

Critical Issue on Plasma Equilibrium for CS-less Tokamaks

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Roles of Center Solenoid (CS) in conventional tokamak

CS serves as....

- Flux supply to the plasma
CS is the most efficient flux supplier w/o affecting equilibrium configuration
- Plasma shaping tool if properly segmented
Mid-plane segment effectively pushes plasma surface to attain high elongation and triangularity

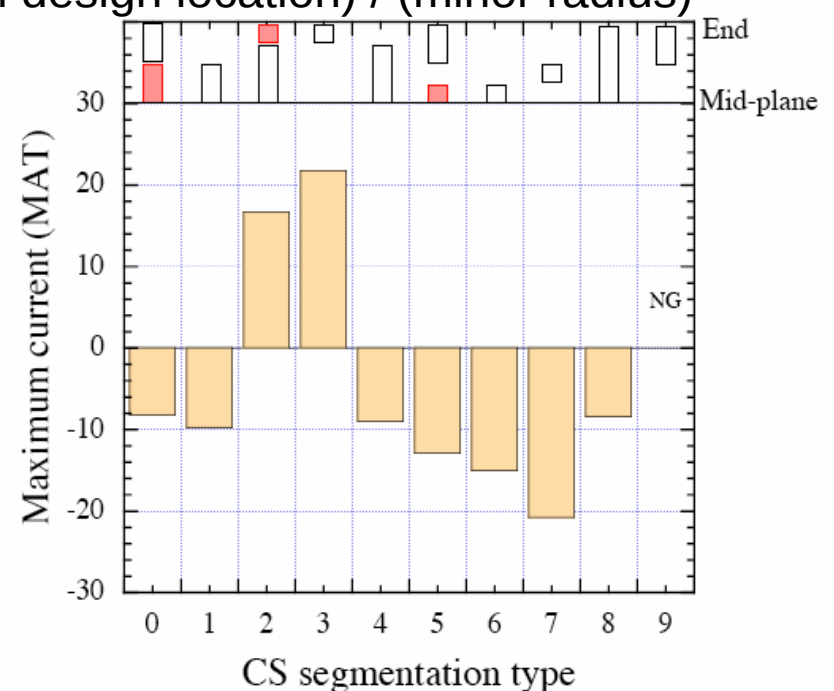
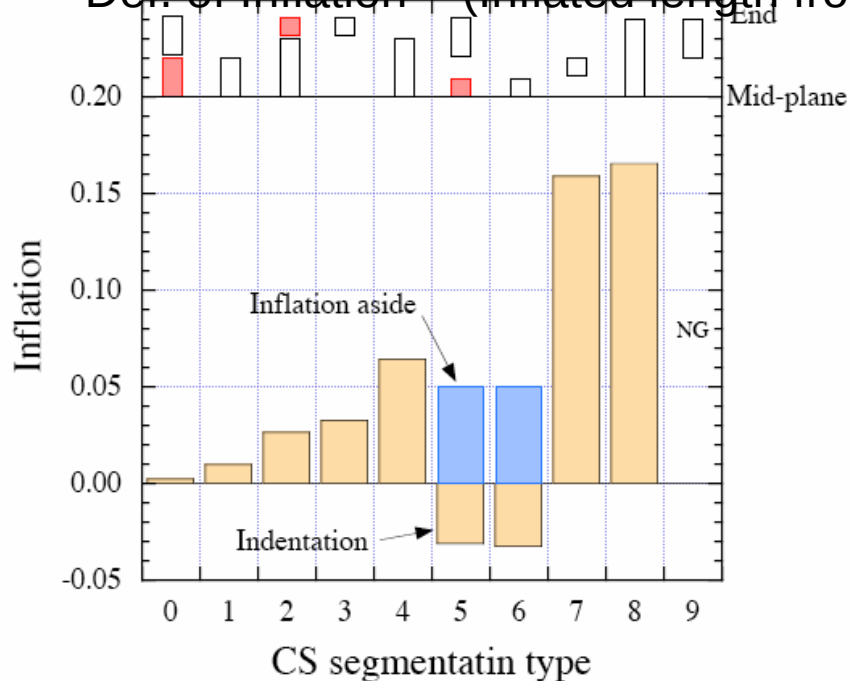
Segmentation of CS is essential for shaping

Proper CS segmentation suppresses inflation of inner plasma surface with relatively small current

Inflation prevents sufficient shaping of plasma

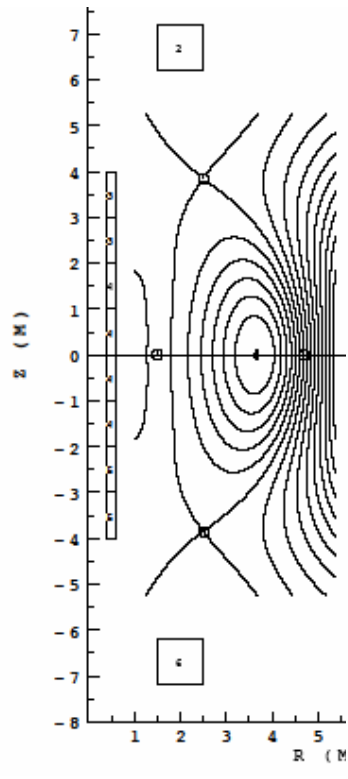
Uniform CS has no shaping effect

Def. of Inflation = (Inflated length from design location) / (minor radius)

