Stabilization of tokamak plasma by lithium streams

Leonid E. Zakharov,

Princeton University, Princeton Plasma Physics Laboratory

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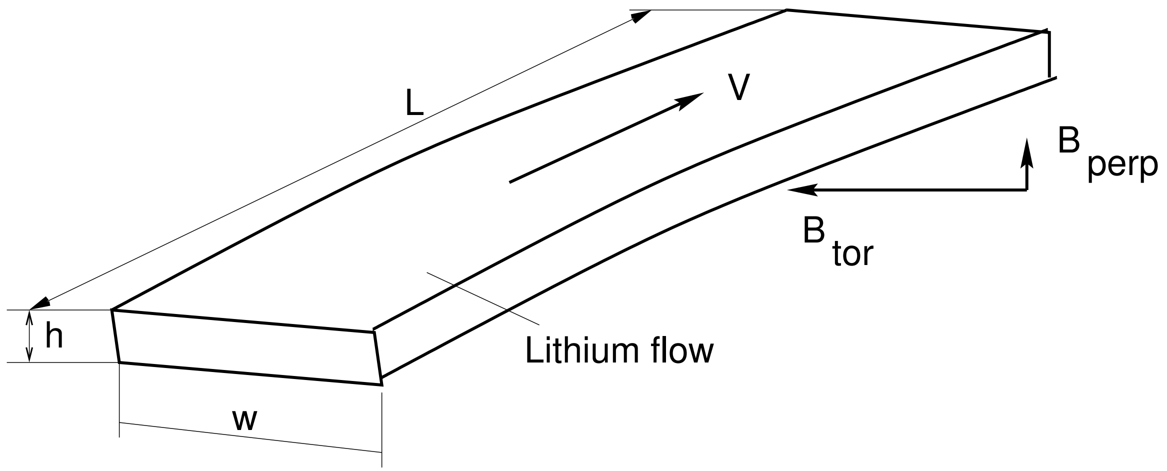
OUTLINE

1. Basics of liquid lithium MHD.
2. Flow pattern of magnetic propulsion.
3. Theory of stabilization.
4. Flow locked mode.
5. Prospects for high beta.

1 Basics of liquid lithium MHD

There 3 magnetic Reynolds numbers which control lithium MHD in tokamaks

$$\begin{aligned} \text{dynamics}: &\quad \Re_0 \equiv \mu_0 \sigma L V, \\ \text{electro-dynamics}: &\quad \Re_1 \equiv \mu_0 \sigma h V, \\ \text{dynamics}: &\quad \Re_2 \equiv \mu_0 \sigma \frac{h^2}{L} V, \\ &\quad \mu_0 \sigma \simeq 4 \ \left[\frac{sec}{m^2}\right]. \end{aligned} \tag{1.1}$$



Characteristic flow parameters:

$$\begin{aligned} V = 20\ m/sec \rightarrow & \rho\frac{V^2}{2} \simeq 1\ [atm], \\ B = 1\ T \rightarrow & \frac{B^2}{2\mu_0} = 4\ [atm], \\ B = 5\ T \rightarrow & \frac{B^2}{2\mu_0} = 100\ [atm]. \end{aligned} \tag{1.2}$$

