Plans for MHD control in JT-60SA based on JT-60U results

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US/Japan workshop on MHD control, Nov. 6-8, 2006, PPPL

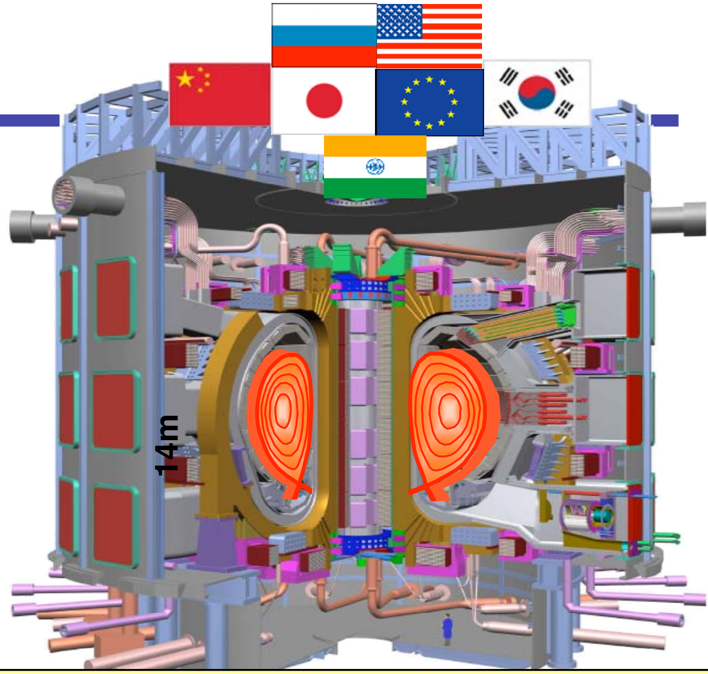
Outline

1. Concepts of JT60-SA
2. MHD control of JT60-SA
    1. Plasma shape control
    2. Internal profile control
    3. Control by ECCD: ST, NTM
    4. Control by coils: RWM
3. Summary

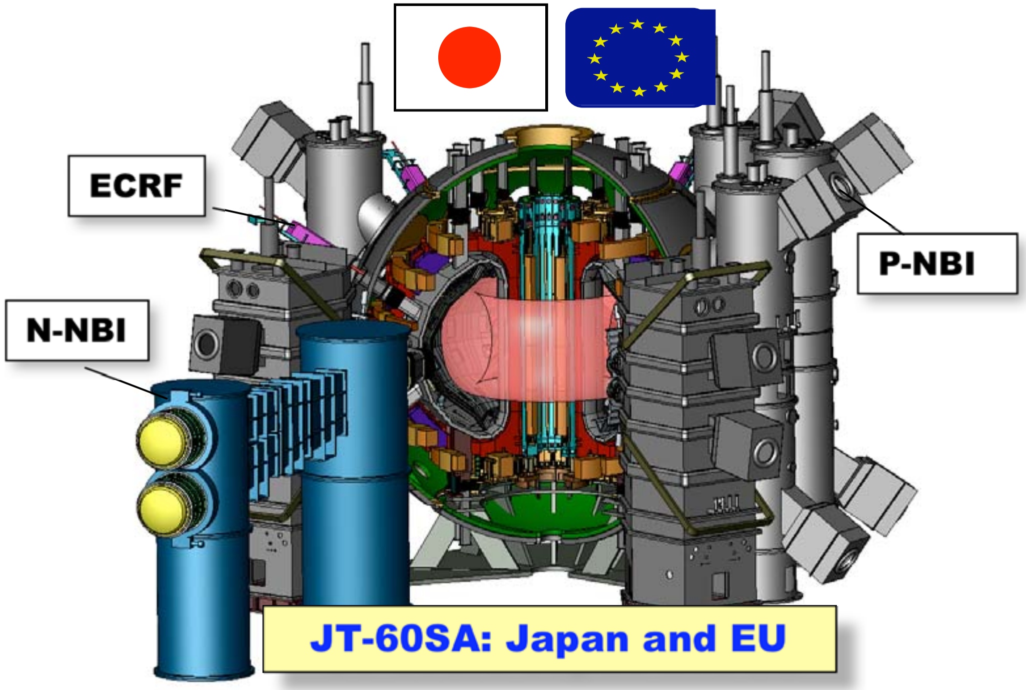
Mission of JT-60SA Program

**JT-60SA (JT-60 Super Advanced)
is a combined program of**

- ITER Satellite Tokamak Program of JA-EU
- Japanese National Program



ITER : India, China, Korea, US, Russia, EU, Japan



JT-60SA: Japan and EU

**Mission of JT-60SA
is
to support
and supplement
ITER toward DEMO.**

Contributors to JT-60SA Program

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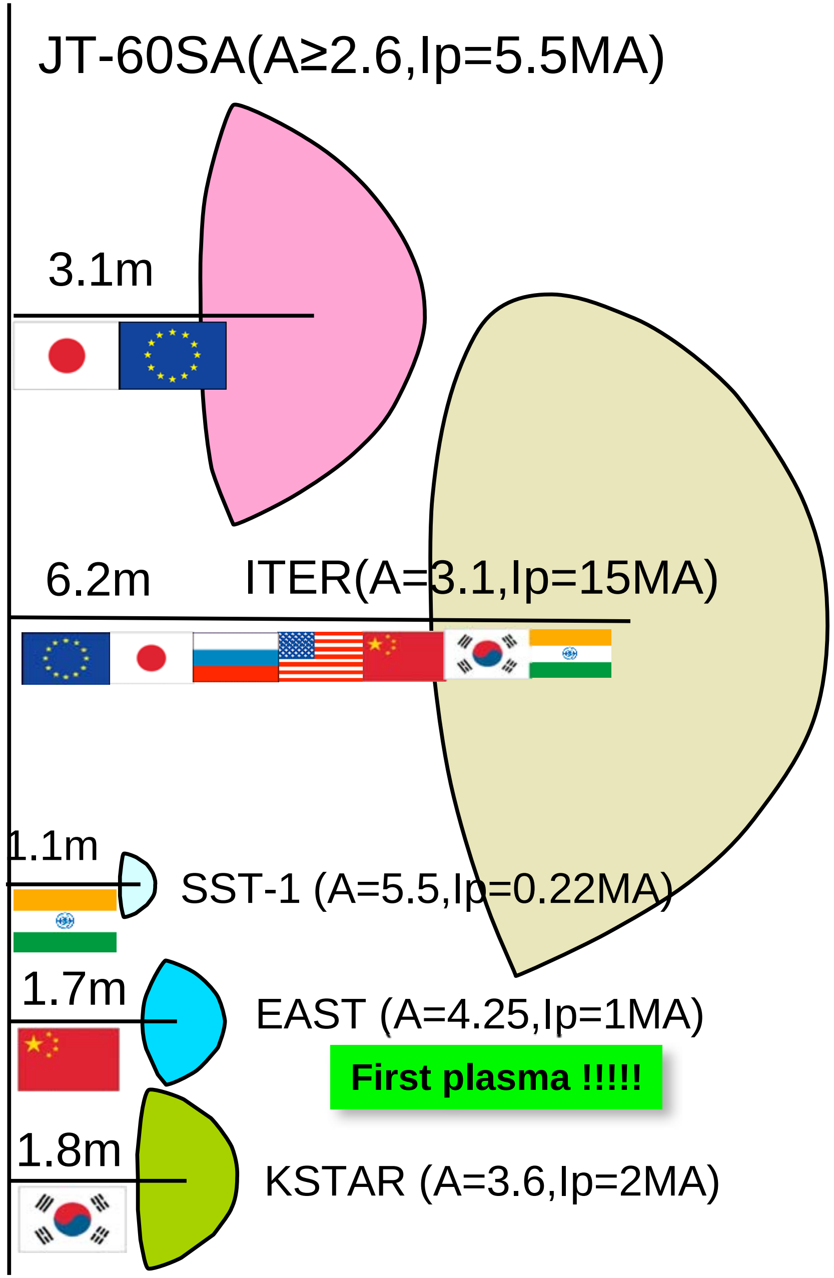
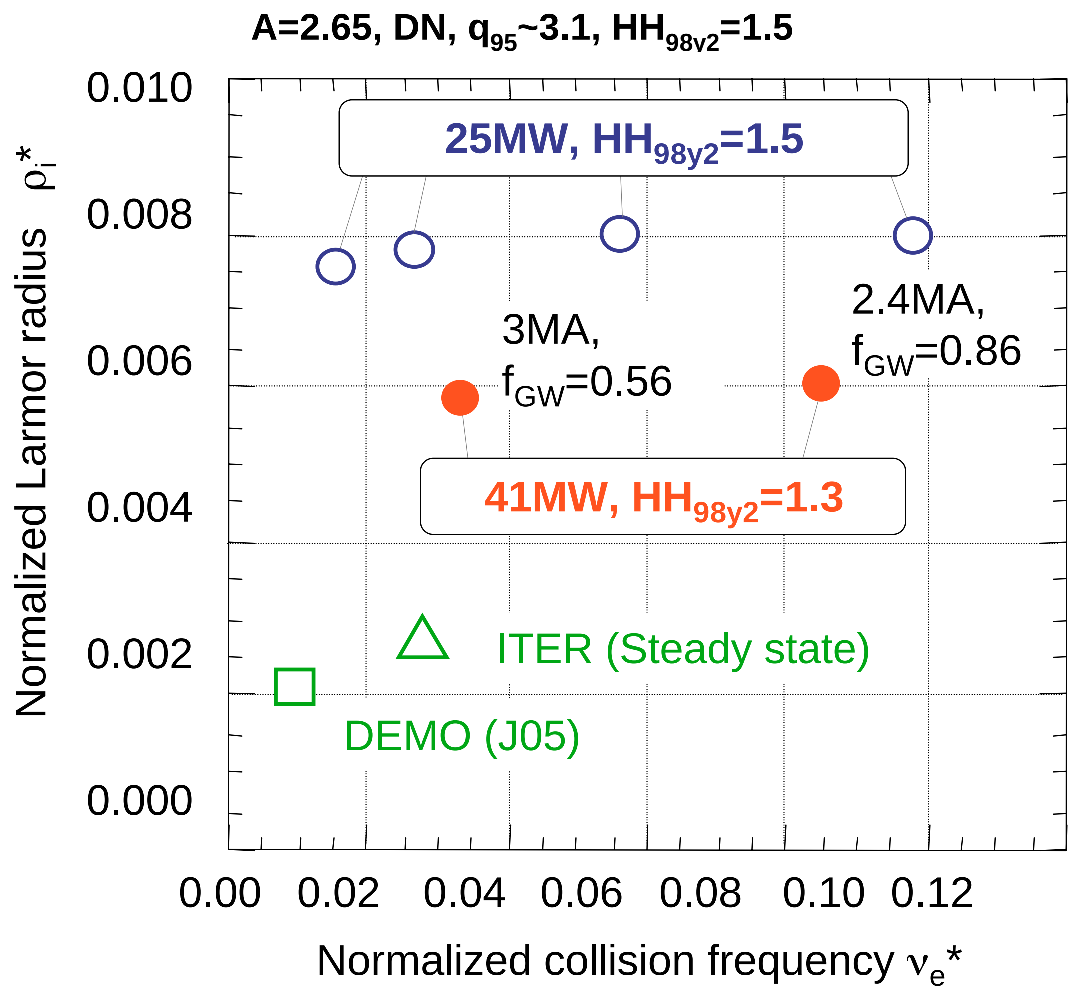
1st satellite tokamak WG at NAKA

National Review Committee

World families of fully superconducting tokamaks

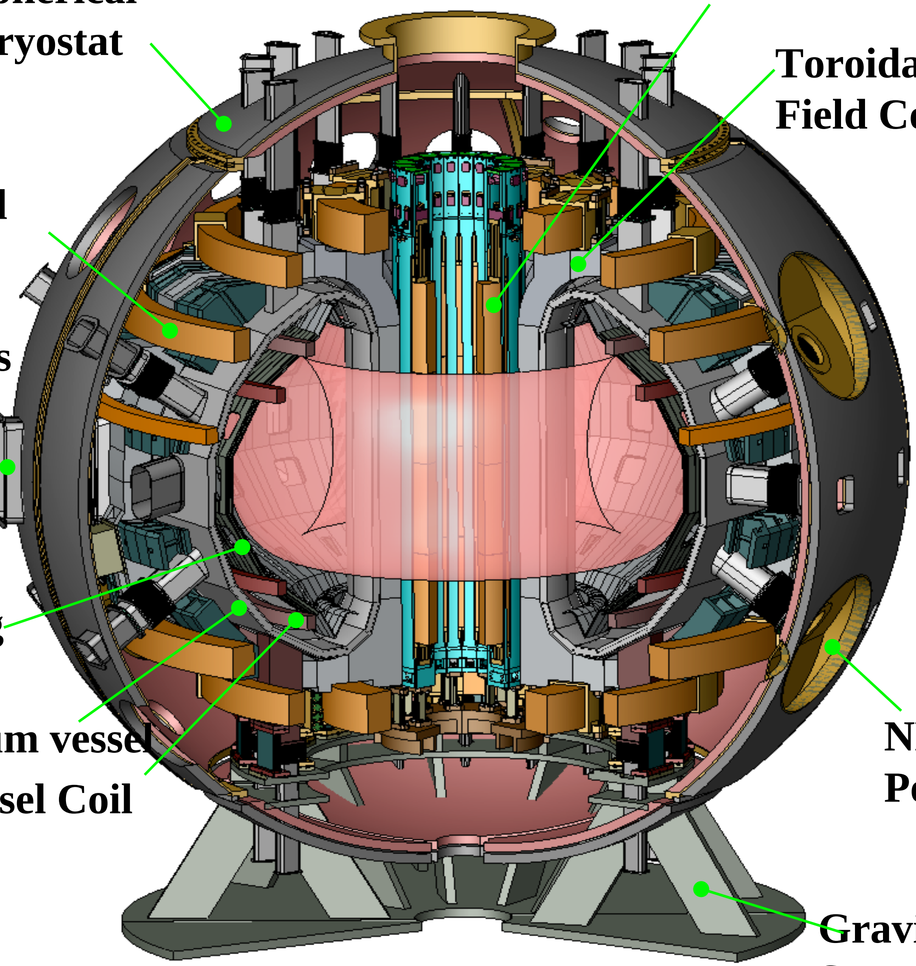


JT-60SA is capable to approach collision-less small gyro-radius plasma.



Basic Machine Parameter of JT-60SA

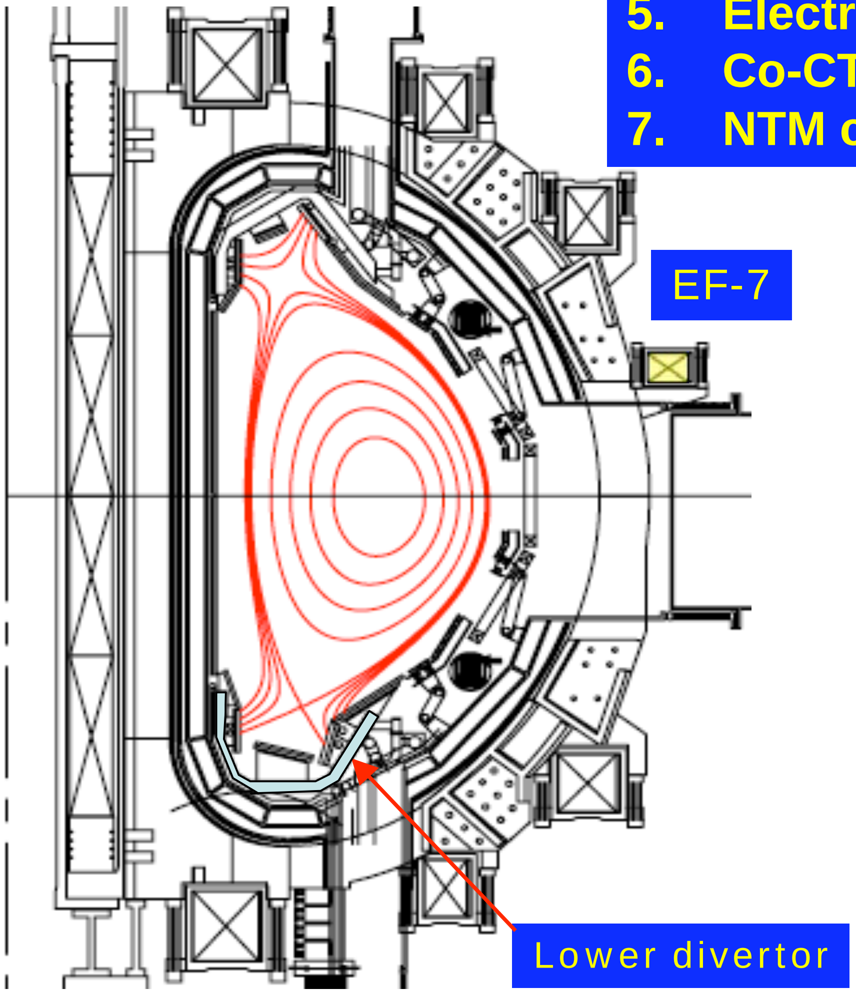
D_2 main plasma + D_2 beam injection



Plasma Current I_p	5.5MA
Toroidal Field B_t	2.68T
Major Radius R_p	3.06m
Minor Radius a_p	1.15m
Elongation κ_{95}	1.76
Triangularity δ_{95}	0.45
Safety Factor q_{95}	3.11
Volume V_p	$127m^3$
Flattop Duration	100 s (8Hr)
Heating & CD power	41MWx100 s
Perpendicular NBI	16 MW
Tangential Co NBI	4 MW
Tangential CTR NBI	4 MW
N-NBI	10 MW
ECRH	7 MW
PFC wall load	$10\ MW/m^2$
Annual Neutron	4×10^{21}

