November 6-8, 2006
PPPL, Princeton

Workshop on
"Active Control of MHD Stability
: Active MHD Control in ITER"

RWM Analyses of JT-60SA and JT-60U Tokamak Plasmas

G. Kurita, J. Bialek[#], T. Fujita, H. Tamai,
M. Matsukawa, G. Matsunaga, M. Takechi,
T. Tuda, T. Ozeki, G.A. Navratil[#] and S. Ishida

JAEA, Fusion Research and Development Directorate
[#] Columbia University

OUTLINE for JT-60SA Analyses

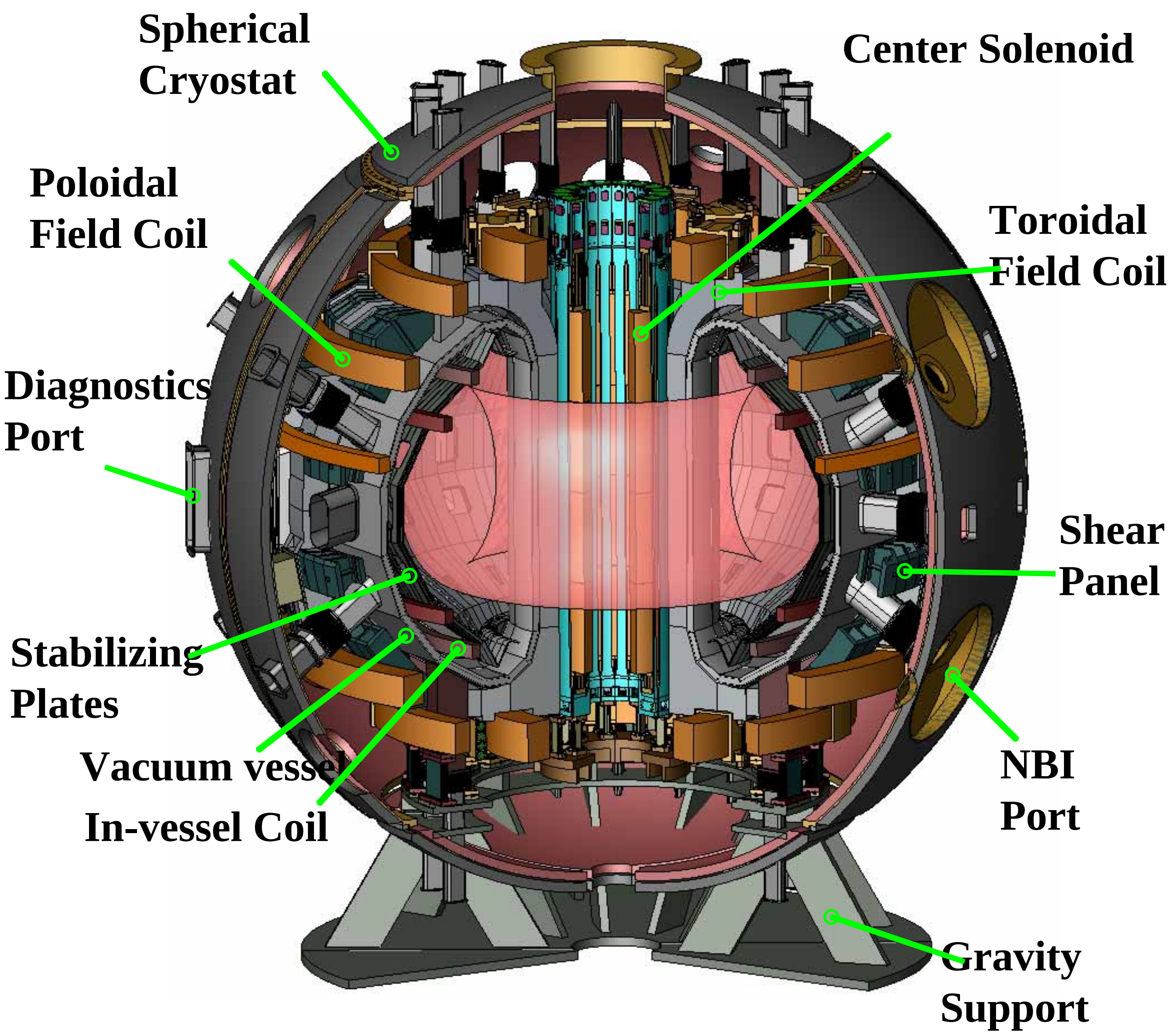
1. Introduction
2. Double-null equilibrium of JT-60SA
3. Configuration of stabilizing plate and Sector coils
4. Critical β_N with passive effect of stabilizing plate and active feedback control
5. Previous results for NCT plasma for reference
6. Summary and next step

RWM Analyses of JT-60SA Tokamak Plasma

- One of research subjects of JT-60SA is demonstration of steady-state high-beta plasma (β_N=3.5 to 5.5).
- To get higher β_N value than no-wall limit (β_N~ 2.56), suppression or control of Resistive Wall Mode is necessary.

- To this end, critical β_N analyses of JT-60SA plasma for n=1 mode using VALEN code are performed, and
- Critical β_N values for passive effect of real geometry stabilizing plate and vacuum vessel, and also with the effect of active feedback control are obtained.

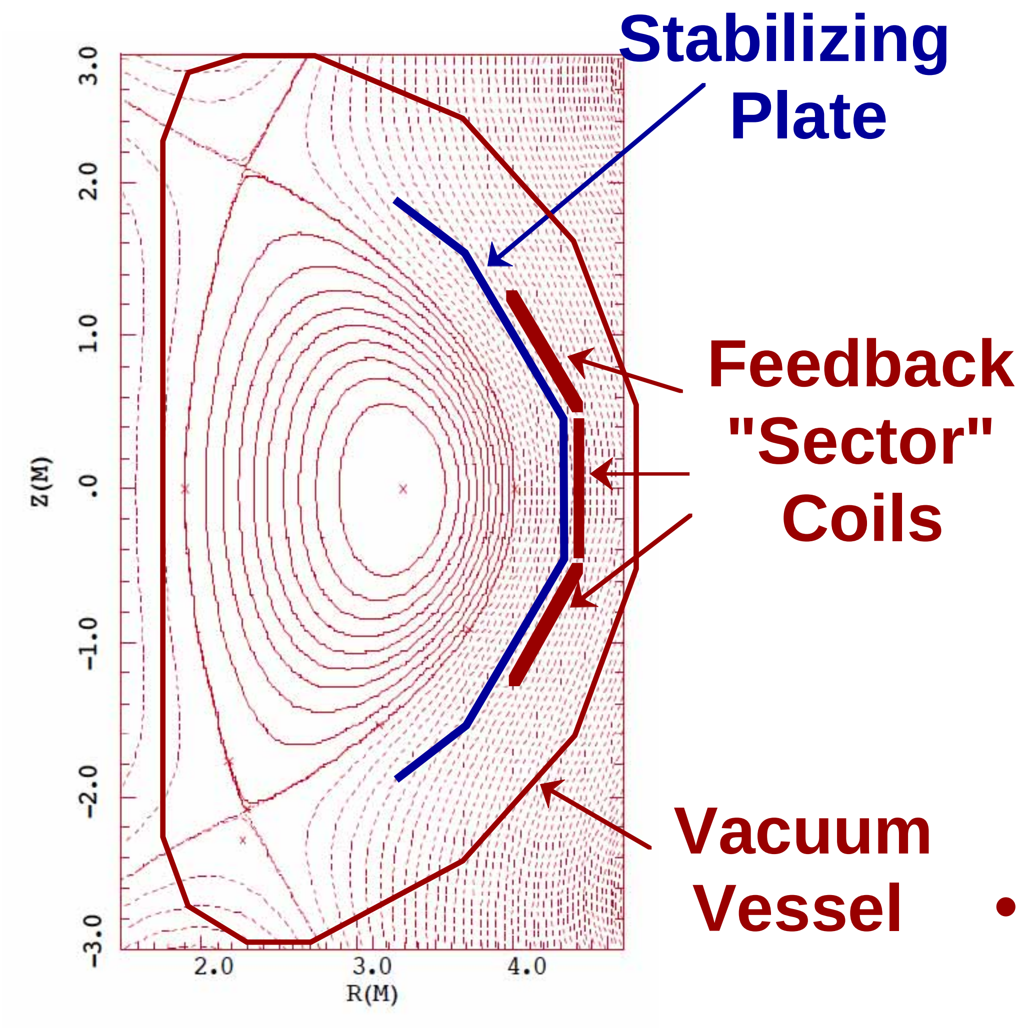
Basic Machine Parameters of JT-60SA



	ITER similar / *high-S for DEMO*
Plasma Current I_p(MA)	3.5 / 5.5
Toroidal Field B_t (T)	2.59 / 2.72
Major Radius (m)	3.16 / 3.01
Minor Radius (m)	1.02 / 1.14
Elongation, κ_{95}	1.7 / 1. 83
Triangularity, δ_{95}	0.33 / 0. 57
Aspect Ratio, A	3.10 / 2.64
Shape Parameter, S	4.0 / 6.7
Safety Factor q_{95}	3.0 / 3.77
Flattop Duration	100 s (8 hours)
Heating & CD power	41 MW x 100 s
N-NBI	34 MW
ECRH	7 MW
PFC wall load	15 MW/m^2
Neutron (year)	4 x 10^{21}

