New insight into the physics of the "sawtooth oscillation" via 2-D visualization

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at

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(Advanced Imaging and Plasma Physics)

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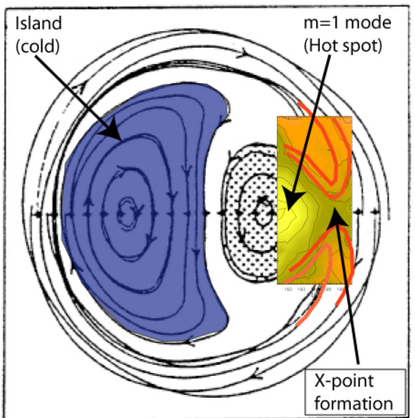
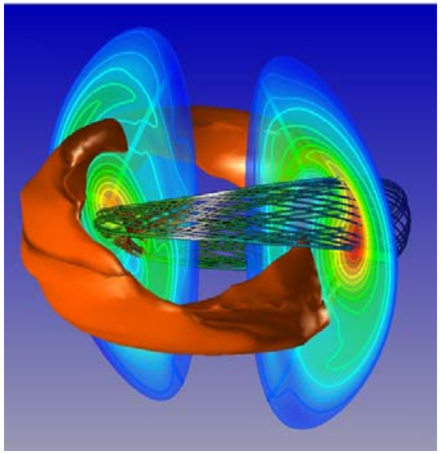


Comparison with the full reconnection model simulation result at the low field side



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2-D visualization in plasma physics

- Experimental verification of the hypothesis and assumptions is essential for the advancement of science

- Comprehensive visualization is the best tool for the verification of complex phenomena in science

Talk

- Magnetic reconnection process of the m/n=1/1 mode ("sawtooth oscillation") in hot plasmas
  - Brief background of the magnetic reconnection process
  - Prominent theoretical models for the "sawtooth oscillation" for the last ~30 years
- Visualization of T_e fluctuations in high temperature plasmas for the fundamental physics of the complex plasma dynamics
  - High resolution (temporal and spatial) 2-D images
- New insight into the physics of the "sawtooth oscillation" via 2-D visualization
  - New findings of the physics of "sawtooth oscillation" (*PRLs, **96**, 195003 & 195004, '06* and PoP, **13**,55907, '06)
  - 3-D random localized reconnection process

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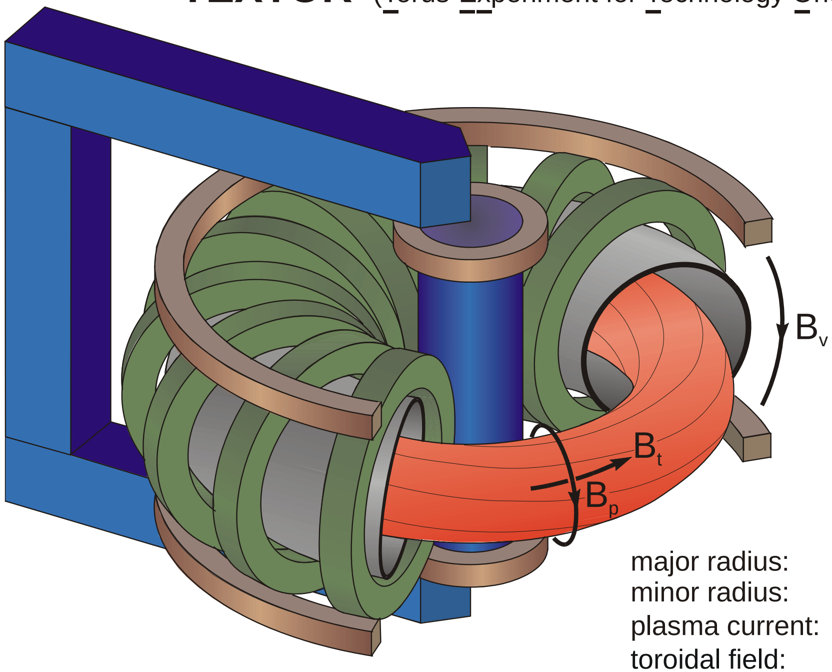
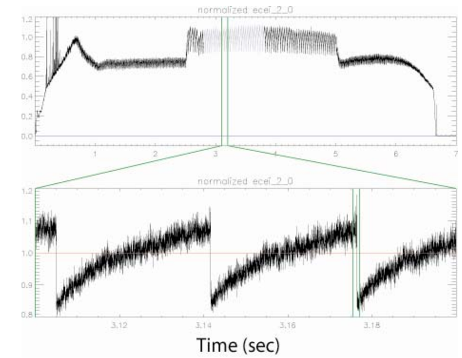
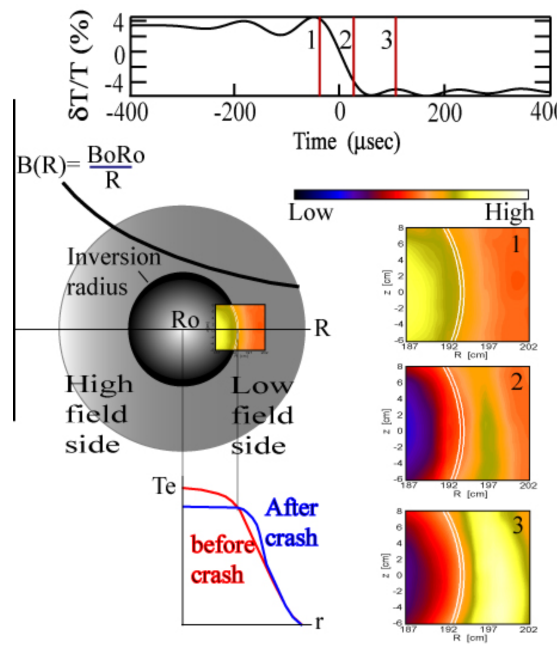
Classical m/n=1/1 instability (sawtooth oscillation)

TEXTOR (Torus-Experiment for Technology Oriented Research)





major radius:	1.75 m
minor radius:	0.50 m
plasma current:	≤ 0.5 (0.8) MA
toroidal field:	≤ 2.8 T
pulse length:	≤ 10 sec



- Sawtooth oscillation is a magnetic self-organization via reconnection

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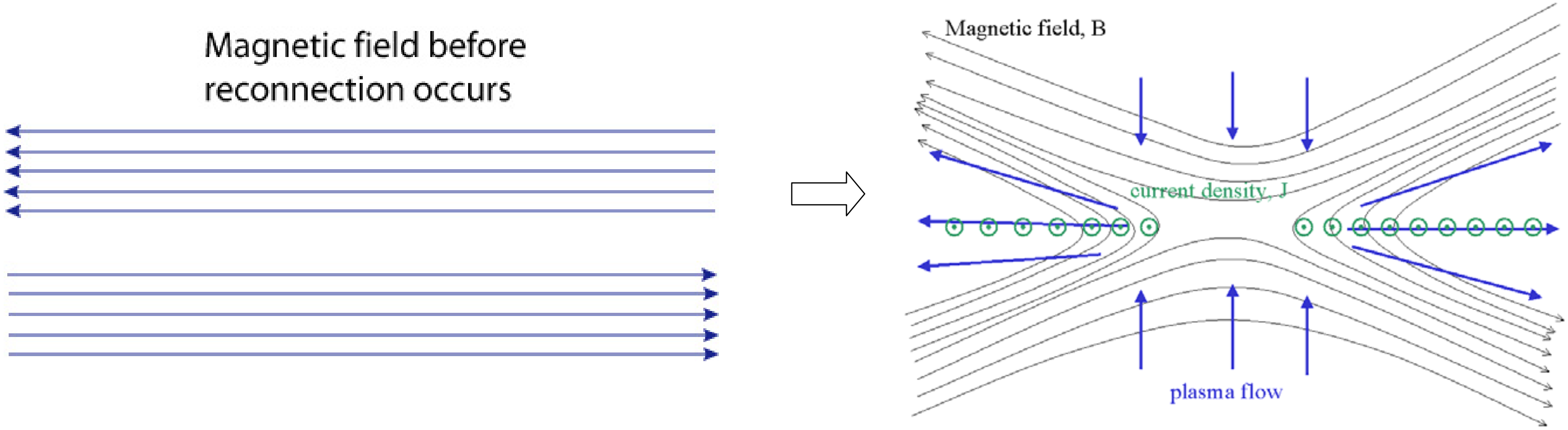
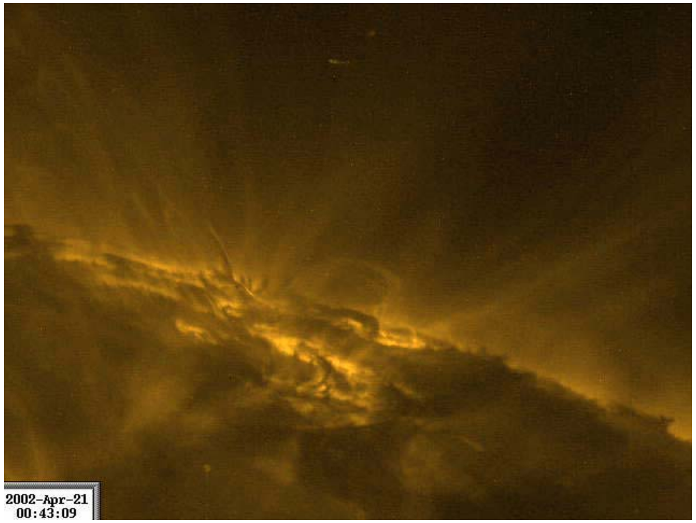
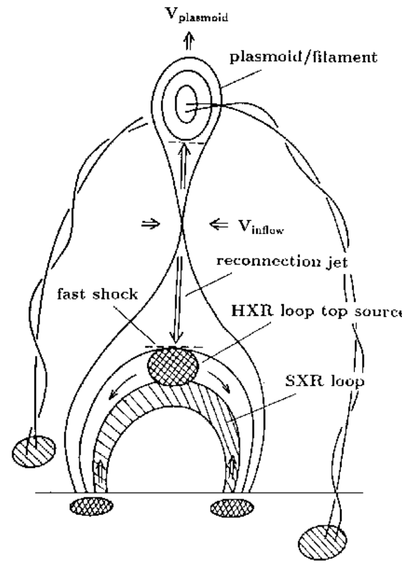
What is the magnetic reconnection process?

- *Topological changes of magnetic domain occur when two magnetic surfaces with an opposite direction are merged*
- *Once the reconnection process takes place, the speed is an order magnitude faster than theoretical model derived from the first principle*
  - *Magnetic energy can be removed and plasma pressure can be redistributed through the modified local magnetic lines*
  - *Electron temperature is known to be well tied to the magnetic field line*



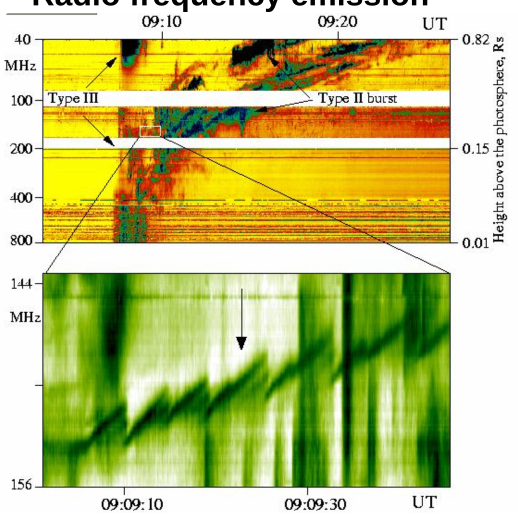
Reconnection process phenomena





Discovery of Loop top HXR source led to Unified model (Shibata et al 1995)

Radio frequency emission



Klassen et al. A.A. 370 (3) L41-L44,2001

- Striking similarity of the sawtooth crash between tokamak and solar flare plasmas

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Sawtooth oscillation and full reconnection model

- Sawtooth oscillation: a periodic growth (*long*) and decay (*sudden*) of the core pressure of the toroidal plasma (S. von Goeler, 74):
- Full reconnection model *(B. Kadomtsev, '76)*
  - *m/n=1/1 mode becomes unstable for q(0)<1, where q represent a degree of the helical twist of the magnetic field line*
  - *Pressure driven instability near the steepened pressure gradient region due to the kink motion of the m/n=1/1 mode leads to the reconnection*

