The prospects for high-beta tokamaks with Li walls[1]

Leonid E. Zakharov,

Princeton University, Princeton Plasma Physics Laboratory

In collaboration with

A. Glasser (LANL), S. Jardin, J. Manickam (PPPL)

US-Japan High Beta Workshop

General Atomic, San Diego CA
September 8-10 1999

[1] **This work is supported by US DoE contract No. DE–AC020–76–CHO–3073.**

OUTLINE

1. Why Li walls ?
2. Magnetic propulsion of liquid Li.
3. Plasma profiles in the non-recycling regime.
4. High-beta in tokamaks.
5. Summary.

1. Why Li walls ?

Li is unique in many aspects. For high beta, two of them are important:

1. In the liquid form (T $> \ 180^o \ C$), Li can be magnetically propulsed along the plasma facing surfaces in the tokamak chamber.

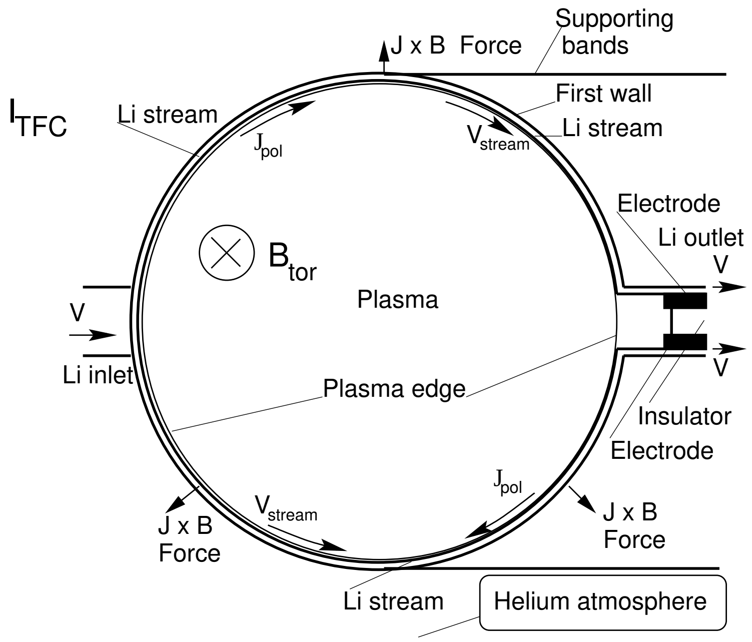
   This allows to stabilize the plasma by the boundary conditions in the most effective way, i.e., by putting the stabilizing wall right at the plasma boundary.

2. Intense ($V \simeq 20 \, m/sec$) magnetic propulsion allows to keep Li temperature limited (T $< 300^o \, C$) and its evaporation negligible.

   A property of Li to absorb plasma particles, (H, D, T) allows to establish in the tokamak a unique, stationary, non-recycling regime with plasma profiles having excellent stability and confinement properties.

2. Magnetic propulsion of liquid Li

Magnetic propulsion of a liquid metal in the toroidal magnetic field of tokamaks has been discovered in December of 1998.

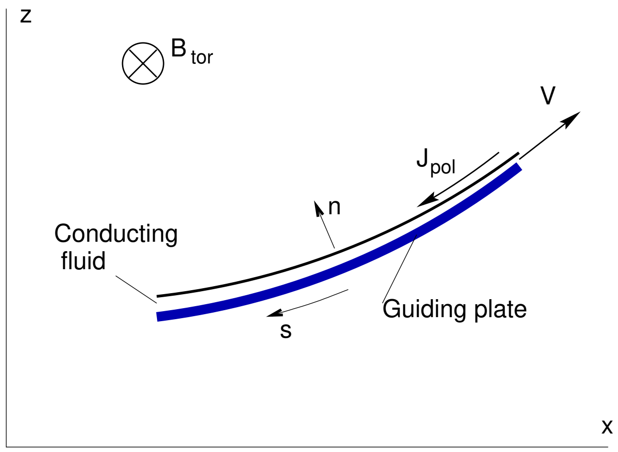


The streams, of $\simeq$ 1 cm in thickness are held by the $\mathbf{J}_{pol} \times \mathbf{B}_{tor}$ electromagnetic force. Streams are driven from the large field side to the small field side by inhomogenuity of the toroidal magnetic field.

