



TSC Simulation of ITB Crash and Following Disruption Dynamics on JT-60U High- β Reversed Shear Plasmas

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Motivation

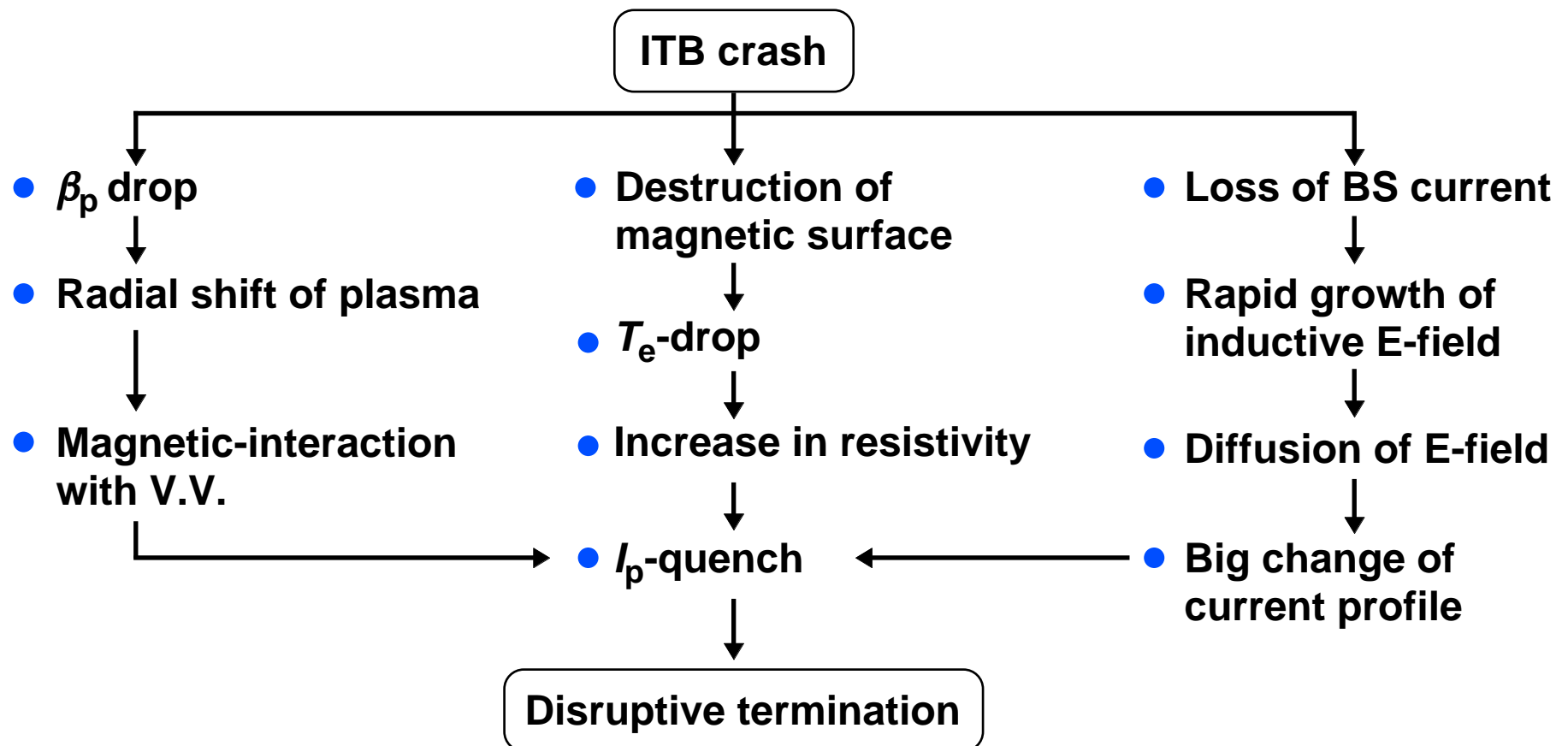
- While Reversed Shear (**RS**) operation with Internal Transport Barrier (ITB) is most promising candidate mode for advanced scenarios, sudden disruption limits the performance and feasibility of advanced tokamak reactors.
- In JT-60U, fast current quenches have been observed in high performance **RS** discharges, and its physics reason is not well understood at present.

Y. Kawano *et al.*, 30th EPS, St. Petersburg, Russia, 2003.

Elucidation of the variety of JT-60U disruption characteristics of high β , **RS** plasmas is necessary, taking account of ITB-generated, high Bootstrap (BS) current, self-consistently.

Contents

- A self-consistent study with high BS current using Tokamak Simulation Code (TSC) clarified a detailed process of ITB crash and following disruption dynamics of JT-60U high β , RS and Positive Shear (PS) plasmas.



TSC Modeling

- Momentum eq.

$$\frac{\partial m}{\partial t} + F_v(m) = j \times B - \nabla p$$

m : plasma momentum density
($=\rho v$)

$F_v(m)$: artificial viscosity operator
instead of $v \cdot \nabla v$

- Ohm's law : $j_{oh} = j_{total} - j_{bs}$

$$E + v \times B = \eta j_{oh}$$

- Faraday's law

$$\frac{\partial B}{\partial t} = -\nabla \times E ;$$

$$B = \nabla \phi \times \nabla \Psi + g \nabla \phi$$

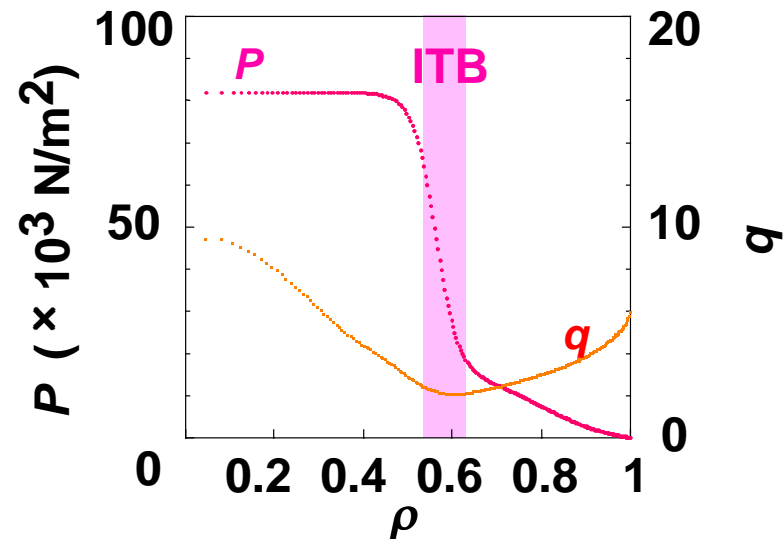
- ITB structure

Pressure profile prescribed, being consistent with magnetic shear profile.

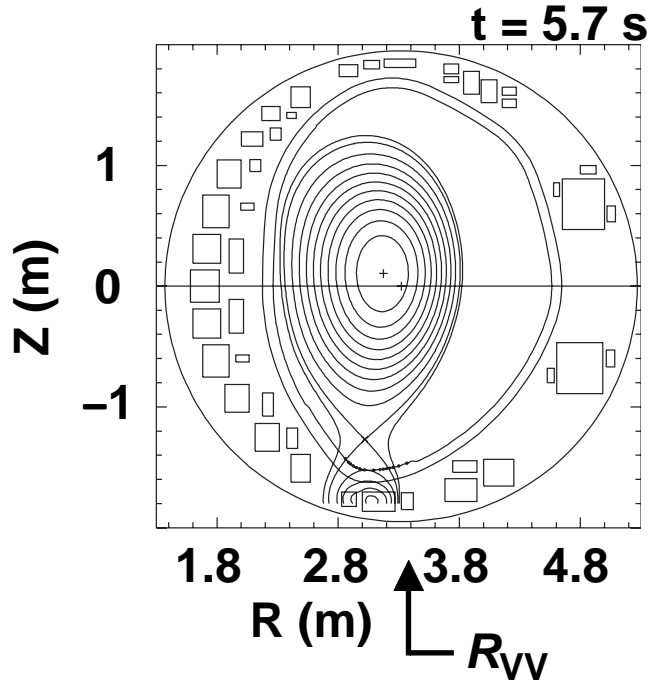
- BS current

$$\langle j_{bs} \cdot B \rangle = L_{31} [A_1^e + Z_i^{-1} T_i / T_e (A_1^i + \alpha_i A_1^e)] + L_{32} A_2^e$$

S.P. Hirshman, Phys. Fluids (1988).



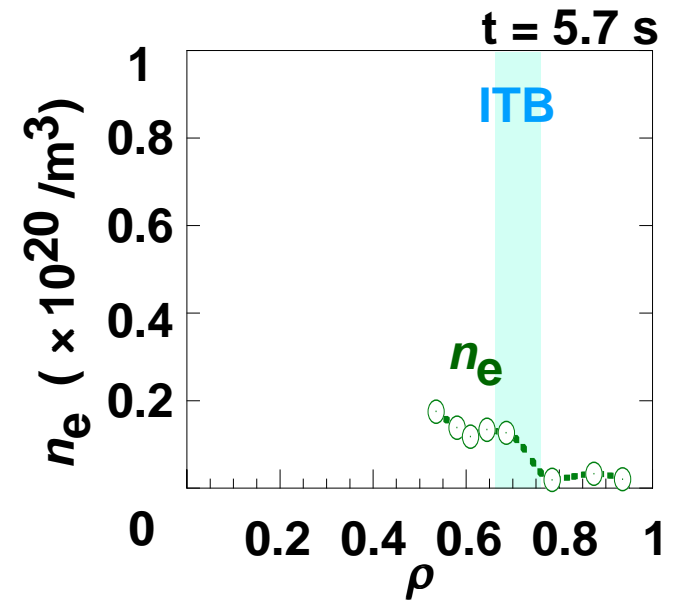
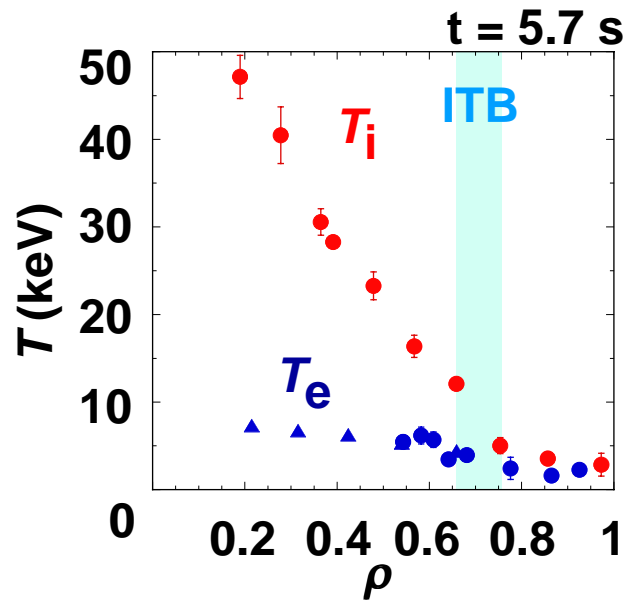
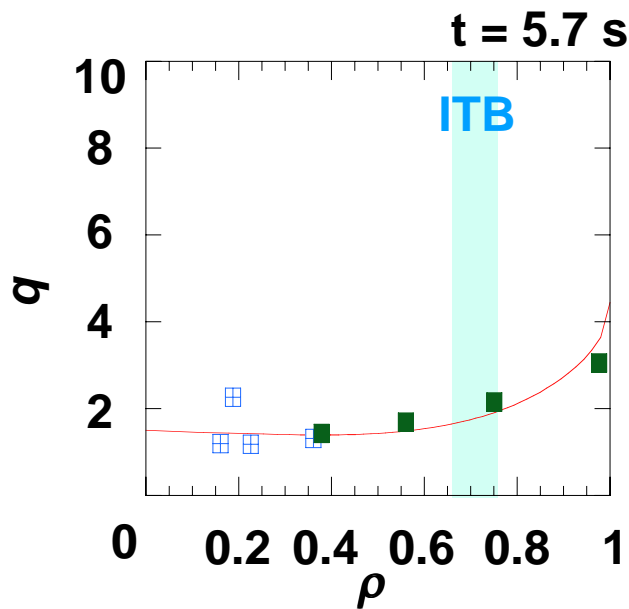
➔ ITB crash due to a forced β_p drop introduced to trigger disruptions.



