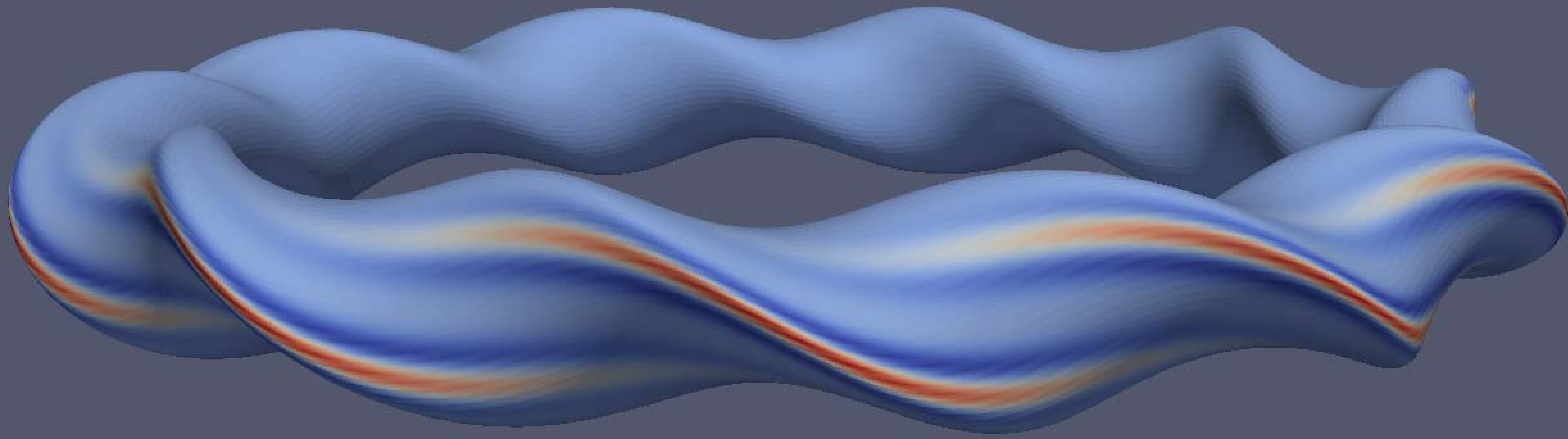
Observation of localized mode in the bad curvature region at the core-density-collapse event in the Large Helical Device



S. Ohdachi*[12], K. Tanaka[1], K. Y. Watanabe[1], N. Nakajima[1], Y. Takemura[1], Y. Suzuki[12], J. Varela[3], S. Sakakibara[12], R. Sakamoto[12], J, Miyazawa[1], I. Yamada[1], K. Ida[12], M. Yoshinuma[12], K. Toi, T. Morisaki and LHD Experiment Group

[1] *National Institute for Fusion Science, Japan*

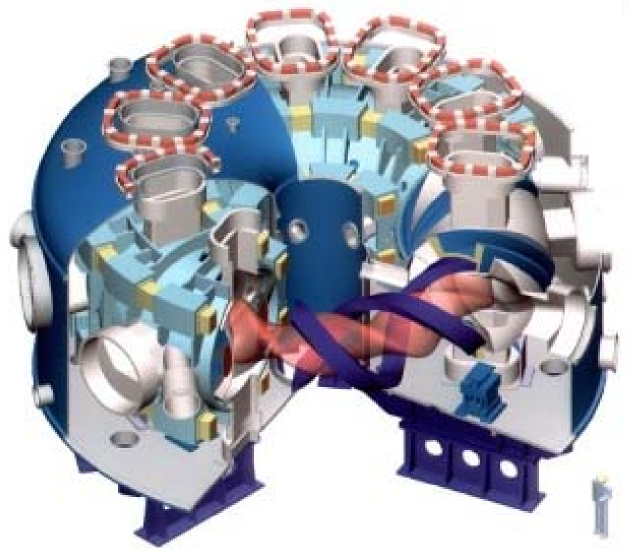
[2] *SOKENDAI(The graduate university for advanced studies), Japan*

[3] *Observatoire de Paris, France*

5th APTWG meting at Dalian.

Content of my talk

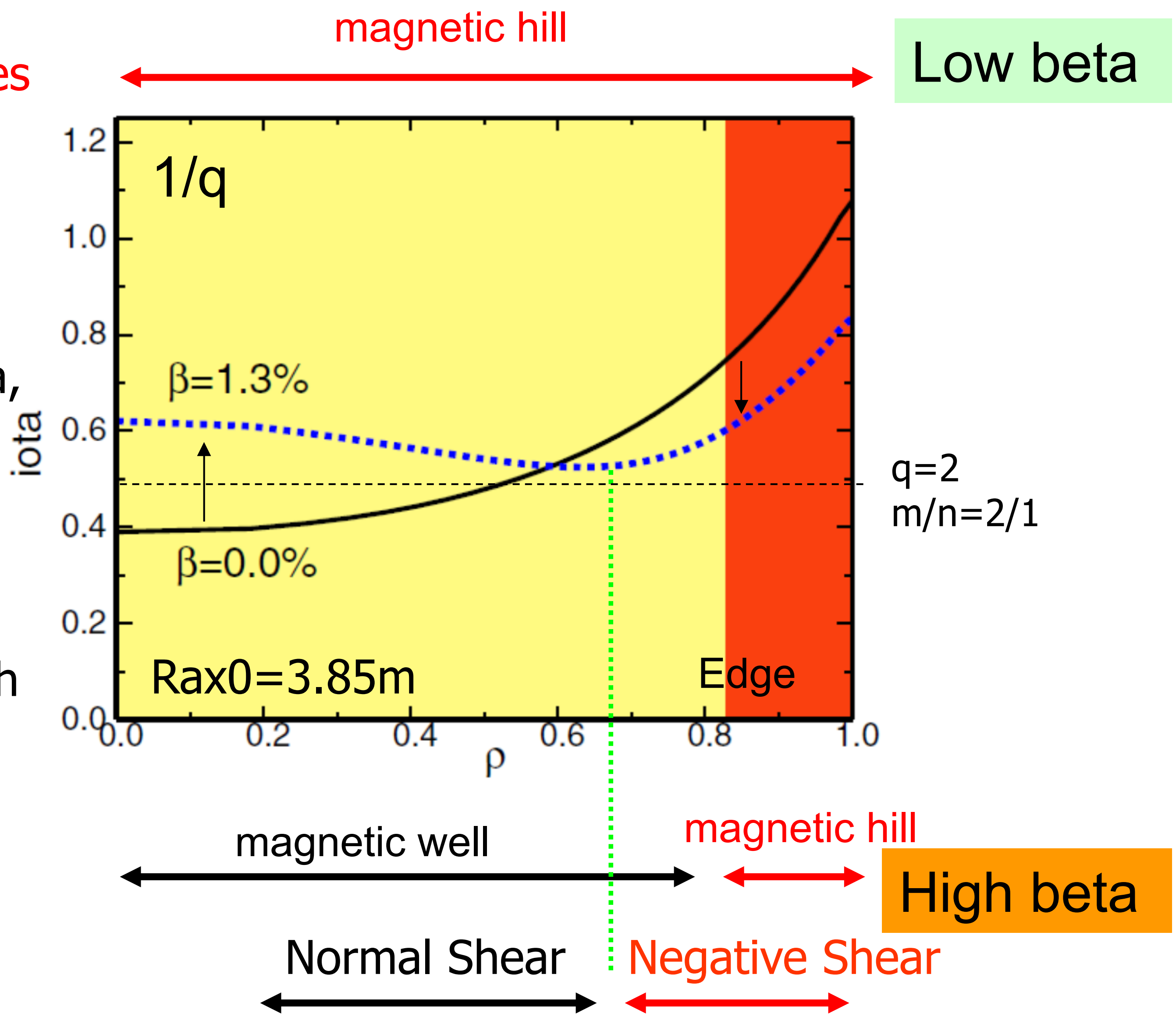
- Introduction
  - MHD property of the Large Helical Device
  - Hn-Ballooning mode destabilized in the negative shear region.
- Core Density Collapse phenomena
  - Super Dense Core / Internal Diffusion Barrier discharge in LHD
  - Core density collapse and pre-cursor oscillations.
  - Observation of the pre-cursor oscillations.
  - Comparison to the stability boundary.
- Summary



L = 2, m=10 Heliotron type device
R = 3.5 - 3.9m, a ~ 0.6m

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 gradient.



N. Nakajima Phys. Plasmas **3** 4545,4556(1996)

Ballooning mode in positive/negative shear region

Potential energy of the incomprresive high-mode-number ballooning mode is written as,

Nakajima, PoP **3**(1996)4545

$$\delta W = \frac{1}{2}\int d\tau \left(|\mathbf{k}_\perp|^2 (\hat{n}\cdot\nabla\Psi) r - \frac{2}{B^2}\hat{n}\times\mathbf{k}_\perp\cdot\kappa\times\hat{n}\times\mathbf{k}_\perp\cdot\nabla P \Psi^2 \right)$$

Stability related with local shear

Destabilized by the pressure gradient in the bad curvature (κ) region

Tokamak

$$\hat{s}_q = s_q - \alpha\cos\eta$$

$$s_q = (\rho/q)(dq/d\rho): \text{Global shear}$$

$$\alpha = -R\beta' q^2 (>0): \text{Pressure gradient}$$

$$\hat{s}_q: \text{Local shear}$$

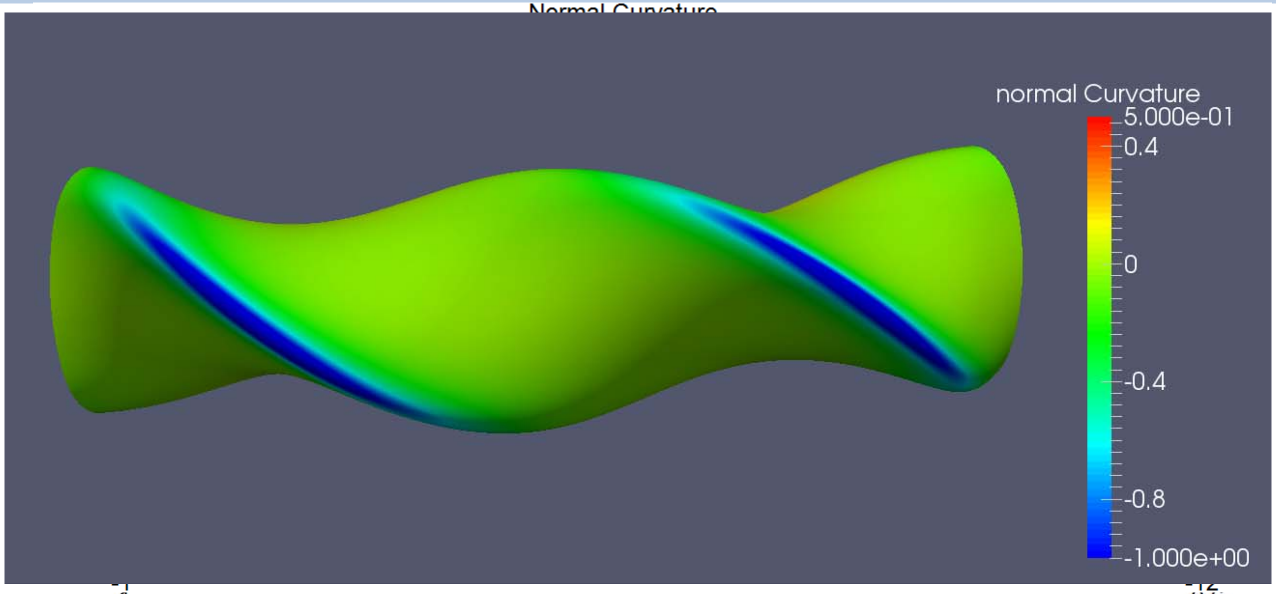
s_q > 0 is required for $\hat{s}_q$ = 0 in Tokamakst

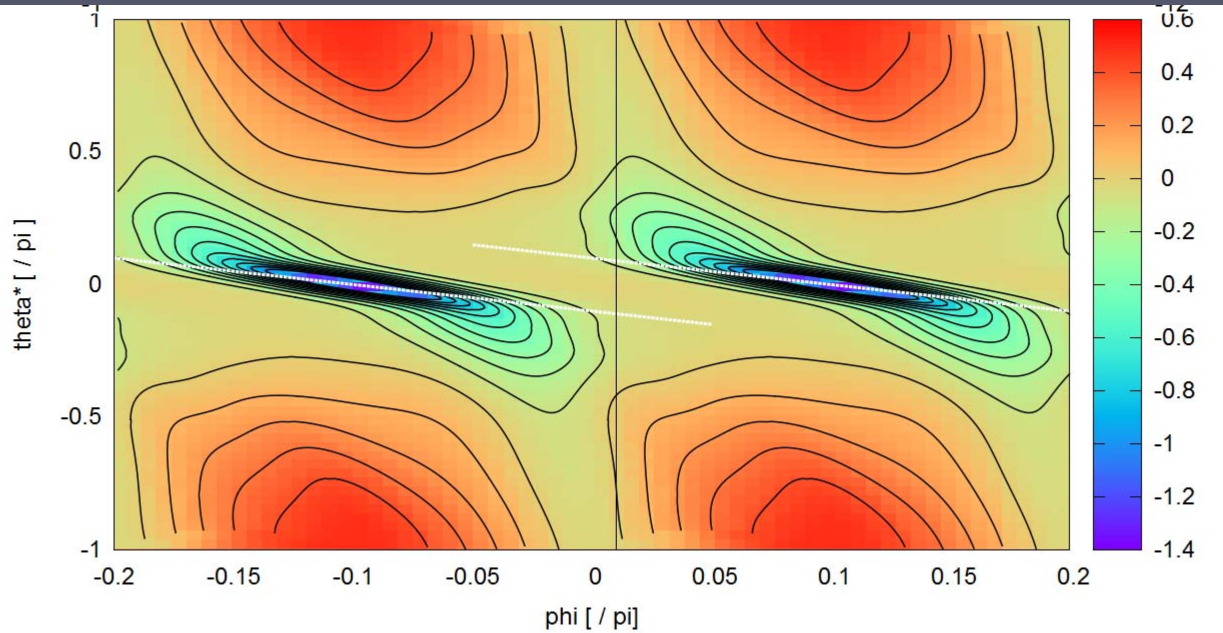
Planar Heliotron

$$\hat{s}_q = s_q - \alpha\frac{1+3s_q+\rho\beta''/\beta'}{4}\cos\eta$$

Since s_q is negative, local shear can be zero.
Local shear can be reduced in the outward region. High-n ballooning mode can be destabilized in the bad curvature region with $\hat{s}_q$ = 0

Normal Curvature





β_0 = 4%

- As beta increases, toroidal effects becomes larger. Bad curvature region is quite localized.

