MHD Stability and Equilibrium on Current Hole configuration

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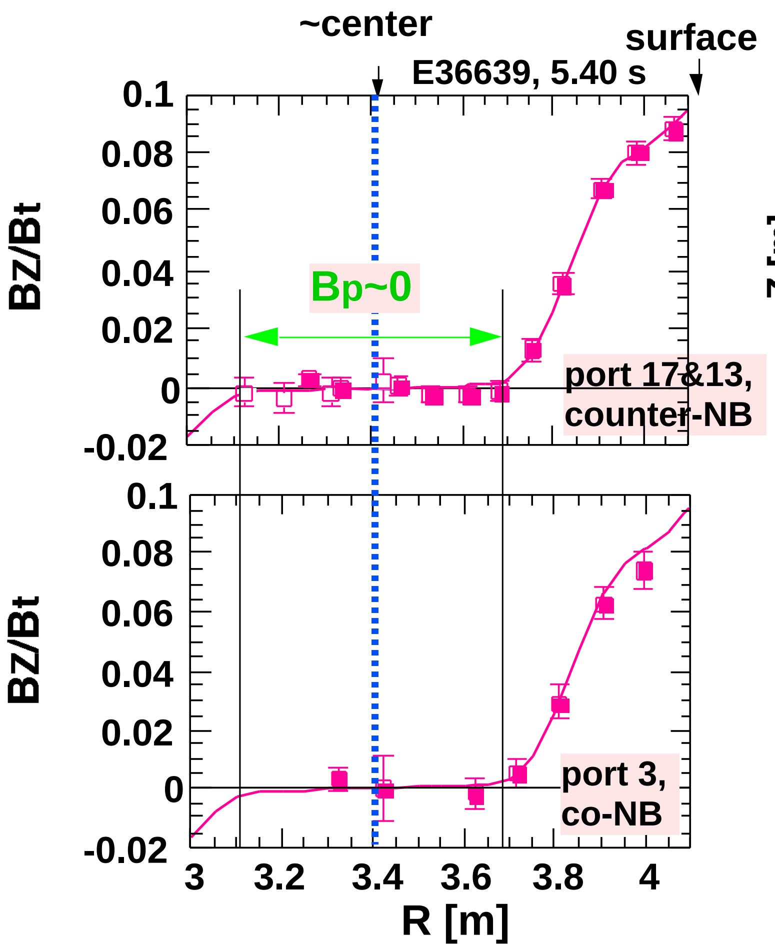
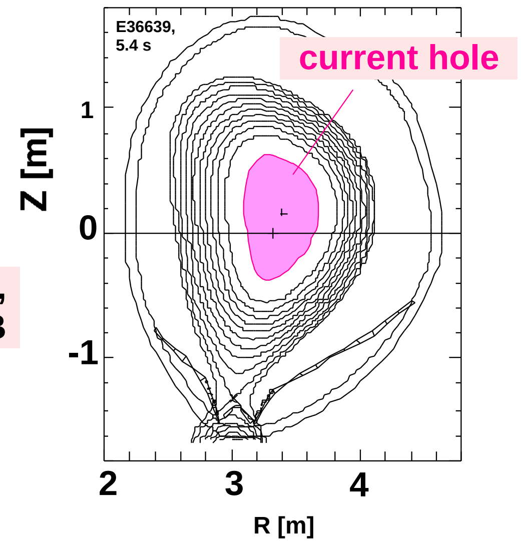
III. Summary

Observation of Current Hole

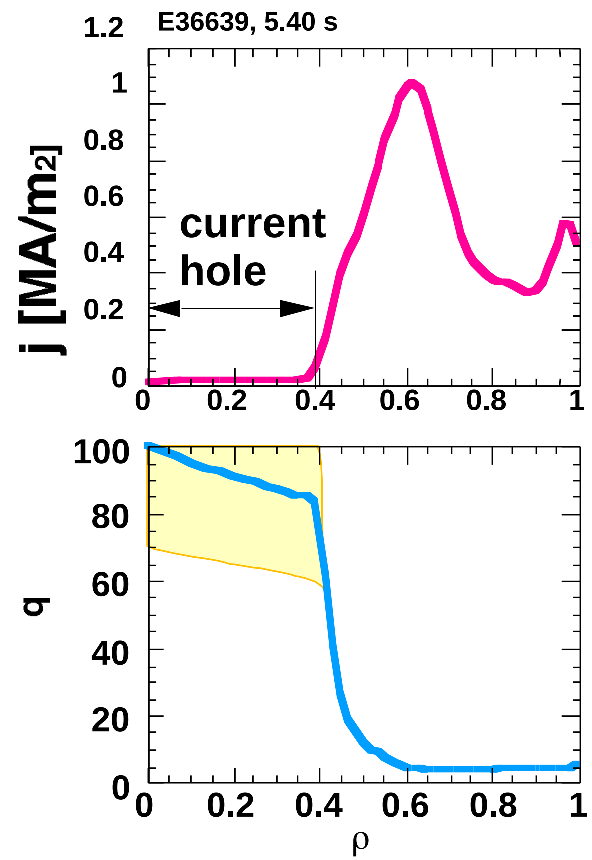
- **Projected angle was ~0 in a central region for both MSE viewing co and counter beams.** ➨ **E_r effect was small and B_p~0**
- **Very small current in a central region; |j(0)| <~ 0.07<j>**
- **Equilibrium with q(0)~100 almost agrees with MSE data.**

