TSC Simulation of Disruptive Current Termination on JT-60U Reversed Shear Plasmas

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Motivation for Study on Disruption Dynamics

- **Disruptive termination has been studied and clarified.**

e.g. Vertical Displacement Event avoidance at neutral point

(Y. Nakamura et al., Nucl. Fusion 36, 643 (1996).)
(R. Yoshino et al., Nucl. Fusion 36, 295 (1996).)

Measurements of positive current spike (I_p spike) with a flattening of current profile in DIII-D disruptive Normal Shear (NrS) plasmas.

(P.L. Taylor et al., Phys. Rev. Lett. 76, 916 (1996).)

Contrary to common belief of occurring negative I_p spike in Reversed Shear (RS) plasmas, positive I_p spike has been observed in JT-60U.

- **Disruptions of RS plasmas have not been well understood.**

Understanding of disruption dynamics of RS/NrS plasmas is important for long-pulsed tokamak reactors like ITER.

Contents

- **Various I_p spikes, positive I_p spike or negative I_p spike, was observed at the thermal quench in JT-60U experiments.**

The mechanisms has not been well understood.

- **Tokamak Simulation Code (TSC) can model realistic JT-60U disruptions which simulates experiments, incorporating such physics as:**
  - **Effects of pressure drop (β_p drop) including shell structure outside plasmas**
  - **Dynamics of rapid I_p profile change inside plasmas**

A new understanding explicates the I_p spike behavior of tokamak disruptions in detail .

JT-60U Experiment in contrast to Analytical Model

- A radial shift of plasma through β_p drop results in a positive I_p spike during a thermal quench phase.

$$\delta\tilde{I}_p = -\frac{\delta\tilde{\beta}_p}{2\left[\ln\left(\frac{8R_p}{a}\right) + \frac{1}{2}(l_i - 1) - 2\left\{(n-1)\left(\ln\left(\frac{8R_p}{a}\right) + \frac{1}{2}(l_i - 3) + \beta_p\right) + 1\right\}\right]}$$

$\approx -0.05\,\delta\tilde{\beta}_p \; (\delta\tilde{\beta}_p < 0)$ $\quad (\because \delta\psi = 0, \delta F_R = 0)$ $\quad$ n: decay index

(A. Fukuyama et al., Jpn. J. Appl. Phys. 14, 871 (1975).)

→ $\delta\tilde{I}_p$ depends very weakly on R_p (~R_J).

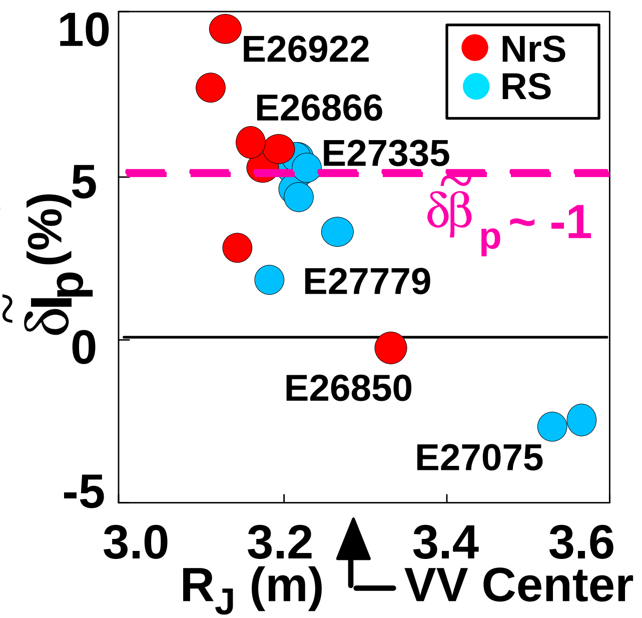
Surprising feature of I_p spike

I_p~2-3MA

β_p~1

qeff~3.5-4.5 (NrS)

qeff~4.5-7 (RS)