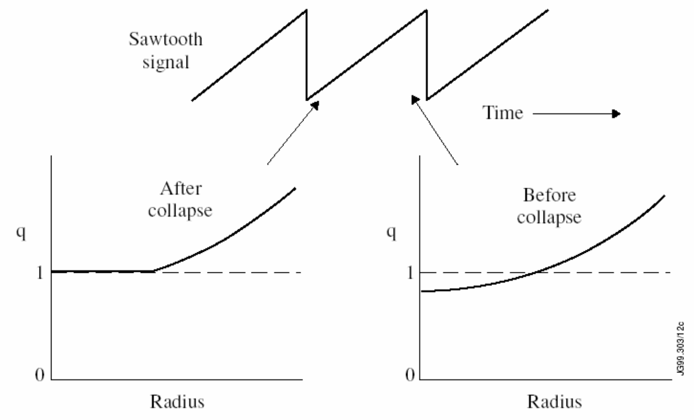
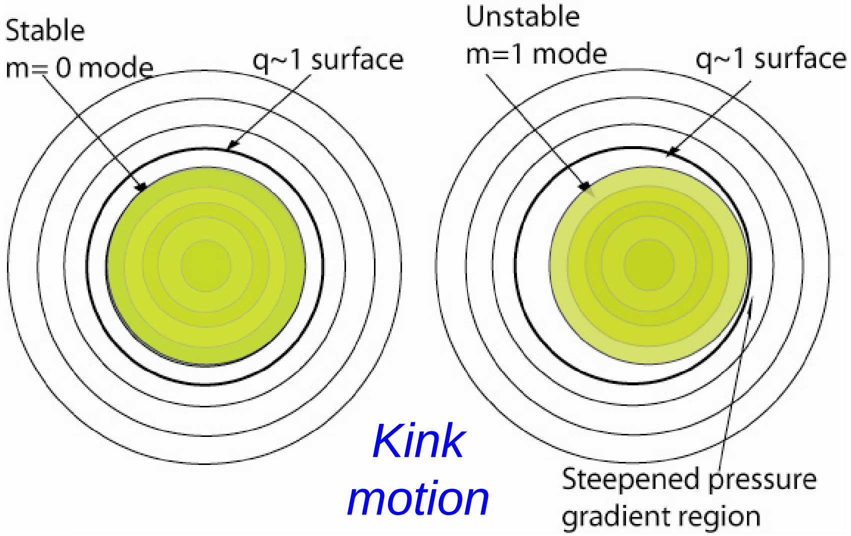
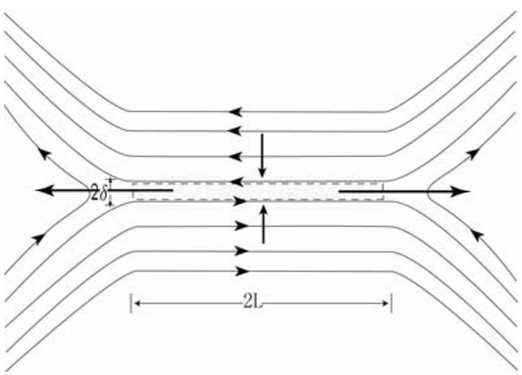


Figure 10.12. Kadomtsev's model predicts a flattening of the q-profile at the sawtooth collapse and the development of an unstable profile with q < 1 during the ramp phase.

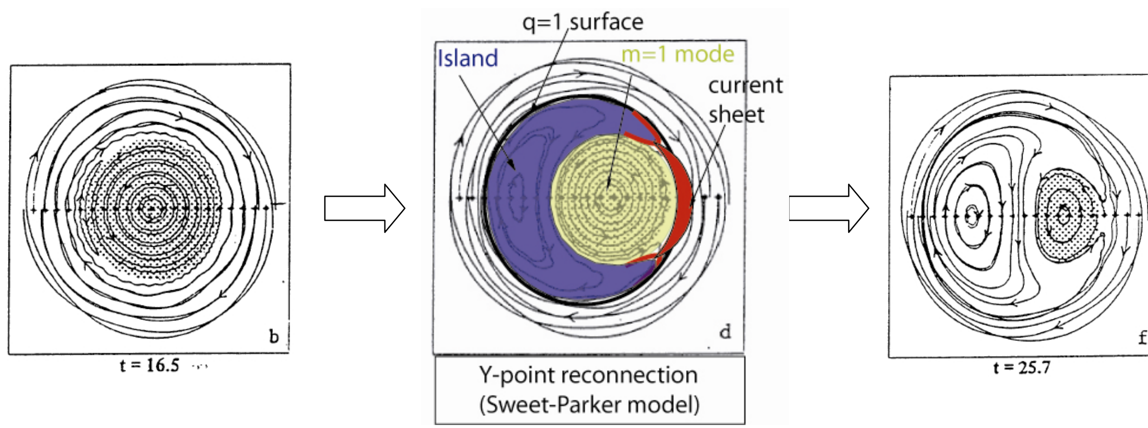


Sawtooth oscillation and full reconnection model

- *Helically symmetric reconnection zone (hypothesis)*
  - *Y-point reconnection process (2-D Sweet-Parker model)*
  - *Long reconnection time (monotonic full growth of the island)*
  - *New model is inevitable because*
    - *Measured crash time was much shorter than the predicted value*
    - *Crash occurs without full growth of the island*
    - *ICRF driven giant sawtooth and precursor less sawtooth*



2-D Sweet-Parker model
(Y-point reconnection)



$$\tau_k \approx \frac{1}{2}\sqrt{\tau_A^* \cdot \tau_\eta}$$

Sykes et al. PRL, 36, 140, 1976
based on MHD fluid in cylindrical geometry

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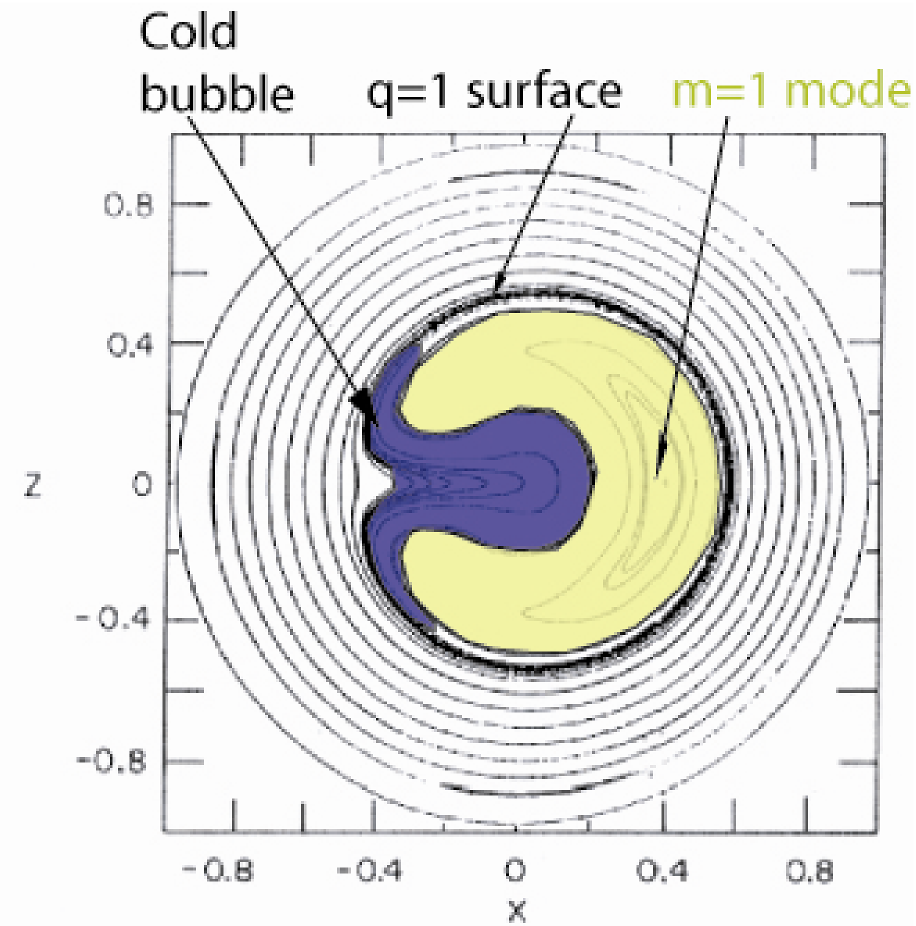
Sawtooth oscillation and quasi-interchange mode

- Quasi-interchange mode model (J. Wesson, ’86) triggered by magnetic instability
- Constant q(0) ~1 and no reconnection process
- *Distinctive cold bubble shape is contrast to the island shape of the full reconnection model*
- This model was initially confirmed by x-ray tomography of the JET plasma (Granetz, ’88)



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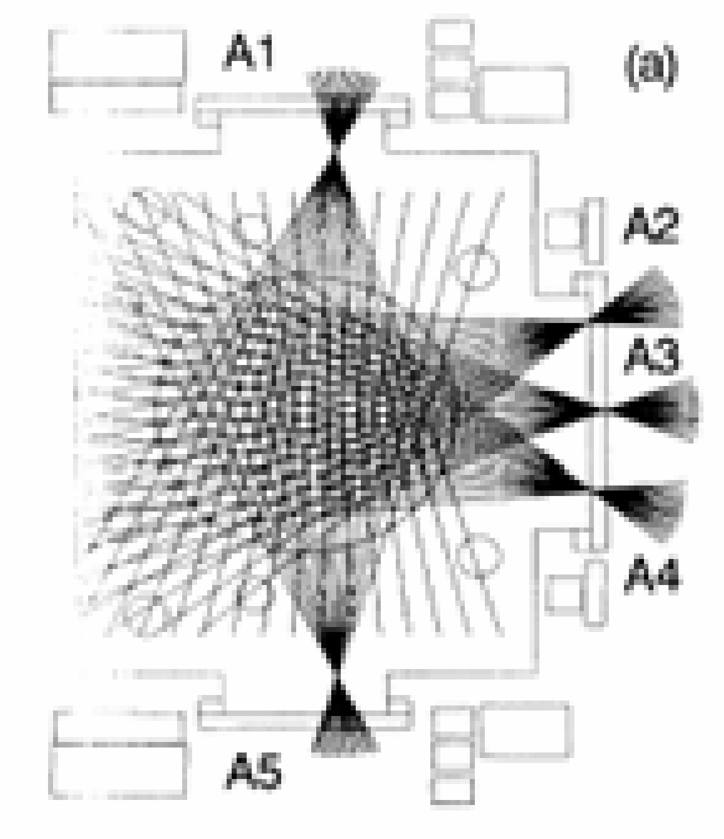
Sawtooth oscillation and quasi-interchange mode

- Reconstruction of 2-D and 3-D images from limited X-ray arrays
  - *Inversion process is complex and unique solution may not feasible with small number of chords*
  - *Parametric dependence of the X-ray signal adds more complexity (T_e, n_e and Z_{eff})*
- *Full reconnection or interchange model dependent upon number of polynomial in inversion process (C. Janicki '89)*



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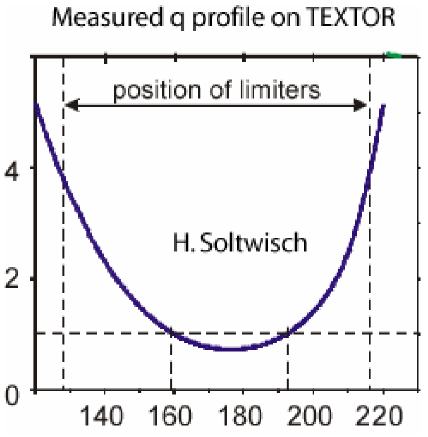
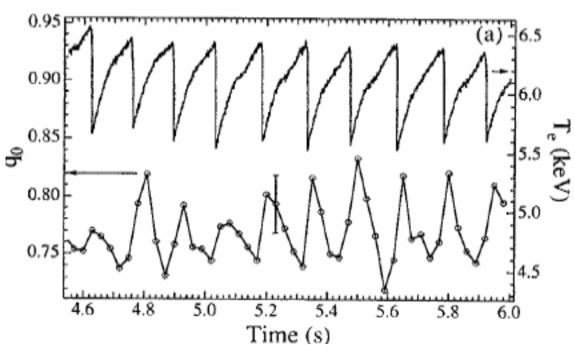
Experimental verification of q-profile