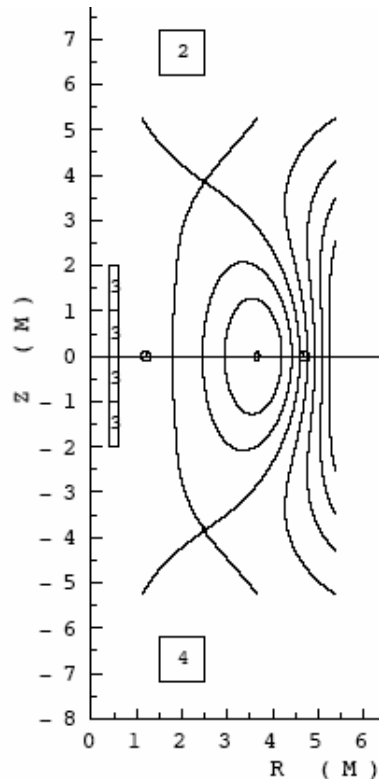


Equilibrium plasma configuration for different CS type

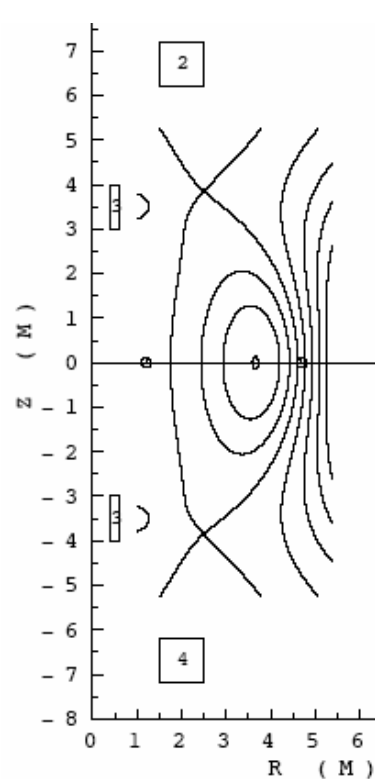
Type 0



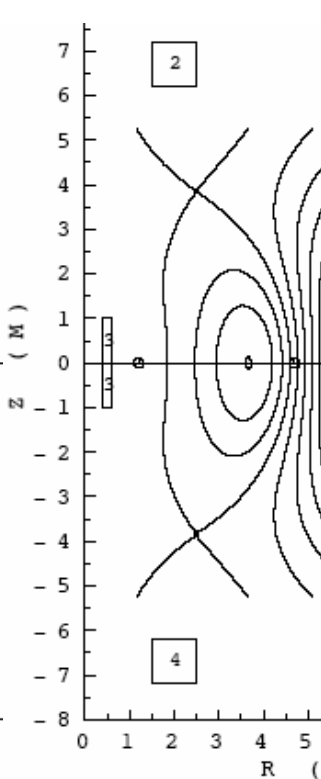
Type 1



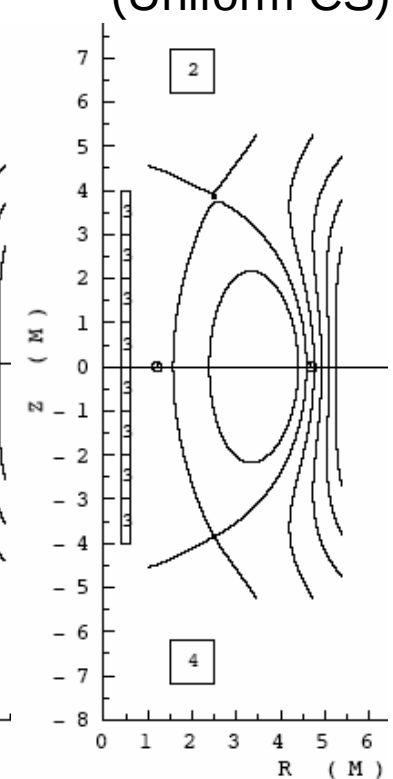
Type 3



Type 6



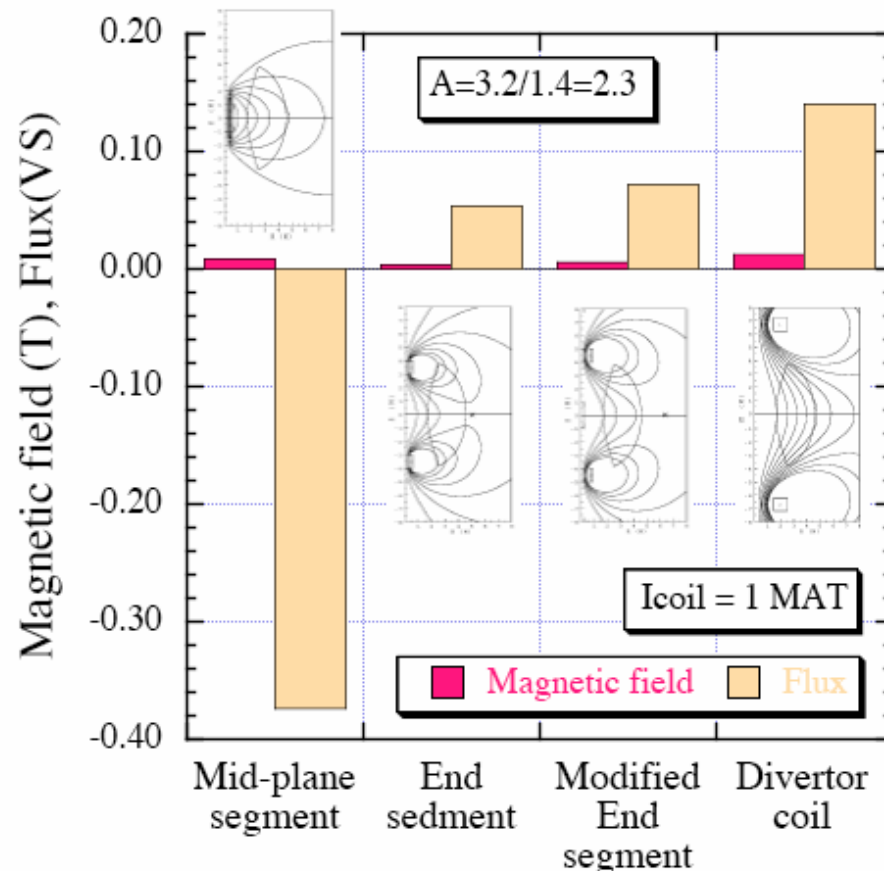
Type 9
(Uniform CS)



Segmentation separately controls flux and magnetic field

Combination of Mid-plane segment and End segments can produce any independent magnetic field and flux in conventional CS tokamak

But CS-less tokamak.....



