The measurement of plasma equilibrium and fluctuations near the plasma edge using a Rogowski probe in the TST-2 spherical tokamak

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Background motivation

Background

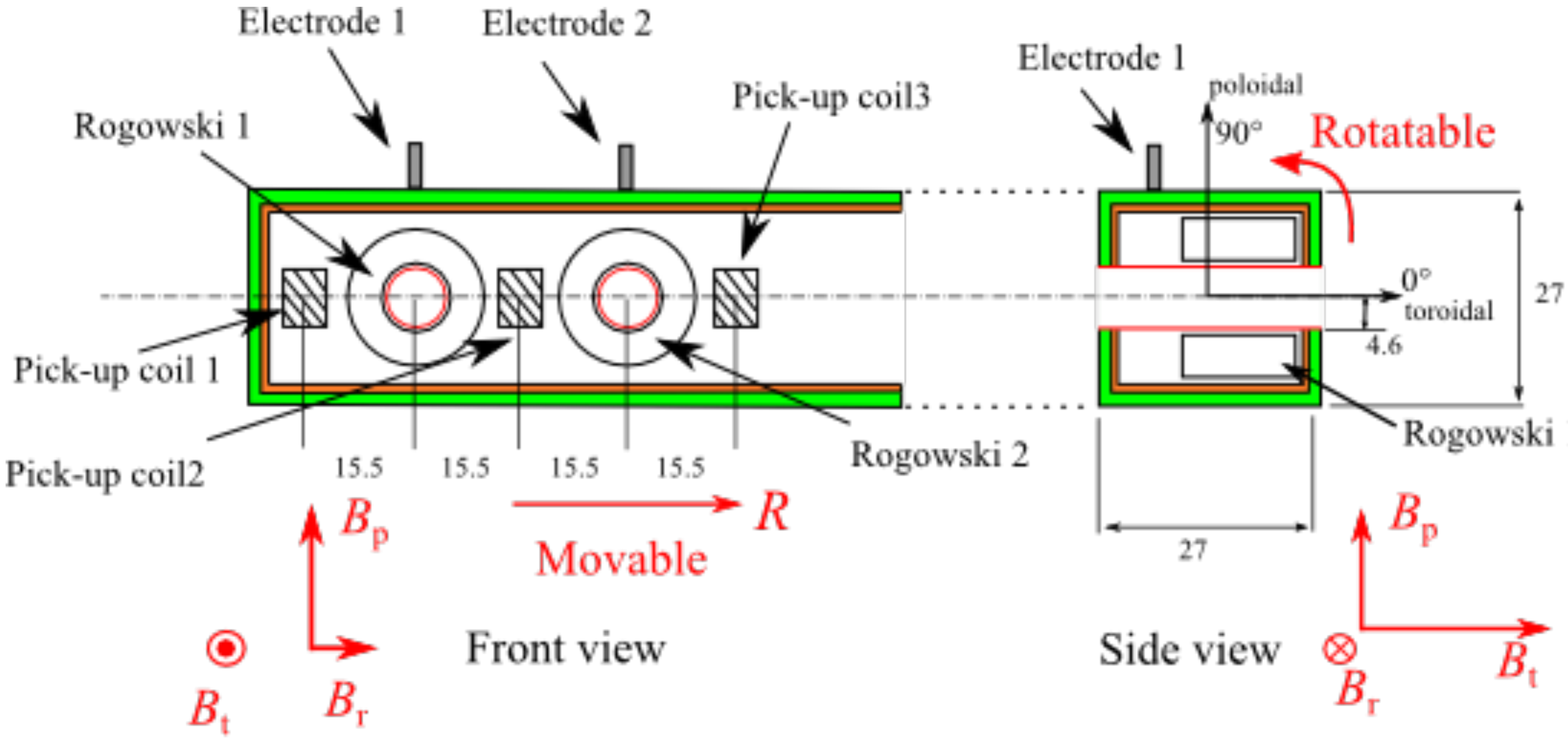
- The measurement of plasma equilibrium and fluctuations important to know tokamak plasma physics.
- Rogowski probe consisting of two multi-layer Rogowski coils with high precession windings, five pick-up coils and two Langmuir probes was fabricated to study plasma equilibrium and fluctuations [1, 2].
- Plasma sheath effect on the edge local current density measurement using the Rogowski probe was evaluated and it was found the effect of the plasma sheath is very small [3].

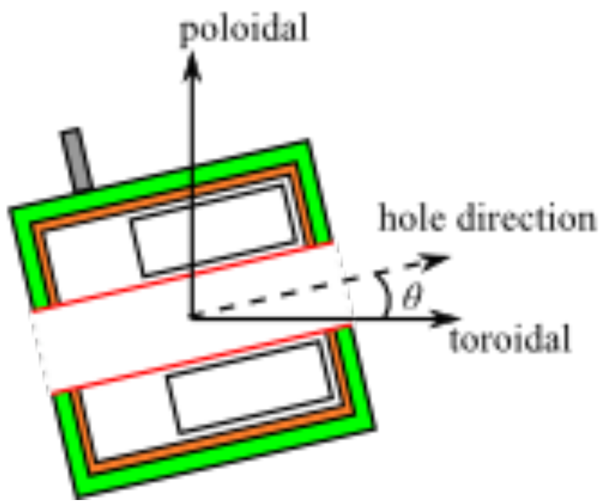
Motivation

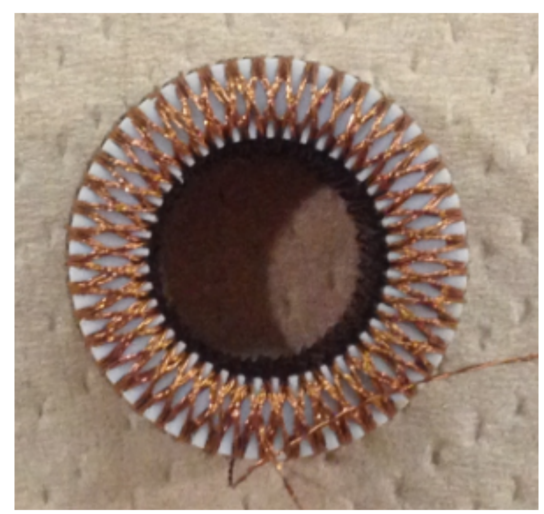
- To measure the edge current density profile and compare the experimentally obtained profiles and calculated profiles by using EFIT code.
- To measure the edge current fluctuations, and to compare fluctuations between current density, ion saturation current and magnetic fields.
- To study IREs (Internal reconnection event) using a Rogowski probe and to reveal the time relation of plasma parameters before plasma current spike.

[1] H. Furui, et al., Plasma Fusion Res. **9**, 3402078 (2014).
[2] H. Furui, et al., Rev. Sci. Instrum. 85, 11D813 (2014).
[3] H. Furui, et al., 'A model of plasma current through a hole to describe the signals of a Rogowski probe', submitted to Rev. Sci. Instrum.