Dynamic pressure losses are determined by $\Re_0$ and $\Re_2$

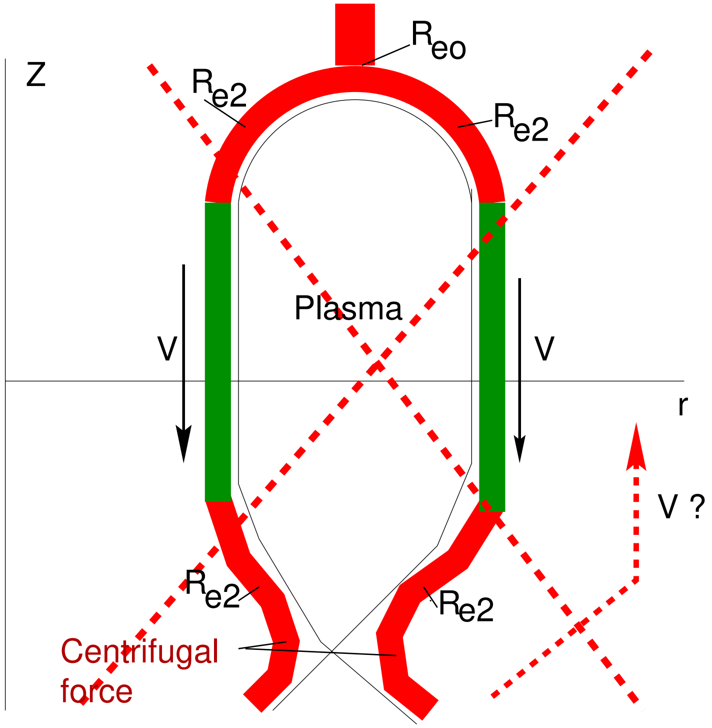
$$\begin{aligned} \Re_0 : \quad & \Delta\rho\frac{V^2}{2} = \mu_0\sigma LV\frac{B_\perp^2}{2\mu_0}, \\ \Re_2 : \quad & \Delta\rho\frac{V^2}{2} = \mu_0\sigma\frac{h^2}{L}V\Delta\frac{B_\parallel^2}{2\mu_0}, \\ & \mu_0\sigma \simeq 4\ \left[\frac{sec}{m^2}\right]. \end{aligned} \tag{1.3}$$

Magnetic fields from the currents in the stream are determined by $\Re_1$

$$\Re_1 : \quad B_{||out} - B_{||in} = \mu_0\sigma hVB_\perp. \tag{1.4}$$

Lithium “water-falls” are incompatible at the basic level with the tokamak strong toroidal field

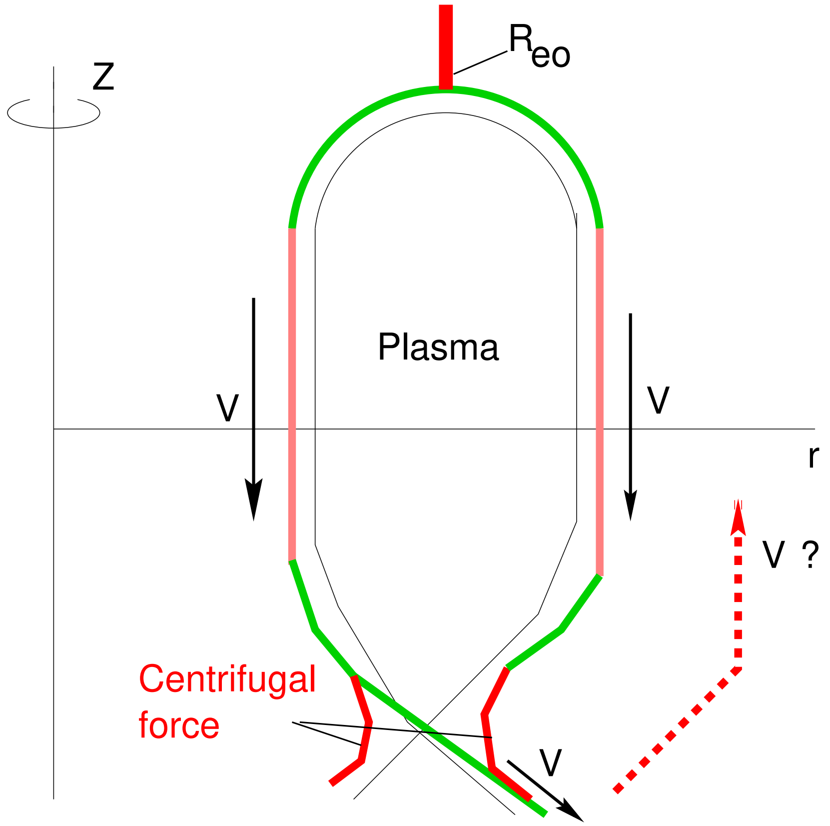
$$
\begin{aligned}
&h = 0.1\ m, \quad L_1 \simeq 0.2\ m, \quad L_2 \simeq 3\ m, \quad V > 2-5\ [m/sec],\\
&\Re_0 = 4L_1V => 1.6,\\
&\Re_2 = 4\frac{h^2}{L_2}V = 4\frac{h}{L_2}(hV) \simeq 0.01-0.025.
\end{aligned}
\tag{1.5}
$$