➨ **"Current hole"**

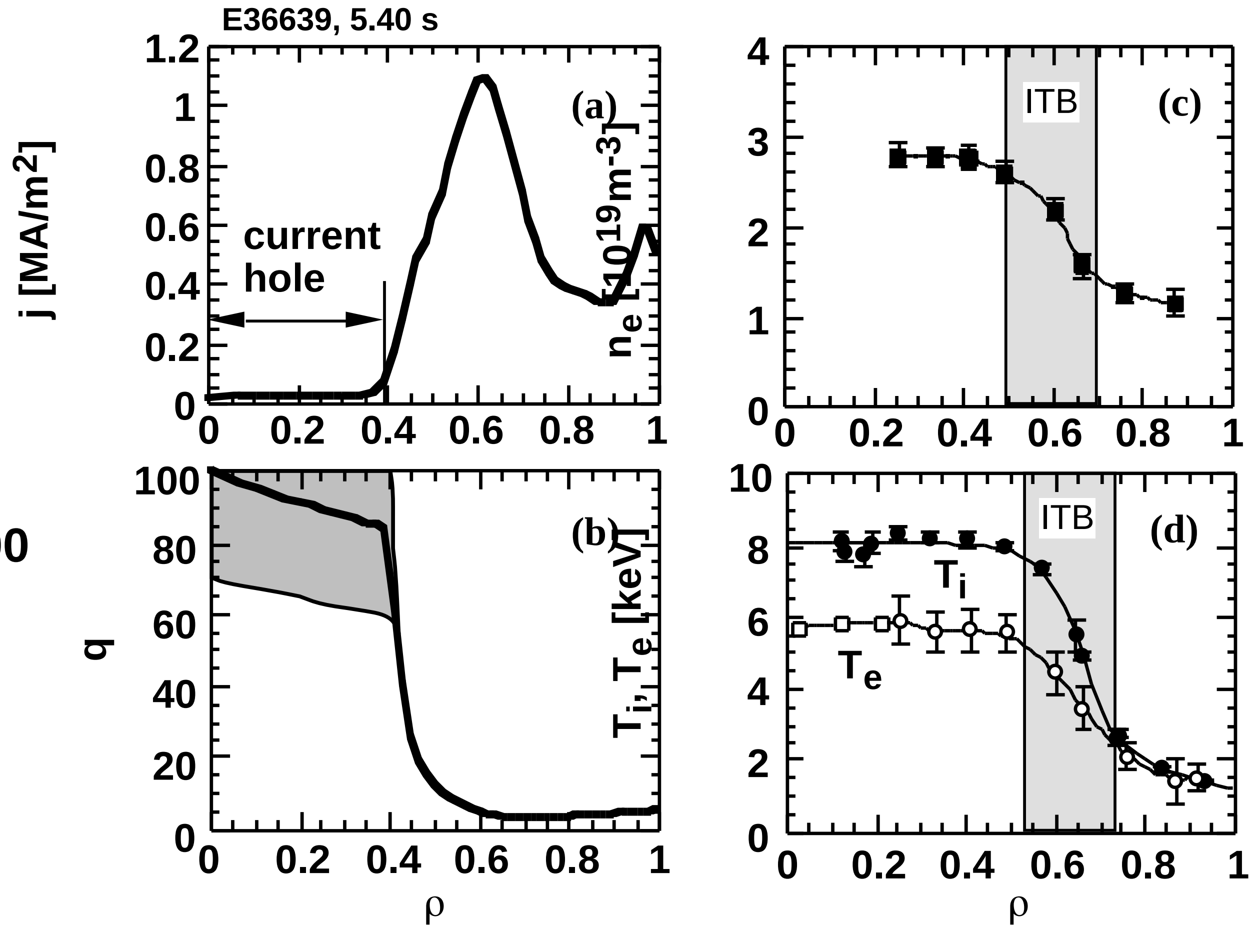




Bt = 3.7 T
Ip = 1.35 MA
q95 = 5.2



Profiles of Current Hole Plasma



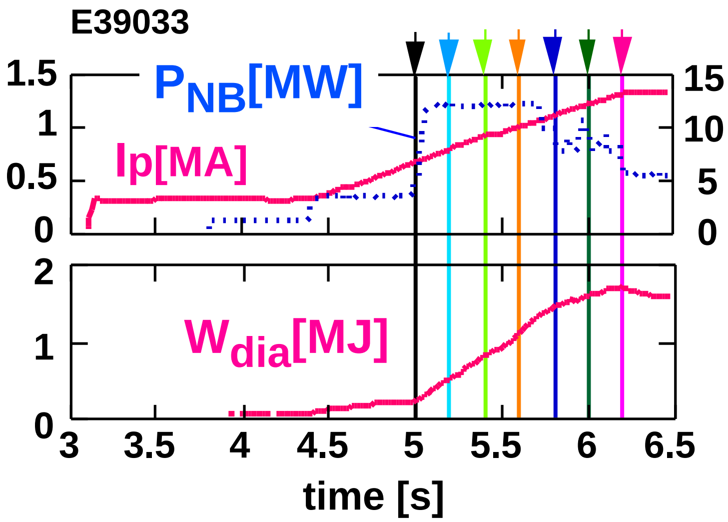
q_0 ~ 100

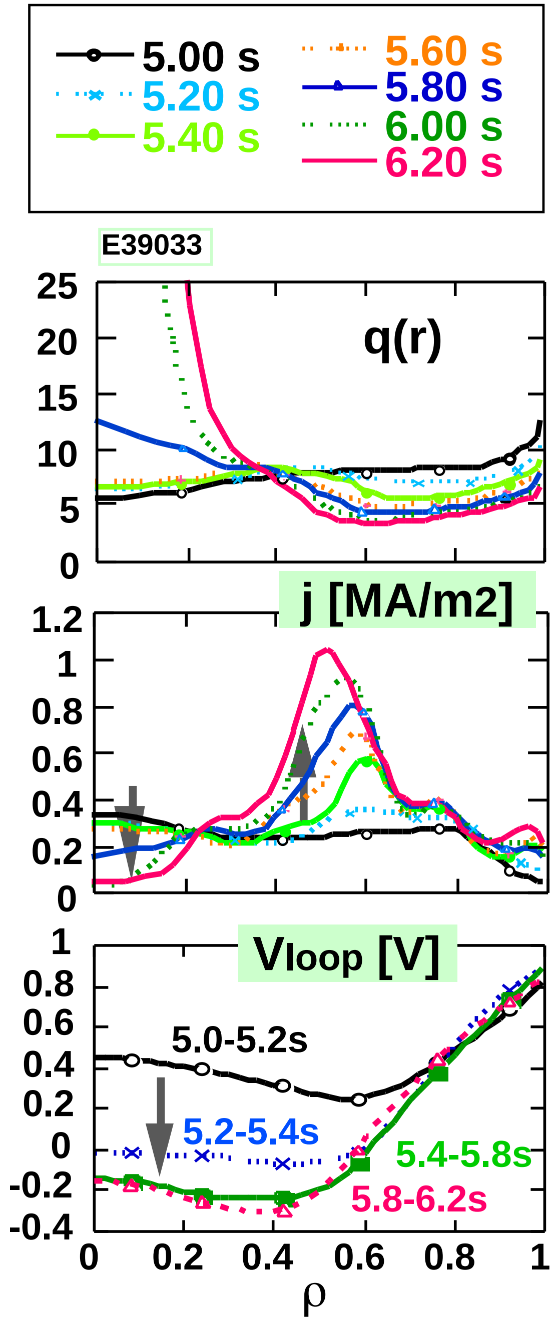
[T.Fujita, et al. Phys. Rev. Lett. Vol 87, 2001]

- Current density is close to zero.
- Density and temperature profiles are flat inside the current hole, but steep gradients (ITBs) are formed outside the current hole.
- q(0) is very large: Strongly hollow current profile.

Formation of current hole

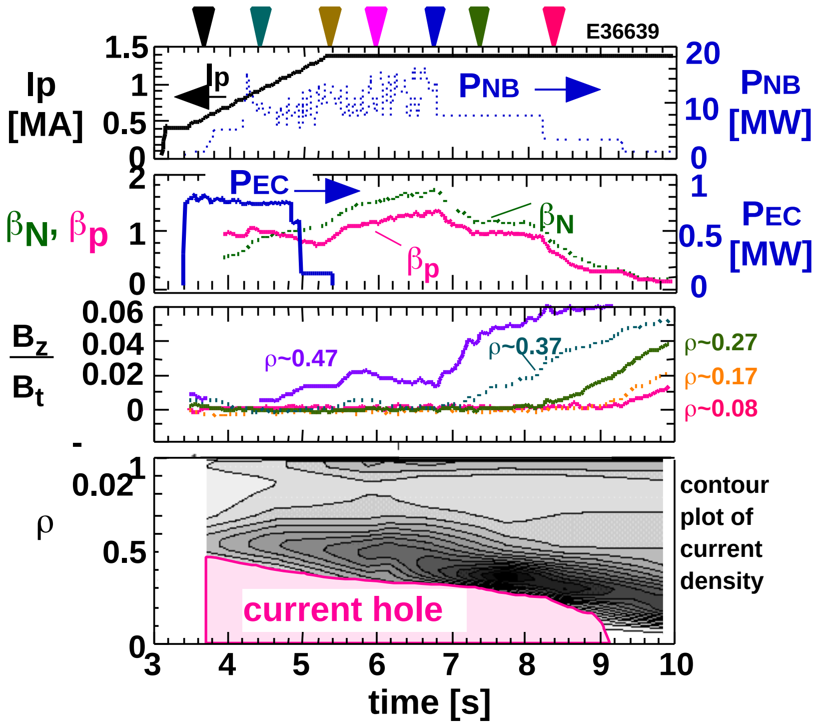
- Central current started to decrease after the growth of off-axis current.
- No counter current drive is expected due to balanced NB injection.
- Negative j(0) was not observed, even though $E_\varphi^{ind}(0)$ was negative.

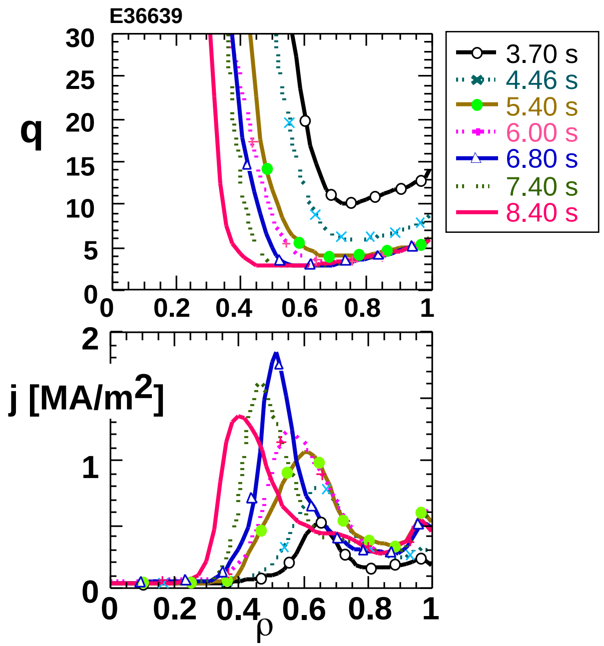




Current hole was sustained stably

- The current hole was sustained for ~5 seconds without any global instabilities though its radius continued to shrink due to the penetration of inductive current.
- High confinement (HH_{98y2}<~1.5) and moderate beta (β_N<~1.7) were obtained.





Termination of High performance in Curr. Hole

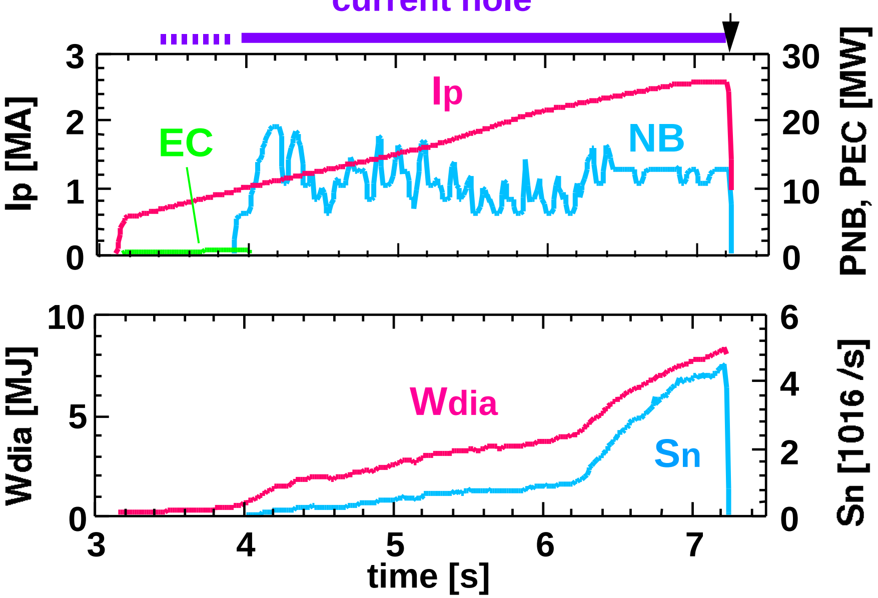
No MHD instability inside the current hole was observed, though the plasma was terminated by collapse.

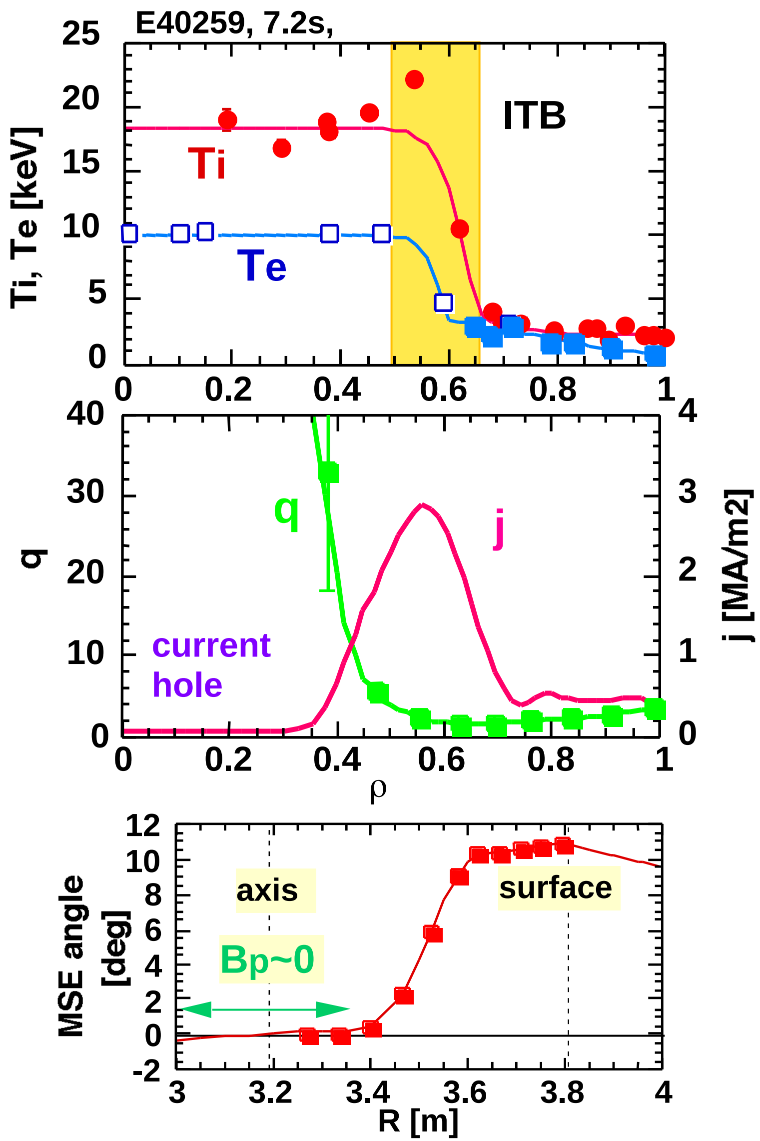
I_p = 2.60 MA, q_{95} = 3.3,

W_{dia} = 8.3 MJ, S_n = 4.6x10^{16} /s,
β_N=1.6, τ_E = 0.89 s, H_{89}=3.0

$n_D(0)\tau_E T_i(0)$ =8.7x10^{20} m^{-3} s keV,

Q_{DT}^{eq} =1.2





It is important to clarify the property of MHD Equilibrium and the stability limit.