D_2 main plasma + D_2 beam injection

Double-Null Equilibrium for JT-60SA Plasma



Typical Double-Null Equilibrium

- **Parameters**

β_N= 4.5

A=(R_c/a=2.95/1.05=) 2.80

I_p=2.40[MA], B_t=2.60[T]

κ=1.94 : κ_{95}=1.79

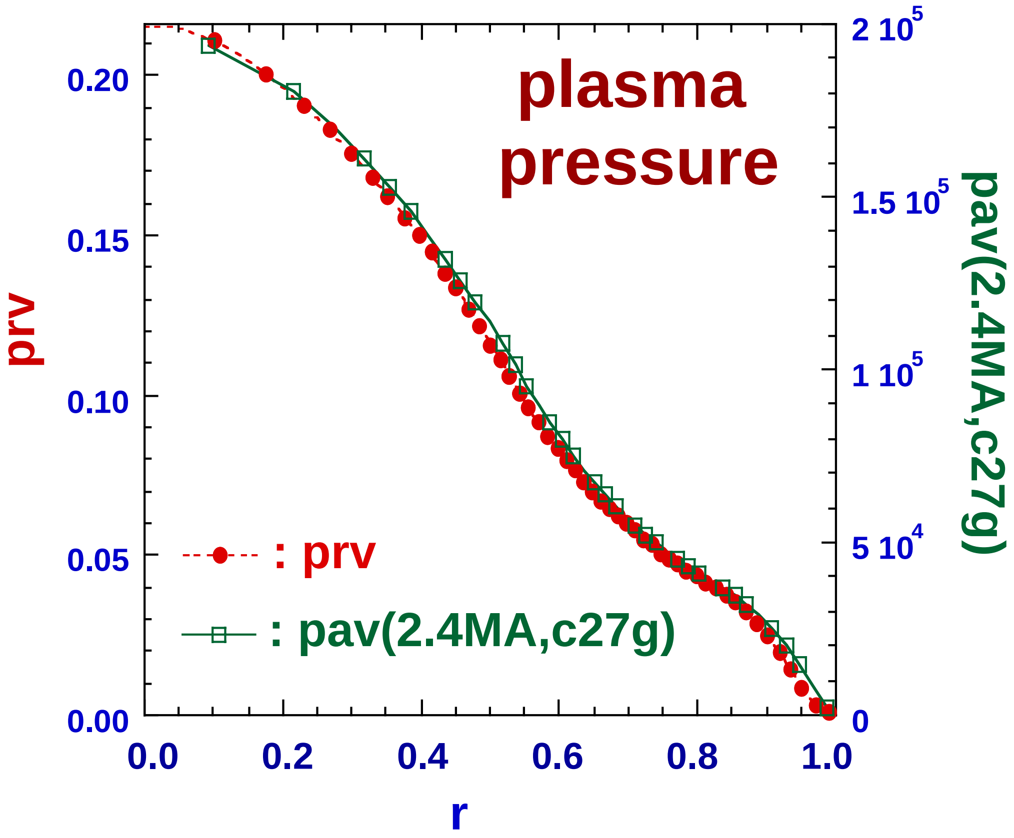
δ=0.60 : δ_{95}=0.41

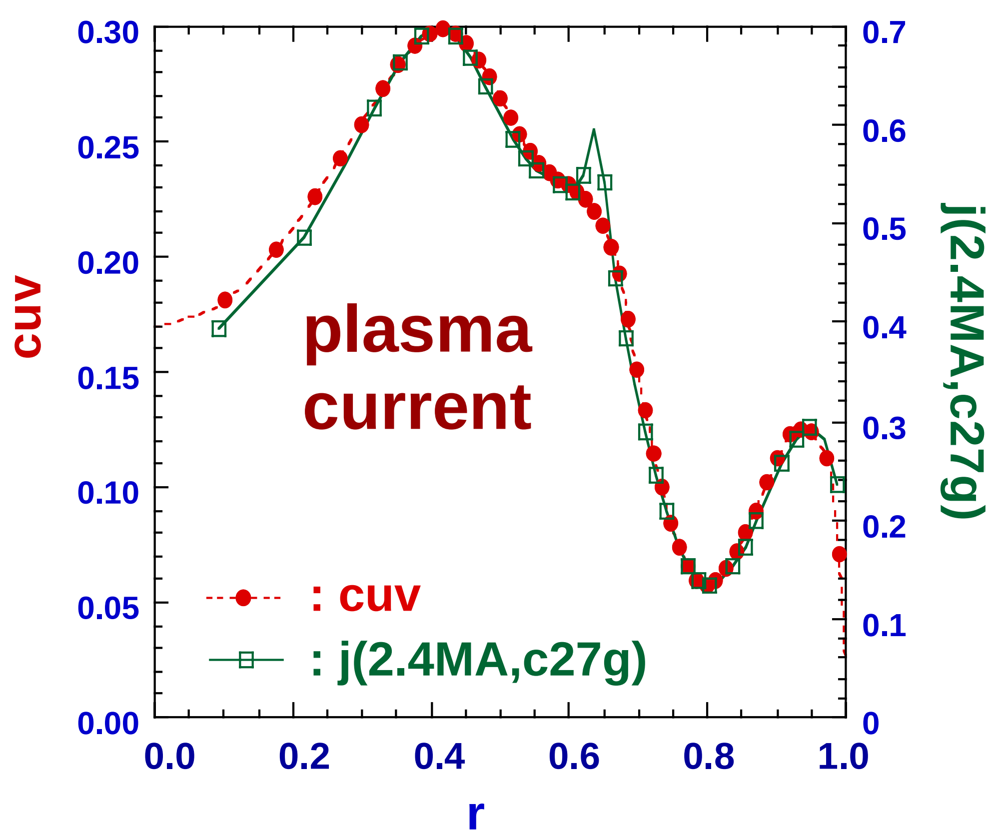
$q_0/q_{95}/q_{min.}$=4.28/ 7.52/ 2.10

li(3)=0.63, p_0/<p>=2.77

- **Up-down symmetric double-null equilibria shown are used in the following critical beta analyses.**

