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Progress of open systems at Budker Institute of Nuclear Physics

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This paper is based on a report at the 2nd International Fusion Plasma Conference & 13th International Conference on Open Magnetic Systems for Plasma Confinement (iFPC & OS 2023), August 21–25, 2023, Busan, Korea and provides a brief overview of the status of work at the Budker Institute on the study of hot plasma confinement in open-type magnetic traps with a linear axisymmetric configuration. The main attention is paid to key problems: magnetohydrodynamics (MHD) stability in regimes with extremely high relative pressure, longitudinal electronic thermal conductivity, stability with respect to the development of kinetic modes and transverse transport. This paper provides an overview of the methods we are developing to address these problems, the experimental and theoretical results achieved and plans for future development. The last section of the article provides brief information about the preliminary design of the gas-dynamic multiple-mirror trap device, the development of which has been completed.

Keywords: fusion plasma, plasma devices, plasma diagnostics

1. Introduction

Research in the field of controlled nuclear fusion at the Budker Institute of Nuclear Physics (BINP, Novosibirsk, Russia) are focused on the development of open-type magnetic traps – mirror cells with a linear axisymmetric configuration (see figure 1). Even in the pioneering works (see, for example, Post 1958) it was shown that, in the simplest configuration, a mirror cell can provide a fusion gain factor $Q \sim 1$ for the deuterium-tritium (DT) fusion reaction. But this cannot be exceeded due to a high level of axial losses of particles and energy. At this level of Q, the mirror cell can only be considered as a neutron source.

To increase the gain factor Q, it is necessary to reduce radically the level of axial losses. This can be achieved in principle in two ways: through additional magnetic sections attached at the ends to the mirror cell and capable of reducing many times axial flows of particles and energy, or in some way radically improving plasma confinement in the trap itself. In past years, a number of methods for such improvement were proposed and investigated: ambipolar, multiple-mirror and gas-dynamic traps, a trap with a rotating plasma and others. A detailed review of past research can be found in Post (1987).

Currently, the BINP is developing two approaches to improving plasma confinement in an open-type magnetic trap (Bagryansky, Beklemishev & Postupaev 2019). One of these approaches is associated with the use of multiple-mirror sections (Burdakov & Postupaev 2018), including helical ones (Beklemishev 2016*b*), where collective effects

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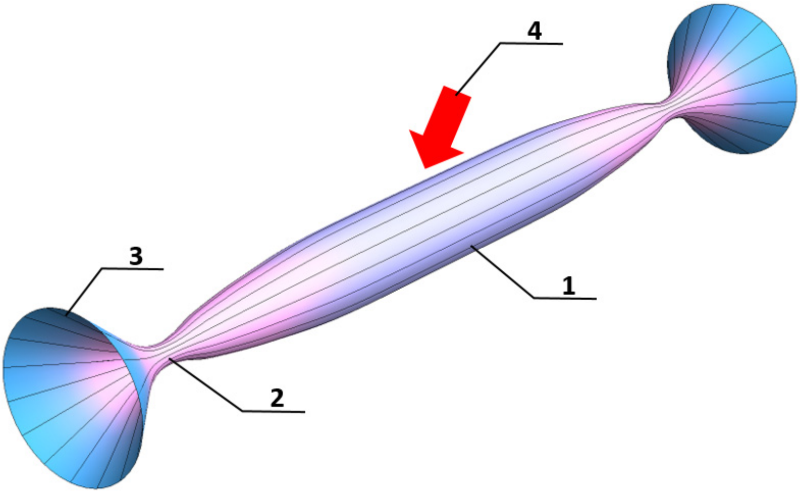

FIGURE 1. Schematic view of a mirror cell in its simplest configuration: 1 – magnetic trap; 2 – mirror plug; 3 – expander; 4 – neutral beams.

play a key role in limiting the flow of particles and energy. The other assumes a transition to the diamagnetic confinement mode (Beklemishev 2016*a*), when the magnetic field inside the plasma column becomes close to zero, and the relative plasma pressure tends to unity ($\beta \to 1$). These approaches are used in the development of a project for a gas-dynamic multiple-mirror trap (GDMT) (Skovorodin *et al.* 2023), which should become a demonstrator of the technologies necessary for the development of nuclear fusion reactors based on an open-type magnetic trap with a linear axisymmetric configuration.

Experimental support for the GDMT project is carried out at several relatively small research facilities: gas-dynamic trap (GDT) (Ivanov & Prikhodko 2013), GOL-NB (Postupaev *et al.* 2022), SMOLA (Sudnikov *et al.* 2022) and compact axisymmetric toroid (CAT) (Bagryansky *et al.* 2016), where key problems associated with the development of the project are studied. These key issues include the following:

- MHD stability of plasma with high relative pressure in an axisymmetric mirror cell;
- stability with respect to kinetic modes associated with the anisotropy of the distribution function of confined ions;
- axial particle flow and axial thermal conductivity;
- transverse transport.

This paper provides a brief overview of the methods we are developing to address these problems, the experimental and theoretical results achieved and plans for future development. The last section of the article provides brief information about the preliminary design of the GDMT, the development of which has been completed.

2. Status of work and methods being developed to solve key problems

A significant part of the research aimed at solving the key problems identified above was carried out using a GDT installation (Ivanov & Prikhodko 2013). Therefore, before proceeding directly to the description of the results of these studies, we provide a brief description of this device.

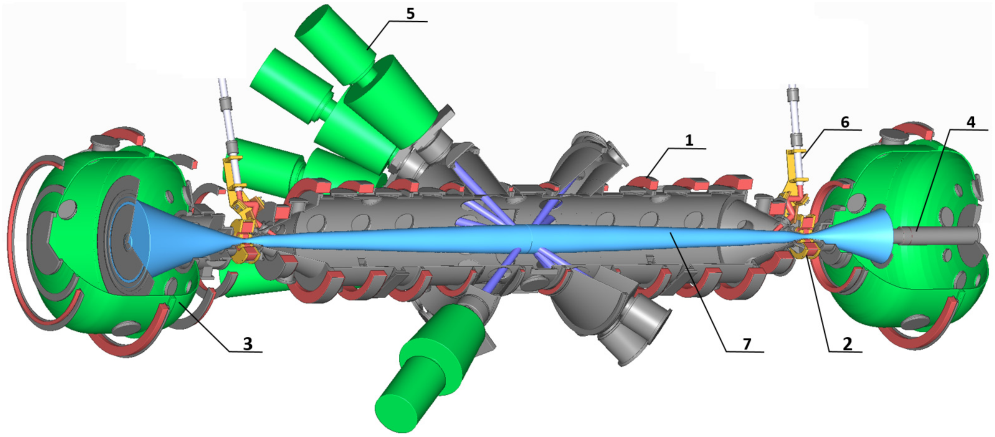

FIGURE 2. The GDT device: 1 – magnetic system coils; 2 – mirror plugs; 3 – expansion tanks; 4 – initial plasma generator; 5 – neutral beam injectors; 6 – waveguides of the ECR heating system; 7 – plasma column.

