# High Beta Plasma Research

**Presented by T. Ozeki**

DOE-JAERI Technical Planning of Tokamak Experiment
and IEA Large Tokamak Workshop on Experimental Planning
JAERI, Naka
7 - 8 February 2001

# Objectives

**Establishment of high beta plasmas in steady-state by**

**- optimization of profiles of pressure, current, rotations, etc.,**

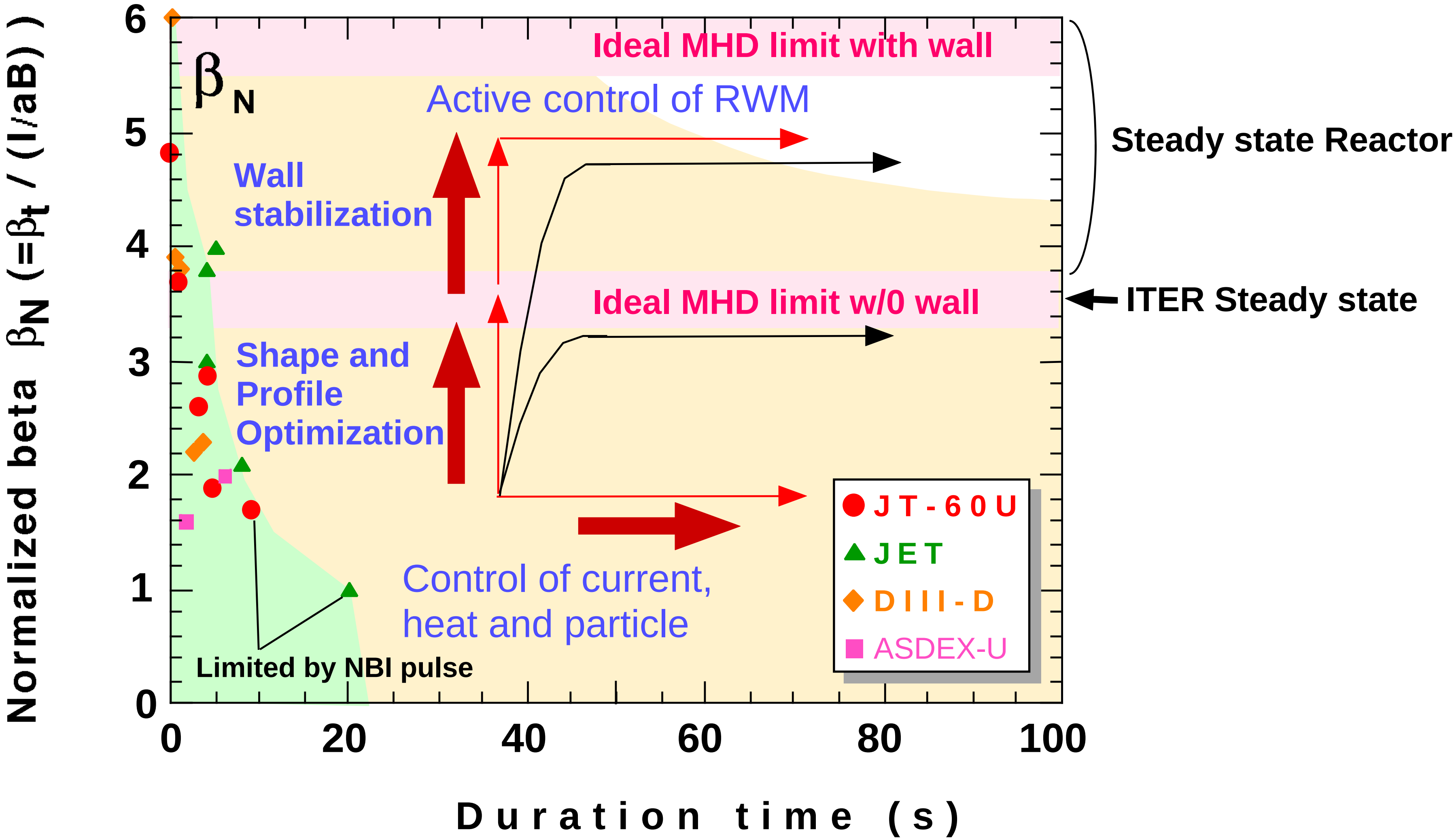
**- optimization of plasma shaping,**

**- establishment of active plasma control**

**for a compact ( or effective ) reactor.**

# Extend to Steady-State, High Beta Regime

*JT-60SC*

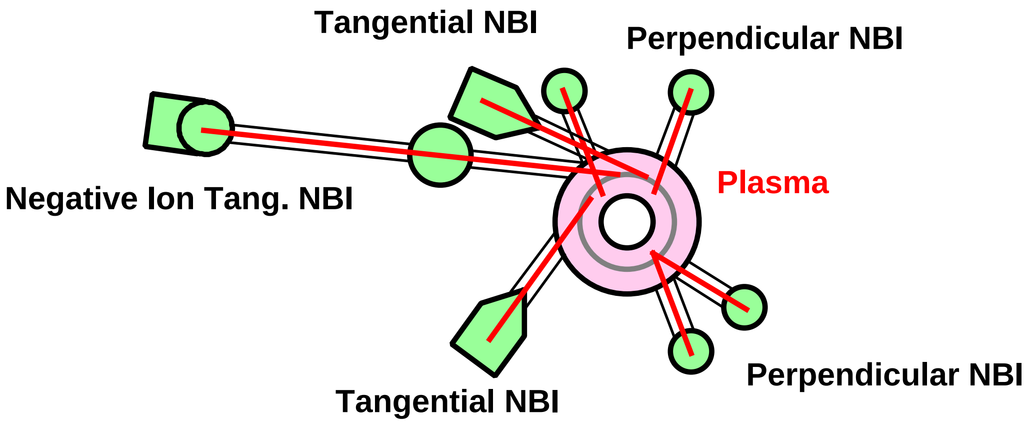


# Production and Sustainment of High beta plasma

***JT-60SC***

**To obtain and sustain high beta plasma, high power heating and current drive system of JT-60 is utilized.**

| | 10 sec | 20 sec | 30 sec | 50 sec | 100sec |
|---|---|---|---|---|---|
| Perpendicular NBI | 20MW | 20MW | 13.3MW | 13.3MW | 6.7MW |
| Tangential NBI | 10MW | 10MW | 6.7MW | 6.7MW | 3.3MW |
| Negative Ion Tang. NBI | 10MW | 7MW | 7MW | 3MW | 3MW |
| ECH | 4MW | 3.75MW | 3.1MW | 2.4MW | 1.7MW |
| Total | 44MW | 40.75MW | 30MW | 25.4MW | 14.7MW |




Top view of JT-60SC

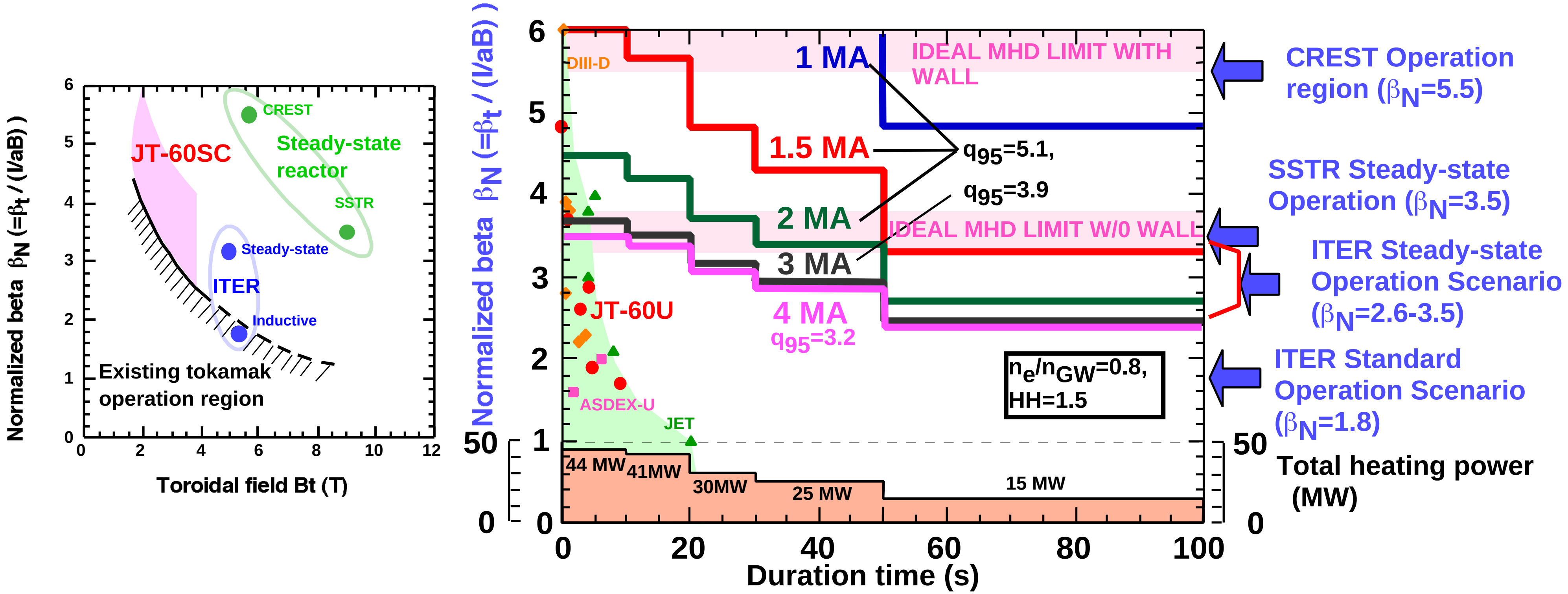
# Investigate New High Beta Regimes

***JT-60SC***

**Very High β : $\beta_N$~6, 10sec, 1.5MA, $\beta_t$=2.1T, $\tau_{li/R}$~15sec**

**High β in SS : $\beta_N$~3, 100sec, 2MA, $\beta_t$=2.8T, $\tau_{li/R}$~20sec**

**High β in High $B_t$ : $\beta_N$~3.0, ~30sec, 4MA, $B_t$=3.8T, $q_{95}$=3.2, $\tau_{li/R}$~40sec**




**Goal: Establish high beta-N plasma**
**- during non-inductive full CD with large bootstrap current fraction,**
**- in a steady-state where the duration time exceeds a current diffusion time.**

# Approach to high beta regime in steady-state and high Bt

(1) Profile control

- Current, Pressure (temperature, density), Rotation

(2) Shape control

- Elongation, Triangularity

(3) Active feedback control

- Neoclassical tearing mode, Resistive wall Mode

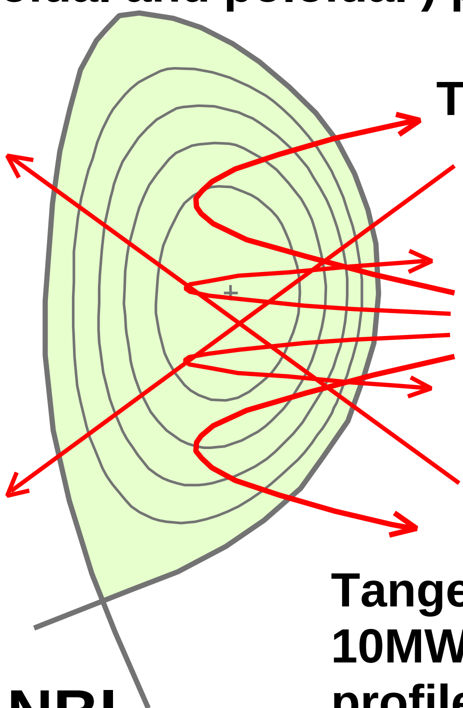
# (1) Profile Control

***JT-60SC***

**ISSUES: In plasmas with large bootstrap fraction and high confinement such as ITB, pressure and current profiles are strongly coupled each other . Seek the best combination of pressure and current profiles.**

**JT-60SC has various facilities for profile control;**

- **Pressure ( temp. and density ) profile controlled by heating and particle source**
- **Current density profile controlled by driven current and bootstrap throu. pressure**
- **Rotation ( toroidal and poloidal ) profile controlled by momentum source**