- $I_p \sim 2.2$ MA, $\beta_p \sim 1.1$, $q_{\text{eff}} \sim 4.3$
before disruption (t = 5.7 s)

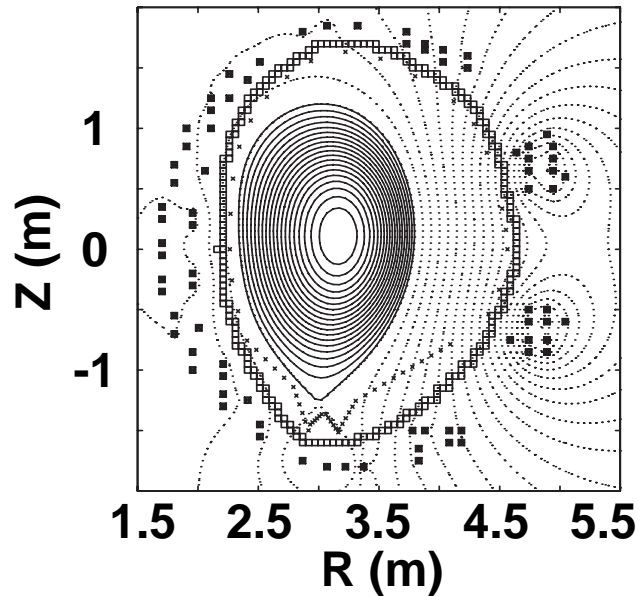
- $Z_J \sim 0.11$ m JT-60U neutral point for VDE avoidance
Y. Nakamura *et al.*, NF (1996).
- $R_J (\sim 3.2$ m) < $R_{VV} (\sim 3.4$ m)
positioned inner than V.V. center
N. Takei *et al.*, 30th EPS (2003).

- n_e and T_i ITB was located at $\rho \sim 0.7$.

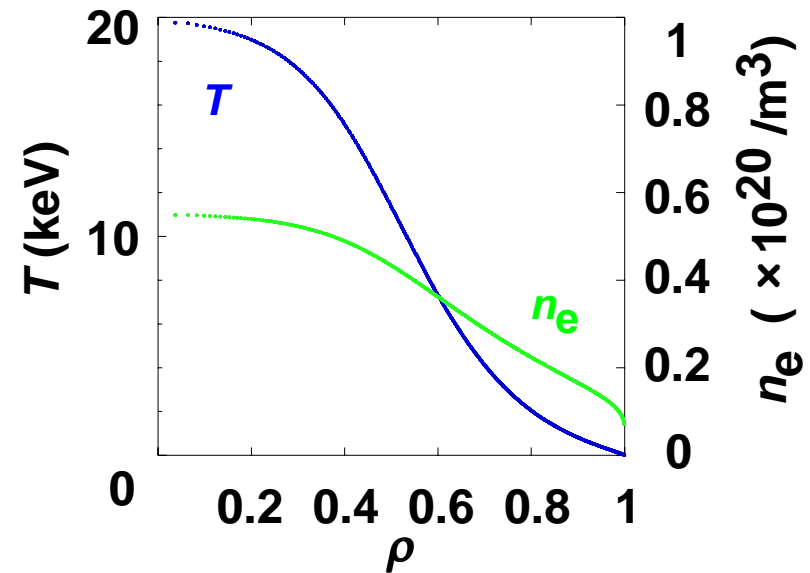
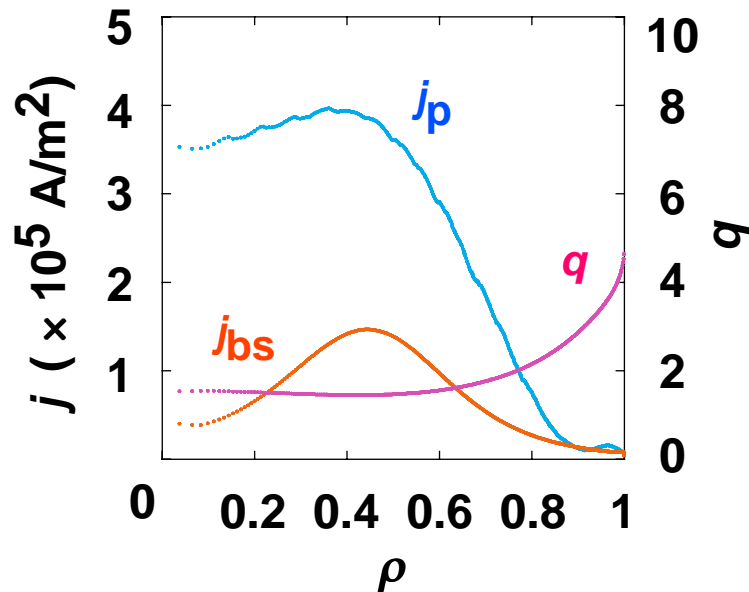
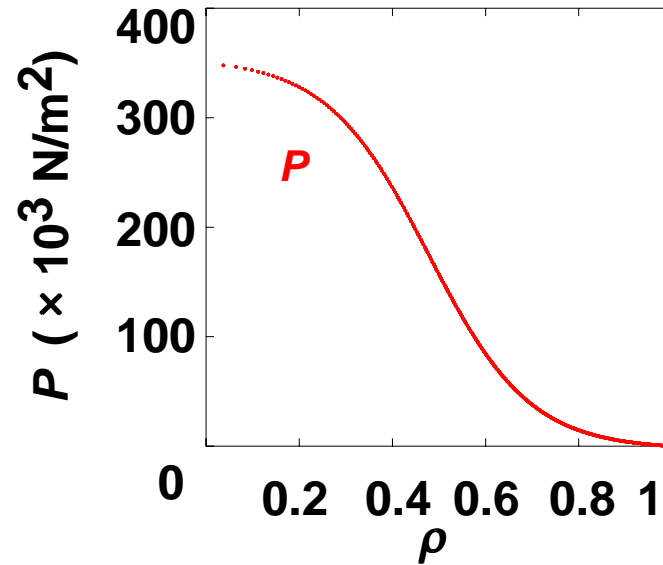


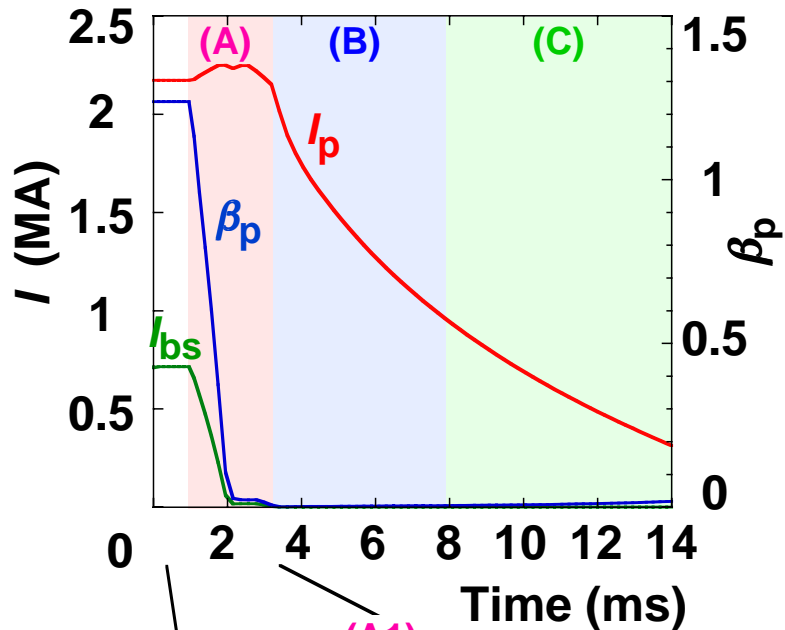
Initial Plasma Condition of TSC simulation

- $I_p \sim 2.2$ MA, $I_{bs} \sim 0.7$ MA, $\beta_p \sim 1.2$,
 $f_{bs}^{TSC} (=I_{bs}/I_p) \sim 0.3$



TSC configuration of JT-60U





(A) ITB crash

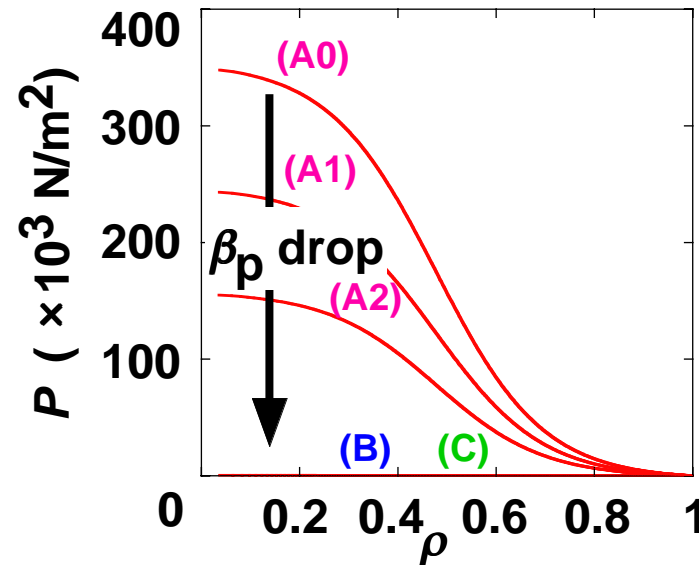
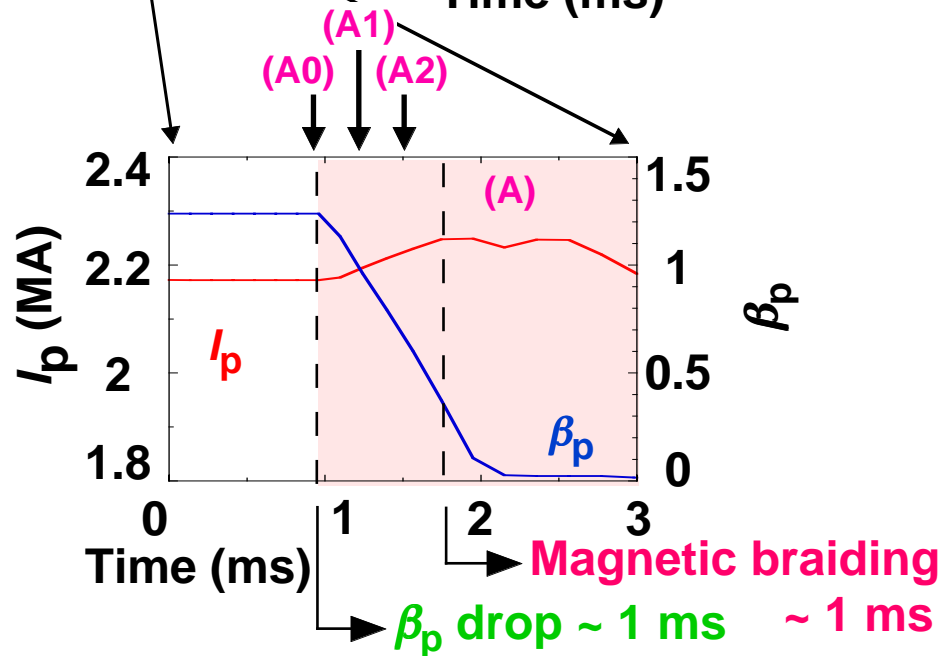
- β_p drop: leading to imbalance of radial force
- "Magnetic braiding": leading to relaxation of j_p profile

P.L. Taylor *et al.*, Phys. Rev. Lett. (1996).

