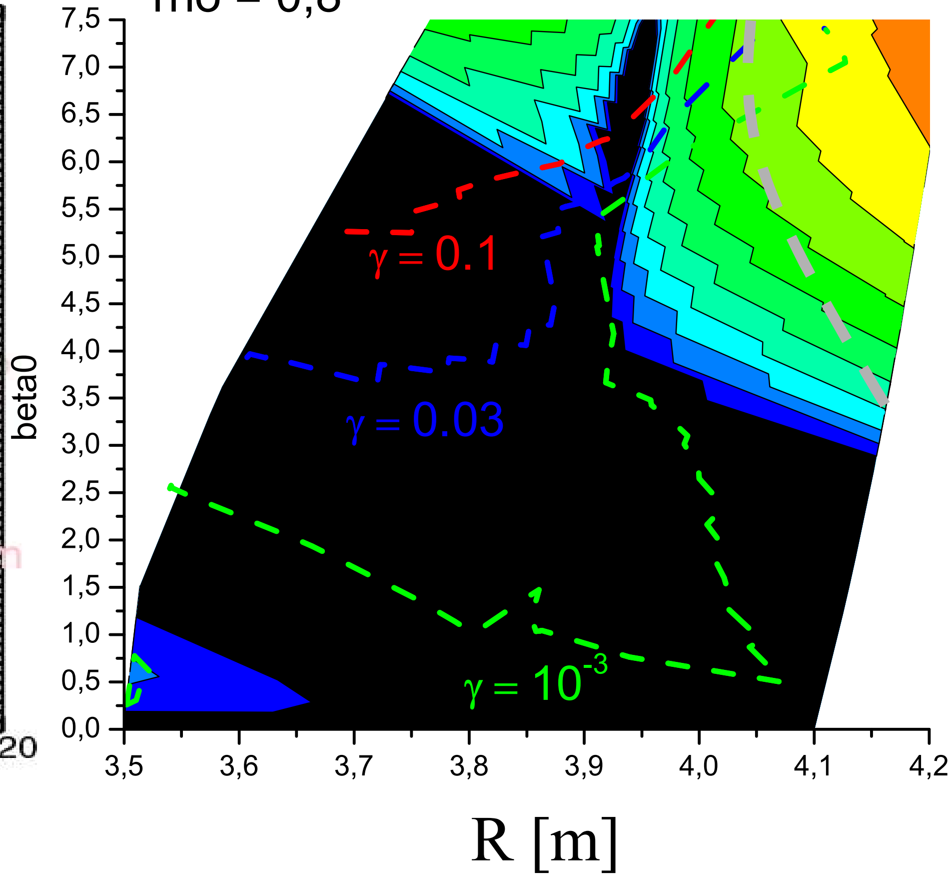
- Eigen fuction with experimental profile is under calculation using CAS3D code.

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



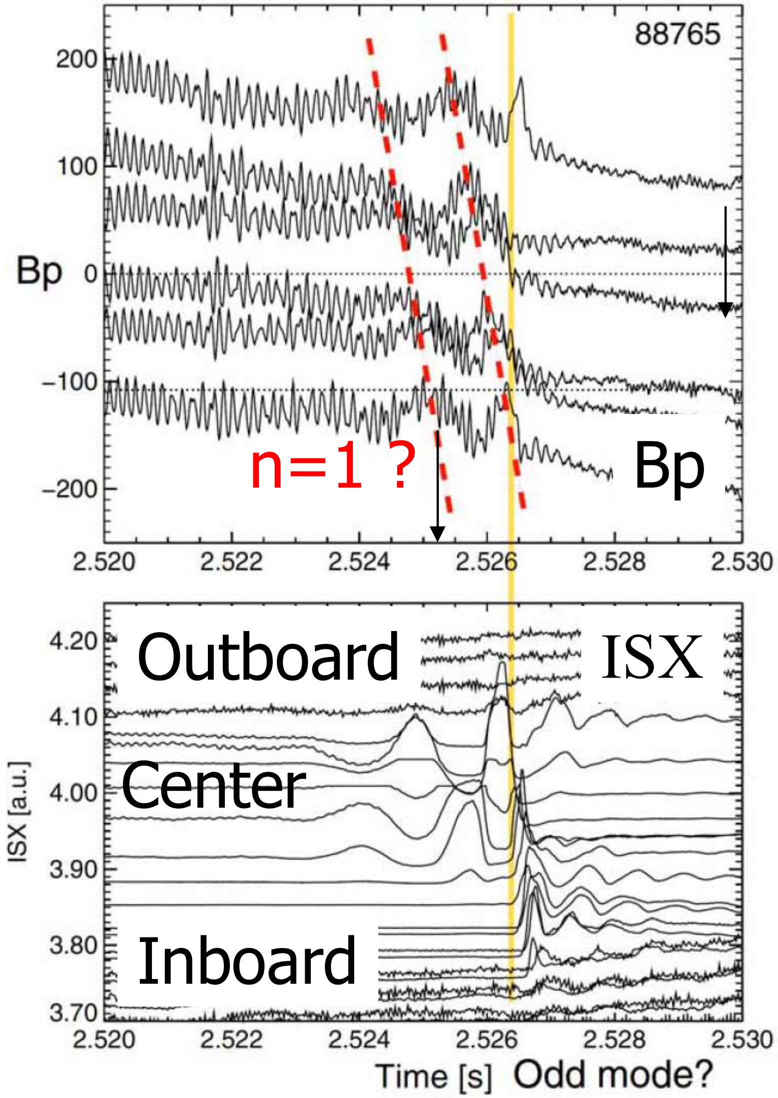
CDC region and Ballooning unstable region





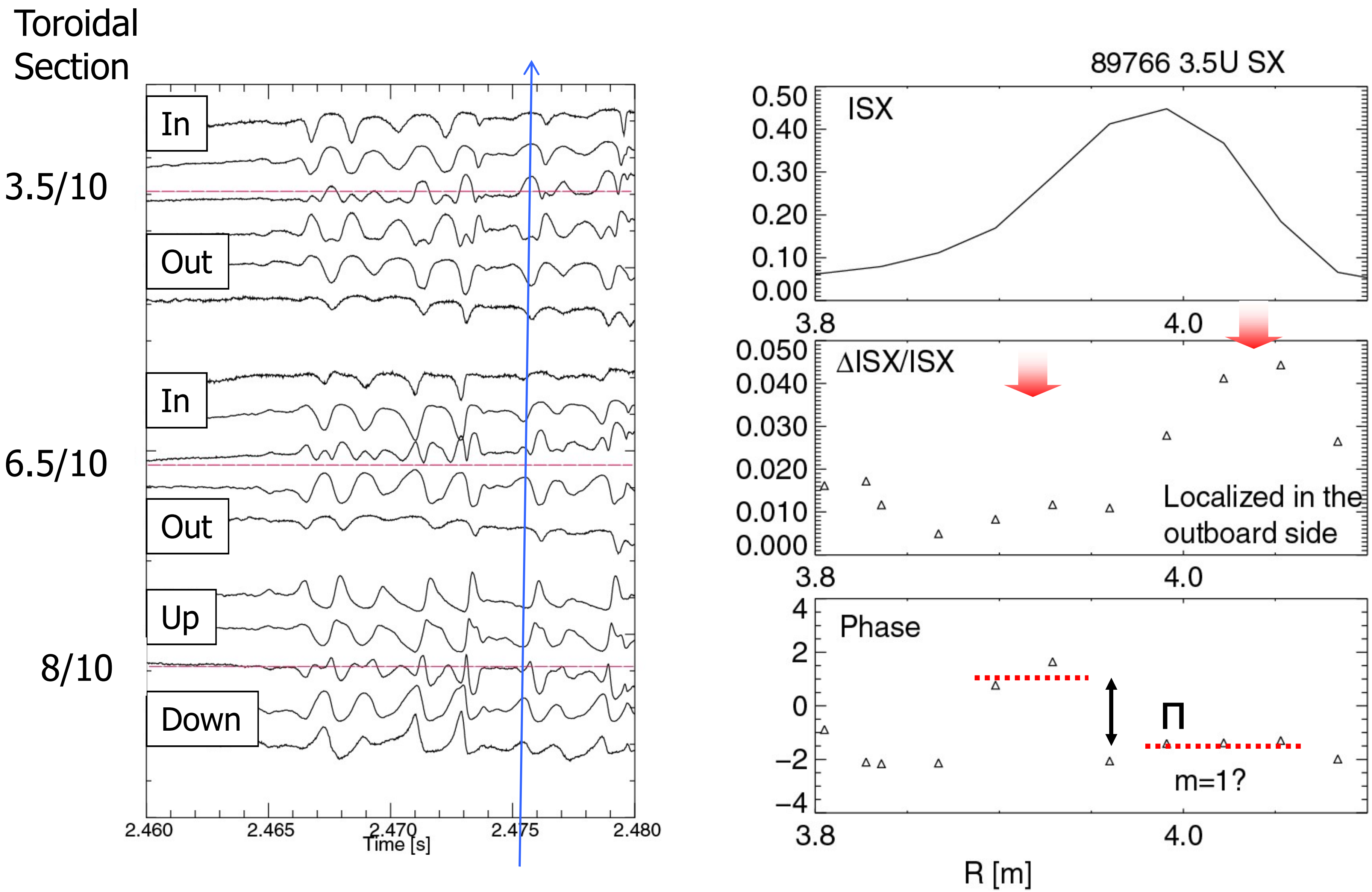
- High-n ballooning mode is unstable in the edge region. It is consistent with the operational limit of IDB/SDC plasmas.
- Stability is calculated high-n ballooning code developed by Prof. Nakajima.