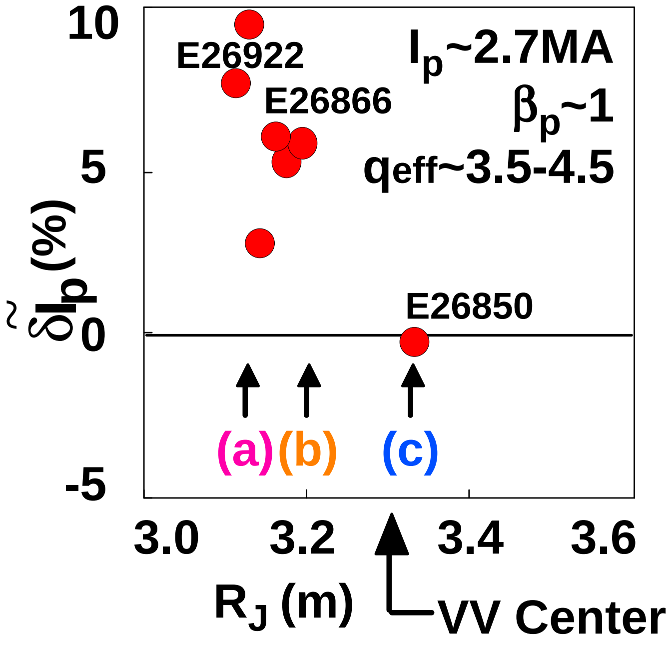


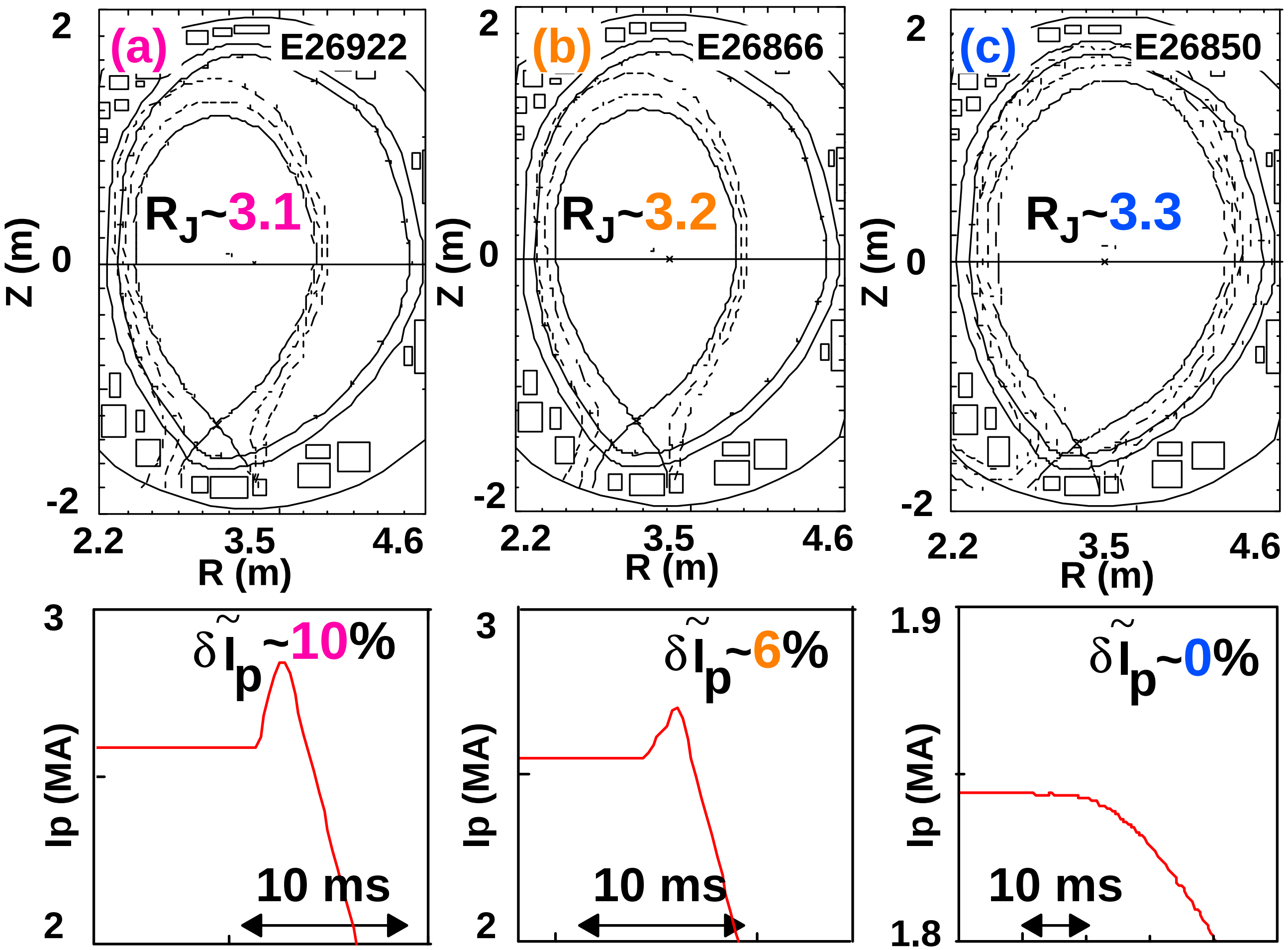
- $\delta\tilde{I}_p$ $(=\delta I_p/I_p)$ with inner I_p center (R_J) was larger than that of outer R_J.
- Maximum $\delta\tilde{I}_p$ (~10%) was observed in NrS discharges at smaller R_J.
- Negative I_p spike (~-5%) was observed in RS discharges at larger R_J.

→ It is found that $\delta\tilde{I}_p$ depends on R_J

Current Spike Observed during High β_p NrS Disruption

$\delta\tilde{I}_p$ depends on R_J.