JT-60SA is optimized for contribution to ITER

1. ITER-shape plasma is produced by EF-7 coil .
2. Almost same Greenwald density of ITER
3. Lower divertor to match ITER tri-angularity.
4. ITER type mono-block divertor for outer target.
5. Electron heating with 10MW N-NB+7MW ECRF
6. Co-CTR rotation control by T-NBI
7. NTM control at two frequency (110GHz&140GHz)



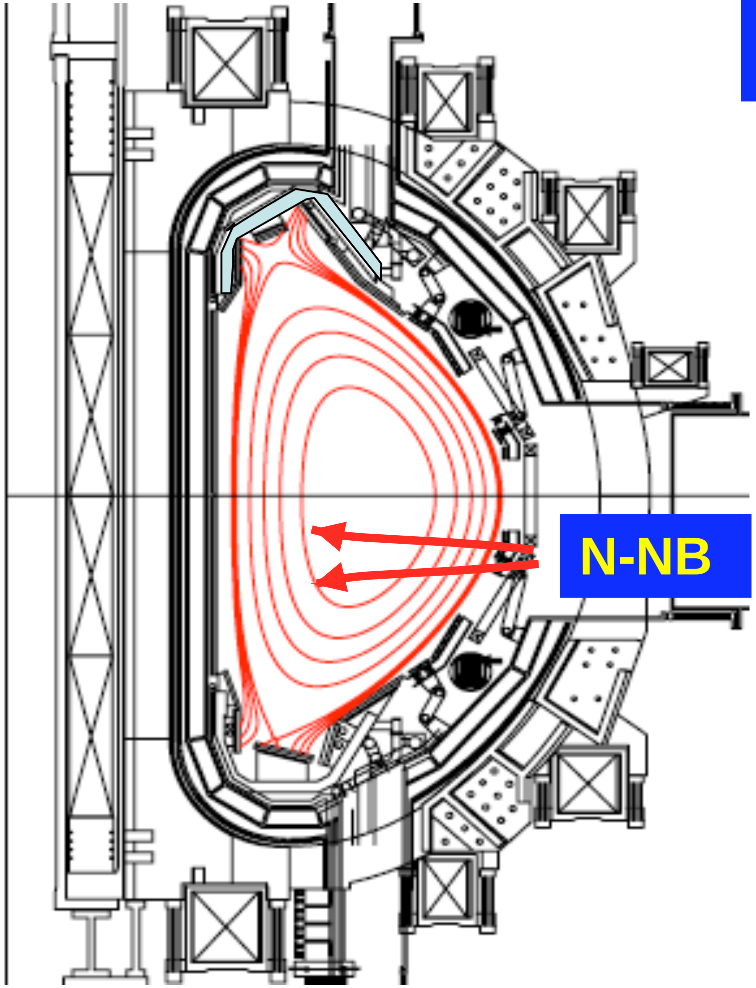
Parameter	ITER	JT-60SA
Plasma Current Ip	15 MA	3.5MA
Toroidal Field Bt	5.3T	2.59T
Major Radius Rp	6.2 m	3.16 m
Minor Radius a	2.0 m	1.02 m
Aspect Ratio A	3.1	3.1
Elongation κ_{95}	1.70	1.7
Triangularity δ_{95}	0.33	0.33
Safety Factor q_{95}	3.0	3.0
Greenwald density n_G	$1.2 \times 10^{20} m^{-3}$	$1.1 \times 10^{20} m^{-3}$

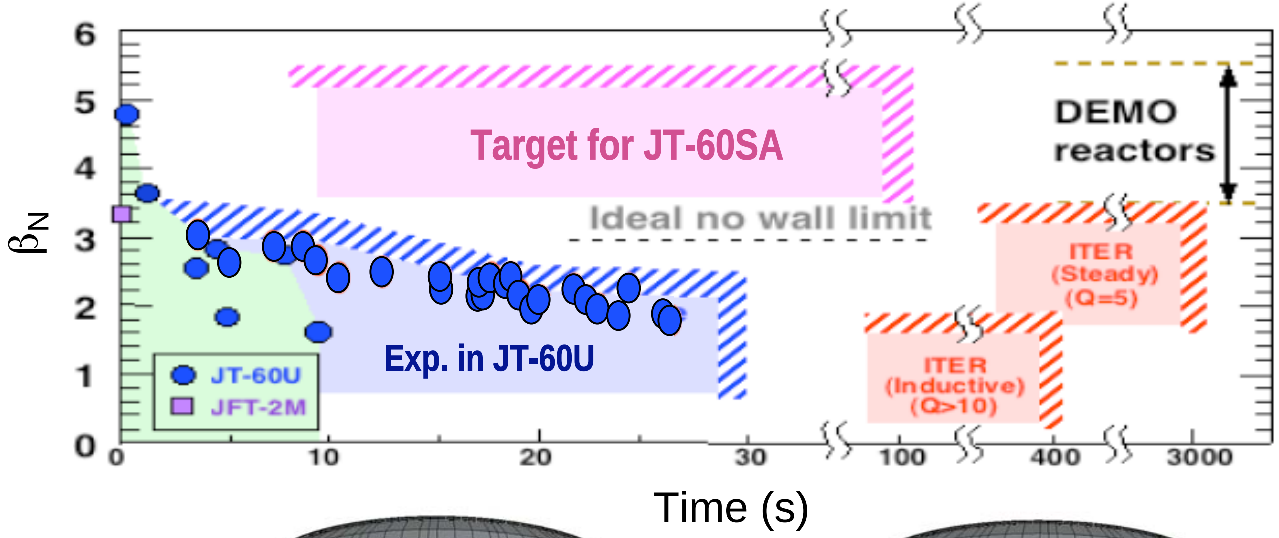
$P=41MW >> P_{th}^{L\text{-}H} \sim 20MW$

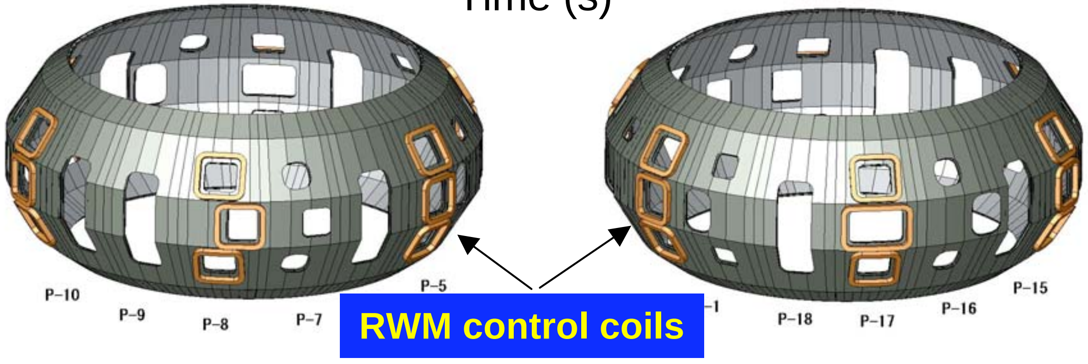
Supplemental role of JT-60SA for DEMO

High beta steady-state operation

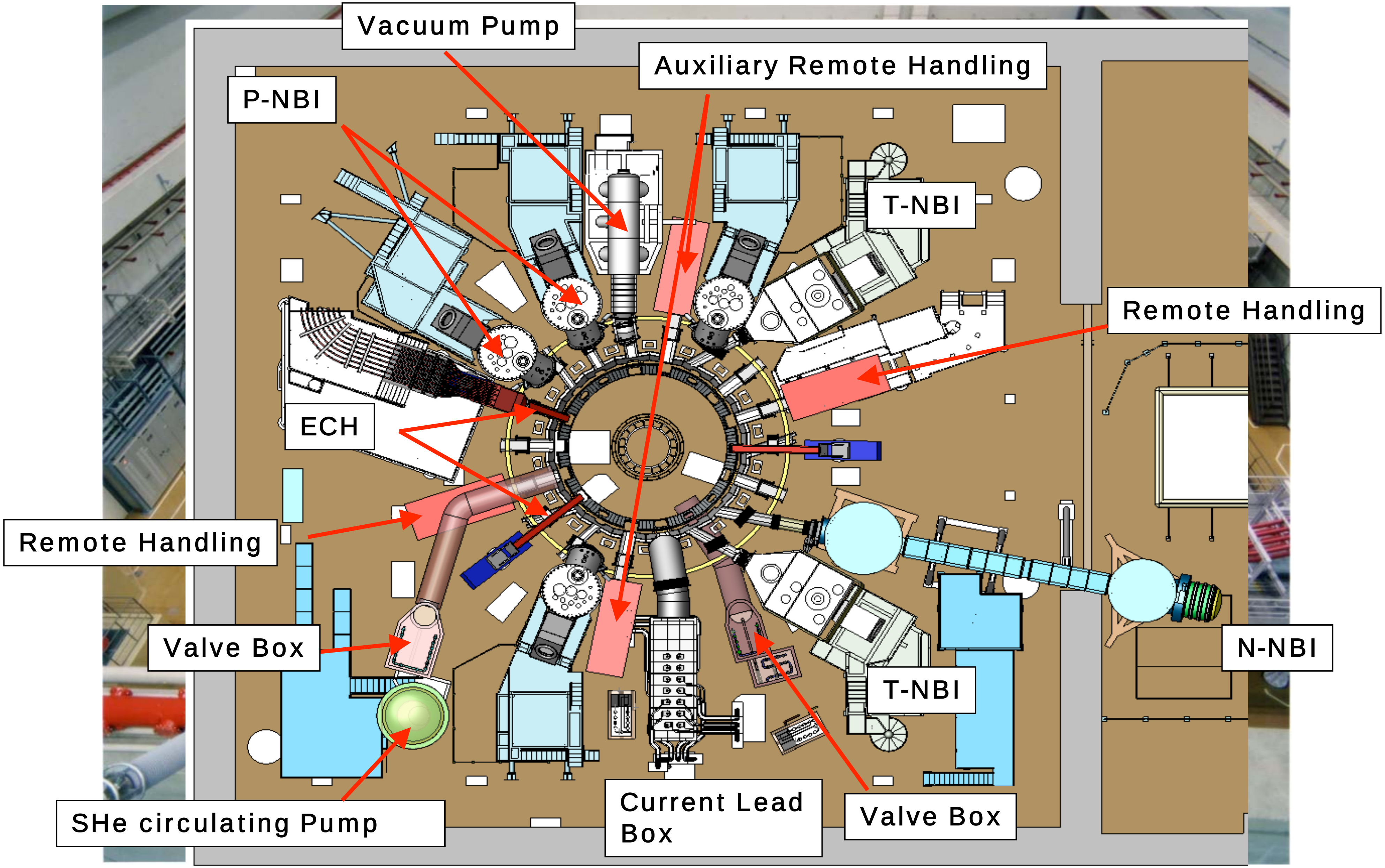
1. Wider shaping opportunities (low A~2.6, DN)
2. Upper divertor to match high tri-angularity.
3. Down-shifted N-NBCD to form reversed shear.
4. Stabilizing plates (SP) for RWM control
5. 6 set of 3 poloidal n=1,2 RWM control coils
6. Ferritic steel on SP to simulate DEMO







Latest Design of Torus Hall Layout



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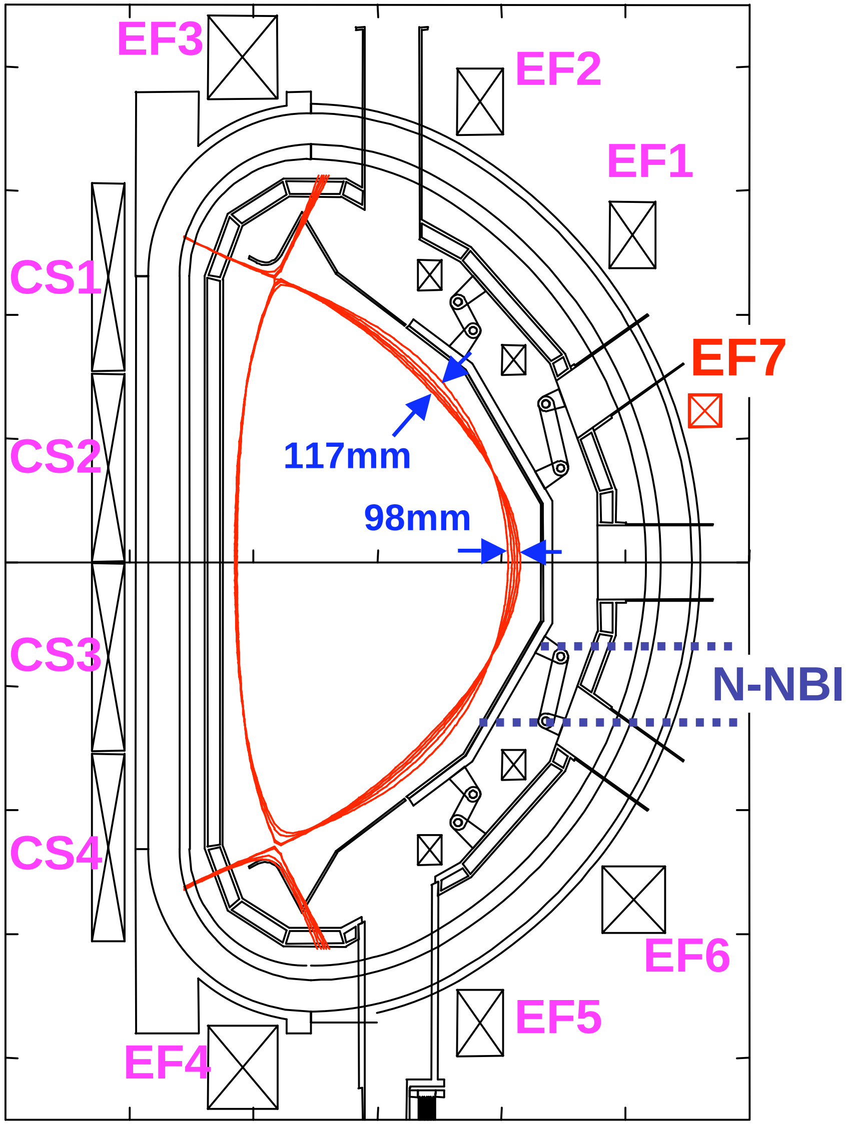
Plasma shape control

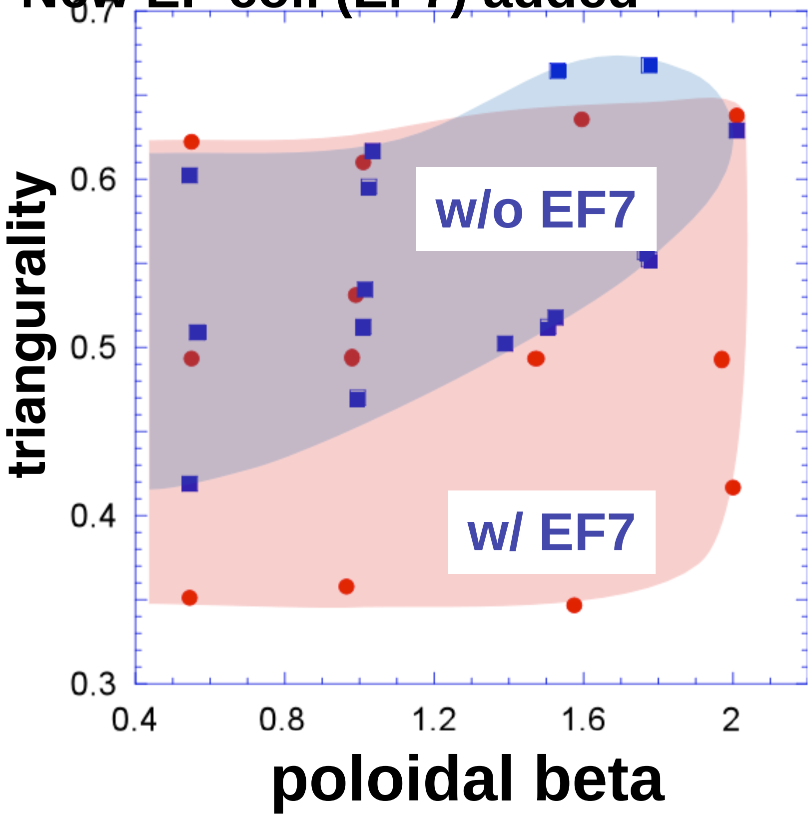
New equilibrium coil



EF1 and EF6 have been moved away from the mid-plane for off-axis N-NB and machine maintenance

