Active MHD Control from Various Approaches in JT-60U and JT-60SC

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Outline of talk

- High beta steady state regime in JT-60U and JT-60SC
- Neoclassical tearing mode
  - Real-time feedback control
- Kink-ballooning mode for current hole plasmas
  - Profile control and wall stabilization
- Resistive wall mode
  - Ferromagnetic wall effect
- Experiment plans for MHD control

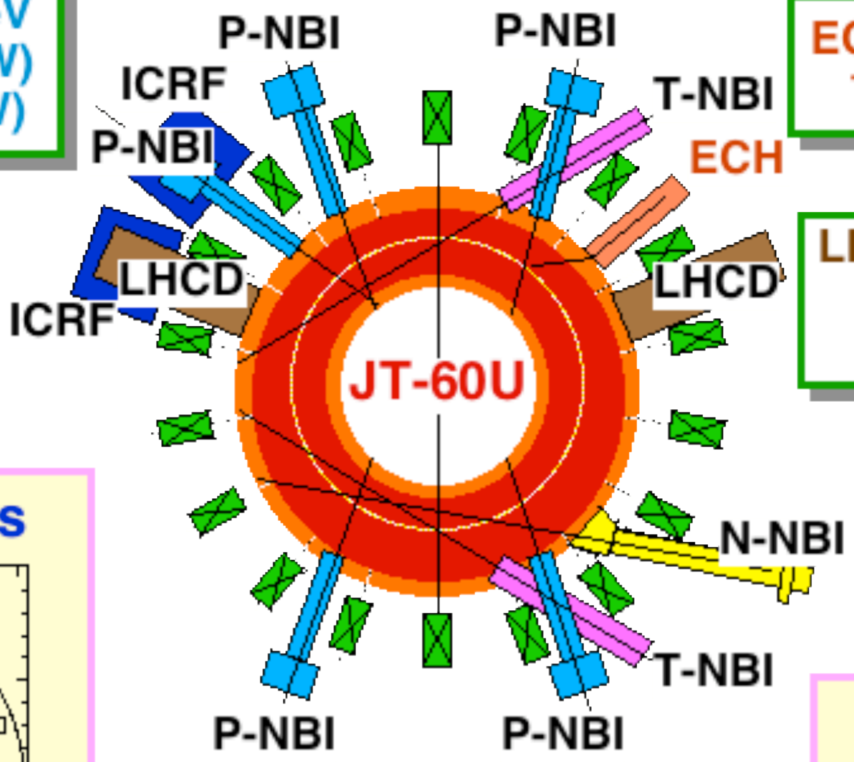
High beta steady state regimes in JT-60U and JT-60SC

- Heating/current drive equipments for JT-60U
- Modification of JT-60
- High beta steady state regimes
- Target areas of JT-60SC

Heating/current drive and divertor equipments in JT-60U

P-NBI : 27 MW / 85keV
Tang. 4 units (10 MW)
Perp. 7 units (17 MW)

ICRF: 4 MW
102 MHz

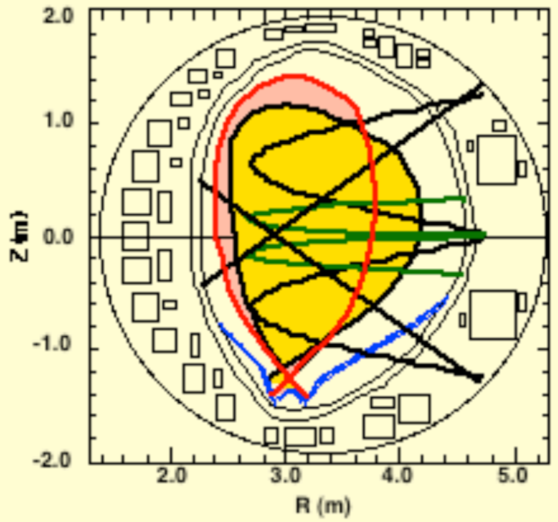


ECH : 3 MW
110GHz, 4 Gyrotron

LHRF: 3.5 MW
2GHz, 2 units
(horiz, upper)

N-NBI :
10 MW / 500 keV

NBI configurations



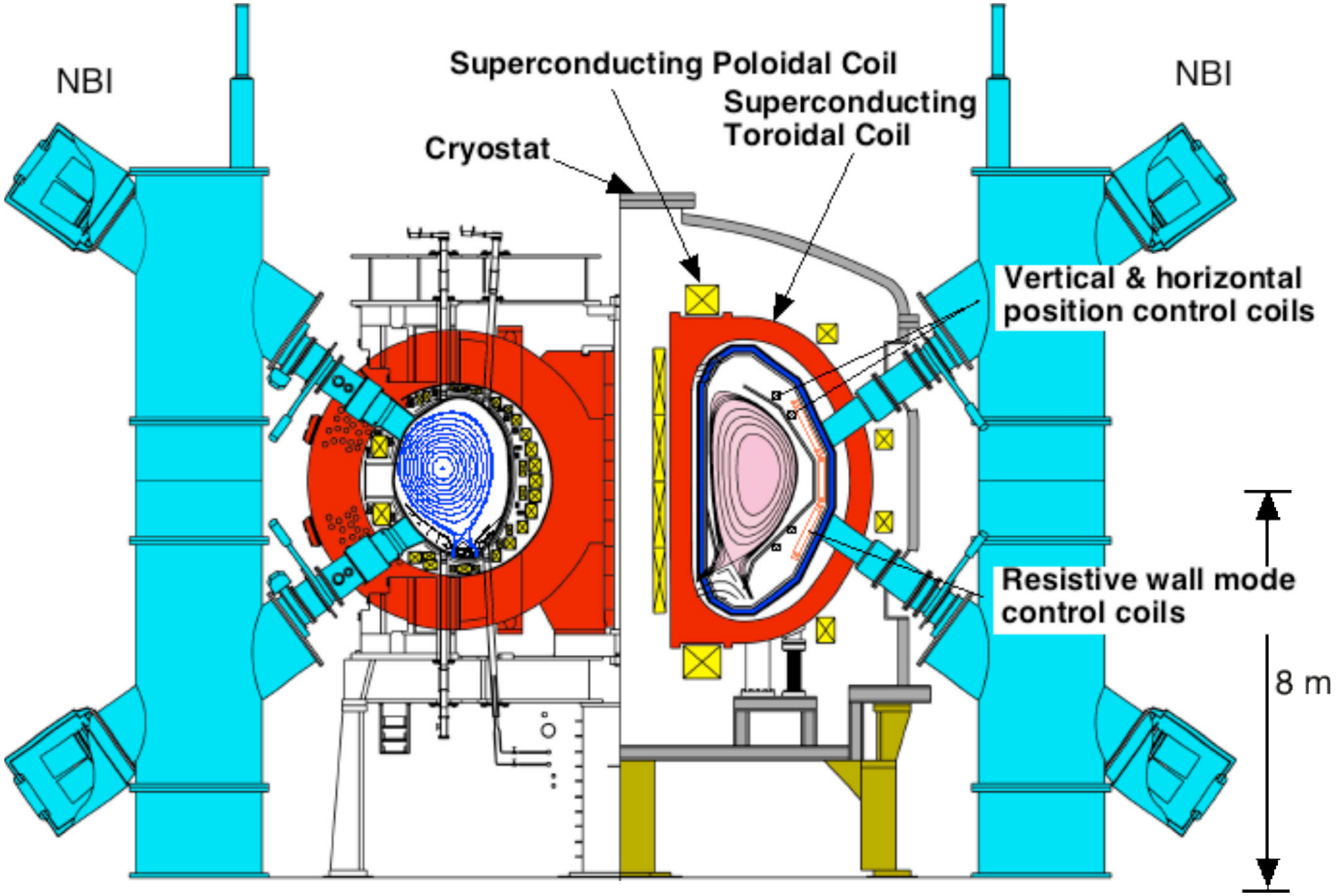
Profile control

Heat and particle control

W-shaped Divertor

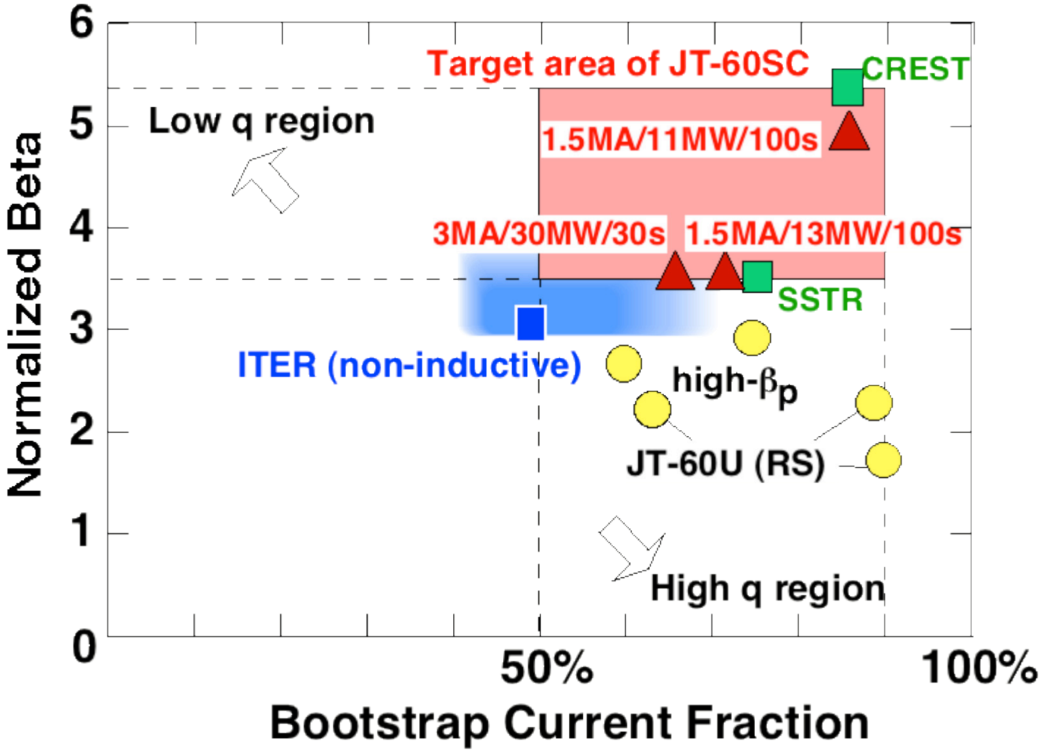
Modification of JT-60 to superconducting tokamak

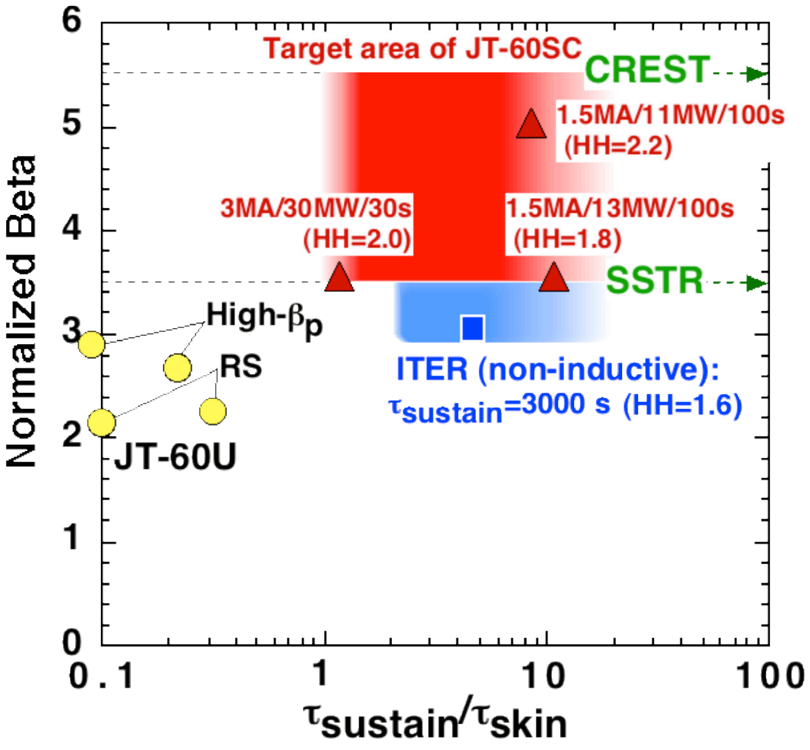
- **Objectives:** to realize high-beta steady-state operation in the use of reduced radio-activation ferritic steel in a collision-less regime.
- **Planning :** JT-60SC ⇒ “National centralized tokamak facility program”.



