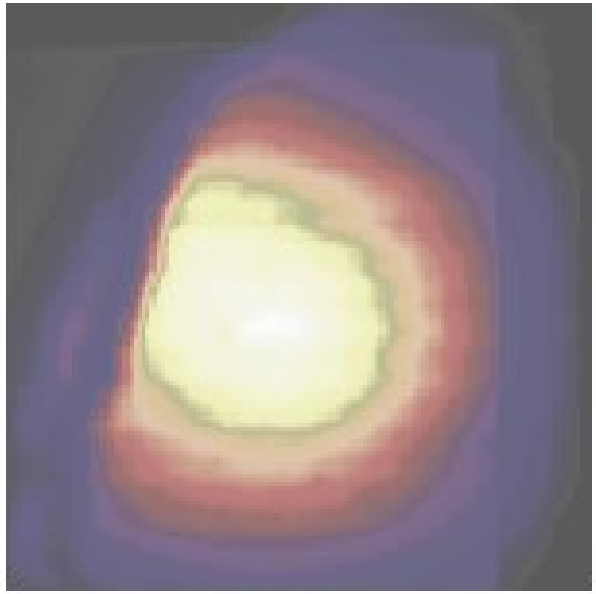
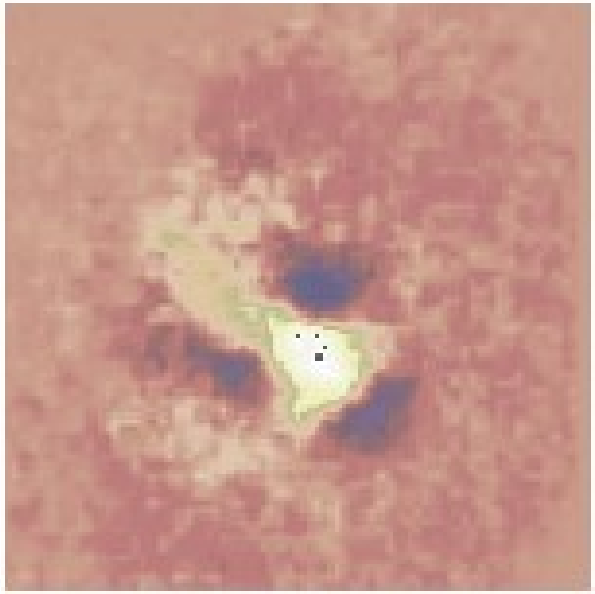
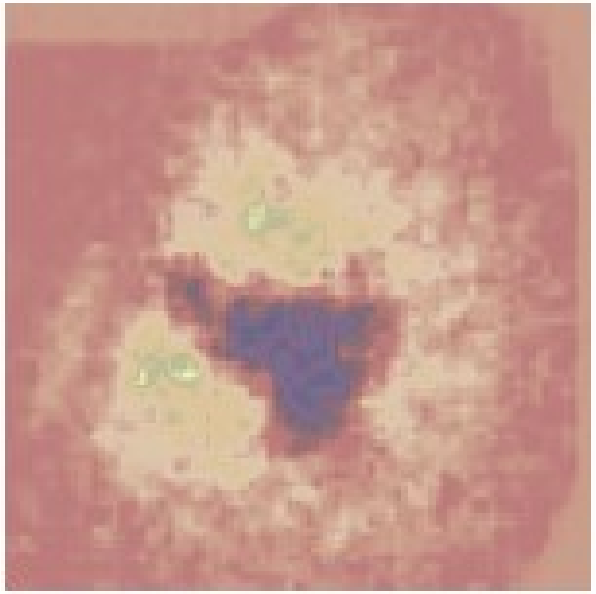
2D-imaging for fluctuation measurement in magnetically confined fusion devices

S. Ohdachi

and the LHD Experimental Group

National Institute for Fusion Science

Outline of my talk

1. Merit of the 2D-imaging.
   - Provide comprehensive view of the complicated phenomena.

2. Tangential view and vertical view in magnetically confined plasmas.

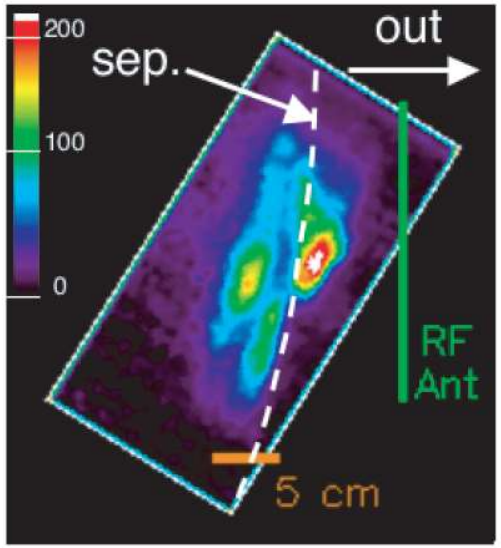
3. LHD Example using SX radiation
   - Direct 2D imaging works well with less magnetic shear region.

4. VUV Telescope system for edge fluctuations.

5. Summary

Advantage of the 2D-imaging in fluctuation measurement

NSTX Gas-puff Imaging example



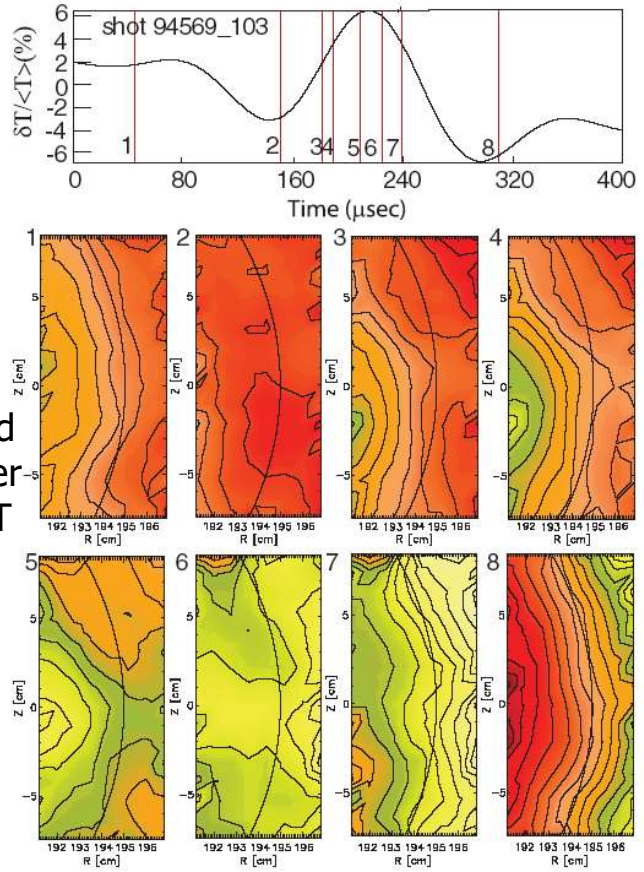
Transport in SOL region is carried by the Blob structure.

S.J.Zweben et.al. Nucl. Fusion **44** (2004) 134–153

- Imaging diagnostics is so effective that even these separated figures tells the physics.

- It is very useful in understanding a complicated phenomena, e.g. fluctuations and transport in fusion plasmas.

Sawtooth Crash with ECE Imaging



Poloidal localized structure transfer the energy at ST crash.

H. K. Park, PRL **96,** 195003 (2006)

2D Imaging Variations

- Radiation from the plasma
  - Visible lights
    - Fast camera (brems.) SOL plasma
    - Gas puff imaging ($\tilde{ne}$) SOL plasma
  - VUV
    - VUV (impurity rad.) Edge plasma
  - SX
    - SX (brems + impurity) Core plasma

Simple but line integrated

Complex but local measurement

- Electron cyclotron emission
  - ECE Imaging ($\tilde{Te}$)

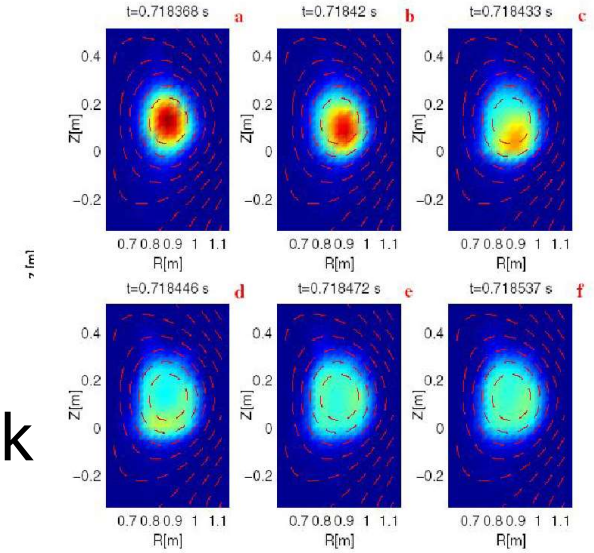
- Active Imaging
  - Neutral beam
    - Beam emission spectroscopy ($\tilde{ne}$)
  - Micro Wave
    - Imaging reflectometry ($\tilde{ne}$)
  - Sheet-like Lithium beam
    - 2D Edge imaging ($\tilde{ne}$)

