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Critical Beta Analyses of Low Aspect Ratio Tokamak

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Outline

- Purpose
- Equilibrium
  1) Slim-CS device
  2) Equilibrium plasma pressure profile
- Stability analyses
  1) Critical β analyses
  2) Aspect ratio dependence on critical β
  3) Critical β for bootstrap current dominant equilibria
  4) Effect of edge pedestal of plasma pressure
- Summary and remained issues

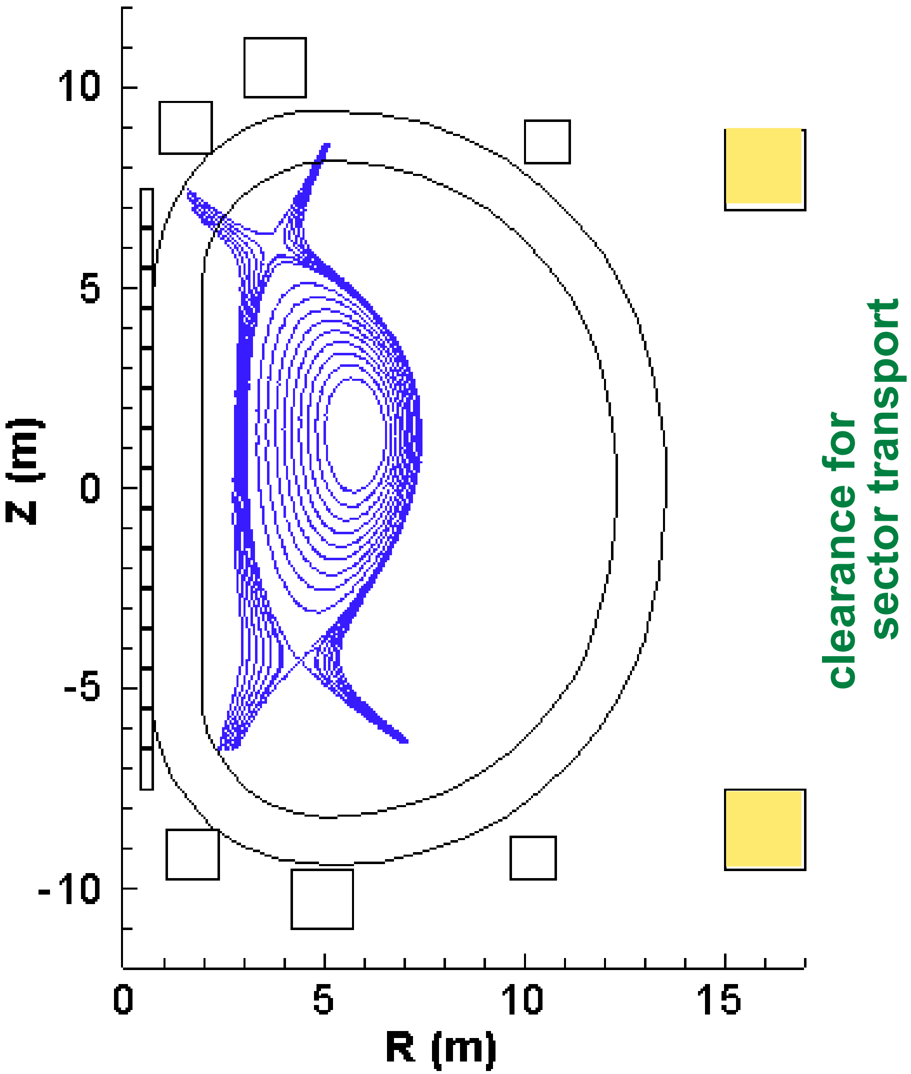
Purpose

- To give design guideline of Slim-CS by executing critical β analyses for equilibrium configuration that is presently adopted in the device

- These analyses include effects of aspect ratio, bootstrap current and also edge pedestal of plasma pressure.

- Equilibrium plasma pressure profiles are mainly determined by given plasma current profile and correlation function obtained by the data of JT-60 experiments with ITB.

Slim-CS Device



・Main parameters

Major radius R_p 5.5 [m]

Minor radius a 2.1 [m]

Aspect ratio A 2.6

On-axis Magnetic field B_T 6.0 [T]

Maximum field B_{max} 16.4 [T]

Plasma current I_p 16.7 [MA]

Fusion output P_{fus} 2.95 [GW]

Normalized beta β_N 4.3

Ellipticity κ_{95} 2.0

Triangurality δ_{95} 0.4

Equilibrium Plasma Pressure Profile

- **Equilibrium plasma pressure profiles are determined by given plasma current profile and correlation function.**
- **The correlation function is obtained by data of plasma pressure and current profiles of JT-60 experiments**

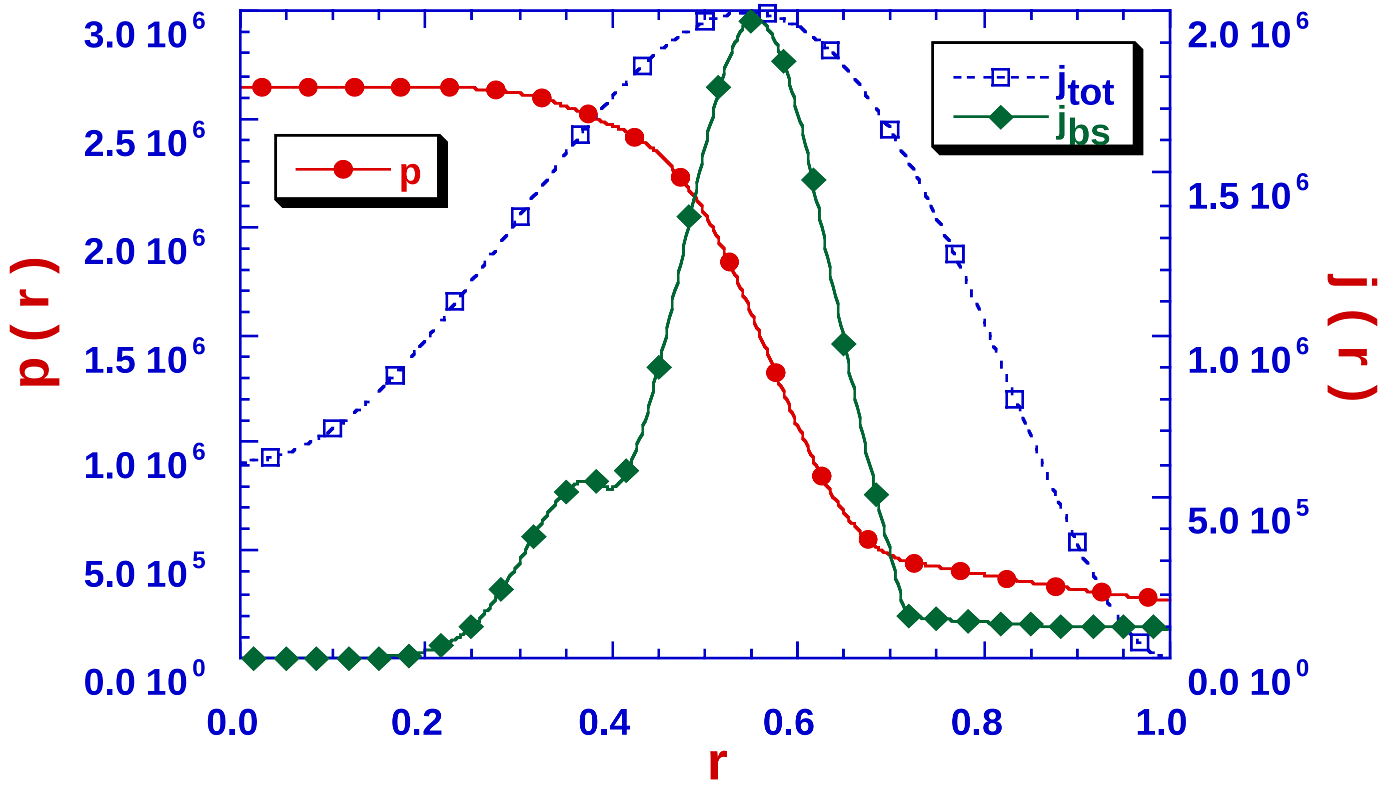
- **Correlation relation**

$$\frac{dp/dr}{p(r)} = F(S) \Rightarrow p(r) = \exp\left(-\int_0^r F(S)dr'\right)$$