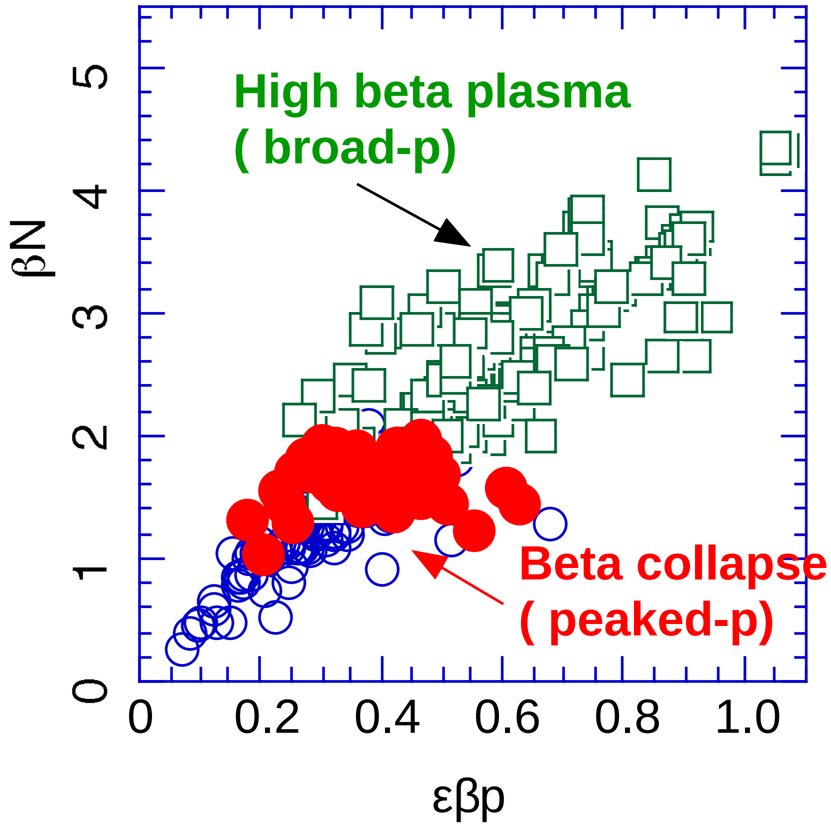

**NBI**

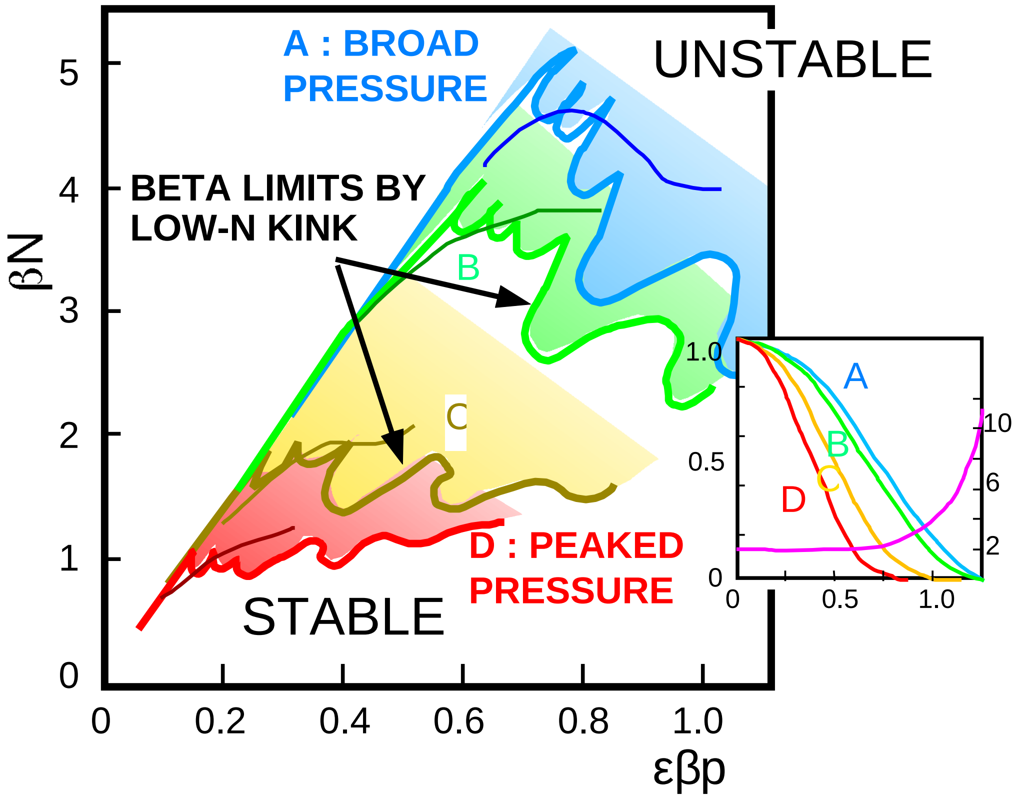

**ECH / ECCD**

# High beta-p operation

*JT-60SC*

**High beta-p plasmas ( positive shear ) in JT-60U;**
**Direction to good stability:**
- **Broad Pressure profile are good for stability.**
- **Current density with high shear is good for low-n stability, and low and negative shear is good for high-n ballooning stability.**

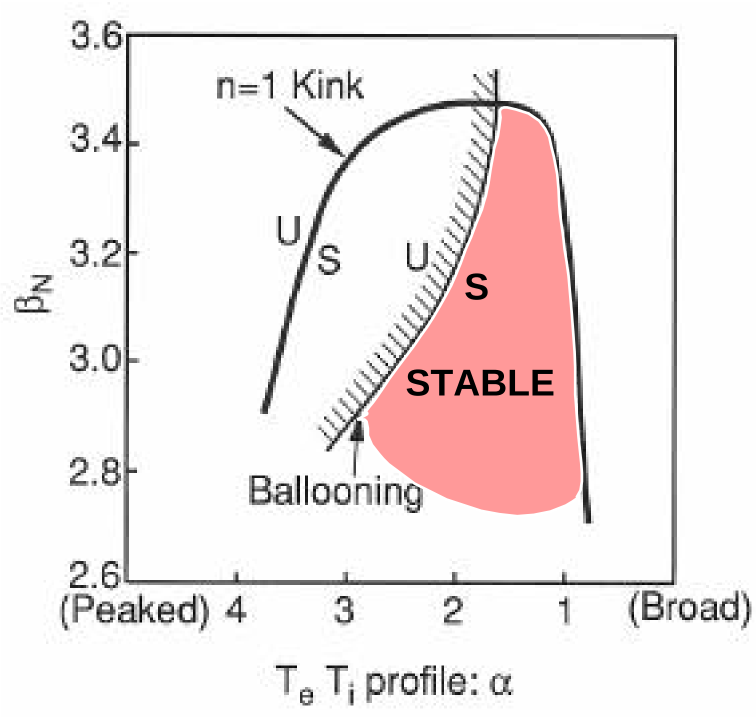


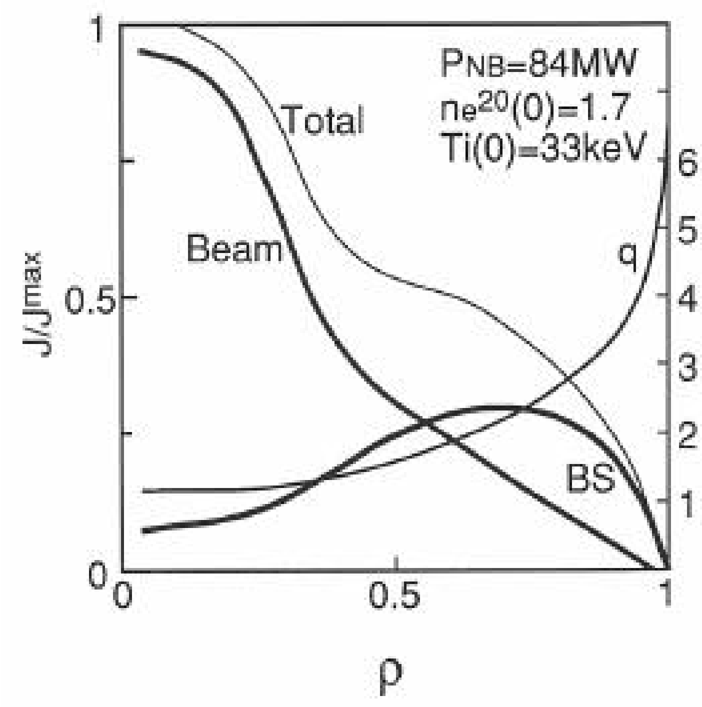



# Self consistent analysis: High beta plasmas ( $\beta_N$<3.5 ) without wall obtained by profile optimization

***JT-60SC***

**Self consistent equilibrium of steady-state, high beta plasma in SSTR configuration**




**ne,ni $\propto (1-\rho^2)^{0.5}$, Te,Ti $\propto (1-\rho^3)^{\alpha}$, SSTR Scenario**
**Monotonic q-profile, low-n kink stable, 1st stable to ballooning mode**
**for rwall / a= $\infty$. fbs=50%**

**Key issue: Self-consistent profile optimization**
**Stabilization of neoclassical tearing mode**

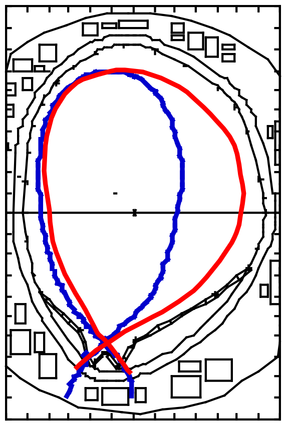
# Reversed shear operation

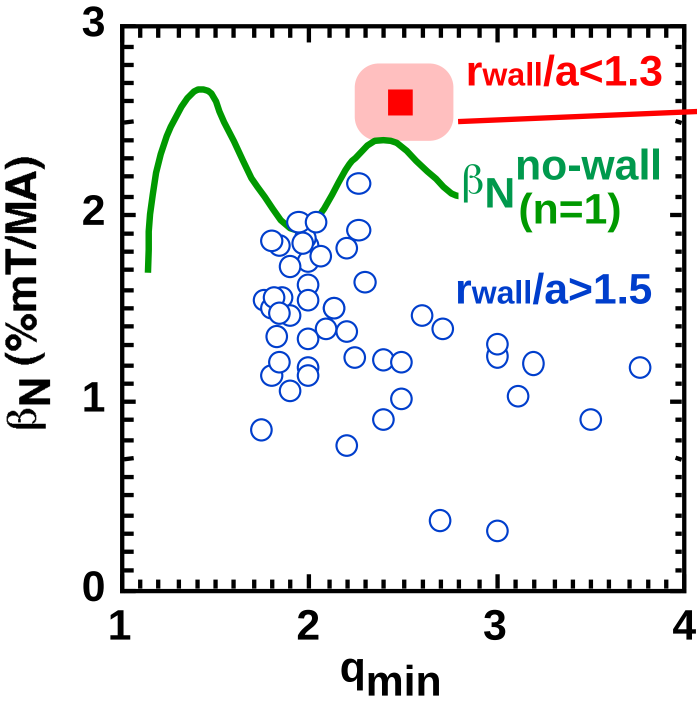
**JT-60SC**

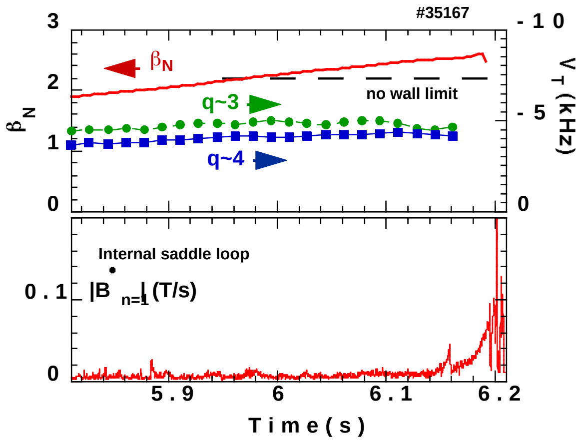
**Reversed shear plasmas is promising for steady state with large bootstrap current.**
**In JT-60U, High $Q_{DT}$(=1.25) was obtained but terminated by the beta collapse.**

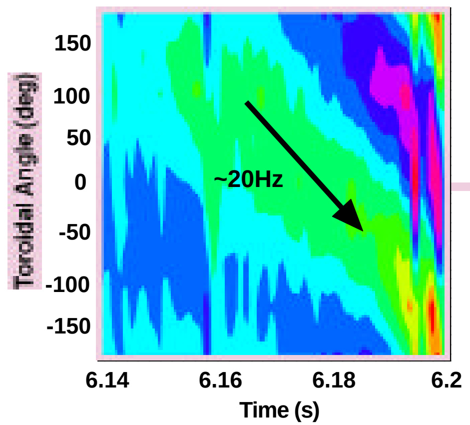
**$r_{wall}/a>1.5$:** • Achievable $\beta_N$ is limited at the **no-wall** ideal stability boundary
• H-mode edge plasma is better stability than L-mode edge.

**$r_{wall}/a<1.3$:** • Achievable $\beta_N$ is improved to be **above the no-wall limit**.
• Improved $\beta_N$ discharges are terminated with appearance of RWM.





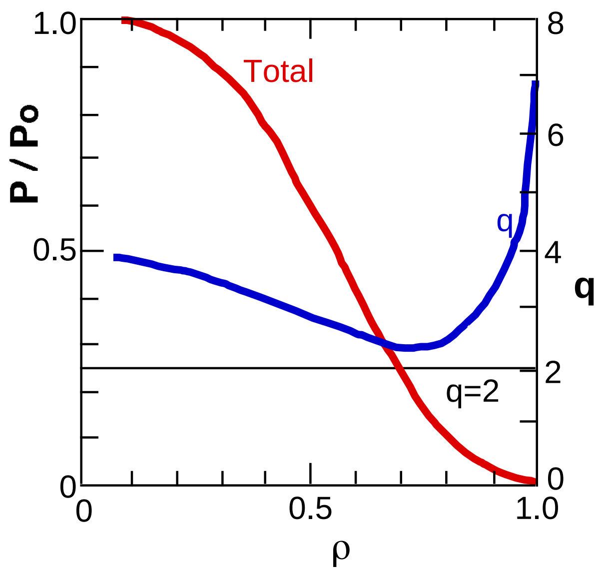



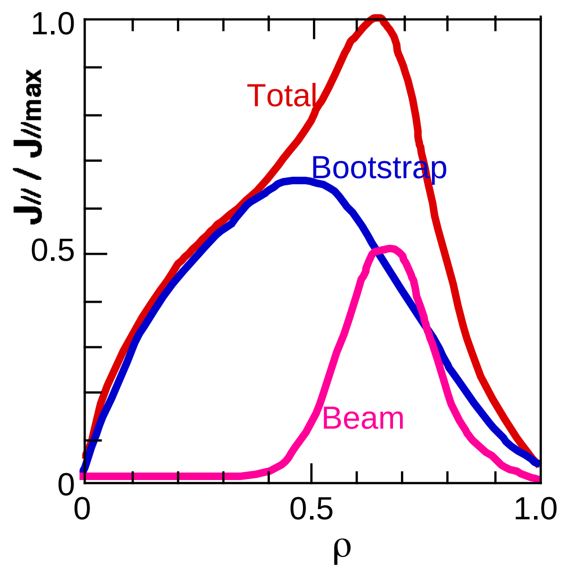

- **n=1** with growth time $\gamma^{-1} \sim 10^{-2}$ s $\sim \tau_{wall}$ ( $\tau_{wall}$ ~ 10ms )
- Rotating in the toroidal direction with $f \sim 20$ Hz $\sim 1/(2\pi\tau_{wall})$
- No clear reduction was observed in the toroidal rotation frequency