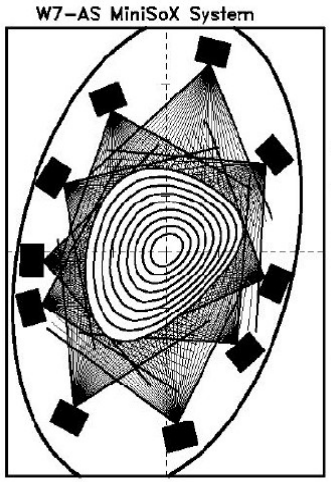
$\tilde{}$

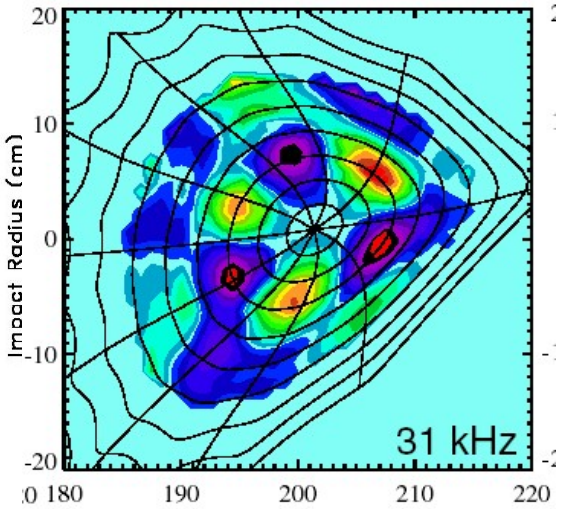
Poloidal Tomography System

TCV

Tokamak







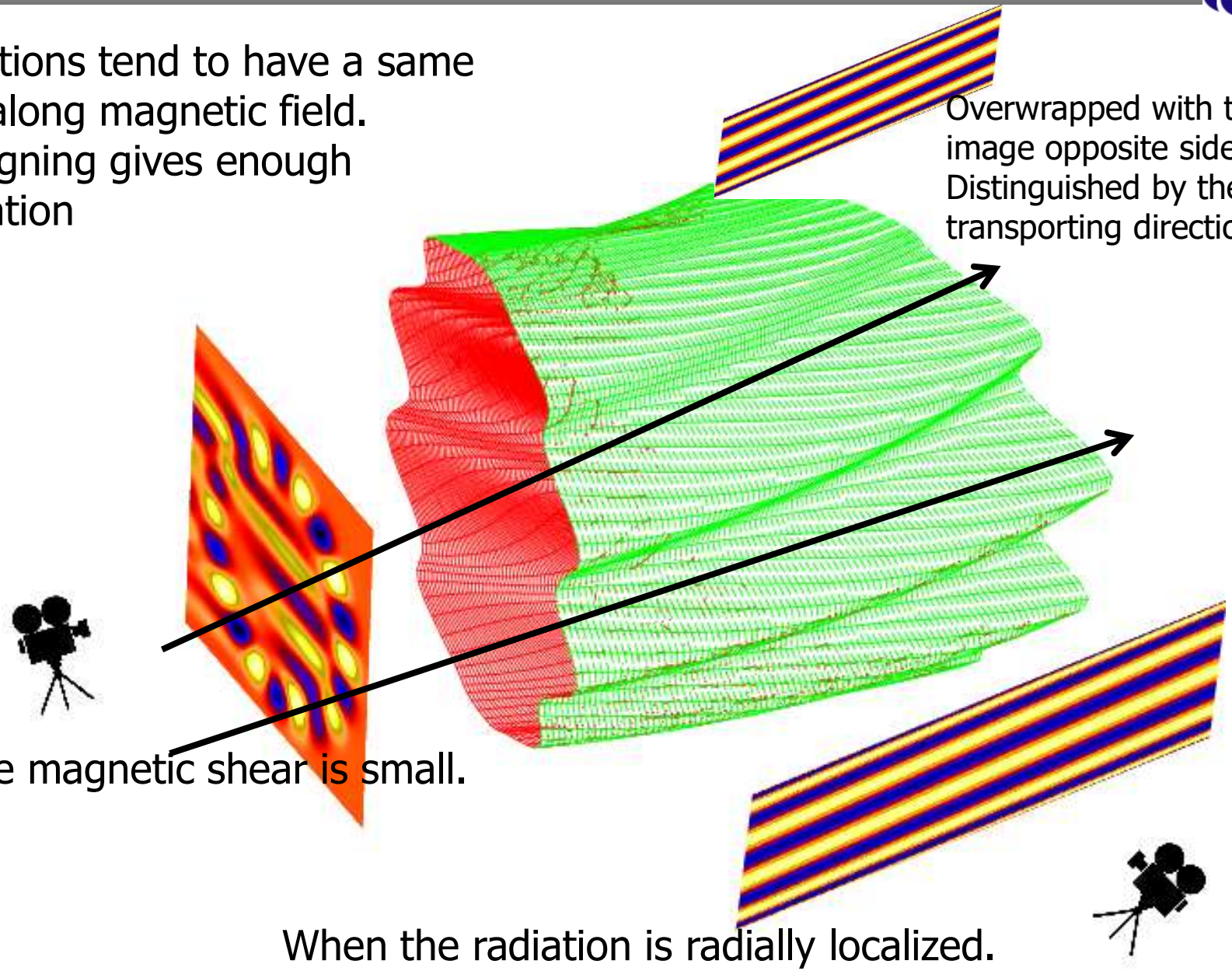
- Radiation is line-inetegrated. Reconstruction of the emission profile is required.

- Many detectors (~2 x m) surrounding plasma are needed for good reconstruction.
- Due to the neutron flux onto the detectors, they can not be used in larger devices. In Large Helical Device, e.g. , such a configuration can not be realized by the large helical coil system.

Viewing Angle and the magnetic field

Fluctuations tend to have a same phase along magnetic field.
2D imagning gives enough information

Overwrapped with the image opposite side.
Distinguished by the transporting direction.



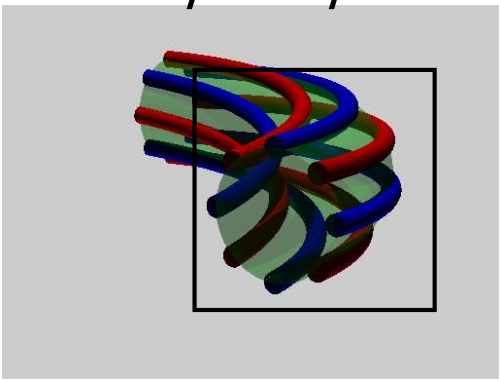
When the magnetic shear is small.

When the radiation is radially localized.

Merit of the tangentially viewing

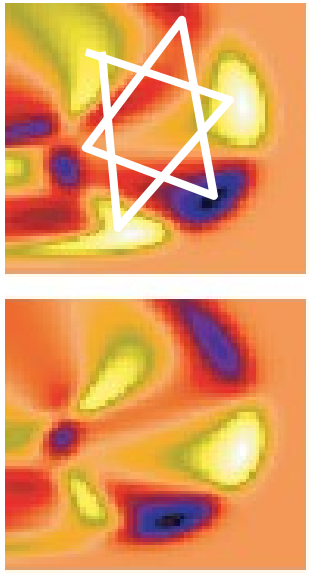
$k_{\perp} >> k_{//}$

m/n=3/2

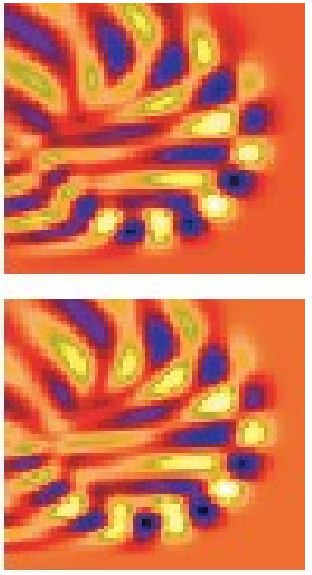


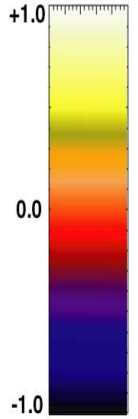
Tangentially viewing
on simple torus

m/n=3/2



m/n=10/5





- Poloidal mode number can be distinguished from the raw data easily without complicated reconstruction.

- When the perturbations are localized on magnetic field lines, tangentially viewing measurements give a good contrast even for high mode numbers.

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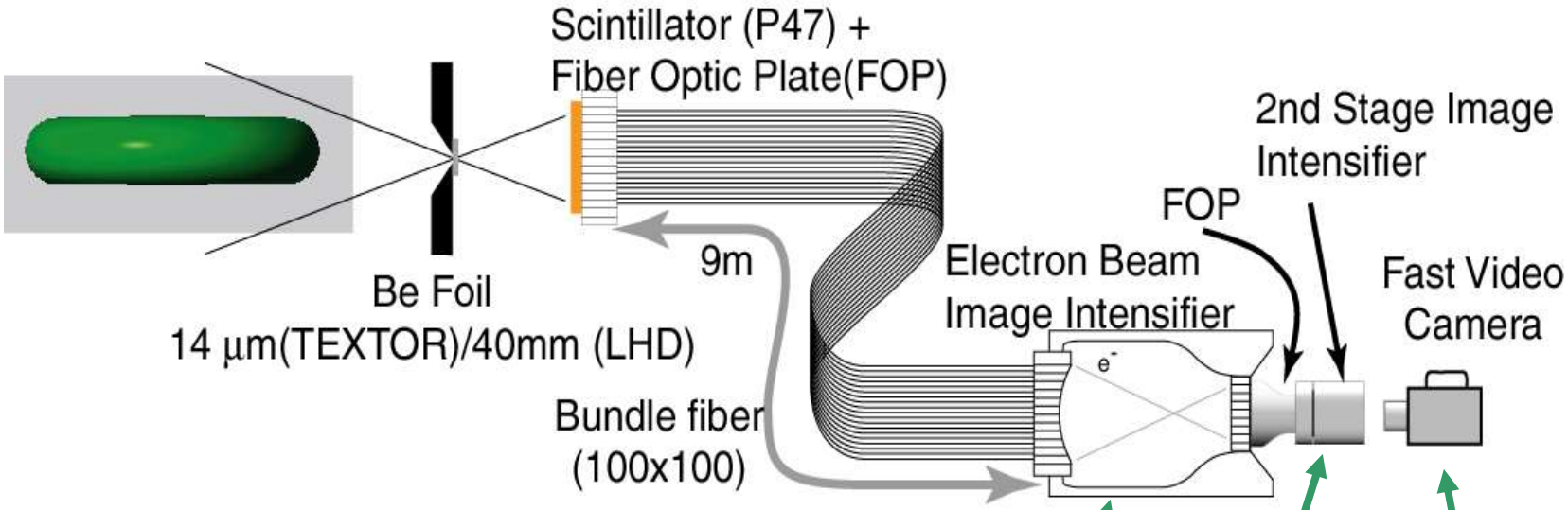
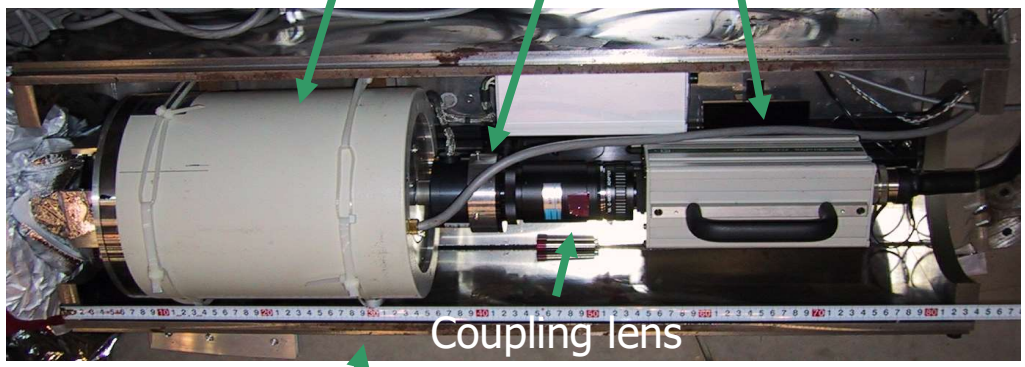
Hardware of the camera system

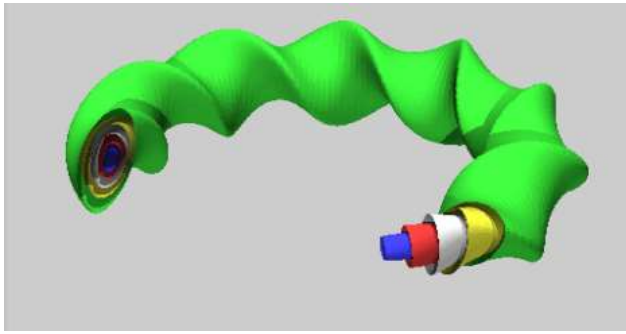


- Fast video camera
  - KODAK:4540MX / Vision Research: Phantom
  - 30fps-4500fps(256x256)
  - ~20kHz(256x256 new)
- Fluctuation measurement is realized from fast optical system with large diameter scintillator screen(10cm).