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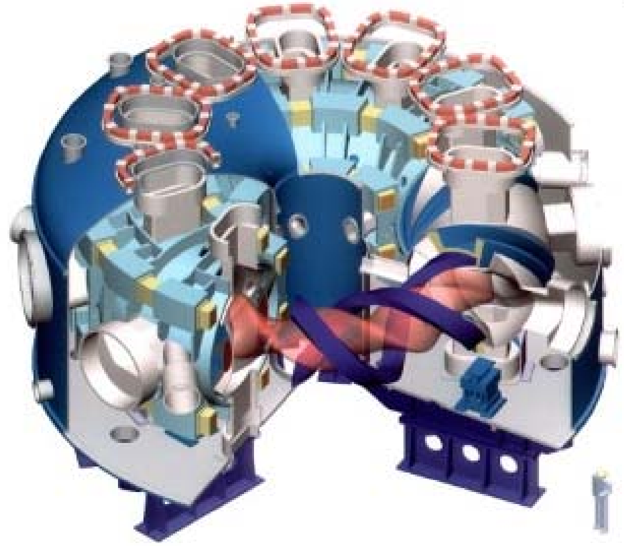
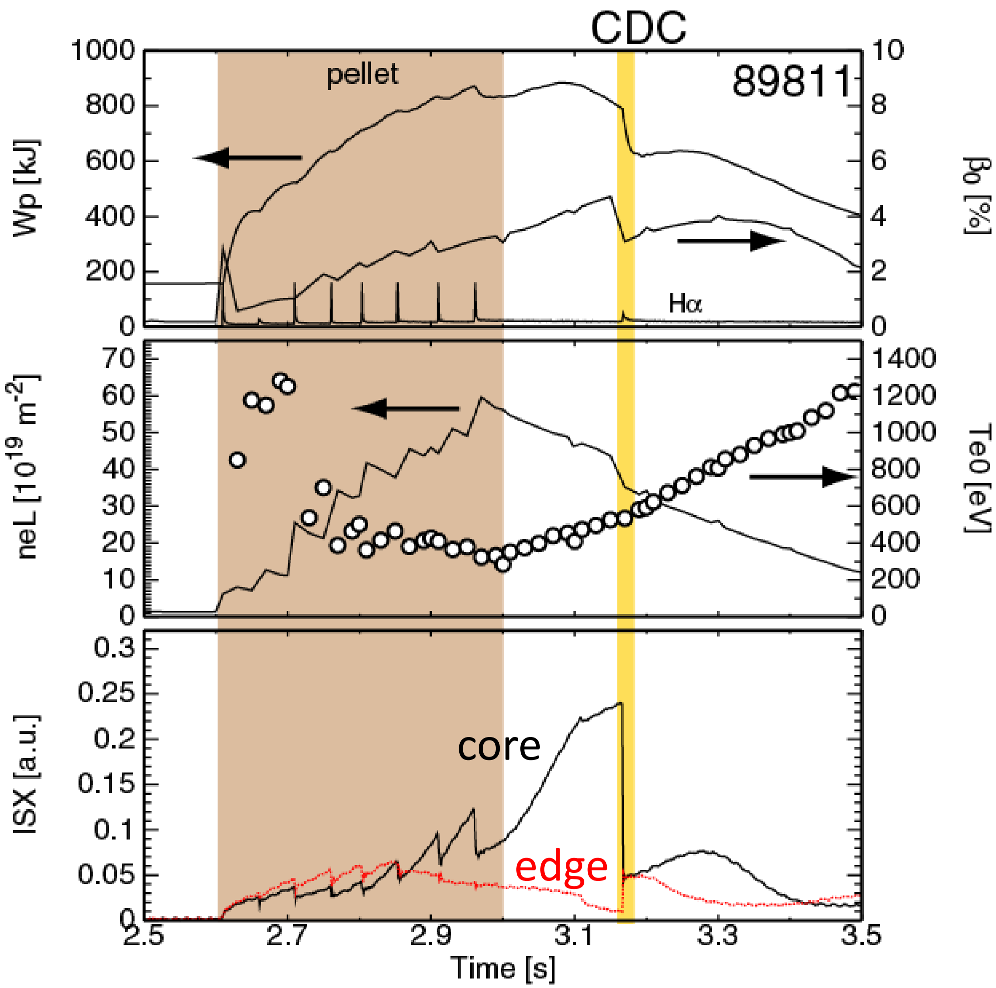


L = 2, m=10 Heliotron type device
R = 3.5 - 3.9m, a ~ 0.6m

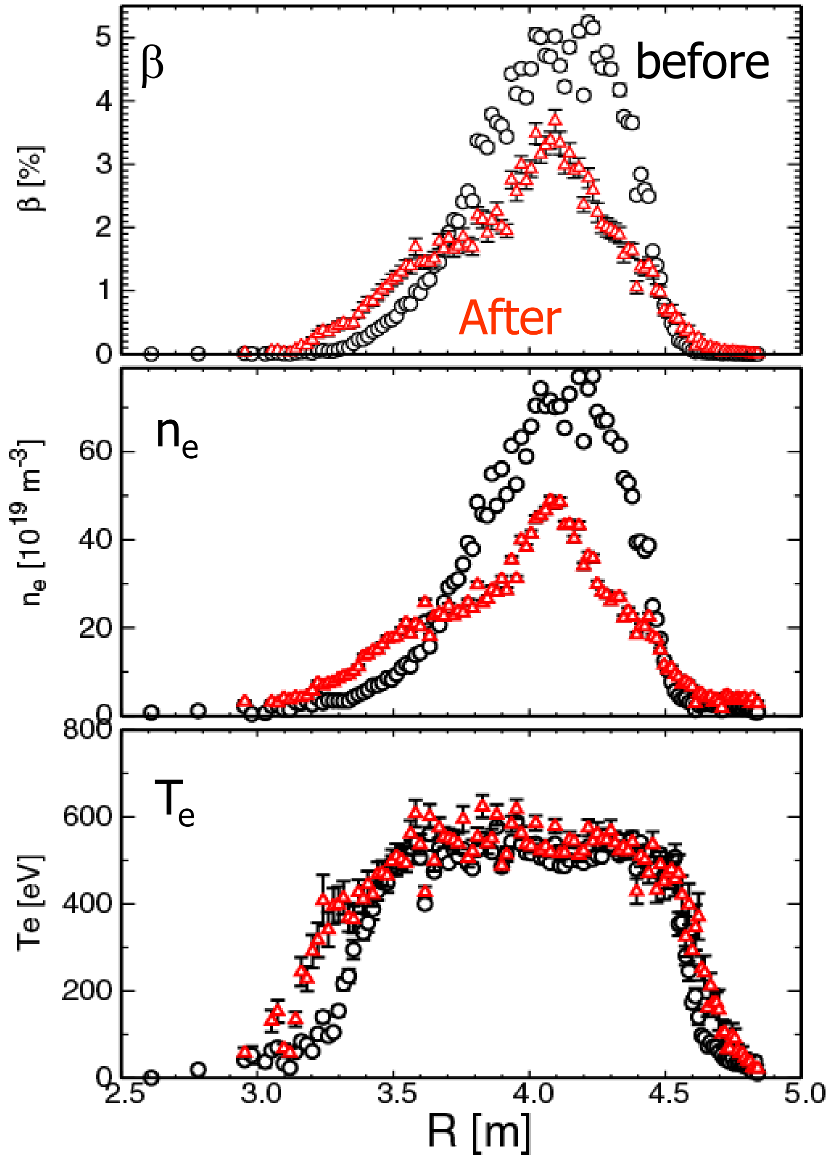
- Summary

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 space is restricted by them.



Profile changes with CDC events



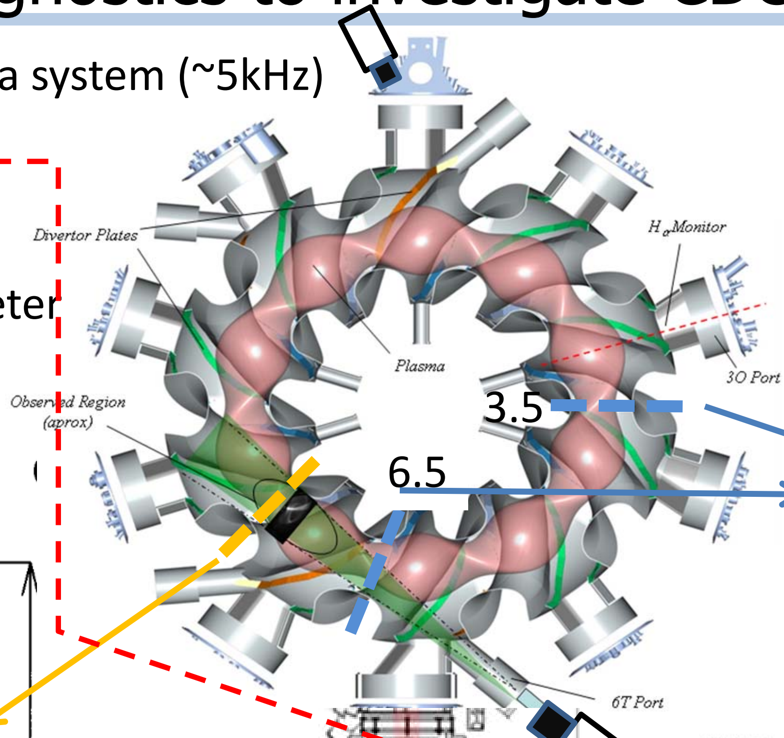
- Central beta/density decreases by up to 50%.
- Whole plasma is affected; rapid increase in I_{is} at divertor probes is observed with CDC.
- The drop of the electron density in the core is obvious. Though we have named this event 'Core Density Collapse' due to this characteristic.

$\Rightarrow$ Core plasma is transferred to the edge region by a convective manner.

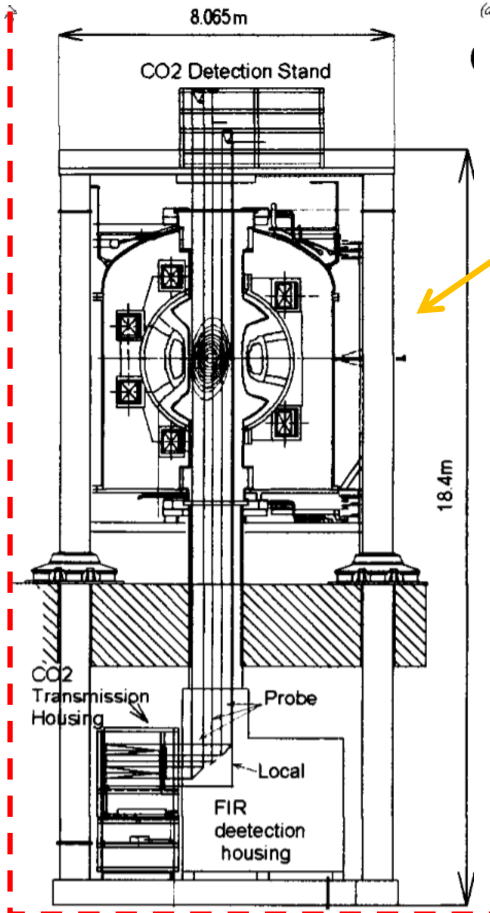
Diagnostics to investigate CDC Phenomena

2D VUV camera system (~5kHz)

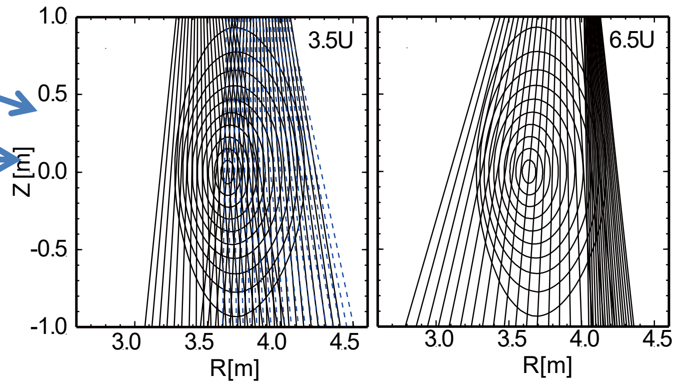
ECE measurement is not usable.
ne ~10^{20} m^{-3}

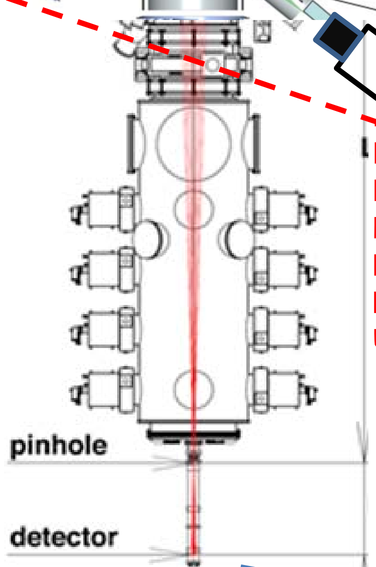


Co2 80ch Laser
Imaging interferometer
(~100kHz)

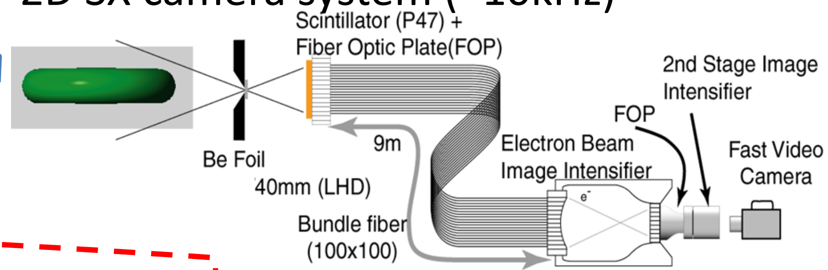


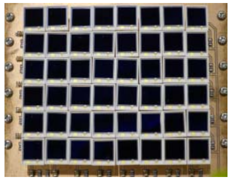
SX Radial Arrays 40ch(~50kHz)





2D SX camera system (~10kHz)