2.1. *The GDT device*

The GDT device is an axisymmetric mirror machine with a high mirror ratio $R = 35$ and a distance between the mirrors of 7 m (see figure 2).

The magnetic field in the central plane is 0.35 T. An arc-type plasma generator creates the initial plasma. The main means of heating is a neutral beam system, consisting of eight modules with a total power of up to 5 MW and an operation time of 5 ms. The energy of neutral deuterium atoms is 22–25 keV. Under conditions of heating by neutral beams, the plasma density lies in the range $(1\text{–}5)\cdot 10^{19}\ \text{m}^{-3}$, the electron temperature reaches 250 eV. When auxiliary electron cyclotron resonance (ECR) heating is used, the electron temperature reaches $\sim$ 900 eV (Bagryansky *et al.* 2015*a*,*b*). The ECR heating is carried out by two gyrotrons with a total power of $\sim$ 800 kW, a frequency of 54.5 GHz and an operation time of up to 10 ms. The time sequence of operation of the main systems of the GDT device during the plasma discharge is organised as follows:

- the magnetic system turns on and the magnetic field reaches the required values;
- then the plasma generator is turned on and within 4 ms the trap is filled with warm target plasma;
- 0.5 ms before the end of the plasma generator operation, the neutral beam system is turned on, and operates for 5 ms;
- in the process of neutral beam injection, the balance of warm plasma particles is maintained by injection of hydrogen or deuterium gas into the peripheral region of the plasma column using two gas boxes located near magnetic plugs.

2.2. *Key problem 1 – MHD stabilisation of plasma in steady state under conditions of high β and significant limitation of axial losses*

It is well known that the axisymmetric magnetic configuration of the mirror cell is not favourable for ensuring MHD stability of the plasma. To suppress transverse plasma losses associated with the development of MHD instabilities, we use the vortex confinement method (Beklemishev *et al.* 2010), which has proven itself well in experiments at the GDT facility. To implement vortex confinement, it is necessary to create a zone of differential plasma rotation in the radial peripheral zone of the plasma column. This is achieved by

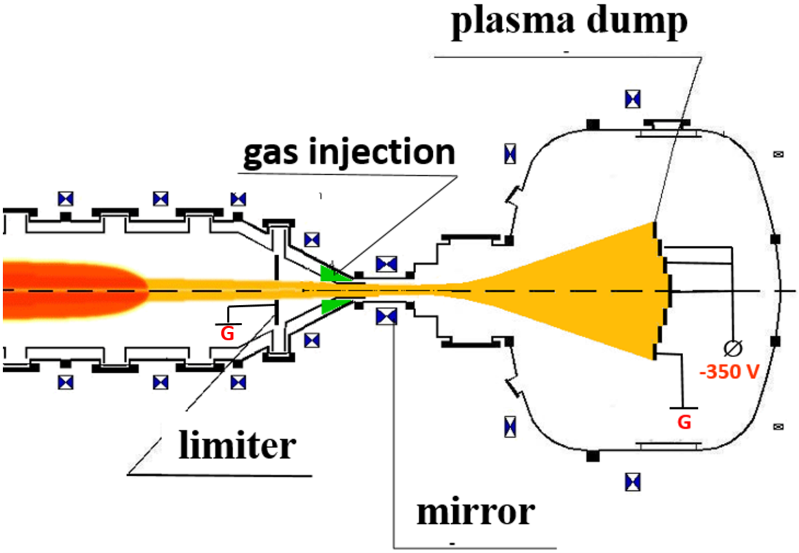

FIGURE 3. Method for implementing of vortex confinement.

applying an electrical bias to the electrodes of the sectioned plasma absorber (see figure 3). In this case, a potential jump and differential rotation occur in the peripheral region of the plasma column due to $E \times B$ drift in crossed electric and magnetic fields. A necessary condition for the implementation of vortex confinement is also the effect of finite Larmor radius (FLR) effects (Rosenbluth, Krall & Rostoker 1962). Differential rotation, together with the action of FLR effects, modifies the convective motion of plasma during the development of MHD modes, transferring MHD oscillations to a saturation mode with closed flow lines in the cross-section of the plasma and small oscillation amplitudes relative to its radius (Prikhodko *et al.* 2011).

The use of the vortex confinement method makes it possible to achieve relative pressure values up to $\beta = 8\pi \cdot P_{\perp}/B_v^2 \approx 0.6$ (Simonen *et al.* 2010), where $P_{\perp}$ is the transverse plasma pressure and B_v is the vacuum magnetic field. An obvious disadvantage of vortex confinement is the need for direct electrical contact of the plasma with the absorber electrodes. If the plasma flow into the expander is severely suppressed, the electrical contact may be broken. Thus, the use of vortex confinement becomes problematic when implementing plans to limit axial losses in order to maximise the power gain Q for potential fusion applications.

The solution to this problem is planned in two steps:

(i) Transition to high beta mode using vortex confinement.
(ii) Suppression of losses during the development of MHD instabilities due to the interaction of diamagnetic currents in the plasma with image currents in conducting structures surrounding the plasma.

The results of a recent analysis by Kotelnikov, Prikhodko & Yakovlev (2023) predict the effectiveness of this method of MHD stabilisation, starting from the β values achievable using vortex confinement.

The first steps in this direction have already been taken:

- The magnetic configuration was changed in such a way that the volume of the region occupied by hot ions was reduced by approximately half compared with the previously used basic magnetic configuration. In addition, the density of the warm target plasma was optimally increased to achieve the values of the captured power of atomic beams at which the plasma diamagnetism reached its maximum value. These measures made it possible to achieve an average beta value $\langle \beta \rangle = 20\,\%$.
- Motional Stark Effect (MSE)-diagnostics (Lizunov *et al.* 2011; Lizunov, Donin & Savkin 2013) were prepared to measure the radial profile of the magnetic field inside the plasma and to calculate local β values.
- A system of magnetic probes located outside the plasma column was also prepared for measuring the distribution of the magnetic field associated with diamagnetic currents inside the plasma.

