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Multiple-mirror trap: a path from Budker magnetic mirrors to linear fusion reactor

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Contents

Abstract. **This review is focused on multiple-mirror traps for high-temperature plasma confinement that were proposed by Budker, Mirnov, and Ryutov and independently by Logan, Lichtenberg, and Lieberman in the early 1970s. The proposed magnetic system solved problems with the kinetic instabilities of classical open traps and significantly increased the plasma lifetime. We review the history of this field and discuss its achievements and prospects.**

Keywords: G I Budker, plasma, multiple-mirror trap, GOL-3, fusion reactor

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1. Introduction

Early studies of controlled nuclear fusion greatly affected the physics of high-temperature plasma, and its development up to its present state was motivated just by these studies. Most of the known modern concepts of magnetic confinement of plasma were proposed in the early 1950s. The same ideas were often suggested by researchers who not only worked independently of each other but could not have known anything about the existence of colleagues involved in similar research. A well-known example of this kind is the invention of an adiabatic magnetic trap for plasma confinement. This idea was proposed by G I Budker, who was at that time a collaborator of I V Kurchatov in Moscow, and by R Post of the Livermore Laboratory. Unclassified publications of the trap concept [1, 2], which was later called the Budker–Post magnetic mirror trap, appeared only several years after the beginning of studies.

The idea of a magnetic mirror trap appeared simple and very attractive technologically. The physics of confinement of charged particles forming a plasma was based on the conservation of the magnetic moment of particles moving in a slowly varying magnetic field [3]. It was shown in experiments [4, 5] that individual charged particles are confined in the trap just as predicted theoretically: a particle experienced up to 10^9 reflections from strong magnetic field regions (magnetic mirrors) bounding the trap.

Problems appeared in attempts to fill a magnetic mirror trap with a sufficiently dense plasma, which proved to be unstable. It was found that the simplest Budker–Post trap does not satisfy the stability criterion [6]. More complex magnetic systems satisfying the 'minimum B' rule have demonstrated stable plasma confinement [7]. However, this solution to one of the problems of the classical magnetic mirror trap was not helpful in solving other problems. The adiabatic confinement principle leads to the anisotropy of the velocity distribution of plasma particles. Therefore, the magnetic mirror trap was prone to kinetic instabilities, resulting in rapid plasma losses from the trap (see, e.g., review [8]). Detailed model calculations of fusion reactors with the simplest open traps showed that under the optimistic assumptions of the absence of kinetic instabilities and of losses caused only by binary collisions, the fusion gain factor Q (the ratio of the reaction power to the power of plasma heating systems) reaches the value at most about 2.

This considerably diminished the popularity of open traps in the world. Research in this area was continued only in a few scientific centers in the world, including the Institute of Nuclear Physics, Siberian Branch of the USSR Academy of Sciences (INP) headed by G I Budker in Novosibirsk. According to recollections of Budker's colleagues and collaborators (see, e.g., [9]), he was a continuous generator of new ideas, many of them being then implemented in operating facilities. This creative atmosphere at the INP led in the early 1970s to several proposals for improved concepts of open traps.

One such scheme was the idea of a multiple-mirror trap, proposed by Budker, Mirnov, and Ryutov [10] in 1971. The same idea was published almost simultaneously by a group at the University of California, Berkeley [11]. Ryutov recalled in [12] that the problem of searching for a physical solution free of kinetic instabilities in classical open traps led Budker to the idea of a system in which the ion mean free path would be much smaller than the trap length.

This simple formulation applied to a plasma with fusion parameters meant a drastic (by several orders of magnitude) increase in the plasma density in the new system compared to that in other magnetic confinement systems traditionally considered in plasma physics at that time. The ideas of new configurations for dense plasma confinement were discussed by the authors of [10] at the home of Budker, who was recovering at that time after his first heart attack [12]. The solution was elegant and nontrivial: instead of a classical magnetic mirror trap, which was not suitable as a reactor, they proposed to use a chain of such magnetic mirror traps located next to each other. For a sufficiently dense plasma, such a solution guaranteed the absence of kinetic instabilities and a good enough plasma confinement time in the trap. Here, we note another nontrivial proposal by Budker. For the first model experiment that was to confirm the new principle of confinement of a very dense hydrogen plasma with a temperature of about 10^8 K, a very rarefied cesium plasma with a temperature of only 1500 °C was chosen.

Everywhere in what follows, in accordance with the tradition of the high-temperature plasma physics, temperature is measured in electron-volts (1 eV = 11,604 °C); the Boltzmann constant is then equal to unity and disappears from formulas.

The aim of this paper is to review the results of theoretical and experimental studies of multiple-mirror plasma confinement, including new projects and ideas. The results of studies performed at the GOL-3 (Russian acronym of Corrugated Open Trap) facility, whose concept and scientific tasks were still formulated with Budker's participation, are considered in the greatest detail. Additional information on the physics of open traps can be found in reviews [13, 14]. In the Appendix, for the convenience of the reader, we present a table with brief descriptions of facilities at the Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences (BINP) mentioned in this review. In view of the broad scope of readers of the journal, we reduced the number of formulas to the minimum and increased the number of explanations, even when these can be obvious for specialists.

2. Idea of multiple-mirror confinement. The theory

A classical multiple-mirror trap is a system with a corrugated magnetic field (periodically modulated over its length). The simplest scheme of such a configuration, presented in Fig. 1, shows part of a long magnetic system. The main parameters of this system are the corrugation period (the length of the unit cell of the multiple-mirror system) l, the total trap length L, the total number of corrugation periods $N = L/l \gg 1$, and the mirror ratio $R = B_{\max}/B_{\min}$, where $B_{\max}$ and $B_{\min}$ are the magnetic inductions at maxima and minima. The magnetic system in Fig. 1 can be represented as a large number of magnetic mirror traps closely spaced along a common magnetic axis. We consider the destiny of a single charged particle placed in this magnetic system. It is known [3] that if the Larmor helix pitch of a particle is much smaller than the characteristic spatial scale of the magnetic field variation, there are two invariants of motion: the total energy of the particle and its magnetic moment, the first one being exact and the second one being adiabatic. It is then easy to show that the 'longitudinal' energy $W_{\parallel}$ of particle motion is described by the expression

$$W_{\parallel} = \frac{mv_{\parallel}^2}{2} = \frac{mv^2}{2} - \frac{mv_{\perp}^2}{2} = W - \mu B\,, \tag{1}$$

where m is the particle mass, $v_{\parallel}$ and $v_{\perp}$ are the components of the particle velocity vector along and perpendicular to the magnetic induction vector, and $\mu = mv_{\perp}^2/2B$ is the magnetic moment of the particle. It follows from (1) that if the particle moves from a weak-magnetic-field region (for example, from the central plane of one of the cells of a multiple-mirror system) toward a stronger field (a magnetic mirror), the longitudinal motion velocity gradually decreases. If $W > \mu B_{\max}$, the particle passes through the magnetic mirror and escapes to the system end along the magnetic field. We call such particles transiting. If $W < \mu B_{\max}$, the particle is reflected from the increasing magnetic field. Because the same magnetic mirror also exists on the other side of the multiple-mirror system cell, the particle turns out to be confined inside a particular Budker–Post magnetic mirror trap. The condition separating these two particle populations has the form

$$\sin\theta_0 = \left.\frac{v_{\perp}}{v}\right|_{B=B_{\min}} > \sqrt{\frac{B_{\min}}{B_{\max}}} = R^{-1/2}\,, \tag{2}$$

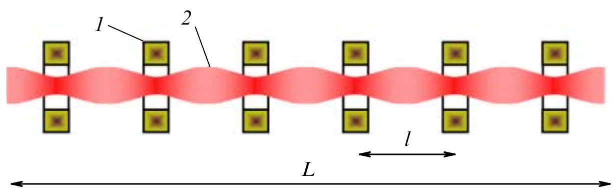

Figure 1. Schematic of the magnetic system of a multiple-mirror trap: (*1*) magnetic-system coil, (*2*) plasma boundary, (*l*) corrugation period, (*L*) trap total length.

where θ_0 is the angle between the velocity vector and the magnetic field. The separatrix in the velocity space looks like a cone with the cone angle θ_0, which is usually called the loss cone. It is interesting that the velocity $\dot{\mathbf{r}}$ of the Larmor center of the particle trajectory in the drift approximation is

$$\dot{\mathbf{r}} = v_{\parallel}\mathbf{h} + \frac{c}{B^2}[\mathbf{E}\times\mathbf{B}] + \frac{v_{\parallel}^2}{\omega_H}[\mathbf{h}\times\boldsymbol{\kappa}] + \frac{v_{\perp}^2}{2\omega_H}\left[\mathbf{h}\times\frac{\nabla B}{B}\right], \quad (3)$$

where $\mathbf{h}$ is the unit magnetic field vector, $\mathbf{E}$ is the electric field strength, ω_H is the cyclotron frequency, and $\boldsymbol{\kappa} = \mathrm{d}\mathbf{h}/\mathrm{d}s = (\mathbf{h}\nabla)\mathbf{h}$ is the curvature vector of field lines. We can see from (3) that in the case of an axially symmetric configuration, all three types of drift motions (in crossed fields, centrifugal, and gradient) are directed along the binormal to the field line. The drift surface is axially symmetric and the magnetic flux captured in it is also an adiabatic invariant [15].

The requirement of a high plasma density became a key idea that dramatically changed the character of plasma confinement in a multiple-mirror system and made this configuration an independent branch in the physics of magnetic plasma confinement. In a classical magnetic mirror trap, a particle passes many times over the entire distance between mirrors until it scatters into the loss cone, but in a multiple-mirror system the mean free path must be small compared to the trap length, $\lambda \ll L$.

This simple requirement transformed the multiple-mirror trap into a system exhibiting quite interesting physics. Indeed, a problem with open traps with low-density plasmas is that the depletion of the loss cone and the distribution function of particles lead to the appearance of numerous kinetic instabilities. In a long multiple-mirror system, the loss cone is almost completely filled due to frequent collisions, and such instabilities do not develop.

We now consider the behavior of a test particle in a multiple-mirror trap filled with plasma. We assume that initially, a transiting particle is moving along the device. Because of the condition $\lambda \ll L$, the particle scatters after some time at some angle and is then captured in one of the trap cells. Later, after new collisions, the particle enters the loss cone and leaves this cell. A key factor is that the escape direction is random and is independent of the initial direction of motion. This process then repeats many times, until the particle reaches the magnetic system end.

Thus, due to collisions the motion of a particle along the magnetic field becomes one-dimensional random walk with a random step and direction. Such processes are described by the diffusion equation, in which the distance traveled by the particle is proportional to the square root of time,

$$\Delta z(t) \sim \sqrt{Dt} \sim \sqrt{\frac{\lambda^2}{\lambda/v_{T\mathrm{i}}}\,t} = \sqrt{\lambda v_{T\mathrm{i}}\,t}\,, \quad (4)$$

where $\Delta z(t)$ is the time dependence of the mean ion displacement, D is the diffusion coefficient, and $v_{T\mathrm{i}}$ is the thermal ion velocity (hereafter, subscripts e and i refer to the plasma ions and electrons). In other words, the particle confinement time in a trap depends on its length quadratically. It is the understanding of this fact that allows us to call the authors of [10, 11] the discoverers of multiple-mirror plasma confinement.

Systems with a corrugated magnetic field were also theoretically considered earlier (see, e.g., [16–18]). However, all these papers addressed other aspects of plasma physics (mainly, stability). Two papers can be considered the closest precursors of the idea of multiple-mirror confinement. In [19], the idea of a small-scale corrugation of a magnetic field on the plasma surface was proposed (the precursor of multipole 'magnetic walls' widely used at present). The author of [20] noted the diffusion character of the motion of particles, but, based on Monte Carlo simulations and experiments on electron beam scattering in the gas filling a multiple-mirror system, erroneously concluded that the plasma confinement time depended on the setup length linearly, which would make such a configuration meaningless.

