Fusion prospects of axisymmetric traps with multi-mirror end plugs

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We show that a combination of the GDT-type central mirror with multiple-mirror end plugs can combine sufficient energy content with low axial losses and thus provide much better overall Q_{DT} than conventional gasdynamic mirrors. In particular, a neutron source with $Q_{DT} \sim 0.1$ can be 30m long, while a 300m-long device should be able to reach $Q_{DT} \sim 10$. Though admittedly far from realization, the concept allows construction of relatively low-power and cheap fusion devices and scales even to the DD-fusion. The GDMT project, based on this concept and proposed for construction in Novosibirsk, is outlined.

Axially symmetric mirrors, such as the gas-dynamic trap (GDT) in Novosibirsk, have low transverse particle and heat losses. This allows good confinement of fast ions, which in the case of neutral beam injection form the population of "sloshing ions". Its density may be even higher than that of the "warm" background plasma, which is generally needed just to provide the microstability. As a result, such traps are ideal for the beam-target or beam-beam fusion, making the GDT-like devices good Neutron Source candidates. However, prospects of pure mirrors for fusion energy are bleak due to high axial losses and rather low electron temperature.

Figure 1: Schemes of the GDT and the GOL-3 traps at the Budker institute.

Better axial confinement at a high plasma density can be achieved in multi-mirror configurations [1]. Namely, if the scattering length of particles out of the loss-cone is less than the trap length, the axial loss processes become diffusive. If it is roughly equal to the cell length, the loss rate is reduced by the factor of the number of cells. However, this is the theoretical maximum reduction, as in the hydrodynamic regime the plugging effect is small. Classical Coulomb scattering is too weak at fusion temperatures and containable pressures to provide optimum confine-
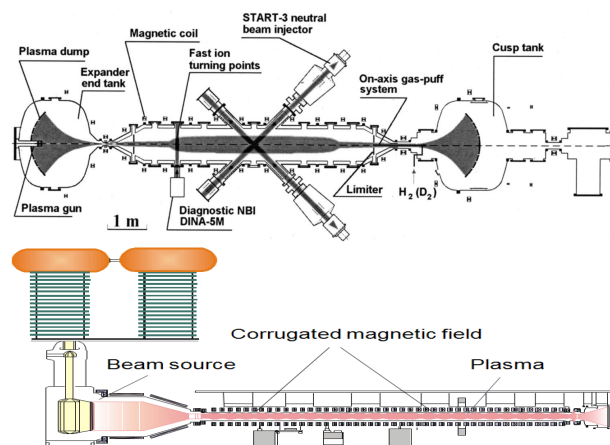
ment. Fortunately, the collective scattering is just as good. Evidence of improved confinement due to "bounce" oscillations in cells of the multiple-mirror trap was observed in GOL-3 experiments. We argue that even if such collective scattering is not present due to inherent instability of the outflow, suitable oscillations can be induced by an external source, such as a pulsing electron beam.

BINP mirror traps perform better than expected, are small, cheap and versatile. A lot of new promising physics has been discovered. The achievable power density is much larger than in tokamaks, $\beta \sim 60\%$ is reached in GDT. The weakness of open traps is the high axial loss rate via the electron channel. We argue that we understand this process and can reduce it by lowering the

Figure 2: Price scaling for fusion traps.

ion loss rate. In case of diffusive flow the axial confinement improves as a second power of length, while the cost is proportional to it. As shown in Fig.2, small tokamaks are drastically more efficient than small traps, but large tokamaks are too expensive. If the GDMT position on the graph is validated and the optimistic theoretical scaling holds, the multiple-mirror schemes will be applicable for advanced-fuel fusion.

The GDMT proposal

The aim is to prove the concept while going to longer pulses and higher electron temperatures. Q_{DT} is optimized by utilizing beam-beam fusion within the sloshing-ion population. The cen-

Figure 3: Scheme of the GDMT.

tral vacuum volume is from the "Hydrogen Prototype" project so that the NBI angle is $\alpha \approx 30^0$. One can use 8 focused injectors of BINP design, 1 MW, 40 keV, 1 s each. The central mirror can use existing copper coils and the power-feed from existing generators of the HP (for extra $\sim 1.5 \cdot 10^7$\$ the solenoid can also be made superconducting). One should minimize the plasma radius (the limit is due to NBI trapping, $a = 10$ cm), and maximize the "effective" length (available space is ~ 30m). The length of multi-mirror plugs is optimized to be $L_{mm} \approx L/4$, so
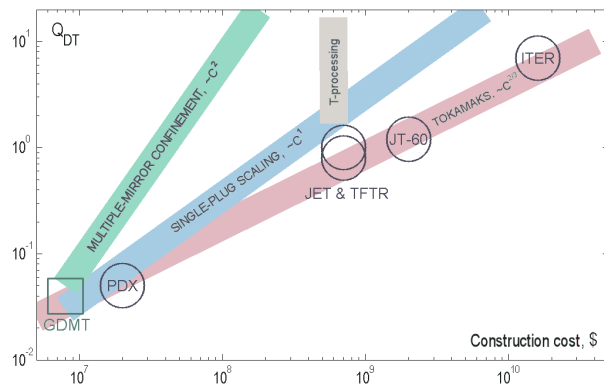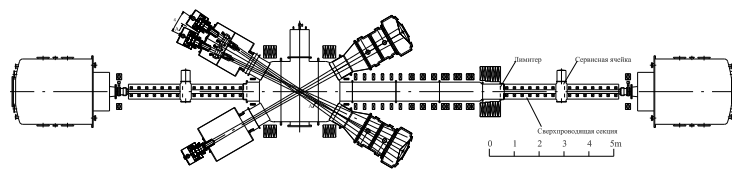
that $L_c = 10$ m, $L_{mm} = 5$ m); Due to heat loads during 1s pulses only superconductig multi-mirror coils are feasible. Learning to use superconducting technology is better with cheapest setup, so that the maximum field is limited by NbTi wire as $B_{max} < 7T$, and the magnetic mirror ratio is $k < 8$. Asymmetric scheme is chosen for convenient placement of NBI systems.