$$S = r\,\frac{dq/dr}{q(r)} \qquad \beta_p \Rightarrow p(0)\ \ \&\ \ I_p = J_0$$

Equilibrium plasma current and pressure profiles

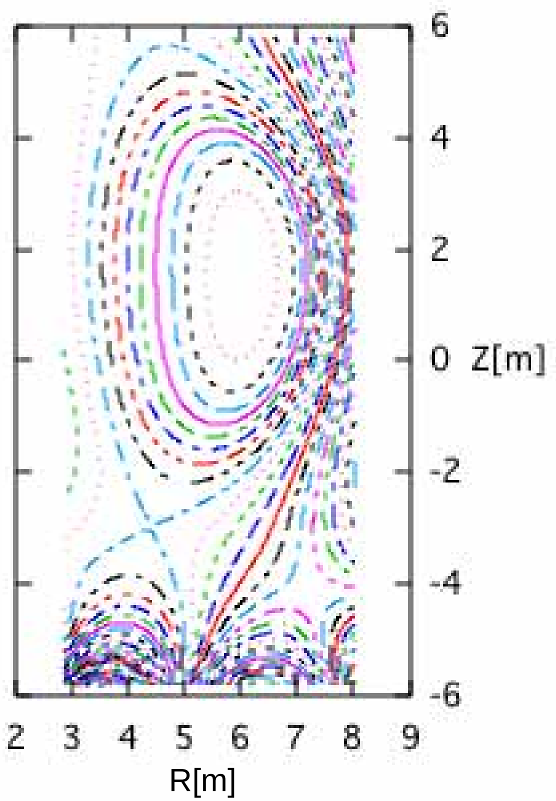
- **Plasma current profile** : $j(r) = j_0[(1- r^2)^2 - 0.95\ (1- r^2)^3]$



- The bootstrap current profile driven by pressure profile with internal transport barrier (ITB) becomes current hole like.

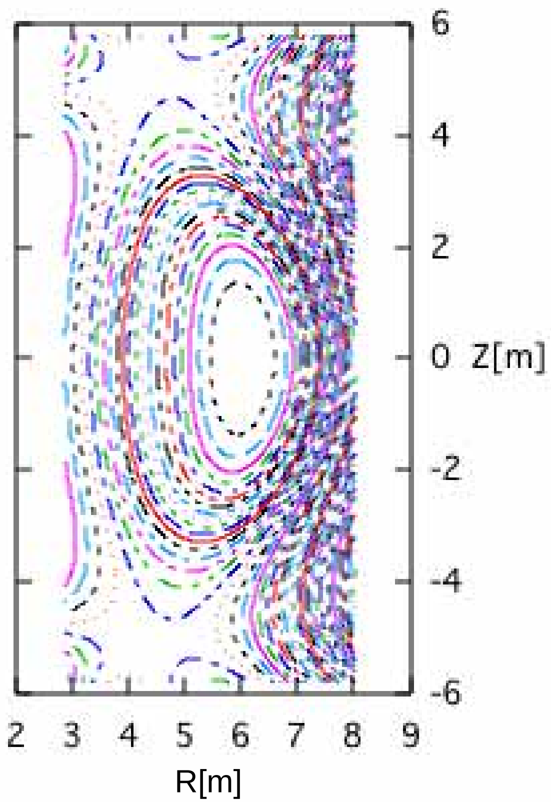
Comparison between Up-Down Asymmetric and Symmetric Equilibria

- **Equilibria are calculated by MEUDAS equilibrium code**



RAXIS = 6.03694
ZAXIS = 1.58113
RMAJ = 5.45028
RPLA = 2.14310
RPMAX = 7.59338
RPMIN = 3.30718
VOLUME= 911.27550
ELLIP = 2.00404
TRIG = 0.41030
EL95 = 1.88866
ELIPUP= 1.89997
TRIGUP= 0.35172
ELIPDW= 2.10811
TRIGDW= 0.46888
TRUP95= 0.26737
TRDW95= 0.26268
LI = 0.62644

Up-Down Asymmetric Equilibrium



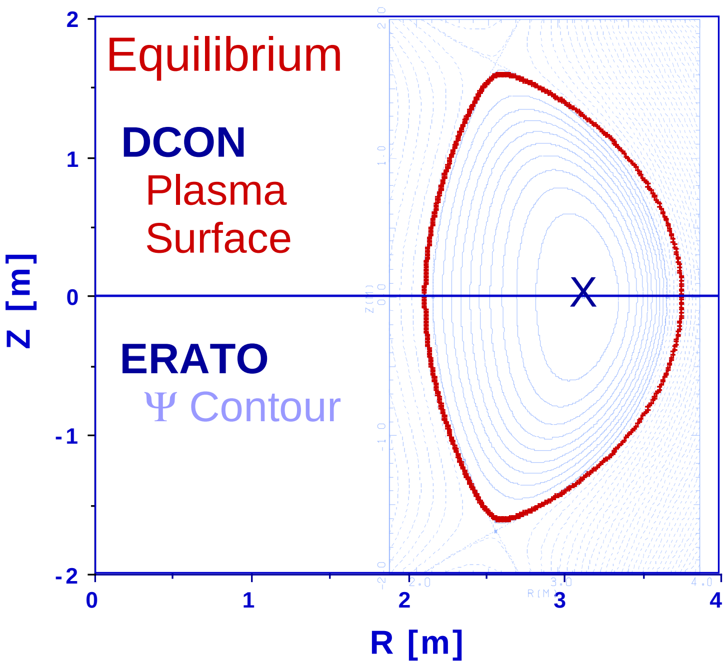
RAXIS = 6.04333
ZAXIS = 0.00000
RMAJ = 5.45580
RPLA = 2.13650
RPMAX = 7.59230
RPMIN = 3.31930
VOLUME= 938.38318
ELLIP = 2.18328
TRIG = 0.30469
EL95 = 2.00981
ELIPUP= 2.18328
TRIGUP= 0.30469
ELIPDW= 2.18328
TRIGDW= 0.30469
TRUP95= 0.22969
TRDW95= 0.22969
LI = 0.61284