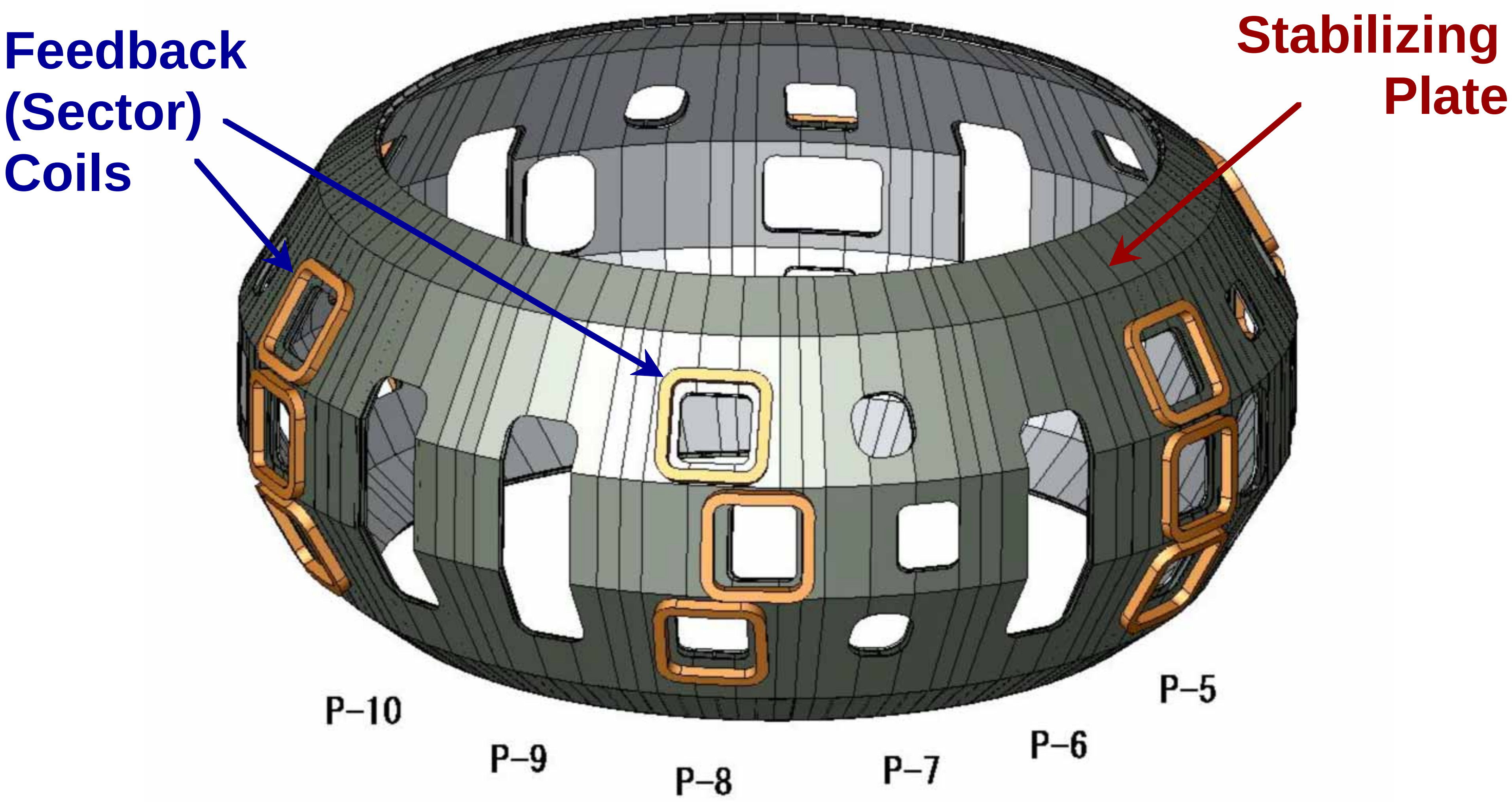
Plasma Pressure and Current Profiles





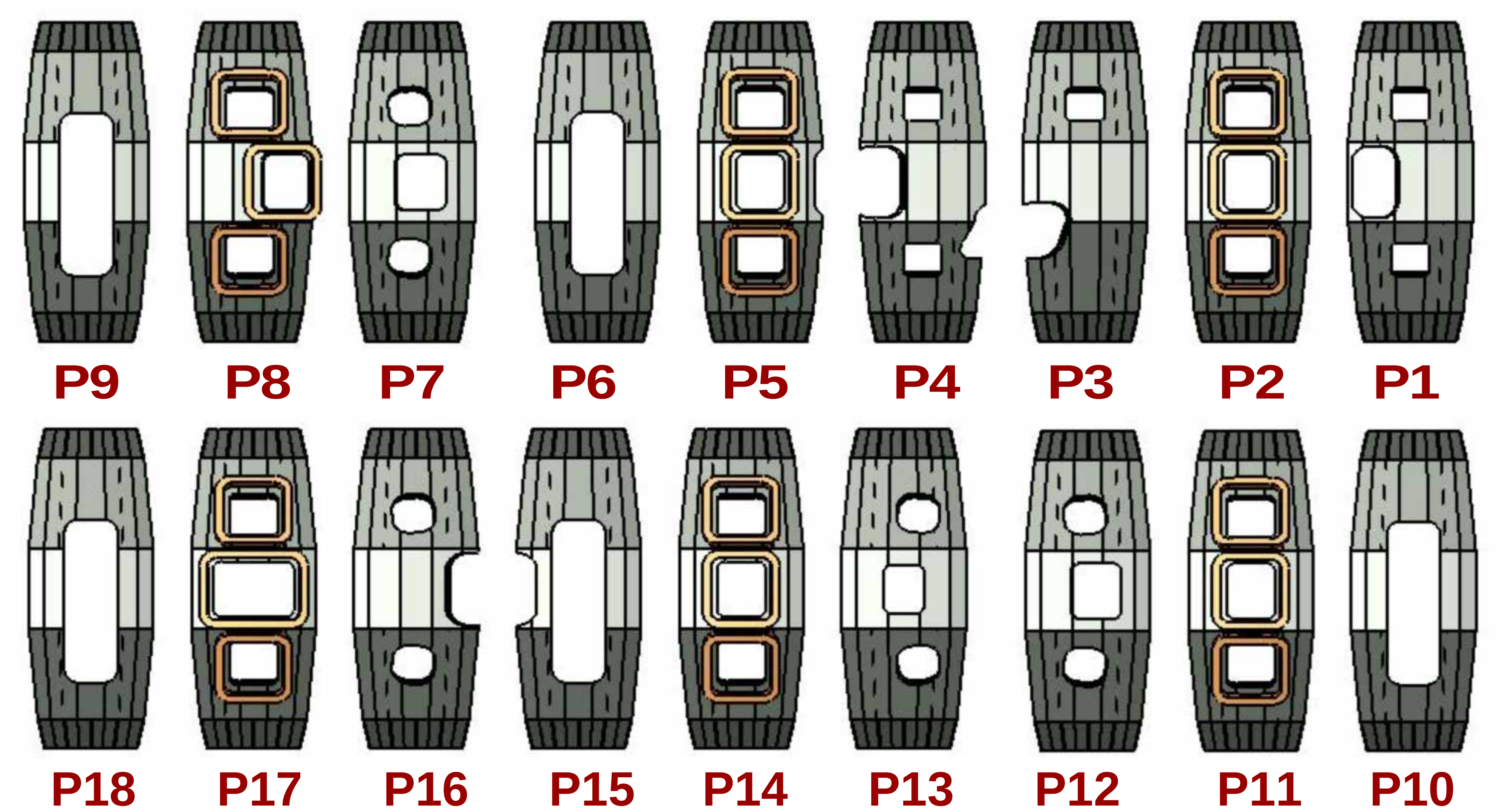
- **Green curves** are plasma pressure and current profiles vs. plasma minor radius obtained with transport analyses.
- **Red curves** are plasma pressure and current profiles used in the critical beta analyses.

Birds-Eye View of Stabilizing Plate and Sector Coils



- Main flux made by feedback coil current can be reached easily to plasma in this configuration of stabilizing plate and sector coils.

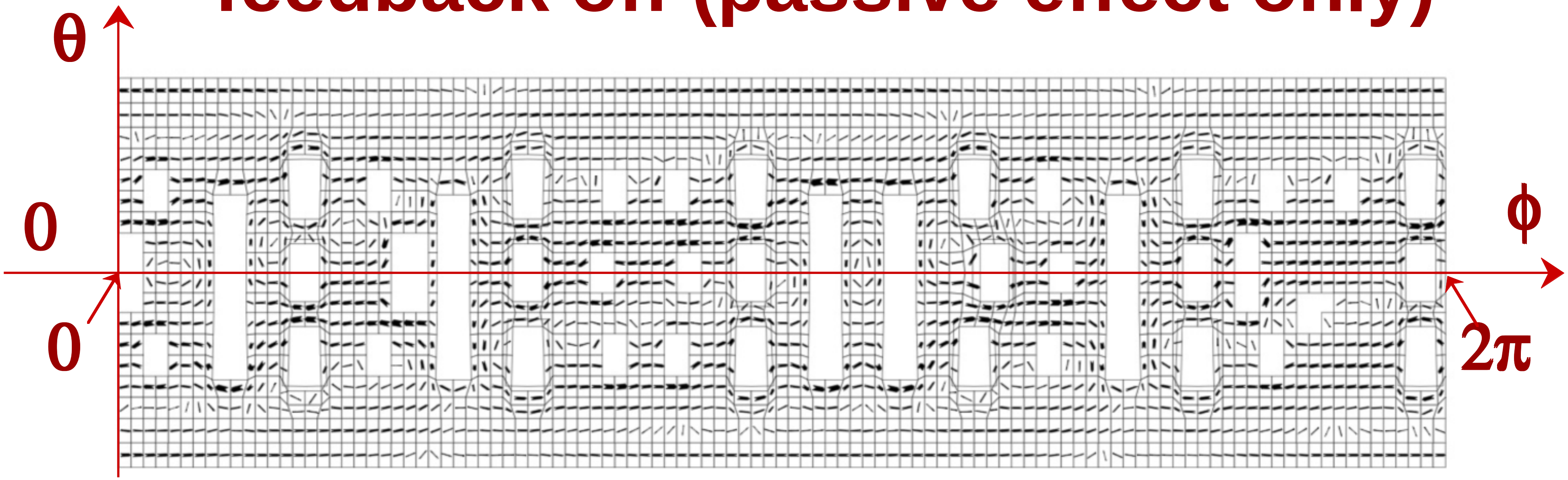
Expanded View of Stabilizing Plate and Sector Coils



