球状トカマクにおけるMHD事象の解析
Analysis of MHD events in spherical tokamaks

東条寛、山口隆史

東京大学新領域創成科学研究科

H. Tojo, T. Yamaguchi,
M. Gryaznevich[a], A. Ejiri, Y. Takase, Y. Adachi, T. Oosako, S. Kainaga,
J. Sugiyama, M. Sasaki, T. Masuda

Graduate School of Frontier Sciences, The University of Tokyo Kashiwa, Japan
[a] *EURATOM/UKAEA Fusion Association, Culham Science Centre, OX14 3DB, UK*

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What is an Internal Reconnection Event (IRE)?

❑ **IRE is a very common instability observed in Spherical Tokamaks**

❑ **Three-dimensional resistive MHD simulations:**

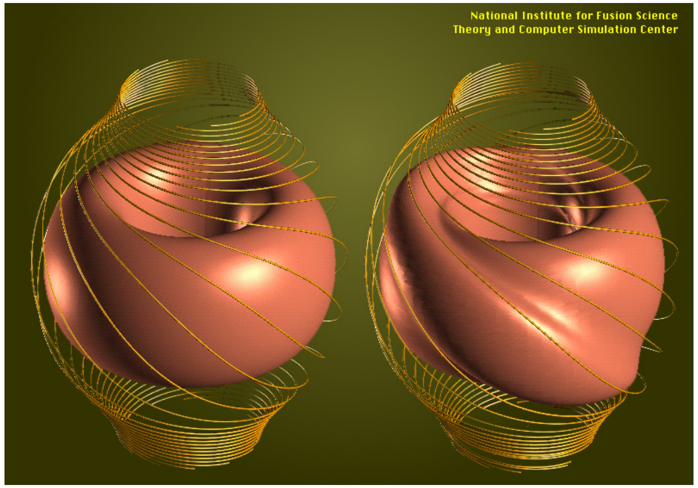
Naoki Mizuguchi, Takaya Hayashi, Phys. Plasmas, **7**, 940 (2000)

1. Plasma deformation

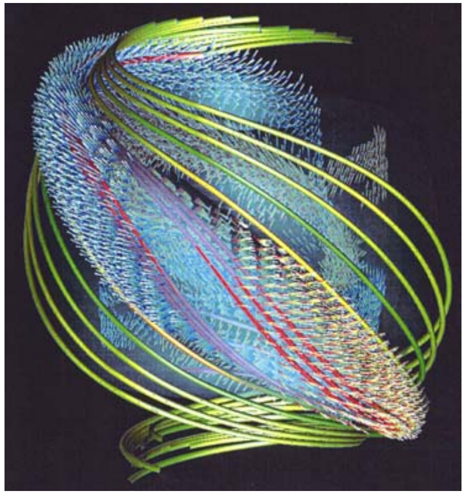
- IRE is a magnetic reconnection between inside and outside magnetic flux

2. During IRE plasma energy is lost along field lines through fast parallel transport

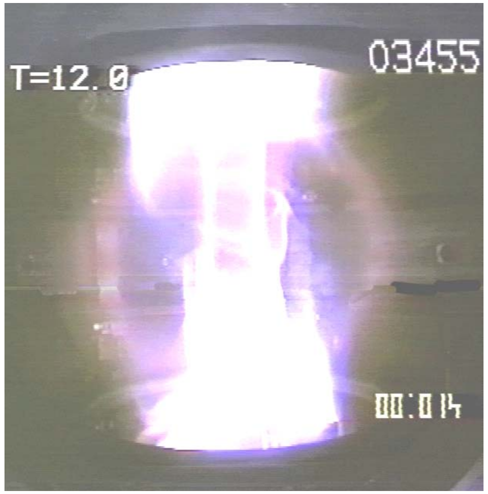
Plasma deformation



Energy flow

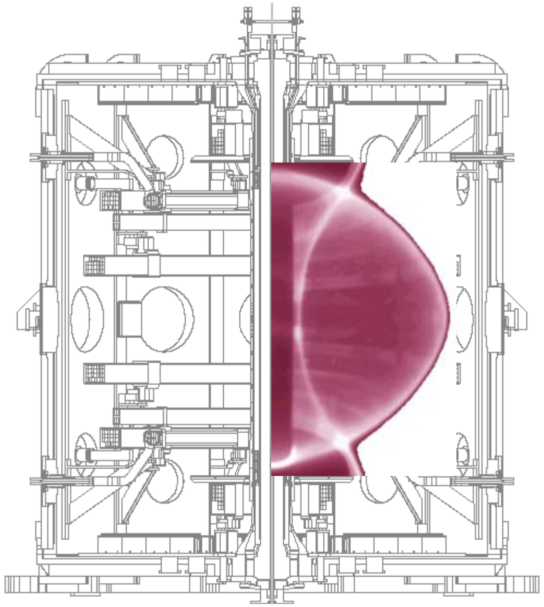


CCD picture, START



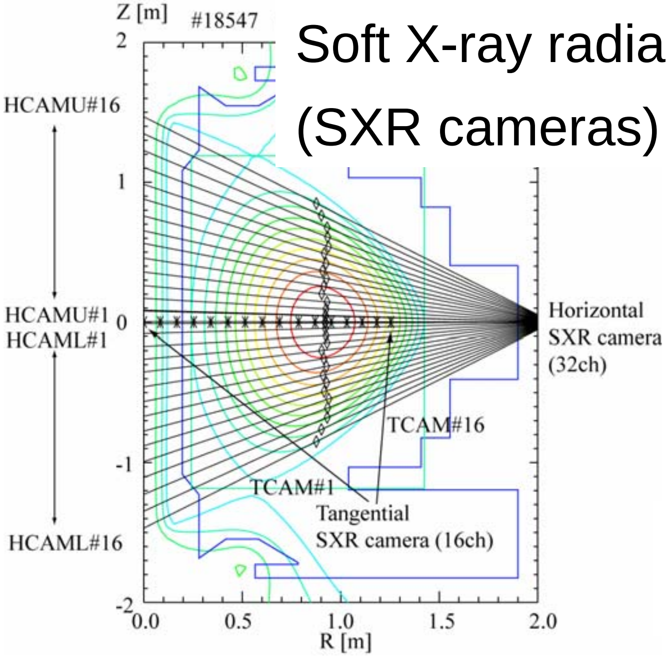
❑ Helical deformation, followed by reconnection, is caused by **linear and non-linear** growth and coupling of **pressure-driven** modes

Mega Ampere Spherical Tokamak (MAST)



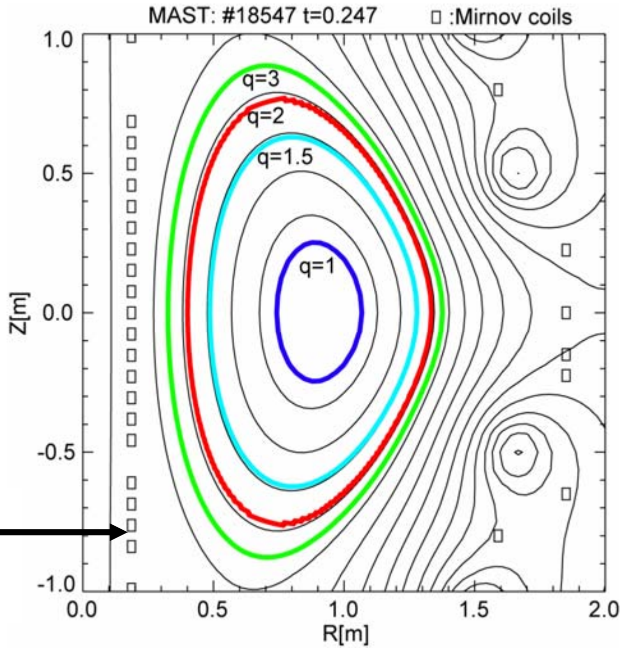
MAST parameters

- R_0 (Major radius)~0.85m
- a (Minor radius)~0.65m
- A ($=R_0/a$)>1.3
- I_p<1.5MA
- pulse length ＜0.7s
- β_t (toroidal beta)<17%



Soft X-ray radiation cameras

(SXR cameras)



