

Fusion Prospects of Axisymmetric Magnetic Mirror Systems

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Abstract. Studies of magnetic mirrors for fusion started 60 years ago. The evolution of mirrors was driven by needs to stabilize curvature-driven instabilities and reduce axial losses. It turned them into highly sophisticated and huge tandem mirrors with axial ambipolar confinement, thermal barriers and quadrupole magnetic stabilizers [1,2]. Too late it was recognized that quadrupole fields cause resonant radial losses, and that placing stabilizers behind barriers reduces their effectiveness. Tandem mirrors lost competition to toroidal devices in 1987 and are almost extinct. A side branch of open traps went for simplicity, high- β and good fast-ion confinement inherent in axially symmetric mirrors [3]. These traits allow lower cost of construction and servicing, lower engineering and materials demands, promise a path to advanced-fuels fusion. Axially symmetric mirrors are of particular interest as neutron sources or fusion-fission hybrids. They might still have an edge as pure fusion reactors. Axially symmetric mirrors at the Budker Institute of Nuclear Physics in Novosibirsk currently represent the frontline of mirror research. We discuss recent experimental results from the multiple-mirror trap, GOL-3 [4], and the gas-dynamic trap, GDT [5]. The next step in this line of research is the GDMT program that will combine the GDT-style fast-ion-dominated central mirror with multiple-mirror end plugs [6]. This superconducting device will be modular and built in stages. The first stage, GDMT-T, will be based on 5m, 7T superconducting solenoid (multiple-mirror plug of the full device). Its scientific program is oriented primarily on PMI studies.

1. History of mirror research

The idea to use adiabatic confinement of plasma particles for controlled fusion originated in early 50's independently in US, where it is attributed to R.F. Post, and in USSR, where it was proposed by G.I. Budker. By that time, the magnetic mirror phenomenon itself was already known from astrophysics, while the magnetic confinement for fusion was being explored for toroidal configurations. The story of development of mirror traps for fusion is dramatic: there were periods of high hopes and booming growth, periods of innovation and sudden twists in construction, periods of disappointment and neglect. In 1957 Rosenbluth predicted that mirrors will be unstable to flute-interchange modes. However, in 1958, when first sizable mirror devices OGRA (in USSR) and DCX (in US) entered operation, no such instability was identified. It wasn't observed until 1961, when Ioffe confirmed its existence on PR-2 machine and proposed to use quadrupolar field corrections to stabilize the flute modes.

In 1964 the second generation of mirrors (DCX-II, Phoenix, MTSE) entered service equipped with "Ioffe rods". However, it was quickly realized that the quadrupolar field generated by "baseball"-shaped coils should be inherently more stable, and thus is much more effective than Ioffe rods. At this time the "baseball" coils became the trademark feature of mirror research. However, the OGRA-II device in Kurchatov Institute tried another approach, namely, the feedback stabilization, and it was, surprisingly, successful, even though in 1967 there was no computerized equipment. Unfortunately, this way of confinement was later abandoned, but the experiments are still an inspiration.

At about the same time, in 1967, theory severely downgraded prospects of mirror confinement for fusion. Analysis of losses due to Coulomb scattering of particles into the loss cone vs. fusion gains, done by Sivukhin, showed that the magnetic mirrors cannot hope to achieve the Q-factor above 1.2-1.5. Besides, there were known instabilities, enhancing axial losses, in particular DCLC, the drift loss-cone instability, caused by anisotropy of the distribution function with the empty loss cone. However, these unfavorable predictions led to a period of intense theoretical research and rapid innovations in the design of mirrors rather than to the closure of activity. It became apparent, that only a drastic improvement of axial confinement (in comparison to a simple mirror trap) together with plasma stabilization can lead to success.

Meanwhile, in Livermore the “baseball”-shaped 2X-family of traps was developed (2X, 2XII, Alice, culminating in 2XIIB). In these experiments the way to stabilize the DCLC-instability by pumping a small fraction of cold external plasma into the loss cone was found and tested. Development of the neutral beam injection technology allowed achievement of the then record ion temperature of 10keV and beta around 70% in 2XIIB in 1975 with 12MW 20keV NBI. Success of 2XIIB prompted design of the next-step project – the huge Magnetic Fusion Test Facility (MFTF). Its construction started in 1977.

In 1971 Budker et al., and Logan et al. independently proposed the idea of a multiple-mirror trap. It seeks to improve the axial confinement by considering plasma outflow through a sequence of mirrors, rather than through a single mirror throat. Unfortunately, it promised improvement only in very dense plasmas, which placed such traps in the domain of inertial machines rather than steady-state reactors. In 1974 Pastukhov derived his famous formula allowing evaluation of axial confinement in mirrors with axial ambipolar electric fields. In 1976 Dimov, Fowler, and Logan independently proposed the idea of a “tandem mirror” or an “ambipolar trap”. In it the specially-produced populations of hot ions in small plugging mirrors at both ends of a solenoid produce ambipolar barriers, stifling the plasma outflow (Fig.1).