Equilibrium and Stabilities of high q_0/q_{min} plasmas

MHD equilibrium code

Grad-Shafranov equation;

$$-\Delta^*\Psi = \mu_0 R j(R, \Psi)$$

$$j(R, \Psi) = Rp'(\Psi)+(1/\mu_0 R)*F(\Psi)F'(\Psi).$$

was solved for the prescribed parameter of p' and $\langle j_{||} \rangle$ profiles.

(1) The deceleration factor in the iteration of Grad-Shafranov equation solver was introduced.

(2) Radial mesh was accumulated near the plasma center, because the very small grad-ψ inside the current hole region.

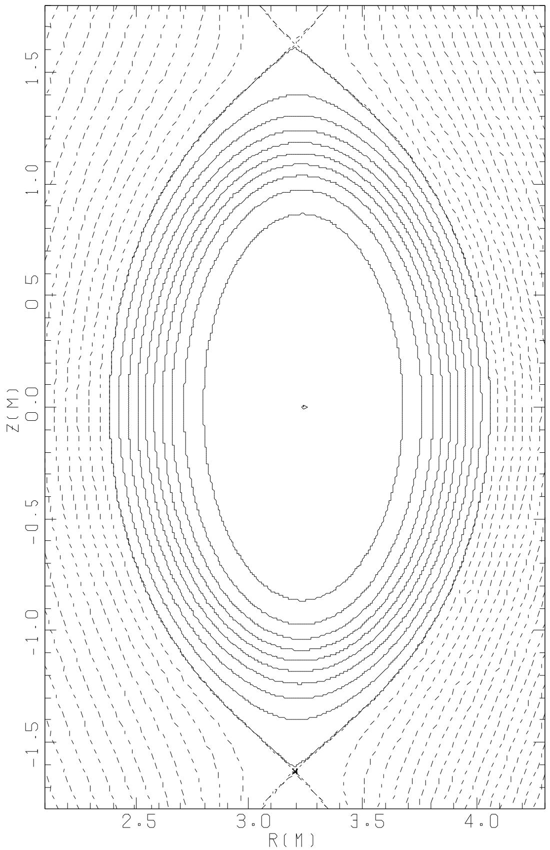
MHD stability code

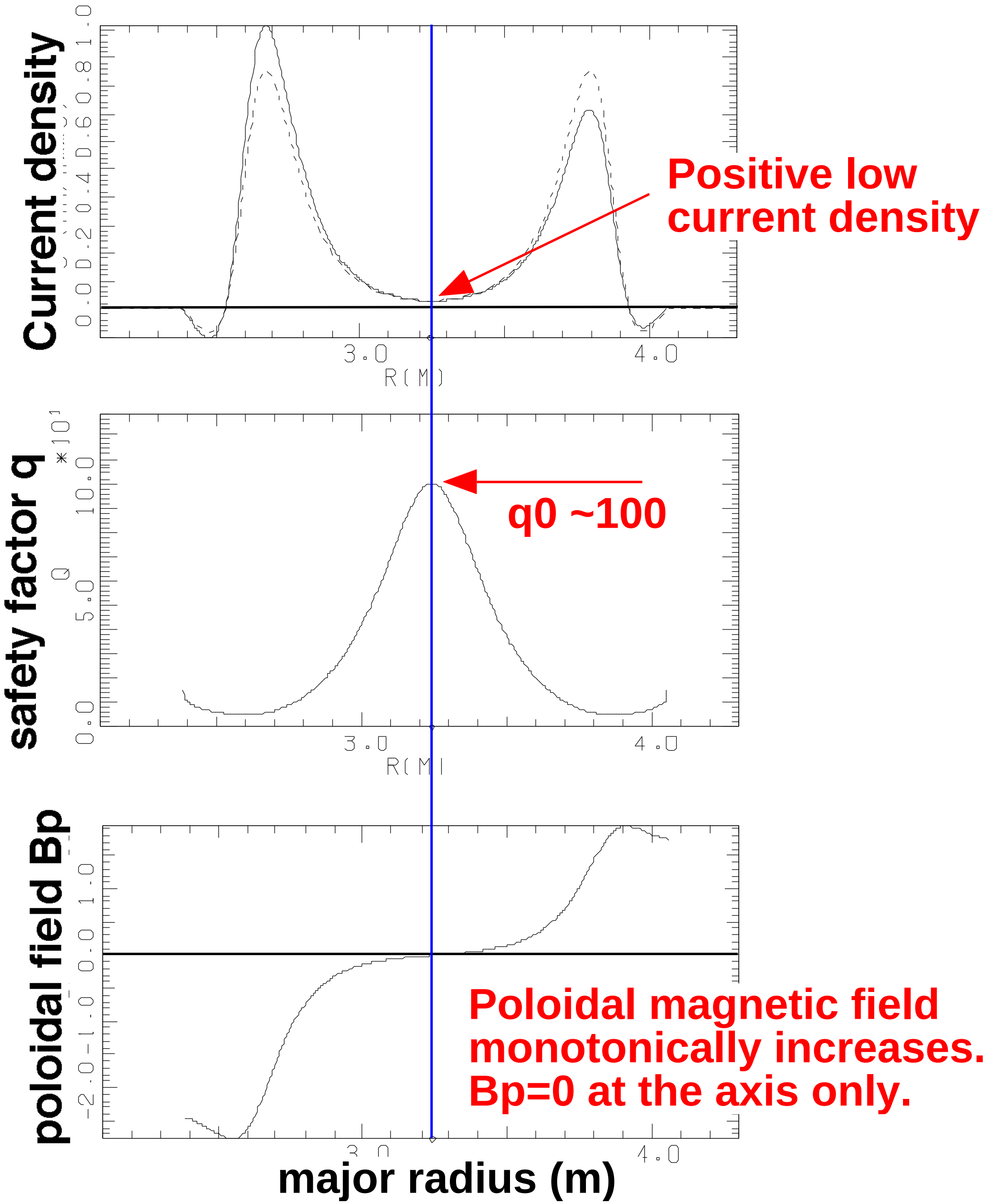
Low n ideal MHD stability code in the toroidal configuration : ERATO-J

Equilibrium of high q_0/q_{min} plasmas with low β

- **Equilibrium with high q0 of ~100, qmin~5 can be produced.**
- **Current density at the magnetic axis is finite (~ few % of the maximum).**