- Current profiles
  - Central q value remains at ~ 0.7 (TEXTOR; H. Soltwisch, '88 &TFTR; F. Levinton, '94)
- Little changes in the measured magnetic energy contradicts to the previous theoretical models
- Leads to new idea – Ballooning mode model





A part of stored magnetic energy is released during the crash period of 100 $\mu sec << \tau_{sp}$ ***(TFTR)***

Sawtooth oscillation and ballooning mode model

- Ballooning modes ("pressure finger") predominantly at the low field side can lead to a localized reconnection
- Global stochastic magnetic field (hypothesis) is introduced for slow magnetic energy release and fast heat transport
- Consistent with the 3-D local reconnection model (Yamada & Nagayama, et al., ('94)

High Field side Low field side

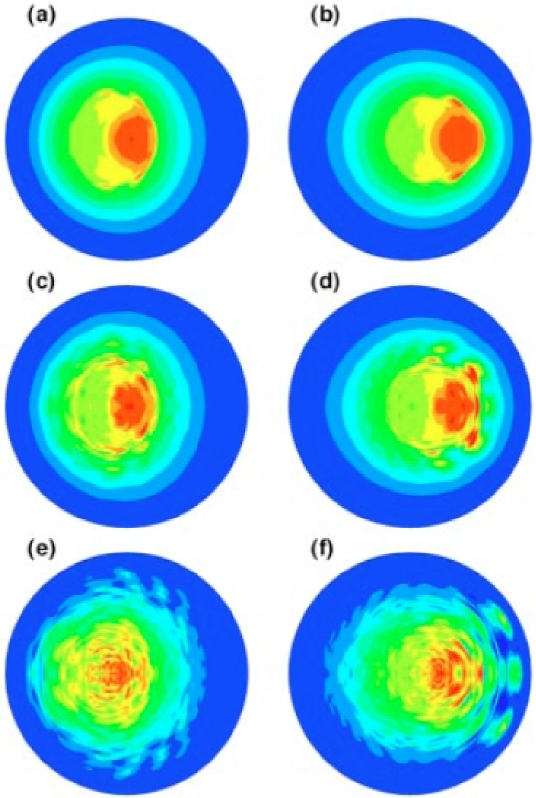


FIG. 2. Pressure contours for the β=4% simulation. The axisymmetry center line is located at the middle of the page. (a), (b) at $t=1.205\times10^{-2}$, (c), (d) at $t=1.230\times10^{-2}$, and (e), (f) at $t=1.265\times10^{-2}$.

Y. Nishimura, et al. ('99)

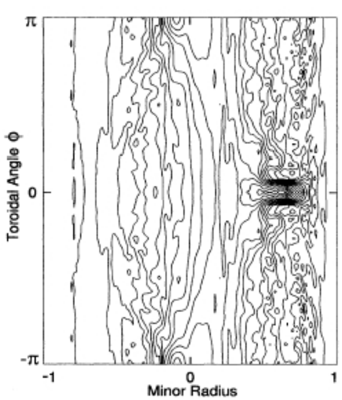


FIG. 5. The pressure contours on the midplane of the torus.

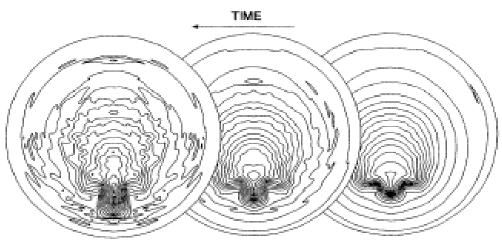
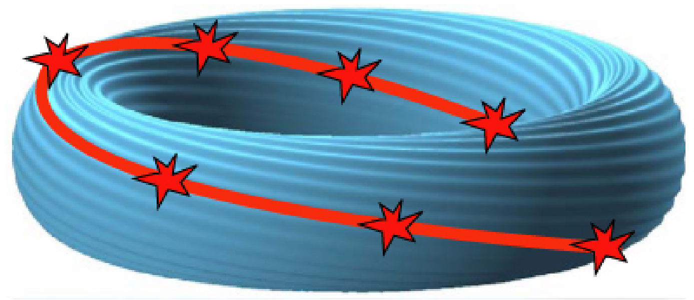


FIG. 4. The nonlinear time development of the pressure.

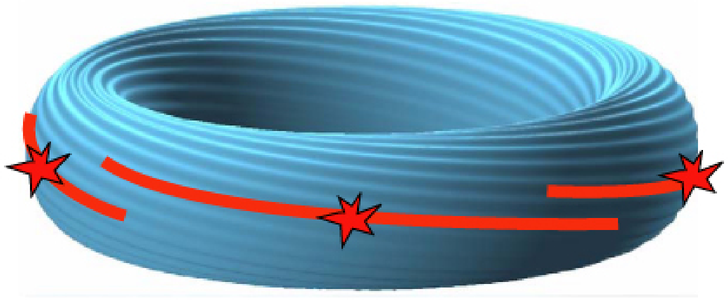
W. Park, et al. ('96)

Studies suggest a 3-D localized reconnection



Full reconnection (Helically symmetric crash)

Kadomtsev model predicted a full reconnection (pressure and magnetic energy are changing together

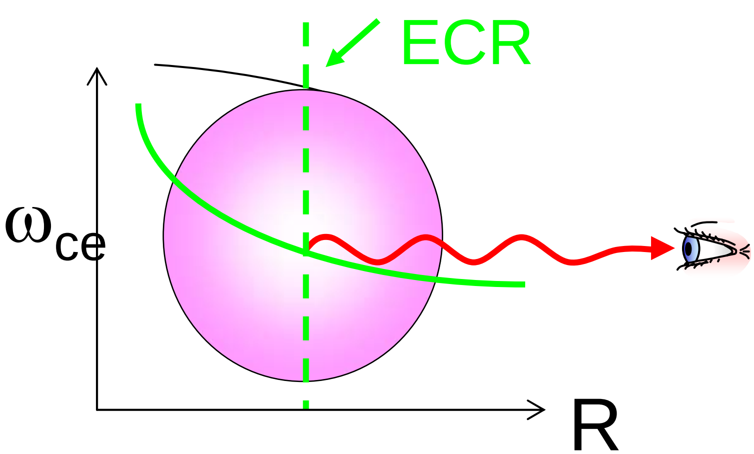


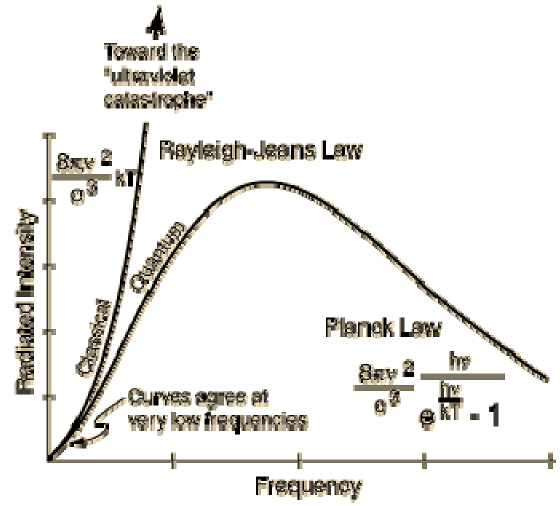
3-D Local reconnection (localized crash at low field side)

Localized T_e breakup; Y. *Nagayama '94),*
Little magnetic energy change; *(Levinton, '94)*
⇒ Ballooning based models
W. Park et al. & Y. Nishimura et al

Critical steps and hypothesis are partially verified (not conclusive) by X-ray tomography and 1-D Electron Cyclotron Emission (ECE)

Electron cyclotron emission





- Electromagnetic (EM) waves are emitted at the electron cyclotron resonance (ECR) layer at a series of discrete harmonic frequencies:
  - $\omega_n = n\omega_{ce}$, $\omega_{ce}(R) \propto B \propto 1/R$
  - If the plasma is Maxwellian and optically thick, the emission can be described as blackbody radiation in the Rayleigh-Jeans limit
  - Intensity: $I(\omega) = I_B(\omega) \approx \dfrac{T_e \omega^2}{8\pi^3 c^2}$

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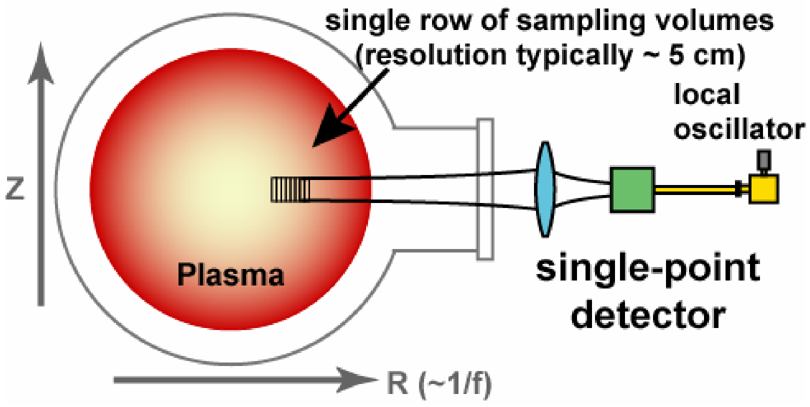
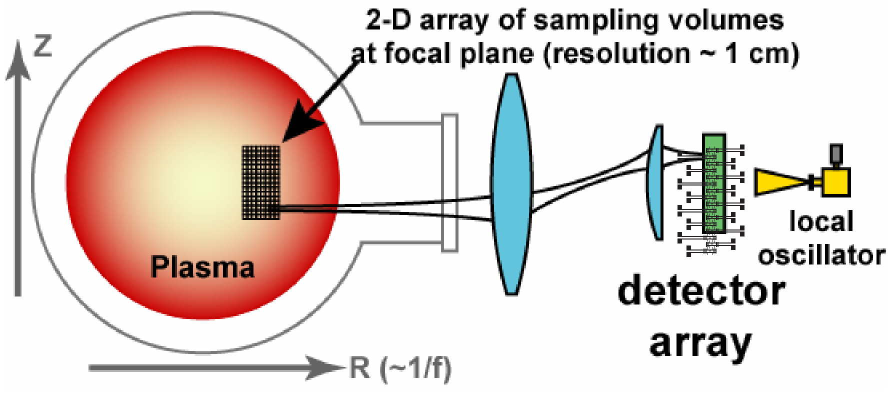
Microwave camera with zoom lens



Conventional 1-D ECE system



2-D ECE imaging system

- ECE measurement is an established tool for electron temperature measurement in high temperature plasmas
- Sensitive 1-D array detector, imaging optics, and wide-band mm wave antenna, and IF electronics are required for 2-D imaging system
- T_e fluctuation measurement
  - Real time fluctuations can be studied up to ~1% level
  - Fluctuation studies down to 0.1 % level have been performed using long time integration

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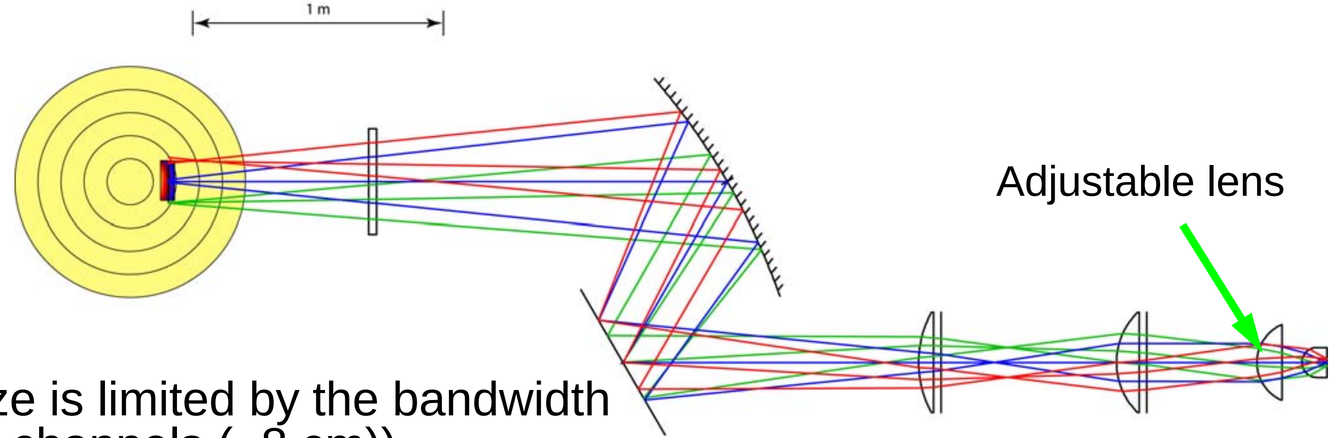
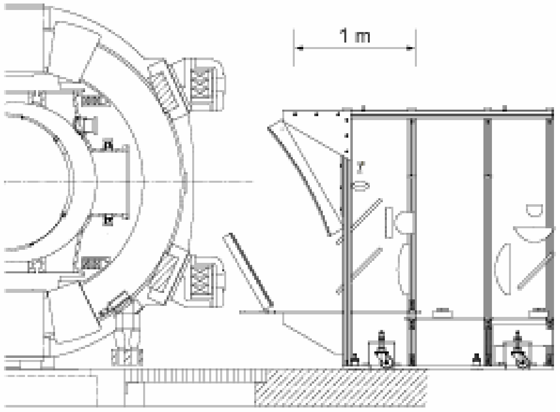
Characteristics of 2-D ECEI imaging on TEXTOR

128 channels
(16 x 8)
Spatial resolution
(2 cm x 1 cm)
Time resolution =
5 μsec.