Further steps in this direction are planned in the near future:

- Operation time of neutral beam injection (NBI) will be increased from 5 to 10 ms in order to further increase the plasma diamagnetism.
- A recently upgraded microwave heating system will be used to increase $\langle T_e \rangle$, the plasma diamagnetism and $\langle \beta \rangle$.
- In modes with the maximum achieved value of diamagnetism, measurements will be made of the radial profiles of the magnetic field inside the plasma and the distribution of the magnetic field associated with diamagnetic currents near the plasma boundary.
- Using the results of Kotelnikov *et al.* (2023) and the results of measurements, conductive structures surrounding the plasma with an optimal shape for MHD stabilisation will be designed.
- Conductive structures will be fabricated and assembled at the GDT facility.
- The efficiency of this method of MHD stabilisation will be studied in a real experiment.

2.3. *Key problem 2 – stable confinement with respect to kinetic modes*

As already noted in the introduction, since the times of the classics it has been known that Coulomb kinetics predicts the maximum value of power gain for a reactor based on a simple mirror cell at the level of $Q \approx 1$. For example, calculations presented in Yurov & Prikhodko (2016*a*) predict $Q = 1.35$ for the synthesis of D–T $\rightarrow^{4}$ He(3.5 MeV) + n(14.1 MeV). With such a value of Q, the mirror cell could be efficient source of neutrons. However, the development of kinetic instabilities may prevent the achievement of such a value of Q.

The presence of a loss cone in phase space and associated anisotropy of the ion distribution function in the velocity space causes the generation of several types of electromagnetic waves in the plasma, which leads to an increase in the ion scattering rate into the loss cone and a radical decrease in the ion confinement time.

What we do know about kinetic instabilities from researches under the GDT program?

(i) Alfvén ion cyclotron instability is well studied and a recipe for how to avoid its influence is known – oblique neutral beam injection (Zaytsev *et al.* 2014).
(ii) The global acoustic mode does not lead to noticeable losses (Skovorodin, Zaytsev & Beklemishev 2013).
(iii) Drift cyclotron loss-cone instability (DCLC) is being actively investigated theoretically and experimentally.

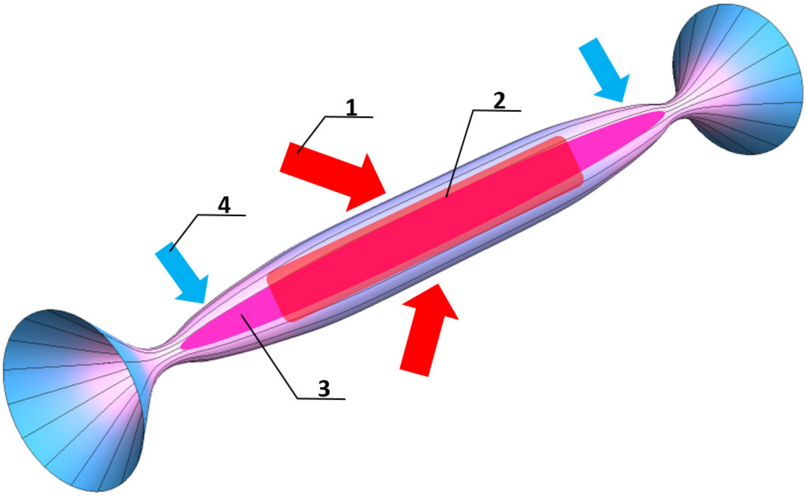

FIGURE 4. Schematic view of a neutron source based on GDT: 1 – neutral beams (oblique injection); 2 – population of hot ions; 3 – warm ions with an isotropic distribution function; 4 – injected flow of cold particles.

According to the results of numerous studies in past years (Post 1987), DCLC poses the greatest danger to ion confinement in a mirror cell. In a number of works in past years (see, for example, Ioffe *et al.* 1974; Kanaev & Yushmanov 1975; Kanaev 1979), a method for DCLC stabilisation was proposed and justified. The stabilisation method consists in creating a population of ions with an isotropic distribution: $n_{isotr}/n \approx$ a few per cent is enough to suppress instability.

Using the results of numerical simulation (Yurov & Prikhodko 2016*b*) for a neutron source (NS) based on a GDT (see figure 4), we will show how the use of this DCLC stabilisation method affects the power gain Q. In the NS model, intense heating of warm ions occurs due to collisions with hot ions. In this case, the frequency of Coulomb collisions of warm ions decreases and becomes insufficient to fill the loss cone, that is, their distribution function becomes anisotropic. To maintain an isotropic distribution, it is necessary to inject large flows of cold particles, which leads to an increase in longitudinal losses and a decrease in Q to $\approx 4\,\%$ (Bagryansky *et al.* 2004). The search for the possibility of significantly increasing Q in a NS based on GDT and, at the same time, avoiding the development of DCLC is currently the subject of our theoretical (Kotelnikov, Chernoshtanov & Prikhodko 2017; Kotelnikov & Chernoshtanov 2018) and planned experimental studies.

2.4. *Key problem 3 – axial energy confinement (axial thermal conductivity)*

The problem of the longitudinal thermal conductivity of plasma in open traps has been studied theoretically in sufficient detail in a number of works in past years (see, for example Konkashbaev, Landman & Ulinich 1978; Ryutov 2004). Due to the special importance of this problem, we carried out a series of our own theoretical (Abramov *et al.* 2019; Skovorodin 2019) and experimental (Soldatkina *et al.* 2017, 2020) studies, which demonstrated good agreement. Thus, the conclusion of previous works was confirmed that, with the correct design and operating mode, the expander is capable of limiting the longitudinal energy flow to a level corresponding to the energy $\varepsilon \approx 8kT_e$, which on average is transferred by one electron–ion pair leaving the trap. Here, T_e is the electron temperature and k is the Boltzmann constant. In this case, the influence on longitudinal losses of non-ambipolar effects associated with the electrical biasing on the plasma absorbers, which is used to organise vortex confinement, deserves special attention. Experiments in the near future will be devoted to studying this problem.

