March 5~7, 2008
UCSD, La Jolla

US/Japan Workshop on
Fusion Power Plants and Related Technologies
with participation of EU

Critical Beta Analyses of Low Aspect Ratio Tokamak

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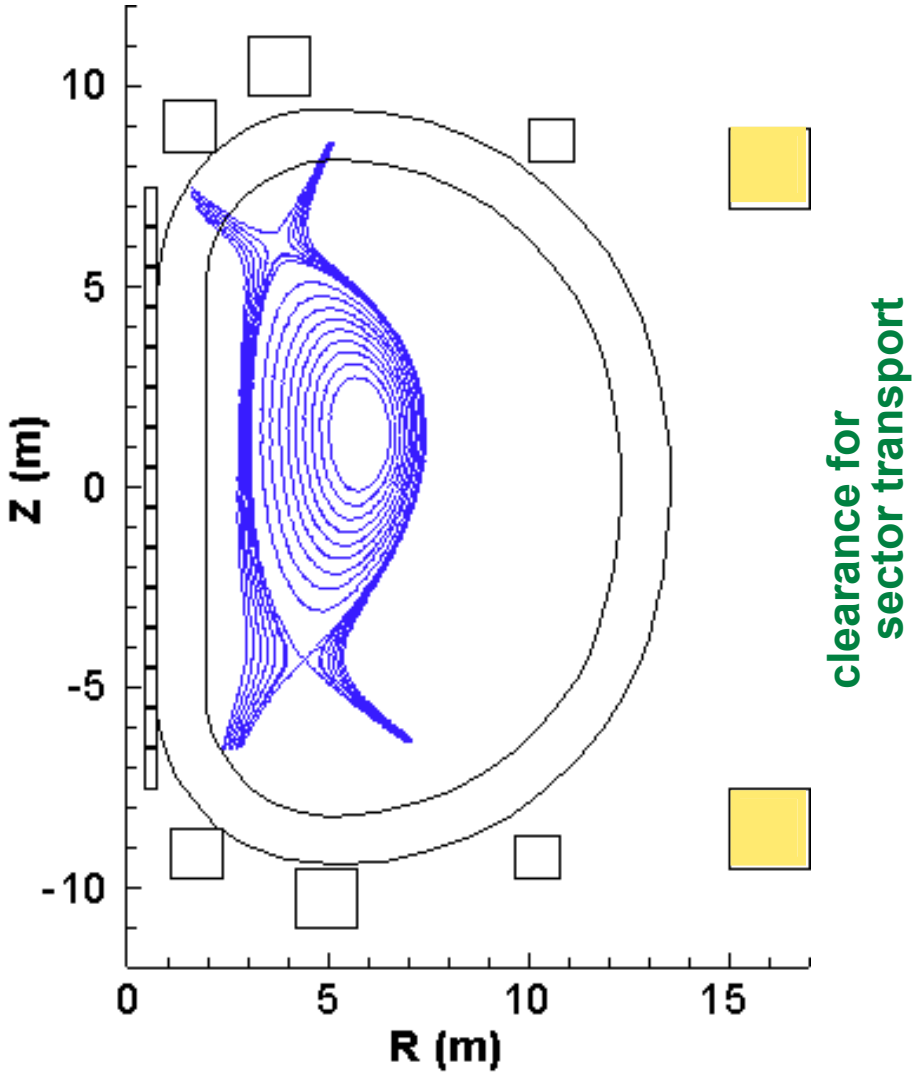
Outline

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

Purpose

- To give design guideline by executing critical beta analyses for equilibrium configuration that is presently adopted in Slim-CS device
- In these analyses, equilibrium plasma pressure profiles are determined by plasma current profile and correlation function obtained by JT-60 experiments with ITB. Dependence of critical β_N on aspect ratio for these equilibria are also investigated.
- Critical β for bootstrap current dominate Slim-CS (A=2.6) equilibrium is analyzed.

