Superconducting Morozov's Ring for refuelling and Controlling Plasma Profiles[1]

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Abstract

The Morozov transporter ring represents a current carrying metal ring moving across the high-temperature plasma volume while spending only a finite time (1-100 ms) inside the plasma. Inside the plasma the ring is magnetically insulated from the plasma electrons and is electro-statically insulated from the ions (by the electric charge delivered to the surface of the ring by the most energetic ions or alpha-particles). Depending on the magnetic flux, the local magnetic configuration near the ring represents either FRC or levitron with an inverse (and, thus, MHD stable) plasma pressure gradient localized at the separatrix. Inside the separatrix, the confinement of positive (energetic) particles represents a new, interesting mixture of magnetic confinement with the strong electrostatic effects. Both warm (high speed) Morozov's rings and Super-conducting (low speed) rings can be possibly developed for many applications.

The Super-conducting Morozov's Rings (SMR) is the most clean implementation of the Morozov idea of an autonomous object inside the high temperature plasma. Being non-perturbative for the plasma, SMRs can significantly enhance the diagnostics capabilities of the present day mid-size or large tokamaks or stelalrators (NSTX, JET, JT-60, Tore-Supra, LHD, etc) which have a significant portion of hot ions or alpha-particles. In addition, SMRs can be used as a transporter of the plasma fuel, which can be released locally at any desirable point inside the plasma. This opens unique opportunities for controlling the plasma profiles and for the transport studies.

SMRs could be especially important for the JET D-T experiments where the fusion alpha-particles can provide an extreme in the electro-static screening of ions. Also, D-T refuelling with SMRs might free the neutral beam lines from contamination by the tritium.

Abstract

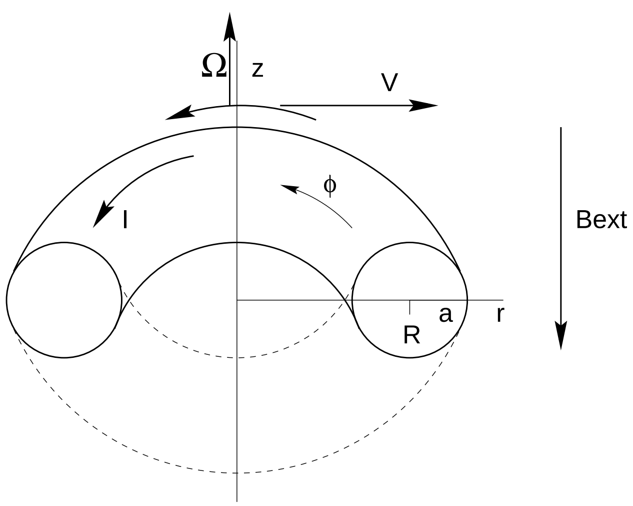
From the development point of view, NSTX could be the key machine for initial assessment and application of SMRs. A relatively low toroidal magnetic field at the outer half of the plasma cross-section simplifies the use of superconductors for the ring and, thus, developing the initial technology. On the other hand, the control of the plasma profiles is especially important for NSTX in order reconcile the bootstrap current alignment with the MHD stability at high-betas.

1. Background and Significance

There is a general plasma physics problem of creating an autonomous probe, which can penetrate into the high-temperature plasma without damaging the plasma.

Related and more challenging set of problems exists in the fusion research, such as refueling the tokamak or stellarator fusion reactors, plasma profile and burn control in the reactors, helium exhaust.