$$\boxed{\rho\frac{V^2}{2} \ll \Re_2\Delta\frac{B_{tor}^2}{2\mu_0}}$$

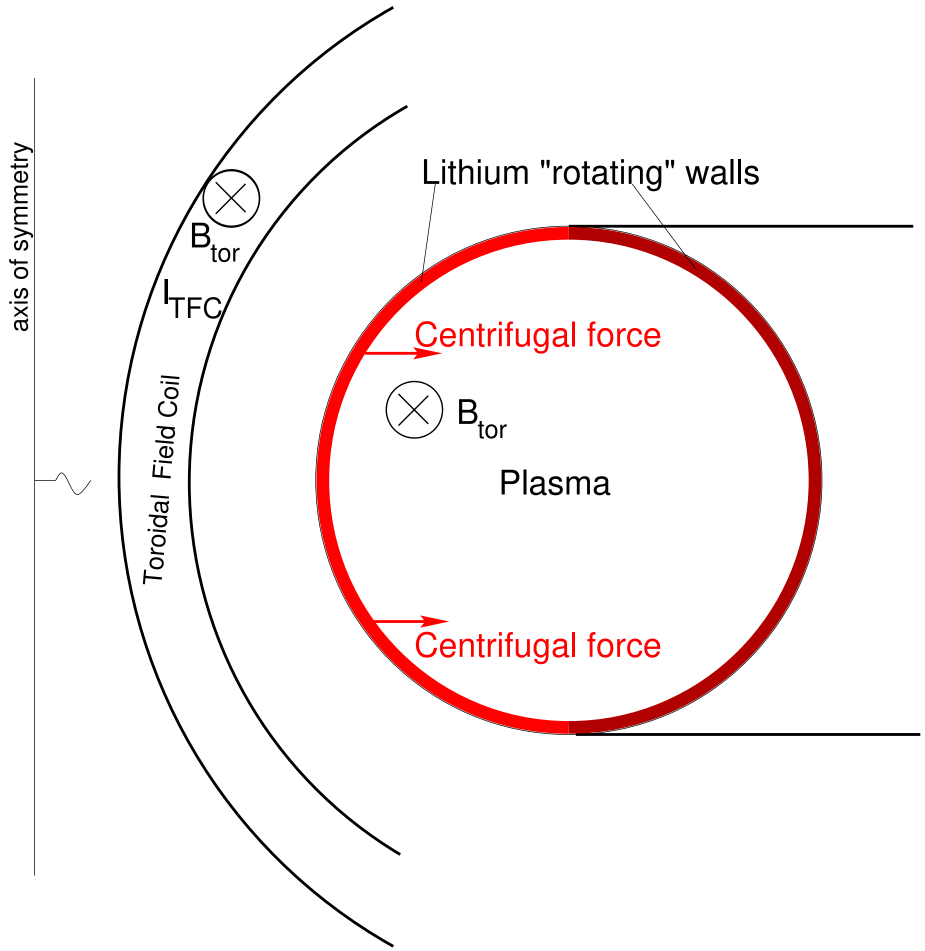
Momentum driven thin walls have a lot of unresolved problems in lithium MHD

$$h = 0.01\ m, \quad L_1 \simeq 0.02\ m, \quad L_2 \simeq 3\ m, \quad V \simeq 20\ [m/sec],$$
$$\Re_2 = 4\frac{h^2}{L_2}V \simeq 1.3 \cdot 10^{-4}. \tag{1.6}$$