⇒decrease in 'squareness' and triangularity controllability

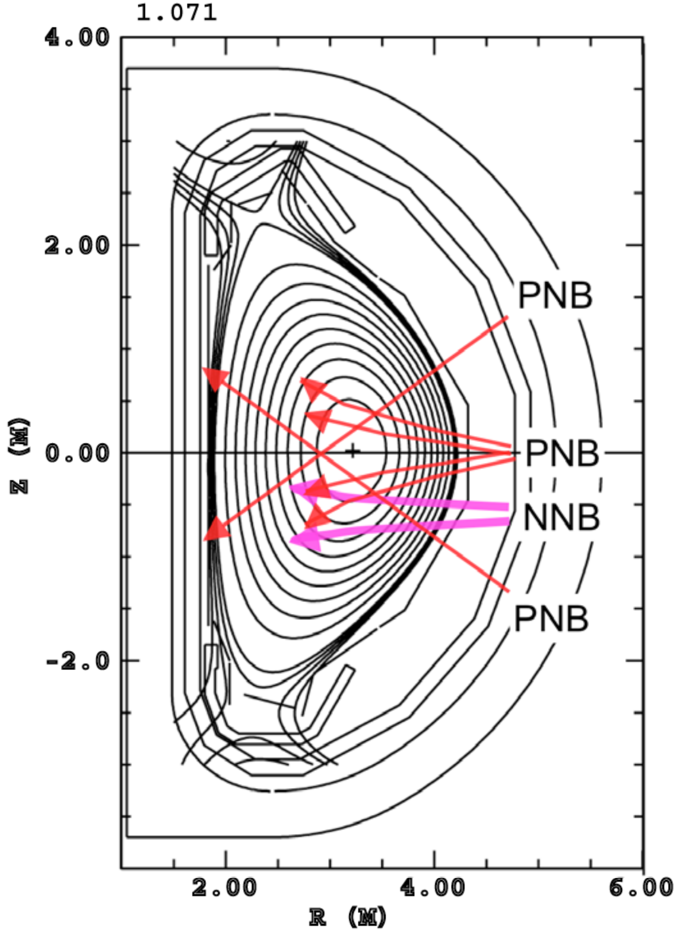
⇒ New EF coil (EF7) added



Plasma shape control (2) **Divertor geometry**

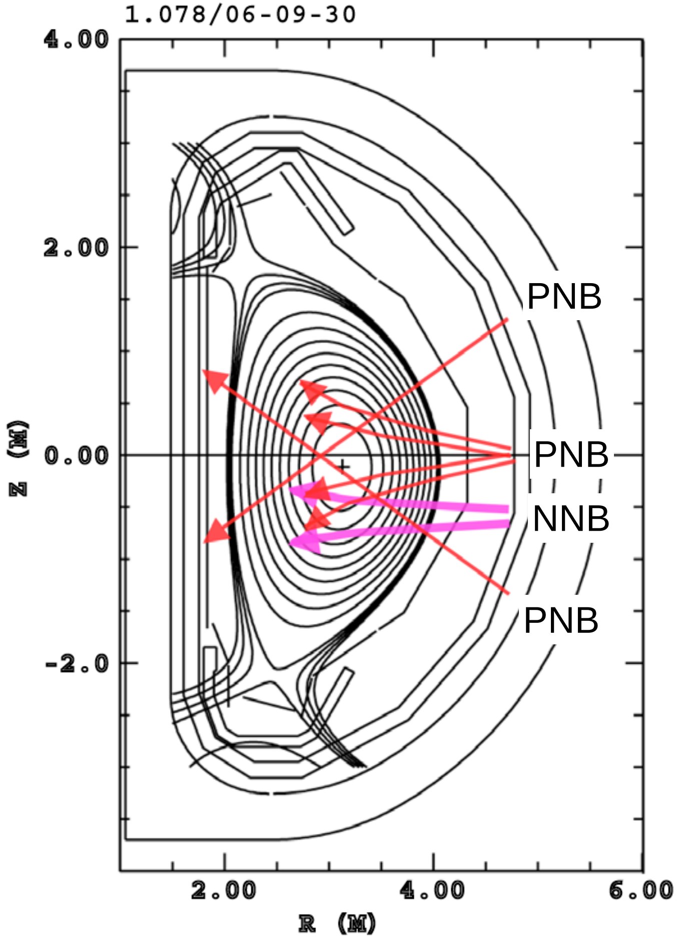
For high S

USN, I_p = 5.5 MA, B_t = 2.7 T, q_{95} = 3.4, A = 2.65, κ_{95} = 1.74, δ_{95} = 0.41 and S = 5.98.



For ITER-like shape

LSN, I_p = 3.5 MA, B_t = 2.6 T, q_{95} = 3.0. A = 3.10, κ_{95} = 1.71, δ_{95} = 0.33 and S = 4.4,

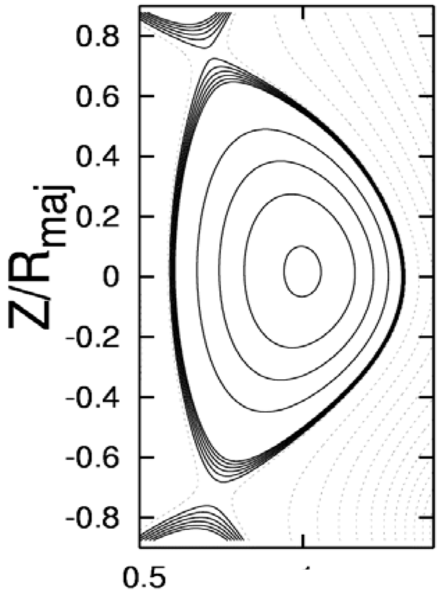


Stability near the edge: ELM (high-S case)

$$\beta_p = 0.8\ (\beta_N \approx 3.11),\ \ I_p[MA] = 5.0\ (\text{high-S}),\ \ 5.1\ \ (\text{high-S flat}), B_t[\text{T}] = 2.6$$

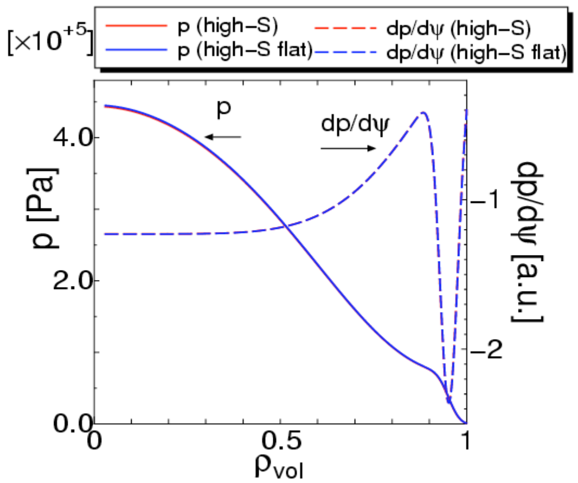
R_{maj}[m] =3.03,
a[m] =1.14,
S=5.96

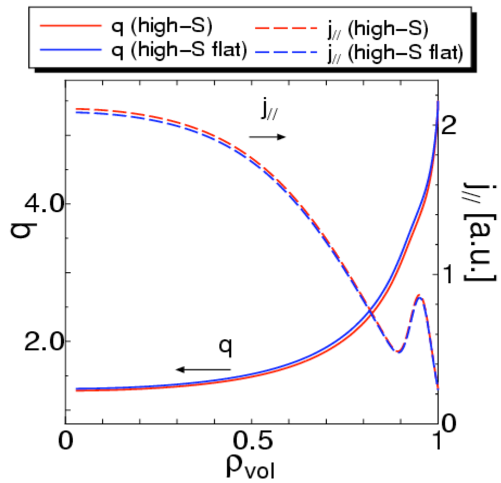
$S := q_{95} I_p / a B_t$



$$\kappa_{up} = 2.03, \kappa_{dw} = 1.90, \delta_{up} = 0.64, \delta_{dw} = 0.55$$

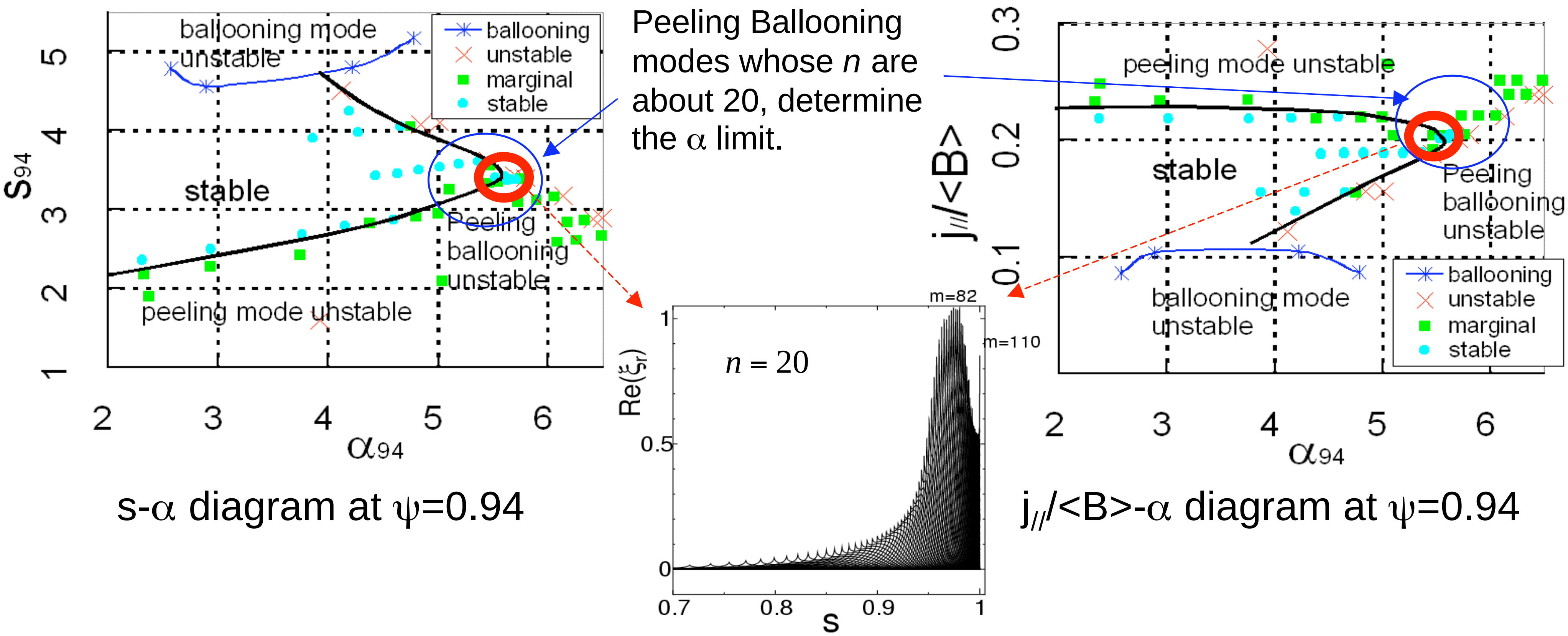
$$\sigma_{dw} = 14.67(\text{black}),\ 2.54(\text{red})$$





- In JT-60SA, the shaping parameter *S* [8] will reach to about 6.
- By changing the pressure and current profiles near the pedestal, the stability of tokamak edge plasma is investigated.
- The range of *n* of the MHD modes to be analyzed is from 1 to 60, and infinity (ballooning mode stability).
- In this strong shaping and small aspect ratio equilibrium, the stability of ideal ballooning modes will be more stable than that in ITER-like Eq.

Stability Analysis Result (high-S)



s-α diagram at ψ=0.94

$j_{//}$/<B>-α diagram at ψ=0.94

- In high-S Eq., the maximum pressure gradient (=5.61) becomes larger than that in ITER-like Eq.(=4.36), as expected.
- The n number of the peeling-ballooning mode determining the α limit is about 20, which is larger than that in ITER-like Eq.

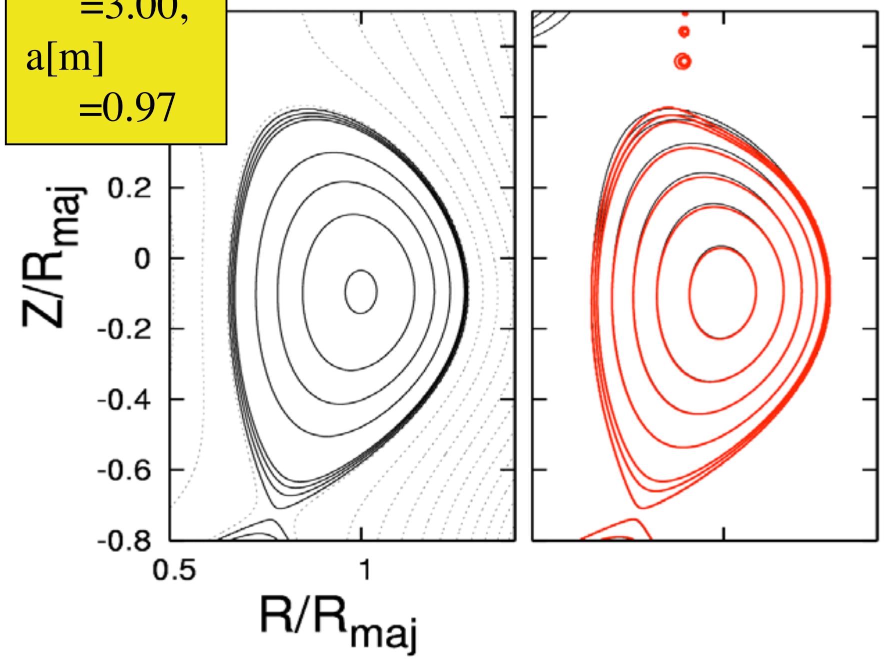
Equilibrium of JT-60SA (ITER-like Eq.)

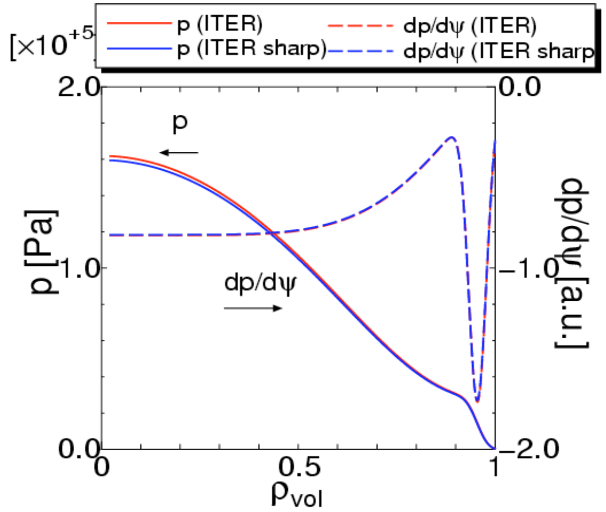
R_{maj}[m] =3.00,
a[m] =0.97

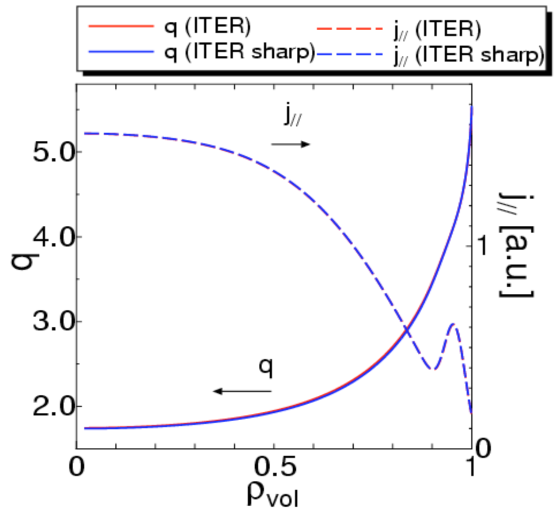
$$\beta_p = 0.9\ (\beta_N \approx 3.13),\ \ I_p = 2.59\,(\text{ITER - like}),\ 2.56(\text{ITER - like sharp}),\ B_t[T] = 2.49$$

$$\kappa_{up} = 1.35, \kappa_{dw} = 2.32, \delta_{up} = 0.34, \delta_{dw} = 0.60$$