→ Destruction of magnetic surface (e.g., tearing mode)

(B) Current profile change

(C) Shrinkage of plasma

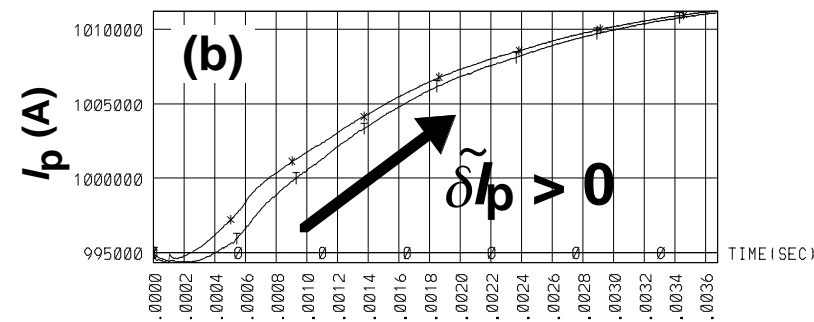
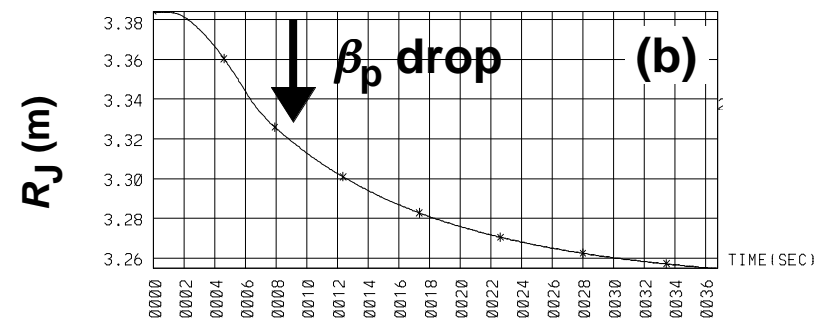
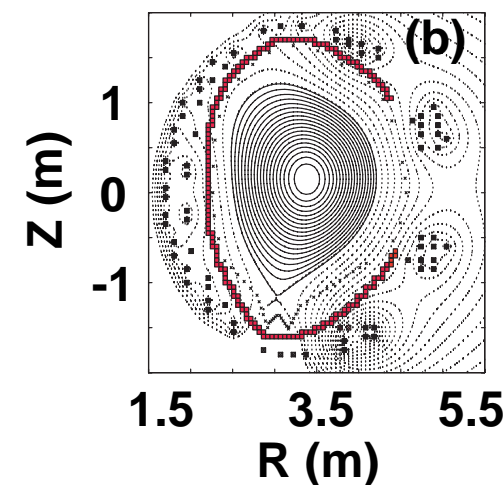
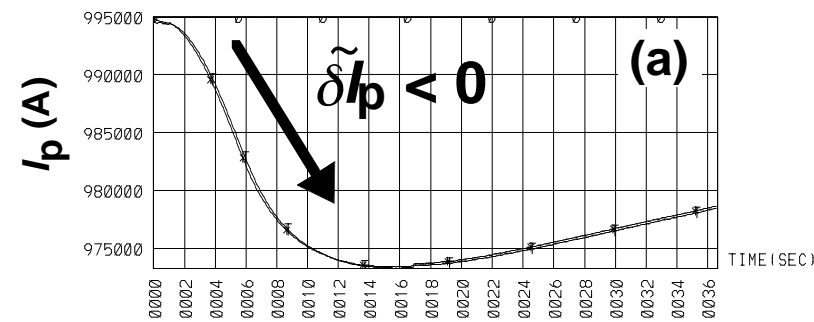
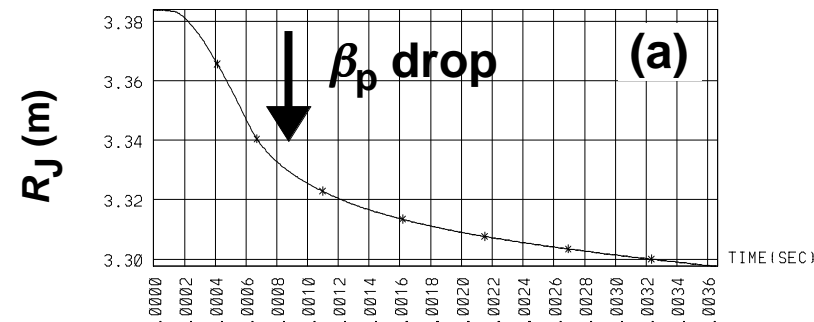
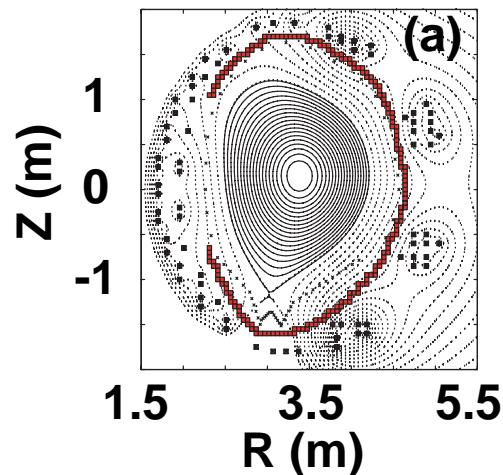
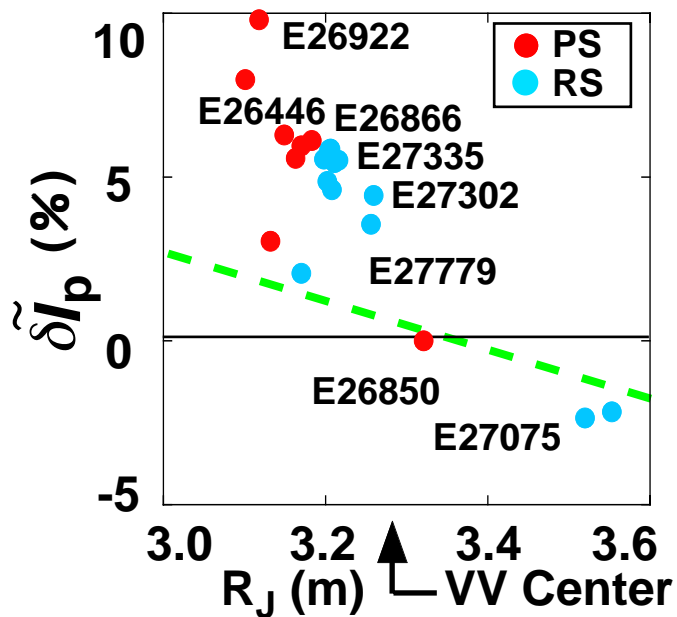


Radial Shift due to β_p Drop & Current Spikes

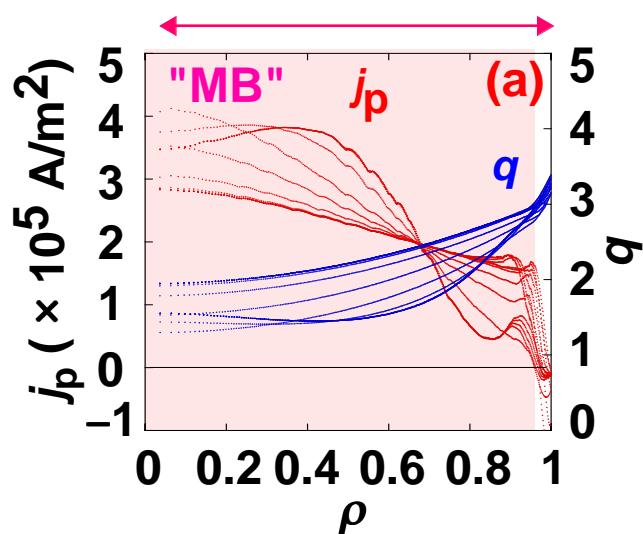
- Eddy current effect on $\tilde{\delta}l_p$ is opposite depending on the plasma radial position:

(a) outer $\tilde{\delta}l_p < 0$,

(b) inner $\tilde{\delta}l_p > 0$.



Model of Magnetic Braiding



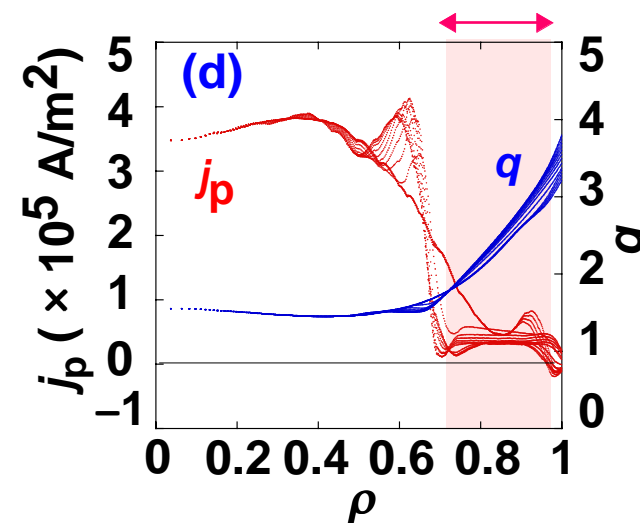
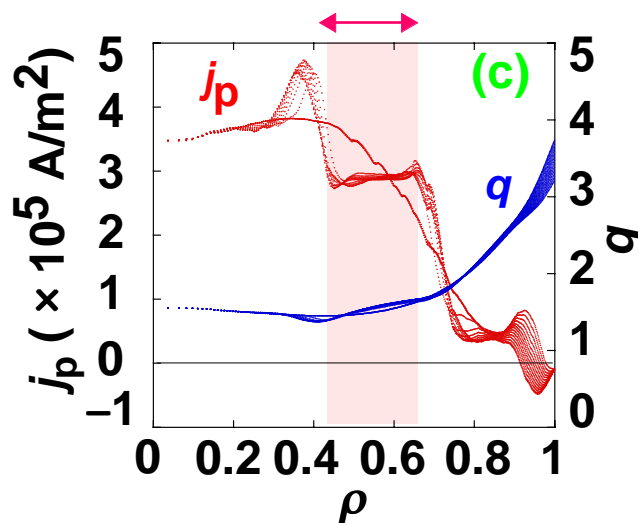
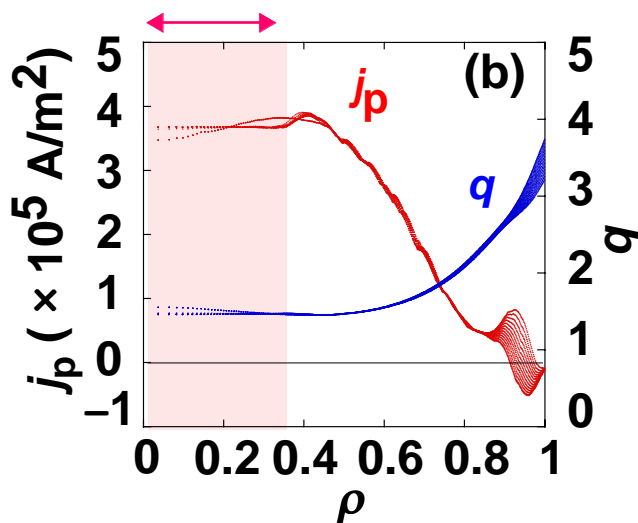
- $E + v \times B = \eta j - \frac{B}{B^2} \nabla \left(\lambda \frac{j_{||}}{B} \right)$

λ : arbitrary positive function

A.H. Boozer, J. Plasma Phys (1986).