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.

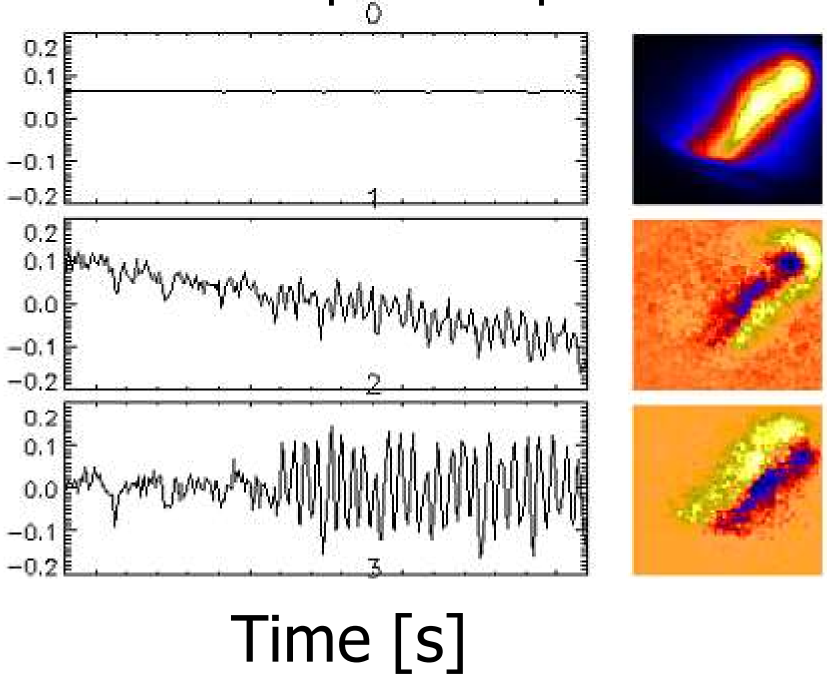
Toroidal and radial structure of oscillations

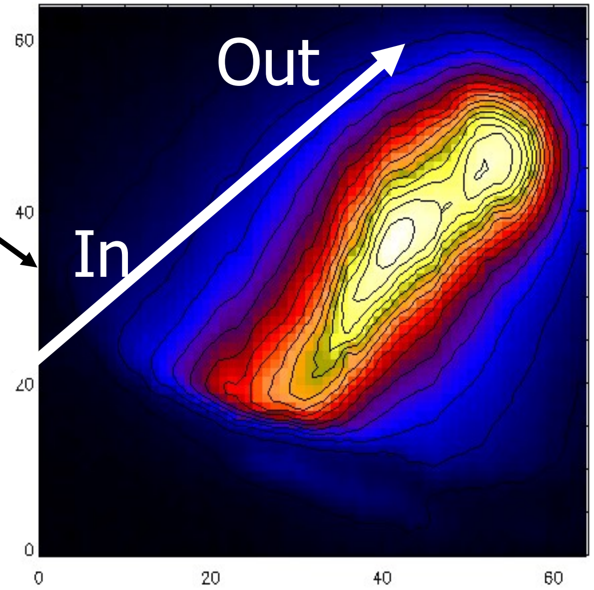


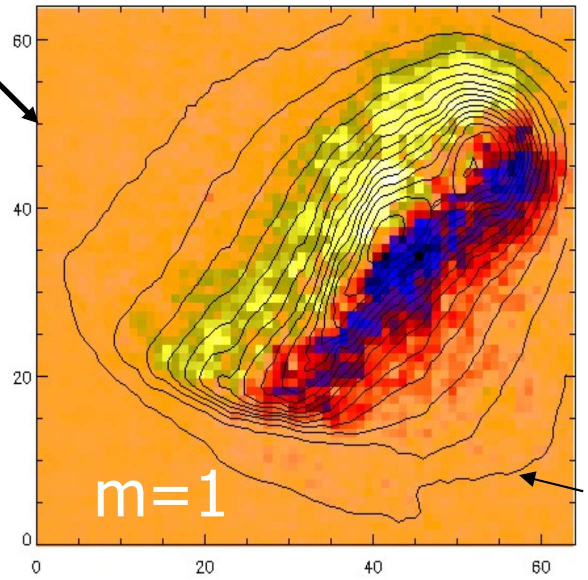
- Core m=1 structure is rotating with localized toroidally.

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

SVD decomposed experimental image

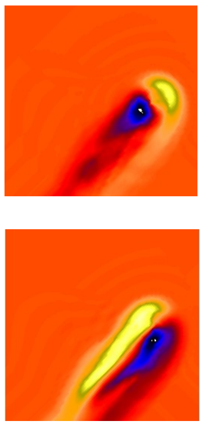






Data is consistent with the simulated image assuming core localized m= 1 mode. Radial profile is assumed by

$Exp(-((\rho-0.15)/0.1)^2)$.