In tokamaks, $\mathbf{J}_{pol} \times \mathbf{B}_{tor}$ can be so large that the liquid Li is capable of withstanding the possible electromagnetic forces during potential disruptions.

$$B_\phi \equiv B = \frac{0.2 I_{pol}}{r}, \tag{2.1}$$

The geometry of the guiding plate surface, contacting with the fluid,



is described by parametric equations

$$r = r(s), \quad z = z(s), \tag{2.2}$$

where r, z are the cylindrical coordinates, and s is a coordinate along the plate, measuring the distance from some reference point

$$r = r_i, \tag{2.3}$$

and n is a perpendicular coordinate.

In the thin layer approximation

$$n\frac{\partial}{\partial s} \ll 1 \tag{2.4}$$

the dynamics of the fluid can be analitically analyzed.

The height $h(s)$ of the fluid is determined by the continuity condition

$$h = \frac{\frac{dM}{dt}}{2\pi\rho RV}. \tag{2.5}$$

The the diamagnetic drag parameter P_D

$$P_D \equiv \frac{\mu_0 \sigma h^2 V}{12r}\frac{I_{TFC}}{I_{Li}} \ll 1 \tag{2.6}$$

determines the drag force due to magnetic pumping.

2-D Li velocity is determined by equation

$$\frac{1}{2}\rho V^2 = \frac{1}{2}\rho V_i^2 - \left(1 - \frac{n}{h}\right) h_i J_i B_i \left(1 - \frac{r_i^2}{r^2}\right). \tag{2.7}$$

3. Plasma profiles in the non-recycling regime

With idealy absorbing walls, i.e., in the non-recycling regime, the plasma profiles are determined by the particle continuity equation

$$\Gamma \equiv Snv = const = (\Gamma)_a, \tag{3.1}$$

where the central fuelling of the plasma is asumed, and by the energy balance

$$\begin{aligned} &\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int_0^r P dv, \\ &\left(\frac{5}{2}\Gamma T\right)_a = \int_0^a P dv \end{aligned} \tag{3.2}$$

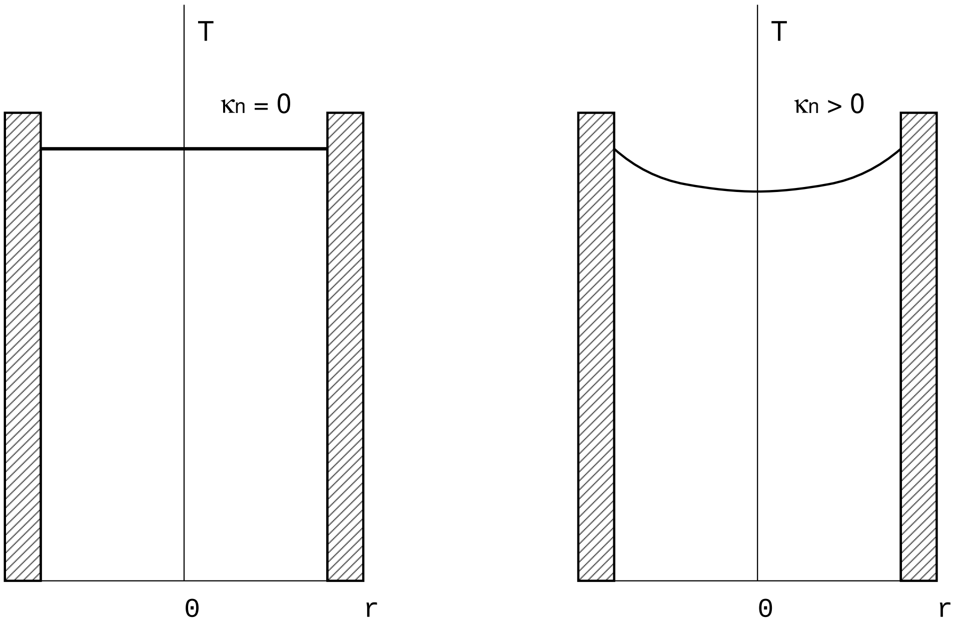
or

$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) + \int_r^a P dv = \left(\frac{5}{2}\Gamma T\right)_a . \tag{3.3}$$

The energy confinement time in this regime is determined by the particle confinement.