- **Toroidal rotational symmetry of middle sector coils is a little bit broken by sector coils of P8 and P17.**

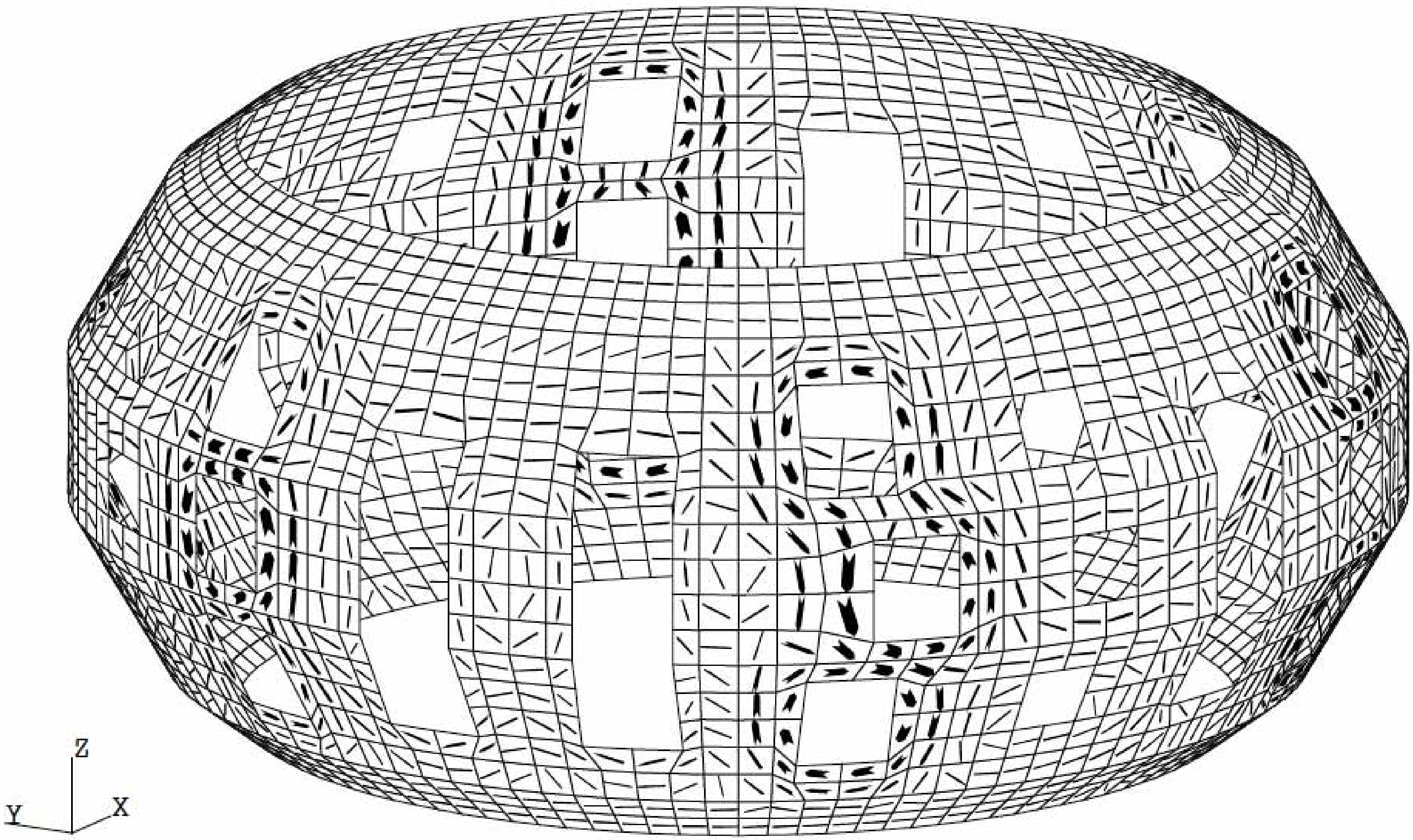
Eddy Current Pattern on Stabilizing Plate

feedback off (passive effect only)



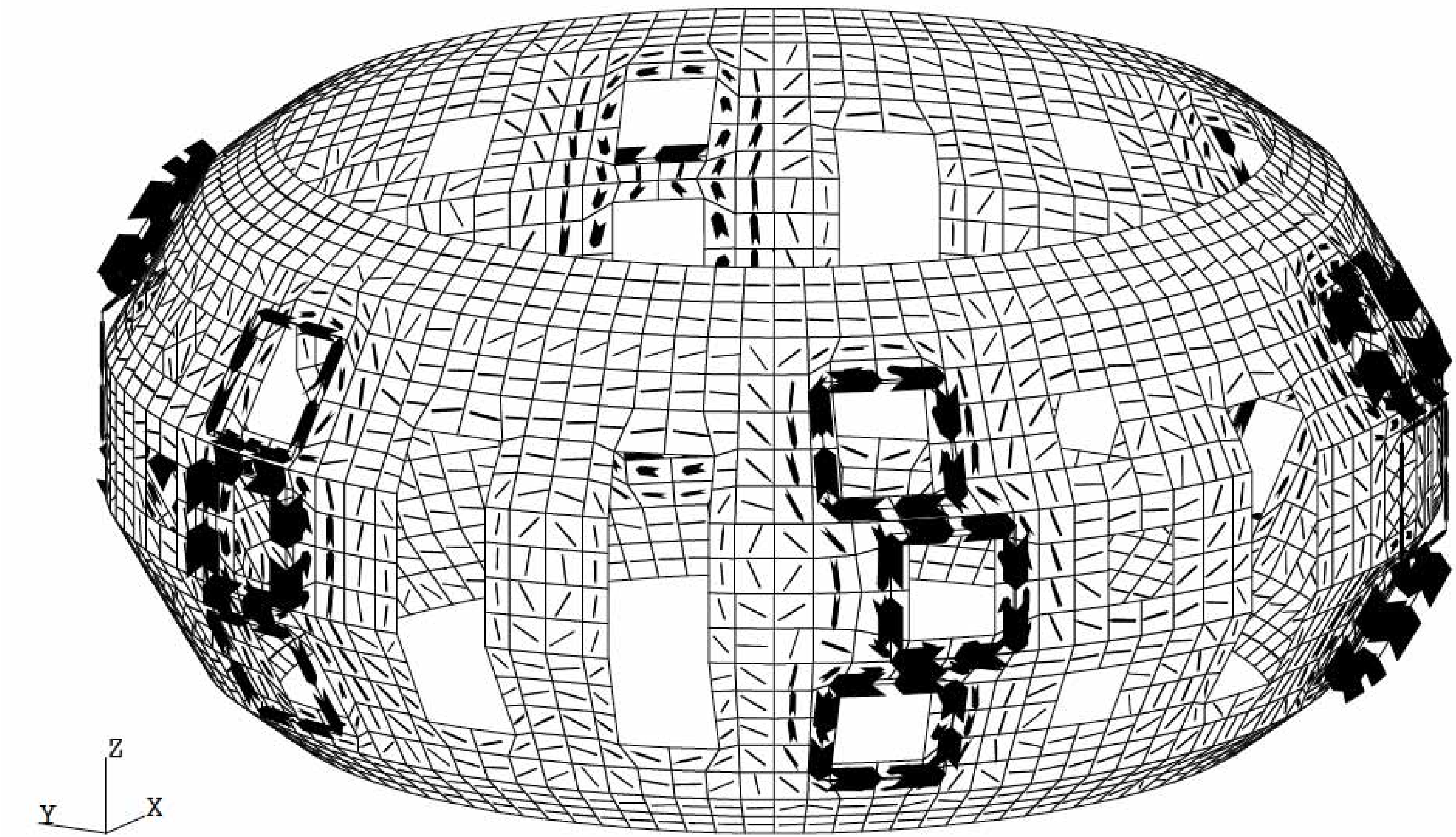
- Distortion of eddy current pattern due to the holes in stabilizing plate increases the growth rates, and **reduces ideal β_N limit about 8%** for our previous analyses of NCT plasma.
- Almost the same reduction is expected for JT-60SA plasma, but the hole shape for better passive stabilizing effect had better been investigated to **incease ideal β_N limit**.