# Reversed Shear, High beta plasmas obtained by the profile optimization and wall stabilization

***JT-60SC***

**Self consistent reversed shear equilibrium of steady-state, high beta plasma with large bootstrap current in SSTR configuration**




**βN=3, βp=1.6, fbs=65%, SSTR scenario**

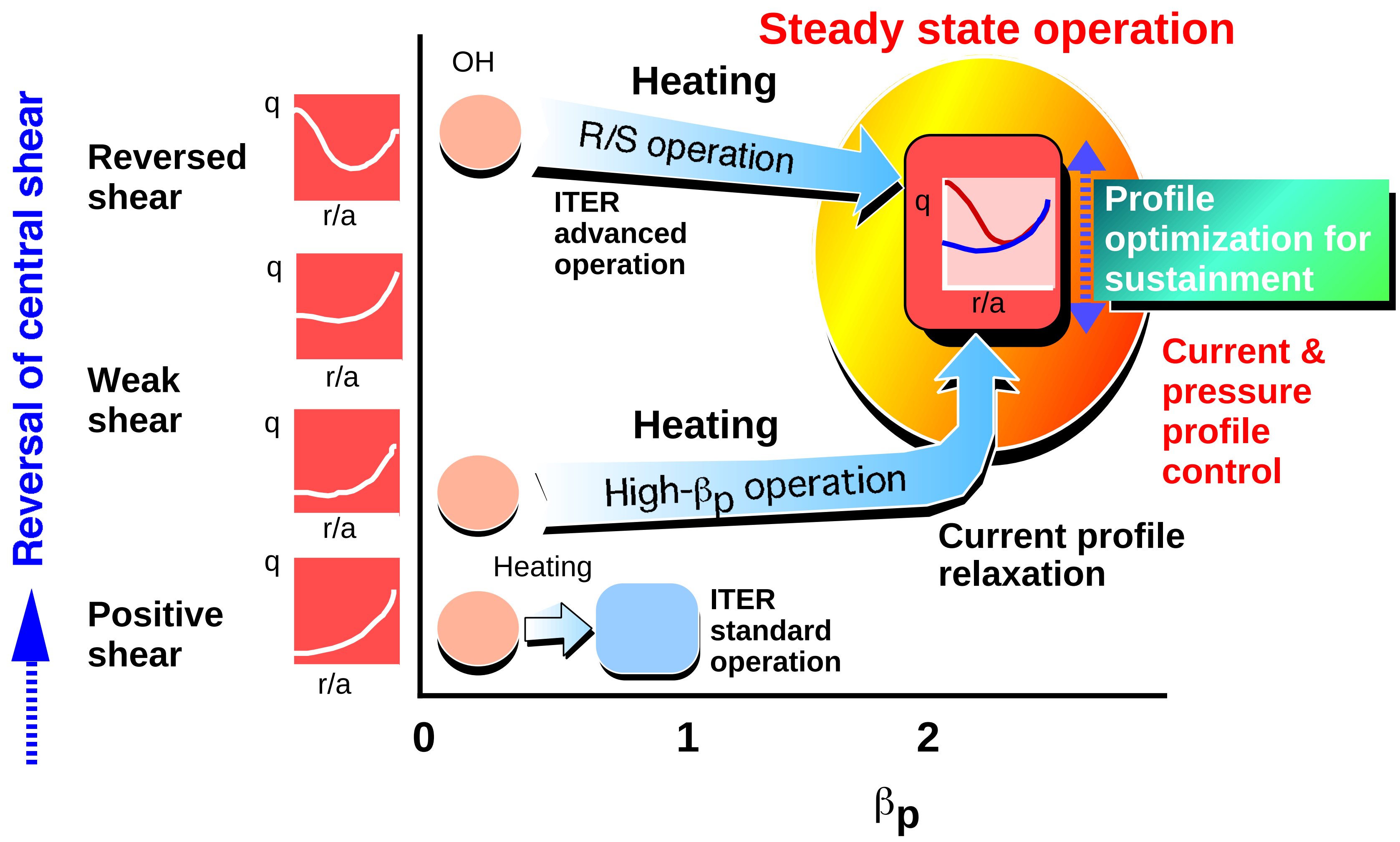
**Low-n kink stable, 1st stable to ballooning mode for $r_{wall}$ / a= ∞**

**βN increases up to >4 and fbs up to >80% by the wall stabilization: $r_{wall}$/a=1.2.**

**Key issue: Sustainment profile optimization**
**Stabilization of resistive wall mode**

# Profile Optimization toward Steady State Operation

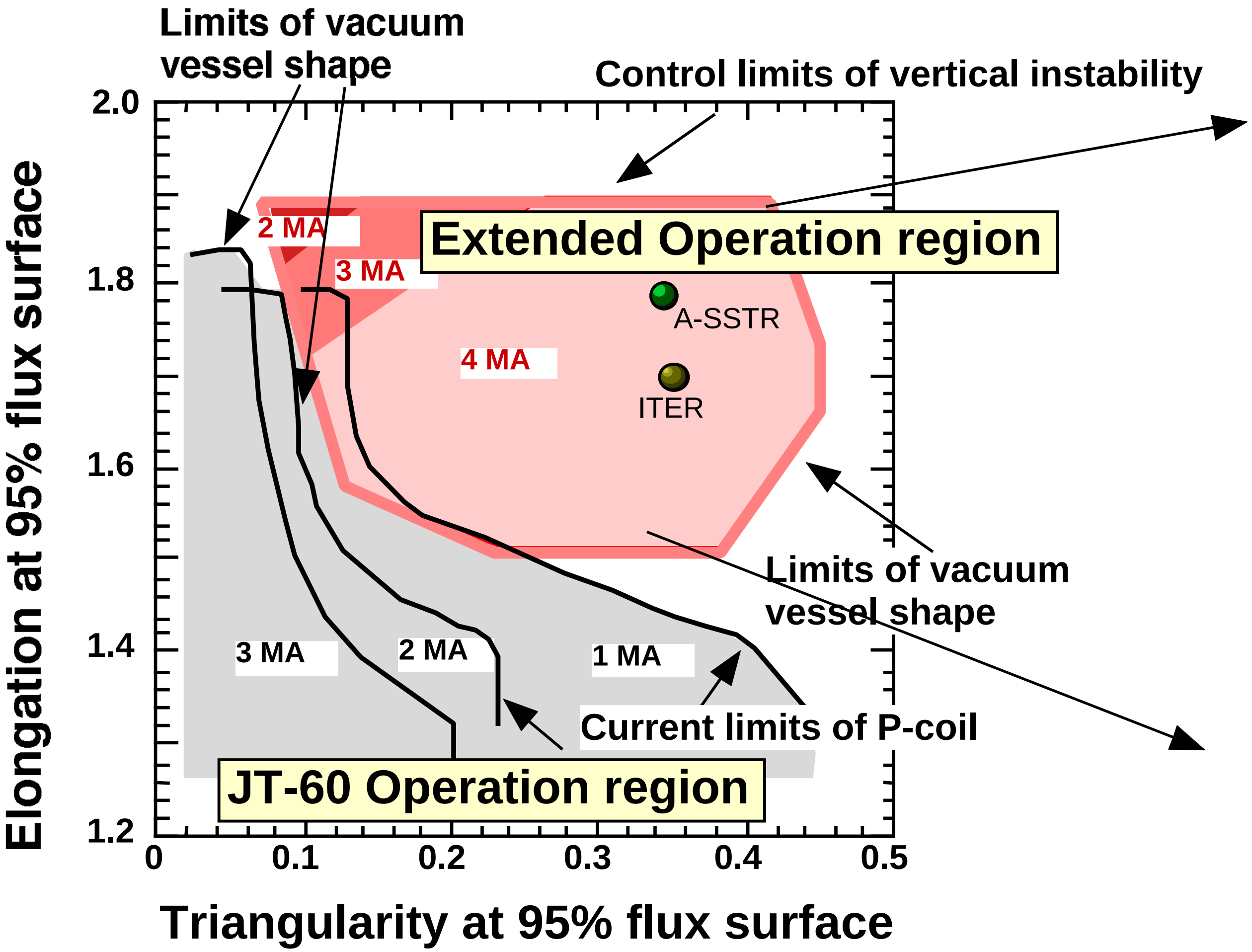
***JT-60SC***

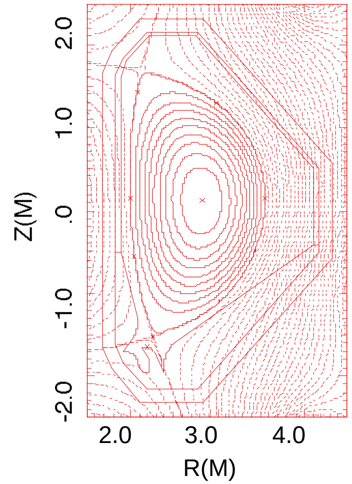


# (2) Shape Control

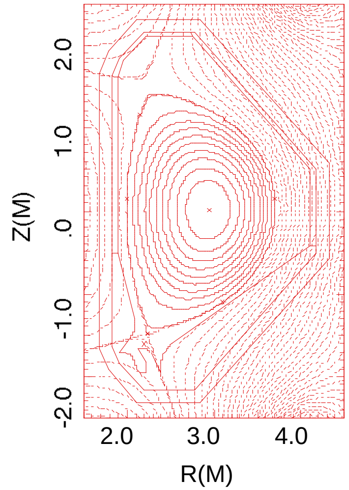
***JT-60SC***

**ISSUES: Investigate effects of elongation and triangularity on the edge stability and the confinement. Optimization of both shapes and profiles.**




Limited by vertical instability.



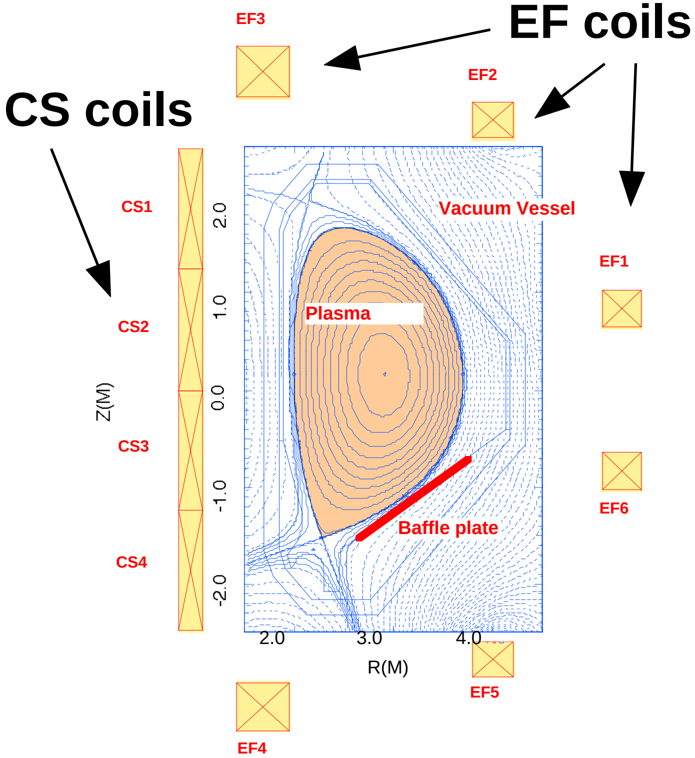

Limited by vacuum vessel.