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

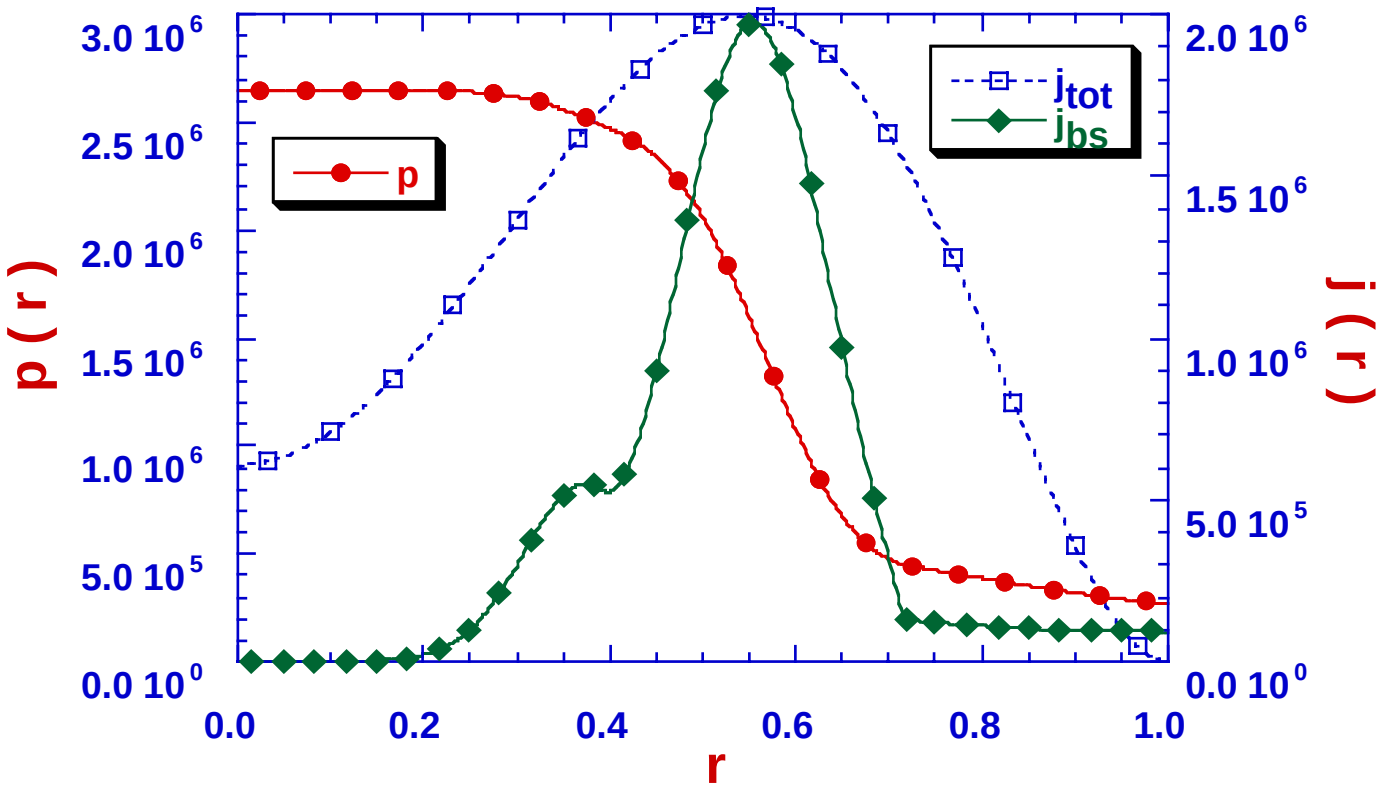
- Correlation relation

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

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

Equilibrium plasma current and pressure profiles

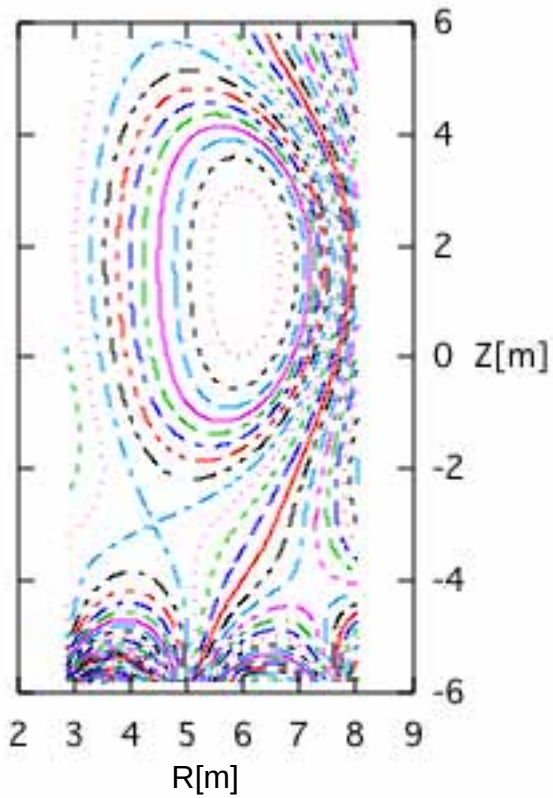
- **Plasma current profile** : $j(r) = j_0[(1- r^2)^2 - 0.95\,(1- r^2)^3]$



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

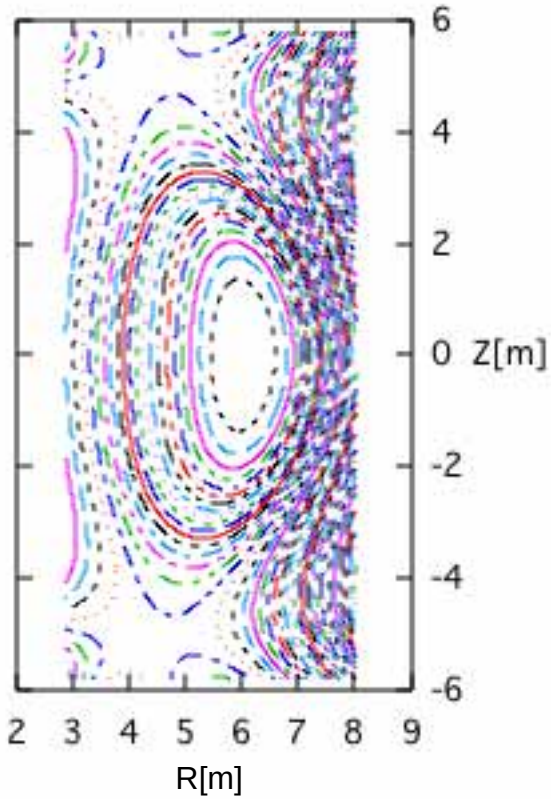
Comparison between Up-Down Asymmetric and Symmetric Equilibria