Position of the Mirnov coils at a poloidal section

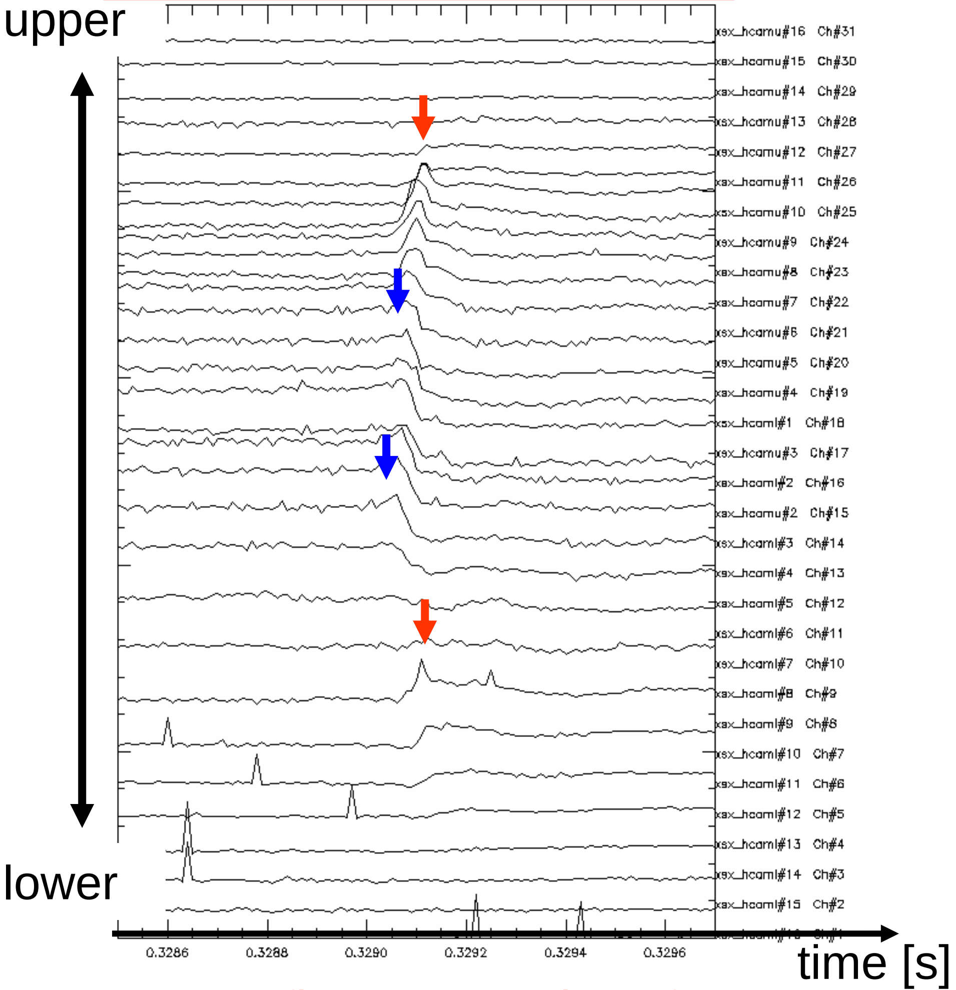
Objective of the IRE study

- ❑ **To Isolate unique physics of IREs (in contrast to sawteeth, etc.)**
    - ❑ SXR cameras and Mirnov coils are used to study mode structure

- ❑ **To investigate the drive of this instability (is it pressure driven, as predicted by theory? or not)**
    - ❑ Pressure profile evolution studies before the reconnection
    - ❑ need to classify first sawtooth, mode coupling and energetic particle mode.

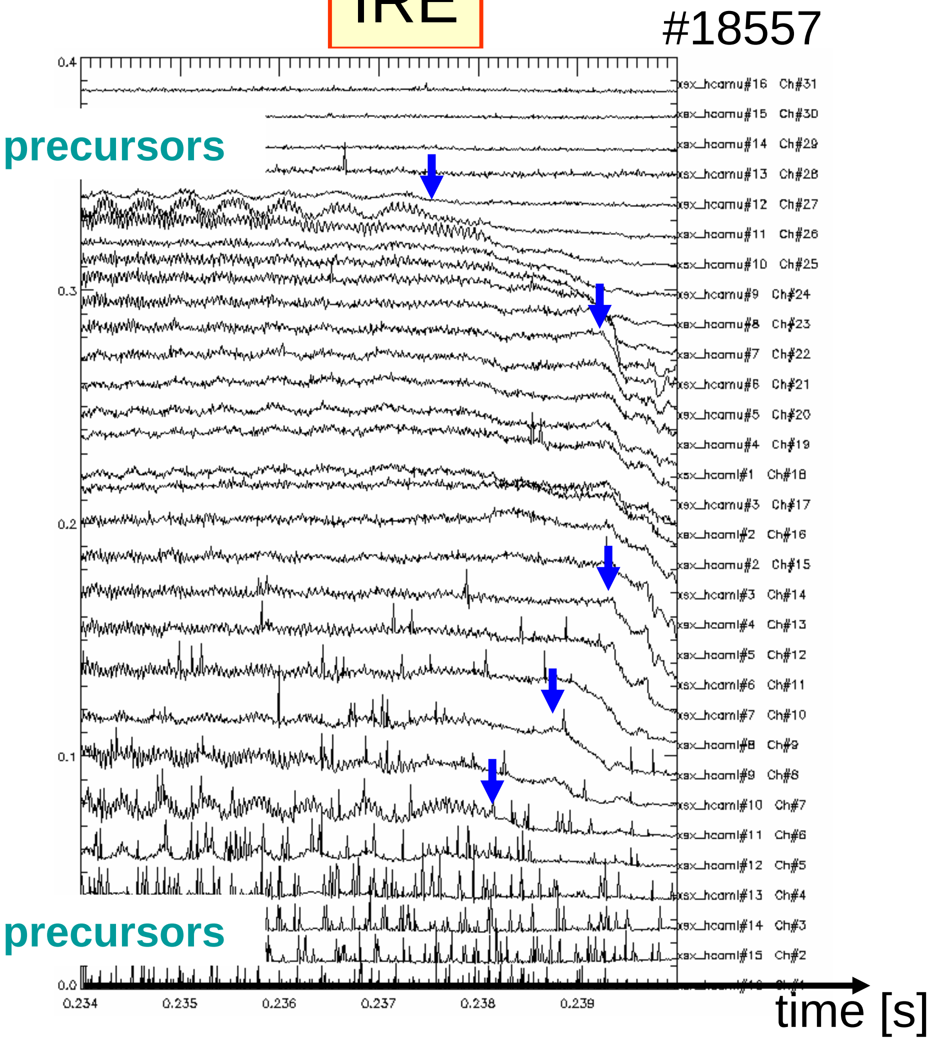
Difference between sawtooth oscillation and IRE

Sawtooth oscillation



SXR profile: propagation of decrease **from the core** (q=1)

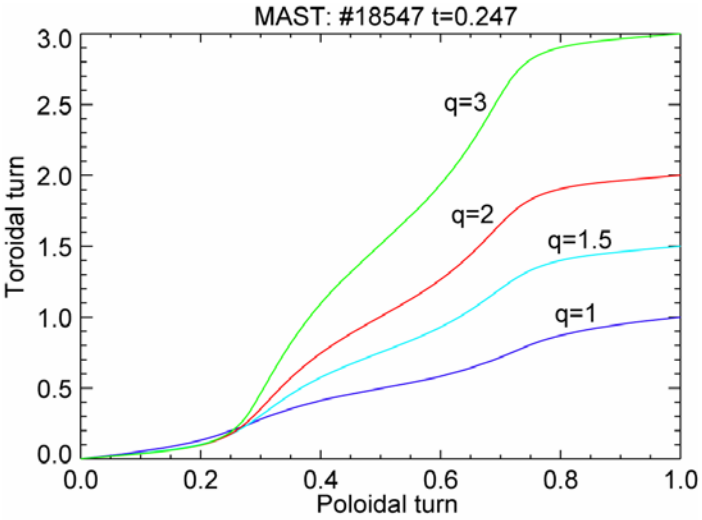
IRE



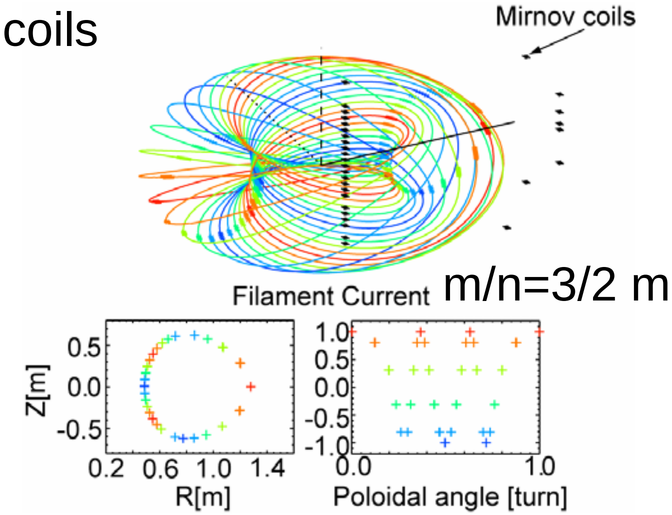
SXR profile: some precursors, propagation **from the outside to the core**

Three dimensional poloidal mode analysis

Trajectories of magnetic lines at rational surfaces (EFIT)



Distributed filaments along the magnetic lines for calculation magnetic fields at Mirnov coils



m/n=3/2 mode

finding best fit for signals of Mirnov coils (B_z)

