BPSI

核燃焼プラズマ統合コード研究会
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Axisymmetric Tri-Magnetic-Islands Equilibrium of Strongly-Reversed-Shear Tokamak Plasma

- An Idea for the Current Hole -

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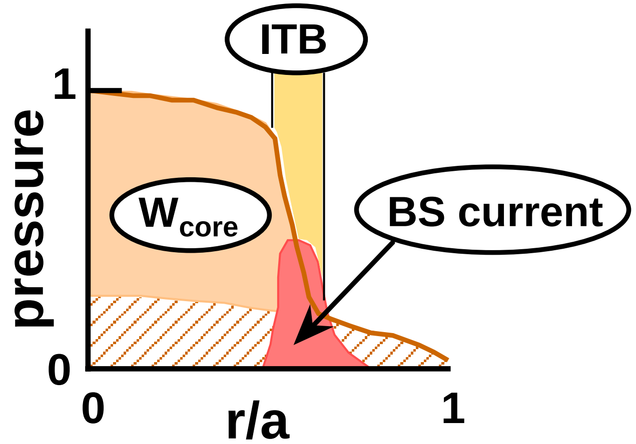
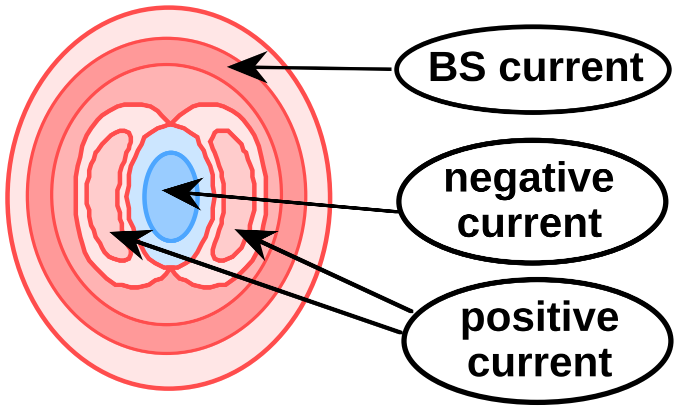
Content

Confinement and Transport of RS Plasmas with ITB

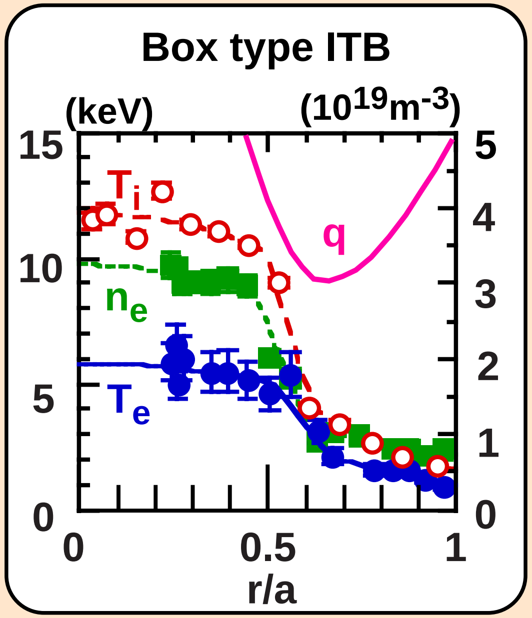


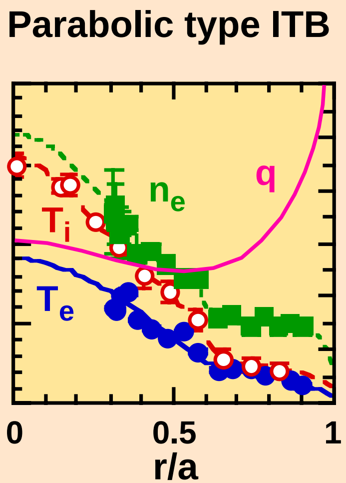
Axisymmetric Tri-Magnetic-Islands (ATMI) Equilibrium

