# Studies of Improved Confinement in Heliotron J

*Presented by*

**MIZUUCHI Tohru**

*for Heliotron J Team*

# Contents



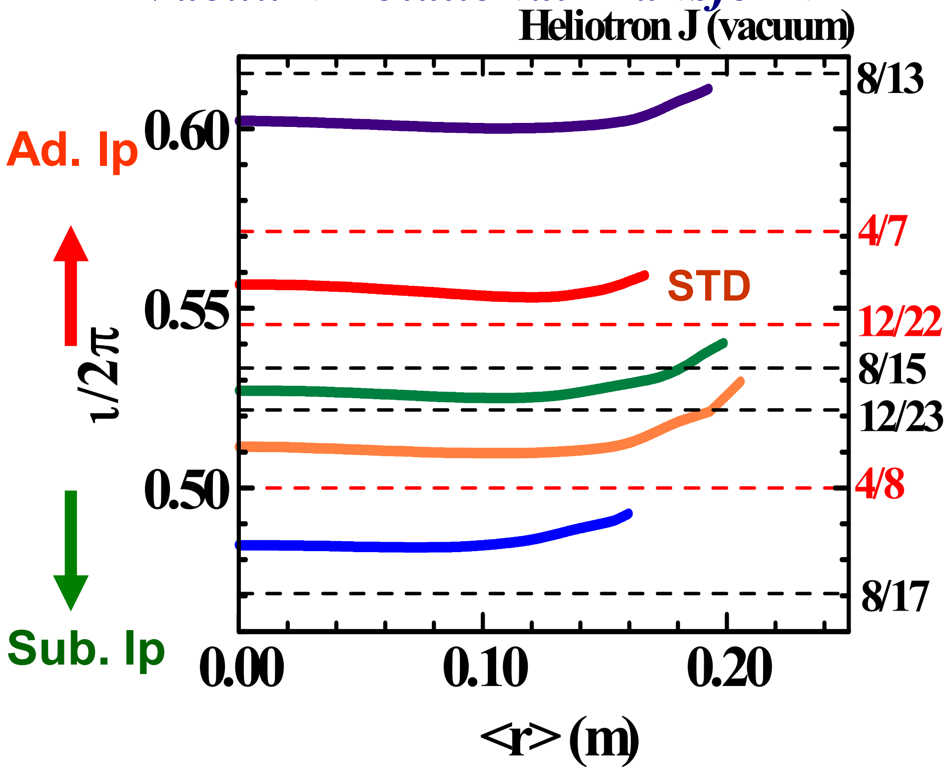


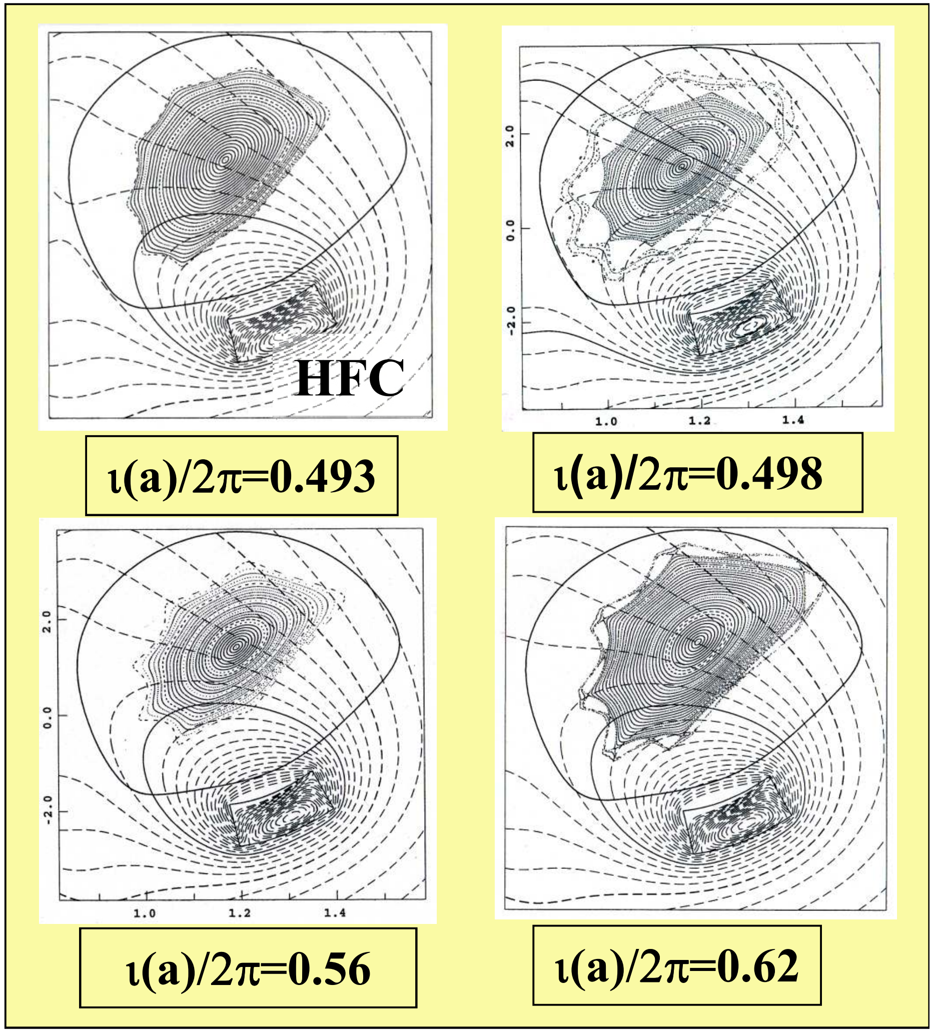
*Due to the time limitation, this talk will focused on "Transition".*
*For other topics, please contact me or refer the proceeding*

# The edge magnetic surfaces are strongly modified by the resonant conditions.



***Vacuum Rotational Transform***



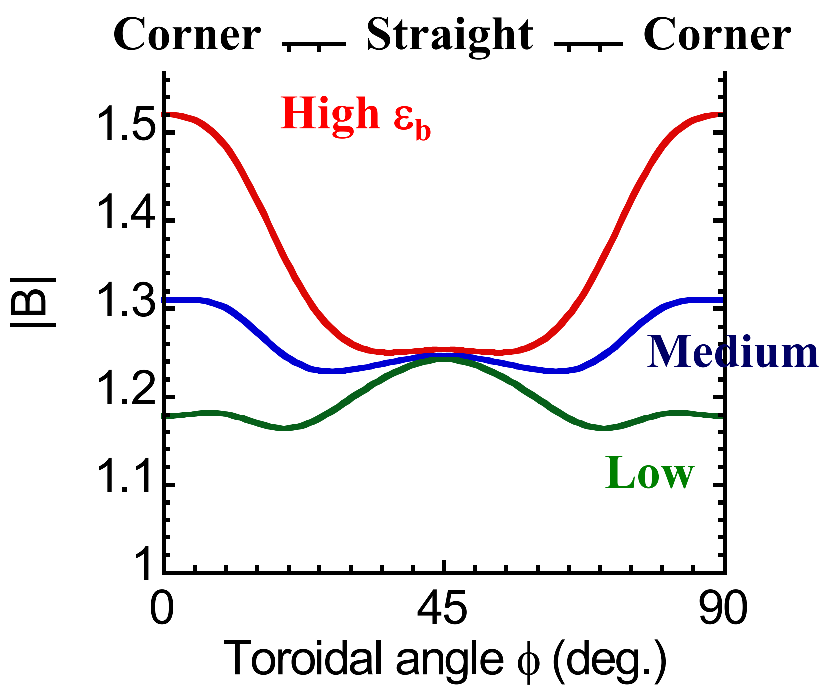

The effects of rational surfaces have been studied is not only from the MHD activities but also from the appearance of transport barriers viewpoints.

# Bumpiness Control

## ∇B drift can be suppressed with bumpiness control.



***Magnetic field strength at plasma axis***




**High $\varepsilon_b$ : Higher mirror ripple**

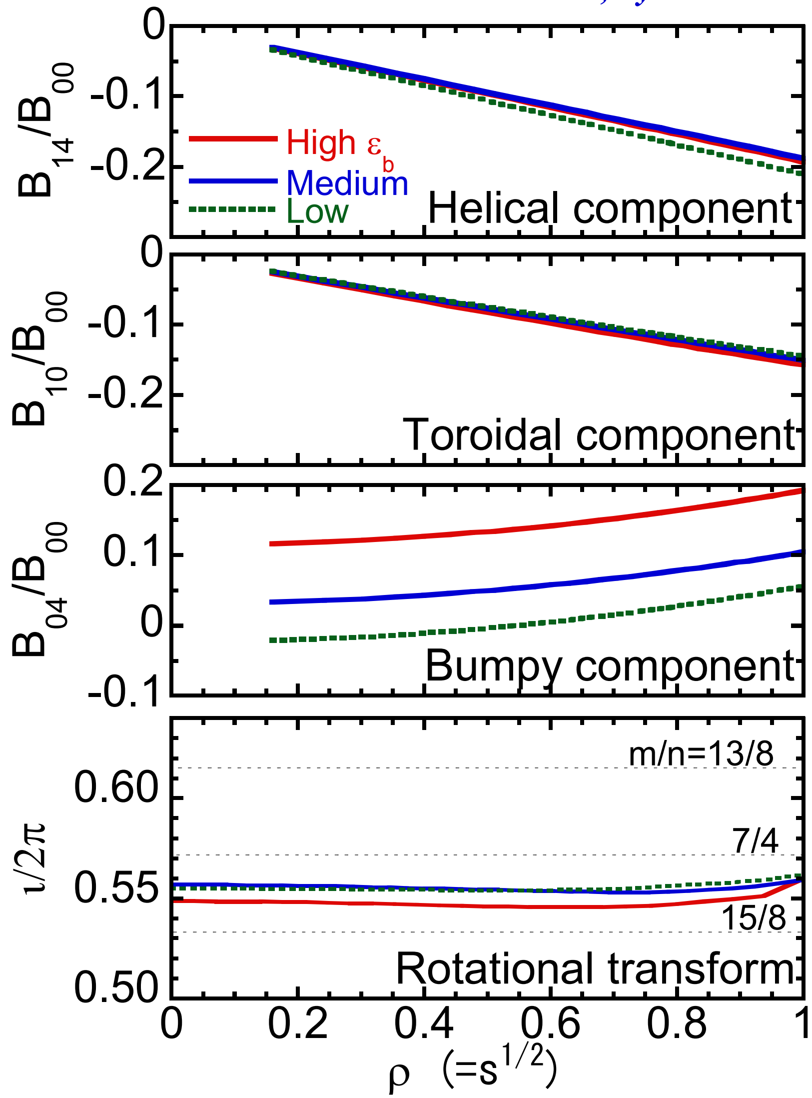
**Low $\varepsilon_b$ : Mirror field reversal (at axis)**

