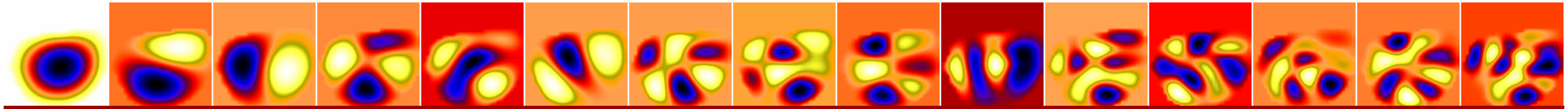
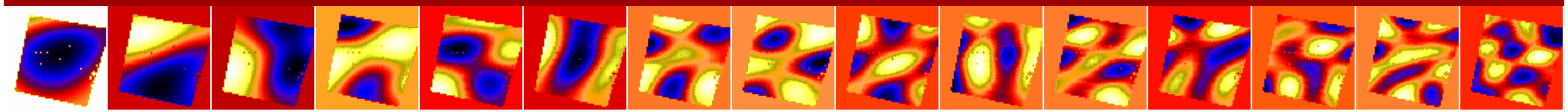


Tangential SX imaging for visualization of fluctuations in toroidal plasmas

S. Ohdachi, K. Toi, G. Fuchs
and the LHD Experimental Group
National Institute for Fusion Science



Outline of my talk

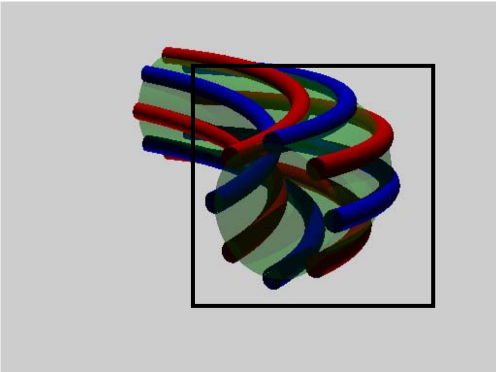
1. Merit of the tangential imaging using SX radiation.
2. Camera Hardware. Sample Movies in LHD.
3. Provide comprehensive overview of the complicated phenomena
   - ✓ Comparison of the sawtooth in Tokamaks and Heliotron plasma
4. Analysis (tomographic inversion using PT method)

5. Future plan for smaller scale fluctuations
   - ✓ VUV telescope system

Merit of the tangentially viewing camera

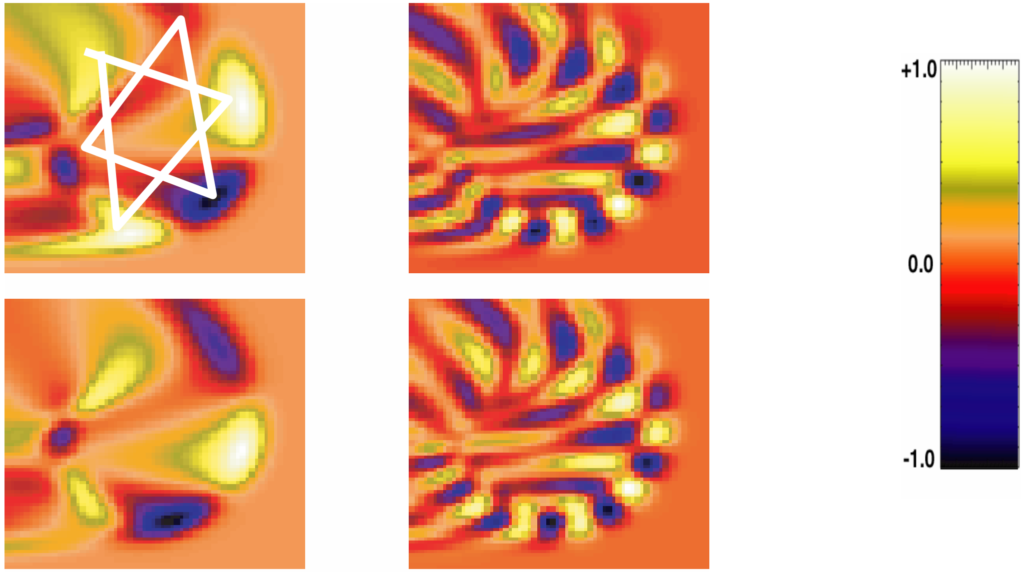
$$k_{\perp} >> k_{//}$$

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.

History of tangential imaging (SX)

From X-ray radiation, we can study core plasma.

(Edge plasma for Bolometer, Visible lights measurements)

- 1980s
  - Nagoya Univ. (CLEO, MCP, S. Takamura et. al., Nucl. Fusion Vol. 23 (1983) 1485)
  - PPPL (PBX-M, P20+MCP, R. J. Fonck et. al., RSI Vol. 59 (1988)1831)

Hard X-ray(super thermal elc.)

- 1990s
  - PPPL (PBX-M, SXII, S. von Goeler et. al., RSI Vol. 65 (1994)1621)

Estimation of equilibrium

  - NIFS (LHD, SX CCD, Y. Liang et. al., RSI, Vol.72 (2001)717)
  - PPPL + IPP Juelich + NIFS

Fluctuation study

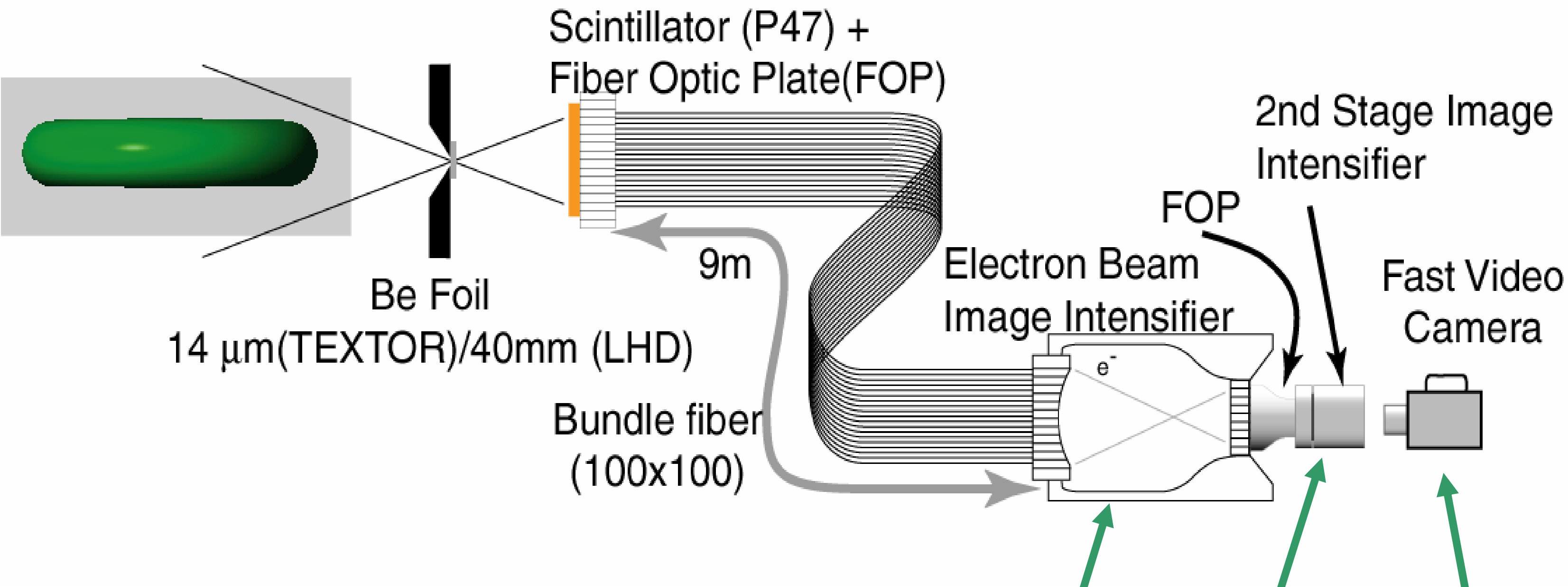
    (Concept, S. von Goeler, RSI Vol. 61(1990) 3055)