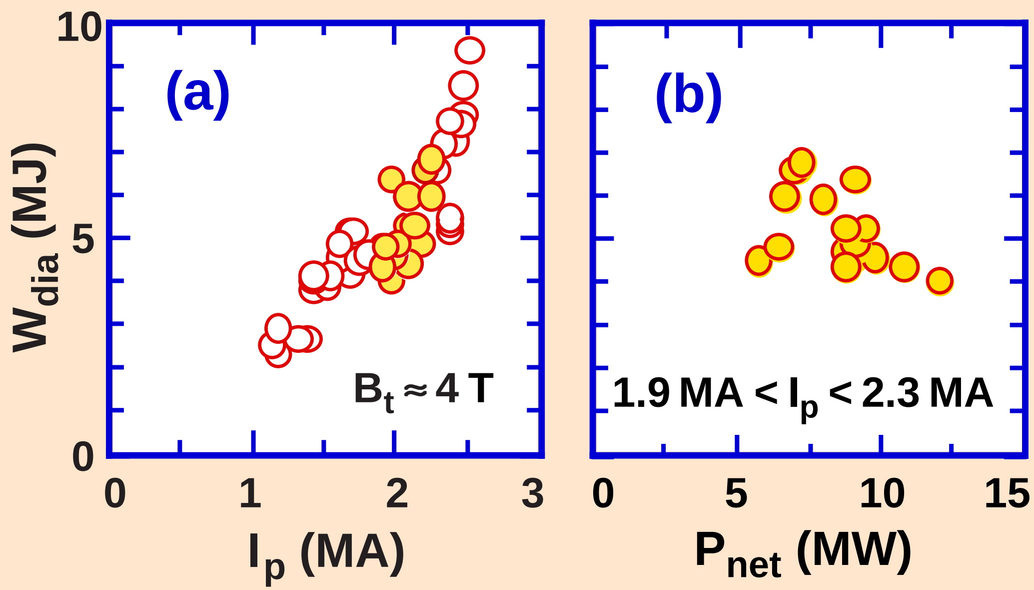


Confinement and Transport of RS Plasmas with ITB

T. Takizuka et al., "Energy Confinement Scaling for Reversed-Shear Plasmas with Internal Transport Barrier in JT-60U", Plasma Phys. Control. Fusion 44 (2002) A423.







JT-60U database

L-mode edge, Box type ITB

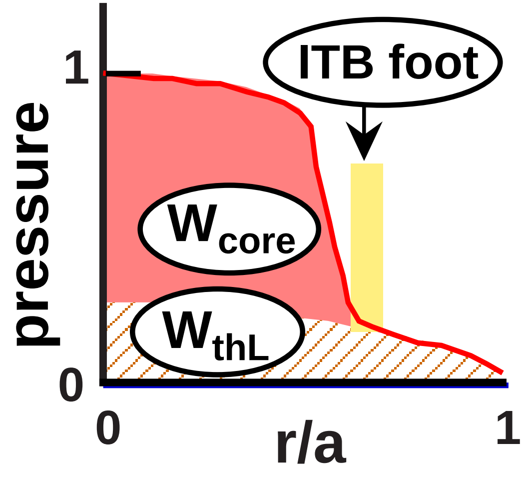
Stored energy depends strongly on plasma current I_p ($W_{dia} \sim I_p^{1.4}$), but little on heating power P_{net} ($\equiv P_{NB}$ - dW/dt)