**Constant parameters :**

**- $R_{ax}/\langle a_p \rangle$ = 1.2 m/0.17 m, $V_p \sim 0.7$ m$^3$**

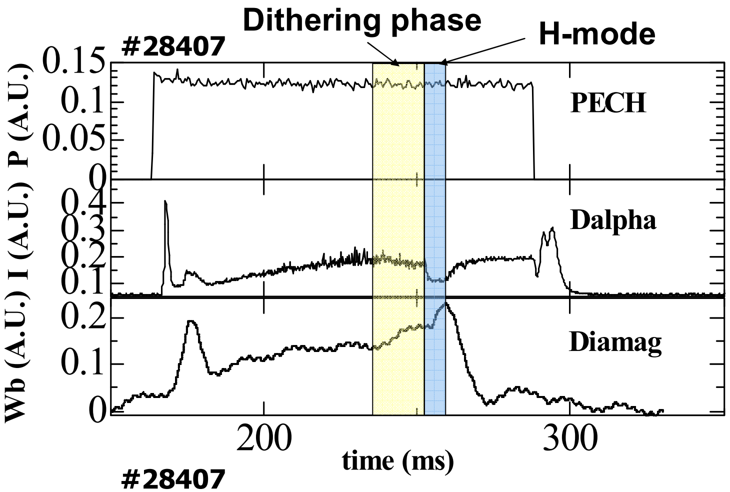
**- Edge rotational transform**

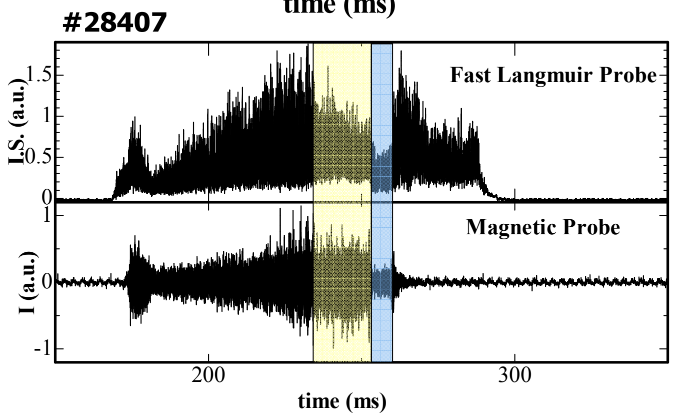
**- Magnetic well in entire region**



# The Heliotron J experiments have revealed the existence of the spontaneous transition to improved confinement mode.



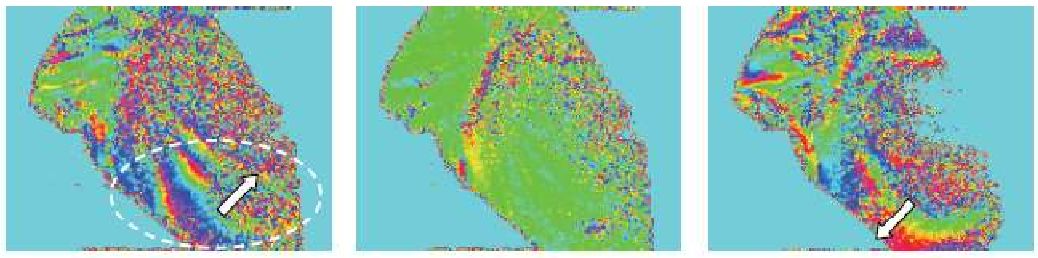



***ECH-only plasma***

- **Observation with fast cameras revealed the existence of filament structure parallel to B in the peripheral plasma turbulence.**
- **Phase image analysis suggests**
  - ✓ **The CCW poloidal rotation of the filament structure during the L-mode.**
  - ✓ **During the L-H transition, this rotation speed decreases.**
  - ✓ **After the transition, it restarts the movement but in CW direction.**

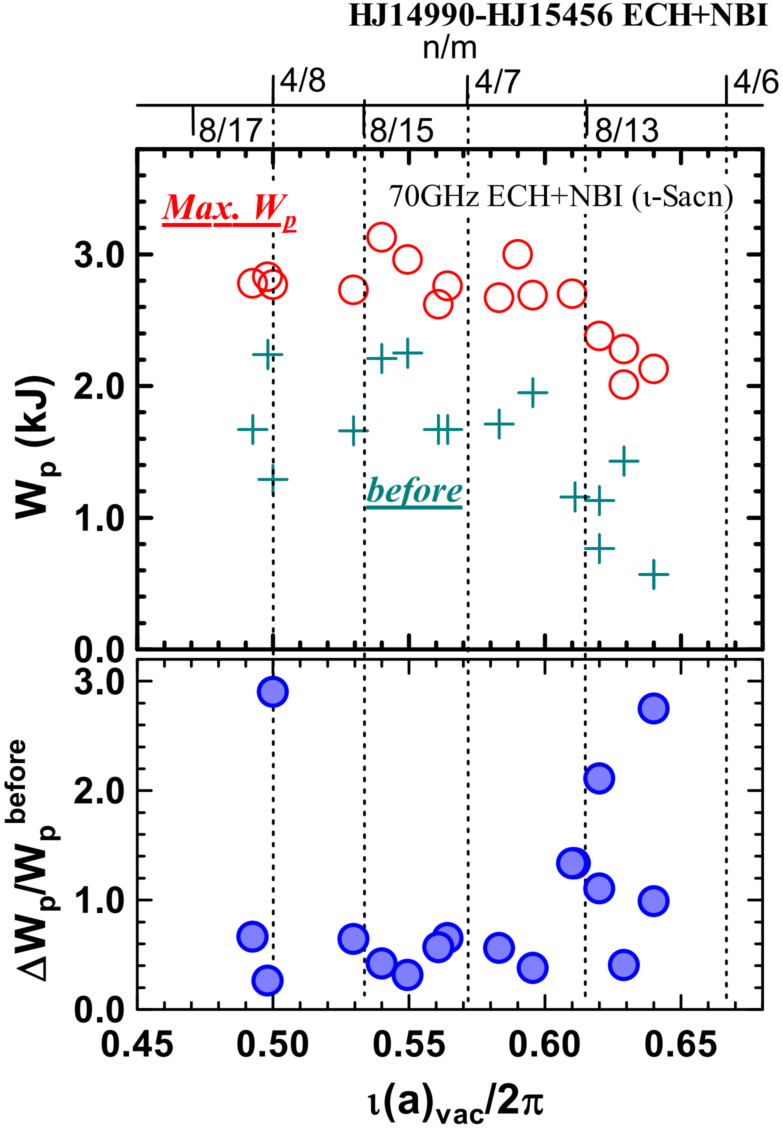
*Ref. Nishino, C09 (Tue)*



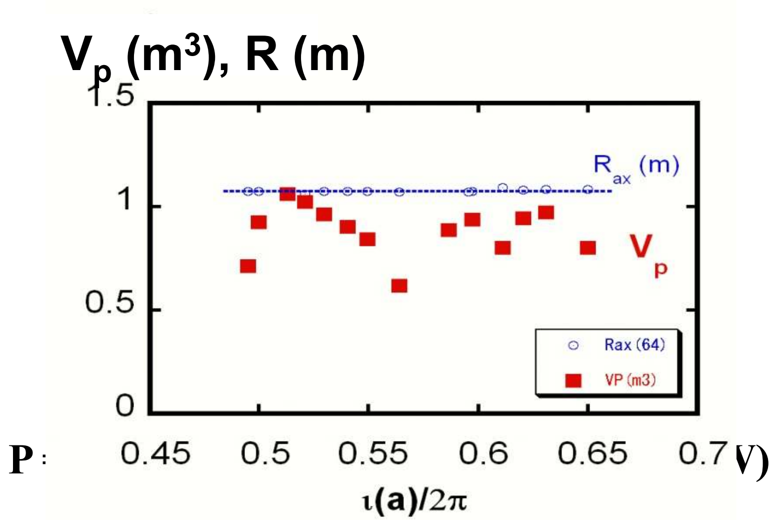
L-mode L-H transition H-mode

# Before the transition, $W_p$ strongly depends on $\iota(a)/2\pi|_{vac}$, but it is moderated after the transition.






- The transition phenomena were observed almost all $\iota(a)/2\pi$ cases for the input power range in the experiment (ECH+NBI).
- Some configurations show a remarkable improvement but the others show a slight improvement.

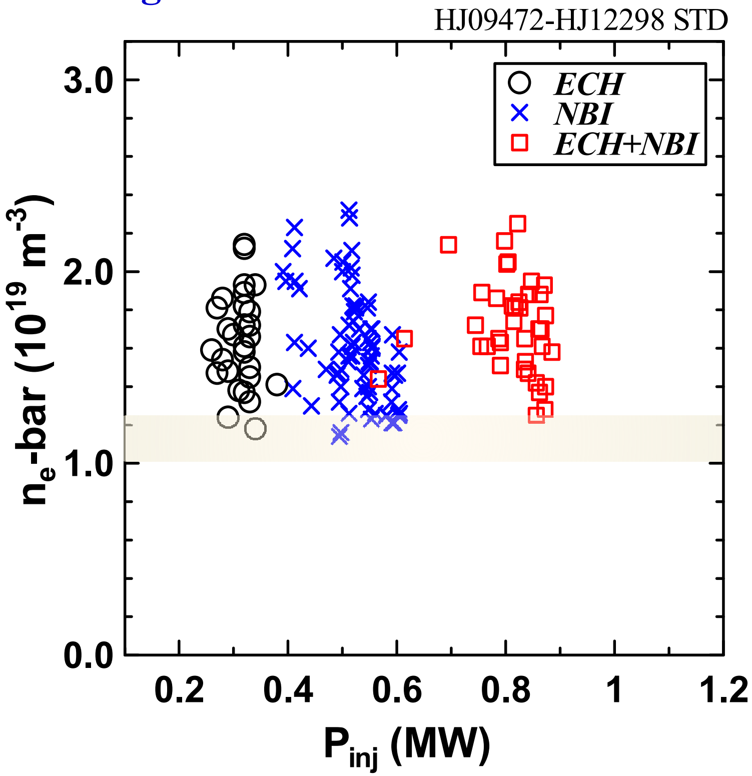


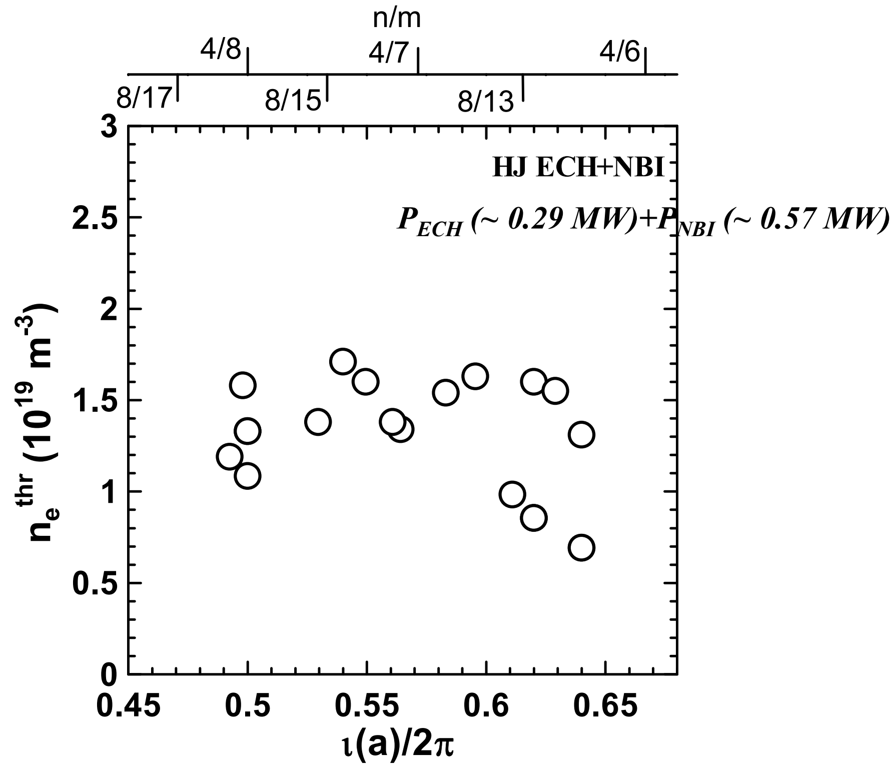
# One robust condition to the transition is the core density.