Rogowski probe



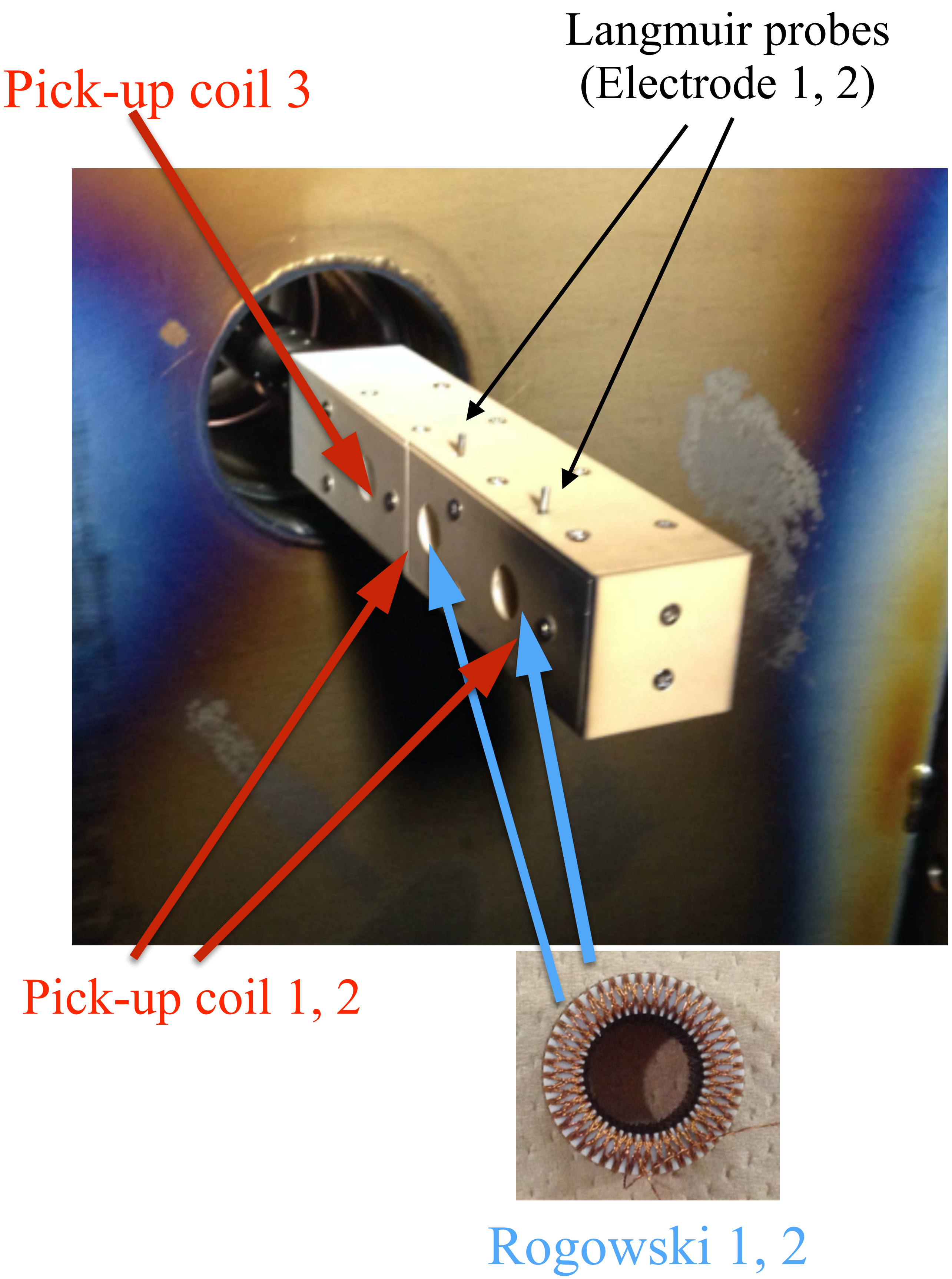


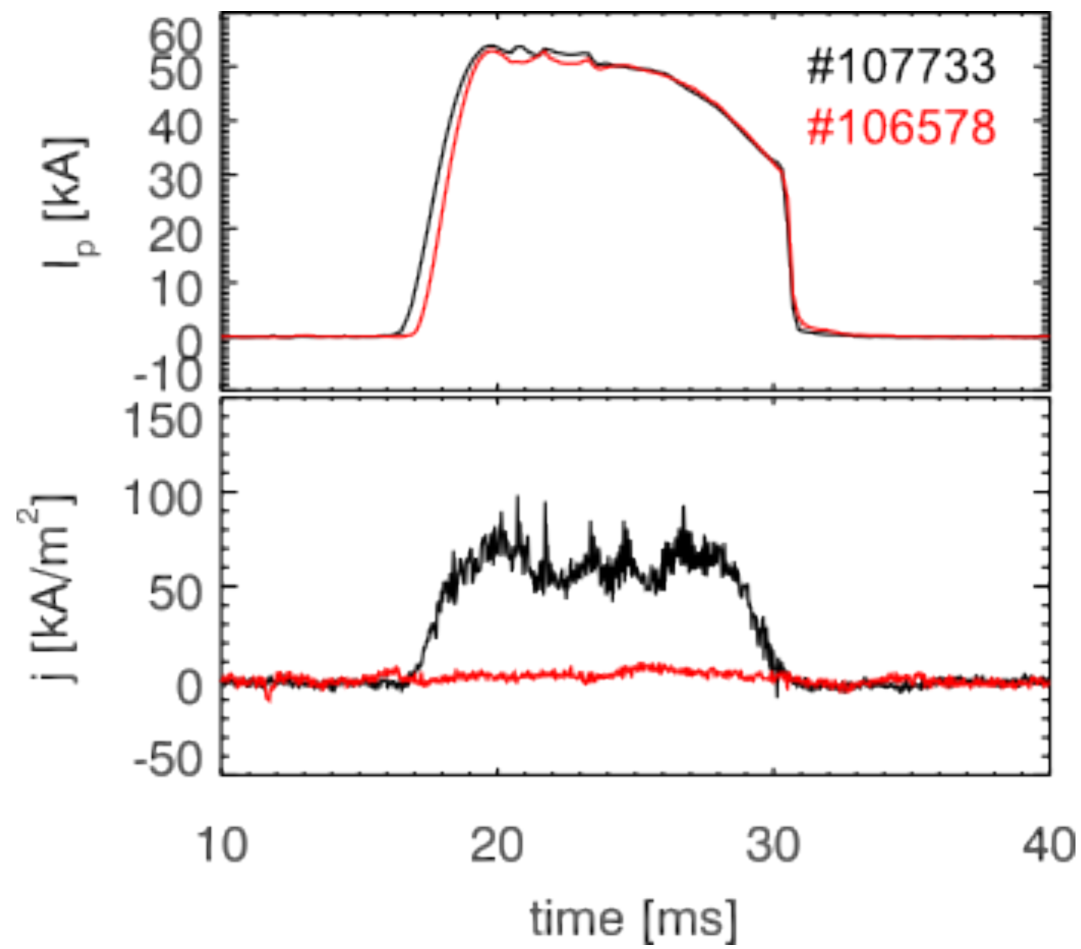


- 360 turn
- thickness : 12 mm
- Cable thickness : 0.12 mm
- Inner radii : 12 mm
- External radii : 21mm
- Core material : Peek

- Movable along mayor radius *R*
- Rotatable in toroidal-poloidal plane
- Measure the current density profile including the current density direction in toroidal -poloidal plane

Measurement of local current density using the Rogowski probe

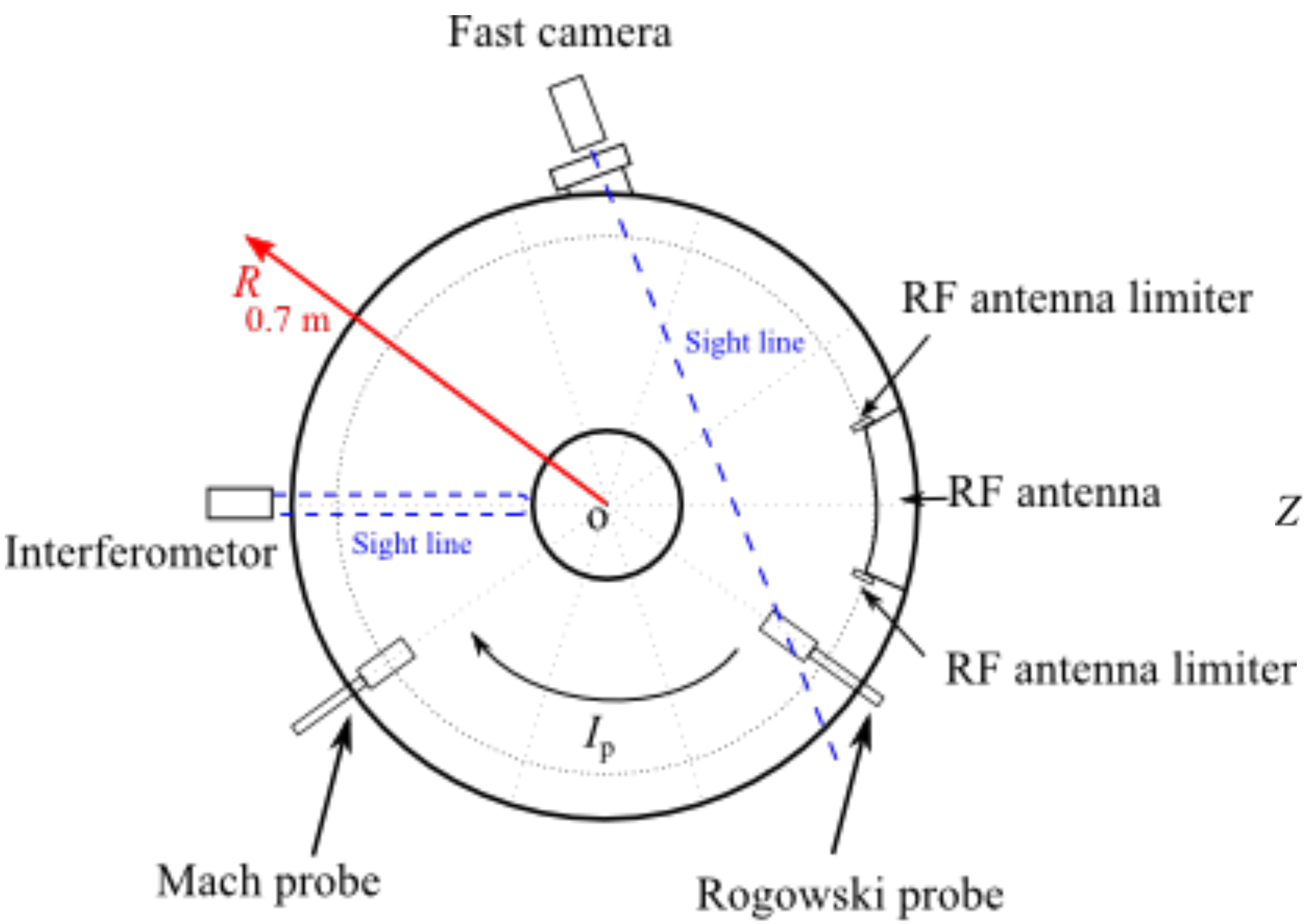




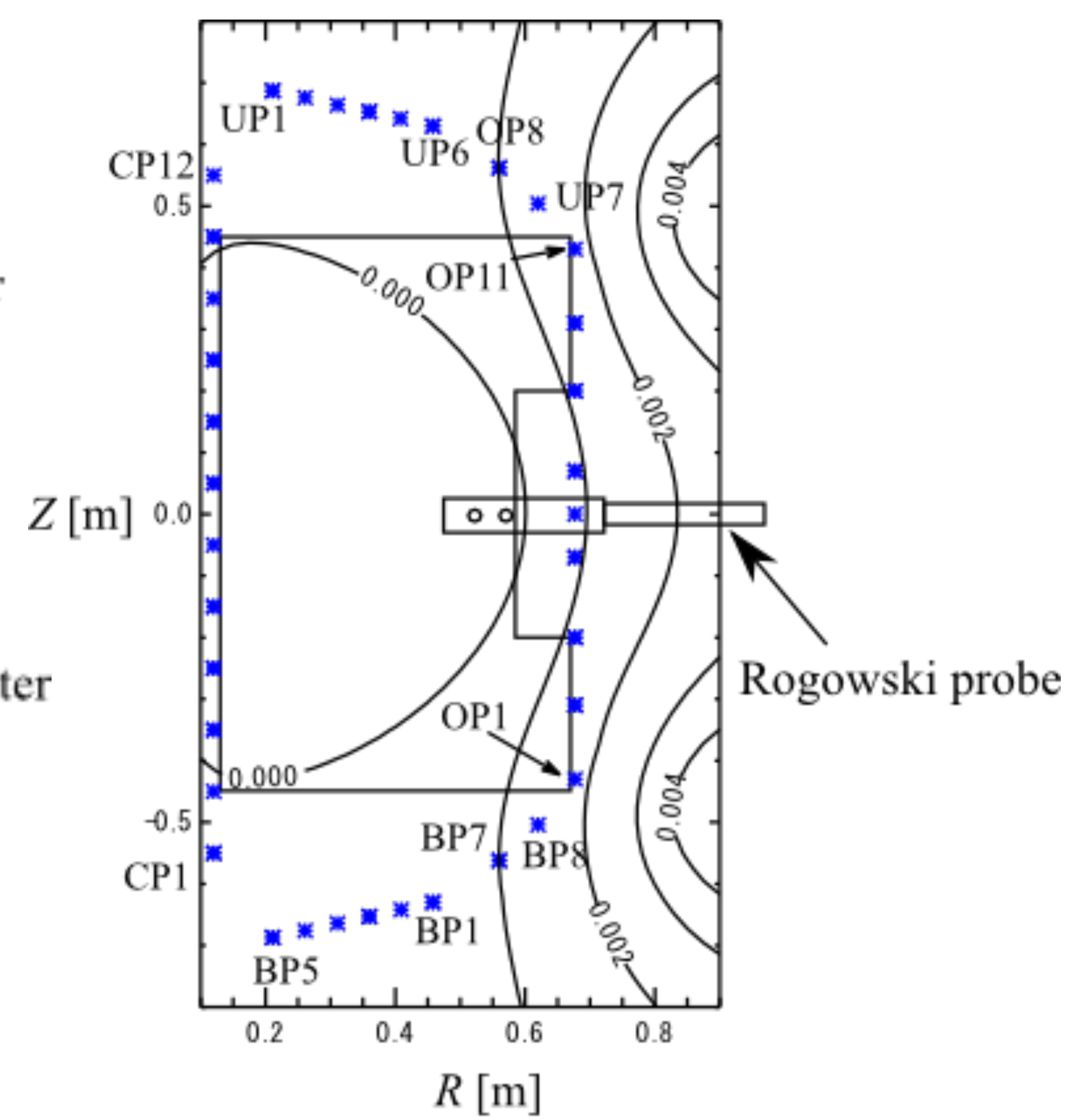
- Black : Open hole
- Red : Closed hole
- θ : 0°
- Noise signal for closed hole case is very small compared with the signal for open hol case

