High Beta ST Formation from FRC and Its Ballooning Stability

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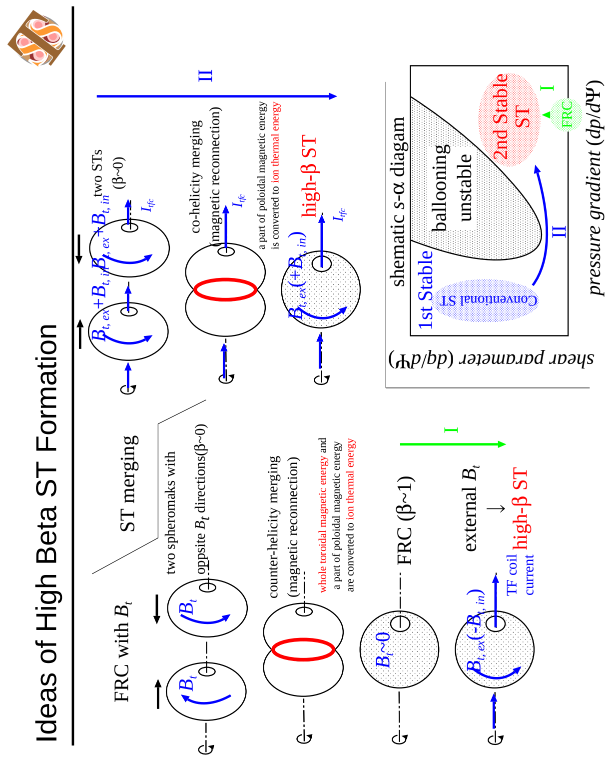
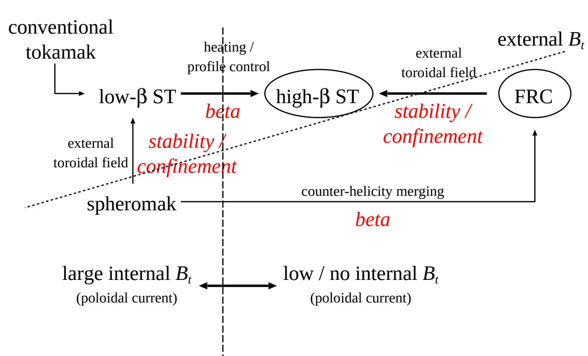
Abstract

Ultra-high-beta (> 50%) spherical tokamak has been produced in TS-3 merging experiment using two types of CT/ST merging. Co-helicity merging of two STs was observed to heat ions significantly and to increase β value of a merged ST 2-3 times as large as that of a single ST. Counter-helicity merging of two spheromaks formed an FRC with ion temperature up to 200[eV] and further fast application of external toroidal magnetic field transformed an FRC into an ultra-high-β ST. A new finding is that the ultra-high-β ST had an "absolute minimum B" configuration together with diamagnetic toroidal field and hollow toroidal current profile. Both high-β STs have largest pressure gradient and magnetic shear around the plasma edge, indicating the formation of ultra-high-β ST in the second stability regime for ballooning mode. Heating power was varied by factor 10 by varying reconnecting magnetic field angle and strength. It was found that the high-β ST decayed quickly due to large magnetic fluctuation if its pressure gradient exceeds the threshold value. Stability limit in s-α diagram against ballooning mode will be reported based on experimental and computational analyses.



Introduction

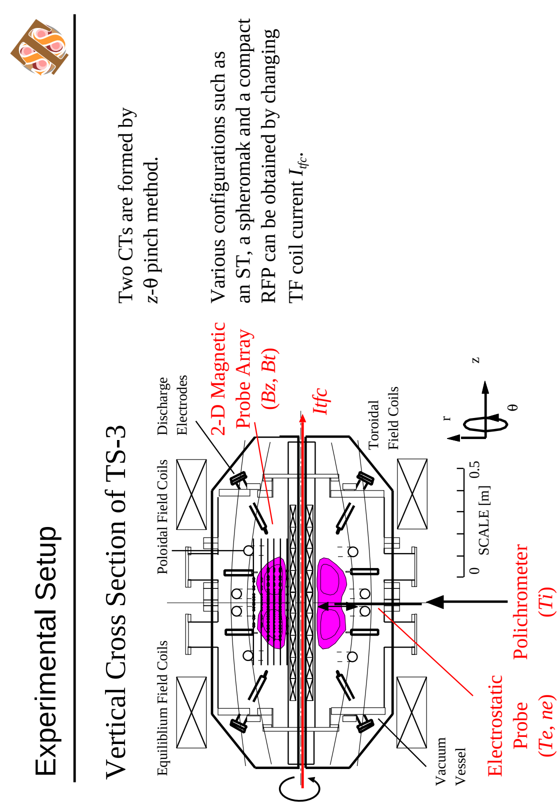
What is a high-β spherical tokamak (spherical torus)?