The tandem-mirror idea proved to be extremely popular and successful. In 1978 GAMMA-6 in Japan provided evidence of formation of ambipolar barriers and improved confinement, and a much bigger machine, TMX, entered operation in Livermore. In 1979 TMX reached its peak parameters of $\beta=40\%$, $T_e\sim 250\text{eV}$, $n_e\sim 3\times 10^{19}\text{m}^{-3}$ with 7MW NBI, which produced 1keV-high ambipolar barriers. These plasma parameters are essentially still unsurpassed in other open traps. In the same year a further improvement on the idea of a tandem mirror, the thermal barriers, was proposed by Baldwin and Logan. Shaping of the profile of the ambipolar potential by heating electrons in an additional plugging mirror promised thermal insulation of the electron component from the end walls. The invention caused hasty mid-work corrections in the design of MFTF, which became MFTF-B; TMX was modified to become TMX-U.

Ryutov and Stupakov showed that a large neoclassical-like resonant transport should be present in non-axisymmetric quadrupole fields. The problem could be addressed by making the main trap body symmetric, while retaining quadrupole anchors at far ends of the device.

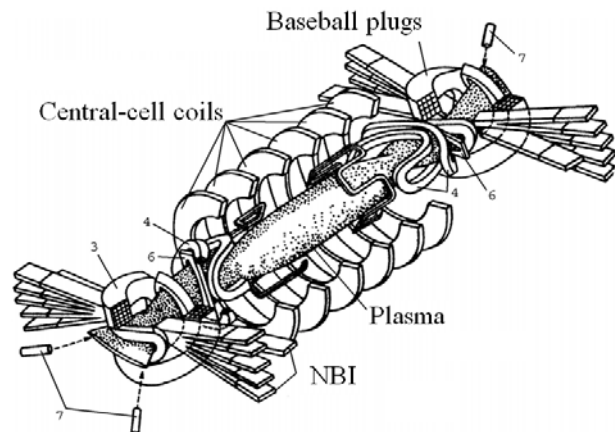


FIG.1. Scheme of a tandem mirror (TMX).

New sophisticated facilities - TARA (in US), GAMMA-10 (Japan), AMBAL (USSR) entered the construction stage.

The period 1978-87 can be called the Golden Age of mirror research. Besides tandem mirrors, flourishing in US, other confinement schemes emerged: in 1979 Mirnov and Ryutov proposed the gas-dynamic trap, in 1983 successful experiments on PSP-2 confirmed efficient centrifugal confinement in supersonically rotating plasma. In 1982-84 a comprehensive analysis of fusion technologies and perspectives for tandem mirrors was completed by the TASKA team. As the tandem-mirror design became more and more complex, the time and resources spent on each unit multiplied. Furthermore, complex plasma shape caused additional instabilities and transport. In particular, placing poorly-conducting thermal barriers between the main trap body and quadrupole anchors reduced their stabilizing efficiency. Thus, the early results of newly-constructed facilities were disappointing, especially in comparison with tokamaks. This led to a sudden and abrupt end of the open-traps program in US and of the Golden Age of mirrors. Faced by a choice of spending limited budget on tandem mirrors or on TFTR, the US DoE made the decision in favor of tokamaks. In 1987 the mirror research in US was terminated. MFTF-B was dismantled right after completion. Nevertheless, some die-hard activity in other countries persisted.

GAMMA-10 in Japan remains the world-largest and most sophisticated mirror trap to this day. It achieved ambipolar enhancement of axial confinement by 10^3 as compared to a single mirror. Unfortunately, the price of this success was a severe limitation on beta ($\sim 2\%$), due to various drift instabilities and associated radial transport. Construction of AMBAL in Russia continued through 90's, but it was plagued by accidents and the lack of resources. It was never finished. The Hanbit device was constructed in S. Korea from parts of the US TARA trap. It is now decommissioned too.

Many new stabilization schemes for fully axisymmetric mirrors were proposed by D.D. Ryutov, R.F. Post and others [3]. As a result, in 1988 a new generation of axially symmetric traps entered the scene: the small-size ICRH-heated tandem mirror HIEI in Japan, the gas-dynamic trap GDT, and the multiple-mirror trap GOL-3 in Novosibirsk. By 1993 the main ideas behind stabilization of the gas-dynamic trap, the expander- and FLR-stabilization mechanisms were confirmed. HIEI reported promising results on suppression of radial transport by limiter biasing.

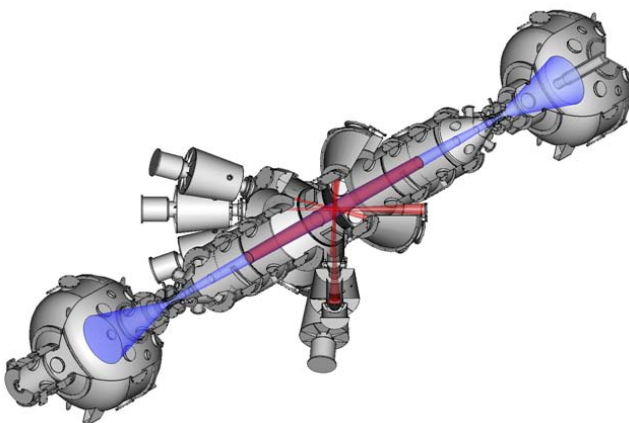


FIG.2. GDT is a classical mirror with sloshing injected ions, stabilized by warm collisional plasma. The plasma outflow is limited by the nozzle effect.