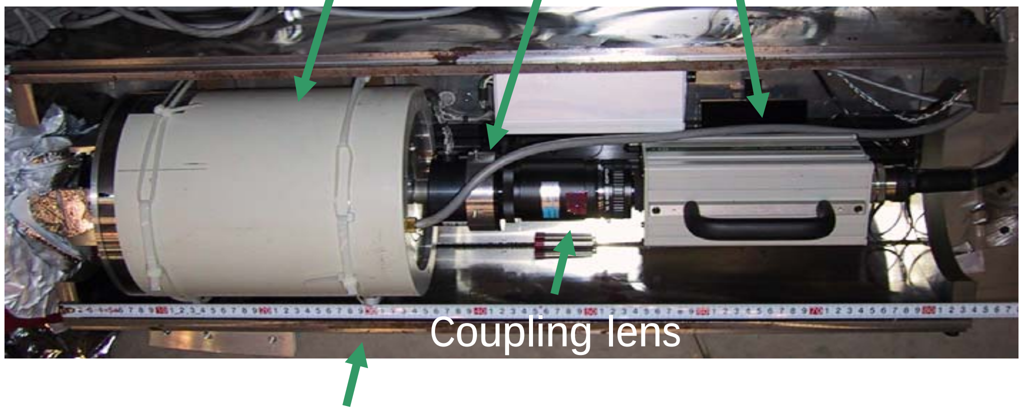
    (TEXTOR, SXII + NTSC Camera, G. Fuchs et. al., EPS 23J(1999)757)

    (LHD, TEXTOR, SXII + Fast Camera, S. Ohdachi et. al., RSI vol.74(2003)2136)
  - PPPL (NSTX, SXII + Fast CCD on-chip memory, R. Feder, B. Stratton et. al.)

Spatial structure of the MHD fluctuation has been measured with our camera system.

Hardware of the camera system



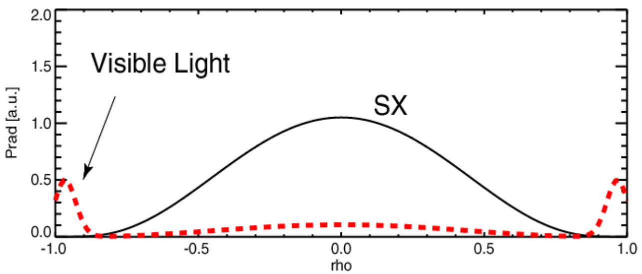


Iron magnetic shied 2.5cm in thickness

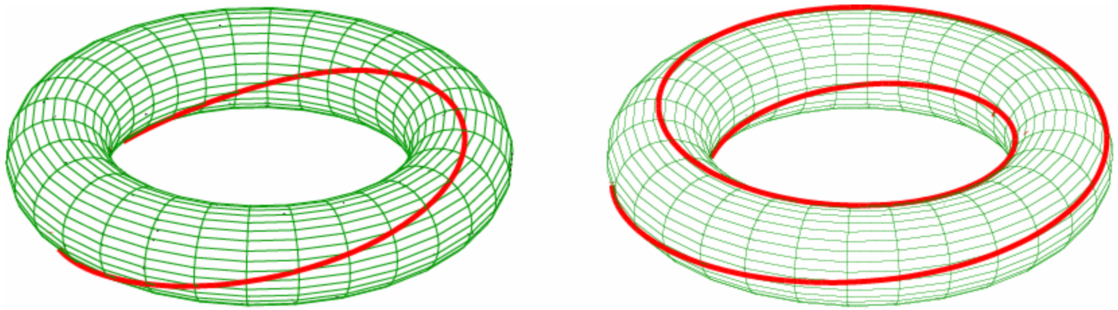
- Fast video camera
  - KODAK:4540MX / Vision Research: Phantom
  - 30fps-4500fps(256x256)
  - ~20kHz(256x256 new)
- Fluctuation measurement is realized from fast optical system with large diameter scintillator screen(10cm).

Tangential view --SX and Visible light

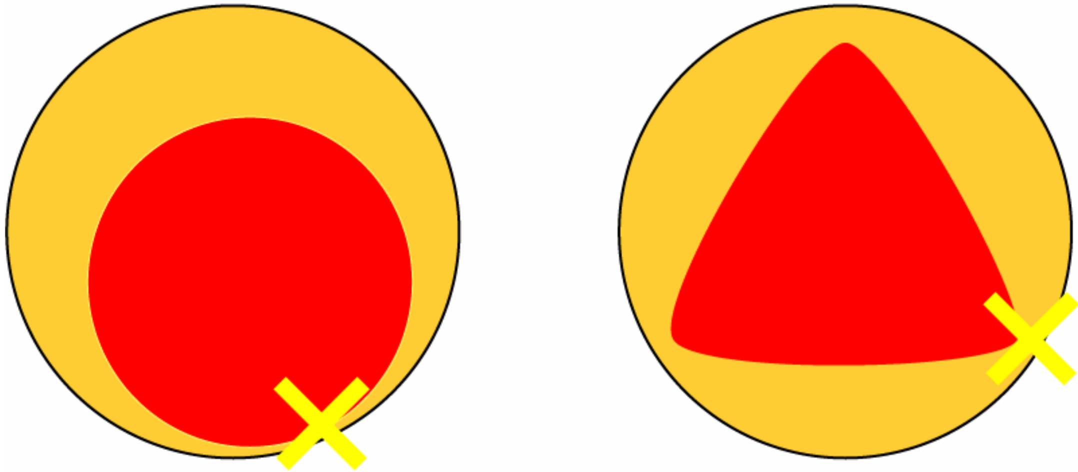
- Using SX radiation, information from the core plasma can be obtained.
- In SDC(SuperDenseCore) plasma, large Shafranov-shift can be seen.



Fluctuation study Helical deformation and relaxation events

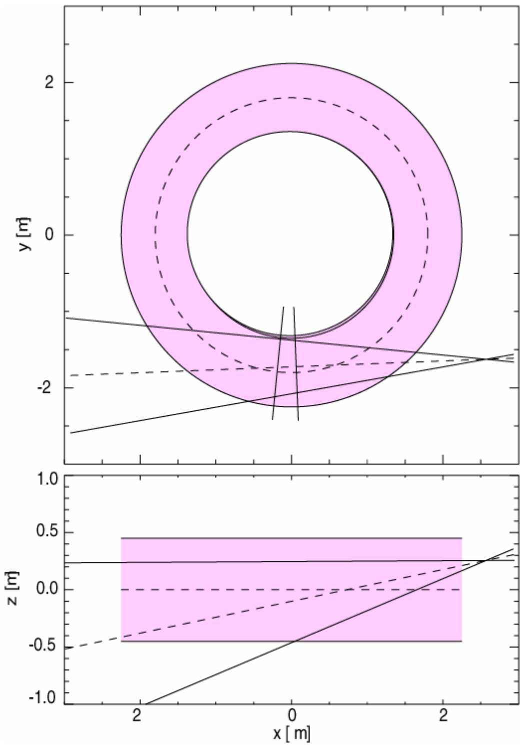


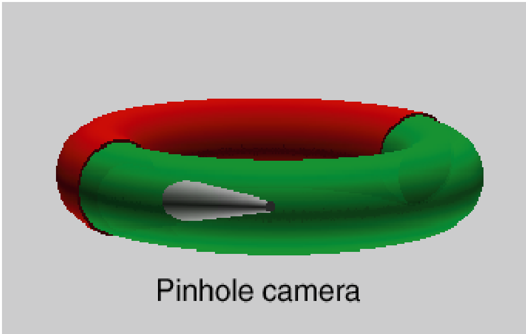
Safety Factor q = 1, q = 3



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

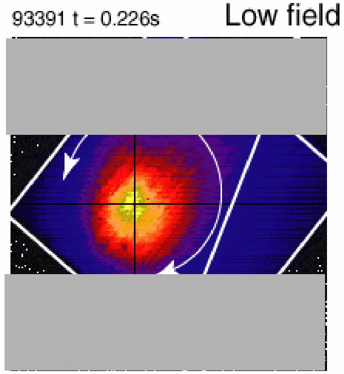




This frame is frame of imaging fiber bundre.

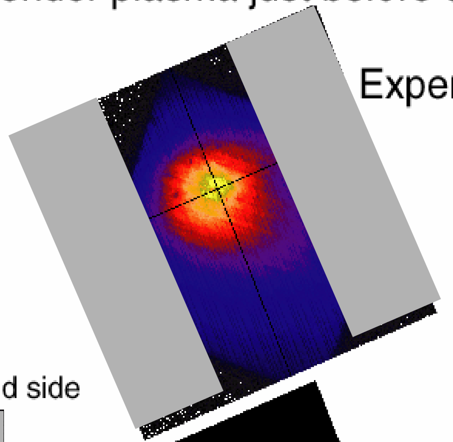
Frame are rotated from the convienience in the installation.