- Radial image size is limited by the bandwidth of the system (8 channels (~8 cm))
  - LO frequency and/or B field change can extend the radial coverage
- Poloidal image size is limited by front end optics designed for MIR (16 channels (~16 cm))
- Relatively calibrated for fluctuation study $\Delta T_e(r,t)/<T_e(r,t)>$;< > is time average temperature and constant for this study
  - Time resolution; ~ 5 μs
  - Real time signal at ~1% level of T_e fluctuation (~10eV)
  - Sub ~1% level of fluctuation was studied with integration time



ECEI/MIR system on TEXTOR

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Relevant TEXTOR plasma parameters

- Global parameters:

$B_T = 2.3T$ $\quad I_p = 400kA$ $\quad \beta_T \approx 1.0\%$

$B_p(a) \cong 1.6kG$ $\quad P_{nbi} \cong 3MW$ $\quad \beta_p \cong 0.4$

- Plasma parameters:

$V_A(B_T) \cong 3.8\times10^8 cm/s$

$V_A(B_p) \cong 1.7\times10^7 cm/s$

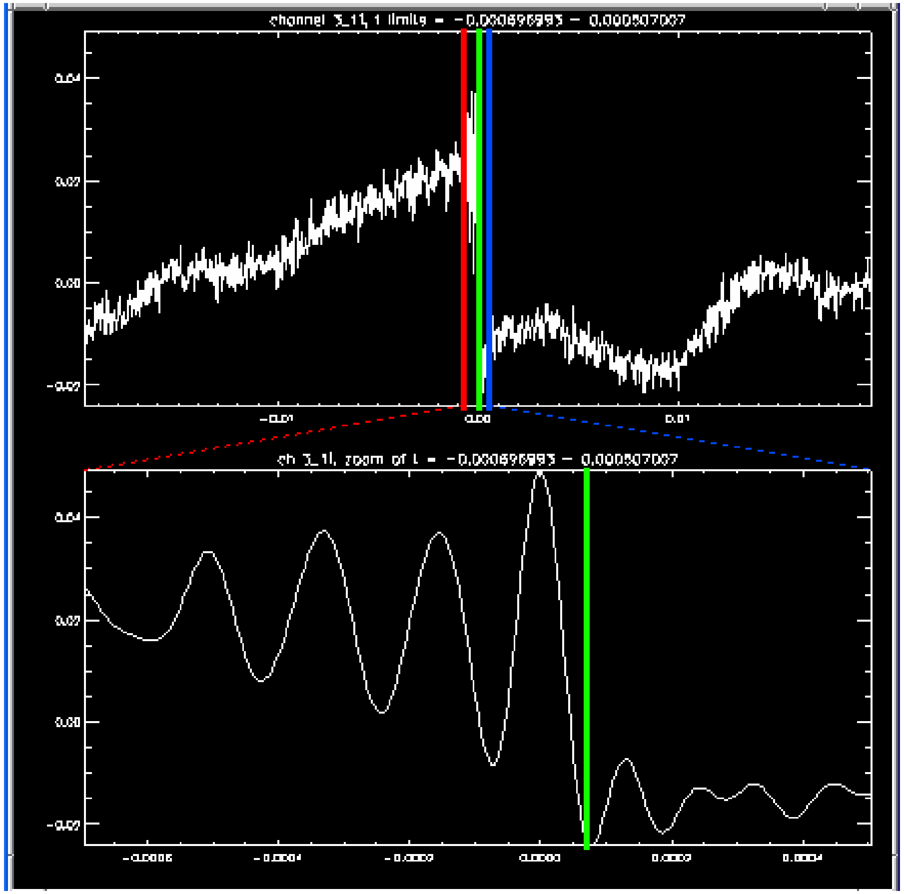
$V_{the} \cong 2.0\times10^9 cm/s$

$C_s \cong 3.5\times10^7 cm/s$

$V_{rot} \cong 6.5\times10^6 cm/s$

$\eta \approx 1.3\times10^{-6} ohm\cdot cm$

$$\frac{\Delta T_e}{< T_e >}$$

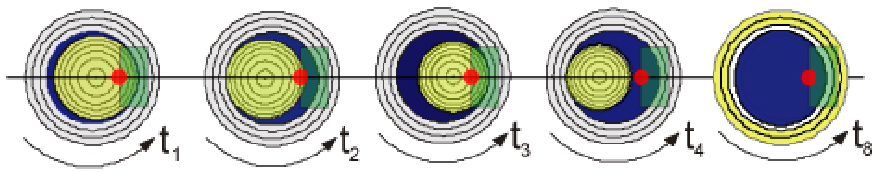


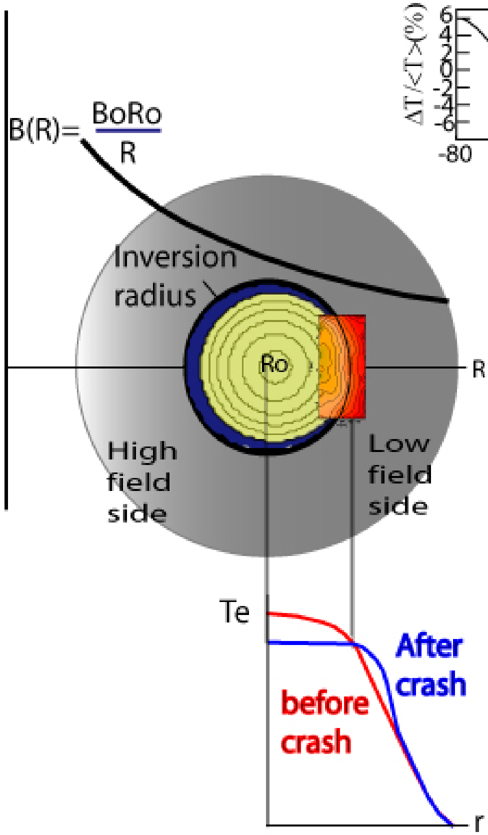
$Time(\mu \sec)$

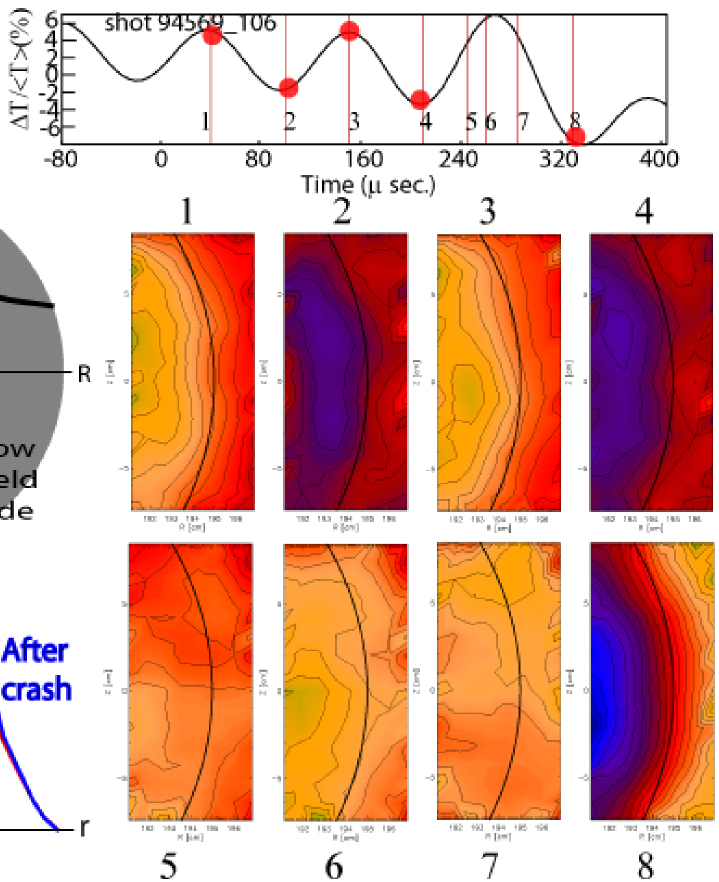
- full reconnection time:

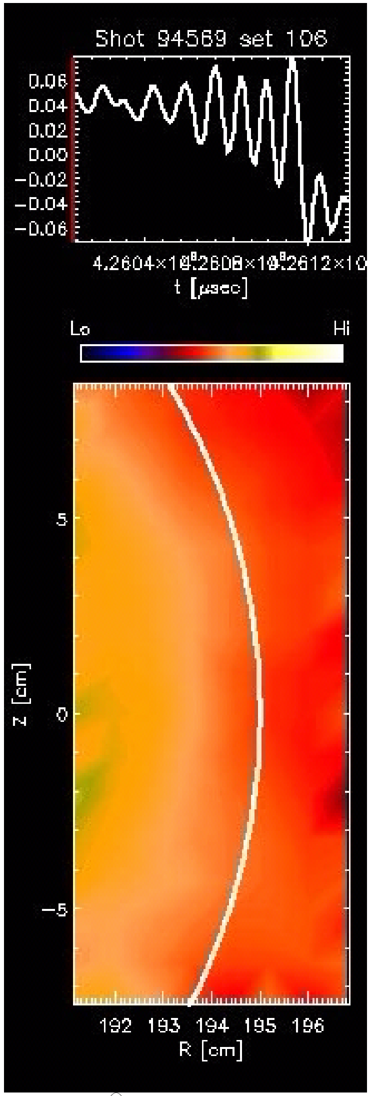
$$\tau_k \approx \frac{1}{2}\sqrt{\tau_A^* \cdot \tau_\eta} \approx 650\mu\text{sec}.$$