H. Furui, et al., Rev. Sci. Instrum. 85, 11D813 (2014).

Experimental setup



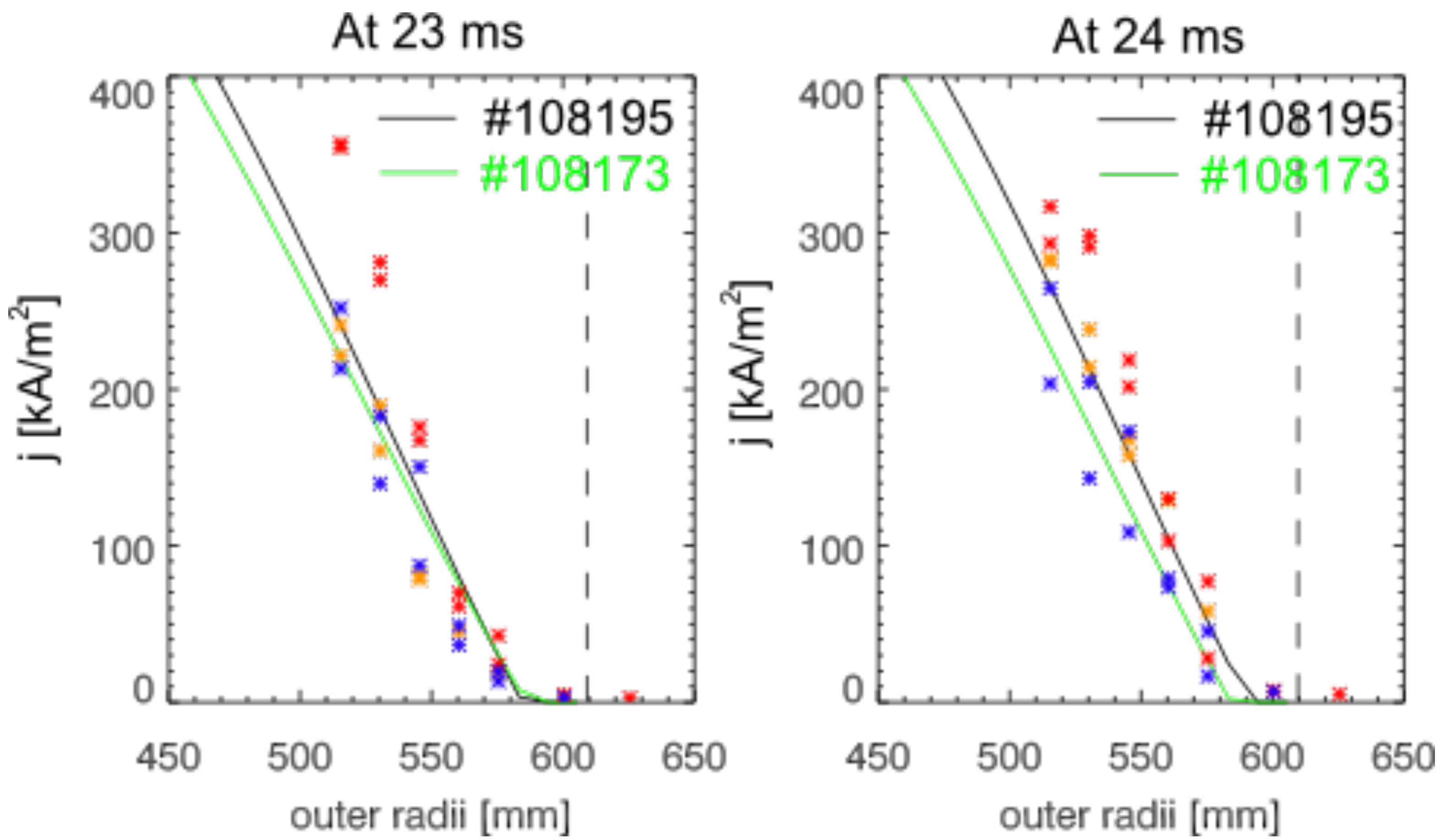
Top view at Z = 0

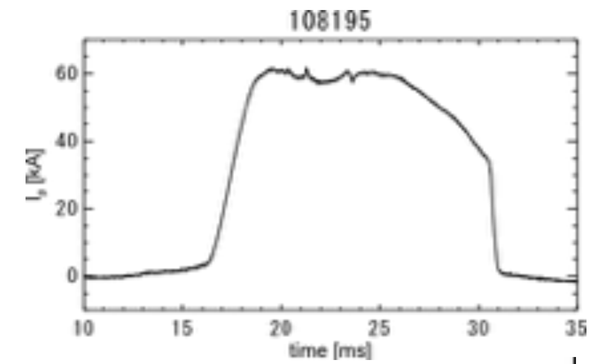


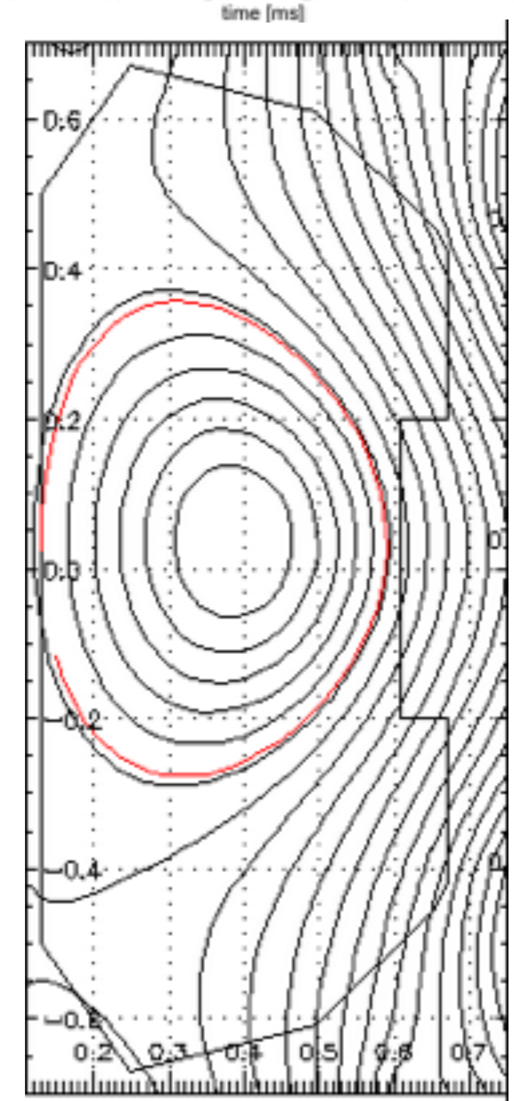
Poloidal cross section

- Blue symbols in poloidal section : locations of pick-up coils in TST-2.
- Interferometer in top view measures line-integrated density at $Z = 0$.
- Fast camera detects visible light emissions up to 1,000,000 frame per second

Current density measurement for inboard-limited plasma discharge ($R_{LCFS} < R_{ant\text{-}lim}$)







Magnetic surface at 24 ms
red line : LCFS

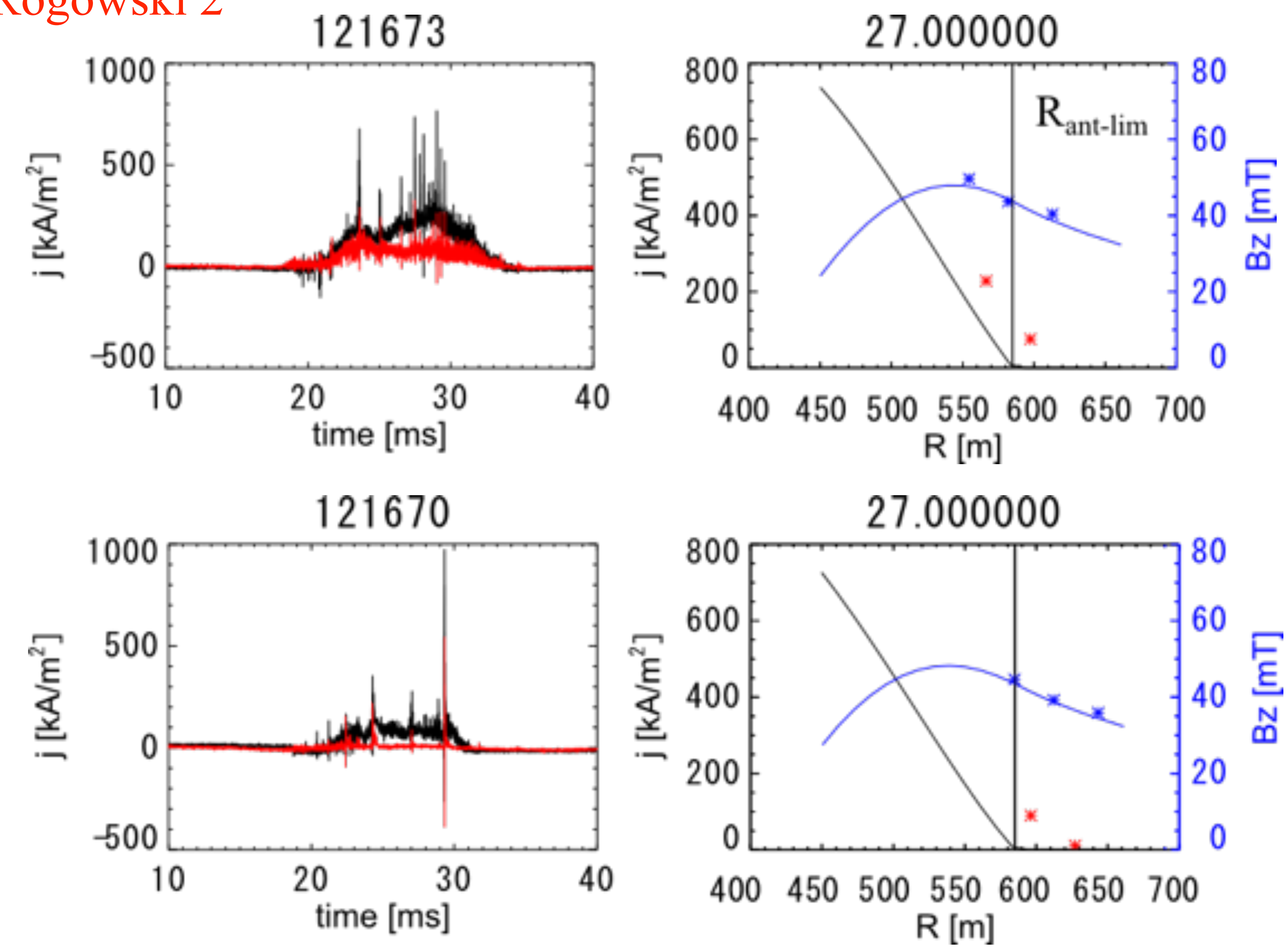
- Symbols : experiments ((blue, red, orange) = (10°, 15°, 20°))
- lines EFIT (black w/o probe insertion, green w/ deep probe insertion)
- Good agreement between experiments and EFIT was obtained where R < 550 mm
- No agreement where R > 550 mm

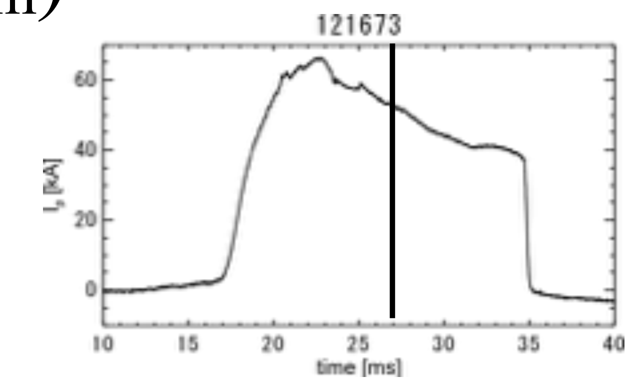
H. Furui, et al., Rev. Sci. Instrum. 85, 11D813 (2014).