2.5. *Key problem 4 – transverse transport*

Although experiments at the GDT device currently demonstrate a lower level of transverse energy losses relative to axial ones, further research is necessary. This problem is closely related to the problem of maintaining the balance of warm ions as well as controlling the radial plasma density profile in order not only to minimise transverse losses, but also to achieve conditions under which the radial limiters are not subjected to excessive thermal loads. Let us recall that the balance of warm plasma particles in the GDT is maintained by gas injection into the peripheral region of the plasma column near magnetic mirrors and limiters (see figure 3). This leads to the fact that the plasma density near the limiters turns out to be comparable to the plasma density at the core of the column. To demonstrate the significance of this problem, let us estimate the energy flux density per limiter for a typical operating mode of a GDT device. According to measurement data, the plasma density near the limiter is $n \approx 10^{19}\ \mathrm{m}^{-3}$, and the electron temperature is $T_e \approx 50$ eV. Assuming that the temperatures of electrons and ions of warm plasma near the limiter are equal, the plasma is deuterium and that each electron–ion pair brings energy $\varepsilon \approx 8kT_e$ to the limiter, we calculate the energy flux density

$$q \approx nv_i \cdot 8T_e \approx 45\ \mathrm{MW\ m^{-2}}. \tag{2.1}$$

It can be seen that, even with such low values of n and T_e, the energy flow to the limiter is unacceptably high.

A solution to the problem may be to change the cold particle injection method to maintain a balance of warm plasma particles. If we abandon injection into the peripheral region of the plasma column and implement injection directly into the internal region, then we can assume that, in this way, it will be possible to minimise the plasma density near the limiter and, accordingly, the thermal loads. We are currently considering two ways to implement such an injection:

(i) injection of neutral beams of low energy;
(ii) injection of high-energy plasma jets with a frequency of ~ 1 kHz.

The development of low-energy neutral beam injectors is included in the GDT research program. Beams with an energy of $\approx$1 keV and an equivalent current of $\approx$100 A are supposed to be formed according to the 'acceleration–deceleration' principle (Pincosy & Turner 1987). Currently, the corresponding technology is being tested at a special stand.

To implement the second method of particle injection it is required to develop an injector with a gas efficiency of $\sim$1 and a pulse repetition rate of $\approx$1 kHz, which will ensure the flow of cold particles into the internal region of the plasma column at a level of several kA. Figure 5 shows a possible implementation of this type of injection from the expander side. Currently, testing of the high-energy plasma jet injector on the stand has been completed and preparations are underway for its use at the GDT device. The injector is a coaxial system designed on the principle of a Marshall gun (Marshall 1960) and capable of generating a jet of hydrogen or deuterium plasma with a density of 10^{21}–$10^{22}\ \mathrm{m}^{-3}$, a speed of $\approx 100\ \mathrm{km\ s}^{-1}$ and a duration of 20 μs.

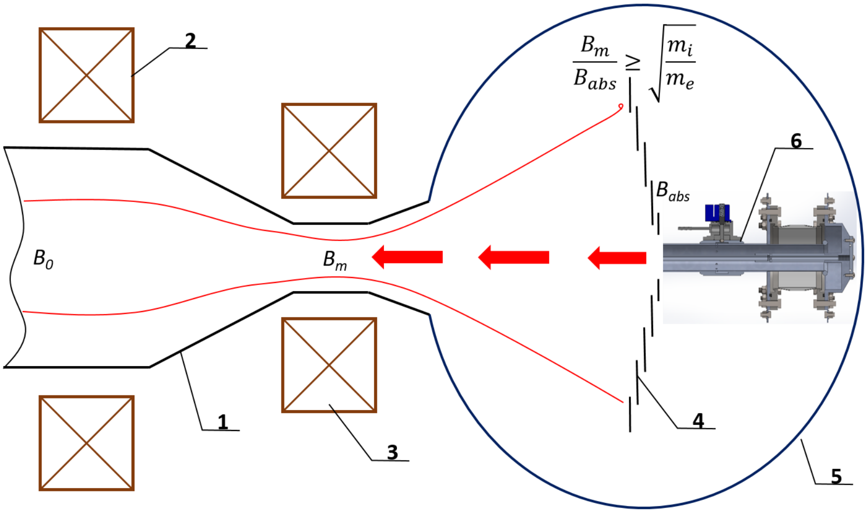

FIGURE 5. Possible method of injection of a high-energy plasma jet from the expander side: 1 – central cell; 2 – central cell coils; 3 – mirror plug coils; 4 – plasma absorber; 5 – expander tank; 6 – plasma gun.

3. Our approaches to improve axial confinement

In Beklemishev (2016*a*), within the framework of magnetic hydrodynamics, the equilibrium of plasma in a GDT is considered under the condition $\beta \rightarrow 1$, that is, when the magnetic field inside the plasma column is $B \rightarrow 0$. Let us recall that, in the opposite case, when $\beta \ll 1$, the characteristic time of particle confinement relative to longitudinal losses in a GDT is given by a simple gas-dynamic estimate (Mirnov & Ryutov 1979)

$$\tau_{\parallel gdt} = \frac{RL}{2v_i}, \tag{3.1}$$

where $R = B_m/B_v$ is the mirror ratio, that is, the ratio of the magnitude of the magnetic field in the mirror to the value of the vacuum field in the central plane of the trap, L is the length of the trap and v_i is the thermal velocity of the ions. Formally, as $\beta \rightarrow 1$, the mirror ratio tends to infinity, but in fact, confinement in this limit is determined by the thin layer (see figure 6)

$$\tau_E \propto \sqrt{\tau_\perp \tau_\parallel} = \sqrt{\frac{4\pi\sigma a^2}{c^2} \cdot \tau_\parallel} = \frac{a}{\lambda}\tau_\parallel. \tag{3.2}$$

Here, $\tau_\perp$ and $\tau_\parallel$ are the characteristic particle confinement times relative to transverse and longitudinal losses, σ is the transverse conductivity of the plasma, a is the radius of the plasma column and λ is the thickness of the transition layer. In the magnetic hydrodynamics approximation

$$\lambda = \frac{c}{2}\sqrt{\frac{RL}{\pi\sigma v_i}}. \tag{3.3}$$

It is important to note that the radius a is determined by the energy stored in the plasma, which in the case of $\beta \rightarrow 1$ corresponds to the energy of the vacuum magnetic field in the volume occupied by the plasma. That is, a has a certain value and depends on the heating power of the plasma and its energy lifetime.