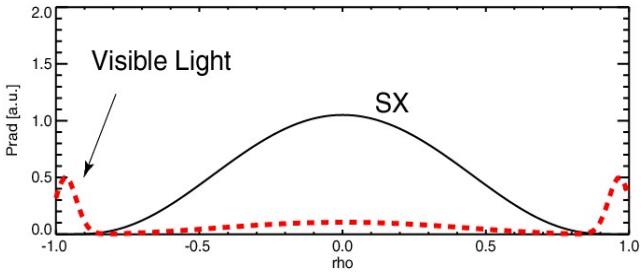


Iron magnetic shied 2.5cm in thickness

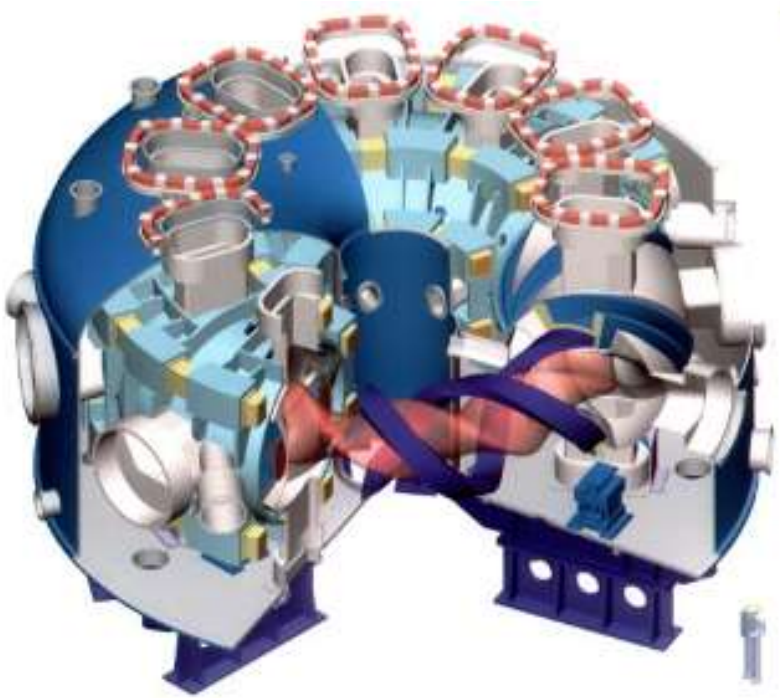
Tangential view --SX and Visible light

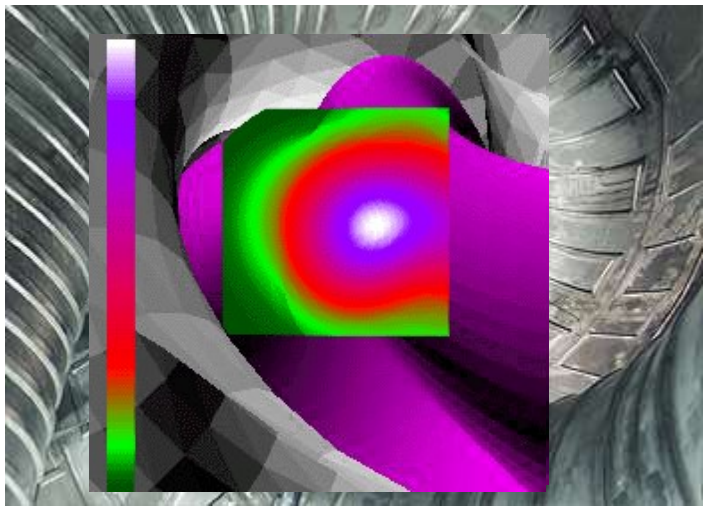


- mation from the ined.
-) plasma, large een.