- 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



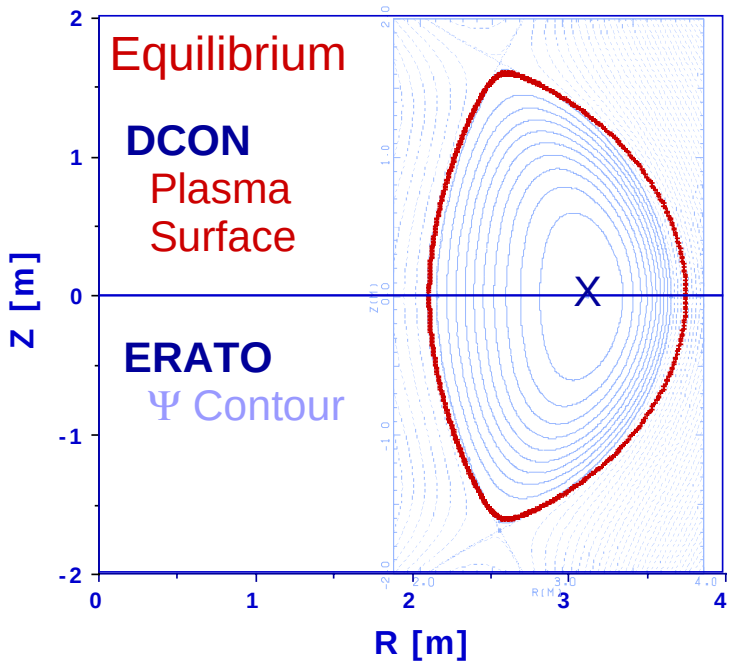
RAXIS = 6.04333
ZAXIS = 0.00000
RMAJ = 5.45580
RPLA = 2.13650
RPMAX = 7.59230
RPMIN = 3.31930
VOLUME= 938.38318
ELLIP = 2.18328
TRIG = 0.30469
EL95 = 2.00981
ELIPUP= 2.18328
TRIGUP= 0.30469
ELIPDW= 2.18328
TRIGDW= 0.30469
TRUP95= 0.22969
TRDW95= 0.22969
LI = 0.61284

Up-Down Symmetric Equilibrium

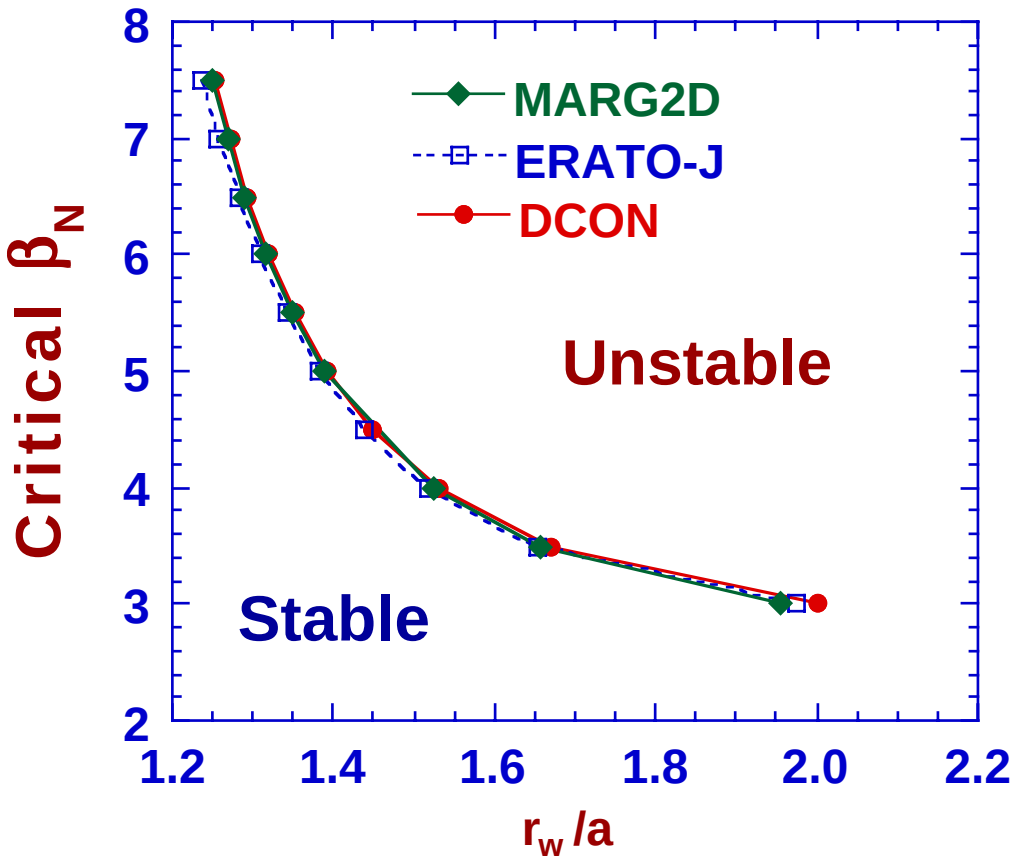
- Symmetric equilibria are made of lower part of asymmetric ones.

Benchmark Test of MHD Stability Codes

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



Equilibrium Configuration (JT-60SC)