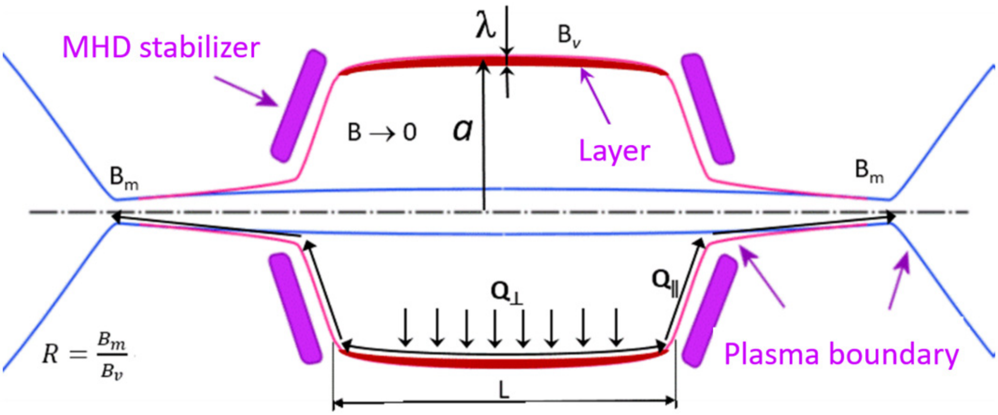

FIGURE 6. Schematic representation of a diamagnetic trap.

With classical transverse and gas-dynamic axial losses, this confinement scaling is sufficient to fulfil the Lawson criterion in a trap 30 m long, with a radius of 1 m at a field of 10 T with an order of magnitude margin for DT fusion.

Analysis of the confinement of individual particles in such a diamagnetic trap gives a much more complex picture. Work (Chernoshtanov 2022) considers three types of particles whose confinement is determined by the sign of the azimuthal angular momentum:

(i) $P_\theta < 0$ (motion in the direction of cyclotron rotation) – absolute confinement;
(ii) $P_\theta > 0$ with the conservation of the adiabatic invariant associated with a large difference in the times of reflection from the mirrors and the 'walls of the magnetic bubble' – the confinement is determined by the characteristic time of violation of the adiabaticity of the motion;
(iii) $P_\theta > 0$ in the absence of conservation of the adiabatic invariant – chaotic motion and the minimum confinement time $\tau \sim R_v \cdot \tau_b$, where R_v is the mirror ratio in the vacuum field, and τ_b is the time of flight from plug to plug.

A rough estimate for randomly moving particles (case 2) shows that a strongly collisional Maxwellian plasma with $T = T_e = T_i$ predicts significant improvement in comparison with $\tau_{\parallel gdt} \sim R_v L/(2T/m_i)^{1/2}$

$$\tau = \frac{a}{\lambda}\tau_{\parallel gdt}, \tag{3.4}$$

where $\lambda \sim \rho_i$ is the ion gyro-radius.

Unfortunately, the solution of the kinetic problem of plasma confinement in a diamagnetic trap by analytical methods does not seem possible. In these circumstances, we are planning work in two directions:

- For adequate implementation of numerical modelling, development of a semi-implicit particle-in-cell code for modelling high-beta plasma is underway (Berendeev, Timofeev & Kurshakov 2024).
- For the corresponding experimental studies, the commissioning of the CAT installation (Bagryansky *et al.* 2016) is being completed. The CAT is briefly described in the next section.

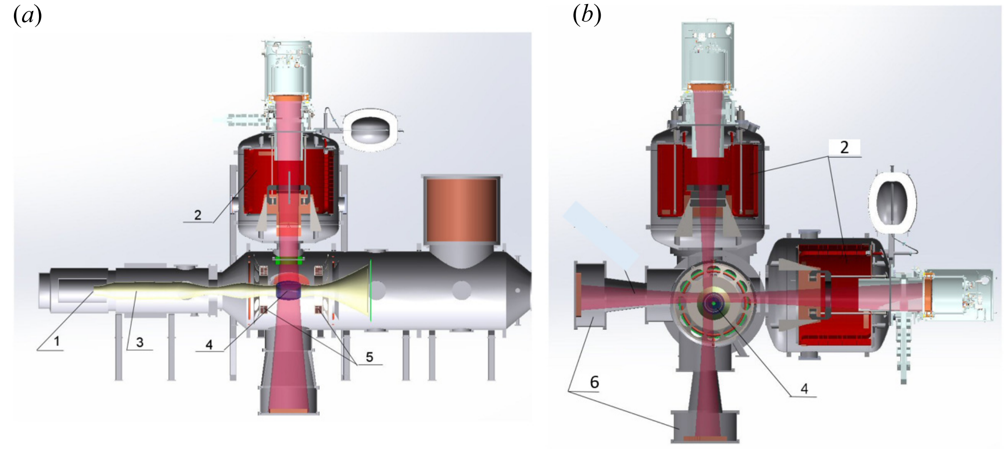

FIGURE 7. The CAT: a – side view; b – front view; 1 – target plasma generator; 2 – neutral beam injectors; 3 – plasma transport section; 4 – hot ion plasmoid; 5 – mirror coils; 6 – neutral beam dumps.

3.0.1. *Supporting experiment CAT*

The CAT (compact axisymmetric toroid) experimental device is being developed to solve the following problems:

- testing technologies of a confinement and stabilisation of the plasma with $\beta \rightarrow 1$;
- validation of developed computational codes;
- proofing technique of the field-reversed configuration formation due to injection of powerful neutral beams.

The CAT is an axisymmetric mirror cell with a relatively small volume ($\sim$10 l), distance between mirrors $L = 0.6$ m, magnetic field in the central plane $B = 0.2$ T and mirror ratio $R = 2$ (see figure 7). A special generator with an electric-arc gas discharge creates the target plasma. It is assumed that two neutral beams will be injected into the target plasma at an angle of 90° to the axis of the mirror cell. The energy of neutral beams of hydrogen or deuterium is 15 keV, the equivalent current is 2×120 A and the equivalent current density at the plasma boundary is 3.5 A cm^{-2}.

The status of the device commissioning work is as follows:

- work on the generation of target plasma with optimal parameters is completed;
- neutral beam modules are fully assembled;
- installation and adjustment of power supply systems for atomic injectors is being completed;
- commissioning of the device in full is scheduled for the beginning of 2024.