Birds-Eye View of Eddy Current Pattern w/o Coil Current in Case of Feedback on



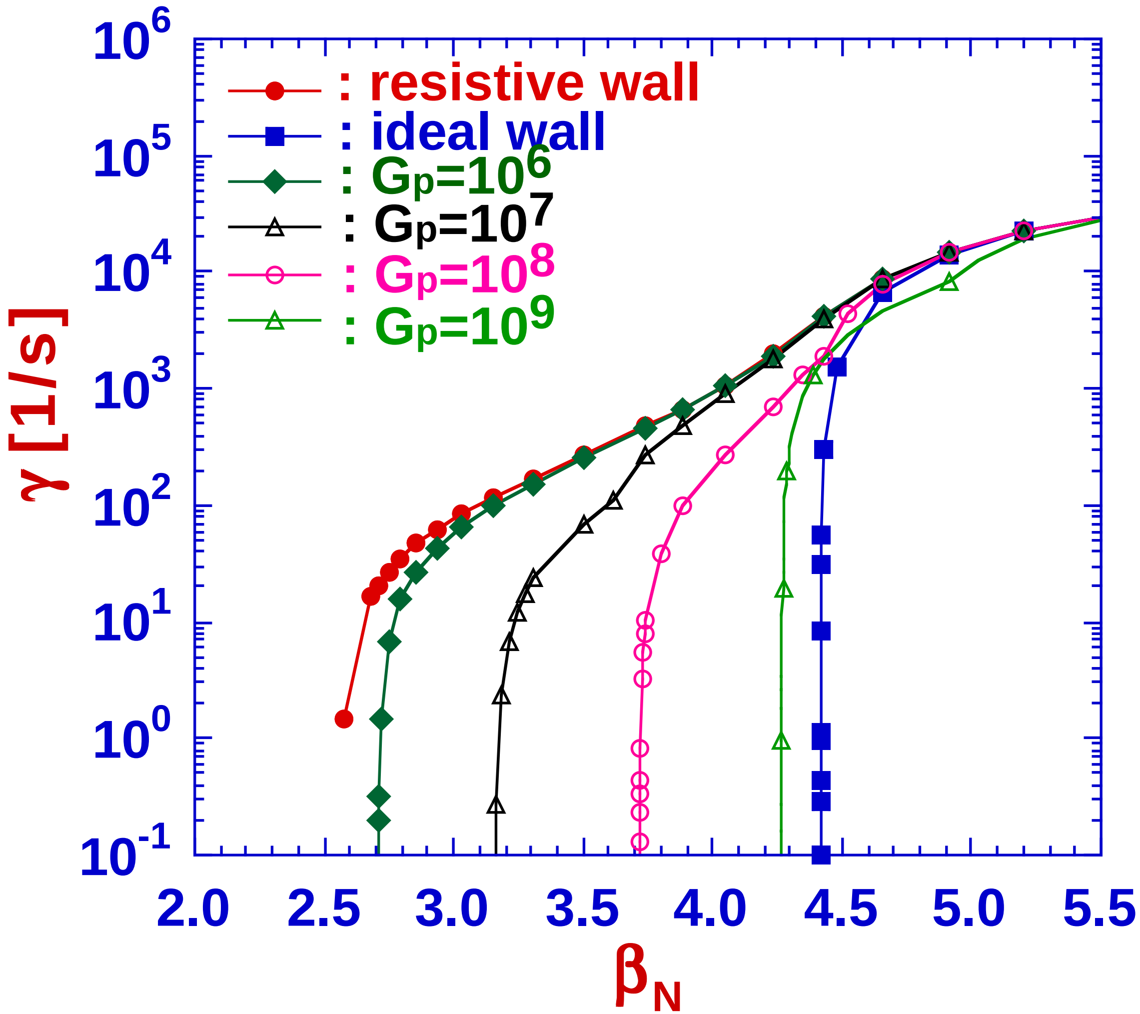
- **Eddy current by feedback coil current is superimposed.**

Birds-Eye View of Eddy Current Pattern with Coil Current in Case of Feedback on



- Maximum feedback coil current is estimated to be 2.3 [KAT] in ideal feedback case.

Critical β_N with Active Feedback Control



$V_{coil} = G_p \, \Phi_{sensor}$

- G_p is proportional gain.
- Φ_{sensor} is perturbed poloidal flux detected by poloidal field sensor placed at center of each coil.

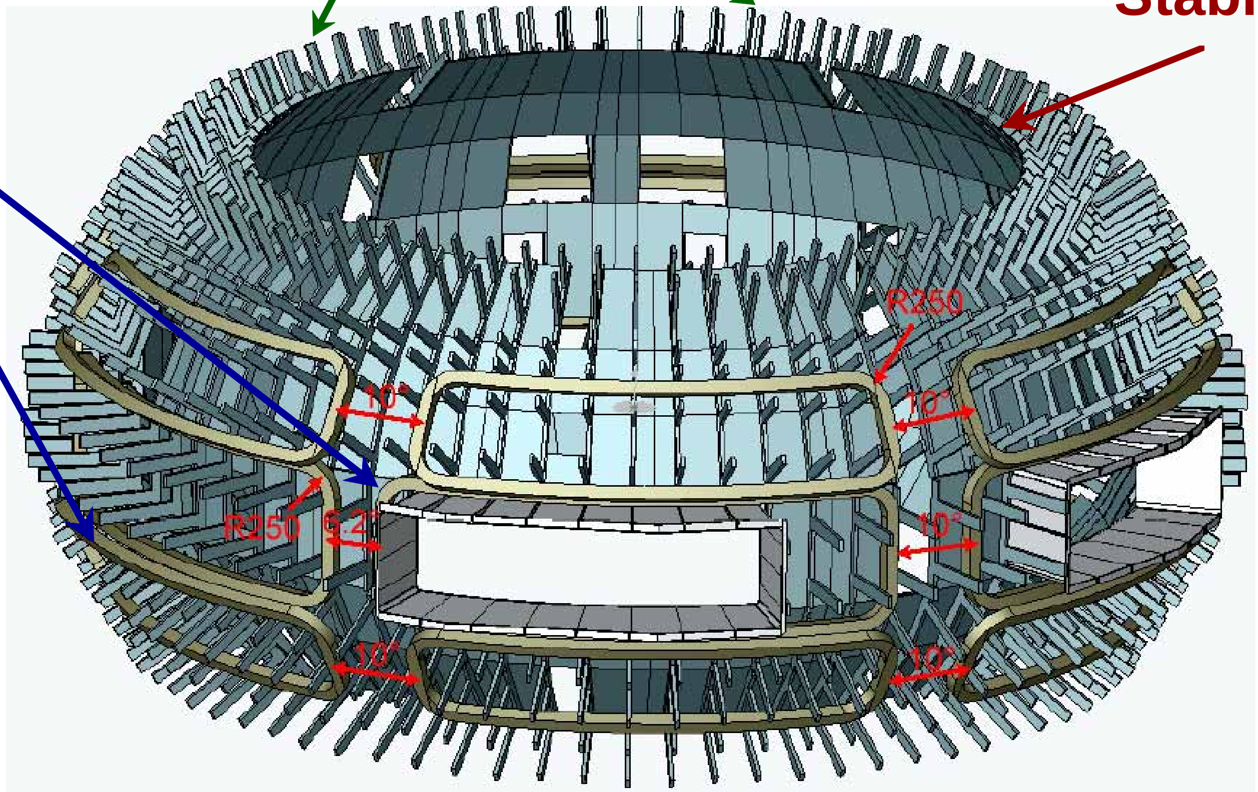
$$C_\beta = \frac{\beta_N - \beta_N^{no\text{-}wall}}{\beta_N^{ideal\text{-}wall} - \beta_N^{no\text{-}wall}}$$

$\beta_N^{no\text{-}wall} = 2.56$

$\beta_N^{ideal\text{-}wall} = 4.42$

- Maximum critical β_N with active feedback control for the present design of JT-60SA plasma is 4.26, which corresponds to C_β=0.91.