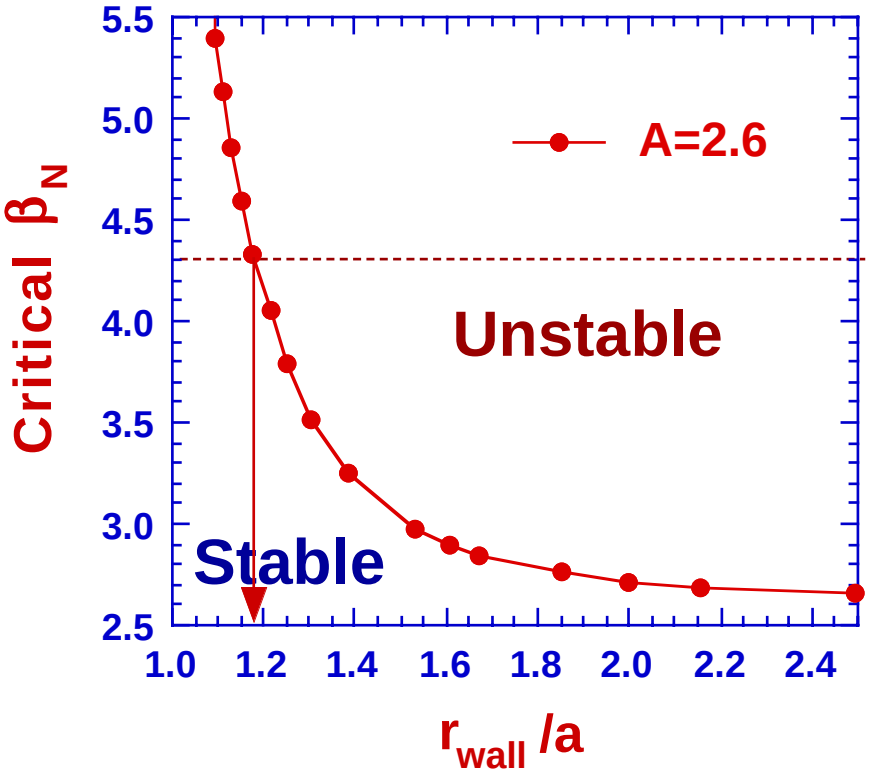


Stability Diagram

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

Critical β Analyses using MARG2D Code

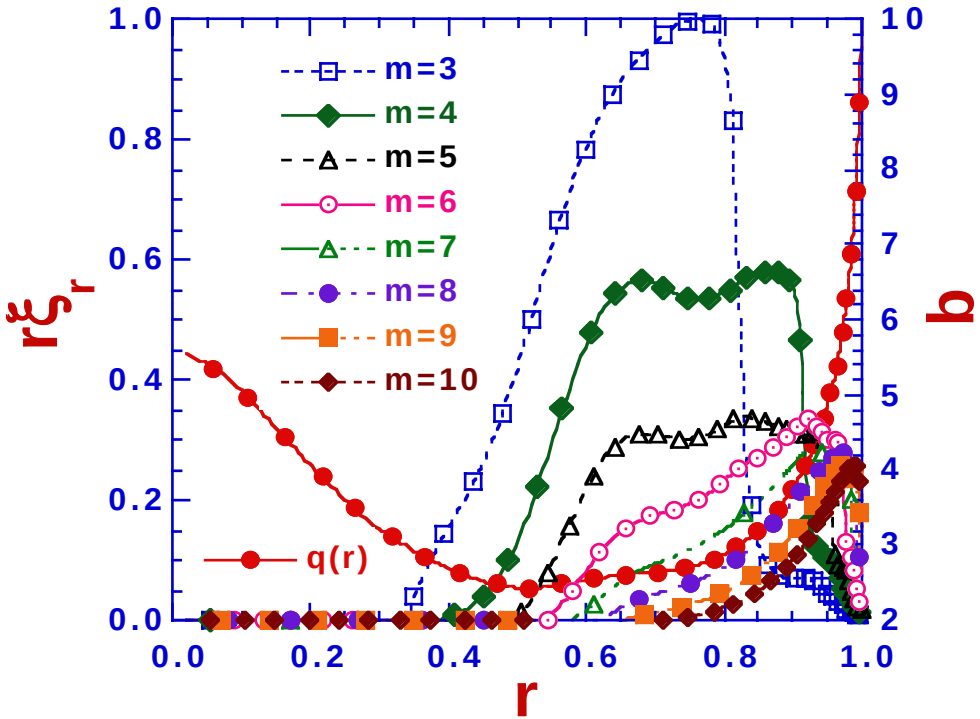
- Conformal ideal wall
- Toroidal mode number : n=1



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 Eigenfunctions : 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.