3.1. *Multiple-mirror systems*

3.1.1. *The GOL-NB experiment*

The idea of plasma confinement in multiple-mirror magnetic systems was proposed in the early seventies of the last century (Budker, Mirnov & Ryutov 1971; Logan *et al.* 1972). Figure 8 explains the principle of plasma confinement in such systems. If the ion mean free path λ_i is less than the trap length L, but greater than the corrugation scale l, the plasma flow becomes diffusive. In the thermonuclear temperature range,

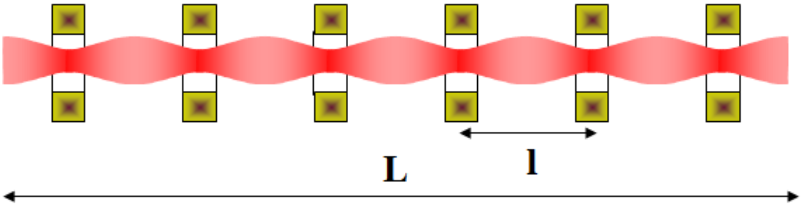

FIGURE 8. Schematic view of a multi-mirror magnetic plasma confinement system.

paired Coulomb collisions provide the required dissipation rate at extremely high densities $\sim 10^{22}$–10^{23} m^{-3}. Therefore, initially the concept of a multiple-mirror reactor assumed a pulsed mode of operation.

In experiments on the GOL-3 multiple-mirror trap (Astrelin, Burdakov & Postupaev 1998), improved ion confinement was discovered at a moderate density of $\sim 10^{20}$–10^{21} m^{-3}. Improved confinement at moderate plasma densities indicates anomalous ion scattering, which is interpreted as a result of interaction with collective plasma oscillations at the bounce frequency of the corrugation cells. This circumstance opens the way to the use of multiple-mirror sections in a stationary reactor to limit longitudinal losses of particles and energy.

The mission of the GOL-NB device (Postupaev *et al.* 2022) is direct demonstration of multiple-mirror confinement in a steady state mode under the condition when the ion path length relative to Coulomb scattering $\lambda_{ii\,\mathrm{Coulomb}} \gg L$. The GOL-NB (see figure 9) is an axisymmetric mirror cell with additional magnetic sections connected to the ends. Additional sections are solenoids consisting of a set of individual coils that have independent power sources. By controlling the currents in the coils, it is possible to implement within the sections both a longitudinal field profile close to uniform and a multiple-mirror configuration (see figure 9*b*).

The status of the device at the time of writing this text is as follows:

- target plasma with $n \approx 3 \times 10^{19}$ m^{-3} and $T = 5$–10 eV is obtained;
- neutral beam injectors have been commissioned ($U = 25$ keV, $P_\Sigma \approx 1, 1$ MW);
- plasma stabilisation system (edge-biasing) has been worked out.

In the near future, work will be continued in the following directions:

- study and optimisation of the physics of plasma heating by neutral beams;
- study of fast ion population parameters;
- implementation of a multiple-mirror configuration and studying the effectiveness of limiting longitudinal losses by multiple-mirror sections;
- development of auxiliary heating systems (ICRH ion cyclotron resonance heating).

3.1.2. *Helical mirror SMOLA*

The idea of a multiple-mirror magnetic system with a helical configuration to limit longitudinal particle flows and plasma energy is based on plasma rotation in a helical magnetic field (Beklemishev 2016*b*). Figure 10 illustrates a possible design of a mirror cell with screw multi-mirror sections. Plasma rotation occurs due to $E \times B$ drift in crossed electric and magnetic fields. The radial electric field inside the plasma is created by an electrical bias on radially sectioned electrodes located in the area of the expanders. In a rotating reference frame, plasma is influenced by running mirror cells. Running mirror cells transfer momentum to the particles trapped between them. Friction between trapped and passing particles causes plasma to be ‘pumped’ along the system back into the trap. In

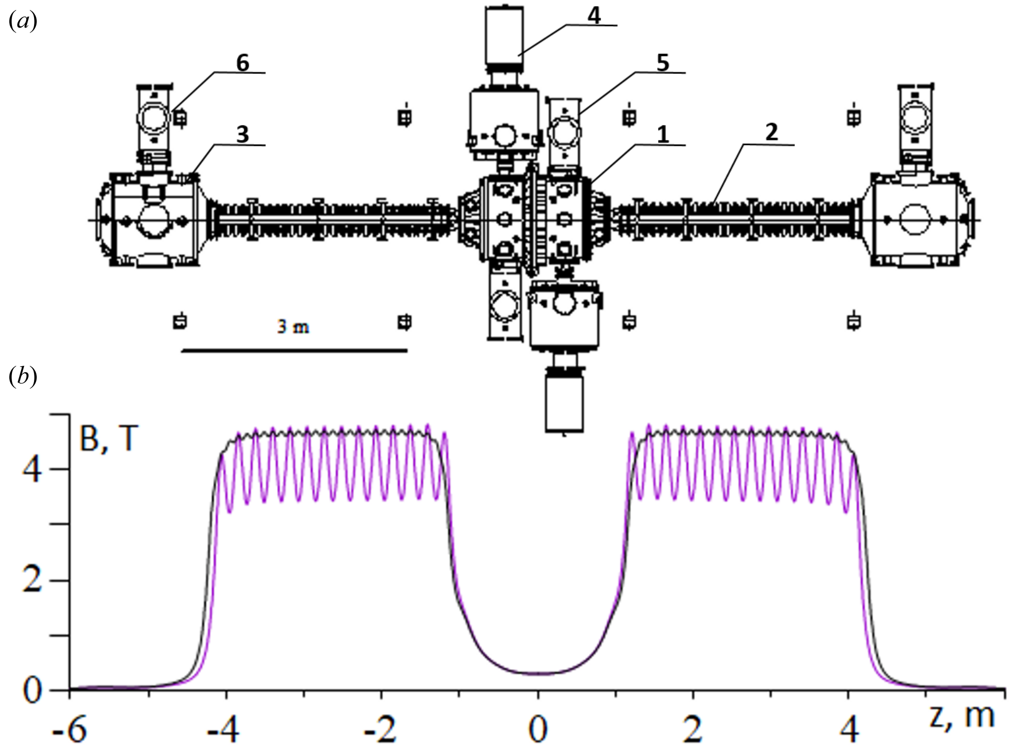

FIGURE 9. The GOL-NB installation. a – Top view of the device: 1 – central cell; 2 – additional sections; 3 – expander tank; 4 – neutral beam injectors; 5 – neutral beam dumps; 6 – vacuum pumps. b – Magnetic field configurations with solenoidal and multiple-mirror shape.