Besides progress in theory, the last 20 years of mirror research were marked by steady progress in plasma parameters in axially symmetric mirrors. By 2006 the GDT team reported $\beta=60\%$, $T_e\sim 200\text{eV}$, $n_e\sim 3\times 10^{19}\text{m}^{-3}$ by using limiter biasing for stabilization with turned-off expanders. (The scheme of GDT is shown in Fig.2.) The GOL-3 team observed plasma heating (of both, ions and electrons) up to 3keV during turbulent heating by the relativistic electron beam. After the heating phase the collective multiple-mirror enhancement of confinement was found, which was 10^2 times better than predicted at densities $\sim 10^{20}\text{m}^{-3}$ with Coulomb collisions.

The story of the demise of classical tandem mirrors cannot be taken as an indication of the failure of ambipolar confinement or mirror research in general. It rather indicates that the quadrupole stabilizers are not suitable for fusion applications. In a more general way this thesis can be formulated as follows:

- the confinement area should be axisymmetric to avoid resonant losses;
- any form of plasma stabilization that depends on anchors outside of the confinement area loses effectiveness at reduced axial losses;
- axial symmetry is required for sustained plasma rotation that is in turn needed for good axial confinement.

The second statement applies to gas-dynamic traps as well as to tandem mirrors; and to expanders, cusps, non-paraxial cells as well as to quadrupole anchors if placed behind ambipolar barriers. For the same reason, the gas-dynamic trap in its pure form should not be used as a fusion reactor; it would have either poor confinement time or become unstable if we try to improve it. Hence, from the start GDT was planned as a prototype low-Q neutron source for materials science.

The third statement deserves a detailed explanation. The ambipolar potentials in plasma vary not only along the field lines, but across them, in radius, as well. The reason for this is the usual dependence of plasma temperature and density on radius. But the radial electric fields translate into the ExB rotation of the plasma column. The reverse is also true: if the plasma rotation is changed in some way, for example, due to radial momentum transport in non-axisymmetric field, due to turbulent convection or plasma biasing, this will also affect the axial confinement. The ambipolar balance follows from quasineutrality and current closure conditions:

$$n_e = Zn_i, \quad j_{||e} + j_{||i} = B \int \text{div} \vec{j}_\perp \frac{d\ell}{B}.$$

Here the right-hand side term represents currents due to rotational momentum transport. It was usually neglected in the theory of tandem mirrors. However, simple estimates show that its relative value is governed by dimensionless parameter, $\rho_{i*} L/a^2$, where L is the trap length, a is its radius, and ρ_{i*} is the ion Larmor radius, calculated via the value of potential. This parameter is of order unity in current conditions and is going to grow on the way to fusion. This proves the importance of interplay between rotation and the axial confinement theoretically. In recent GDT experiments a direct experimental proof was obtained: it was possible to influence the direction of rotation via the momentum injection with NBI. It turned out that the enhanced rotation in the ambipolar direction improved the axial confinement by a factor of two as compared to the zero-momentum case, while the reverse rotation resulted in significant degradation of confinement.

2. Current status

There are three relatively large traps (>10m) in operation: the tandem mirror GAMMA-10, and axially symmetric GDT and GOL-3. One should also mention a medium-sized centrifugal trap MCX in US.

2.1. Gas Dynamic Trap

The Gas Dynamic Trap (GDT) is a version of the classical Budker – Post mirror trap, but with a very high mirror ratio, so that its length exceeds the mean free path with respect to ion

scattering into the loss cone $\lambda_{ii}\ln R/R$ (see [3,7]). Under these conditions, the plasma is collisional and, therefore, is close to being isotropic and maxwellian. Its outflow is limited by the nozzle effect, so that the axial confinement time of ions can be estimated as $\tau \sim RL/V_{Ti}$, and *it cannot get worse* due to turbulent scattering, since the loss cone is already full. The original aim in construction of GDT was to test the idea of a mirror cell for beam-beam fusion in relatively cold background plasma as a neutron source. This cell is axially symmetric for good confinement of beam ions. The beams are injected obliquely at 45° to the axis, forming sloshing-ion population. The sloshing ions can be stable to kinetic modes in presence of the warm background plasma, which is also needed for flute-mode stabilization of the system. However, the high gas-dynamic losses of the warm plasma keep it at low electron temperature, so that the confinement of fast ions is limited by drag losses.

The GDT magnet and neutral beam systems are shown in Fig.2. The vacuum chamber consists of a cylindrical central cell 7m long and 1m in diameter, and two expander tanks attached to the central cell at both ends. A set of coils mounted on the vacuum chambers produces an axisymmetric magnetic field with a variable mirror ratio ranging from 12.5 to 30 when the central magnetic field is set to 0.3T. In some experiments this configuration was modified by adding compact mirror cells at both ends of the. The basic parameters of this device and the plasma parameters typical for the operational regime are listed in Table I.