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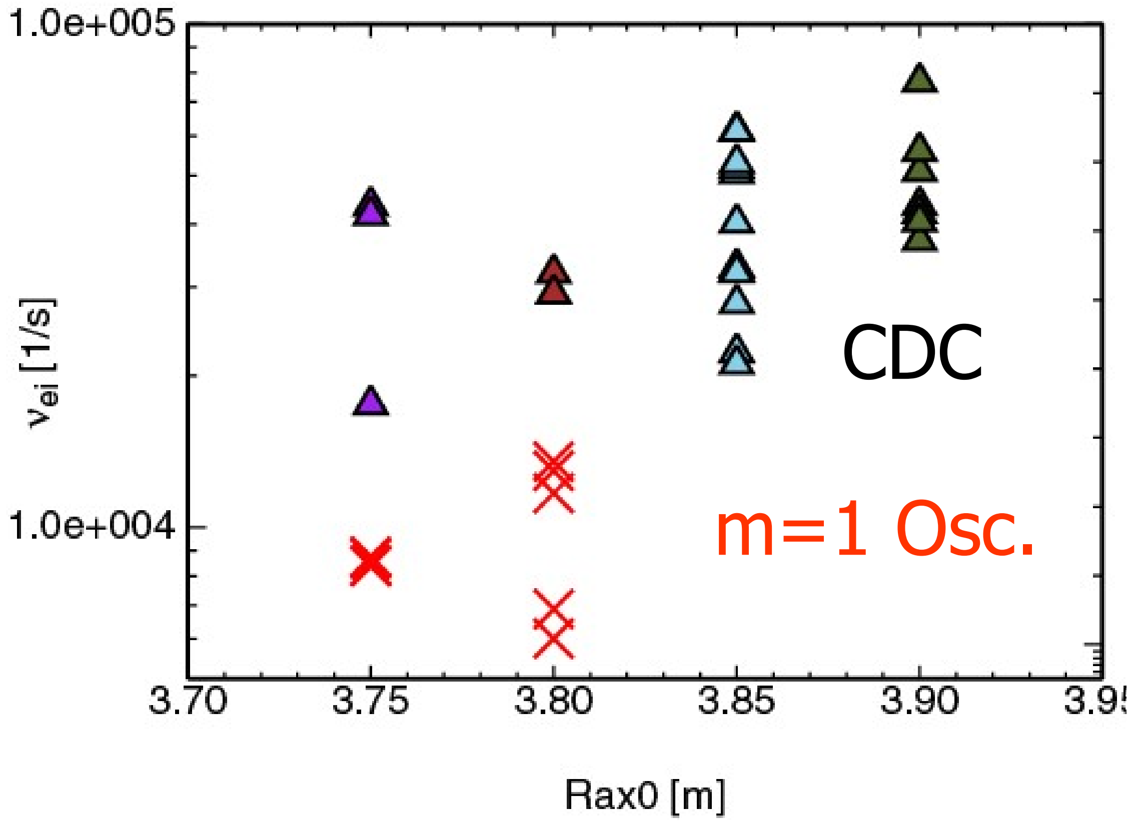
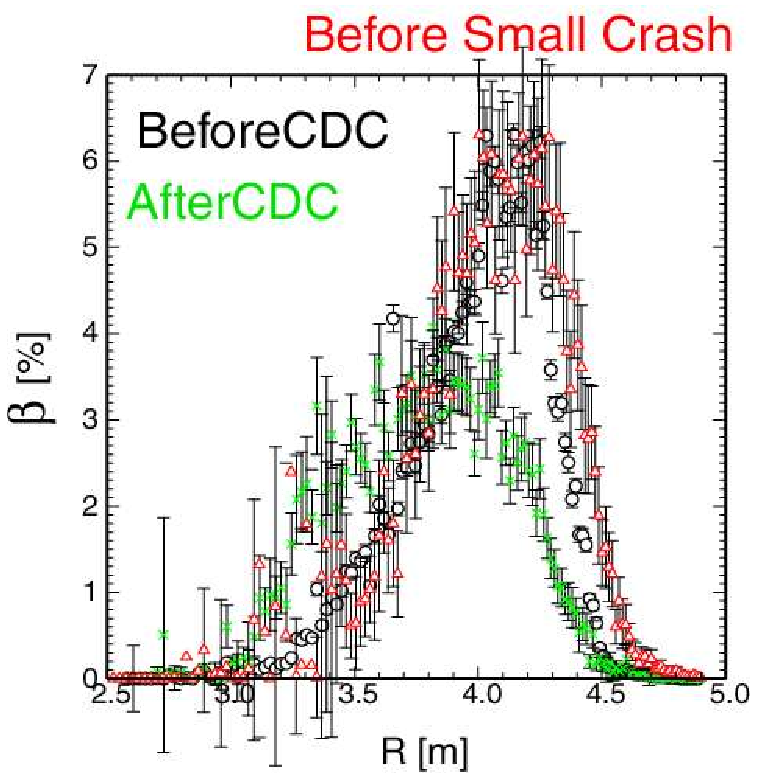
Contour line is from stationary image above.

Collisionality is different

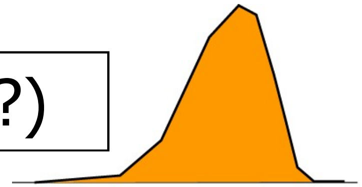




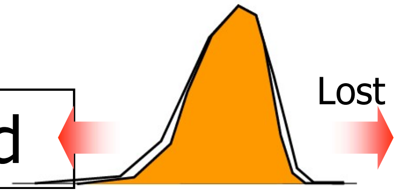
- With a lower magnetic field, achievable density is lower.
- With similar pressure profile with lower collisionality plasma, no CDC is observed. Only low frequency oscillations are observed in such condition.

Mechanism of Core Density Collapse

Flattening of the edge plasma (Ballooning modes?)