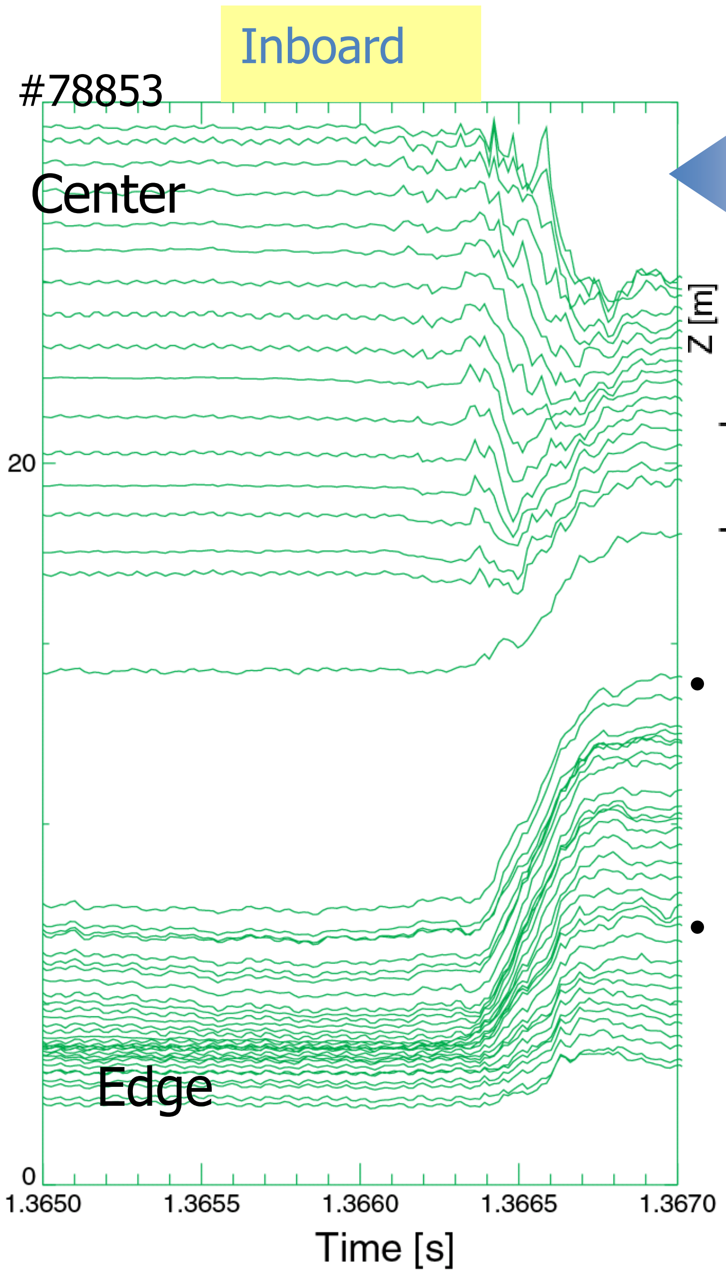


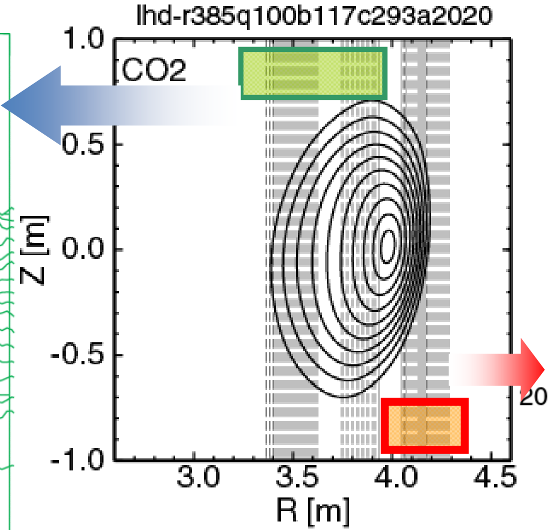


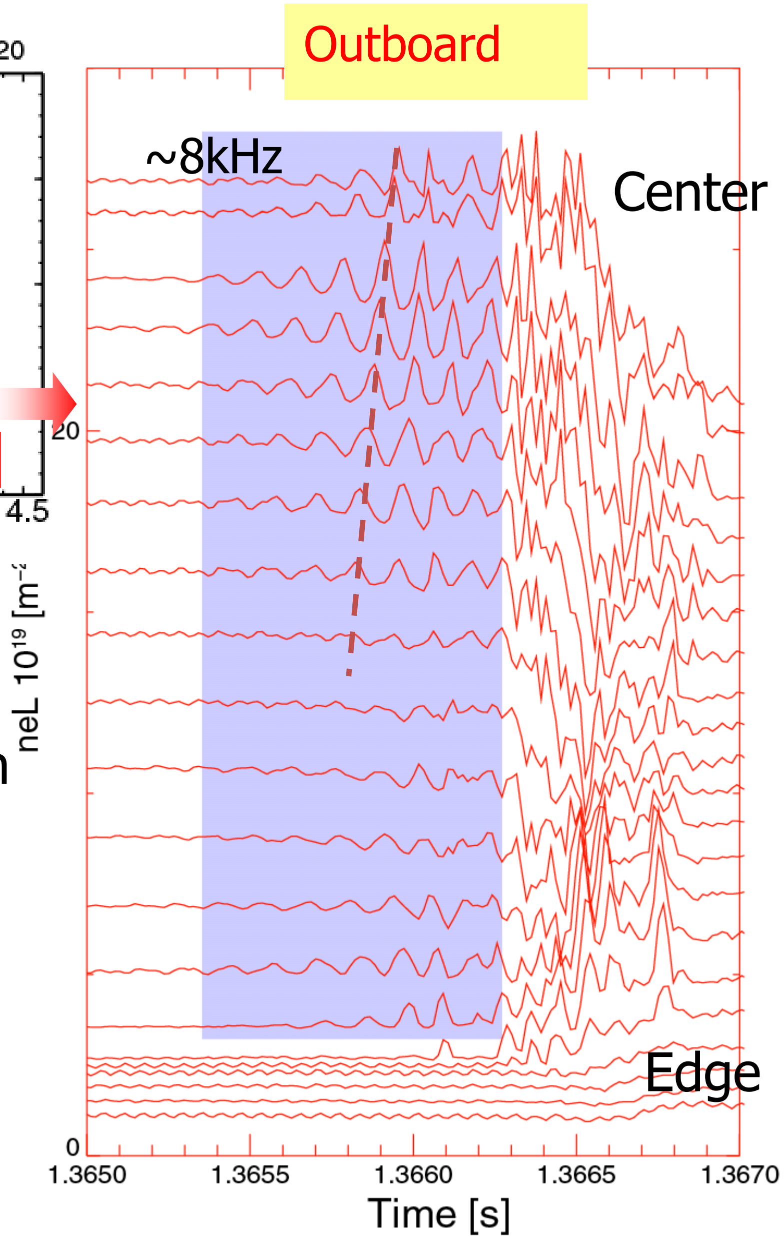
10mmx10mm PIN diode

2D SX Detector Array 6x8 (~50kHz)

Pre-cursor observed in CO2 interferometer

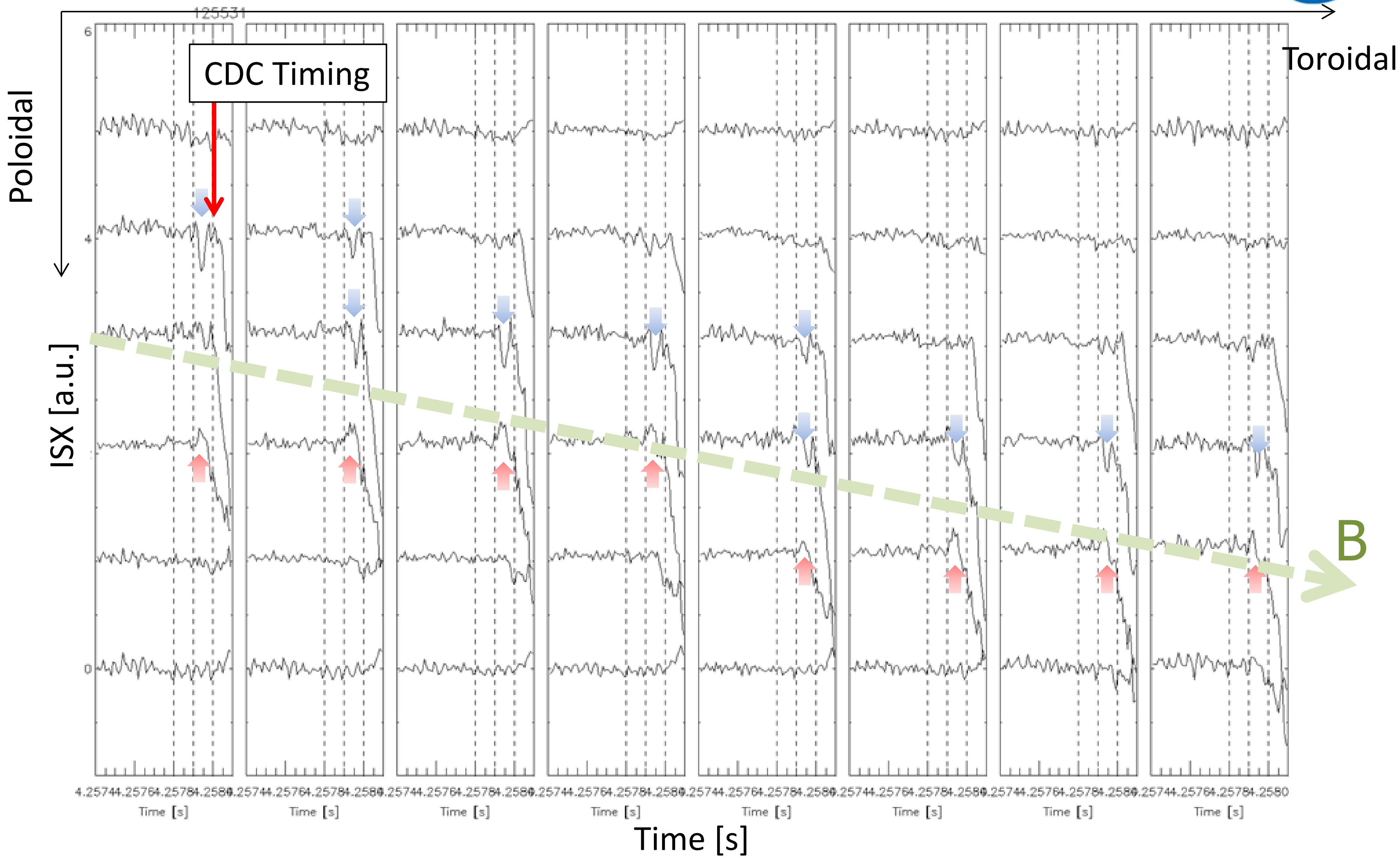






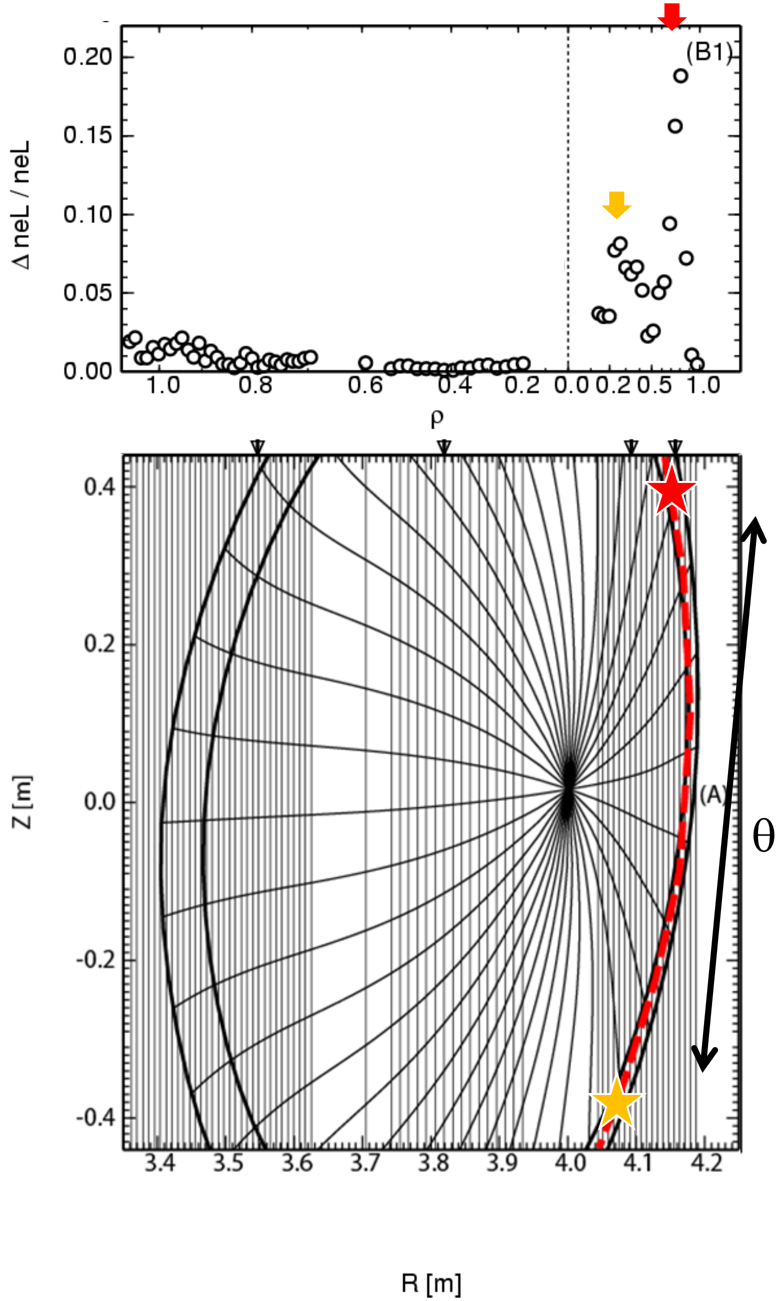
- Oscillations just before CDC is observed only in outboard side.
- Pre-cursor is distinguished in relatively low Bt (2.0T) experiments.

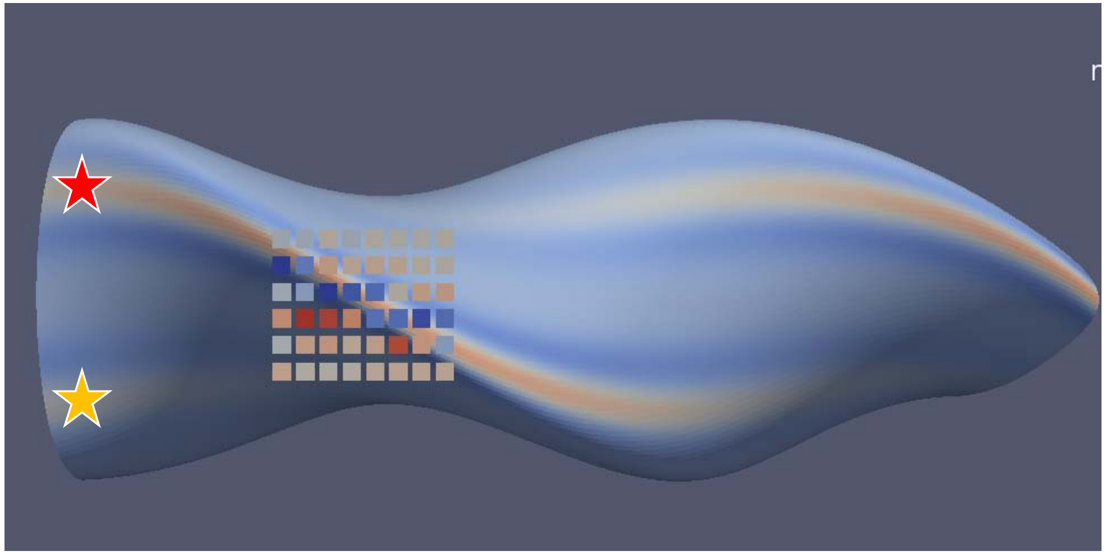
Observation looking at the bad curvature region



- Just before the collapse, a rapid deformation is sometimes observed.
- The structure of the deformation is well aligned and localized to the local magnetic field.