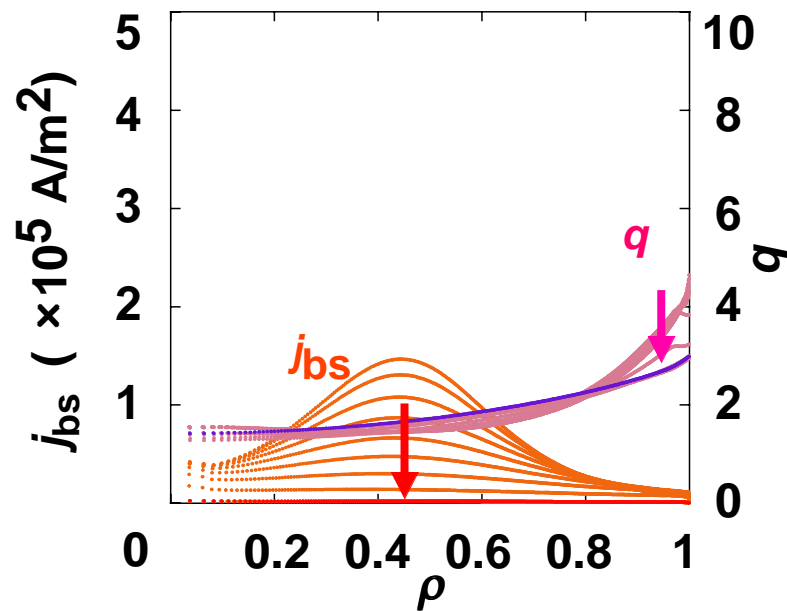
- "MB" over whole region causes a substantial I_p , l_i changes as observed in DIII-D.

P.L. Taylor *et al.*, Phys. Rev. Lett. (1996).



- Inside "MB" causes local j_p relaxation there, but little I_p , l_i changes.
- "MB" at plasma boundary causes small I_p , l_i changes.

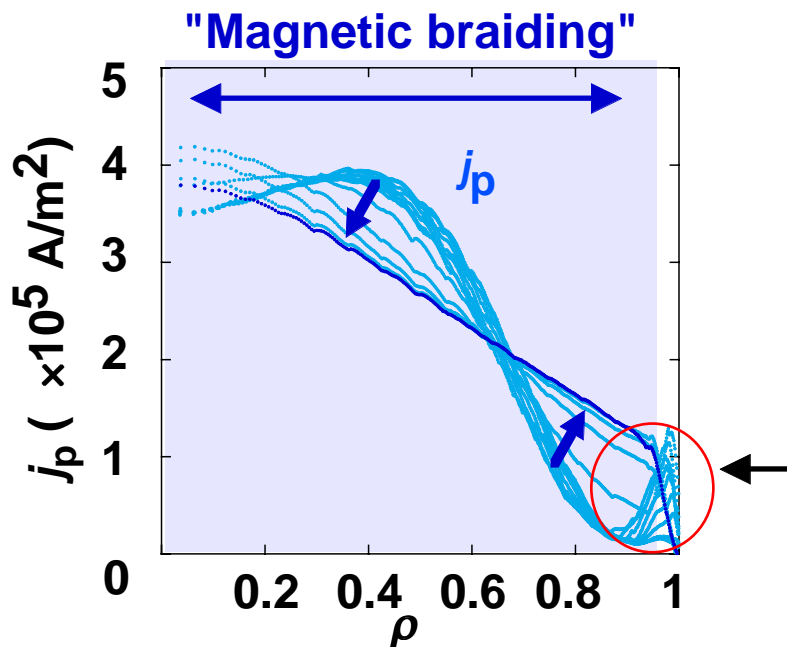
(A) ITB Crash (β_p drop & Magnetic braiding) (t = 1 - 3 ms) TSC



- Due to β_p drop, BS current disappears quickly.

- However, j_p and q profiles were left almost unchanged.

➔ BS current was fully replaced by transiently induced current. ("Return Current")



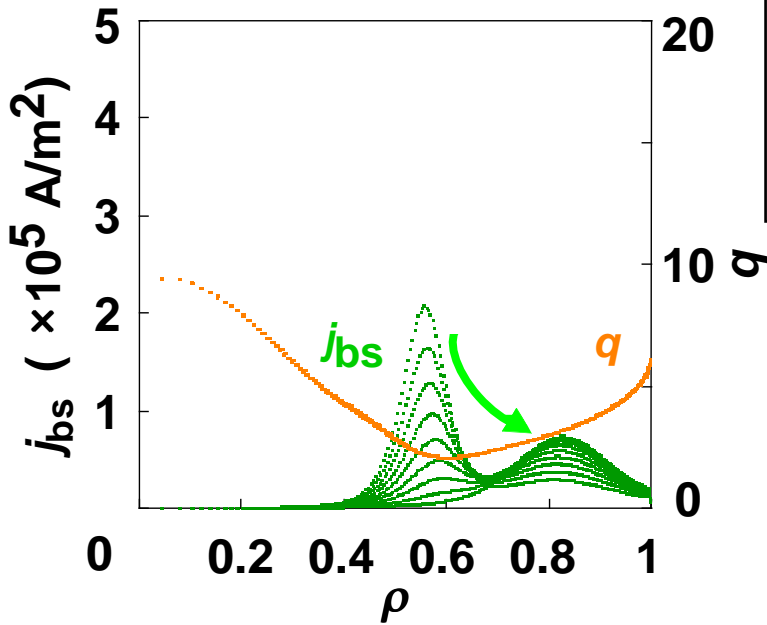
- Radial shift ➔ Positive I_p spike

- "Magnetic braiding" relaxes

j_p profile. ➔ Positive I_p spike

Positive I_p spike due to the inward plasma shift (Eddy Current Effect)

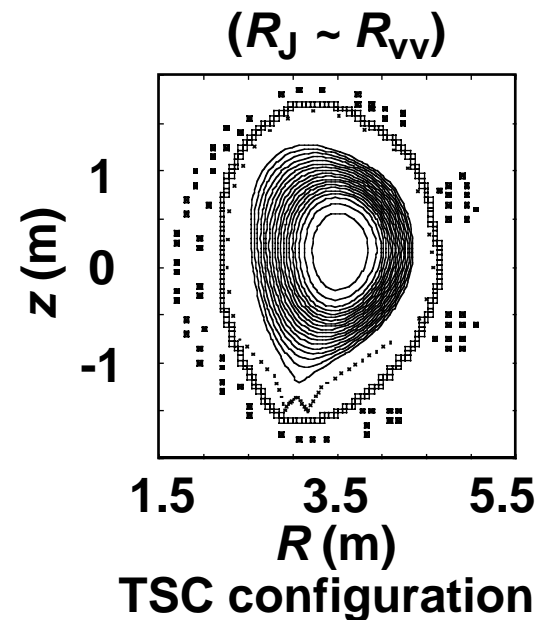
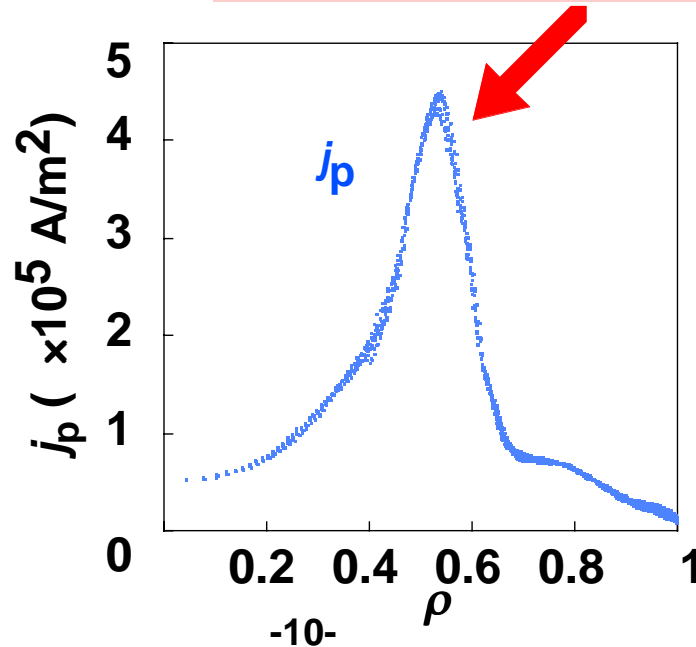
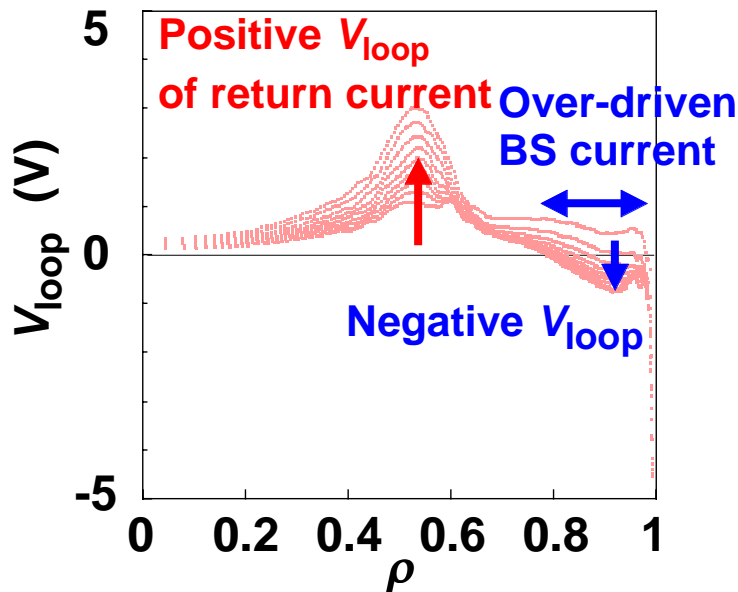
"Return Current" conserves the j_p and q profiles during pure β_p drop



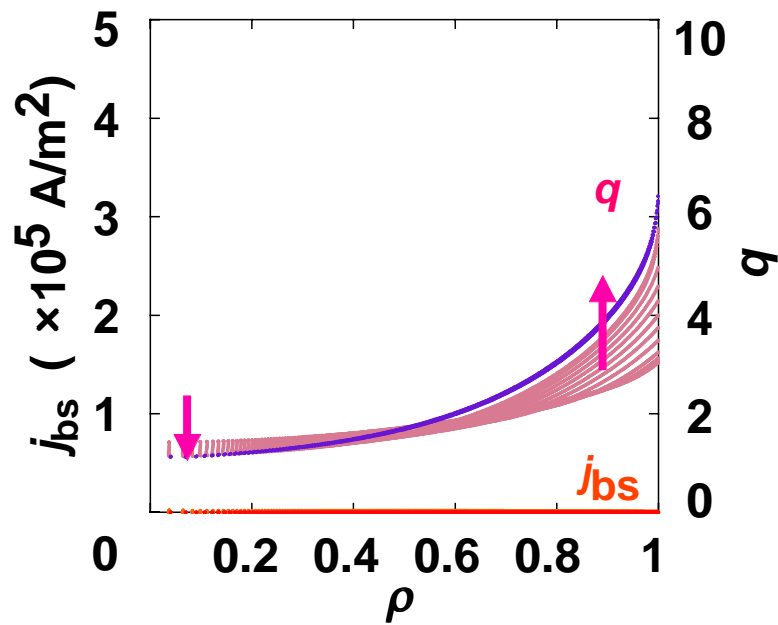
To remove the eddy current effect arising at plasma boundary, plasma was positioned at center of JT-60U V.V. ($R_J \sim R_{VV}$).

- Due to β_p drop, BS current disappears quickly and V_{loop} was induced around the ITB region.

j_p profile left unchanged.