Low β (~0.0) plasma

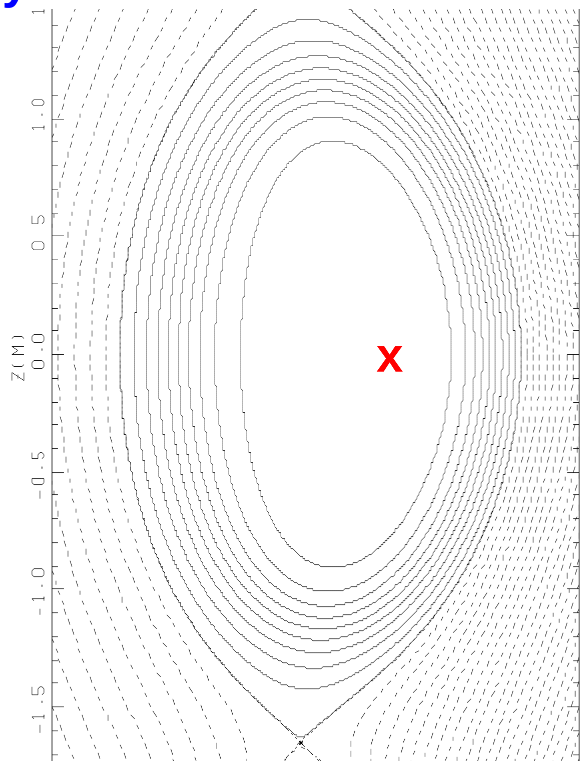




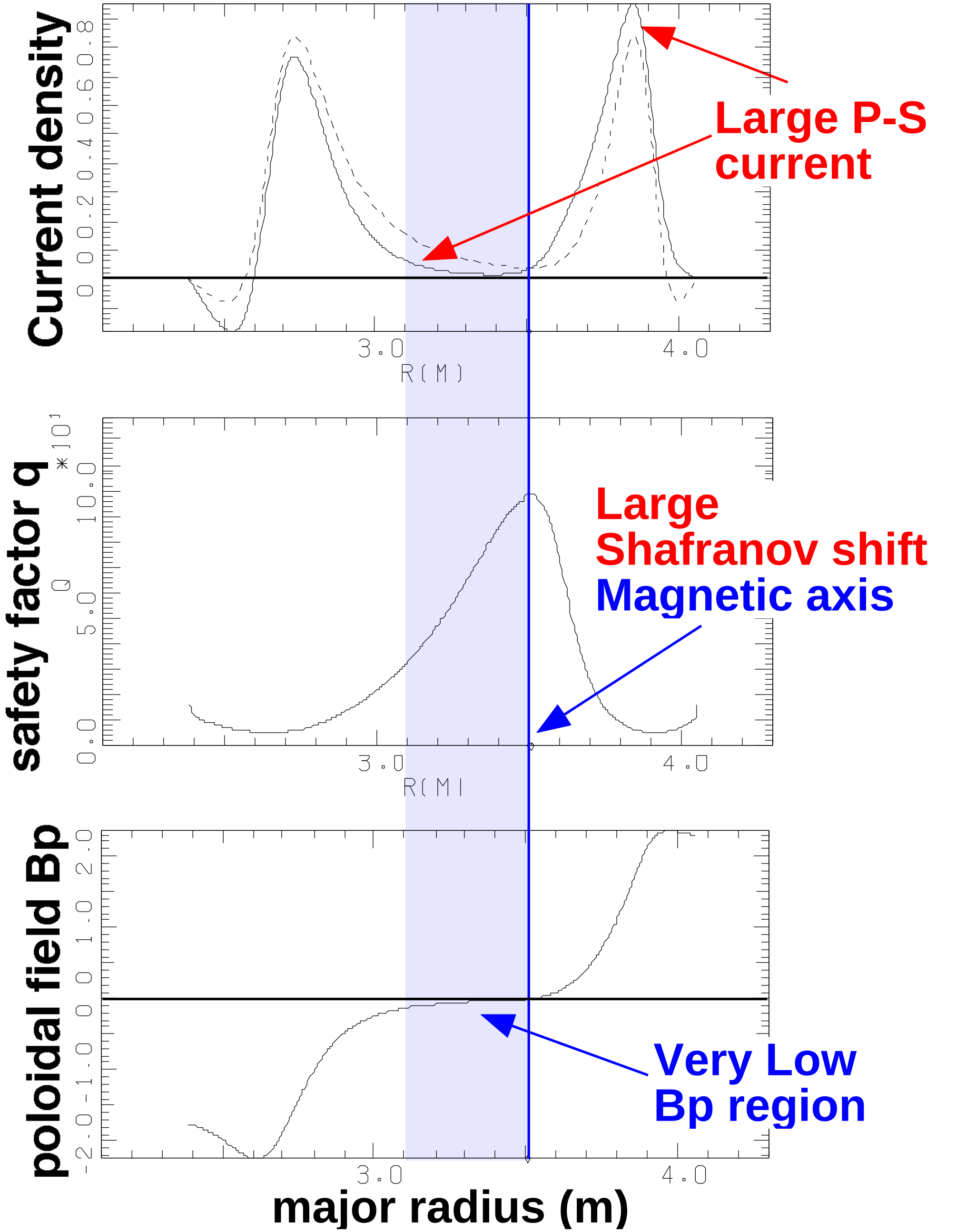
Equilibrium of high q_0/q_{min} plasmas with finite β

- Equilibrium with high q0 of ~100, qmin~5 and βp~1.5 can be produced.
- Large Shafranov shift ($\varepsilon\beta p_{(core)}$~0.8).
- Pfirsch-Schluter current reduces the total current density and the poloidal field in inboard side.
- Current density at the magnetic axis is very few % of the maximum.

$$\frac{dp}{d\psi} \quad (1-\psi)$$



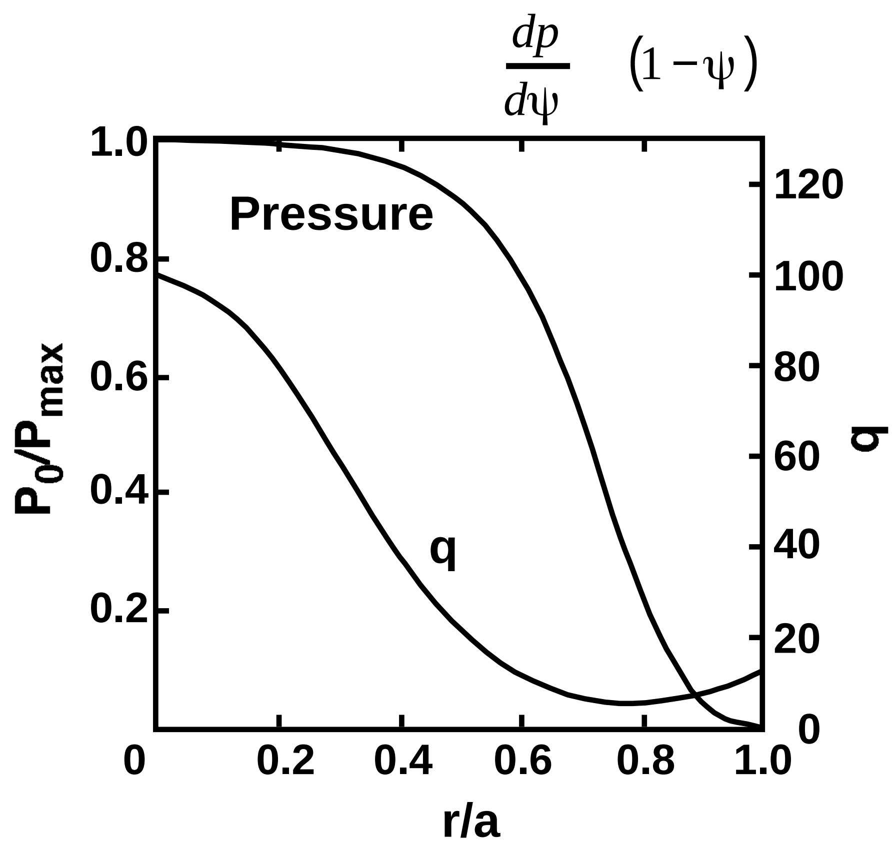
The P-S current may produce the null point in the low field side.

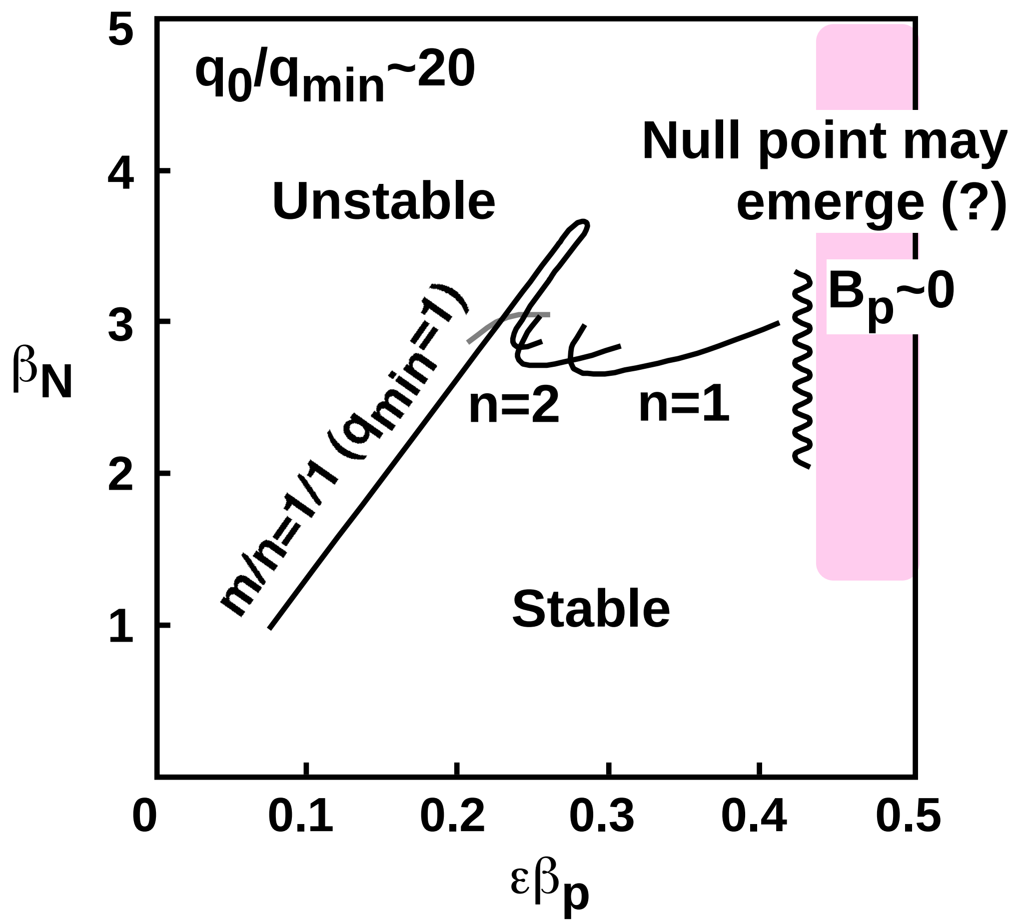


Stability Limit due to the Ideal MHD mode

Beta limits due to the kink-Ballooning modes by ERATO.

ERATO: Low n ideal MHD stability in the toroidal configuration.