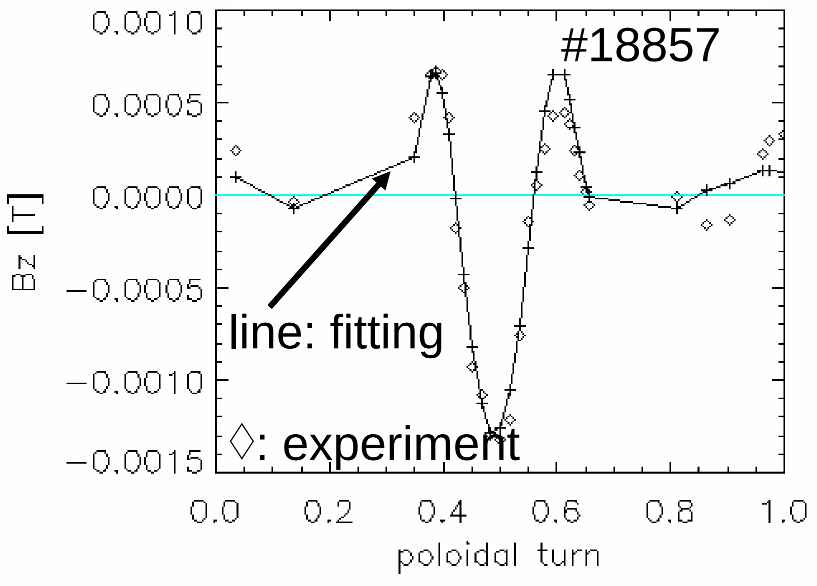
signals of Mirnov coils (B_z)

↔

Parameters:

- Toroidal position of unique filaments (ϕ_{offset})
- Maximum current of filaments (I_{fil})

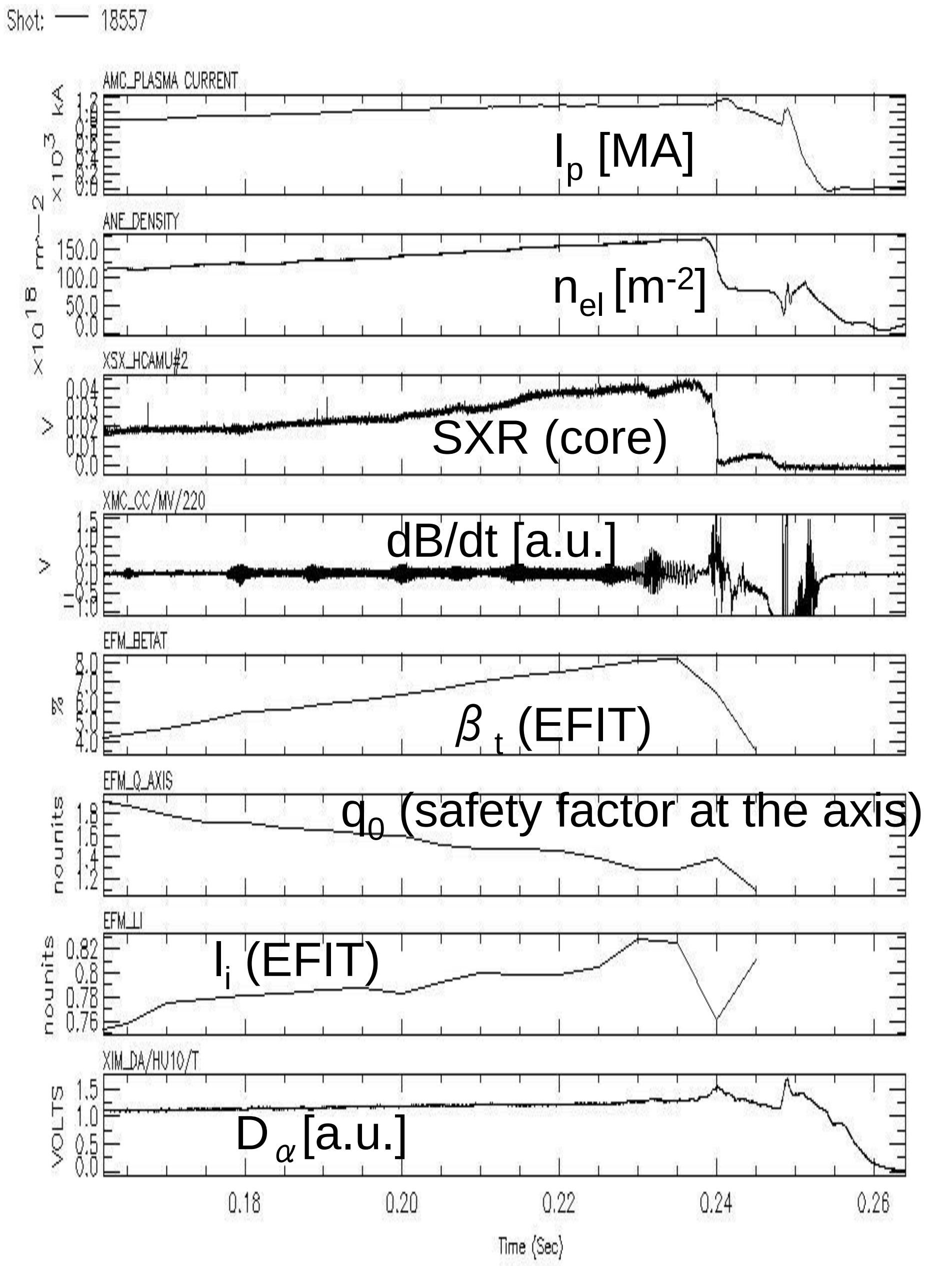
2/1 mode, t=0.23215s

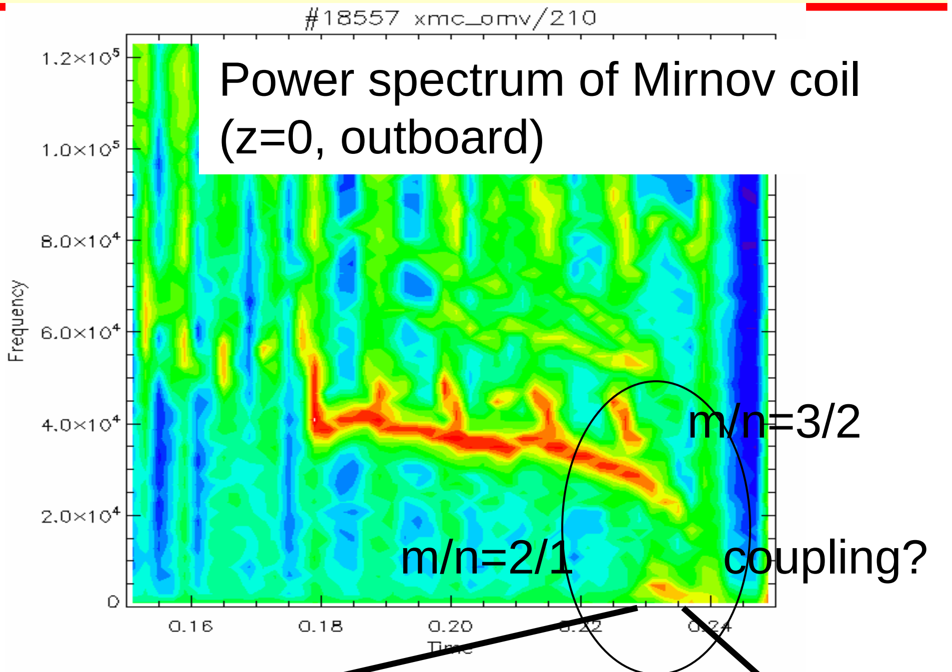


line: fitting

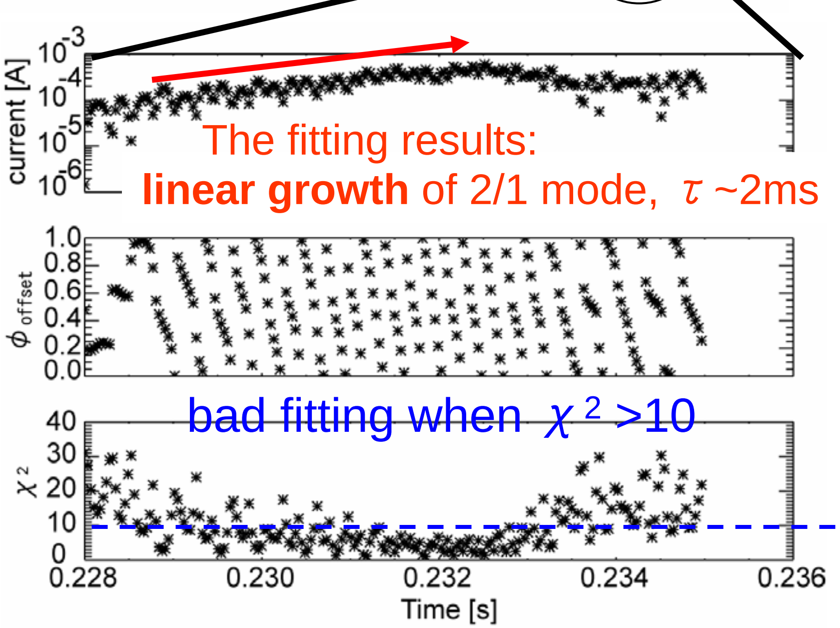
◊: experiment

Major IRE: time evolution of the precursors





Power spectrum of Mirnov coil
(z=0, outboard)