Up-Down Symmetric Equilibrium

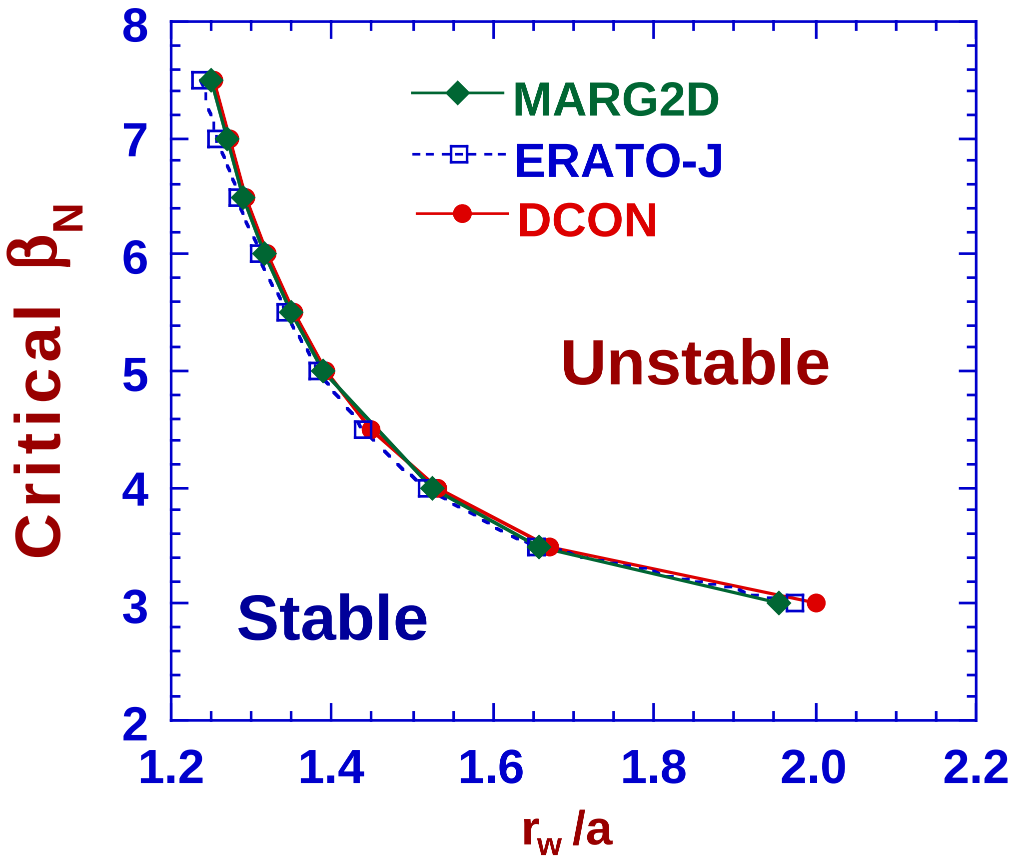
- **Symmetric equilibria are made of lower part of asymmetric ones.**

Benchmark Test of MHD Stability Codes

- Conformal ideal wall
- Toroidal mode number: n=1



Equilibrium Configuration (JT-60SC)

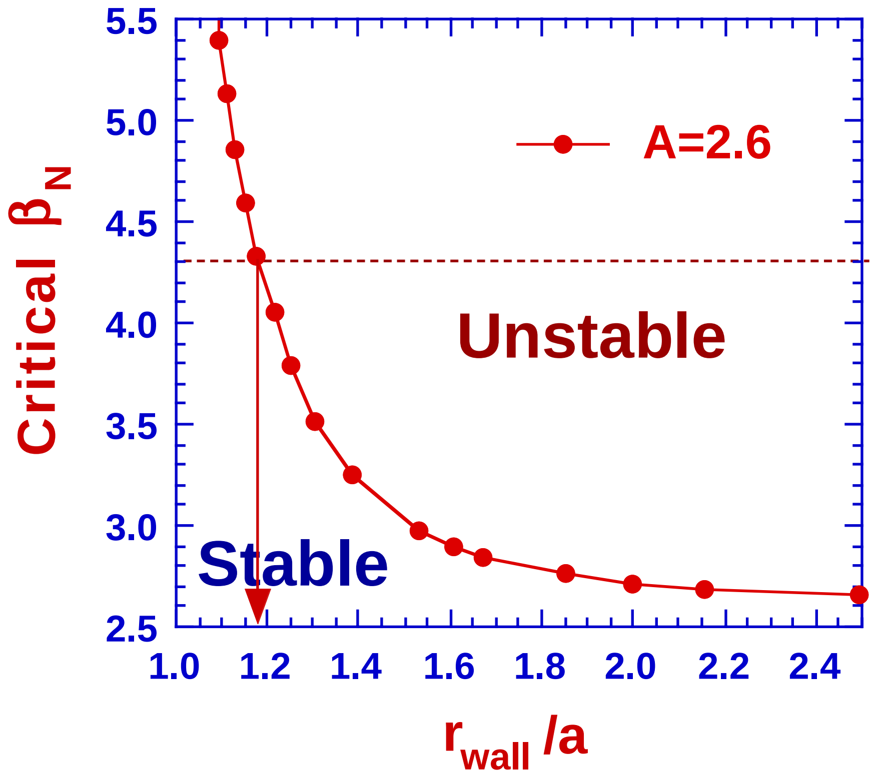


Stability Diagram

- 3 MHD Stability codes show almost the same critical beta values for JT-60SC up-down symmetric equilibria.

Critical β Analyses using MARG2D Code

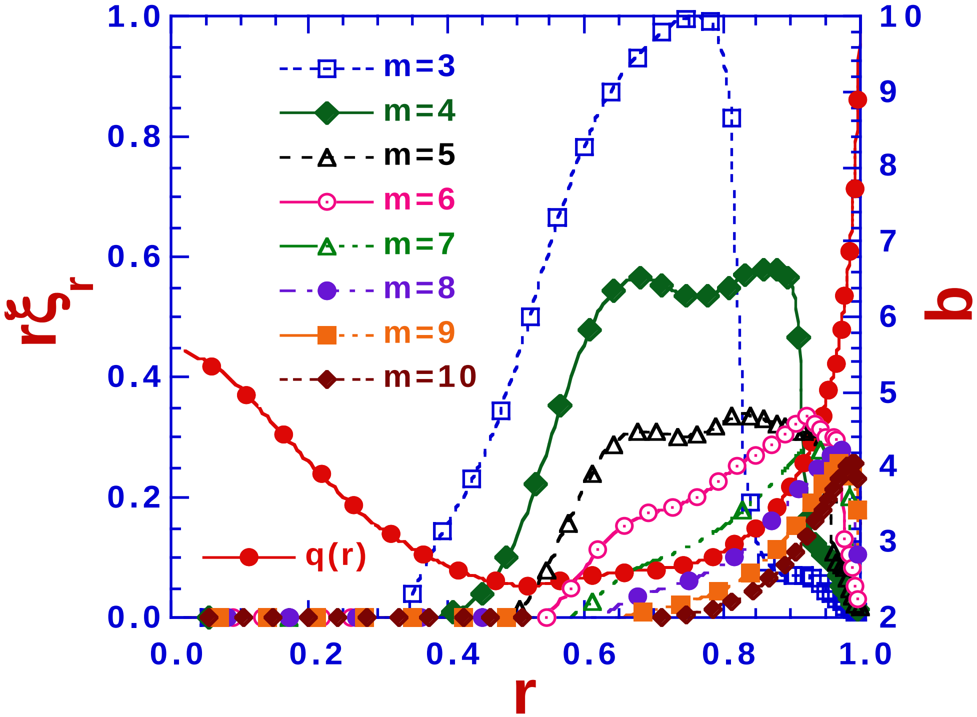
- Conformal ideal wall
- Toroidal mode number
  : n=1



Stability Diagram for up-down symmetric Slim-CS equilibria

- The position of r_{wall} must be less than 1.2a for β_N=4.3 of Slim-CS plasma to be stable for the equilibrium of plasma current and pressure profiles with ITB of JT-60 experiments.

Typical Eigen Functions : β_N=4.3



- Toroidal mode number : n=1

ξ_r : Plasma normal displacement

q : Safety factor

m : Poloidal mode number

- Stabilizing effect of conducting wall is small, because (m=3) internal mode is most unstable and dominant mode.