TABLE I: Parameters of the GDT device

Mirror to mirror distance	7 m	Total injection power	up to 5.7 MW
Magnetic field at mid-plane, in mirrors	Up to 0.35 T 2.5-15 T	Injection angle	45°
Bulk plasma density	$1-6 \times 10^{19} \text{m}^{-3}$	Fast ion density in turning point regions	$\approx 5 \times 10^{19} \text{m}^{-3}$
Radius at the mid-plane	14 cm	Mean energy of fast ions	$\approx 10 \text{keV}$
Electron temperature	up to 250 eV	Maximal local plasma β	up to 0.6
Energies of D/H neutral beams	20-25 keV	Pulse duration	5 ms

The original scheme of plasma stabilization vs. flute modes was based on the use of flow expanders with favourable field curvature beyond mirror throats. With high axial losses the plasma outflow could provide stabilization. However, there was an important unexpected achievement of the GDT team in the physics of confinement. It is the successful implementation of the vortex-confinement scheme for plasma stabilization by means of plasma biasing [8]. The influence of vortex confinement on radial transport also includes strong pinch effect in sloshing ions. The vortex confinement is cheap both in terms of spent power and in construction costs, and is predicted to be useable in fusion conditions. In GDT, the vortex confinement allows operation at higher beta (0.6 vs. 0.2) than the original scheme with the same heating power.

The GDT team employed a set of biased radial limiters and radially segmented end walls to control the electric field in the plasma. Then a reasonable radial confinement was obtained even when the MHD-stabilizing expanders or cusp cells were not engaged. The threshold electrode bias for stable operation was $\sim 150-250 \text{V}$, i.e., of the order of the electron temperature. Plasma activity in this regime was monitored through measurements of the signals from the azimuthal and axial arrays of magnetic coils installed at the vacuum chamber walls [9]. Coherent $m=1$ or $m=2$ modes were observed, which is indicative of a highly

dissipative environment caused by the end-wall dissipation of current through the wall sheath

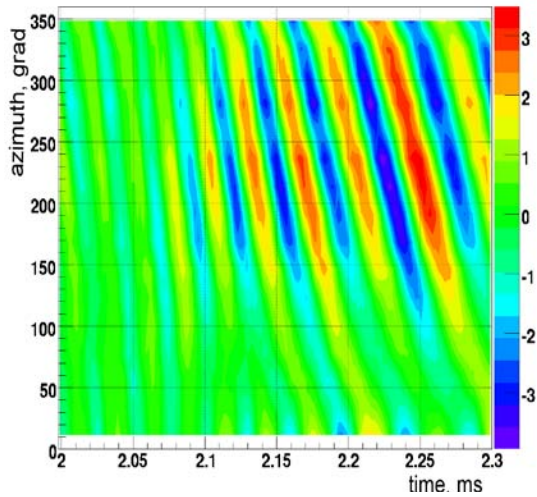


FIG.3. Signals from azimuthally distributed magnetic probes vs. time in the vortex-confinement regime of GDT

(Fig.3). It can be seen that the modes with small azimuthal numbers dominate. It is due to strong FLR effects in the hot ions. The mode rotation frequency in these experiments was close to the estimated growth rate of the flute instability, so that one can conclude that the sheared plasma rotation has a significant effect in these experiments.

The stored plasma energy in the regime with sheared plasma rotation at the periphery increases almost linearly during the beam injection. Thus, one can conclude that the transverse energy losses are quite negligible in the plasma energy balance. Density of the fast ions with a mean energy of 10-12keV reached $\approx 5 \times 10^{19} \text{m}^{-3}$ in the turning point regions and substantially exceeded that of the target plasma ($1.5\text{-}3 \times 10^{19} \text{m}^{-3}$ at the mid-plane). This resulted in

the development of peaks of the ambipolar potential and the considerable reduction of plasma axial losses in the region near the plasma axis.

Comparison of plasma parameters achieved so far in GDT with different MHD stabilizing end-cells and with induced plasma rotation without the stabilizers is presented in Table II.

TABLE II. Parameters of GDT-plasma achieved with different MHD stabilizers.

Parameter	Expanders	Cusp end cell	Vortex confinement
B_{\min} , T	0.2	0.22	0.3
B_{\max} , T	2.5-15	2.5-15	2.5÷15
n_e , 10^{19}m^{-3}	3-20	4.5	3-6
a_p , cm	≈ 6.5	5-10	6-7
T_e , eV	5-20	90-110	250
NB pulse, ms	0.25	1.2	5
PNB, MW	-	2- 4.2	2.5-5.7
Fast ion density, m^{-3}	1×10^{18}	1×10^{19}	5×10^{19}
β_{\max}	≈ 0.1	≈ 0.2	0.6

The microstability of the central solenoid has not been a problem for GDT. However, recently at high plasma parameters, a distinct mode at 1.15MHz (close to $0.5f_{ci}$ at the midplane) was detected as shown in Fig.4. Axial wavelength was measured to be $\lambda_{\parallel} = 104 \pm 4$ cm. At present, these fluctuations are relatively weak and do not affect the total plasma energy content, but they correlate with “sawteeth” oscillations observed in the measurements of plasma diamagnetism at the fast-ion turning points. The GDT-team found only a weak heating of the end-loss ions correlated with the onset of these fluctuations. For comparison, without the fluctuations the mean energy of end-loss ions was $\langle E \rangle = 1 \pm 0.03$ keV and increased to 1.1 ± 0.03 keV when the fluctuations appeared [9].