The fitting results:
linear growth of 2/1 mode, τ ~2ms

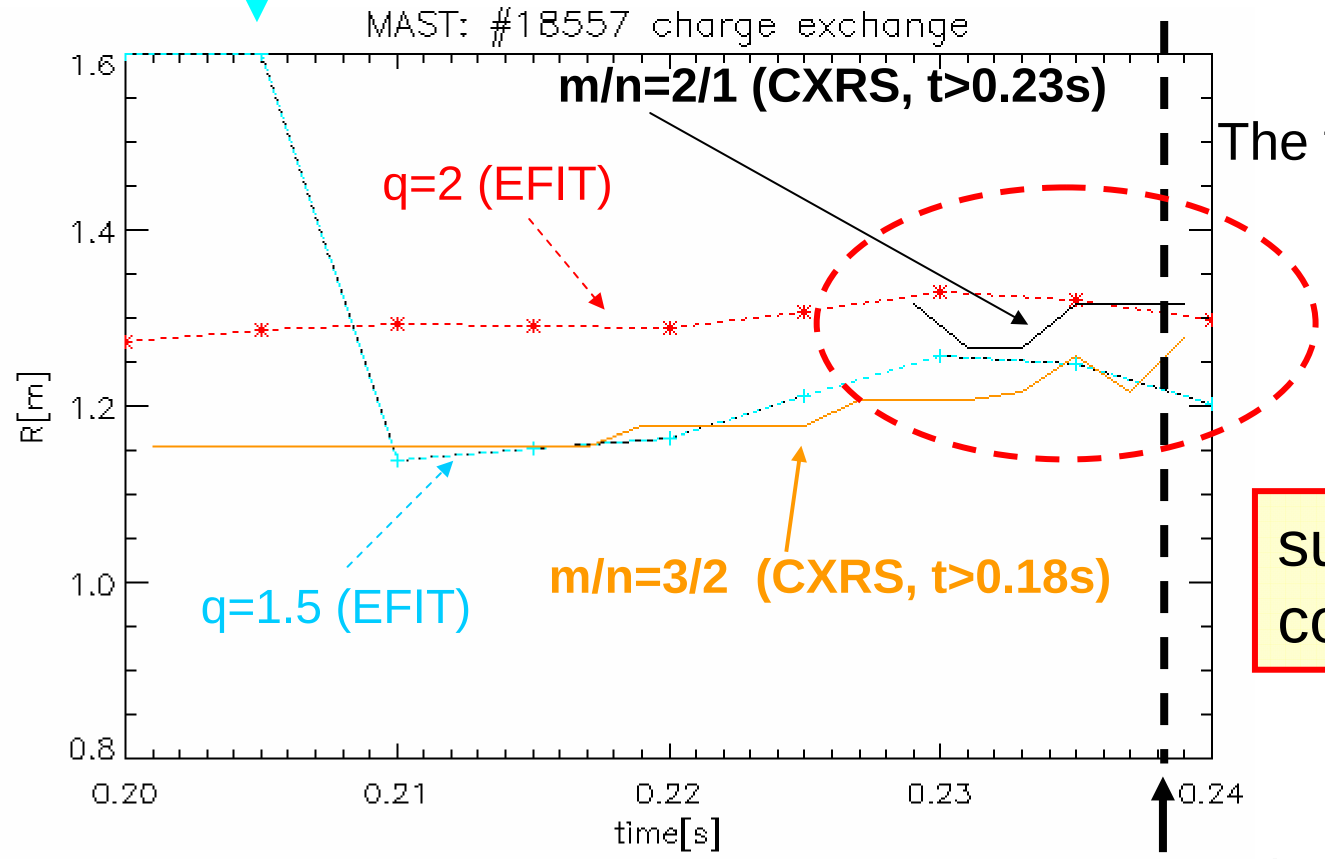
bad fitting when $\chi^2 > 10$

mode positions from CXRS (preliminary results)

no q=1.5 surface on the EFIT results

For the 2/1 and 3/2 modes, radial positions are calculated by toroidal speed and frequency of the signal of Mirnov coils

NOTE: ignoring poloidal rotation



m/n=2/1 (CXRS, t>0.23s)

q=2 (EFIT)

q=1.5 (EFIT)

m/n=3/2 (CXRS, t>0.18s)

The two mode approach

suggesting mode coupling

collapse starting on SXR

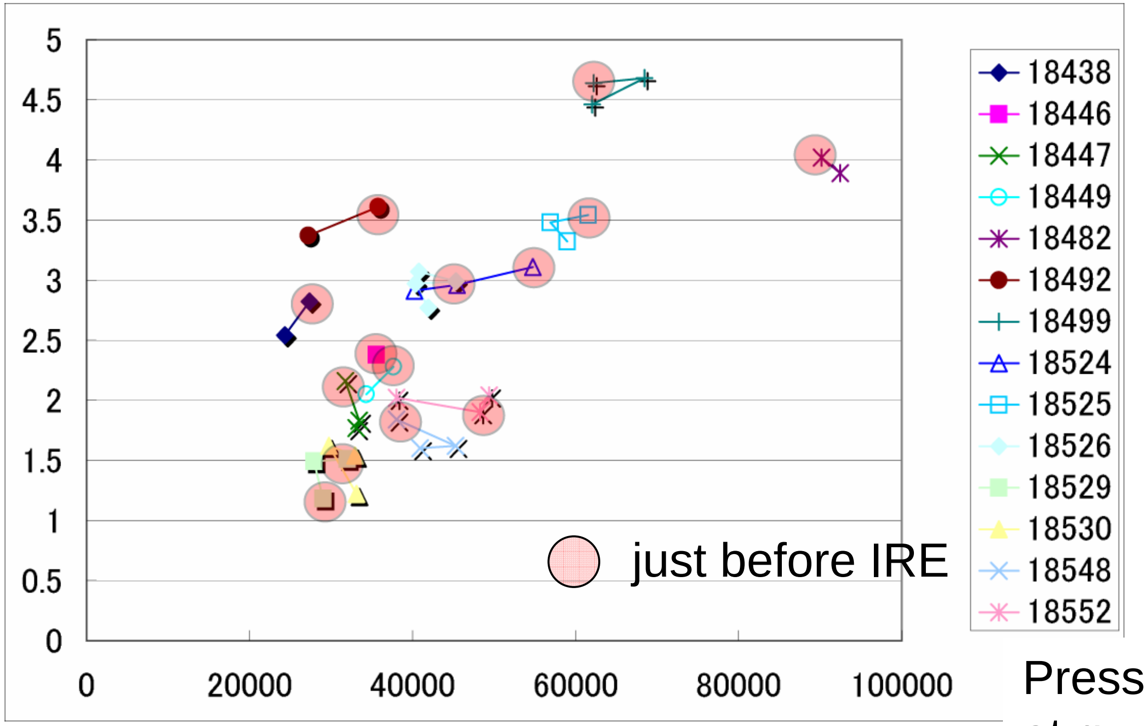
- ❑SXR profile also shows co-existence of 2/1 and 3/2 mode

IRE drive: pressure-driven modes?

- Critical pressure gradient has been measured using kEFIT[1] in discharges

Magnetic shear

$$S = \frac{r}{q}\frac{dq}{dr}$$



Pressure gradient at q = 2

Critical pressure gradient at q = 2 increases with magnetic shear suggesting pressure-driven nature of IREs

[1] L.C. Appel et al., Nucl. Fusion **41** (2001) 169.

Summary for IRE study

- ❑ Difference between IRE and sawtooth oscillation can be identified in the propagation of decrease on SXR profile.