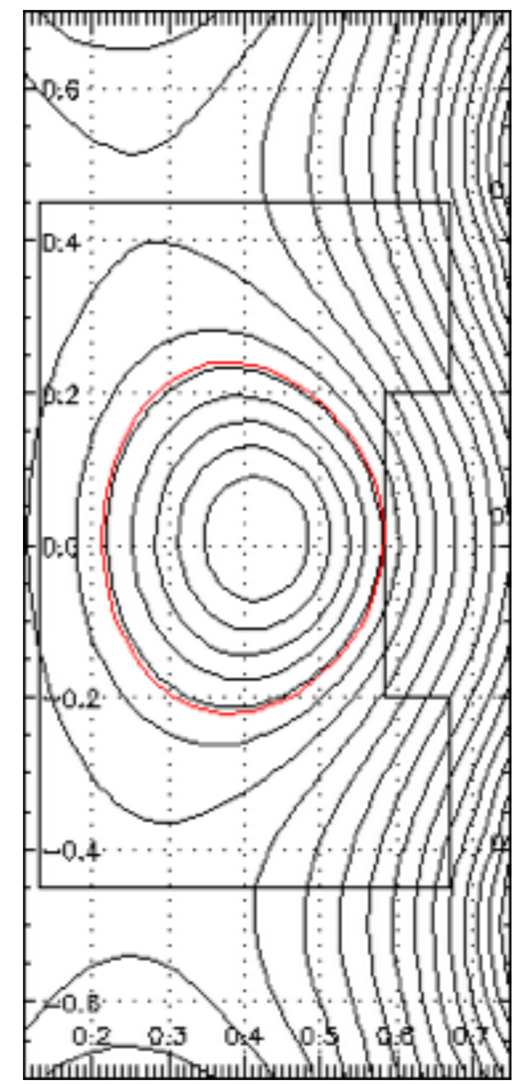
Current density measurement for outboard-limited plasma discharges ($R_{\mathrm{LCFS}} = R_{\mathrm{ant\text{-}lim}}$)

Rogowski 1
Rogowski 2

Symbols : Experiment
Lines : EFIT



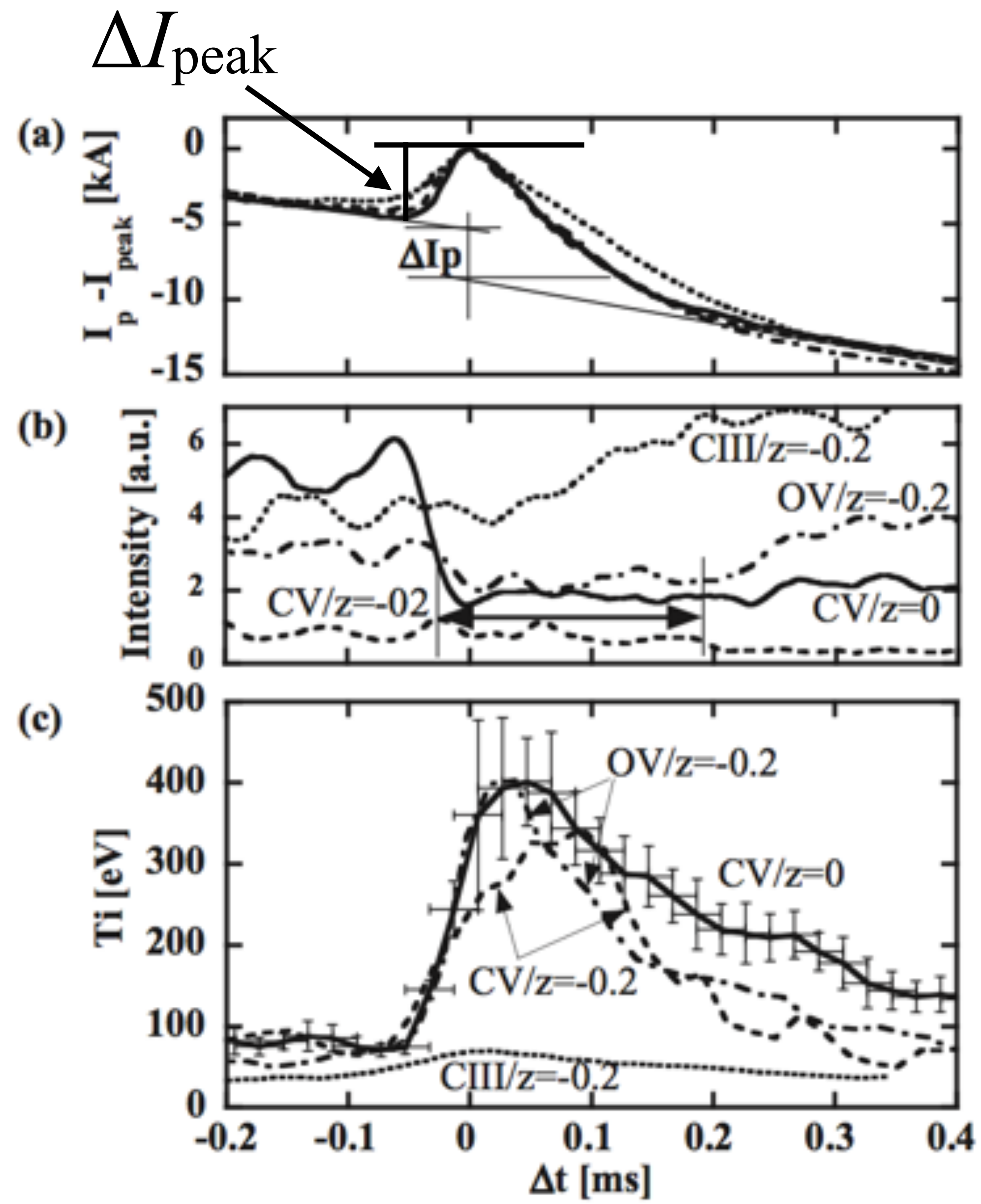


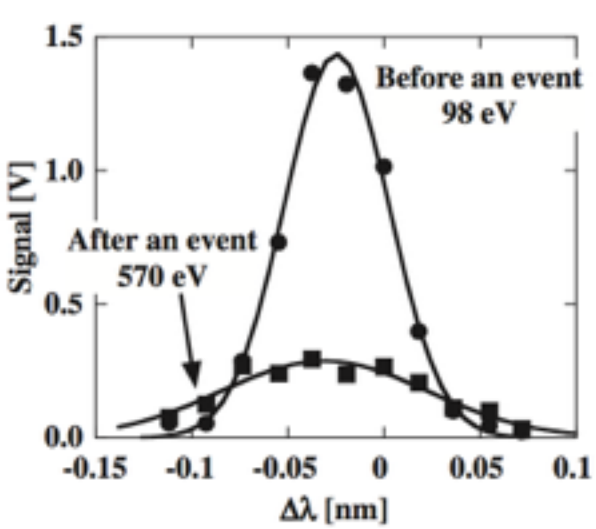


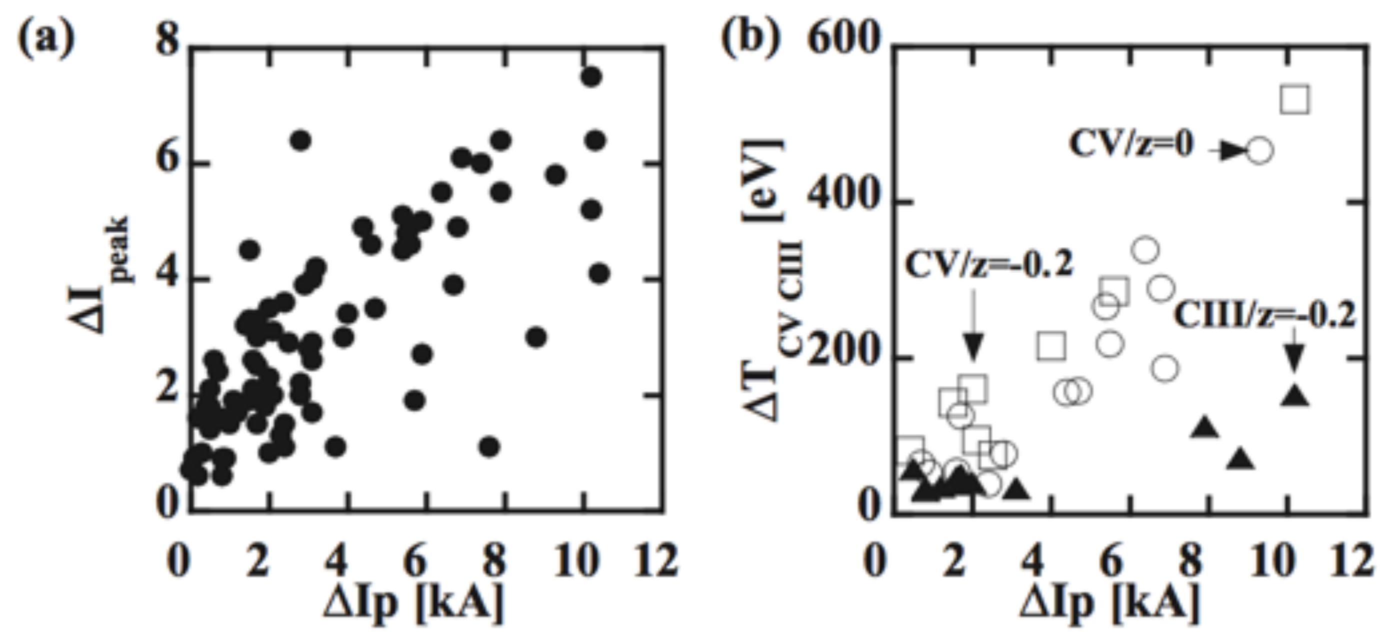
Magnetic surface at 27 ms
red line : LCFS

- Clear signal was observed even if the Rogowski coils are located behind the limiter ($R > R_{\mathrm{ant\text{-}lim}}$)
- The location for $j = 0$ from the experiment is far from $R_{\mathrm{ant\text{-}lim}}$.
- Current density profile cannot be reconstructed by EFIT code in outboard-limited plasmas case.