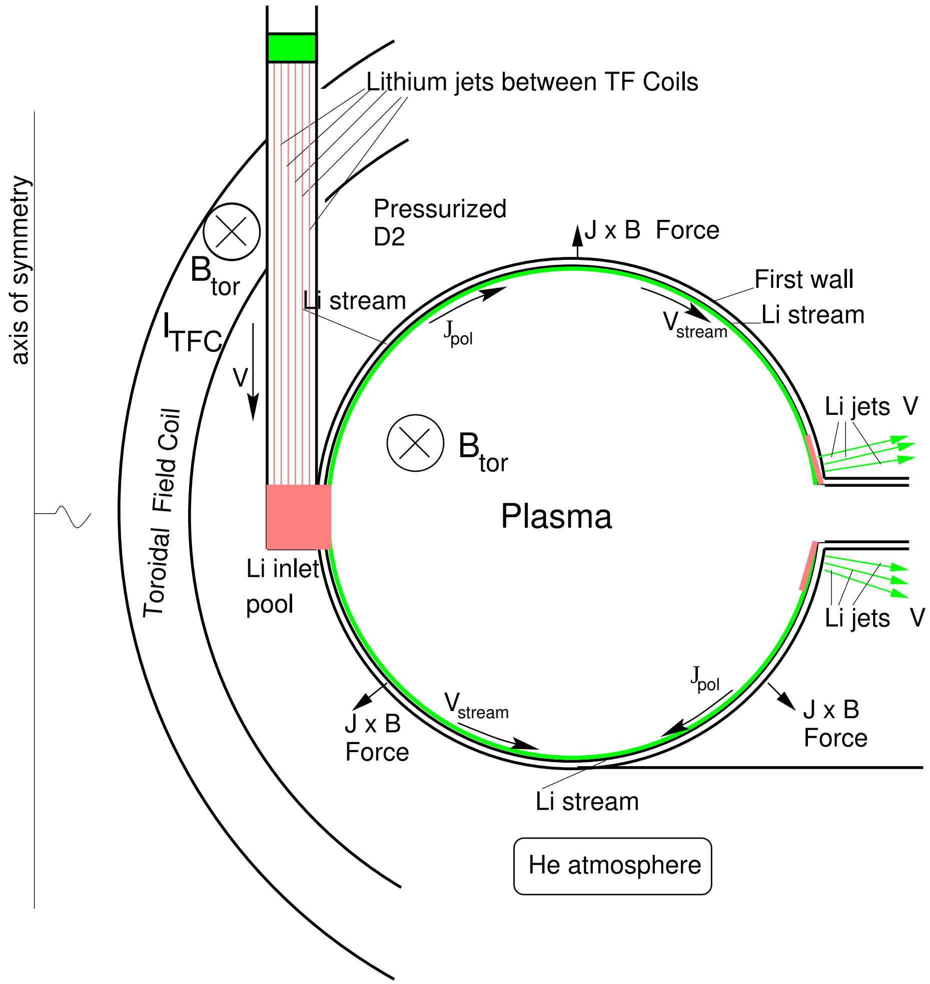
$$\boxed{\Re_0 = 1.6, \qquad \rho\frac{V^2}{2} < \Re_0\frac{B_{pol}^2}{2\mu_0}}$$

"Rotating" liquid lithium walls are incompatible with tokamaks.



- no inlet/outlet
- poloidal rotation damps as $R\rho\frac{dV}{dt} \simeq \Re_2 \frac{B_{tor}^2}{2\mu_0}$
- toroidal rotation is impossible due to centrifugal force.

Magnetic propulsion makes MHD of intense lithium streams compatible with tokamaks.