- ❑ Comparison with the three dimensional MHD simulation
  - ❑ **linear growth**: 2/1 mode confirmed, τ ~2ms
  - ❑ **non-linear growth**: directly not confirmed, but close co-existence of 2/1 and 3/2 mode. (CXRS and SXR profile)

- ❑ Pressure profile evolution suggest stability effect of shear at q=2

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  - ❑圧力分布の時間発展

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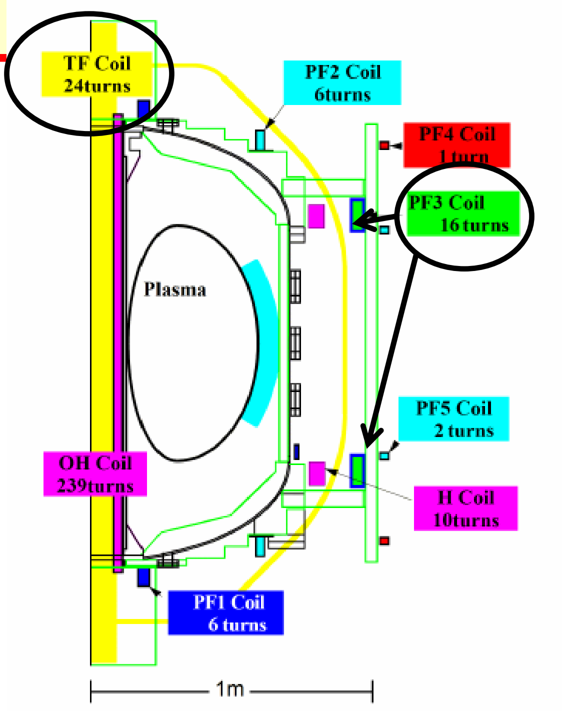
球状トカマクTST-2

	通常放電	ECH startup
大半径	R～ 0.38 m	
小半径	a ～ 0.25 m	
アスペクト比	A～ 1.5	
トロイダル磁場	B_t ～ 0.3 T	～ 0.1 T
プラズマ電流	I_p ～ 120 kA	～ 1.5kA
放電時間	Δt ～ 20 ms	～ 100 ms