High beta steady state regime for JT-60SC

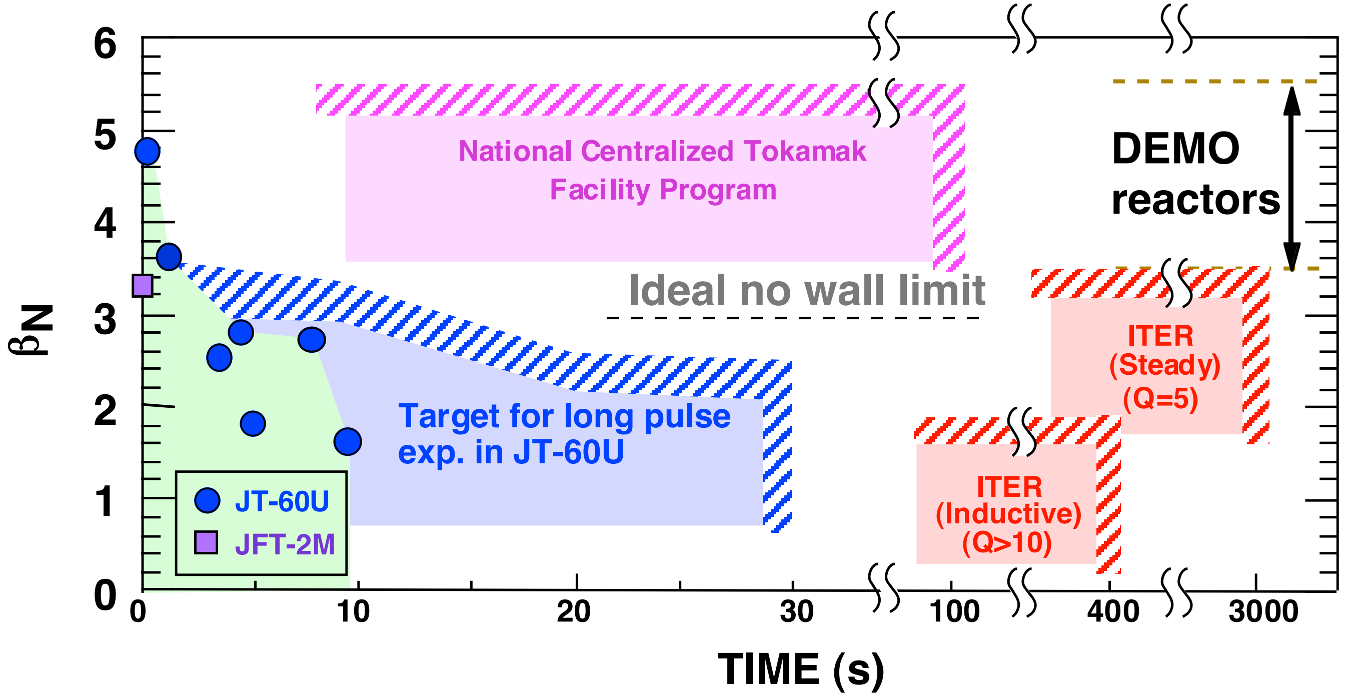
- The JT-60SC target area is compared with reactor designs and the data on full current drive advanced discharges in JT-60U





- Full current drive high-performance plasmas were achieved in JT-60U with HH_{y2}=1.3-2.3 for high-β_p and reversed shear discharges
- Operation scenarios in JT-60SC can be projected to the target area.

High beta steady state research regimes



- JT-60U will implement **long pulse experiments** from Dec. 2003;
  - Discharge duration:15 s (3 MA/4 T) ⇒ up to 65 s (1 MA/2.7 T)
  - Heating duration:10 s (32 MW) ⇒ up to 30 s (17 MW)
- The NCTFP (JT-60SC) heads for high beta steady state regime to establish control scheme of **self-organized plasmas with $\beta_N > \beta_N^{\text{no wall}}$, $\tau_{Dis}/\tau_{skin} \gg 1$ and $V_{loop}=0$**.

⇒**Self-consistent integration** of key performances and **its controlled sustainment** are highly challenging issue, but must be eventually accomplished.

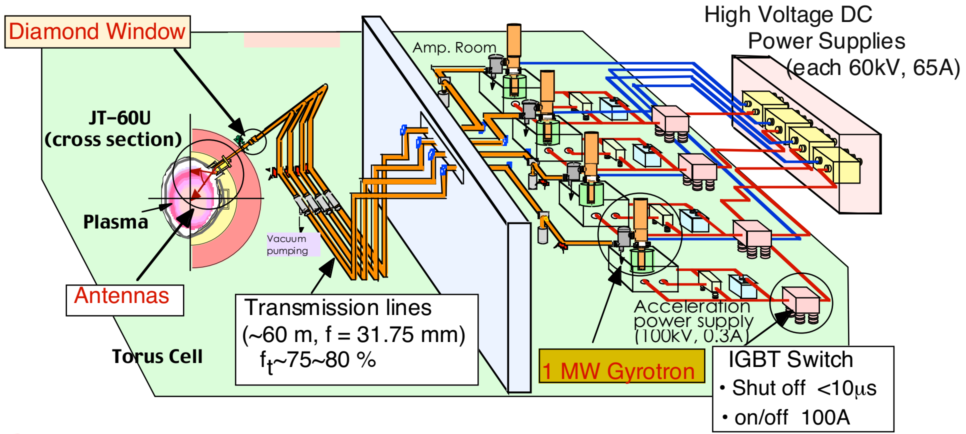
Neoclassical tearing mode

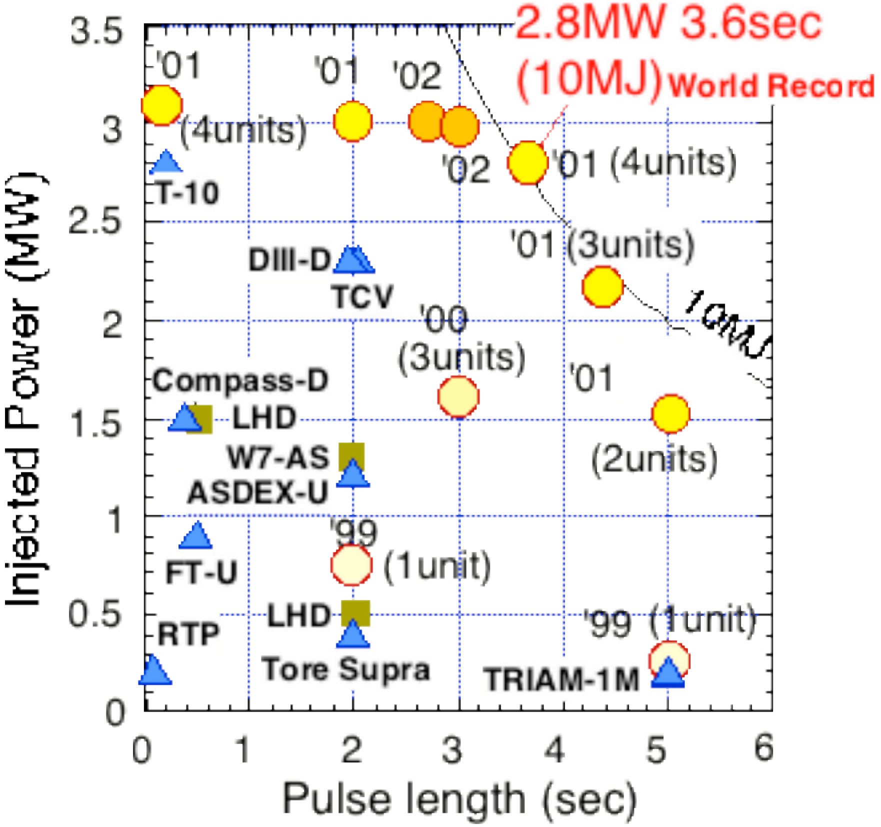
- Real-time NTM feedback control scheme
- Complete stabilization of NTM
- Late and early EC injection
- Application to JT-60SC
- Application to ITER

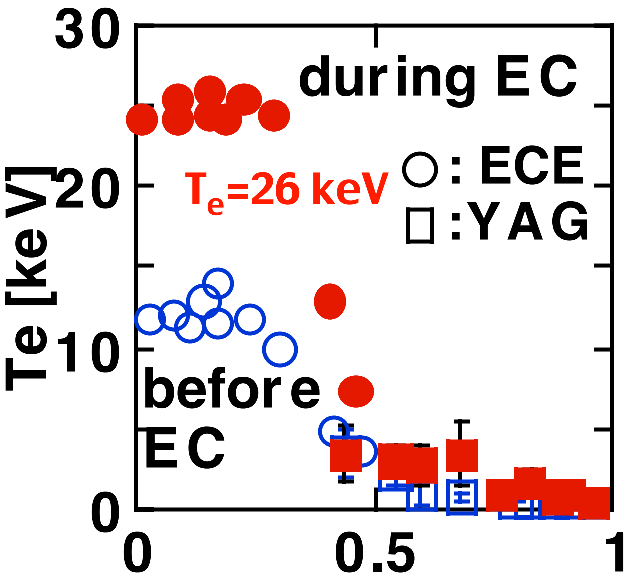
ECRF system enhancing
Electron heating and local current drive

- 4 units (two antennas) gyrotron
  -->10 MJ injection (2.8 MW/3.6 s)

- Toroidal/Poloidal beam scan
  --> ECCD, NTM control

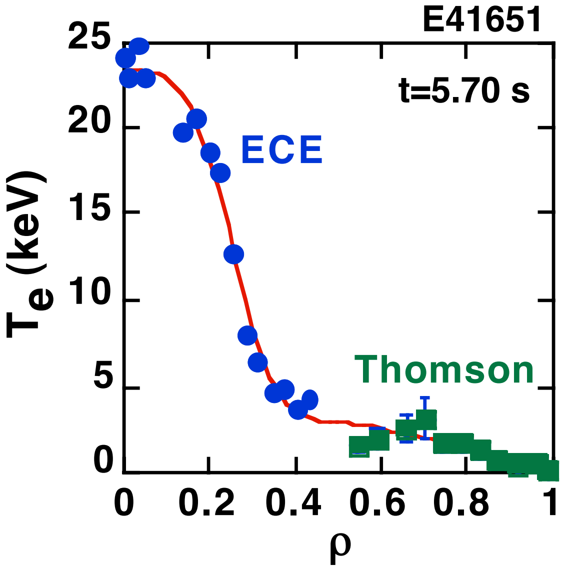


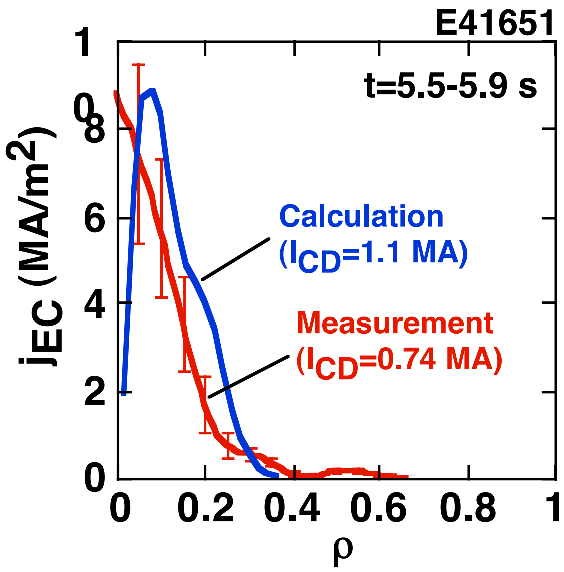


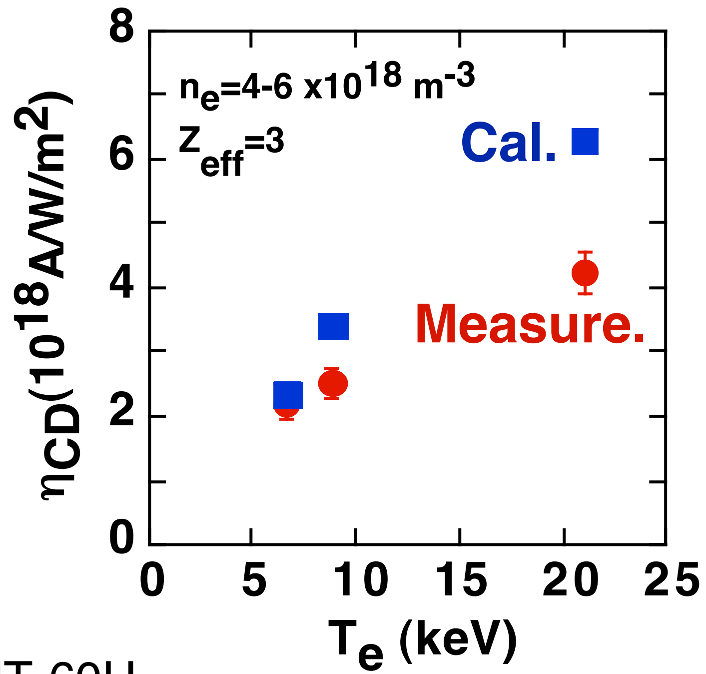


P_{LH}=1.9 MW, P_{EC}=2.9 MW, n_e~0.5×10^{19} m^{-3}

ECCD in a hot electron regime with RS





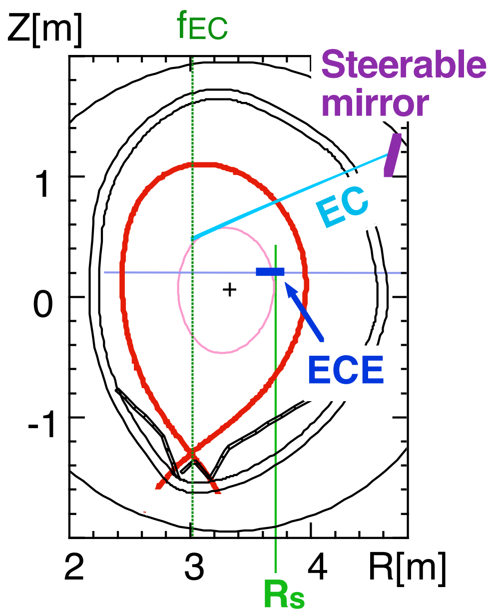


- 110GHz EC system with 4 gyrotrons are used in JT-60U.
- Combination of ECH and ECCD (2.9 MW) produced $T_e(0)$=23 keV for 0.8 s.
  ⇒ T_e range for ECCD evaluation has extended by a factor of 3 from ~7 keV.