## The value of the threshold line-averaged density is not sensitive to the heating method, $P_{inj}$ level, $\iota(a)/2\pi|_{vac}$.



STD configuration



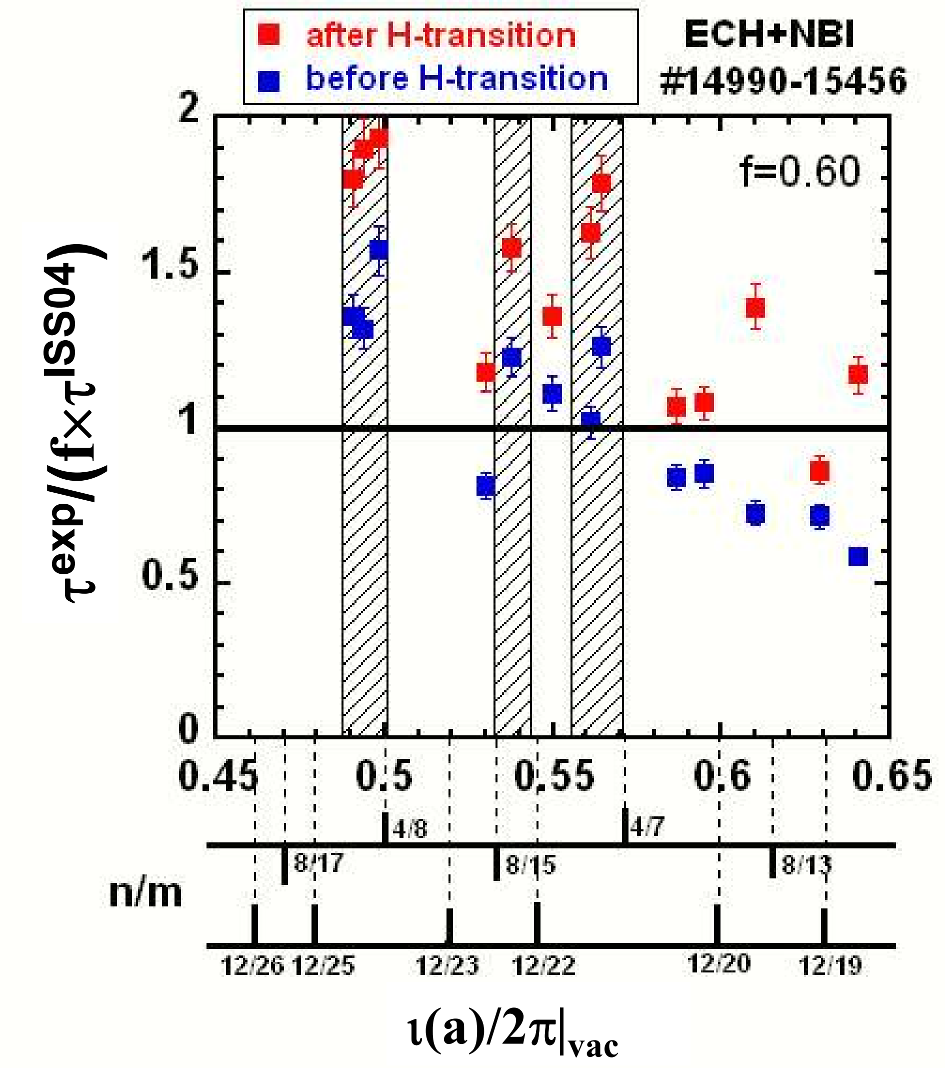




- The threshold density is a robust condition of the transition.
- The threshold density (lower density limit for the transition) is ~ 1-2×$10^{19}$ m$^{-3}$.
- Only for higher values of $\iota/2\pi$, some exceptional low threshold density cases are observed. ⇔ MHD activities?

# the "quality of improvement" based on ISS04 seems to depend on the configuration.

*F. Sano, et al., Nucl. Fusion 45 (2005) 1557.*






- Iota-windows for high quality H-mode close to the low-mode rationals
- All configurations basically have "stellarator shear" (vacuum) ⇒ hard to get edge flux surfaces on the "right-side" of the rationals.
- Difference in the poloidal viscous damping among the configurations can cause the difference in the "quality"?
  - Still open question.
    - Bias experiment will give us some information.

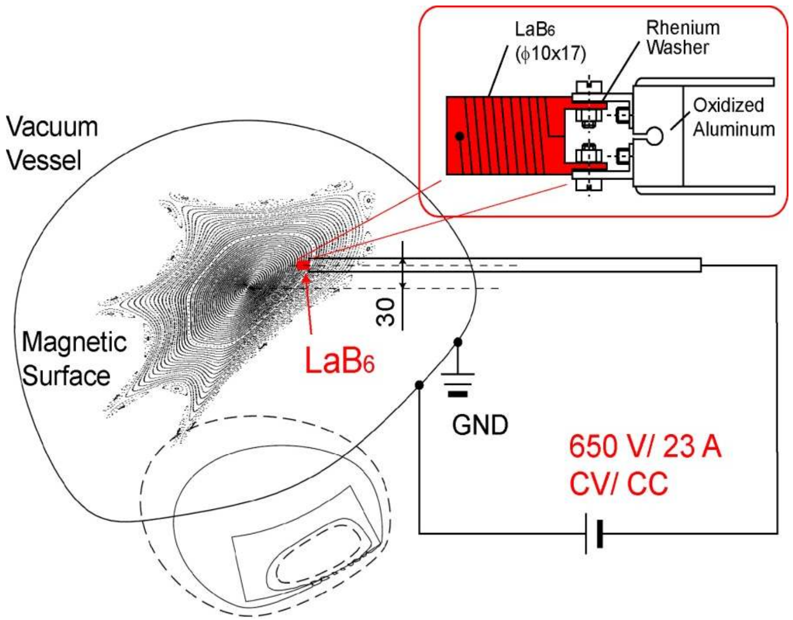
# Electrode Bias Exp. in Heliotron J under a Low Field Condition

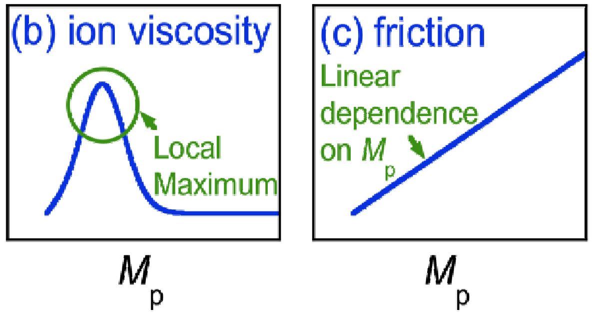
*S. Kitajima, et al., Tohoku Univ.*

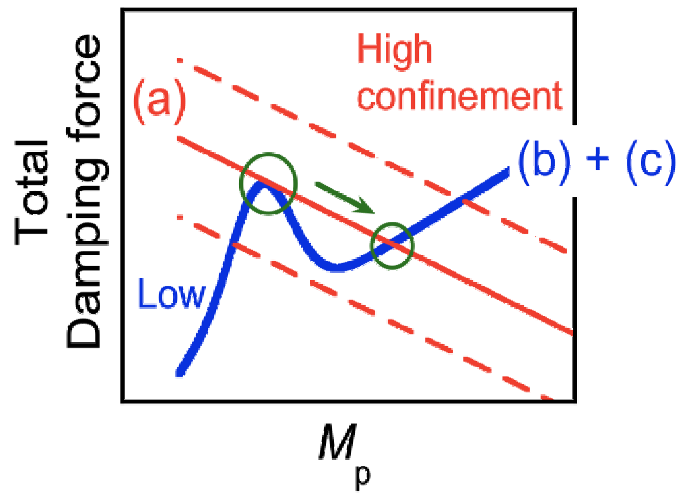
**Externally controlled torque could give us a lot of (but NOT sufficient) information on the viscous damping.**



## Electrode of $LaB_6$ (Hot Cathode)



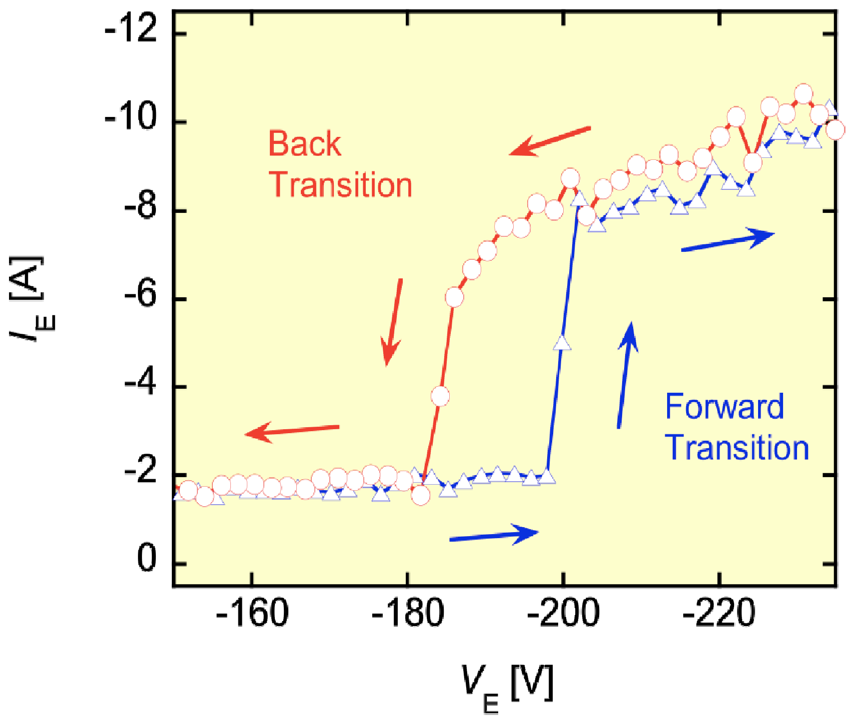

*Note: This experiment was performed under a special configuration for 2.45GHz ECH discharge.*