**Extend to high elongation and high triangularity region Consistency to the divertor is under consideration.**

**li=0.7~0.85, p(0)/<p(r)>~2.5, βp=0.6~1.2, Separatrix is not on the dome.**

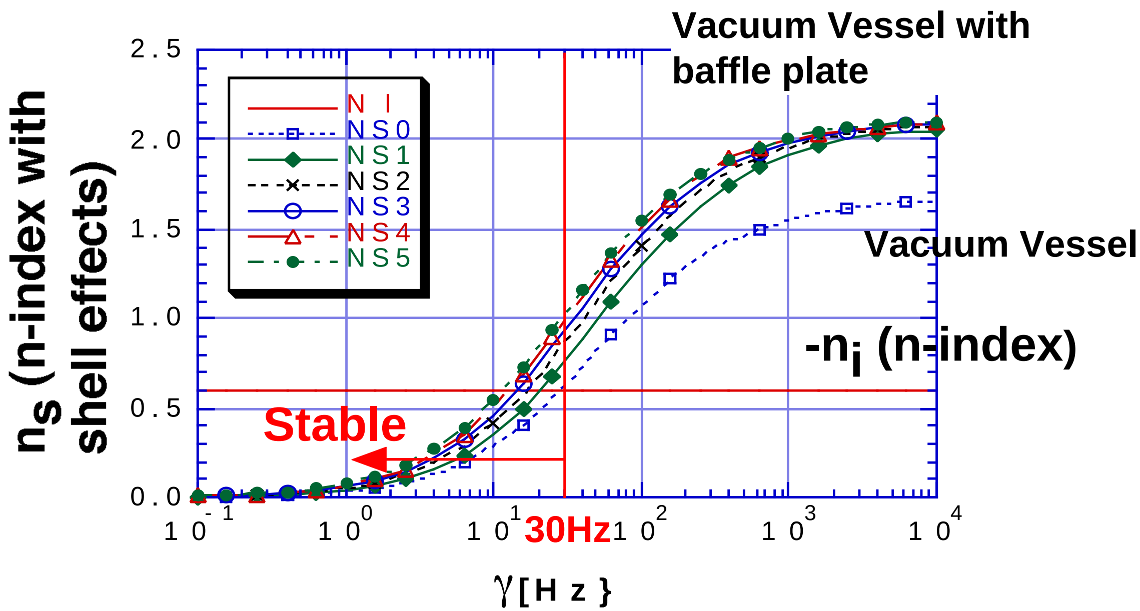
# Vertical instability

***JT-60SC***




**li=0.5, βp=1.2, k95=1.8, δ95=0.35**

**Growth rate is reduced by baffle plate.**

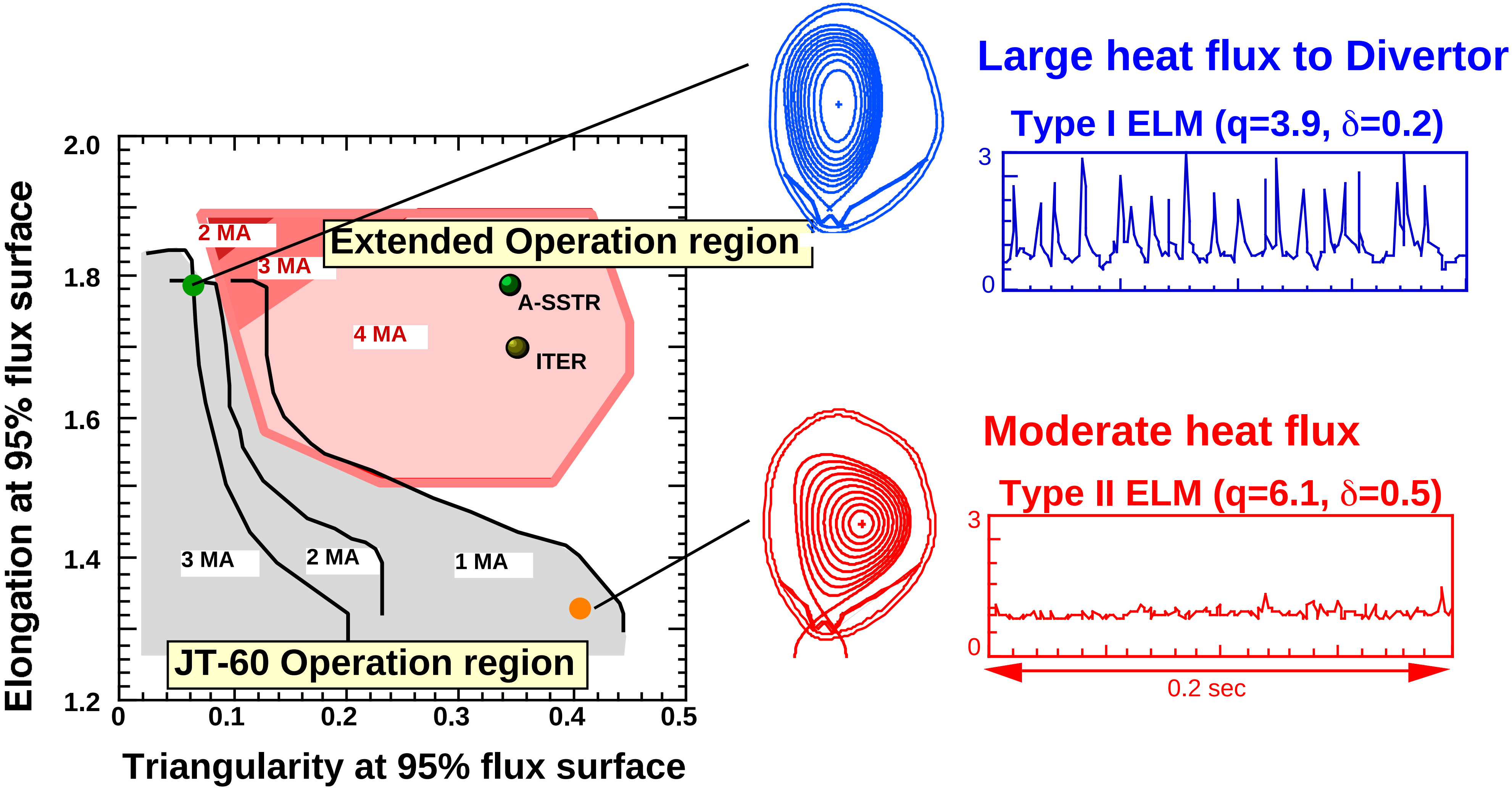



**Growth rate less than 30Hz is stabilized by poloidal coils ( CS coils and EF coils).**

## Vertical instability is stabilized under k<1.9

# Development of suitable ELM by plasma shaping

*JT-60SC*



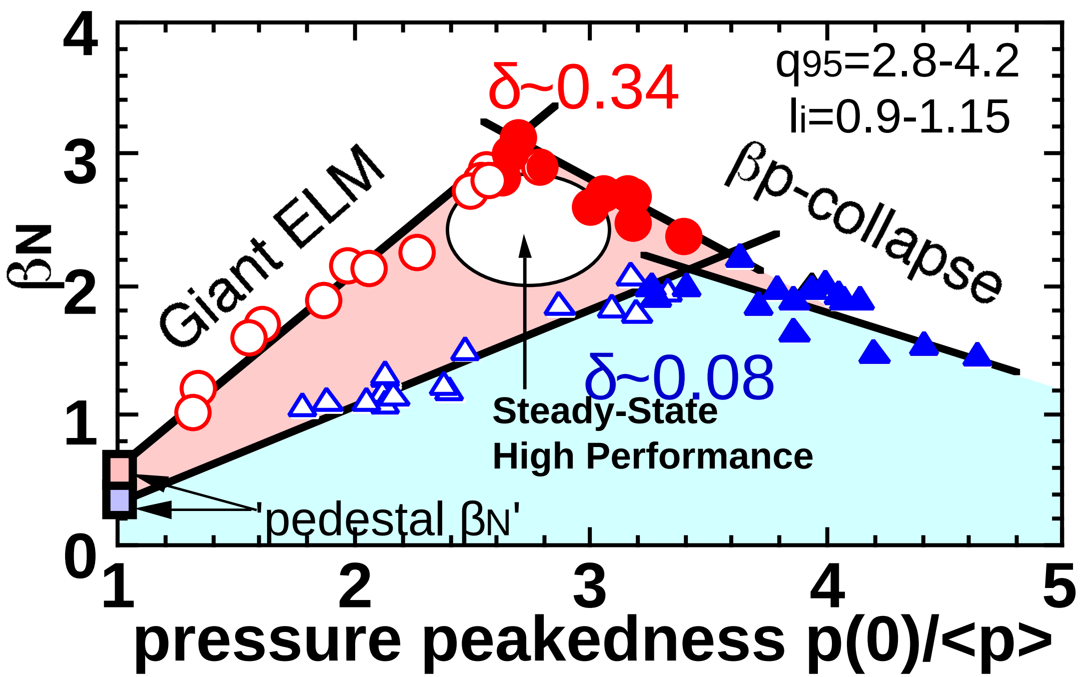

In JT-60U, the high triangularity demonstrated the moderate ELM.
In the plasma edge, plasma may exist in the 2'nd stability of ballooning mode.

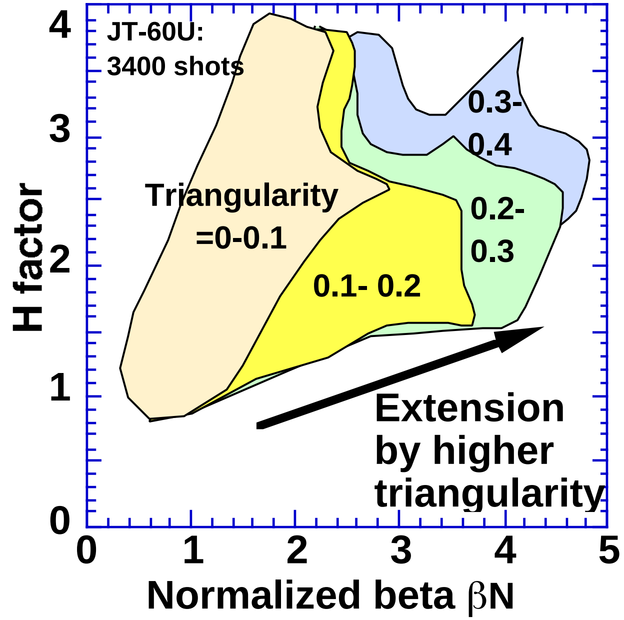
# Synergistic effects of shape and profile optimization

***JT-60SC***

**The highest $\beta_N$ is obtained at a medium peakedness of p(r) :**

**: ELM & $\beta_p$-collapse (low-n ideal kenk-ballooning)**




**At high-δ: $\beta_N$ increases by ~50%.**

**The optimum p(0)/<p> becomes smaller.**

Y. Kamada et al., Proc. 16th IAEA Conf. Montreal, Vol.1, p247

# (3) Active feedback Control

*JT-60SC*

- NTM stabilization is key issues for positive shear plasma:
  - Identify Islands by ECE, magnetic probe, etc
  - Stabilize by ECCD/ECH

- RWM stabilization is key issues for high beta plasma above the ideal beta limit without wall:
  - Identified by sensor coils inside Vacuum Vessel
  - Stabilize by feedback coils inside Vacuum Vessel

- Real time feedback control of NTM and RWM is key issue to find a solution of Steady State and High Beta plasma.

# Regime of NTM unstable in JT-60SC

*JT-60SC*

**Objectives**: Establish NTM control technology for reactor relevant conditions at high beta-N during non-inductive full CD with a large bootstrap fraction.

**ITER-FDR Physics R&D [Sauter]**

$$\beta_N \approx 5.2\ \nu_e^{*0.3}$$

**JET [IAEA, Yokohama 1998]**

$$\beta_N \quad \nu_e^{*-0.2} \quad \rho^{*0.6}$$

**DIII-D [Lahaye 2000]**

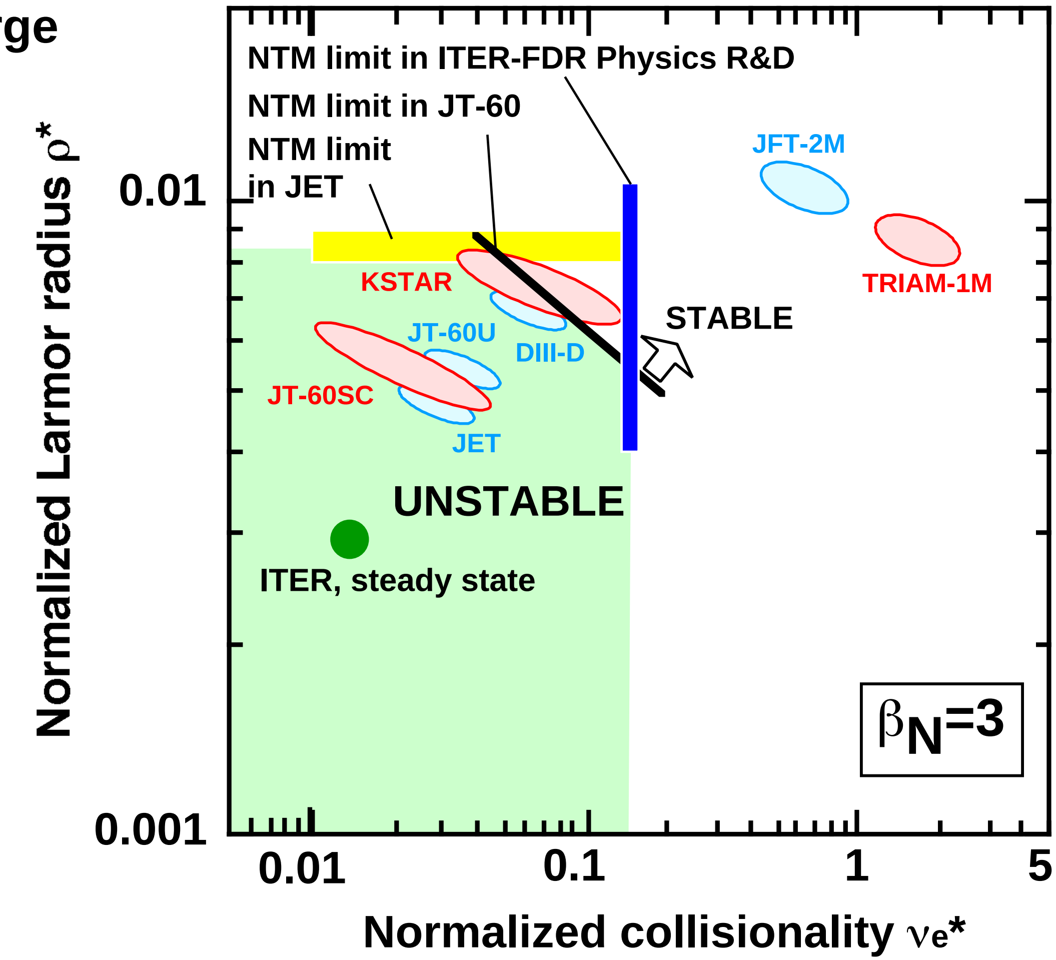
$$\beta_N \quad (\nu_i^{*}/\varepsilon\omega_{e*})^{0.43} \rho^{*1.3}$$

**ASDEX [Lahaye 2000]**

$$\beta_N \quad (\nu_i^{*}/\varepsilon\omega_{e*})^{0.25} \rho^{*1.1}$$

**JT-60 [IAEA, Sorrento 2000]**

$$\beta_N \quad \nu_e^{*0.4} \rho^{*}$$



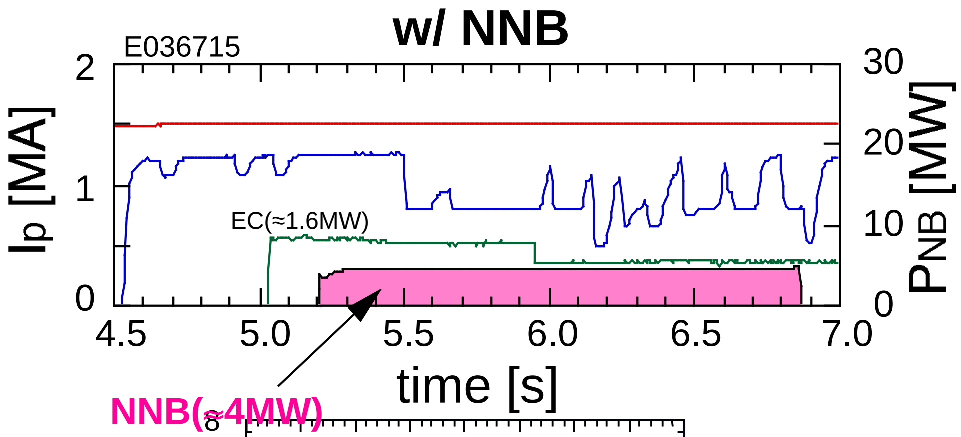

**Onset $\beta N$ of JT-60SC is ~1-2.2**

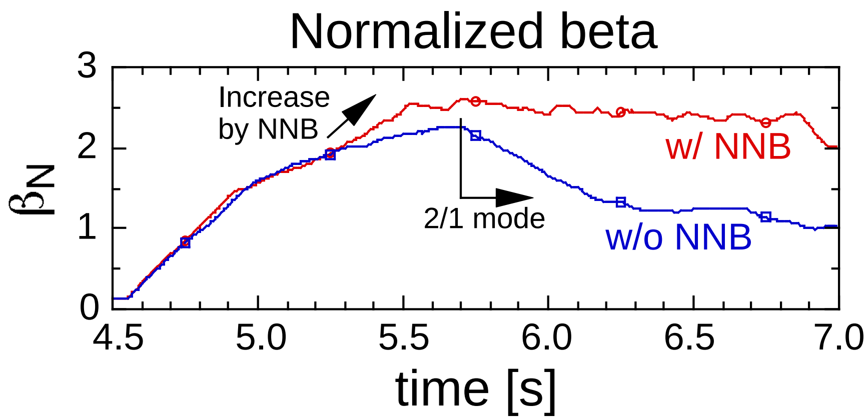
**($\nu_e$*~0.01-0.05, $\rho$*=0.004-0.005 )**