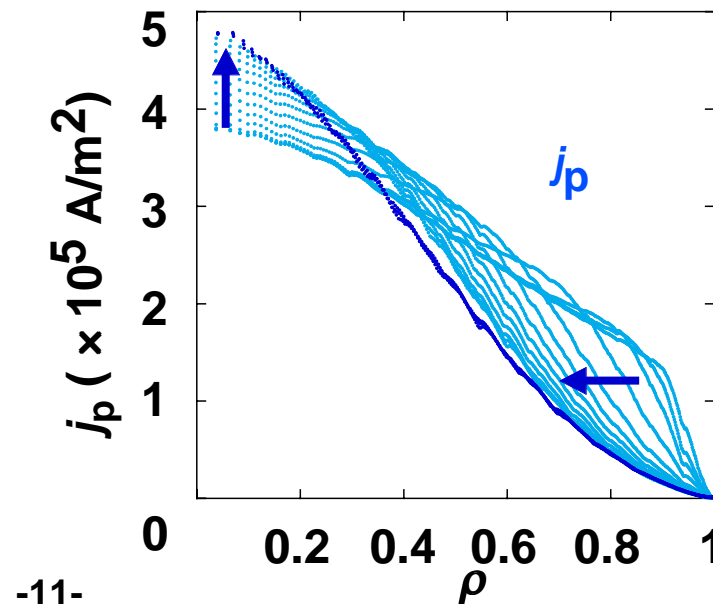
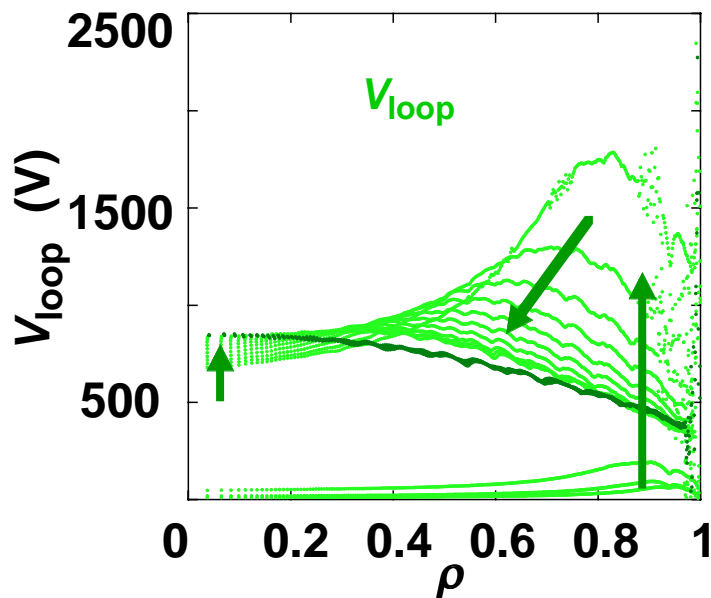


(B) Current Profile Change due to V_{loop} Relaxation ($t = 3 - 8$ ms) TSC

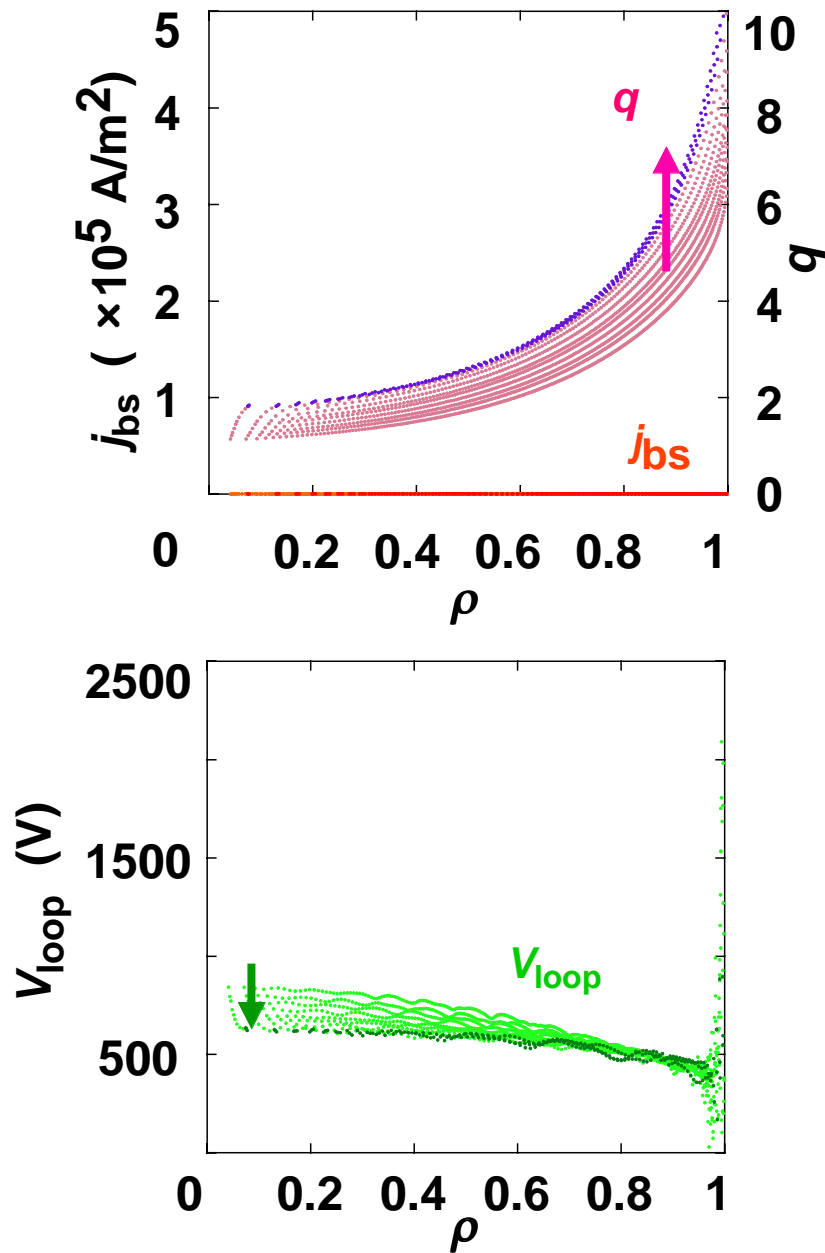


- As T_e drops, V_{loop} grows rapidly, and then diffuses into core region.
- Always keeping the similar positive shear profile, V_{loop} relaxation leads to a centrally peaked j_p profile.

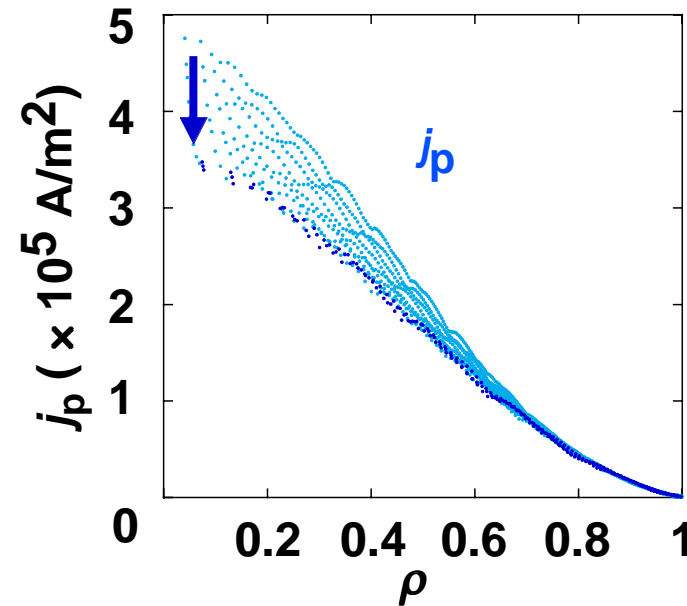
➔ The l_i change is smaller than that of RS plasmas as shown later.



(C) Shrinkage of Plasma Cross-Section (t = 8 - 14 ms) TSC

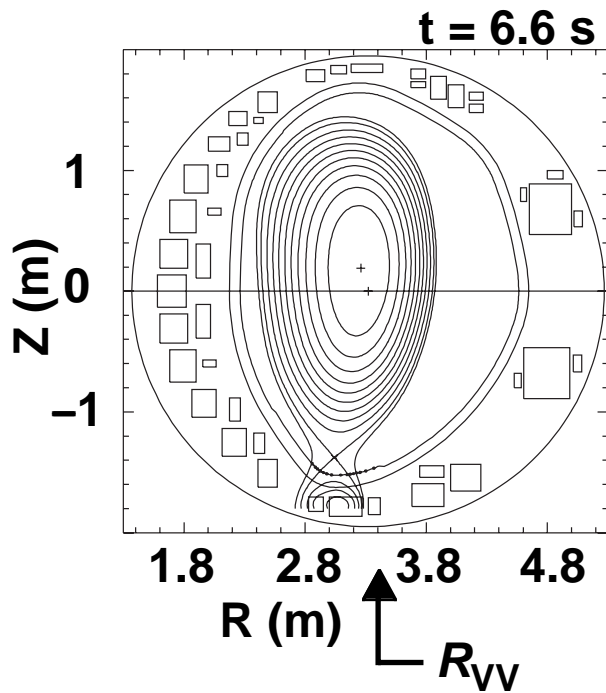


- Without appreciable change in V_{loop} , j_p and q profiles, plasma current simply decays according to L/R time.



Here, a profile change arising from more flattened T_e profile was assumed.

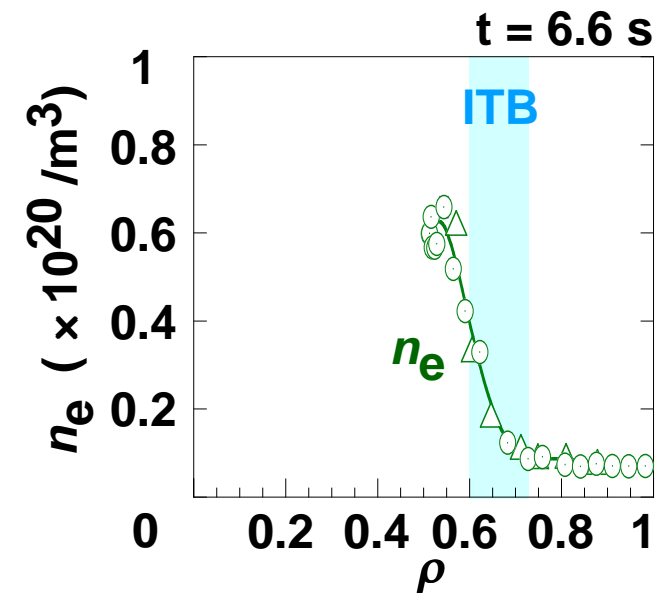
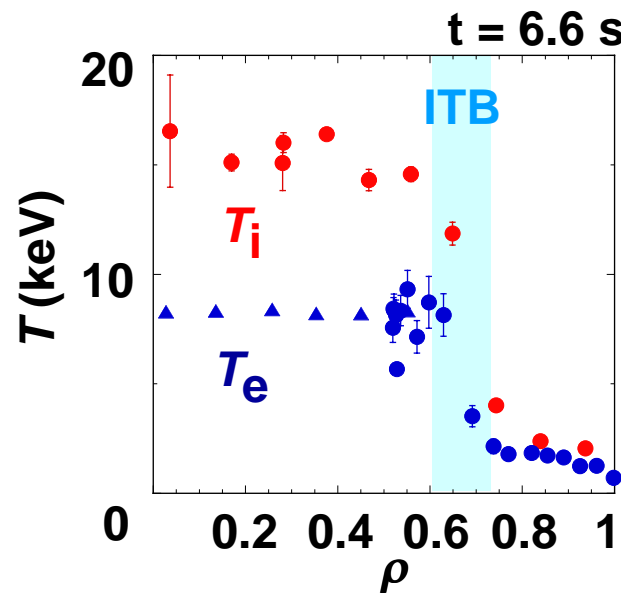
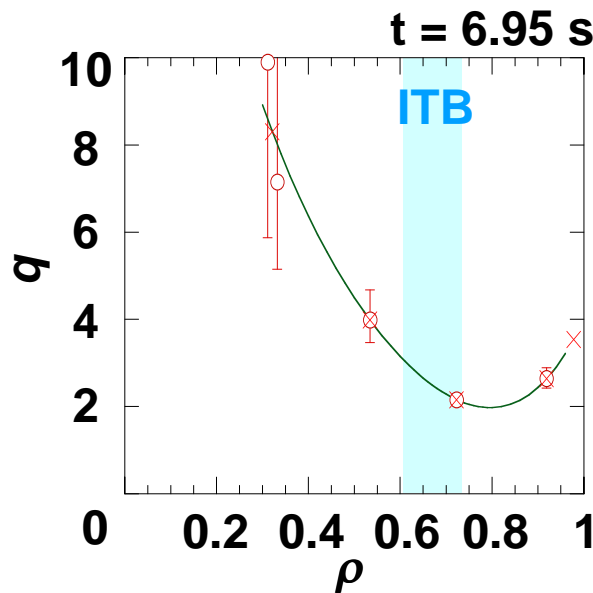
JT-60U High Performance RS Plasma (E27302) Y. Koide *et al.*, PPCF (1998).