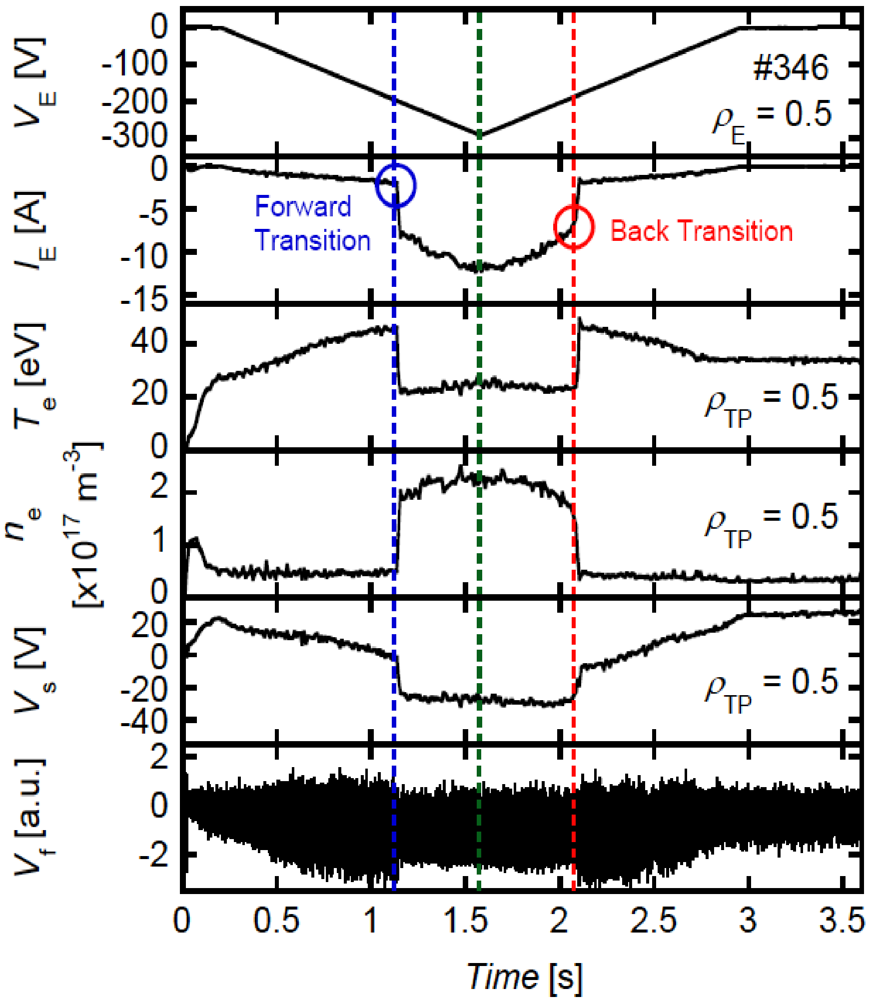
# Time Evolution of a Biased Discharge

<u>Triangular voltage was applied in order to give rise to forward/ back transition.</u>



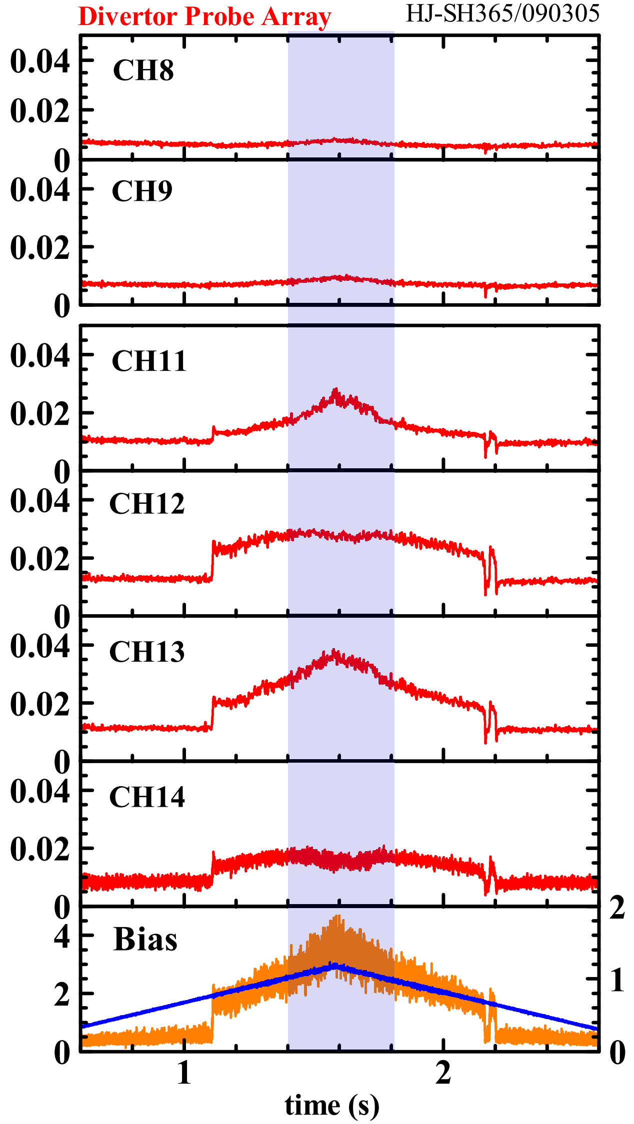
- **Rapid increase of $I_E$ and $n_e$.**
- **$V_s$ changed from positive to negative.**
- **Drop in the fluctuation level.**
- **Clear hysteresis of $I_E$.**

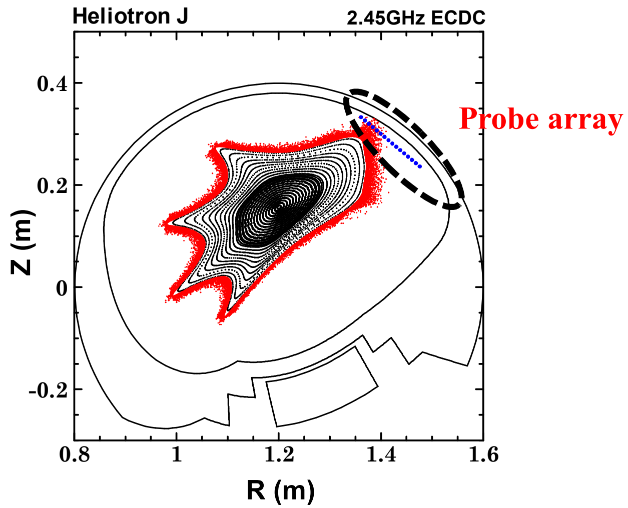


# Bias Exp. suggests
# plasma rotation can modify the edge field topology.





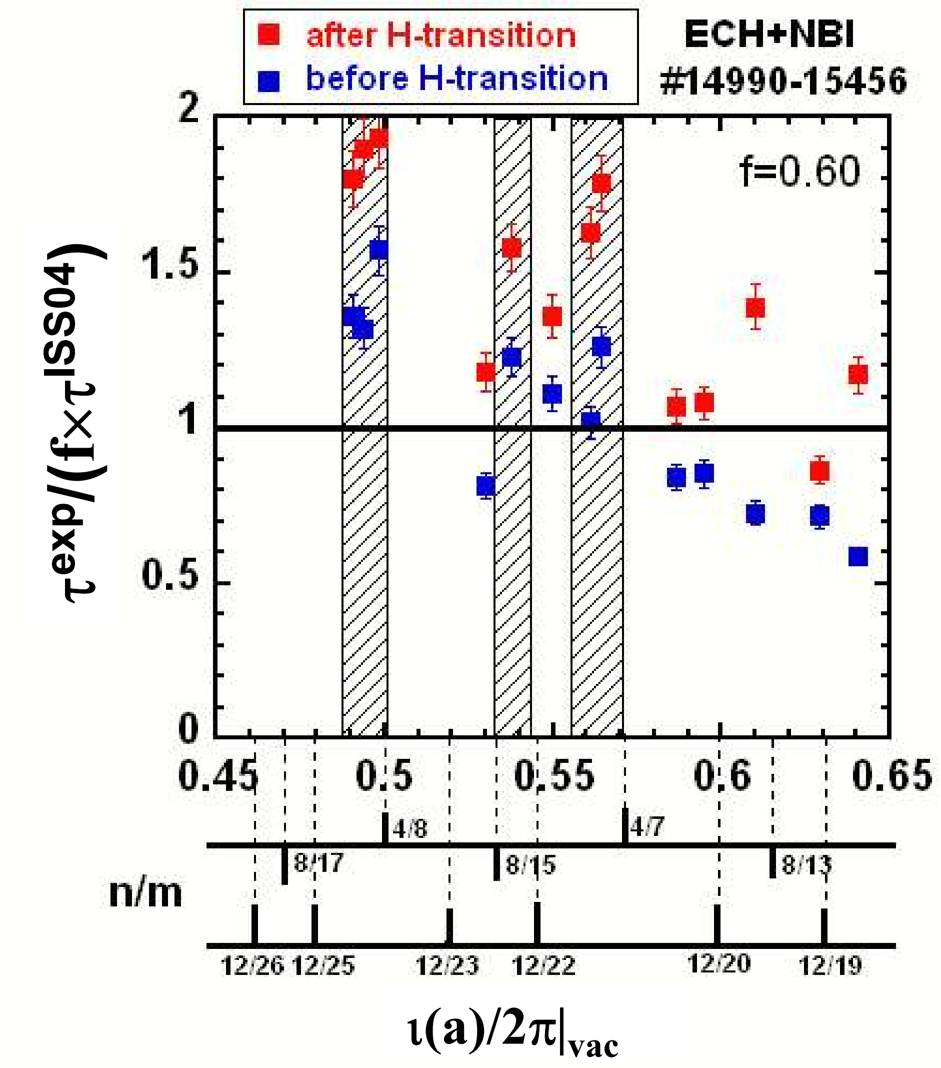




**Time traces of ion-saturation currents at divertor probe array during biasing:**
**Increase for some channels,**
**but decrease for other channels.**
**→ Modification of edge field topology!**

# The "quality of improvement" based on ISS04 seems to depend on the configuration.

*F. Sano, et al., Nucl. Fusion 45 (2005) 1557.*






- **All configurations basically have "stellarator shear" (vacuum) ⇒ hard to get edge flux surfaces on the "right-side" of the rationals.**
- **Difference in the poloidal viscous damping among the configurations?**

- **But, is that all?**
  - ***How about the "plasma effects", especially effects of (non-induction) plasma current.***
  - ***Experiments suggest the change of the iota and/or the size of the confinement region.***

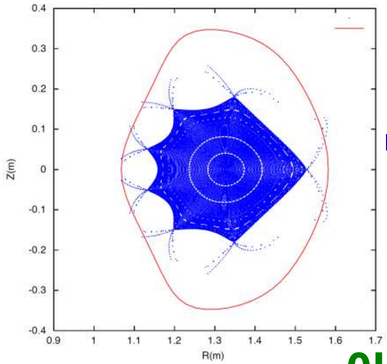
# HINT2 predicts the change of the field topology caused by plasma current:

$$\beta(s) = 0.5\cdot(1-s)^2\ [\%],\ \ j_p = j_{p0}\cdot(1-s)^2$$

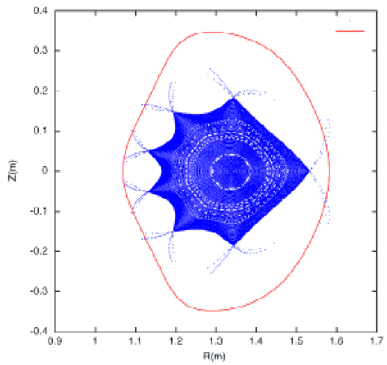
*IAE, Kyoto University*

- "Additive" plasma current can modify not only the ι/2π-profile but also the "shape" of magnetic surfaces.
- Asymmetric effect of plasma current due to the "proximity" to a low-mode rational number.