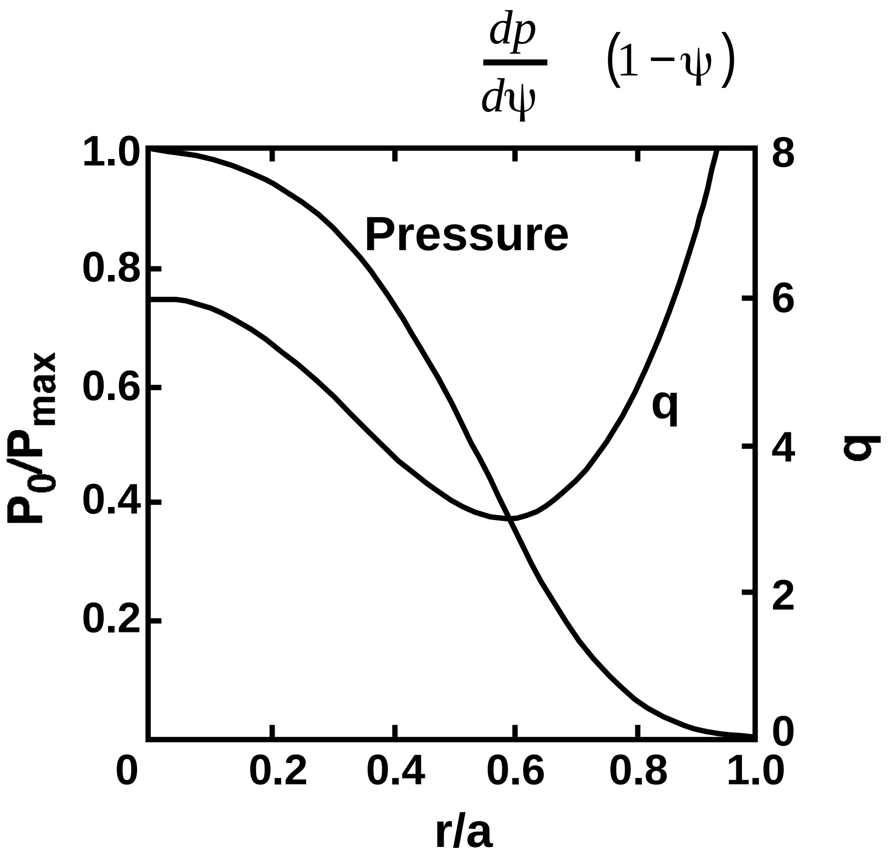


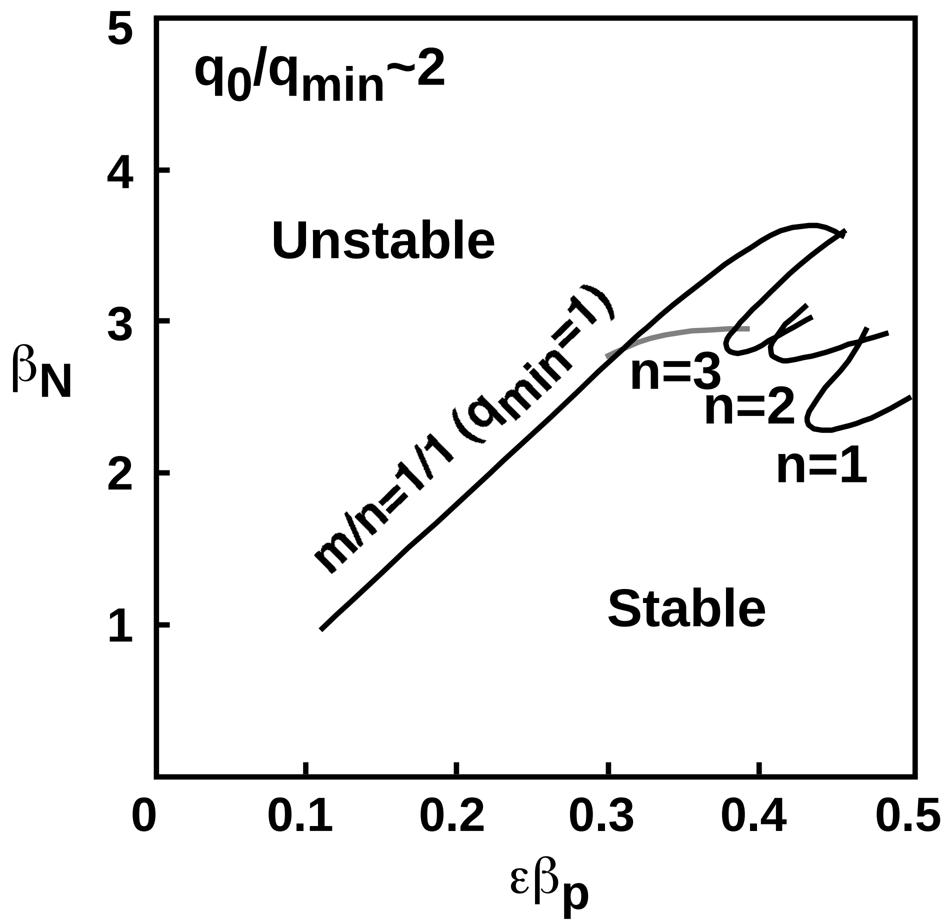


Beta limits in the strongly hollow current is β_N~2.5-3, that is similar to those in the standard hollow current. In the high β_p region, the null point may emerge.

Stability limit of normal reversed shear plasma

As a reference, beta limits of normal R/S plasmas (q0/qmin~2)



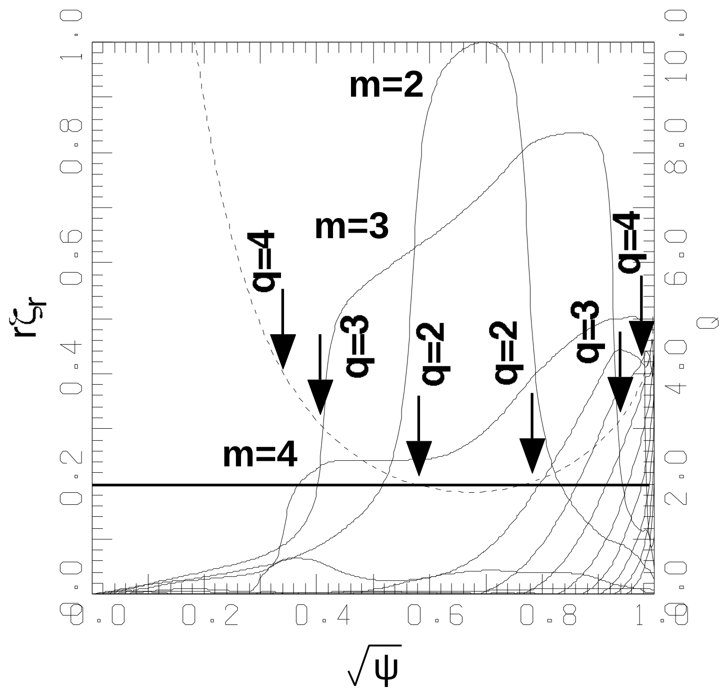


Beta limits is about 2.5-3, but profiles are not optimized.