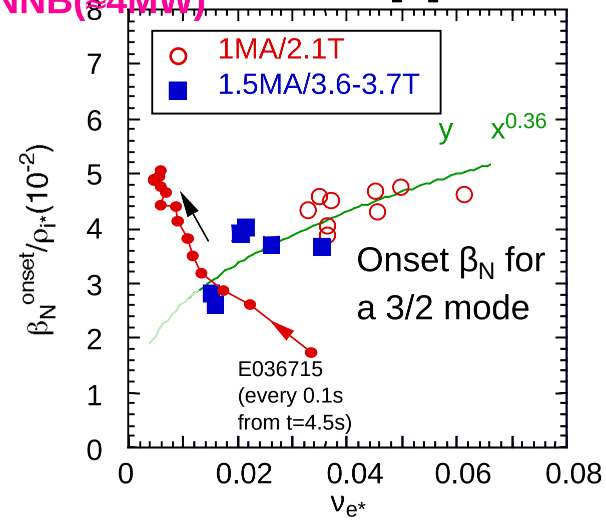
# No tearing mode was observed in discharge with NNB

*JT-60SC*

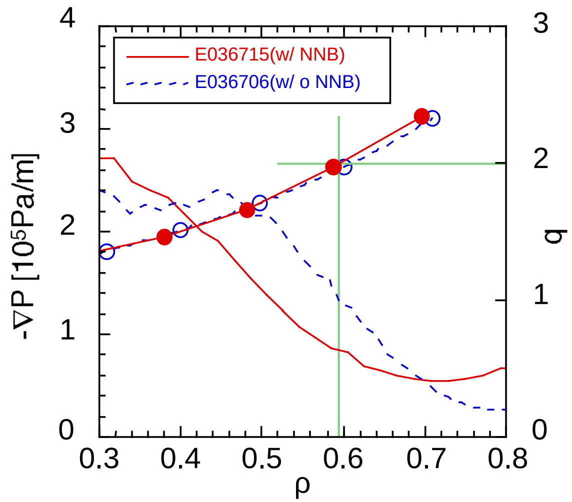
- **Beta value is exceed the onset beta scaling with NNB.**
- **Without NNB, a 2/1 mode appears at t=5.7s.**



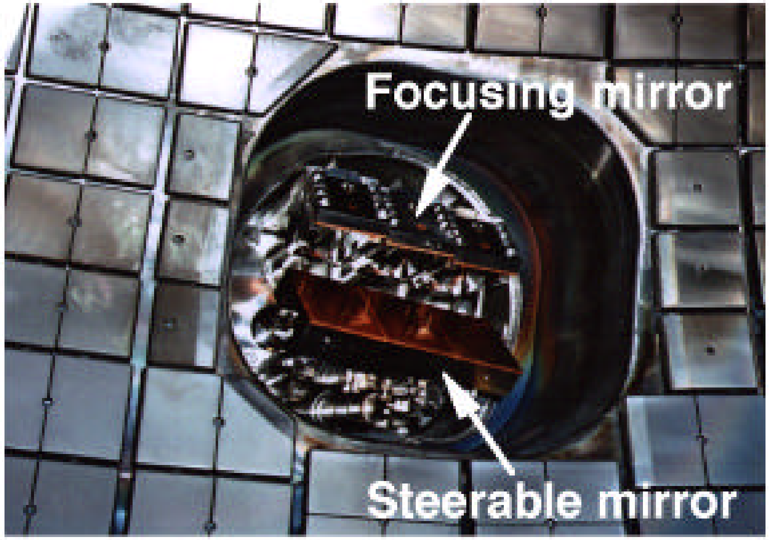

**Reduction of pressure gradient at the mode rational surface may improve the stability for NTM.**

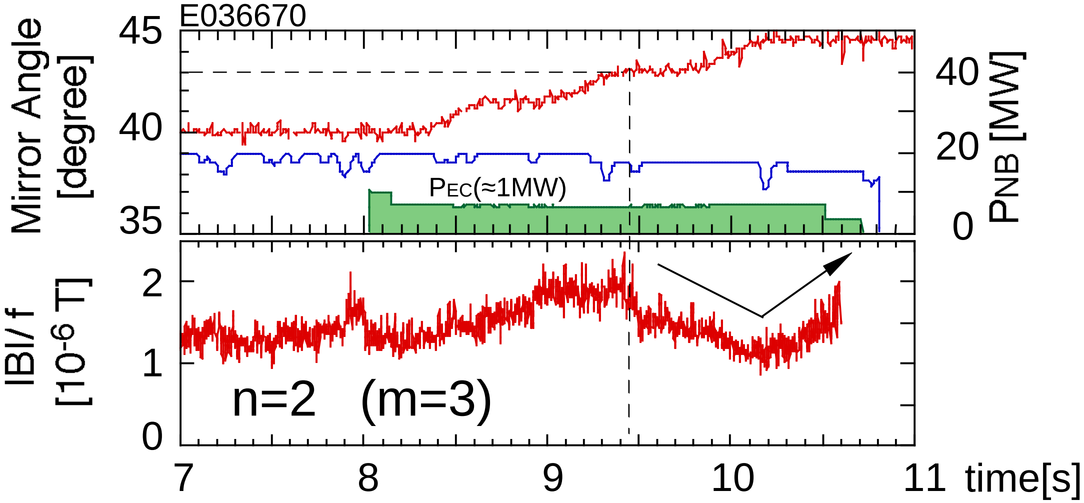



**Key issue: Investigation for profile optimization for the NTM supression.**

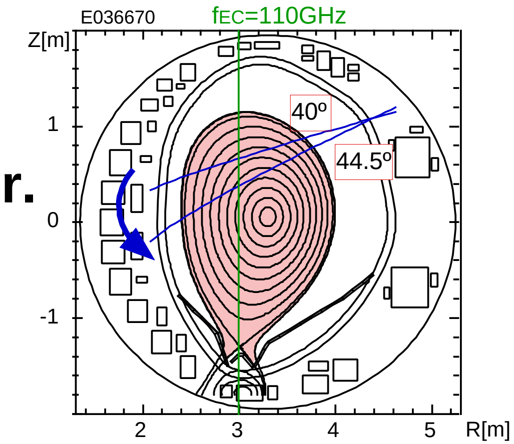
# NTM Stabilization by ECCD System

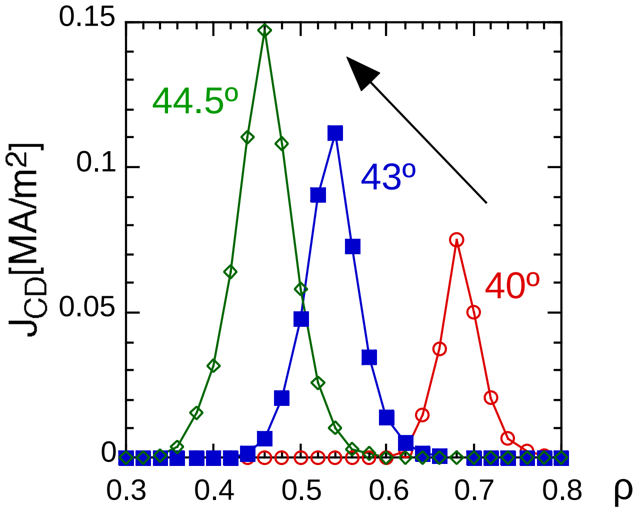
***JT-60SC***




- **Design value:110GHz; 1 MW at each gyrotron output ( x3 )**
- **Poloidal injection angle can be changed by the steerable mirror.**



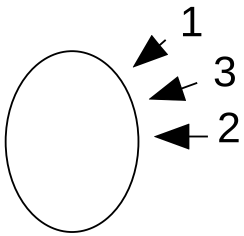



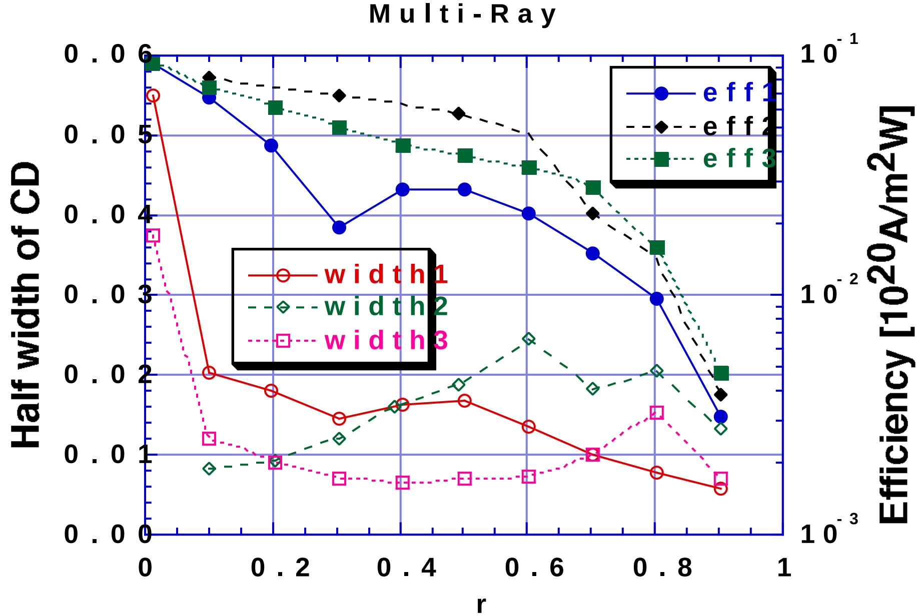

- **Magnetic perturbations with n=2 decreases at the injection angle of 43º.**
- **Complete stabilization was also obtained in low beta plasma.**

# EC Current Drive Efficiency

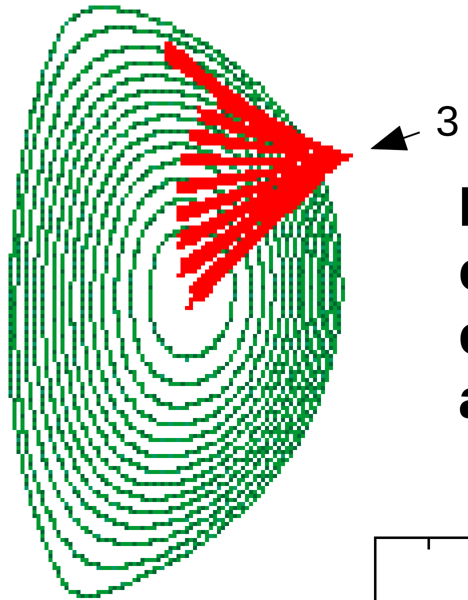
*JT-60SC*

**Evaluation of current drive efficiency by ray tracing analyses**

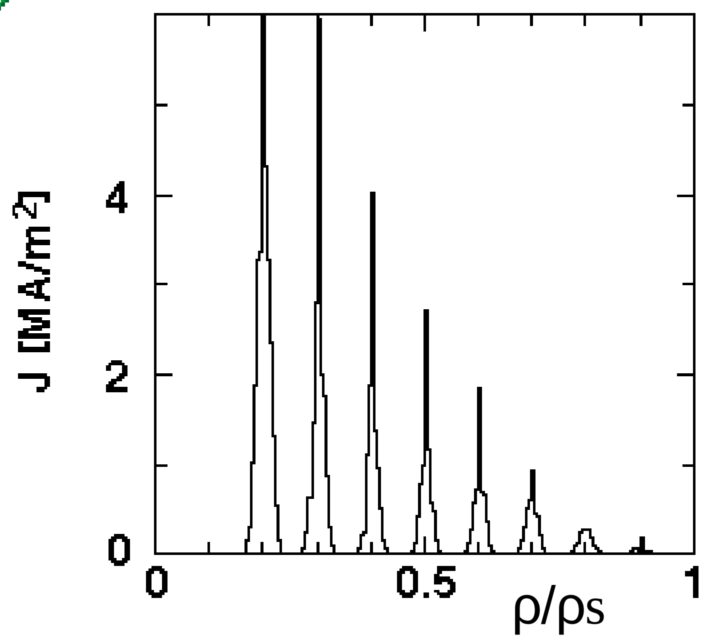



- **Angle 3, correspond to the port, is good current drive efficiency.**
- **Teo=15keV, neo=5x$10^{19}$m$^{-3}$ with parabolic profile.**
- **$f_{ECW}$=110GHz, fundamental resonance of O-wave.**