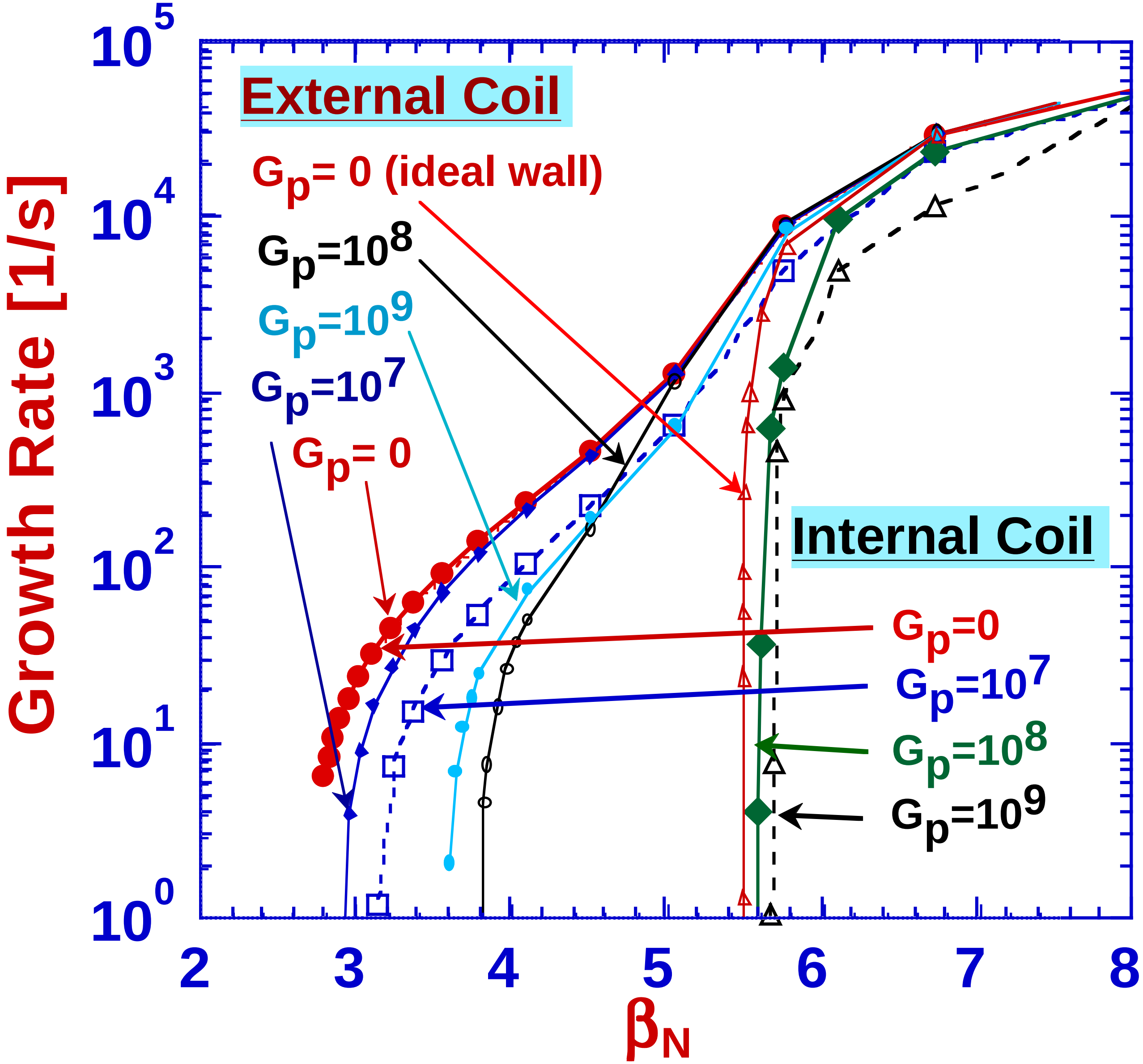
Birds-Eye View of Sector Coils and Stabilizing Plate with Port Holes and Edge Cut Out for NCT Device



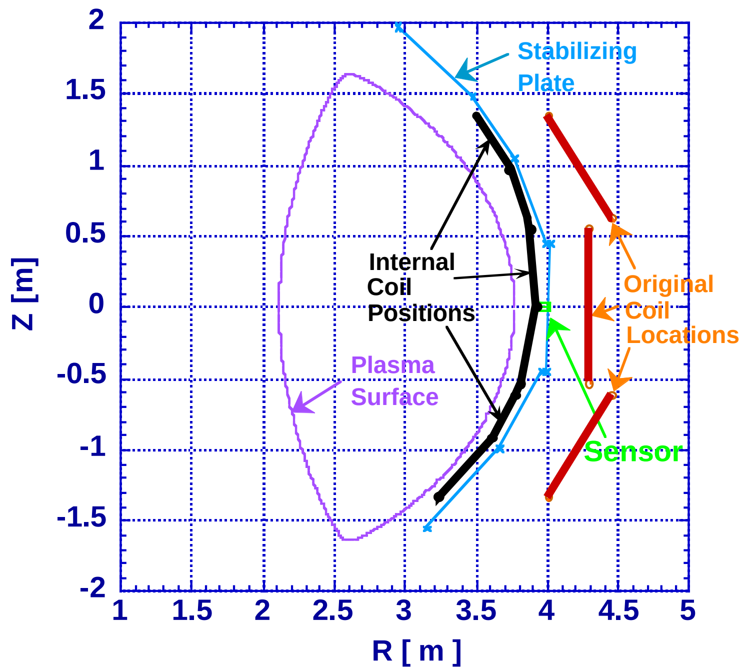
- Sector coils cover almost all stabilizing plate in toroidal direction independently of the shape and position of port hole.

Comparison between External & Internal Feedback Coils

----- Previous analyses for NCT plasma* -----



*** Equilibria are different from those of JT-60SA.**



	β_N	C_β
Int.	5.6	~ 1.
Ext.	3.8	0.37
(SA	4.26	0.91)

Summary and Next Step : JT-60SA

- Maximum critical β_N with active feedback control, obtained for up-down symmetric JT-60SA plasma, is 4.26, which corresponds to C_β=0.91.
- The value of C_β is greatly improved compared to the previous value for NCT plasma of C_β=0.37.

- To increase critical β_N value, we must increase critical β_N value with ideal wall, which can be done by optimization of plasma current and pressure profiles, and also increasing the passive effect of stabilizing plate.
- Analyses of n=2 RWM

OUTLINE for JT-60U Analyses

1. Introduction
2. Double-null equilibrium of JT-60U
3. Current driven RWM experimental data and calculated growth rates by dispersion relation and AEOLUS-FT code
4. Growth rate versus edge safety factor value with ideal and resistive walls for various wall position
5. Summary and next step

Current Driven RWM in JT-60U OH Plasma

- In JT-60U tokamak, RWM experiments focusing on the stabilizing effects of the wall have been performed using current-driven RWM in OH plasmas.
- A current driven external kink modes are usually observed by decreasing the edge safety factor, and when q_a becomes less than 3, an m/n=3/1 MHD instabilities are observed in JT-60U plasma.
- The growth time of the unstable mode is 10 ms, which is much slower than usual external kink mode, and it is considered to be RWM.

Basic Equations : Full Set of Resistive MHD Equations

- **Linearized resistive MHD equations with plasma flow**

$$\rho_0 \frac{\partial \vec{v}}{\partial t} = -\rho_0 \left(\vec{v}_0 \cdot \vec{\nabla}\right)\vec{v}_0 - \vec{\nabla} p + \left(\vec{j}_0 \times \vec{b}\right) + \left(\vec{\nabla} \times (\vec{b}/\hat{\mu}) \times \vec{b}_0\right)$$

$$\frac{\partial \vec{b}}{\partial t} = \vec{\nabla} \times \left(\vec{v}_0 \times \vec{b} + \vec{v} \times \vec{b}_0 - \eta \vec{\nabla} \times (\vec{b}/\hat{\mu}) \right)$$

$$\frac{\partial p}{\partial t} = -\left(\vec{v}_0 \cdot \vec{\nabla}\right) p - \left(\vec{v} \cdot \vec{\nabla}\right) p_0 - \Gamma p_0 \vec{\nabla} \cdot \vec{v}$$