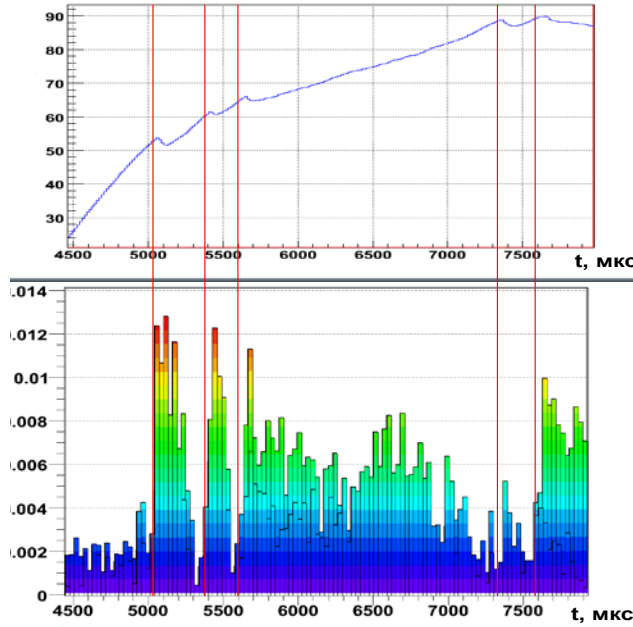


FIG. 4. *a* - plasma diamagnetism measured at turning point; *b* - amplitude of oscillations with $f \sim 1.15 \text{ MHz}$

Because these fluctuations have frequencies below the minimum ion-cyclotron frequency, this mode may be the AIC mode [10], rather than the higher-frequency loss-cone instability [11]. Modification of the instability threshold and the characteristics of the unstable perturbations in the GDT are considered in [12]. These theoretical results were found to be in agreement with experimental observations. In particular, the polarization vector of oscillations rotates in the direction of ion rotation in the magnetic field and the wave propagates from the center of solenoid to the ends. Then, the observed “saw teeth” relaxations in plasma diamagnetism at the turning points can be explained by axial redistribution of plasma pressure due to increase of angular spread of the freshly-injected ions, which

are in resonance with the unstable wave.

After several modifications the GDT parameters reached the record (set by TMX), $\beta > 40\%$, $T_e \sim 250 \text{ eV}$, $n_e \sim 3 \times 10^{19} \text{ m}^{-3}$, in a transient state, while the electron temperature grows all 5ms of injection. Estimates show that tripling the injection time would increase the temperature by 50%, but this would also exceed the β limit on confinement. Thus, GDT surpassed expectations of designers and reached its limits. The plasma parameters are in fact close to those set for the Hydrogen Prototype program, which was conceived as the final stage before construction of the actual neutron source.

2.2. Multiple-mirror trap GOL-3

In a solenoid with periodically changing magnetic field the plasma outflow can be much slower than the direct axial expansion (with sound speed) if there is an effective interaction of trapped and passing particles. This happens if the plasma density is in a certain range, i.e. the inequality $L \gg \lambda_{ii} \gg \ell$ holds, where ℓ is the distance between the neighbouring field maxima and λ_{ii} is the ion mean free path. Then, the axial plasma expansion becomes diffusive in character, so that the plasma stays in the trap for $\tau \approx R^2 L^2 / \lambda_{ii} V_{Ti}$, where $R = B_{\max} / B_{\min}$ is the mirror ratio of corrugation [13].

The recent experiments on plasma heating and confinement in the GOL-3 device were done with multi-mirror configuration. In this case the length of the system was 12m with 55 mirror cells along the axis (Fig.5). The magnetic field in cells was $B_{\max} = 4.8 \text{ T}$, $B_{\min} = 3.2 \text{ T}$. The vacuum chamber consisted of a stainless steel tube with inner diameter of 10 cm. The plasma diameter was 6-8 cm. The preliminary plasma (hydrogen or deuterium) with typical density of 10^{21} m^{-3} was produced by oscillating direct discharge ($U = 30 \text{ kV}$, $I = 3 \text{ kA}$, $T = 120 \text{ } \mu\text{s}$).

The GOL-3 trap was designed for heating by a short but powerful pulse of relativistic electron beam (REB) with turbulent dissipation. The main parameters of the beam passing along the plasma in the GOL-3 are as follows. The energy of electrons is 1 MeV, maximum REB

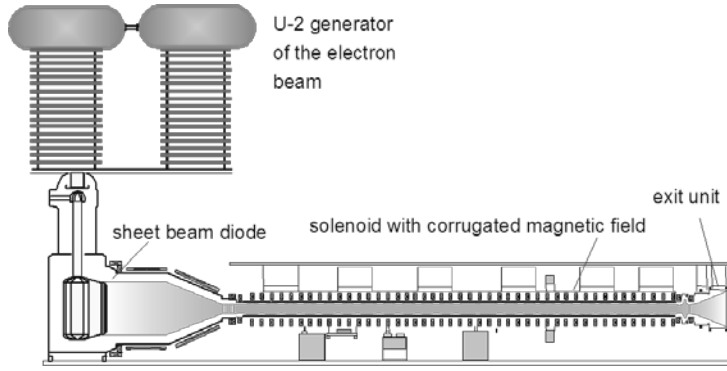


FIG. 5. Layout of GOL-3.