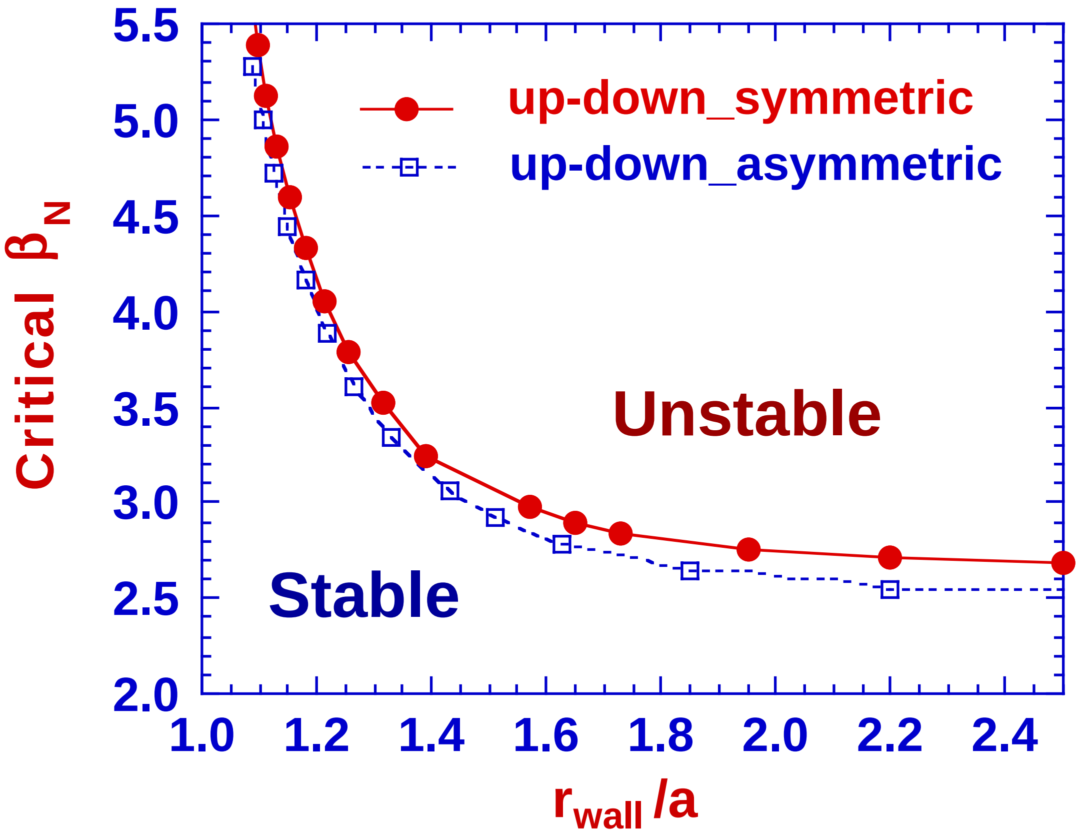
 ---> low critical β_N value

- If q_{min} becomes less than 2, m=2 internal mode becomes unstable, and the value of critical β_N further reduces.

Comparison of Critical β_N between Up-Down Symmetric and Asymmetric Equilibria

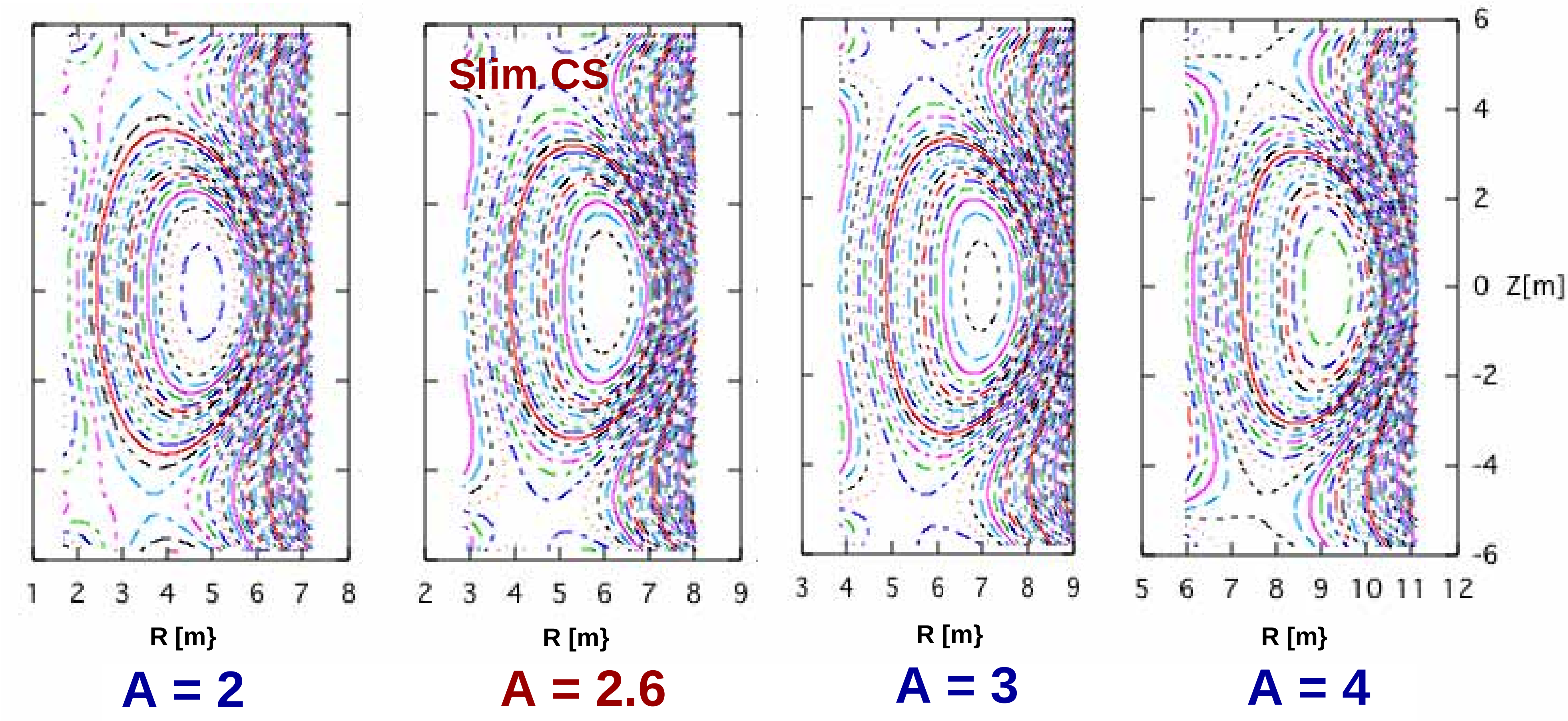
- Conformal ideal wall
- Toroidal mode number : n=1

- A=2.6 : Slim CS case



- Almost the same curves of critical β_N are obtained between up-down symmetric and asymmetric equilibria.

Contours of Poloidal Magnetic Flux for Different Aspect Ratio Equilibria : β_N=4.3



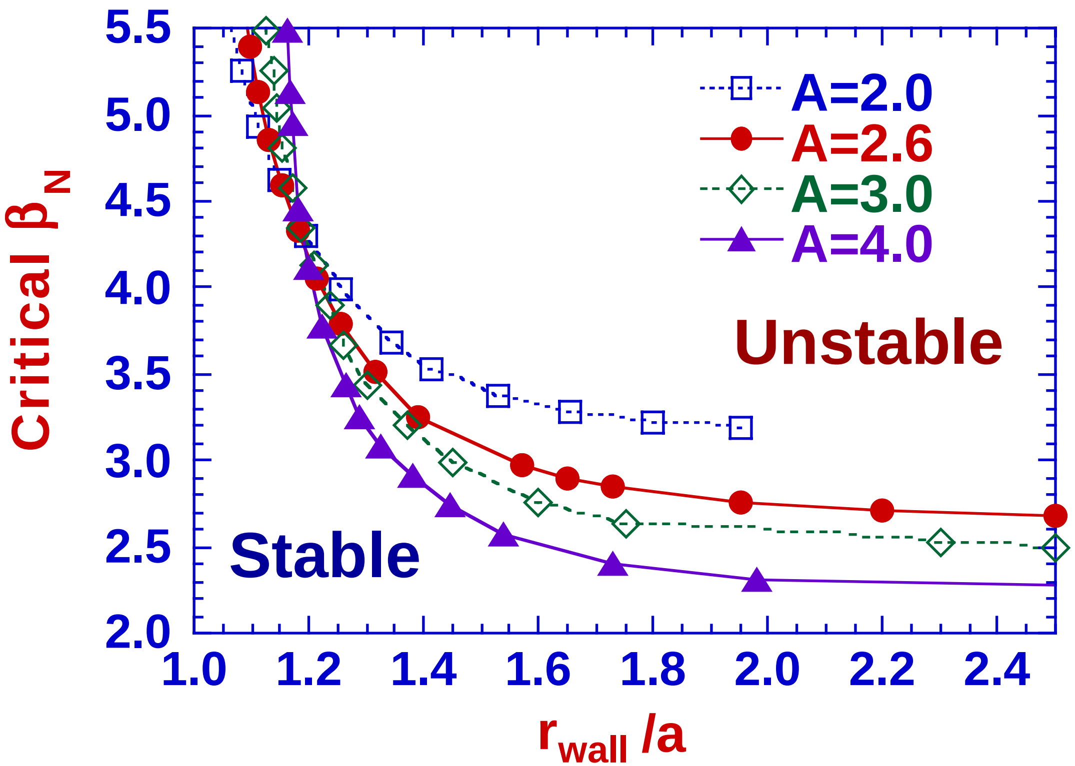
• Only the major radius increases as the aspect ratio increases.