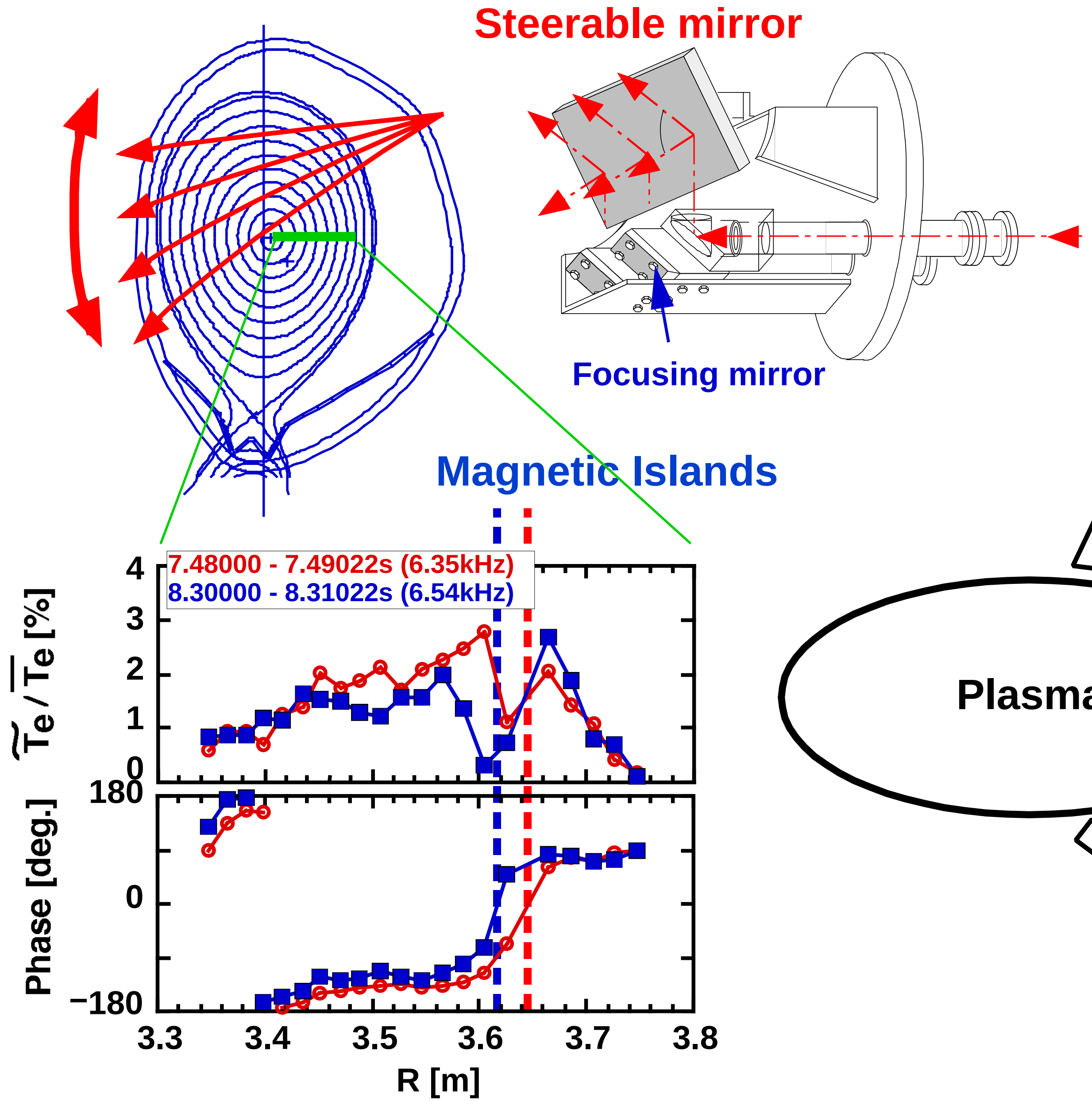


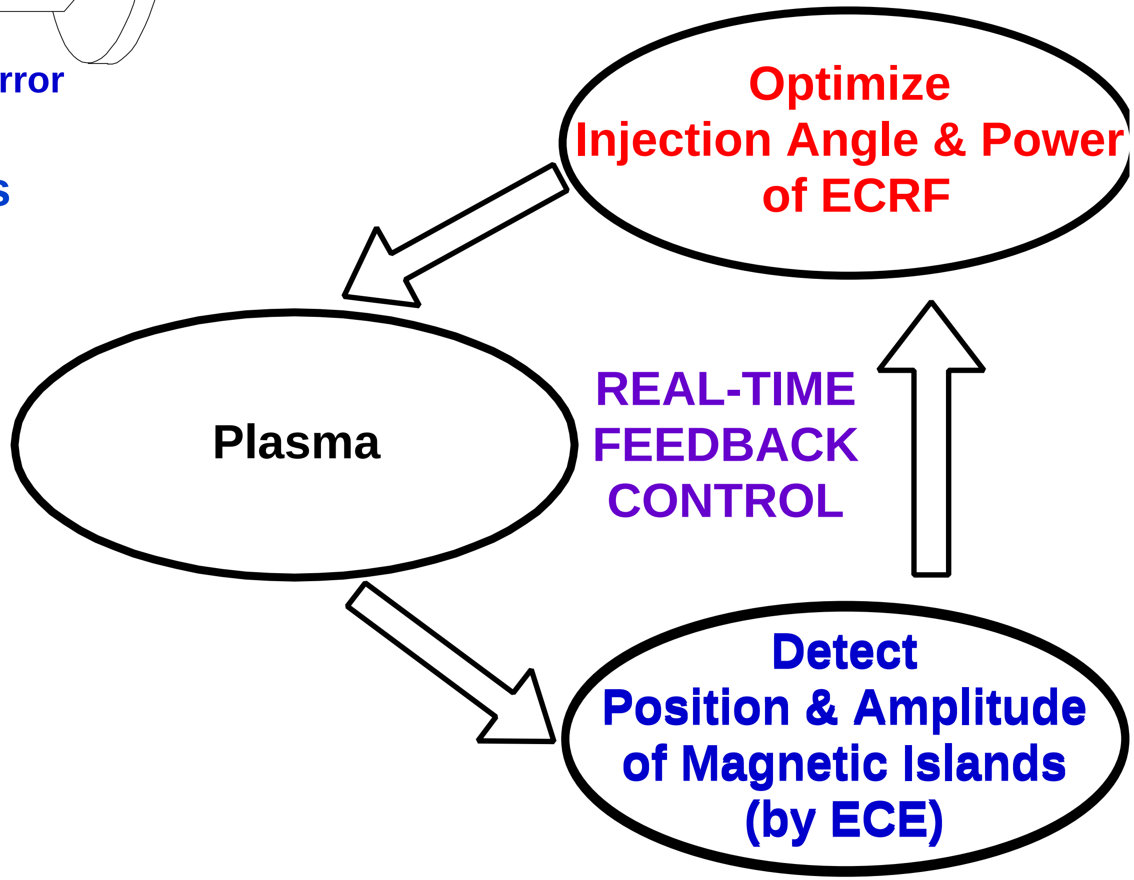

**Localized driven current can be expected by the angle 3.**



# Real-Time Feedback Control of NTMS will be Demonstrated on JT-60U to Prove Reliability of Steady State High Beta Operation on JT-60SC

***JT-60SC***



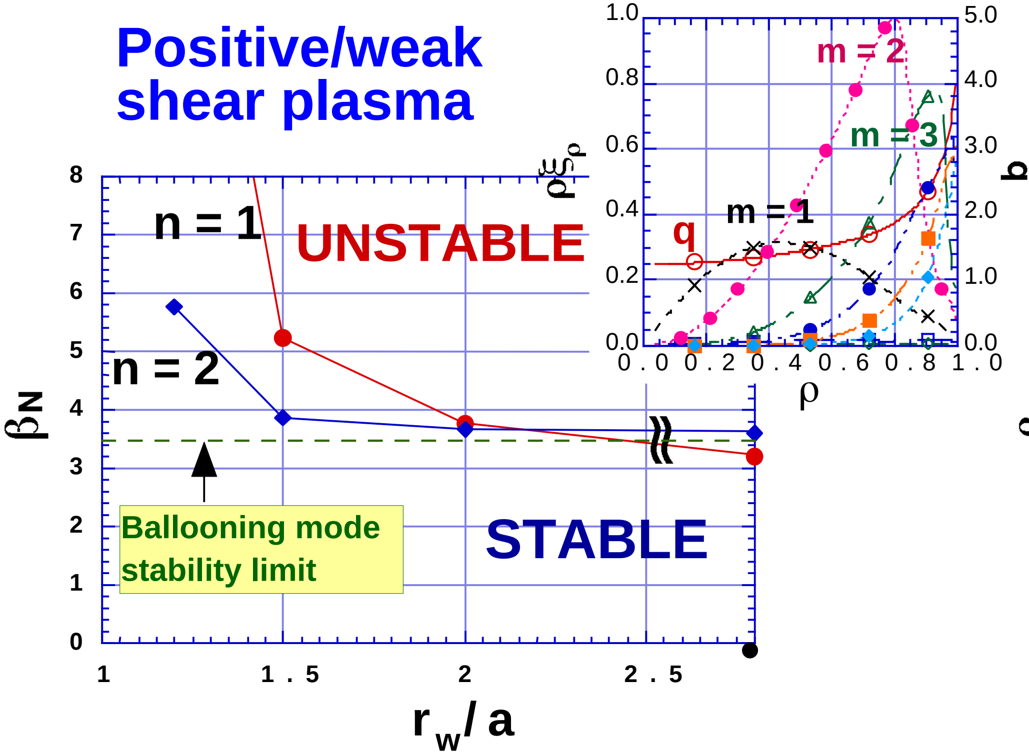



# Stability with the wall

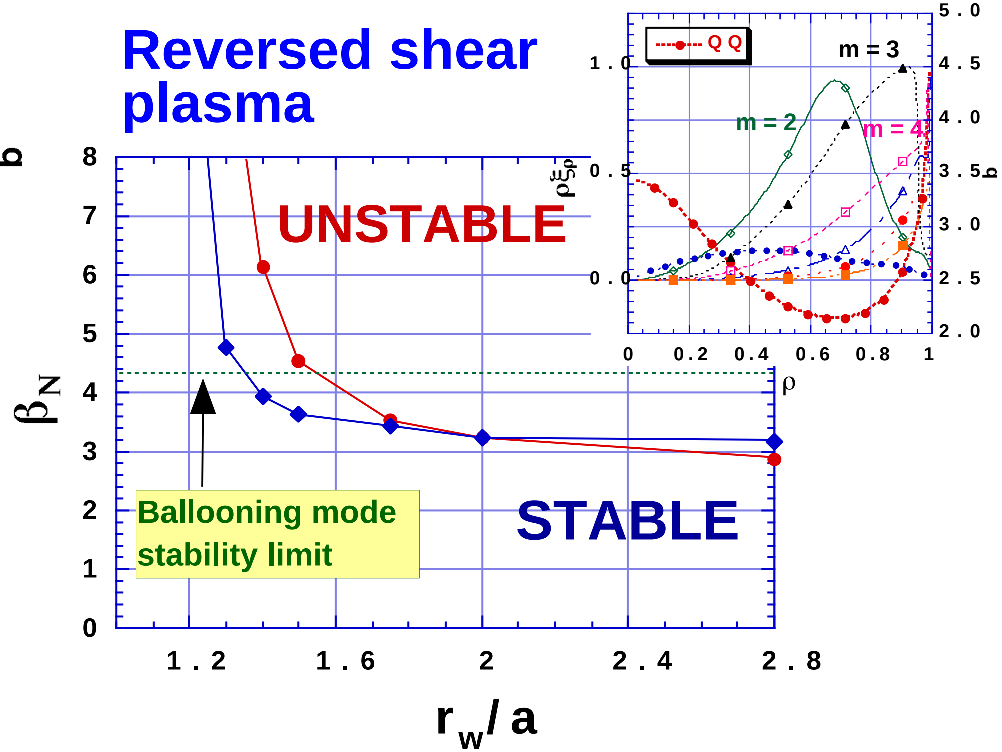
**JT-60SC**

- **Objectives** Establish RWM control technology for reactor relevant conditions;
  - at high beta-N over ideal MHD limit w/o wall
  - during non-inductive full CD with a large bootstrap fraction

## Positive/weak shear plasma




## Reversed shear plasma




**Significant Improvement of Ideal MHD Stability by the Wall**

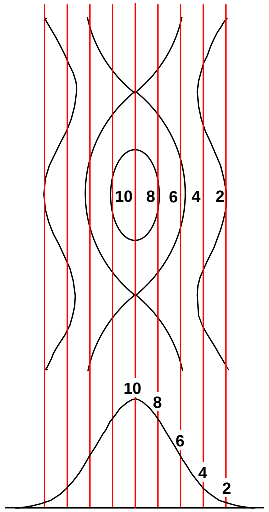
**Low-n kink and high-n ballooning mode stability in JT-60SC configuration.** $R_0 = 2.8$ m , $a = 0.85$ m , $\kappa_{95} = 1.8$ , $\delta_{95} = 0.35$