Reconnection process via visualization



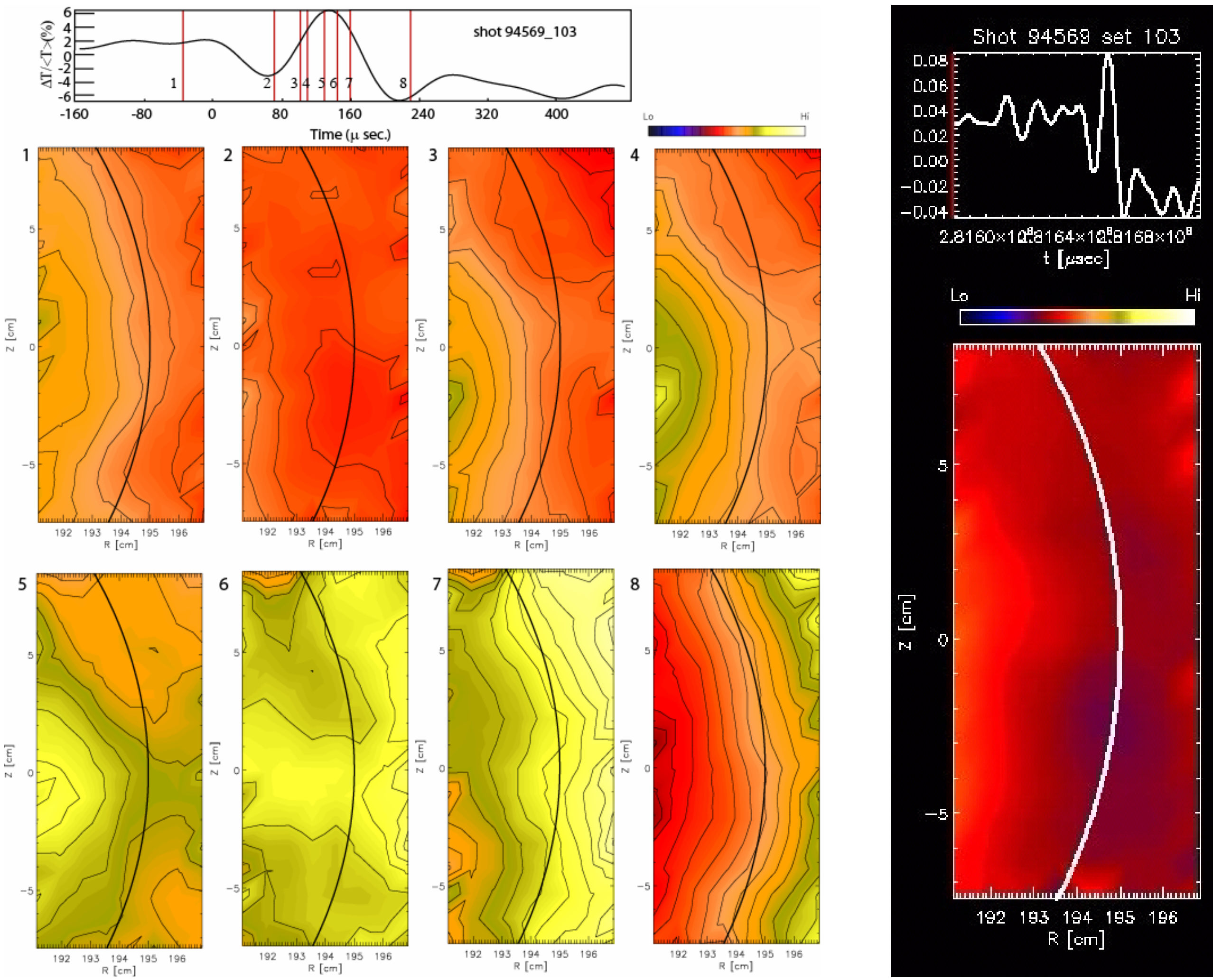






Reconnection ("x-point") at low field side

- Sharp T_e point (#4) is similar to the "Pressure Finger" of the Ballooning mode
- Reconnection starts with "X-point" (#5) and the poloidal opening grows to ~15 cm (#6)
- Reconnection at the low field side is consistent with the pressure driven Ballooning model
- Reconnection time scale is < 100μs



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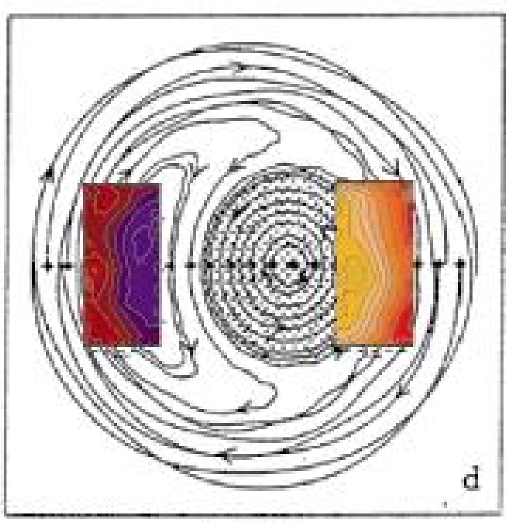
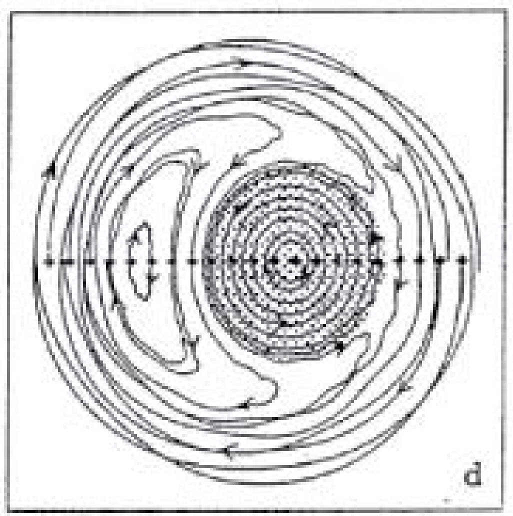
Comparison with the full reconnection model

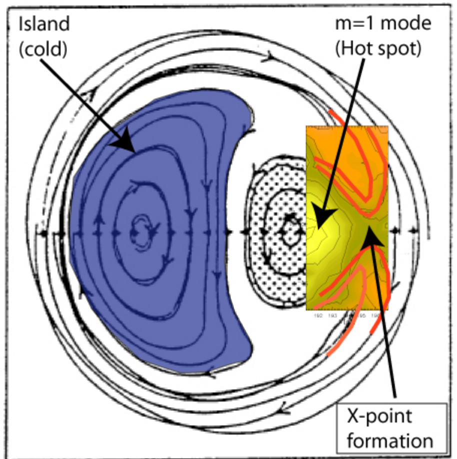
- Remarkable resemblance between 2-D images of the hot spot/Island and images from the mature stage of the simulation result of the full reconnection model (tearing type) (Sykes et al. single fluid MHD model)
  - Magnetic topology change (reconnection) occurred as the island is formed (slow reconnection)
  - No clear heat flow during precursor phase until a sharp temperature point is developed
  - Reconnection following the “sharp temperature point” forms “X-point”



t = 23.1



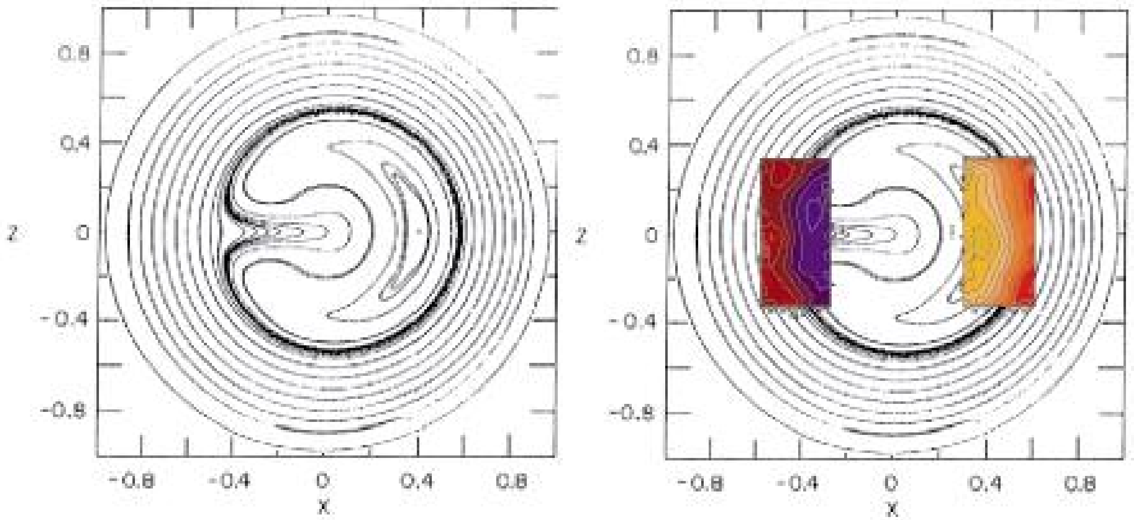
t = 23.1



Comparison with the full reconnection model simulation result at the low field side

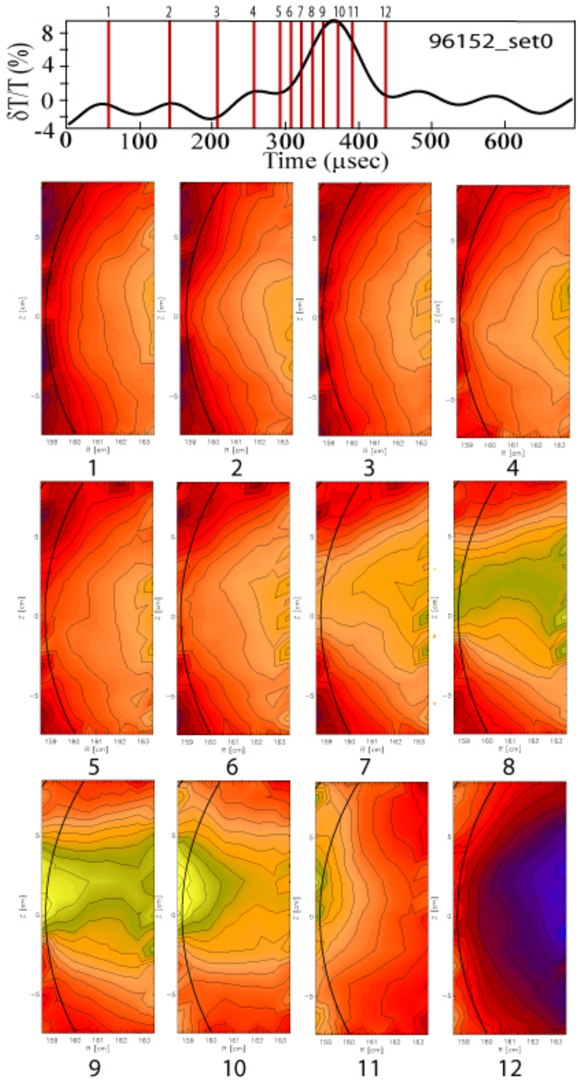
Comparison with the quasi-interchange model

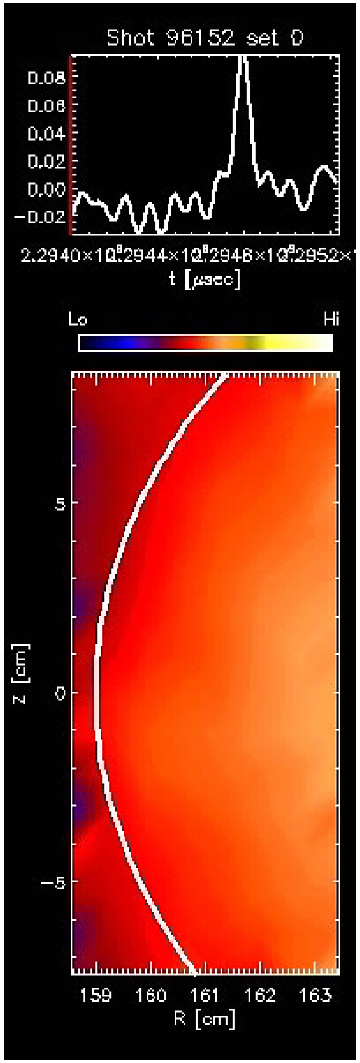
- No clear resemblance between 2-D images of hot spot/island and projected images from the quasi-interchange model
  - The observed images of the hot spot are close to circle not part of the crescent
  - The observed images of the island are vertically elongated shape, not oval shape
- This model does not require any type of magnetic field reconnection
  - Reconnection does occur following the pressure driven mode in the experiment.