$$\sigma_{up} = 2.04(\text{black}),\ 3.94(\text{red})$$

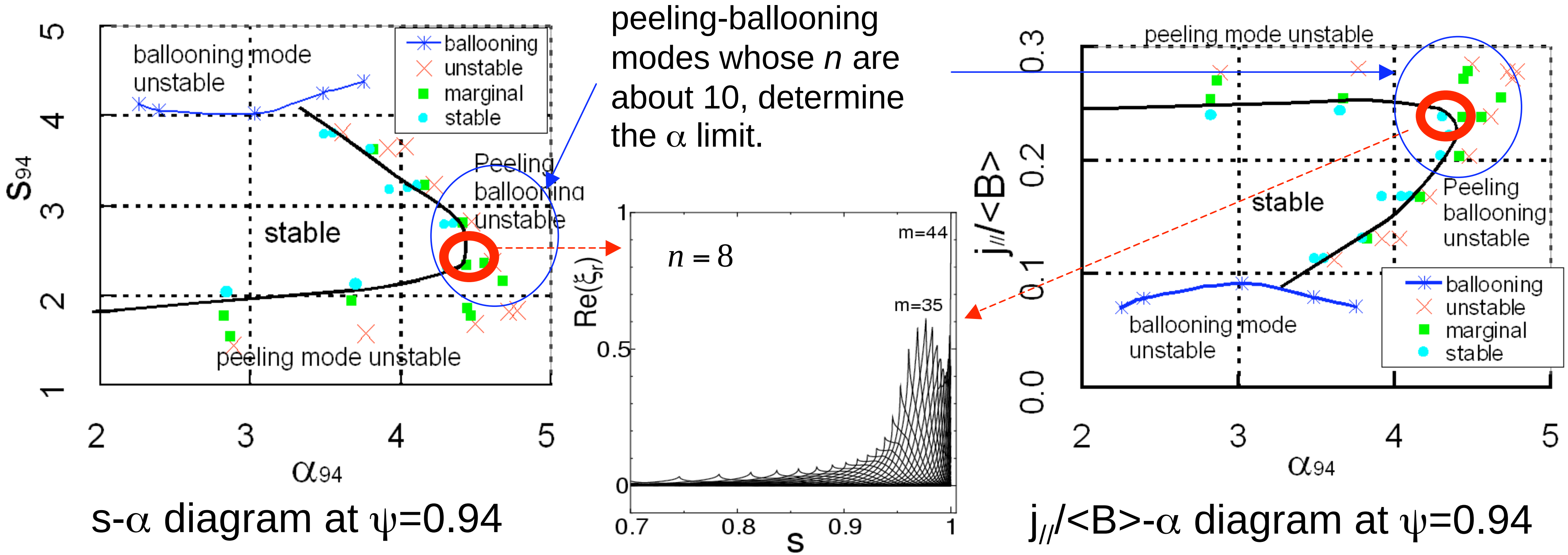






- The profiles of dp/dψ and ($j_{//}$/<B>) are same as those in high S Eq.
- The effect of the sharpness is also investigated.
- The range of *n* of the MHD modes to be analyzed is from 1 to 60, and infinity (ballooning mode stability).
- By changing the shape at the top, we investigate the stabilizing effect of the sharpness σ. ($\sigma=(1/r_c)/(1/a)$, r_c: curvature radius, *a*: minor radius)

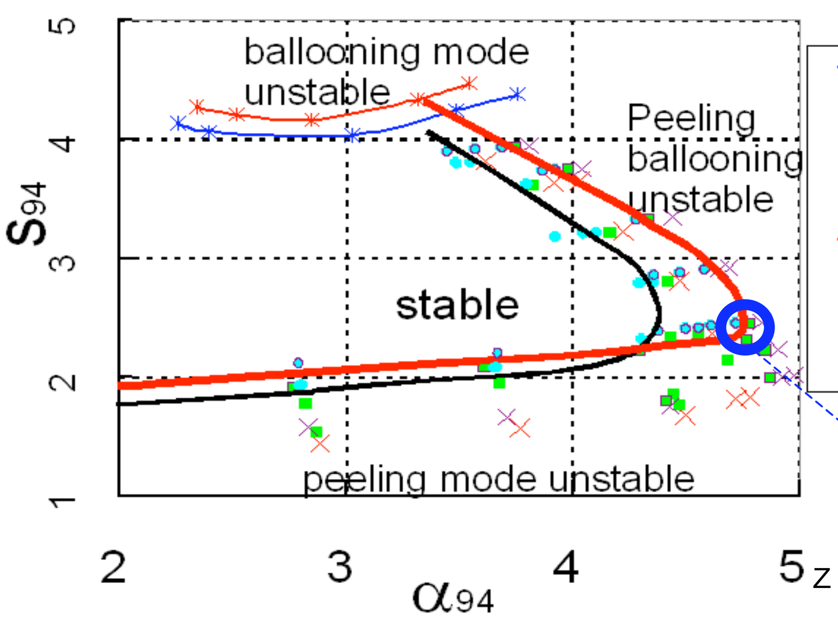
Stability Analysis Results (ITER-like)



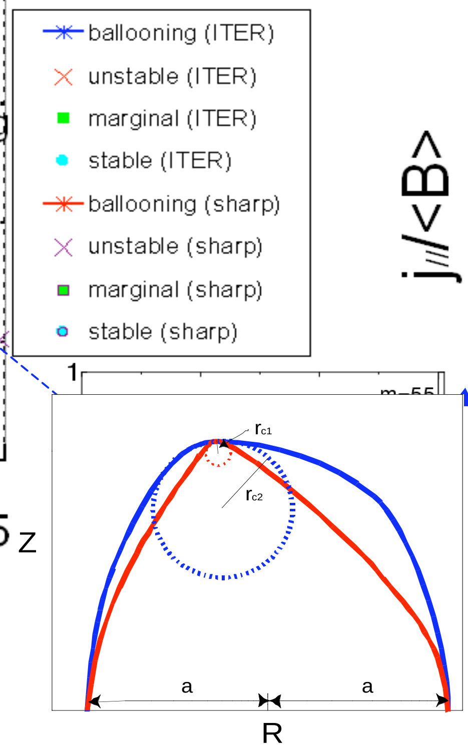
s-α diagram at ψ=0.94 $j_{//}/\langle B\rangle$-α diagram at ψ=0.94

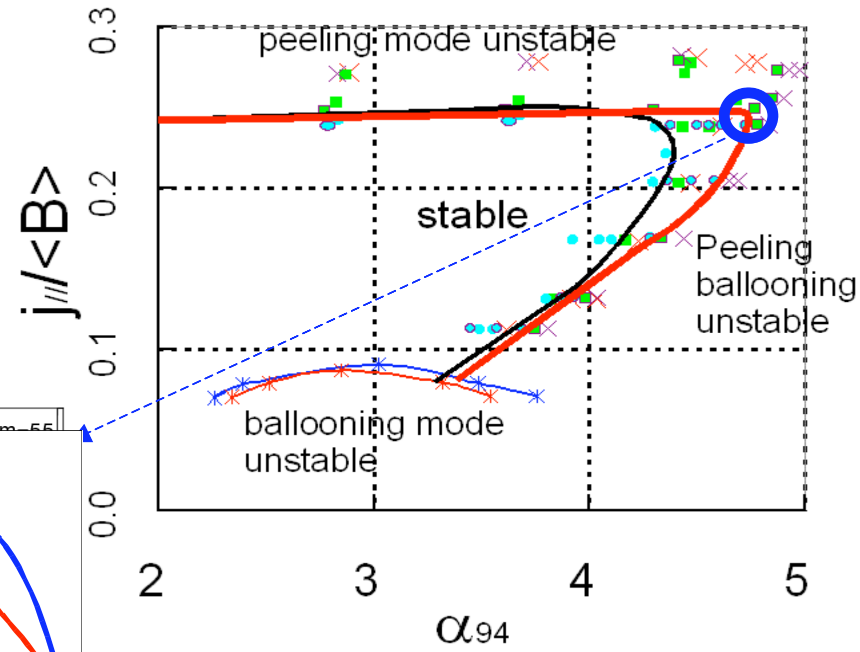
- In this ITER-like equilibrium, the maximum pressure gradient (α_{94}=4.36) is determined by the stability of peeling-ballooning modes whose *n* are from 8 to 13.
- The marginally unstable eigenfunction, whose n=8, localizes near 0.9<s<1.0 (0.86<ρ_{vol}<1.0).

Effect of the Sharpness in ITER-like Eq.



s-α diagram at ψ=0.94





$j_{//}/\langle B\rangle$-α diagram at ψ=0.94

- As mentioned in [5], the sharpness σ has an impact on the stability of the ballooning mode and the peeling ballooning mode.
- In this case, the stable limit of α increases from 4.36 to 4.76 as σ_{up} changes from 2.04 to 3.94.
- The *n* number and the width of the eigenfunction determining the α limit is similar to those of the eigenfunction in ITER-like Eq.

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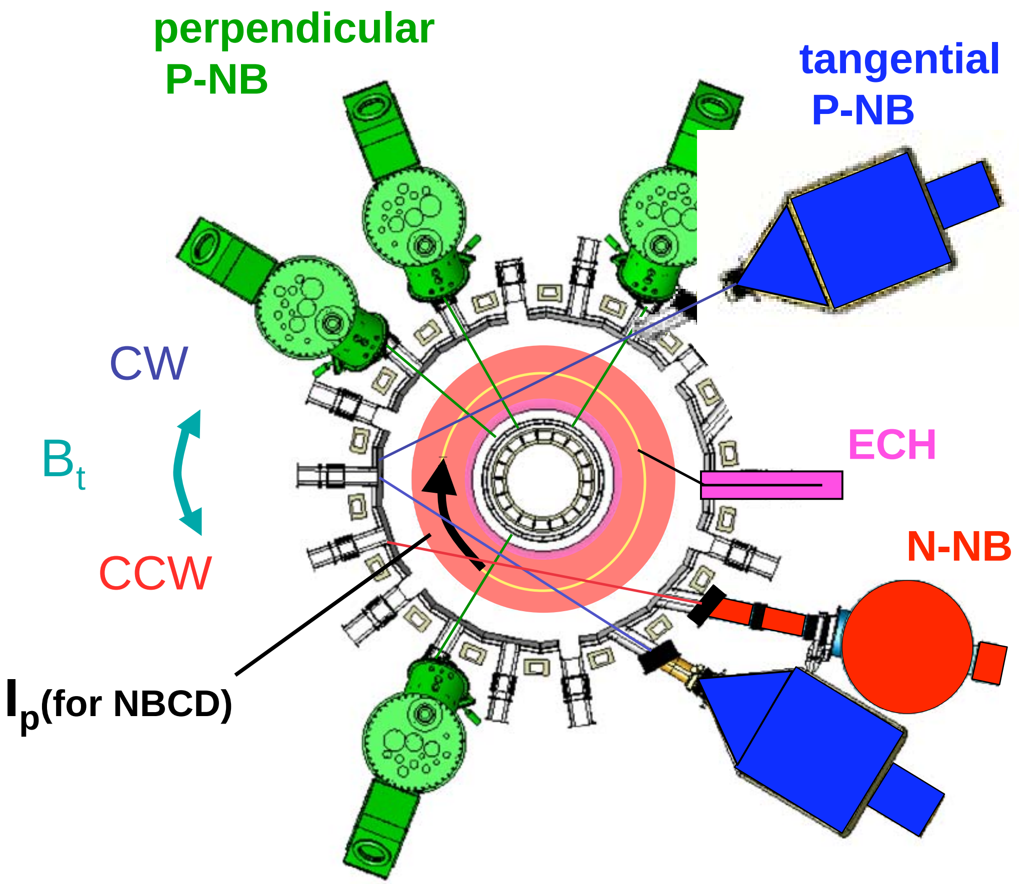
Profile control by H&CD systems

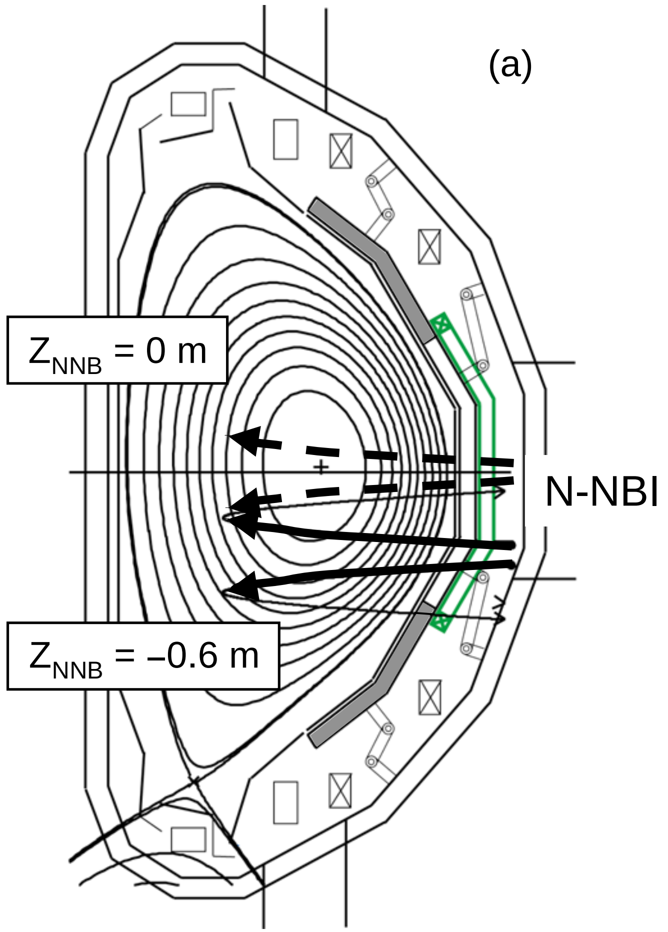
N-NB and ECRF have been upgraded.
Tangential units of P-NB are balanced.



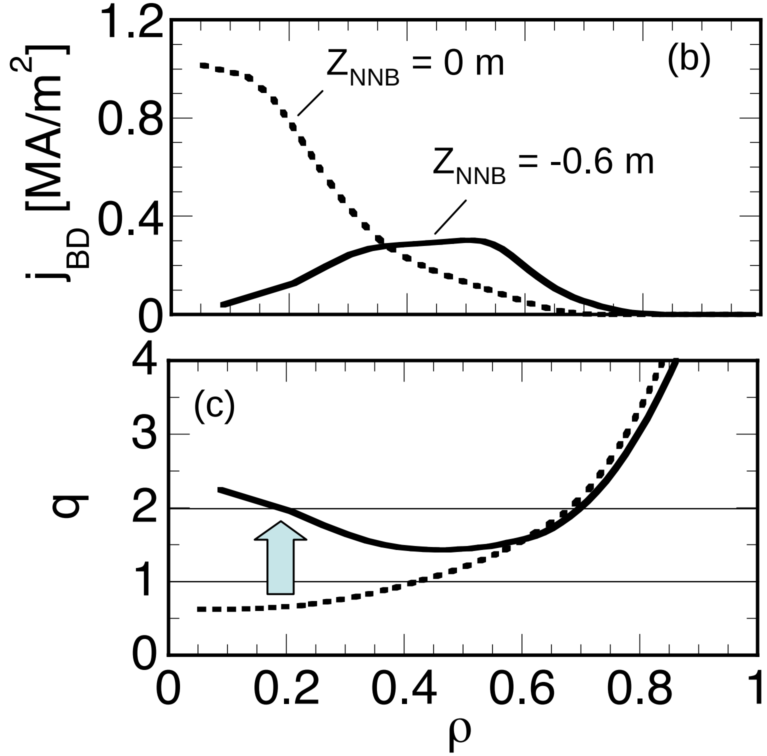
		2005	2006
N-NB	co	3 MW, 400 keV, 1 source	10 MW, 500 keV 2sources
P-NB		22 MW, 85 keV	24 MW, 85 keV
	co	4u	2u
	ctr	0	2u
	pep	8u	8u
EC		(1.7 MW) ~90 GHz	7 MW (3 MW at 110 GHz, 4 MW at 140 GHz
total		25 MW (26.7MW)	41 MW

Profile control by N-NB system

Since q_{min}>1 or suppression of sawtooth instability is believed necessary to achieve high beta and high confinement, it has been decided to shift the N-NBI beam lines downward, to obtain a broad current profile with weak/reversed magnetic shear

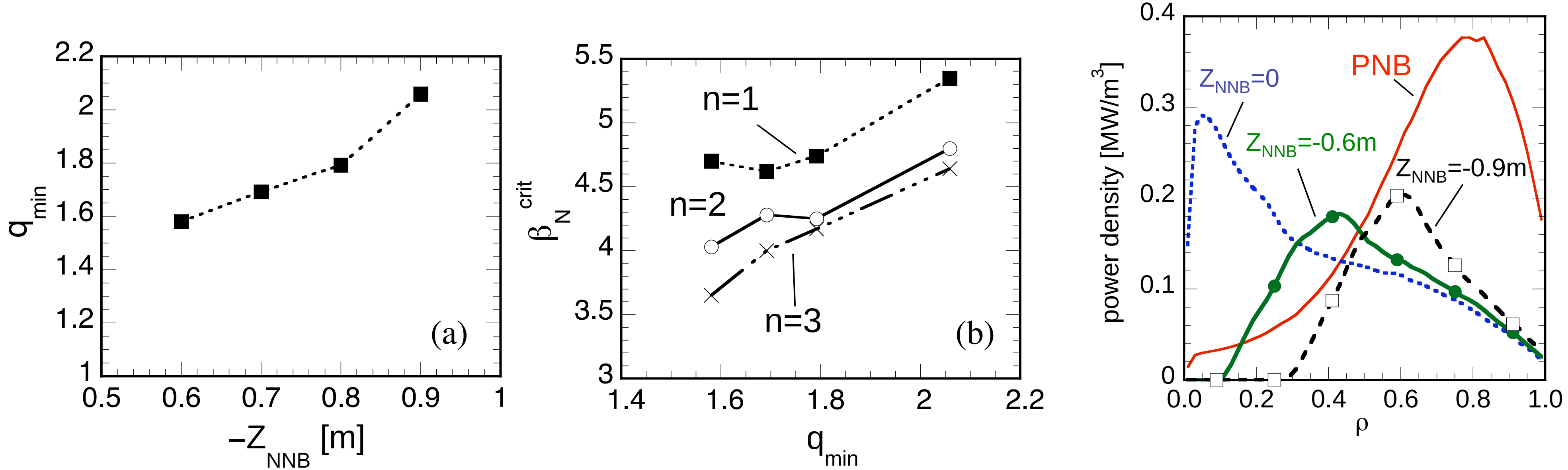


The question is how much the beam lines should be lowered.