- $I_p \sim 2.5$ MA, $\beta_p \sim 1.2$, $q_{\text{eff}} \sim 4.8$
before disruption ($t = 6.95$ s)

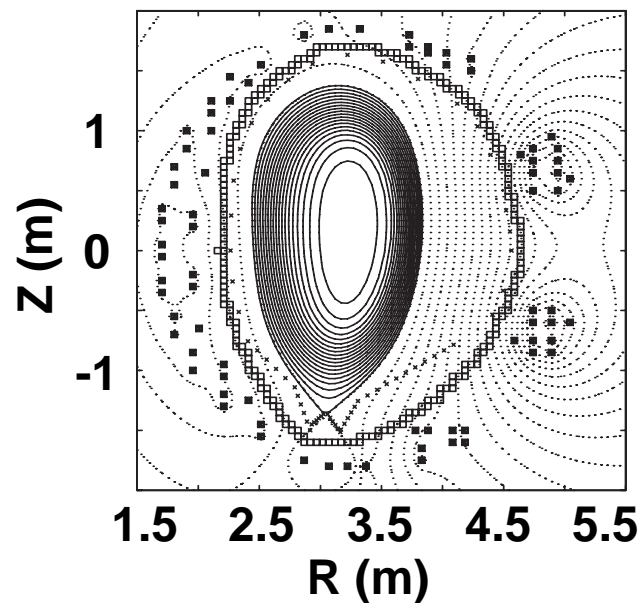
- $Z_J \sim 0.19$ m JT-60U neutral point for VDE avoidance
- $R_J (\sim 3.2$ m) $<$ $R_{VV} (\sim 3.4$ m)
positioned inner than V.V. center, same as E26446

- Strong ITB was located at $\rho \sim 0.6$.

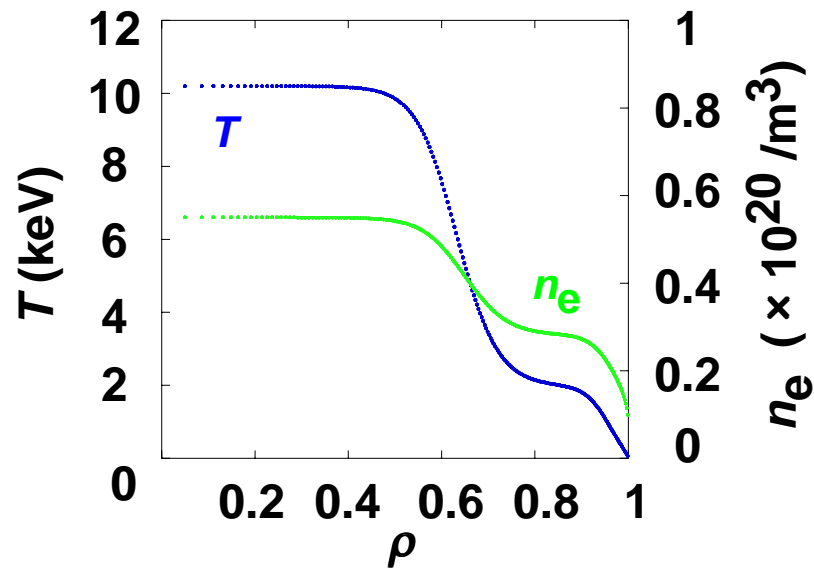
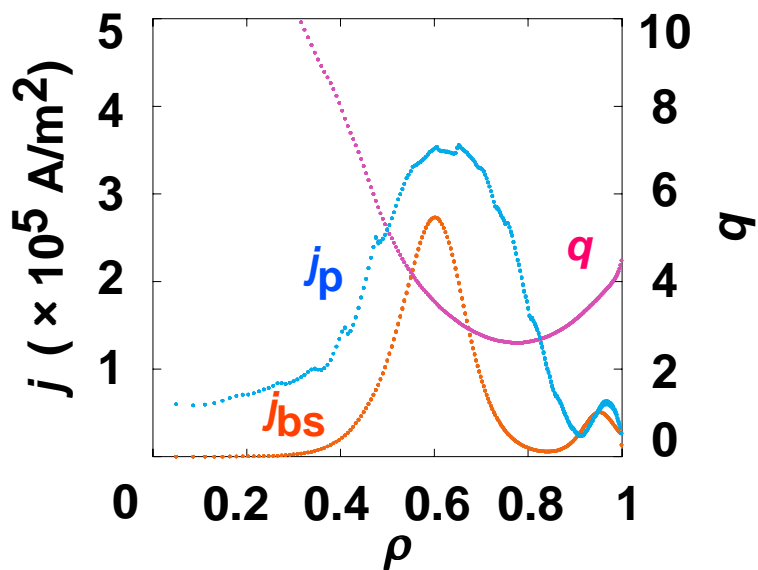
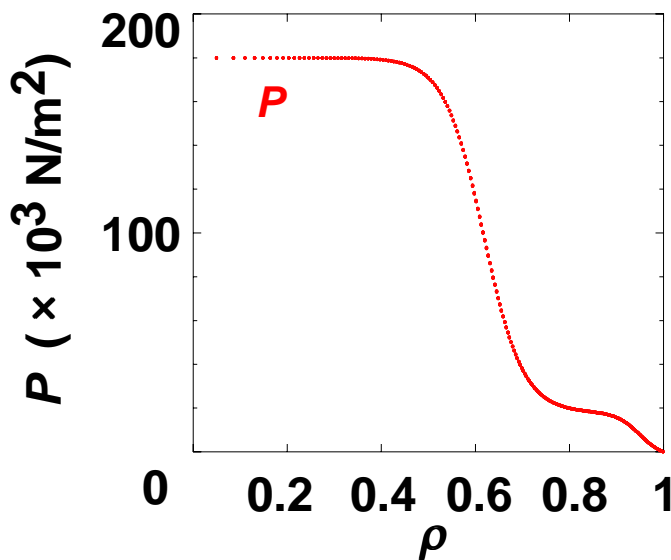


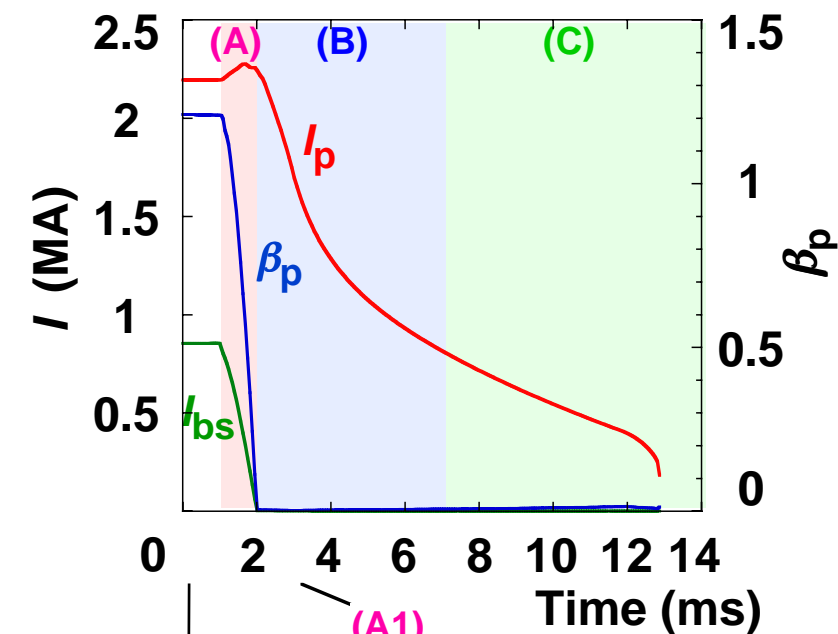
Initial Plasma Condition of TSC simulation

- $I_p \sim 2.2$ MA, $I_{bs} \sim 0.85$ MA, $\beta_p \sim 1.2$,
 $f_{bs}^{TSC} (=I_{bs}/I_p) \sim 0.4$



TSC configuration of JT-60U





- Same ITB crash as E26446 was modeled in TSC simulation.

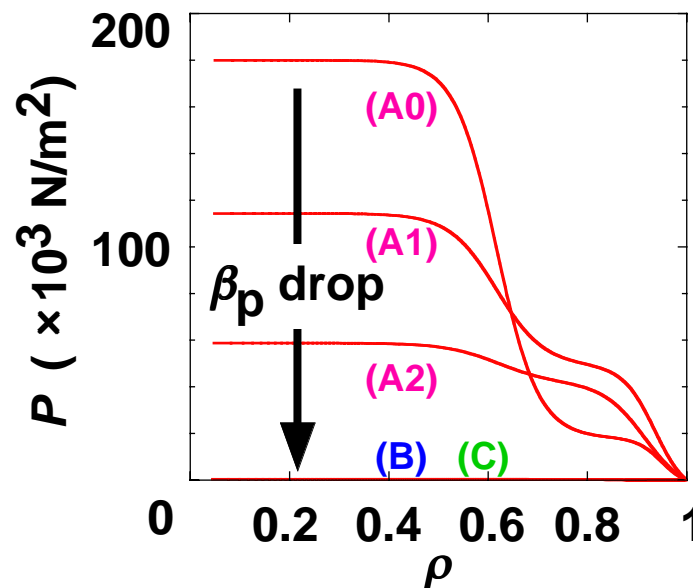
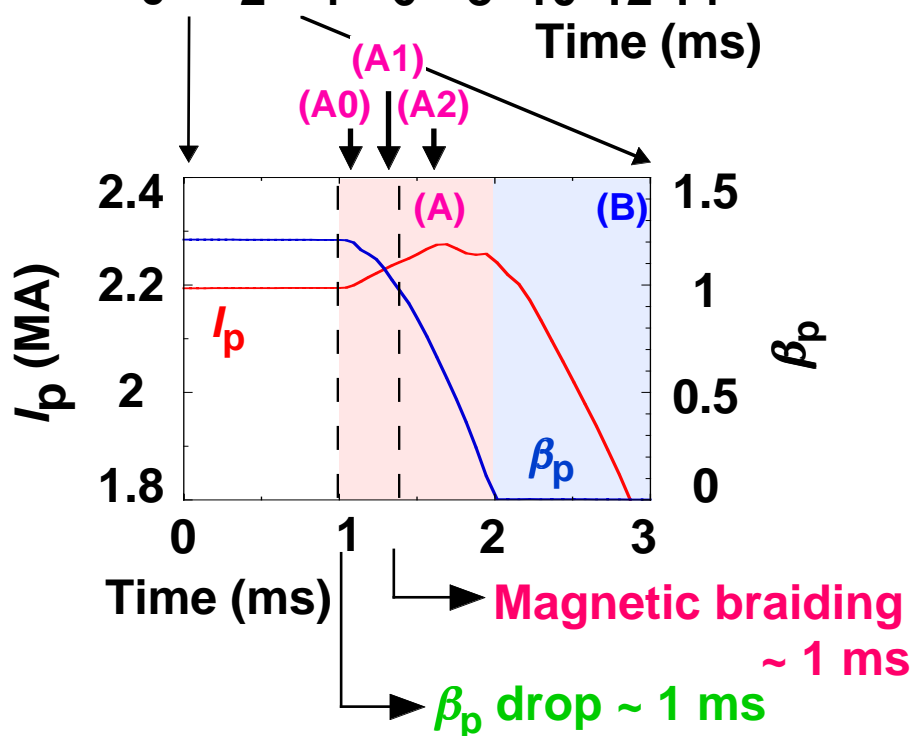
(A) ITB crash
 (β_p drop & magnetic braiding)