Mid-plane segment and End segment of conventional CS both has inflation suppression effect

Current direction of End segment should be opposite to that of Mid-plane segment

Divertor coils also have suppression effect but the curvature of magnetic line of force is less than required

All has its own characteristic combination of field and flux

Issues in CS-less tokamak equilibrium

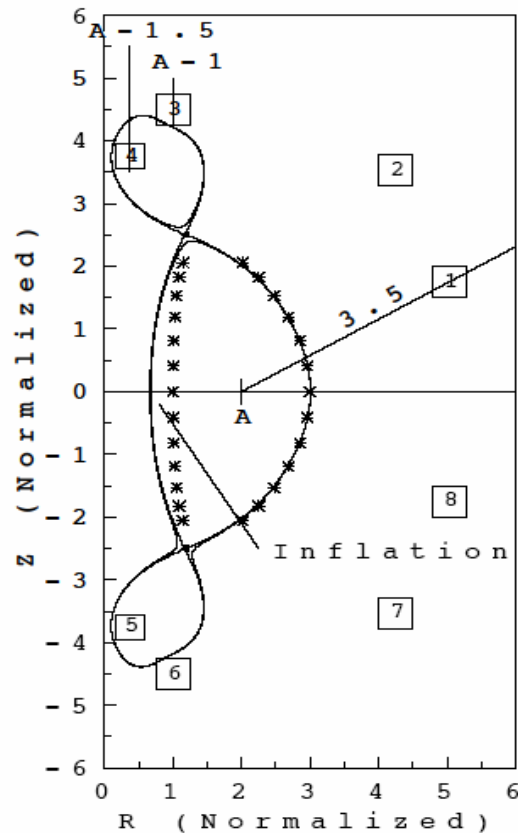
- Inflation of inner plasma surface
- Lack of flux controllability
- Separatrix separation in single null divertor plasma

Only divertor plasma is studied

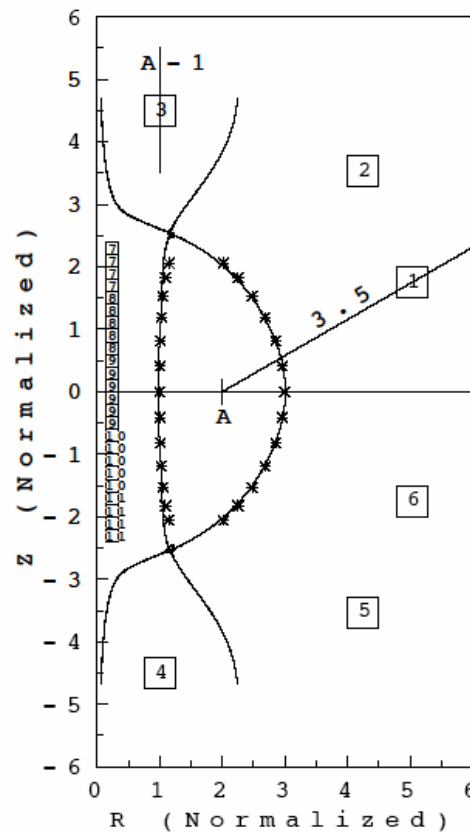
No constraint on coil current is set in the equilibrium calculation to clarify physics aspect

The first issue : Inflation of inner plasma surface

w/o CS



w/ CS



Without CS, inner plasma surface uncontrollably inflates from design location

Inflation prevents to attain high elongation and high triangularity

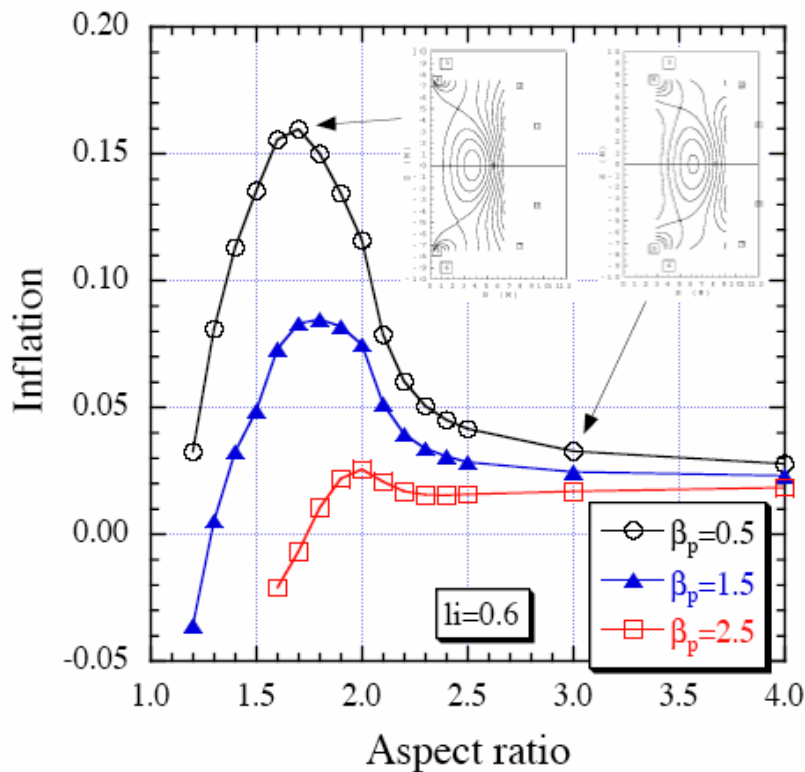
Asterisks show reference plasma surface ($A=2$)