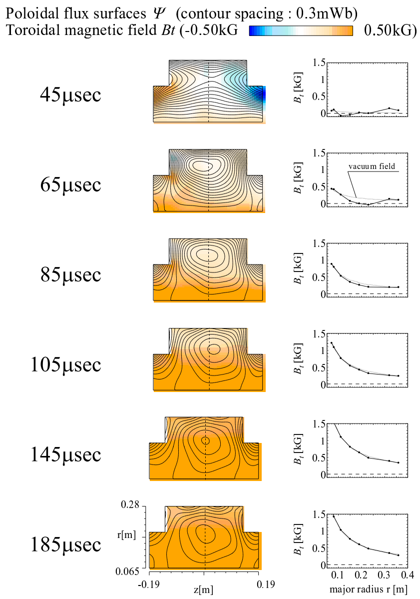
We can think of a high-β ST as an improved form of an FRC.

Two ways to high-β ST
- FRC with external toroidal field
- ST merging

-> ballooning stability (second stable?)



Formation of a high-β ST from an FRC



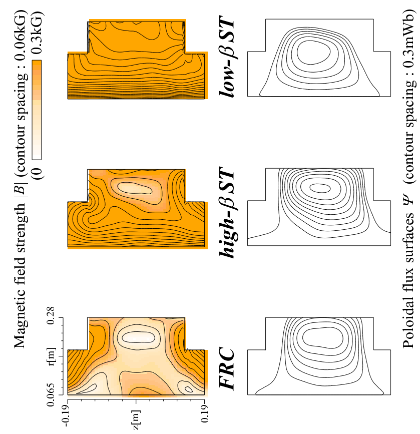
Absolute minimum B in a high-β ST from an FRC

diamagnetic B_t

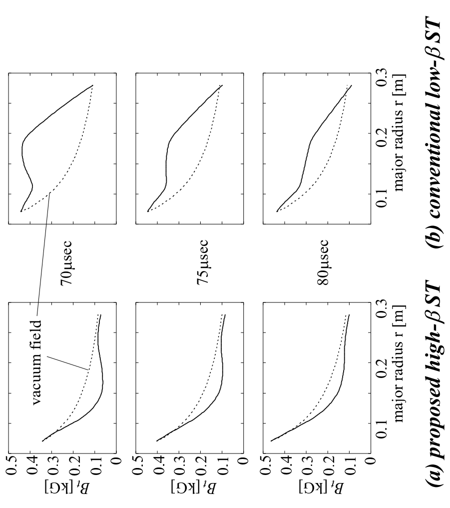
→ absolute minimum B

→ stability against ballooning mode

improvement on confinement



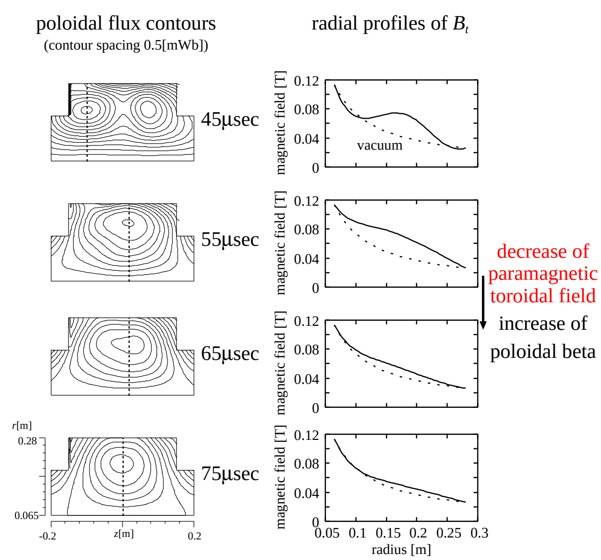
Comparison of B_t profiles between high and low β STs



The high-β ST (FRC+B_t) have a diamagnetic B_t profile.