(B) Current profile change

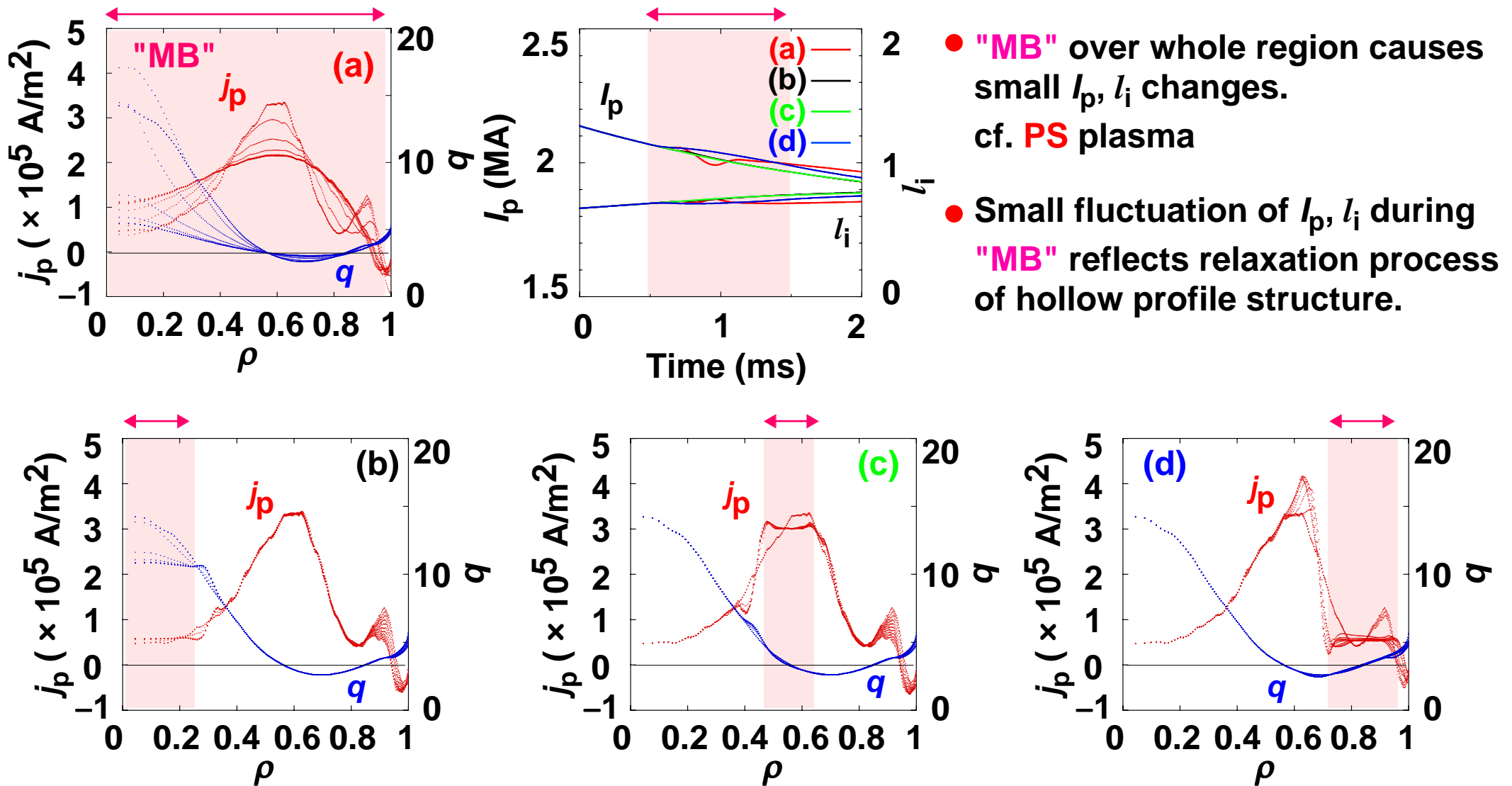
➔ A faster current decay in phase (B) was observed.

cf. E26446

(C) Shrinkage of plasma



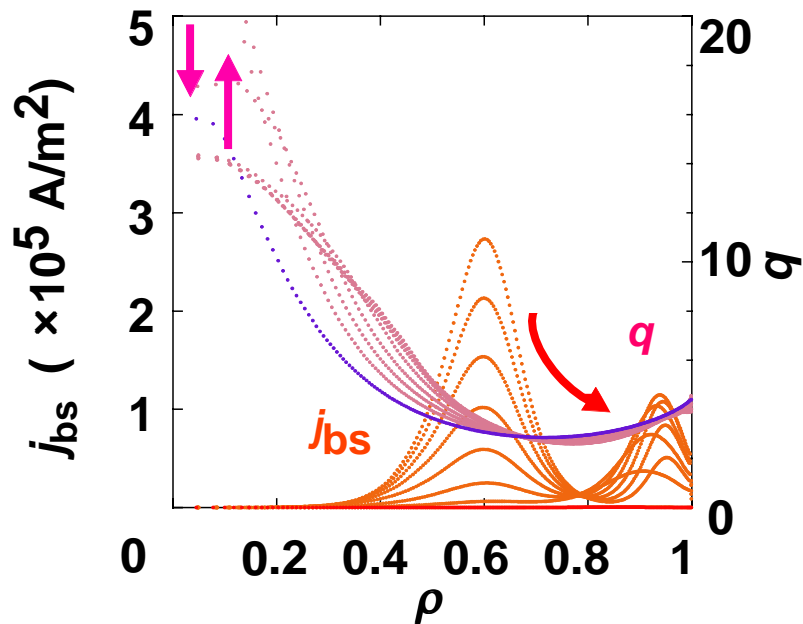
Model of Magnetic Braiding



- "MB" over whole region causes small I_p , l_i changes. cf. PS plasma
- Small fluctuation of I_p , l_i during "MB" reflects relaxation process of hollow profile structure.

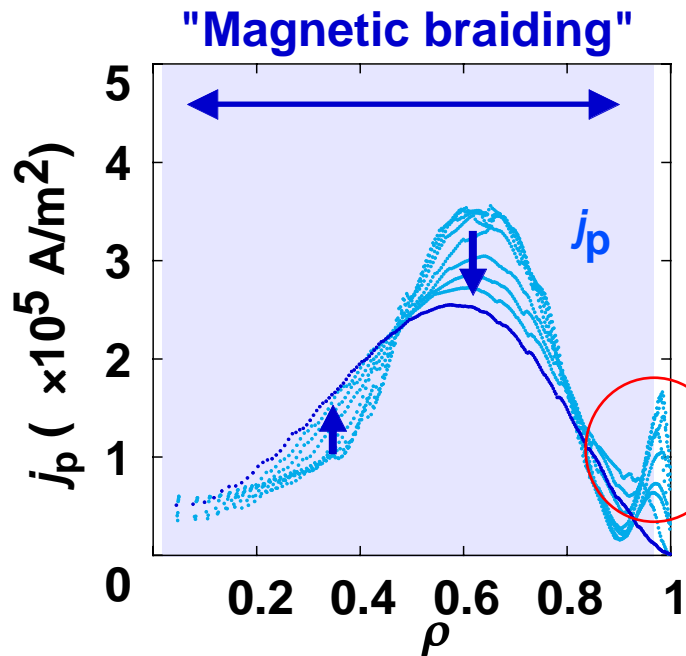
- Inside "MB" causes little I_p , l_i changes.
- "MB" at boundary causes small I_p , l_i changes like PS plasmas.

(A) ITB Crash (β_p drop & Magnetic braiding) (t = 1 - 2 ms) TSC



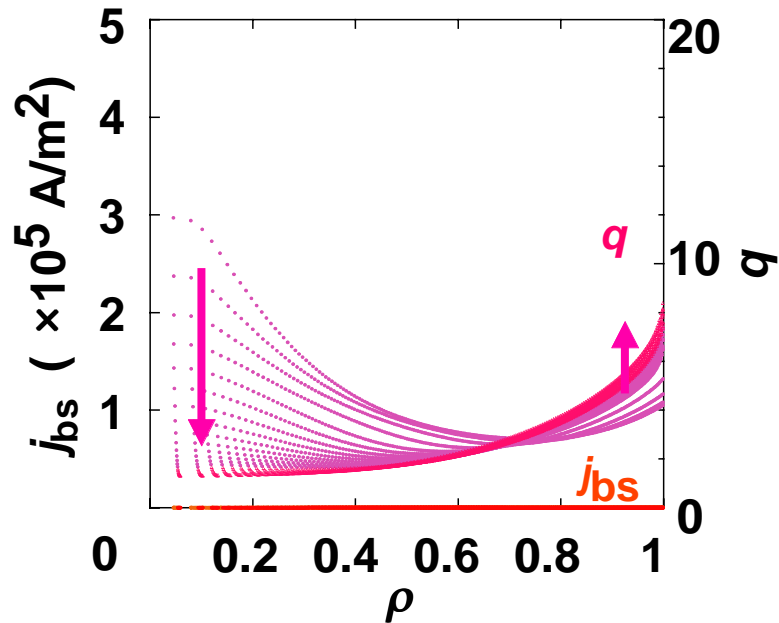
- Due to β_p drop, BS current disappears quickly.
- However, j_p and q profiles were left almost unchanged.
- ➔ BS current was fully replaced by "Return Current".