In a model case with δ-functional energy and particle sources, the temperature profiles has inverse gradient, which compensates the thermal conduction

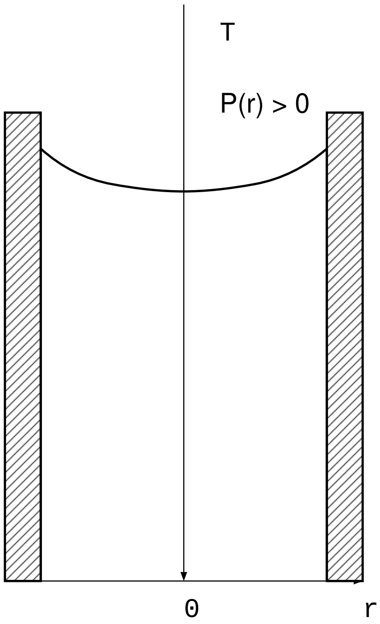
$$\frac{5}{2}\Gamma(T - T_a) - S(\kappa_T \nabla T + \kappa_n \nabla n) = 0. \tag{3.4}$$



For $\kappa_n = 0$, the solution is the flat temperature profile, while for $\kappa_n > 0$, the temperature gradient is inverse.

A diffuse energy source in the non-recycling regime also leads to inverse temperature profiles

$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) + \int_r^a P dv = \left(\frac{5}{2}\Gamma T\right)_a . \tag{3.5}$$



With the current distribution

$$j_{||} \propto T \tag{3.6}$$

the stability is dramatically improved and corresponds to the second stability zone.

Thus, in the non-recycling, the density profile (assuming central fueling) is determined by

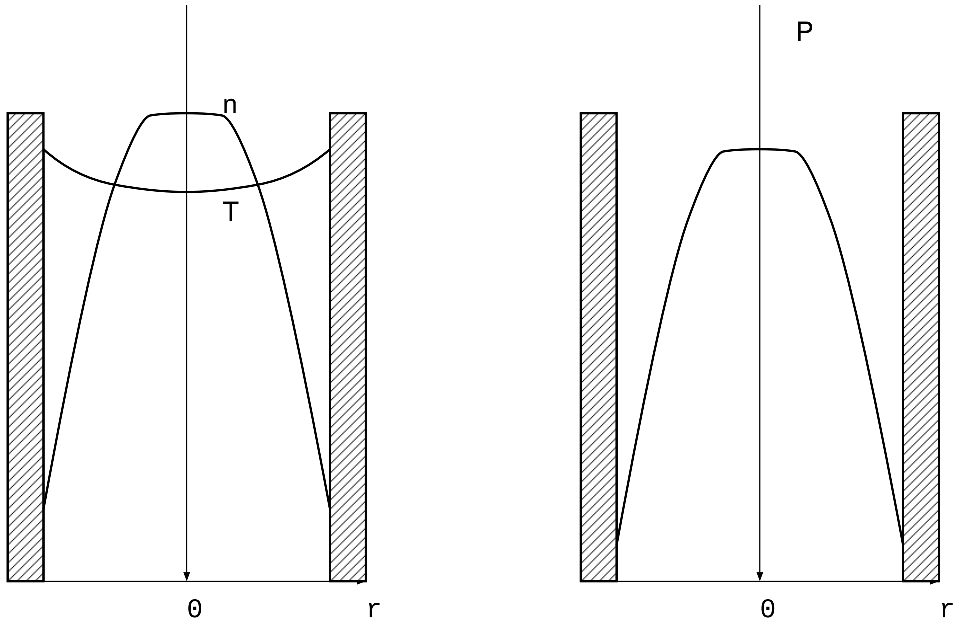
$$n = \frac{\Gamma}{S v_{diff}}, \tag{3.7}$$

the temperature profile has inverse gradient

$$T' < 0, \tag{3.8}$$

and the pressure profile is peaked and has a finite pedestal at the plasma edge

$$p(a) > 0. \tag{3.9}$$



4. High-beta in tokamaks

With a conducting walls at the plasma edge, the plasma exhibits superior stability even in the circular cross-section.