Large Helical Device

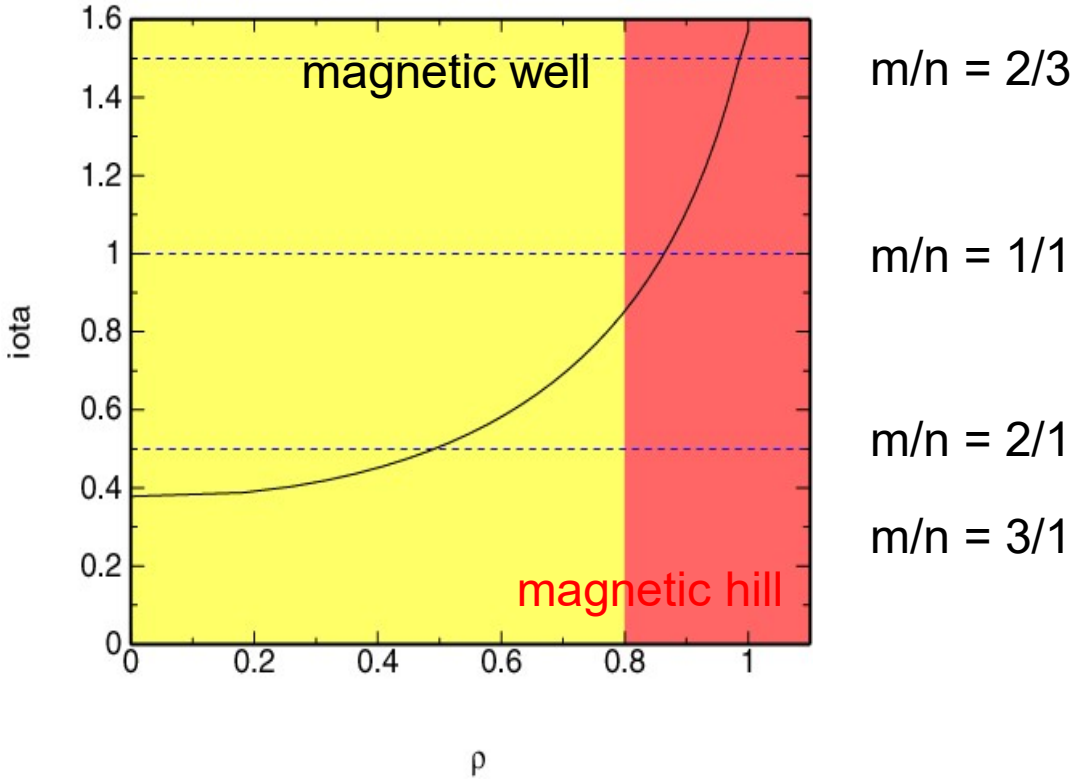




L = 2, m=10 Heliotron type device

R = 3.5 - 3.9m, a ~ 0.6m

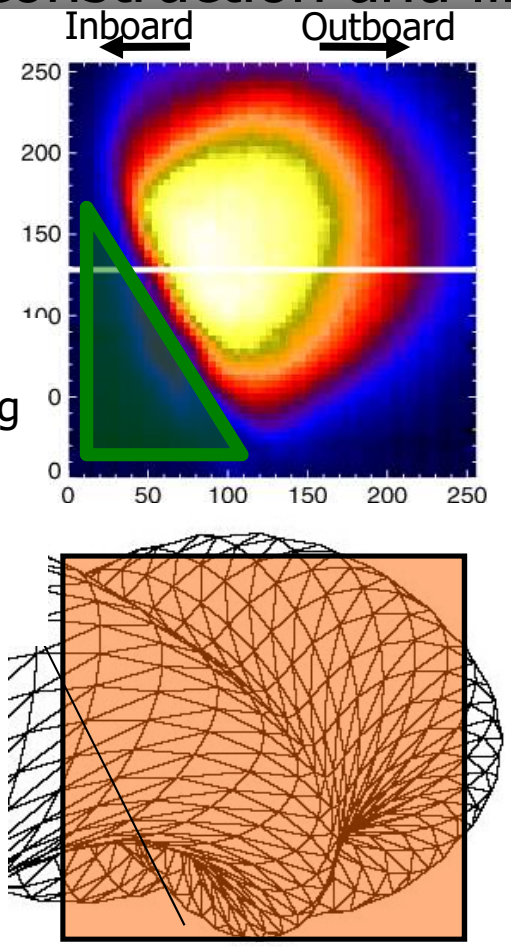
B_t = 0.4 – 2.8 T

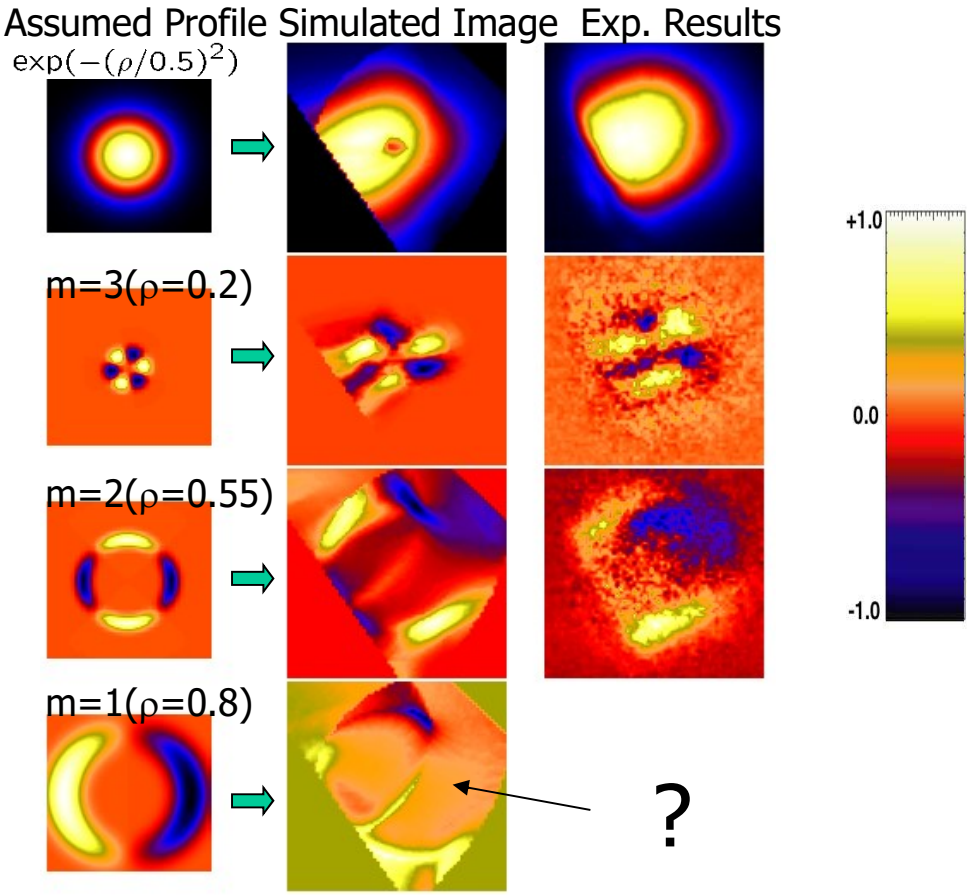


- Magnetic shear is opposite to Tokamak plasmas

Reconstruction and line-integrated images

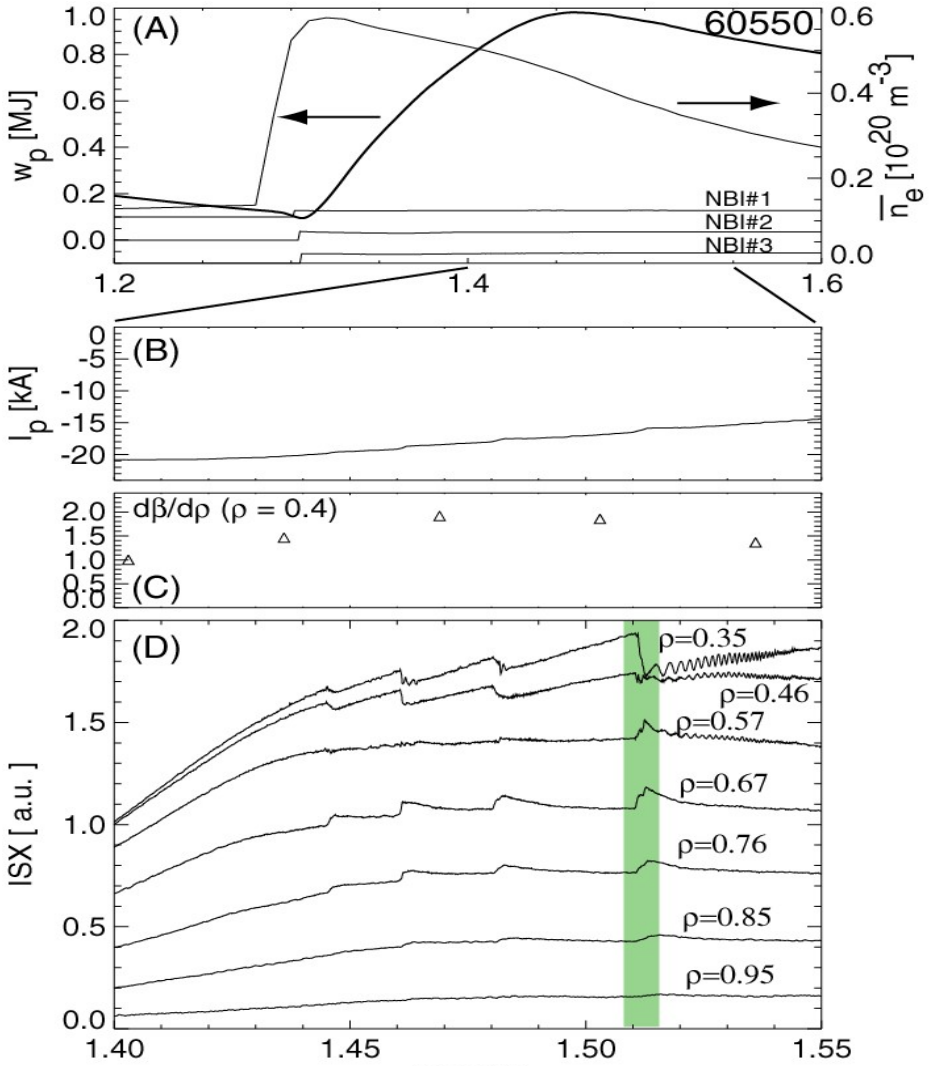
Left-Bottom area is missing from the geometrical reason.





– If the perturbations are localized in the core, where the magnetic shear is small and the flux surface is close to the simple torus, the line-integrated image is quite similar to the poloidal emission profile.

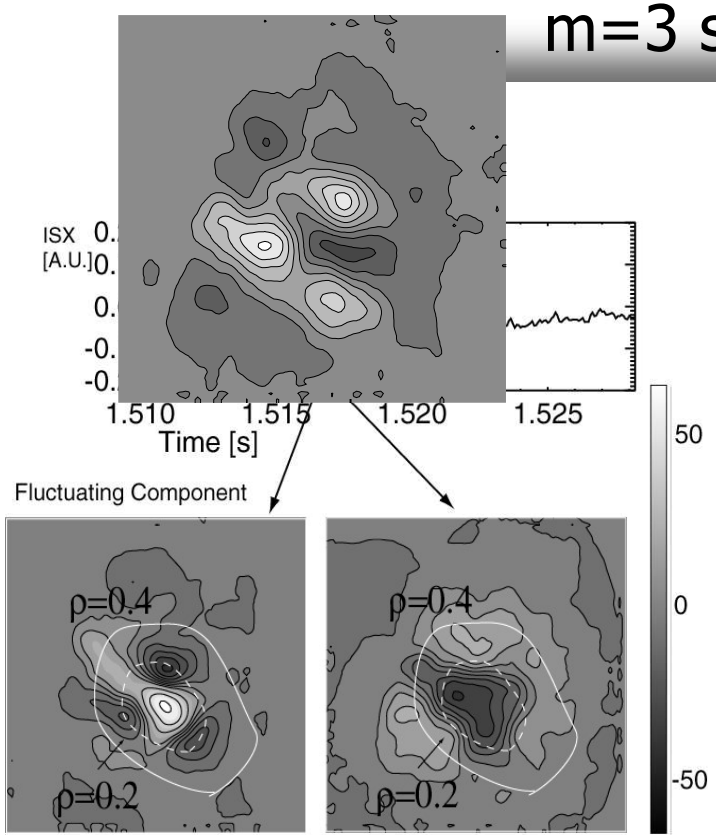
Sawtooth-like phenomena observed in LHD

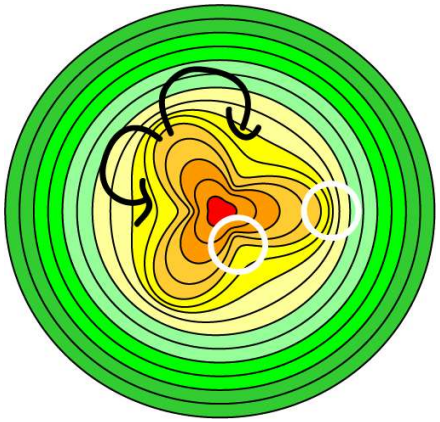


- In order to heat core plasma, NBI #1-4 is used just after the pellet injection.
- While the plasma is being recovered, the pressure profile is peaked.

- Sawtooth-like repeated events are observed in the SX radiation.
- Last one is the largest and accompanied by m=3 post-cursor oscillations which persist for 0.1 – 0.3s.