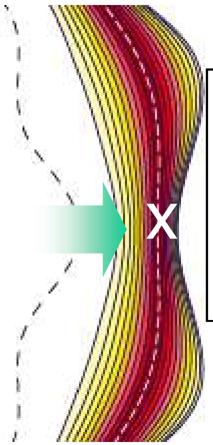


Pressure gradient in the core region is steepened



Collisional

Less collisional

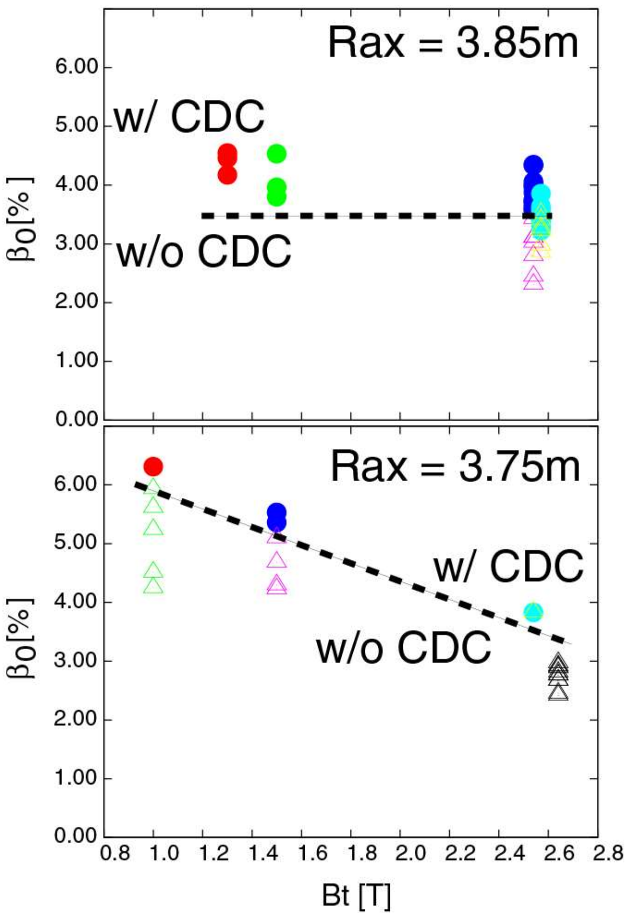


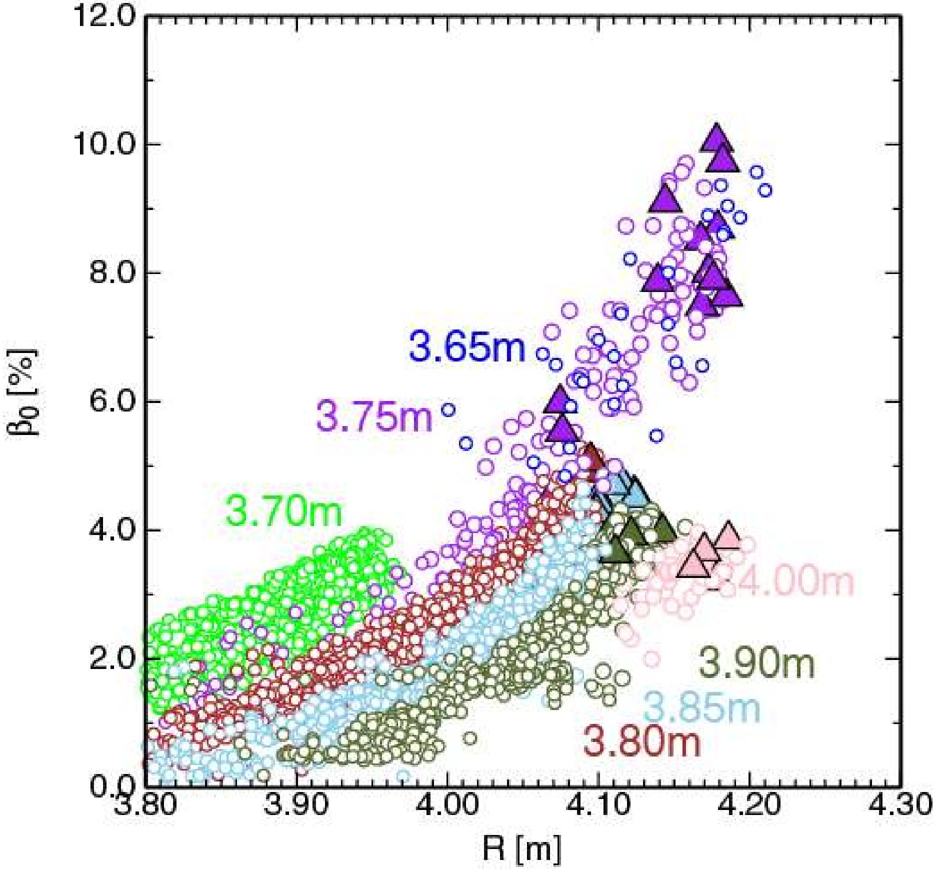
Magnetic reconnection in the outboard side of the plasma.

m = 1 large-amplitude oscillations are observed. Cause of the core oscillation has not been clarified.

In reactor relevant plasmas, CDC might not be destabilized by its low collisionality.

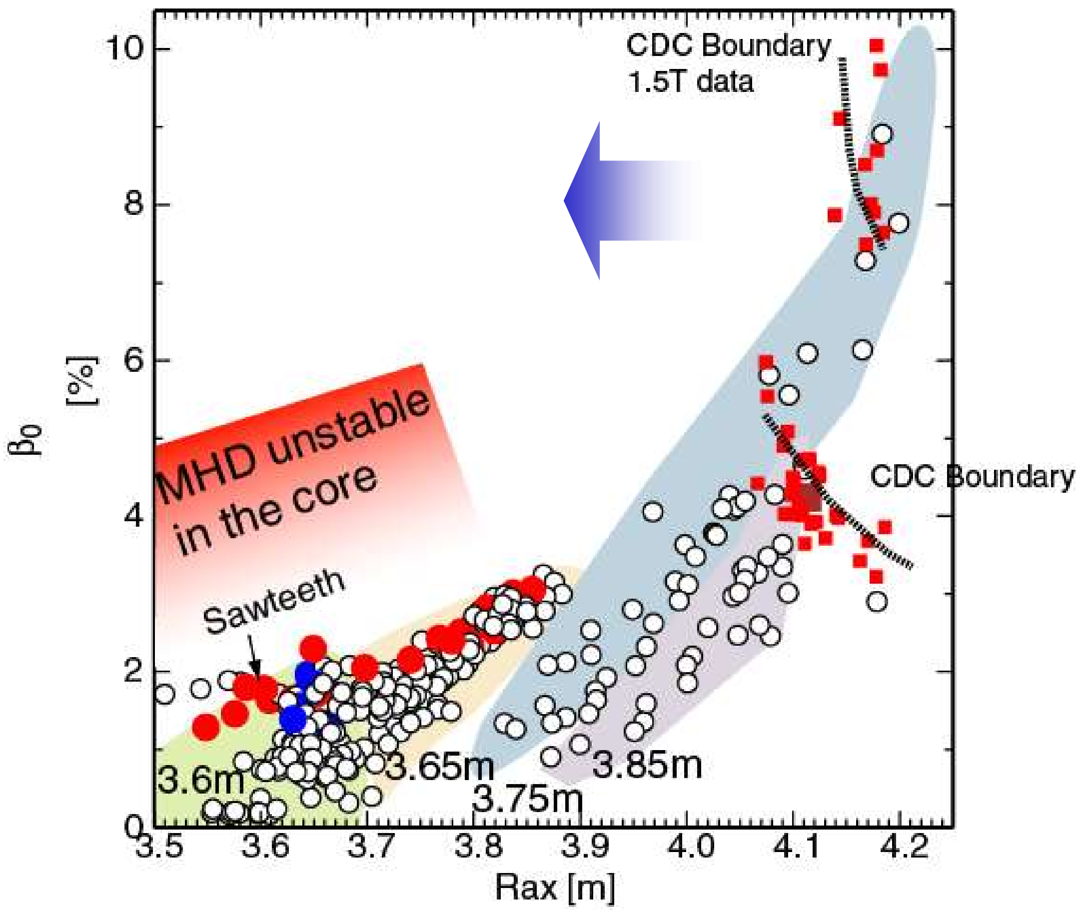
Higher central beta in inward shifted case





- In relatively inward-shifted cases(3.65m< R_{ax0} < 3.75m), higher central beta value can be obtained with lower magnetic field. In R_{ax0}< 3.7m, CDC has not been observed.

Operation Regime of high-beta plasmas

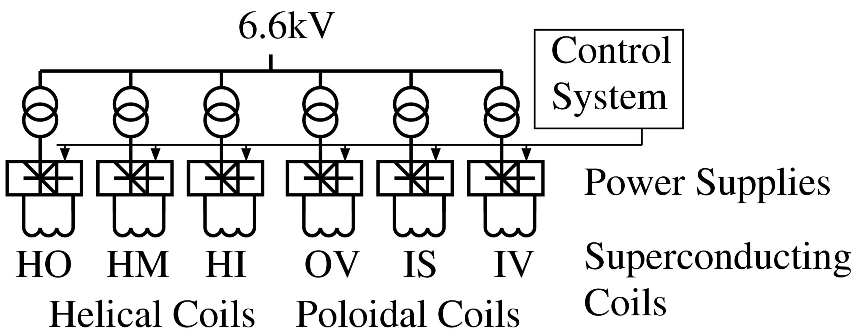


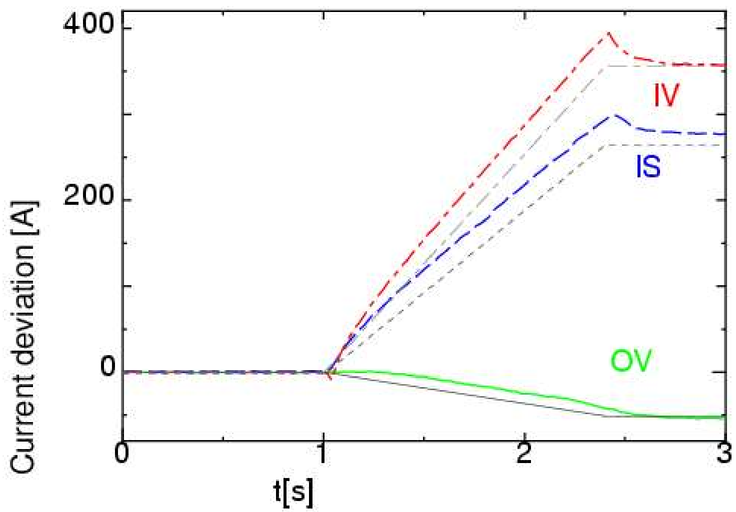
- When the magnetic axis is shifted inward, 2/1, 3/1 sawtooth is unstable. (effects are smaller.)
- In outward shifted cases, CDC limits the increase of the central beta values.
- By vertical elongation, where Shafranov shift is reduced, higher central beta has been achieved.
- By the real-time control of the magnetic axis, we can expect higher plasma beta plasma without MHD instabilities