We present an analysis of ballooning and $n = 1, 2, 3$ MHD stability for TFTR geometry. Note, that for the conventional walls TFTR was getting unstable at

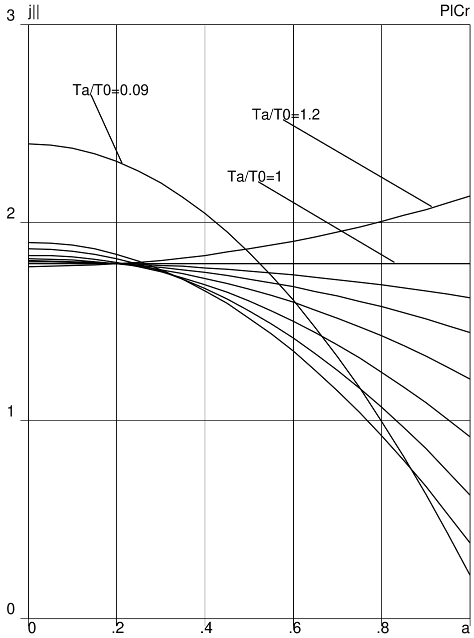
$$\beta > 1\ \%. \tag{4.1}$$

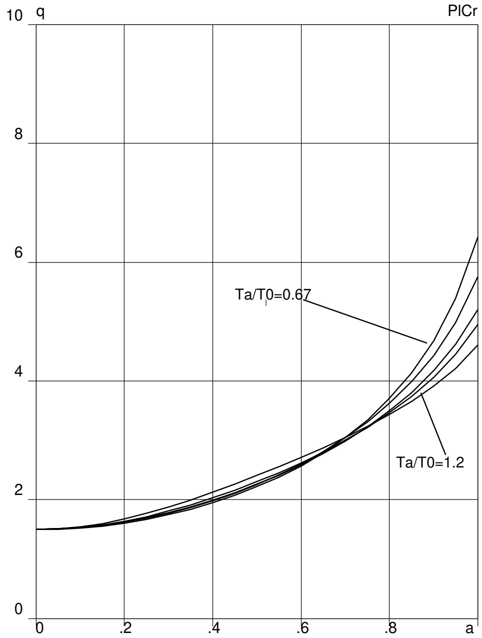
Codes used for stability calculations of TFTR non-recycling configurations

- Esc - equilibrium
- BALLON, DCON - ballooning stability
- PEST-II, DCON - n=1,2,3 stability

5. High-beta in tokamaks

Current density profiles has been chosen as determined by the classical Ohm's law





$j_{||}$-profiles $\quad$ q-profiles

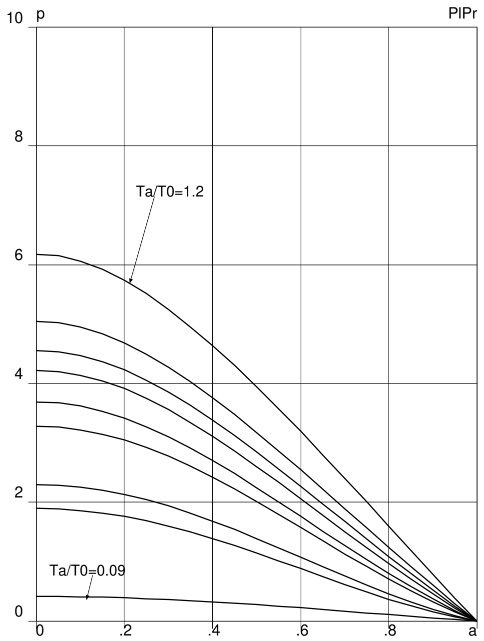
with ratio $j_{||}(a)/j_{||}(0)$ as a parameter and $q_0 = 1.5$.

$$\frac{dp}{d\Psi} = const, \quad a = \sqrt{\frac{\Phi}{\Phi_{edge}}}, \tag{5.1}$$