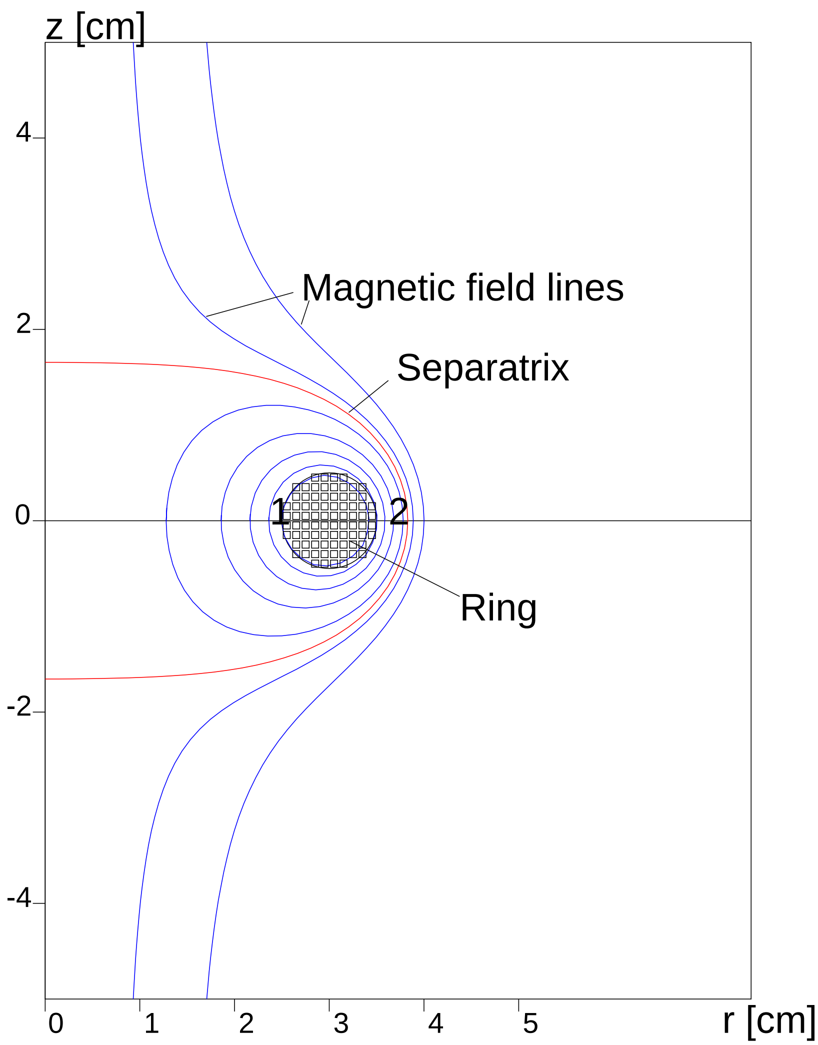
Potentially the idea of A.I.Morozov (1988, published in Sov. J. Plasma Phys. v.17, p.71, 1991) about magnetized autonomous probe inside the high temperature plasma suggests a possible solution to those problems.