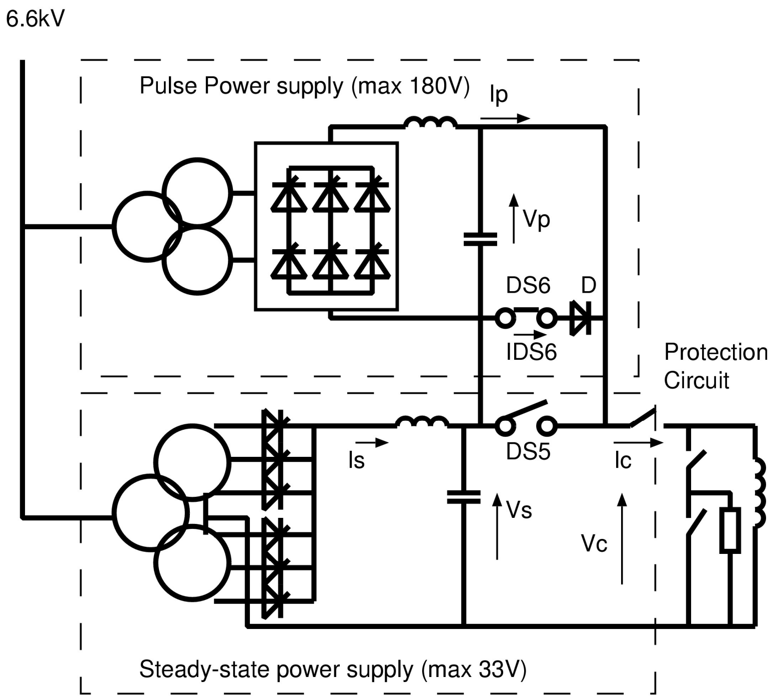
Specification of PC Power Supply

Capacity of PC PS was increased

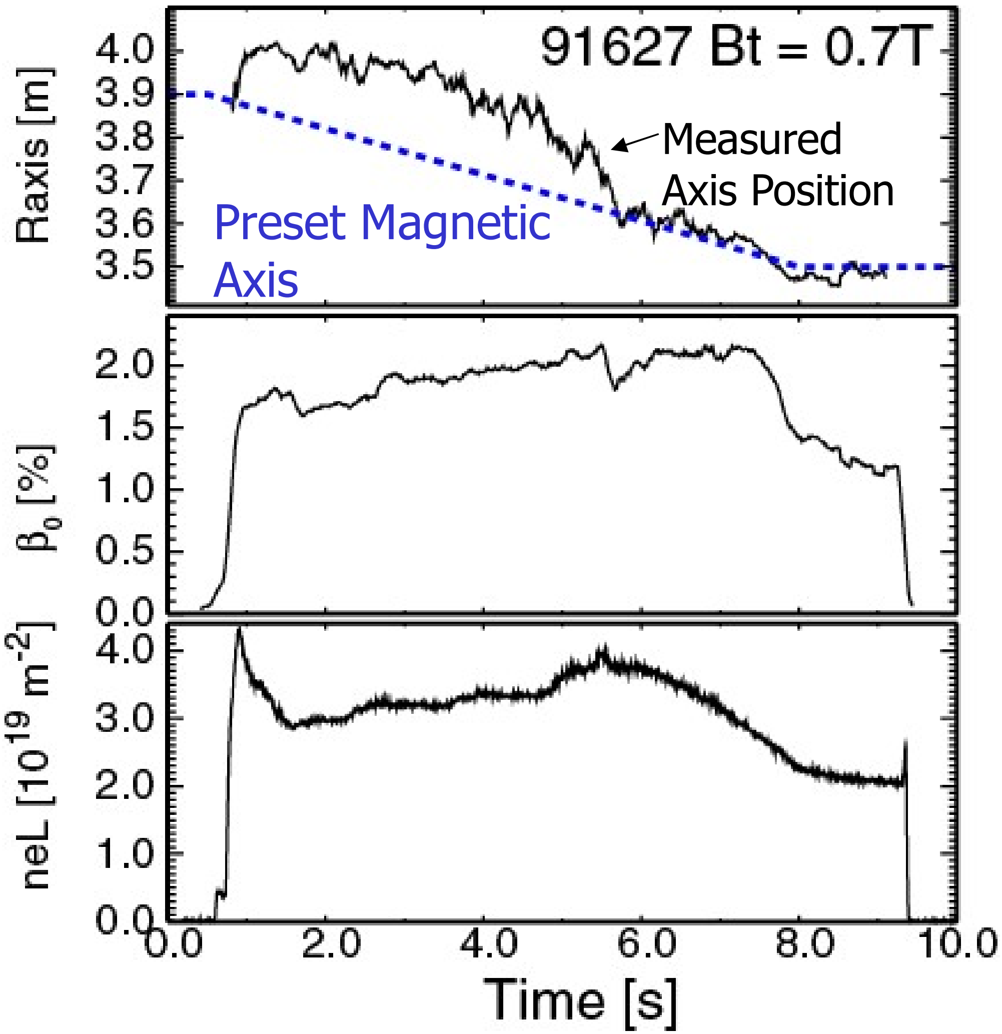
- IS, IV coils : < 6. 2 kA
- H 45 V, P 213 V (SS H 45 V, P 33 V)
- Operation with ≤ 1.5 T is available
- Fixed B_t or Fixed I_{HC} operations







Example of magnetic axis swing



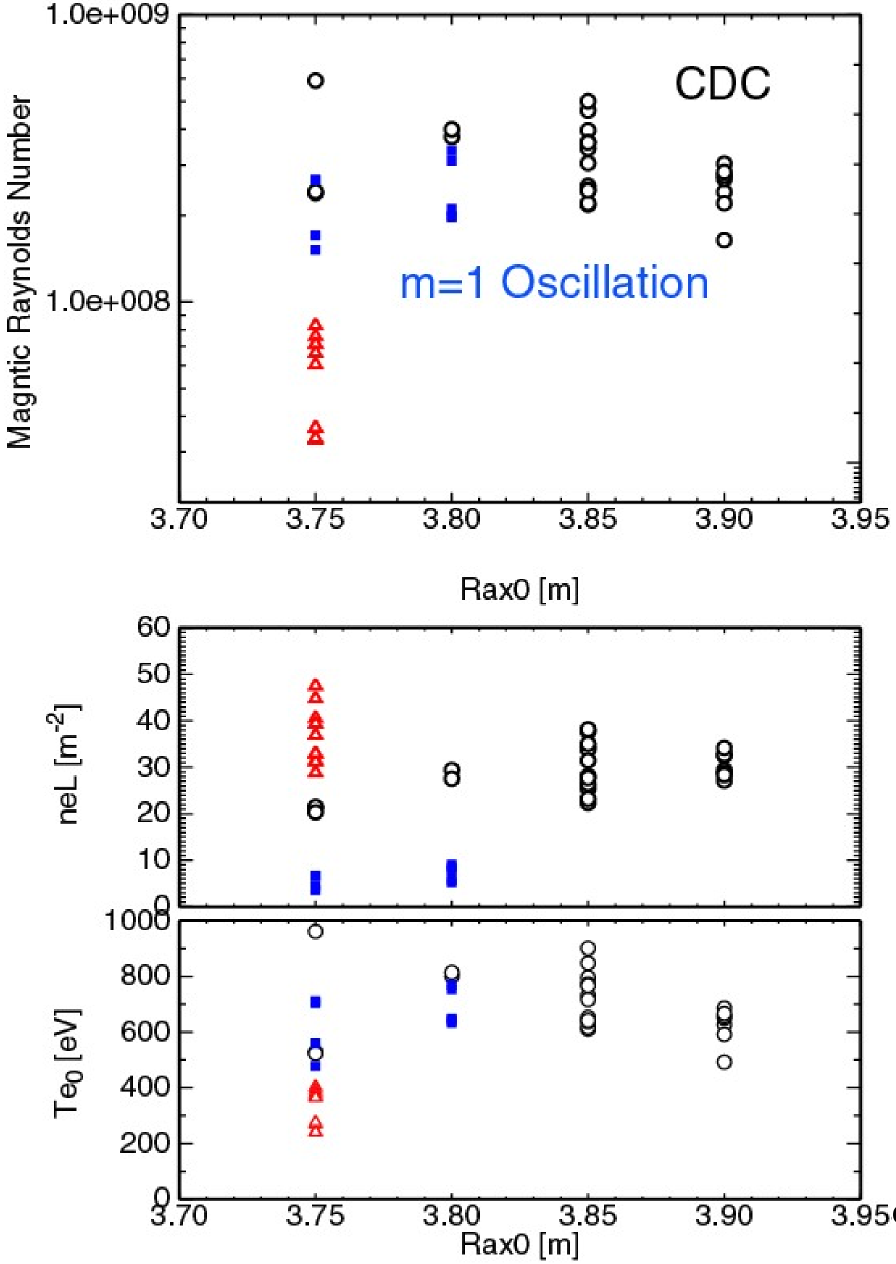
- In this discharge, shift with 40cm/8s is successfully done with Bt = 0.7T.
- So far, typical time scale of the IDB/SDC plasma is smaller than the time constant of the control.
- Relation of the magnetic axis position and the core MHD instabilities will be also presented in this conf.
- S. Sakakibara: "Study of MHD Characteristics by Magnetic Axis Control in high-beta plasmas of LHD" (P3-08)