Low field side

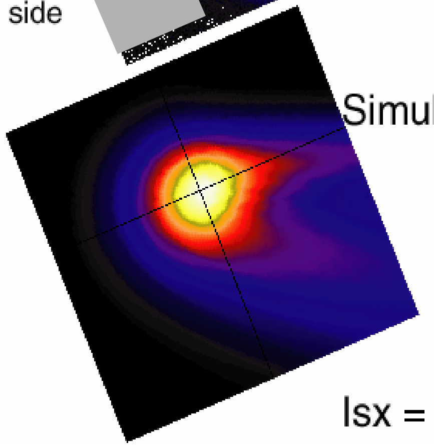


High field side

(slender plasma just before disruption)



Experiment

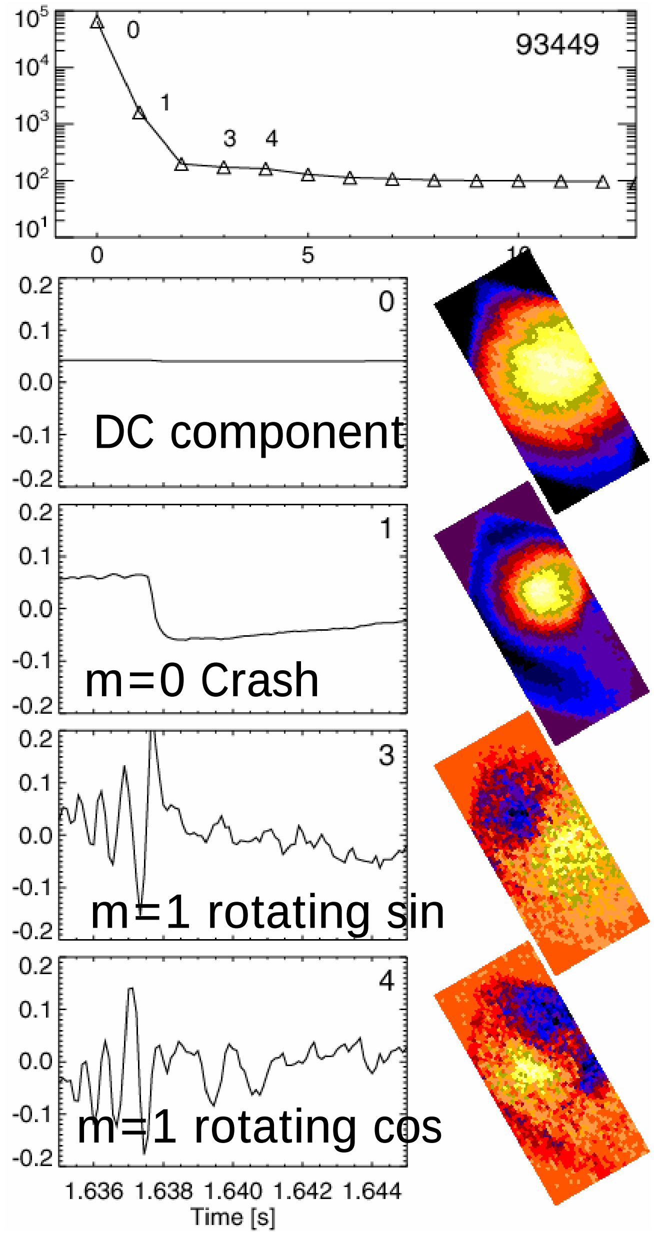


Simulation

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

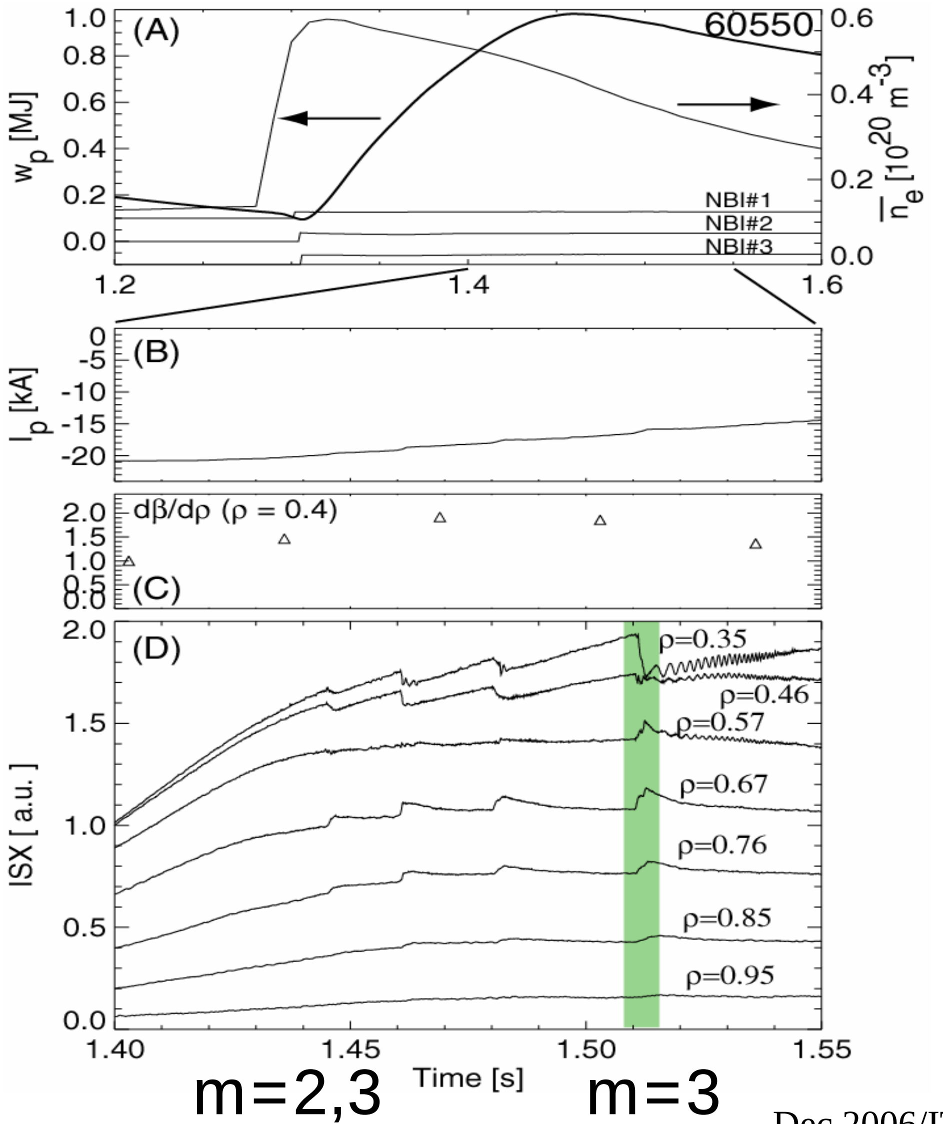
- Field of view is tilted. With old camera, it is also fairy narrow when we want to measure with higher framing rate, e.g. 9kHz.