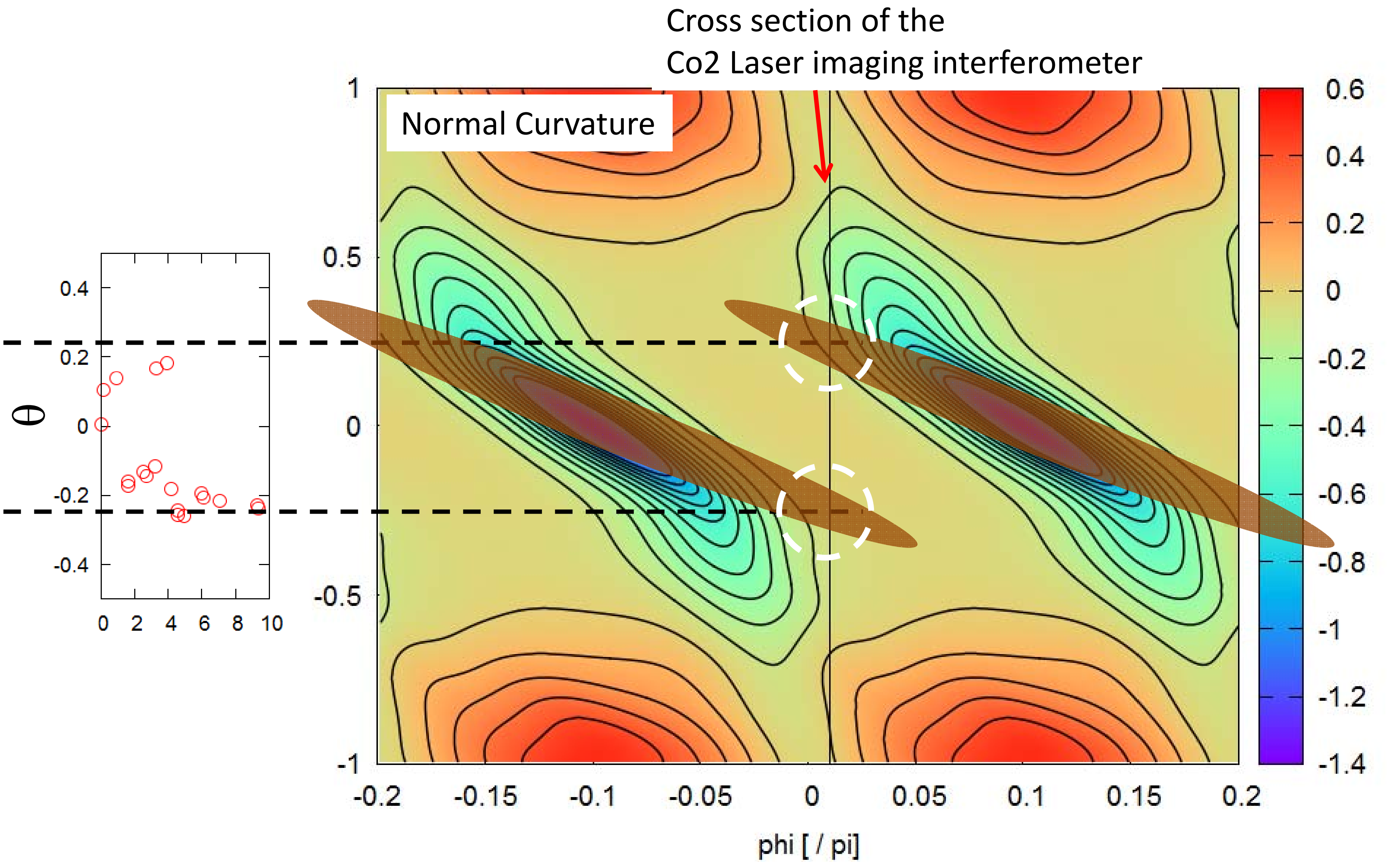
A model of the localized mode structure





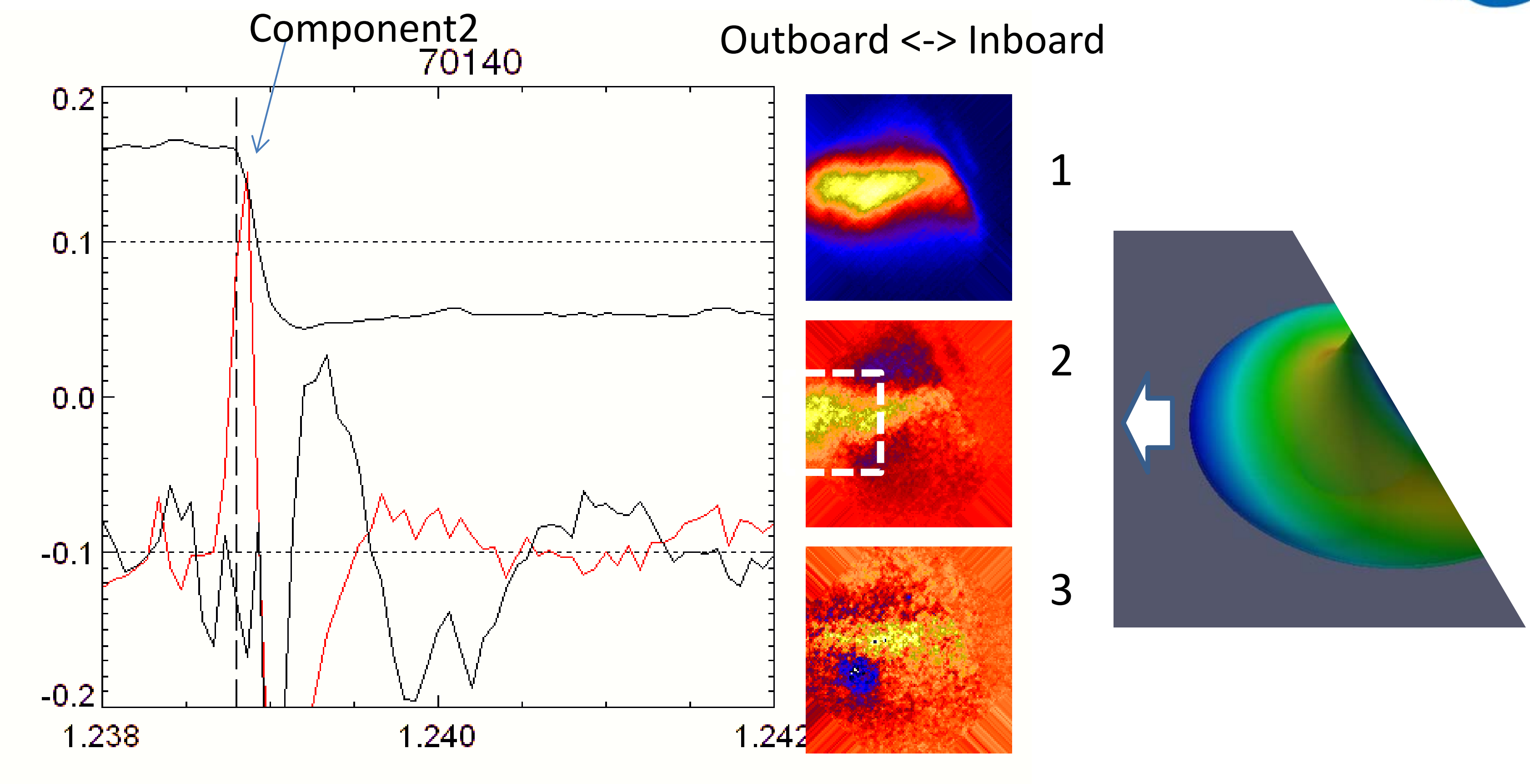
- If the radial mode is quite localized, multi-chord measurement can be used for obtaining θ dependence.
- If we assume the mode structure, fairly localized to the bad curvature region (ρ=085~0.95), observed characteristics of the pre-cursor oscillations, e.g. two peaks in the CO2 fluctuation measurement can be understand.

Two peaks in fluctuation measurement



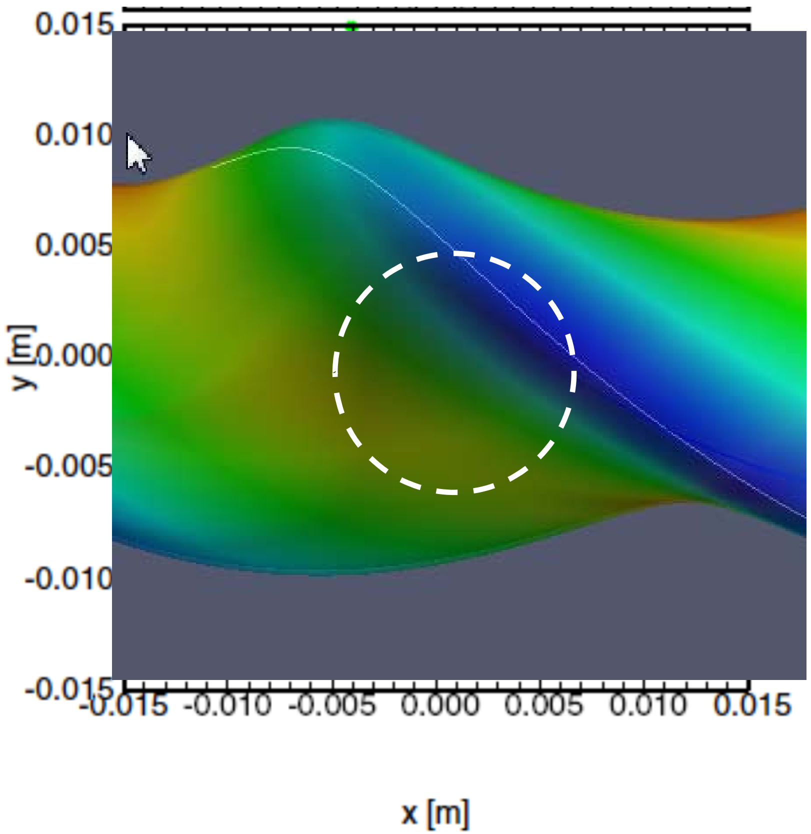
- If we assume a localized mode in the bad curvature region, it agrees well.

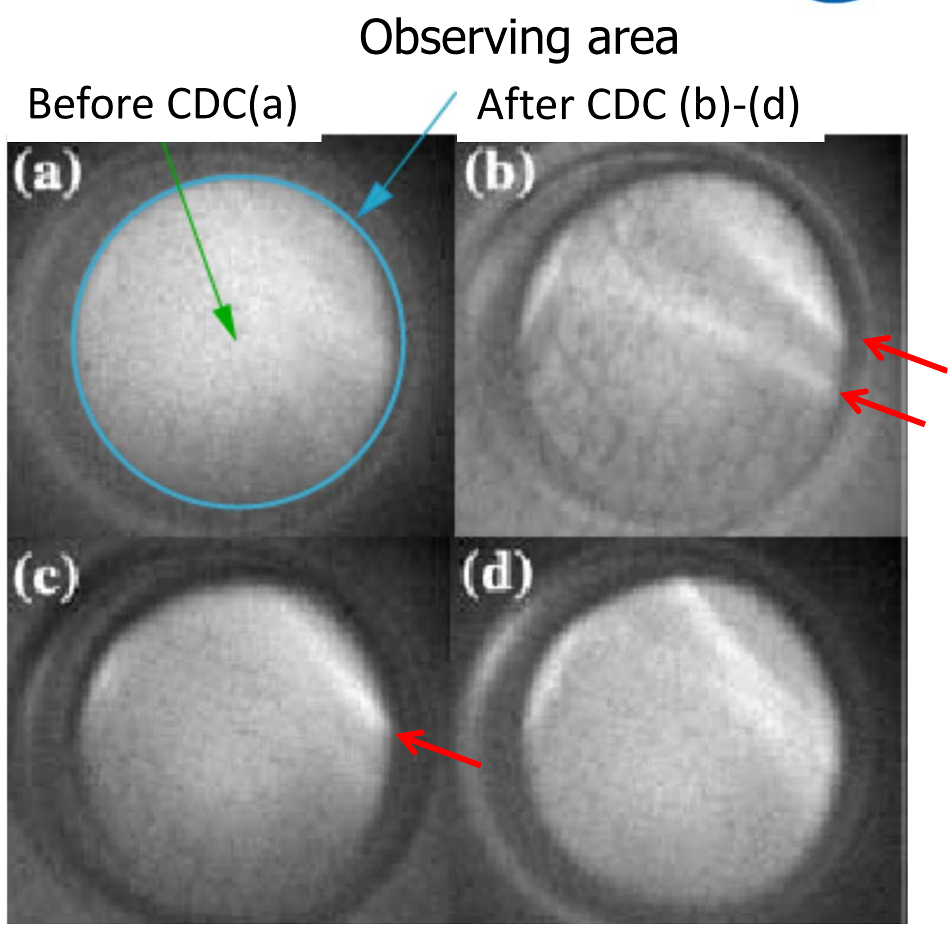
Observation by Tangentially viewing camera



- Framing rate is not high enough to catch the pre-cursor.
- At the timing of the CDC, ejection of the narrow structure towards the outboard side can be seen. (Component 2 of SV decomposed image.)
- Might be consistent with the ballooning picture.