Observation of the crash at high field side (kink)

- Reconnection is localized in poloidal plane similar to the low field case
- A few attempts (pointed T_e finger near the mid-plane) are made before the final puncture (#6 & #7)
- Reconnection starts with a small hole and it grows up to ~10 cm (#10)
- Heat flow is highly collective similar to the low field case
- Nested field line pushes the heat out and island sets in (#11 and #12)





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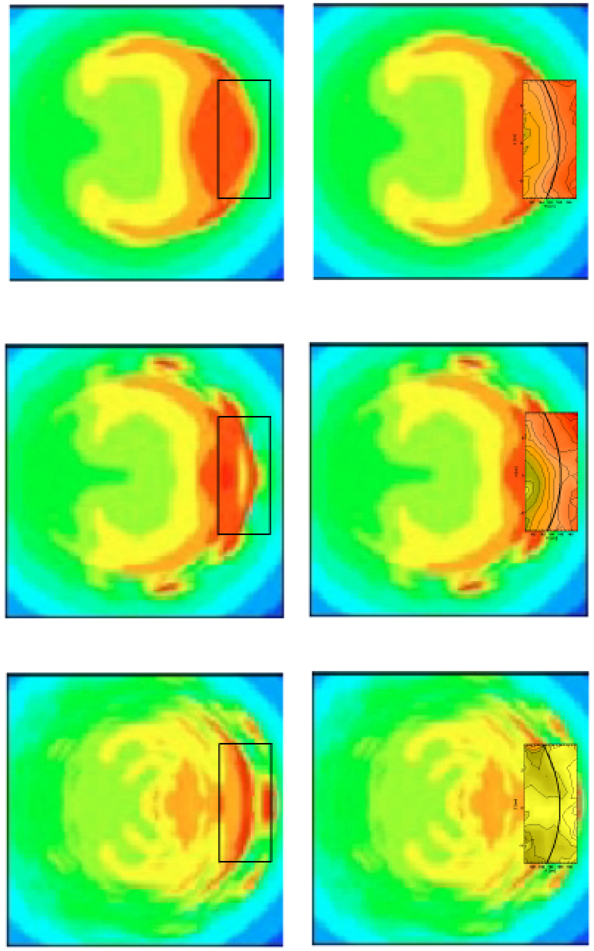
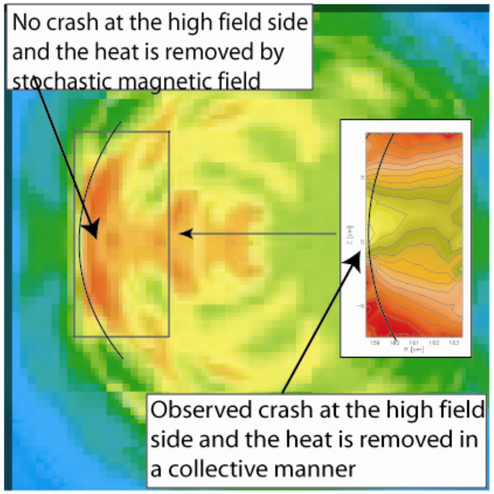
Comparison with the ballooning mode model



- Low field side
  - Similarity: "Pressure finger" of the simulation at low field side (middle figure) is similar to those from 2-D images ("a sharp temperature point")
  - Difference: Heat flow is highly collective in experiment while stochastic process of the heat diffusion is clear in simulation.

- *High field side*
  - *Reconnection at high field side is forbidden in Ballooning mode model*

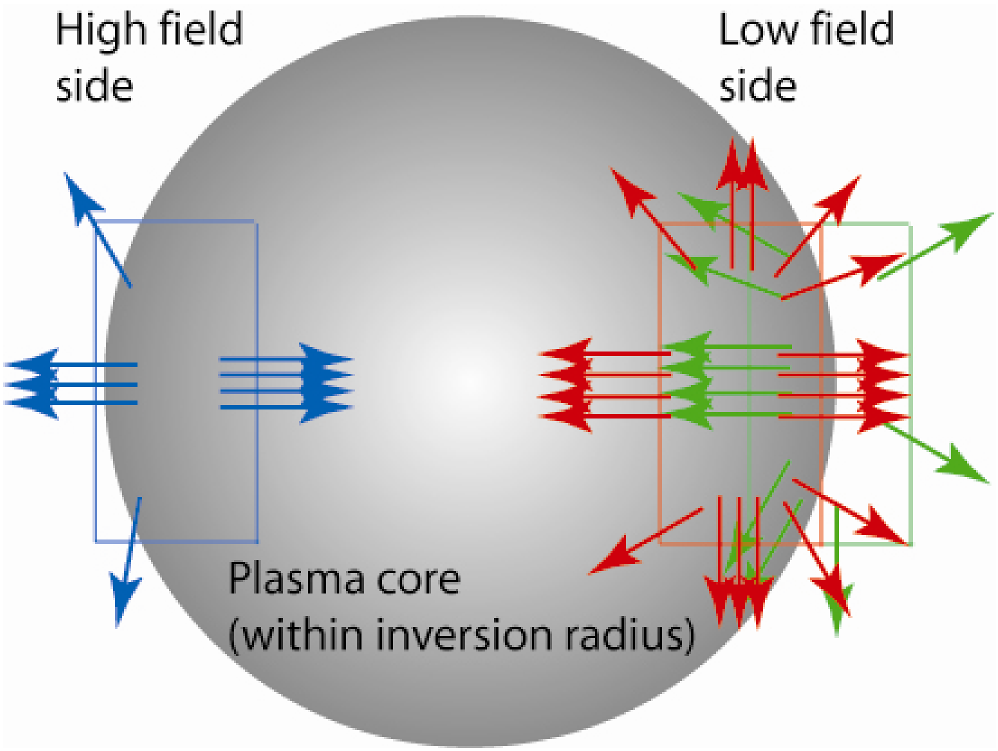


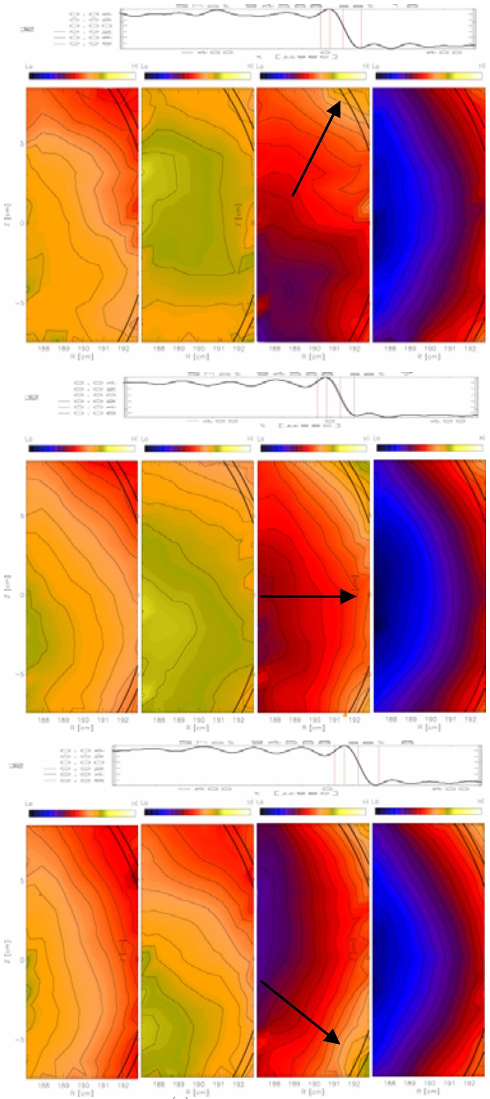
Comparison with the Ballooning model simulation result at the high field side

Simulation results from Nishimura et.al.
Plasma condition (β_p ~0.4 and β_t ~2 %) is similar to the experimental results

Statistics of the crash pattern

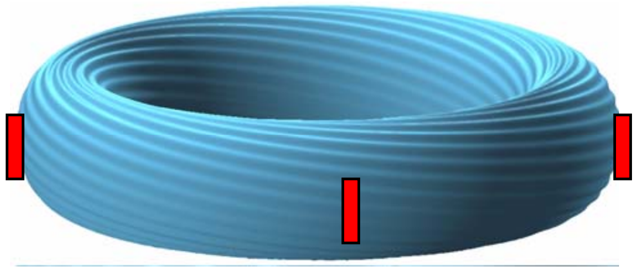
- Crash direction has been observed everywhere in high and low field sides
  - Effective poloidal view can be larger than the actual one (almost twice)



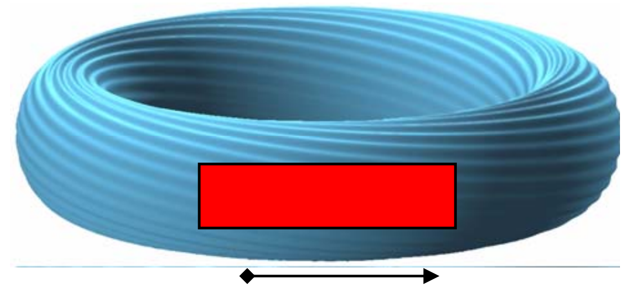


Helical symmetry of the toroidal reconnection zone

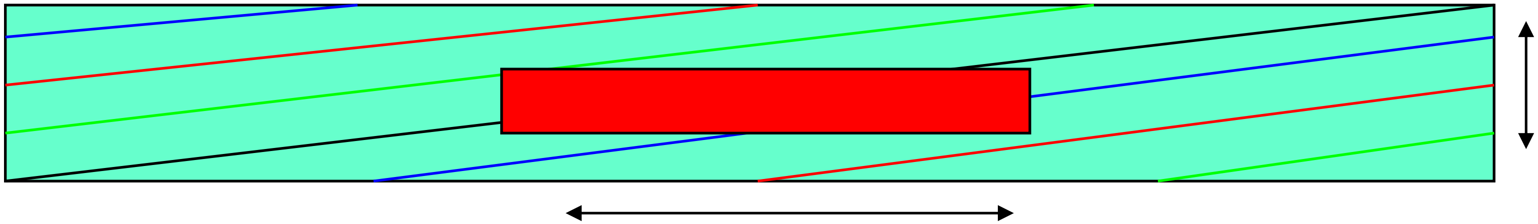
- Proof of helical symmetry of the toroidal reconnection zone
  - Requires multiple viewing along toroidal direction
- Rotating plasma provides an extended toroidal view
  - Window size is a function of the rotation speed
- Entire view can be projected on 2-D space spanned by poloidal and toroidal views