Eigenfunction

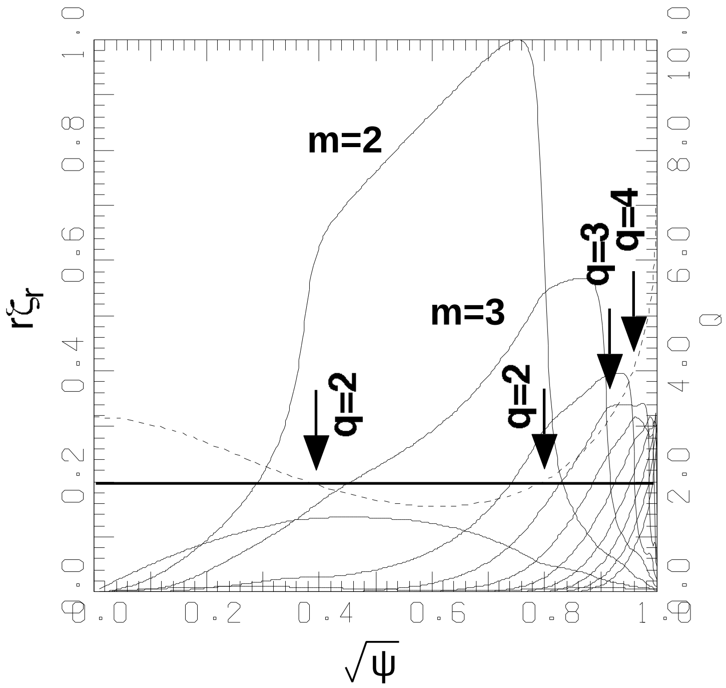
q_0/q_{min}~20,

q_{min}=1.85, β_N=3.0



q_0/q_{min}~2,

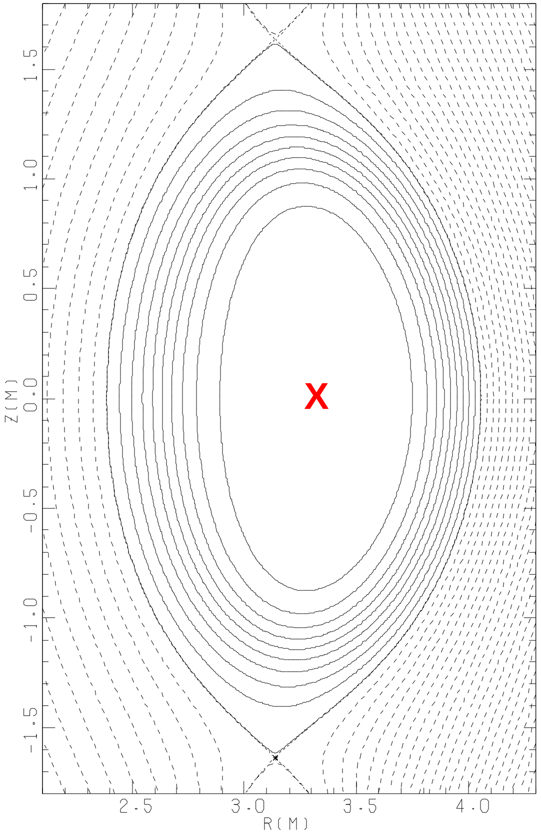
q_{min}=1.56, β_N=2.73

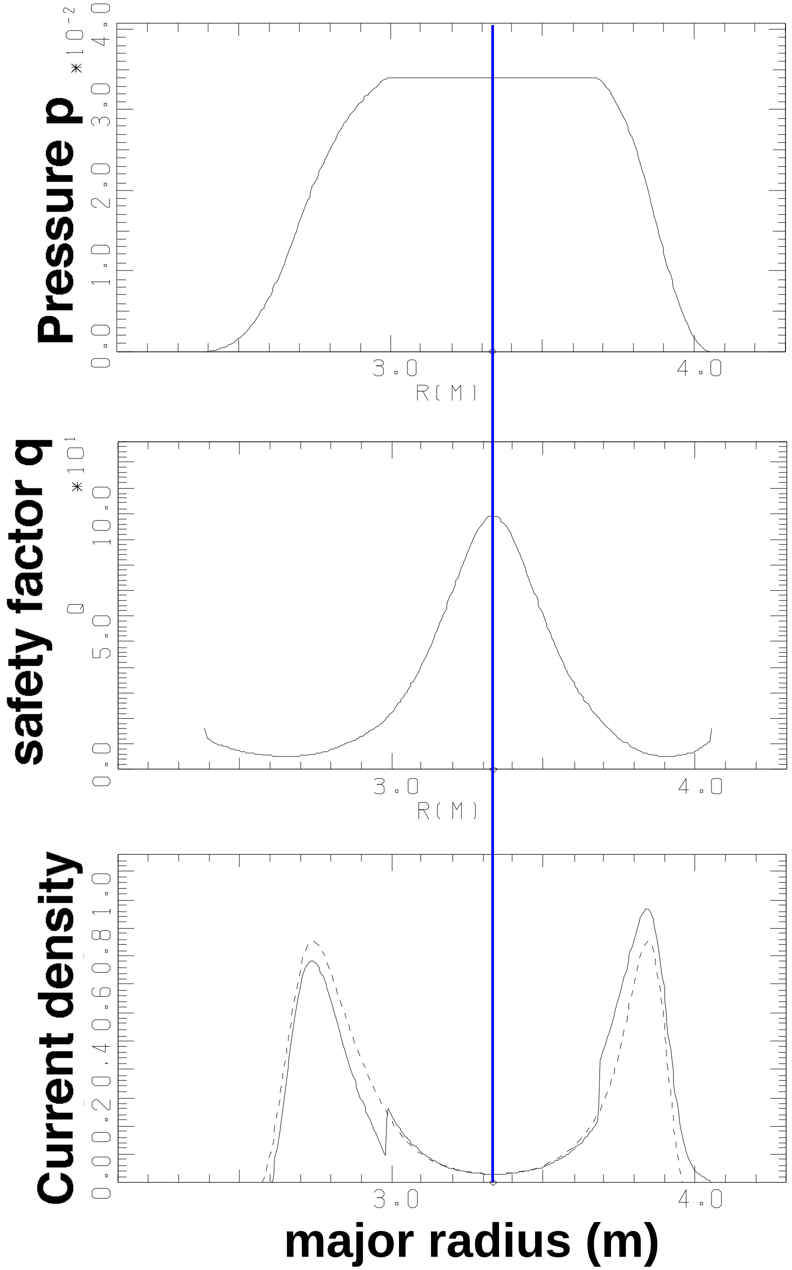


The unstable mode is resonant with inside and outside rational surfaces and the mode coupling is stronger for high q_0/q_{min}.

Equilibrium of high q_0/q_{min} plasmas with flat p

- Equilibrium with high q0 of ~100, qmin~5 and βp~1.5 can be produced.
- Small Shafranov shift (εβp(core)=0.0).
- No Pfirsch-Schluter current in the central region.
- Current density at the magnetic axis is very few % of the maximum.

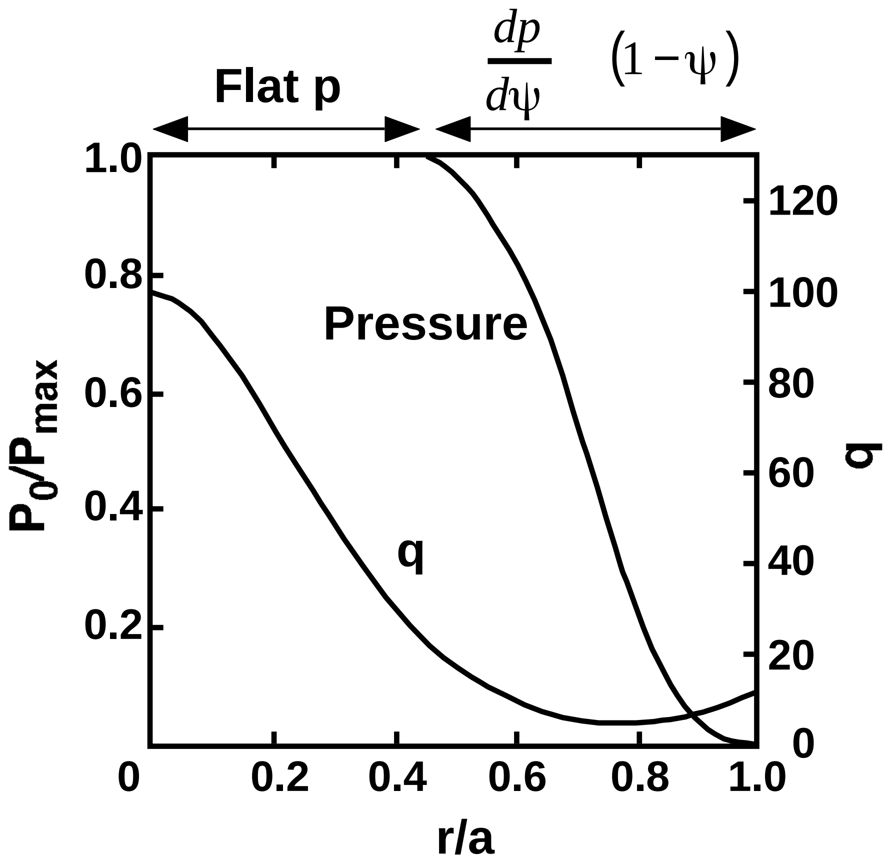


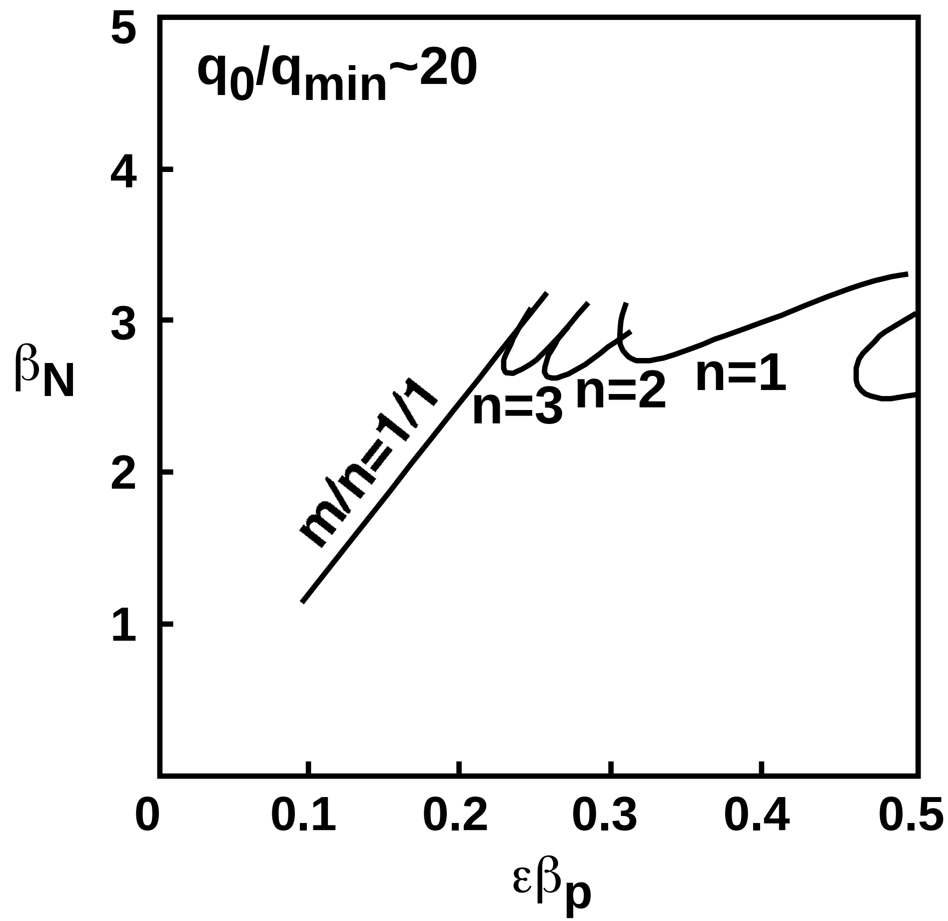


Stability limit of high q_0/q_{min} with flat p

Beta limits are similar to those of the parabolic profile case.

Stability property is mostly determined by the outer current and pressure profiles.