$\delta\tilde{I}_p$ with smaller R_J
> $\delta\tilde{I}_p$ with larger R_J

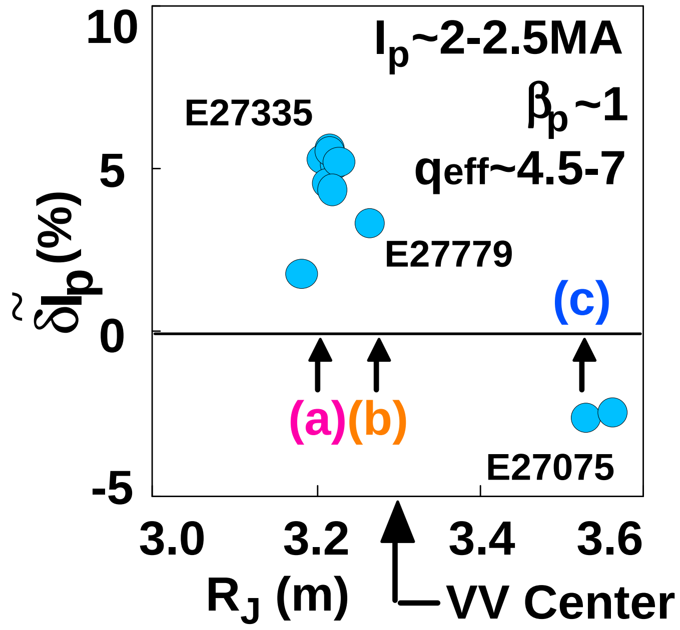
$\delta\tilde{I}_p$~10%
with R_J~3.1m

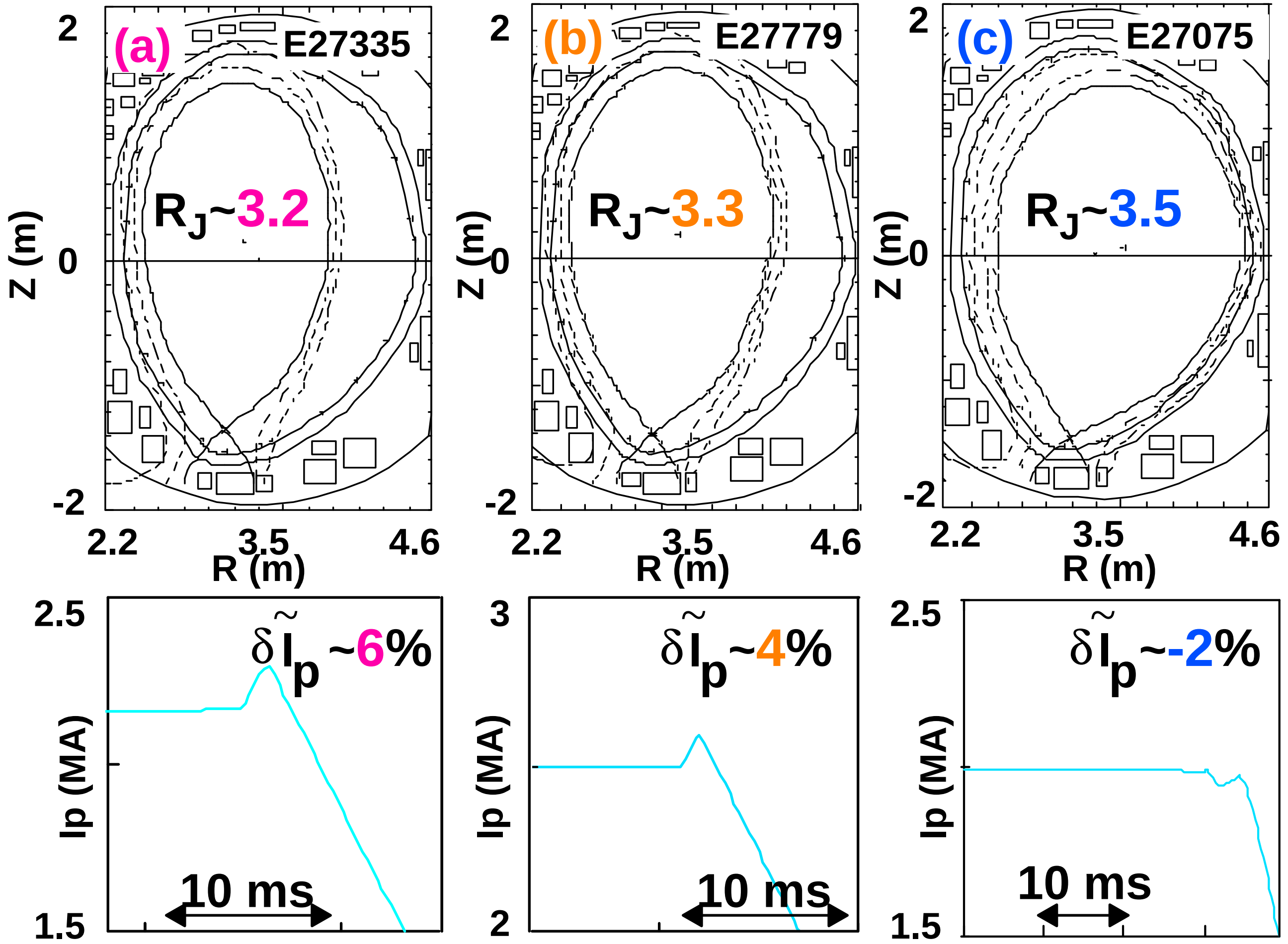
$\delta\tilde{I}_p$~6%
with R_J~3.2m

$\delta\tilde{I}_p$~0%
with R_J~3.3m

Current Spike Observed during High β_p RS Disruption

$\delta\tilde{I}_p$ depends on R_J.