The first detailed theoretical investigation of a new concept was performed in [21], where the physics of multiple-mirror confinement was rigorously considered kinetically. Various aspects of the theory concerning processes in multiple-mirror traps were considered by different groups in [22–63] (presented in chronological order). The only previous review on multiple-mirror plasma confinement with a detailed presentation of the theory should be mentioned [64], as well as papers [65, 66], in which different plasma flow regimes in a system with a multiple-mirror magnetic field were described in the greatest detail.

Different multiple-mirror confinement regimes are distinguished by two dimensionless parameters, λ/l and R. The first determines the role of collisions at the scale of one corrugation period, and the second determines the fraction of locally trapped particles. Following [66], we call the different regimes as follows: small-scale corrugation, $l \ll \lambda$ (the S1 – S3 and xS regimes in the terminology in [66]); middle-scale corrugation, $l \sim \lambda$ (M); large-scale corrugation, $l \gg \lambda$ (L and xL); weak corrugation, $R - 1 \ll 1$ (W); moderate corrugation, $R - 1 \sim 1$ (M); and strong corrugation, $R \gg 1$ (S). The full notation of a regime includes indices related to each of the dimensionless parameters (for example, SWR2).

Not all of the plasma flow regimes in a multiple-mirror system are of interest from the standpoint of efficient plasma confinement. However, in any real device, the main plasma parameters vary at the initial stage in a wide range, from the plasma startup to the achievement of the working point, and therefore different confinement regimes can be successively realized.

It is convenient to use the flow velocity u as the main parameter characterizing the plasma confinement quality:

$$nu = -D\,\frac{\partial n}{\partial z} \;\Rightarrow\; u = -\frac{D}{n}\frac{\partial n}{\partial z} \approx \frac{D}{L}\,. \quad (5)$$

The flow velocity is related to the particle confinement time in the trap $\tau \simeq L/u$, which can also be used to estimate the effective mean braking force F acting on a transiting ion in the moderate corrugation regime (numerical coefficients of about unity are omitted): $F \approx m_{\mathrm{i}}u'\nu_{\mathrm{ii}} \approx m_{\mathrm{i}}u\nu_{\mathrm{ii}}$, where m_{i} is the ion mass, u' is the directional velocity of transiting particles, and ν_{ii} is the ion–ion collision rate. In the stationary case, the braking force is balanced by the longitudinal pressure gradient:

$$nF = -\frac{\mathrm{d}p}{\mathrm{d}z} \sim \frac{nT}{L} \;\Rightarrow\; u \sim \frac{T/L}{m_{\mathrm{i}}\nu_{\mathrm{ii}}} \sim v_{T_{\mathrm{i}}}\left(\frac{\lambda}{L}\right) \ll v_{T_{\mathrm{i}}}\,. \quad (6)$$

Figure 2 shows estimates [66] of the plasma escape velocity from a magnetic system of the GOL-3 facility, described in detail in Section 6. Calculations were performed for the ion temperature $T_{\mathrm{i}} = 1$ keV.

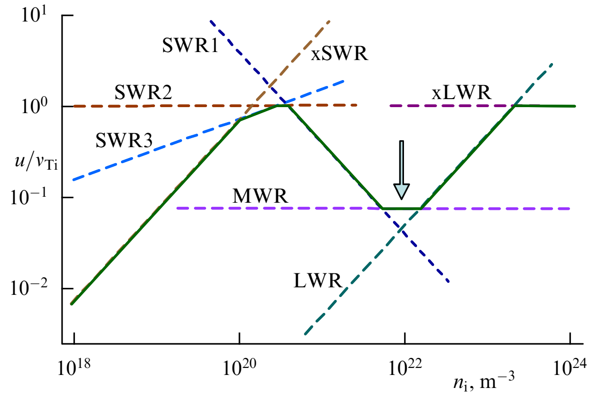

Figure 2. Theoretical estimate [66] of the ratio of the flow velocity u to the ion thermal velocity v_{T_i} as a function of the hydrogen plasma density for $T_i = 1$ keV and the parameters of the magnetic system of GOL-3 $R = 1.5$, $l = 22$ cm, and $N = 55$. The dashed straight lines show estimates for different regimes, which are presented for clarity outside the formal applicability region as well (see the regime notation in the text). The solid broken line corresponds to the total dependence. The arrow indicates the regime in which the multiple-mirror magnetic system provides the best plasma confinement.

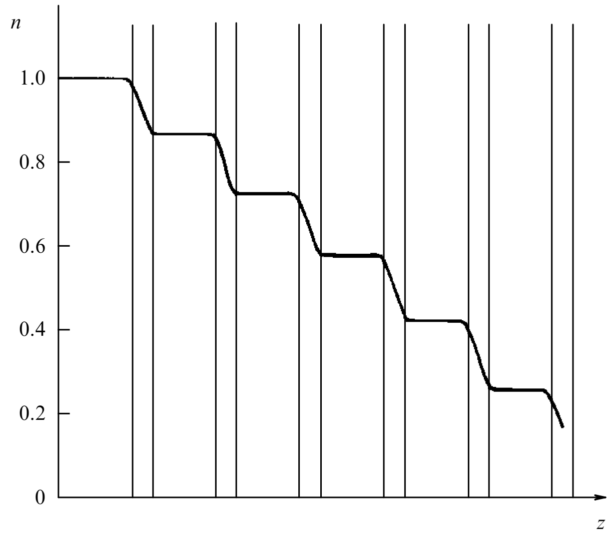

Figure 3. Dependence of the normalized plasma density on the longitudinal coordinate measured in numerical calculations from the trap center to its edge [48]. The vertical straight lines indicate near-mirror regions (expanded for clearness). A system of 15 magnetic mirror traps with the optimized (changing along the length) mirror ratio was simulated. The abscissa scale is nonlinear.

In a low-density plasma (the xSWR regime), a multiple-mirror system decomposes into a set of magnetic mirror traps. After scattering into the loss cone, an ion escapes from the trap. The confinement time determined by the ion–ion collision time decreases with increasing density. As in the Budker–Post magnetic mirror trap, the plasma in this regime is anisotropic and is subject to various kinetic instabilities. As the plasma density increases, the system passes to the SWR3 regime, in which the filling of the loss cone begins near the separatrix. A further increase in the density leads to the gradual filling of the loss cone at $\lambda \sim L$ (SWR2). In this regime, plasma expands almost freely with an approximately thermal velocity. The transition to the SWR1 regime is caused by the appearance of repeatedly scattering particles, which are again trapped in one of the cells of the magnetic system.

The MWR middle-scale corrugation regime corresponding to the condition $\lambda \sim l$ is optimal for the operation of a multiple-mirror magnetic system. Most theoretical and experimental studies in this field are devoted just to this regime. A specific feature of this regime is the independence of the confinement time from the mean free path:

$$\tau \approx \frac{L}{v_{T_i}} \frac{L}{l} (R-1)^2 \equiv \frac{L}{v_{T_i}} N (R-1)^2 \,. \qquad (7)$$

It is interesting that for a moderate corrugation depth with $R = 2$, the pressure range in which this regime exists degenerates into a point (see [64]). There is an analogy between the SWR regime and the plateau regime for neoclassical diffusion in tokamaks [67], when a trapped particle completes only part of the banana orbit between collisions and the diffusion coefficient weakly depends on the collision rate.

In the LWR regime, the plasma flow becomes strongly collisional, the escape flow is determined by the longitudinal viscosity (see [68]), and, for an even higher density, the role of magnetic field corrugation becomes negligible and plasma expands along the magnetic field with the thermal velocity.

The simple estimates presented above were obtained under some quite important assumptions (for example, the temperature is constant along the length and radius, the system is very long, and the scattering is completely classical). Nevertheless, such a consideration is useful for gaining a qualitative understanding.

The solution to the problem of the longitudinal plasma density profile in the middle-scale corrugation regime was obtained in [28] and later in [48]. It has a characteristic staircase form (Fig. 3). Within one cell of the multiple-mirror trap, plasma parameters change weakly, and the pressure drop occurs almost entirely near the magnetic mirrors. In this case, a solution with 'steps' with close heights was obtained by optimizing mirror ratios in individual cells of the system.

A multiple-mirror system is not magneto-hydrodynamically stable by the criterion in [6], and therefore additional measures are required for plasma stabilization. The methods providing plasma stability in open traps are known and were tested experimentally in different facilities (see, e.g., review [69]).

3. First experiments in Novosibirsk and Berkeley

The idea of multiple-mirror confinement turned out to be quite simple and attractive. The first experiments were performed in Berkeley [70] and Novosibirsk [71] shortly after the appearance of theoretical proposals made in these research groups. The facilities had a similar structure and close plasma parameters. The sources of the low-temperature alkali plasma were systems of a Q machine type [72]. A plasma jet from the source passed through a magnetic system.

The Shchegol (Russian acronym for Alkali Corrugated Open Trap) facility at the INP [29] had a vacuum chamber 240 cm in length and 6 cm in diameter (Fig. 4). The magnetic system could produce a multiple-mirror field with $N = 14$ and $l = 16$ cm with the profile shown in Fig. 4 or a quasi-solenoidal field with a $\sim 15\%$ axial modulation. A cesium vapor flow with controlled concentration was incident from the source on a tungsten electrode heated to 2450 K; ionization occurred on the surface of the electrode. The main diagnostics were performed with movable probes (each

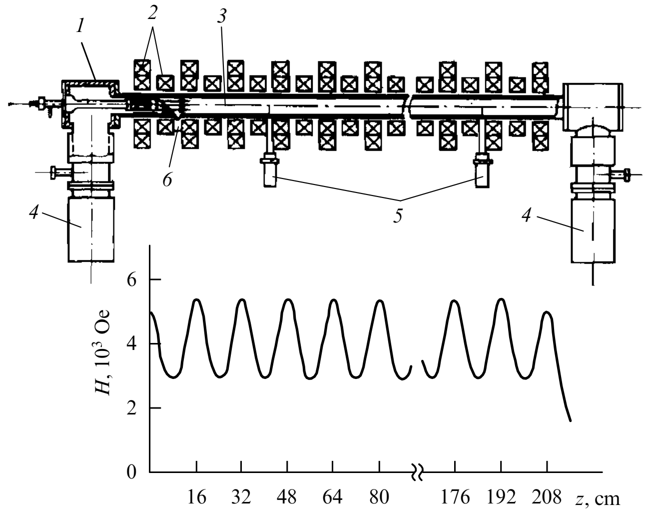

Figure 4. Schematic of the Shchegol facility [71]: (*1*) ionizer; (*2*) magnetic-system coils; (*3*) vacuum chamber; (*4*) magnetic discharge pumps; (*5*) probes; (*6*) cesium vapor source. Bottom: the longitudinal magnetic field profile in the multiple-mirror regime.

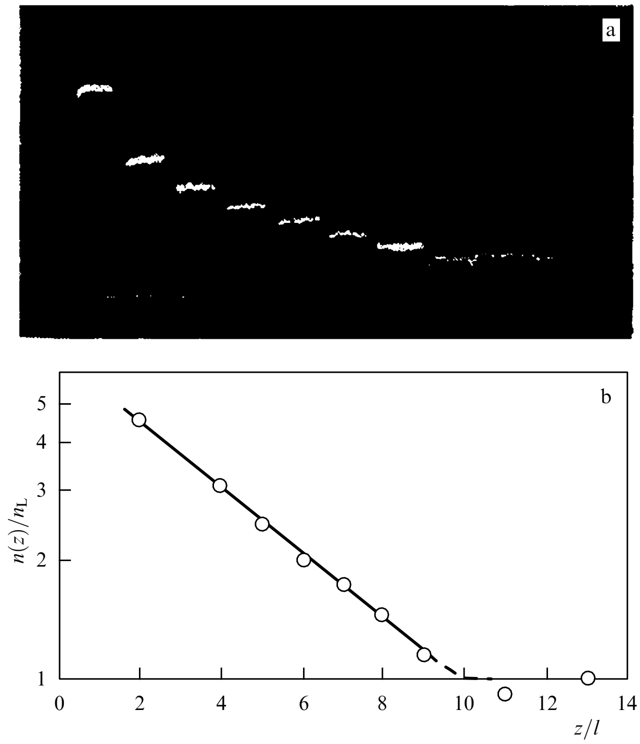

Figure 5. Plasma flow in a multiple-mirror system at the Shchegol facility [74]. (a) Probe signals from different corrugation cells successively fed to an oscilloscope input (stationary operation regime of the facility). (b) Dependence of the concentration on the cell number.

probe was made of a tungsten wire 4 μm in diameter inserted into a quartz capillary 100 μm in diameter with an open part in the form of a semi-loop about 5 mm in length); up to seven probes worked simultaneously.