- Measured ECCD current reached I_{CD}=0.74MA while the calculation is 1.1 MA.
  ⇒ Measured η_{CD} =4.2 x 10^{18}A/W/m^2 at T_e = 21 keV at the CD location.
- Possible cause of discrepancy is negative $E_{//}$ inductively induced and non-linear effects, which are not included in the linear Fokker-Planck code analysis.

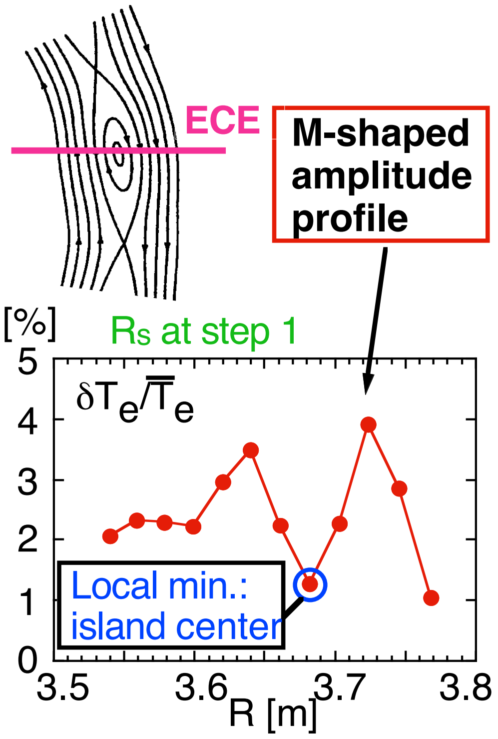
Real-time NTM feedback stabilization system

- NTM stabilization is required for sustaining high beta plasmas.
- Mode location can be changed in time ⇒ Real-time NTM FB stabilization
- Complete NTM stabilization was demonstrated using the real-time NTM FB stabilization system in JT-60U.



Real-time calculation of plasma shape with a given q-profile

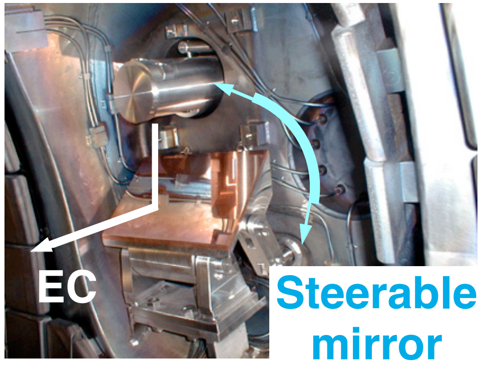
Rough estimation



M-shaped amplitude profile

Local min.: island center

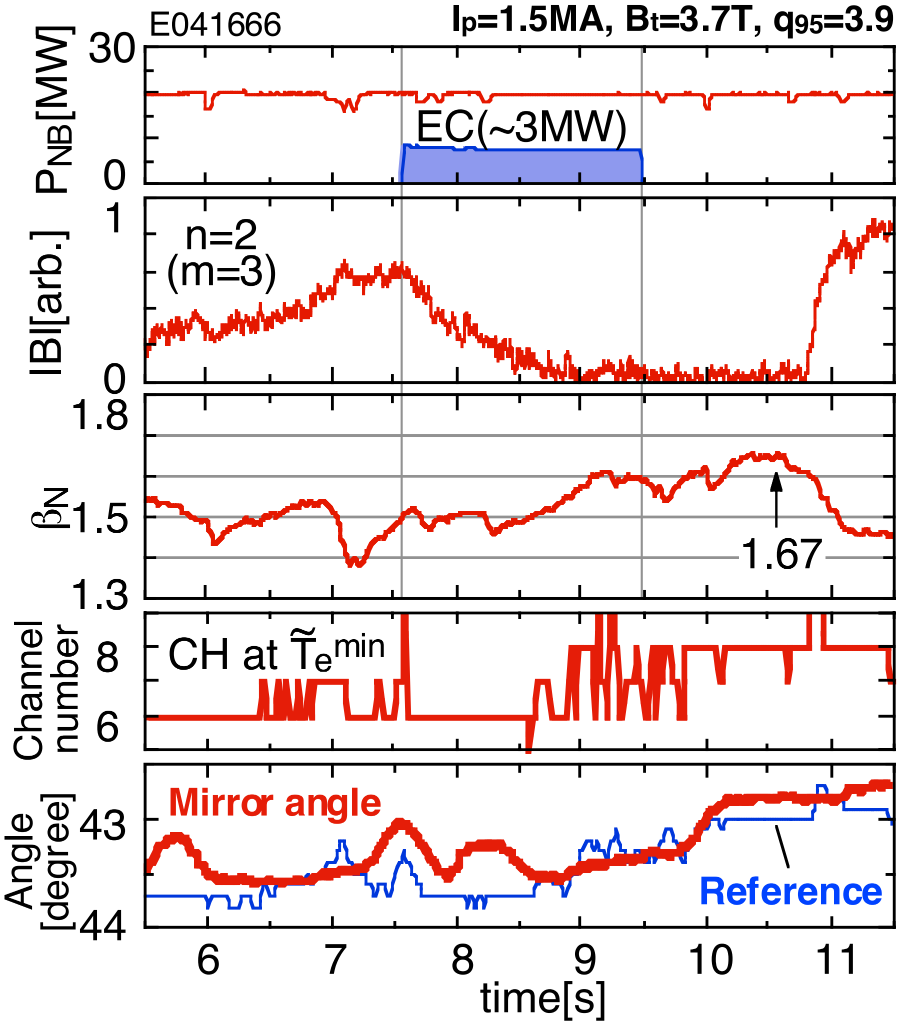
Fine tuning

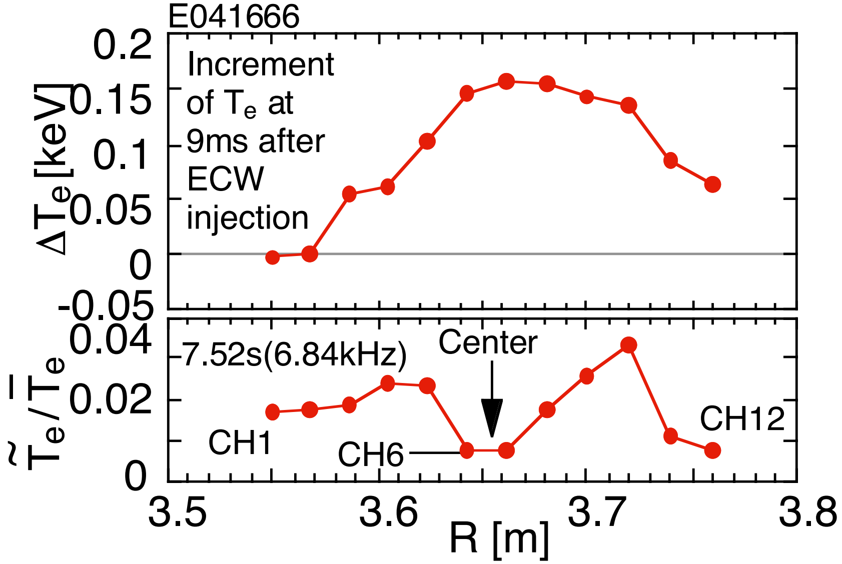


- Calculation: 10ms
- Mirror scan: $\Delta R_{dep}/\Delta t \sim 10$cm/s

EC mirror steering

Complete stabilization of m/n=3/2 NTM with real-time feedback control system

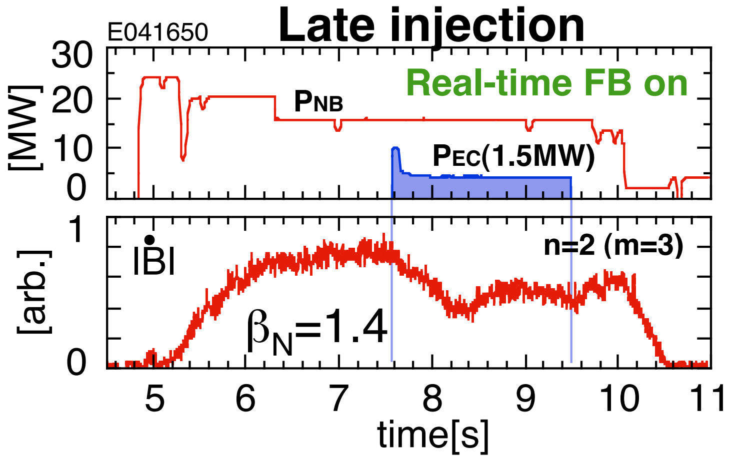


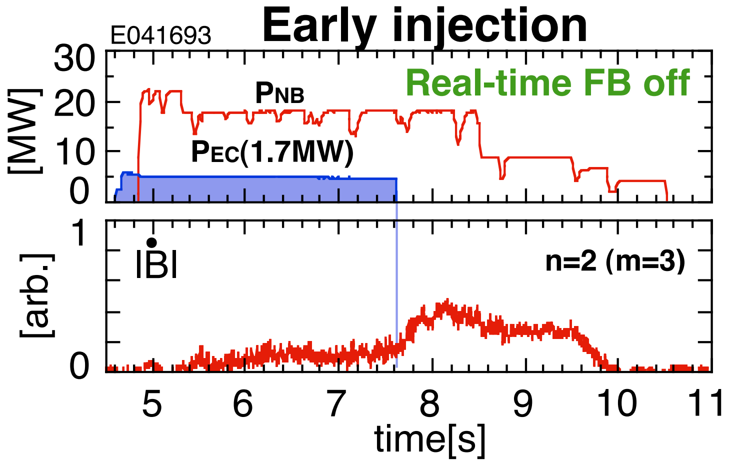


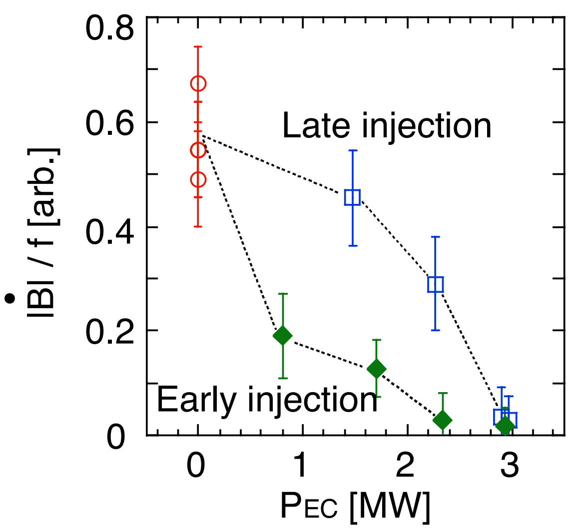
- β_N increased by the stabilization, and even after the EC turn-off
⇒Confinement improvement:
HH_{98y2}: 1.0 ⇒1.1

A. Isayama et al., Nucl. Fusion 43 (2003)1272

Effective NTM suppression control



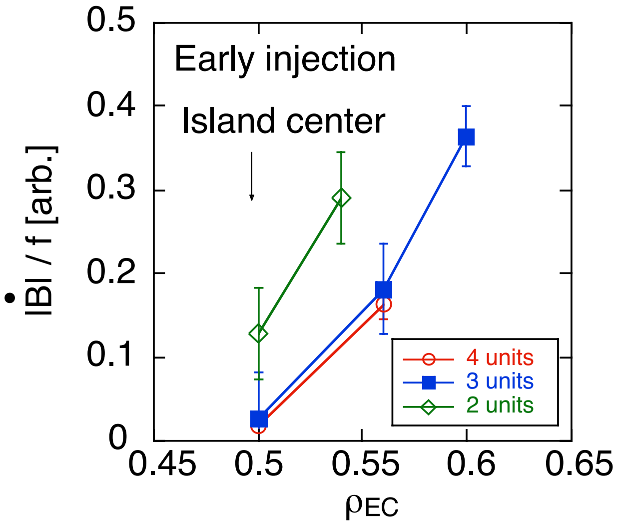




Effectiveness of NTM suppression

Injection timing

Injection location



- Early injection is effective.
- Center injection is effective.

⇒ Suppression control can be effectively made for saving EC power by using early and island-center injection.