m=1 type normal sawtooth in TEXTOR Tokamak



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

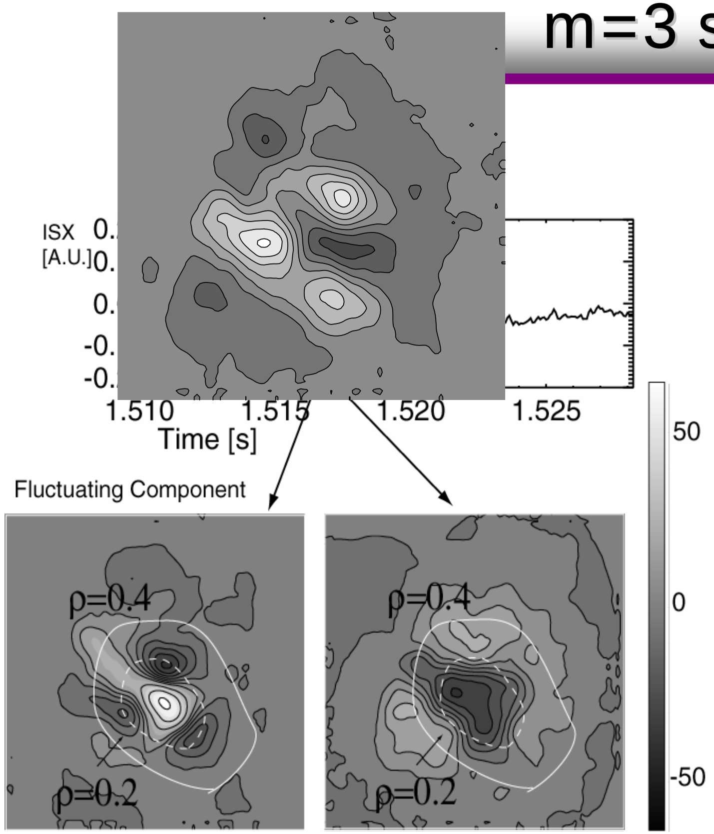
Sawtooth-like phenomena observed in LHD

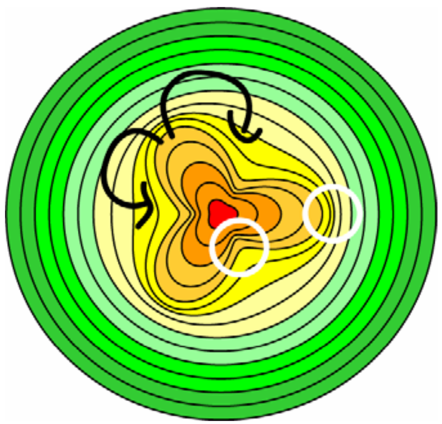


- In order to heat core plasma, NBI #1-4 is used just after the pellet injection.
- While the plasma is being recovered, the pressure profile is peaked.

- 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 =0.4, SX intensity in the outer region increases.
- Reconnection due to the interchange-mode driven flow may make the reconnection.

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Merits / Draw-backs

- Simpler hardware than those in poloidal tomography system.
- We can get images covers wide area in poloidal cross section. We can make use of the human insight via pattern recognition of the structure of the fluctuations.

- ✘ Dynamic range (14bit/~10bit) and framing rate (300kHz/~20kHz) of the present system is not as good as poloidal array system.
- ✘ Difficulty in reconstruction.

- Radiation profile at a poloidal cross section is needed when we want to compare with the theories.
- With reconstructed images, we can study two dimensional effect;
  - e.g. magnetic island shape/size?
  - e.g. ST (Where does the reconstruction take place?)
  - e.g. Ballooning-like nature of the MHD activities.

2D Tomography methods

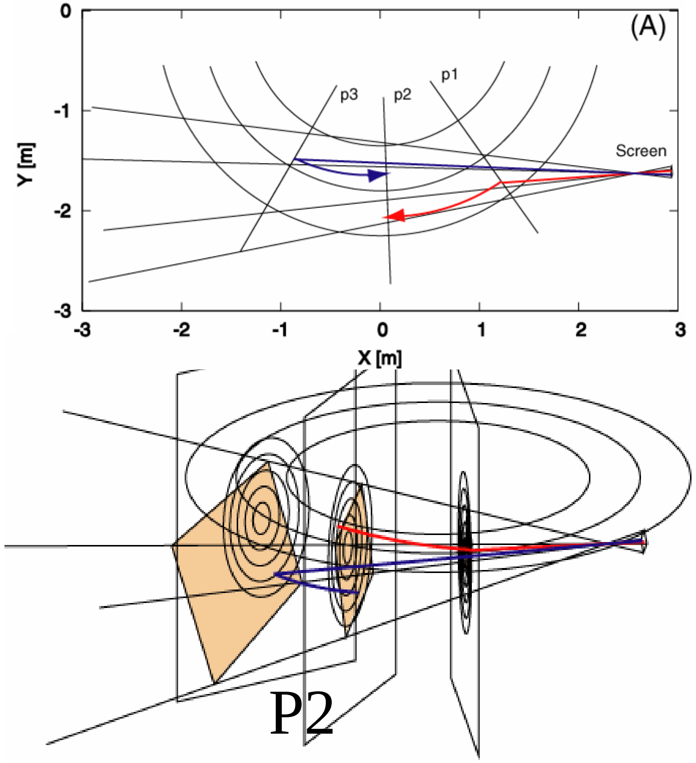
- It is better to make the full use of rich experience in 2D reconstruction in fusion plasma, since it worked well under difficult conditions.

- Series expansion methods (Fourie-Bessel expansion, Cormack,Nagayama ..)
  - shape of the flux surfaces are assumed
- Matrix based methods (ill-posed problem; regularization is needed)
  - Radiation profile using arbitrary grids can be reconstructed; estimate the shape of the flux surfaces is also possible(e.g. W7-AS).

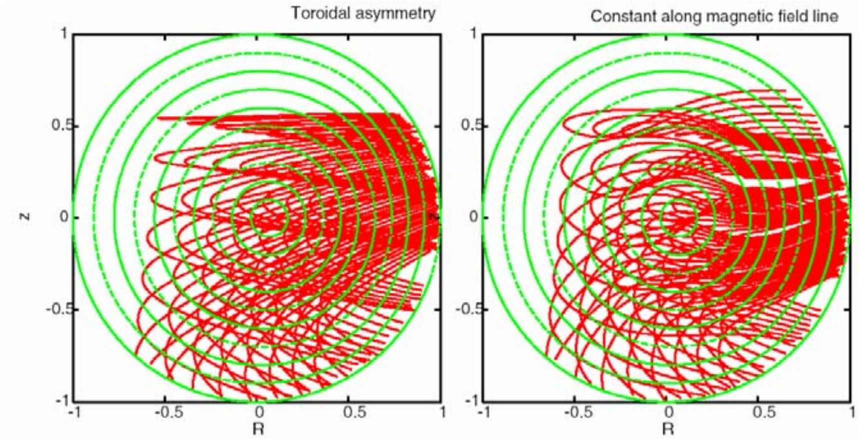
$$g = Af,$$
$$g = \{g_1, g_2, \cdots g_N\} \text{ : Measured data}$$
$$f = \{f_1, f_2, \cdots f_M\} \text{ : Local Emissivity}$$

minimization of $\Sigma(|g - Af|^2) + O(f)$,
$O(f) = \Sigma|f|^2$: Tikhonov-Phillips normalization
$O(f) = \Sigma|\nabla f|^2$: Methods by Iwama
$O(f) = -\Sigma(f \log(f))$: Maximum entoropy method

Constant radiation along field lines



Equivalent line of sight



- 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.