- Radial shift ➔ Positive I_p spike
- "Magnetic braiding" relaxes j_p profile. ➔ Small positive I_p spike



➔ Positive I_p spike due to the inward plasma shift (Eddy Current Effect)

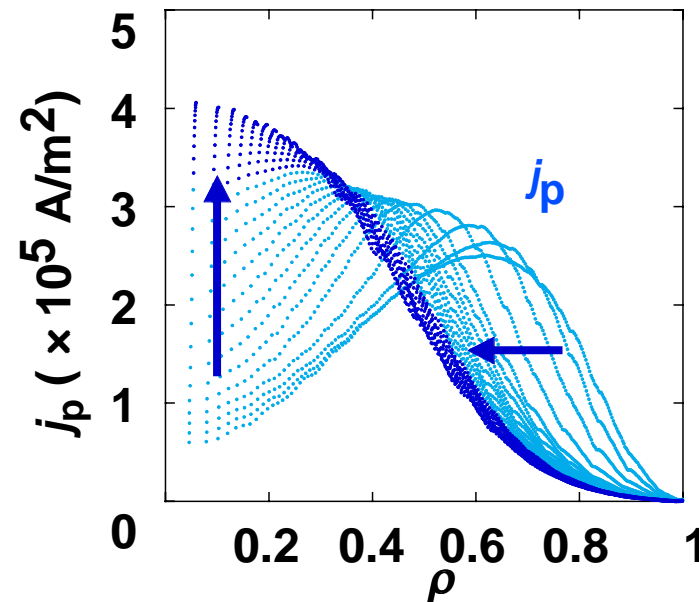
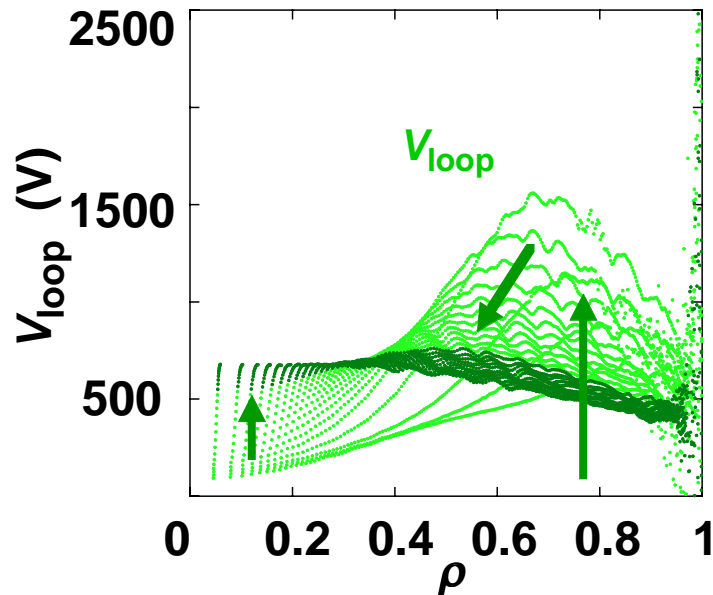
(B) Current Profile Change due to V_{loop} Relaxation (t = 2 - 7 ms) TSC



Particular Feature

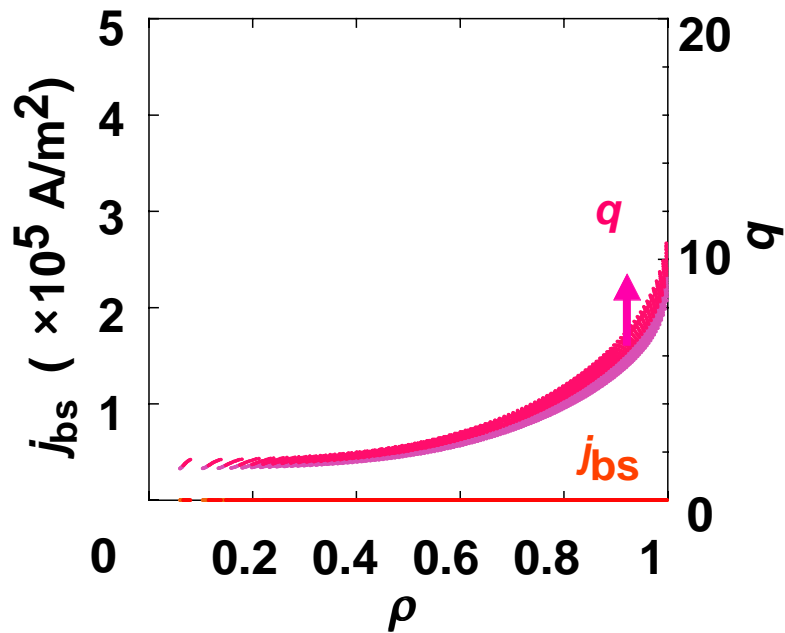
V_{loop} relaxation leads to significant change of survived hollow j_p profile to centrally peaked.

- The rapid increase in internal inductance results in a faster current decay than the other phases; specific to RS plasma.



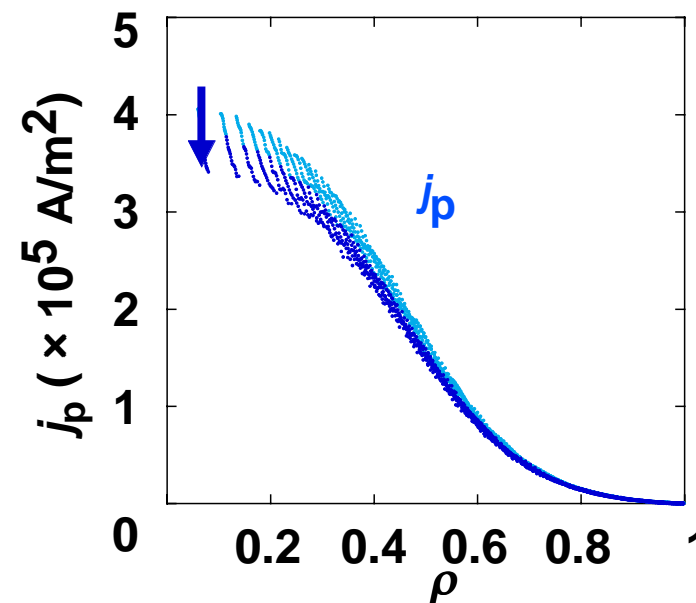
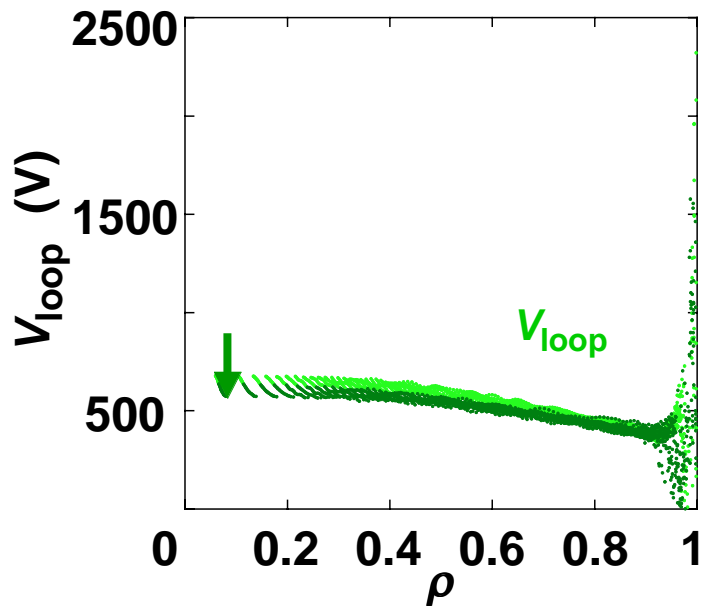
Now, checking direct MSE measurements of j_p profile in this phase of JT-60U.

(C) Shrinkage of Plasma Cross-Section (t = 7 - 14 ms) TSC



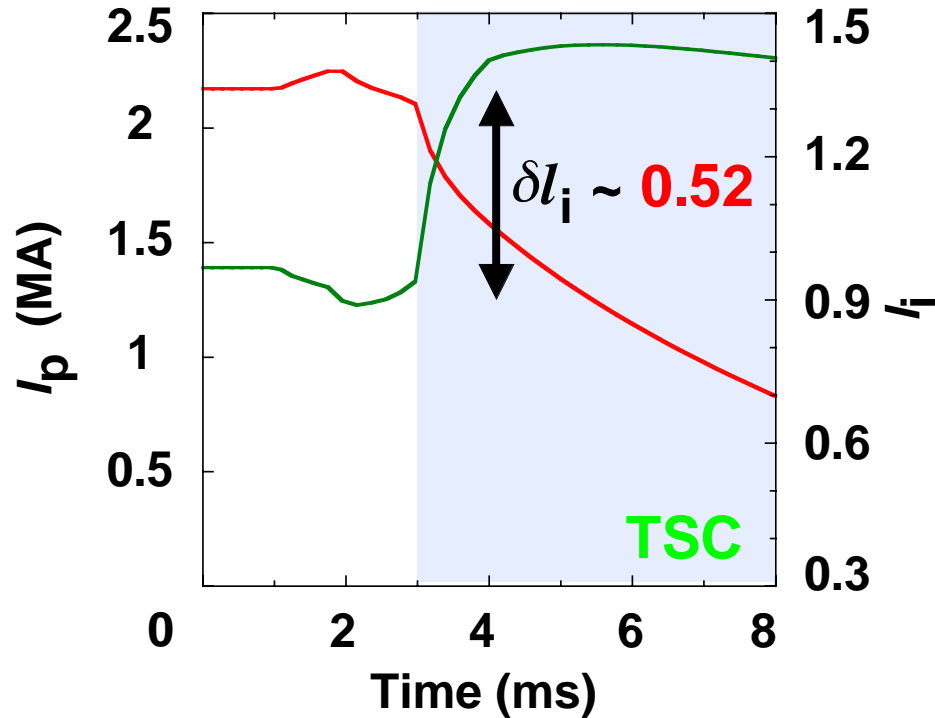
- Without appreciable change in V_{loop} , j_p and q profiles, plasma current simply decays according to L/R time.

- Disruption dynamics is similar to that of **PS** plasma.

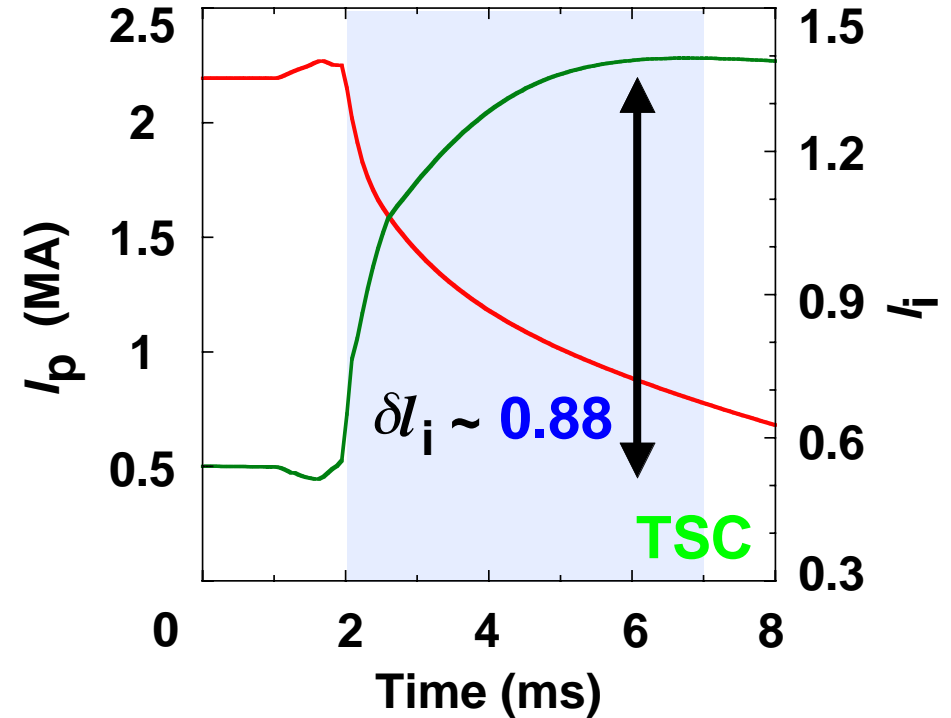


Fast Current Decay due to an Increase in Internal Inductance

● PS plasma



● RS plasma



$$\delta l_i \text{ (PS plasma)} < \delta l_i \text{ (RS plasma)}$$

➔ The rapid increase in the internal inductance of RS plasma results in a faster current decay than that of PS plasma.

Conclusions

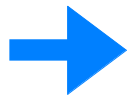
- TSC simulation of ITB crash clarified detailed evolutions of inductive $V_{I_{loop}}$ and j_p profiles during high β_p disruption, being self-consistent with BS current and relevant "Return Current".
- Experimentally observed disruption dynamics of high β plasmas were also reproduced as follows:

(A) Plasma current spike

- β_p drop causes positive spike when the plasma is positioned closer to the inner side of the vacuum vessel.
- Relaxation of current profile due to destruction of magnetic surfaces leads to significant increase in plasma current, particularly in **PS** plasmas.

(B) Current quench phase

Faster current quench in **RS** plasmas than **PS** plasmas was demonstrated, consistent with the JT-60U experiment.



Modeling of Disruption Dynamics in High β , Burning Tokamak Plasmas, and Avoidance Scenarios.