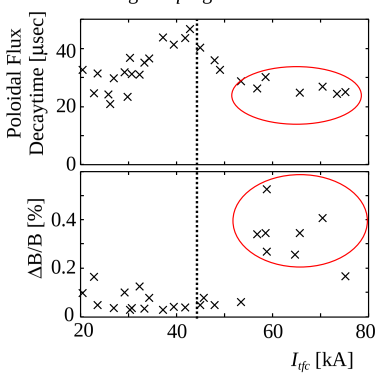
Diamagnetic poloidal current decays in the same time scale of paramagnetic current in a low-β ST.

high-β ST Formed by ST Merging



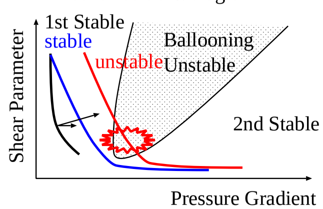
Quick Decay observed in Merging high-q ST

Extension to higher-q region

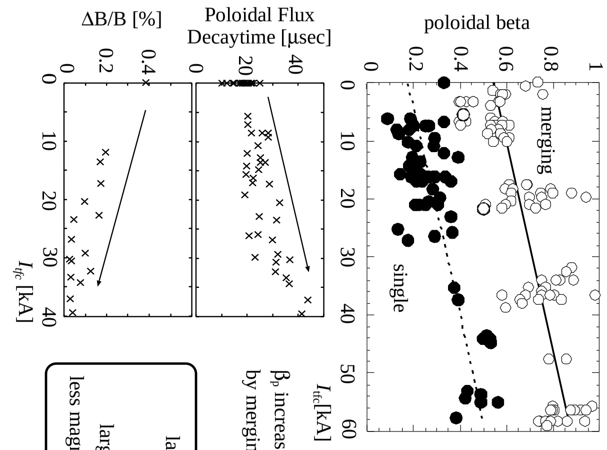


When TF coil current is larger than 45kA, a merging ST decayes quickly with large magnetic fluctuation near separatrix(r=0.8a).

Ballooning instability caused by heating of ST merging?



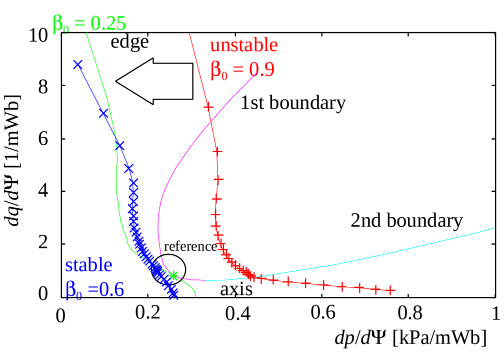
High β Values of Merging ST



β_p increased 2-3 times by merging.

larger I_{tfc}
↓
larger β_p, τ_Ψ
less magnetic fluctuation

Numerical Analysis by BALOO Code



"BALOO" can find the most unstable perturbation (high-n limit) and check stability of that.

s-α profiles of the two cases (I_{tfc}=40, 70kA) are examined by BALOO.

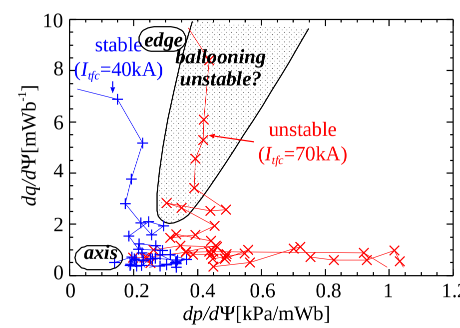
Stability limits (1st, 2nd) are calcurated for the reference flux surface of a marginal? unstable profile which has the same function as the unstable but has lower β than that.

The merginal? unstable profile crosses the 1st stability limit.

Comparison of s-α profiles

$s_{(dq/d\Psi)}$-$\alpha_{(dp/d\Psi)}$ profiles of a stable case(I_{tfc}=40kA) and an unstable case (70kA).

<- calcurated from 2 D magnetic probe arrays.