Inflation has aspect ratio dependence

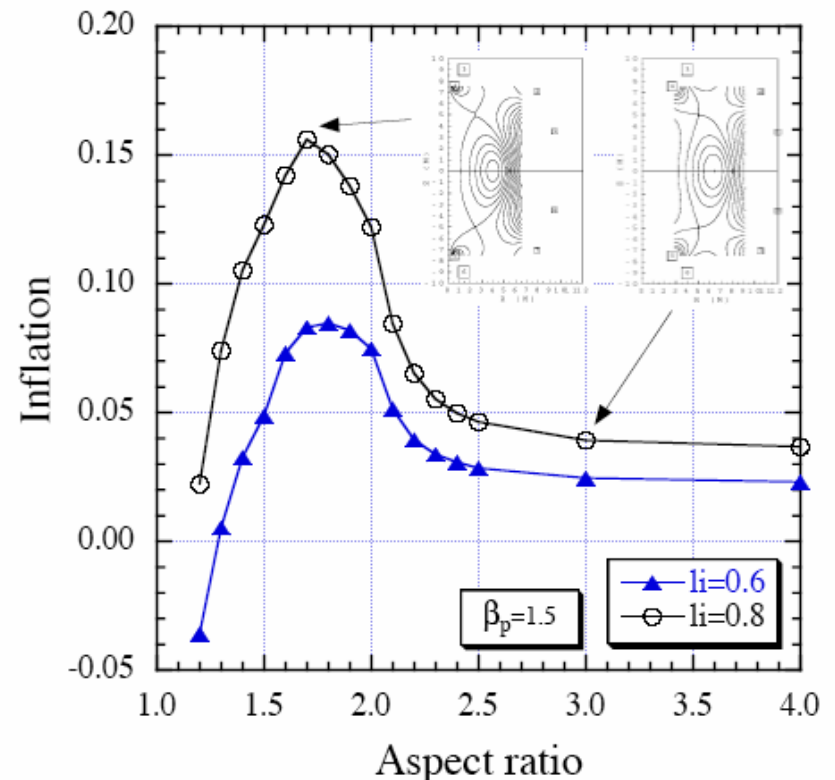
Inflation is large in low β_p and peaked current plasma