IREs (Internal reconnection events) in TST-2



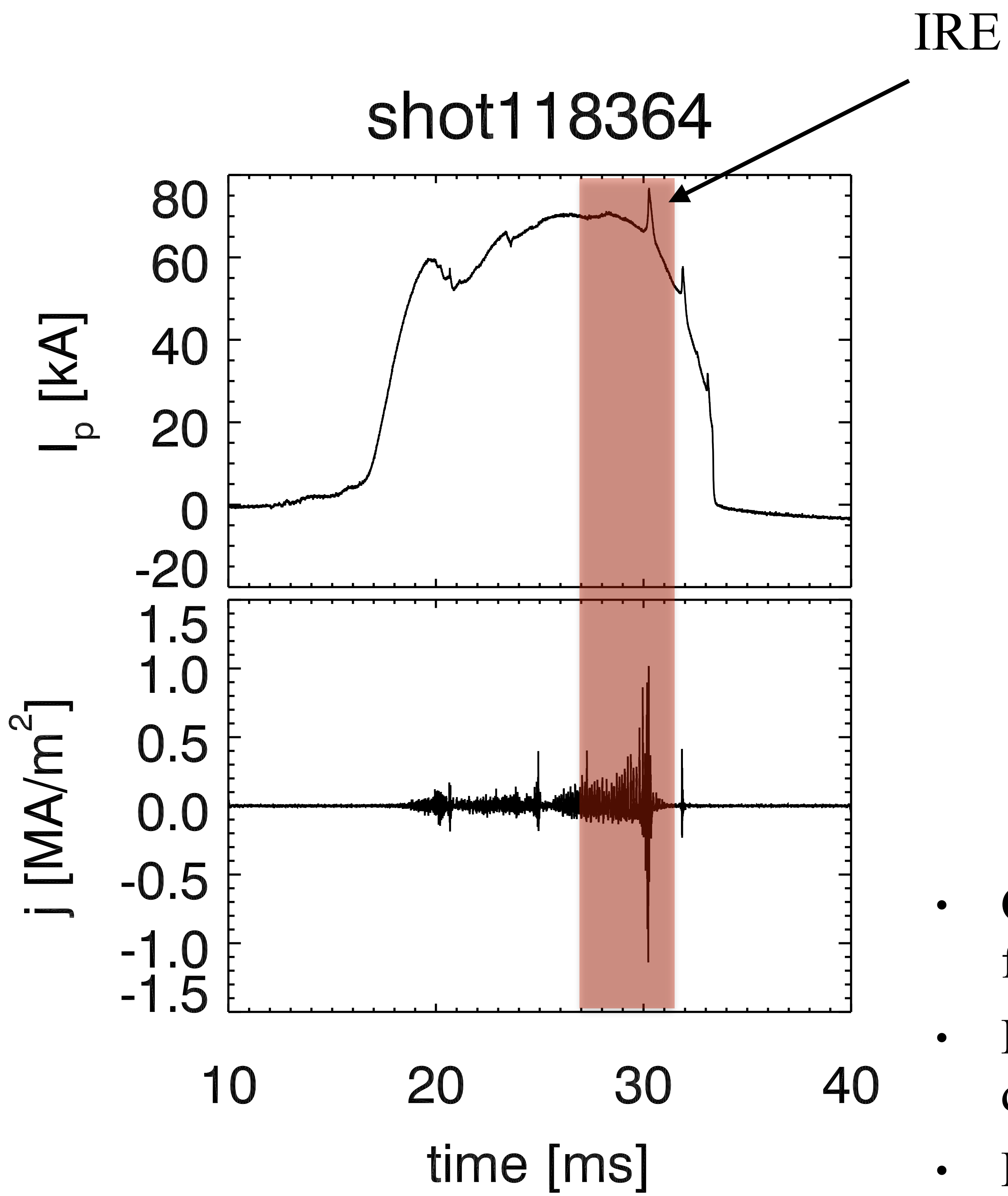


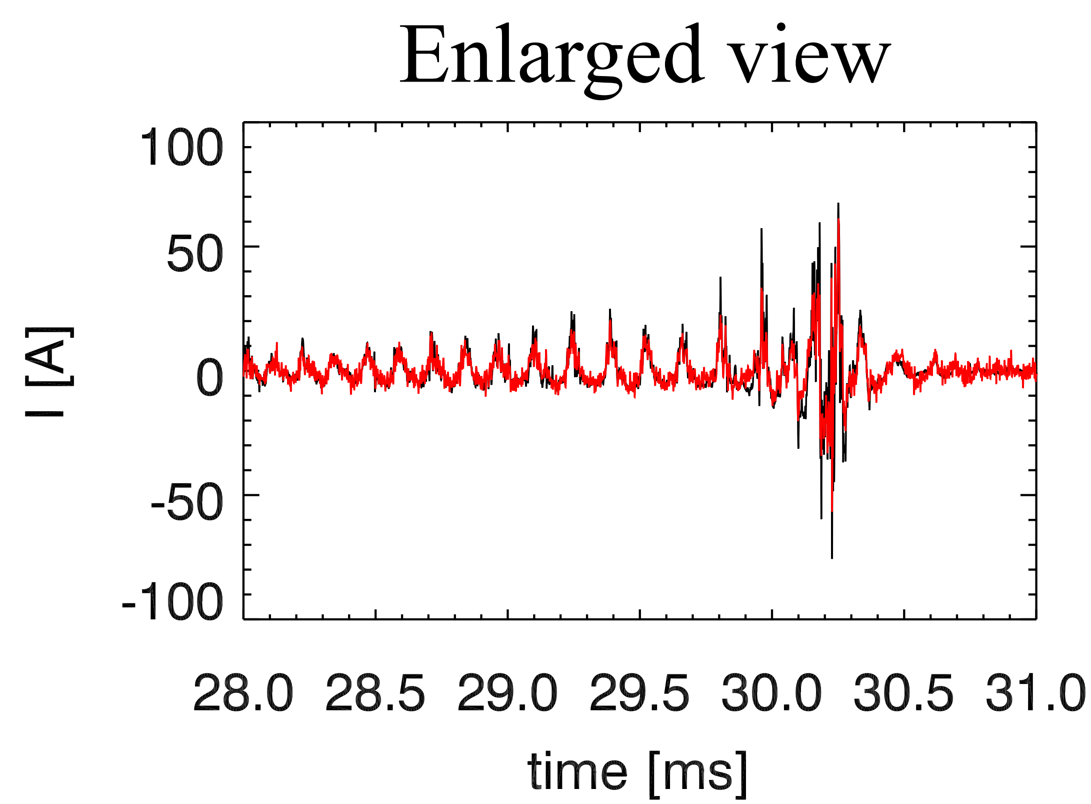


- IREs are a representative MHD phenomena for spherical tokamaks.
- IREs can cause a significant energy loss and have possibilities to damage plasma facing components.
- In TST-2, ion temperature T_i increase was observed during IREs and it was found T_i increases with the increase of ΔI_p (or ΔI_{peak}).
- We have no precedent of direct (or actual) measurement of local current density during IREs.