$\delta\tilde{I}_p$ with smaller R_J
> $\delta\tilde{I}_p$ with larger R_J

$\delta\tilde{I}_p$~6%
with R_J~3.2m

$\delta\tilde{I}_p$~4%
with R_J~3.3m

$\delta\tilde{I}_p$~-2%
with R_J~3.5m

Shell effect on the current spike under the β_p drop ? TSC simulation

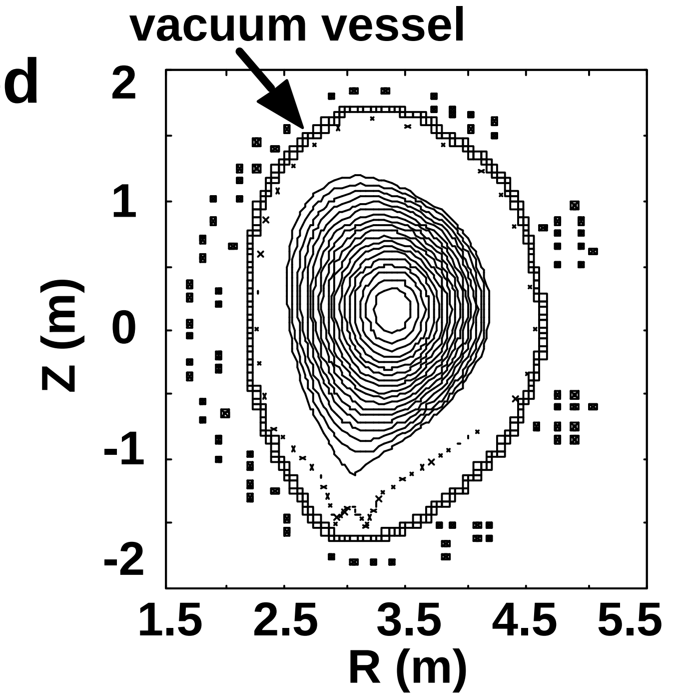
TSC Modeling of Axisymmetric MHD

- **Usual set of MHD eqs. with modified momentum eq.**

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

m : plasma momentum density (= ρv)

Fv(m) : artificial viscosity operator instead of $\mathbf{v} \cdot \nabla \mathbf{v}$



TSC configuration of JT-60U

- **Free-boundary axisymmetric MHD** → **Realistic plasma configuration (TSC, DINA)**
- **Disruption dynamics including shell structure** → **β_p drop (TSC, DINA, ASTRA)**
- **Resistive diffusion of I_p profile** → **Current flattening (TSC etc.)**

→ **TSC enables us to realistically simulate with experiments.**

Current Spike due to β_p Drop at Outer Position (R_J=3.8m) TSC

β_p drop ($\delta\tilde{\beta}_p \sim -1$) leads to inward shift ($\delta R_J \sim -0.2$m) and results in $\delta\tilde{I}_p \sim -3\%$.

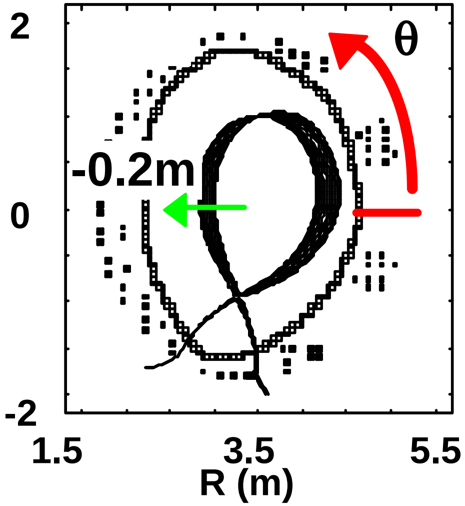
- **Analytical model without shell effects**

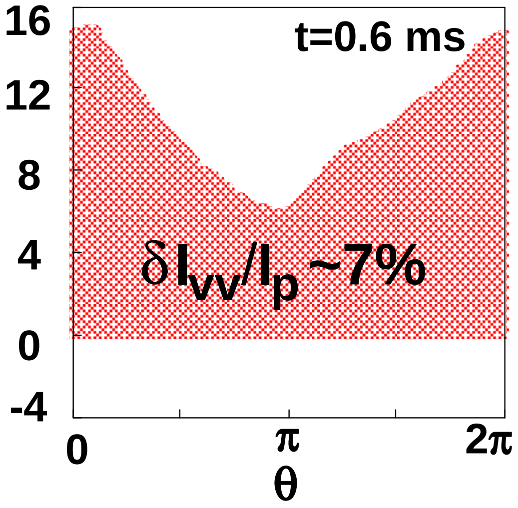
The β_p drop results in a positive I_p spike.