It is preferable to design CS-less tokamak at $A > 2.3$

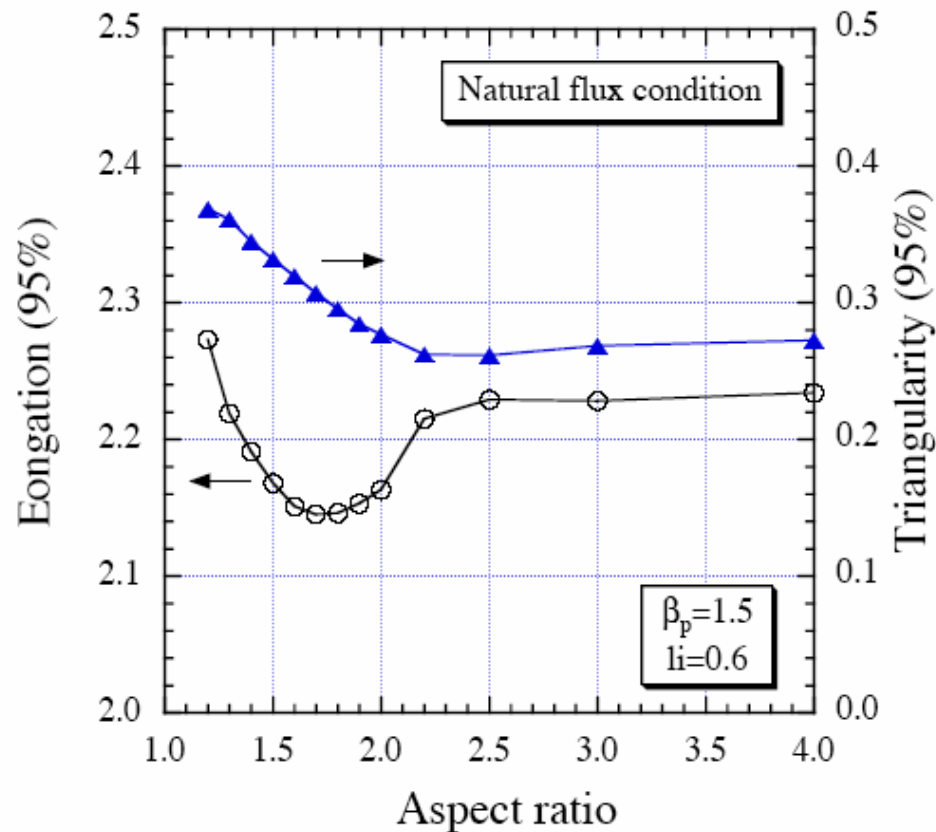
$\beta_p = 0.5 - 2.5$



$li = 0.6, 0.8$



Elongation and Triangularity at 95% magnetic surface

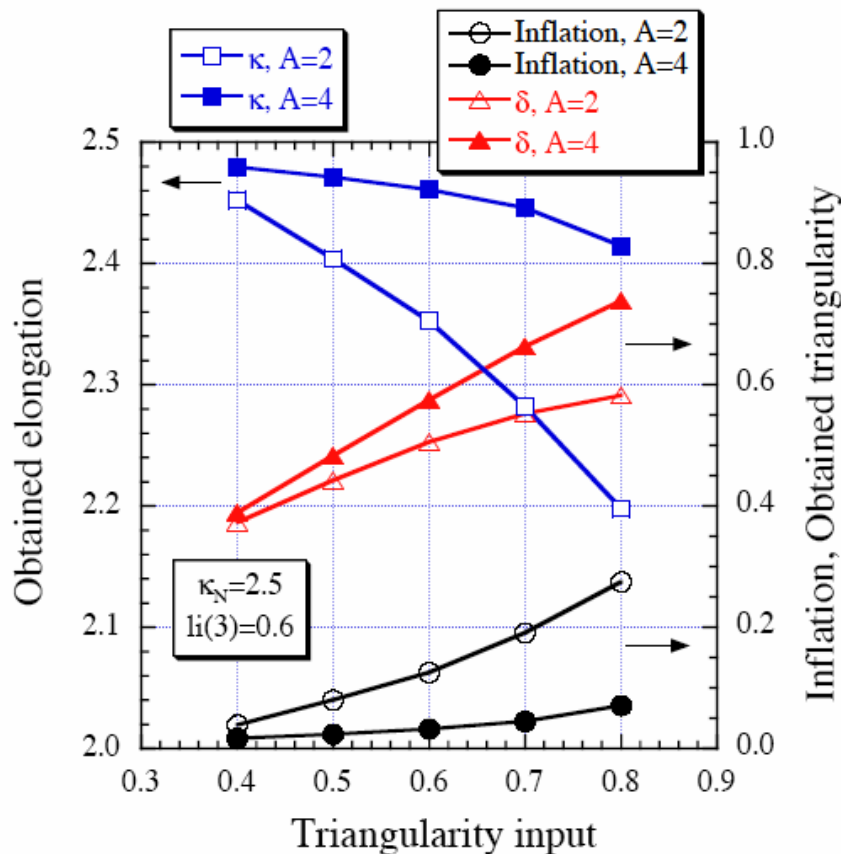


Elongation at 95% magnetic surface has a depression around the aspect ratio that corresponds to maximum inflation

Triangularity on the contrary increases continuously with decreasing aspect ratio

Elongation and triangularity inputs at x-point are fixed

Raising elongation and triangularity simultaneously is limited



At $A=2$, triangularity cannot fully follow up the input value due to increasing inflation

Elongation also decreases from input value (2.5) with increasing triangularity input

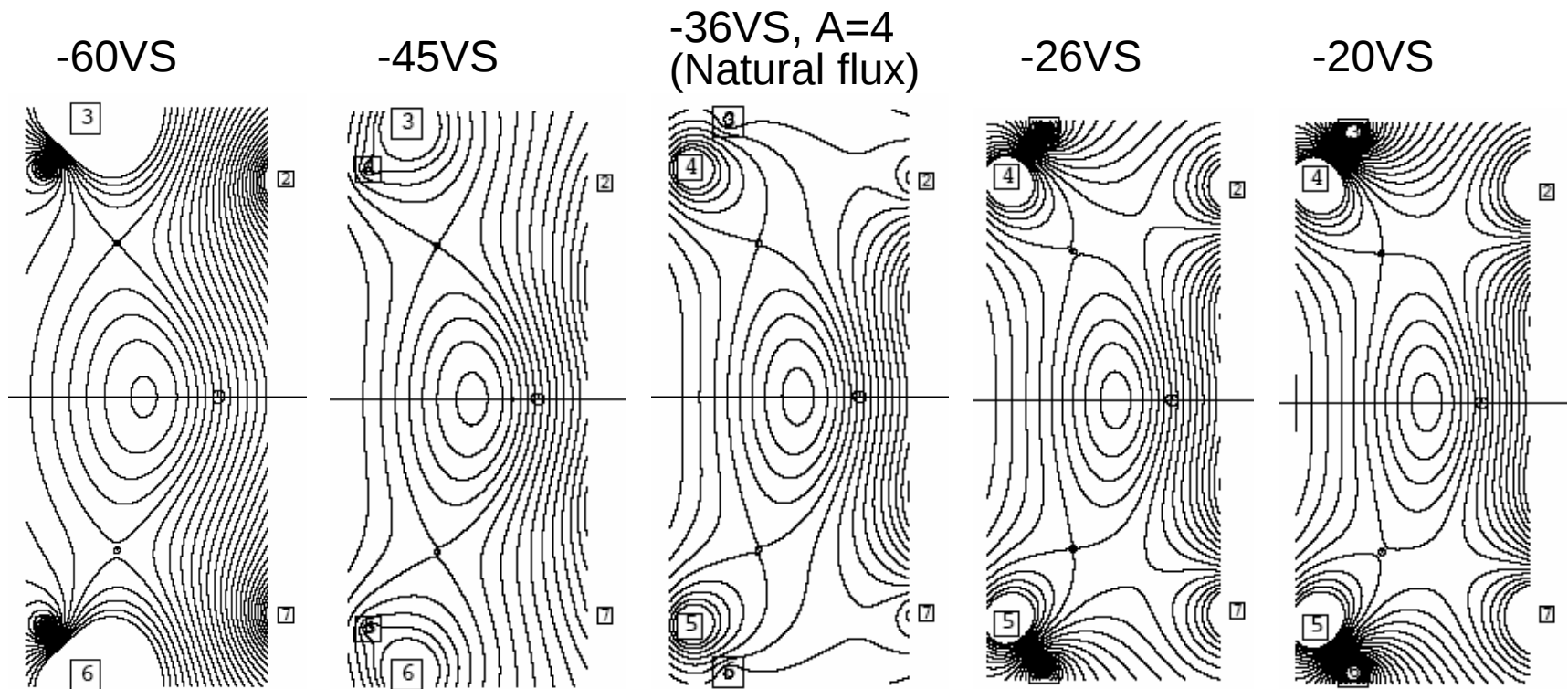
Elongation and triangularity are evaluated at x-point