Eigenfunctions in SVD methods

minimization of $\Sigma(|g - Af|^2) + \Sigma|\nabla f|^2$

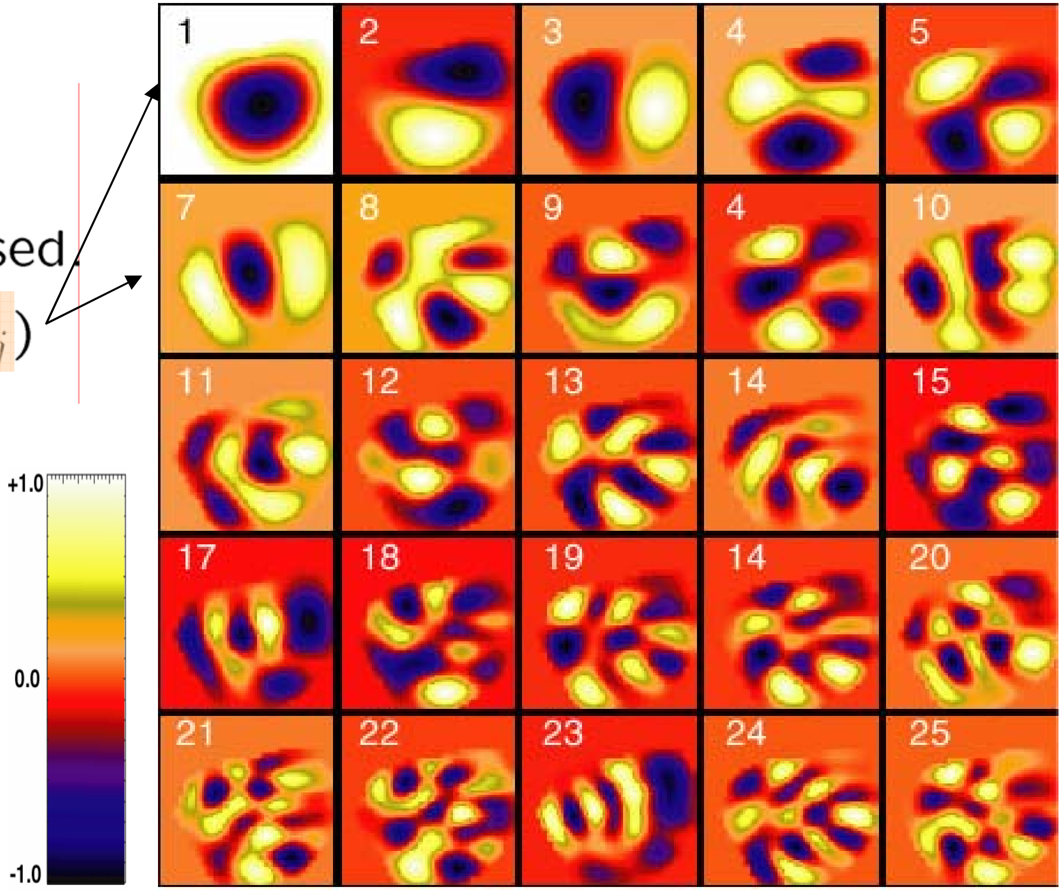
$\mathbf{g} = H\mathbf{f}$

$A = HC^{-1} = U\Sigma^t V$

is sigular value decomposed.

$$\mathbf{f} = \sum_{j=1}^{p} [(\mathbf{u}_j \cdot \mathbf{g})/\sigma_j](C^{-1}\mathbf{v}_j)$$

Coefficient can be determined by correlation.

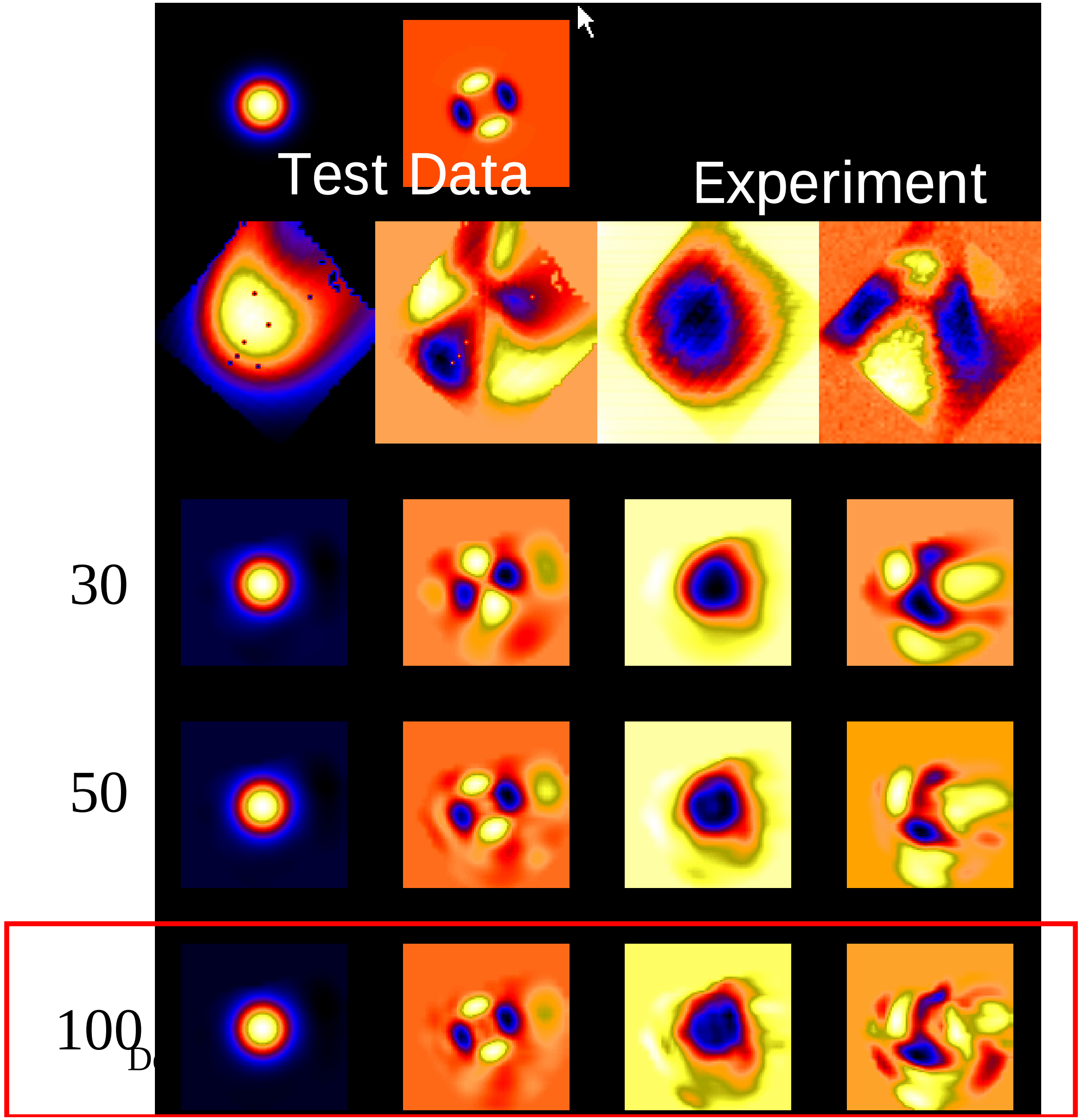


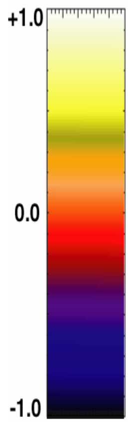
- Solutions are composed by the series of the images.
  - Higher components have a smaller structures. -> We can neglect higher component for the stable reconstruction.

Reconstruction and number of terms

- Reconstruction of the test data and experimental data(TOPOS).
- ~100 terms are optimal for reconstruction.