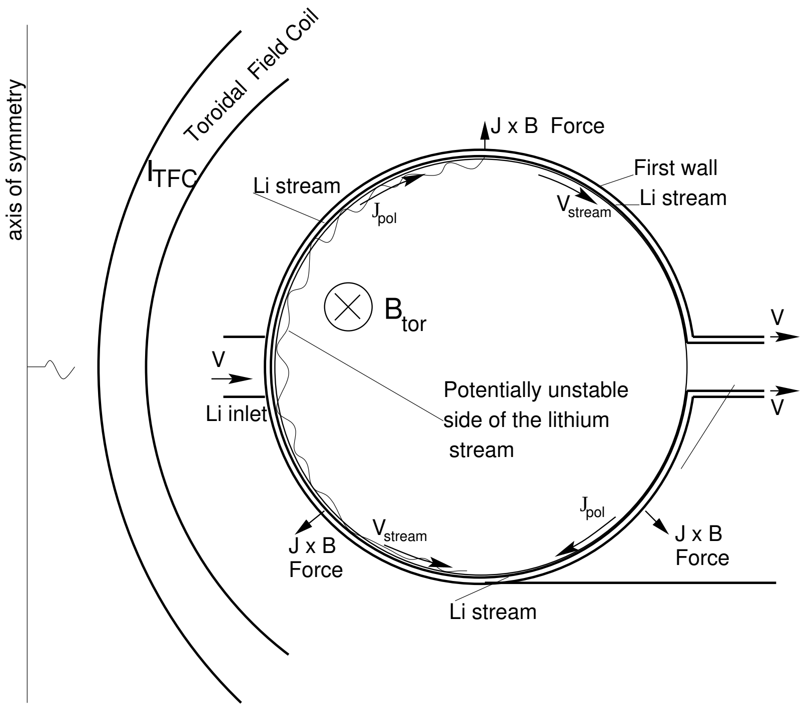
Driving pressure

$$p_{wall}|_{outlet} > 1\ atm, \quad p_{wall}|_{inlet} - p_{wall}|_{outlet} > 1\ atm. \tag{2.1}$$

Flow parameters

$$V \simeq 20\ m/sec, \quad h \simeq 0.01\ m, \quad \Re_1 = 0.8. \tag{2.2}$$

Stream are robustly stable due to centrifugal force



$$\boxed{\rho\frac{\langle V^2\rangle}{2} > \frac{a}{2R}p_{wall}n_r}$$

Flow pattern of magnetic propulsion eliminates the possibility of mode locking into the conducting wall (“Rotating” walls do nothing).

The theory includes an arbitrary geometry of the guide wall

$$\begin{aligned} \mu_0\tilde{\mathbf{j}}_w &\equiv \frac{\nabla\rho\times\nabla I}{\delta a} = -\frac{I'_\varphi}{J_w}\mathbf{e}_\theta + \frac{I'_\theta}{J_w}\mathbf{e}_\varphi, \\ J_w &\equiv r_w(\theta)h(\theta)\sqrt{g_{\theta\theta}}, \quad g_{\theta\theta} = (r_w)'^2_\theta + (z_w)'^2_\theta. \end{aligned} \tag{3.1}$$

It links the electric current in the streams with parameters which can be extracted from existing numerical codes

$$(\mathsf{D}_v - \mathsf{D}_p)\vec{\psi}(a) = -i\mathsf{M}\vec{I}. \tag{3.2}$$

It formulates the equation for electric current in the streams and leads to a dispersion relation for the growth rate

$$(\mathsf{D}_v - \mathsf{D}_p)\vec{\psi} = \mu_0 h\sigma\gamma(\mathsf{M}\mathsf{S}^{-1}\mathsf{M})\vec{\psi} + i\Re_1(\mathsf{M}\mathsf{S}^{-1}\mathsf{V}\mathsf{M})\vec{\psi}. \tag{3.3}$$

Dispersion relation for the cylindrical case

$$a\Delta'_m \psi_m = \tau_{res}\gamma\psi_m + \Re_1 \sum_k (m+2k+1) v^*_{2k+1}\psi_{m+2k+1}, \tag{3.4}$$

where

$$\tau_{res} = \mu_0 \sigma h a, \quad v_{2k+1} = \frac{2}{i\pi(2k+1)}, \quad v_{2k} = 0. \tag{3.5}$$

There is coupling with a nearest satelite modes and then, with each second satelite mode.