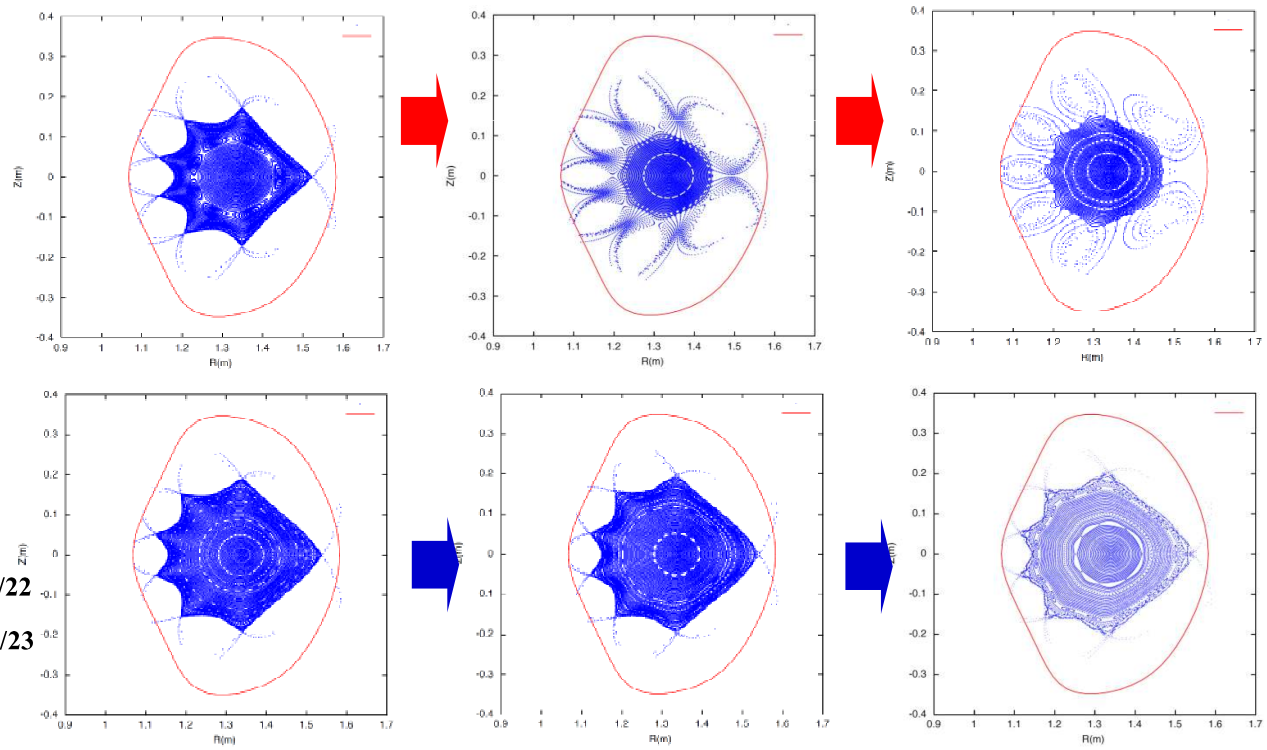
vacuum



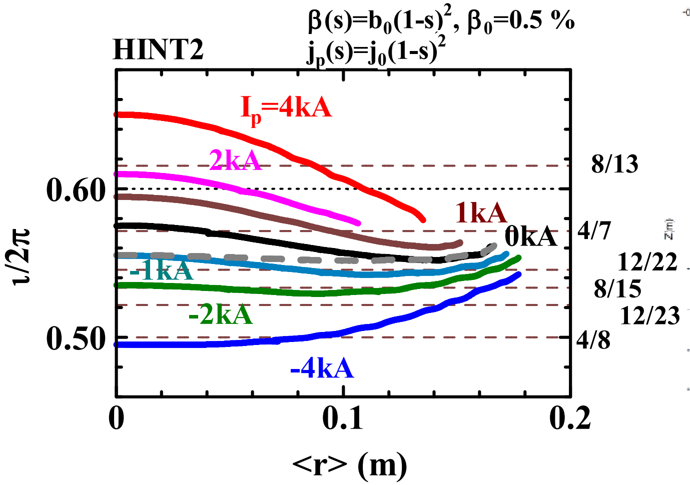

0kA




ad. 1kA    ad. 2kA    ad. 4kA



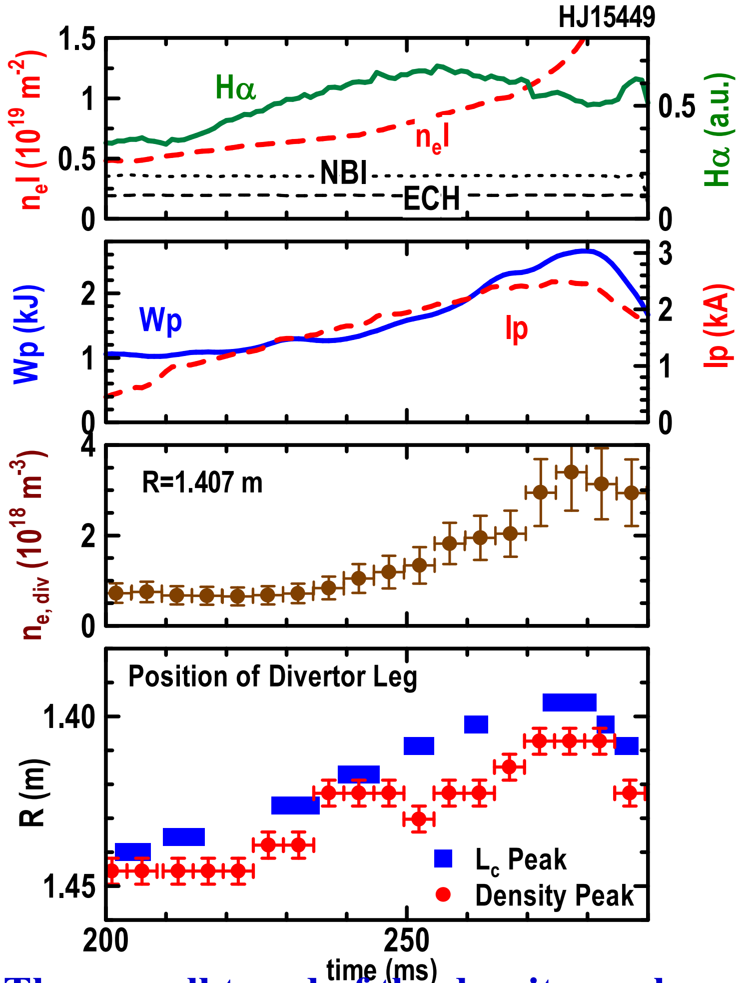

sub. 1kA    sub. 2kA    sub. 4kA



# Experiments suggest the change of the edge field topology during a plasma shot.

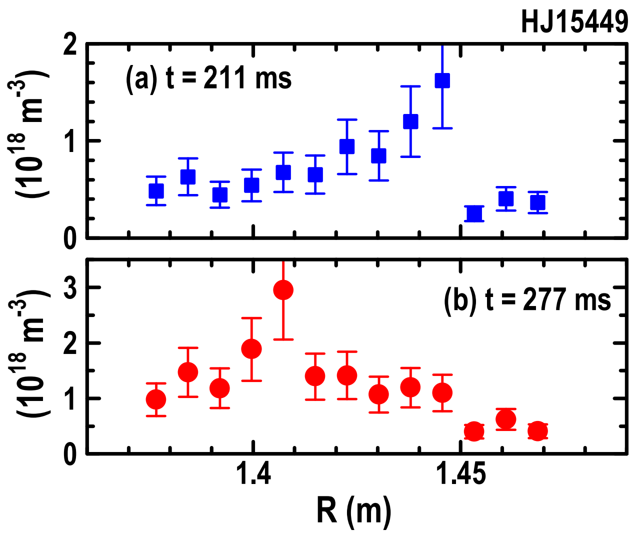
## ECH (≈ 0.3 MW) + NBI (≈ 0.7 MW, co-injection) @ STD






- **The overall trend of the density-peak-position shift seems to be well synchronized with the change of $W_p$ or $I_p$.**

- **The observed non-inductive toroidal plasma current is gradually increases as increase of the stored energy.**
  - ***In the density range shown in the figure, the observed plasma current is considered to mainly consist of the bootstrap current and the NB induced current.***