A. Ejiri, *et al*., Nucl. Fusion **43** (2003) 547-552

Measurement of local current fluctuation

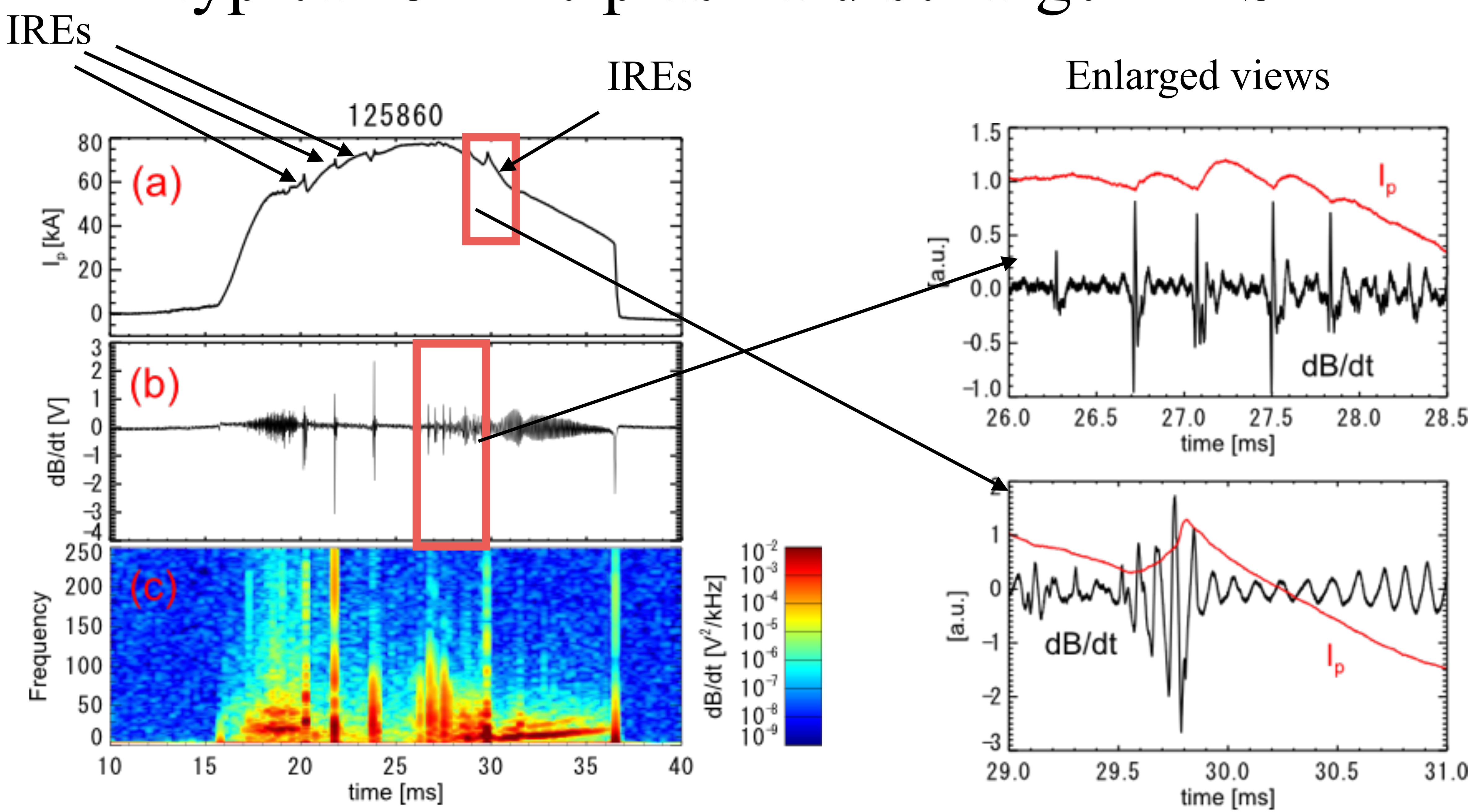




black : Measured by Rogowski 1
red : deduced from pick-up coil 1 and 2

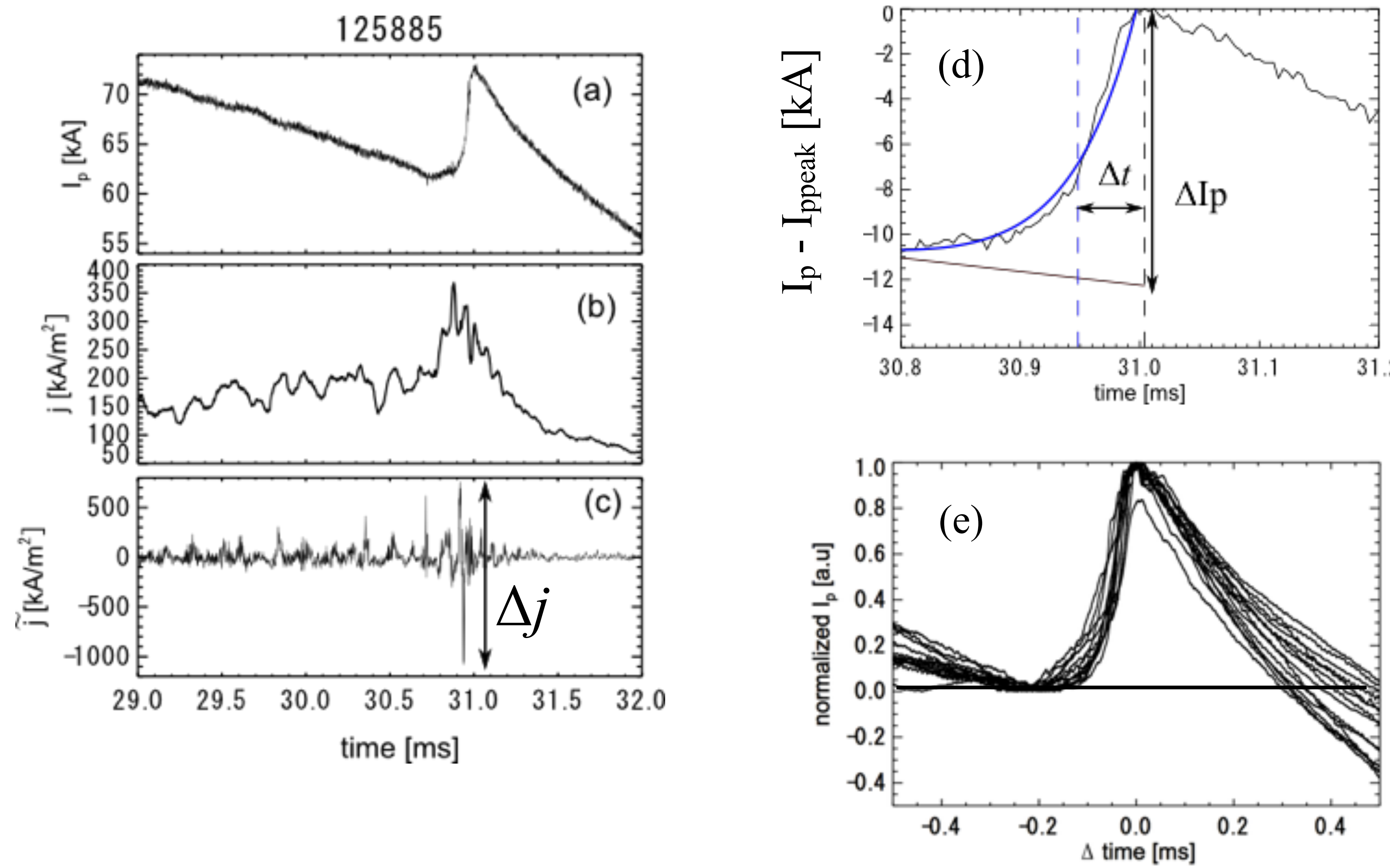
- Currents measured by Rogowski 1 and deduced from pick-up coil 1 and 2 agreed each other.
- Local current fluctuation in TST-2 was demonstrated.
- Especially at IRE, both negative and positive currents are observed.

A typical Ohmic plasma discharge in TST-2



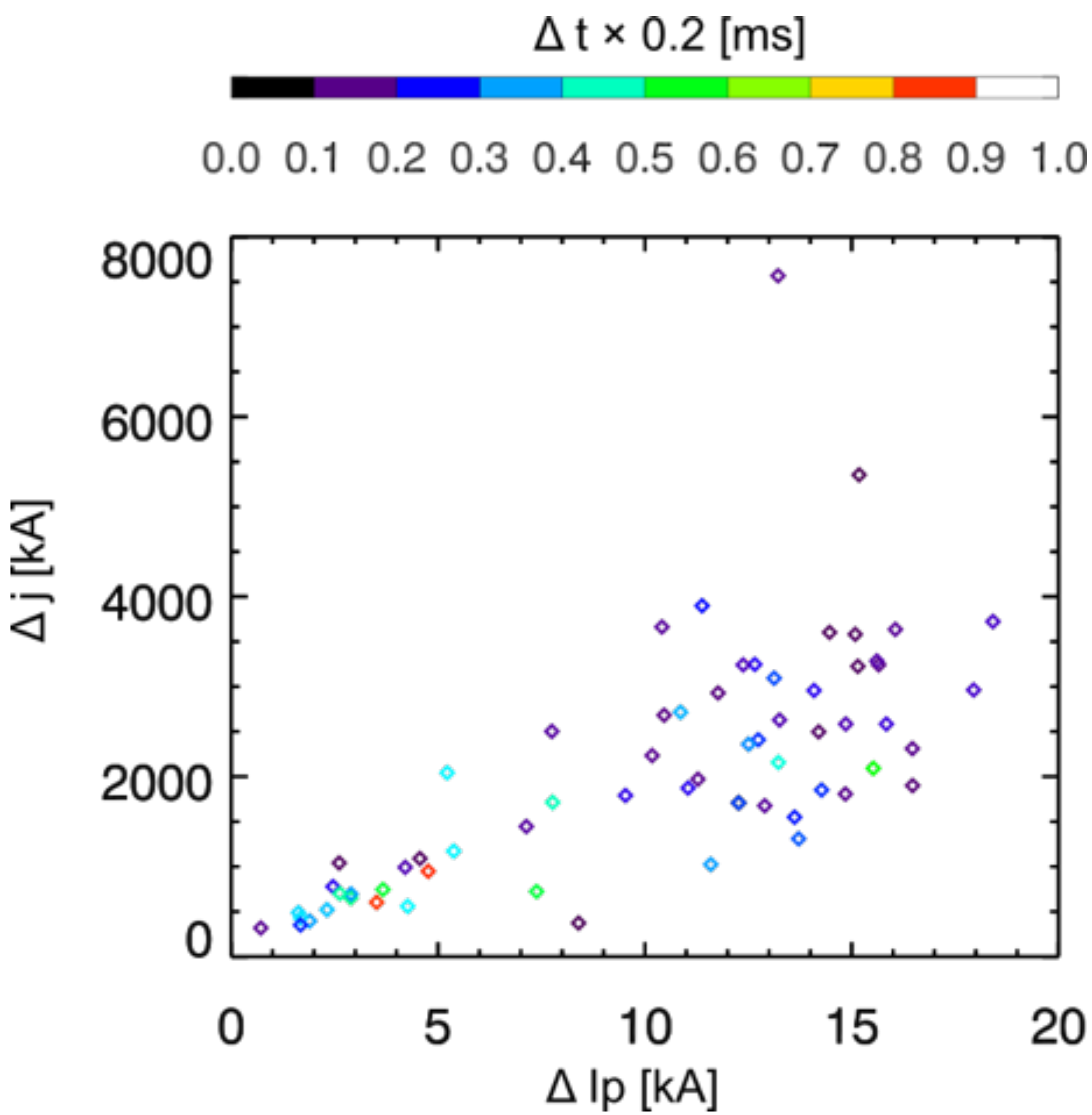
- In TST-2, IREs are observed during a plasma discharge.
- *dB/dt* (at (*R*, *Z*) = (0.7 m, 0 m)) fluctuations from 10 - several hundreds kHz at IREs.
- Sawtooth oscillations from 26 to 28.5 ms.
- Forms of I_p spikes and *dB/dt* for IREs and sawtooth oscillations are appeared to be different.

Characterization for IREs



- Plasma current I_p (a), slow time change of current density j, (b), fluctuation of j above 2 kHz (c) enlarged view for I_p (d), and shot variance of normalized I_p spikes.
- ΔI_p and Δj : magnitude of I_p spike and local current j spike caused by IRE.
- Δt : time scale for IRE
- (e) shows normalized I_p spikes calculated using ΔI_p (for Δt = 0.4 ± 0.1 ms). IRE can be characterized by using Δt.

Relations between ΔI_p, Δj and Δt



- Δj appears to increase with the increase of ΔI_p.
- Above $\Delta I_p > 5$ kA, the scatter of the data points increases.
- Typical Δt can be seen as 0.3 - 0.6 ms.
- Clear relation between ΔI_p and Δt, and Δj and Δt cannot be see.