$$\delta\tilde{I}_p \approx -0.05\,\delta\tilde{\beta}_p \sim 5\%$$

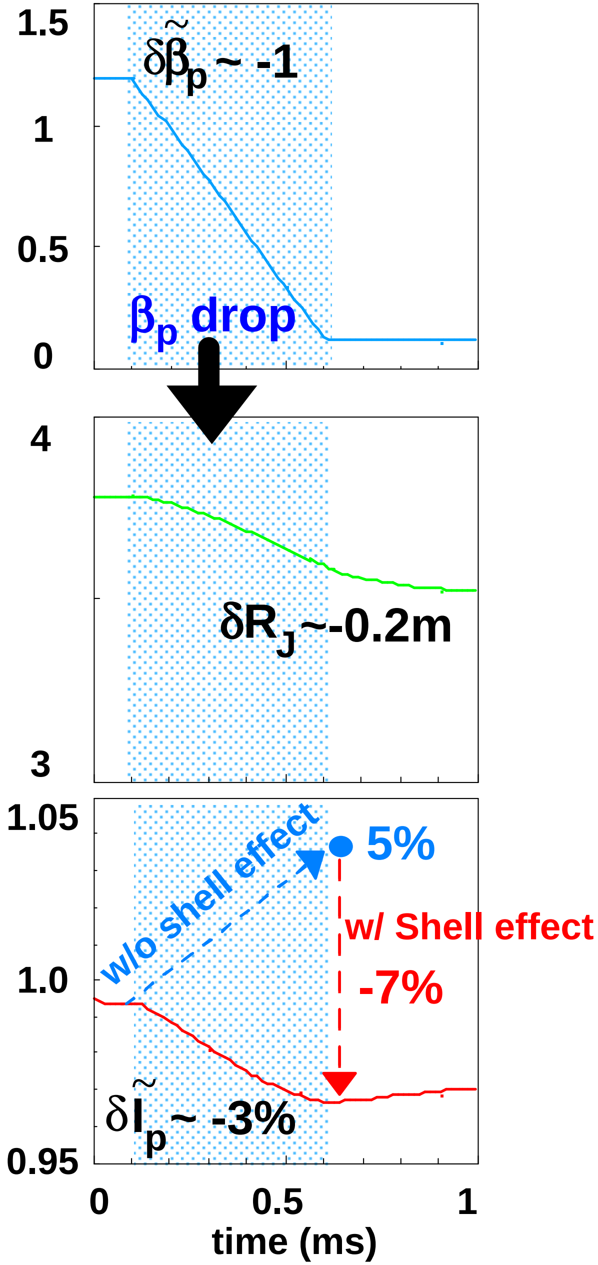
- **TSC simulation**

Induced toroidal eddy current in the vacuum vessel





→ **Negative I_p spike**



Current spike due to β_p Drop at Inner Position (R_J=3.1m) TSC

β_p drop ($\delta\tilde{\beta}_p$ = -0.5) leads to inward shift (δR_J~ -0.1 m) and results in $\delta\tilde{I}_p$ ~1%.

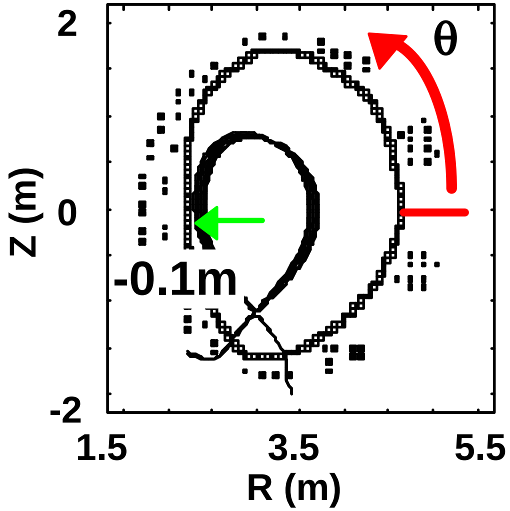
- **Analytical model without shell effects**

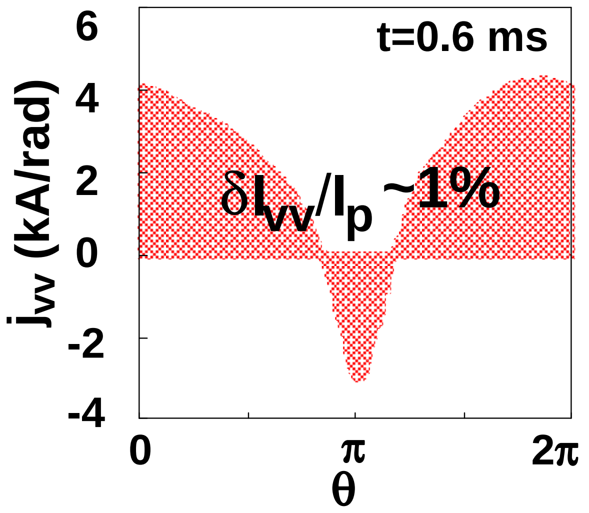
The β_p drop results in a positive current spike.