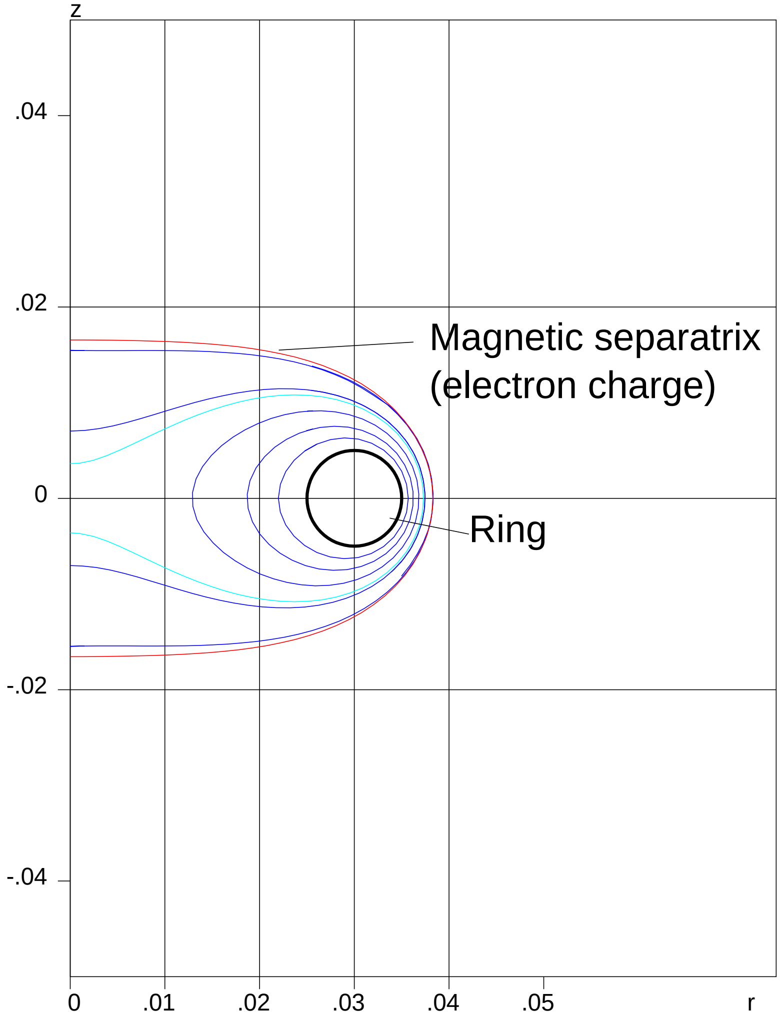
Morozov's ring with an electric current, gyroscopic rotation. Magnetically insulated from electrons. Electrostatically insulated from ions.

Can travel inside the high-temperature plasma. Can deliver the fuel to any point in the plasma core. Can carry the diagnostics.

2. Example



Magnetic configuration of the ring.



Electric configuration of the ring.

Autonomous probe can carry some diagnostic means (e.g., mirrors, transmitters, particle counters, luminiferous screens, microchips, etc) which can be used for

precise local measurements of the plasma parameters.

It can also release locally trace ammount of a neutral gas (e.g., by ablating a frozen matter with a laser beam), thus, opening opportunities

for precise studies of local transport and MHD processes in HIGH-temperature plasmas.

Development of Morozov’s rings opens unique opportunities for

plasma profile and stability control

in large tokamaks (or stellarators) or other facilities.

3. Gyroscopic stabilization

In order to have a separatrix of the proper shape, the ring should be oriented in the diamagnetic, unstable, direction with respect to the toroidal magnetic field.
Thus, it should be gyroscopically stabilized by a fast rotation

$$\begin{aligned} &\Omega \quad [rad/sec] > 10^5 \sqrt{\frac{0.2\pi IB}{M}} \quad \sqrt{\frac{[MA][T]}{[g]}}, \\ &\frac{\Omega}{2\pi} = \frac{10^5}{2\pi}\sqrt{\frac{0.2\pi \cdot 0.5 \cdot 5}{500}} = 892\ [1/sec] \simeq 60\ 000\ [rpm] \end{aligned} \tag{3.1}$$

4. Physics

Morozov ring represents a NEW plasma confinement configuration, where the current carrying superconducting or cryogenic (normal conducting) ring is completely insulated from the high-temperature plasma

- The plasma electrons are magnetically confined from reaching the ring
- Energetic ions and the α-particles are electrostaically screened from the ring.

The Morozov ring contains many common physics with FRC, Levitated rings, which are under studies in special fusion programs. The BIG difference between Morozov's rings and FRC, Levitrons is that the magnetic configuration of the ring is completely MHD stable

$$-\frac{d\ln p}{d\ln r} < \frac{4\gamma}{2+\gamma\beta} \tag{4.1}$$

5. Variations of Morozov's rings

The most essential property of a Morozov's ring is its dipole magnetic field.

Variations of MMRs:

1. Low temperature superconductors ($T < 20^o\ K$).
2. High temperature superconductors ($T < 75^o\ K$).
3. Cryogenic normal conductors ($T < 100 - 150^o\ K$)
4. Permanent magnet disks (room T, proposed by S. Zweben)

This proposal has introduced a new element in the physics of MMR, i.e., the self-consistent electrostatic shielding from the energetic ions (or α-particles).