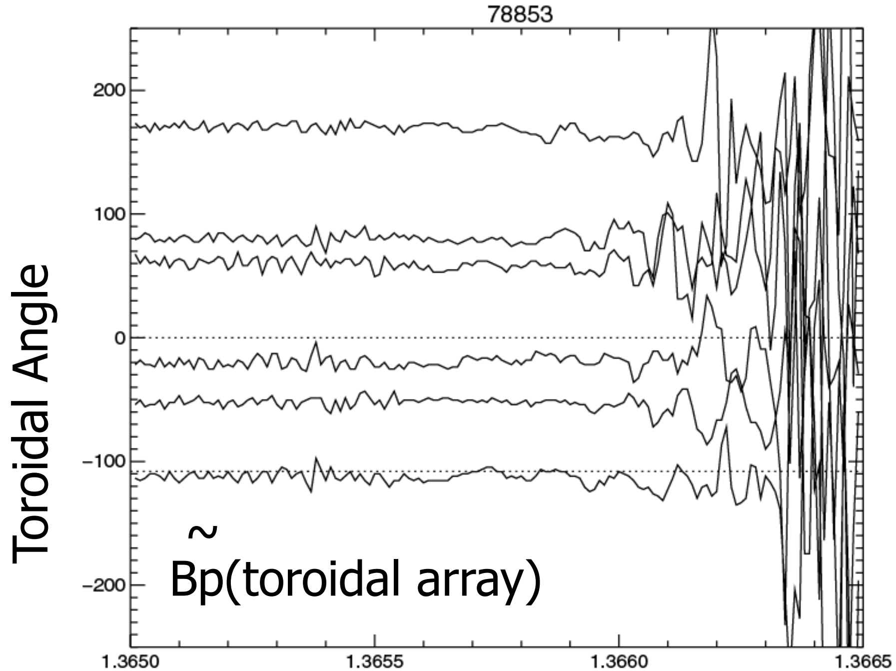
Filament-like structure can be seen

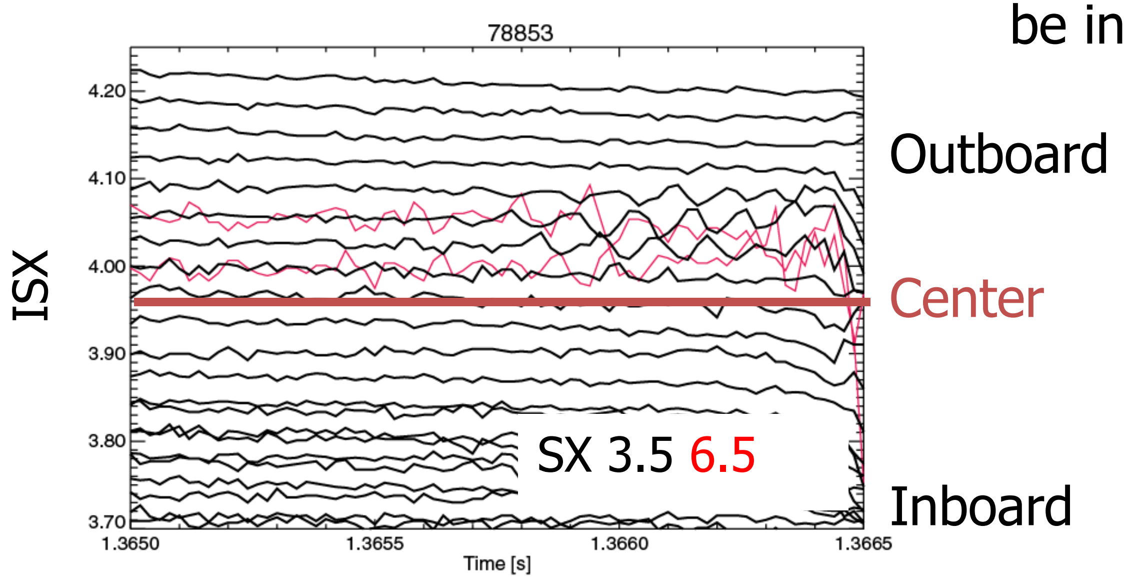




- After the collapse events, filament-like structures aligned to the magnetic field direction are observed by VUV camera which measures density fluctuations.
- This filaments or blobs might be ejected by the excitation of the ballooning mode. Deformation of the pre-cursor might be well localized.

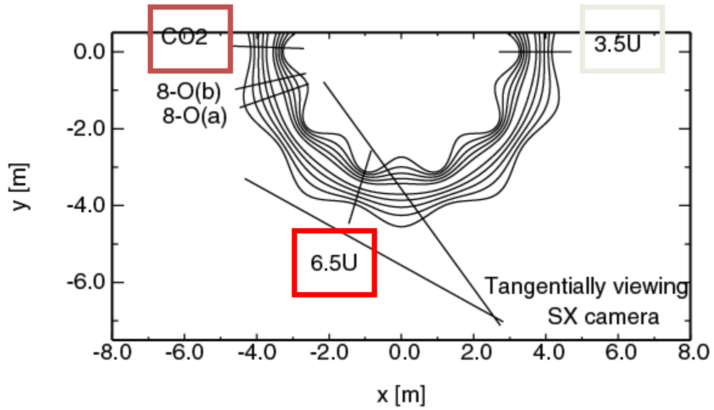
pre-cursors are observed at many sections.



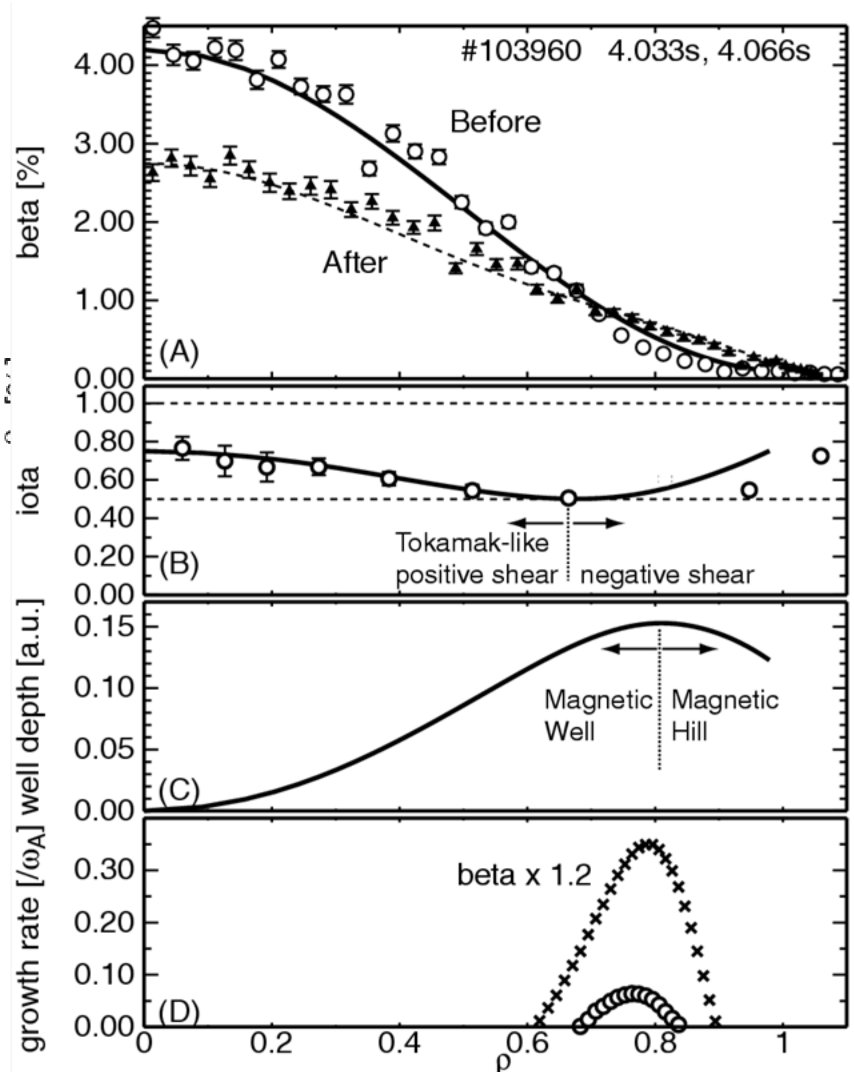


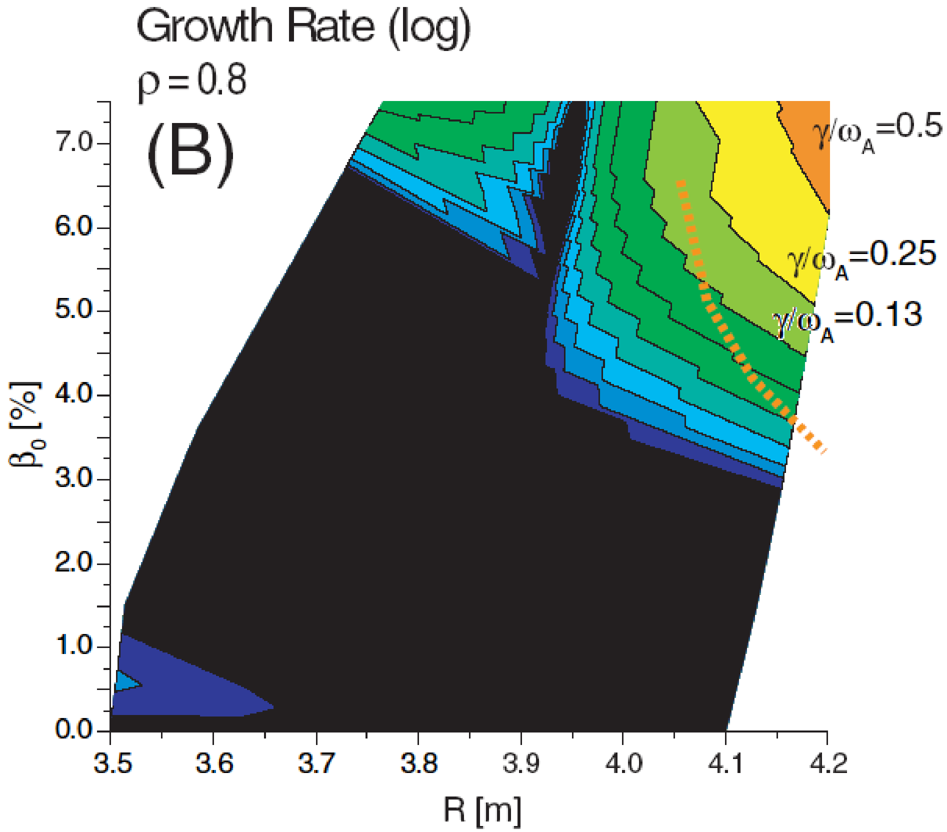
- Precursors, localized at outboard side are observed in different toroidal sections, by SX arrays. Precursors can be observed in the magnetic probes?

- There is no clear structure in the toroidal phase difference. (sometimes n~2). Toroidally separated mode structure might be independent.



CDC region and Ballooning unstable region





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

zed by magnetic axis position and the

- CDC appears where growth rate of the ideal Hn-Ballooning mode is rapidly increasing (HnBal code).

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 Hn-Ballooning mode, destabilized by the 3D nature of the plasma.
  - Pre-cursor activities in density fluctuations is observed. Profile of the amplitude is quite asymmetric; localized in the outboard side.
  - The structure might be localized in the perpendicular (to the magnetic field) direction as well, since there are two peaks in the pre-cursor oscillations at the vertically elongated section.

  - Unstable region of High n ideal ballooning modes agrees well with the operational limit.
    - (High n in Fourier space. Localized in real coordinate)

  - Comparison of the mode structure with 3D MHD code, such as MIPS code will be made soon.

Sα diagram for Tokamak & Stellarator

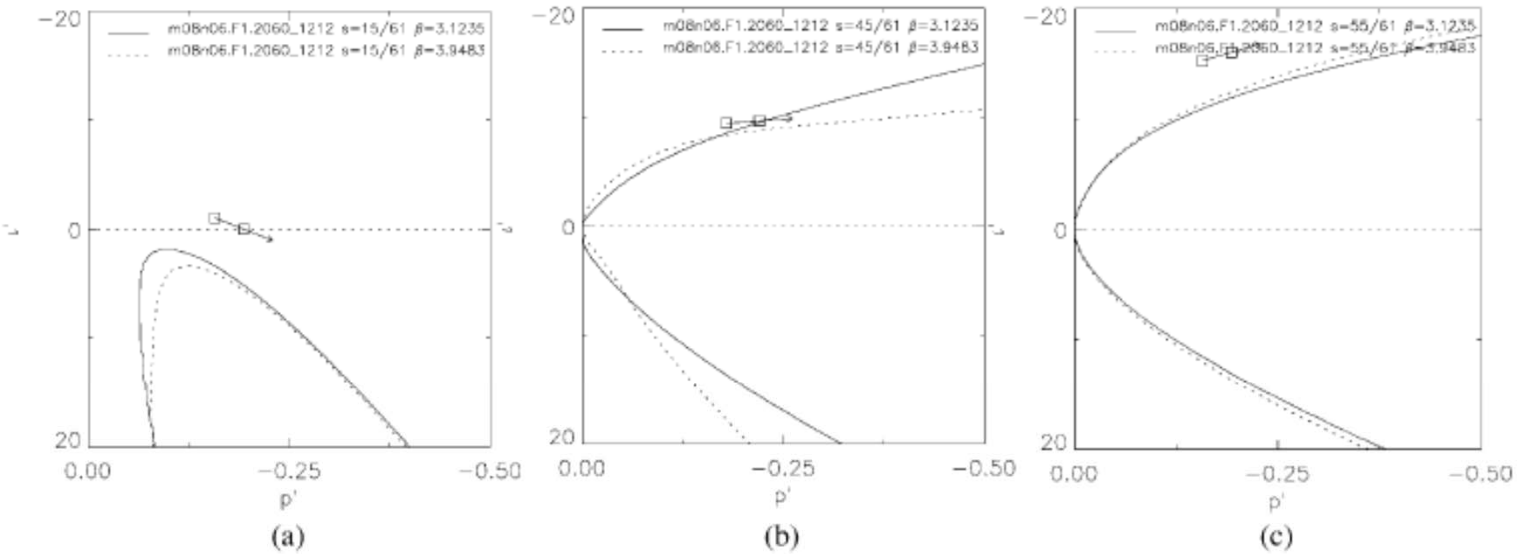
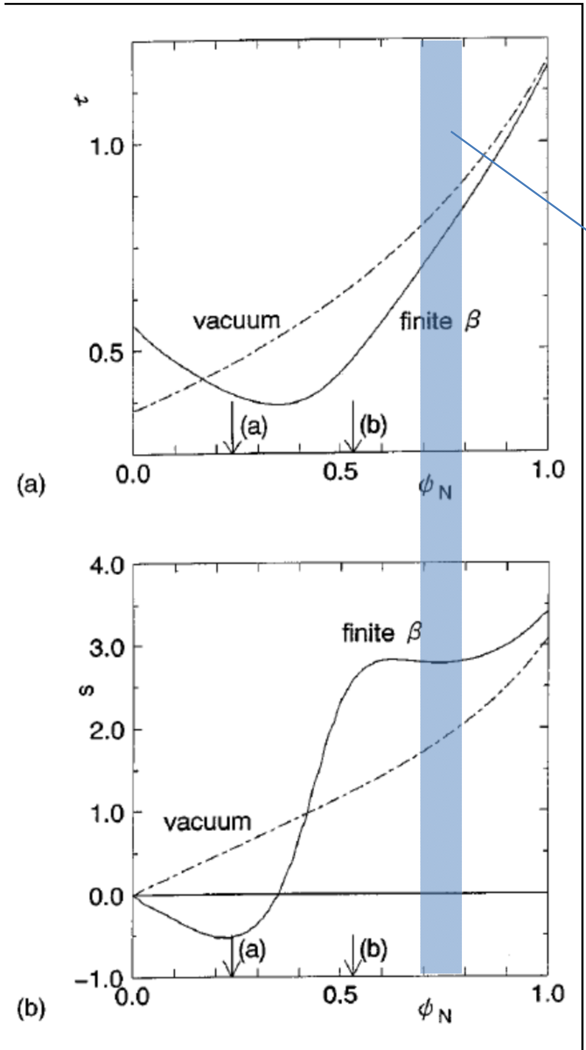
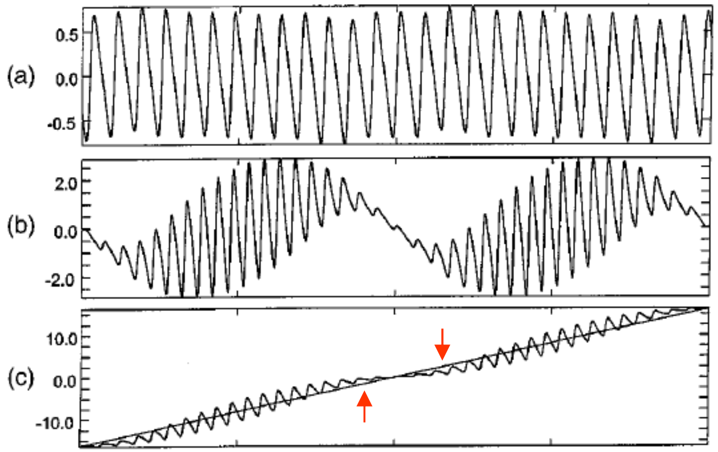