The second issue : Lack of flux controllability

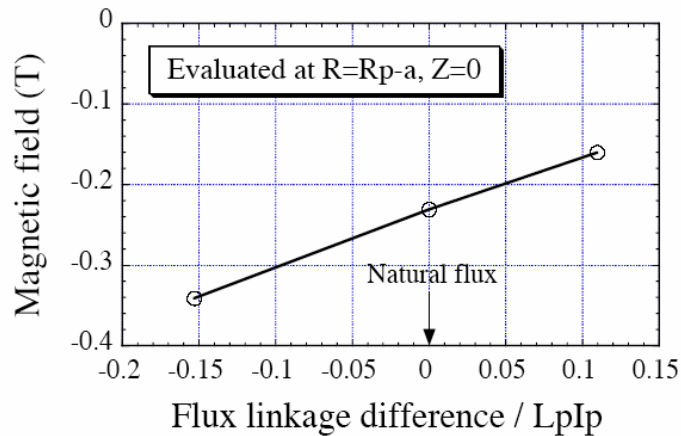
Plasma shape changes with flux linkage

Negative change in flux linkage from natural flux makes inflation

Positive change induces multiple x-points formation resulting in abrupt distraction of equilibrium



Lack of flux controllability (continued)

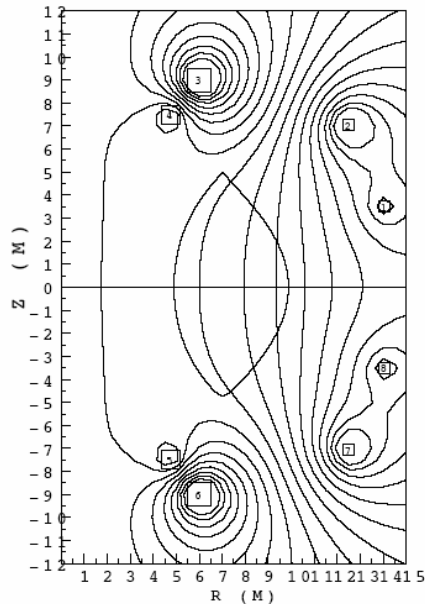


Magnetic field at inner plasma surface depends linearly on change in flux linkage

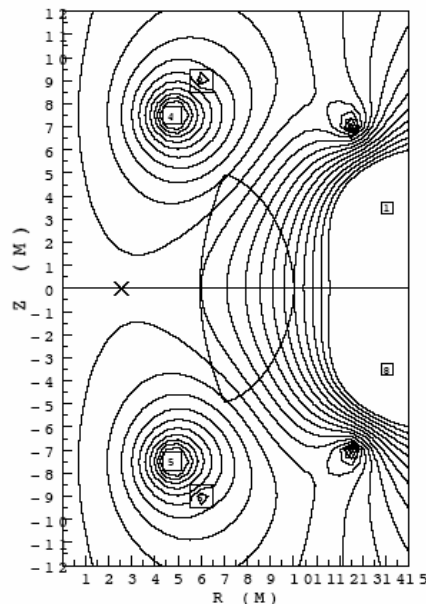
Inflation is dominated by flux linkage

Natural flux is a resultant flux of equilibrium calculation w/o any constraint on flux

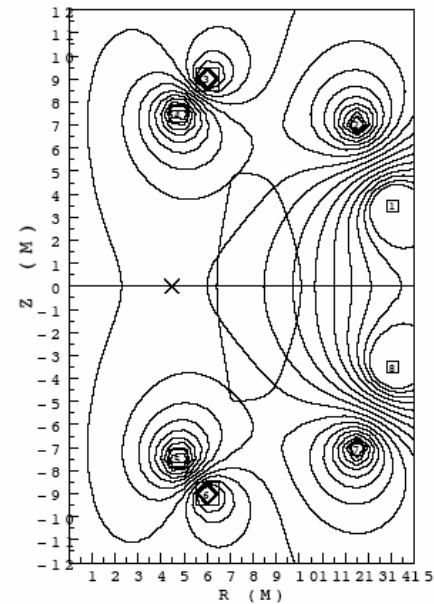
-60VS



-36VS (Natural flux)