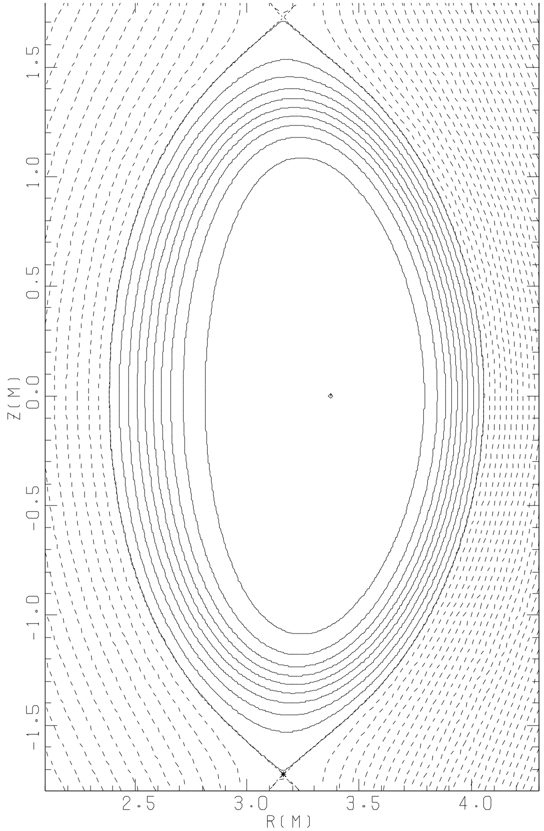


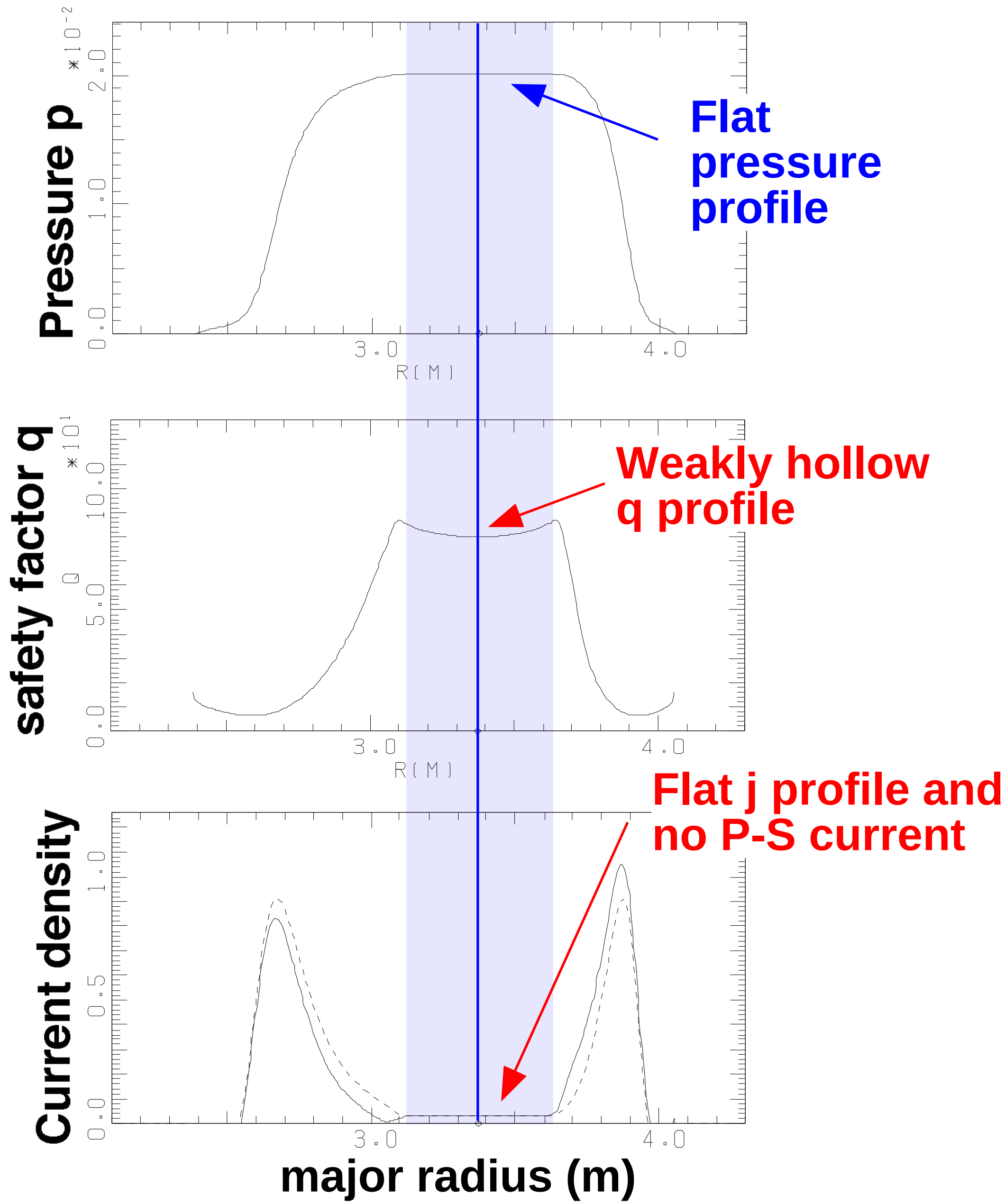


No P-S current in the core region, then the null point may not emerge in the high βp region.

Equilibrium of high q_0/q_{min} plasmas with flat j

- **Equilibrium with high q0 of ~80, qmin~6 and βp~1.0**
- **Small Shafranov shift ($\varepsilon\beta p_{(core)}$=0.0).**
- **No Pfirsch-Schluter current in the central region.**
- **Current density at the magnetic axis is very few % of the maximum.**

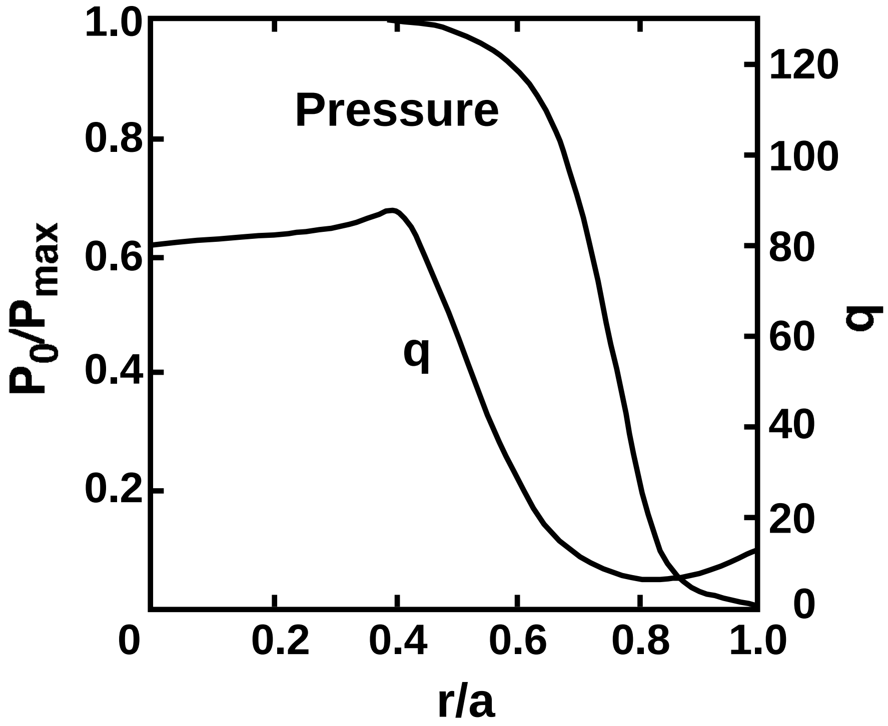


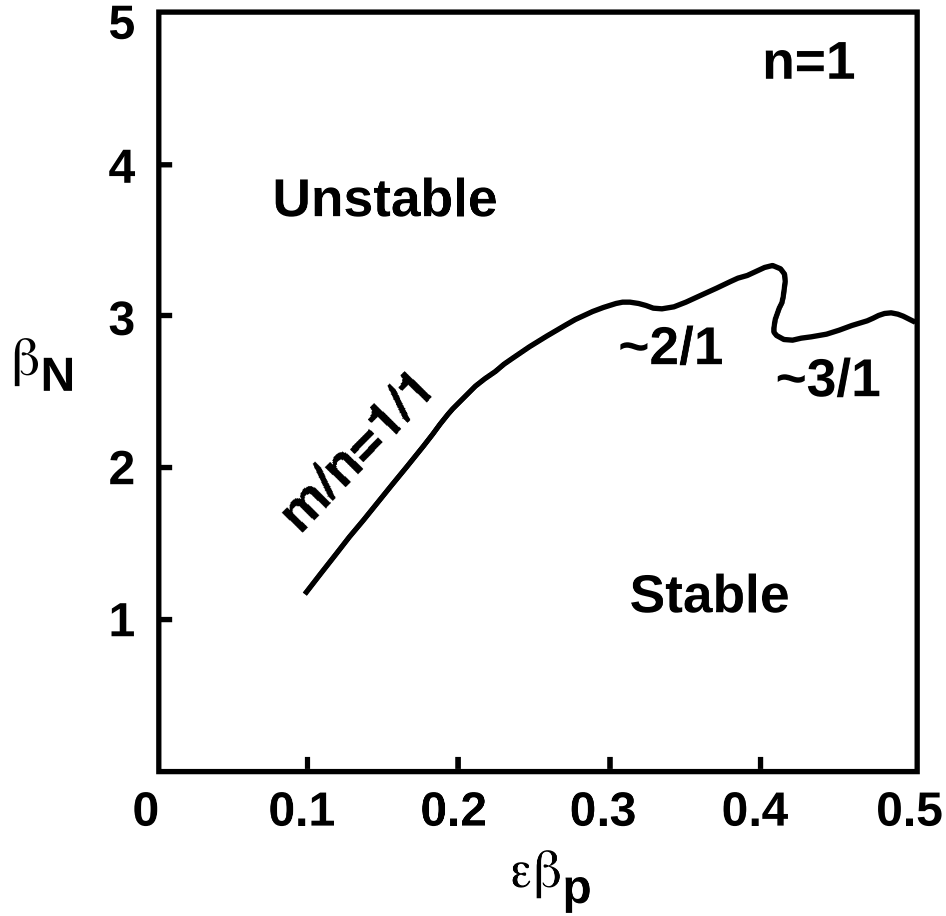


Stability limit high q_0/q_{min} plasmas with flat j

Beta limits due to the n=1 kink-Ballooning modes is similar to those in the normal reversed shear plasma.

The stability boundary is not clearly depend on the single m/n mode.





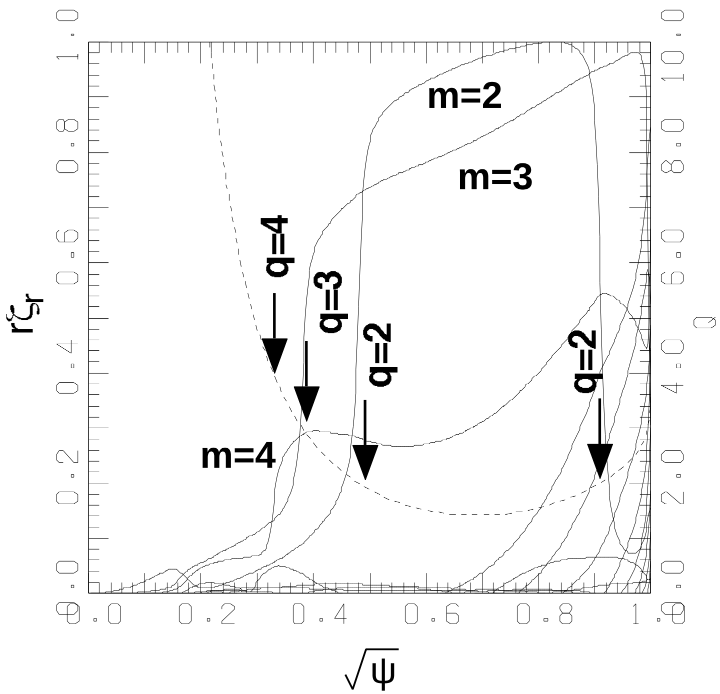
No significant MHD instability was obtained inside the current hole region, if the p- and j-profile are flat and the current density is positive.