Summary

- In IDB/SDC plasmas, increase of the central beta is limited by the CDC events when preset magnetic axis R_{ax0} is larger than 3.8m
- By CDC, core plasma is collapsed within 1ms. Maximum decrease in the central beta is abound 50%

- From detailed analysis of CDC event, decrease of the edge density appears first. Unstable region of ideal ballooning modes agrees with the operational limit.
- After the shrinking of the plasma core region moves radially. In collisional plasmas, CDC appears. In less collisional conditions, large amplitude m=1 oscillation appears. Origin of m=1 oscillation is not clear.
- When vacuum magnetic axis is smaller than 3.75m, CDC boundary can be passed with reduced magnetic field.
- Control of the magnetic axis will be efficient to achieve high-central beta plasmas.

Magnetic Reynolds number at CDC

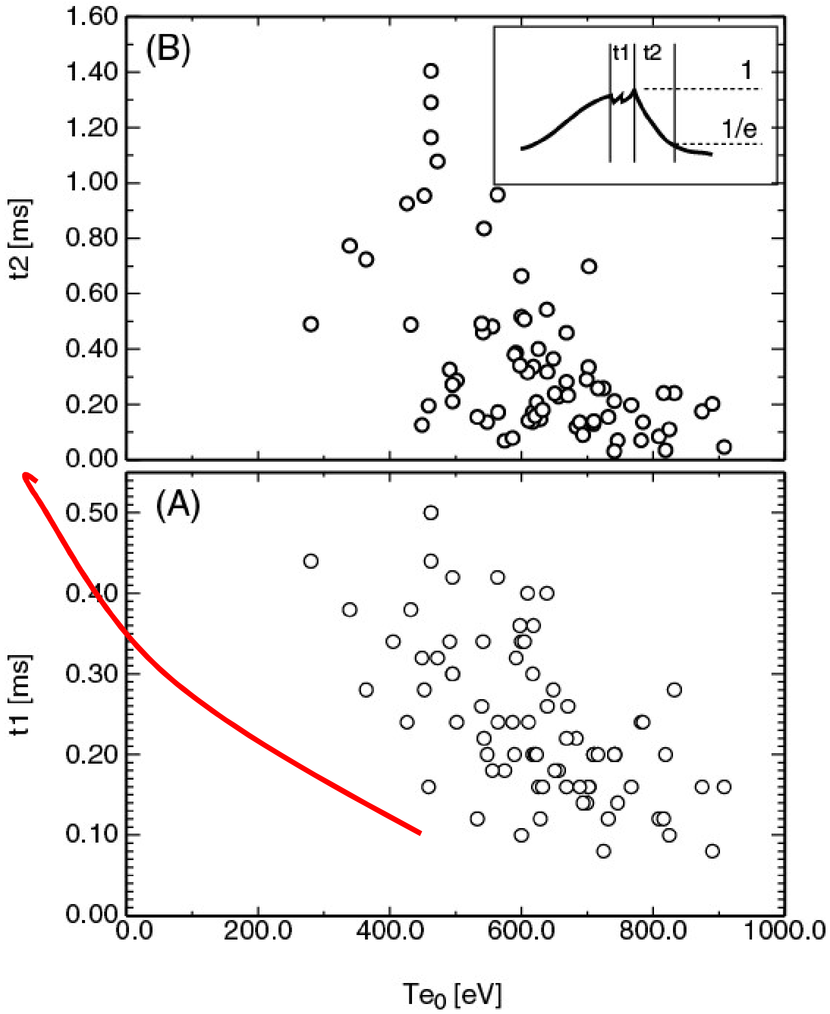


- Magnetic Reynolds number shows that with increased plasma parameters, CDC still appears.

- In high density reactor (Bt = 10T, Te0 = 5keV, ne = 1.25×10^{21} m^{-3}, R = 7.2m, a = 1.6m), S = 2×10^{10}. We need care CDC in this plasma parameters.

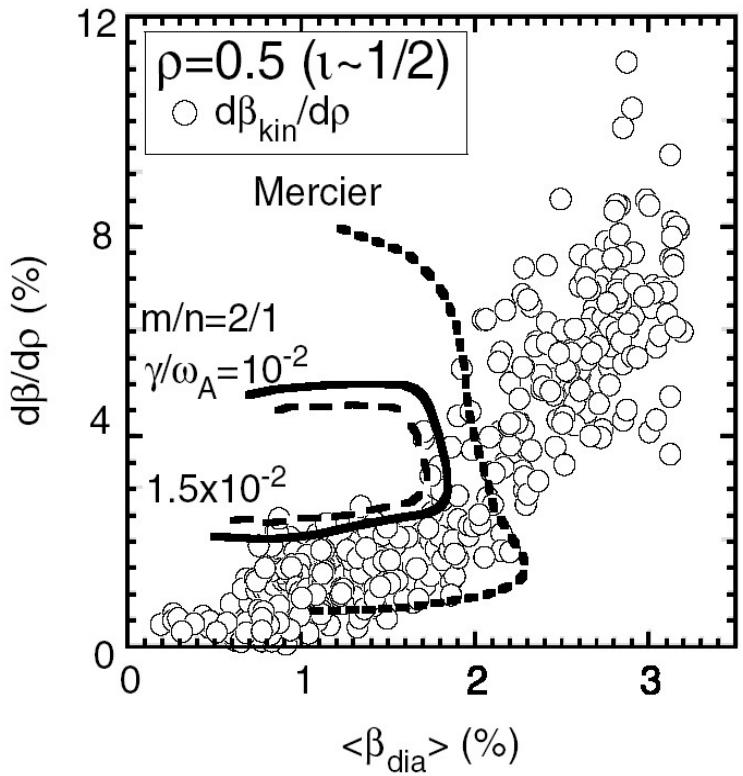
- ν_{ei} = 1.4x104 [1/s]

Time scale of crash time



- With reduction of the magnetic field, CDC becomes smaller and slower.