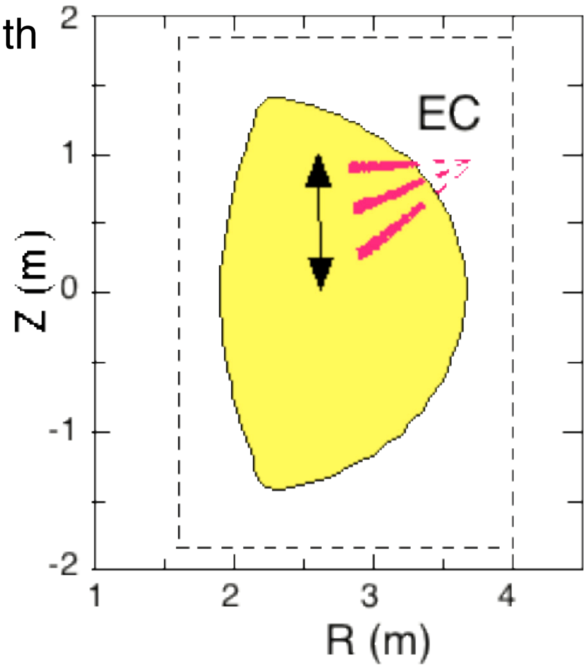
NTM stabilization by ECCD for JT-60SC

- 1.5D transport code with enhanced diffusivities within island width
- Modified Rutherford equation

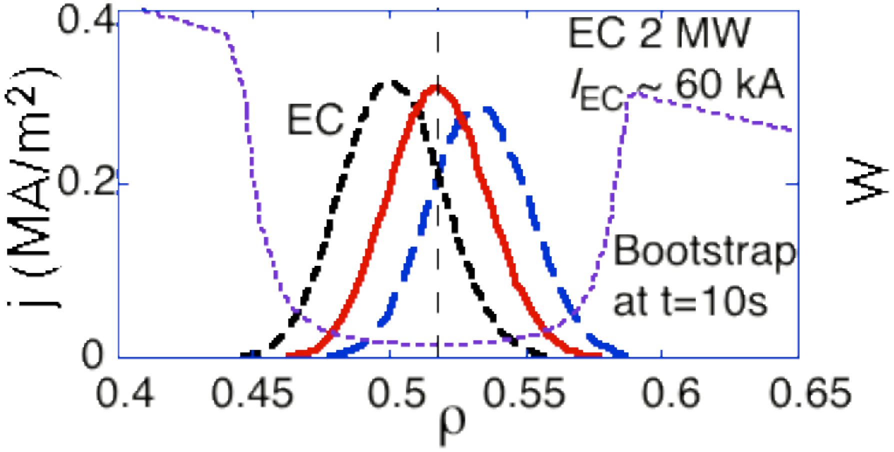
$$\frac{\mu_0}{\eta}\frac{dW}{dt} = \underbrace{k_1(\Delta' - \alpha W)\langle|\nabla\rho|^2\rangle}_{\text{Classical}} + \underbrace{k_2\mu_0 L_q j_{BS}\left\langle\frac{|\nabla\rho|}{B_p}\right\rangle\frac{W}{W^2+W_d^2}}_{\text{Bootstrap}}$$

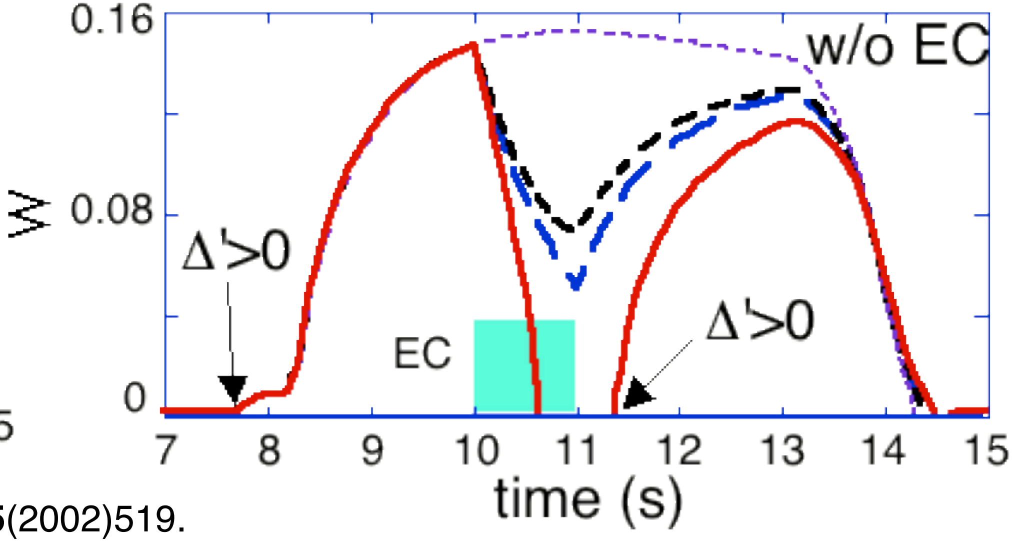
$$\underbrace{-k_3\varepsilon_s^2\beta_p\frac{L_q^2}{\rho_s L_p}\left(1-\frac{1}{q^2}\right)\langle|\nabla\rho|^2\rangle\frac{1}{W}}_{\text{GGJ}} \underbrace{- k_4\varepsilon_s^{1.5}\beta_p\left(\frac{\rho_{pi}L_q}{L_p}\right)^2\langle|\nabla\rho|^4\rangle\frac{W}{W^4+W_p^4}}_{\text{Polarization}}$$

$$\underbrace{-k_5\mu_0\frac{L_q}{\rho_s}\left\langle\frac{|\nabla\rho|}{B_p}\right\rangle\eta_{EC}\bar{j}_{EC}\frac{1}{W^2}}_{\text{EC}}$$



- Relativistic Fokker-Planck eq. & ray tracing method for fundamental O-mode EC wave of 110 GHz





N.Hayashi, et al., J.Plasma Fusion Res. SERIES **5**(2002)519.

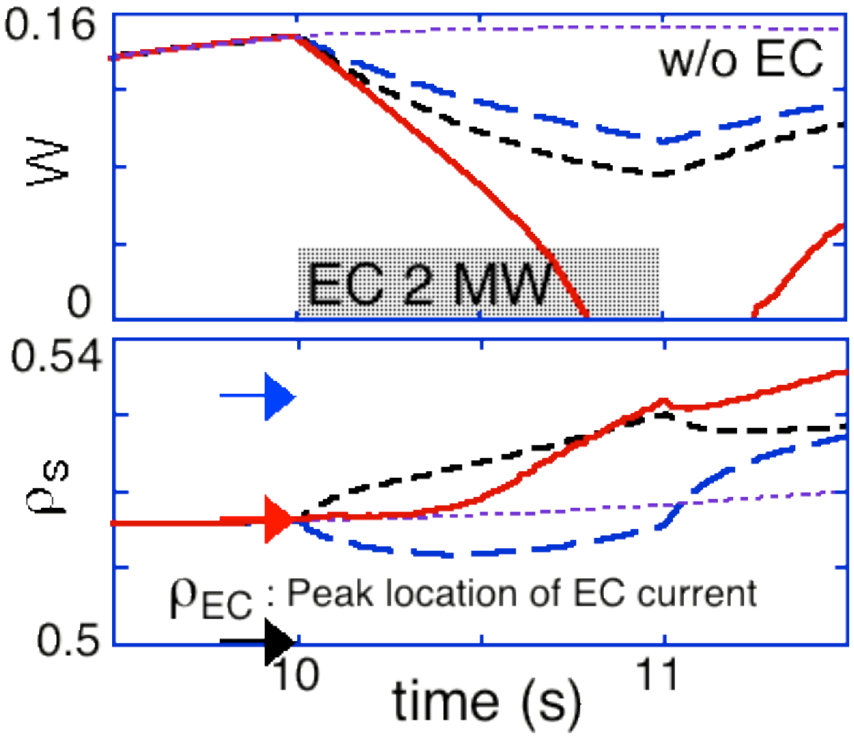
Simulation on NTM stabilization by ECCD for JT-60SC

- EC current moves the rational surface ρ_s through the background current profile modification without real time FB control.

⇨ EC current profile becomes further off-center.

⇨ Decreasing the stabilizing efficiency of EC.

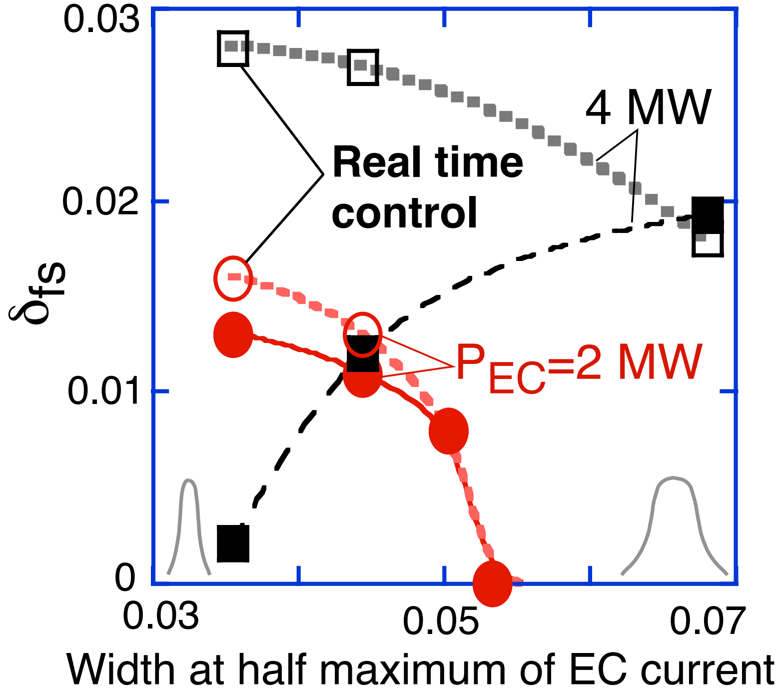
  - High EC current by high EC power induces larger movement of ρ_s.



N.Hayashi, et al., J.Plasma Fusion Res. SERIES **5**(2002)519.

Conditions of full stabilization

- EC current located in the range of $\delta_{fs} = \rho_{EC}^{+} - \rho_{EC}^{-}$ can fully stabilize NTM.
- Low EC current and peaked EC current profile are effective in the full stabilization.
- Real time control of the EC current location enlarges δ_{fs} especially for high EC power.



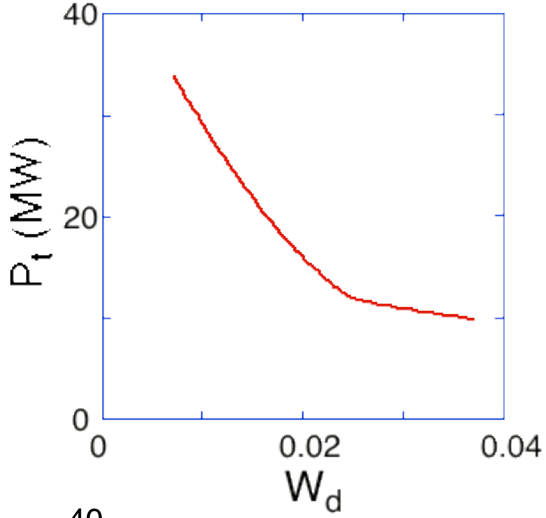
Evaluation of ECCD power necessary for real time NTM feedback stabilization on ITER

ECCD power necessary for the NTM stabilization depends much on some parameters in modified Rutherford equation.

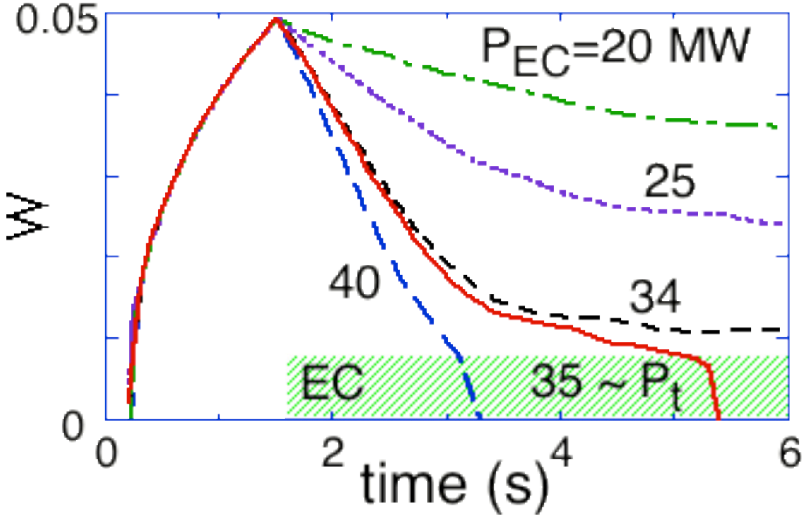
$$\frac{\mu_0}{\eta}\frac{dW}{dt} = \underbrace{k_1\Delta'(W)\left\langle|\nabla\rho|^2\right\rangle}_{\text{Classical}} \underbrace{+ k_2\mu_0 L_q j_{BS}\left\langle\frac{|\nabla\rho|}{B_p}\right\rangle\frac{W}{W^2+W_d^2}}_{\text{Bootstrap}} \underbrace{- k_3\varepsilon_s^2\beta_p\frac{L_q^2}{\rho_s L_p}\left(1-\frac{1}{q^2}\right)\left\langle|\nabla\rho|^2\right\rangle\frac{1}{W}}_{\text{GGJ}}$$

$$\underbrace{- k_4\varepsilon_s^{1.5}\beta_p\left(\frac{\rho_{pi}L_q}{L_p}\right)^2\left\langle|\nabla\rho|^2\right\rangle\frac{1}{W^3}}_{\text{Polarization}} \underbrace{- k_5\mu_0\frac{L_q}{\rho_s}\left\langle\frac{|\nabla\rho|}{B_p}\right\rangle f\eta_{EC}\bar{j}_{EC}\frac{1}{W^2}}_{\text{EC}}$$

Parameter dependence

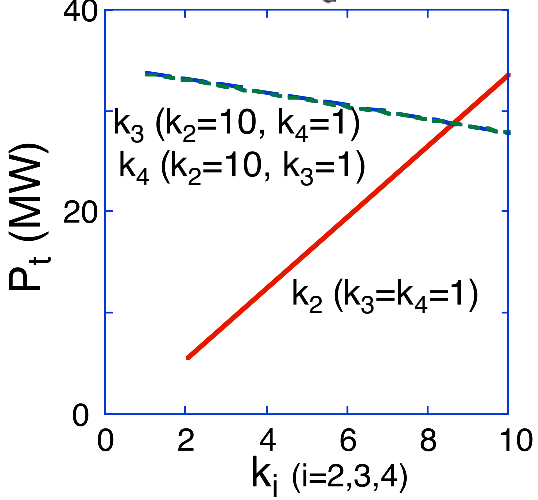


ITER inductive scenario #2 (k_2=10, k_3=k_4=1)



$P_{EC} > P_t$: Condition for full stabilization

Dependence of P_t on W_d and k_2 is strong.