Stability improvement by profile control

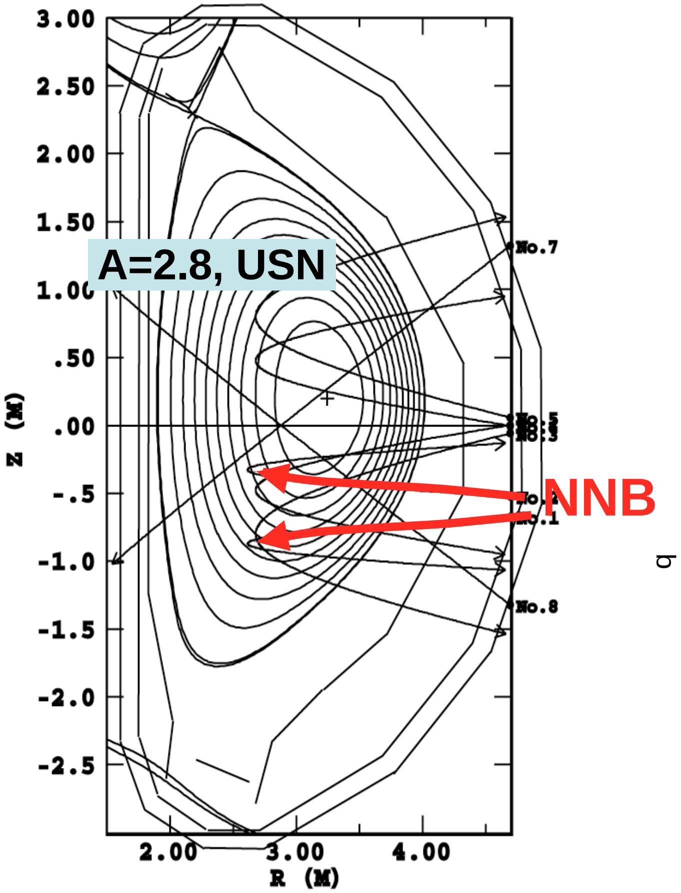
The q_{min} increases with a larger shift of N-NB; q_{min} ~1.6 for Z_{NNB} = –0.6 m and ~2 for Z_{NNB} = –0.9 m (2.4 MA full CD, A=2.8, Z_{axis}=0.07m, β_N~4, f_{BS}~70%).
The ideal wall limit increases with q_{min}.
The power deposition of N-NB gets hollows as the N-NB position is moved downward.
Considering the MHD stability and central heating, the shift of 0.6 m is taken as a standard point for the present design.

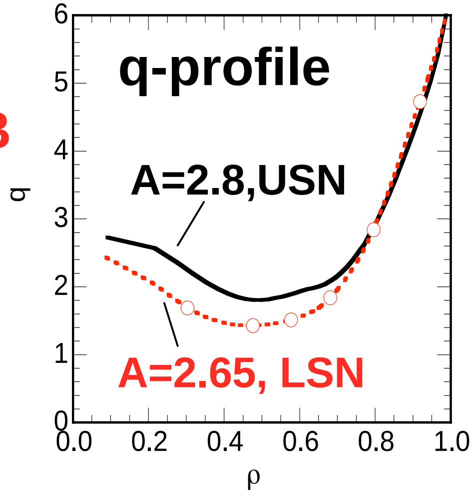


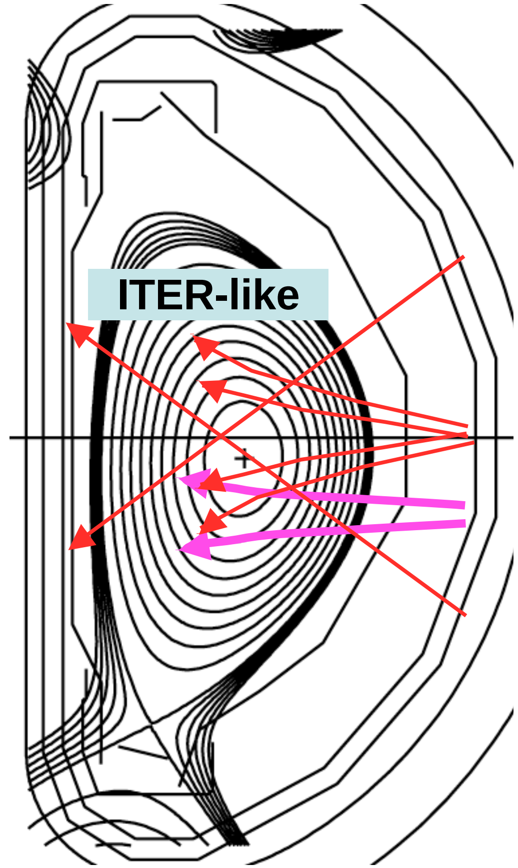
N–NB system(3)

Far off-axis current drive for achieving qmin ~2 is possible by using a USN configuration with its magnetic axis elevated

Near on-axis heating is also possible by using a LSN configuration with the axis lowered.





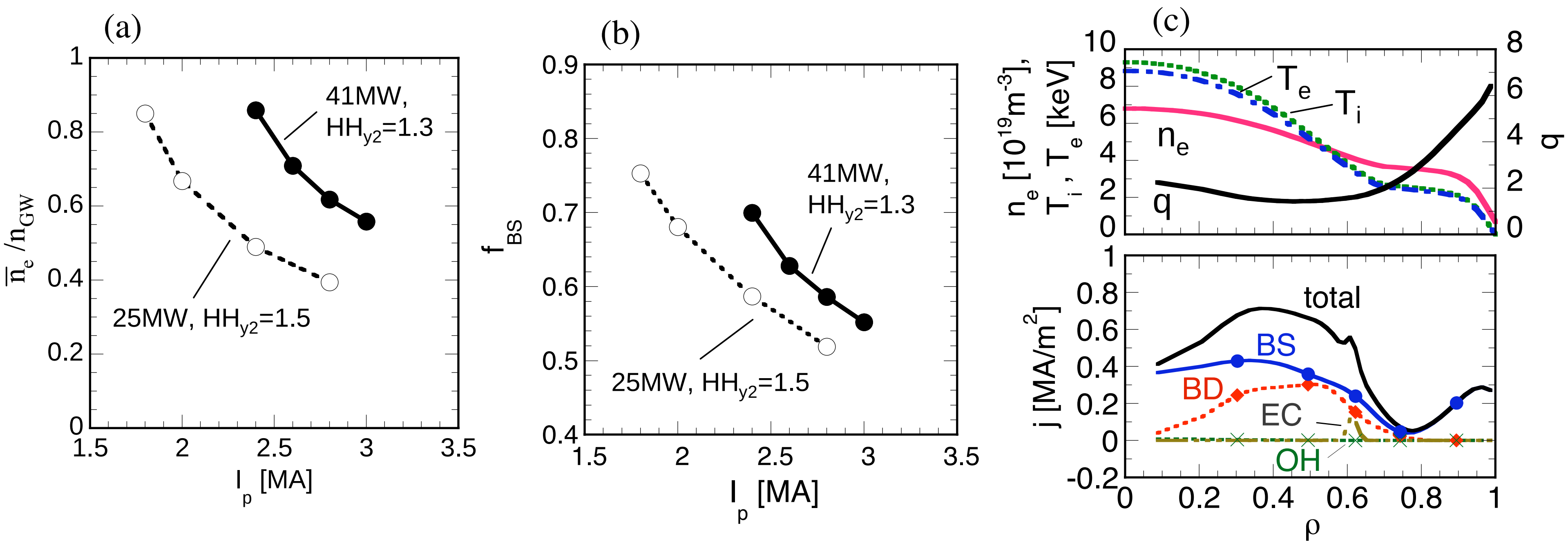


Extended region for full-CD operation

A = 2.65 and a shift of 60 cm of N-NB (Z_{NNB} = -0.6 m).

A full CD operation with a high normalized density of ne-bar/n_{GW} = 0.86 (= 4.9×10^{19} m^{-3}) is possible at I_p = 2.4 MA for HH_{y2} =1.33 and total power of 41 MW. The fraction of the bootstrap current ('BS') is f_{BS} = 0.70. The resultant q profile has a broad weak shear region with q_{min} ~ 1.5.

A, q95, κ, β_N, β, HHy2 and fBS are very close (within 10%) to those in a DEMO design with a slim center solenoid proposed by JAEA



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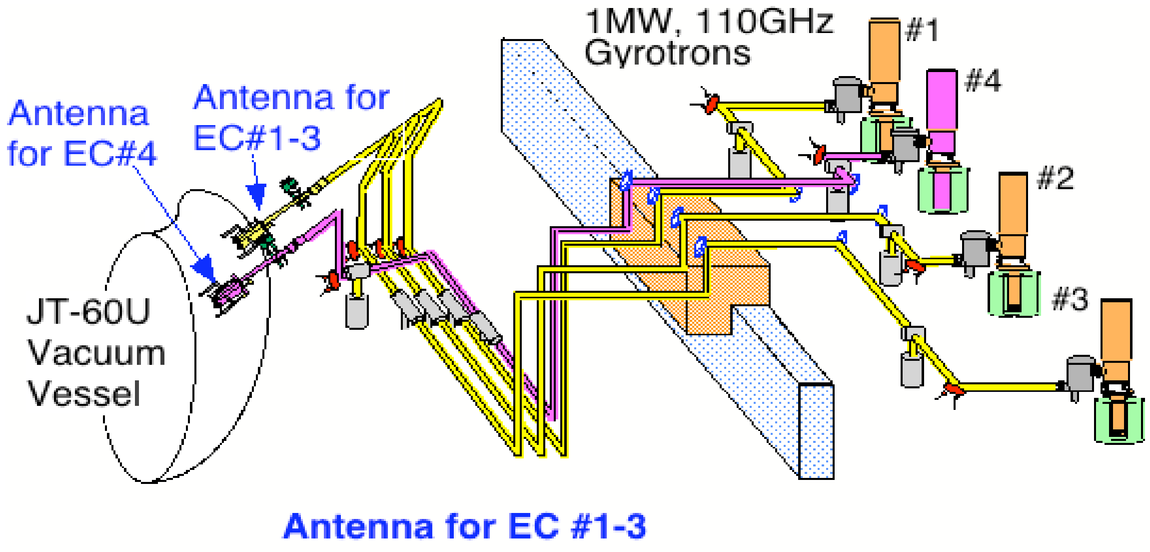
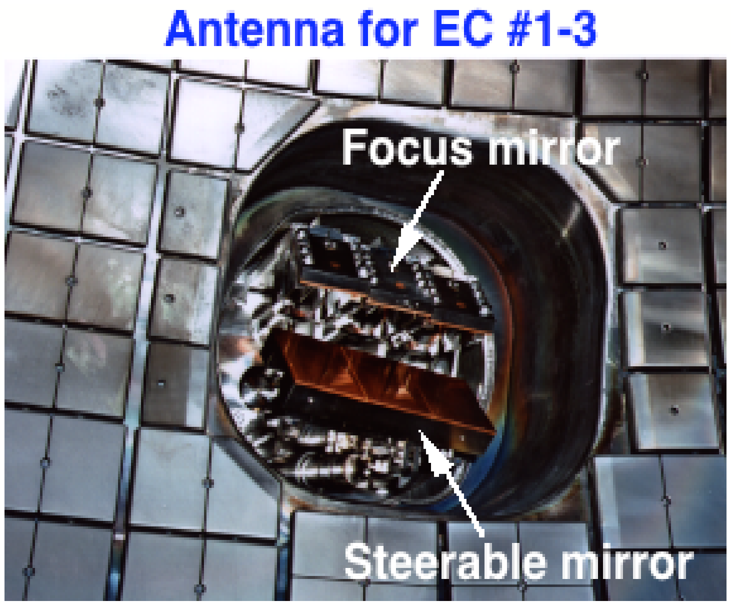
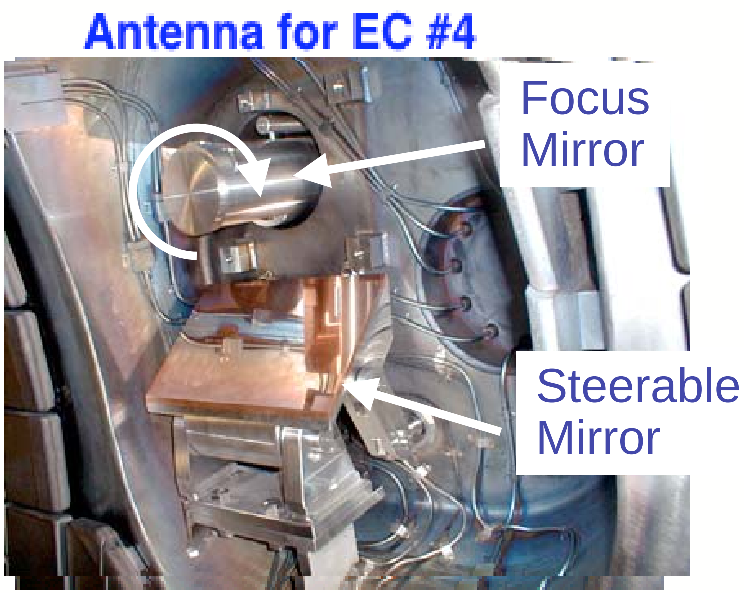
ECRF System in JT-60U

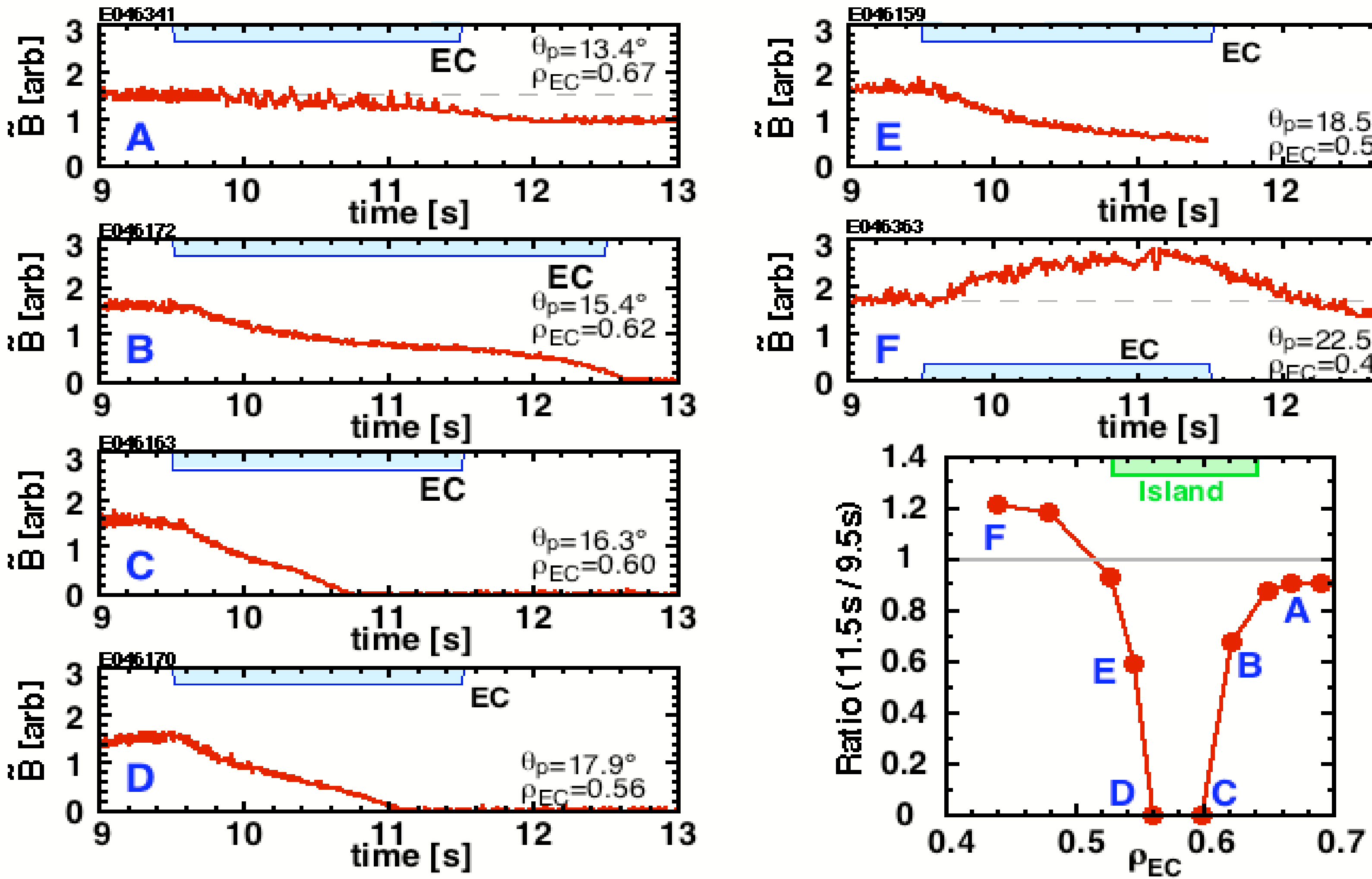


**The real-time NTM stabilization system:
the detection of the mode location and the optimization of the injection angle of electron cyclotron (EC) wave are performed in real time**