コンパクトな核融合炉である球状トカマクではCSを除去する必要がある。

電子サイクロトロン波による
プラズマの生成と維持
加熱装置：マグネトロン
2.45 GHz, 5kW

ECH start-up



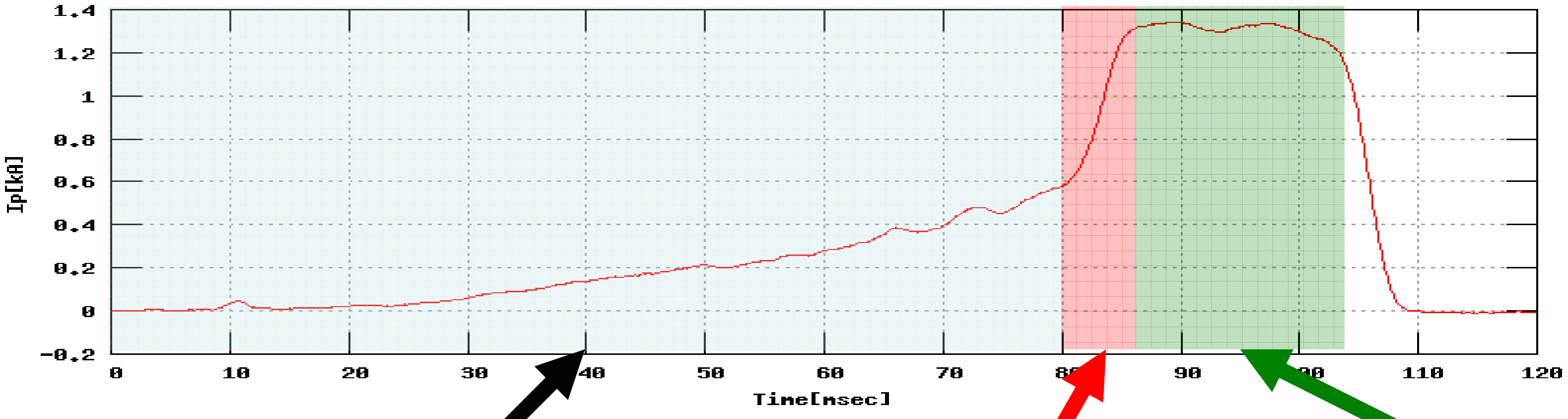
❑ 目的

プラズマのマクロな変形を画像から解析し、
電流ジャンプを研究する。

❑ 実験条件

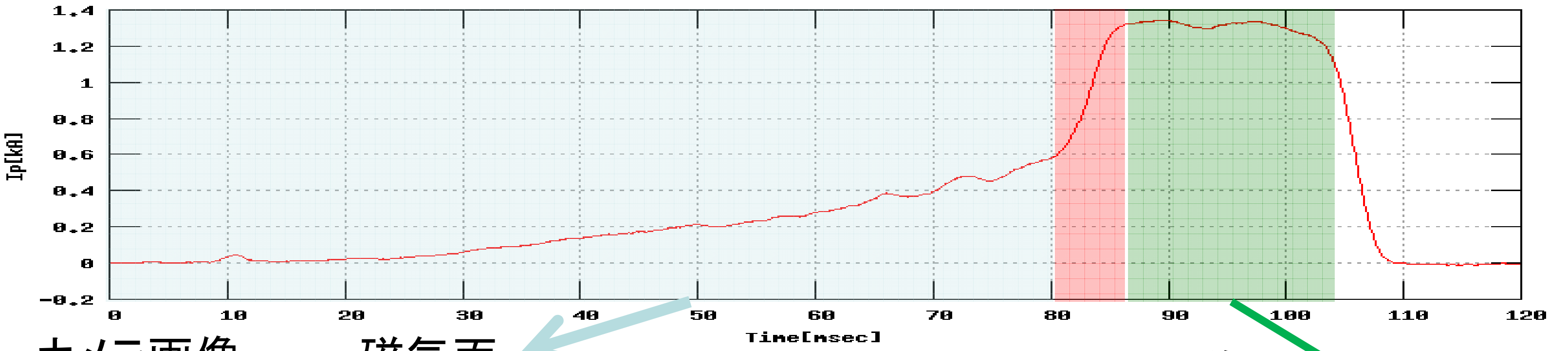
PF3を使用して立ち上げ

CCDカメラ 2000fps（可視光領域）

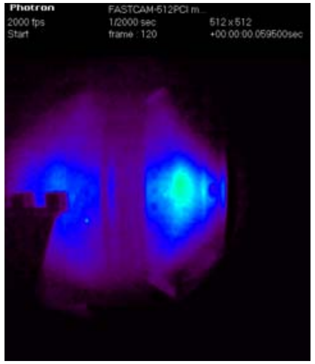


開いた磁気面　電流ジャンプ　閉じた磁気面

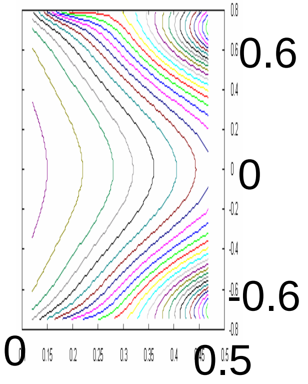
磁気面の様子



カメラ画像

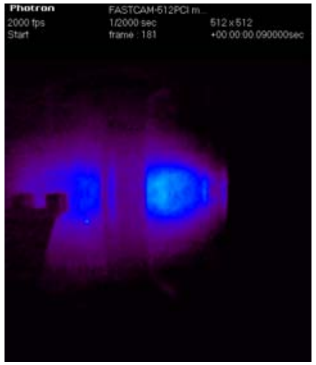


磁気面

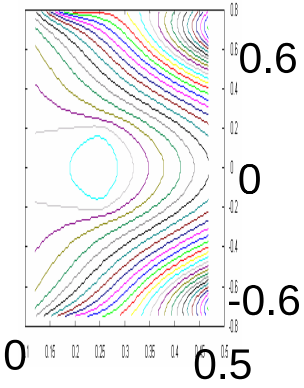


電流
ジャンプ

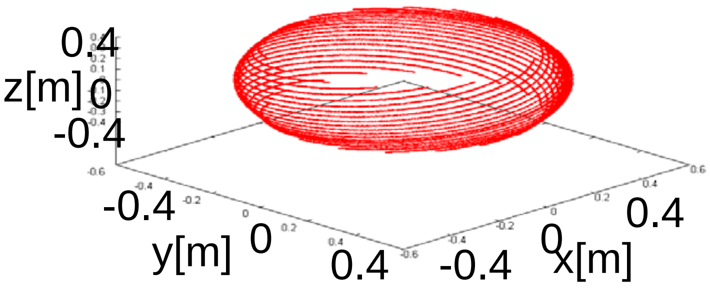
カメラ画像



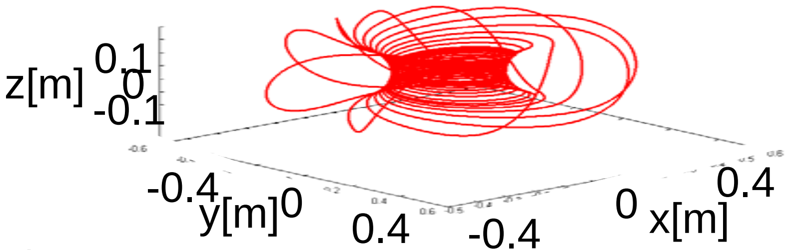
磁気面



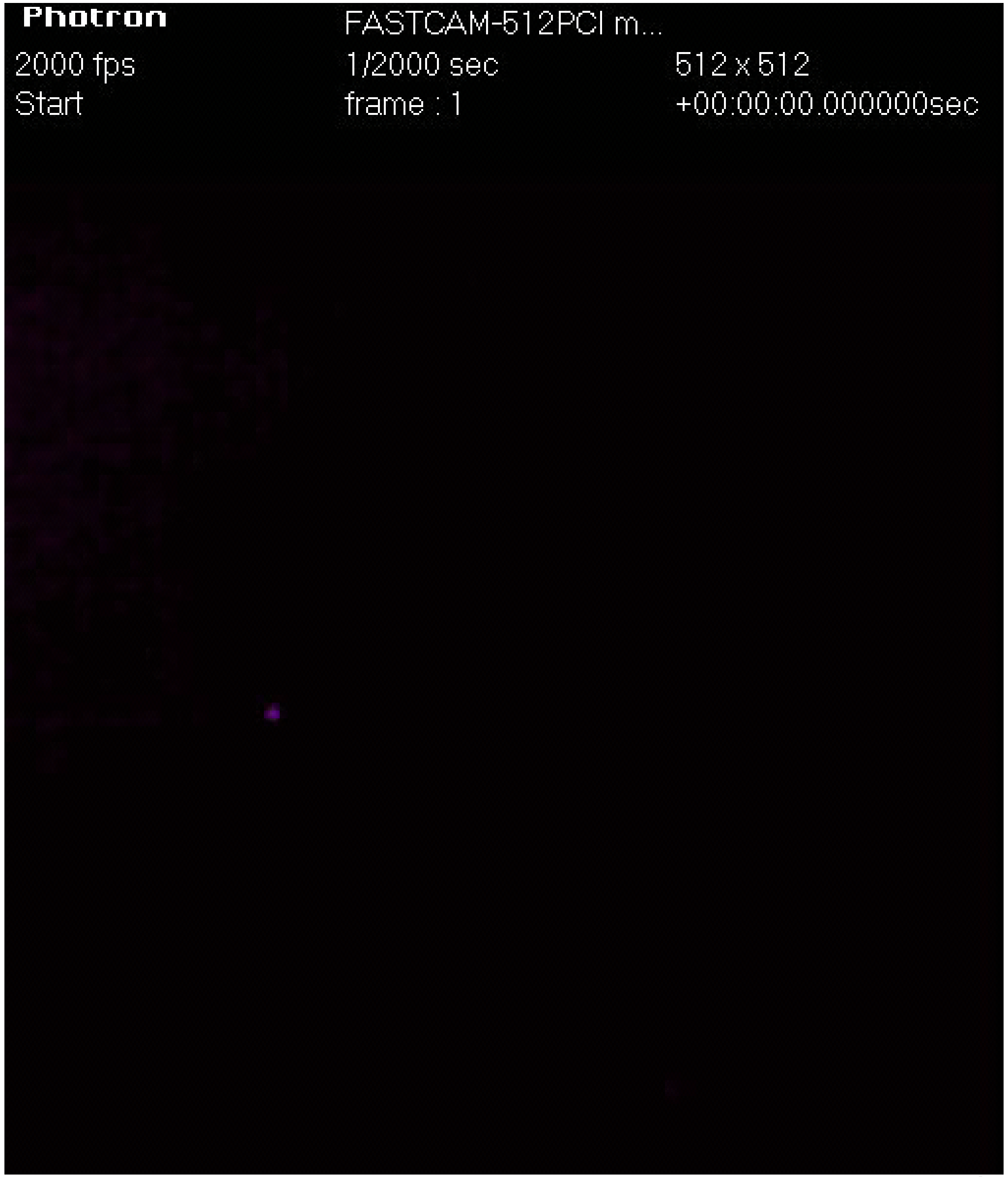
捕捉電子の軌道

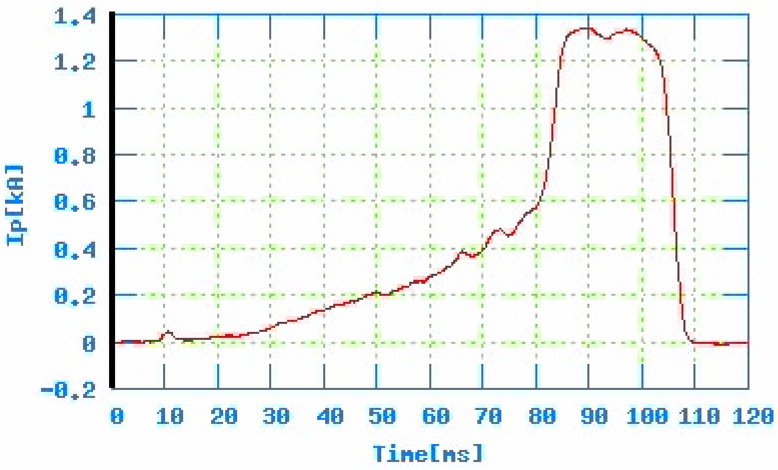


非捕捉電子の軌道

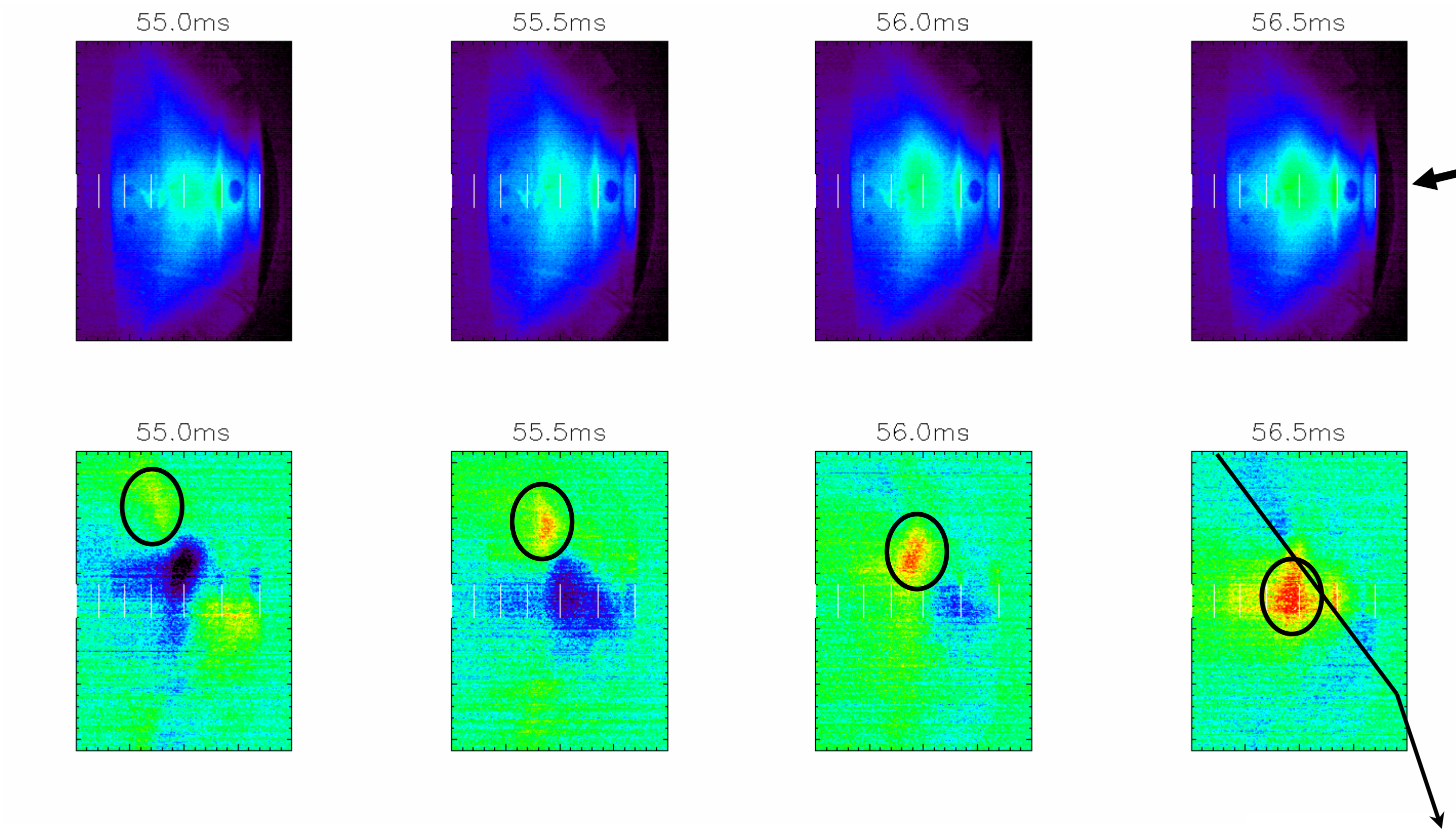


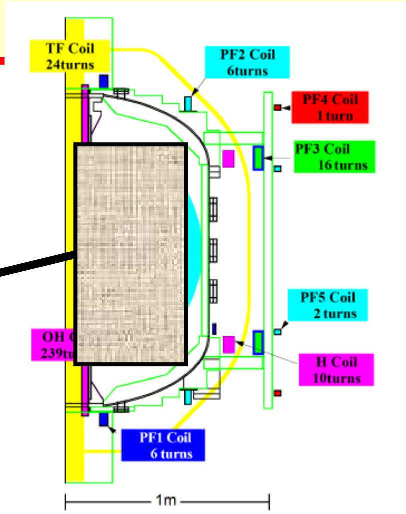
カメラ画像

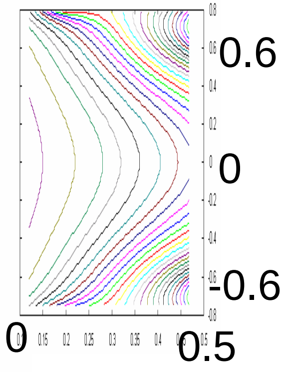

Photron
FASTCAM-512PCI m...
2000 fps
1/2000 sec
512 x 512
Start
frame : 1
+00:00:00.000000sec