Working hypotheses

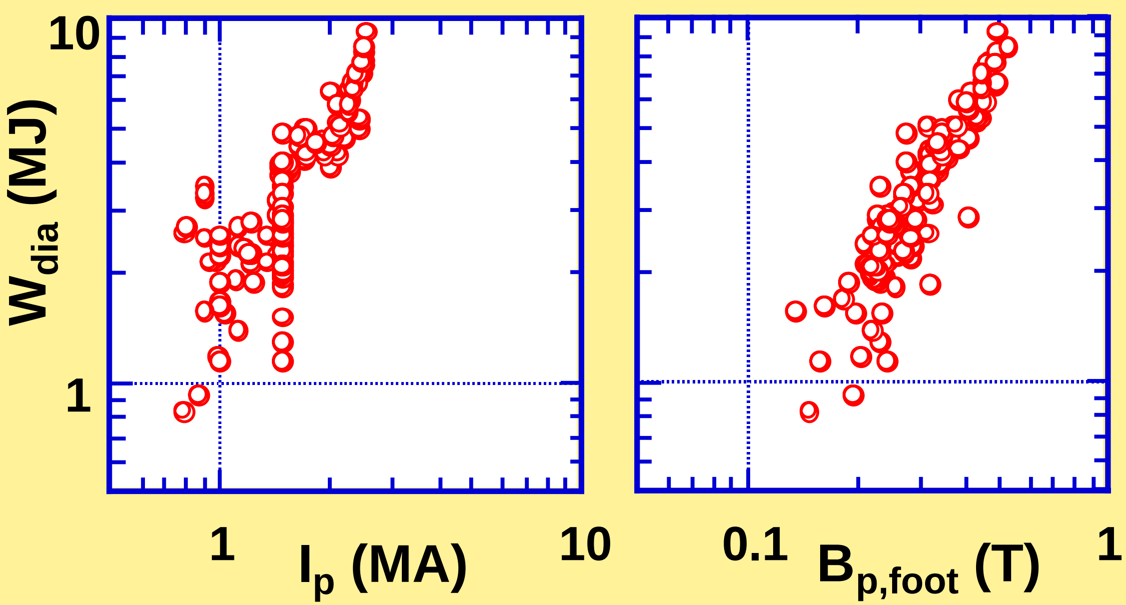
(1) Stored energy is govered not by the heat flux through ITB but by the plasma parameters around ITB.

(2) Stored energy is devided into L-mode base part and core part inside ITB.

[$W_{thL} = 0.026\, M^{0.3}\, I_p^{0.5}\, B_t^{0.39}\, R^{1.44}\, a^{0.92}\, \kappa^{0.88}\, n_{19}^{0.5}\, P^{0.33}$]



W_{dia} depends more strongly on **$B_{p,foot}$** than on **I_p**



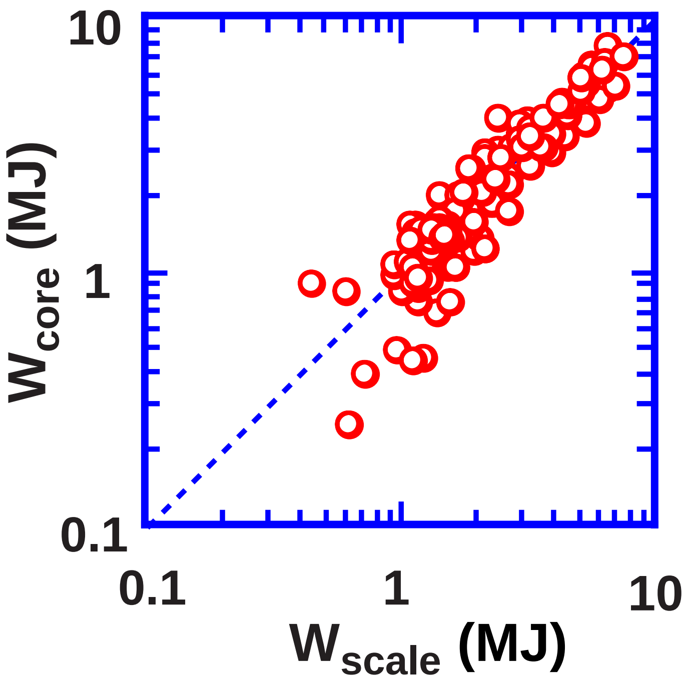
W_{core} can be expressed by a dimensionally-correct form without including **P** :

$$W_{core} \sim B_{p,f}^{2} \times V_{core}$$

Energy Confinement Scaling

$$W_{scale} = C\,\varepsilon_f^{-1} B_{p,f}^{\,2} V_{core}$$

Analysis of Database under the above hypotheses



r = 0.95, σ = 22 %

$$\varepsilon_f \beta_{p,core} = \text{const.} \ (\approx 1/4)^*$$

Indication of MHD Equilibrium Limit

B_t	:	2.1 ~ 4.1 T
I_p	:	0.8 ~ 2.6 MA
P_{NB}	:	4 ~ 19 MW
ε_f	:	0.12 ~ 0.19
V_{core}	:	9 ~ 25 m^3
W_{core}	:	0.3 ~ 7.7 MJ