GDMT consists of linked modules with different functionality:

- The large tank is exclusively the NBI zone, but as an option it can also house the divertor. Deployment of 2 NBI in each of 4 ports allows 9° angular distance within each pair. With inclinations of different pairs by 0, 45, 65, 82 degrees to the port plane the injection distribution becomes spreaded. Anisotropy of the population of sloshing ions will be reduced.
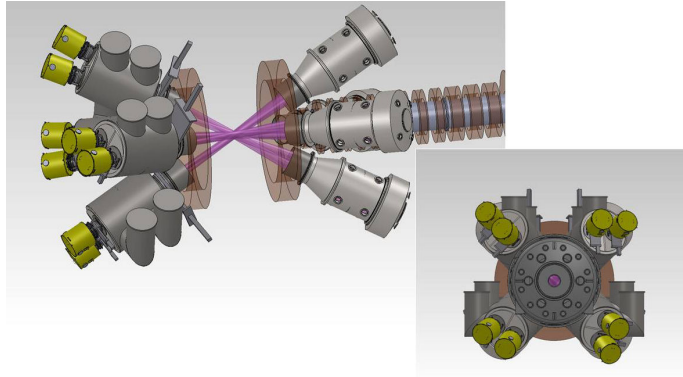

Figure 4: NBI: 8 MW / 40 keV / 1s in 8 beams.

- The solenoid is the zone of accumulation and trapping of fast ions ("active zone" in reactor), it corresponds to extended reflection point of fast sloshing ions in GDT.

The minimum-field well ($B_{min} = 0.8T$) is needed for efficient capture of ion beams (a=10cm). The "shoulder" ($B = 2.5 \div 4T$) is the extended reflection point for accumulation of fast ions (the "active zone"). Plasma with maximum of $\beta \sim 30\%$ resides in favorable field curvature, but the full MHD-stability is not achievable. Flute convection is going to be suppressed by vortex confinement as in GDT [2]. With proper biasing, ions should have minimum potential energy near the trap axis, this should reproduce the pinch effect in ions as in GDT.

- Superconducting multiple-mirror modules serve for suppression of the plasma outflow. Nb-Ti coils support up to 7T. The mirror ratio of cells is variable $k_{mm} \sim 1.3 - 2$, cell length is $\ell_{mm} \sim 40$ cm, 9 cells on each end of the trap in 3 sections. Two cells are open for service and diagnostics.

Figure 5: Central cell profiles.

- Expanders are end-cells needed for suppression of the electron heat flux. They also house the
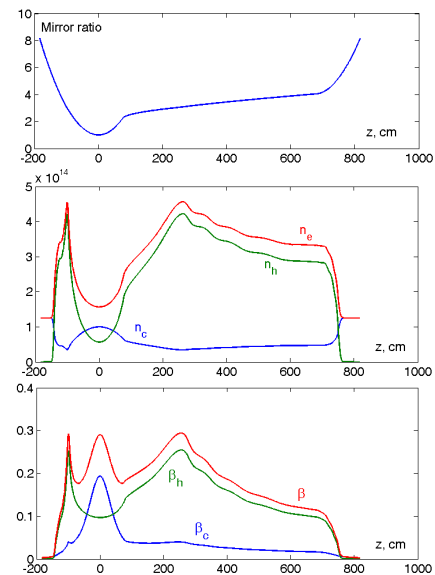
electron beams and the plasma sources.

- The electron beam needs development for:

- Charge injection (central electrode of the vortex confinement);

- Auxiliary stimulation of anomalous ion collsionality in multi-mirror plugs $(\lambda = \ell)$

- *Auxiliary* heating of electrons via plasma turbulence or by trapping and collisional thermalization;

Thus the needed EB parameters are: 2x100Ax50keV=10MW, or 100MW in one pulse , $1\mu s$ pulse duration, $\sim 1ms$ between pulses, total operation time 1 second.

The following table summarizes projected plasma parameters in GDMT as compared to existing traps. The main increase is in the discharge duration, that would allow achieving equilibrium at high electron temperatures, and in the triple product.

	GDMT[1]	GDMT[2]	GOL-3	GDT
Plasma radius, $a[cm]$	10	12	4	14
Effective mirror ratio, k_{eff}	10...20	60...100	—	30
Warm density, $n_c[10^{20}\mathrm{m}^{-3}]$	1	0.3	15	0.3
Hot ion density, $n_h[10^{20}\mathrm{m}^{-3}]$	1.5	3.5	0	0.3
Central T_e [keV]	0.4	1.2-2	0.1-3	0.2
Relative pressure, β	0.15	0.4	0.35	0.6
$n\tau T_i[10^{20}\mathrm{m}^{-3}\mathrm{s}\ \mathrm{keV}]$	0.06	0.2	0.02	0.005
Duration, $[s]$	1	1	0.001	0.005
Fusion efficiency, Q_{DT}	2%	8-10%	0.2%	0.2%

Conclusion Combination of the GDT- and the multiple-mirror concepts is made possible by recent advances in mirror physics. Multimirror improvement of axial confinement via collective scattering makes gasdynamic traps competitive as fusion devices. The GDMT proposal is aimed to prove the concept while achieving the neutron-source parameters even in the worst-case scenario.

References

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