Ip[kA]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
10
20
30
40
50
60
70
80
90
100
110
120
Time[ms]

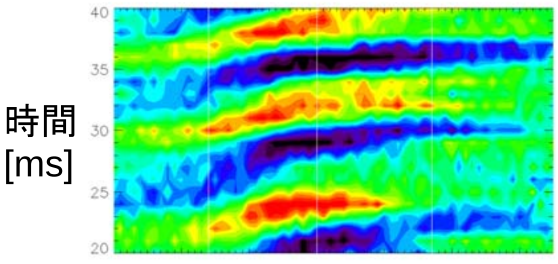
電流ジャンプ前の揺動





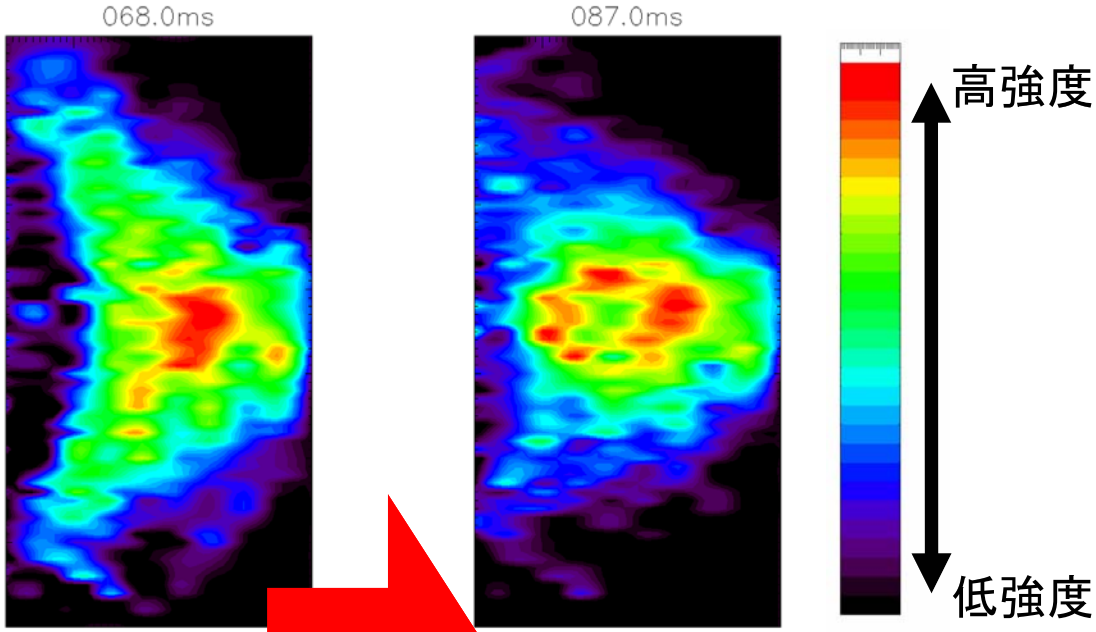


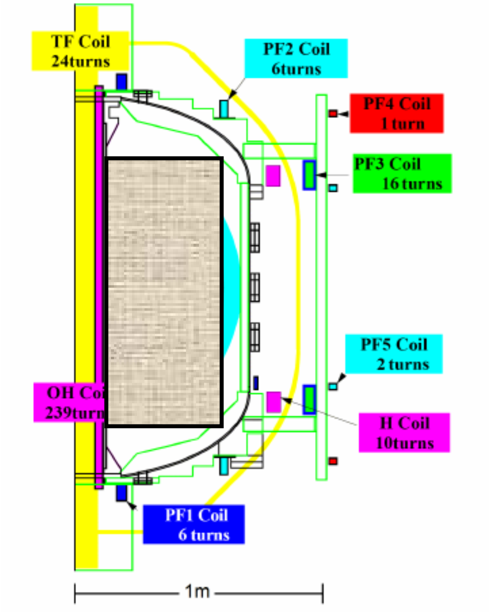
プラズマが磁気面を横切りながら、外側に向かって移動する。
電流ジャンプ時の構造形成に影響を与えている。



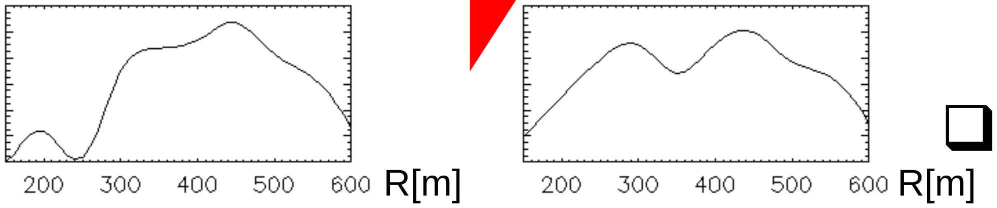
揺動の時間変化

ポロイダル断面（abel変換による像再生）





電流ジャンプ



赤道面の発光強度分布

- □ 三角形の形状から円形に変形している。
- □ 電流ジャンプ後の断面では中心の放射強度が弱くなっている。

TST-2 における ECH start-up 実験のまとめ

- 電流ジャンプ前後の画像を解析し、それぞれについて以下のことがわかった。

□ 電流ジャンプ前

- 磁気面が開き、プラズマの形状はアーク状の構造を伴う三角形の構造をしている。
- プラズマの揺動が、磁気面の形成に深くかかわっている可能性がある。

□ 電流ジャンプ後

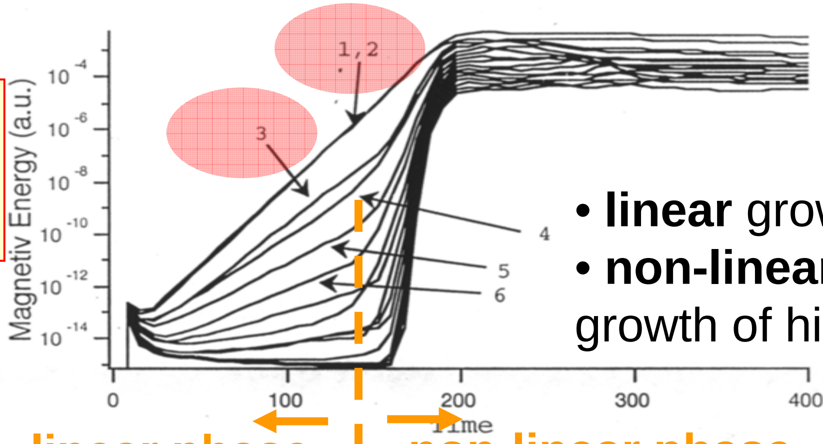
- 磁気面が閉じ、プラズマのポロイダル断面は円形に変化している。
- 揺動がなく、安定している。

Three different cases have been analyzed by Hayashi:

- **Three-dimensional resistive MHD simulations, 3 different cases:**

Case 1:

high-β, q(0) < 1

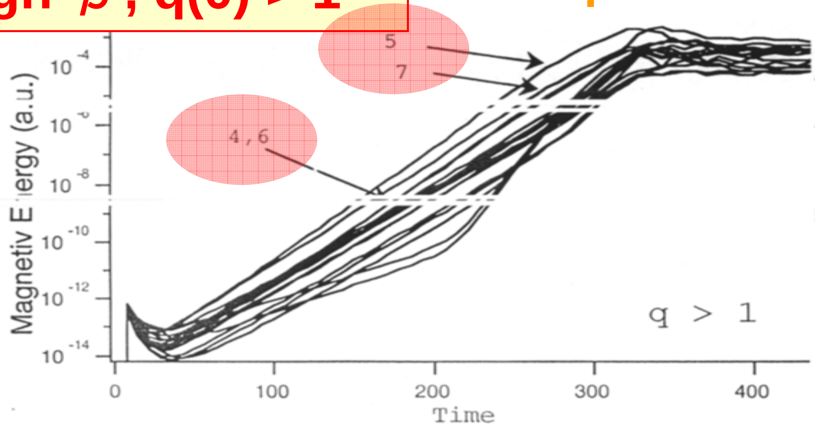


- **linear** growth of low-*n* modes
- **non-linear** coupling and fast growth of high-*n* modes