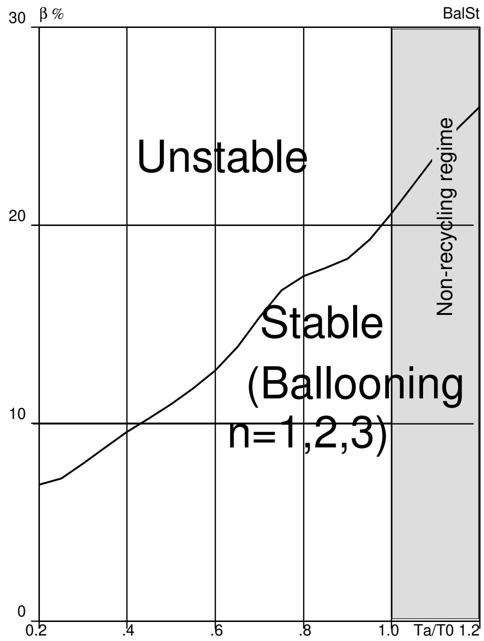
where Φ is the toroidal flux.

6. High-beta in tokamaks

Marginaly pressure dramatically increases with increase in edge temperature pedestal.



marginal p-profiles



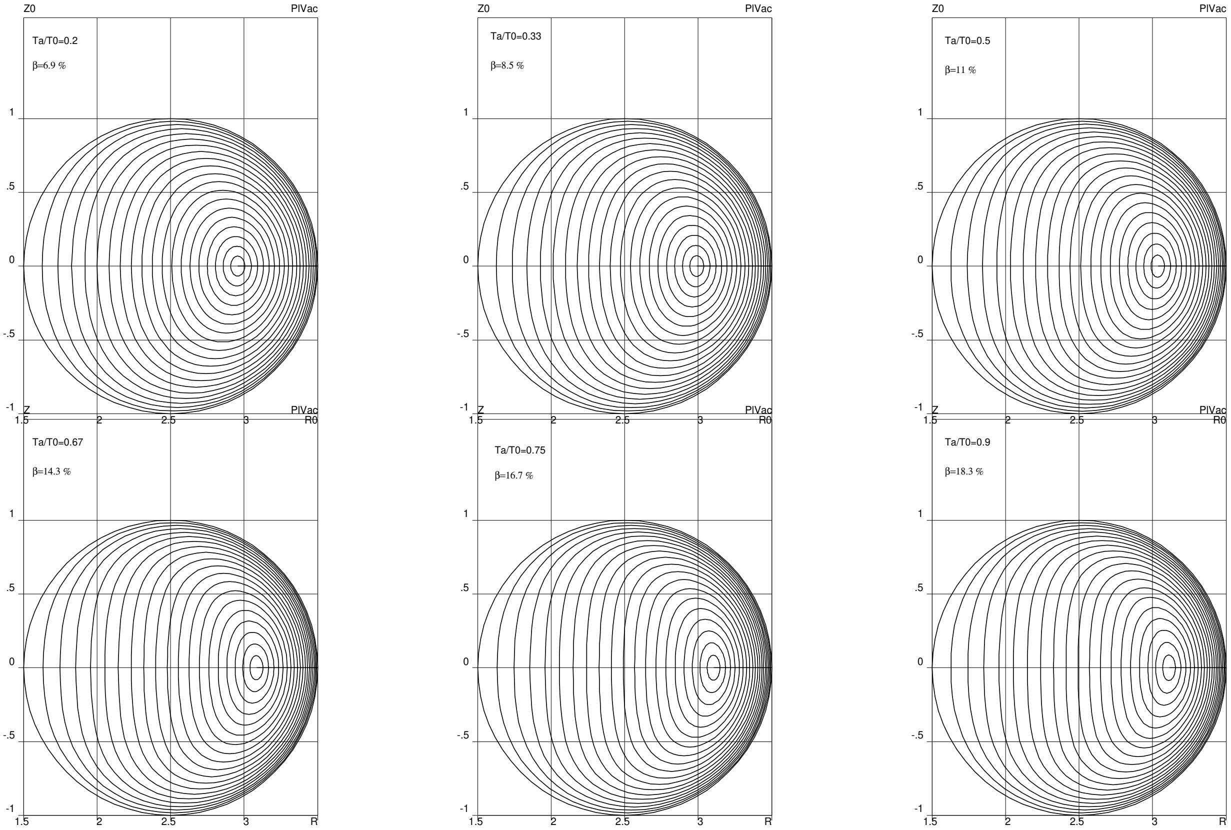
β vs T_a/T_0

$$\beta \equiv \frac{2\mu_0 \langle p \rangle}{B_{ext}^2}, \tag{6.1}$$

where $\langle p \rangle$ is the volume averaged pressure.