m=3 sawtooth-like relaxation

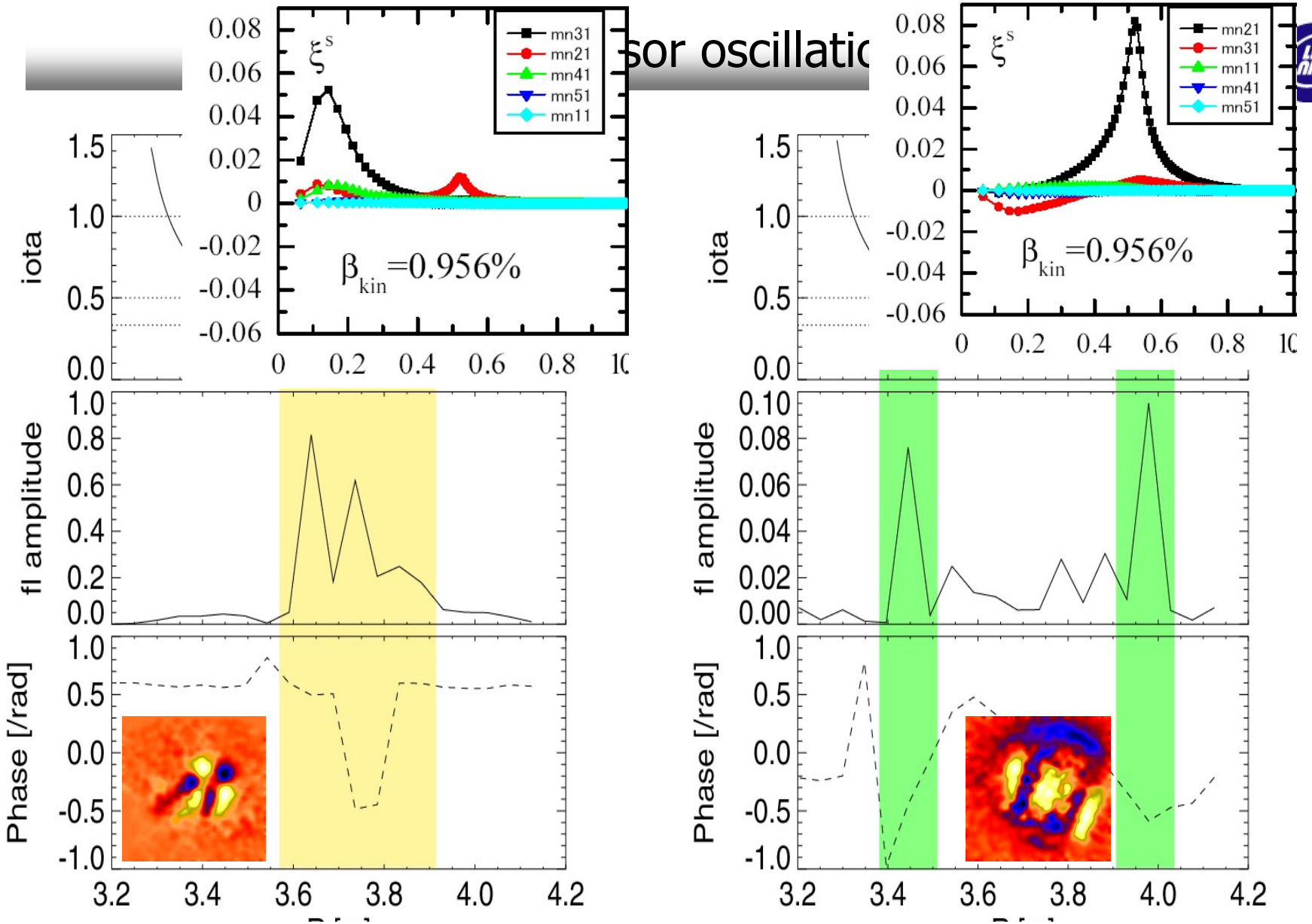




B2

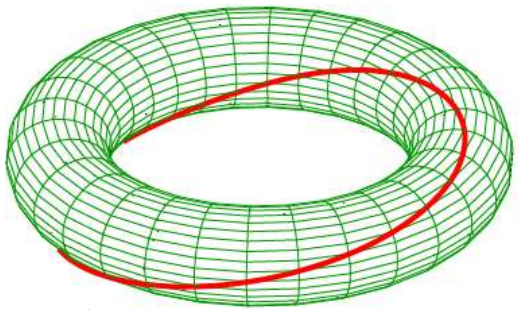
- Before the crash m = 3 deformation can be seen by tangentially viewing soft X-ray camera.
- After the triangular structure reaches ρ=0.4, SX intensity in the outer region increases.
- Reconnection due to the interchange-mode driven flow may make the reconnection.

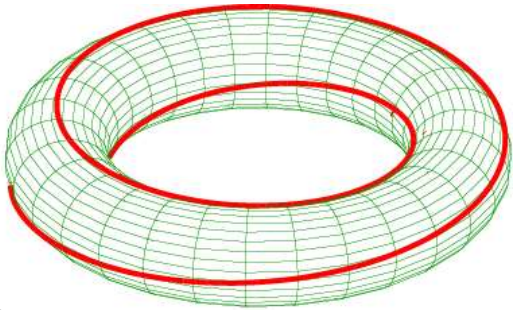
sor oscillatic



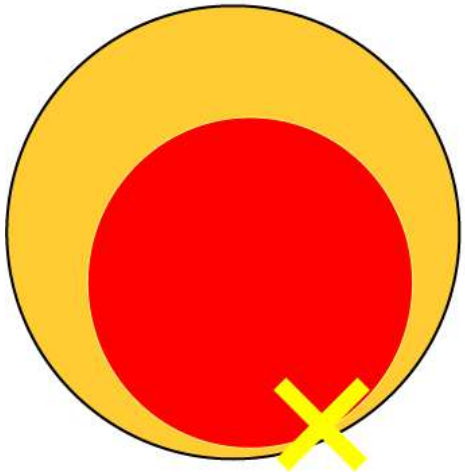
- Radial profile of the core-mode(m=3) and annular type mode (m=2) are similar to the eigen-function calculated by TERPSICHORE.

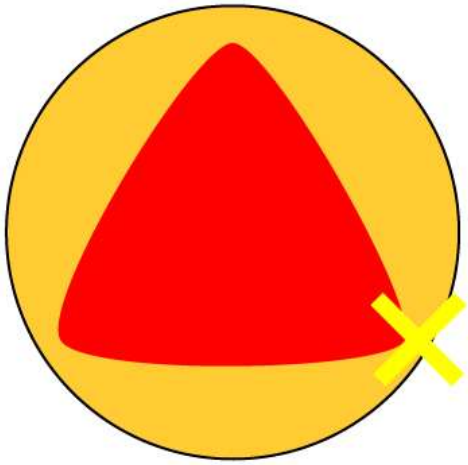
Helical deformation and relaxation events





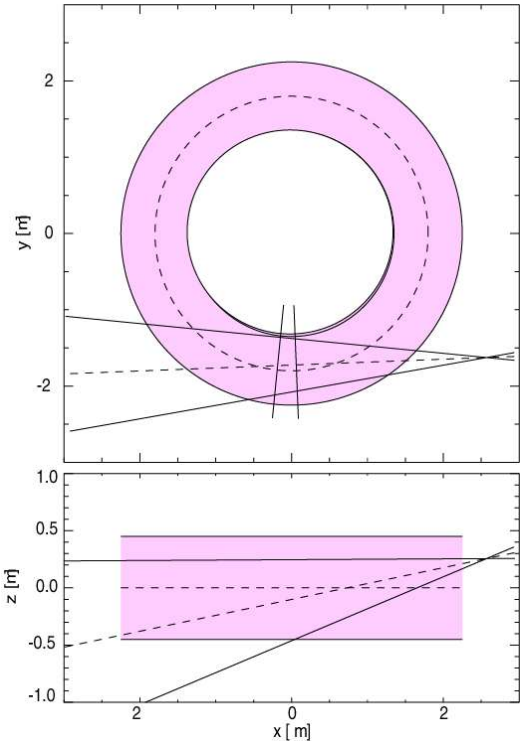
Safety Factor q = 1, q = 3

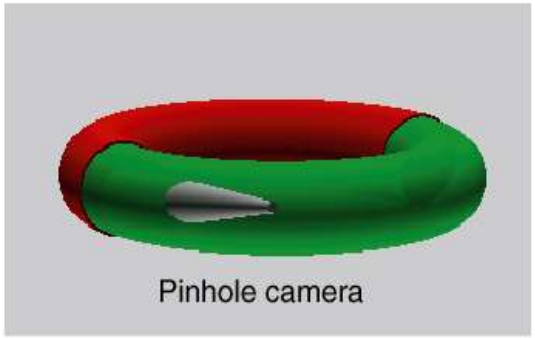




Helical deformation of the flux surface is the cause of the sawtooth activity. Here, other type of the relaxation events will be shown.

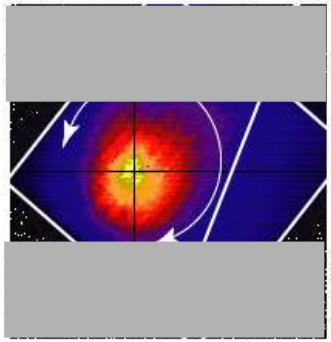
TEXTOR Field of view



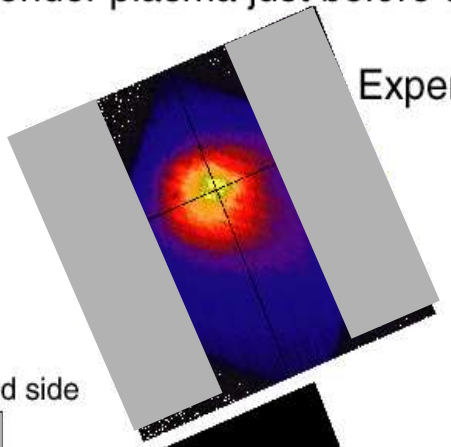


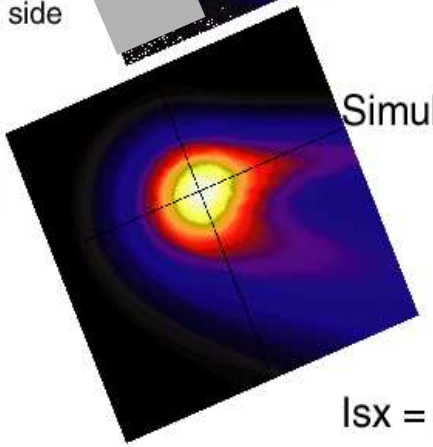
This frame is frame of imaging fiber bundre.

Frame are rotated from the convienience in the installation.



(slender plasma just before disruption)

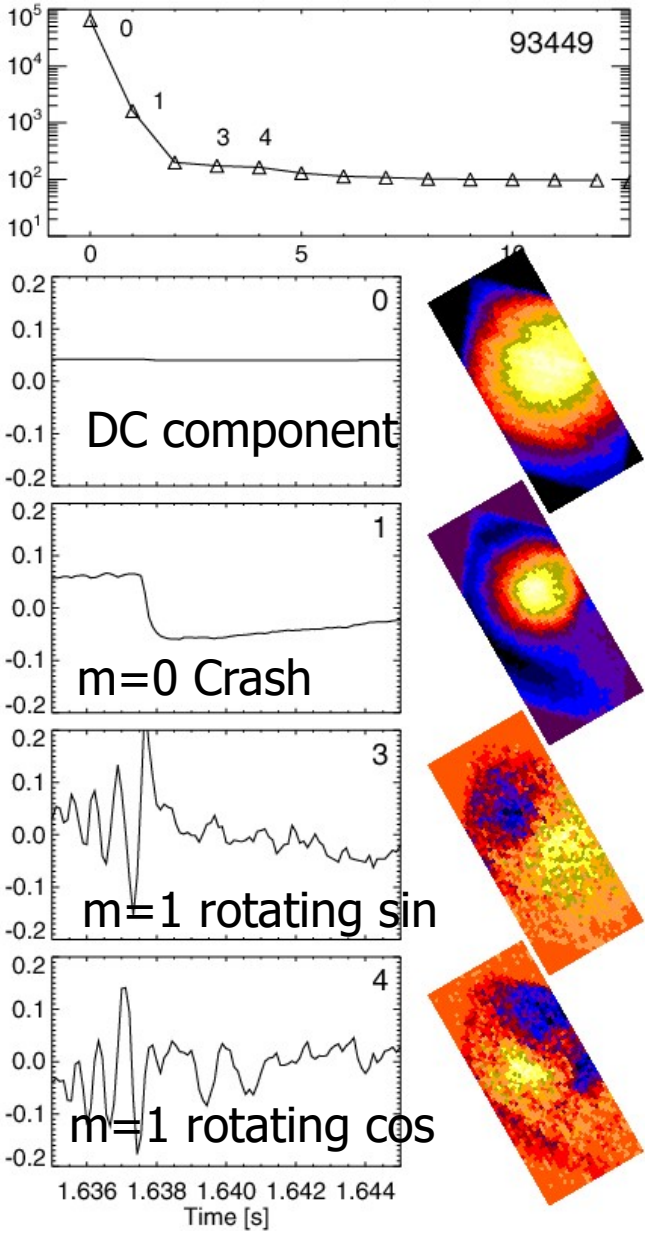




$Isx = \exp(-(\rho/0.2)^2)$

- Field of view is tilted. With old camera, it is also fairy narrow when we want to measure with higher framing rate, e.g. 9kHz.