Critical β_N vs.Wall Position for 4 Aspect Ratio Cases

- Equilibria for each aspect ratio are calculated with the following condition:

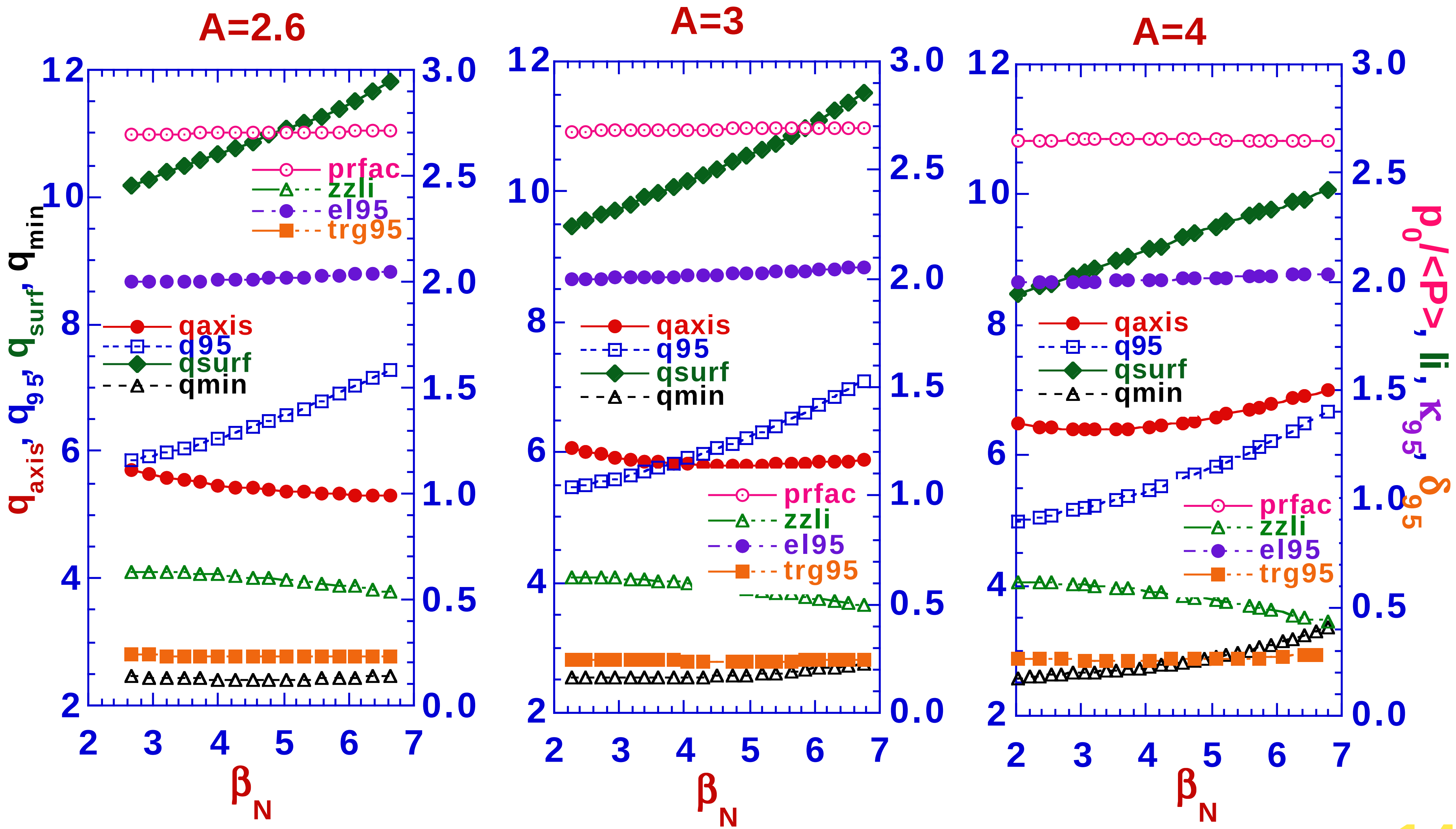
  - $R_p I_p$ = const.

  to keep almost the same safety factor values.



- Critical beta value for no wall case are higher for lower aspect ratio cases, however, they become to be lower if the ideal wall is placed near the plasma surface for these equilibria of fixed plasma current and pressure profiles.

Comparison of Dependency of Equilibrium Values on β_N



- Main difference in dependency on β_N appears in q_{min} values.