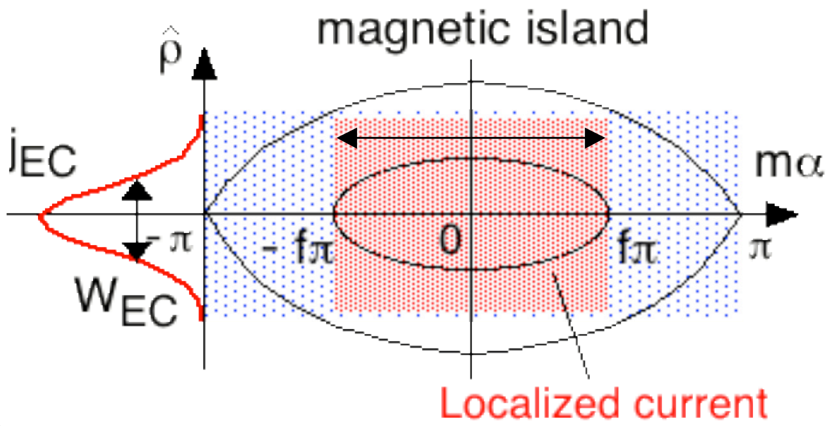
N.Hayashi, et al., submitted to Nucl. Fusion.

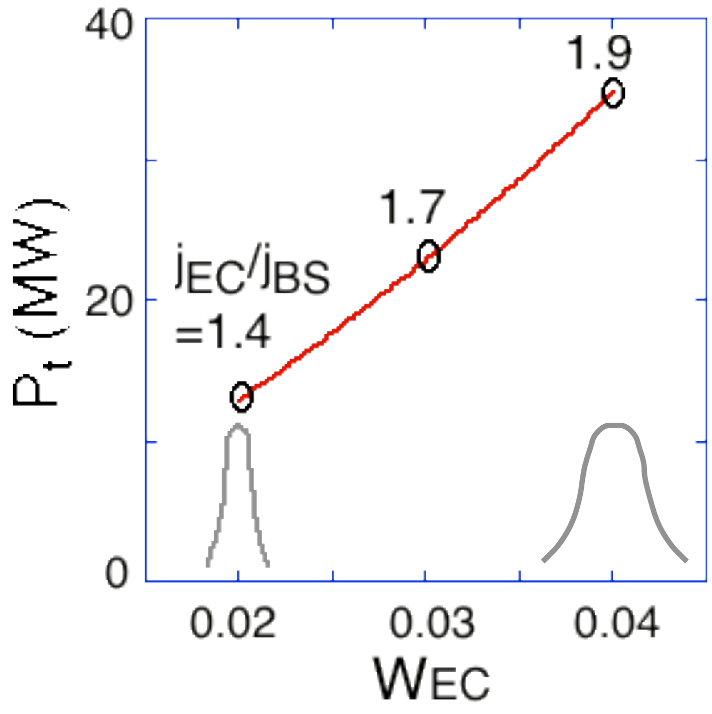
Evaluation of ECCD power necessary for NTM stabilization on ITER

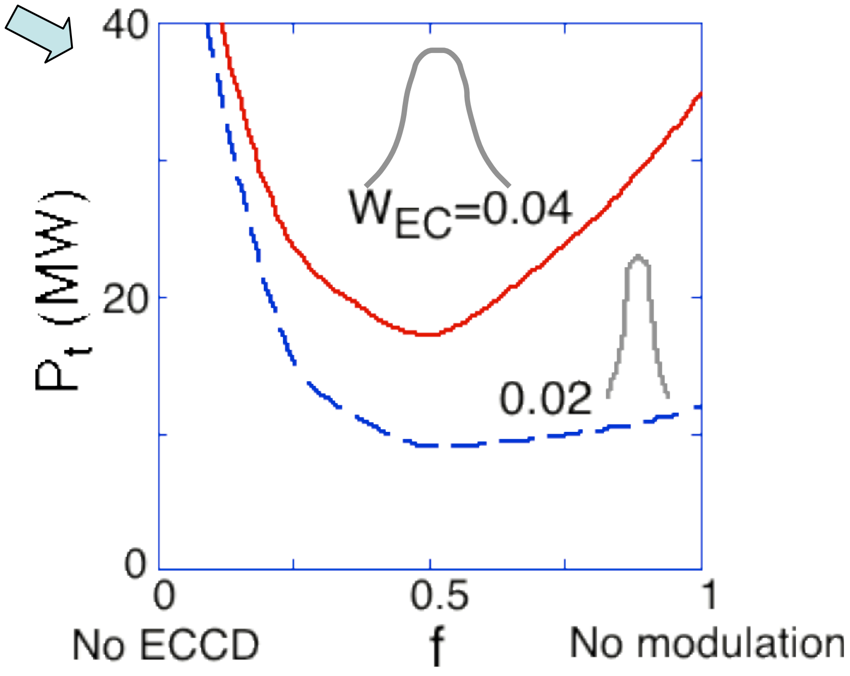
- Effects of the EC current peakedness and the EC power modulation on P_t are investigated.

- When the width of EC current profile W_{EC} becomes half, P_t is reduced to half or less.

- EC power modulation is inessential for P_t reduction if the EC current can be peaked.







N.Hayashi, et al., submitted to Nucl. Fusion.

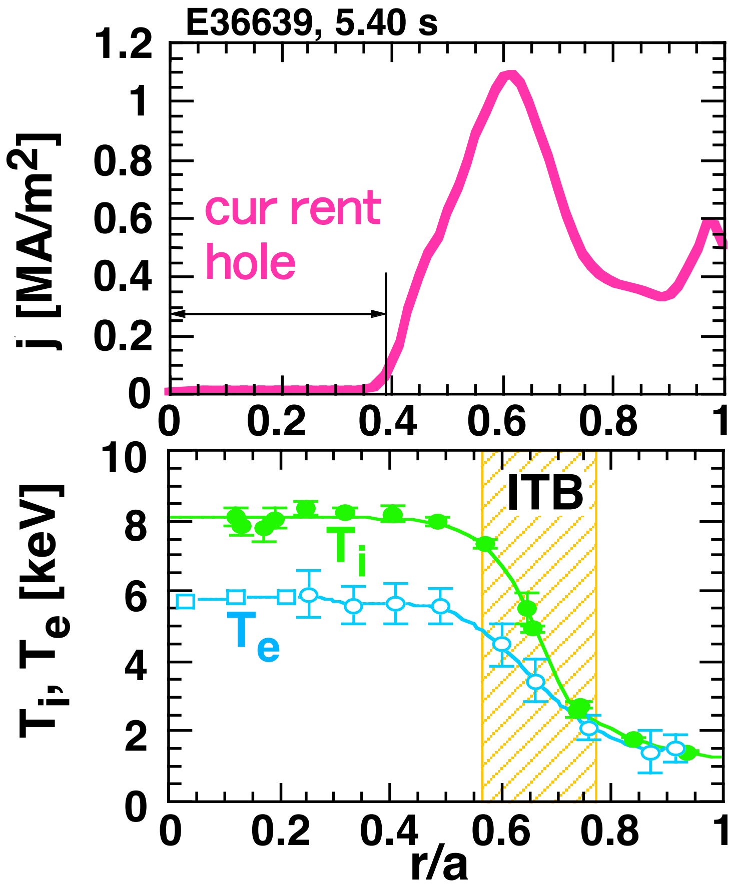
Kink-ballooning mode for current hole plasmas

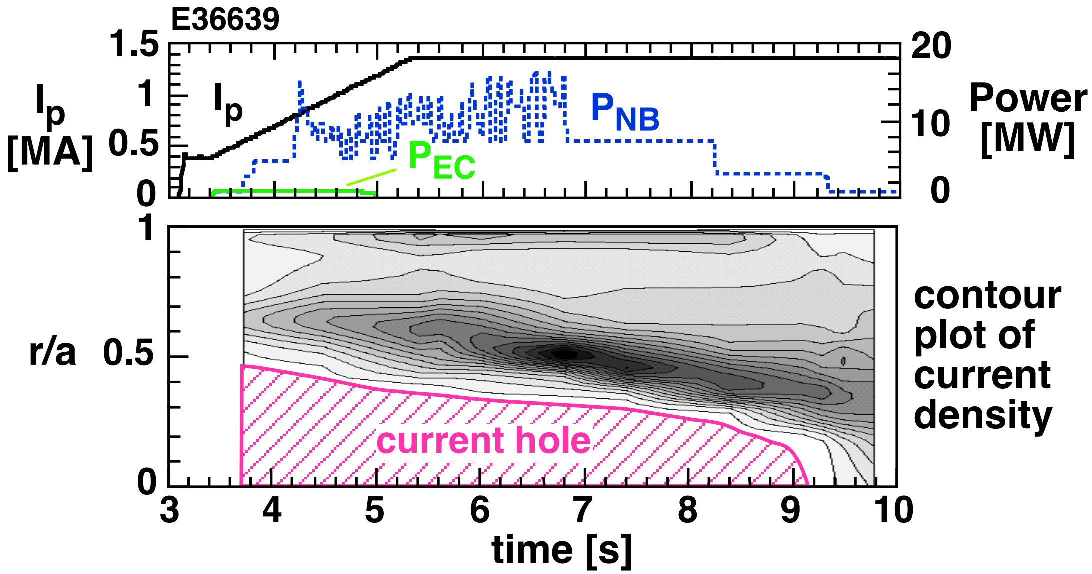
- **Current hole**

- **Very high bootstrap current plasma with a current hole**

- **Profile control and wall stabilization effects**

Discovery of Current Hole

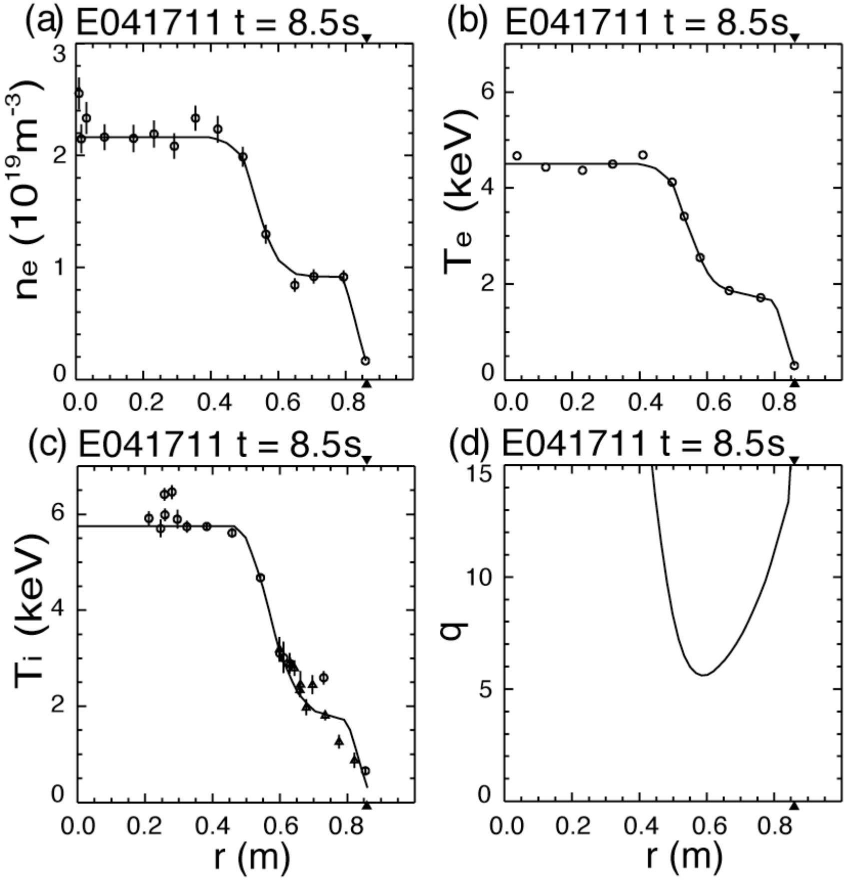


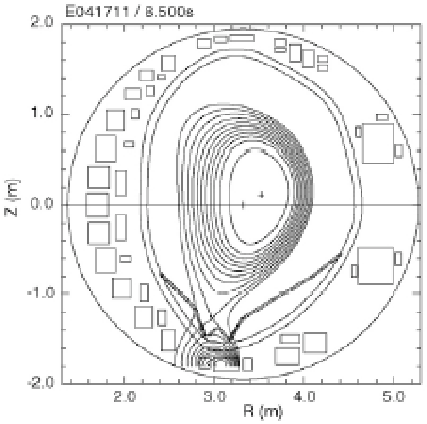


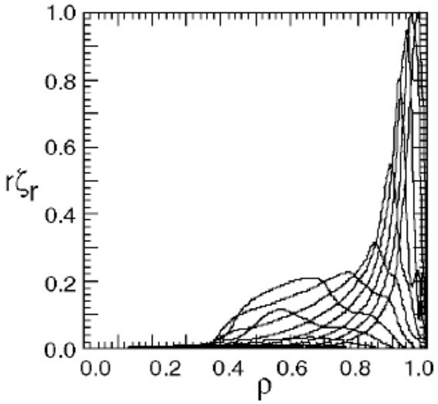
- Widely extends to 40% of minor radius.
- Persists for several seconds without any global instabilities.

- A region where almost no toroidal current exists, current hole, is formed in the center of a reversed shear plasma.
- Current hole coincides with the growth of bootstrap current in ITB.