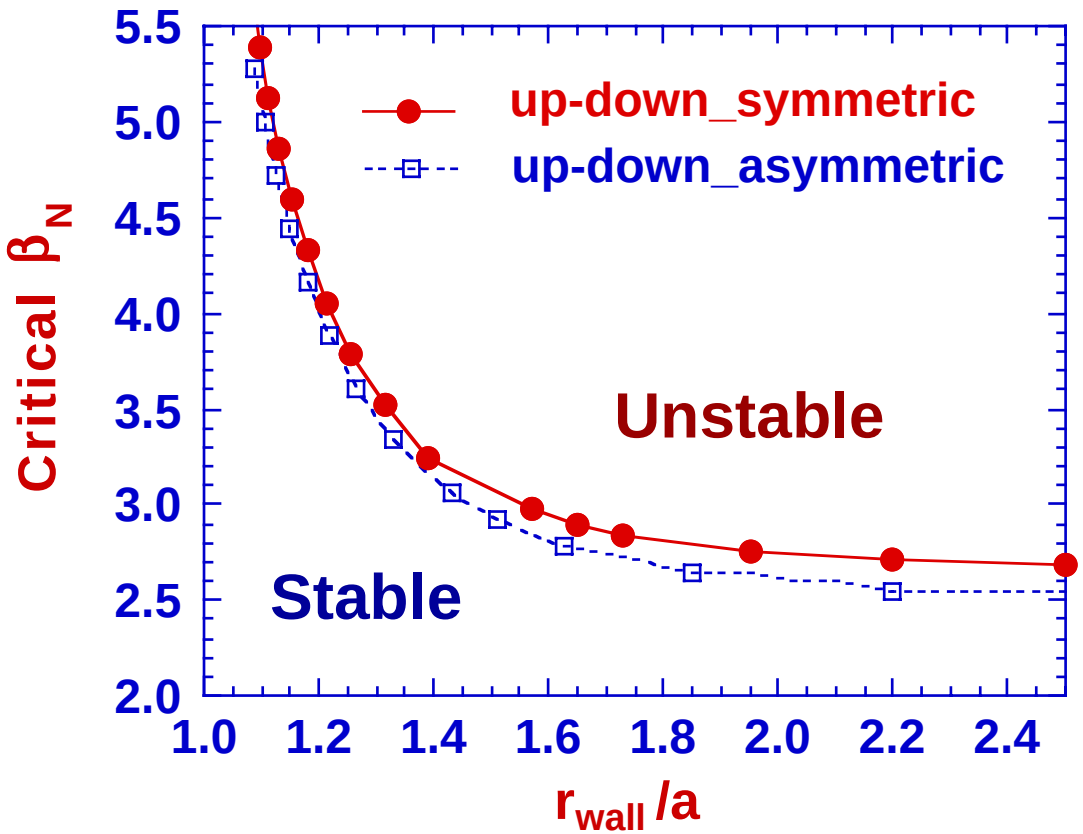
---> low critical β_N value

- 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

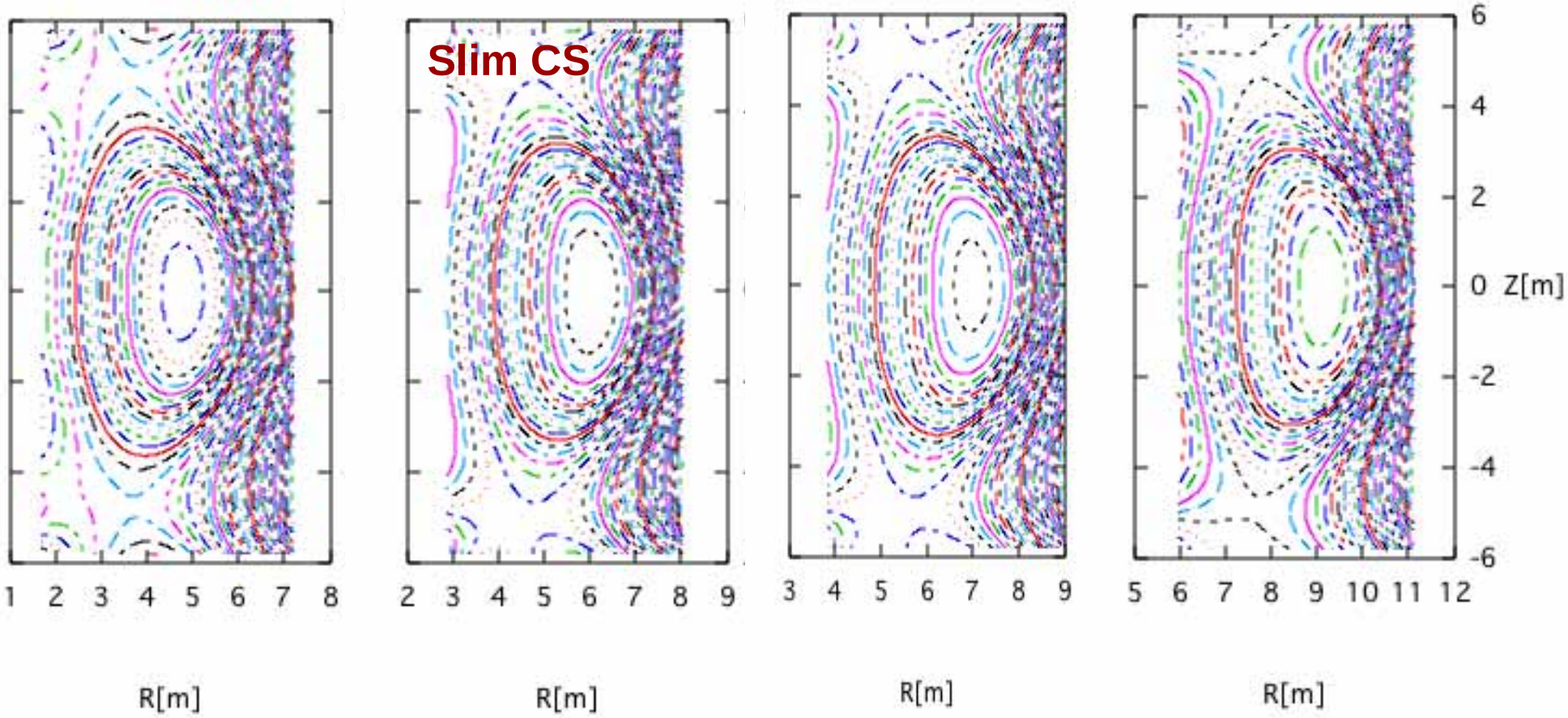
- Conformal ideal wall
- Toroidal mode number : n=1