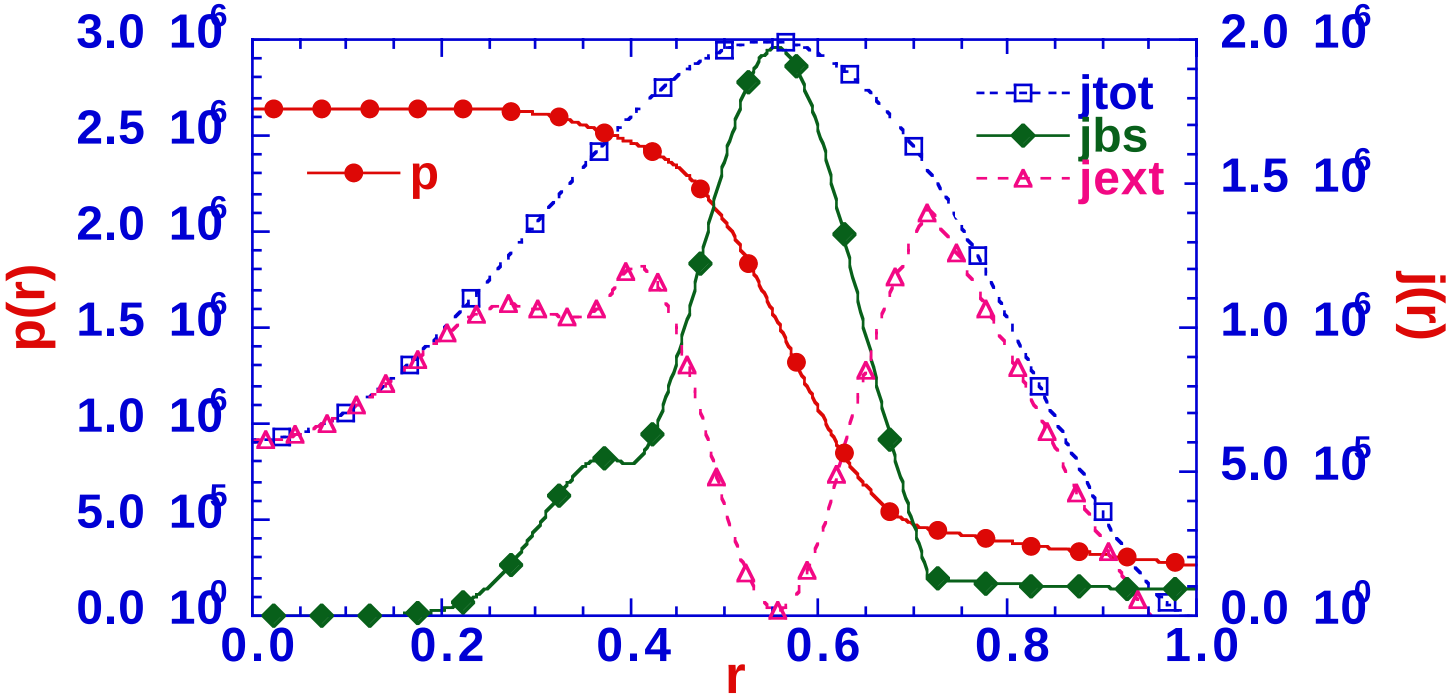
Brief Explanation for Previous Result

- **Inverse phenomenon of aspect ratio dependency of critical β_N appeared for small wall position is attributed to increment of q_{min} for high aspect ratio plasma, that is, increment of q_{min} stabilizes the MHD mode in spite of increment of beta.**

----> If we make the value of q_{min} to be fixed for all case, we can always get higher critical β_N for lower aspect ratio plasma with ITB .

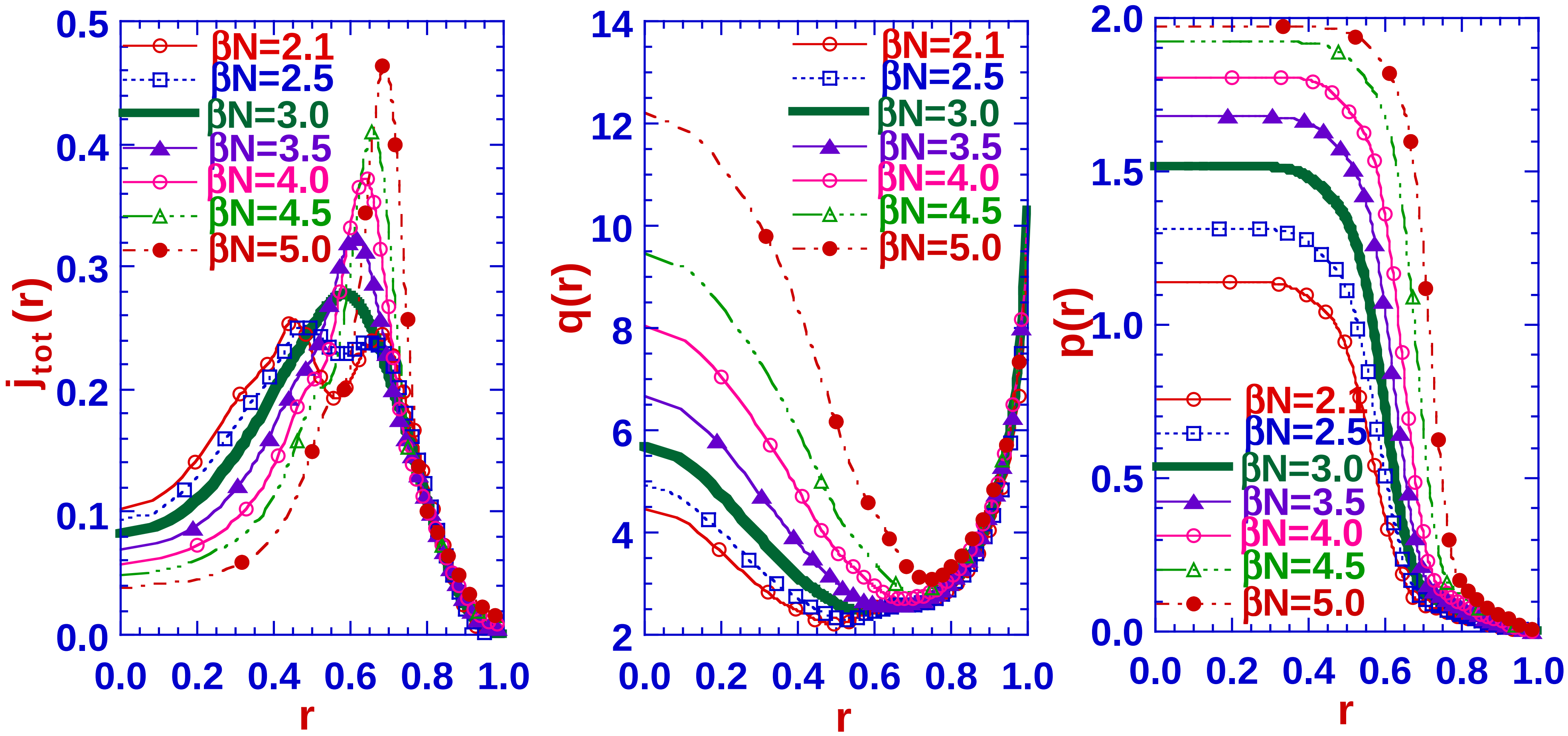
Bootstrap Current Dominant Equilibria

- Plasma current and pressure profiles for equilibrium of β_N = 3 (A=2.6)



- Total plasma current is calculated by : $j_{tot}(r) = j_{bs}(r) + \alpha\, j_{ext}(r)$, where j_{bs} is bootstrap current for each β_N, and j_{ext} is externally driven current, whose profile is fixed to β_N=3 equilibrium, and α is a constant value determined by the condition of total plasma current constant.

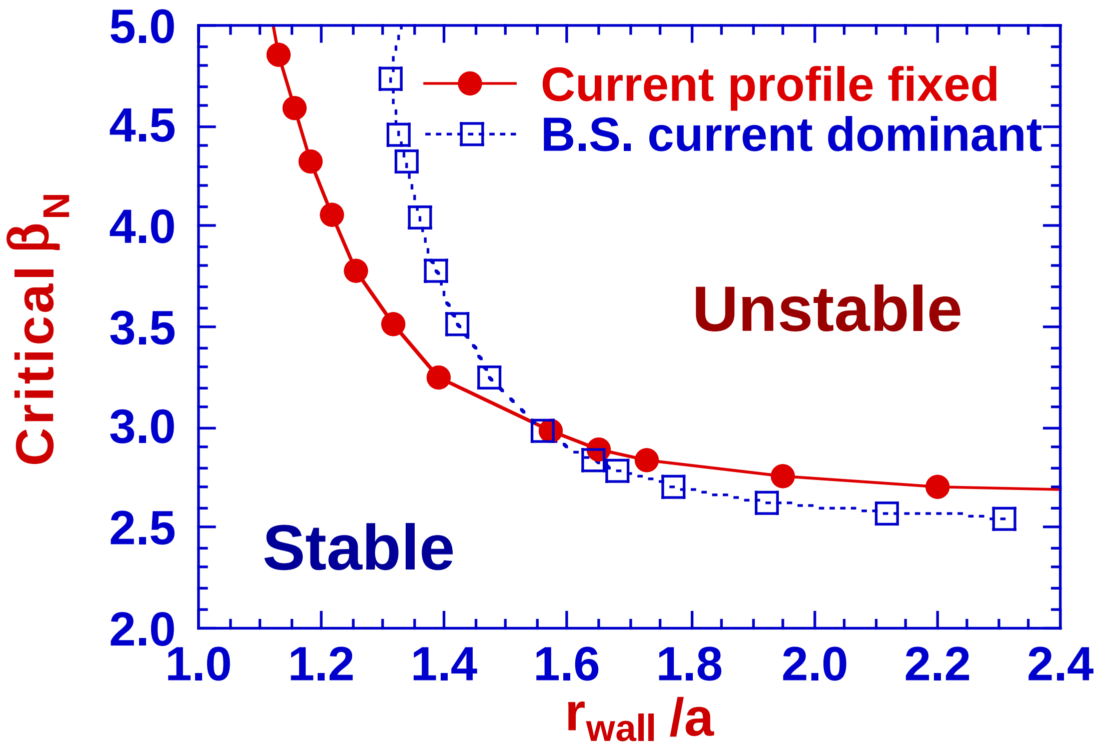
Change of Plasma Current and Safety Factor Profiles due to Increase of Plasma Pressure



- As plasma pressure increases, central value of plasma current decreases, and values of central q and also q_{min} increase.