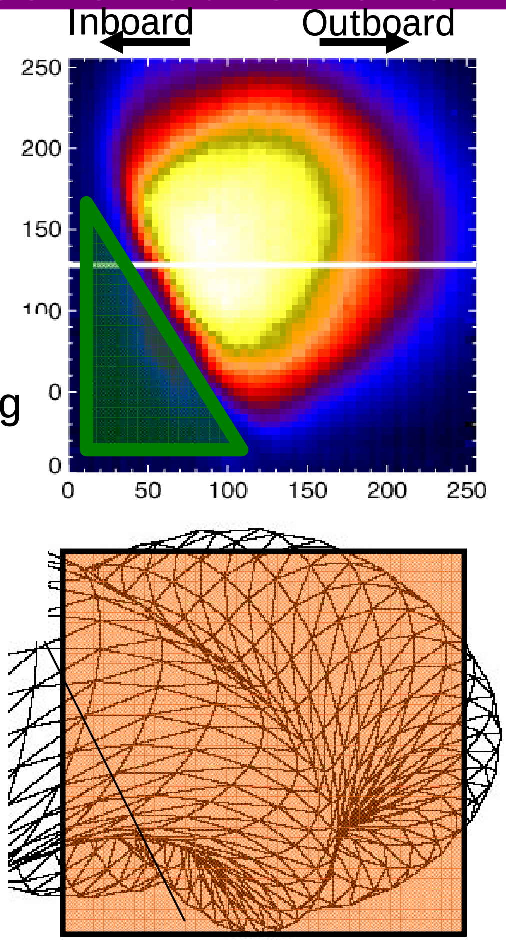
DED m=2 island

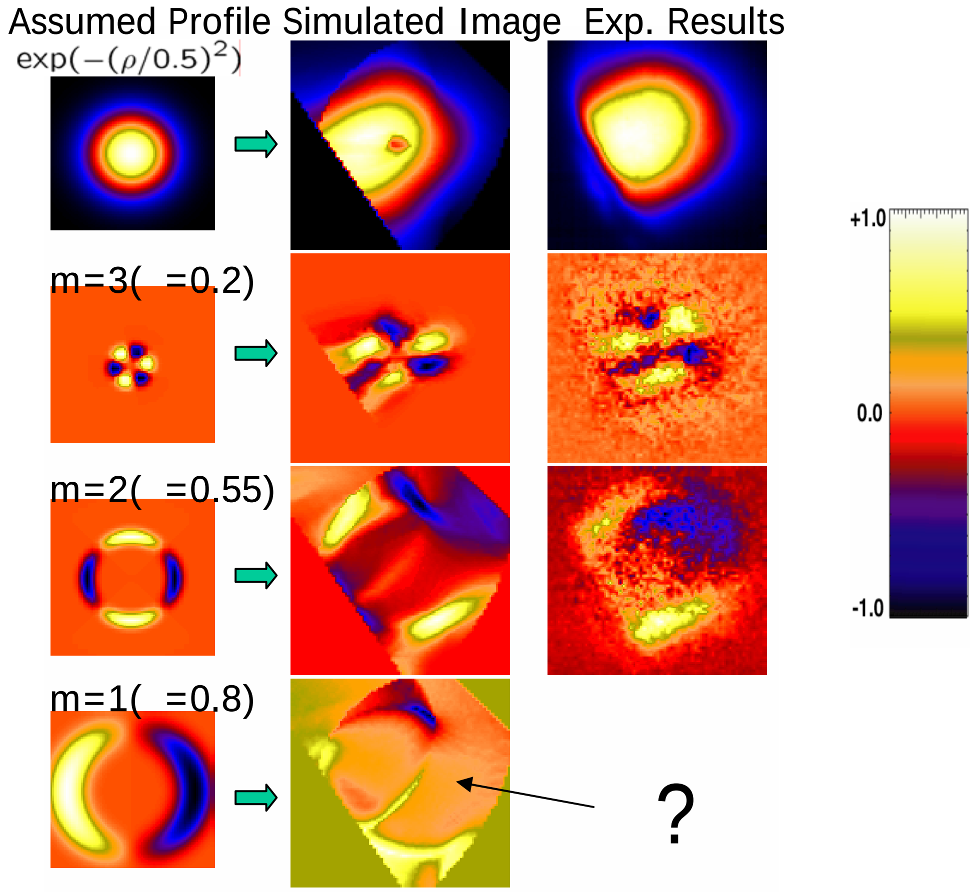




Reconstruction and line-integrated images

Left-Bottom area is missing from the geometrical reason.





- Reconstruction of the image is more difficult than the conventional transform because the reconstruction strongly depends on the equilibrium determination.
- Operation at the ore of the Heliotron-type device / edge in Tokamak device is preferable.

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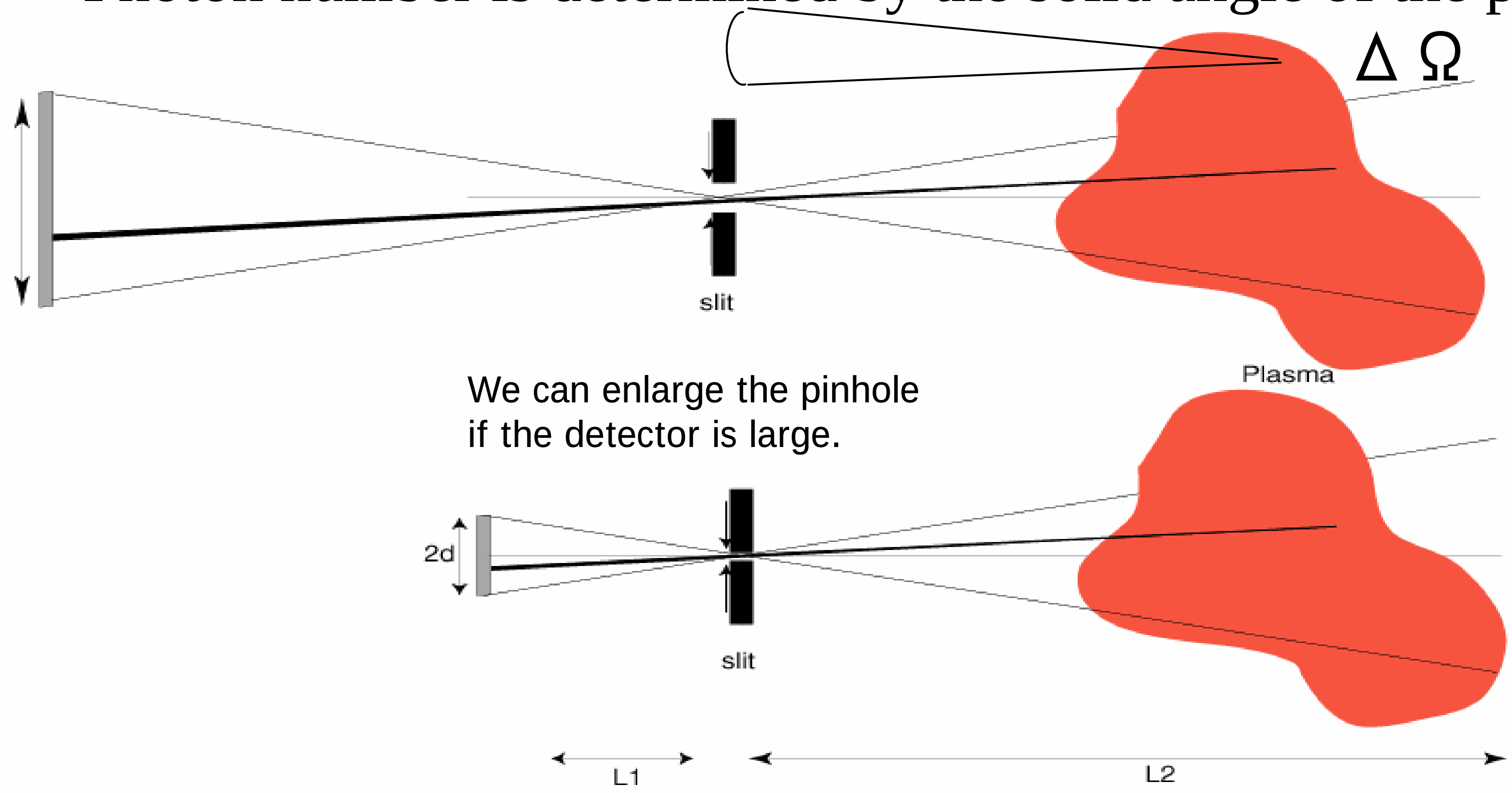
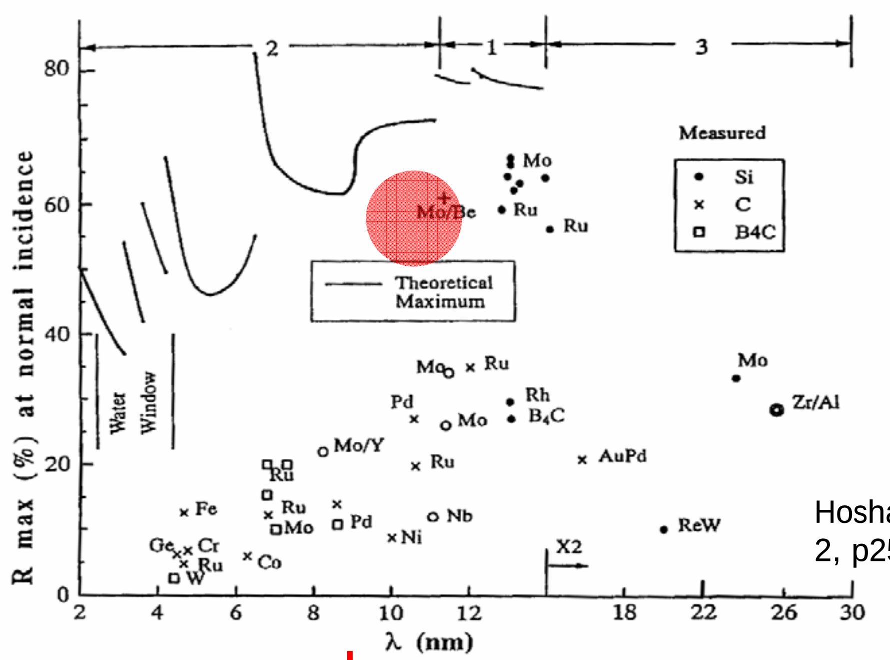
Framing rate is determined by pinhole size

Photon number is determined by the solid angle of the pinhole.