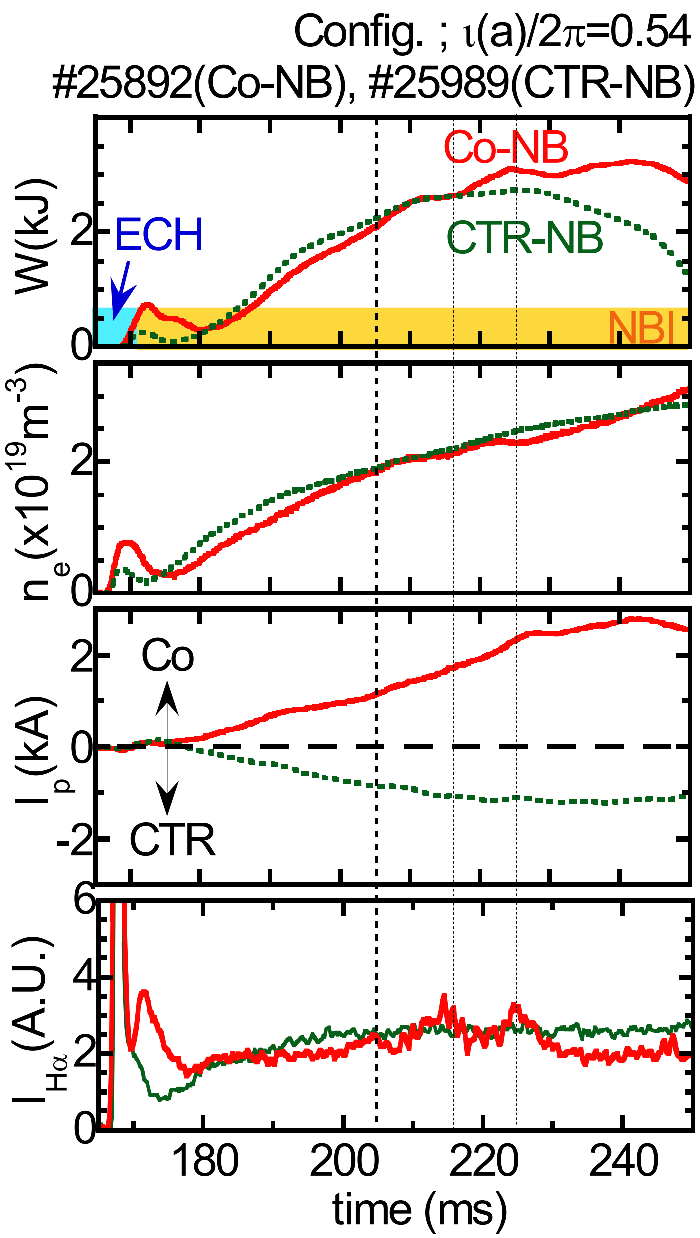



- **The profiles of the diverted plasma density at t = 211 and 277 ms.**
  - ***At 211 ms, the density distribution is consistent with that expected from the vacuum field topology.***
  - ***At 277 ms, the density peak position shifts inward about 4 cm compared to the position at 211 ms.***

# Comparison between Co/CTR NBI-only plasmas

## *- No transition in CTR NBI -*



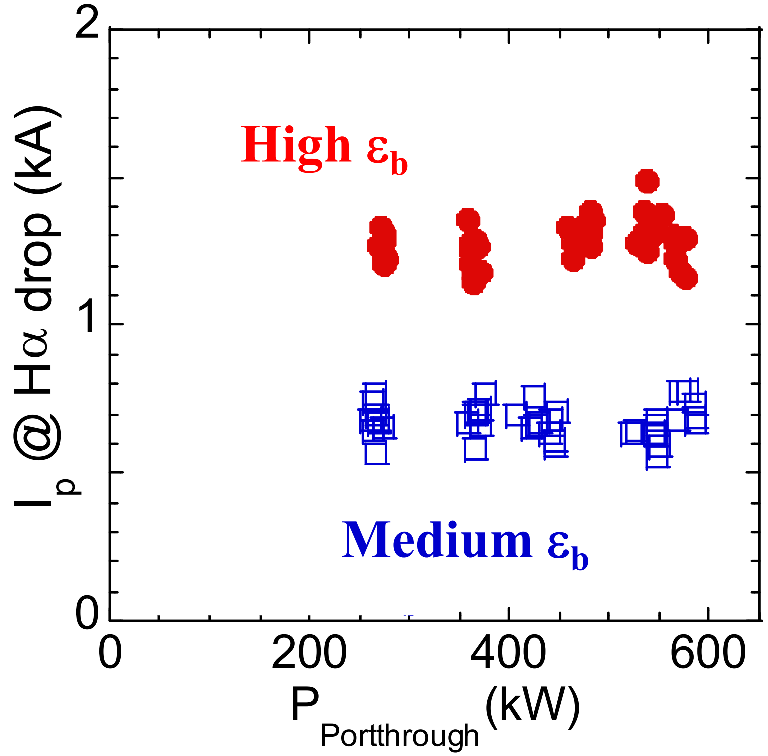



- **In Co-NBI, the transition were observed, but no transition in CTR-NBI.**
  - ☞ **Difference in the transition condition between these NBI-only plasmas due to**
    - ☐ **Deformation of ι/2π**
      - ☐ **Position of rational surface,**
      - ☐ **Shear,**
      - ☐ **Shape of LCFS,**
    - ☐ **Direction of momentum input ?**

# The transition is observed when the plasma current reaches a critical value.



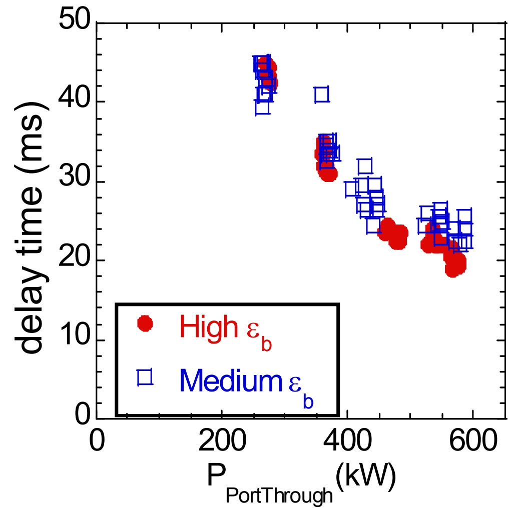
*Dependence of $I_P$ at transition on $P_{NB}$*




*− In high $\varepsilon_b$ case, higher $I_p$ was required.*

- **The critical value of the plasma current depends on the configuration;**
  **0.7±0.1kA in middle $\varepsilon_b$**
  **1.3±0.2kA in high $\varepsilon_b$ cases.**
- **The observed time delay would be related to the growing-up time of the current.**

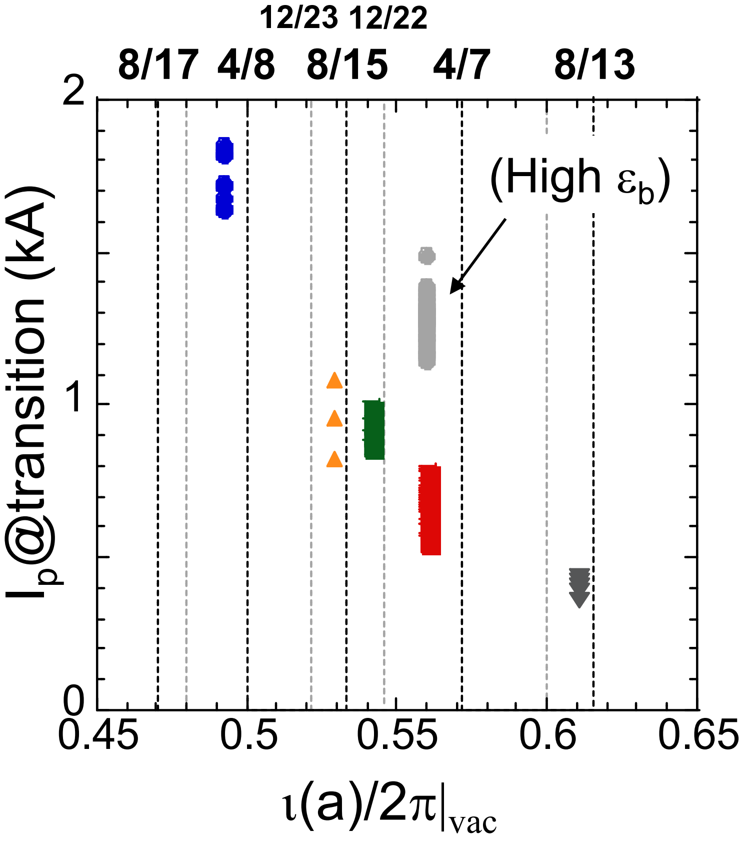
*Dependence of delay time on $P_{NB}$*




**The effects of the plasma current on the field configuration should depend on the vacuum rotational transform. → *$\iota(a)/2\pi|_{vac}$-scan experiment.***

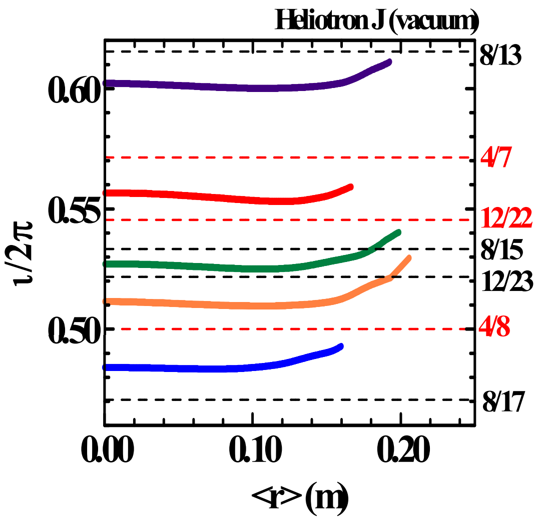
# The critical current for *NBI-only plasma* strongly depends on $\iota/2\pi|_{vac}$.