Stationary plasma



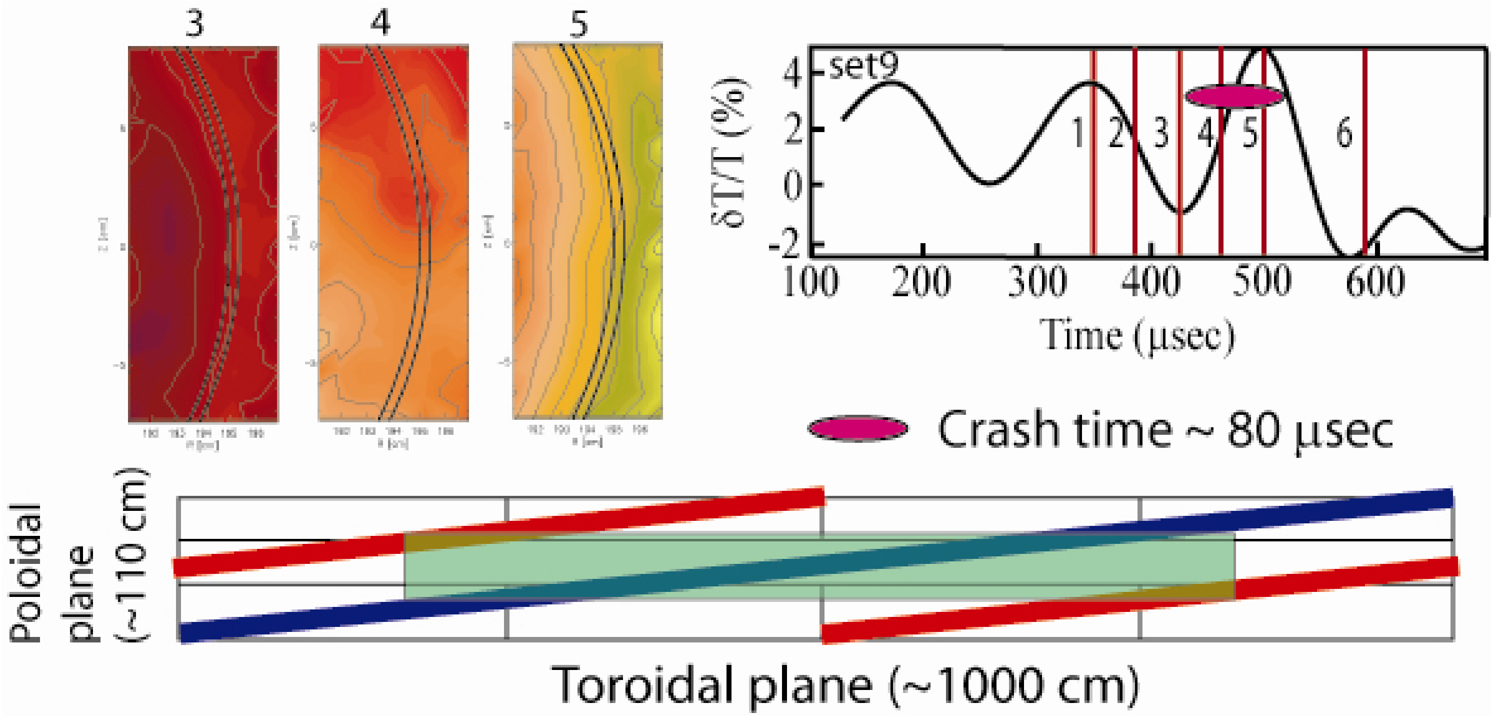
Rotating plasma



Poloidal direction

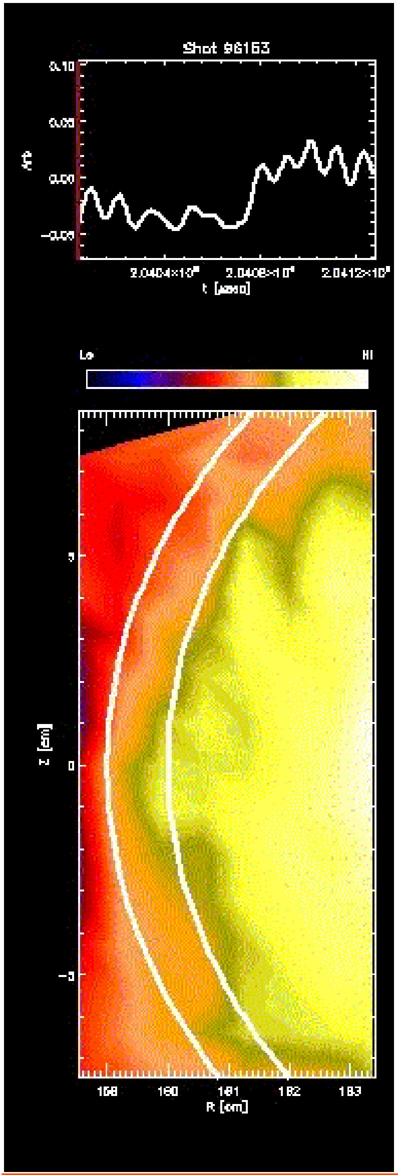
Toroidal direction

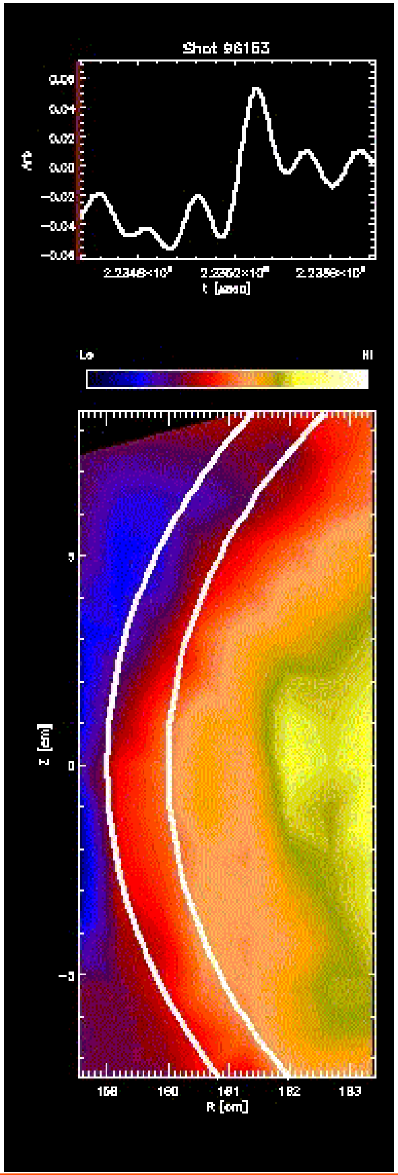
Toroidal extent of the reconnection zone



- V_r ~7-8 x10^6 cm/sec gives the toroidal window of ~ 650 cm for the crash time (~80 - 90 μsec)
- In a helically symmetric reconnection zone, chance of no reconnection zone in the viewing window is slim

High field side crash (abnormal cases)





- Example of off-mid plane crash observed (right side) at high field side: 1-D measurement at the mid-plane will be difficult to interpret
- Hot spot runs away from high field side (indication of the crash other than at the high field side – left side): In a slowly rotating plasma, one may need two imaging systems to prove the helical symmetry

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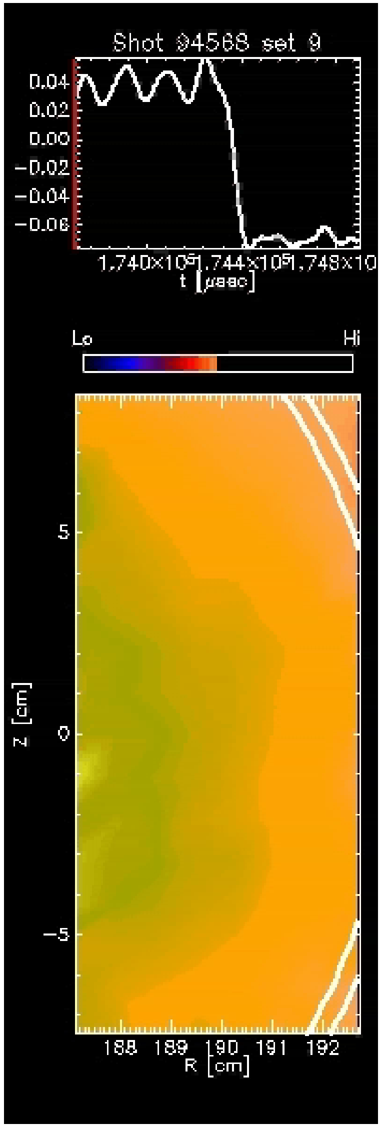
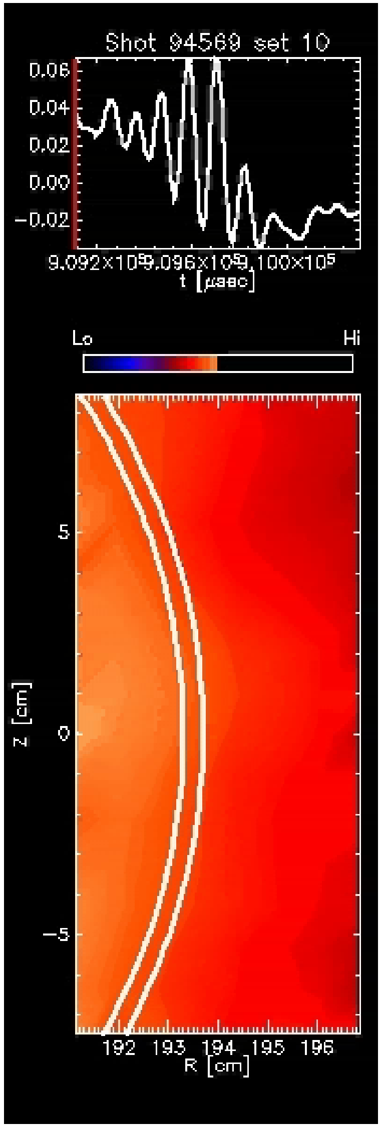
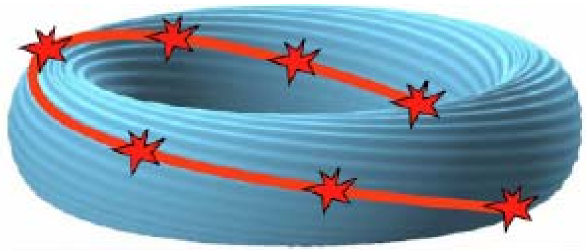
Low field side crash (fast rotating plasmas)



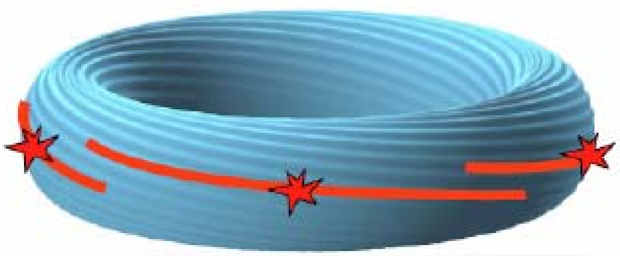


- Off-mid plane crash is also observed (right side) at the low field side (moving to the top)
- Crash pattern runs away from low field side (indication of the crash other than at the low field side – left side): no trace of reconnection zone during whole crash time scale
  - 1/4 of ~40 frames has similar crash pattern
  - Reconnection event has to be not only localized but also random phenomenon

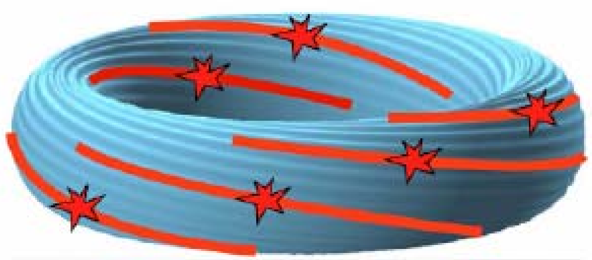
Random 3-D localized reconnection



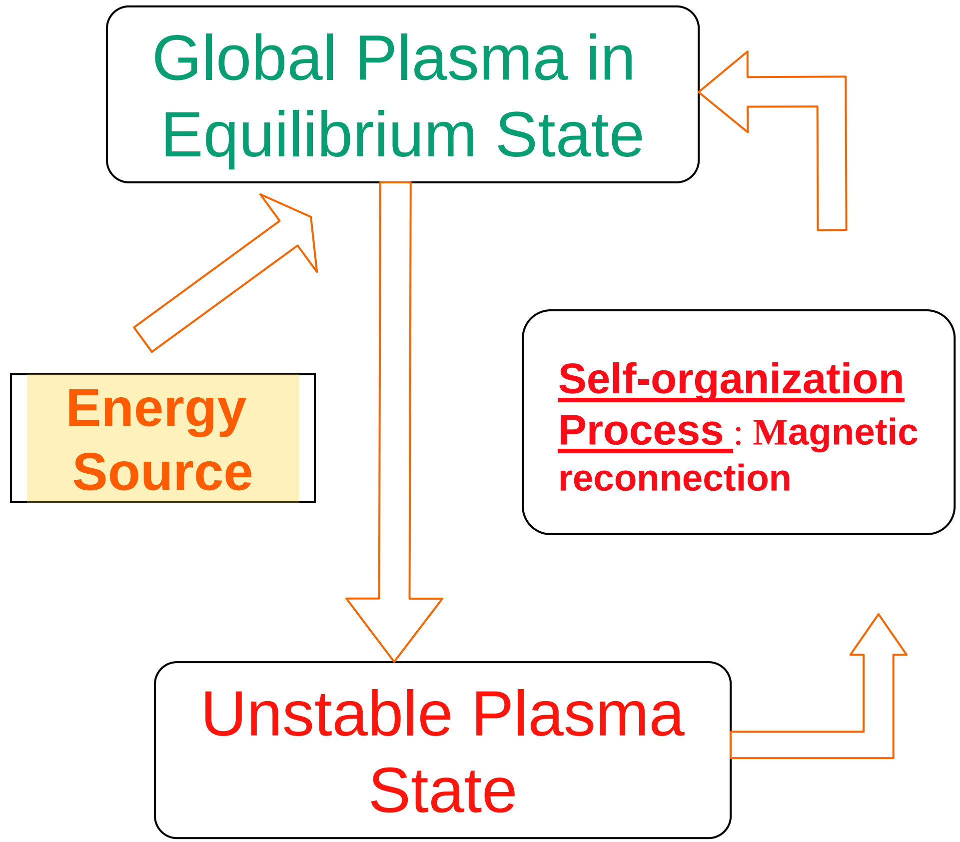
Full reconnection (Helically symmetric crash)



3-D Local reconnection (localized crash at low field side)



Random 3-D Local reconnection (localized crash everywhere)