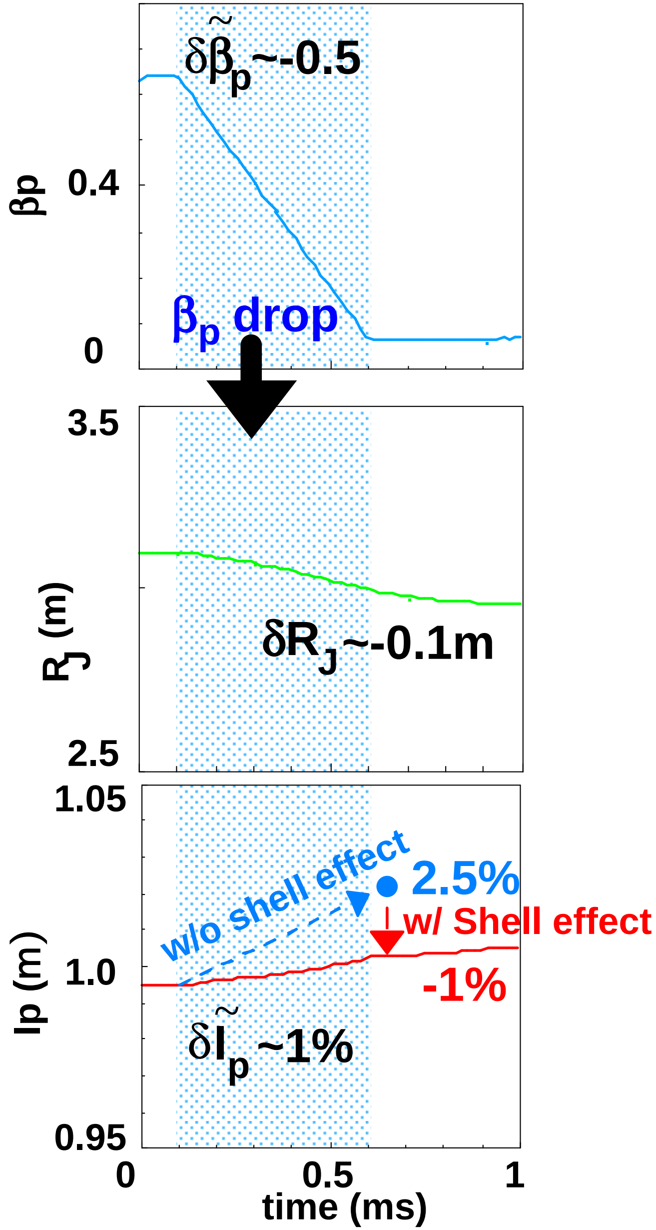
$$\delta\tilde{I}_p \approx -0.05\,\delta\tilde{\beta}_p \sim 2.5\%$$

- **TSC simulation**

Induced toroidal eddy current in the vacuum vessel







→ **Increasing I_p**

→ **The effect of β_p drop results in the R_J dependence of $\delta\tilde{I}_p$.**

Abrupt Change in Current Profile

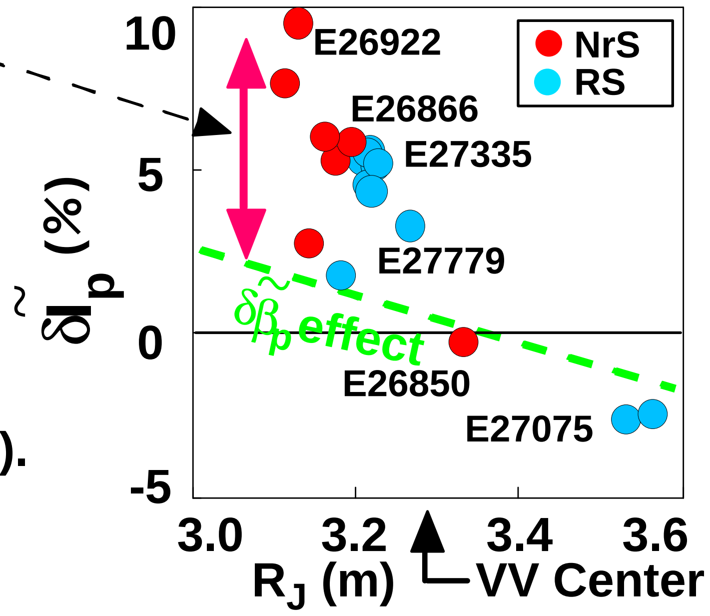
$\delta\tilde{\beta}_p$ effect is insufficient to explain $\delta\tilde{I}_p$.