Fig. 12. The $d\iota/d\psi - dP/d\psi$ stability diagram (a) in the plasma core, (b) in the plasma periphery, and (c) in the plasma edge. The horizontal and vertical axes correspond to $-s_q$ and α in the $s_q - \alpha$ diagram of tokamak plasmas. The solid (dashed) curves indicate the stability boundary of high-mode-number ballooning modes for $\beta = 3\%$ ($\beta = 4\%$). Two squares attached to the arrow in each graph indicate the positions of (ι', P') corresponding MHD equilibria at $\beta = 3\%$ and $\beta = 4\%$. The arrows denote the direction of the shift of (ι', P') corresponding to the MHD equilibrium as β increase from $\beta = 3\%$ to $\beta = 4\%$. The MHD equilibria are the same as those in Figs. 10 and 11.

Local Shear





$$\int -(\hat{s}-s)d\eta$$ vacuum

$$\int -(\hat{s}-s)d\eta$$

$$\int -\hat{s}d\eta$$ finite β

- Disappear at the outboard region.

Both Normal Curvature and Geodesic curvature affect

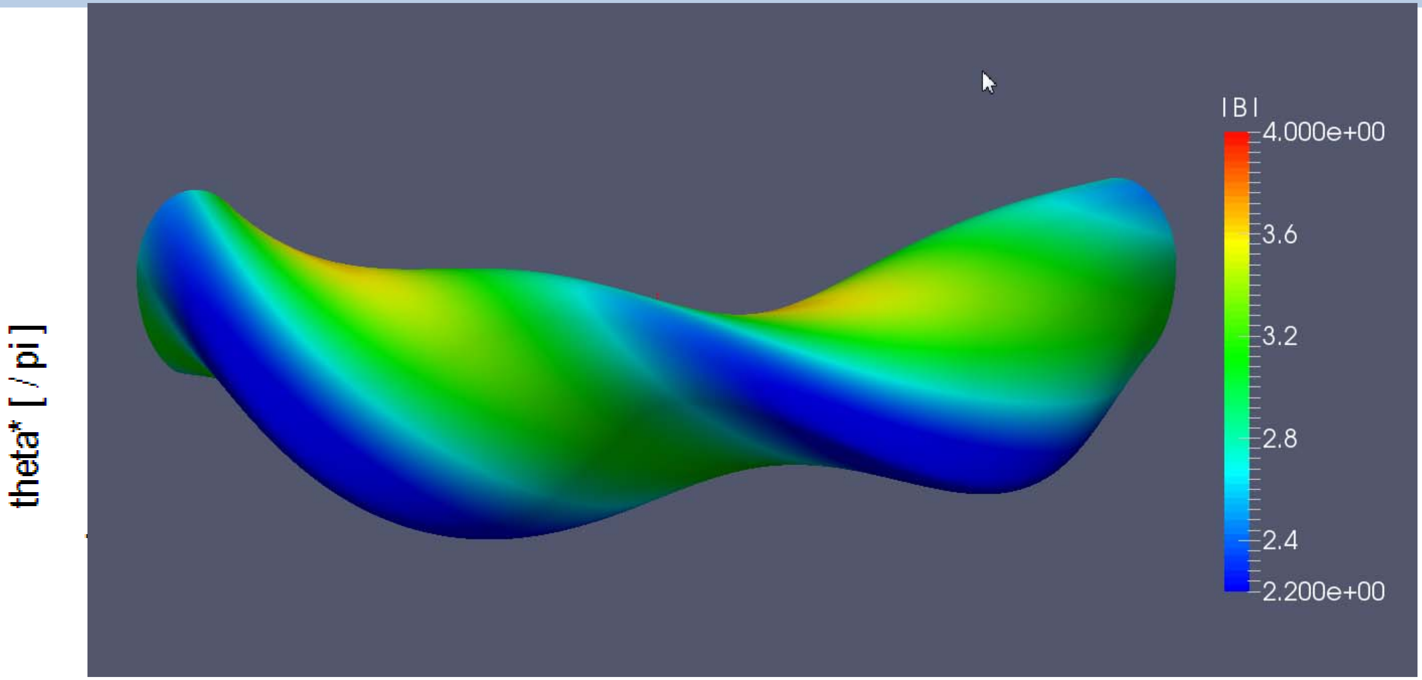
Solving the ballooning eigenvalue equation in VMEC coordinates (cont.)

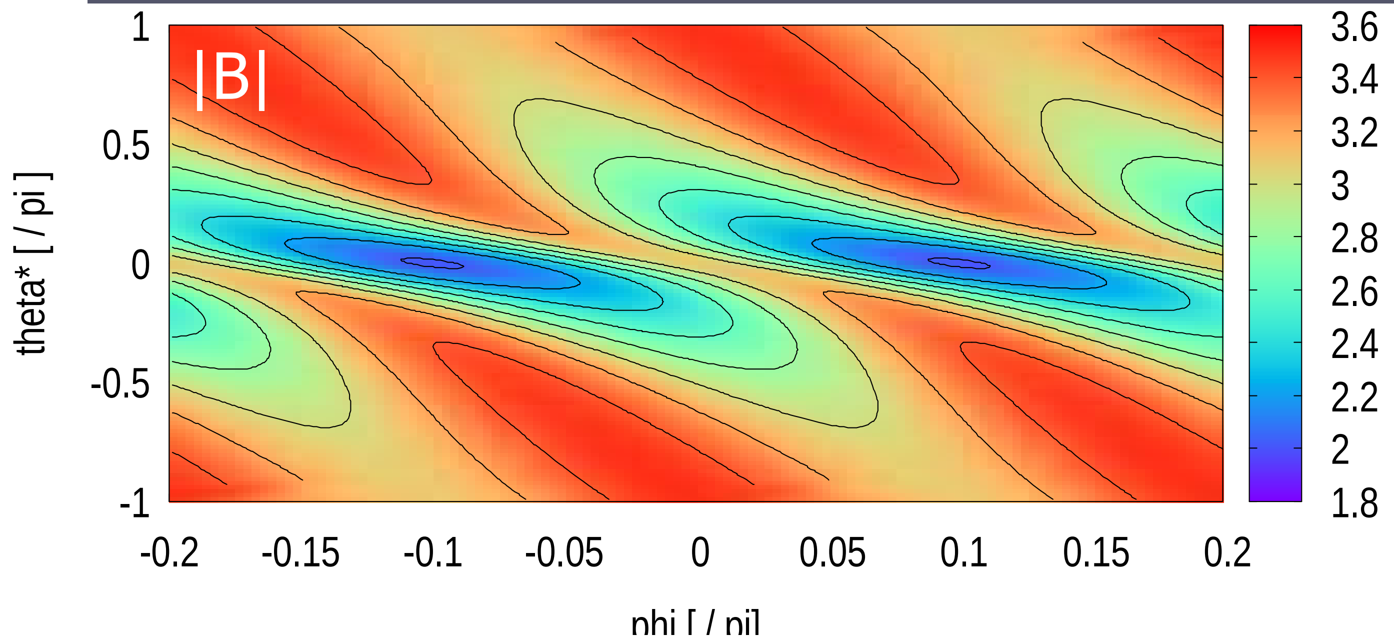
- The curvature that appears in the ballooning equation depends on both the VMEC normal and geodesic curvatures [see R. Sanchez, S. P. Hirshman, and H. V. Wong, *Computer Physics Communications* **135**, 82 (2001) for details]

$$\kappa_s = \kappa_{s_V} + \kappa_{\theta_V} \left(\frac{\iota' \zeta_V - \partial \lambda_V / \partial s_V}{1 + \partial \lambda_V / \partial \theta_V} \right)$$

  - Where the terms with subscript V refer to VMEC coordinates and λ_V is the VMEC lambda
  - We will plot the normal curvature, κ_{sV}, and the geodesic curvature, $\kappa_{\theta V}$, in VMEC coordinates

Magnetic field strength is modulated by Helical Coil





$\beta_0 = 4\%$

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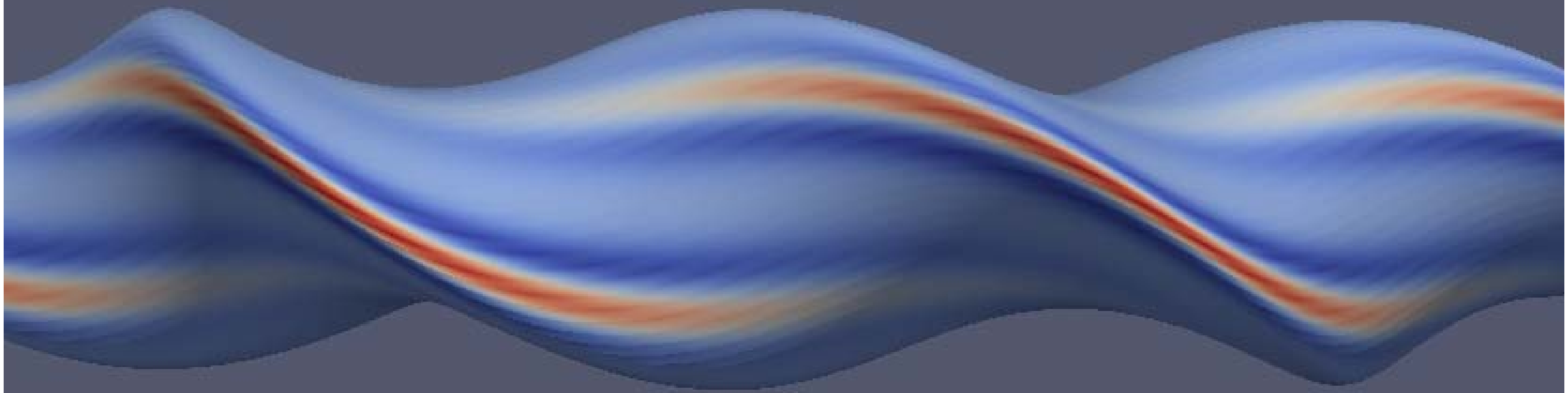

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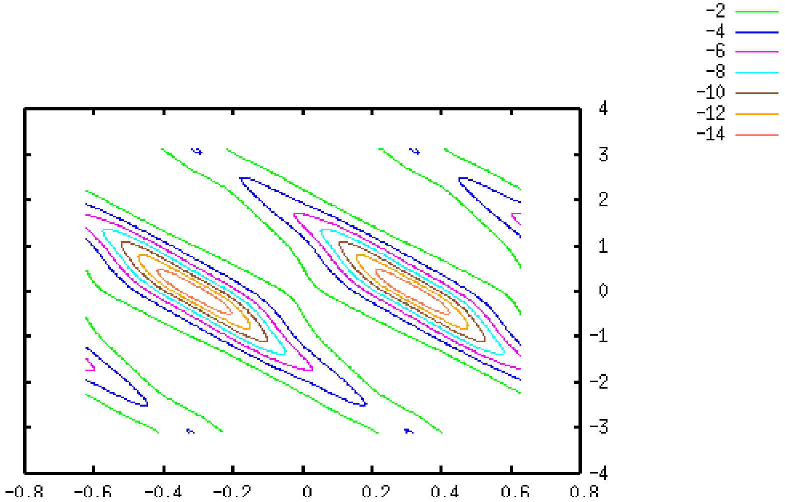
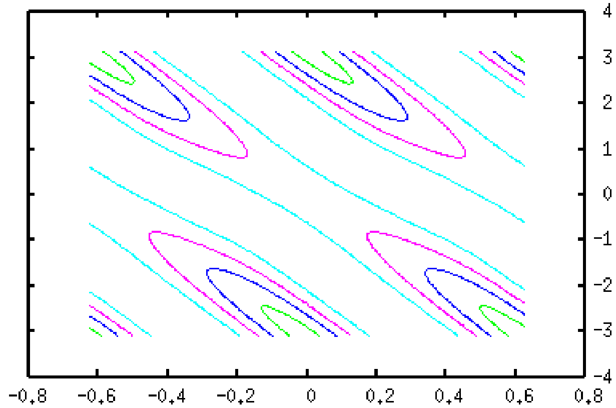
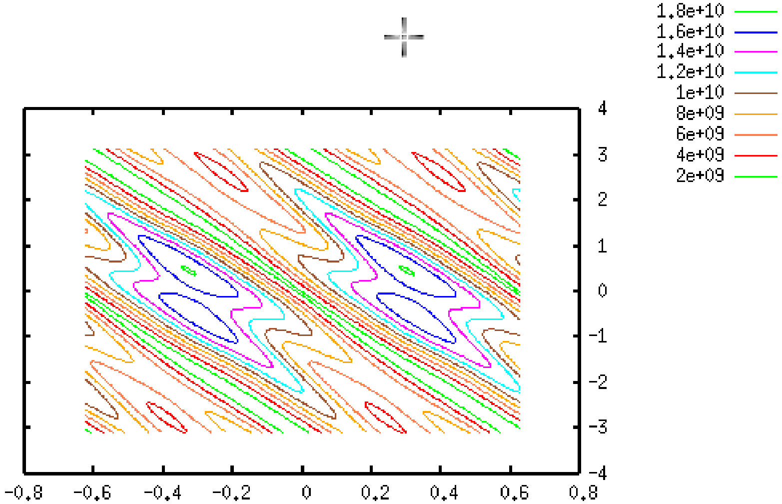
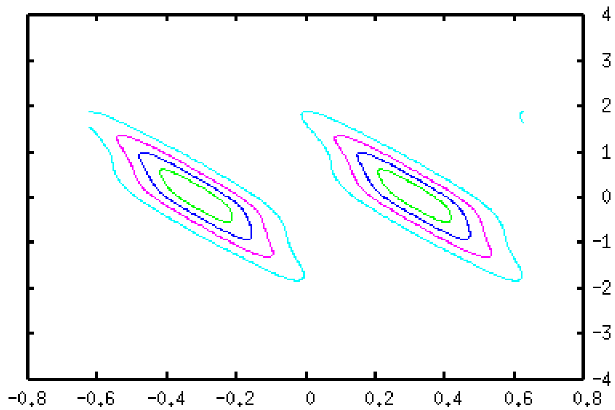