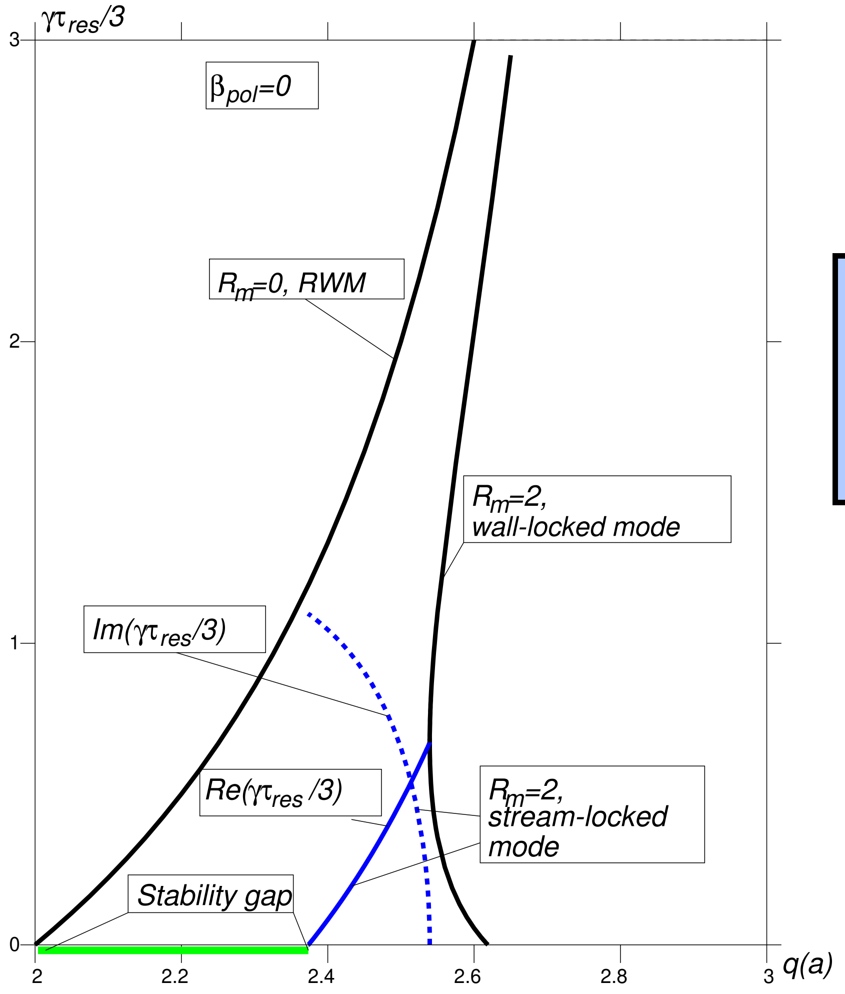
Three harmonics approximation immediately shows the stabilizing effect

$$\begin{aligned} & a\Delta'_m - \tau_{res}\gamma \\ & + \frac{m(m+1)\Re_1^2|v_1|^2}{a\Delta'_{m+1} - \tau_{res}\gamma} + \frac{m(m-1)\Re_1^2|v_1|^2}{a\Delta'_{m-1} - \tau_{res}\gamma} = 0. \end{aligned} \tag{3.6}$$

It also shows possibility for the mode, which is locked into one of streams.