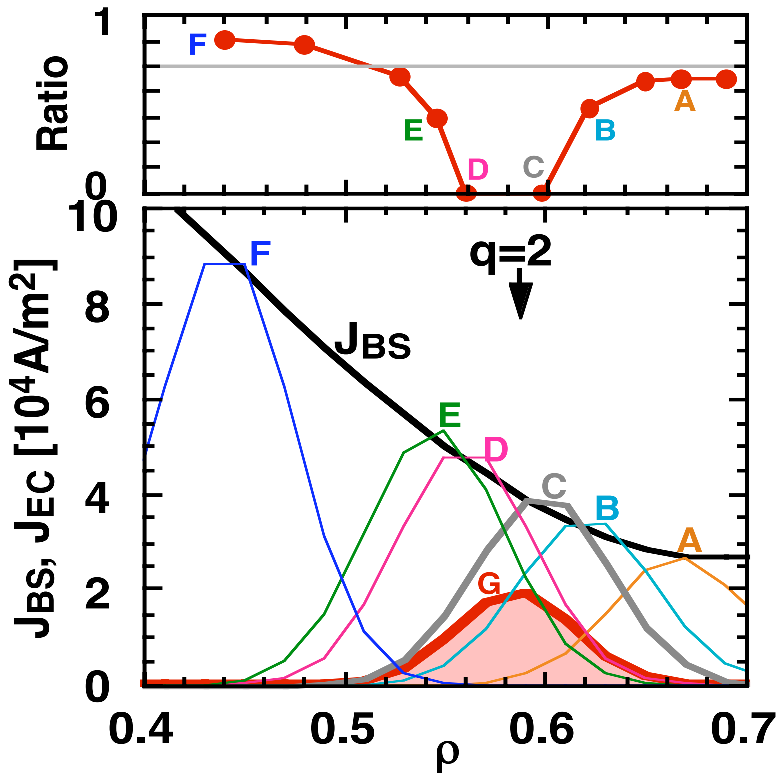
NTM has been completely stabilized in JT-60U m/n=2/1 by ECCD at q=2 (ρ~0.6)

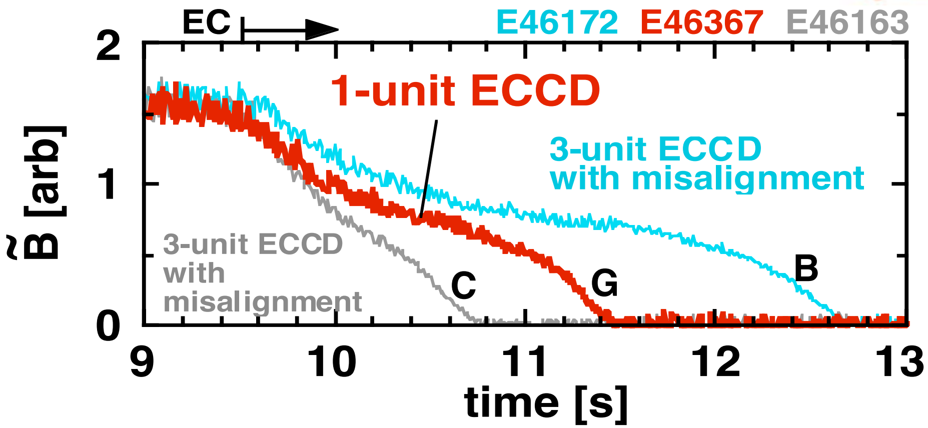


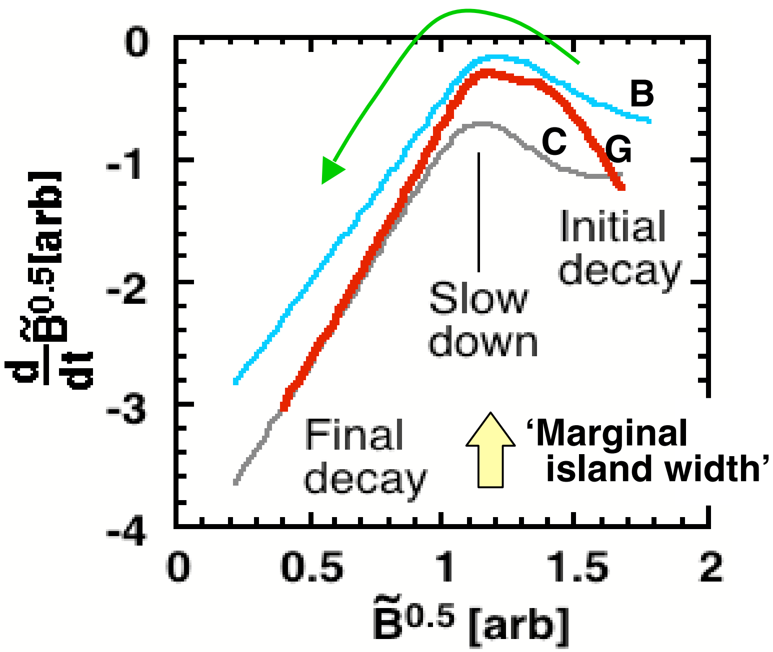
- **Stabilization** for misalignment <~W/2
- **Destabilization** for misalignment ~W

"Precise injection is important"

Further optimization of ECCD location enabled complete stabilization at J_{EC}/J_{BS}~0.5

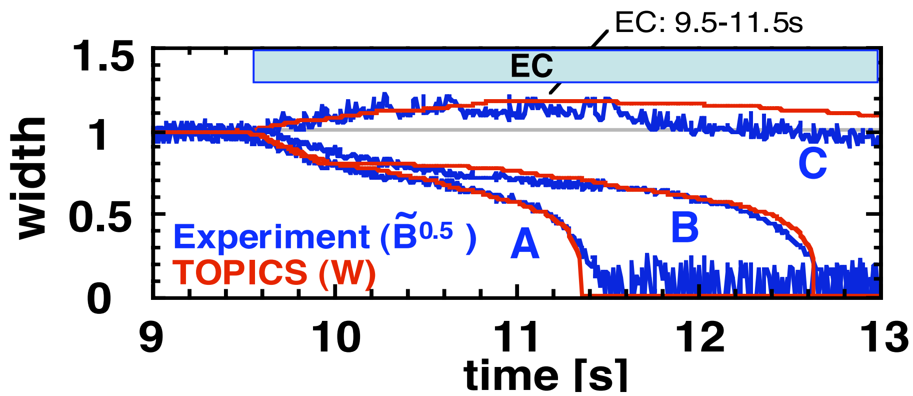


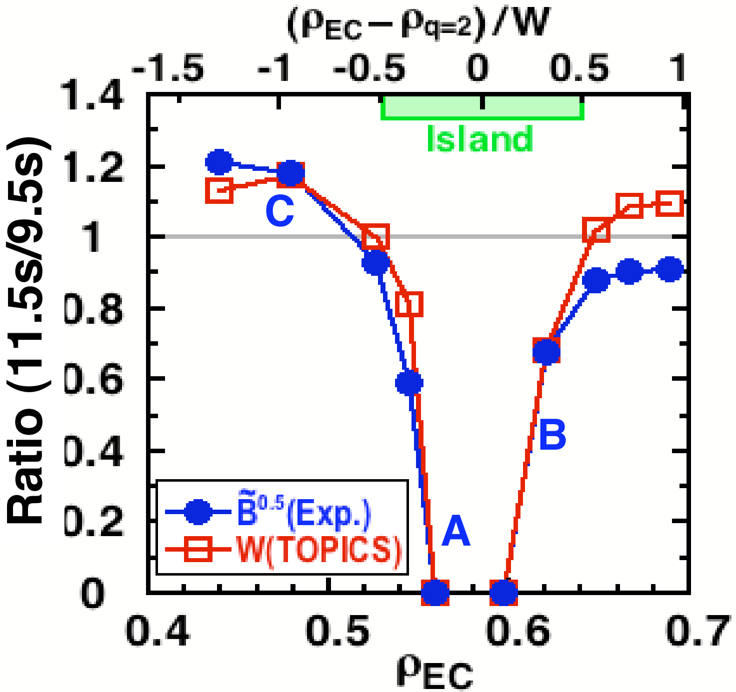




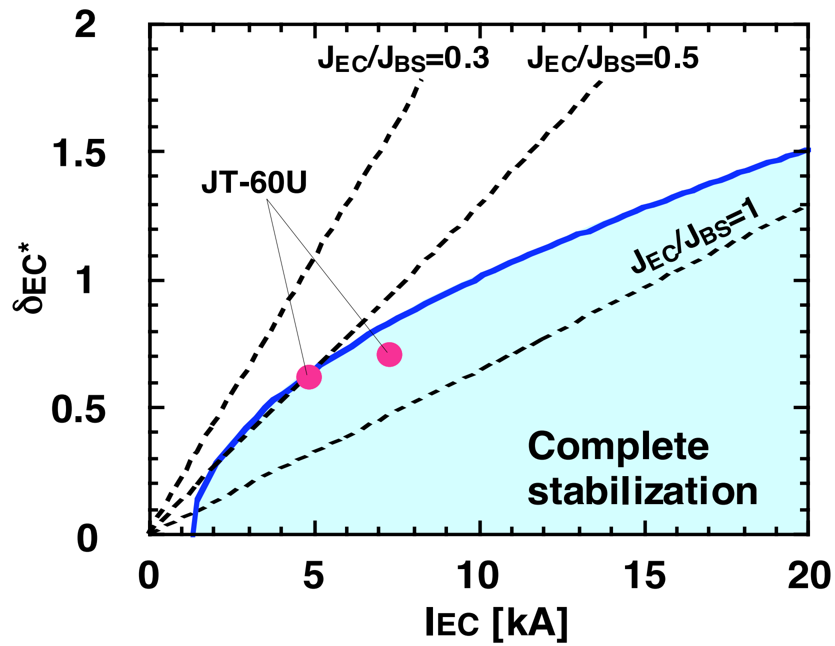
- Although longer time is needed, 2/1 NTM was completely stabilized with J_{EC}/J_{BS}~0.5
- Temporal evolution: 3 phases
  Similar behavior even for different EC location & current

TOPICS simulation with modified Rutherford equation well reproduces experimental results.





• Good agreement with the same coefficient set



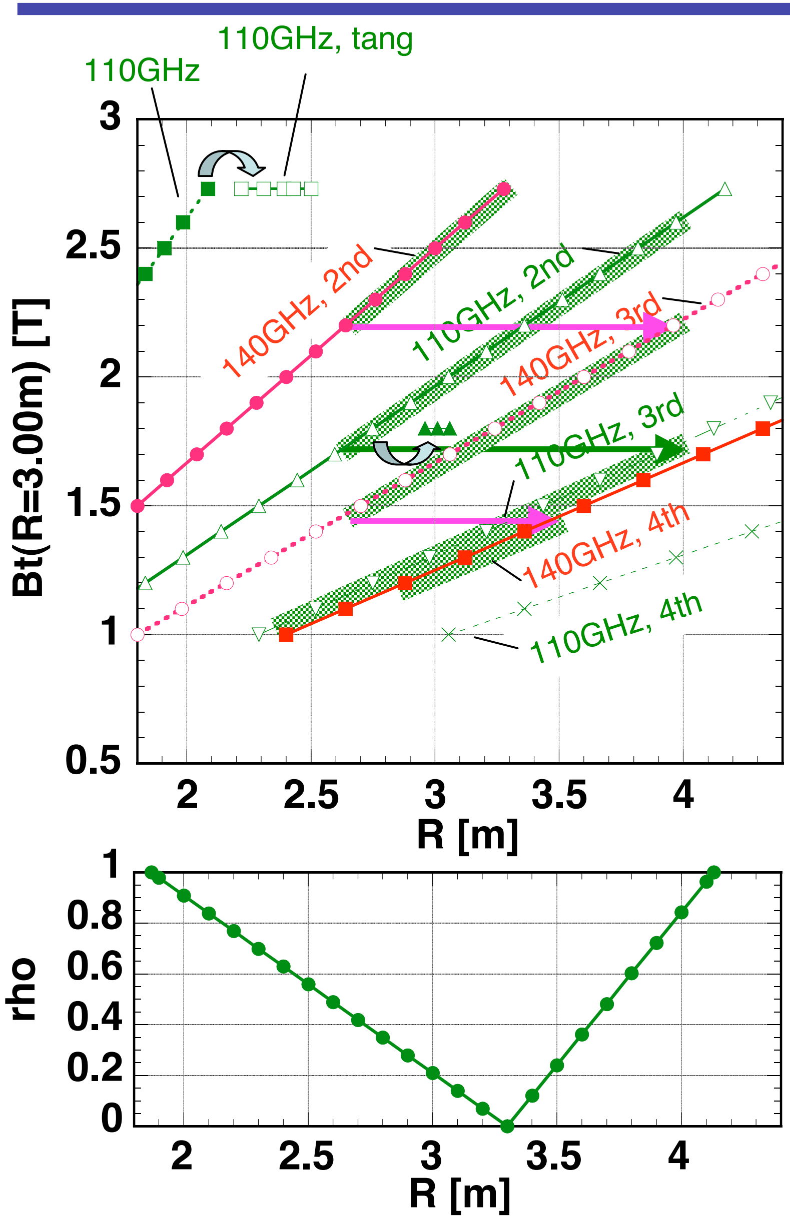
The consistent analysis shows:

- **ECCD width has stronger effect** than amount of EC-driven current.
- **Precise ECCD control has enabled complete stabilization with smaller value of j_{EC}/j_{BS} :**

$J_{EC}/J_{BS} \sim 0.5$

[A. Isayama, IAEA FEC 2006]

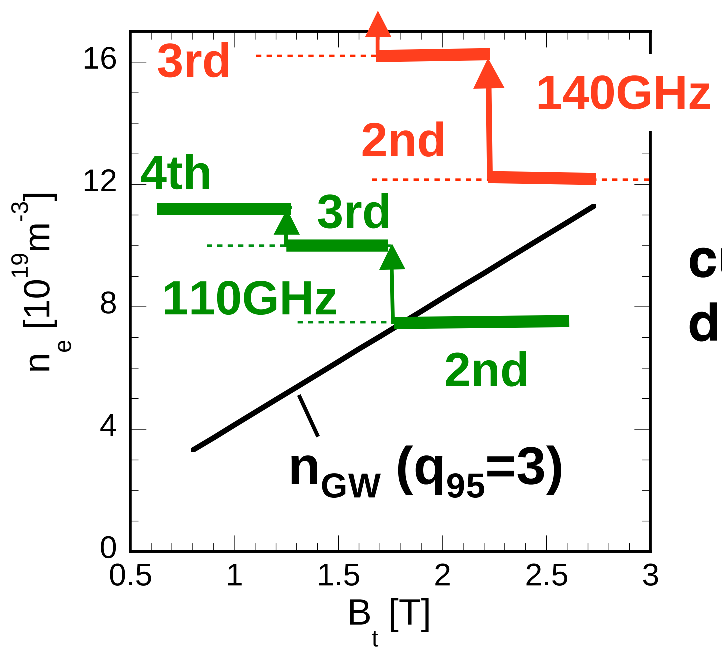
ECRF system of JT-60SA



140 GHz, 4 MW for high-density plasmas
3rd resonance (small CD) appears below 2.2 T

110 GHz, 3 MW: ECCD for 1.7-2.5 T

A wide range of Bt covered by two frequencies.