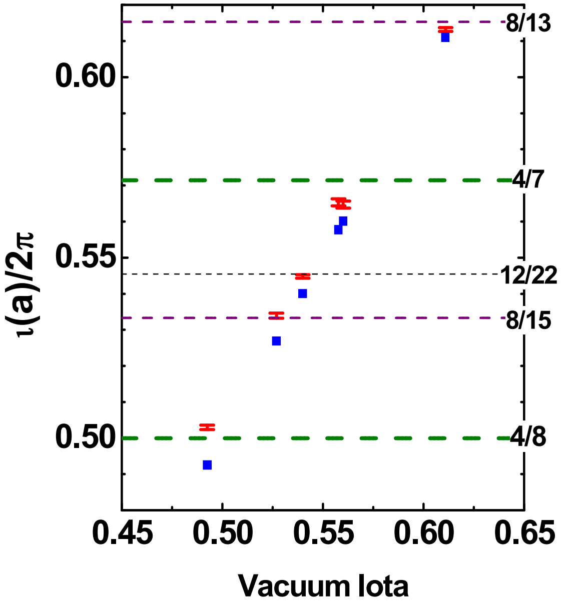



**0.25 MW < $P_{inj}$ < 0.6 MW,**
**$n_e \sim$ 1.5-2×$10^{19}$ $m^{-3}$**

*Radial profile of iota*



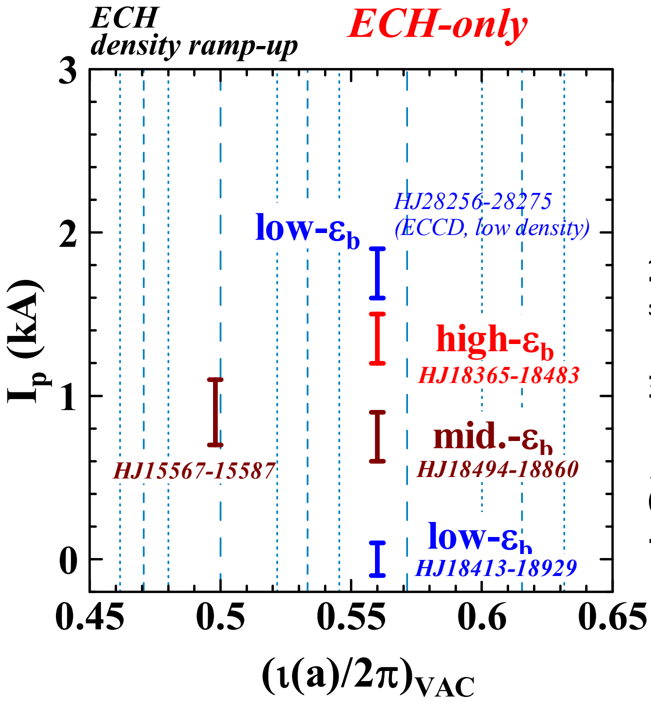

HJ *Close to Rationals?*

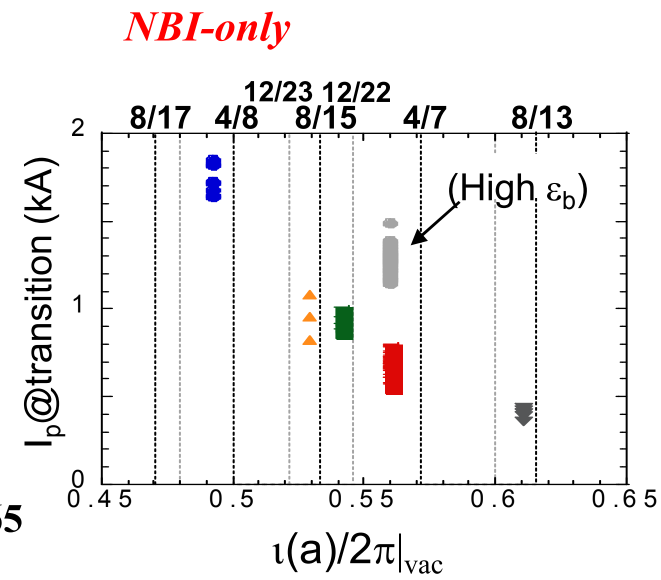


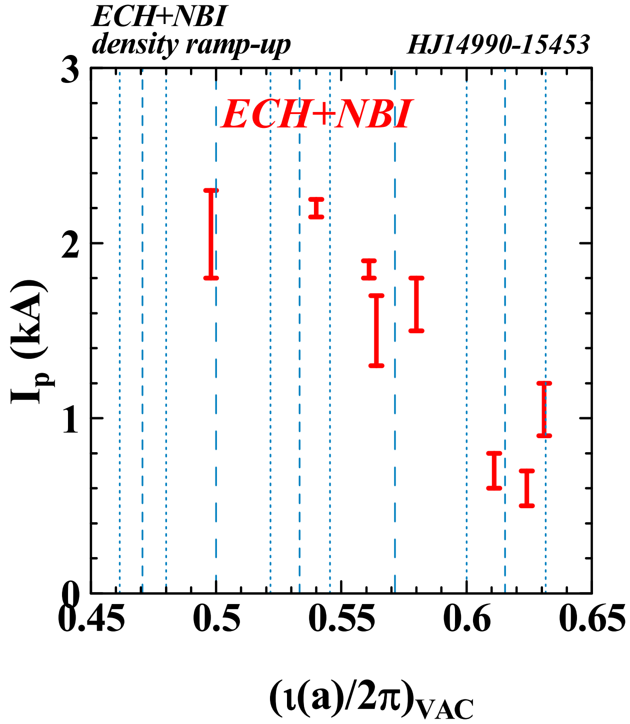

- ☞ ***So far, the transition was observed only in Co-NBI (ad. NBCD) plasmas ($P_{inj}$ < 0.6 MW).***
- ☞ **A "critical current" for the transition exists for all config.**
- ☞ **Does the change in the rotational transform caused by non-inductive plasma current trigger the transition? → Check other heating cases.**

# Comparison of the plasma current at the transition for *ECH-, NBI-, and ECH+NBI-plasmas*





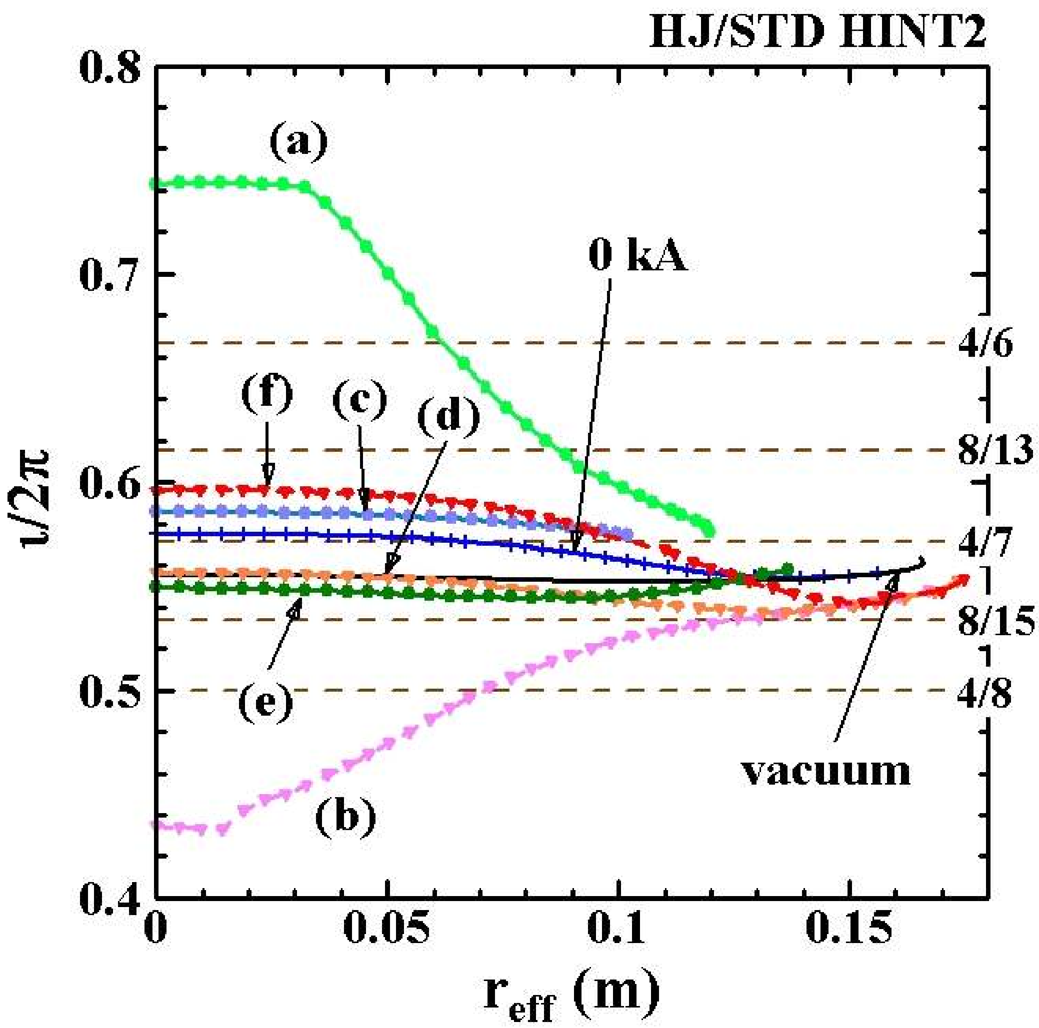



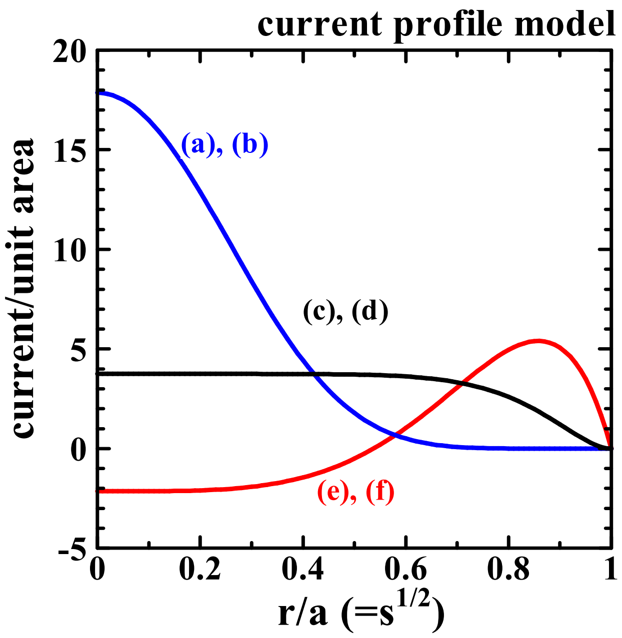

- $I_{p,NET}$ itself seems not a key factor?
  ➔ Need profile data!

# Even for the same net current, the deformation of ι/2π and the shape of the magnetic surface strongly depend the current profile.

## - MODEL CALCULATION -






*$\langle\beta\rangle \sim 0.32$ %, $p=p_0(1-s^2)^2$*

(a) $j=j_0(1-s)^8$, $I_{net}=+2.0$ kA

(b) $j=j_0(1-s)^8$, $I_{net}=-2.0$ kA

(c) $j=j_0(1-s^4)^2$, $I_{net}=+2.0$ kA

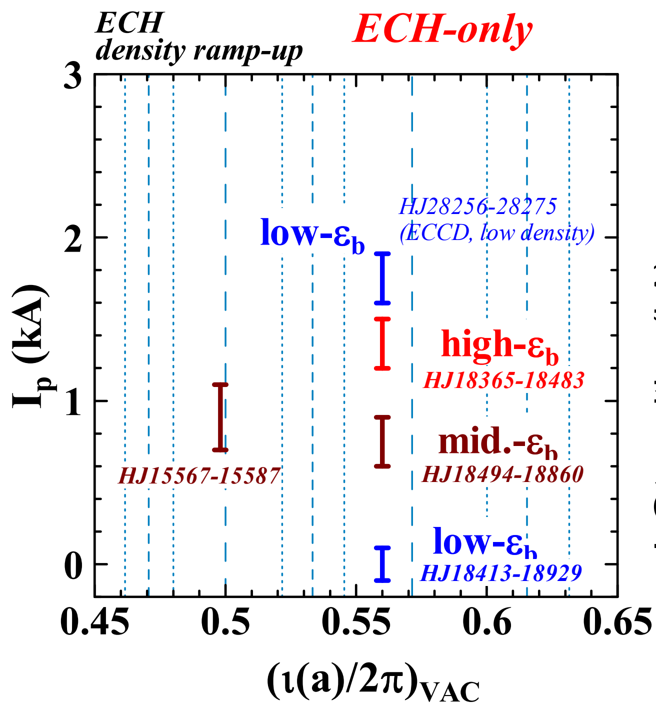
(d) $j=j_0(1-s^4)^2$, $I_{net}=-2.0$ kA

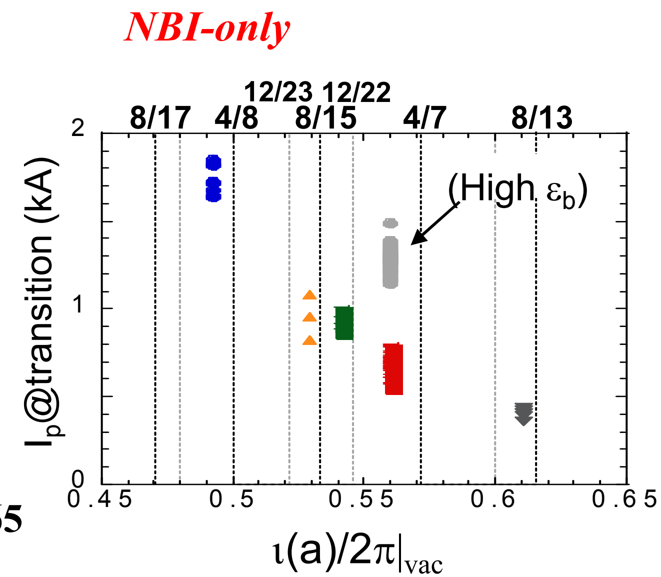
(e) $j=j_0(60(1-s^2)s^2-5(1-s^2))$, $I_{net}=+2.0$ kA