The results of the experiments were published in [71, 29, 73, 74]. The main result was the conclusion that in using a multiple-mirror magnetic system, the longitudinal change in the plasma density corresponds to the expected theoretical dependence $n(z) \approx n_L \exp\left[(L-z)/\lambda_L\right]$, where $n_L = 10^{16}$ m^{-3} in the plasma density at the magnetic system output and $\lambda_L = 85$ cm. This result is presented in Fig. 5 [74]. It is interesting that in experiments with a pulsed trap filling with plasma, the start of the plasma density increase was delayed as the plasma jet front propagated through a given cell. The authors explained this by the fact that the accumulation of plasma in a cell of a multiple-mirror system requires the plasma flow front to be at a distance of about the ion mean free path.

The Multiple-Mirror Experiment device at the University of California, Berkeley initially had five corrugation periods with $R = 2.2-3.7$ and $L = 28$ cm. The alkali metal plasma (potassium or lithium) was produced from vapors on the surface of a hot tungsten ionizer. The plasma density was varied in a broad range $n \sim 10^{15}-10^{17}$ m^{-3}, which allowed the authors to observe the transition from the short-corrugation regime to the long-corrugation regime. A schematic of the device in the initial version [70, 75] is presented in Fig. 6. Later [75, 76], the quasi-uniform field regime was also mentioned, which the authors called the long mirror trap regime.

Plasma diagnostics were performed in the experiments in [75, 76] with a Langmuir probe and a movable collector for measuring the saturation ion current. The spatial distribution of the plasma density was studied in different regimes. We here present only one result demonstrating a change in the plasma flow type in different regimes (Fig. 7) [70, 75].

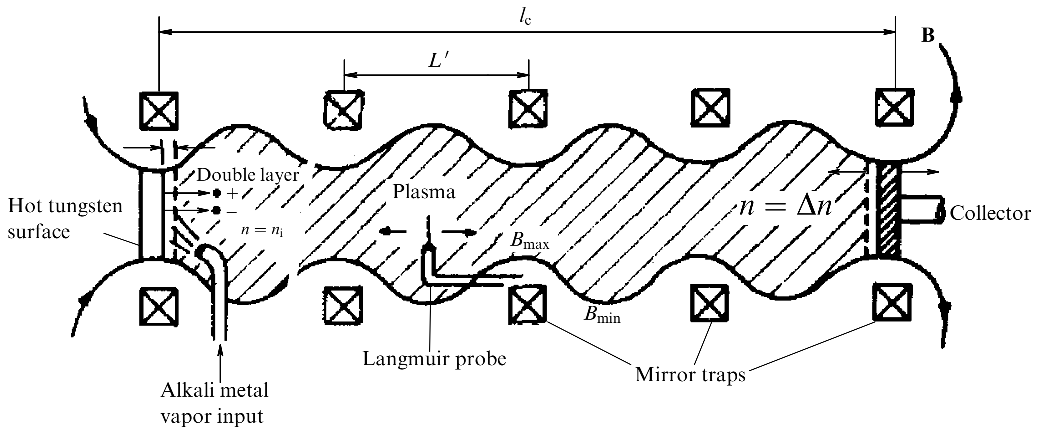

Figure 6. Schematic of the Multiple-Mirror Experiment facility in Berkeley [70]. The plasma volume is hatched.

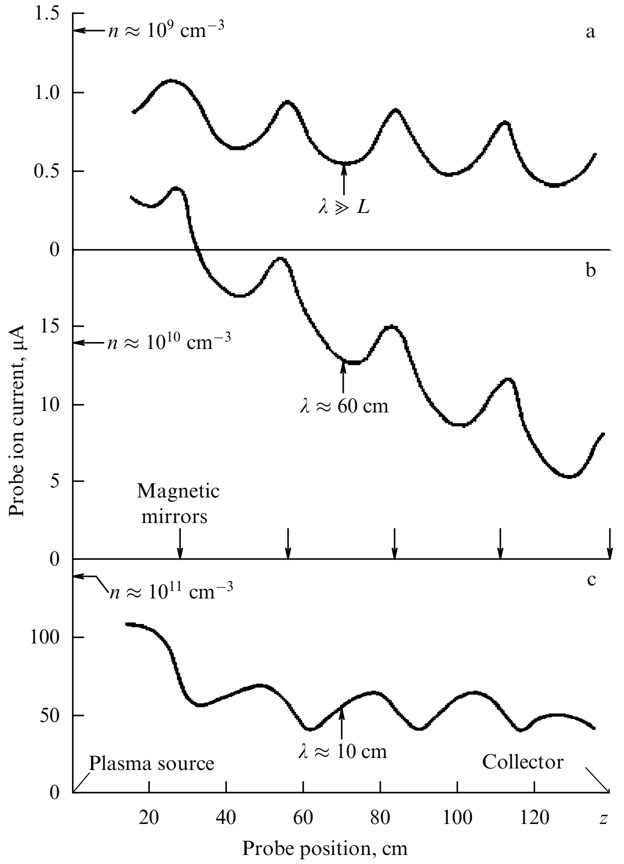

Figure 7. Dependence of the saturation ion current of a Langmuir probe on its position measured in the Multiple-Mirror Experiment facility in Berkeley [70] for (a) low-, (b) intermediate-, and (c) high-density plasmas. The arrows show the positions of the plasma source, magnetic mirrors, and collector. For each case, the mean free path is shown.

Figure 7 shows differences in the plasma flow in a multiple-mirror magnetic system. In the low-pressure regime $\lambda \gg l$, the plasma flow weakly decreases, and the plasma density has maxima in the regions of the magnetic mirrors. For the intermediate density $\lambda \sim l$, a considerable decrease in the density is observed caused by multiple-mirror confinement effects. The plasma confinement time in this regime turned out to be 16.4 times longer than that in a single magnetic mirror trap [75], demonstrating good agreement with the theory, which predicted a 15-fold increase in the plasma confinement time in this regime. In the case of high-density plasma, $\lambda \ll l$, the plasma flow decays weakly in the system. In this case, the flow regime changes and density minima are observed in the region of the magnetic mirrors.

Plasma was stabilized in these two experiments due to the magnetic field lines tying into a conducting end ionizer. In subsequent experiments on the modified version of the device at Berkeley with $N = 7$ and $r = 4.2$, methods of the additional stabilization of plasma with a feedback system were investigated [77].

Both the first experiments in Novosibirsk and Berkeley for testing the idea of multiple-mirror plasma confinement demonstrated the overall agreement with the theoretical prediction of the presence of a range of parameters in which the plasma flow is to experience a strong deceleration due to a corrugated magnetic field.

4. Subsequent experimental studies

After the first successful demonstration of the principles of multiple-mirror confinement in alkaline plasma devices, studies in this area were continued in larger devices, in both laboratories and elsewhere.

The device in Berkeley was updated for investigations with a denser and hotter hydrogen plasma, with $N = 7$, $l = 23$ cm, $B_{\max} = 0.5$ T, and $R = 1.5-5.4$. The magnetic system was supplemented with conductors producing a quadrupole field at the plasma periphery to provide the magnetohydrodynamic (MHD) plasma stability. Besides the Q machine, hydrogen plasma with $n \sim 10^{19}$ m^{-3} and $T \sim 10$ eV was produced with a theta pinch source. After the studies ended [78, 79], the research group continued investigations on a larger device.

The next facility, which was called the Berkely Ten Meter Multiple-Mirror Device in early papers and the MMX later, was the largest multiple-mirror system until the beginning of studies at the GOL-3 facility in Novosibirsk. The magnetic system contained eight connected quadrupole traps with $l = 75$ cm, $R = 2-4$, and $B_{\min} = 0.11-0.21$ T [80]. This device differed from others not only by the magnetic system type satisfying the 'minimum B' rule but also by relatively short magnetic mirrors. The plasma was produced by a theta pinch and a Marshall gun, which could operate simultaneously. Because of the quadrupole magnetic system, the shape of the plasma cross section changed in the course of propagation along the magnetic field (Fig. 8), and the axial ratio of the ellipse changed from 10 for $R = 2$ to 25 for $R = 4$ [81].

This device was used for extensive studies of plasma confinement, stability, oscillations, heating, and stabilization by feedback and a cusp (configuration in which the magnetic field in the mirrors is counter-directed) [49, 53, 80–86]. These experiments revealed the main disadvantage inherent in the features of the quadrupole magnetic system. Large neoclassical transverse losses (transport processes in systems without the axial symmetry and with the radial displacement of the trajectory of particle's Larmor center in collisions that can greatly exceed the Larmor radius) prevented distinguishing the effects related to the physics of multiple-mirror confinement. Transverse transport was the main mechanism of losses for $n = 10^{19}-10^{21}$ m^{-3}, $T = 3-8$ eV and was strong for $n = 10^{17}-10^{19}$ m^{-3} at the decay stage.

A corrugated magnetic field was also used in some other facilities for studying the physics of multiple-mirror confinement and other problems of plasms physics. We present only one reference for each of these facilities [87–95].

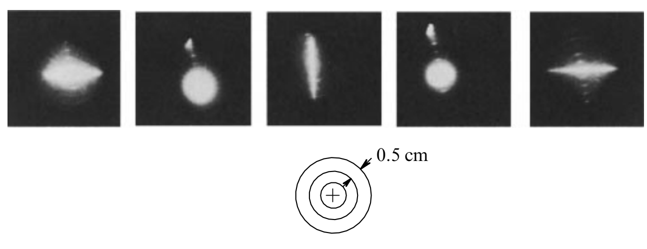

Figure 8. Shape of magnetic surfaces in the MMX facility obtained by electron-beam tracing [81]. Cross sections in the mirrors and middle planes of two adjacent trap cells are shown. Circles at the bottom show the spatial scale of the images.

The Novosibirsk research program aimed at developing a multiple-mirror reactor did not include the creation of a facility with a low-temperature hydrogen plasma as the next step after experiments with the Shchegol facility. Budker planned to build three increasing-scale GOL-1, GOL-2, and GOL-3 facilities. The final aim of this work was announced to be the creation of a pulsed fusion reactor with $\beta \gg 1$ (here, the parameter β is calculated by the magnetic field in a plasma). The only technology at that time that could provide the power required for rapid plasma heating was the injection of high-current relativistic electron beams (REBs). Therefore, the research program involved theoretical studies of plasma confinement problems with $\beta \gg 1$, as well as theoretical and experimental investigations of the physics of the collective interaction of REBs with plasma.

The interaction of REBs with plasma was studied at the GOL-1 facility [29] with $L = 7.5$ m, the beam energy content $W \sim 1$ kJ, and $\tau < 50$ ns. In most experiments, the magnetic field was uniform, and only in [96] was the corrugation with $R = 3.2$ produced in the second half of the magnetic system. For the GOL-2 facility [97], only an REB generator with $W = 20$ kJ was built [98], which was used for studying the collective acceleration of ions proposed in [99, 100]. The program was finalized with a proof-of-concept project of a subreactor class GOL-3 trap, for which the use of a multiple-mirror magnetic field, fast collective heating by an electron beam, transverse plasma confinement with $\beta \gg 1$, and MHD stabilization by a conducting wall were proposed.