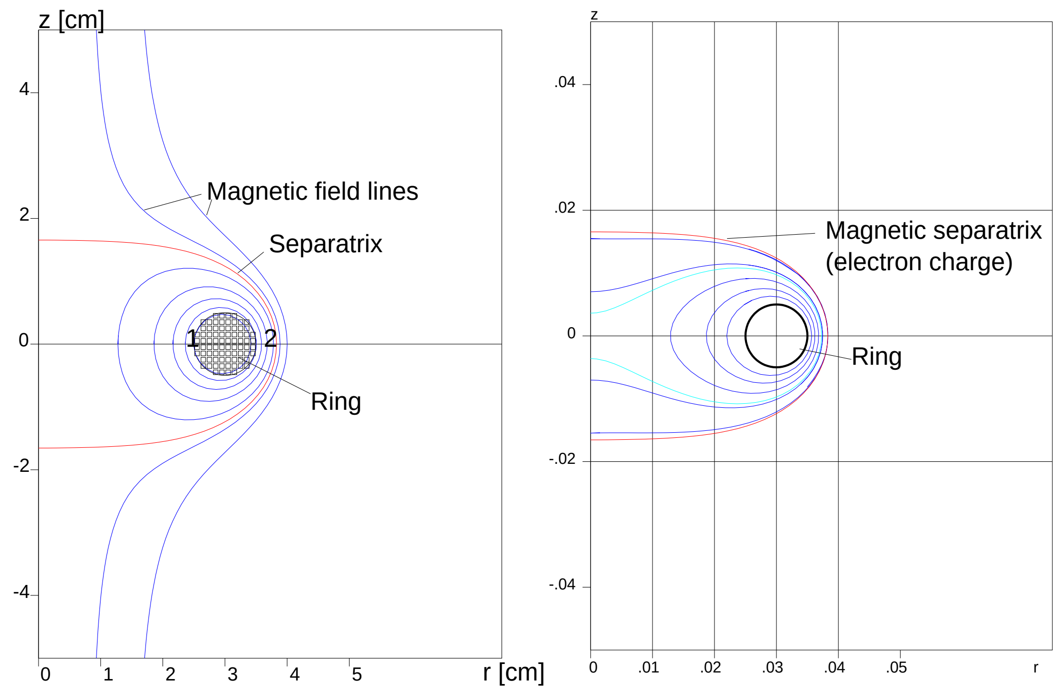


Fig.1. Magnetic and Electrostatic configuration

R [cm]	3	B_{ext} [T]	5	Ψ [Vsec]	0.01425
a [cm]	0.5	I [MA]	0.356	Ψ_{ext} [Vsec]	-0.01425
b [cm]	0.5	B_0 [T]	2.430	W_α [J]	40.79
T [kV]	30	B_1 [T]	13.57	q [C]	2.331e-05
ρ_e [cm]	0.0058	B_2 [T]	-14.91		
ρ_D [cm]	0.3494	B_{sep} [T]	-10.11		
ρ_T [cm]	0.428	U [MV]	1.75		
ρ_α [cm]	1.890	N_α	0.728e+14		