Typical time relations before and after plasma current spike

Fig. 1

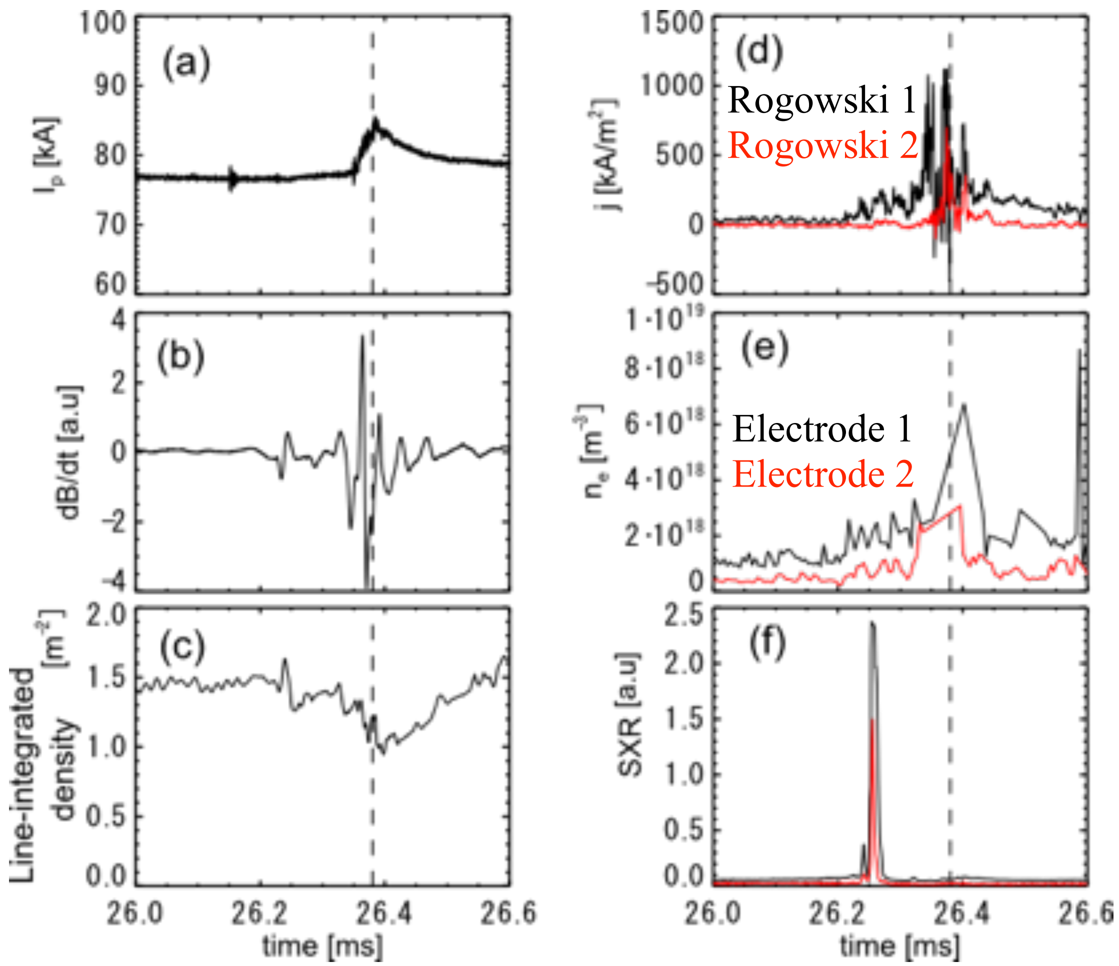
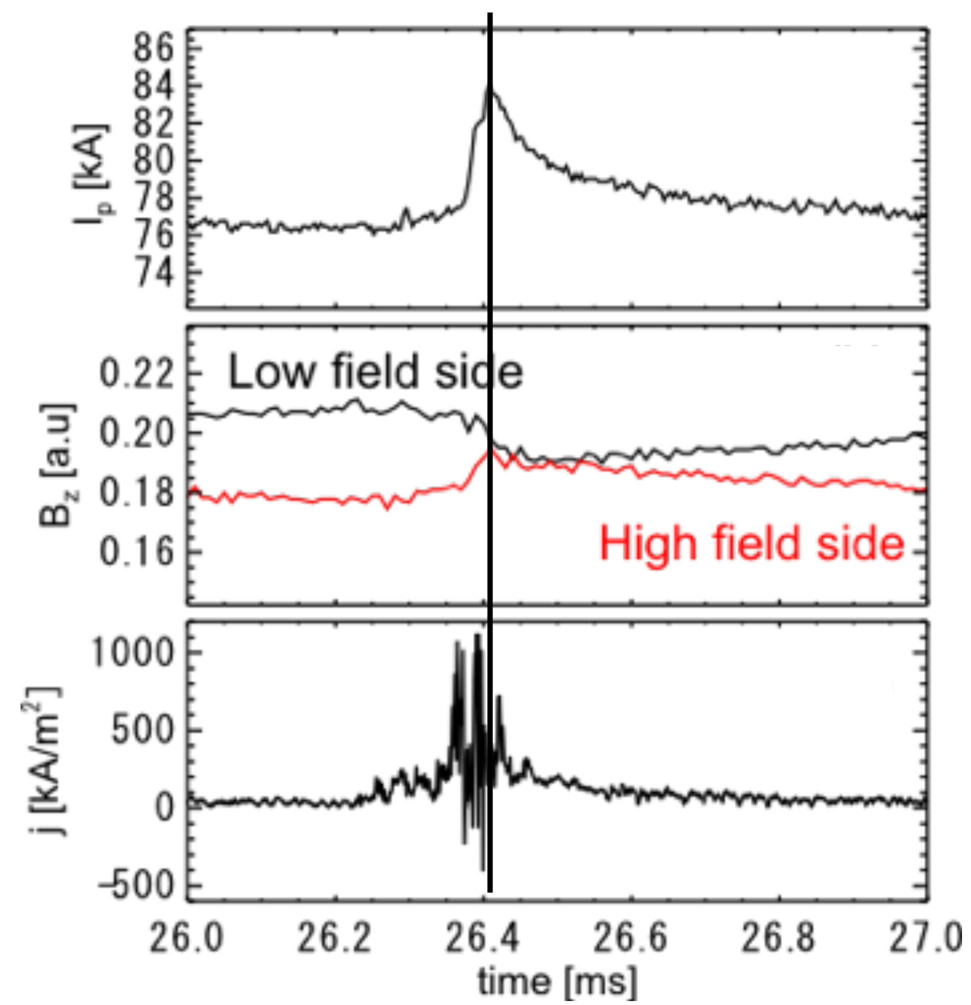
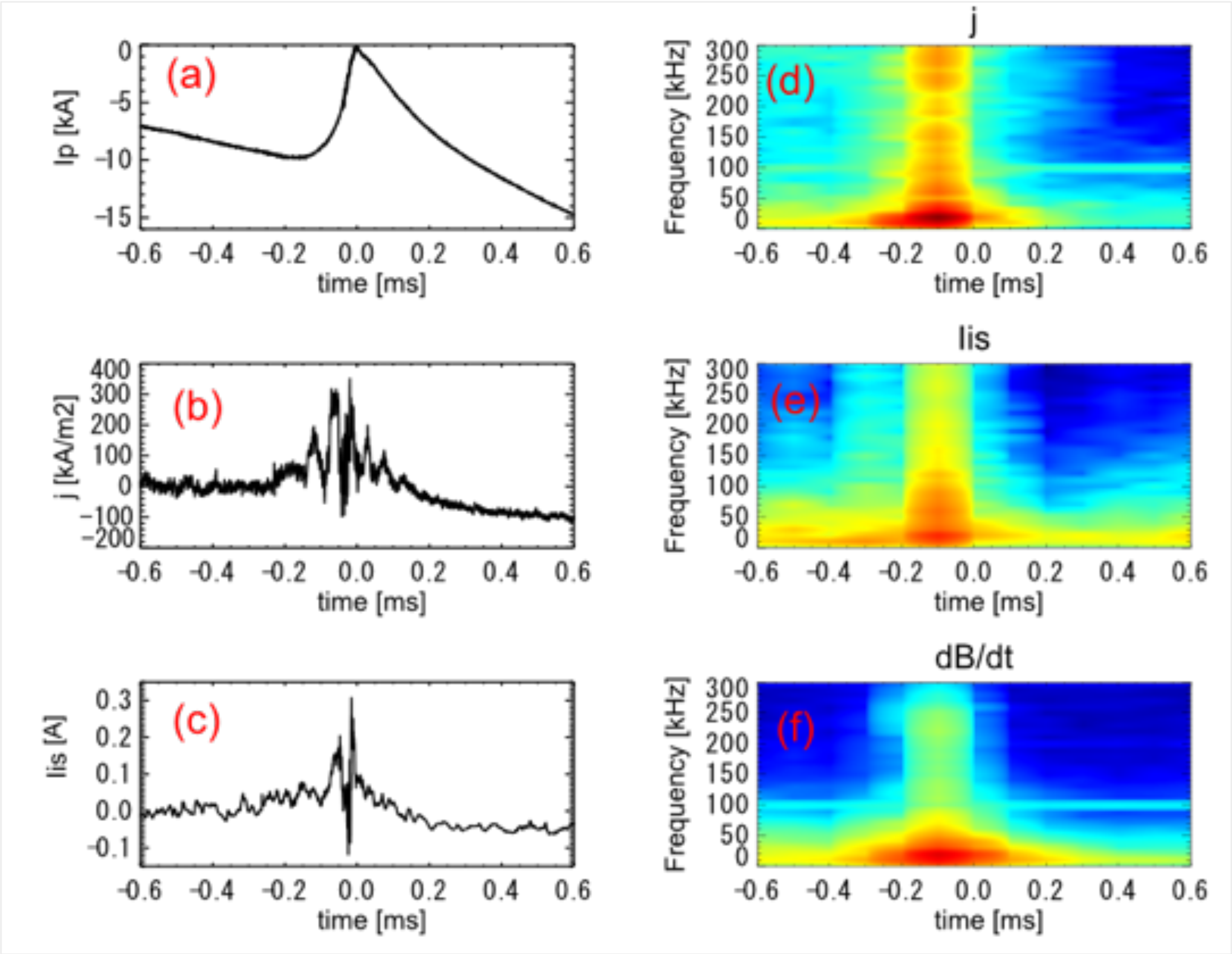


Fig. 2



- Fig. 1 → Before the peak of plasma current,
  - edge current density, j, and edge density n_e starts to increase.
  - dB/dt starts to fluctuate.
  - line integrated density starts to decrease.
  - SXR (up to 400 eV (red), several keV (Black)) shows sharp spike
- Fig. 2 → After the increase of edge current density j,
  - large fluctuations for j appeared
  - with the start of j fluctuation, B_z in high and low field side start to increase and decrease
- As a result, plasma moves from outside to inside, plasma current shows a spike.

Time relations for averaged plasma current, edge current density and ion saturation current

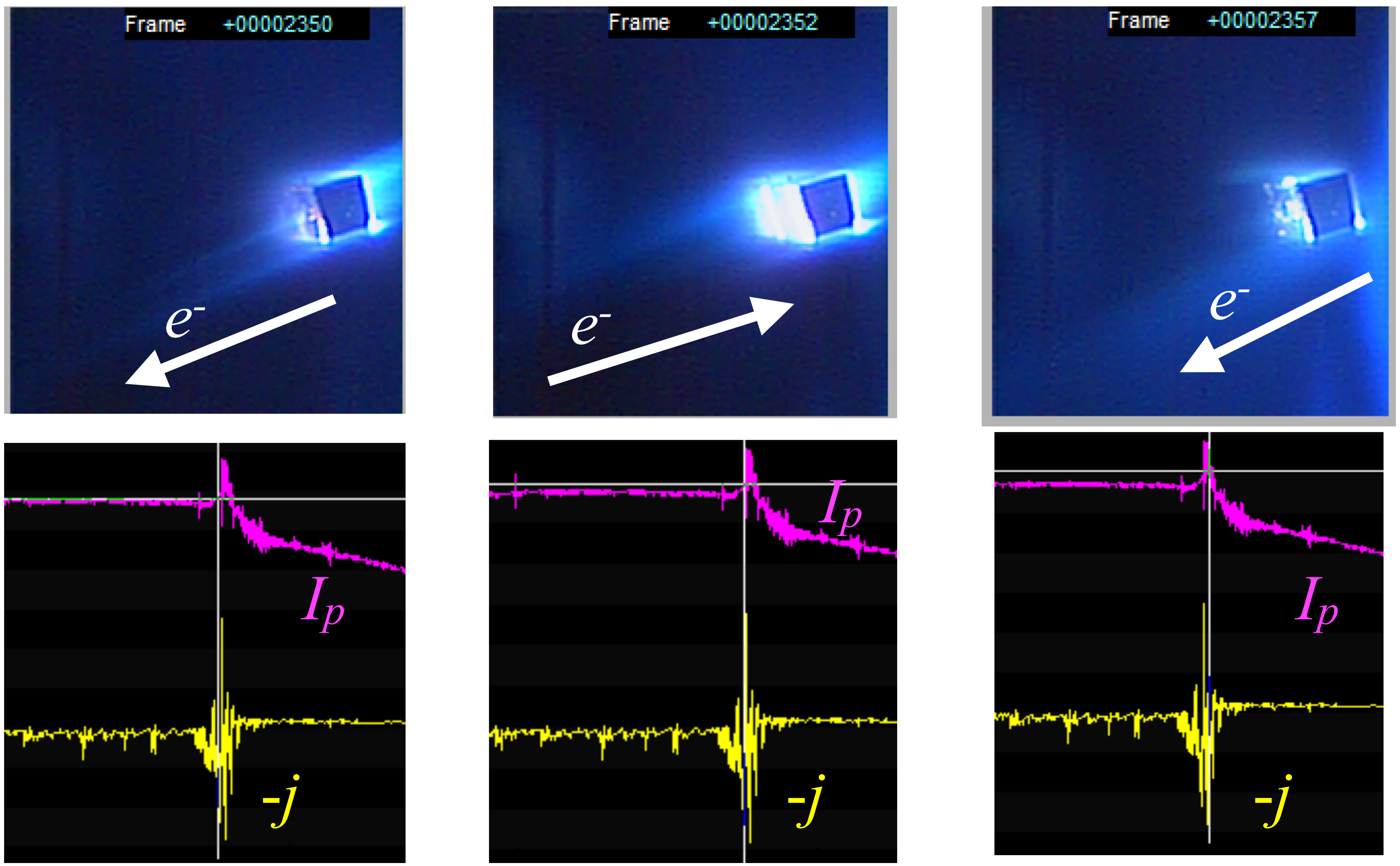


Averaged over 18 shots with various ΔIp cases and with $\Delta t = 0.4 \pm 0.01$ ms