Peaked pressure profile in pellet discharges

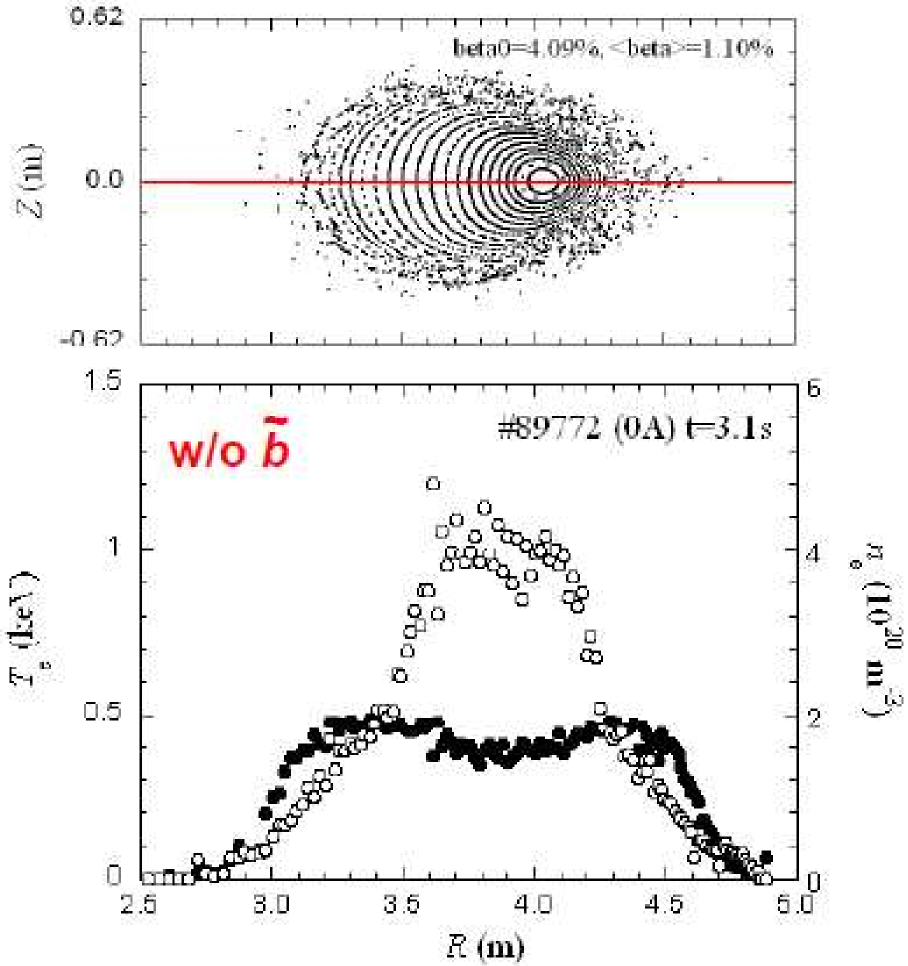


K. Y. Watanabe, et. al. Nucl. Fusion **45** (2005) 1247

- Density profile is hollow one in normal discharges.
- After the pellet injection, in the density decaying phase, the pressure gradient becomes steep.

IDB/SDC plasma and stochastisity

- Will be discussed in Morisaki's talk.
- I08 Morisaki" Effect of Nonaxisymmetric Perturbation on Profile Formation"

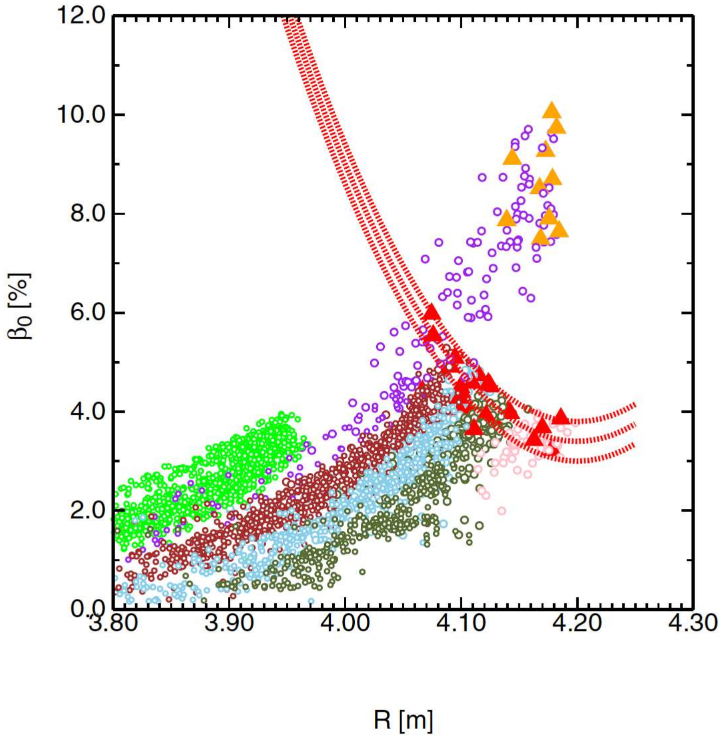


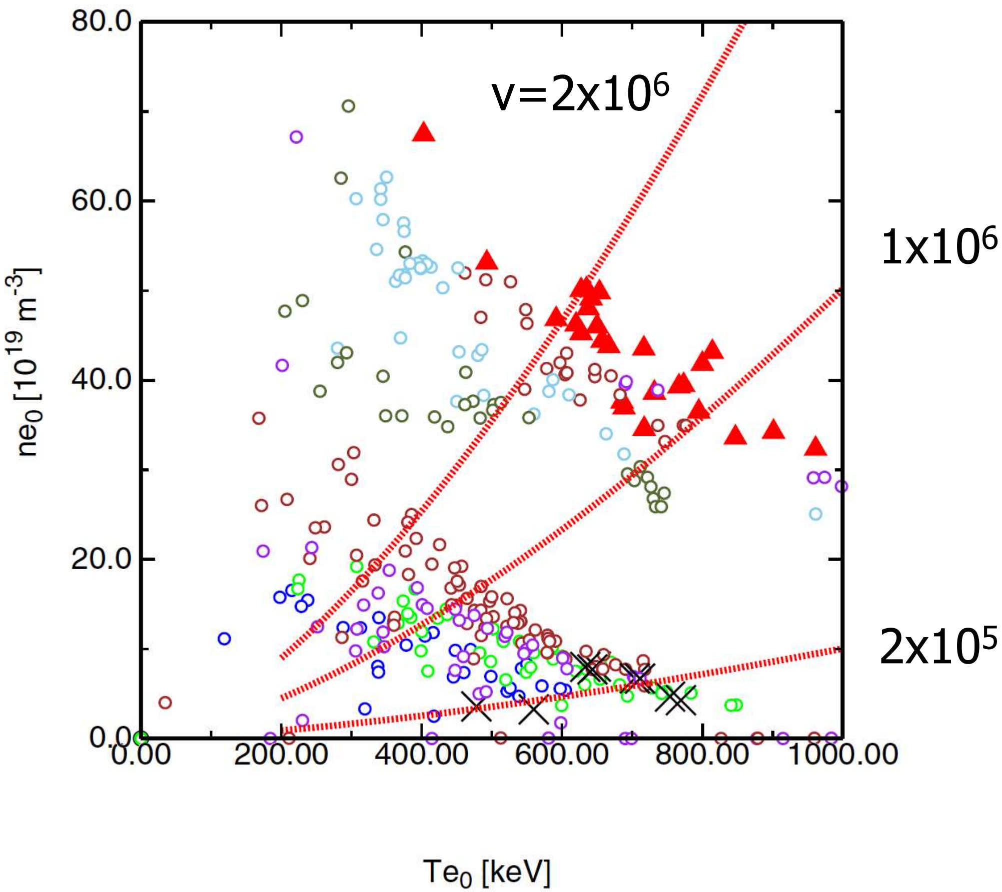
By HINT2 calculation,

(*can calculate 3D equilibrium even in the stochastic region*)