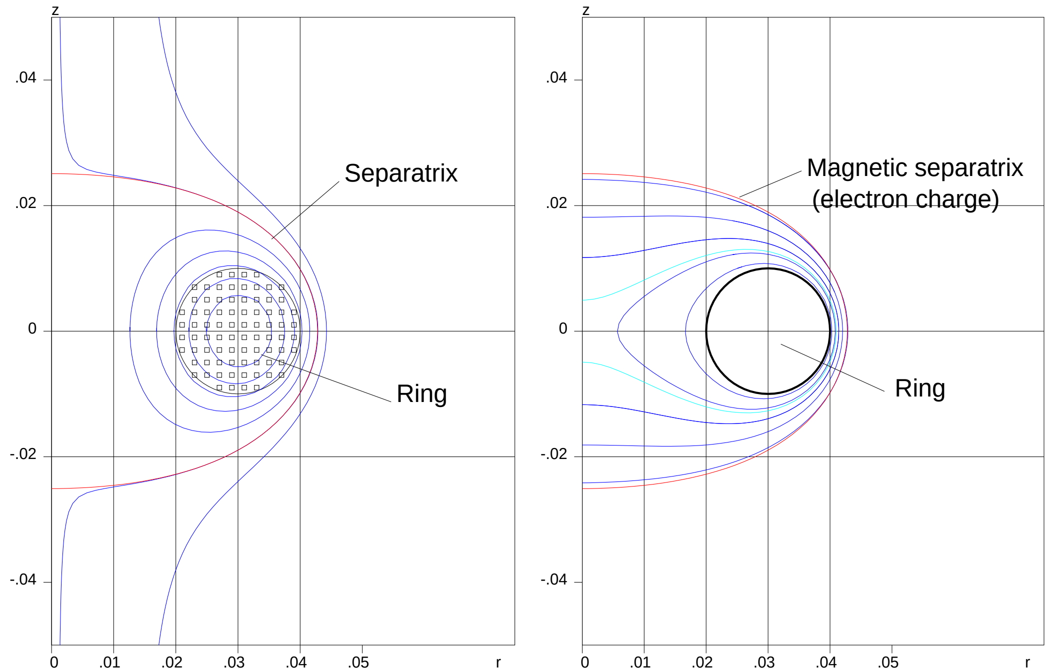


Fig.2. Magnetic and Electrostatic configuration

R [cm]	3	B_{ext} [T]	5	Ψ [Vsec]	0.01455
a [cm]	1	I [MA]	0.527	Ψ_{ext} [Vsec]	-0.01454
b [cm]	1	B_0 [T]	5.879	W_α [J]	71.60
T [kV]	30	B_1 [T]	11.53	q [C]	4.091e-05
ρ_e [cm]	0.0063	B_2 [T]	-10.88		
ρ_D [cm]	0.384	B_{sep} [T]	-9.215		
ρ_T [cm]	0.470	U [MV]	1.75		
ρ_α [cm]	2.074	N_α	1.278e+14		