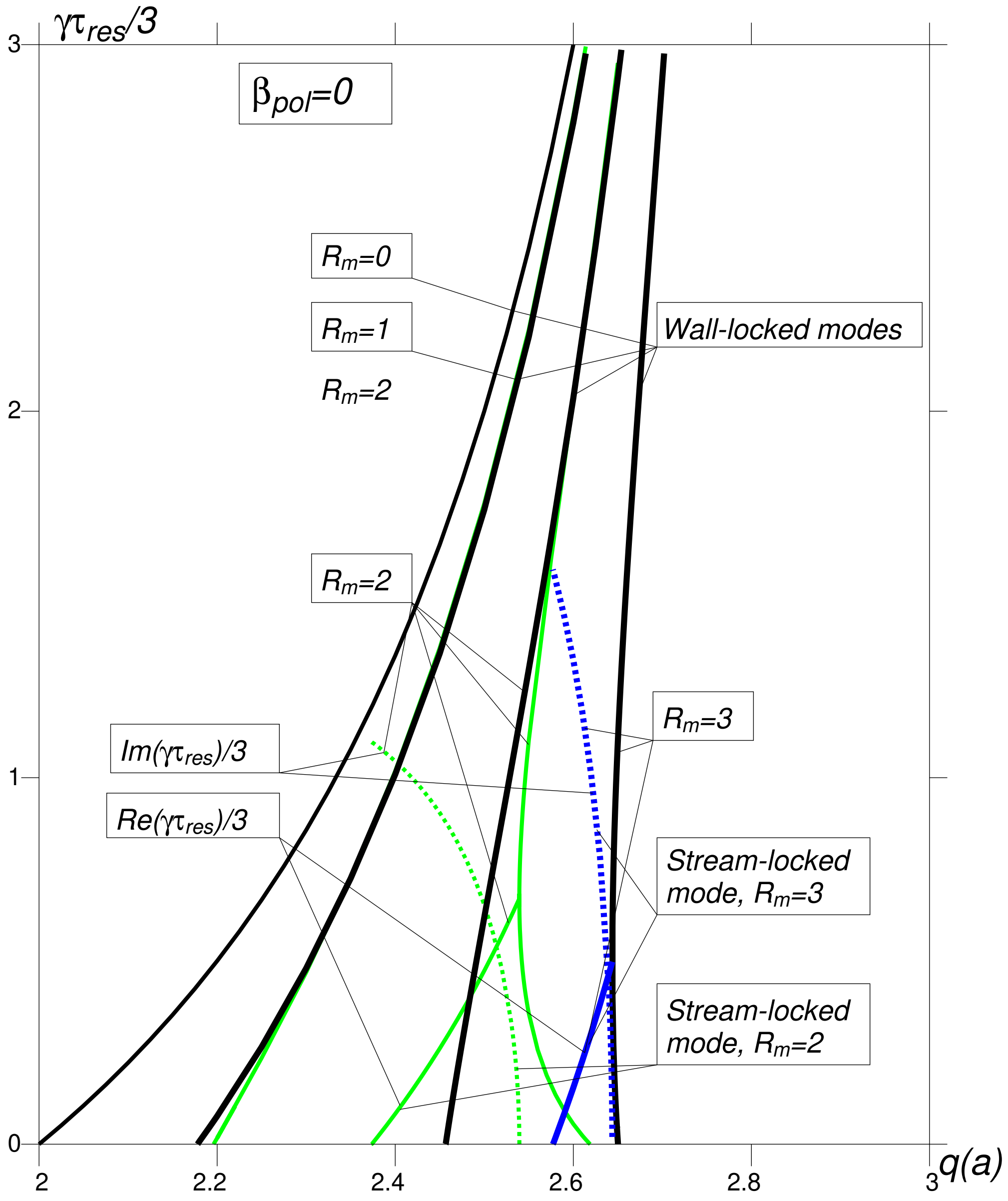
Resistive wall mode is well affected by the flow.

Flow-locked mode determines limits of stabilization.