The initial GOL-3 design assumed that the magnetic system would be a central region for REB relaxation, with two multiple-mirror sections with $l = 0.5$ m, $B_{\min} = 6$ T, $R = 2$, and $N = 15$ attached. According to the estimate, the plasma with $n \approx 10^{23}$ m^{-3} and $T \approx 1$ keV should have, a thermal energy of the order of 1 MJ and the confinement time of 100 μs [101] (Fig. 9). In the framework of the GOL-3 program, electron beam generation and magnetic compression technologies were developed at the U-1 generator of microsecond beams at 130 kJ and the current density 5 kA cm^{-2} [103].

A key element of the Novosibirsk program for developing multiple-mirror traps was the technology of collective plasma heating by REBs. It is known that plasma physics has developed as an independent scientific field from applied studies of beam–plasma interactions [104]. A complete bibliography in this field contains many thousands of articles, and we therefore mention only several papers concerning plasma heating in multiple-mirror traps. The first papers on REB plasma heating [105–109] appeared shortly after the development of REB generators.

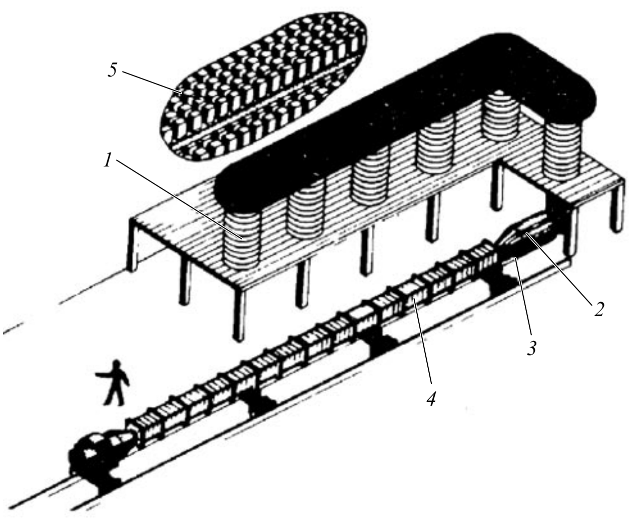

Figure 9. General view of the GOL-3 facility as suggested in [102]: (*1*) energy storage for an REB generator; (*2*) beam generation region; (*3*) system of magnetic compression of the beam; (*4*) multiple-mirror trap; (*5*) capacitor bank of the magnetic field supply system.

From the standpoint of physics, it was necessary to solve the problem of efficient energy transfer from the beam to the plasma over a distance on the scale of the facility length. The classical deceleration of relativistic beams in plasma due to binary collisions cannot solve this problem because the characteristic 1 MeV electron deceleration length in a plasma with a density of 10^{21} m^{-3} is a few thousand kilometers. Therefore, it was necessary to theoretically and experimentally find those conditions under which much more efficient collective REB deceleration mechanisms would arise.

From the theoretical standpoint, the problem of efficient plasma heating differs from the classical problem of electron beam relaxation in a plasma with the excitation of Langmuir oscillations in several aspects: real high-current beams have a noticeable initial angle spread, the key parameter, the ratio of the electron beam density to the plasma density, is $n_b/n \sim 10^{-3}$, and the interaction rapidly passes to the nonlinear stage. In addition, during the interaction, the electron beam virtually instantaneously acquires the energy spread, the plasma is located in a magnetic field, etc. It was also necessary to elucidate mechanisms ensuring energy transfer from Langmuir oscillations to plasma. We note only several earlier studies in this field [110–116] and detailed review [117].

Experiments at the INP were performed at the INAR (the first demonstration of a collective relaxation efficiency up to a few dozen percent) [118–121], INAR-2 [122], GOL-1 [123, 124], and GOL-M [125–128] facilities. These facilities were equipped with the most advanced diagnostic systems among facilities of that class, which provided the elucidation and efficient use of the main features of collective beam relaxation and plasma heating. As an example, we present the result of the INAR-2 facility [122] in which, for $n_e = 3 \times 10^{21}$ m^{-3} and the electron beam current density 10 kA cm^{-2}, a relaxation length of about 10 cm was achieved for the total beam energy losses $\Delta W/W_0 \approx 40\%$ at a length of 75 cm. We note that the REB energy was mainly transferred to suprathermal plasma electrons. At small-scale research facilities, only a part of this energy was acquired by the main electron component, the rest of the energy being lost at the ends. The electron distribution function was essentially non-Maxwellian and the ions remained cold.

The result of work on the beam heating program was the development of plasma heating technology in open magnetic traps.

5. Projects of reactor-class facilities

Reactor applications of multiple-mirror systems were explicitly considered already in the first work in this field. Besides purely multiple-mirror configurations, reactors were proposed containing a central zone in which the main energy release occurs (Fig. 10) [129]. The main studies of the reactor prospects in this area were performed in Novosibirsk and Berkeley. Both research groups developed their own

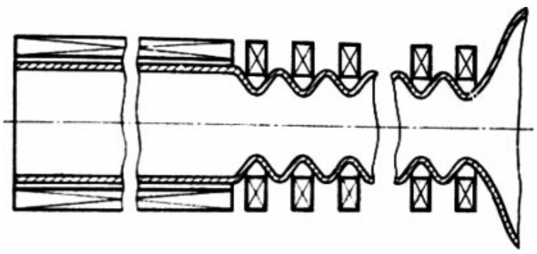

Figure 10. Schematic of half the fusion reactor with the end multiple-mirror section limiting the longitudinal losses [129].

approaches to the reactor problem, which strongly differed in the value of the projected relative plasma pressure β.

The project of the reactor group in Berkeley assumed the classical magnetic plasma confinement for $\beta < 1$. Assuming that stationary magnetic fields with an induction of 20–30 T are technologically feasible, we see that the fusion plasma density is limited by the value $n \sim 10^{22}$ m^{-3}. The relatively low plasma density leads to a large ion mean free path at the fusion temperature, resulting in a large total length and the unit power of the reactor.

The authors of [75] considered the concept of a system consisting of a superconducting solenoid producing the uniform field $B_{\min} = 20$ T and copper mirror coils with the field $B_{\max} = 30$ T. Mirror coils were located in a neutron flux inside a blanket and should have consumed about 10% of the reactor power. The use of a relatively low-temperature plasma during optimization proved to be advantageous. The authors pointed out that the injection efficiency of neutral beams was improved due to beam–plasma reactions. The final parameters of the system were as follows: the temperature at the trap center $T = 4.5$ keV, $n_{\mathrm{i}} = 8 \times 10^{22}$ m^{-3}, corrugation period $l = 5$ m, and 20 corrugation periods on each side. The longitudinal ion confinement time was 30 ms. The plasma radius of 3 cm was chosen based on the cost of 1 kW of power in the USA at that time. The total thermal power of this system with $Q = 2$ was 12 GW for the 3 GW electric power net. Neutral or electron beams with the characteristic parameters of 100–150 keV and 20–30 kA proposed for stationary heating should have the same 3 GW power. In subsequent papers [36, 40, 44, 49, 53, 130–135], non-Maxwellian nonisothermal plasma was considered, and other ideas about reactor optimization were discussed.

At the INP, a different approach was developed to building a multiple-mirror reactor with a high-density plasma $n \sim 10^{24}$ m^{-3} and the plasma pressure exceeding the magnetic field pressure, $\beta \gg 1$. Purely magnetic confinement becomes impossible at these parameter values. Such a reactor could operate only in a pulsed regime for the pulse lengths such that the plasma confinement could be provided due to the magnetic flux conservation inside the conducting walls of a rigid vacuum chamber (so-called wall confinement). In this case, the magnetic field is used to suppress the transverse transport. The pulsed operation regime of the reactor allowed varying the mean thermal power by changing the duty factor.

The first estimates of parameters of the pulsed multiple-mirror reactor [129] were quite optimistic: the total length of the system was estimated as 10 m for the mean magnetic induction 10 T and $R = 3$. The plasma density was in the range $n = 3 \times 10^{23} - 10^{24}$ m^{-3}, the total thermal energy and the energy of electron beam heating were estimated as 100 MJ, and the ion lifetime was estimated as 100 μs. For $\beta \gg 1$ and

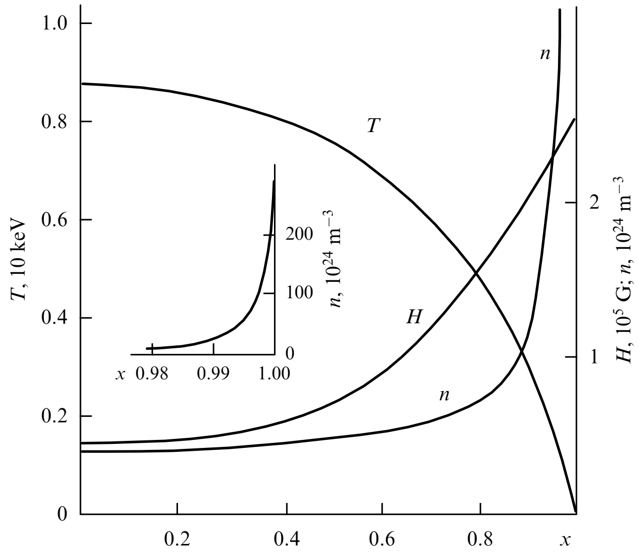

Figure 11. Calculated dependences of the magnetic field strength H, density n, and temperature T on the normalized radius x for a pulsed reactor [27].

the magnetic flux conservation inside a conducting vacuum chamber, the shape of the magnetic surface and the mirror ratio are determined by the vacuum chamber shape due to the appearance of skin currents.

The idea of the wall confinement of hot plasma is not new and was considered in the early fusion program (see, e.g., [136]). Due to the high plasma density allowed by the wall confinement scheme, pulsed reactors proved to be more compact.

An important problem considered in the study of pulsed systems is the radial distribution of plasma parameters. The radial equilibrium condition $8\pi n(r) T(r) + B^2(r) = \mathrm{const}$ implies that the plasma density must rapidly increase closer to the wall due to the decrease in the temperature. In this case, the main part of the plasma is at a low temperature and contributes insignificantly to the useful power (Fig. 11). At the plasma periphery, due to the high density, the role of the radial energy transport drastically increases because of bremsstrahlung radiation, whose power is proportional to $n^2\sqrt{T}$.

A reactor project worked out in greater detail was discussed in [97]. The plasma in the central section of this reactor with a uniform magnetic field had the density decreased to 10^{21} m^{-3} to provide efficient relaxation of counterpropagating electron beams injected from the two ends of the system. The region with the decreased plasma density was required to avoid the restriction $n_{\mathrm{b}}/n \geqslant 10^{-3}$ on the density ratio of the beam and plasma electrons. When this ratio was lower, it was impossible to obtain a high enough beam relaxation efficiency. Next, the energy released by the beam in the central region of the reactor was transferred by fast electrons to the adjacent dense-plasma regions due to binary collisions. This scheme (Fig. 12) was called the method of two-stage dense-plasma heating [96]. In fact, region *3* of a rarefied plasma serves as a peculiar device transforming the 1 MeV electron flux into the electron flux with a typical energy of a few tens of keV and hence a higher current density.