v_0 : plasma flow

$\hat{\mu}$: relative permeability

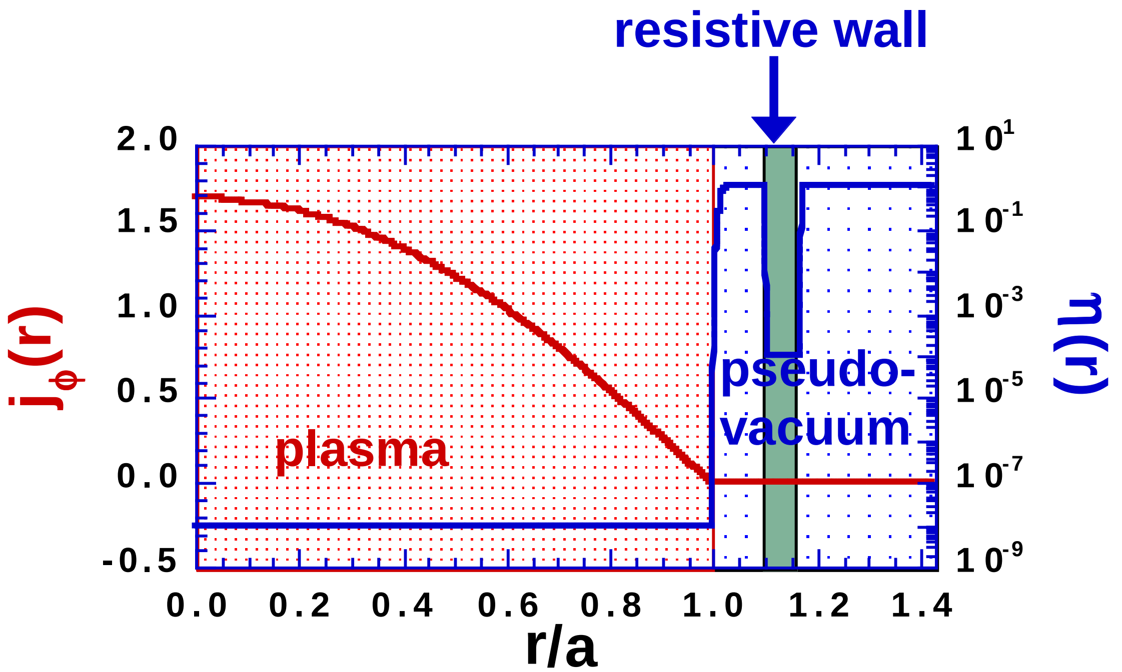
Γ : specific heat ratio

- **Pseudo-vacuum model**
  - parabolic current profile and
  - resistivity profile of