- 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



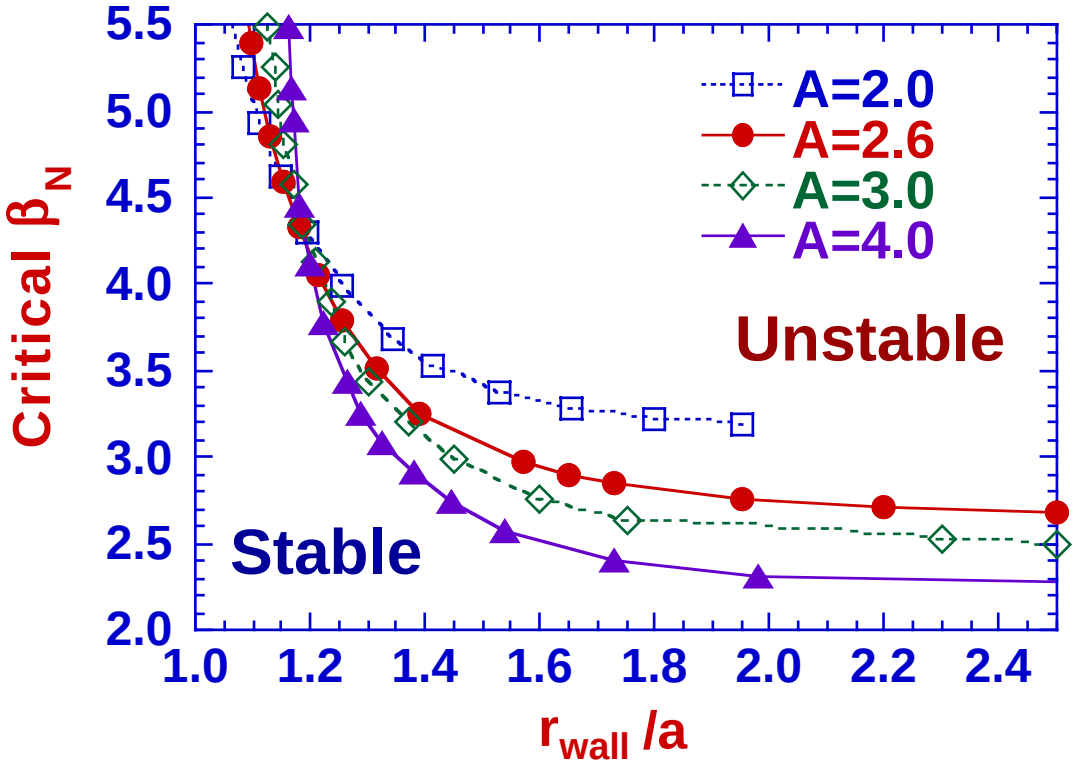
A = 2 A = 2.6 A = 3 A = 4

Critical β_N vs.Wall Position for 4 Aspect Ratio Cases

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

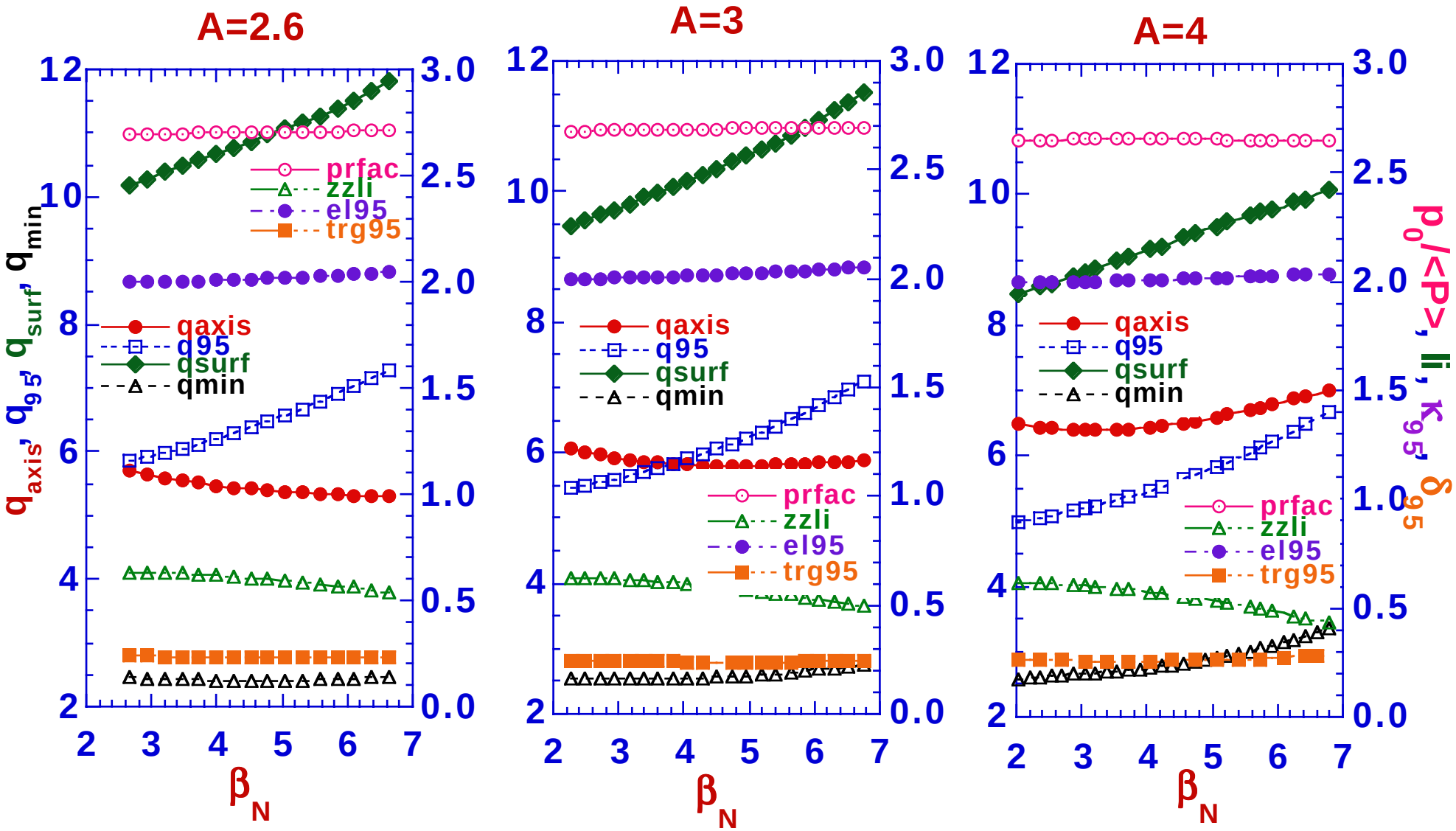
  - $R_p I_p$ = const.