**Wall stabilization is pronounced in reversed shear plasmas.**

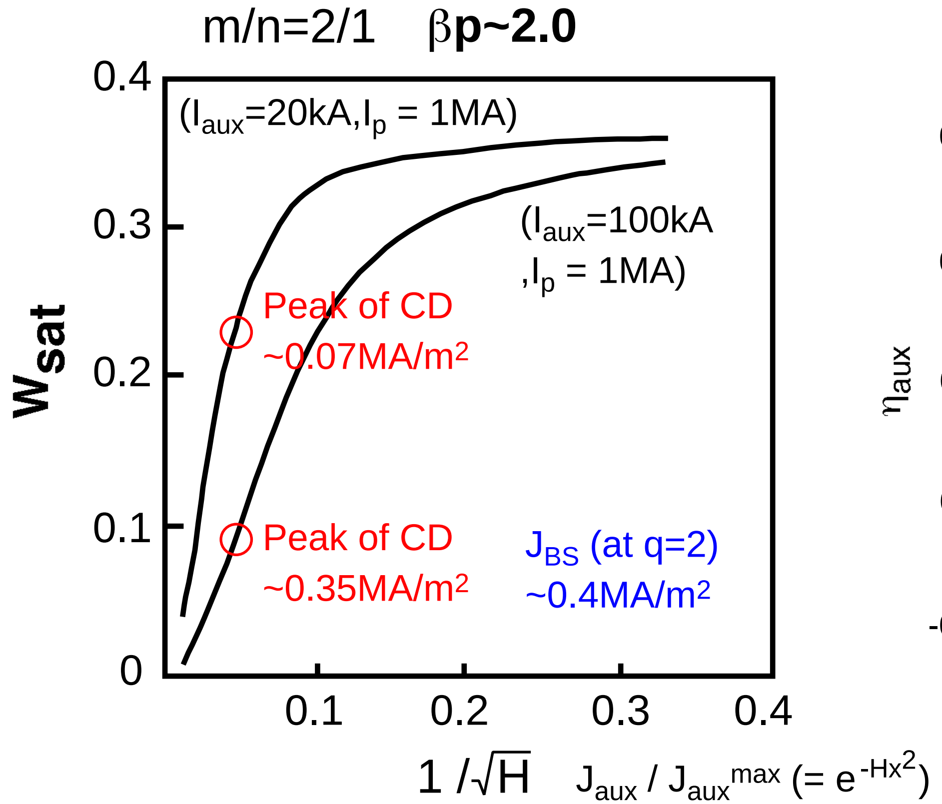
# Stabilization of NTM

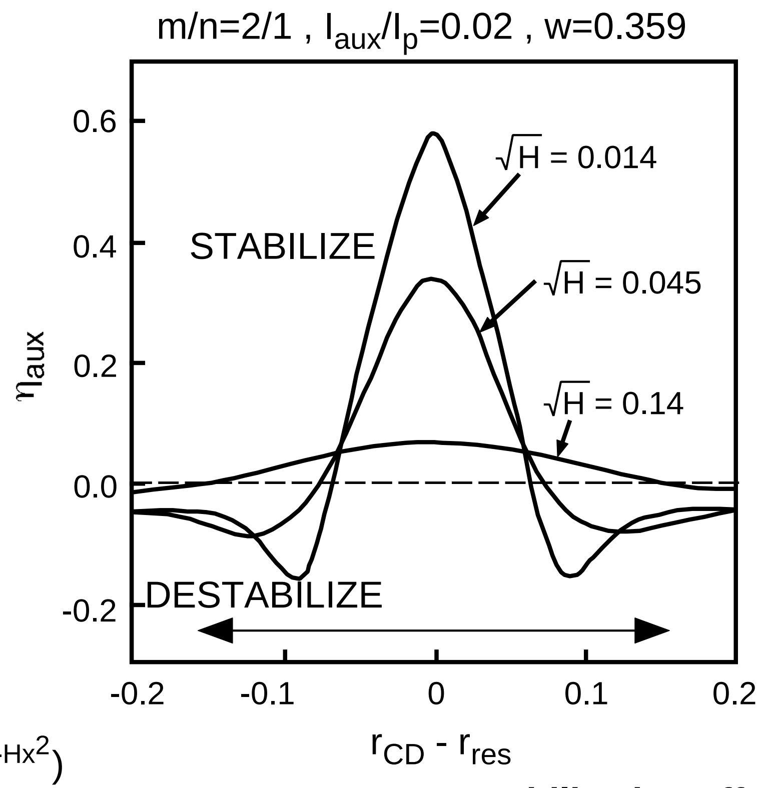
***JT-60SC***

- **βN~3.2, q0~1.2, Broad Pressure (A), low li~0.8**




**ECCD is not modulated to the island.**




**Stabilization effect is sensitive to the relative location.**

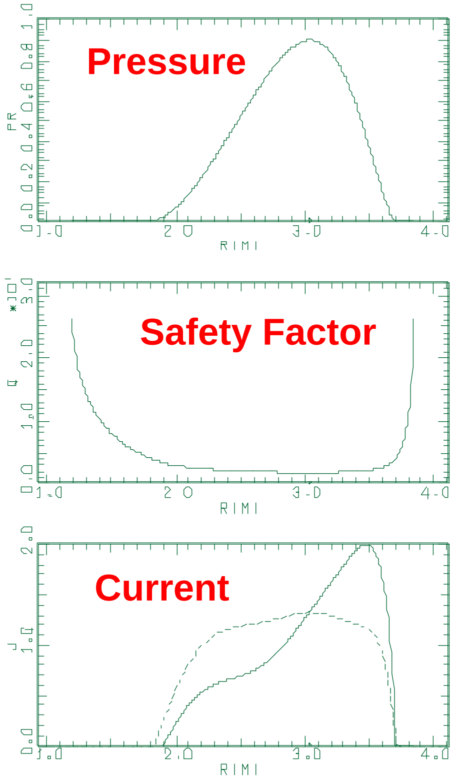
- **When current drive efficiency is ~0.05 near r=a/2, R0=0.28m, neo=5x10$^{19}$m$^{-3}$, EC power of 4MW drives the local current of ~150kA.**
- **Significant stabilization of NTM by ECCD can be expected.**
- **Real time feedback using ECE, etc., and ECCD is key issue.**

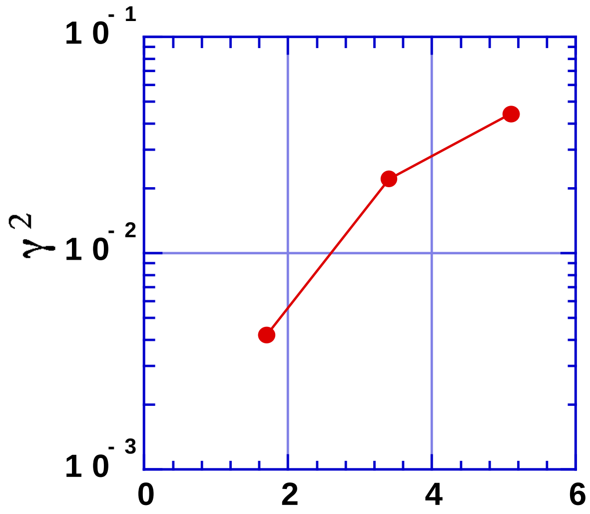
# Preliminary Analysis: RWM in JT-60SC

*JT-60SC*

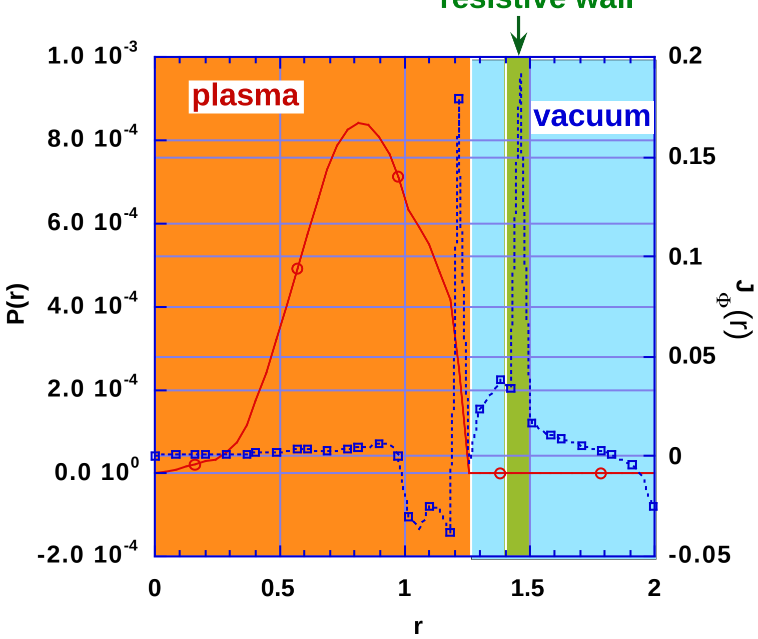
**JT-60SC Equilibrium of $\beta_N$=3.4**

**Resistive MHD calculation with resistive wall effects. (full set MHD model)**
**Vacuum is represented by pseudo-vacuum occupied by high resistive plasma**




Growth Rate



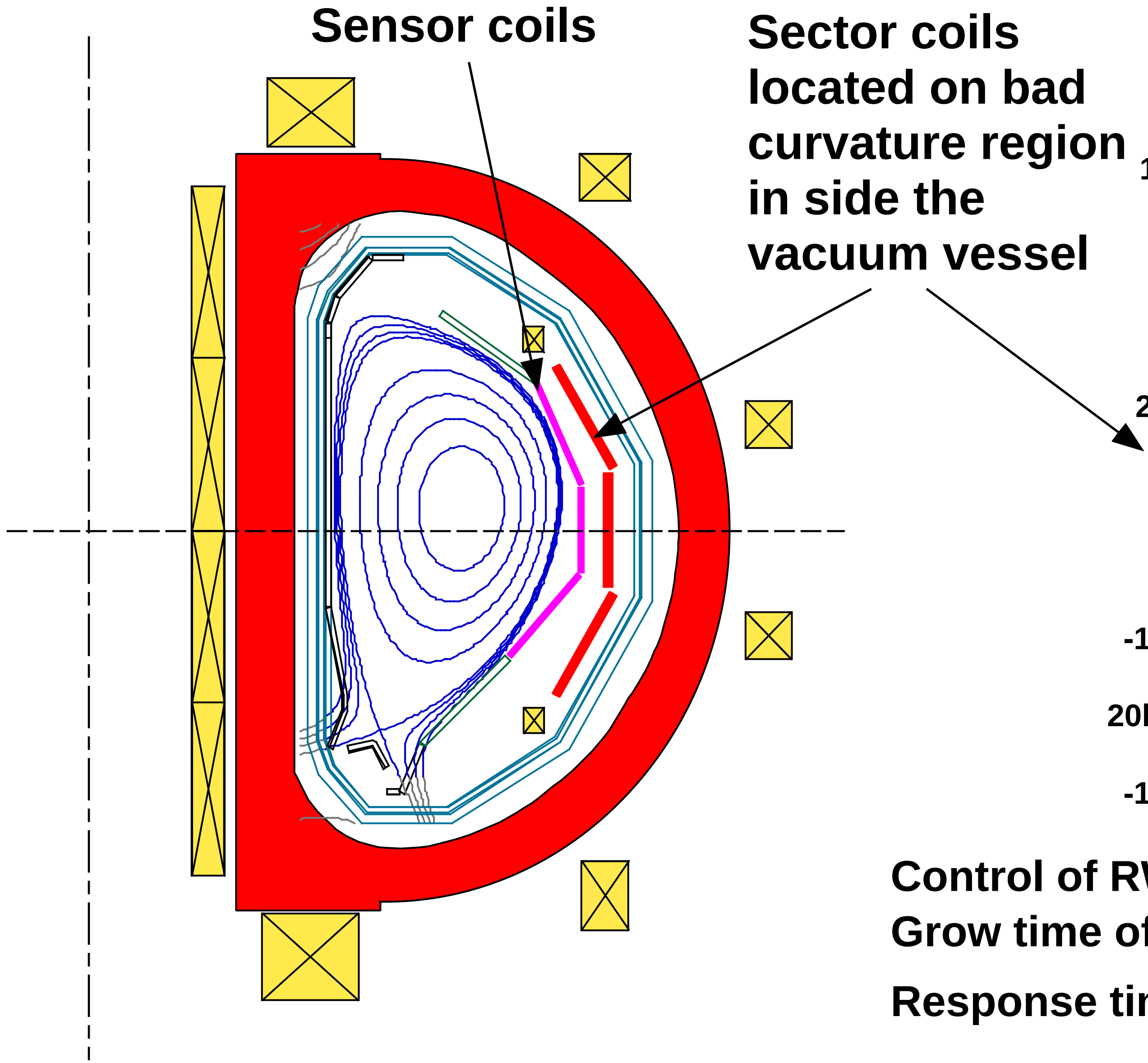

Eigen Function (m/n=4/1)

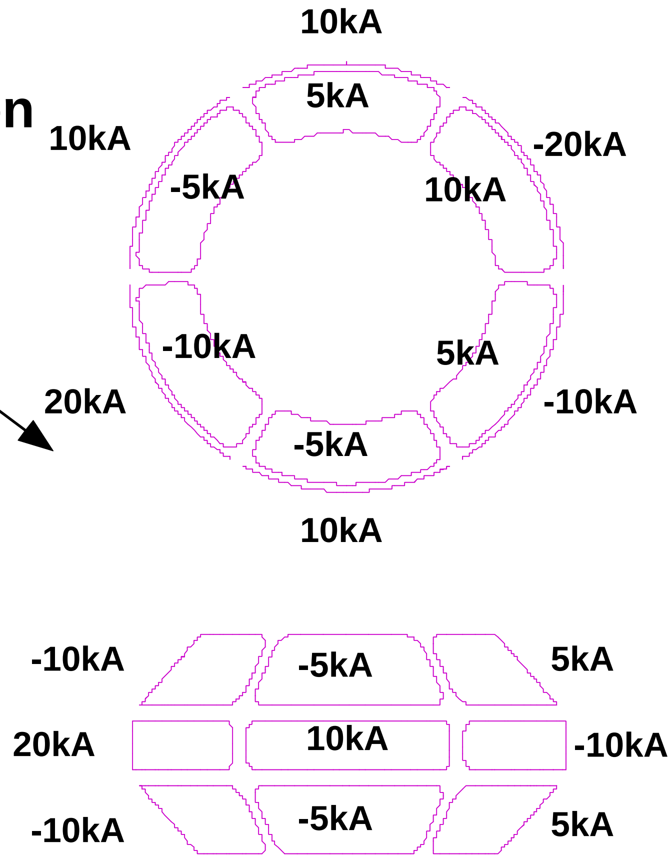
$r_{wall}$ / r=1.16

**Destabilization of RWM is confirmed.**

# Tool of RWM Stabilization

***JT-60SC***




**Control of RWM for n=1,2 modes**

**Grow time of RWM~$\tau_{wall}$~40ms**

**Response time of sector coils ~24ms<$\tau_{wall}$**

**Issue: Algorithm of real time feedback for stabilization**

# Neutral Point Analysis by TSC Simulation

***JT-60SC***

- **Vertical Displacement Event (VDE) induced during disruptions is suppressed by the neutral point.**