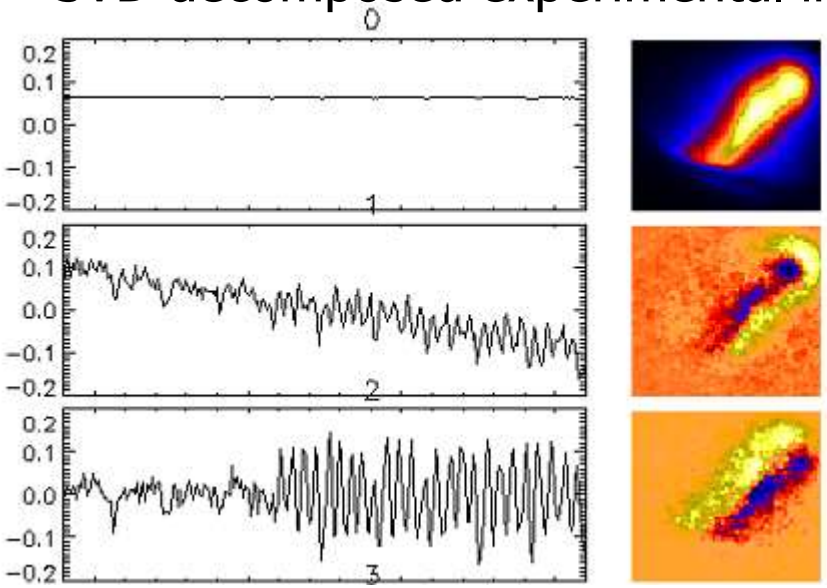
m=1 type normal sawtooth in TEXTOR Tokamak

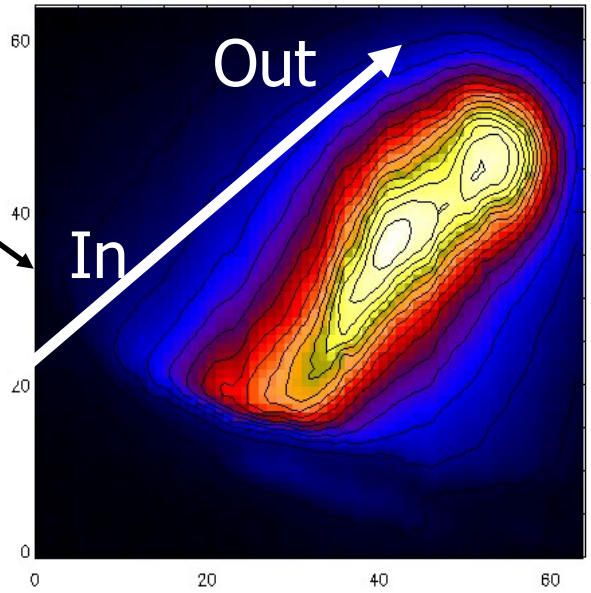


- Using Singular Value Decomposition, Video images can be separated into orthogonal components.

m= 1 structure in the core (non resonant?)

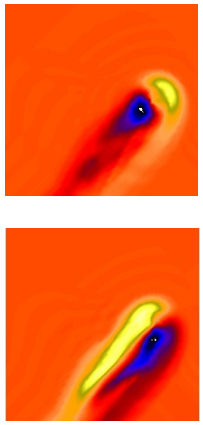
SVD decomposed experimental image

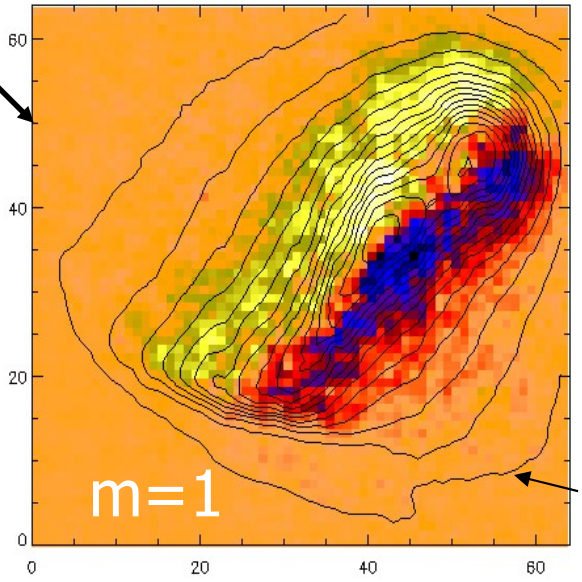




Data is consistent with the simulated image assuming core localized m= 1 mode. Radial profile is assumed by

Exp(-((ρ-0.15)/0.1)^2) .

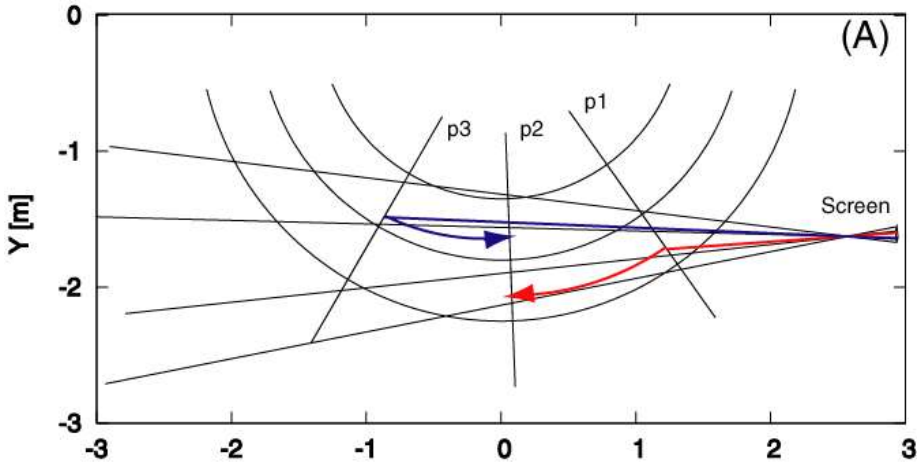


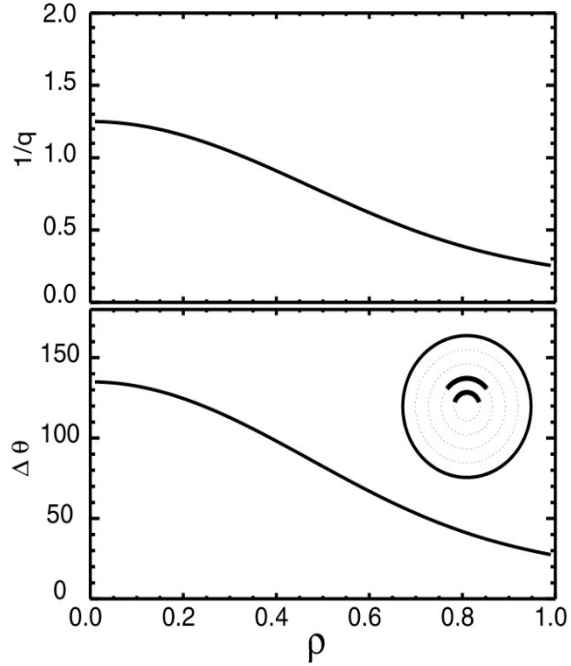


Contour line is from stationary image above.

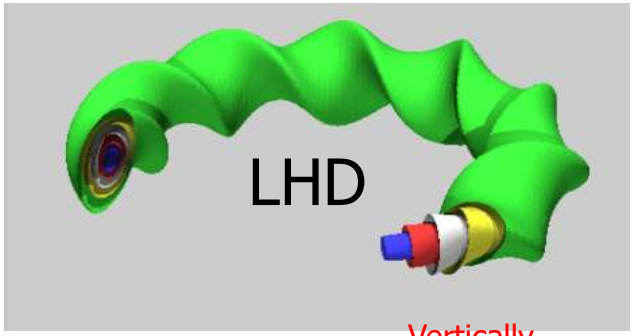
When reconnection is required?

TEXTOR(circular tokamak)

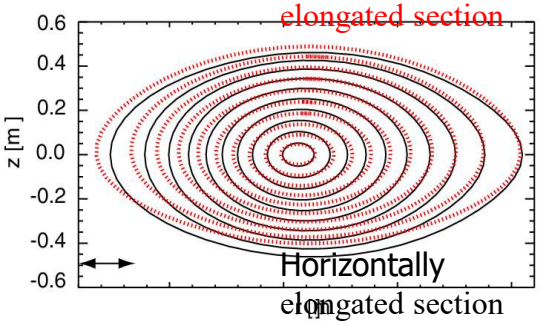


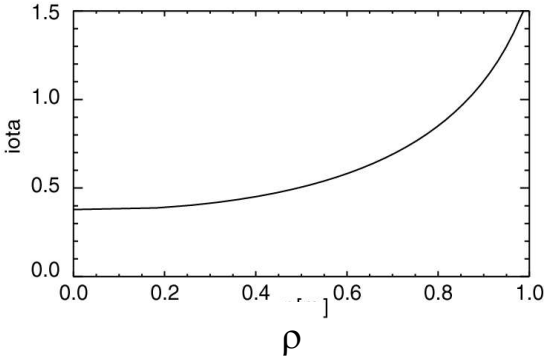


- Line of sight is projected to a poloidal plane in order to make a reconstruction.
- Equilibrium information is needed to make plot the sight lines on a poloidal plane.