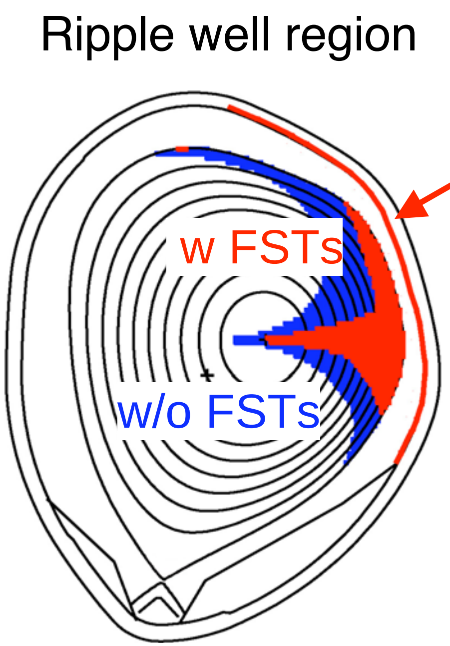


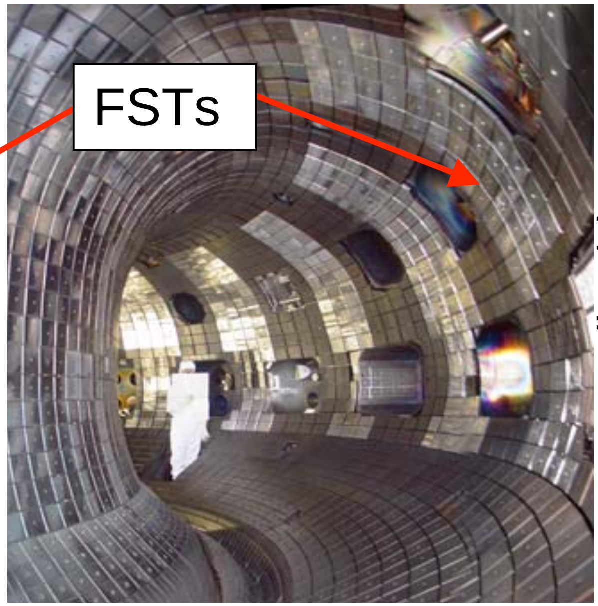
cut-off density

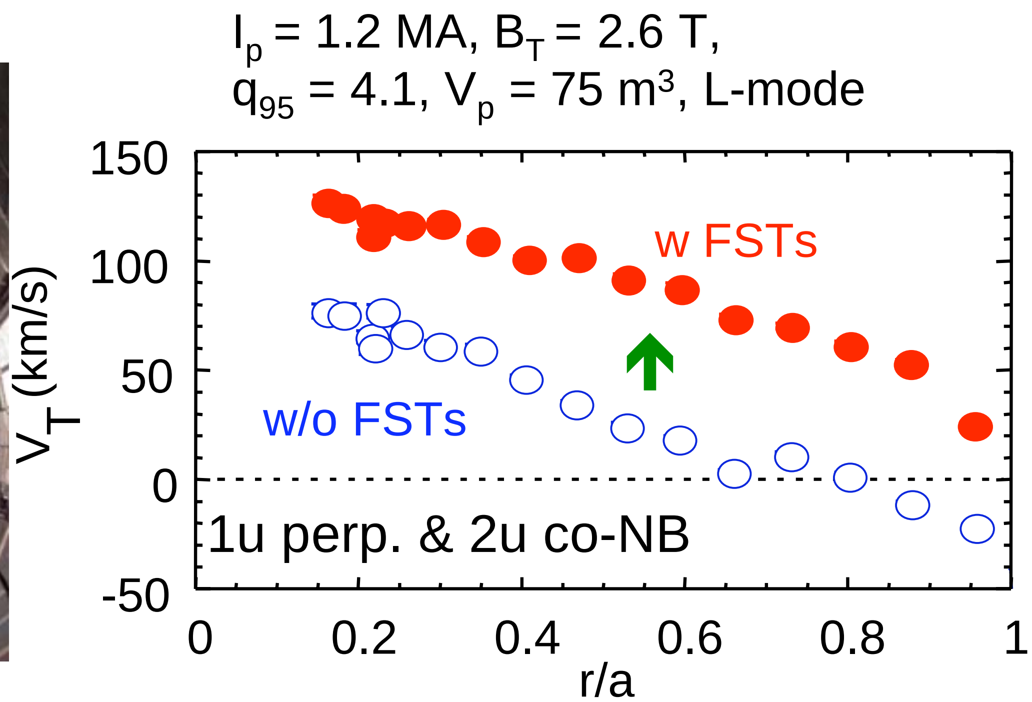
1. Concepts of JT-60SA
2. MHD control of JT-60SA
    1. Plasma shape control
    2. Internal profile control
    3. Control by ECCD: ST, NTM
    4. **Control by coils: RWM**
3. Summary

Installation of ferritic steel tiles in JT-60U

- **Reduction of ripple loss decreased fast ion loss in the large volume plasma and increased the net heating power.**
- **The region of high β_N discharges was extended and integrated performance in long high β_N plasmas was improved by the increase of the net heating power, the plasma close to the wall, and the change of the rotation.**

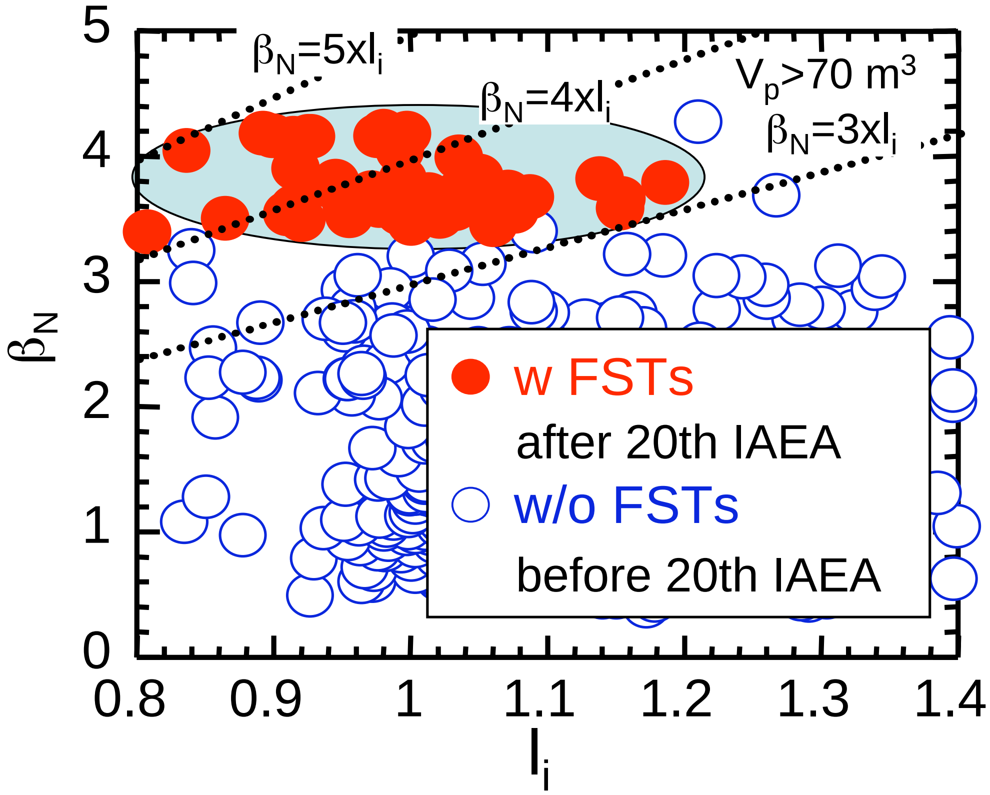


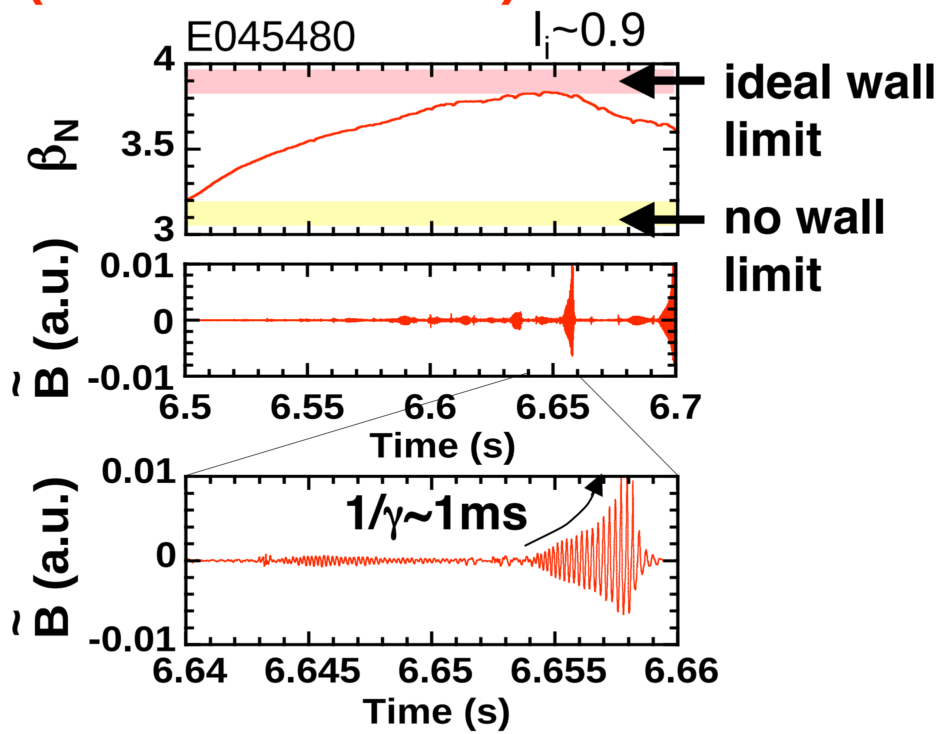




β_N reaches ideal wall limit.

- **High β_p ELMy H-mode plasma :** B_T=1.58 T, I_p=0.9 MA, δ_0~20 cm **(d/a=1.2)**
- **Increase in net heating power due to the FSTs installation allows to access high β_N up to 4.2 with l_i=0.8-1.**
- **n=1 (m~3) mode at high beta region.**
- **Growth time of 1/γ~1 ms (< τ_w~10 ms) before collapse.**
- **RWM is suppressed by plasma rotation (100km/s at r/a=0.3).**

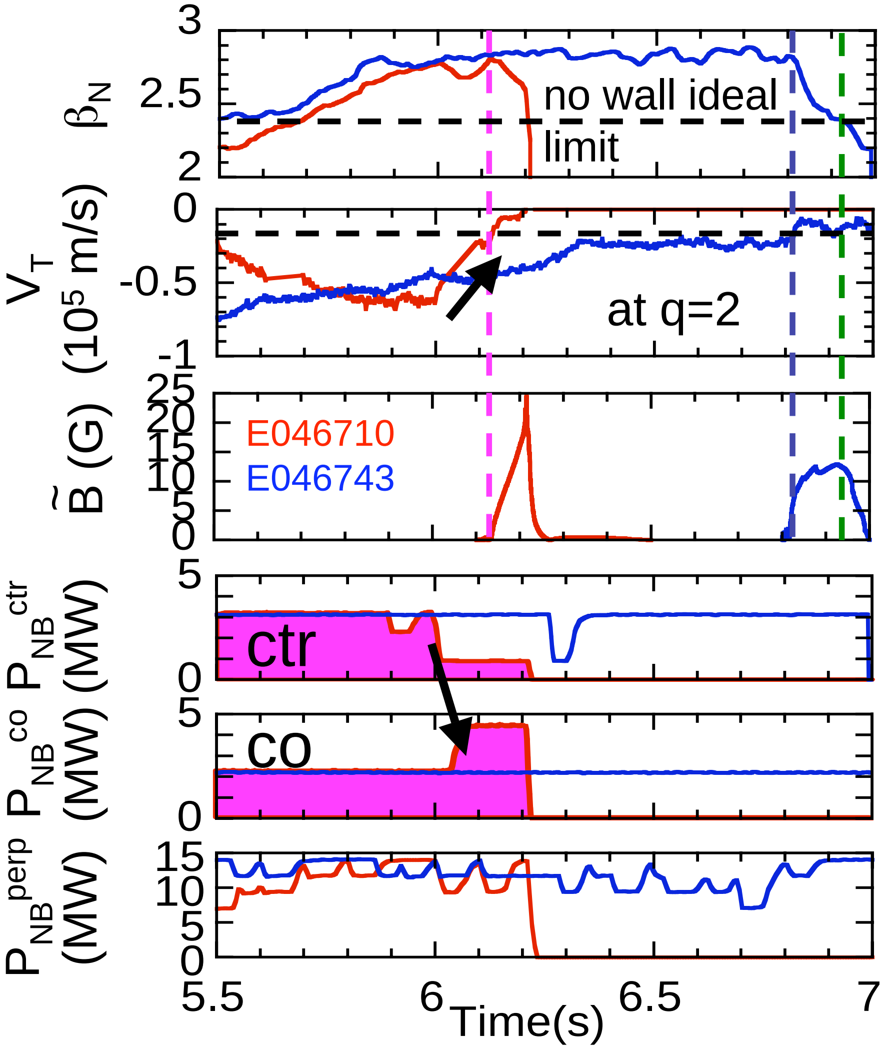




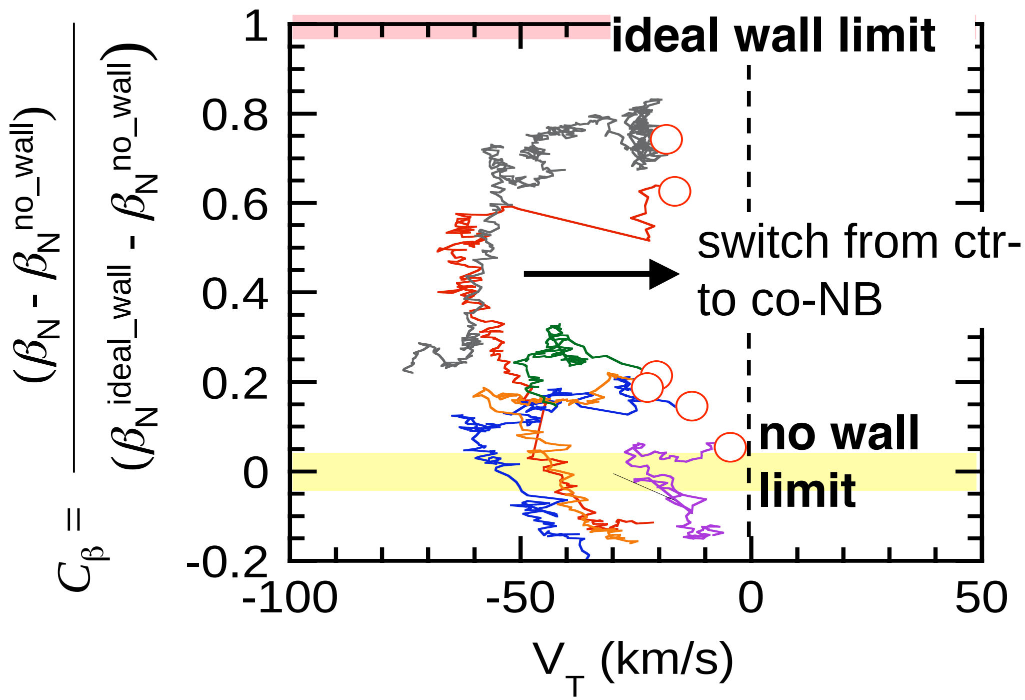
M. Takechi (EX/7-1Rb)

Small critical rotation velocity of V_C/V_A~0.3% is found for suppressing RWM.