edge region is **ergodized** in SDC

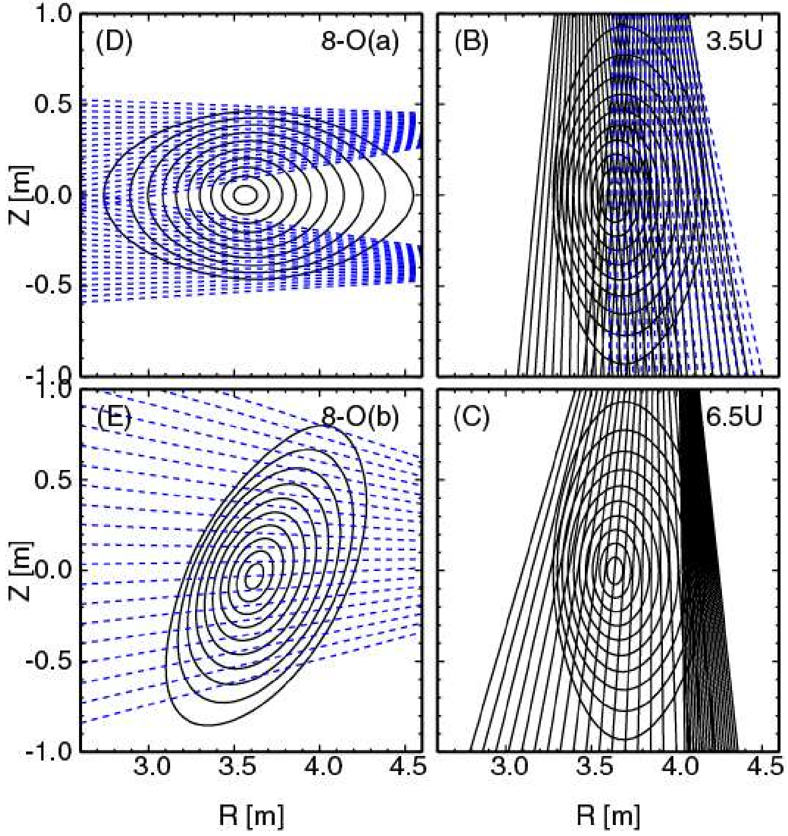
Collisionarity



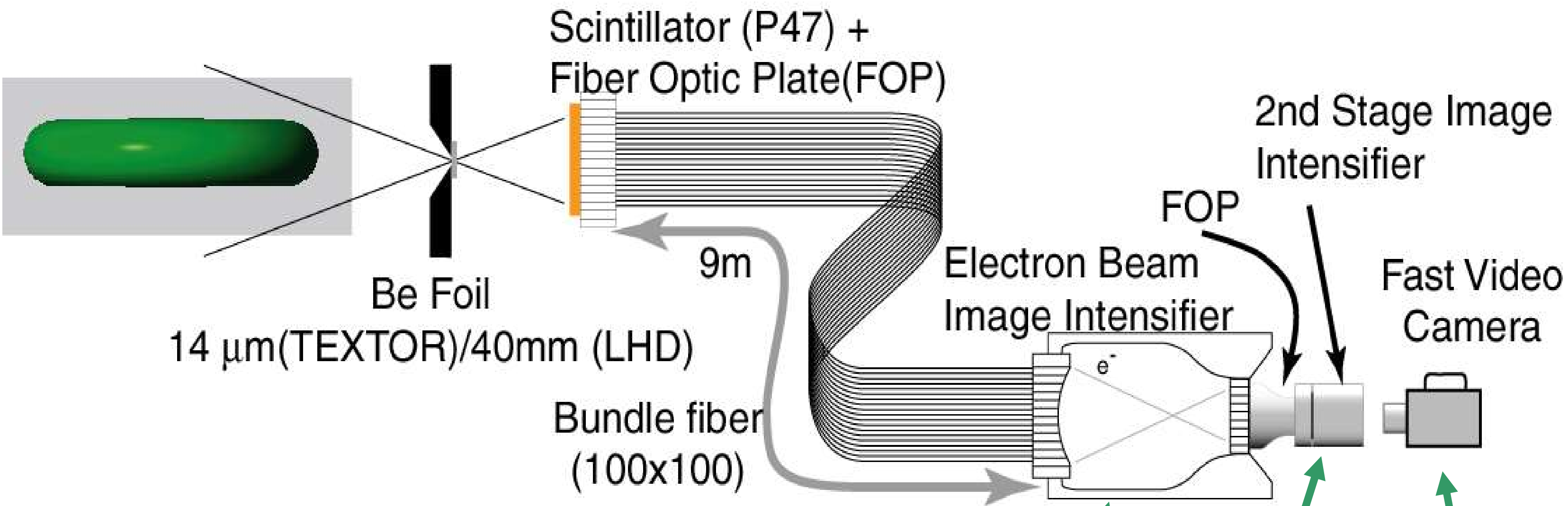


- CDC in Bt > 1.5T. m=1 oscillation in Bt < 1.0

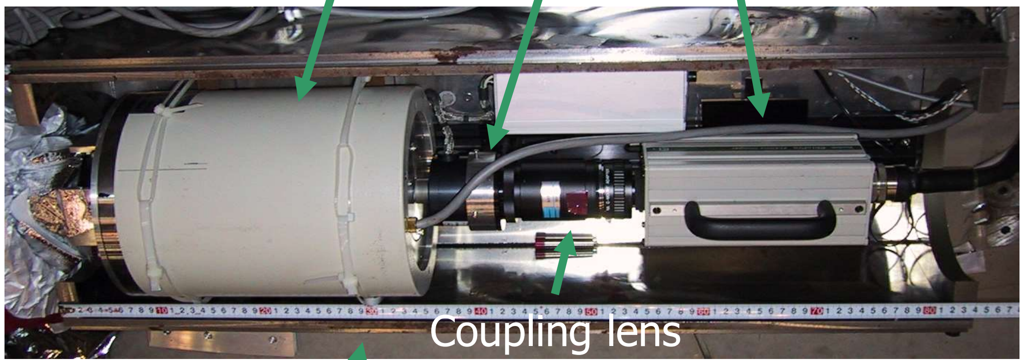
SX measurement



Hardware of the camera system



- Fast video camera
  - KODAK:4540MX / Vision Research: Phantom
  - 30fps-4500fps(256x256)
  - ~20kHz(256x256 new)
- Fluctuation measurement is realized from fast optical system with large diameter scintillator screen(10cm).



Iron magnetic shied 2.5cm in thickness

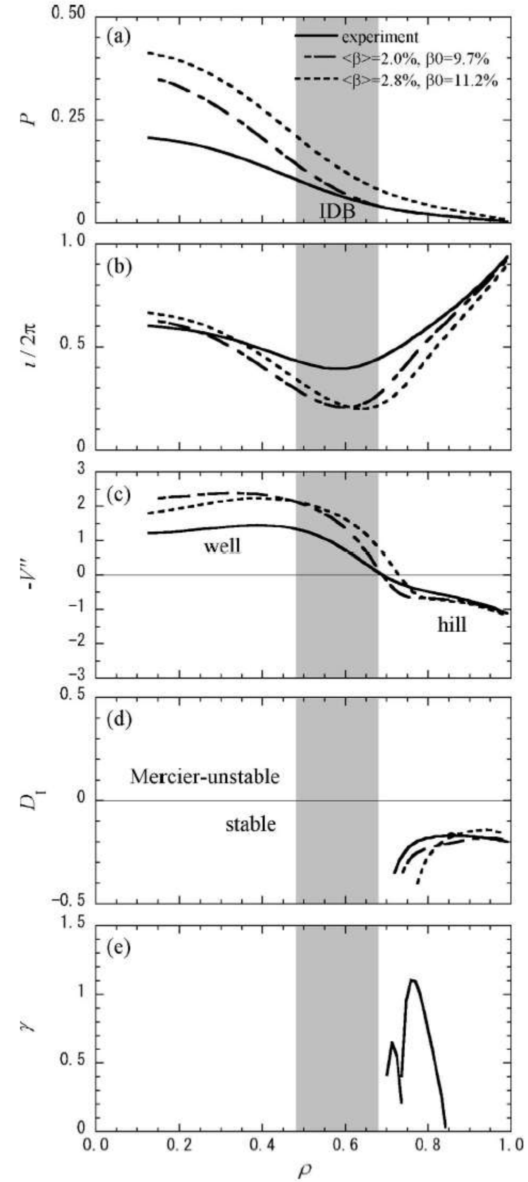


FIG. 6. Radial profiles of (a) pressure P, (b) normalized rotational transform $\iota/2\pi$, (c) magnetic well and hill V", (d) Mercier criterion D_I, and (e) growth rate of the ideal ballooning mode γ.