GOL-M, at REB current and plasma densities in proportion $n_{\text{beam}}/n_e \sim 3 \cdot 10^{-4} - 10^{-3}$, the strong Langmuir turbulence is excited in plasma. That leads to rise of relatively slow density fluctuations because of appearance of collapsing cavities [14] or excitation of ion sound turbulence [15]. According to [16], in the case of REB-plasma interaction, the coefficient of electron thermal conductivity instead of $\chi_{\parallel} \sim v_{Te}^2/v_{ei}$ is equal to $\chi_{\parallel} \sim v_{Te}^2/\Gamma$, where Γ is the growth rate of the beam instability. The estimates presented in [15] show that if the level of turbulence is $W/nT \sim 15\%$, the electron thermal conductivity is 10^3 times lower than in the classical case without turbulence. Approximately this level of turbulence was observed in the INAR and GOL-M experiments (see [17]). So, the problem of thermal insulation of plasma and heating of electrons in open systems with REB is solved, though only during the injection time. Just after switch-off of the beam the plasma electrons in GOL-3 are cooled to $T_e \approx 100-150$ eV in just 10 - 20 μs . Though the turbulence level in GOL-3 is not measured as in GOL-M, in order to explain the experimentally observed maximum value of electron temperature of above 2 keV one should assume that the electron thermal conductance is also three orders of magnitude lower than the classical one.

After cooling of electrons the main plasma energy is contained in ions. During this time significant neutron radiation was recorded for deuterium plasma [16] (see Fig.6). It means that ions are also heated to above 1keV, and it occurs very fast, in 10 μs of the beam pulse. This effect is caused by a several phenomena. The REB-plasma interaction depends on the ratio of n_b/n_e , so that the power transfer from the beam into plasma in the mid-plane of each cell is less than in mirrors. Taking into account the effect of suppression of thermal conductivity along the system, it follows that the electron temperatures and pressures will have large axial gradients. This was confirmed with injection of REB ($j_b \sim 1\text{kA}/\text{cm}^2$) in preliminary plasma ($n_e \sim 10^{21}\text{m}^{-3}$) placed in 12m-long homogeneous magnetic field with one mirror cell [18]. Due to axial gradients of pressure, plasma streams originate from the opposite mirrors toward the cell middle. This parallel motion of ions is later thermalized in shocks [17]. For $n_e \sim 3-5 \cdot 10^{20}\text{m}^{-3}$ the thermalization time is estimated at 20–30 μs .

In contrast to electrons, the hot ions live in GOL-3 for a rather long time of the order of 1 millisecond. It means that the multi-mirror confinement “works”, although the requirements of the theory are not fulfilled (the density is too small for Coulomb scattering). The cause of this phenomenon is illustrated by regular oscillations of the neutron flux in Fig.6. Their period is approximately $T \approx \ell/V_{Ti}$, and scales accordingly with changes of cell size and ion temperature [16]. Such behaviour of neutron radiation can be explained by excitation of the bounce instability [17]. The bounce oscillations facilitate collective scattering of transit ions and trapped particles, so that the effective ion mean free path decreases by two orders of magnitude to $\lambda_{i\text{ eff}} \sim \ell$ (Fig.7).

current is up to 30 kA, typical current density of the REB in the plasma is 1-1.5 kA/cm^2 , the beam duration is 8-10 $\cdot 10^{-6}\text{s}$, so that a typical energy of the REB in experiments is 120 kJ.

The typical duration of the diamagnetic signal in GOL-3 is about 1ms as compared to 10 μs of the beam pulse. As it was shown on the another device,

In the multi-mirror configuration the problem of MHD stability exists. However, taking into account the geometry of the REB current, the current for creation of the preliminary plasma, and the net current, it is possible to obtain sheared structure of magnetic field where plasma is MHD stable. In detail this experiment and computer simulation are presented in [18].

Progress towards creation of multiple-mirror fusion reactor needs new tools and techniques for heating and plasma stabilization to be developed. First of all, duration of the electron beam must be increased by at least an order of magnitude, while keeping the high current density and brightness of the beam. Using an electron emitter based on high-current arc discharge seems a promising solution of the problem. The GOL-3 team developed such an electron beam gun with a pulse length of $\sim 100 \mu\text{s}$, accelerating voltage $\sim 150 \text{ kV}$, current density in plasma of $1\text{--}2 \text{ kA/cm}^2$ and $\sim 100 \text{ kJ}$ beam energy content. This beam was successfully injected into the GOL-3 plasma; plasma heating, charge deposition and other interesting phenomena were observed.

A next step in the development of multi-mirror systems requires new methods of plasma heating in addition to the existing high-power REB. Neutral beam injection is considered to be an effective tool for auxiliary plasma heating in GOL-3. Special interest is in simultaneous application of long-pulse electron beam, which would suppress the heat conductivity, and high-power neutral beam injection to produce fast ions in plasma.