- **Less counter rotation due to the FSTs installation enables to change the rotation in co-direction close to zero.**



- **V_C~15 km/s**
- **Growth time of 1/γ~10 ms (~ τ_w)**
- **No increase in V_C for higher C_β .**
- **Large impact on ITER & DEMO.**



M. Takechi (EX/7-1Rb, Fri.)

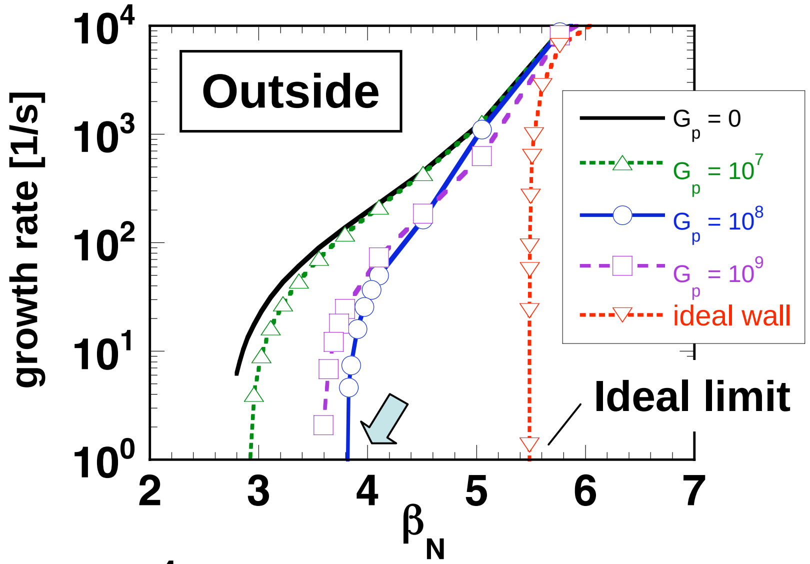
RWM control coils

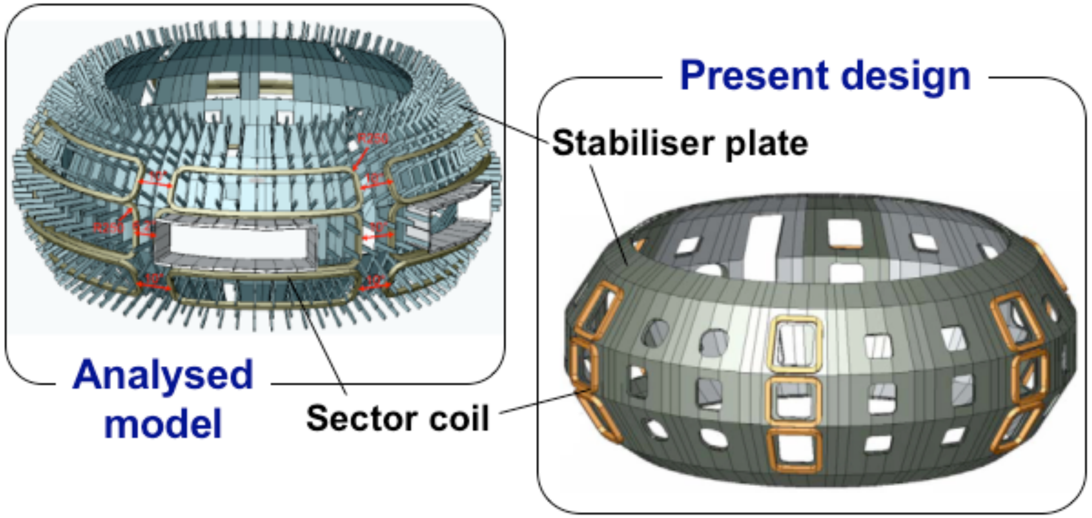
RWM stabilisation by feedback control of sector coils (VALEN code analysis*)

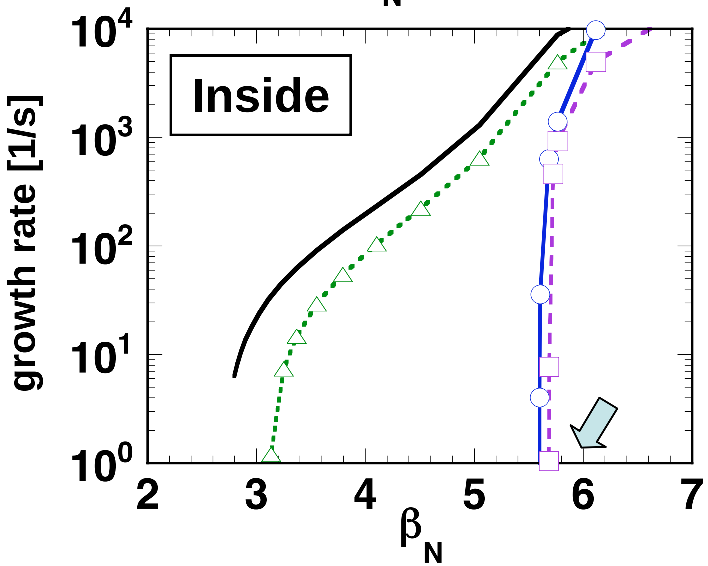
Achievable β_N depends very much on the location of sector coil

outside stabiliser plates : β_N~3.8
inside stabiliser plates : β_N~5.6

- **Sector coils are located on the port entrance in the present design (Analysis ongoing)**







RWM stability

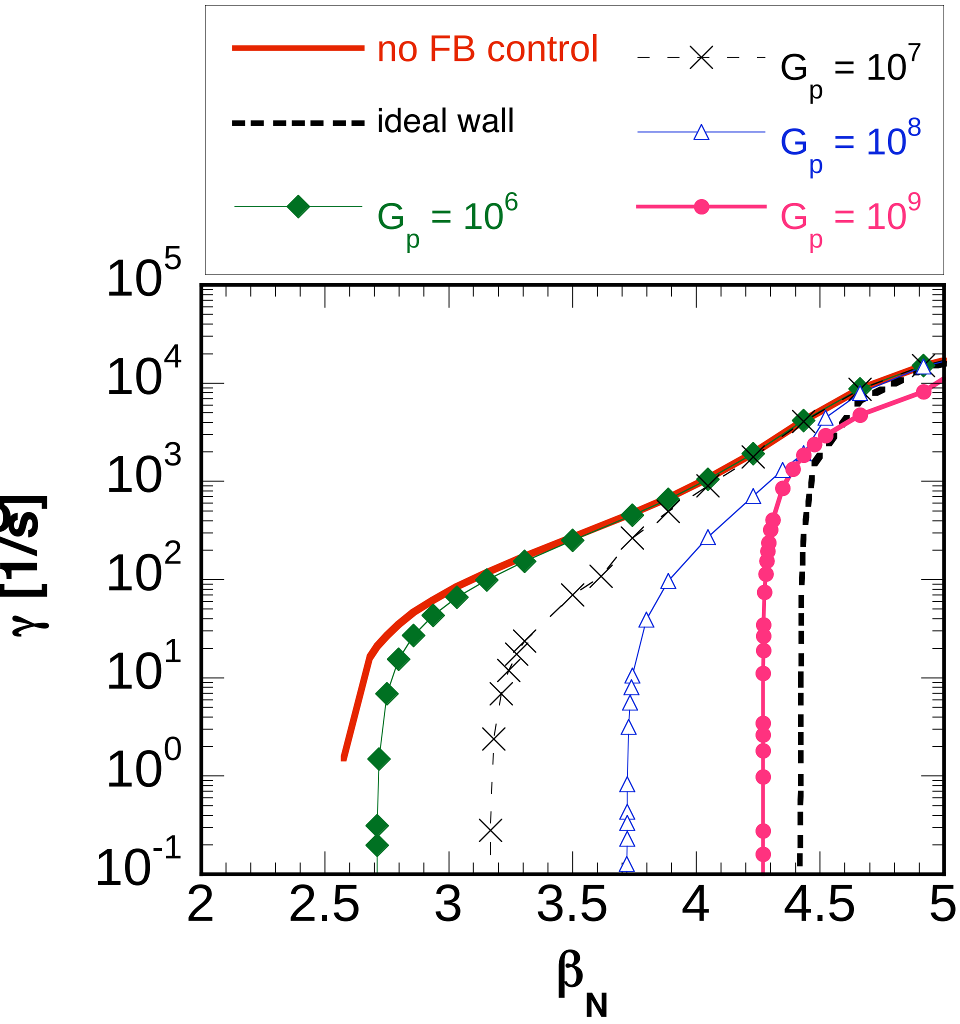
Bialek, Navratil Columbia U.

18 coils, 20 kAT, 1 G (10-4 T) of m=3, n=1 component of radial magnetic field.

The result of VALEN analysis for n=1 modes.
A = 2.8,
r_w/a = 1.3 on the outer mid-plane.

p(r) and j(r) consistent with the ACCOME analysis, where q_{min} ~ 2.1.

β_N = 4.3 is expected, which is close to the ideal wall limit ($\beta_N^{ideal\text{-}wall}$ = 4.42), while the no-wall limit is $\beta_N^{no\text{-}wall}$ = 2.56. Hence $C_\beta = (\beta_N - \beta_N^{no\text{-}wall})/(\beta_N^{ideal\text{-}wall} - \beta_N^{no\text{-}wall})$ = 0.9 and very efficient RWM stabilization is expected.



Summary

JT-60SA is planed as a largest SC tokamak to support and supplement ITER toward DEMO.

Design on some components in JT-60SA including poloidal field coils, RWM control coils, ECRF and N-NB systems, have been optimized for plasma control toward high beta steady-state operation.

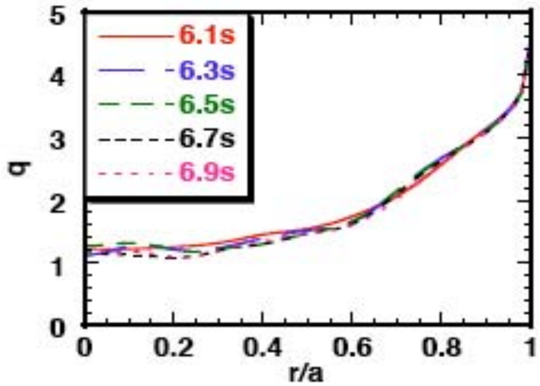
Shape control: an additional equilibrium field coil of EF7
Profile control: lowered beam line of N-NB and ECRF
NTM control: two frequencies ECRF
RWM control: coils along the port hole
have been decided.

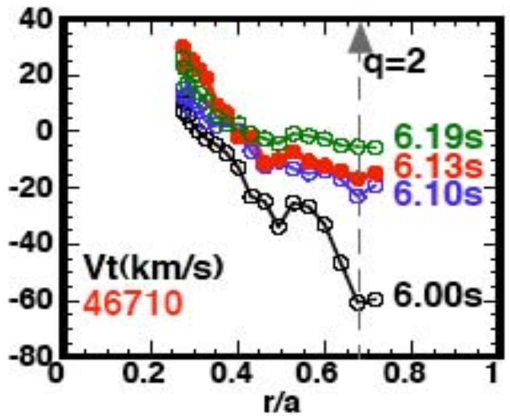
The construction of JT-60SA will take 7 years and 3 years of experiments are foreseen in 10 years of BA period.

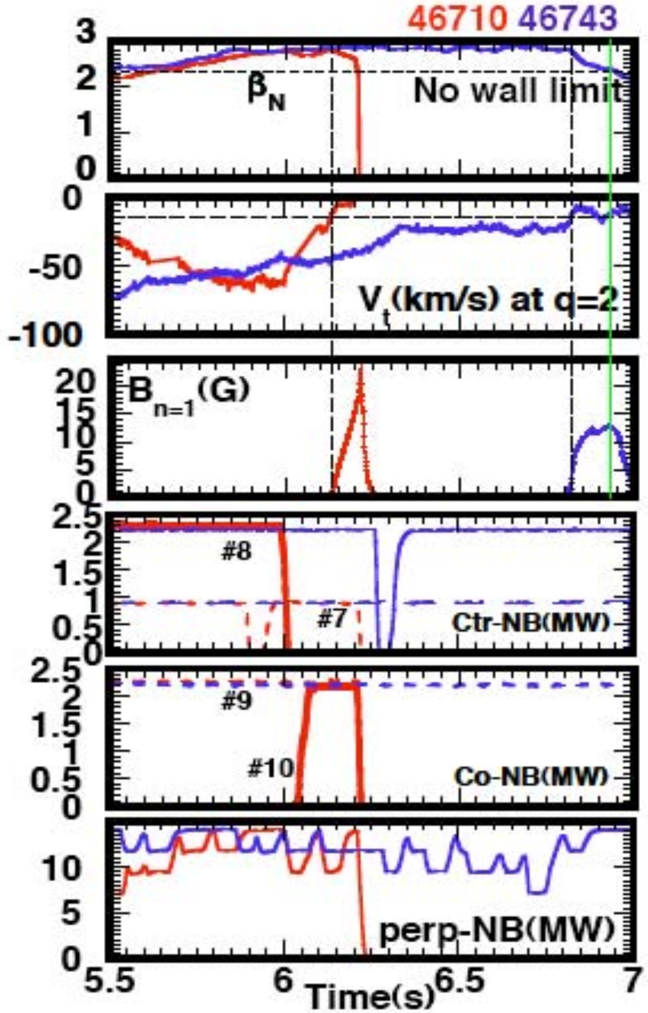
RWM is suppressed by plasma rotation

JT-60U

- β_N is kept constant and change the tangential NB from ctr-NB to co-NB.
- Rotation can be controlled by changing tangential NB combination
- Disruption or collapse occurs at Vt~10 km/s ->n=1 mode grow with $1/\gamma$ ~10 ms .
- The mode suppressed after $\beta_N < \beta_{N\ \text{no-wall limit}}$
- To investigate the effect of beta on critical rotation, we change the constant β_N.





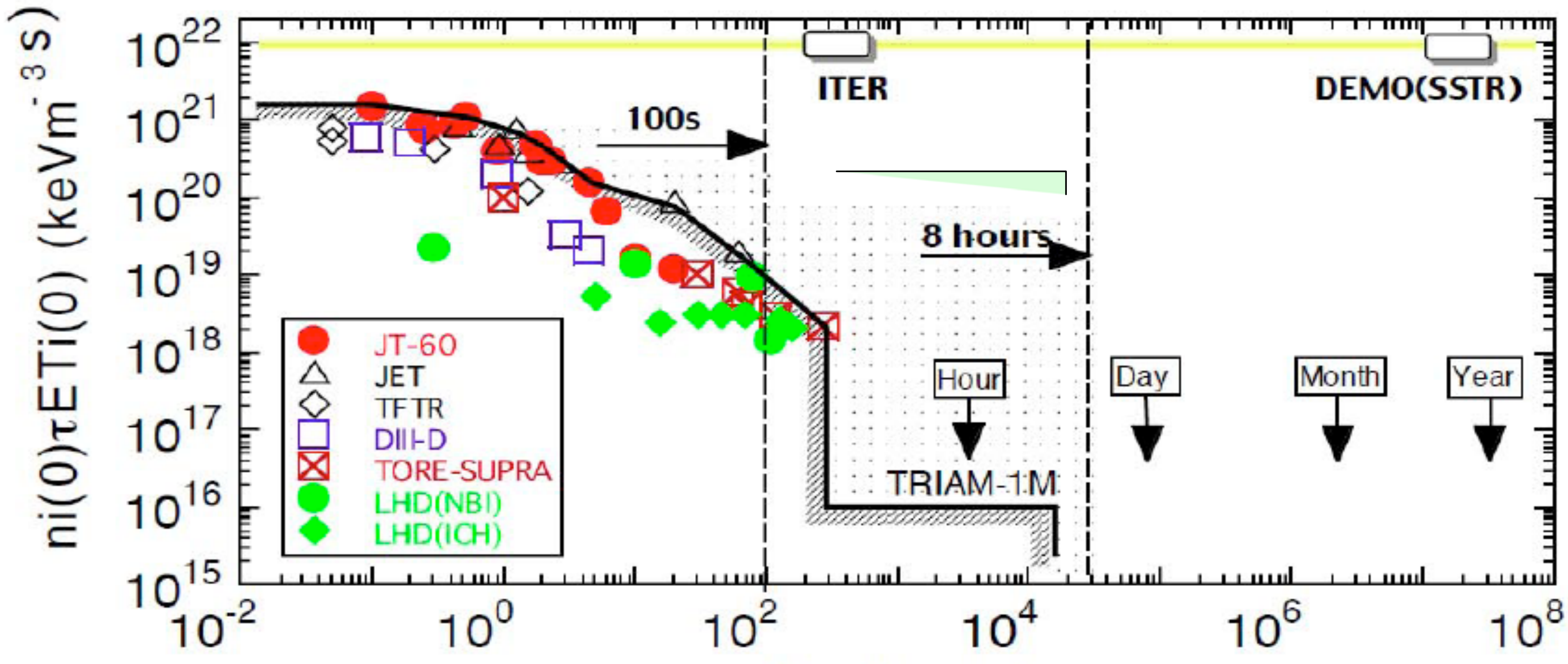


Scientific Mission (II) (long term)

Expand operation regime of high beta steady-state for DEMO

Long pulse operation : ~8 hours

1. **Particle exhaust for long pulse and development of DEMO relevant PFC**
2. **Development of reliable operation and reduction of disruption probability**



Overview of the MARG2D code

- MARG2D solves the eigenvalue problem associated with the 2-D Newcomb equation with the artificial weight function[1].
- With the vector potential method for calculating the vacuum energy, MARG2D realizes to identify the stability of the wide *n* range ideal MHD modes[2,6].
- By using both the artificial weight function and the physical inertia, the marginal stability condition can be identified, and the compression-less growth rate can be estimated.

$$N\mathbf{Y} = -\lambda R\mathbf{Y}\ , \quad (\mathbf{Y} = r\xi_r)$$

N : Newcomb operator

ξ_r : displacement in the r direction

$$R_{l,m} \propto \begin{cases} (m/q-n)^2 & \ldots l = m \\ 0 & \ldots l \neq m \end{cases} \longrightarrow R\mathbf{Y} = \rho(\mathbf{Y} + (\mathbf{V} - \beta\mathbf{Y}))$$

m : poloidal mode number

n : toroidal mode number

q : safety factor

$\mathbf{V}$: displacement vector in the $\nabla\psi \times \mathbf{B}$ direction

ρ : plasma density

β : unorthogonality of the coordinate

[6] N.Aiba et al., TH/P8-1, 21st IAEA FEC,Chengdu, China (2006).