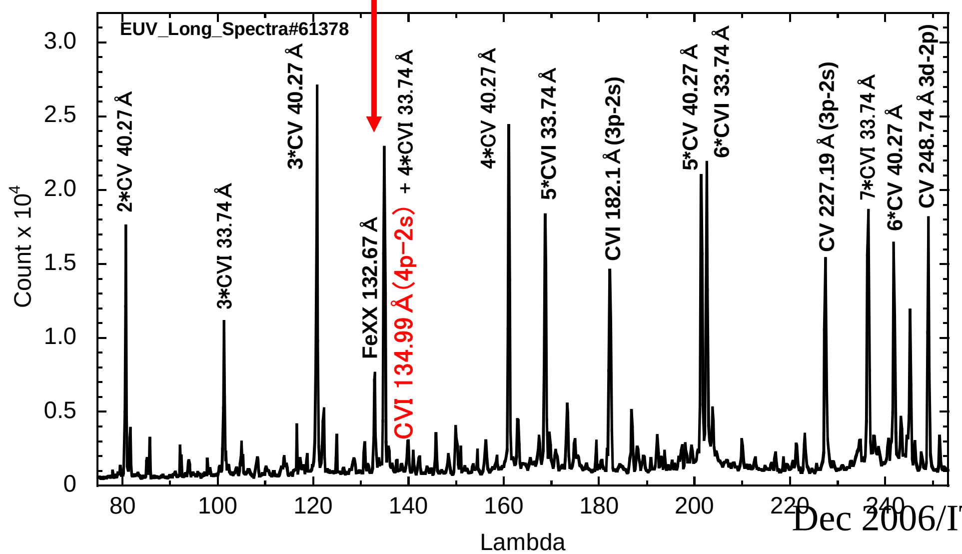


- In pinhole camera, brightness of the optical system is determined by the size of the detector , when we want keep the spatial resolution.
- We need to form image using some optical components in SX region if we want to avoid to use a larger detector.
- In pinhole system , contribution along the sight-line is constant. In optical-system, contrast is better at the focus point; better for fluctuation study

Reflectance of the multi-layer mirror



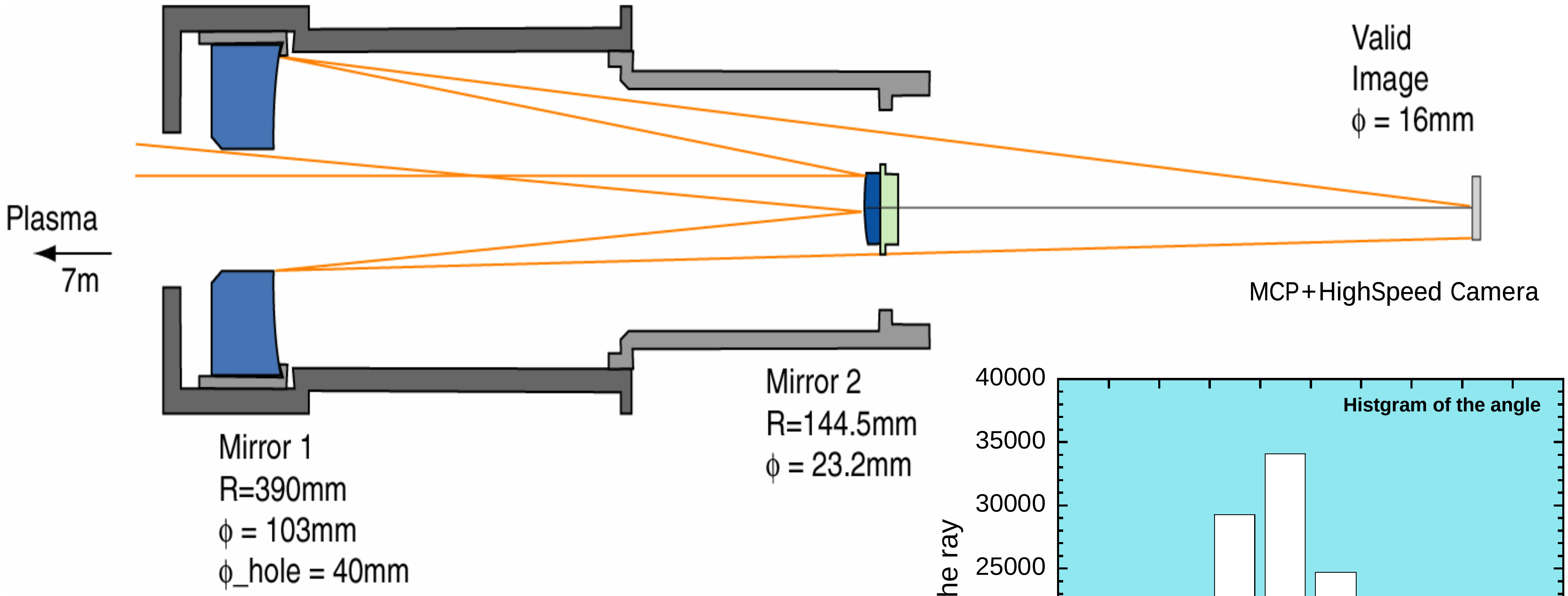
Hoshako,Vol9(1996) 2, p25



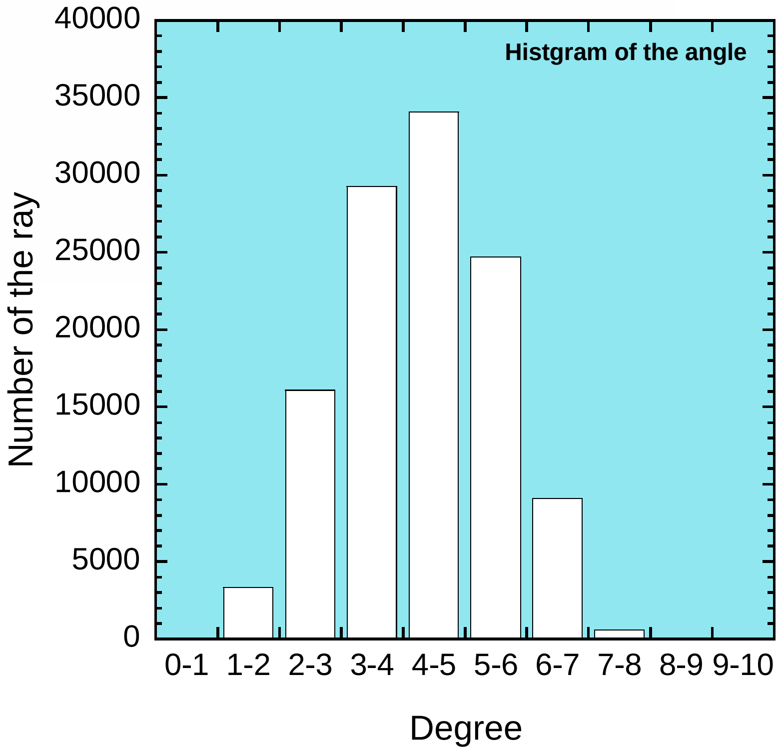
Measured by S. Morita

- The best reflectance can be obtained Mo/Be mirror (13.5 nm), which is available commercially. (EUV lithography for next stage)
- CVI(4p-2s) line emission (13.499nm) can be used.

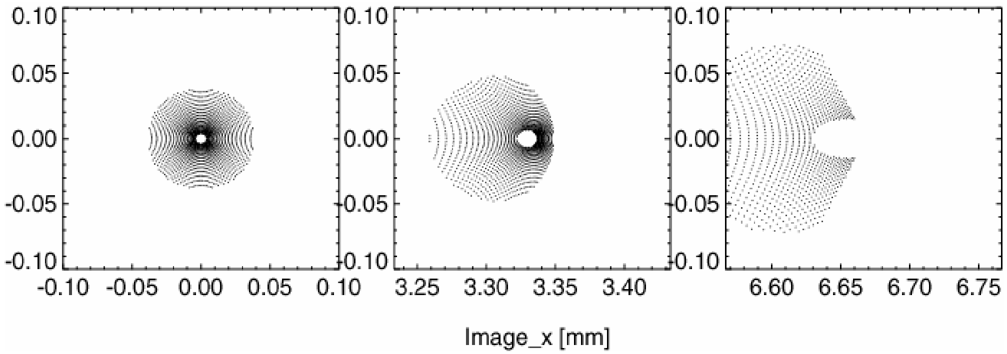
Telescope using Inverse-Schwarzschild optics