This reactor-class device with $Q = 1$ was designed to have a length of about 60 m for $B_{\max} = 15$ T and $R = 2$. According to calculations, the plasma should have the parameters

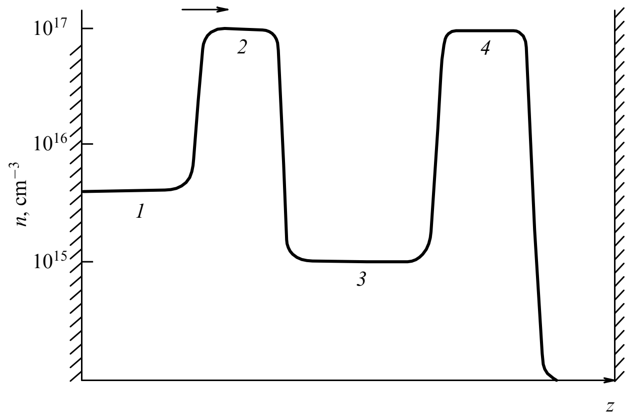

Figure 12. Longitudinal plasma density profile in the two-stage heating scheme [96]. (*1*) Electron-beam transport region, (*2*) and (*4*) multiple-mirror dense plasma confinement regions, (*3*) central beam-relaxation region. The arrow indicates the motion direction of beam electrons.

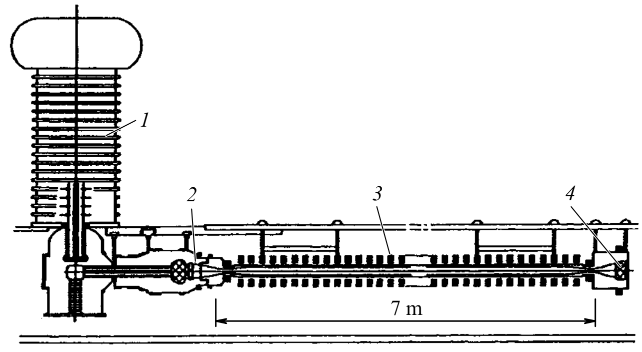

Figure 13. Schematic of the first stage of the GOL-3 facility; (*1*) U-3 electron beam generator, (*2*) megavolt diode, (*3*) magnetic system with a plasma chamber, (*4*) output unit with a start-plasma producing system.

$n = 6 \times 10^{23}$ m^{-3} and $T = 5$ keV in the optimized variant. A two-sided injection of the beams was assumed, each of them having an energy content of about 100 MJ (3 MeV, 200 kA, 200 µs). Because plasma directly touches the wall surface in the case of wall confinement, the use of porous walls impregnated with liquid lithium was assumed.

The physics of a pulsed reactor was studied in numerous publications [27, 30, 33, 97, 137–140]. A more detailed consideration of various physical and engineering aspects of the reactor operation [141] resulted in a much less optimistic project of a hybrid system in which a multiple-mirror reactor was a neutron source for a blanket producing the fuel for fusion reactors. The length of this system reached 1 km for $Q = 0.7$ and the power gain of the blanket was 7. The thermal power was estimated as 1.6 GW. The main factor limiting the system lifetime was the deterioration of the conductivity of chamber walls due to accumulation of radiative defects.

Conceptual studies of multiple-mirror reactors have come a long way from the optimism of the first estimates to the rather pessimistic engineering developments. At present, researchers at the BINP are developing projects for reactor-class systems combining the best qualities of several types of open traps. In these schemes, discussed in Section 7, the sections of a multiple-mirror field operate not separately but in combination with other technologies providing efficient plasma confinement. This allows expressing some cautious optimism as regards open-trap reactors using not only the D–T plasma but also fuels without tritium.

6. GOL-3 multiple-mirror trap

The GOL-3 facility was constructed in the new plasma research building at the BINP in 1985. This facility was the largest multiple-mirror trap in which a plasma with subfusion parameters was obtained and studied for the first time in such systems. By the time research began, the techniques of generating 100 kJ, 5 µs REBs had been developed. Such beams were generated in megavolt vacuum diodes with a relatively low electric field strength for obtaining a long pulse duration. Because of this, the initial current density was low and the beam was then compressed in the increasing magnetic field to obtain the required value of 1–2 kA cm^{-2} at the input to the plasma. This technology resulted in a large initial angle spread of the beam, deteriorating the efficiency of its collective relaxation in plasma. The research plan included several stages:

(1) The search for conditions for efficient 100 kJ REB energy release in the plasma with $n \sim 10^{21}$ m^{-3} in a uniform magnetic field;

(2) the study of the two-stage heating scheme in a dense plasma;

(3) the increase in the magnetic system length and improvement in the energy characteristics of REBs;

(4) the study of plasma heating and confinement in a multiple-mirror configuration of the magnetic system.

At the first stage of studies, the facility was a 7 m plasma system with a magnetic field up to 4.5 T in a solenoid and up to 12 T in single-end mirrors [122]. An electron beam was generated in a planar diode of the U-3 accelerator, compressed in the magnetic field, and injected into the plasma through a thin separating foil burnt in each shot. The starting plasma was produced by a high-current discharge along the entire chamber [142]. A diagram of the setup is presented in Fig. 13. The main experimental results are published in [143, 144].

In these experiments, the electron temperature of 1 keV for the electron density $n_e = (0.8-1) \times 10^{21}$ m^{-3} was achieved for the first time in open plasma confinement systems [144]. The electron beam lost up to 25–30% of its initial energy, but only about 5% of the initial beam energy remained in the plasma by the pulse end, the rest of the energy being carried to the ends by fast electrons. The difference between the energy lost by the beam and the energy remaining in the plasma is not critical. This difference is partially related to the small length and low density of the plasma at the research facility. The reactor-class facility was assumed to be large enough for not only providing a region with a uniform field for beam relaxation but also producing long enough regions with a dense plasma capturing fast electrons in the two-stage heating scheme discussed in Section 5.

The dependence of the REB relaxation efficiency on the plasma density was the same as in experiments with nanosecond beams: for a density below a threshold, energy losses were almost constant; above the threshold, the heating efficiency began to rapidly decrease. The plasma heating was nonuniform over its length. The higher plasma temperature and the longer beam injection period considerably changed the physical picture of plasma heating. Processes related to the motion of ions (which were simply neglected in previous experiments), the resistive decay of the return current (which

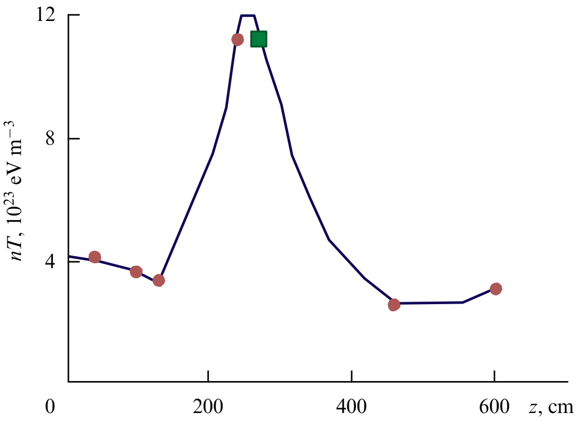

Figure 14. Longitudinal distribution of the plasma pressure in an operation with a dense plasma bunch at the facility center [150]. The square is the Thomson scattering data ($T_e = 0.18$ keV and $n_e = 6 \times 10^{21}$ m^{-3}); circles are diamagnetic measurements.

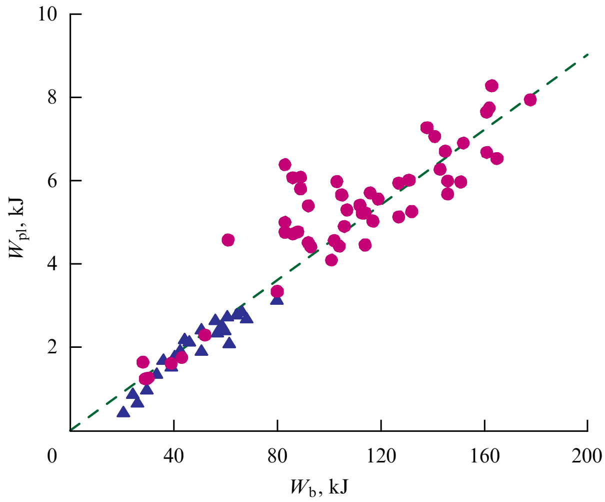

Figure 15. Dependences of the final plasma energy content on the input beam energy content for the first (triangles) and second (dots) stages of GOL-3. The dashed straight line corresponds to $W_{pl}/W_b = 4.5\%$.

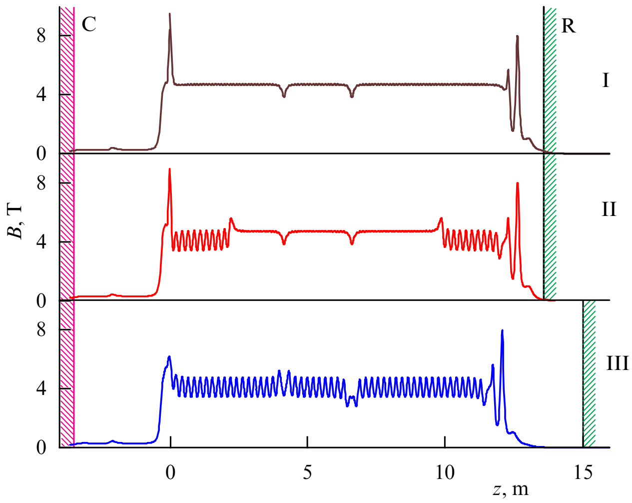

Figure 16. Examples of GOL-3 magnetic-field configurations: (I) uniform field, (II) corrugation with $R \approx 1.5$ in the end regions 2.2 m in length, (III) completely corrugated system (solenoid is shortened to 103 coils and an output expander is mounted), (C) cathode position, (R) beam receiver position. Irregularities at $z = 4.1$ and 6.6 m are related to the chamber design.

could result in a loss of system stability), and electron heat conduction (which was insignificant previously because of the low temperature) became highly important.

An interesting new result was the discovery of the efficient thermoisolation of an REB-heated plasma due to the suppression of longitudinal electron heat conduction by a factor of $\sim 10^3$ [145]. This effect was directly demonstrated in dedicated experiments [146]. It was found later that the suppression of the longitudinal heat conduction at the beam heating stage is one of the main components of the mechanism of the fast collective heating of ions at the GOL-3 facility [147–149].

The 7 m plasma length allowed the first experimental test of the idea of two-stage heating of a dense plasma. The dense plasma regions were produced by pulsed gas injection with the local density up to 10^{25} m^{-3}. It was demonstrated that energy did concentrate in the dense plasma region and the plasma pressure was several times higher than the plasma pressure in the region of efficient beam–plasma interaction (Fig. 14) [150]. Up to half the energy lost by the electron beam was transferred to the dense plasma. The maximum specific energy content in a dense bunch was restricted by its expansion along the magnetic field with a speed of the order of the ion sound velocity. The study of dense plasma clusters also allowed measuring the spectrum of fast electrons produced in the beam–plasma interaction with high accuracy [150]. Experiments with dense bunches showed that theoretical requirements for the density uniformity at the $\Delta n/n \ll 1$ level adopted earlier are too stringent.

The second-stage GOL-3-II facility differed from the first one by the fact that the magnetic system length was increased to 12 m, which now consisted of 110 coils, and by the use of a U-2 accelerator as an REB source. An electron beam with $W \leqslant 200$ kJ and $\tau \leqslant 10$ µs was injected into the plasma [151]. Accordingly, higher local plasma parameters were obtained [152, 153], including a highly nonuniform initial density distribution over the plasma length. The efficient longitudinal thermoisolation at the heating stage ensured the preservation of the linear dependence of the efficiency of energy transfer to the plasma (Fig. 15).