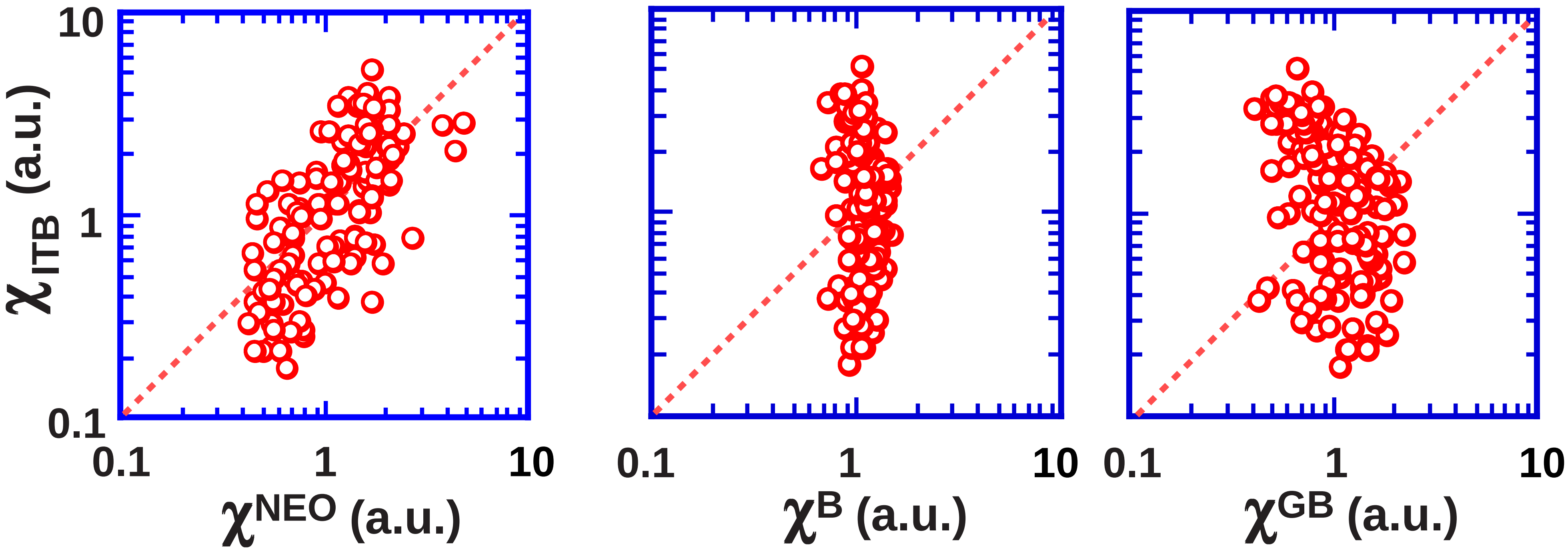
* $B_{p,f}$ is measured at the outer midplane.

When averaged $B_{p,f}$ used,

$$\varepsilon_f \beta_{p,core} > 1/2 .$$

"Neoclassical transport of ITB" is not inconsistent with the data, though the core stored energy is independent of P_{net}

$\chi_{ITB} \propto P_{net}/(S_f n_{e0}|dT/dr|_{ITB})$ $\chi^{NEO} \propto \varepsilon_f^{0.5} n_{e0}/B_{p,f}^2 T_{i0}^{0.5}$