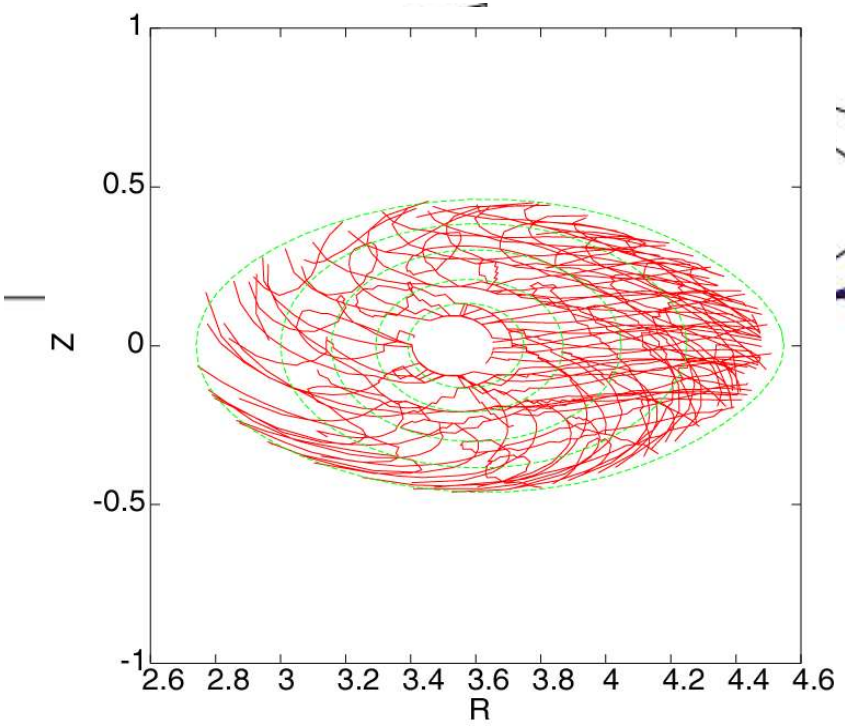
Vertically elongated section





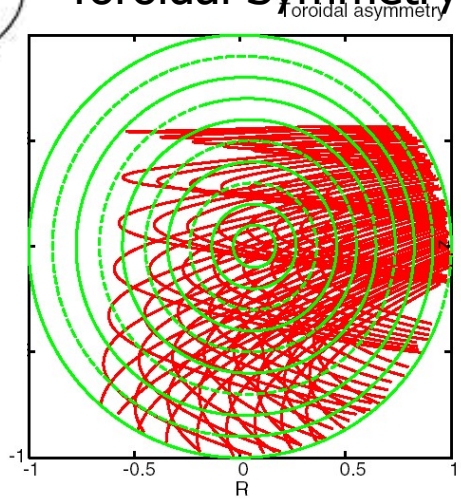
iota=5(l=10) geometry

Constant radiation along field lines

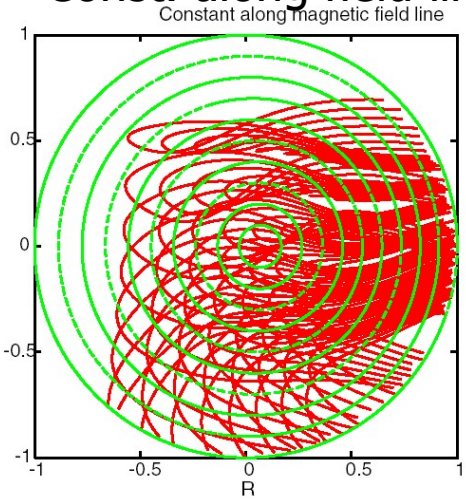


Equivalent line of sight

Toroidal Symmetry

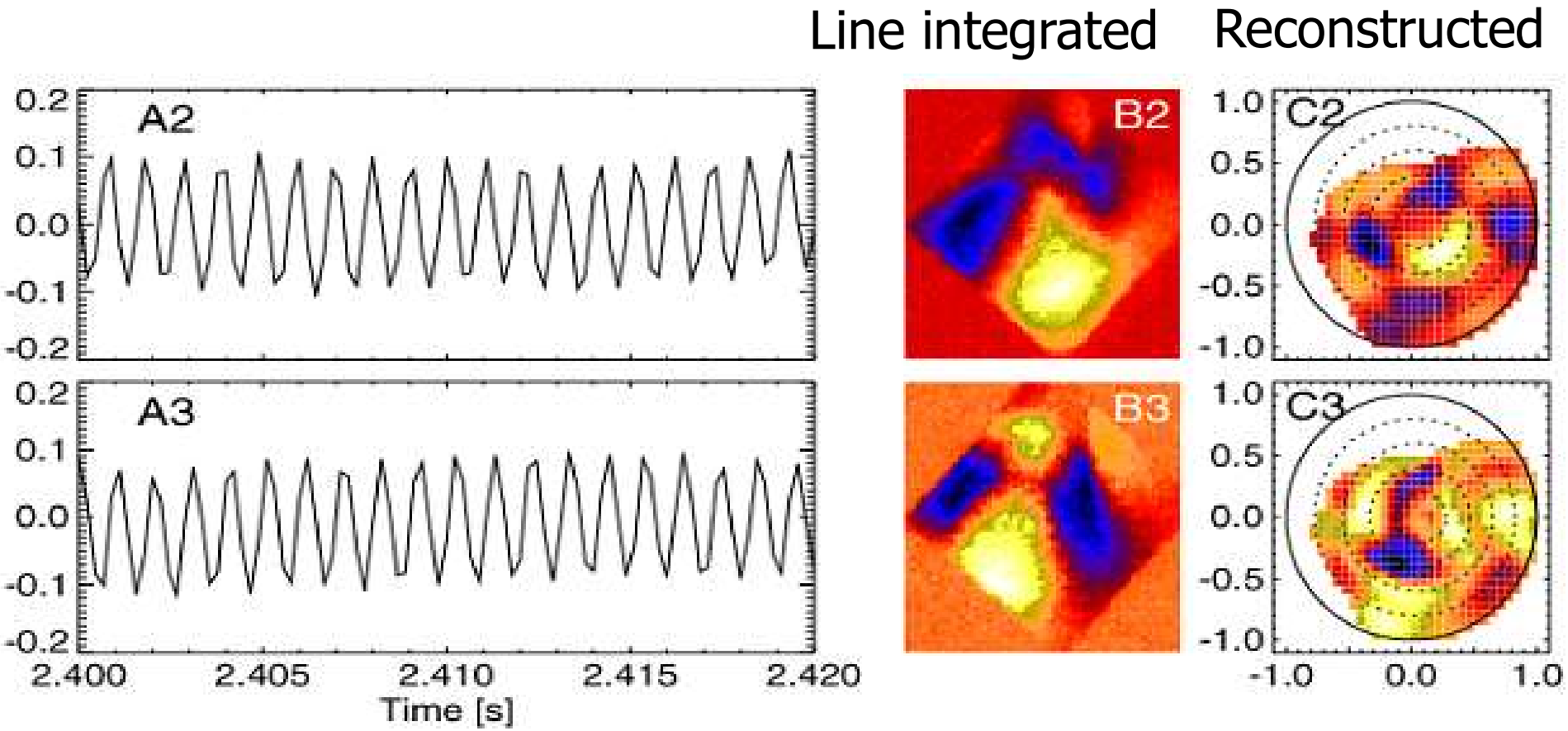


Const. along field lines



- It is not possible to reconstruct 3-dimensional structure from only one projection. If we assume symmetry, 3D reconstruction problem can be reduced to the 2D problem.
- In order to analyze structure at the fluctuating MHD phenomena, constant radiation along magnetic field lines might be good.
- We need to know the equilibrium magnetic field.

Line-integrated image and its reconstruction



- Reconstruction of the emission profile is possible.
- However, it really is needed for understanding, the merit of the diagnostics – simple installation – will be lost.

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   - Provide comprehensive view of the complicated phenomena.

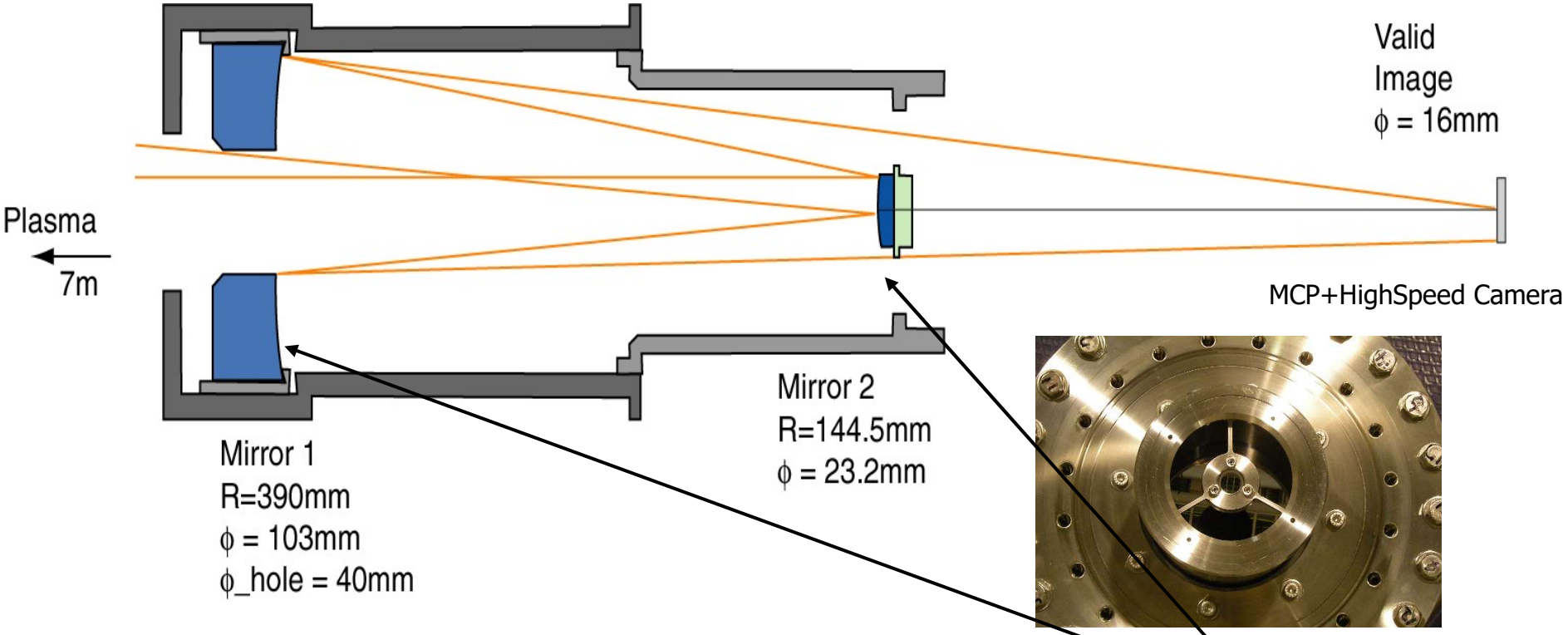
2. Tangential view and vertical view in magnetically confined plasmas

3. LHD Example using SX radiation
   - Direct 2D imaging works well with less magnetic shear region.

4. VUV Telescope system for edge fluctuations.

5. Summary

Telescope using Inverse-Schwarzschild optics

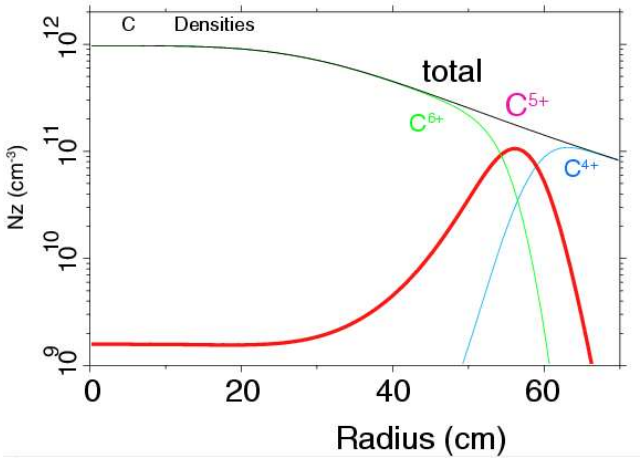


- Magnification is 1/60 in this design.
- Distance from the focal point to the object is 7000mm.
- Incident angle of the mirror is less than 9 deg. Consistent with the restriction of the multi-layer mirror.