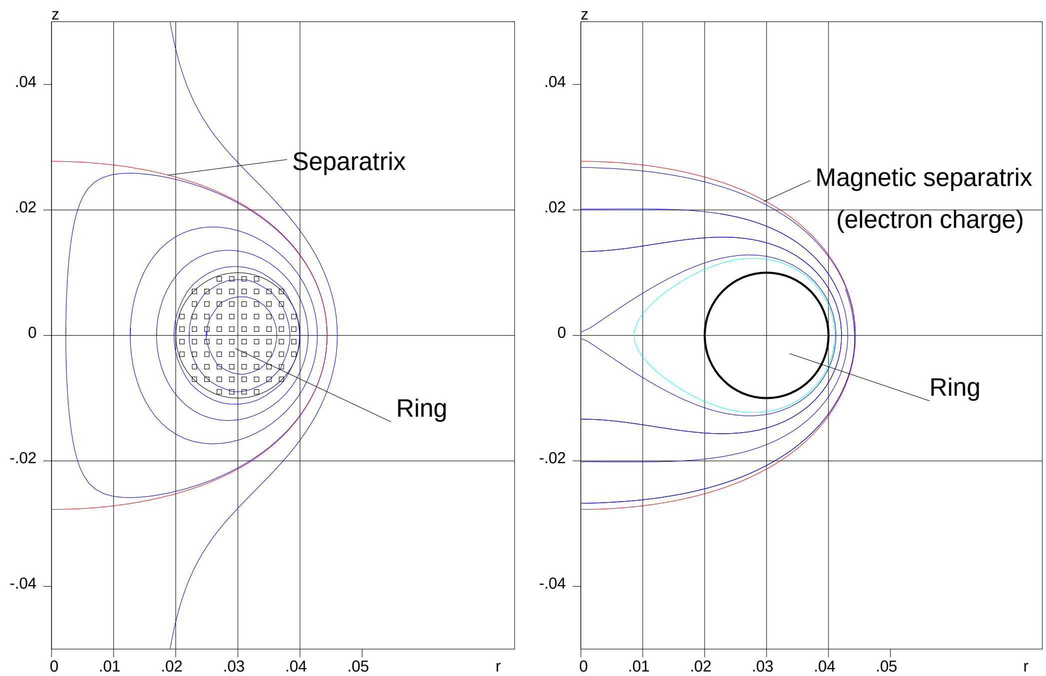
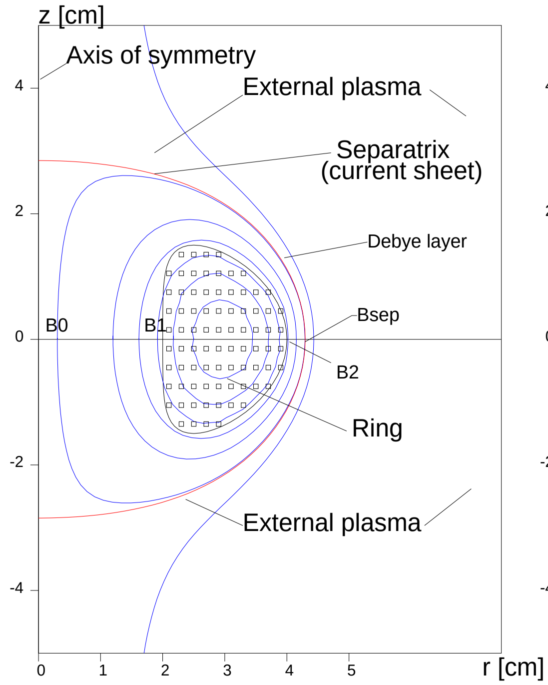


Fig.2a. Magnetic and Electrostatic configuration

R [cm]	3	B_{ext} [T]	-5	Ψ [Vsec]	0.01858
a [cm]	1	I [MA]	0.6	Ψ_{ext} [Vsec]	-0.01454
b [cm]	1	B_0 [T]	7.386	W_α [J]	54.4
T [kV]	30	B_1 [T]	11.53	q [C]	3.109e-05
ρ_e [cm]	0.0065	B_2 [T]	-11.70		
ρ_D [cm]	0.392	B_{sep} [T]	-9.012		
ρ_T [cm]	0.48	U [MV]	1.75		
ρ_α [cm]	2.12	N_α	0.972+14		