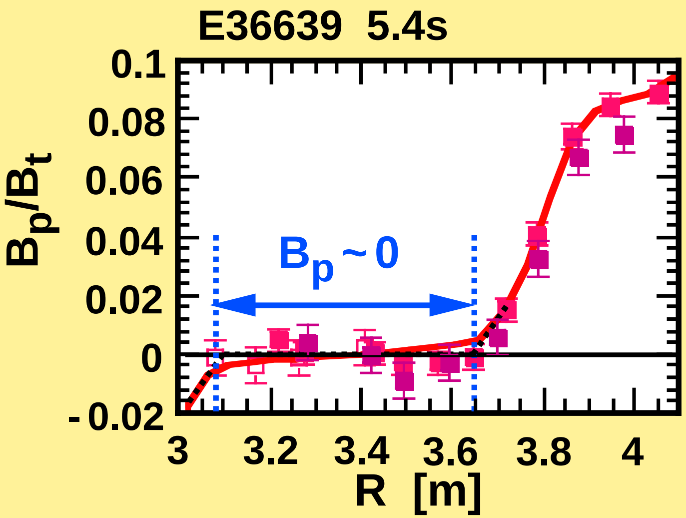


Bohm or GyroBohm transport is inconsistent with the data

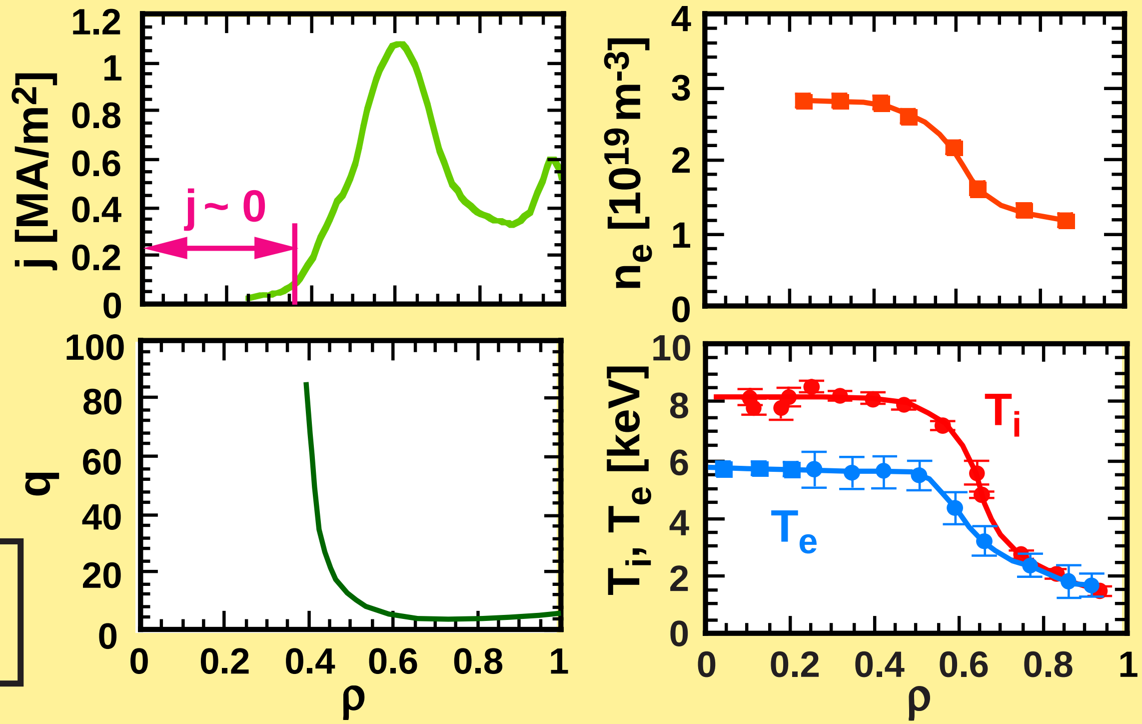
Axisymmetric Tri-Magnetic-Islands (ATMI) Equilibrium
- An Idea for the Current Hole -

T. Takizuka, "Axisymmetric Tri-Magnetic-Islands Equilibrium of Strongly-Reversed-Shear Tokamak Plasma: An Idea for the Current Hole", J. Plasma Fusion. Res. 78 (2002) 1282; http://jspf.nifs.ac.jp/RCPDF/

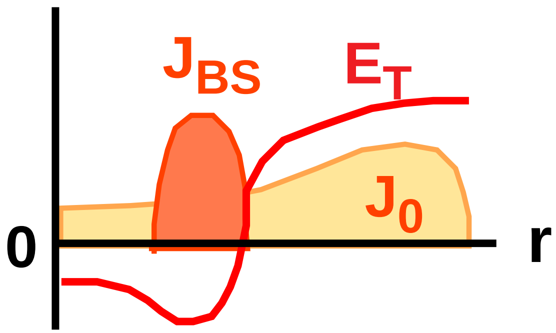
Current Hole in JT-60U Tokamak Plasma



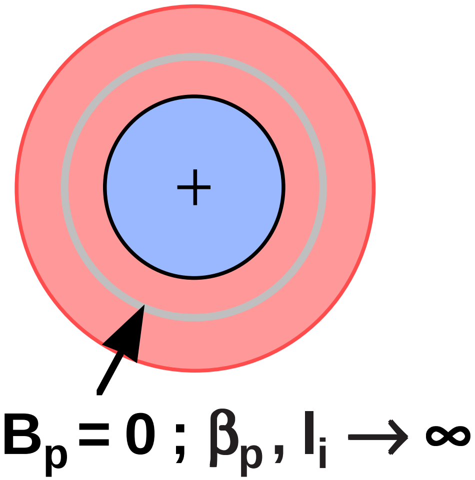
T. Fujita et al., Phys. Rev. Lett. 87 (2001) 245001