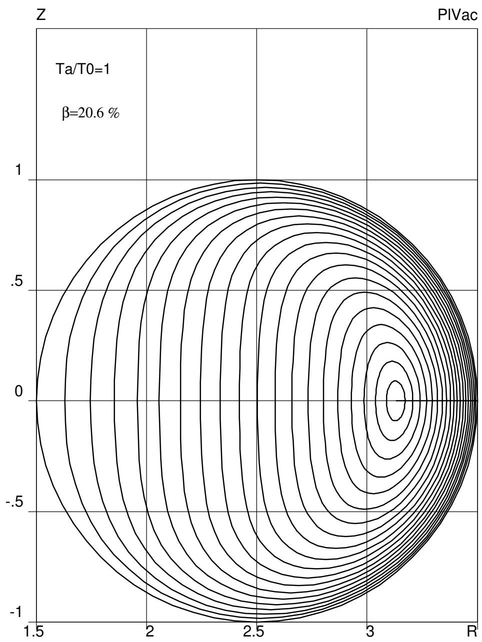
7. High-beta in tokamaks

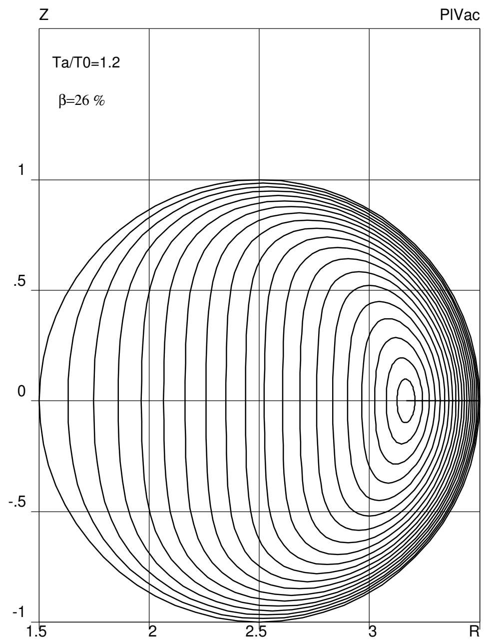
Marginally stable high β configurations



8. High-beta in tokamaks

Marginally stable high β configurations

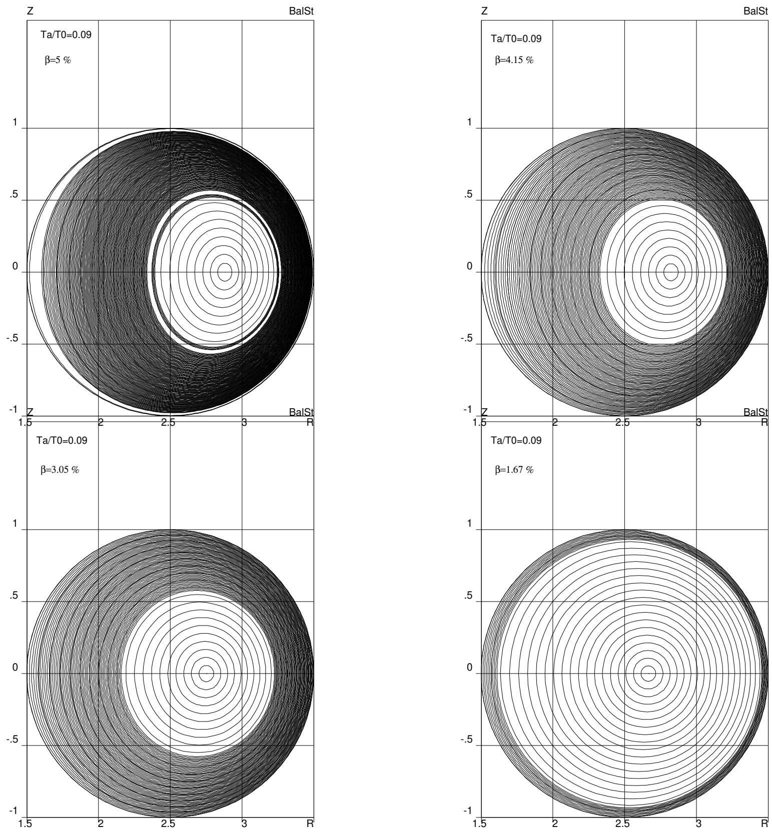




Configurations relevant
to the non-recycling regime

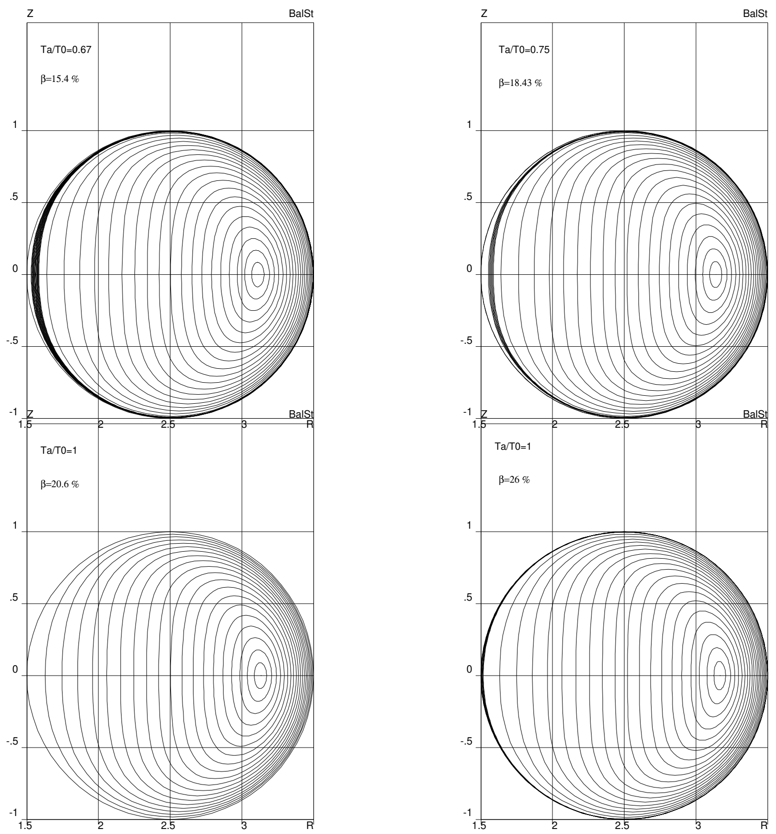
9. High-beta in tokamaks

Ballooning stability at low T_a/T_0



Dark zones are ballooning unstable surfaces when the pressure is above the stability limit.

Ballooning stability at finite T_a/T_0



For the non-recycling profiles, when the pressure is above the limits, the ballooning unstable surfaces are localized near the very edge.

10. Summary

Tokamaks with the Li walls is a way of solving the problem of magnetic fusion, by relying on

1. TFTR experimental results with Li at the plasma edge,
2. non-recycling regime with suppressed thermo conduction transport,
3. the most effective method of stabilizing MHD by conducting walls situated at the plasma boundary,
4. high betas with $\beta > 10\ \%$ in the second stability zone and the simple (e.g., circular) geometry of the plasma cross-section.

<u>No propulsion</u> of liquid Li is required for experimental testing stability and transport of the non-recycling regime.

For a limited but sufficient time ($\simeq$ 1 sec), it can be achieved in tokamaks with the

<u>central fuelling</u>

and with the copper shell walls covered by the

<u>solid or sputtered Li</u>