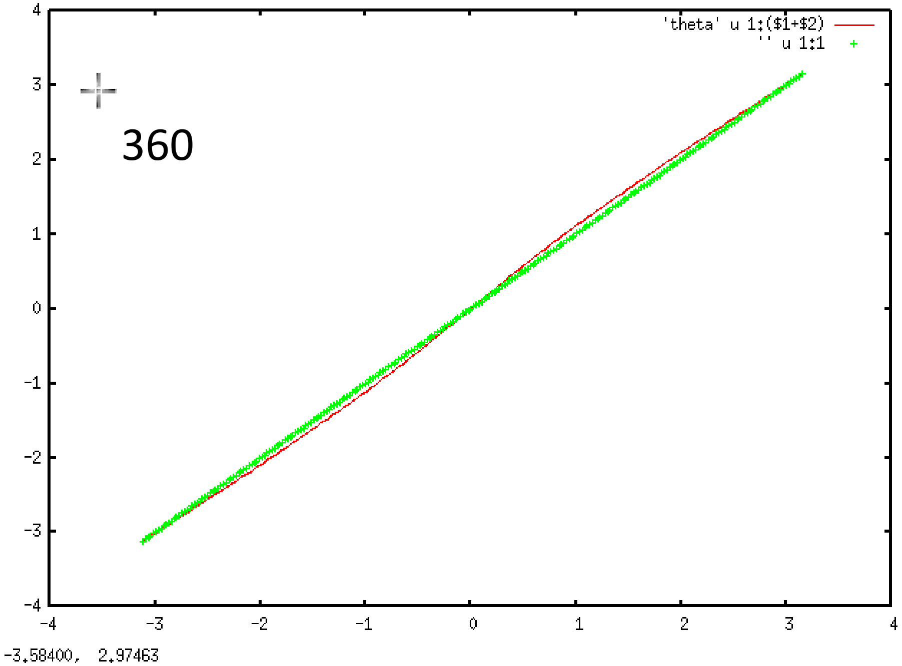




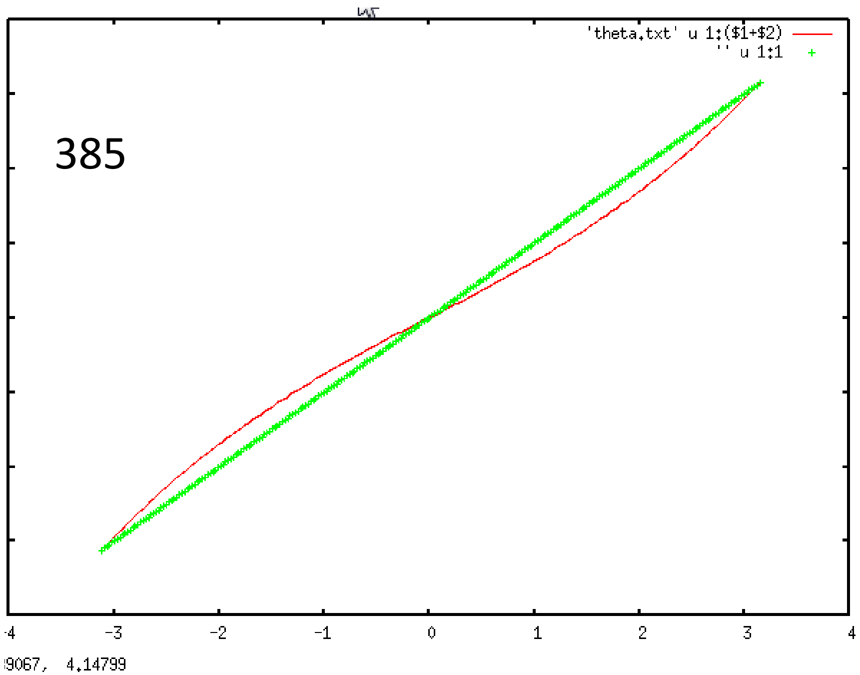
3663, 7.66941

0.278668, 5.69744

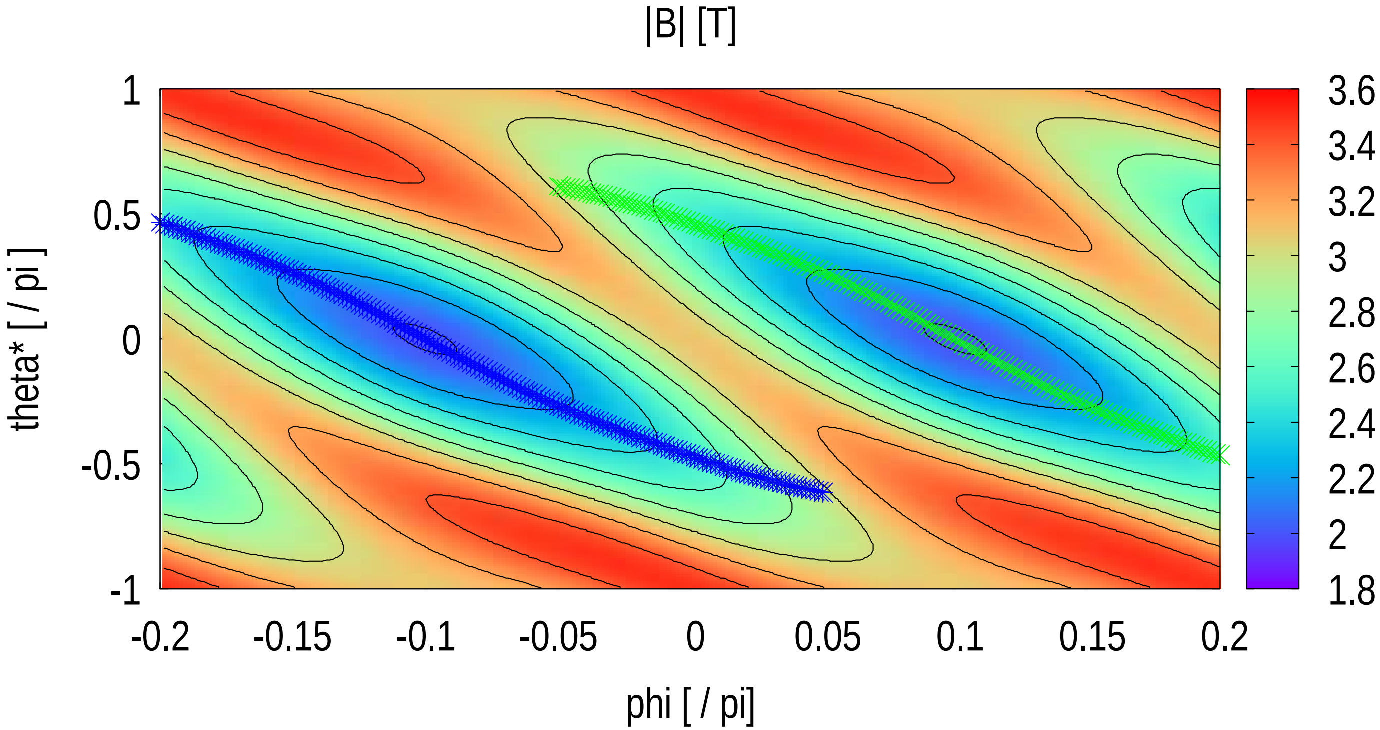
theta, theta*

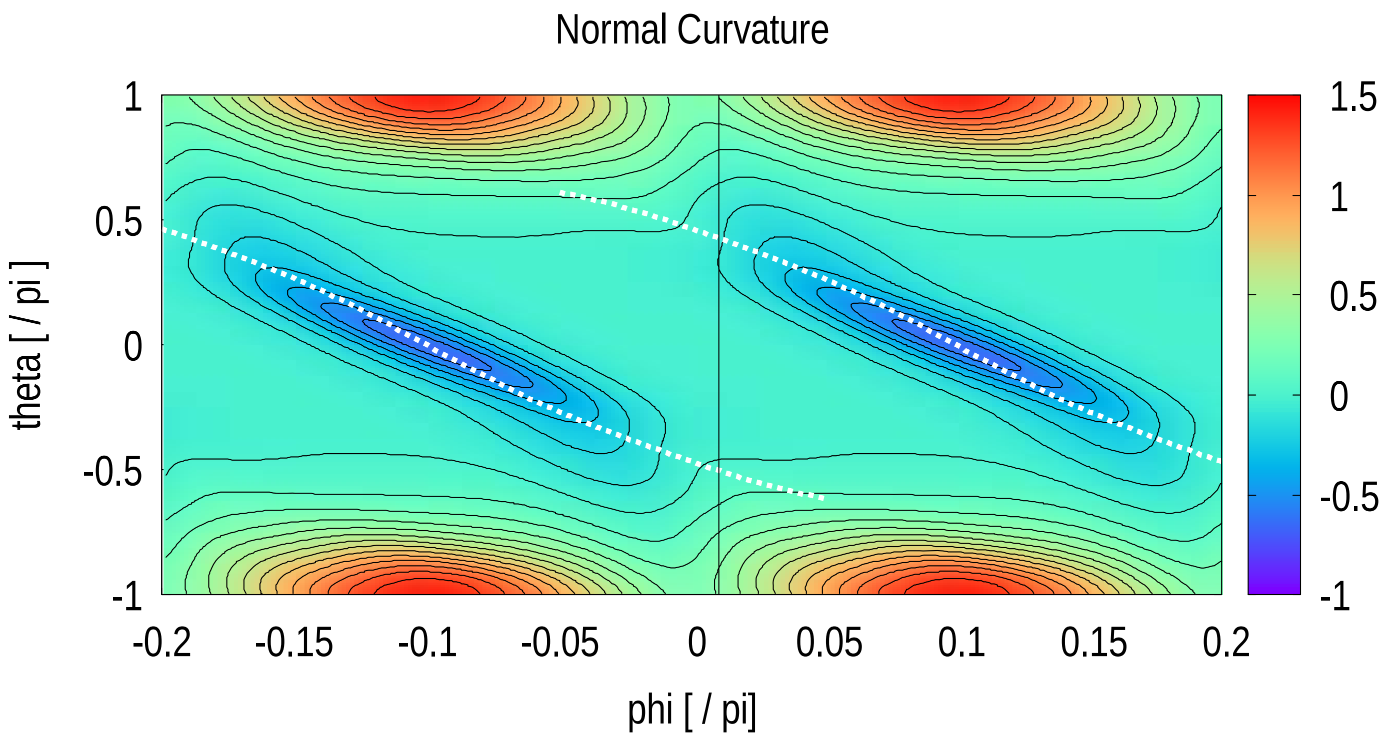


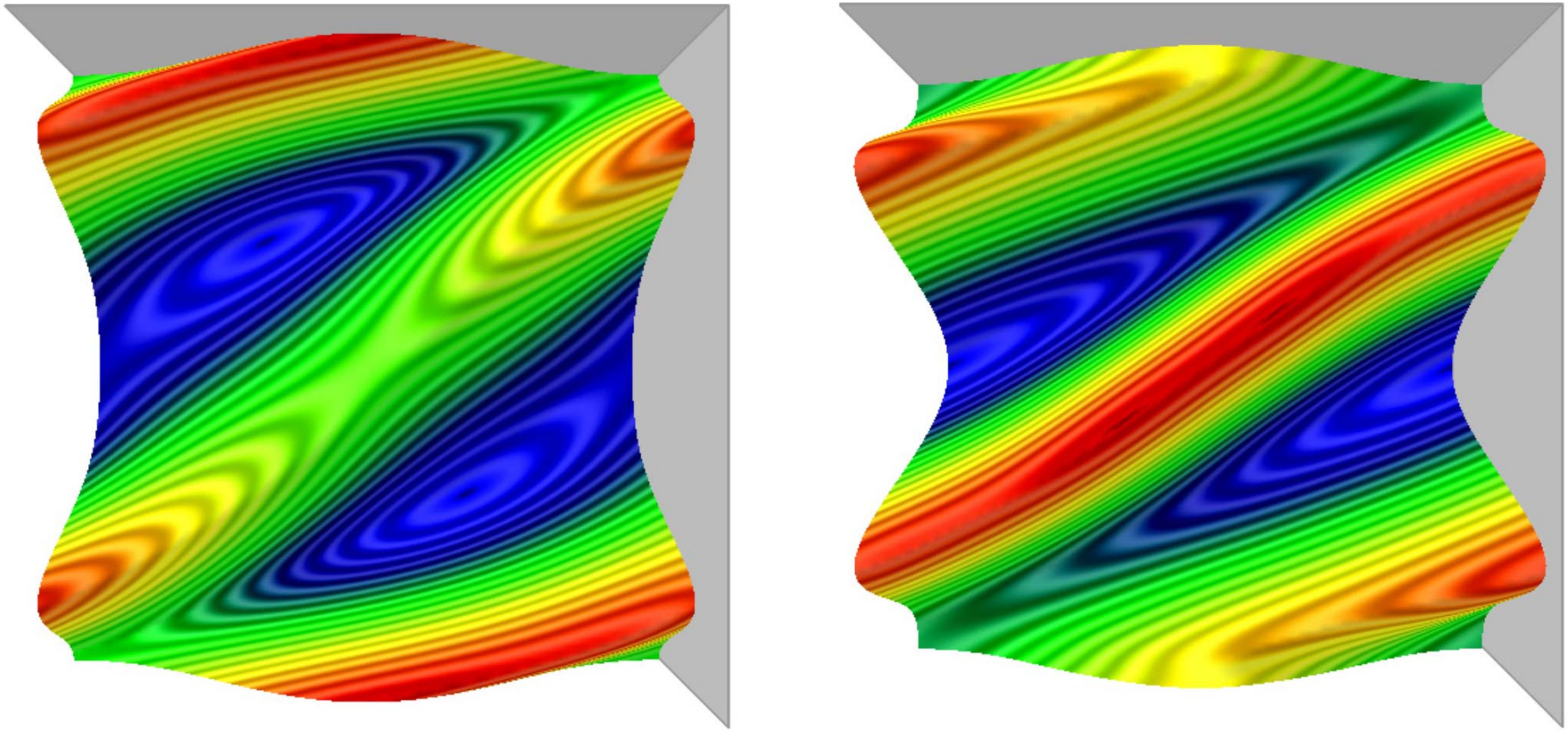
'theta' u 1:($1+$2)
'' u 1:1
360
-3.58400, 2.97463