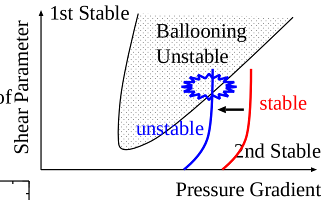


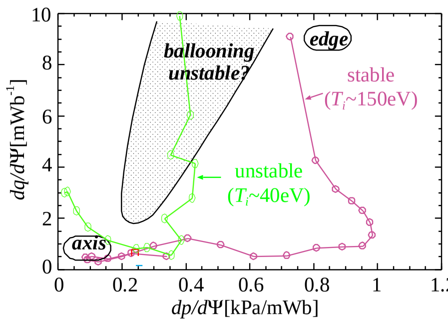
The unstable profile has large pressurre gradient near separatrix (edge).
-> Existence of ballooning stability limit?

Quick Decay Observed in a High-β ST from an FRC

Quick decay was also observed in a high-β ST ($FRC+B_t$).

The instability tend to occur when a temperature of an initial FRC is low.

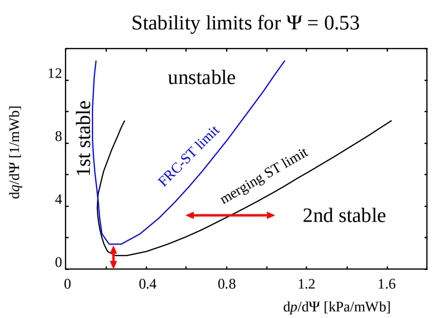




Is the decay also caused by ballooning instability?

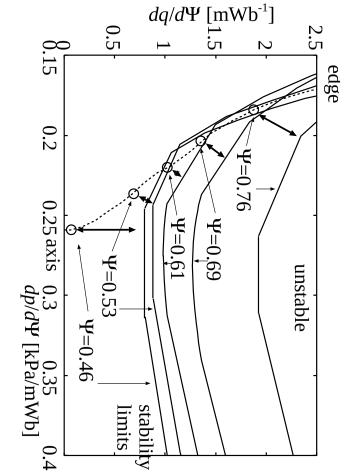
Are their stability limits equivalent each other?

Window Comparison between Merging ST and FRC-ST



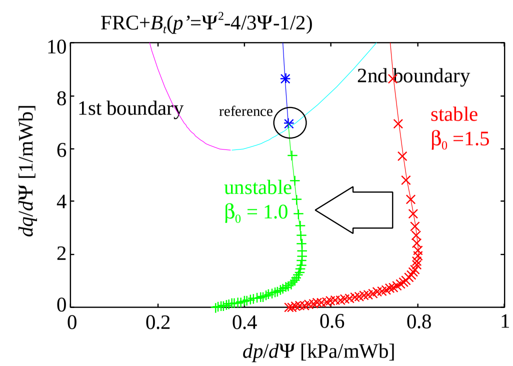
FRC-ST has a higher "window" and a broader 2nd stable region.
-> Effett of absolute minimum B?

Limits for Several Flux Surfaces (Stable ST)



Ψ=0.46, 0.53 exists in the "window" region.
Ψ=0.61 is most close to its stability limit.

Numerical Analysis by BALOO Code II

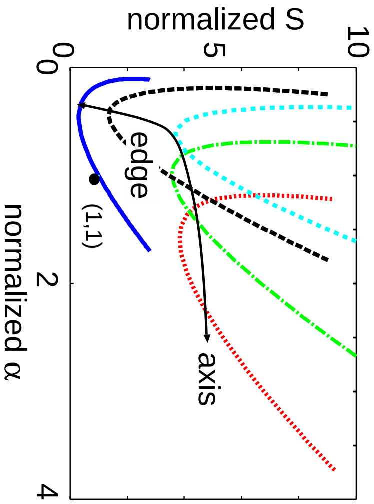


The stable profile becomes unstable when β_0 value is less than 1.

The unstable profile crosses the 2nd boundary of stability.

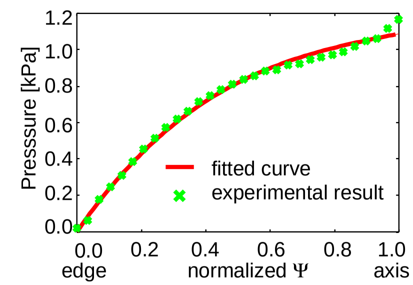
An ST from an FRC with (relatively) low β is unstable for ballooning mode.
The profile crosses a stability boundary of higher pressure gradient side.
An ST from an FRC has a larger window between the 1st and 2nd stable regin than a merging ST. <- Effect of absolute minimum B?