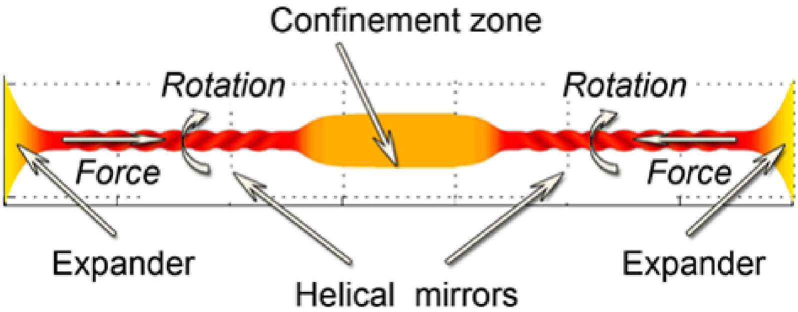

FIGURE 10. Possible arrangement of a mirror trap with helical multiple-mirror sections.

this case, the movement of trapped particles is accompanied by radial drift. The advantage of such a helical system compared with a conventional multiple-mirror system is the more efficient confinement predicted by the theory and the ability to control radial drifts. In addition, the counter flow of trapped ions can stimulate anomalous scattering, which leads to the formation of a population of trapped ions even in conditions of insufficient Coulomb collision frequency.

To test experimentally the principle of helical confinement, a SMOLA device was developed (Sudnikov *et al.* 2022), which is shown in figure 11. The components of

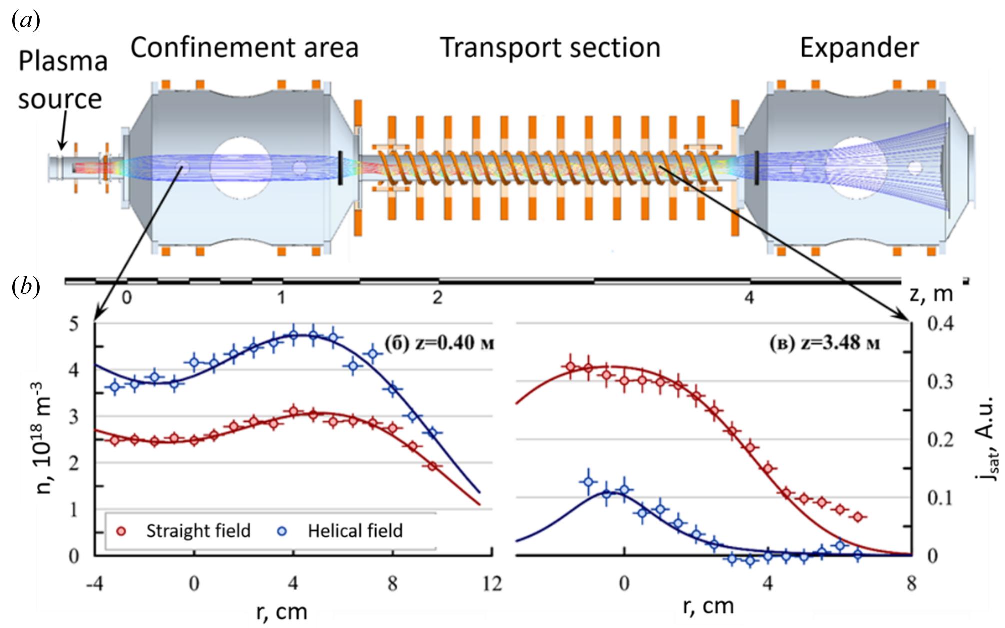

FIGURE 11. a – The SMOLA device; b – main experimental result: on the left – radial profiles of plasma density in regimes with straight and helical field in transport section; on the right – radial profiles of ion flux density in expander region in regimes with straight and helical field in transport section.

the installation are: a plasma source, a confinement area (axisymmetric mirror cell), a transport section and an expander. The transport section can have the configuration of either a simple solenoid or a helical multiple-mirror system.

Figure 11 also shows the main experimental result obtained from the SMOLA set-up. It can be seen that, in the mode with a helical configuration of the transport section, the ion flow into the expander decreases by more than an order of magnitude compared with the solenoidal configuration. In this case, the plasma density in the confinement region increases significantly. Based on the results of experiments at the SMOLA installation, the following conclusions can be drawn:

- Significant suppression of axial flux is achieved.
- The effective mirror ratio exceeded $R = 10$.
- A 1.6-fold increase in plasma density in confinement area was demonstrated.
- The radius of the plasma jet decreases
- A good agreement with the theory is shown.

Further research is aimed at studying the mechanisms of formation of a population of trapped ions under conditions of rare Coulomb collisions, as well as the development a next-generation installation, which will be a mirror cell with two screw sections at the ends.

4. Development of a conceptual design for the next generation facility

The facility being designed should provide a physical basis for thermonuclear systems: a NS and a future thermonuclear reactor based on open-type magnetic traps with a linear axisymmetric configuration. The facility will consist of a central section, multiple-mirror

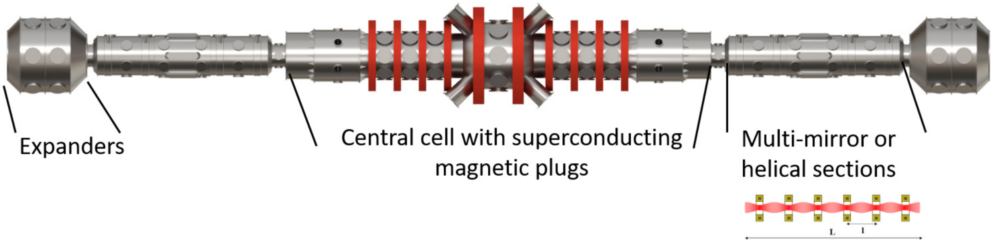

FIGURE 12. Full-scale GDMT device.

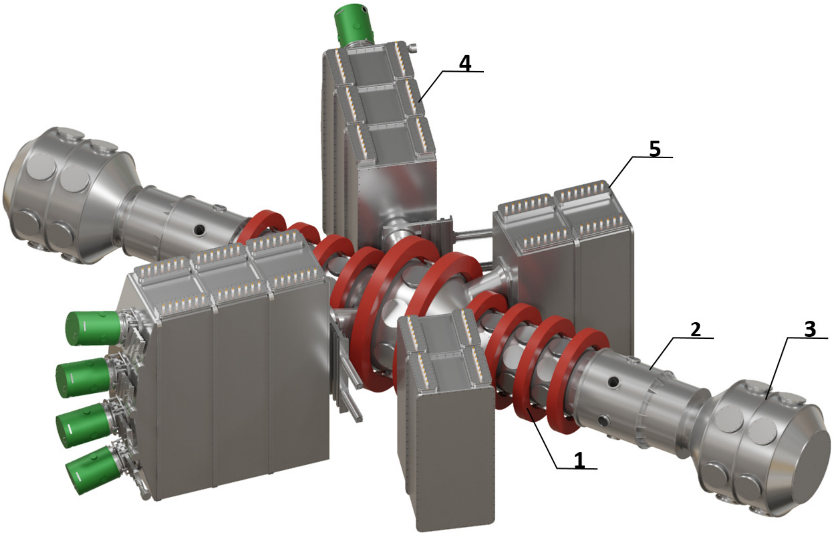

FIGURE 13. Three-dimensional model of first stage GDMT device: 1 - Cu coils; 2 – mirror plugs (HTSC high temperature superconductivity); 3 – expander tanks; 4 – neutral beam injectors; 5 – beam dumps.

sections and plasma flow expanders (see figure 12). It is a step towards improving the GDT, for this reason it was called the GDMT. A detailed description of the GDMT project, its physical justification and the corresponding experimental research program are given in Skovorodin *et al.* (2023).