Generation of Negative Current and Instability of a Single-Magnetic-Axis (SMA) Equilibrium with Central Negative Current



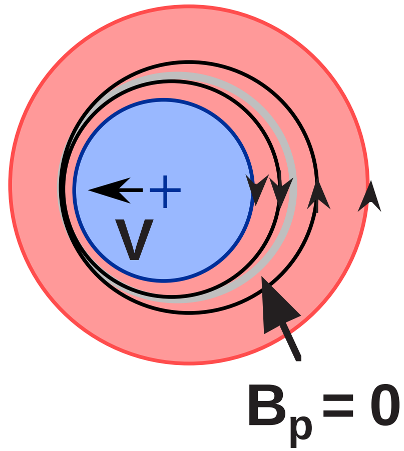
Growth of bootstrap current J_{BS} induces negative E_T at the central region.



Central negative current in a SMA configuration destroys the equilibrium.

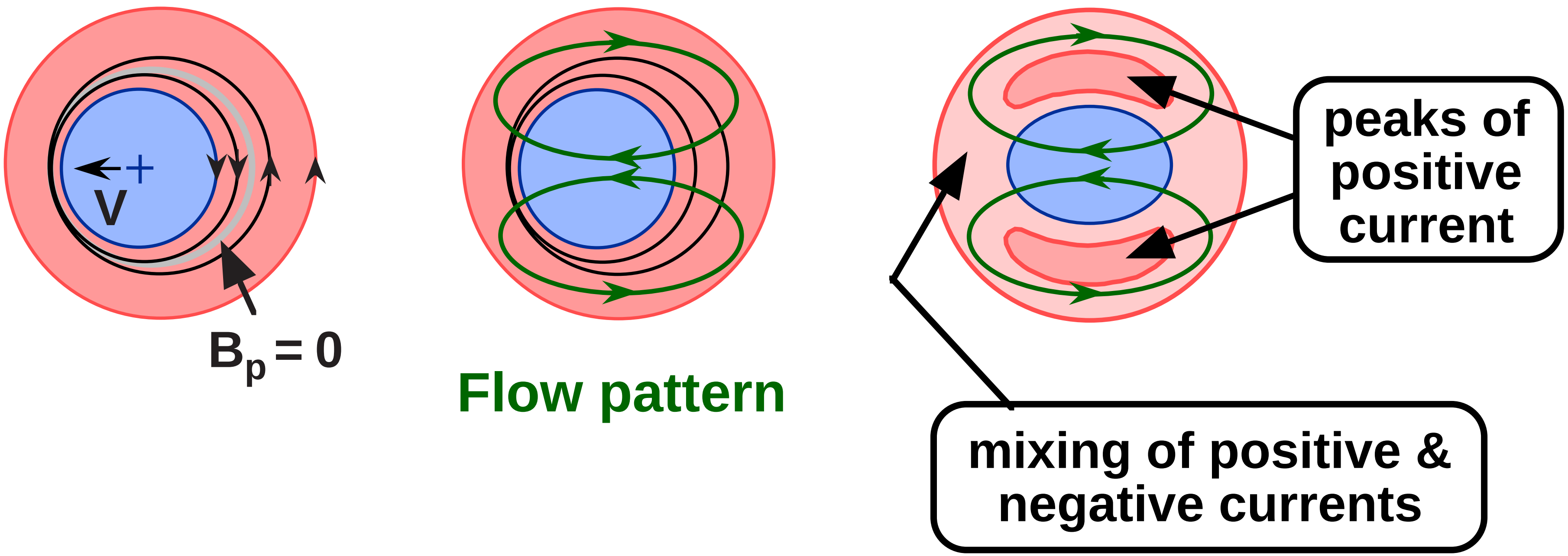
Large Shafranof shift

$$\Delta \sim \varepsilon \Lambda \quad (\Lambda = \beta_p + l_i/2 - 1)$$