The magnetic system of the GOL-3 facility could produce different longitudinal magnetic field profiles (Fig. 16). Studies of the physics of plasma heating and confinement in the partial or full multiple-mirror configuration are published in [154–166]. Experiments were mainly performed with the corrugation $l = 22$ cm, $R \approx 1.5$, $B_{max} = 4.8$ T, and $B_{min} = 3.2$ T. In one experiment [167], the first part of the setup had a stronger corrugation: $l = 44$ cm, $R \approx 2.7$, $B_{max} = 6.0$ T, and $B_{min} = 2.2$ T. The conditions of efficient beam-energy release were found in a corrugated magnetic field. It was found that the technology of plasma heating by an electron beam in a multiple-mirror magnetic field leads to a fundamentally new collective mechanism of fast ion heating [147–149]. As a result, a paradoxical situation was discovered and studied in the experiments: the electron beam mainly heats the plasma electrons, but after the end of the beam injection, the plasma ions rapidly become hot. Because this situation was unusual, the available tools for plasma diagnostics [168–170] were considerably improved [171–181] for verifying this result.

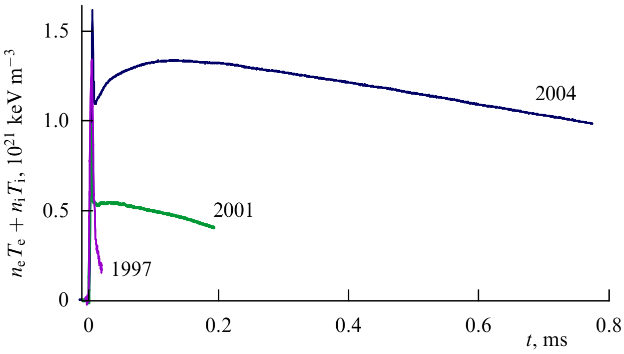

Figure 17. Diamagnetic signals in different configurations: (1997) uniform field, $n_e = 0.9 \times 10^{21}$ m^{-3}; (2001) end sections of a corrugated field 4 m in length, $n_e = 0.3 \times 10^{21}$ m^{-3}; (2004) full corrugation, $n_e = 1.5 \times 10^{21}$ m^{-3}.

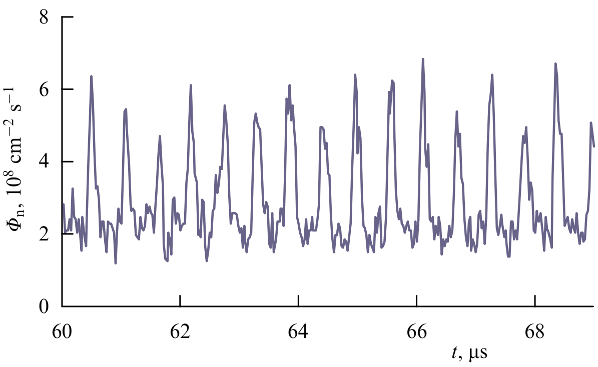

Figure 18. Local neutron flux Φ_n of D – D reactions from one of the cells of a multiple-mirror trap.

The main final result of these studies is presented in Fig. 17, where the dynamics of diamagnetic signals is shown for different magnetic field configurations [156]. We can see that the plasma energy confinement time τ_E strongly increased after passing to the multiple-mirror regime. Under optimal conditions, the value $\tau_E \approx 1$ ms was achieved [156], which corresponds to calculations [66] for a particular magnetic field configuration.

An unexpected result was the experimental discovery of a new plasma flow regime in a multiple-mirror system in which the bounce instability of ions with velocities near the boundary of the loss cone appeared in trap cells and was manifested in experiments as periodic splashes of neutron signals [156, 159] (Fig. 18). Soon, this phenomenon was also theoretically explained [182]. Unlike most other plasma instabilities, this effect proved to be useful because it restricted the plasma flow velocity in regions with a large longitudinal pressure gradient, thereby improving plasma confinement in the trap.

A number of collective processes in the beam–plasma system confined in a multiple-mirror trap led to a great difference between plasma confinement regimes in GOL-3 and theoretical predictions. For example, the value $\tau_E \approx 1$ ms corresponded to theoretical predictions for the best regimes, but this regime was achieved at a much lower plasma density than predicted theoretically. It was thus demonstrated experimentally that various collective effects can be used to ease the requirements for a super-high plasma density in a multiple-mirror reactor.

As mentioned above, a multiple-mirror trap does not satisfy the stability criterion [6]. However, stable beam transport and plasma confinement were achieved in experiments using the forcibly maintained radial structure of longitudinal currents [183–188]. As a result, a magnetic structure with a strong shear was produced.

The possibility of achieving regimes with $\beta \sim 1$ was studied in some experiments. In particular, in [189], a special configuration was used with an additional region with a weak magnetic field in the initial part of the setup, and the local value $\beta = 40\%$ was achieved. In pellet-injection experiments [190], the electron density at the initial formation stage of a dense plasmoid was measured to be $n_e \approx 10^{24}$ m^{-3}; the value of β formally calculated from spectroscopy data was 1. The plasmoid then rapidly expands along the magnetic field and the internal pressure drops.

Thus, the GOL-3 investigations for the first time demonstrated a considerable increase in the subfusion plasma confinement time in a multiple-mirror magnetic field. The scientific tasks of the facility were mainly fulfilled. However, the GOL-3 facility is a unique physical instrument that was used, along with the main program, for research on related topics. Because of the limited scope of this review, we only list them briefly.

During the intense collective electron beam relaxation in the plasma, a high-power plasma flow with hot electrons escapes from the trap through the facility ends. The parameters of this flow allow simulating the action of pulsed loads on materials of the divertor and the first wall of reactor-class tokamaks in the major disruption and edge-localized mode instability regimes. In GOL-3 experiments, samples were placed in a magnetic field up to 10 T at a specific energy release up to 30 MJ m^{-2}. The results of studies of different materials are discussed in [191–202].

Plasma in the GOL-3 facility is a system with a high level of Langmuir turbulence. In such a plasma, the nonlinear conversion of a Langmuir plasmon to a photon can occur at the upper hybrid resonance frequency, and two plasmons can merge into a photon at the second harmonic of this frequency (the reverse decay of a photon into two Langmuir waves plays an important role in laser fusion). In theory, this allows creating a high-power tunable pulsed terahertz oscillator with $n_e > 10^{21}$ m^{-3}. The generation of radiation at frequencies up to 800 GHz was demonstrated in [203–209]. At present, experiments are performed with a plasma system 2 m in length [210].

The final scientific program before the beginning of a major upgrade of GOL-3 (see Section 7.1) was the study of the beam–plasma interaction using an 80 keV, 1–10 MW, 30–300 μs electron beam [211–215]. Although the beam power was four orders of magnitude lower than in experiments with the U-2 generator, plasma with the density $n_e \sim 3 \times 10^{19}$ m^{-3} had time to reach the quasistationary state and was of interest in this respect.

7. Current projects in multiple-mirror systems

7.1 GOL-NB facility

The successful demonstration of the manifold increase in the plasma energy confinement time in the multiple-mirror configuration of the GOL-3 facility allowed addressing the prospects of using the principles of multiple-mirror confinement in reactor-class facilities. Two possible development

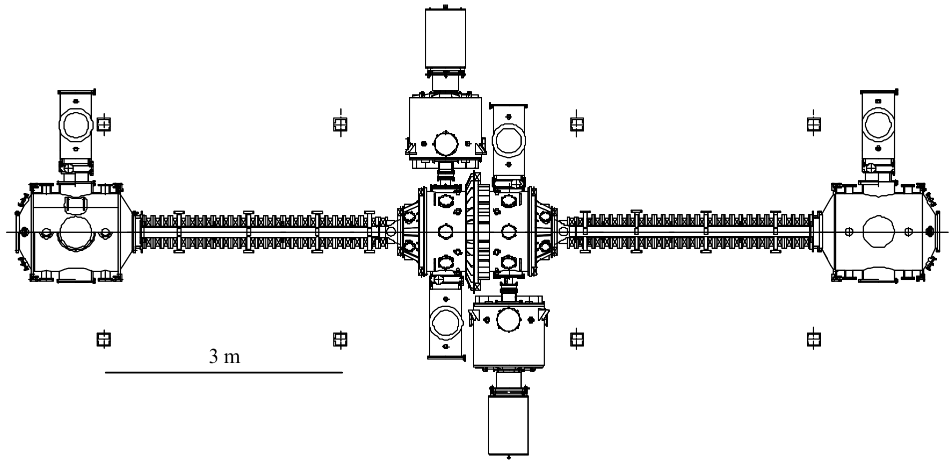

Figure 19. Schematic of the GOL-NB facility in the complete project configuration (top view). The facility consists of a central trap to which are connected two neutral beam injectors, two multiple-mirror solenoids, and two magnetic-flux expanding tanks, one of them containing an arc plasma source and the other, a plasma receiver. Also shown are four modules of the vacuum pumping system. The scale is indicated by the distance between structural columns.

paths were considered. The first assumed direct extrapolation of the GOL-3 results to a larger pulsed facility. The possibility of building a multiple-mirror reactor with the heating by a long-pulse REB was analyzed in [216].

The other possible way of development is the integration of a central gasdynamic trap and end sections with a multiple-mirror field. In experiments with combined plasma heating by neutral beams and electromagnetic waves at the electron cyclotron resonance frequency in the GDT gasdynamic trap facility, the electron temperature up to 1 keV was achieved [217] and stable plasma confinement was demonstrated with $\beta \approx 60\%$ [218]. The mean energy of fast ions in this facility was about 10 keV. Details of the physics of gasdynamic plasma confinement were considered in reviews [219, 220]. The addition of multiple-mirror sections, even with a moderate suppression of longitudinal losses, makes the reactor based on such an open trap quite attractive.

The physics of plasma heating and confinement in a gasdynamic trap significantly differs from that of collective processes studied at the GOL-3 facility. Therefore, it was decided to modify GOL-3 to a system including not only multiple-mirror sections but also a small gasdynamic trap in which plasma should be heated by neutral beams [221]. Because multiple-mirror confinement requires the condition $\lambda \sim l$, the gasdynamic confinement regime in a central trap is to be provided automatically.

A new configuration of the facility was called GOL-NB to maintain the legacy of the GOL line and emphasize a new method of plasma heating by neutral beams (NBs). A schematic of the facility is presented in Fig. 19. The central trap is about 2.5 m in length with the magnetic induction at the central plane up to $B_0 = 0.6$ T and in the mirrors up to $B_{\max} = 4.5$ T. The basic operation regime will be experiments with $B_0 = 0.3$ T for $R \approx 15$. Plasma will be heated by two injectors of 0.75 MW neutral beams [222]. Strong-field solenoids about 3 m in length are located on the two sides of the central trap (28 standard GOL-3 solenoid coils on each side). Depending on the experimental problem, these solenoids can be switched either to the uniform magnetic field regime with $B = 4.5$ T or to the multiple-mirror trap regime with $B_{\max} = 4.5$ T, $B_{\min} = 3.3$ T, and $l = 22$ cm (as in GOL-3 experiments) (Fig. 20). The end tanks are located behind the solenoids, in which the magnetic flux is expanded such that the plasma is delivered to large-area plasma receivers. One of the tanks contains an arc source producing the initial low-temperature plasma. The plasma stabilization at the initial stage will be performed by the vortex confinement technique successfully used in the GDT facility [223]. For this special electrodes will be placed in the chamber to provide differential plasma rotation (see review [69]).

We note an important difference between the GOL-3 and GOL-NB programs. The first was designed as a system that should provide record plasma parameters (in the open trap class). This goal was reached. At the same time, GOL-NB is being built for studying the specific features of operation of multiple-mirror sections. The facility is specially constructed such that the longitudinal channel of losses through mirrors will be dominant. Therefore, direct demonstration of the improvement in plasma confinement in the central trap after switching solenoids into a multiple-mirror configuration will not be masked by secondary processes. It is expected that plasma parameters will be more modest than in the operating GDT facility (a smaller central trap size, a smaller mirror ratio R, and a lower heating power). Numerical simulations of the dynamics of plasma parameters in GOL-NB were performed in [224] assuming that the known physics and technology can be extrapolated to plasma with the parameters that will be obtained at the new facility.