Critical β_N Analyses for Bootstrap Current Dominant Equilibria

- Conformal ideal wall
- Toroidal mode number
  : n=1
- A=2.6
- Up-down symmetric
  equilibria



- The wall position necessary to keep critical β_N of 4.3 in Slim-CS plasma changes from 1.2a in current profile fixed case to 1.34a in this case because of increment of q_{min} within ITB region.

Equilibria with Edge Pedestal of Plasma Pressure

- Following index, ep_i, for amount of edge pedestal is used in these analyses:

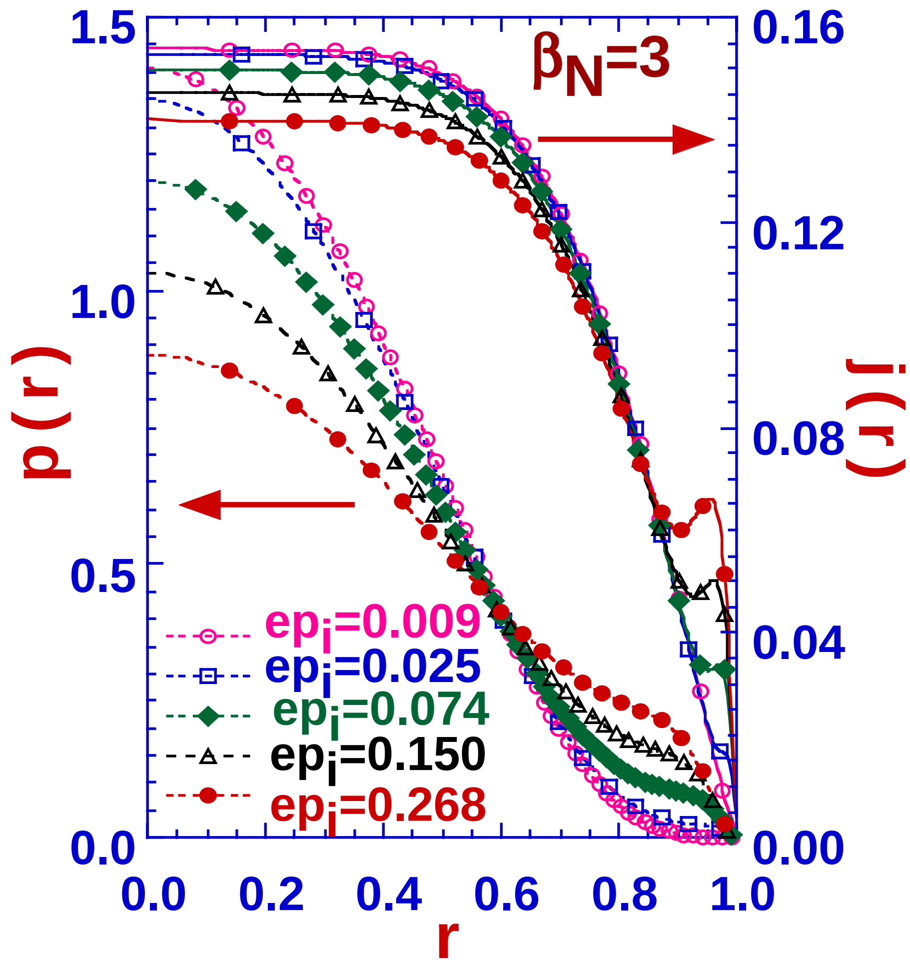
  $$ep_i = p(0.9)/p(0)$$

- Plasma current and pressure profiles are given by:

  $$j(\Psi) = j_0 \left[(1-\Psi^{a1})^{b1} - c\Psi^{d} \ln(\Psi)\right]$$

  $$\frac{dp}{d\Psi}(\Psi) = p_0 \left[(1-\Psi^{a2})^{b2} - c\Psi^{d} \ln(\Psi)\right]$$

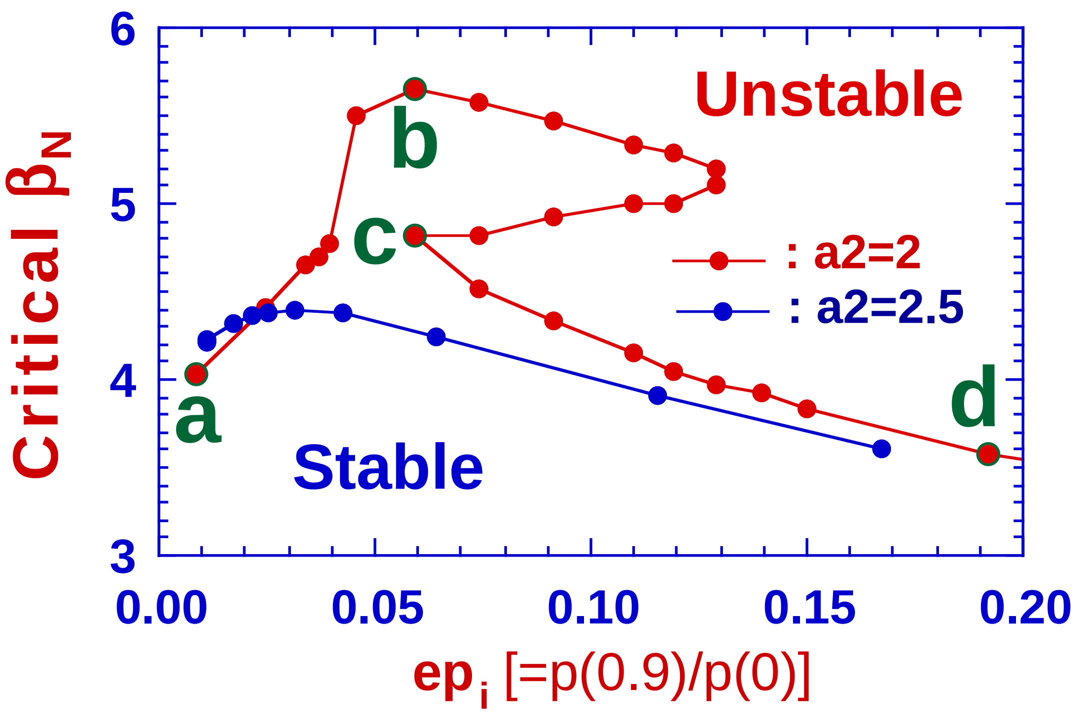
  where second terms represent the edge pedestal effect and parameter **d** determines the index ep_i.



- It is expected that increment of edge plasma pressure increases critical β value by the reduction of internal plasma pressure gradient, until the edge plasma pressure gradient induces the instability.