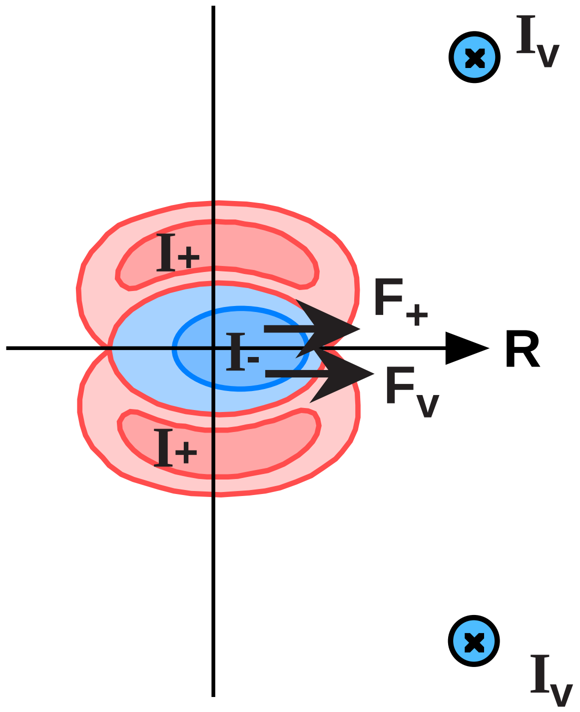
Even in a cylindrical plasma, central negative current in a SMA configuration destabilizes n=0/m=1 resistive MHD mode.

Formation of Three Magnetic Islands (m=2/n=0) through Nonlinear Evolution of m=1/n=0 Instability (?)

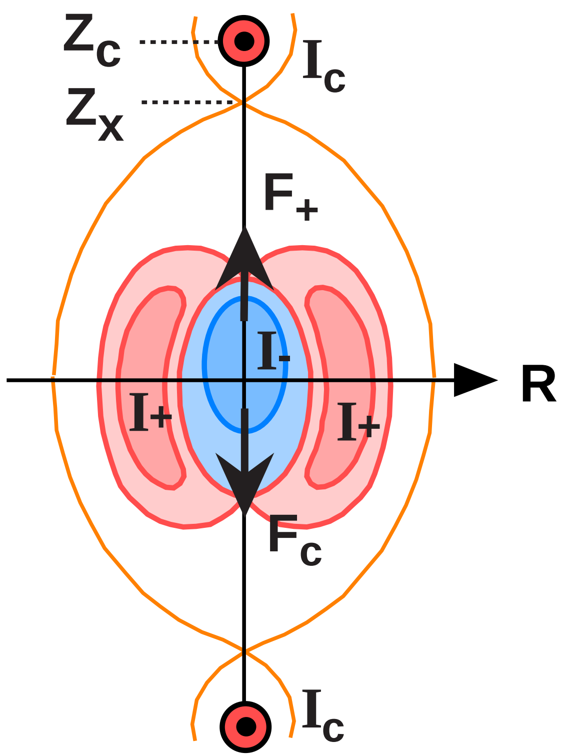


Unstable Configuration (Z arrangement) and Stable Configuration (R arrangement) under the Current Limit

Unstable Z-ar.



Stable R-ar.



Stability Condition (current limit)