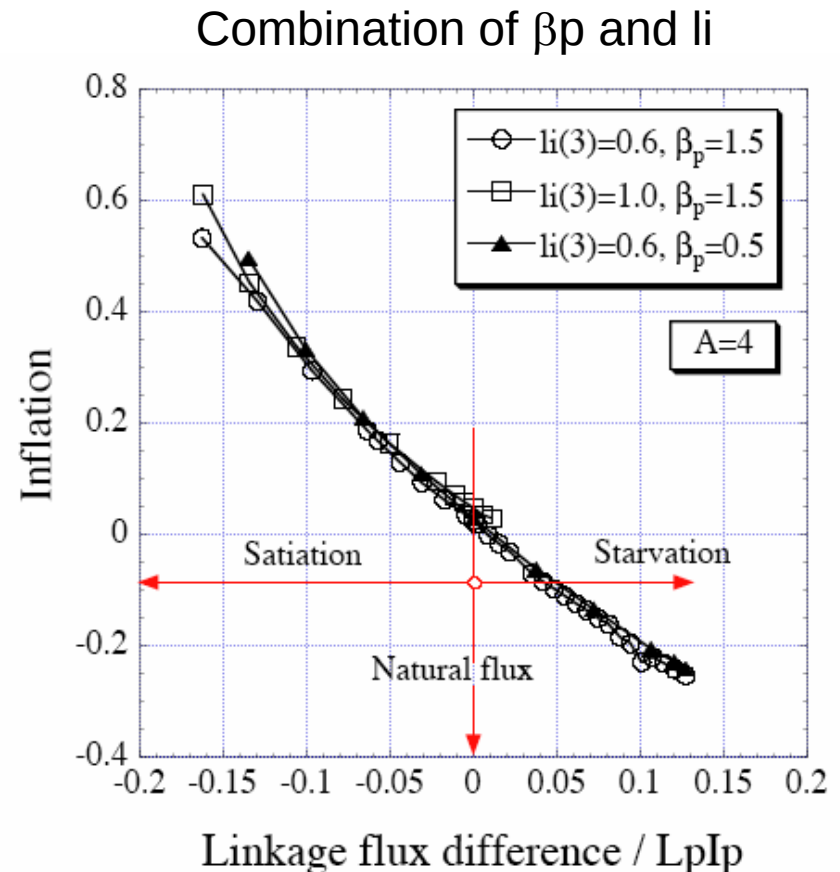
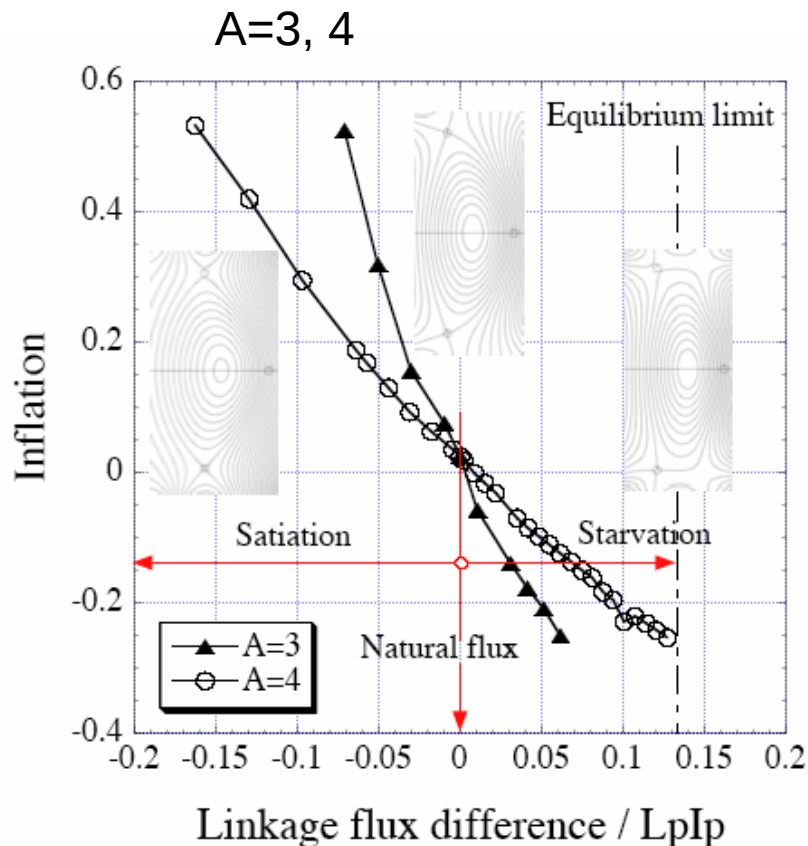
-20VS



Inflation v.s. Flux linkage

Allowable region of flux linkage becomes small at low aspect ratio

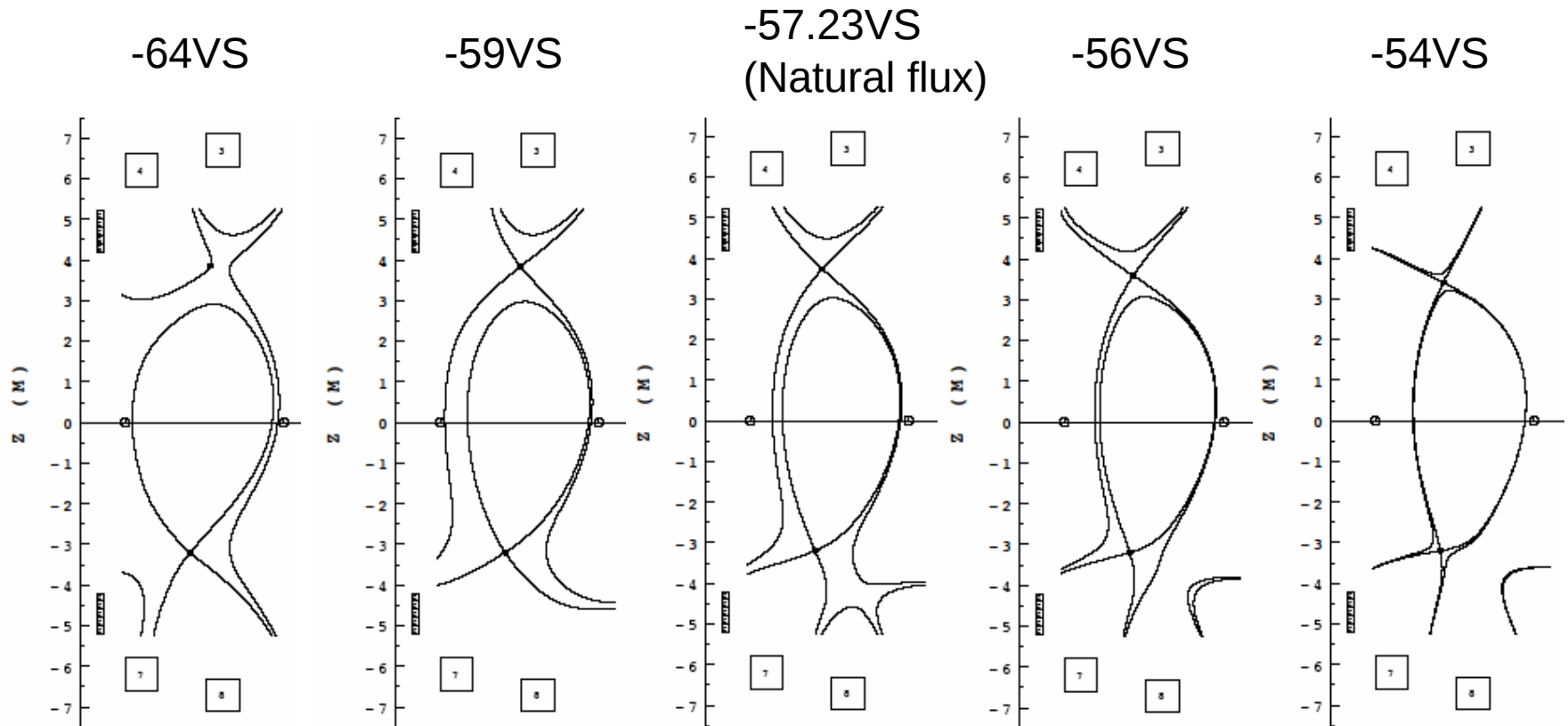
Effects of β_p and plasma current profile are negligible