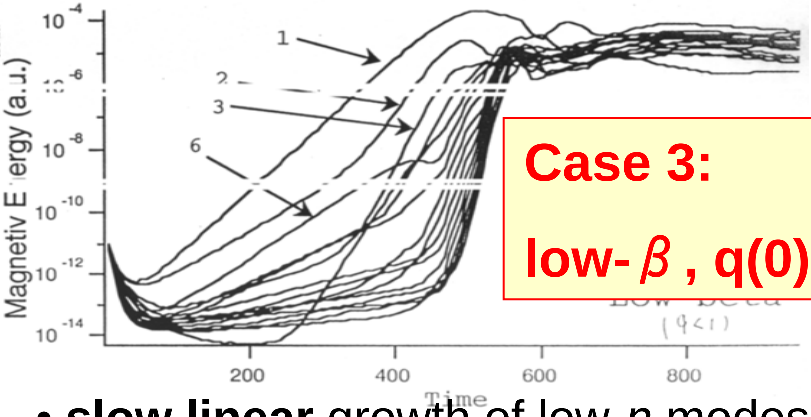
linear phase **non-linear phase**

Case 2:

high-β, q(0) > 1



- **slow linear** growth of high-*n* modes



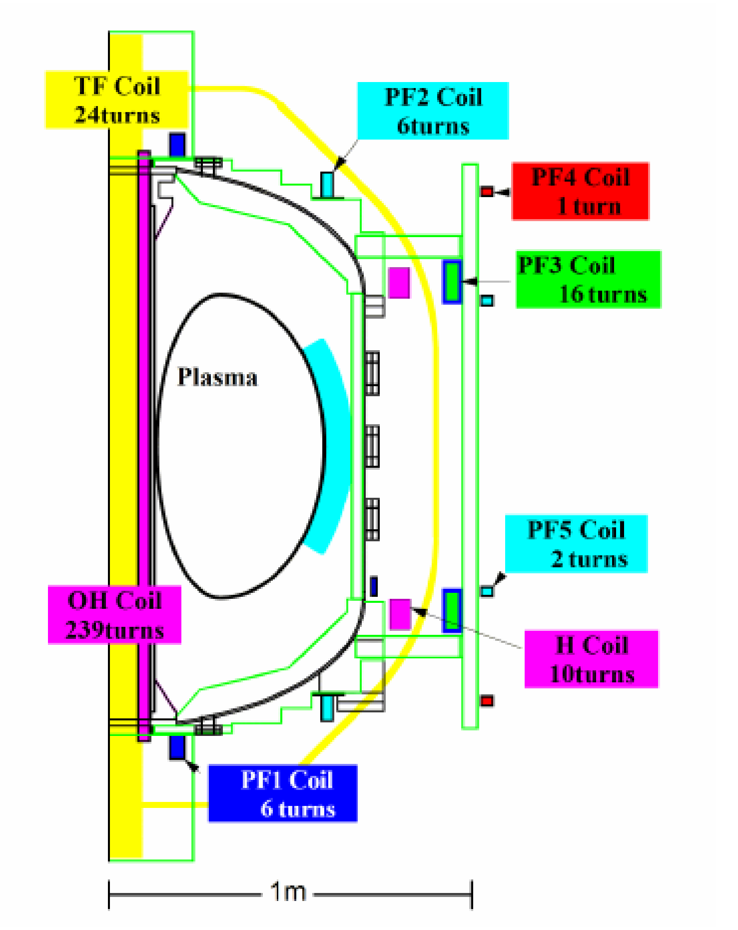
Case 3:

low-β, q(0) < 1

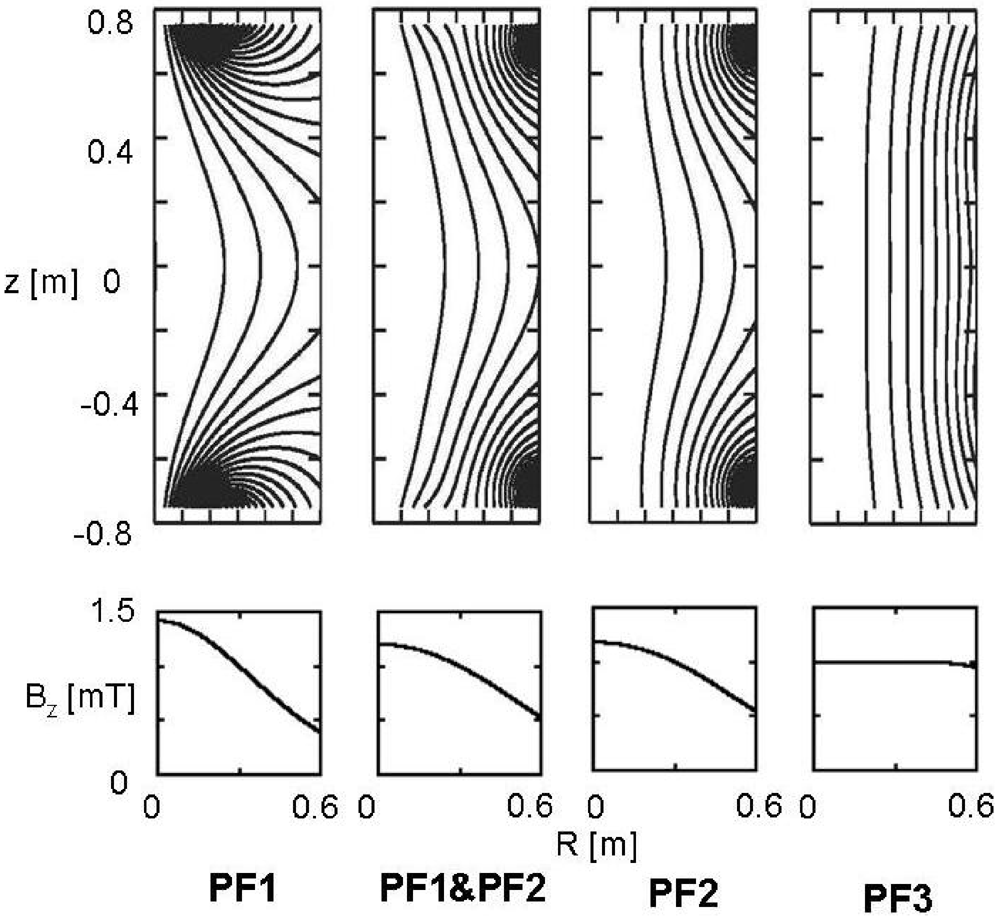
- **slow linear** growth of low-*n* modes
- **non-linear coupling** and **fast growth** of high-*n* modes

- **We compare these simulation with MAST experimental results**

PFコイル磁場配位



装置断面図

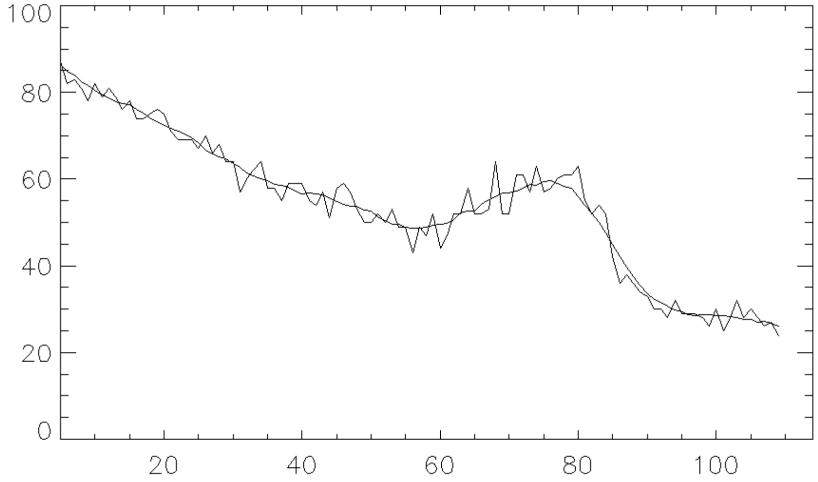


等ポロイダル磁束面
（磁気面）

H.Tojo, T.Yamaguchi, JAEA若手研究会, 17-19/03/2008, Naka

可視化のための構造物除去

- 発光強度の揺動の抽出方法



- ポロイダル断面図の構成方法

一定の範囲の最小値より代表点を抽出

Abel Inversion

Spline 補間