  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.

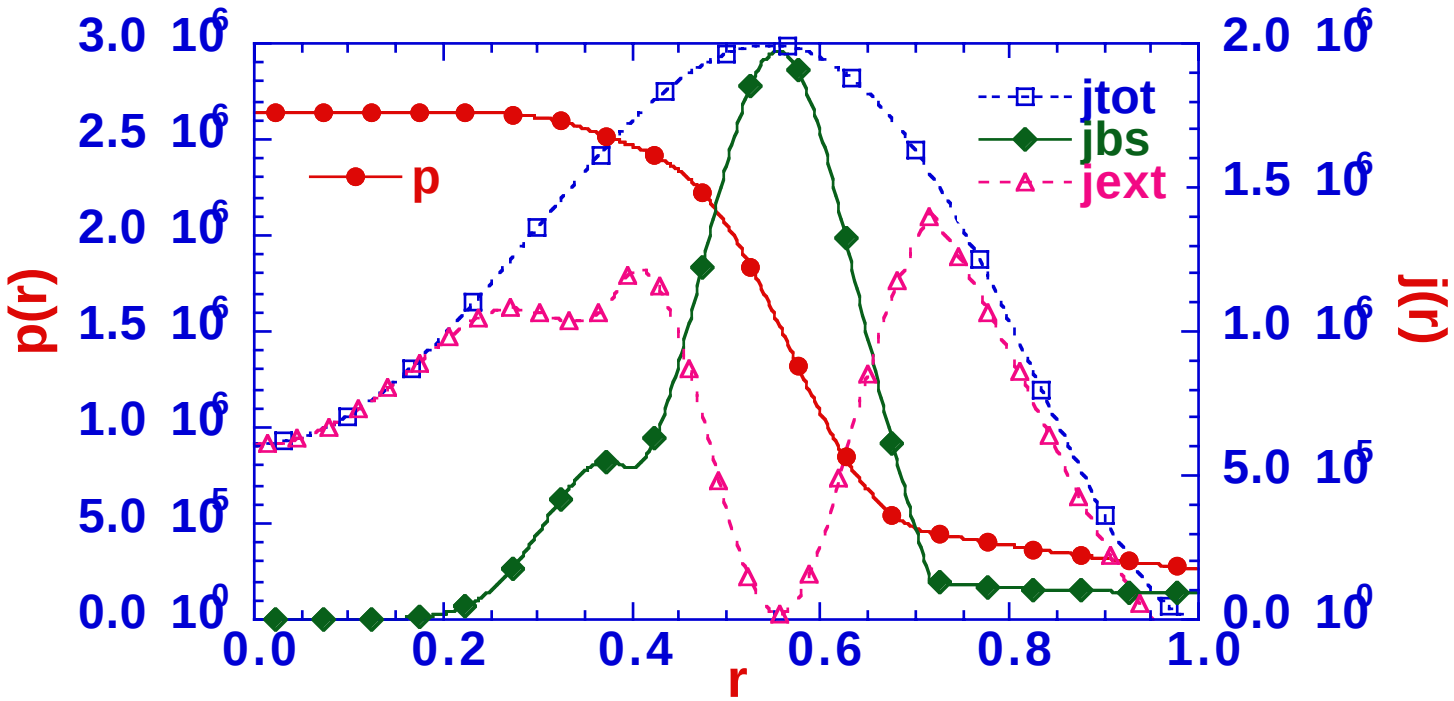
Brief Explanation for Previous Result

- 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 .