The parameter space available for experiments is shown in Fig. 21 [221]. It is expected that plasma parameters in the

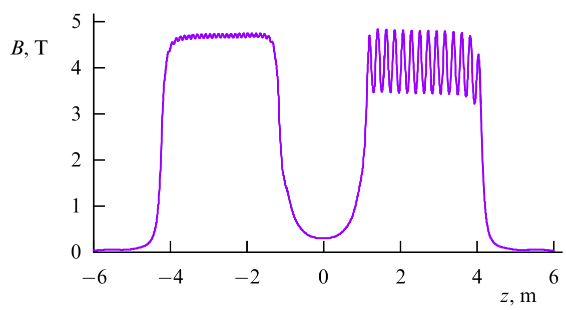

Figure 20. Magnetic field profile along the axis for $B_0 = 0.3$ T. The left solenoid is shown in the uniform field regime, the right one in the multiple-mirror configuration.

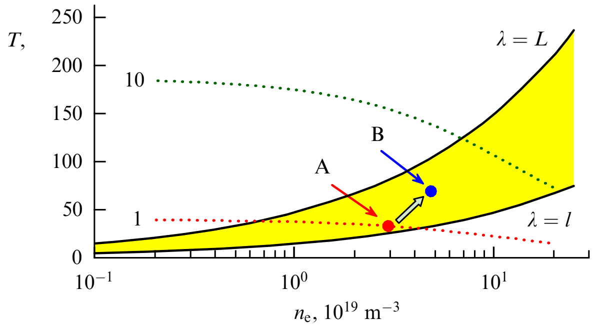

Figure 21. Plasma parameter space for the GOL-NB experiment for switching the strong-field sections (A) to the simple solenoid regime and (B) to the multiple-mirror configuration. Solids curves $\lambda = L$ and $\lambda = l$ restrict the region of the efficient operation of a multiple-mirror magnetic system. The dotted lines calculated in the simple energy balance model correspond to different suppression coefficients of longitudinal losses. Curve 1 (losses are not suppressed) corresponds to the purely gasdynamic operation regime of the trap, while curve 10 corresponds to a 10-fold decrease in the longitudinal losses. Calculation parameters: magnetic fields $B_{\max} = 4.5$ T and $B_0 = 0.3$ T ($R = 15$), the plasma diameter at the center is $2a = 20$ cm, 2×25 keV $\times 30$ A beams are injected.

purely gasdynamic confinement regime will correspond to point A. In passing to the multiple-mirror confinement regime, the operating point will shift to approximately position B (from the different scenarios of the experiment we here choose the one in which the operating point is displaced to the middle part of the band between curves $\lambda = L$ and $\lambda = l$). If the projected plasma parameters are attained in experiments, this will be the first direct demonstration of the efficiency of multiple-mirror sections in the full trap configuration. The GOL-NB experiment duration is limited to 3–5 ms, which is determined by the time of maintaining the magnetic field. The scientific background of the project and its physical program are discussed in more detail in [225].

Designing the GOL-NB facility was initiated in the fall of 2014. The development of this project demonstrates one of the main engineering advantages of open traps: due to its linear topology, the facility can easily be constructed from separate modules, which can be added to the project and introduced to the operation when ready. At present, construction of the facility has begun, which includes both end tanks, a part of the solenoid (34 of 56 coils), and a short temporary section of the chamber to which the injectors of neutral beams are connected. Work on starting up the main elements of the facility is being performed with this system, which completely occupies the part of the experimental area available at present. In particular, the regimes of the initial plasma jet transport from an arc source through strong-field sections are being worked out [226]. Both neutral injectors were developed to project parameters on the primary ion beam [227]. A new system controlling capacity storage that feeds the magnetic system was constructed and tested in experiments [228]. The central coil and its magnetic system coils are being constructed, and the assembly of the facility in its full configuration is planned by the end of 2019.

7.2 Gasdynamic multiple-mirror trap program

The prospects of using the principles of multiple-mirror plasma confinement in facilities with fusion parameters is related to the Gas Dynamic Multiple-Mirror Trap Program (GDMT) at the BINP intended for creating a new generation open trap for demonstrating technologies that can be used in the construction of a fusion reactor. The possibility of creating a neutron source for materials science based on the D – T reaction with a flux density of 2–5 MW m^{-2} in an open gasdynamic trap with two-component plasma has been investigated for several years (see, e.g., [219, 229, 230]). The GDMT project [231] is an attempt to combine the best features of gas dynamic and multiple-mirror traps in one setup. At present, this work is at the conceptual project stage, with updates introduced as new theoretical and experimental results appear.

The GDMT facility is assumed to be a research facility operating with a hydrogen plasma with insignificant radioactivity. The magnetic system of the facility is modular, allowing the gradual development of experimental capabilities and improvements in plasma parameters and facilitating changes in the research program at low cost. Figure 22 shows the GDMT scheme in the initial configuration [231]. According to calculations, the use of sections with a multiple-mirror magnetic field provides an increase in the plasma gain factor from $Q = 0.02$ in the GDT neutron source project [229] to $Q = 0.1$ (recalculated for a D – T plasma). After increasing the system length (by adding the second region with a continuously increasing magnetic field to the left of the central trap and extending sections with the multiple-mirror field), this project will allow obtaining the equivalent value $Q = 0.2$. This is already sufficient for manufacturing a commercially attractive neutron source for materials science and for transmutation of the most dangerous nuclear energy wastes. The facility should work with long pulses, and therefore the magnetic system is assumed to be superconduct-

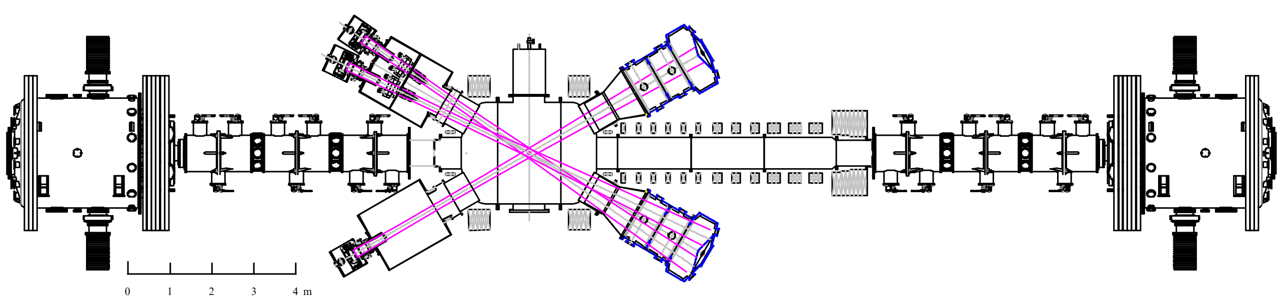

Figure 22. Schematic of the GDMT facility in the initial configuration [231]. The facility consists of the main gasdynamic trap into which neutral beams are injected, a long section of a gradually increasing magnetic field on the right, sections with a multiple-mirror magnetic field on the two sides of the central trap, and tanks of magnetic field expanders.

ing with the magnetic field of 7.3 T in mirrors. The efficient use of the properties of magnetic materials due to a simple axially symmetric coil shape allows working with a cheap niobium–titanium superconductor. Plasma will be heated by eight 1 MW neutral injectors.

The initial GDMT design assumed that plasma in the facility will be two-component. The main power of fusion reactions will be produced by the population of fast ions formed from neutral beams captured in plasma due to recharging or electron-impact ionization. The thermal component of the plasma with a temperature of about 1 keV will provide MHD stability of the plasma as a whole. Fast ions will be gradually decelerated by electrons. The thermalization of these particles occurs faster than their scattering, and they escape through a magnetic mirror. Thus, only the warm component of plasma will be lost along the magnetic field, as occurs now in GDT experiments [220]. The temperature of this component is much lower than the mean energy of fast ions, which considerably reduces the complexity and cost of the development of a multiple-mirror system for decelerating a plasma flow compared to earlier concepts of multiple-mirror reactors.

The GDMT facility is a major engineering object, even in its initial form, and requires special decision regarding its financing and startup of work. At present, physical experiments supporting the GDMT program are being performed on plasma facilities at the BINP. New results of theoretical and experimental work are introduced into the conceptual project of the facility. Some new physical concepts are being considered, in particular, the idea of a diamagnetic trap [232], sections with a helicoidal field (see Section 8), hybrid plasma heating scenarios, and a number of other improvements. Some elements of the new facility are also projected for estimating the correctness of the adopted technological solutions.

8. Improved multiple-mirror trap concepts

8.1 Modifications of multiple-mirror confinement

In Sections 3–7, we considered theoretical and experimental papers that followed the initial idea of plasma confinement in a periodically corrugated magnetic field. Several new ideas appeared in the theory, some of them nontrivial and breaking the existing paradigms of plasma physics. One of them was already mentioned in the context of GOL-3 experiments: the introduction of turbulence into the system suppresses the longitudinal losses along the electron thermal conduction channel, thereby improving the longitudinal confinement. For this reason, the physics of setups with a small mean free path has considerable advantages compared with that of tokamaks and stellarators, where the plasma confinement drastically deteriorates due to turbulence.

The first idea aimed at optimizing the magnetic system is to take a change in the plasma parameters along the axis into account. Because the ion mean free path changes from the middle of a trap to its edge, the corrugation period is adjusted to this change such that the facility operates in the optimal confinement regime at each point along its length. This idea, which was first proposed in [11], being quite obvious, was considered in many papers, of which we mention only [233, 234]. One of the disadvantages of this technique is that the facility becomes optimized for particular plasma parameters, which reduces the possibilities of varying operation regimes. This will not be a disadvantage for reactors, but has not been used in research facilities so far.

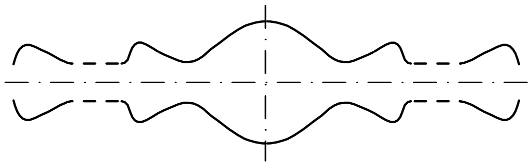

Figure 23. Envelope magnetic field line in a trap with asymmetric mirrors [239].

The second idea is unusual for high-temperature plasma physics, where experimentalists try to exclude foreign impurities from the confinement region. The proposal to add some amount of impurities into a plasma to decelerate its expansion was first made in [235] applied to the problem of inertial nuclear fusion. On the one hand, impurities increase radiative losses and reduce the fraction of hydrogen isotopes in the plasma. On the other hand, some fraction of ions with a large charge can considerably affect the scattering of particles, thereby decreasing the length of a multiple-mirror system. This proposal was studied, e.g., in [75, 233–238]. In particular, the calculations in [238] suggest a 3 to 4.5-fold increase in the fusion gain factor Q (or a decrease in the system length by a factor of 2.5) after the addition of a few percent of neon to the end multiple-mirror sections.

The unit cells of classical multiple-mirror systems are symmetric with respect to their central planes. Therefore, the directions of particle escape from any unit cell are equiprobable. We now consider proposals in which the asymmetry of the plasma flow was produced. The first of them was the idea in [239] of creating sharply asymmetric magnetic configurations (Fig. 23).

Plasma in such a system flows from the central confinement region through asymmetric multiple-mirror sections. A trapped particle moving from the field minimum in the unit cell to the trap edge meets a rapidly increasing magnetic field and is reflected from it due to the magnetic moment conservation. This particle moving to the trap center experiences collisions because of the condition $\lambda \sim l$, and is therefore scattered with some probability into the loss cone during motion through an oblique magnetic mirror and passes to a cell located closer to the center. Thus, in an asymmetric system with a suitable mean free path, random walk of particles with a nonequiprobale escape can be arranged. The plasma confinement time in such systems depends on the system length exponentially. However, the proposal in [239] has not been experimentally tested so far.