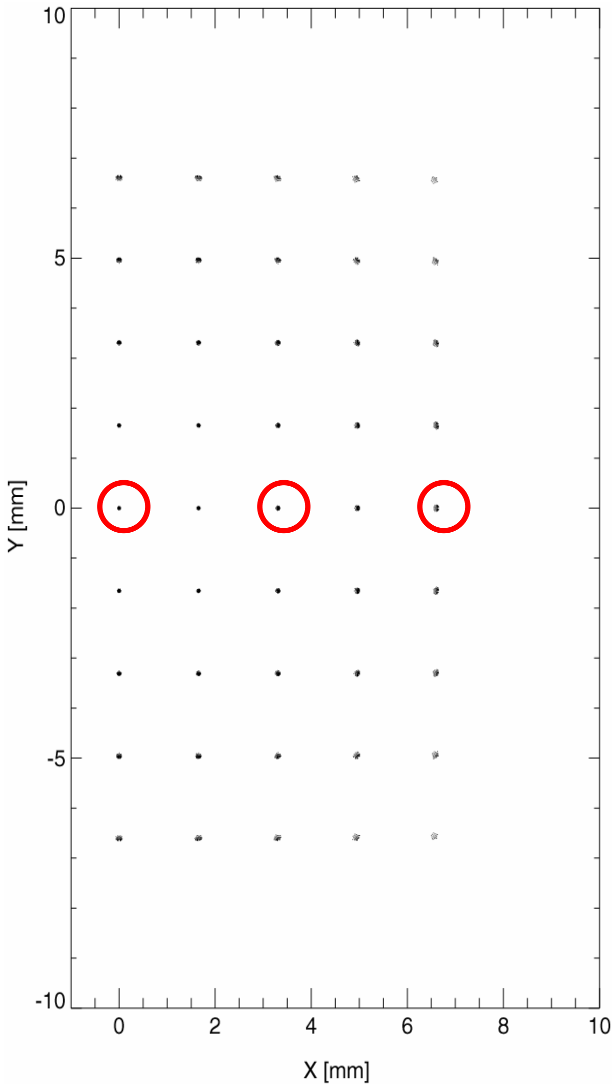


- Magnification is 1/60 in this design.
- Distance from the focal point to the object is 7000mm.
- Incident angle of the mirror is less than 9 deg. Consistent with the restriction of the multi-layer mirror.



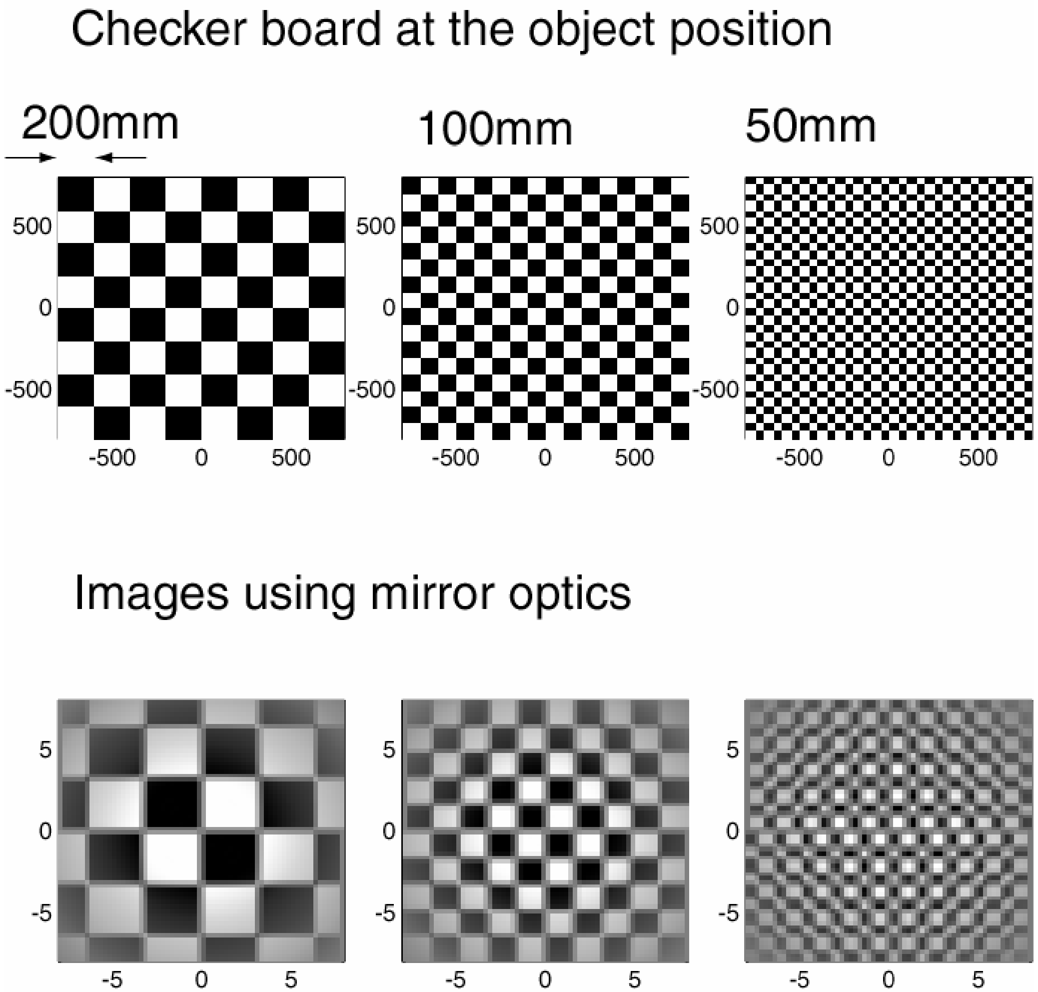
Spot diagram at the image plane



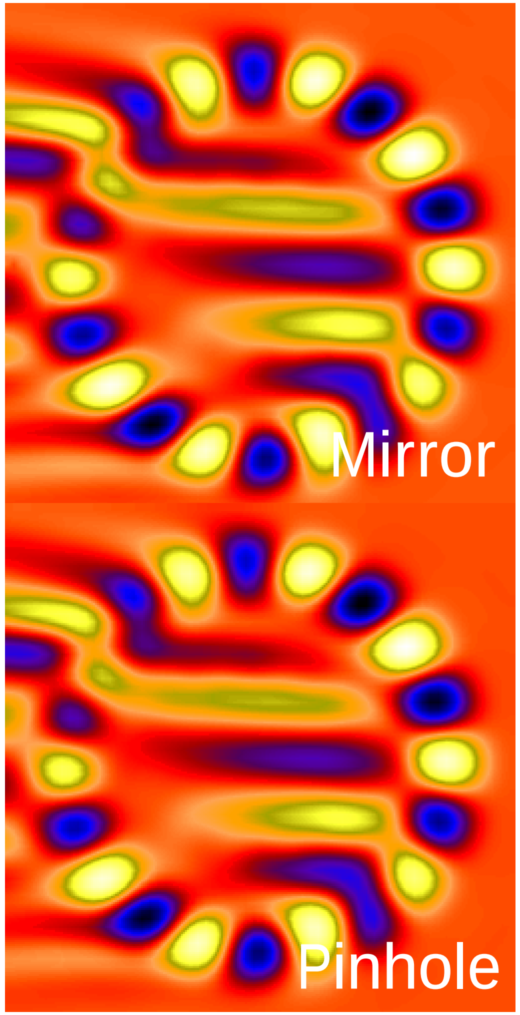


- Spot size is less than 0.05 mm at the center of the image.

Space resolution using mirror optics



TEXTOR Tokamak
R=1.75,a=0.45
r=0.225,m=10



- Fluctuations several mm in wavelength can be detected.
- Even line-integrated cases, poloidal mode number more than m = 10 (k ~1cm-1) can be detected.
- Spatial resolution is almost same with pinhole system.

Summary

- Tangentially viewing SX camera is useful tool for studying the complex phenomena, such as MHD instabilities.
- Spatial structure of the MHD events, e.g. sawtooth activity have been studied.

- Reconstruction of the image at a poloidal cross section is possible. However, it strongly depends on the equilibrium magnetic field. Measurements without the need for the reconstruction may by preferable.

- In order to study the smaller structure, VUV/SX telescope using multi-layer mirror system is being built. Spatial resolution will be improved since we do not need use imaging fibers.
- 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.
- Structure in the order of mm can be detected with the present design of the telescope.

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