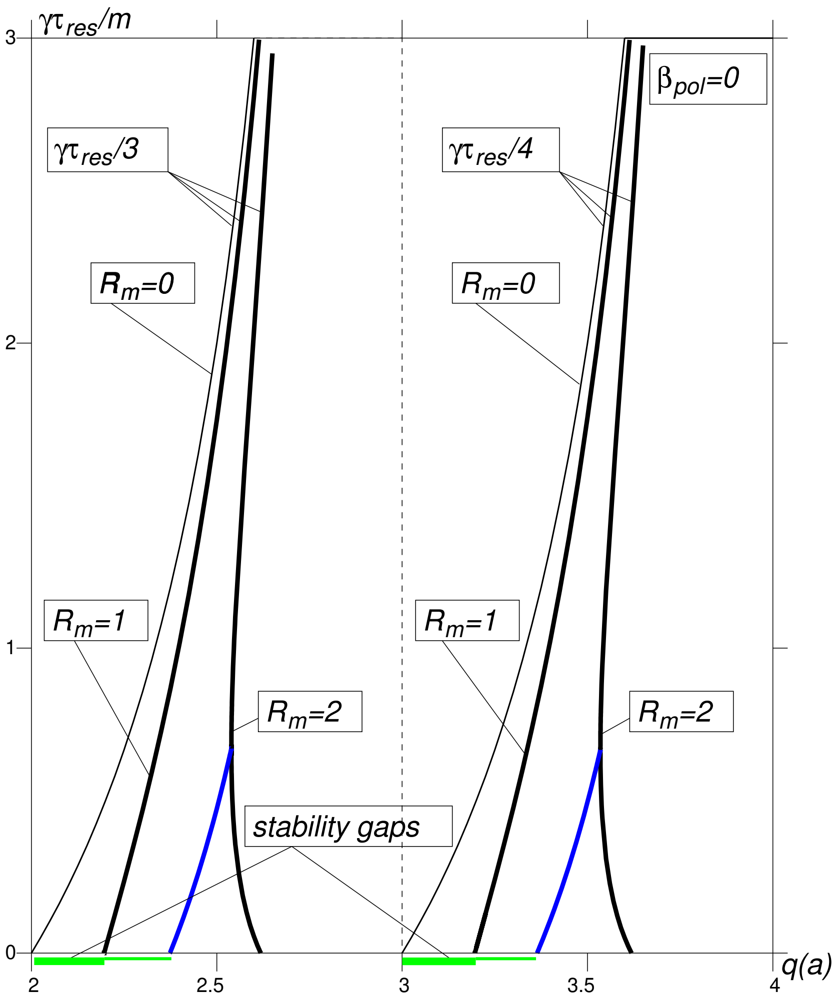


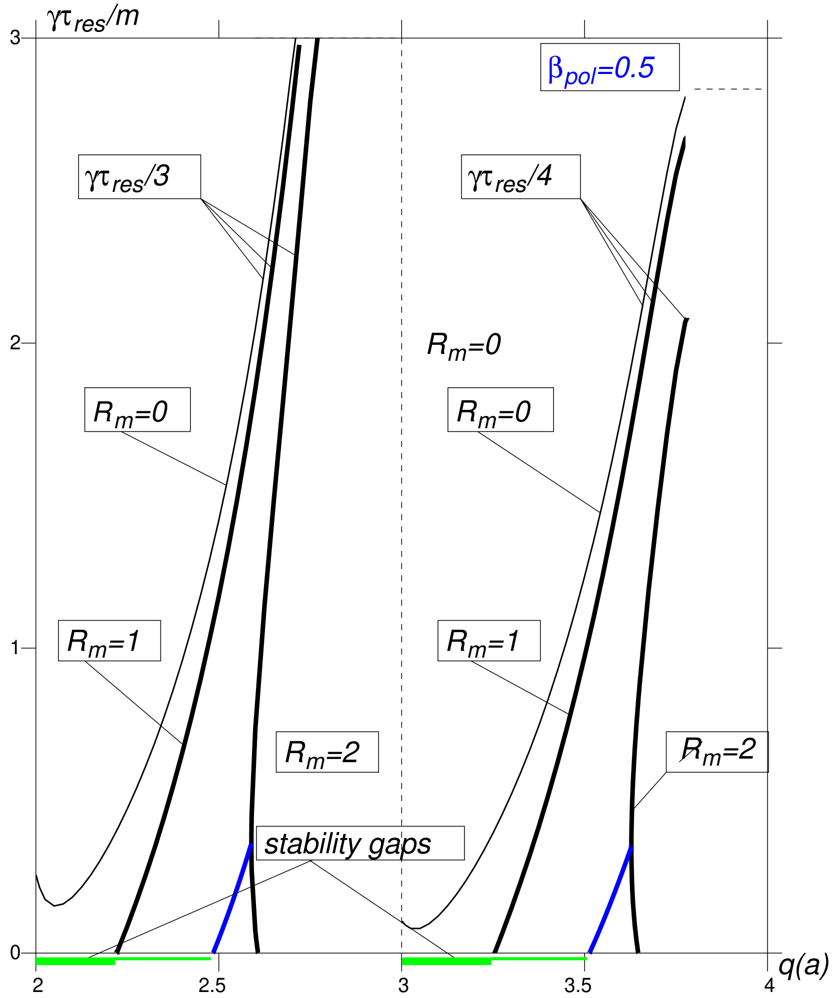
$$a\Delta'_m - \tau_{res}\gamma + \frac{m(m+1)\Re_1^2|v_1|^2}{a\Delta'_{m+1} - \tau_{res}\gamma} + \frac{m(m-1)\Re_1^2|v_1|^2}{a\Delta'_{m-1} - \tau_{res}\gamma} = 0$$

Comparison of 3 harmonics vs full matrix calculations.



Stability gaps are insensitive to m-number. Finite β can be stabilized.





5 Prospects for high beta

Intense lithium streams move the conducting wall surface to the plasma boundary.

This would represent the major effect on stability, allowing feedback system close to the plasma surface.

In addition, the streams themselves contribute to MHD stabilization.

In combiination with an expected low-recycling regime and flattened temperature and current density profile, this would open the path to high betas even in circular machines.