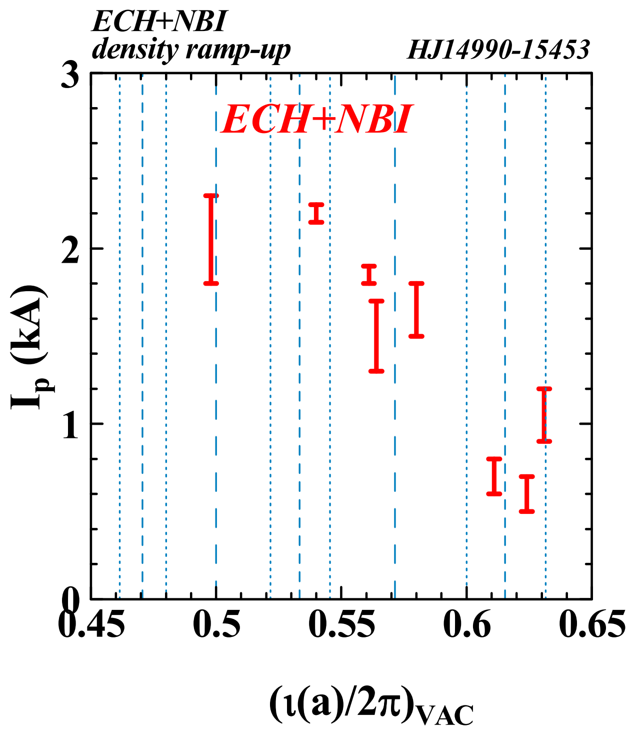
(f) $j=j_0(60(1-s^2)s^2-5(1-s^2))$, $I_{net}=-2.0$ kA

# Comparison of the plasma current at the transition for *ECH-, NBI-, and ECH+NBI-plasmas*





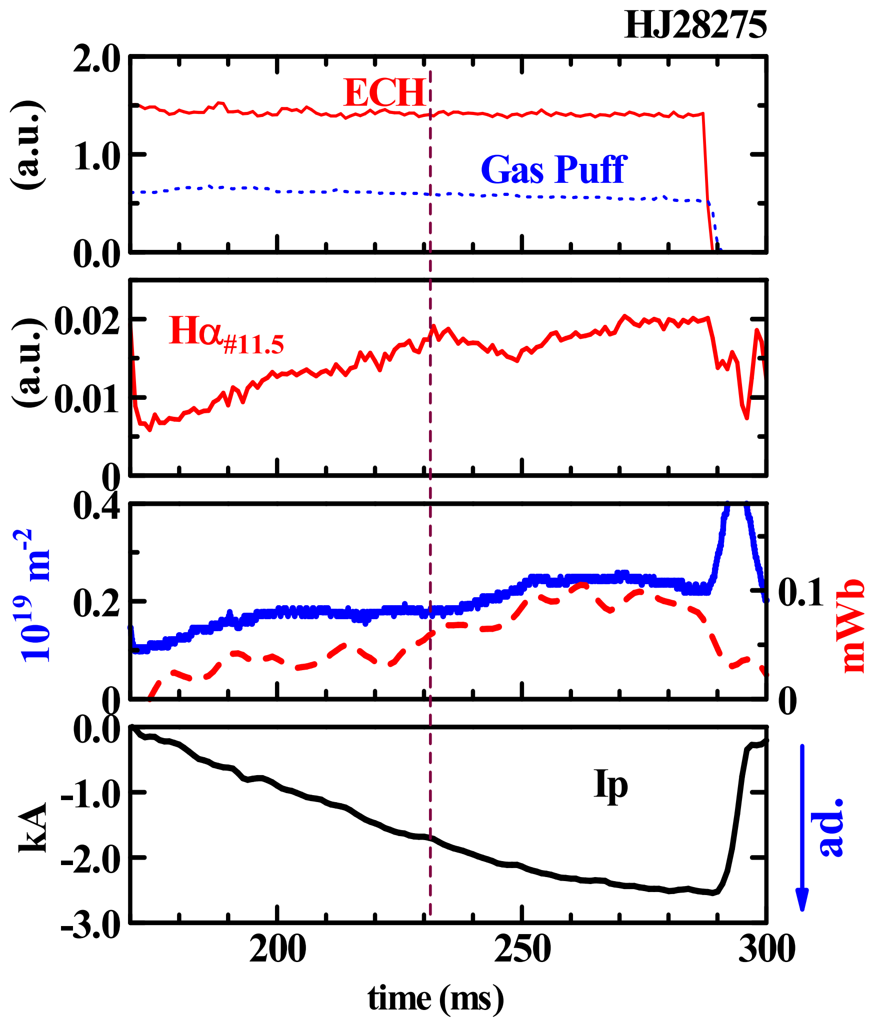




- $I_{p,NET}$ itself seems not a key factor?
  ➔ Need profile data!
  - Even in low density ECH-only plasma lower than the threshold density, the transition can be observed when the EC driven “additive” current is high enough.
- Transition is observed in ECH+NBI plasmas even in the low $\varepsilon_b$ case.

# Transition to a better confinement mode was observed in a high ECCD current discharges.






- Low-$\varepsilon_b$, $\iota/2\pi(a) \sim 0.56$, ECH-only with $P_{ECH} > 0.3$ MW
- The line-averaged density is much lower than the critical low-density limit observed in the previous experiments.
- *No enough experiments, from this point of view, in sub. high ECCD condition.*

# Summary (1)

## *– Transition to improved confinement –*



- **No transition in CTR-NBI-only plasma**
  **Existence of the "critical current" in Co-NBI-only plasma**
  **→ Change in the rotational transform (and/or its radial profile) caused by plasma current and/or the direction of momentum input can trigger the transition in NBI plasma.**
- **No clear current dependence in ECH-only plasma**
  **→ Difference in the transition condition between NBI-only and ECH-only plasmas.**
  **→ ECH should have some effect on the transition condition in NBI plasma.**
- **In low density (lower than the threshold density) ECH-only plasma, the transition can be observed**
  **when the EC driven "additive" current is high enough.**
  **→ Change in the rotational transform (and/or its radial profile) is effective even for ECH-only plasma.**

# Summary (2)

## *– Transition to improved confinement –*



for $n_e > n_{e,th}$

| | ECH-only | NBI-only (Co) | NBI-only (CTR) | NBI (Balance) ECH+NBI (Balance) | ECH+NBI (Co) | ECH+NBI( CTR) |
|---|---|---|---|---|---|---|
| $\iota(a)/2\pi\|_{vac}$ | X only for 0.493 | OK | X | No Data | OK | No Data |
| $\varepsilon_b$ * | △ for high-$\varepsilon_b$ | X for low-$\varepsilon_b$ | X | No Data | OK | No Data |
| $I_{p,th}$ ** | No | Yes | – | | Yes | |
| remarks | Transition is observed in low $n_e$, high $I_p$ | | | | | |

* Data for different $\iota(a)/2\pi|_{vac}$ are necessary.

** Data @ Ip=0 are necessary.

# *Thank you for your attention!*
# *&*
# *Thank you All Contributors for Nice Collaborations!*



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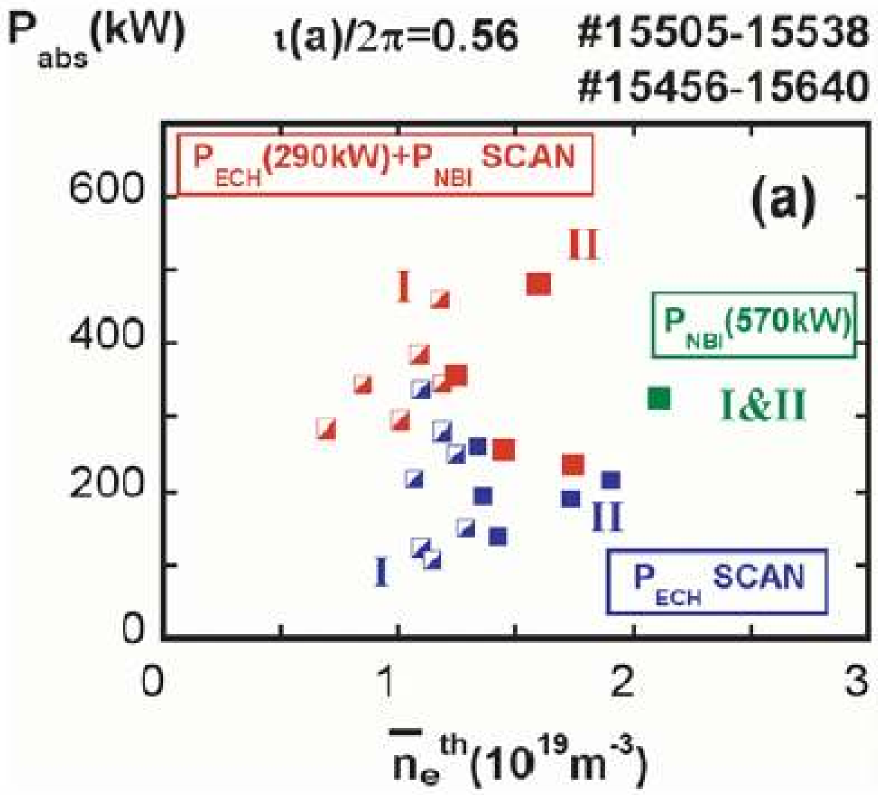
# No clear threshold power for Phase-I






- No clear/simple relation between $n_{th}$ and $P_{abs}$.
- At the $\iota(a)/2\pi \approx 0.493$, ECH-only discharges cannot make a transition. → configuration effects on the power threshold.
- Different power dependence for Phase-I and II?

*F. Sano, et al., Nucl. Fusion 45 (2005) 1557.*