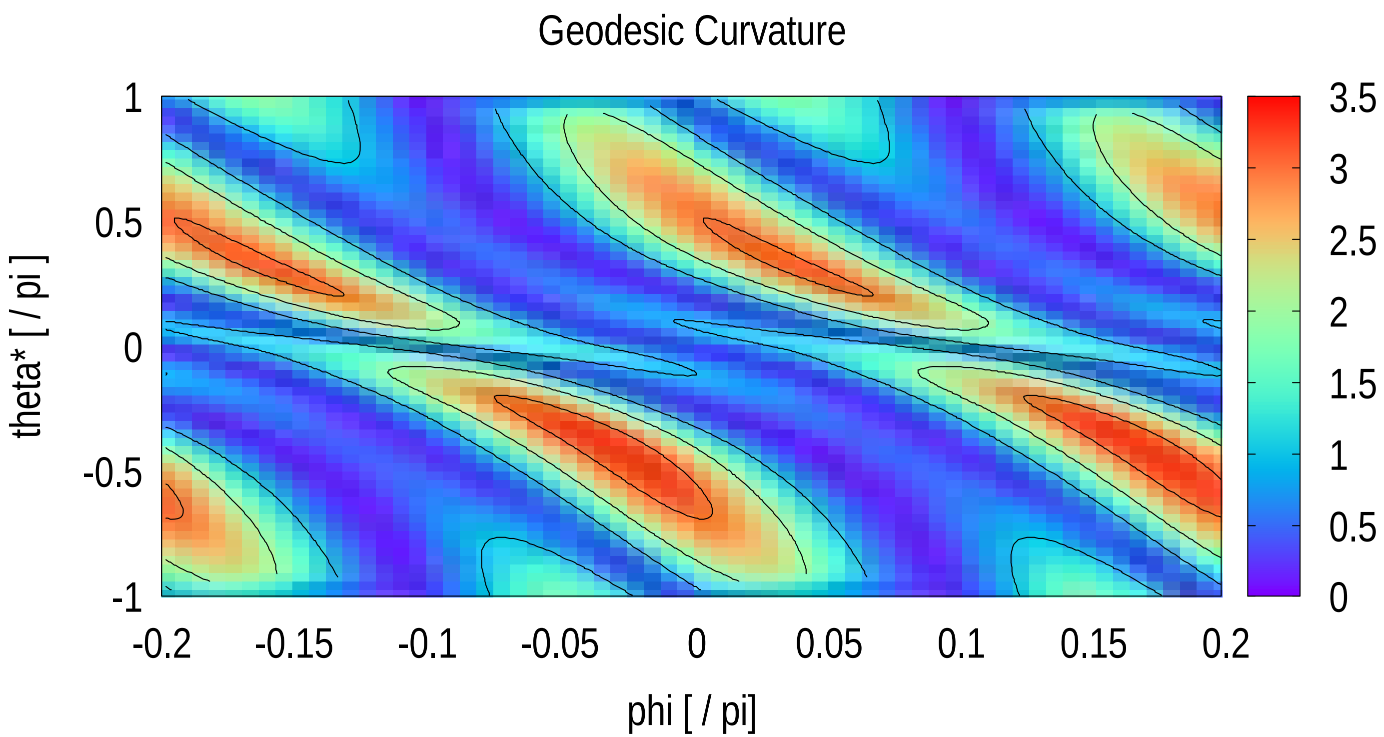
'theta.txt' u 1:($1+$2)
'' u 1:1
385
9067, 4.14799

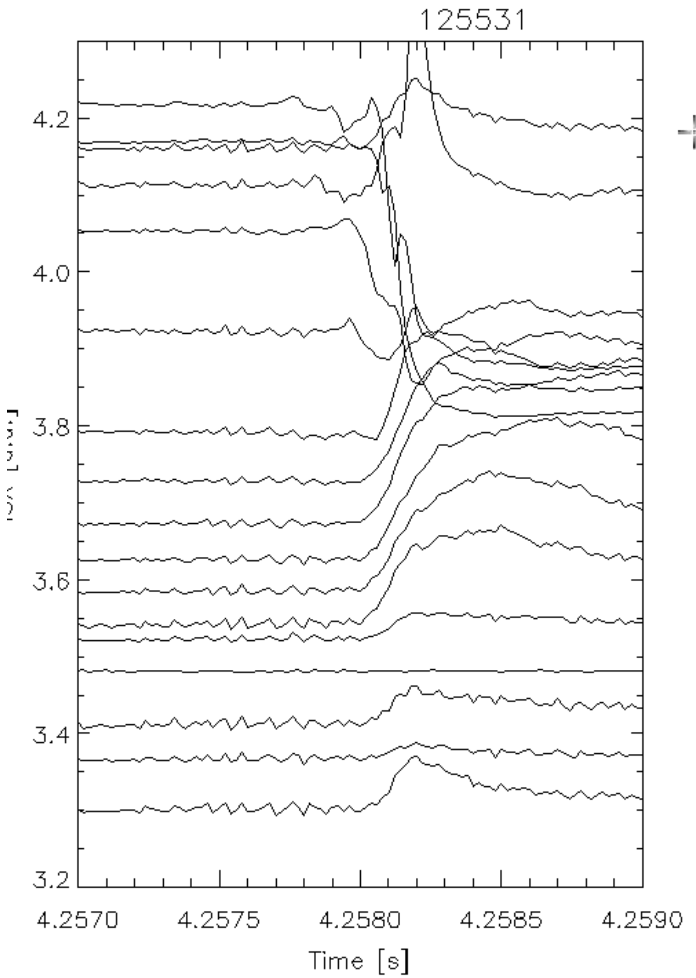

|B| [T]
1
0.5
0
-0.5
-1
theta* [/ pi]
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
phi [/ pi]
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8


Normal Curvature
1
0.5
0
-0.5
-1
theta [/ pi]
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
phi [/ pi]
1.5
1
0.5
0
-0.5
-1



O. Yamagishi, PhD Thesis, Fig. 2.5 LHD b0 = 4%, s = 0.25, 0.75

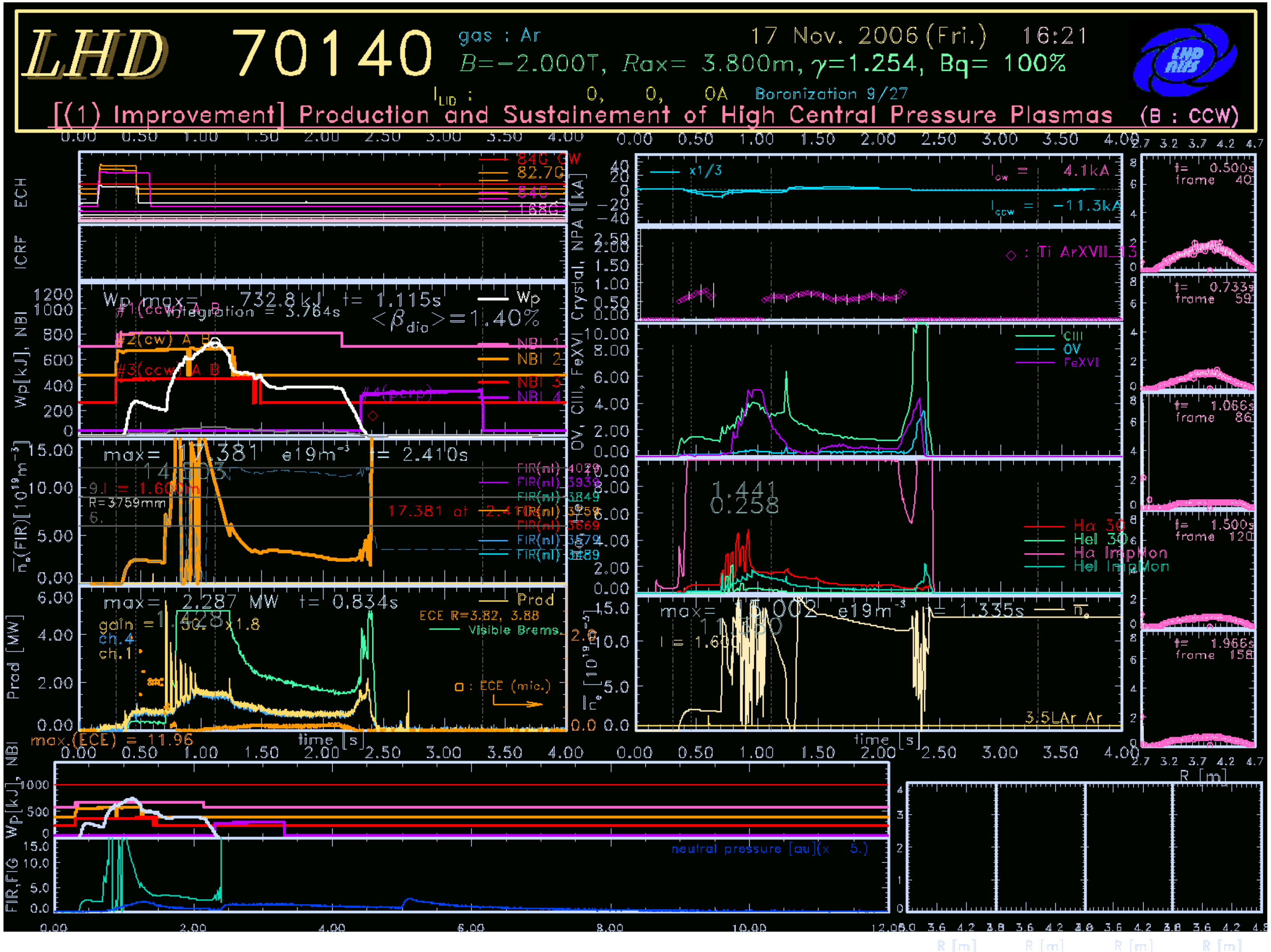

Geodesic Curvature
theta* [/ pi]
phi [/ pi]
1
0.5
0
-0.5
-1
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
3.5
3
2.5
2
1.5
1
0.5
0


125531
4.2
4.0
3.8
3.6
3.4
3.2
4.2570
4.2575
4.2580
4.2585
4.2590
Time [s]

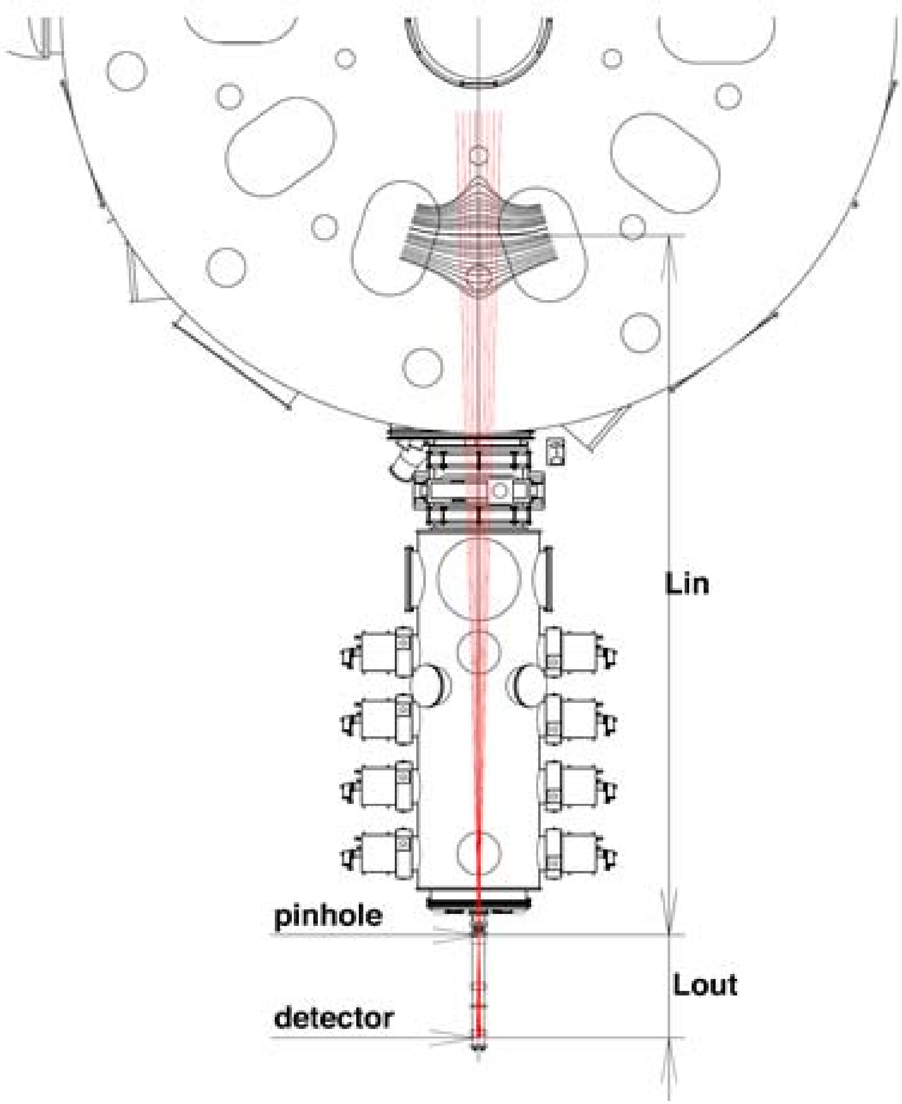
VUV カメラ

124454-124483

124462


LHD 70140
gas : Ar
17 Nov. 2006 (Fri.) 16:21
B=−2.000T, Rax= 3.800m, γ=1.254, Bq= 100%
Boronization 9/27
[(1) Improvement] Production and Sustainement of High Central Pressure Plasmas (B : CCW)
ECH
ICRF
Wp[kJ], NBI
Wp max= 732.8kJ t= 1.115s
<β_dia>=1.40%
NBI 1
NBI 2
NBI 3
NBI 4
max= 17.381 e19m^-3 t= 2.410s
17.381 at 2.4
Prad [MW]
max= 2.287 MW t= 0.834s
ECE R=3.82, 3.88
Visible Brems
max.(ECE) = 11.96
time [s]
x1/3
I_cw = 4.1kA
I_ccw = −11.3kA
Ti ArXVII
CIII
OV
FeXVI
Hα 30
HeI 30
Hα ImpMon
HeI ImpMon
max= 15.002 e19m^-3 t= 1.335s
3.5LAr Ar
R [m]
neutral pressure [au](x 5.)
FIR,FIG

FAST 2D SX array system



- 6 (poloidal) x 8 (Toroidal) SX detector array was installed.
- Fluctuations with Up to 50kHz can be measured.