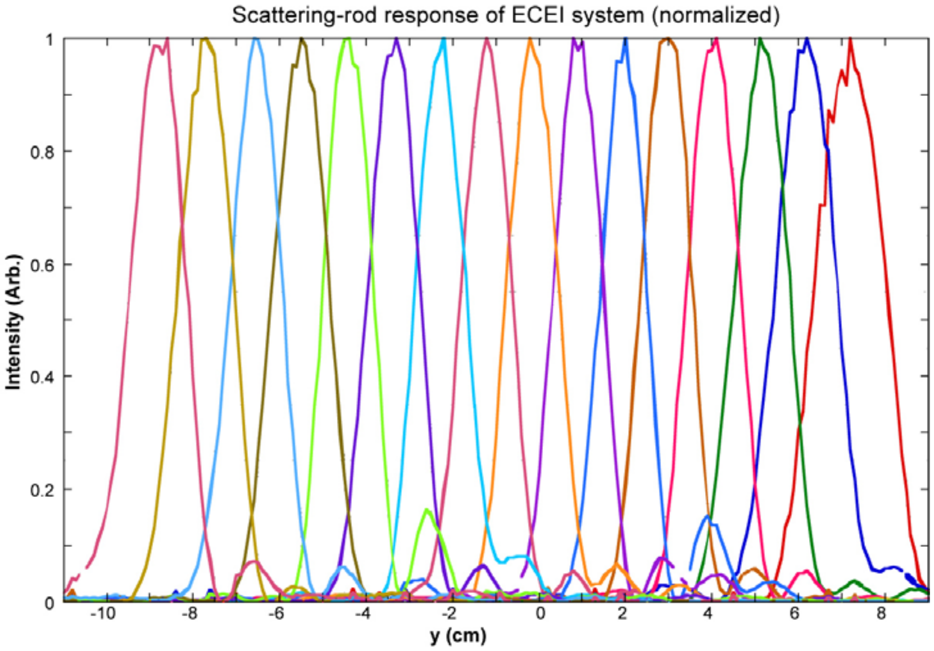


Summary

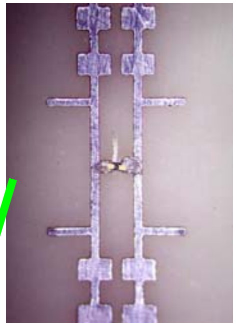
- No theoretical models are consistent with the measured 2-D images
  - Full reconnection model is largely consistent except
    - No reconnection before the pressure point develops
    - Assumption of the helical symmetry is not valid
  - Quasi-interchange model – Inconsistent with the measurement (magnetic instability is not likely a dominant mechanism)
  - Ballooning mode model is partly consistent except
    - 3-D random local reconnection process
    - Global stochasticity of the magnetic field line may not be dominant mechanism for the heat transport

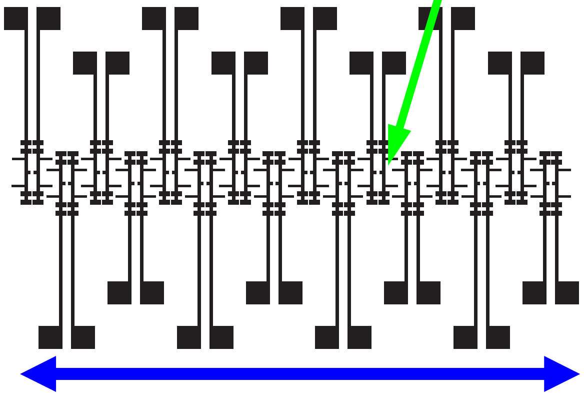
Advances in detector array technology

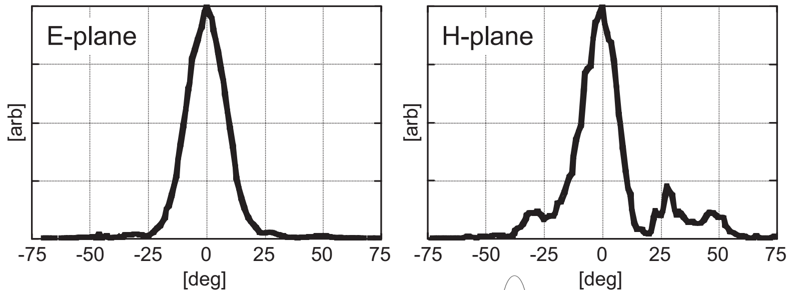
- Improved antenna patterns & power sensitivity of dual dipole array compared to those of the previously employed slot bow-tie array



ECEI system antenna response







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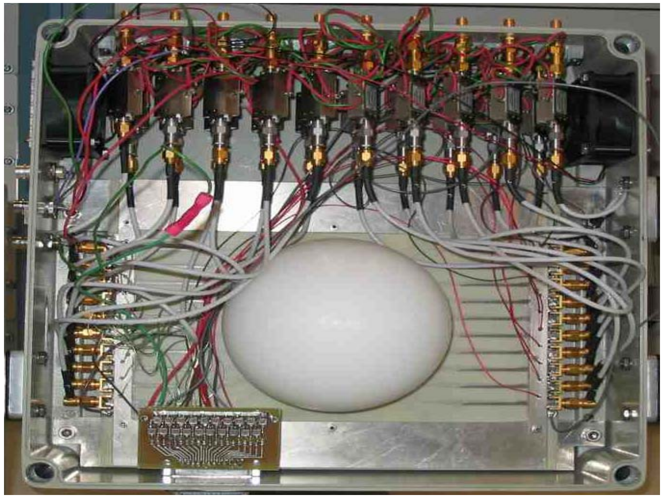
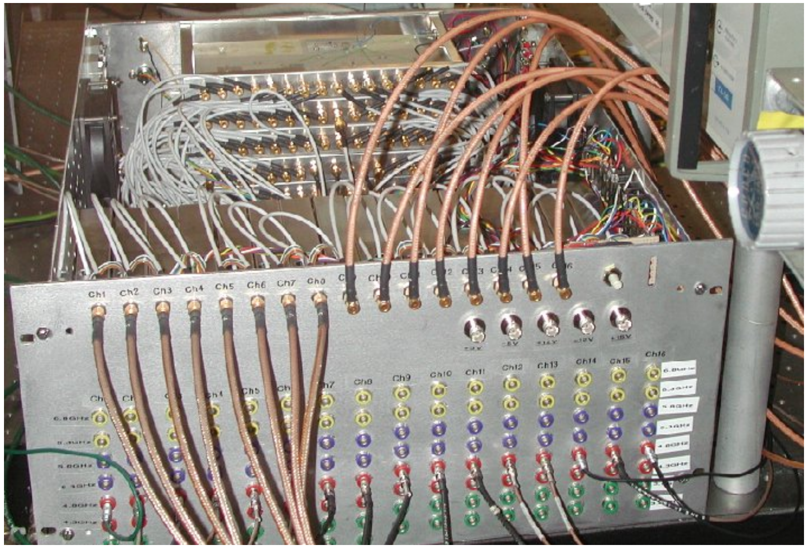
Array box and electronics for ECEI system

- Completed detection array with the substrate lens and low-noise microwave pre-amplifiers.

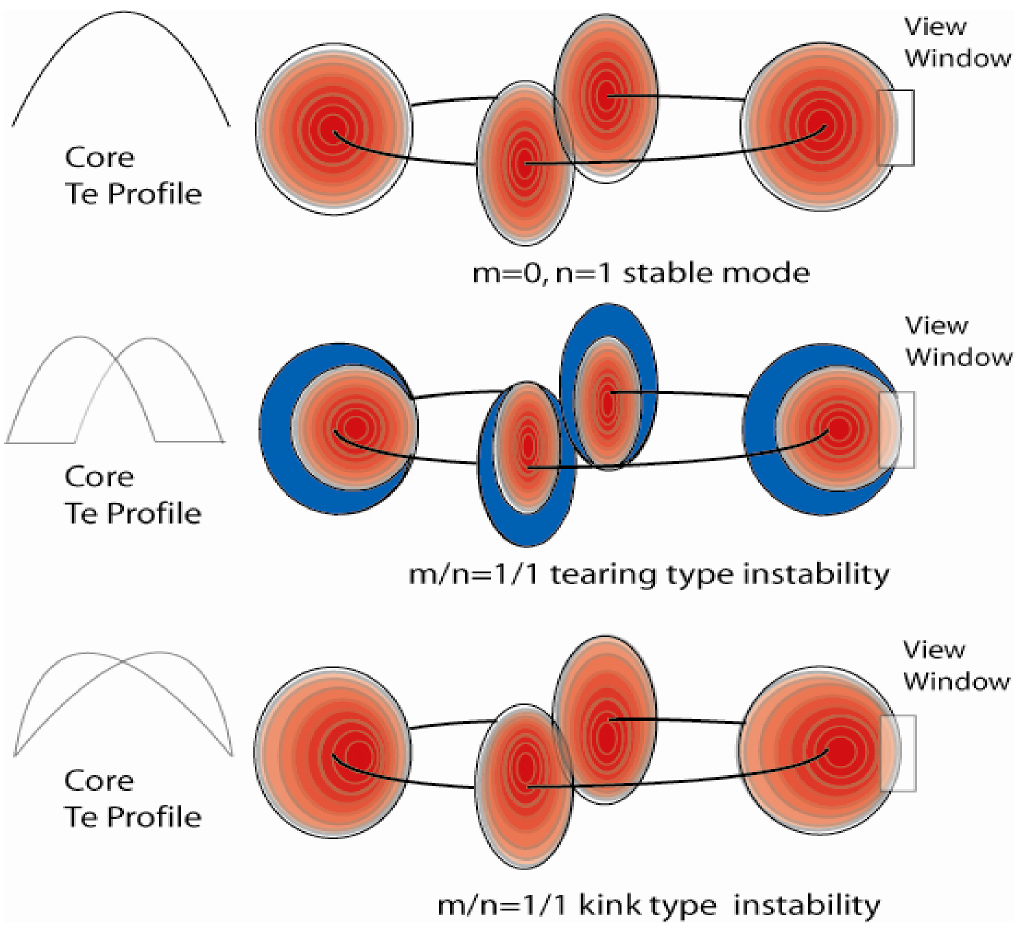




- Completed ECEI electronics box, with 16 SMA array inputs (3-7 GHz) and 128 LEMO outputs (8 outputs per input)

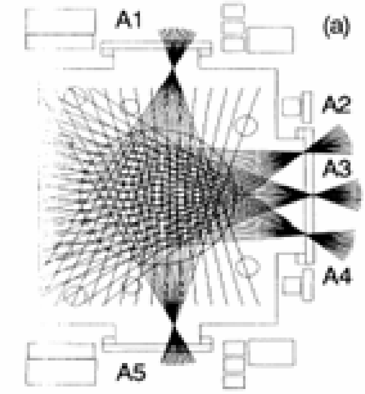
Sawtooth instability

- Stable m/n=0/1 mode in the initial stage
- m/n=1/1 mode develops as the instability grows (kink or tearing instability) and reconnection occurs
  - Tearing mode instability (slow evolution of the island/hot spot)
  - Kink mode instability (sudden crash)
- Reconnection time scale is any different in these two types ?



Study of sawtooth oscillations by X-ray tomography

- X-ray tomography – Needs careful interpretation
  - X-ray tomography supports all theoretical models
    - *Quasi-interchange model; R. Granetz ('88)*
    - *Full reconnection and interchange models dependent upon polynomials: C. Janicki ('89)*
    - *Asymmetries in high & low field side supports 3-D local reconnection- : S. Yamaguchi ('04)*
  - Reconstruction of 2-D and 3-D image from multiple arrays
    - *Inversion process is complex and unique solution may not be feasible in practice*
    - *Parametric dependence of the X- ray signal adds more complexity (T_e, n_e and Z_{eff})*



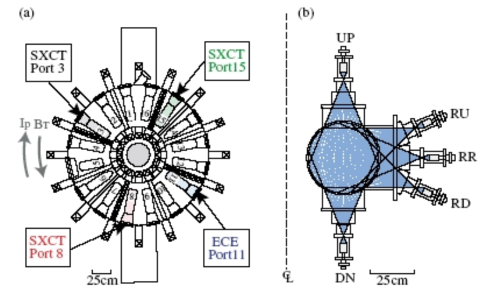


FIG. 1 (color online). (a) Top view of the WT-3 tokamak. (b) Cross-sectional view of the SXCT system.

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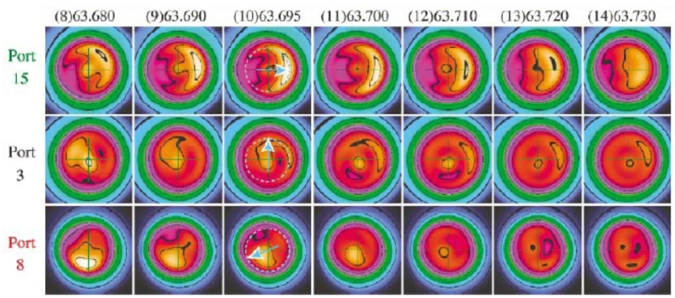

FIG. 2 (color). Time evolutions of the SX images at three ports. In each SX image, the left side is the high field side. The dashed circles denote the inversion circle with r_{inv} = 63 mm.

As the reconnection at the low field side (port #15) is progressing, no clear actions in other ports.

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