The project is planned to be implemented in several stages.

- The first stage involves the development of a central section with superconducting magnetic mirrors and expanders.
- Multiple-mirror sections will be installed to replace single plugs in the next step.

Goals of the first stage:

- Optimisation of the parameters of a NS based on an open-type magnetic trap with a linear axisymmetric configuration.
- Implementation and study of the regime of diamagnetic plasma confinement with $\beta \to 1$.
- Investigation of technologies for the operation of an open-type trap in a stationary confinement mode.

Parameter	Value
Mirror to mirror distance	$\sim$10 m
Plasma radius	10–30 cm
Magnetic field:	
in the centre	0–1.5 T
in magnetic plugs	up to 20 T
pulse duration	2–4 s
NBI (H^0):	
total power	$\sim$22 MW
time of operation	up to 1 s
neutral energy	30 keV

TABLE 1. The key parameters of the first stage GDMT.

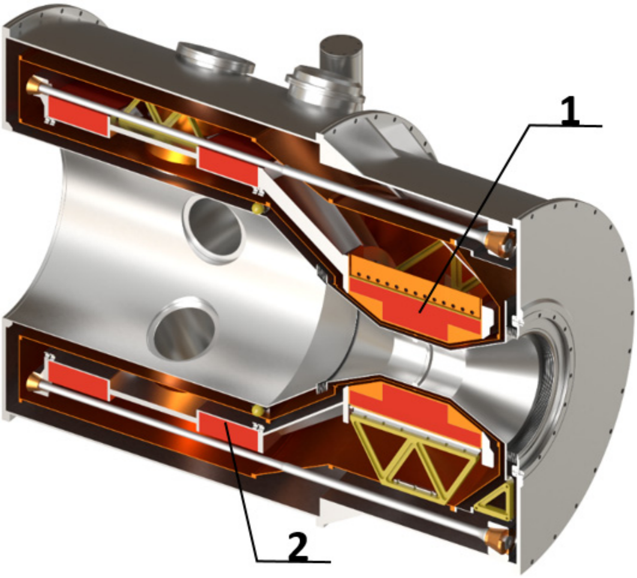

FIGURE 14. Three-dimensional model of the magnetic plug assembly: 1 – mirror coils (HTSC tape); 2 – transfer coils (HTSC current-carrying element).

At the time of writing this text, the development of the preliminary design of the first stage GDMT has been completed. Figure 13 shows its three-dimensional model. Table 1 gives the key parameters of the device.

The magnetic plug assembly (see figure 14) was designed in collaboration with the SuperOx company (SuperOx 2023) using second-generation superconductors.

The inner diameter of the superconducting plug coil is 240 mm, the inner diameter of the vacuum chamber in the magnetic plug is 200 mm.

The NBI system consists of eight modules. Each NBI module is designed to generate a beam of neutral hydrogen atoms with a particle energy of 30 keV and a beam power of 2.75 MW. Figure 15 represents a three-dimensional model of the module.

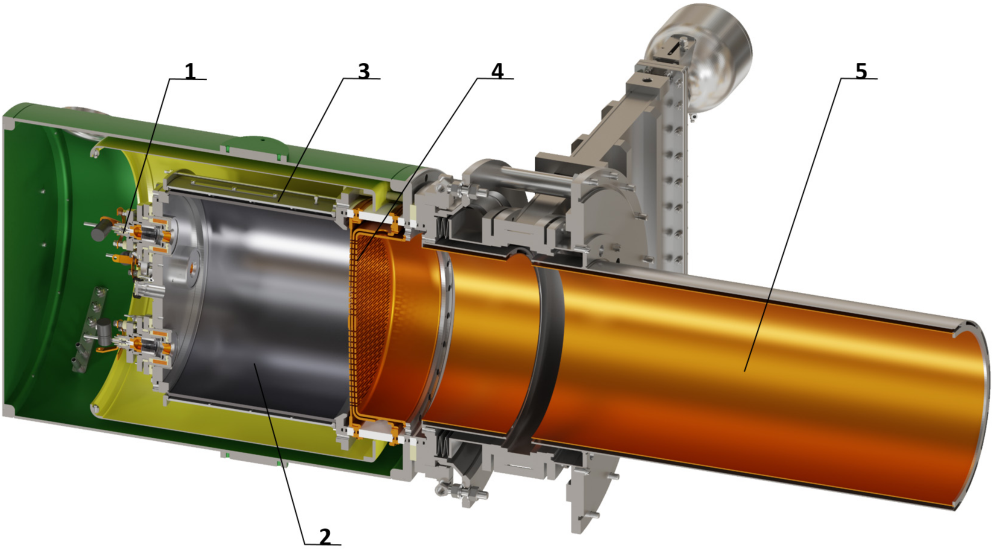

FIGURE 15. Three-dimensional model of the NBI module: 1 – plasma sources (4 pcs.); 2 – discharge chamber; 3 – magnetic wall; 4 – ion-optic system; 5 – neutraliser.

5. Conclusion

The Budker Institute conducts active research aimed at developing technologies necessary for constructing nuclear fusion reactors based on open-type magnetic traps with a linear axisymmetric configuration. The key problems of hot plasma confinement in such systems are studied using theoretical and numerical models, as well as experiments at four facilities. The results of these studies are used to justify the GDMT project – the next generation facility. Some of the key problems have already been largely resolved. These include problems of longitudinal electron thermal conductivity and MHD stabilisation of plasma in an axisymmetric mirror cell in regimes with high $\beta(\beta \sim 1)$. Solving other problems requires additional research, plans for which have been developed and are being implemented.

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Declaration of interest

The authors report no conflict of interest.

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