The idea of symmetry breaking is present in a somewhat changed form in [240–242]. The essence of these proposals is to place a radiofrequency heating system in each cell of the corrugated field directly in front of a magnetic mirror farthest from the center, to deposit energy into the transverse degrees of freedom. Different frequency ranges were studied theoretically. A particle in such a system does not pass through the magnetic mirror farthest from the center in a unit cell, because it acquires a large transverse component of the velocity vector. Moving to the center of the trap, the particle is scattered due to the condition $\lambda \sim l$ and passes with some probability into a cell located closer to the center. However, the correctness of this idea has not been verified in experiments either.

8.2 Helical mirror trap

An interesting theoretical idea, which has long been considered nonrealistic, is the proposal to use running magnetic mirrors, moving from the trap edges to its center with a velocity of about the thermal ion velocity [25]. In such a system, two effects are expected: additional plasma heating during reflection from a moving magnetic mirror and the appearance of a force directed to the trap center. Processes in systems with variable magnetic fields were studied theoretically in [243–245], but they were considered nonrealistic for plasma and magnetic field parameters in a multiple-mirror reactor.

Among the recent theoretical breakthroughs, we mention paper [246], where the original concept of helicoidal multiple-mirror sections was proposed. A magnetic field in such a system consists of the uniform field of a simple solenoid on which the field of a helical coil is superimposed. Such a system closely resembles the magnetic field of a straightened stellarator. If the radial electric field exists in a plasma, particles experience drift in crossed electric and magnetic fields. The plasma begins to rotate. In a rotating reference frame connected with plasma, the helicoidal magnetic field of the coils at rest appears to rotate, with magnetic mirrors running along the axis. The velocity of magnetic mirrors in the plasma reference frame is described by the expression

$$V_z = \frac{chE_{\mathrm{r}}}{2\pi a B_z}\,, \tag{8}$$

where a is the plasma radius, h is the helical coil step, $h \gg a$, c is the speed of light, E_{r} is the radial electric field, and B_z is the longitudinal magnetic field.

The direction of the force acting on the plasma depends on three parameters: the direction of the magnetic field line, the helicity (direction of the helicoidal coil winding), and the direction of the radial electric field. Unlike toroidal systems, open traps can supply the required radial potential distribution from the ends. Therefore, using different helicities of the helicoidal field on the two sides of the main confinement region allows arranging plasma transfer from the trap edges to its center (Fig. 24). In this case, the magnetic system operates as a screw pump, while the energy spent on plasma rotation is supplied from an external source, which supports the required radial potential distribution. This proposal is fully compatible with the vortex plasma confinement technology, in which differential plasma rotation is achieved by supplying the potential to special circular electrodes [223].

We note three interesting features of this proposal. The first is that if either the applied voltage polarity or the magnetic field direction changes, then, instead of energy transfer inside the trap, the plasma flow is accelerated outside. Such a system (more exactly, half the plasma trap shown in Fig. 24) can be used as a plasma engine with variable specific impulse for distant spaceflights [247]. The second feature of the system is the type of neoclassical transfer of particles. Neoclassical effects in toroidal systems enhance the radial transport. Because the potential profile in an open trap with a helical field can be forcibly set at the system end, a configuration can be chosen in which the neoclassical radial drift is directed to the axis [248]. In this case, the neoclassical radial drift counteracts the collisional diffusion across the magnetic field, which leads to the gradual expansion of the plasma flow. The third feature of this scheme is that the motion of magnetic mirrors at a supersonic speed is automatically accompanied by turbulent scattering of trapped particles. The particle confinement time in this system depends on the facility length exponentially.

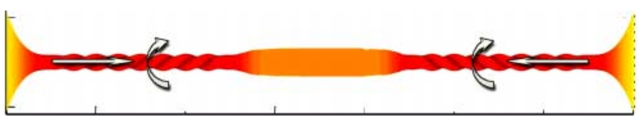

Figure 24. (Color online.) Magnetic surface view in a facility consisting of a central gasdynamic trap with additional sections of a helicoidal magnetic field. Color saturation is proportional to the magnetic induction. The arrows show the plasma rotation direction and the direction of the force acting on the plasma flow.

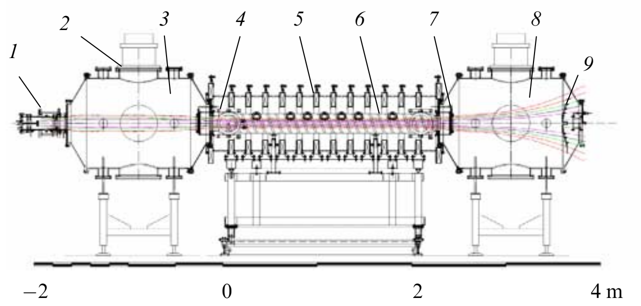

Figure 25. SMOLA device: (*1*) plasma gun, (*2*) turbomolecular pump, (*3*) plasma source tank, (*4*) correction coils, (*5*) solenoid with a uniform field, (*6*) bispiral winding, (*7*) limiters, (*8*) output expander tank, (*9*) sectioned plasma receiver. Curves show several typical magnetic surfaces.

The first experimental facility for testing the idea of controlling a plasma flow with the help of sections with a helical magnetic field is currently being constructed at the BINP with the support of the Russian Science Foundation. The SMOLA device (from the Russian for Spiral Magnetic Open Trap) [249, 250] is a half of the full-scale facility shown in Fig. 24. A schematic is shown in Fig. 25.

Plasma in the SMOLA device is produced by source *1* with an indirectly heated cathode emitting a flow of particles imitating a long central confinement region in the configuration shown in Fig. 24. The plasma fills the corresponding force tube in a tank of source *3* and passes through a magnetic mirror to the drift chamber about 2 m in length. The magnetic system of the drift chamber consists of solenoid *2* and bispiral *6* coils, in which currents are controlled independently. The radial electric field is produced by applying the required voltages to the housing plasma source *1*, limiters *7*, and plasma receiver section *9*. Experiments are planned in both the plasma flow deceleration (multiple-mirror trap) and acceleration (plasma engine) regimes of the facility.

The facility was designed as a relatively simple setup for quickly testing theoretical predictions, and therefore the working magnetic field in the drift chamber is limited to 0.3 T. The design of the SMOLA device began in 2015, and a vacuum system is now completely assembled, and the plasma stream passed from the source to the opposite end of the device. Experimental studies of plasma properties in the trap have begun. The main systems of the facility will be assembled by the end of 2018.

9. Summary

The history of nuclear fusion studies is not straightforward. Most of the many avenues of studies that originated at the initial stage of this research underwent periods of heightened activity and prolonged downturns, followed by new activity periods. This was explained to a large extent by the high rate of studies, with even the conceptual theoretical apparatus of high-temperature plasma physics sometimes being developed under the pressure of experimental work. The ebb and flow was inherent in stellarators, reversed field pinches, reversed-field configurations, and open traps.

The Budker–Mirnov–Ryutov multiple-mirror trap was an answer to challenges encountered on the way of realization of the idea of plasma confinement in the classical Budker–Post magnetic mirror trap. Experiments with plasmas in a very broad range of parameters (from a temperature of 1500° C and a low density in the first-generation devices to the subfusion parameters in the GOL-3 facility) confirmed the main assertions of the multiple-mirror confinement theory. However, the path to a real reactor appeared unfeasible. As a result, interest in this method of plasma confinement extinguished, active research in this field being continued only at the BINP.

Systematic studies of the physics of open traps of different types resulted in the next revision of the accumulated knowledge and integration of the best features of open traps of several types into a synthetic system. In this review, we considered the GOL-NB and SMOLA facilities that are currently being constructed and in a relatively short time should provide the physical foundation for the reactor-class GDMT facility. New theoretical and experimental ideas proposed by several research groups in this project allow us to optimistically assess the reactor prospects of modern open traps originated from the first Budker–Post magnetic mirror trap.

Acknowledgements
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10. Appendix. List of the BINP facilities mentioned in the article

The list of facilities at the BINP mentioned above is presented in the Table, where the name of a facility, one of the references, function, some parameters, and status are indicated. Facilities are listed in the chronological order of their appearance. The maximum values of plasma parameters were usually not achieved simultaneously. The mean electron and ion energies for non-Maxwellian distribution functions are denoted by W_e and W_i. The other notation is defined above in the text. In parentheses is presented the magnetic field

Table. The BINP facilities.

Facility	Function	Parameters	Status
Shchegol [71]	First experiments with an alkali plasma in a multiple-mirror trap	$L = 2.4$ m, $N = 14$, $B = 0.3/0.5$ T, $n \sim 10^{16}$ m^{-3}, $T \sim 0.2$ eV	Closed after completing the program
INAR [119]	First experiment with efficient collective REB relaxation in a plasma	$L = 2.4$ m, $B = 2.5$ T, $W = 0.6$ kJ, $n \sim 10^{21}$ m^{-3}, $W_e \sim 200$ eV	Upgraded to INAR-2
GOL-1 [124]	REB plasma heating in a long solenoid	$L = 7.5$ m, $B = 1.35$ T, $W = 1$ kJ, $n \sim 3 \times 10^{20}$ m^{-3}, $W_e \sim 100$ eV	Upgraded to GOL-M
GOL-2 [97]	Higher-energy REB plasma heating	$W \sim 20$ kJ	Closed at the draft project stage
INAR-2 [122]	REB plasma heating in a strong magnetic field	$L = 0.75$ m, $B = 7$ T, $W = 1$ kJ, $n \sim 3 \times 10^{21}$ m^{-3}, $W_e \sim 500$ eV	Closed after completing the program
GDT [217]	First and only gasdynamic trap	$L = 7$ m, $B = 0.35$ (10) T, $n \sim 2 \times 10^{19}$ m^{-3}, $T_e \sim 1$ keV, $W_i \sim 12$ keV, $\beta \sim 60$ %	Operating
GOL-M [126]	Features of the physics of beam–plasma interaction	$L = 2.5$ m, $B = 2.5$ T, $W = 0.25$ kJ, $n \sim 10^{21}$ m^{-3}, $T_e \sim 50$ eV	Closed after completing the program
GOL-3-I [144]	First stage of the GOL-3 facility, REB plasma heating in a solenoid at $W \sim 100$ kJ	$L = 7$ m, $B = 4.5$ (12) T, $W < 100$ kJ, $n \sim 10^{21}$ m^{-3}, $W_e \sim 1$ keV, $T_i < 50$ eV	Upgraded to GOL-3-II
GOL-3-II [151]	Second stage of the GOL-3 facility with increased parameters	$L = 12$ m, $B = 4.5$ (12) T, $W < 200$ kJ, $n \sim 10^{21}$ m^{-3}, $W_e \sim 3$ keV, $T_i < 50$ eV	Upgraded to GOL-3
GOL-3 [160]	Multiple-mirror trap with REB plasma heating	$L = 12$ m, $N = 55$, $B = 3.2/4.8$ T, $W < 150$ kJ, $n \sim 10^{21}$ m^{-3}, $W_e \sim 5$ keV, $T_i \sim 3$ keV, $\tau_E \sim 1$ ms	Operates with $L = 2$ m [210], part of the infrastructure is used for GOL-NB
SMOLA [250]	Helical mirror trap	Project parameters: $L = 2$ m, $N = 12$, $B = 0.3$ T, $n \sim 10^{19}$ m^{-3}, $T \sim 10$ eV	At the commissioning stage
GOL-NB [225]	Neutral-beam heated gasdynamic trap with multiple-mirror end sections	Project parameters: $L = 8.7$ m, $N = 14 + 14$, $B = 0.3$ (3.2/4.8) T, $n \sim 3 \times 10^{19}$ m^{-3}, $T \sim 50$ eV	Under construction
GDMT [231]	New-generation modular open trap for demonstrating subfusion-class plasma technologies	Equivalent value $Q_{DT} = 0.1 - 1$ is assumed	Conceptual project

strength in mirrors for facilities where it is significant. Before a slash is presented the minimal field strength in a multiple-mirror magnetic system, and after the slash, the maximal field strength.

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