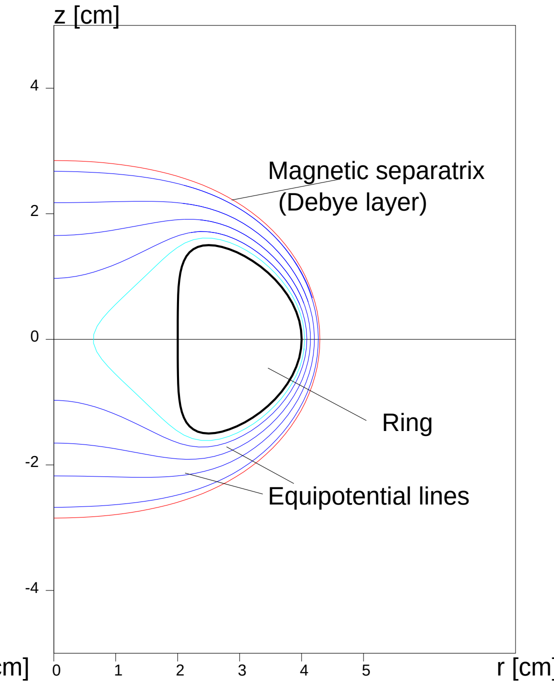


Fig.3. Magnetic and Electrostatic configuration

R [cm]	3	B_{ext} [T]	-5	Ψ [Vsec]	0.0135
a [cm]	1	I [MA]	0.605	Ψ_{ext} [Vsec]	-0.0135
b [cm]	1.5	B_0 [T]	7.183	W_α [J]	80.58
T [kV]	30	B_1 [T]	10.47	q [C]	4.605e-05
ρ_e [cm]	0.0067	B_2 [T]	-9.69		
ρ_D [cm]	0.406	B_{sep} [T]	-8.707		
ρ_T [cm]	0.497	U [MV]	1.75		
ρ_α [cm]	2.195	N_α	1.439+14		

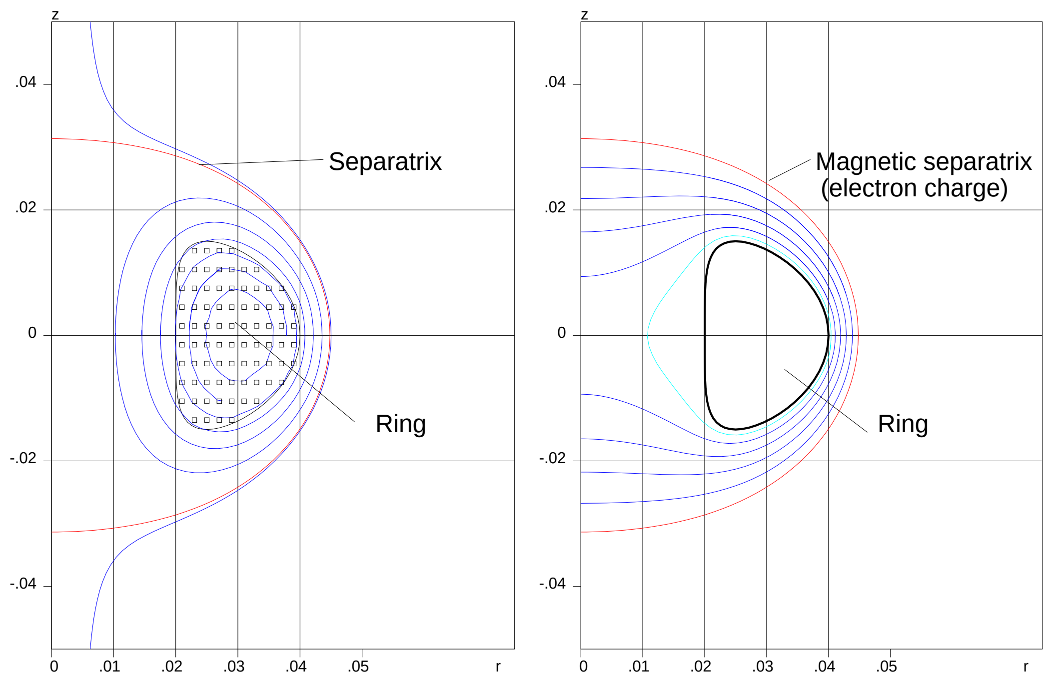
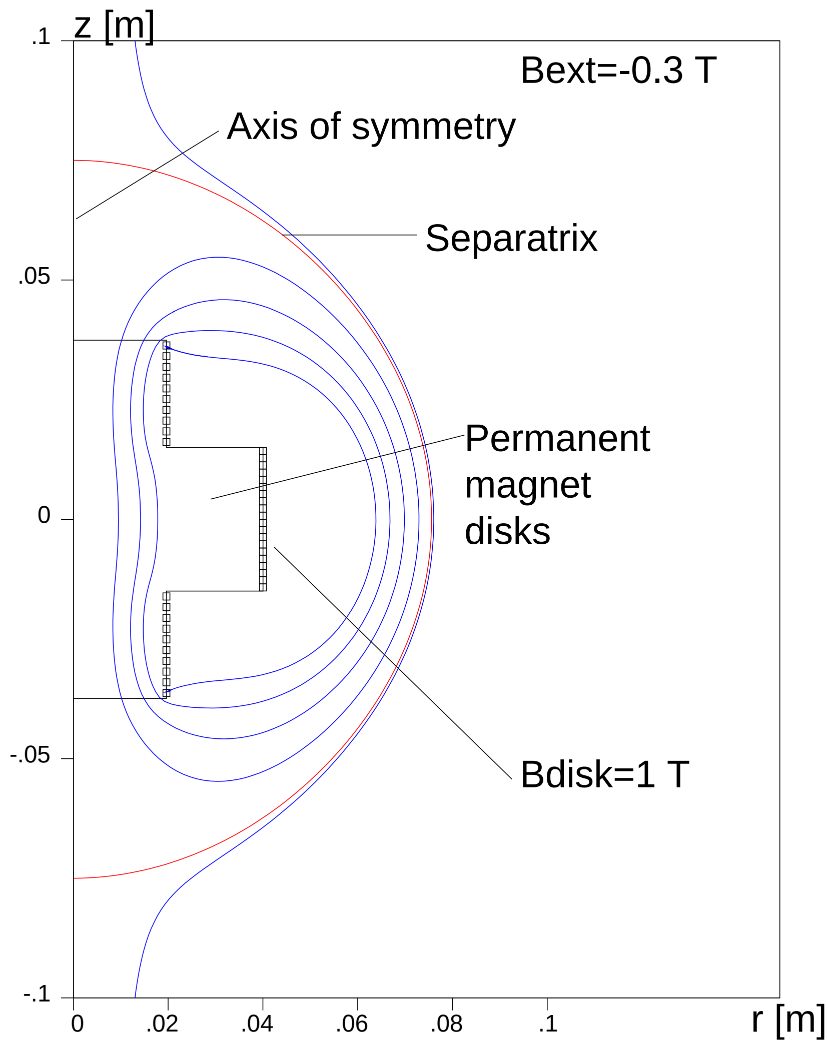