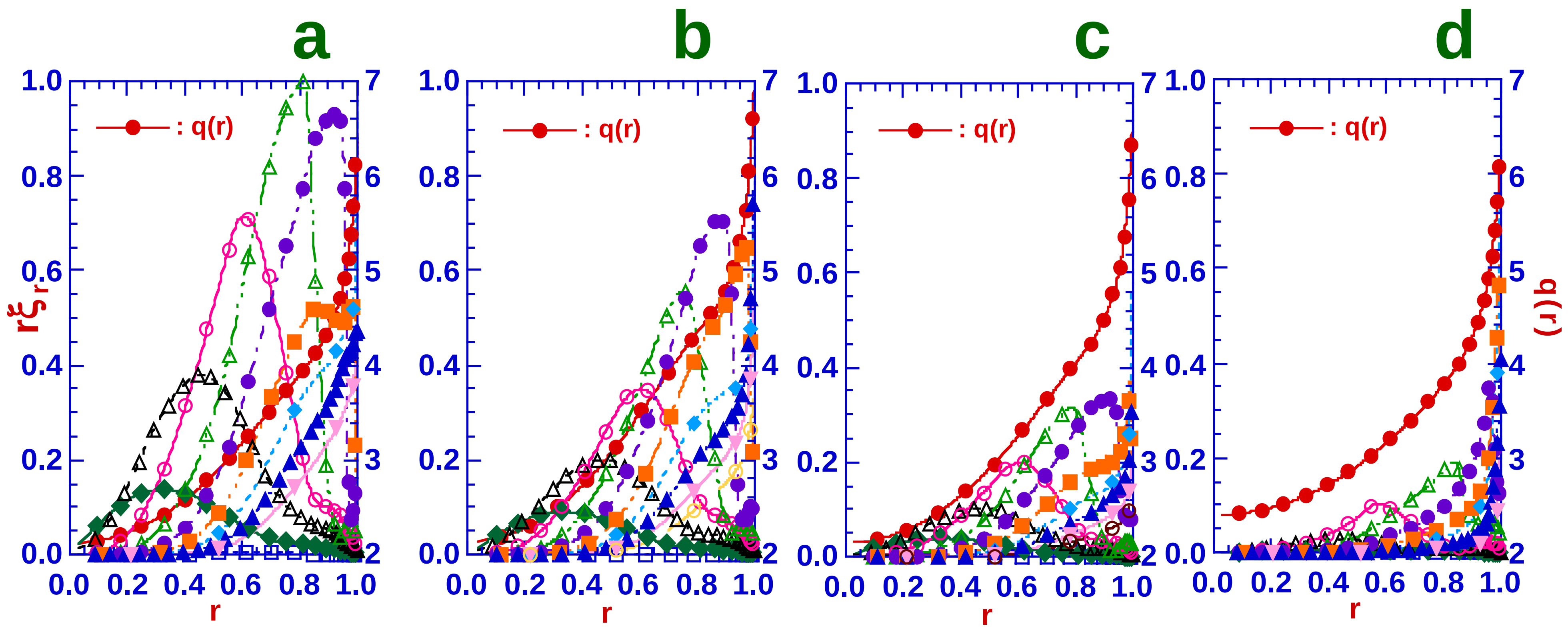
Effect of Edge Pedestal on Critical β_N

- Conformal ideal wall
- Ideal wall position
  : $r_{wall}/a=1.3$
- Toroidal mode number
  : n=1
- Up-down symmetric equilibria



- We obtain the expected critical beta vs. ep_i curve for the pressure profiles of a2=2.5, while the new stability region appears for more peaked pressure profiles of a2=2.
- Eigenfunctions for the points a,b,c and d in the figure are shown in the next view graph.

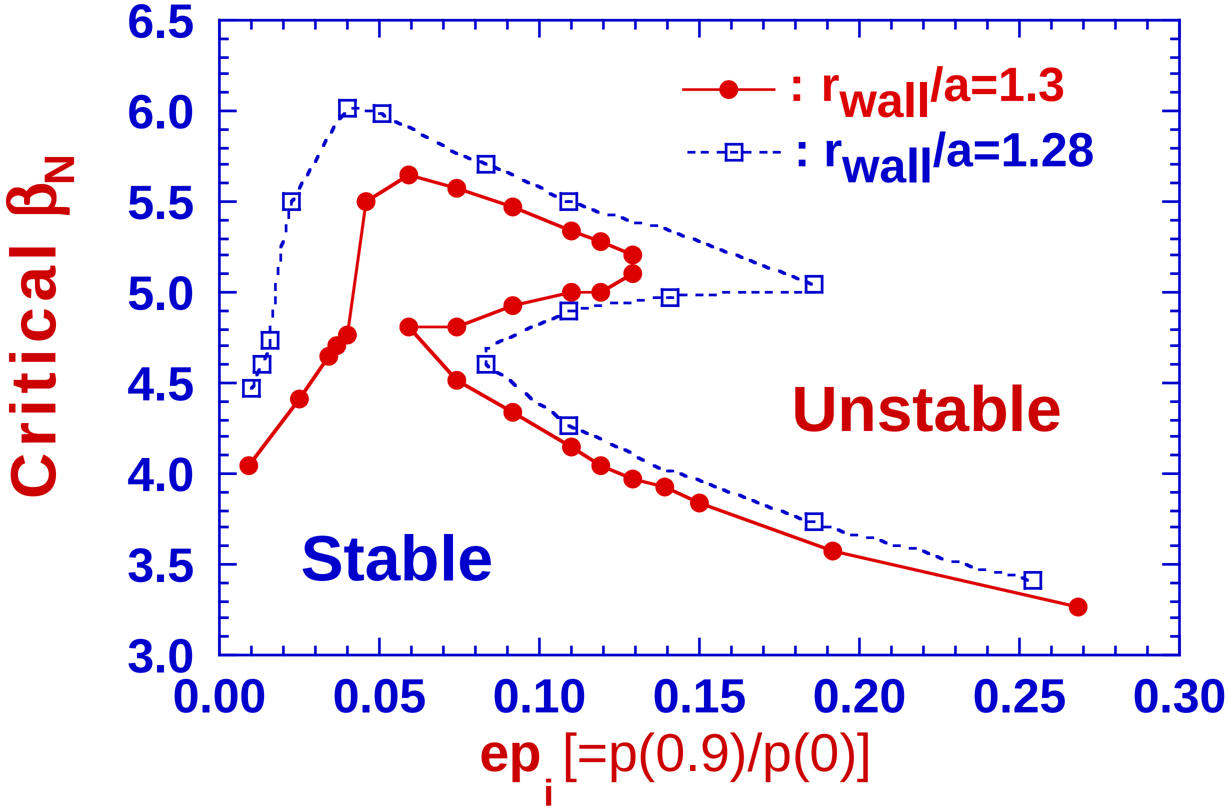
Eigen Functions for Points a, b, c and d in the Stability Diagram



- Eigen functions of plasma radial displacement change from a) beta collapse internal mode type to d) edge localized surface mode type as edge pedestal pressure increases.

Effect of Ideal Wall Position on Critical β_N with Edge Pedestal of Plasma Pressure

- Conformal ideal wall
- Toroidal mode number
  : n=1
- Up-down symmetric equilibria



- Appeared stable region by the increase of edge pedestal of plasma pressure is enlarged, if we can place the ideal wall closer to the plasma .
- Further investigations are needed for these analyses.

Summary

- The position of r_{wall} must be less than 1.2a for β_N=4.3 of Slim-CS plasma to be stable for the equilibrium plasma current and pressure profiles with ITB of JT-60 experiment. The wall position necessary to keep critical β_N of 4.3 changes to 1.34a for bootstrap dominate equilibria because of increment of q_{min} value.

  ---> q_{min} value within ITB region plays a crucial role for critical β_N value of ITB plasma.

- Increment of edge pedestal plasma pressure increases the critical beta value, until the surface bootstrap current due to the gradient of edge pedestal plasma pressure induces the current driven MHD instability.

Remained Issues

- To calculate critical beta for higher modes of n, greater than 1.

- To obtain higher normalized beta values for Slim-CS tokamak with Internal Transport Barrier, following issues are considered.

  - To investigate the effect of high ellipticity, that is the advantage of low aspect ratio tokamak
  - To optimize plasma current and pressure profiles