Another mechanism?

Measurements of current flattening in DIII-D NrS plasmas

P.L. Taylor et al., Phys. Rev. Lett. 76, 916 (1996).

Effect of abrupt change in current profile



Abrupt current profile change model in TSC

- **Ohm's Low modified by Hyper-Resistivity**

(A.H. Boozer, J. Plasma Phys. 35, 133 (1986).)

  - **Destruction of magnetic surface (tearing mode)**
  - **Dissipating energy and conserving helicity**

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

λ: arbitrary positive function

→ TSC models anomalous current viscosity

D.J. Ward, S.C. Jardin, Nucl. Fusion 29, 905 (1996).

Current Profile Change in NrS plasmas (β_p~0) TSC

TSC with the hyper-resistivity reproduced a redistribution in current profile

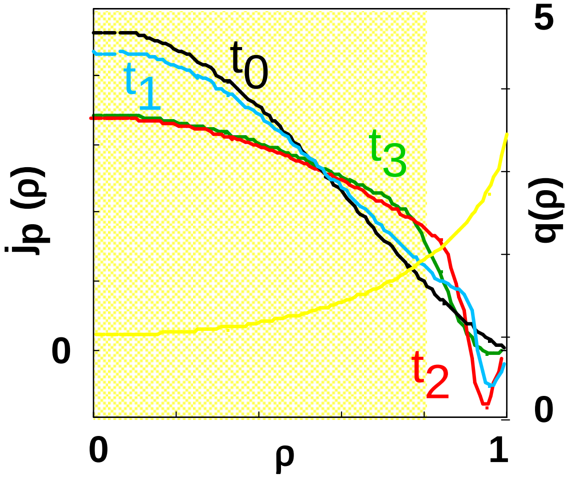
- Hyper-Resistivity causes a lowering of l_i .

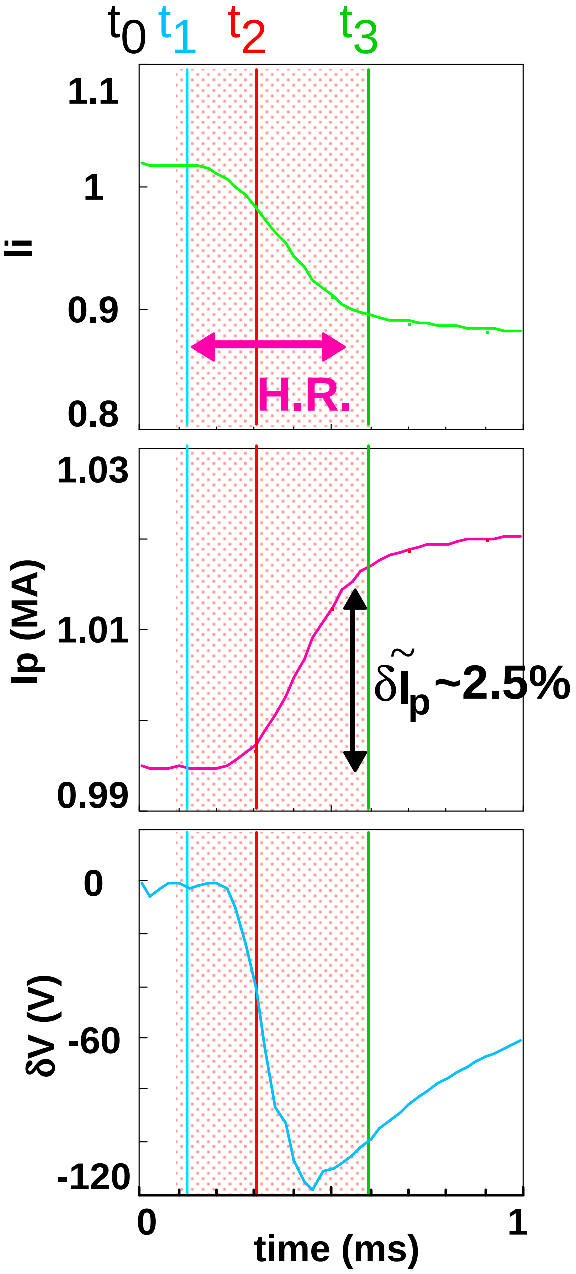
Positive I_p spike

$\delta\tilde{I}_p$ ~2.5%

Negative voltage spike

δV ~-120V





Current flattening explicates both spikes of positive I_p and negative voltage similar to experiments.