High density, short lifetime, small radius plasma and high gas pressure near the wall complicate the NBI use in GOL-3. First experiments with neutral beam injection were

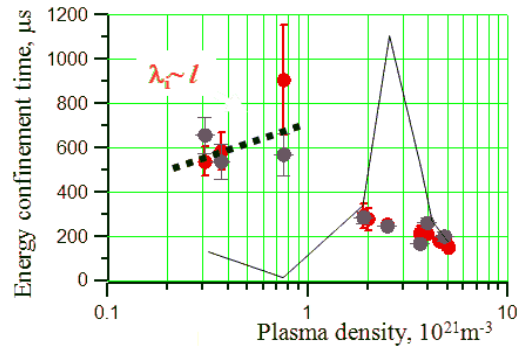


FIG. 7. Energy confinement time in GOL-3 (after beam turn-off) vs. Coulomb and collective-scattering models. The ion temperature is a function of density (much higher than the electron temperature).

directed to adaptation of the technique for use in the conditions of GOL-3 and to study fast ion confinement in turbulent plasma of the multiple-mirror trap. Neutral beam injector based on START-2 design was mounted in the central part of the solenoid for normal injection. In first experiments the beam energy was $15\text{--}18 \text{ keV}$, beam power was $0.45\text{--}0.55 \text{ MW}$, and pulse duration was 0.8 ms . Beam attenuation in plasma was monitored by an array of secondary emission detectors to study the radial density profile via multi-chord attenuation measurements. First NBI experience in GOL-3 was successful. Almost 84% of beam particles were trapped by plasma. We estimate the beam loss due to ionization of neutrals in collisions with the gas on their way to plasma below 20%. We plan to increase the NBI power and apply additional ballistic focusing of the beam in order to increase the beam power density.

GOL-3 reached and outperformed most of its original aims. The electron-beam heating technology works. It simultaneously provides fast ion heating up to 3 keV and suppression of

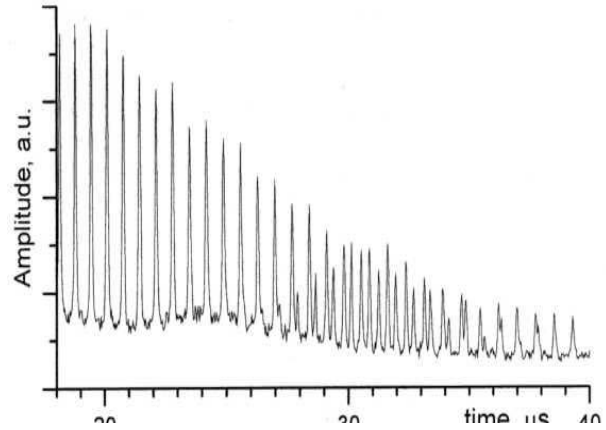


FIG. 6. The flux of DD neutrons from a single cell of GOL-3 trap vs. time since the beam start shows regular oscillations with period $\sim V_T/l$.

axial electron heat conductivity by a factor of $>10^3$. Suppression of heat conductivity is interpreted as due to enhanced collision rate. The multiple-mirror confinement of ions in the corrugated field is also observed. However, the wall-confinement at $\beta > 1$ was not achieved for unknown reasons. This makes the original pulsed-fusion scheme unlikely. Instead, the discovery of low-density anomalous multiple-mirror effect (Fig.7) provides a new, unexpected way to make the multiple-mirror reactor stationary. Performance of GOL-3 and GDT has been exceptional. In fusion parameters they are on par with tokamaks of similar age, like T-10. However, since GOL-3 and GDT are in operation for around 20 years already, it is hard to expect from them any further breakthroughs.

3. Fusion prospects

The viability of mirror traps as alternative fusion devices depends on their ability to be cheaper in construction and operation as compared to tokamaks. It would be also very useful to work with advanced fuels like D-D or D-He³. While there are many obvious engineering advantages to mirror traps, like inherent steady-state operation, lower requirements on divertor materials, modular design, the most important feature is the high energy density (β). The worst drawback is the poor axial confinement, causing the stigma of low electron temperature. Thus, all future traps should aim at improved axial confinement while maintaining stable high-beta regimes at all costs.

In a pure GDT-type system, axial plasma losses are determined by outflow through the end mirrors with ion acoustic speed. The plasma confinement time is then estimated as $\tau \approx LR/V_{Ti}$ and appears to be insensitive to excitation of micro turbulence. If such system is long enough and has big enough mirror ratio, it could be of interest as a high-flux neutron source or even a fusion reactor [3]. The plasma lifetime relevant for a reactor can be provided only if the GDT is 3 - 5 km long, which is not very attractive. In the GDT-based neutron source an oblique injection of DT neutral beams into the target plasma allows generation of neutron flux of $2\text{MW}/\text{m}^2$ or higher, while the plasma Q_{DT} is 3-5% only. For application of GDT as a 14MeV neutron source a length of 10-20m would be sufficient. Such a source could be an attractive option for the facility dedicated to development of fusion materials, consuming $\sim 0.15\text{kg}/\text{yr}$ of tritium and 60MW of electric power. A project to use the GDT-type trap as a neutron driver for a subcritical nuclear reactor or a reactor for burning nuclear waste is being discussed.