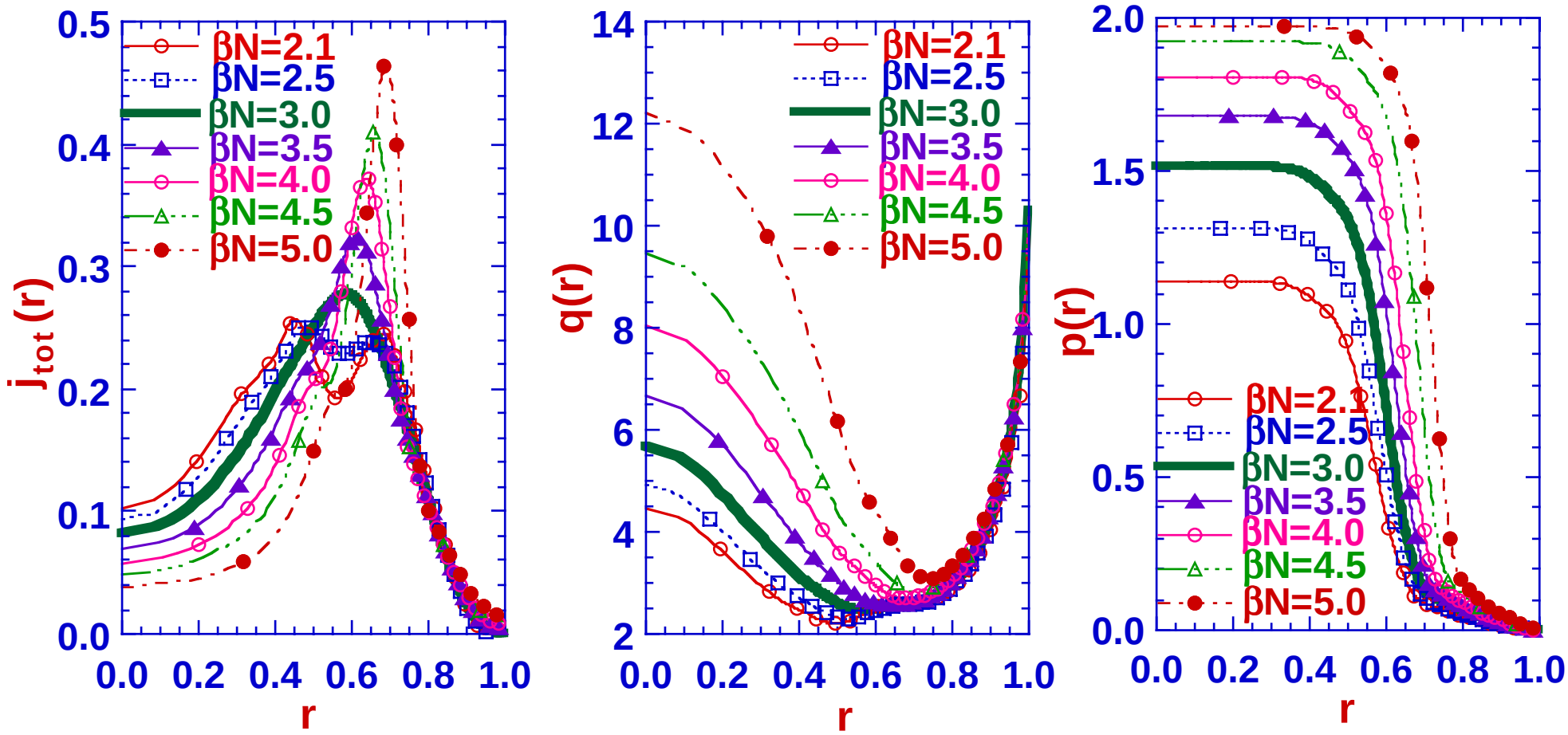
Bootstrap Current Dominant Equilibria

- Plasma current and pressure profiles for equilibrium of $\beta_N = 3$ (A=2.6)



- Total plasma current is caluculated 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.

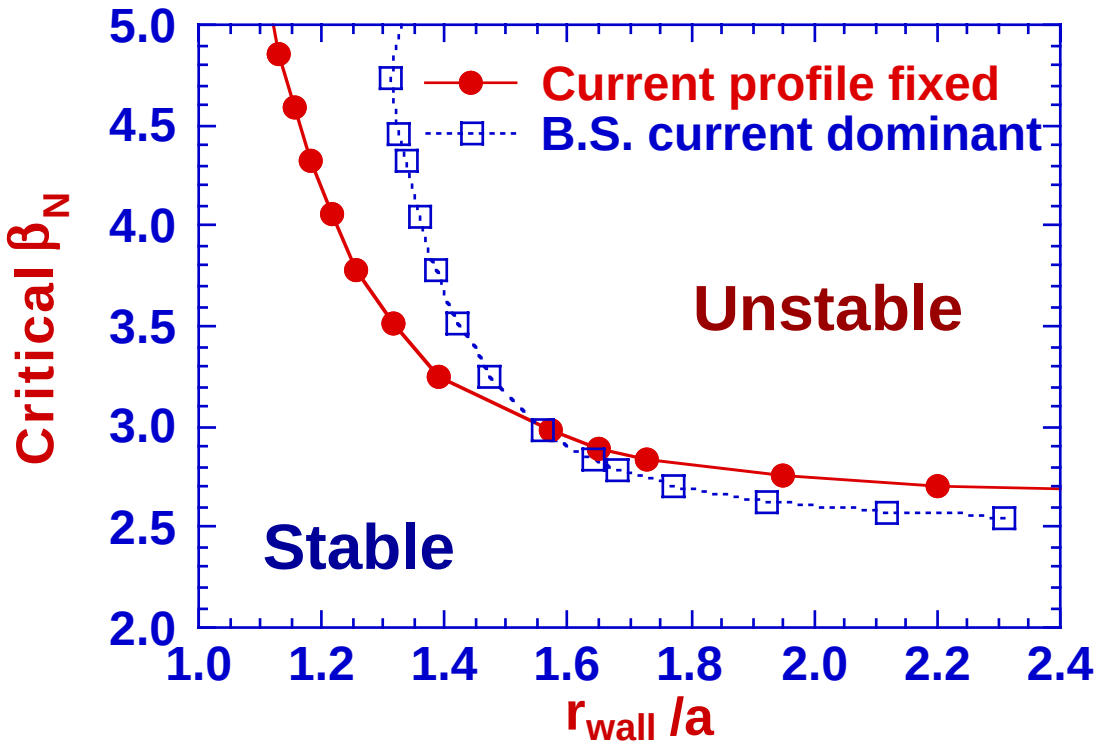
Change of Plasma Current and Safety Factor Profiles due to Increase of Plasma Pressure



- **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.

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 to1.34a for bootstrap dominate equilibria because of increment of q_{min} value.
- Critical β_N 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.

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

Remained Issues

- 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 investigate edge pedestal in order to reduce the pressure gradient within ITB region
  - To optimize plasma current and pressure profiles

- To analyze Resistive Wall Mode for plasma with finite resistive wall