Eigenfunction

Current hole plasma

q_0/q_{min}~12,

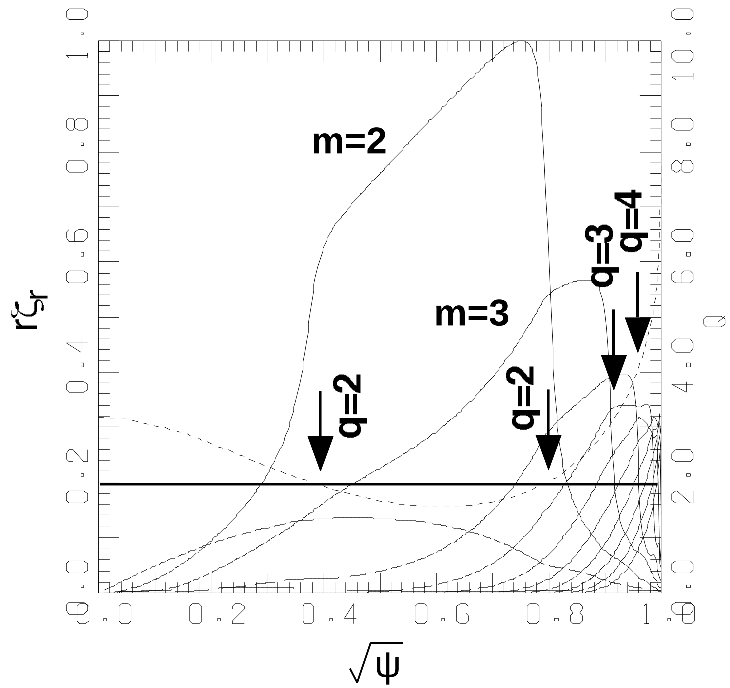
q_{min}=1.42, β_N=2.9



Normal R/S plasma

q_0/q_{min}~2,

q_{min}=1.56, β_N=2.73

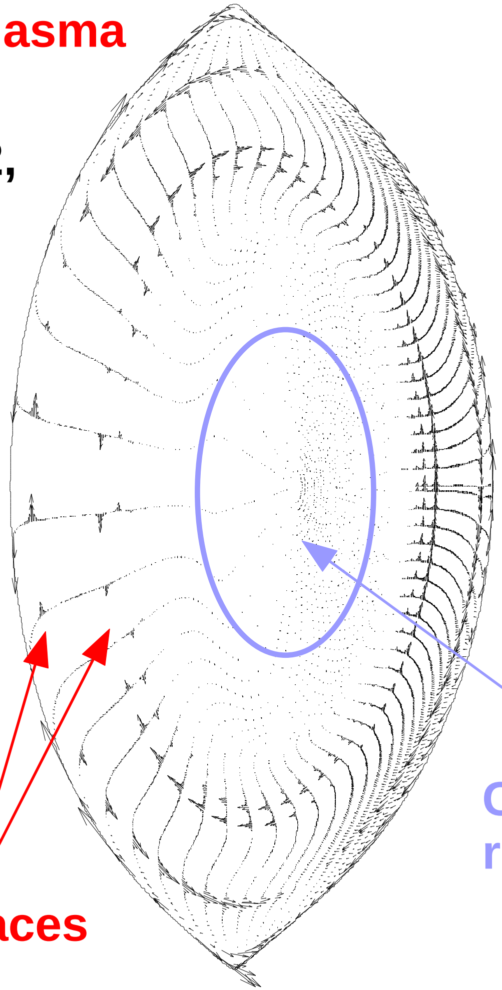


The unstable mode is resonant with internal and external rational surfaces and the mode coupling is stronger for high q_0/q_{min}.

Eigenfunction (2D)

Current hole plasma

q_0/q_{min}~12,
q_{min}=1.42,
β_N=2.9

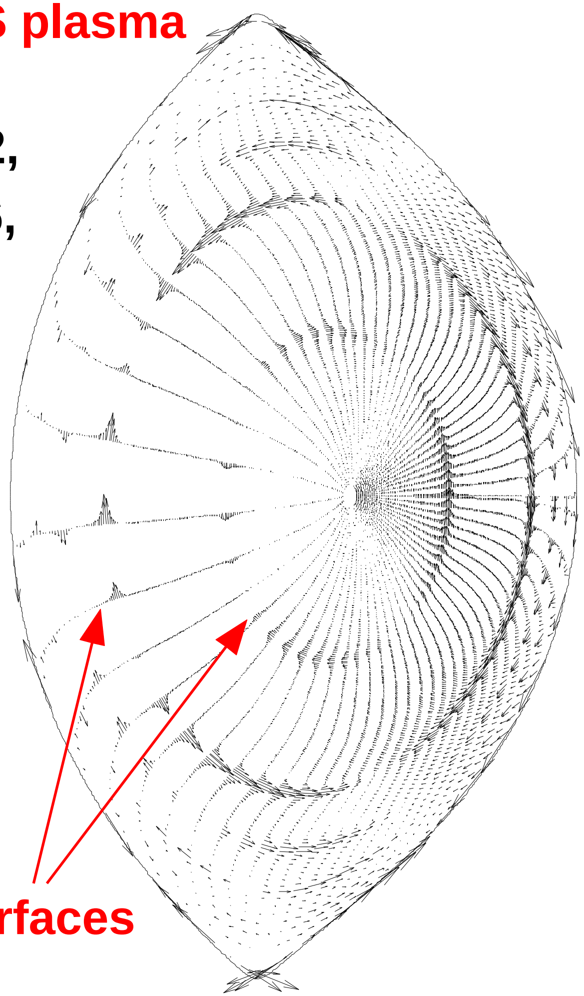


Current hole region.

q=2 surfaces

Normal R/S plasma

q_0/q_{min}~2,
q_{min}=1.56,
β_N=2.73



q=2 surfaces

Eigenfunction localized around the peripheral region for high q0/qmin plasma, while it has a global structure in the normal reversed shear plasma.

Summary

MHD stabilities of the current hole plasmas were investigated.

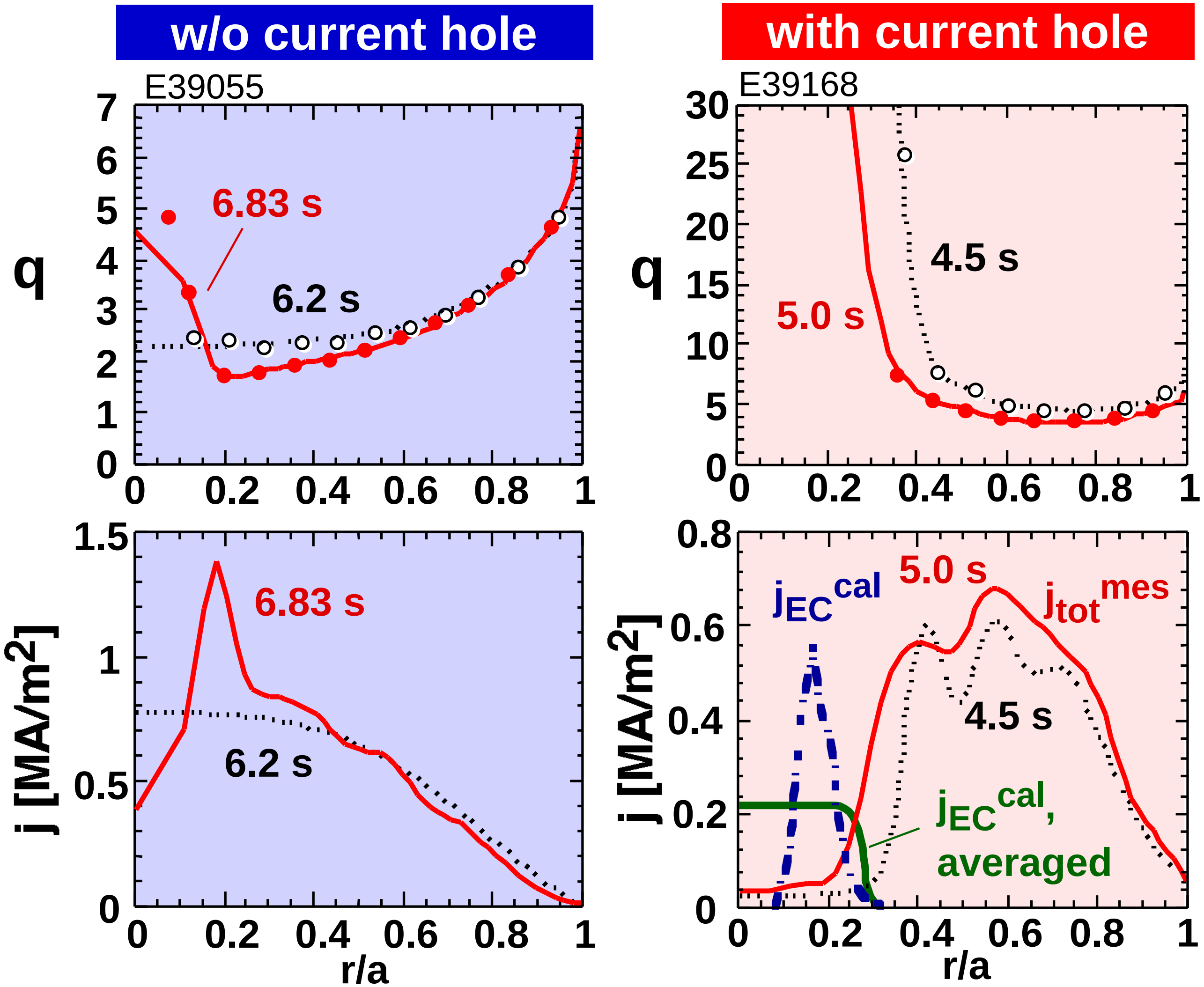
1) Equilibrium with high q0/qmin (~20) plasmas were obtained.
   - The finite current on the magnetic axis is produced, which does not have the null point of the poloidal field.
   - When there is a pressure gradient, as βp increases, the Pfirsh-Schluter current is induced and reduces the poloidal field in the inboard side. The resultant q-profile is similar to the experimental observation.

2) Stability limits of the high q0/qmin plasma do not change very much, but the profiles are not optimized.
   - Equilibrium with flat j near the center has weakly hollow q-profile, but it may not affect the stability when the pressure gradient is small.
   - The eigenfuntion consists of internal and external resonant surfaces.
   - Mode coupling is stronger than the normal R/S plasma.

3) Possibilities of equilibrium with the negative current and the mechanism of the formation and sustainment of the nearly zero current density are remained as a future work.

Central Current is clamped to Zero in JT-60U

- The peaked j_{EC} is not generated in a current hole. As suggested by a flat Te profile, it implies low radial confinement of electron momentum.
- Even if a uniform j_{EC} is generated in the current hole, it should be detected by MSE (green curve).
- Absence of this current suggests that j is clamped to zero in the current hole.
- Absence of the ECCD current in the current hole is also true for the case of counter ECCD.



Issues: The mechanism of the current clamp.
(No clear negative and positive currents are observed.)