In the multi-mirror device the plasma confinement is due to scattering of passing ions in corrugation cells and scales as $R^2 \cdot L^2 / \tau_{ii} V_{Ti}$ if $l \ll \lambda_i \ll L$. It requires high plasma density, in the range of 10^{23} - 10^{24}m^{-3} for the 100m-long reactor. Then the plasma pressure can be balanced by magnetic field pressure only for magnetic fields above 100T, which is not realistic, or by wall confinement, which has not been experimentally observed. Fortunately, the multi-mirror confinement can be effective for reasonable plasma densities 10^{21} - 10^{22}m^{-3} in case of collective rather than Coulomb scattering. It makes multiple-mirror traps suitable for stationary fusion, especially in view of their extremely favorable scaling with length, $Q_{DT} \sim L^2$. There are actually two ways to stationary fusion for multiple-mirror traps. The first is to use gas-filled expanders and rely on the electron beam to suppress the electron heat flux. The other is to use GDT-type pumped-out expanders and suppress electron losses by electrostatic confinement. With our present understanding of the beam-plasma interaction, the first way seems to require very high circulating power just to suppress the heat transport.

The Gas-Dynamic Multiple-mirror Trap (GDMT) is an advanced design of next-generation axisymmetric mirror in Novosibirsk [6]. It uses the new results of GOL-3 and GDT, aiming to improve the axial confinement of GDT scheme with multiple-mirror plugs in collective-scattering mode (Fig.9). For stabilization it will depend on the vortex confinement scheme

aided by biased end-plates, momentum injection by NBI, and charge-injection via the electron-beam. The primary aim of the project is to prove the concept of the steady-state multiple-mirror fusion reactor, and obtain confinement scaling, while going to longer pulses and higher electron temperatures than available in GOL-3 and GDT. In particular, the magnetic and heating systems should be able to support 1s-long discharges, as compared to current duration of a few milliseconds. The secondary aim of GDMT is being a prototype energy-effective neutron source to replace the unrealized project of the Budker institute - the "Hydrogen Prototype" (HyP). Both aims require optimization of the device to yield high overall fusion efficiency, QDT, rather than high and localized neutron flux, as in GDT or HyP. Still, it is utilizing the beam-beam fusion within the sloshing-ion population, but the localized reflection points are replaced by an extended "active zone".

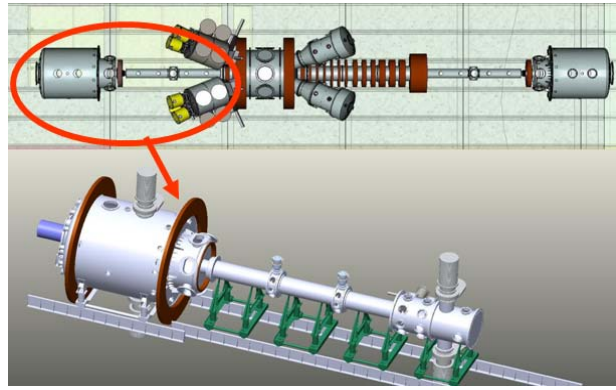


FIG.9. GDMT trap and its first stage, the GDMT-T, superconducting high-field device for PMI studies.

4. Summary and Discussion

One lesson to be learned from the story of magnetic mirrors is that it is risky to place all bets on a single huge device, especially if the understanding of the underlying physics is incomplete. Like it was the case with dinosaurs, only small fast-evolving species can survive the extinction and later evolve into something better. The axially symmetric traps seem to be ready for future.

Significant progress has been achieved in understanding physical phenomena in modern magnetic mirrors, as well as in improvement of plasma parameters towards practical application of fusion. Three methods of suppression of MHD activity were proposed for the GDT trap and all of them were experimentally proven. GDT operates at plasma beta as high as 0.6, $T_i \sim 6\text{keV}$ and electron temperature of 250eV . Stabilization of MHD modes by the shear of magnetic field was successfully demonstrated in GOL-3 experiment. Then, the hot ($T_i = 2\text{keV}$) and dense ($n_e = 10^{21}\text{m}^{-3}$) plasma was confined 1ms without significant MHD activity. For both systems, no physical limitations precluding further increase of plasma parameters were found. A method of plasma heating and electric field control was proposed by means of axial injection of stationary or periodic electron beams. This injection can also suppress the axial electron heat conductivity, which was confirmed in GOL-3 experiments. Electron beams with required characteristics for stationary confinement are in development.

Design of a new linear device for confinement of fusion plasma is under way in the Budker Institute of Nuclear Physics, Novosibirsk. The Gas Dynamic Multiple-mirror Trap (GDMT) combines gasdynamic-type central cell with sloshing ions for beam fusion, and the multiple-mirror end plugs for improved axial confinement. Thus it builds upon and continues both lines of mirror research at the Budker institute: the gas-dynamic approach to construction of the neutron source, and the electron-beam-driven multiple-mirror path to fusion reactors. Combination of the GDT- and the multiple-mirror concepts is made possible by recent advances in mirror physics: the multiple-mirror improvement of axial confinement via collective scattering at low densities, and the vortex-confinement suppression of radial losses in bad-curvature environments. The primary aim of the project is to prove the concept of the

steady-state multiple-mirror fusion reactor, and obtain confinement scaling, while going to longer pulses and higher electron temperatures than available in GOL-3 and GDT.

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