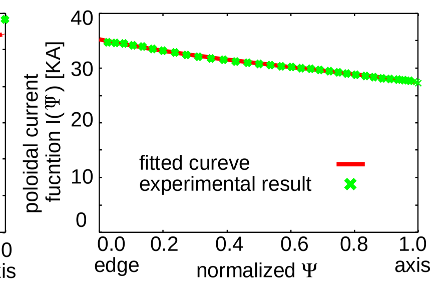
Examination Result



High-β ST from FRC exists in the second stable region. (reconfirmed)

More Accurate Examination--P and I Functions in G. S. Eqs.





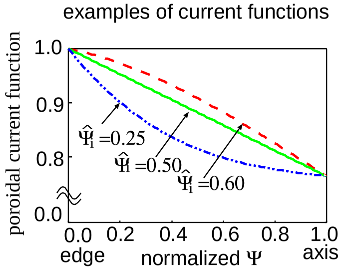
- 3rd polynominal fitting
- Conditions:
  - $P|_{edge}=0$ No plasma exists outside of separatrix.
  - $\left.\frac{d^2P}{d\Psi^2}\right|_{axis}=0$ To avoid influences of measuerment errors near magnetic axis

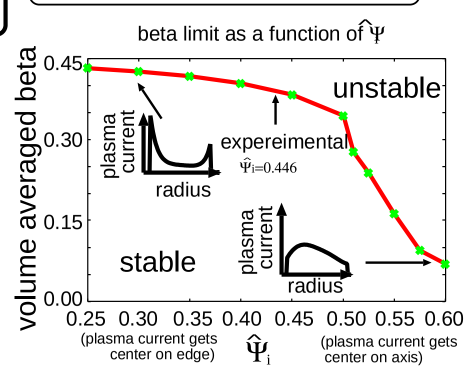
Poloidal Current Profile vs. Ballooning Stability

$\hat{\Psi}_i$: $I(\overline{\Psi}_i) = 0.5(I_{edge}+I_{axis})$

Plasma poloidal current concentrates on edge region ($\hat{\Psi}_i$ <0.5), or magnetic axis ($\hat{\Psi}_i$ >0.5).

Higher β limit was obtained with more edge localized current profile.
β limit decreased significantly when $\hat{\Psi}$ >0.5(constant profile)



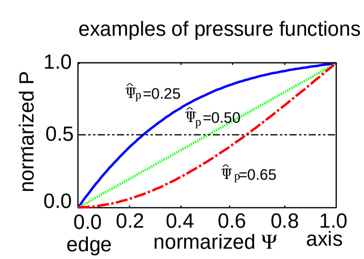


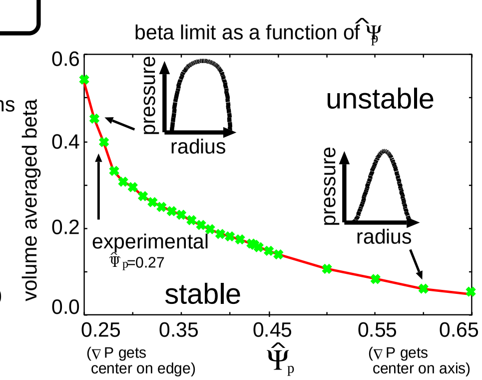
Pressure Profile vs. Ballooning Stability

$\hat{\Psi}_p$: $\overline{\Psi}$ value where $P(\overline{\Psi})=0.50$

Pressure gradient concentrates on edge region ($\hat{\Psi}_p$ <0.5), or magnetic axis ($\hat{\Psi}_p$ >0.5).

Beta limit increased with edge pressure gradient.





Summary

Two approaches to the second stable ST are examined by experimentally and numerically.

From a conventional ST

- ST merging can increase β_p value of an ST, especially high-q ST. However, when I_{tfc} is higher than 45kA, a merging ST decays quickly with large magnetic fluctuation. The unstable profile crosses the 1st boundary of stability.

From an FRC

- An FRC with external B_t makes an absolute minimum B configuration with a diamagnetic B_t profile. An ST with high pressure gradient is stable against ballooning mode and one with (relatively) low pressure gradient has a profile which crosses the 2nd boundary of stability.