1. Fluctuations of j, I_{is} and dB/dt start 0.4-0.3 ms before the peak of plasma current.
2. j and I_{is} at the plasma edge start 0.2 ms before the peak of plasma current.
3. After the increase of j and I_{is}, high frequency fluctuations are induced for j, I_{is} and dB/dt.
4. I_p shows a peak after the decay of high frequency fluctuation. However, 10 kHz.
5. I_p shows a peak after the decay of high frequency fluctuation. However, 10 kH fluctuations still exist after the peak of plasma current

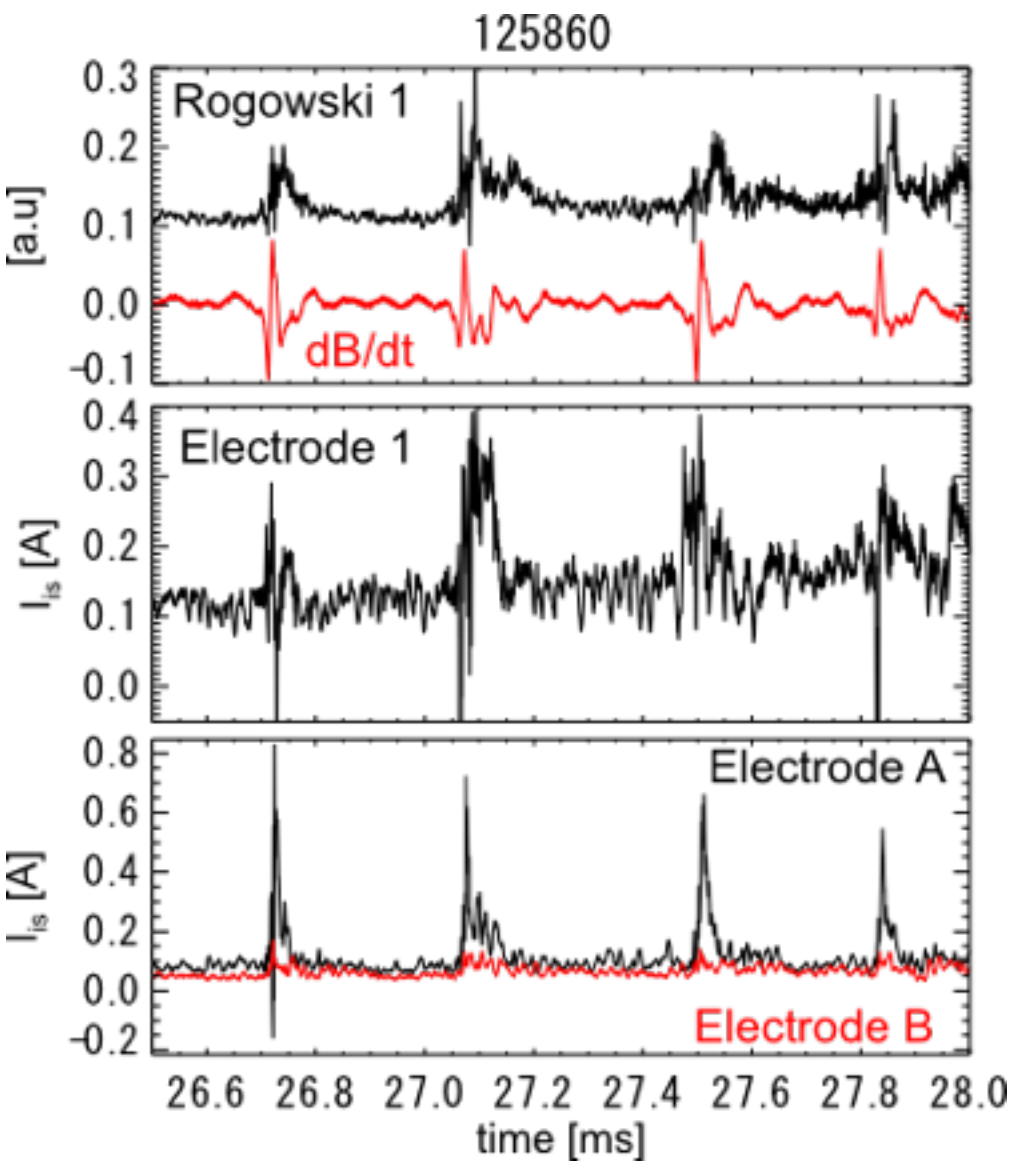
- 10 kHz fluctuations 0.2 ms before the plasma current peak transport the current and density from plasma center to plasma edge.
- Abrupt changes of j and n_e can cause significant high frequency fluctuation.
- After the decay of high frequency fluctuation, plasma moves from outside to inside again.
- As a result, the plasma current shows a peak.

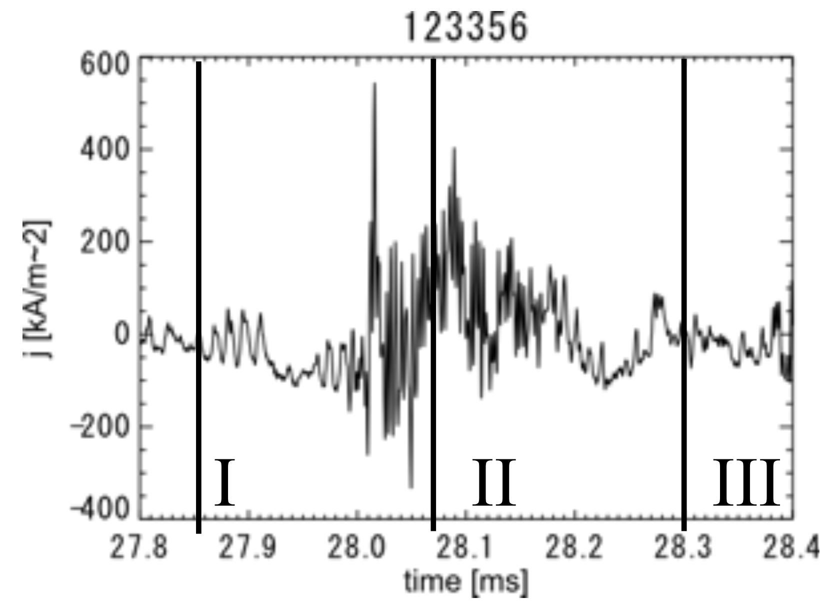
Visible light emissions from the Rogowski probe before and after plasma current spike

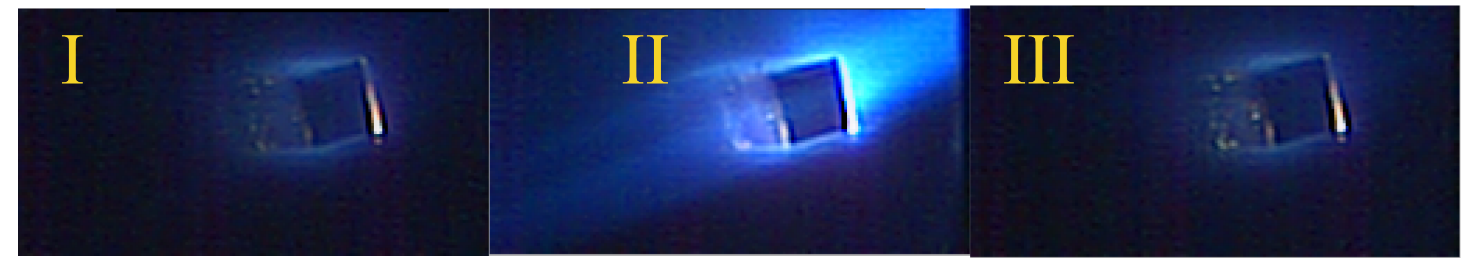


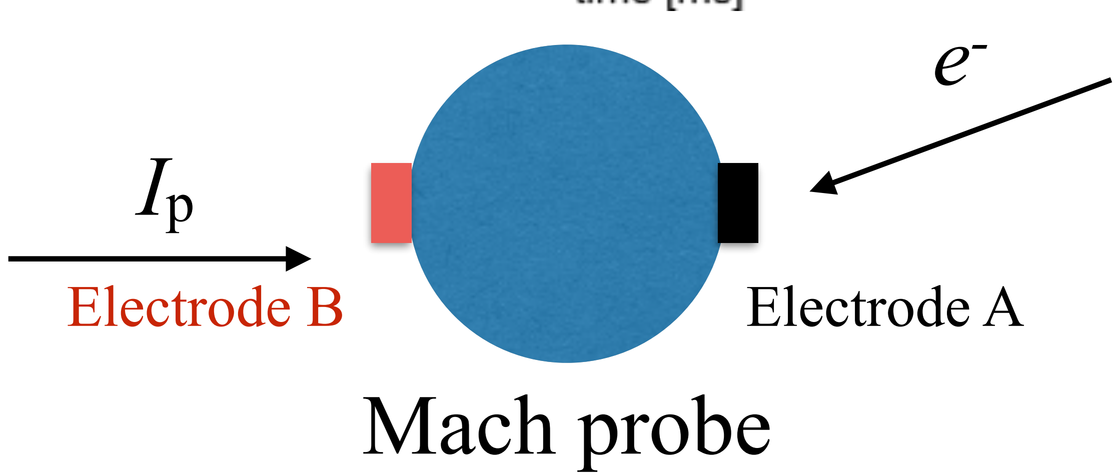
- Visible light emission inverts when the local current signal shows negative spikes.
- This experimental result certainly reveals the existence of negative current at IREs.

Blob like current density signals at sawtooth oscillations of *dB/dt*









- Blob like signals (spikes) can be seen for j, I_{is} (Electrode 1, 2, A and B).
- Spikes for I_{is} have an asymmetric in toroidal direction.
- At the same timing of sawtooth oscillations for *dB/dt*, j and I_{is} show the spikes.
- Visible light emissions also can be observed at the time of spikes.
- It is inferred that current spikes are due to a locally dense filamentary structure passing through the Rogowski coil.

Conclusions

- Measurement of plasma equilibrium and fluctuations were performed using a Rogowski probe.
- Good agreements between experimentally obtained current density profiles and calculated profiles from EFIT code were obtained for inboard-limited plasma case.
- For outboard-limited plasma case, currents behind the limiter was observed and such current cannot be reconstructed by EFIT code.
- Measurement of current density during IREs were successfully carried out and the negative current during IREs were discovered.
- We succeeded in clarifying a time relation of plasma parameters (i.e., current and density fluctuations → transports of them from plasma center to plasma edge → high frequency fluctuations → plasma movement from outside to inside → plasma current spike)
- Blob like spikes are also newly observed and, the visible emission, ion saturation current spikes and *dB/dt* sawtooth oscillations appear at the same time of local current spikes.