Fig.3a. Magnetic and Electrostatic configuration

R [cm]	3	B_{ext} [T]	-5	Ψ [Vsec]	0.0177
a [cm]	1	I [MA]	0.7	Ψ_{ext} [Vsec]	-0.0135
b [cm]	1.5	B_0 [T]	9.096	W_α [J]	59.34
T [kV]	30	B_1 [T]	12.90	q [C]	3.391e-05
ρ_e [cm]	0.0068	B_2 [T]	-10.42		
ρ_D [cm]	0.412	B_{sep} [T]	-8.579		
ρ_T [cm]	0.505	U [MV]	1.75		
ρ_α [cm]	2.227	N_α	1.060+14		

Example of magnetic configuration of the permanent magnet disks



6. Importance for tokamaks

Motivated by the concept of the tokamaks with Lithium walls, the development of Morozov's rings may significantly enhance fusion research in

1. Establishing the low/non-recycling regime in tokamaks
2. Precise measurements of the local transport phenomena
3. Precise plasma profile control for stability
4. Tayloring the bootstrap current, including the near axis current drive

7. Importance for ST and NSTX

Spherical tokamaks are a natural candidate for testing Morozov's rings:

1. The whole concept of spherical tokamaks heavily relies on bootstrap current drive, which should be controllable.
2. Relatively low magnetic field at the magnetic axis facilitates use of the Morozov rings in spherical tokamaks.
3. High local $\beta \simeq 100$ % of spherical and lithium wall tokamaks might open unique additional opportunities for Morozov rings

Even permament magnet disks can be used in low magnetic field (0.5 T) of NSTX.