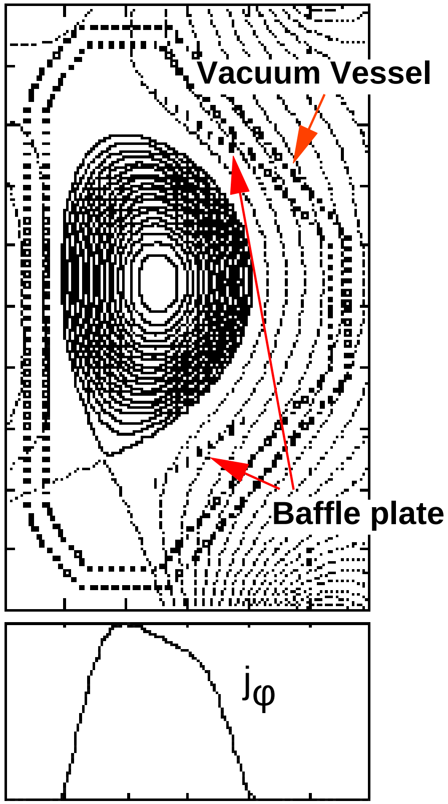
**• TSC Scimulation:**
**Standard Configuration of JT60-SC**

**Plasma**

$I_p$ = 3.0 MA,
($R_{mag}$, $Z_{mag}$) = (2.76 m, 0.20 m),
$l_i$ =0.97, $\beta_p$ = 0.001,
$\kappa$ =1.68, $\delta$ =0.43,
Vol = 51.9 $m^3$,
n-index= -1.3

**Resistive Shell**

**Double-Walled Vacuum Vessel + Up-Down Asymmetric Baffle Plate**



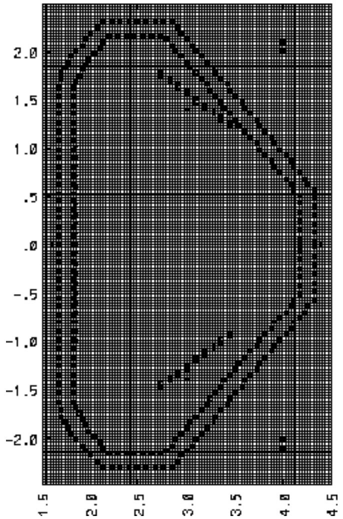

- **Ip-quench rate = ~ 21 $msec^{-1}$ ( ~ eddy current dacay rate of vacuum vessel)**
- **Baffle plate of JT60-SC is positioned upward by + 15 cm.**
- **Without any of active feedback**
- **Vertical shifts (dZ) were measured at 3 msec after the start of Ip-quench.**

# Neutral Point of JT-60SC

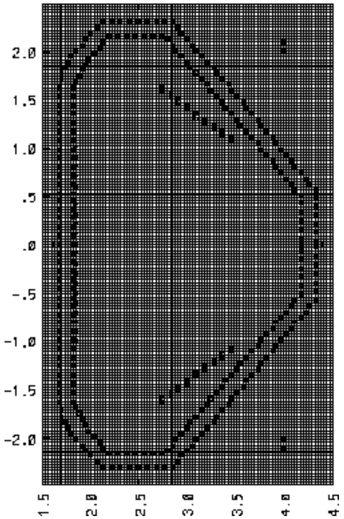
*JT-60SC*

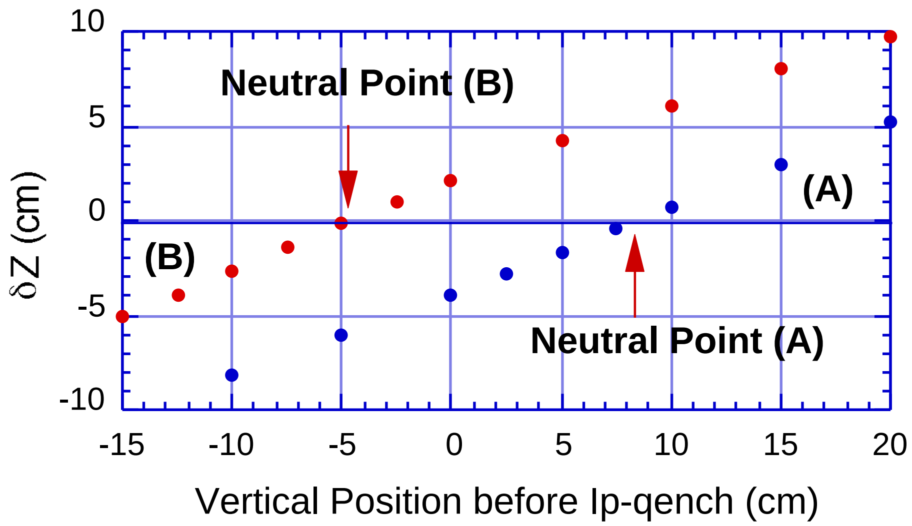
- **Neutral Point of JT60-SC**

**(A) Up-Down Asym. Baffle Plate**



**(B) Up-Down Sym. Baffle Plate**



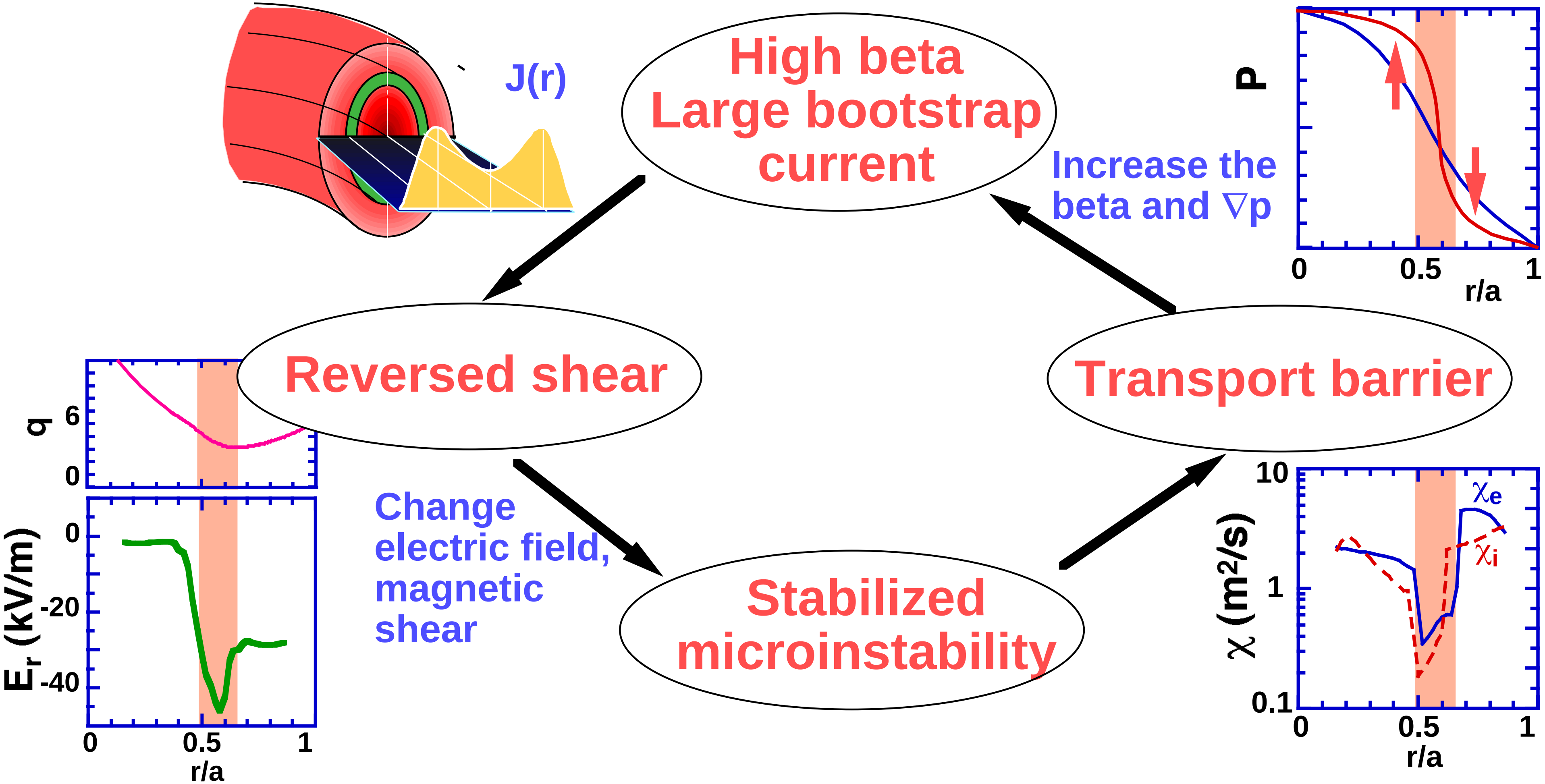



**Baffle plate mainly affects the vertical location of neutral point in JT60-SC.**

- **Neutral Point exists at ~ 8.0 cm above JT60-SC midplane.**
  **( ~ -12.0 cm below the plasma magnetic axis of the standard configuration)**
- **However, optimization of baffle plate design is required.**
- **Effects of plasma shape, current profile, equilibrium field structure on the location of Neutral Point are now under investigation.**

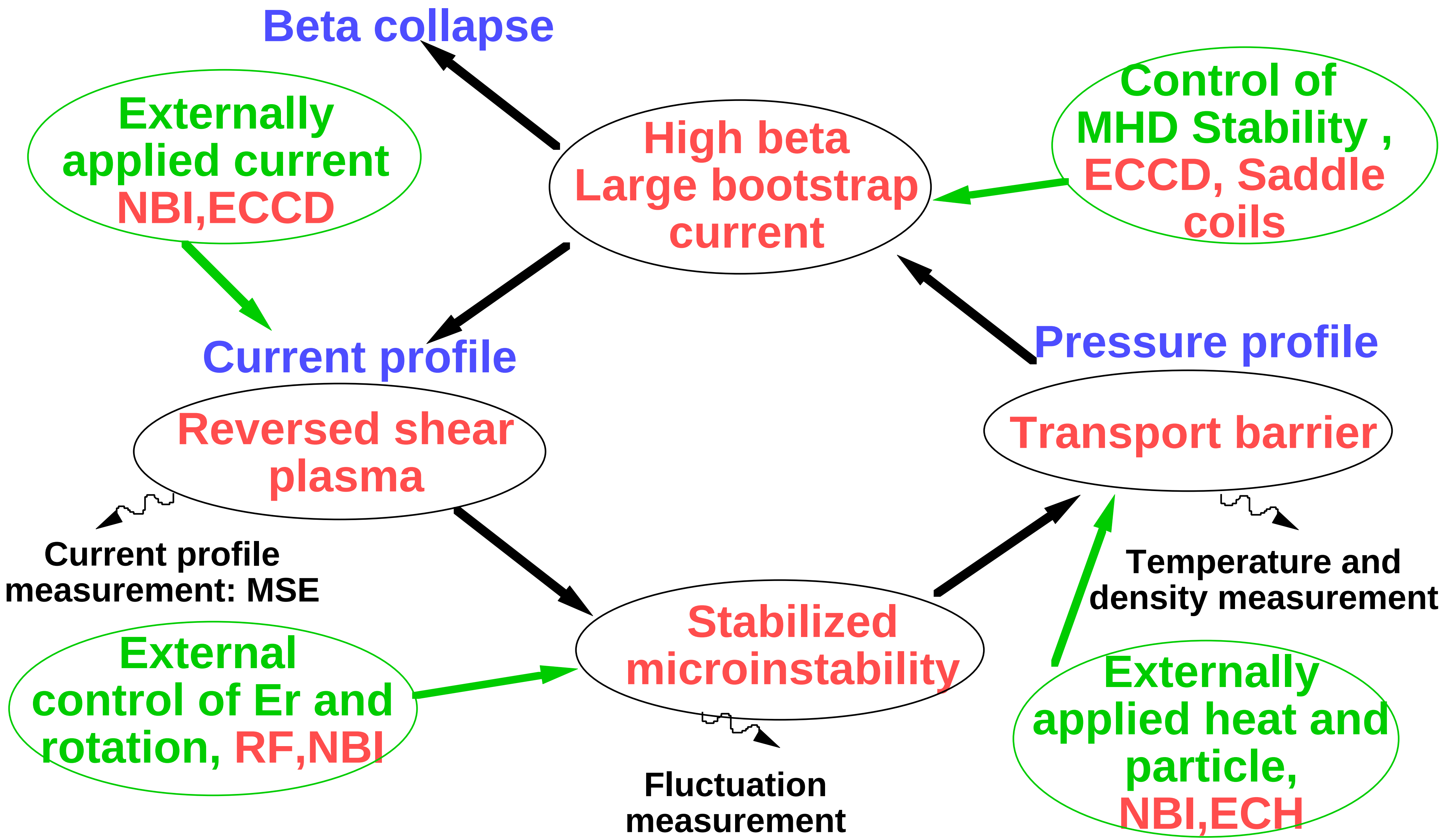
# Physics Issue of High beta and steady-state plasma

## "Intrinsic Positive Feedback" in the High Bootstrap Plasma



# Control of "Intrinsic Positive Feedback"

*JT-60SC*



# Can we obtain the good confinement with ITB in beta plasma, steadily?

***JT-60SC***

- In low beta plasma with low bootstrap current, correlations of each agent (element phenomena) is weak .

  **Answer is Yes.**

- In the steady state and high beta plasma, correlation of each agent with nonlinear characteristics is strong, which makes the chaos and the complexity.

  **Answer is question.**

# Summary

**Establish high beta in steady-state and high Bt plasma by**

- **utilization of high power and flexible NBI system, and ECH/ECCD,**
- **using the active feedback system of ECCD and saddle coils.**

**Exploit the new physics for steady-state plasma**

- **Nonlinear phenomena**
- **Chaos**
- **Complexity**