Single null divertor plasma

Single null divertor plasma ends up with double null divertor transition for positive change in flux linkage

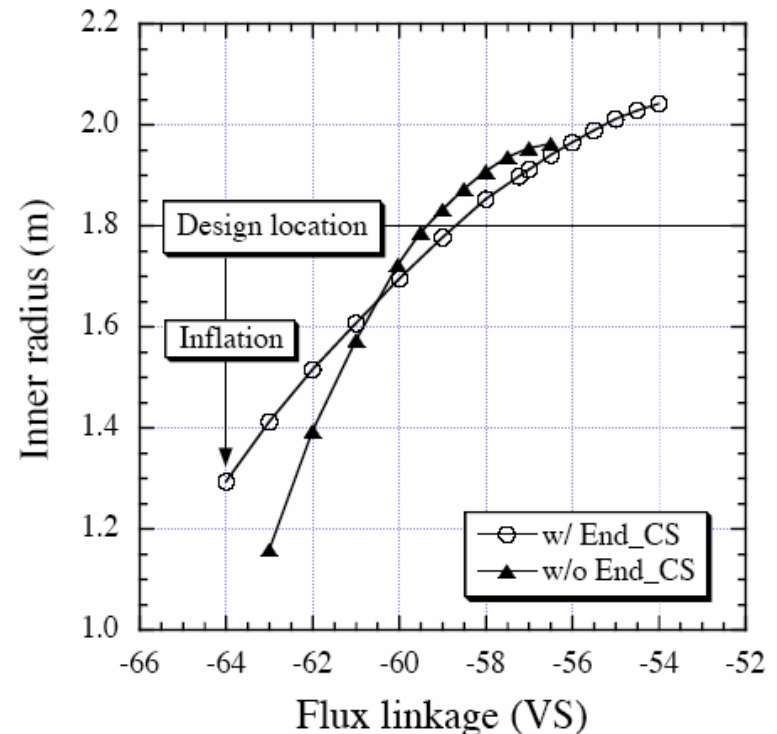
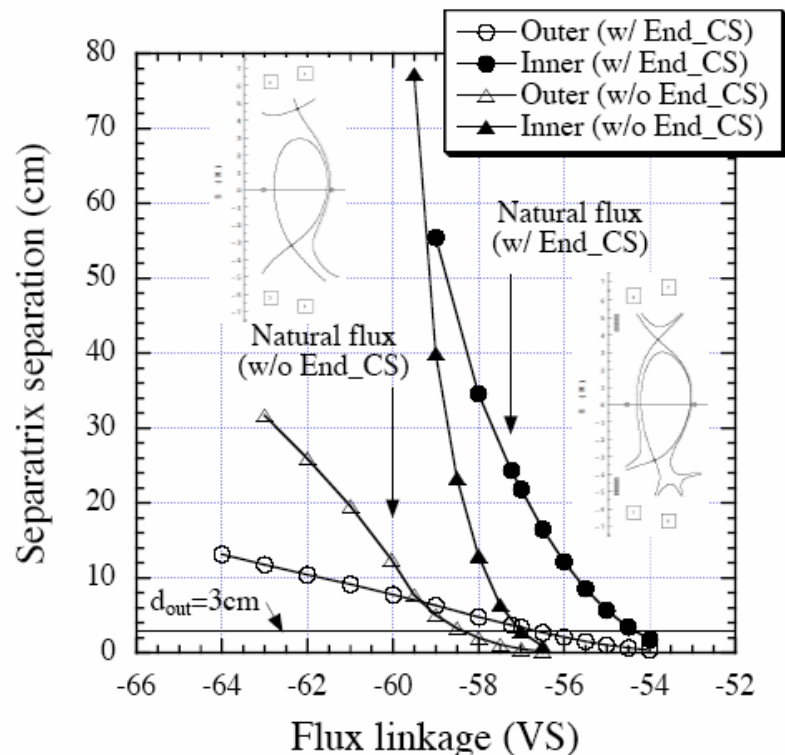
Large negative change break up separatrix, which causes heat flow to the first wall



Separatrix separation is decisive parameter in Single null divertor

Separatrix separation depends on flux linkage

Operational range of flux linkage is very limited to satisfy both constraints on separatrix separation and inflation of inner plasma surface



Summary

In the CS-less tokamak

- Inner plasma surface uncontrollably inflates and the inflation prevents simultaneous attainment of high elongation and high triangularity
- Inflation has aspect ratio dependence and becomes maximum at $A=1.5-2.0$.
- Inflation is larger in low β_p and peaked current plasma
- Region of operational flux linkage is limited due to excessive inflation in negative side of natural flux and abrupt distraction of equilibrium by multiple x-points formation in positive side

Summary (continued)

Single null divertor

- Single null divertor plasma ends up with double null divertor plasma transition in positive side of natural flux
- Separatrix breaks up in the negative side, which may cause direct input of heat flow to the first wall, if the separation is smaller than critical value at outer plasma surface
- Separatrix separation changes with flux linkage
- Operational range of flux linkage is very limited to satisfy both constraints on separatrix separation and inflation of inner plasma surface

(No) Conclusion

- It is difficult to conclude whether CS-less tokamak has advantages or not solely based on the equilibrium aspect
- CS-less tokamak requires sophisticated diagnostics of plasma parameters and electromagnetic quantities, refined plasma control and its fine tuning to maintain design equilibrium
- These things deteriorates operationability
- If all these things resolved, there remains many engineering advantages

Appendix A : Field pattern v.s. Aspect ratio

Field pattern produced by a segment is kept, while magnetic field and flux is larger at large aspect ratio