Mo/Si multilayer mirror can reflect 13.5nm CVI impurity line. We can construct much faster system than pinhole camera.

⇨ faster phenomena

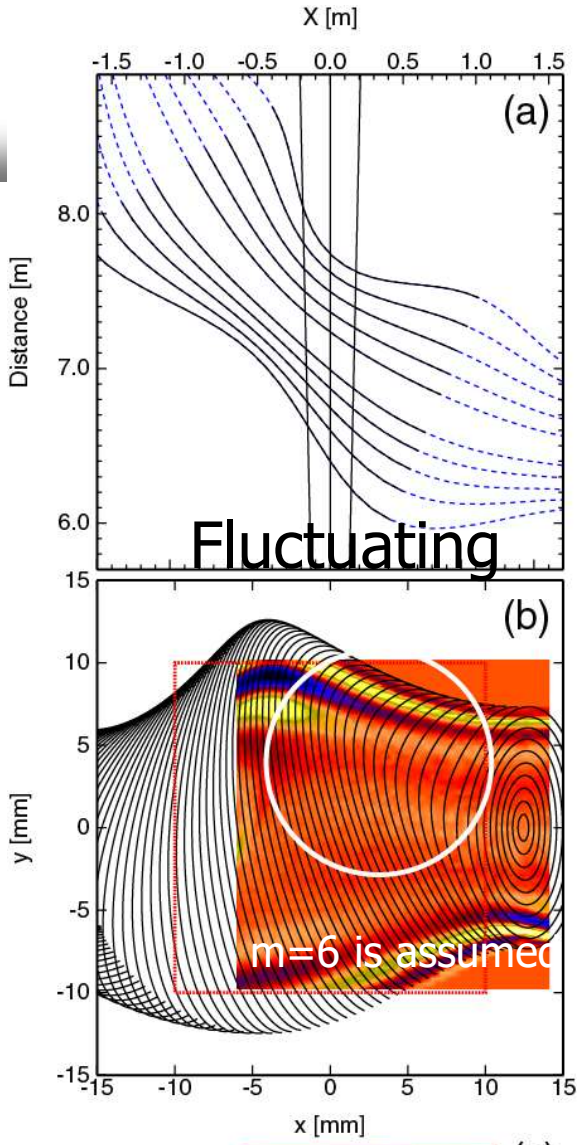
Initial Results



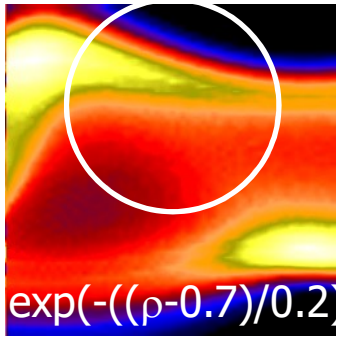
- Semi-vertical view is tried in LHD.
- From initial empowerments, edge localized modes in H-mode are measured.

Static

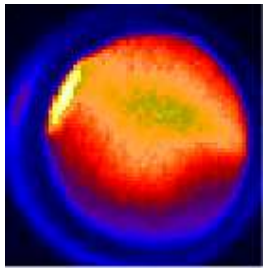
Fluctuating



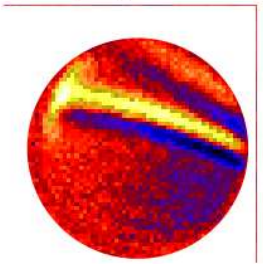
Simulated Image



Experimental Image



Edge flucuations is obvious near the boundary



Summary

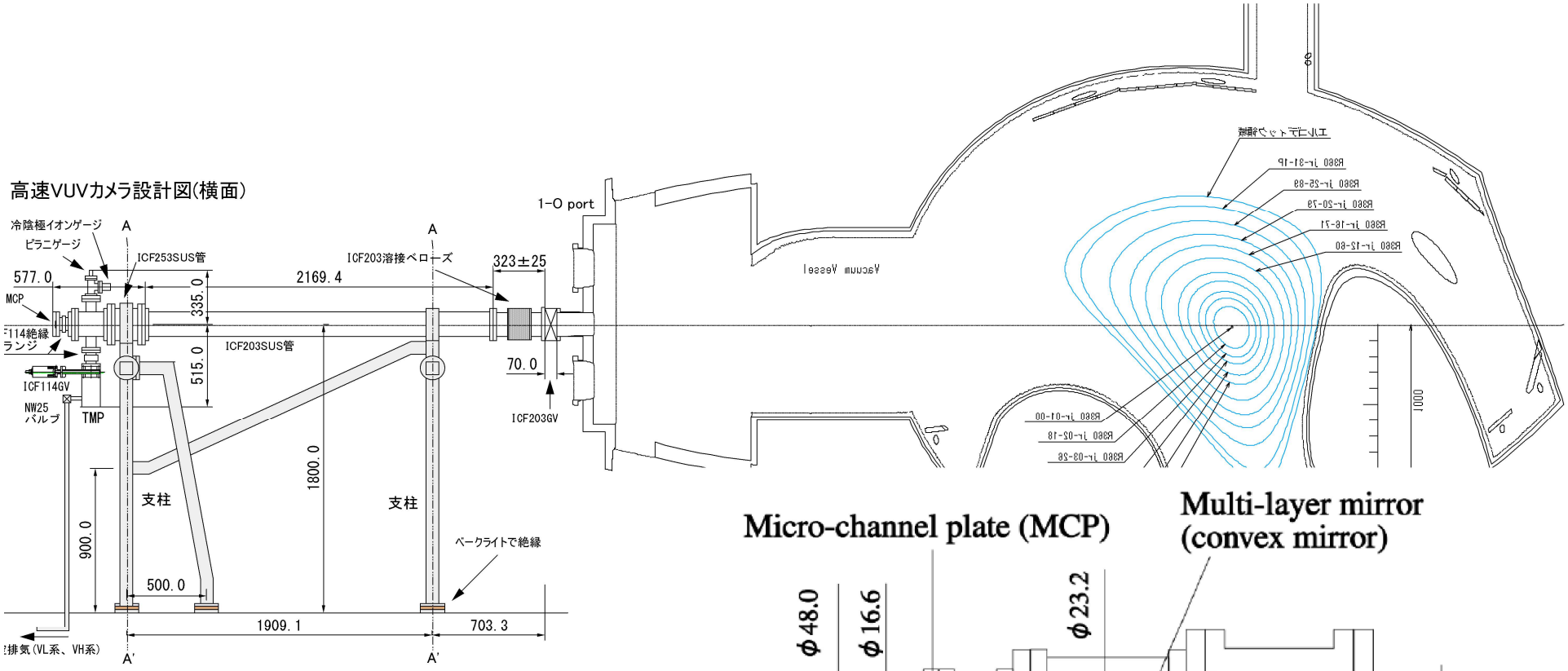
- 2D imaging diagnostics is useful tool for studying the complex phenomena, such as MHD instabilities.

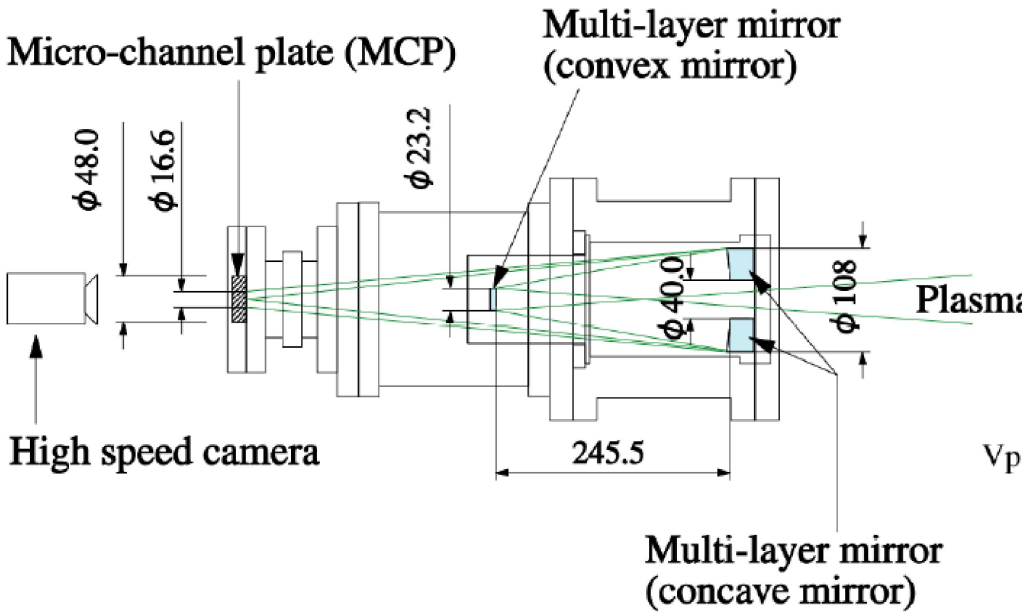
- Simple 2D imaging from using the radiation from the plasma is also effective tool if we operate the system where complicated reconstruction is not needed. Core of the Heliotron type device, edge of the Tokamak plasma is preferable.

- Two example are shown
  - Tangentially viewing SX camera
    - Satooth-like activates in LHD and TEXTOR.
  - VUV Telescope system using multi-layer mirror
    - Since the cross-section of the charge exchange is large in VUV region, brightness of this system is better than those in beam emission spectroscopy using visible light.

This study is supported by NIFS06ULHH509, the MEXT Grant-in-Aid for Scientific Research (B), 17360446, 2005-. and the IAE TEXTOR agreement(NIFS05KETE001).

LHD and fast VUV camera





- Located on the holizontal plane of the LHD.
- Focal length is 7m.