Production of BSC-dominant current hole plasma

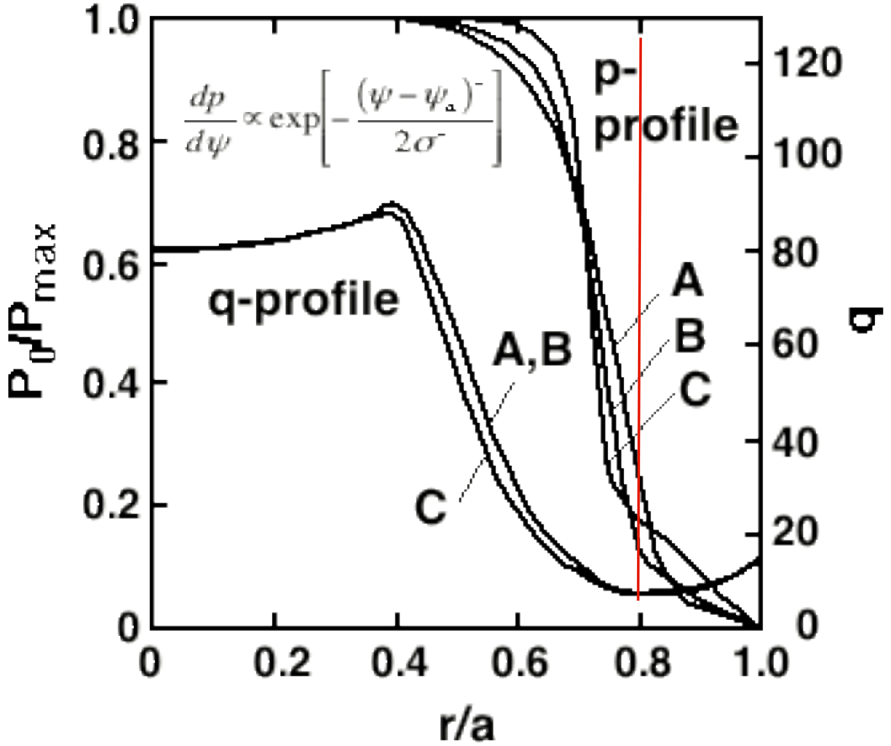


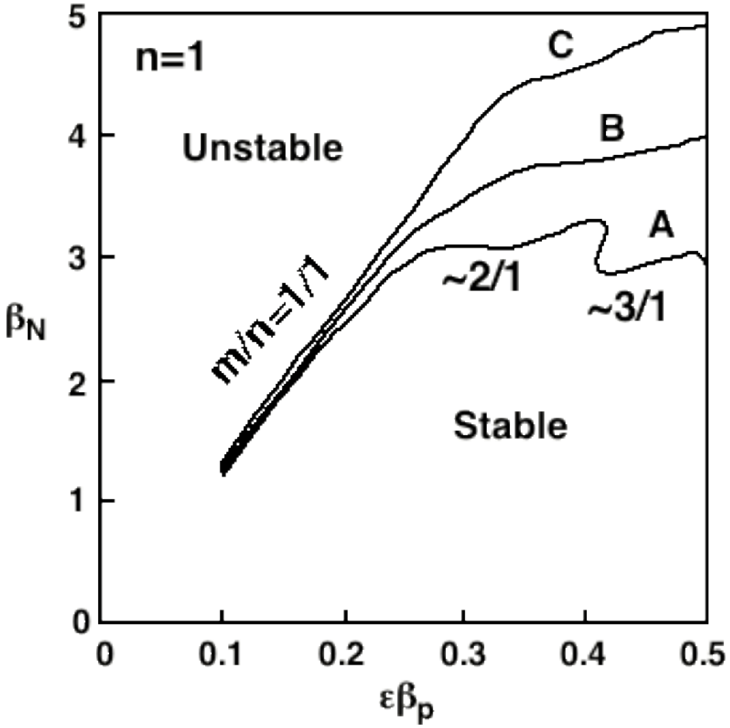




- 90% BSC plasma with current hole was achieved in CS-less current start-up.
- HH_{y2}=1.6, n/n_{GW}=0.5, β_N=1.6, $\varepsilon\beta_p$=1.0
- Collapse at ideal limit without wall ⇒ Stabilization is an important issue.

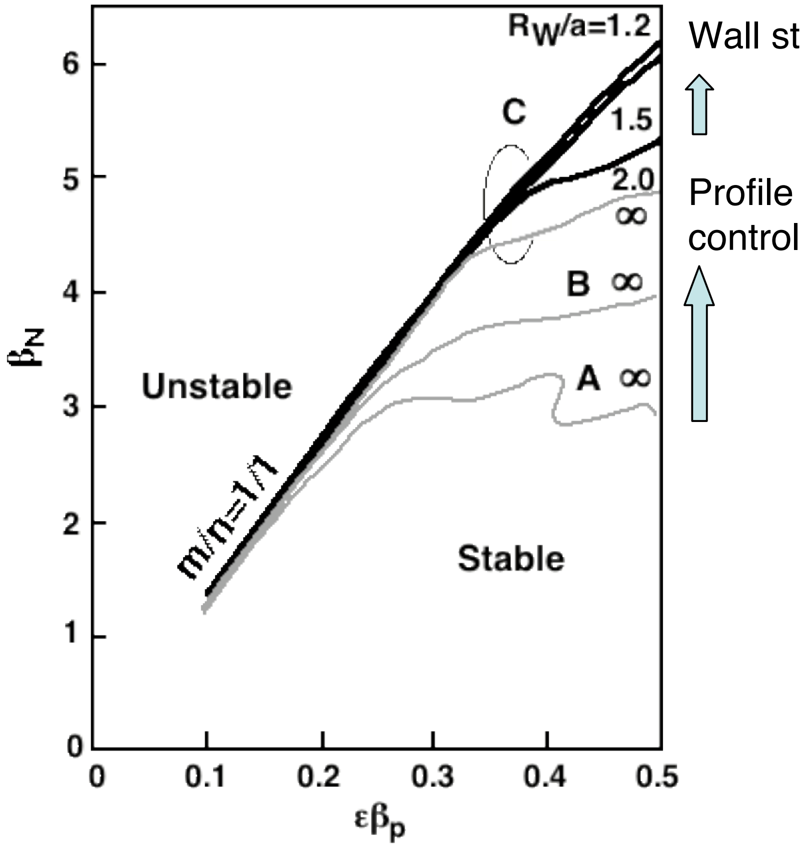
Stability limit improved by profile control for current hole plasmas

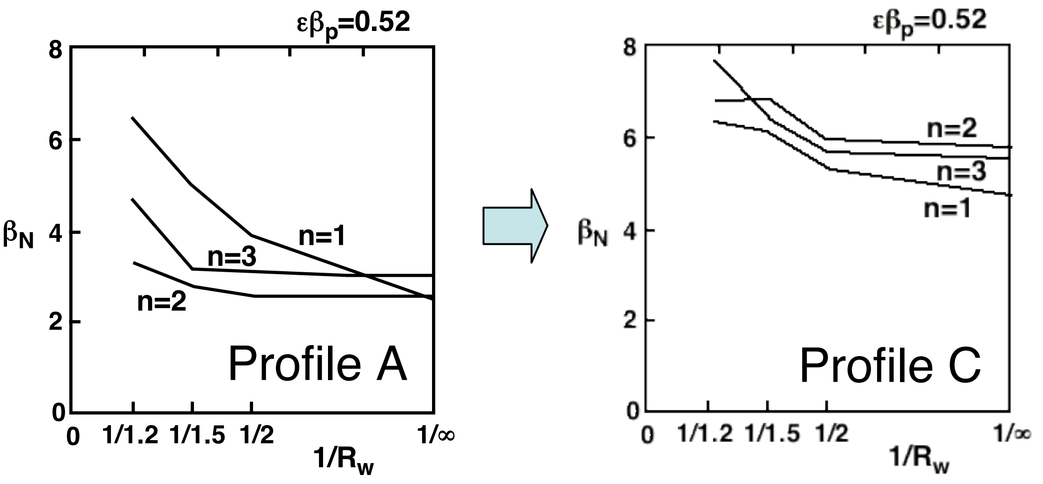




- MHD stability analysis for three typical profiles like observed profiles in JT-60U;
  - From A to C, ∇p becomes large and shifted to the inner side.
  - The q-profile of C is modulated in the large ∇p region.
- Beta limits due to n=1 kink-ballooning modes are significantly improved by adjusting the pressure profile.
- The stability boundary does not clearly depend on the single m/n mode due to mode coupling.

Effective wall stabilization for current hole plasmas





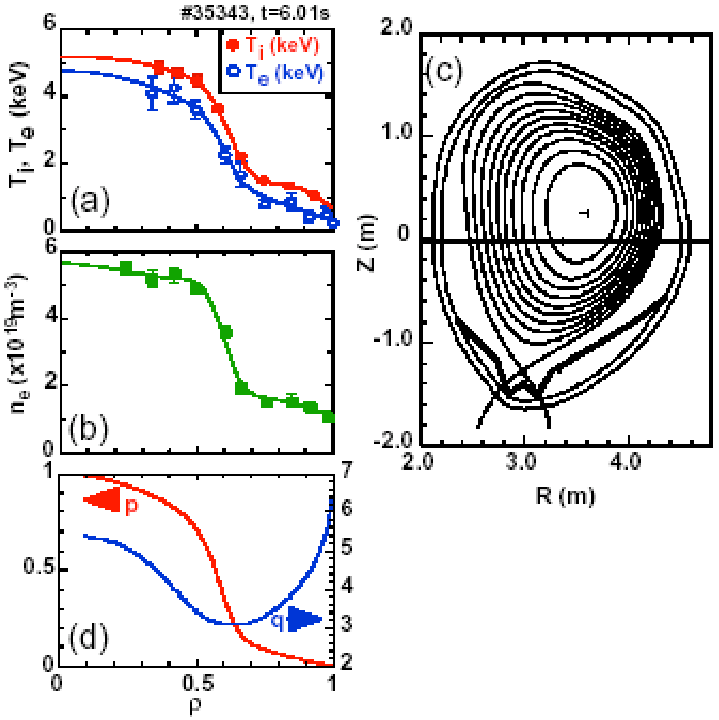
- High n-modes are significantly improved wall stabilization in changing from A to C.

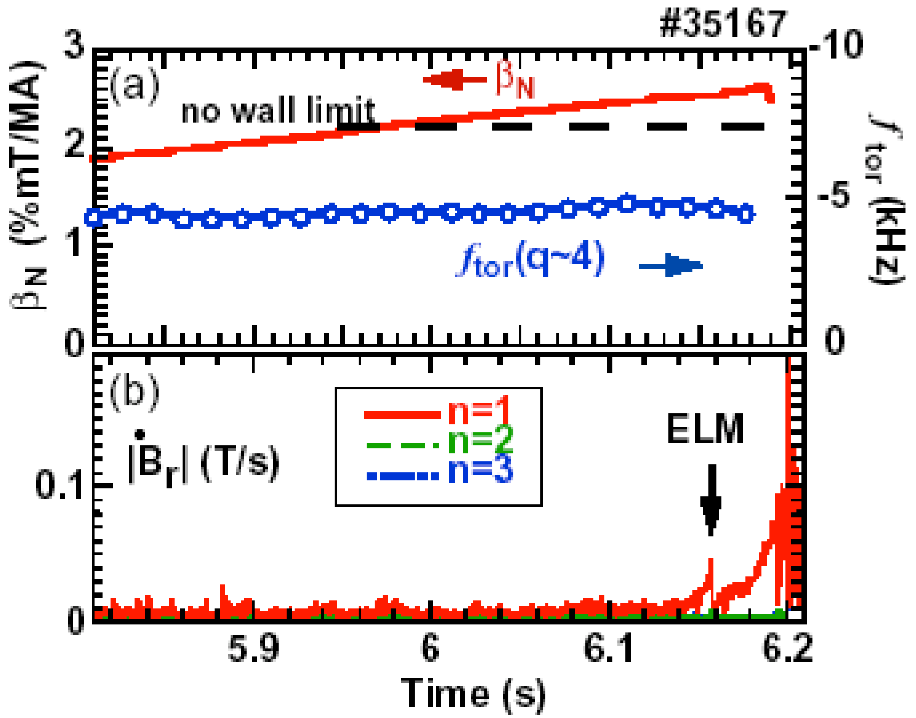
- Due to wall stabilization effect, further improvement of the beta limit is obtained in which higher n-modes are also improved.
- There is a possibility to reach a very high beta region up to β_N~6 with the current hole by profile control and wall stabilization.
- It should be noted that the mode localized near the inner rational surface due to the high pressure gradient may emerge.