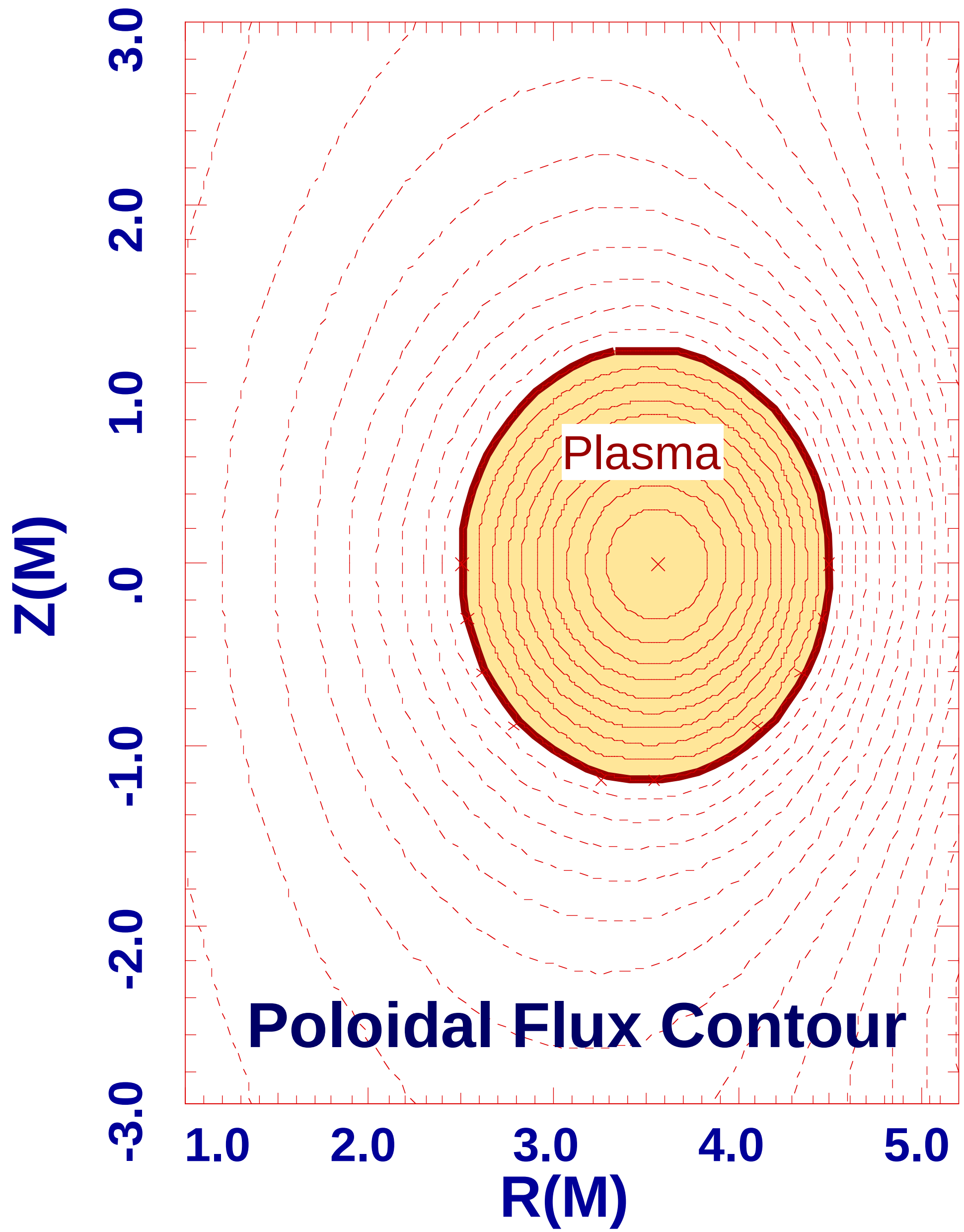
$\eta(r) = 10^{-8}$: in plasma

$\eta(r) = 10^{0}$: in pseudo-vacuum

$\eta(r) = 10^{-4}$: in resistive wall



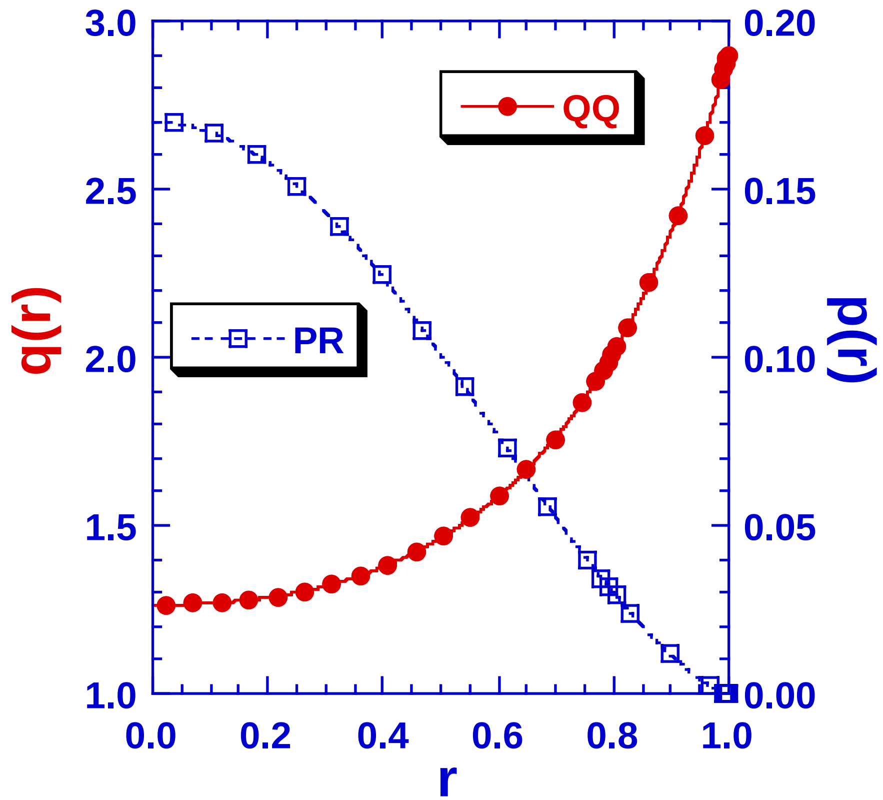
Equilibrium for JT-60U RWM Calculation



- **Parameters**

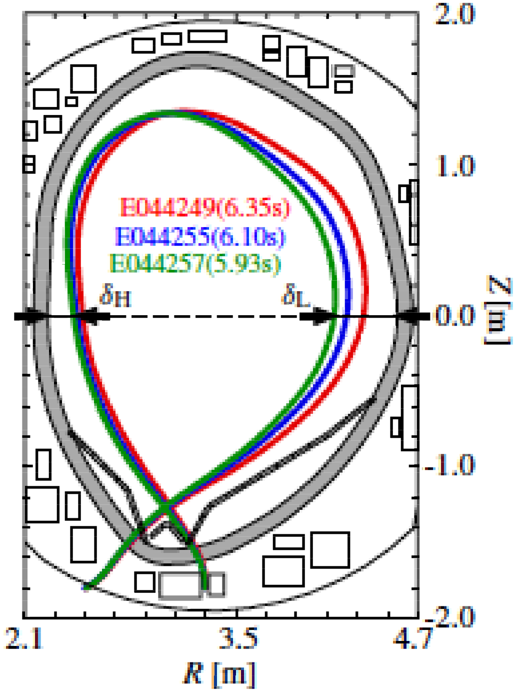
  β_N= 0.2, A=3.5, B_t=3.60[T], li(3)=0.96

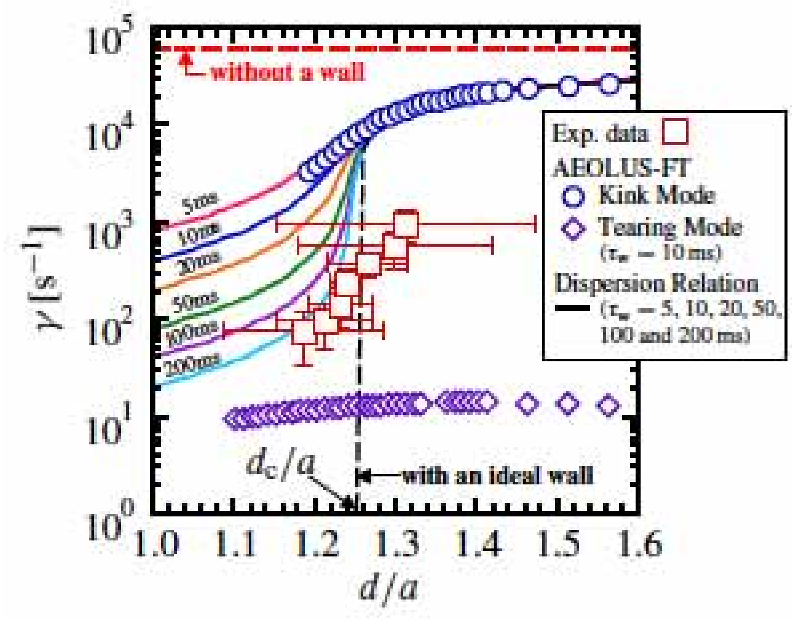
  κ=1.18, δ=0.0, p_0/<p>=2.73



- Typical Safety factor, q(r), and Plasma Pressure, p(r), Profiles

Current Driven RWM Experiment for Wall Effect





- **dispersion relation**

$$\gamma^2 - \Gamma_\infty^2 \left(1 - \frac{d_c}{d} \frac{\gamma\tau_w}{\gamma\tau_w + 1}\right) = 0$$

Γ_∞ : γ without wall

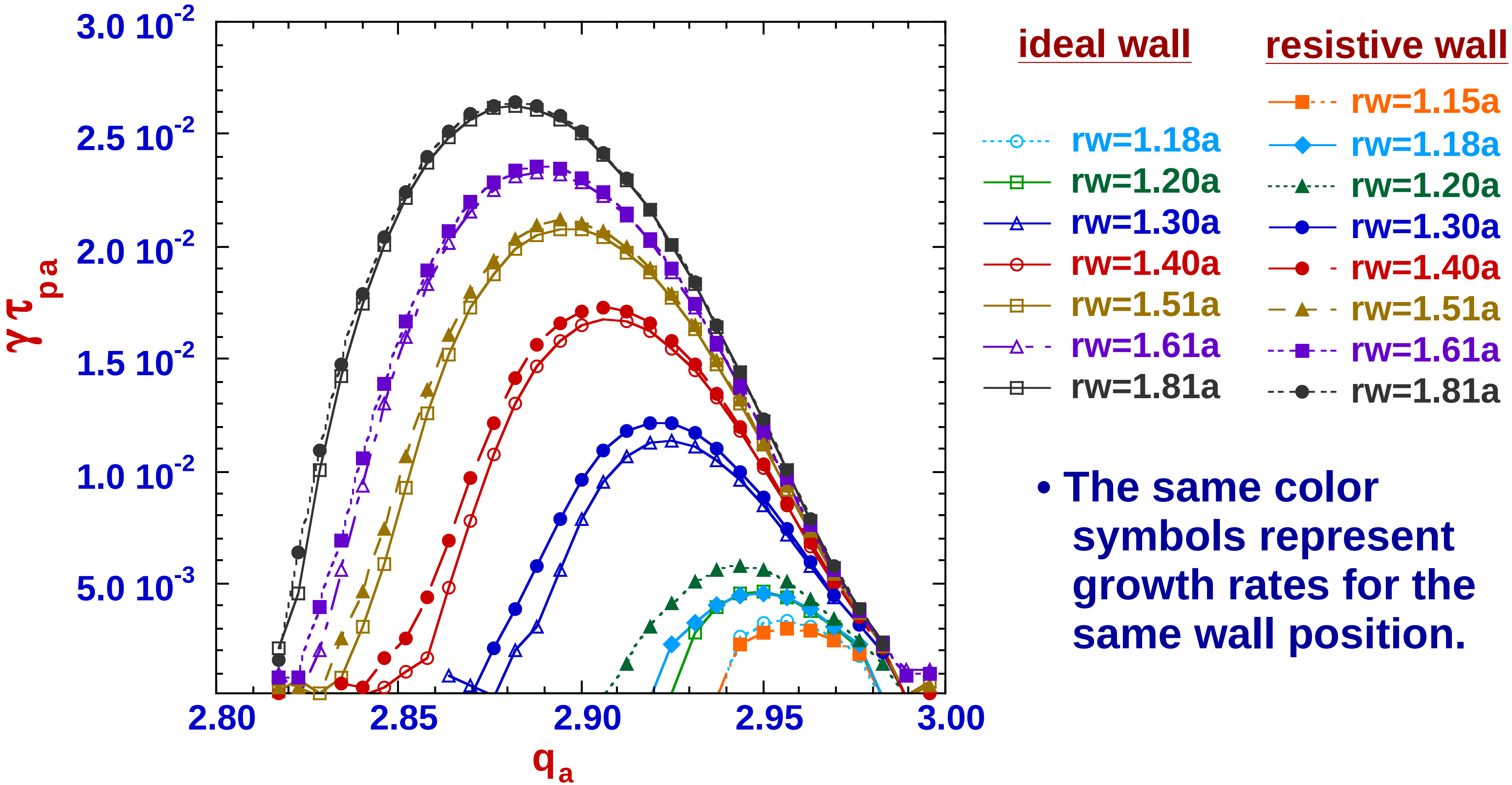
d : wall radius

d_c : critical wall radius for external kink mode

M.S.Chu et al., Phys. Plasmas 2, 2236 (1995)

- **Experimentally obtained RWM growth rates are fairly consistent with those obtained by the dispersion relation and AEOLUS-FT calculation with no plasma rotation and no dissipation.**
- **Further investigations are needed.**

Growth Rate versus Edge Safety Factor Value



- The same color symbols represent growth rates for the same wall position.

- The difference of growth rates becomes larger for smaller wall position between ideal and resistive walls, and only RWM appears for $r_W/a < 1.15$ without ideal kink modes.

Summary and Next Step : JT-60U

- It is shown that the current driven RWM can be observed, when the wall is placed sufficiently close to the plasma surface in I_p ramp-up phase.

- The experimentally obtained growth rates are 10 times smaller than those of AEOLUS-FT and the dispersion relation in the τ_{wall}=10 ms case, and further interpretation is required.
- RWMs in high beta plasma with plasma rotation, observed in JT-60U plasmas, will be analyzed.