Current Profile Change in RS plasmas (β_p~0) TSC

Redistribution of current profile in the same manner as NrS plasmas

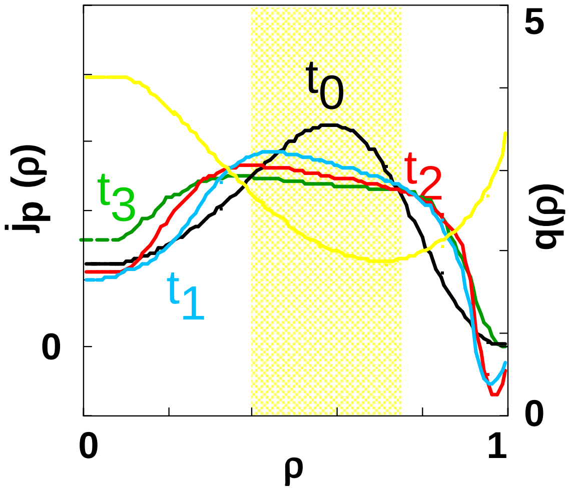
- **Hyper-Resistivity causes a further lowering of l_i .**

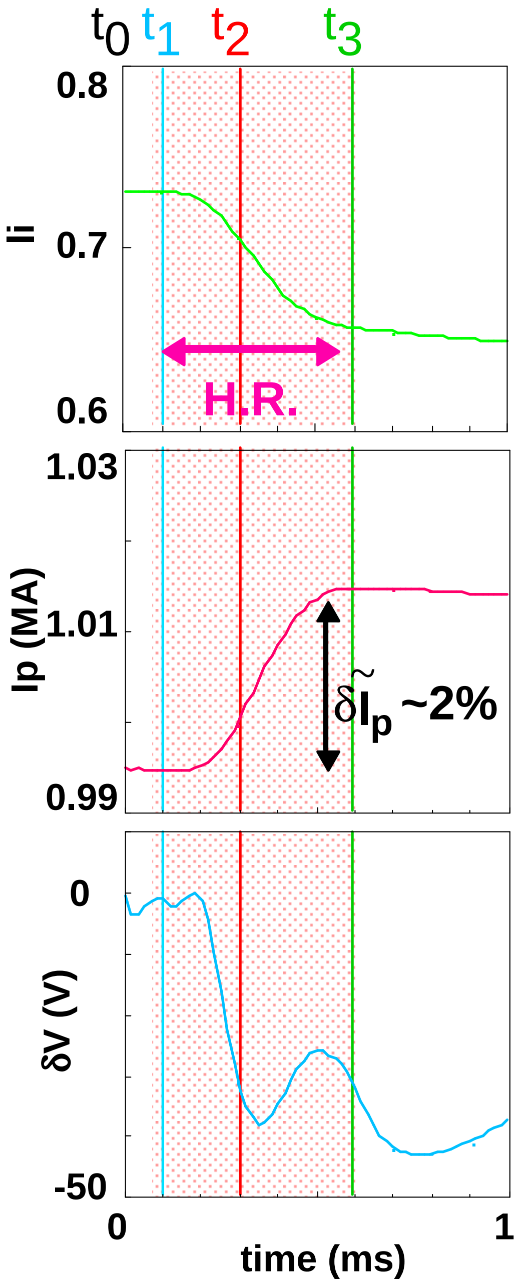
Positive I_p spike

$\delta\tilde{I}_p$~2%

Negative voltage spike

δV ~-40V





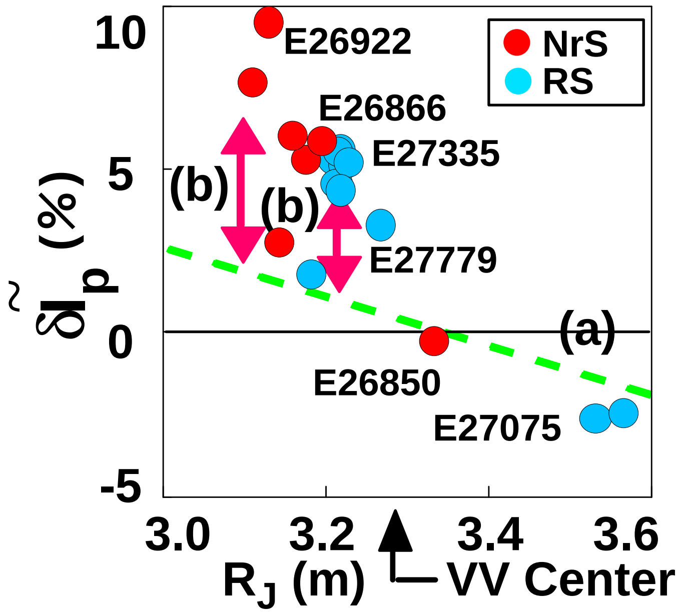
Further lowering of l_i results in both spikes of positive I_p and negative voltage even in RS plasmas.

Conclusions

- **Important effects on I_p spikes**

(a) Induced eddy current in vacuum vessel

β_p drop causes the I_p spike that is positive with smaller R_J while negative with larger R_J. (strong R_J dependence)



(b) Abrupt current profile change

Further lowering of l_i similar to NrS plasmas is a plausible candidate for the mechanism of positive I_p spike observed even in RS plasmas.

- **A new understanding obtained by TSC simulation reasons out the various current spike behaviors of JT-60U RS/NrS plasmas.**