Resistive wall mode

- Observation of RWM in JT-60U
- Ideal beta limit and RWM control tool for JT-60SC
- Stability window for RWM
- Ferromagnetic wall effects on stability window and beta limit

Observation of RWM in JT-60U

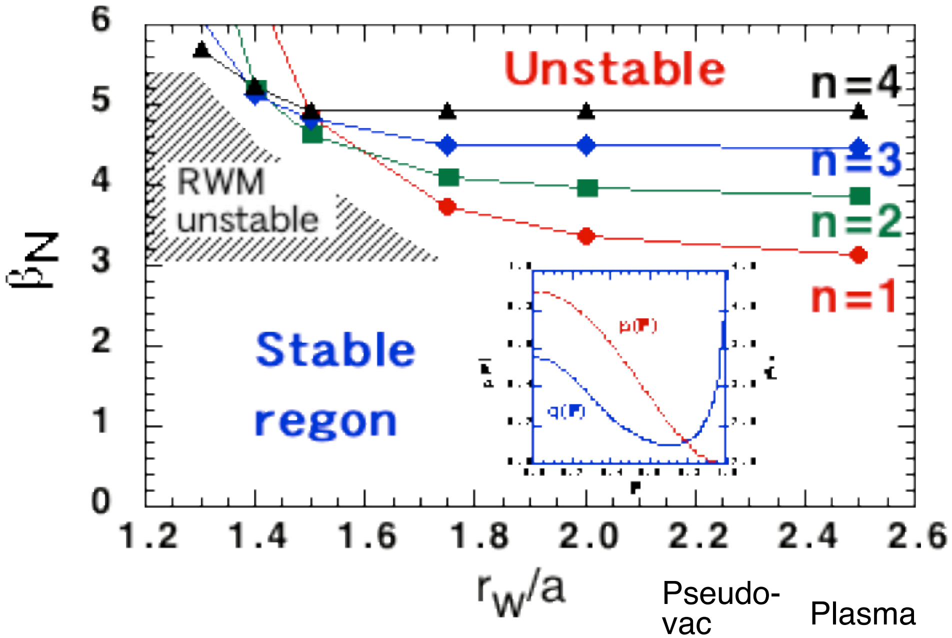




- High β discharges exceeding a no wall limit for ideal low-n kink-ballooning modes are obtained in reversed shear discharges with $r_W/a < 1.3$.

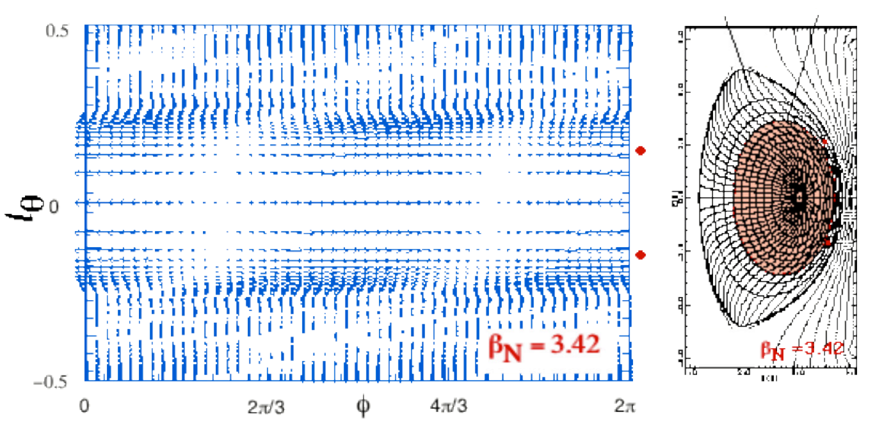
  ⇒RWMs associated with n=1 modes are identified.
- No significant slowing down is observed on f_{tor} near the outer q = 4 surfaces before the growth of the n = 1 mode. Change of f_{tor} during the growth of the n = 1 mode is not measured within the time resolution.
- It is suggested that the toroidal rotation frequency f_{tor}=4 kHz ($\sim10^{-2} V_A/(2\pi R)$) is not sufficient for stabilization of the RWMs.

Ideal stability and control tool in JT-60SC

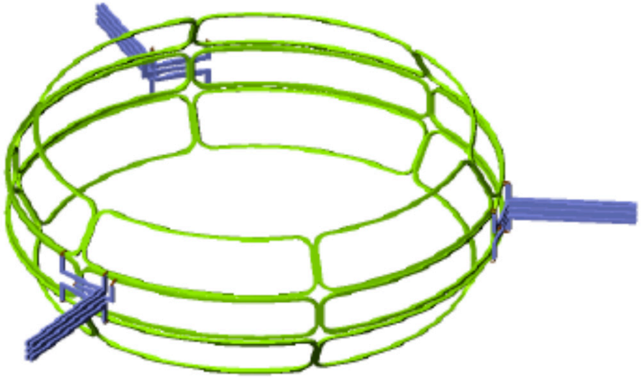


- ERATO-J code analysis shows that ideal kink-ballooning modes can be stabilized up to β_N~5.5 with ideal wall at $r_{wall}/a<1.3$.

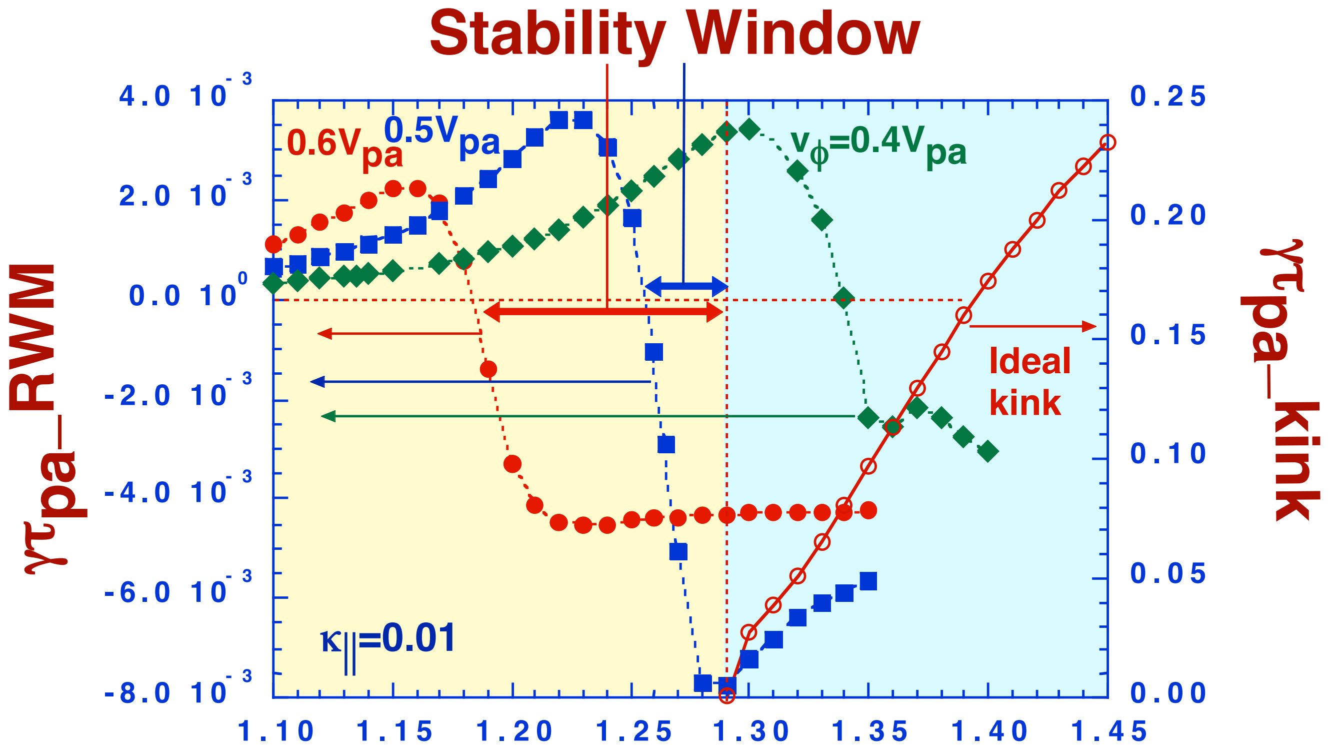
- Resistive wall modes can appear above β_N~3, where 18 sector coils placed in the vacuum vessel are used for suppression.



Eddy current pattern in the resistive wall induced by RWM



Stability window of RWM for a circular tokamak of A=3



- **Parameters**

Ip=1.0[MA], Bt=1.5[T], q_0/q_{surf} =1.85/3.44,
A=(R/a=3/1=) 3, β_N=3.04, β_t=2.09 [%]
κ=1.1 , δ=0.05, $l_i(3)$=0.6, p_0/<p>=2.4

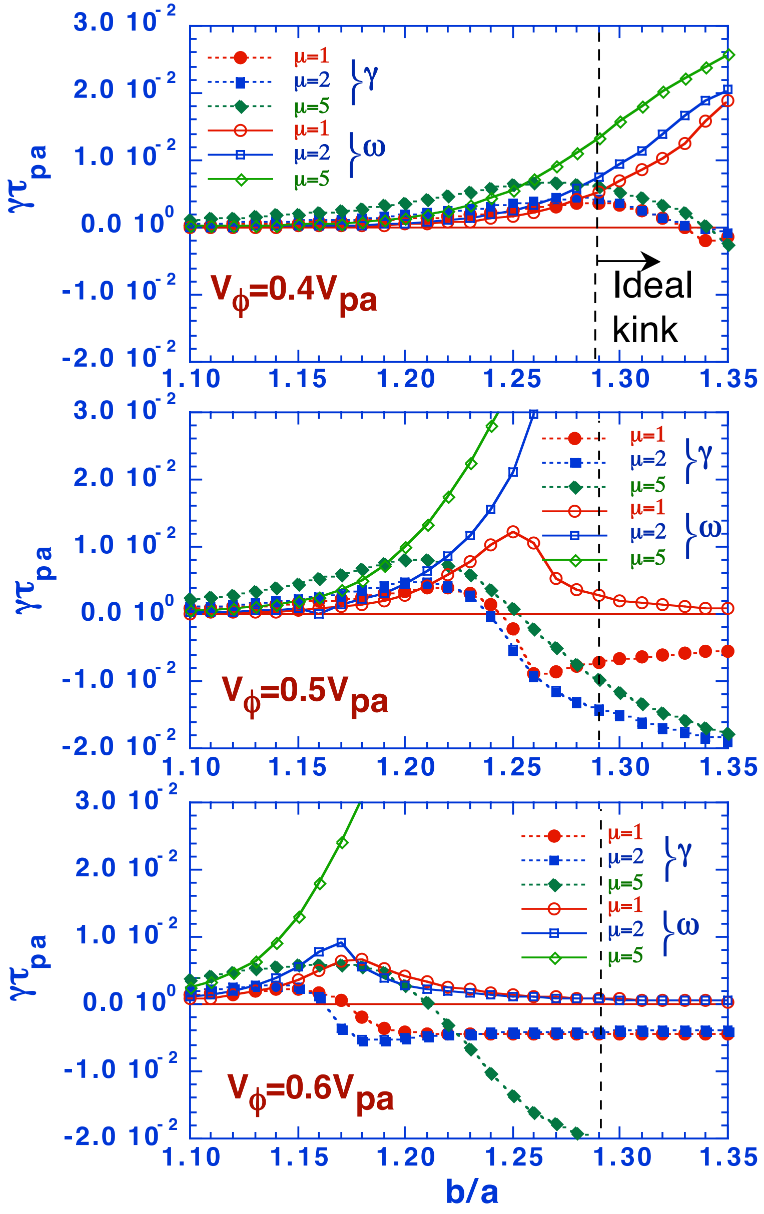
kll : strength of saund wave damping term

- An circular equilibrium with aspect ratio 3 is used with the effect of sound wave damping.
- Stability windows are opened for the toroidal rotation greater than 0.5 V_{pa}.

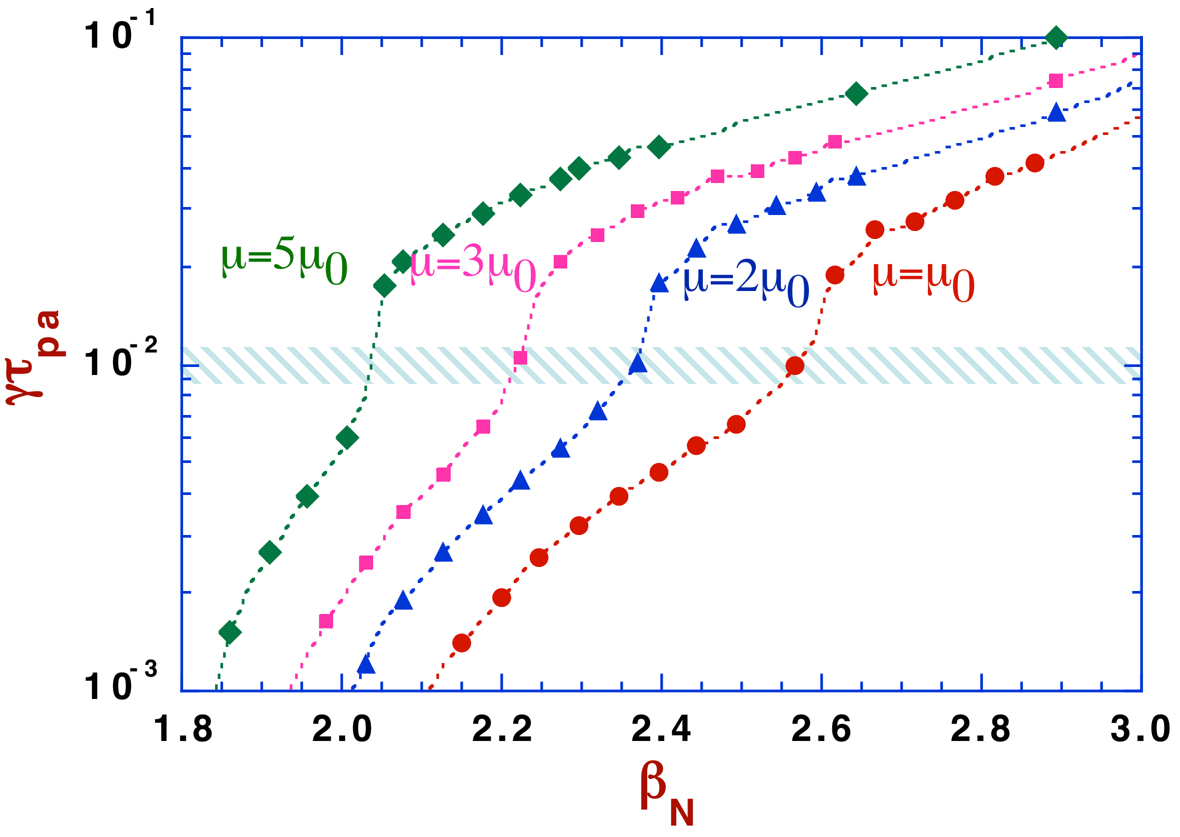
Ferromagnetic wall effects on stability window

- The stability window is found to be opened with increasing the toroidal uniform plasma rotation even considering permeability effect.
- The stability window tends to be reduced with increasing relative permeability, but become wider with the rotation velocity.
- It should be noted that the mode rotation frequency tends to become higher with permeability, which is a different feature from the case without permeability effect.