$F_+ < F_c$

$I_+/(r_1^2 + \delta Z^2) < I_c/Z_c^2$

$I_+/r_1^2 < I_p(Z_c - Z_x)/Z_x Z_c^2$

$q_{ATMI}/q_a > \kappa_1^2 Z_c^2/(Z_c - Z_x)a$

$2I_+/I_- \approx (1+\kappa_1^2)/\kappa_1^2 Z$

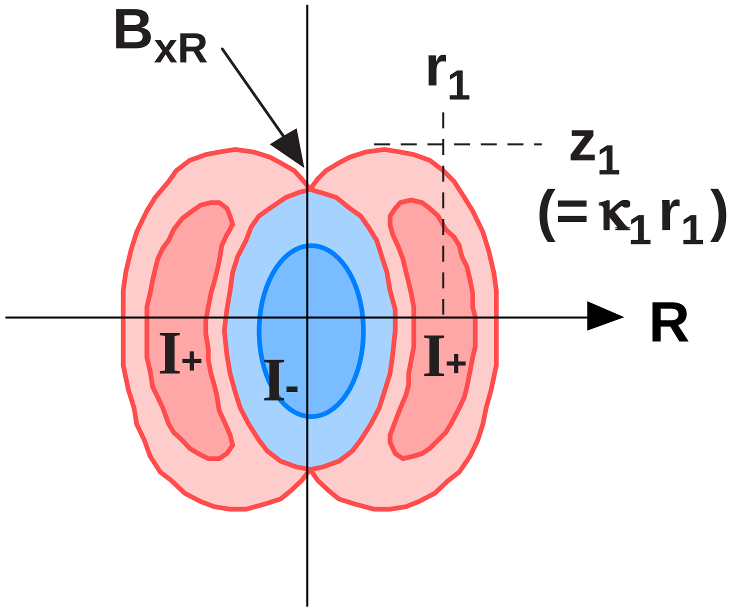
(see 2 page later)

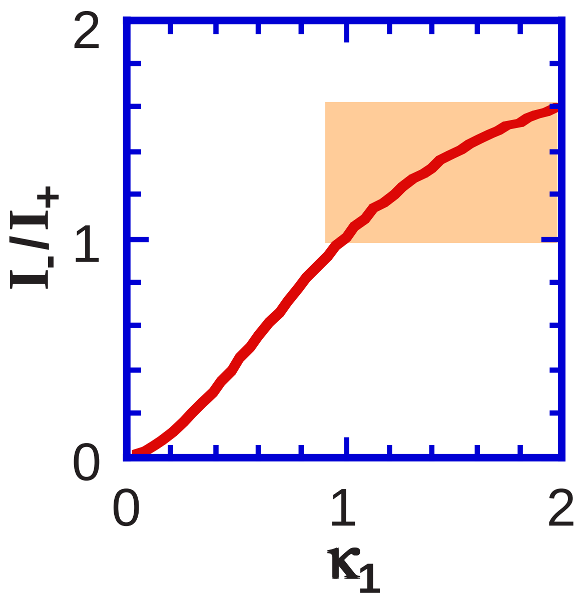
Scenario for the Rotation from Unstable Z-ar. Configuration to Stable R-ar. Configuration

Rotation is not simply explained by MHD theory.

1. Very small B_p at the central region
2. Large ion-orbit size
3. Large radial electric field E
4. E×B rotation from Z-ar. to R-ar.
5. Closed magnetic surfaces of tri-magnetic islands at stable R-ar.
6. Uniform electrostatic potential on each magnetic surface
7. E×B rotation is on the surface, and stable R-ar. does not change its magnetic configuration.

Ratio of negative to positive currents in ATMI $I_-/I_+ \approx 1$





$$B_{xR} \propto 2I_+ z_1/(r_1^2 + z_1^2) - I_-/z_1$$

$$B_{xR} = 0$$

$$I_-/I_+ \approx 2\kappa_1^2/(1+\kappa_1^2)$$

Unbalance current flows out through x-point region by magnetic reconnection process.

Current drive for both co- and ctr- directions is difficult in the current hole region. (ECCD experiment in JT-60U)

Summary

Core Stored Energy : MHD equilibrium limt $\varepsilon_f \beta_{p,core}$ **= const.**

Neoclassical Transport at ITB

Axisymmetric Tri-Magnetic-Islands (ATMI) Equilibrium

Generation of central negative E_T due to the grouth of J_{BS}

Formation of ATMI configuration through the nonlinear evolution of m=1/n=0 MHD instability (?)

ExB rotation to the stable R-ar. configuration (?)

Limit of the +/- current ratio $I_- / I_+ \sim 1$

Difficulty of current drive in the ATMI region

Limit of the ATMI current $q_{ATMI}/q_a > \kappa_1^2 Z_c^2/(Z_c - Z_x) a$

$q_{ATMI} > 40$ for the JT-60U parameters

Current Hole is ATMI Equilibrium

Plasma profile in central region is not flat, but wavy along R direction