⇒ Increasing the importance of phase control for RWM stabilization with ferritic steel wall.



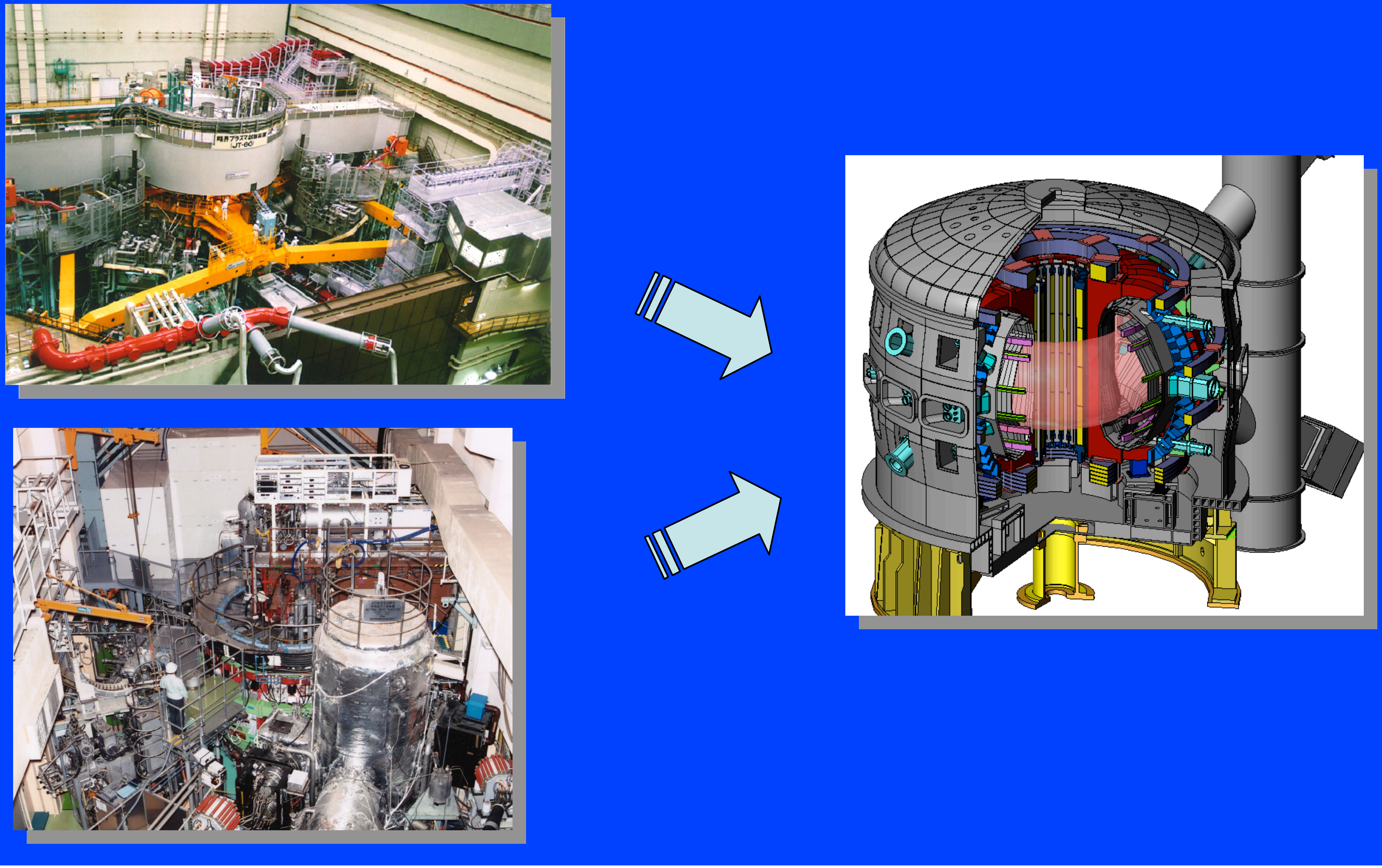
Reduction of the critical beta due to ferromagnetic wall effect



- Due to the permeability effect, the critical beta is reduced by ~8% $\mu=2\mu_0$ and ~20 % for $\mu=5\mu_0$, respectively; μ_s~1.6 in JT-60SC.
- The reduction is estimated at transition region from RWM to kink mode : $\gamma\tau_{pa}\approx10^{-2}$

Coming experiments for MHD control

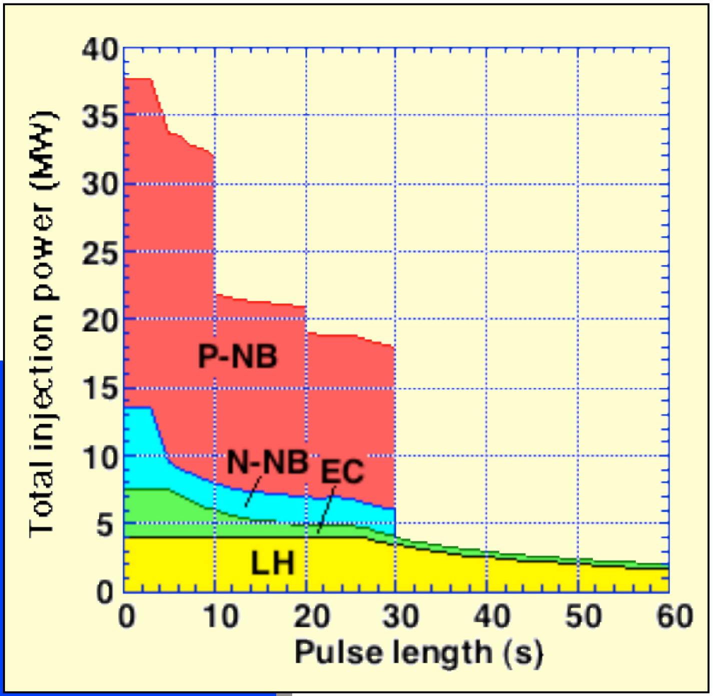
- JT-60 long pulse experiment
- JFT-2M wall stabilization experiment



Long pulse experiment planned in JT-60U

In the next campaign from Dec. 2003,

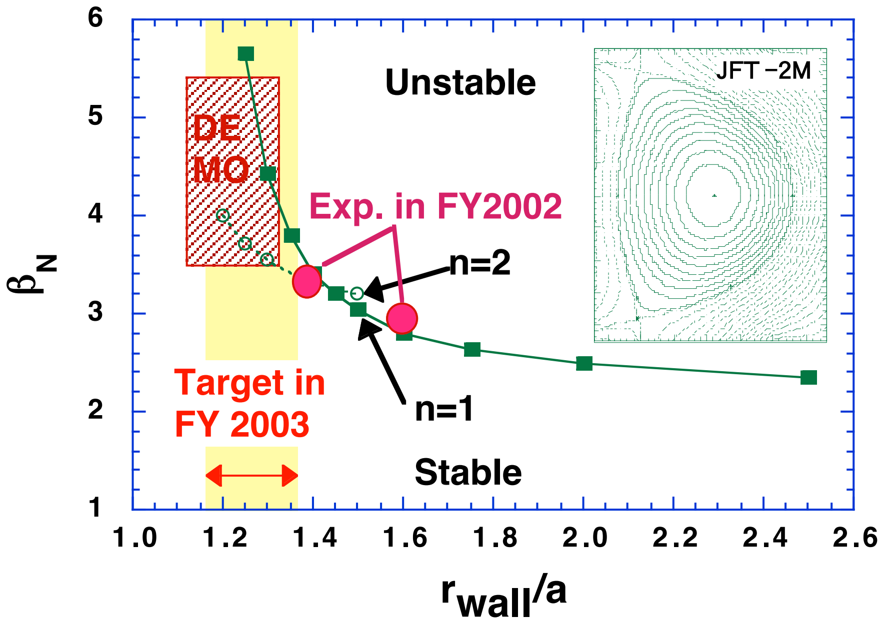
- **Discharge duration:**
  15 s (3 MA/4 T) ⇒ up to 65 s (1 MA/2.7 T)
- **Heating duration:**
  10 s (32 MW) ⇒ up to 30 s (17 MW)

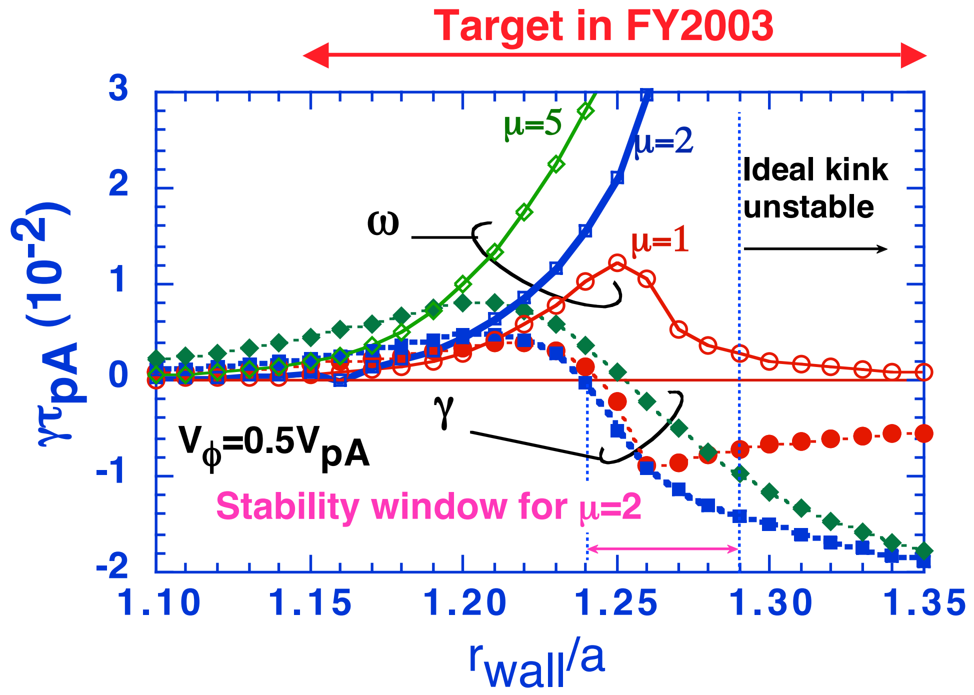


Main objectives:

- **High f_{BS} (>70%) and β_N (2-2.5) for 30s ($\sim\tau_R$)**
  Key control tools;
  –FB control for W_{dia}, S_n and n_e
  –FB control for j(r) ⇐ MSE + LHCD
- **High β_N (3-3.5) near ideal no wall limit for 5-8 s**
  Key control tools;
  –Alignment j(r) to avoid NTM ⇐ N-NBI, tan P-NBI, ECCD
  –FB control for NTM ⇐ ECE + ECCD
- **High density (n_e/n_{GW} > 0.8) and radiative divertor (f_{rad}~80%) compatible with high confinement ($HH_{98(y,2)}$ > 1):**
  Key control tools;
  –Impurity seeding (Ar, Ne), FB control of radiation
  –Repetitive pellet injection (from high-field side)

Wall stabilization experiment planned in JFT-2M





- High beta plasmas with FIW are achieved in FY2002 up to β_N=3.3 close to the ideal beta limit.
- Wall stabilization for ideal kink-ballooning modes with FIW (μ~2-3) to follow the blanket location in DEMO will be investigated in early 2004.

- It is possible to validate theoretical predictions including ferromagnetic and resistive wall effects on ideal MHD;
- β_N limit could be degraded by ~10%
- For μ=2, stability window is not so changed as μ=1, but mode frequency becomes higher.[Kurita et al., APS'03 FP1.030]

Summary

- EC injection has progressed to produce high electron temperature plasmas up to 26 keV. ECCD efficiency and EC driven current reached 4.2 x 10^{18} A/W/m^2 and 0.74 MA, respectively.
- Real-time NTM feedback stabilization has been established to complete stabilization of NTM. Early and island-center injection were demonstrated to be effective for saving EC power. Applications to JT-60SC and ITER are analyzed, showing effectiveness of real-time FB control.
- Current hole was discovered and 90% BSC current hole plasma was produced in JT-60U. For the plasmas, significant stability improvement is found to be possible by profile control and wall stabilization up to β_N~6 at $r_W/a=1.2$.
- Stability analysis of RWM with ferromagnetic wall effect has been carried out. With permeability, the stability window can be open with toroidal rotation but narrowed, and the mode frequency tends to become higher. The beta limit can be reduced by ~8% as compared to the case without permeability effect.
- JT-60U will extend the heating duration up to 30 s with a variety of FB controls and JFT-2M will implement wall stabilization experiment with FIW closer to the plasmas.