The BINP Road Map for Development of Fusion Reactor Based on a Linear Machine

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Abstract. In the paper, we present the Budker Institute long term plans for laying the plasma physics database for an advanced fuel fusion reactor based on the axisymmetric linear magnetic trap. The general approach to development of the reactor utilizes the idea that confinement of a plasma with the highest pressure can be obtained in a linear device with multi-mirror end sections attached at both ends to suppress the axial plasma losses. To develop the required database a stepwise approach is applied, which suggests construction of the several experimental devices with progressively increasing plasma parameters, which incorporate the different constituents of the approach. Ultimately, after successfully proving the ideas in the experiments, a prototype of the reactor will be constructed in the Budker Institute.

INTRODUCTION

While the scientific development of the open confinement systems is less mature than for the tokamak, substantial progress has been made in recent years. Particularly, this is true for the experiment with the gas-dynamic trap (GDT) [1-3] and GOL-3 multi-mirror devices [4], at BINP, Novosibirsk. At GDT, successful application of several methods for stabilization of the most dangerous flute instability has been demonstrated in fully axisymmetric open traps. These methods rely on using partial line tying to the end wall [5], make use of outboard anchors with large favorable curvature of the field lines [5-7], and sheared plasma rotation at periphery induced by the biased limiters and segmented end walls [8], yielding confinement close to that defined solely by axial energy losses [7, 9,10]. Note that other stabilization mechanisms which have emerged in the past and in recent years would also be applicable for the gas dynamic trap. Among those are non-paraxial mirror cell [11], magnetic divertor [12,13], kinetic stabilizer [14], tail-waving feedback stabilization [15], etc. If the MHD modes are stabilized, radial transport in GDT is imperceptible as expected in axisymmetric configurations. Substantial reduction of axial plasma losses was demonstrated at GOL-3 device with the multi-mirror end sections in a wider range of plasma densities than predicted theoretically [4]. Active control of plasma rotation is now routine at GDT, a critical development since it was found that even if the pressure-weighted curvature is favorable, plasma becomes unstable during transient fast accumulation of the energetic ions without such control even at low beta [8]. Essentially, the experiments at GDT and GOL-3 devices have progressed to the point when it becomes possible to consider their results to be used for the first practical applications to fusion. Now, the most attractive options for that would be fusion neutron sources, which are dedicated, for example, to fusion materials development [16,17], or drivers for subcritical fission reactors [18-20]. Note that the GDT concept assumes no significant role of electrostatic plugging of the end losses, as in tandem mirrors [21,22], and does not incorporate complex thermal barrier physics [23]. The GDT plasma contains a large fraction of collisional warm plasma to provide both magneto-hydrodynamic and micro-stability to the plasma.

The features of the magnetic mirrors that are advantageous for pure fusion also make it an interesting candidate for a fusion-fission hybrid (FFH) driver. In particular, the beta value for the mirrors is high. Beta value ~ 60% has already been demonstrated in present day experiments [24], and the upper limit is yet to be determined.

The mirror’s high beta and axial symmetry advantages were confirmed in the fusion neutron source study [16-19], albeit with a large extrapolation from the established mirror database. Note, that the problem of a relatively low energy gain may be offset by the ability to easily couple to direct energy conversion, the relative ease of construction and maintenance due to the basic cylindrical geometry, and the ease of fueling and impurity control. These options do not require high Q values, which are necessary for pure fusion reactors. The relative tradeoffs in physics and engineering embodied in the various magnetic configurations are important to understand in regard to optimizing fusion applications. However, a substantial investigation of the GDT as a neutron source for FFH has been undertaken. To help expose the potential benefits offered by the GDT, an example neutral-beam-driven system based on parameters close to those established in GDT experiment is developed that yields a neutron source rate of ~ 10^{18} n/s, relevant to TRU waste burning requirements. The GDT could also make a relatively compact system with substantial thermal neutron production, but the extrapolation in plasma performance is substantially larger.

After realization of the first step that would be a construction of intense plasma neutron source dedicated for systems with Q value of 5-10% as for the above mentioned applications, the next aim is focused at, would be a development of D-T reactor based on the linear system. For such a reactor the Q value should be of the order of 10. On the following up phase, development of a fusion reactor with advanced fuels can be considered. In particular, the D-D or p-B^{11} would be the options, which impose outstanding physical and technical challenges.

However, before starting the development of the system that would operate as a fusion neutron source the following issues should be addressed. So far, the mirror experiments with relevant plasma parameters, including GDT device, have been operated in a pulse mode. Transition to a steady-state, especially at higher plasma parameters, may highlight physics phenomena and issues, which would not be addressed in the previous generation of the mirror devices. Among those issues are a sustainment of the particle and energy balance in plasma, slow instabilities that may deteriorate confinement, handling of plasma exhaust, etc. GDT has demonstrated plasmas of approaching 60% peak beta by means of vortex MHD stabilization. Will this method scale to higher electron temperature and is the electrode drive mechanism applicable in steady-state regime? At the same time, still it is not clear whether other methods, for example, stabilization by the pressure-weighted average min-B criteria, would be applicable for the plasma parameters of interest. The electron temperature of GDT is approximately 5% of the neutral beam injection energy if an auxiliary ECR heating is applied. Will the electron temperature further increase with transition to steady state conditions?

To address these issues it has been proposed to construct the Gas-Dynamic Multi-mirror Trap (GDMT device). The GDMT is proposed to combine the GDT properties with good plugging capability of multi-mirror traps. The primary aim of the project is to prove the concept of the steady-state multiple-mirror fusion reactor, and obtain confinement scaling, while going to longer pulses and higher electron temperatures than those available in GDT. The secondary mission of GDMT is being a prototype of an energy-effective neutron source to replace the unrealized project of the “Hydrogen Prototype”. To demonstrate that reactor relevant plasma parameters can be achieved in steady-state, the GDMT experiment is designed for plasma pulses with 1-5 s duration at a heating power of upto 50 MW. For this purpose the main heating system is neutral beam injection with the beam energy of 50-60keV (stepwise upgrading from 10 to 50 MW). In addition. an electron-cyclotron resonance heating (ECRH) system providing 2-5MW of microwave power and axial injection of electron beams are foreseen to access beta and equilibrium limits and to study fast ion confinement as well as macro- and micro instabilities.

General view of the GDMT device is shown in Fig.1. The mission of the project is to demonstrate the reactor potential of the axisymmetric linear confinement system. For the development of a credible mirror reactor concept, steady-state operation has to be demonstrated for fully integrated discharge scenarios at high heating power yielding

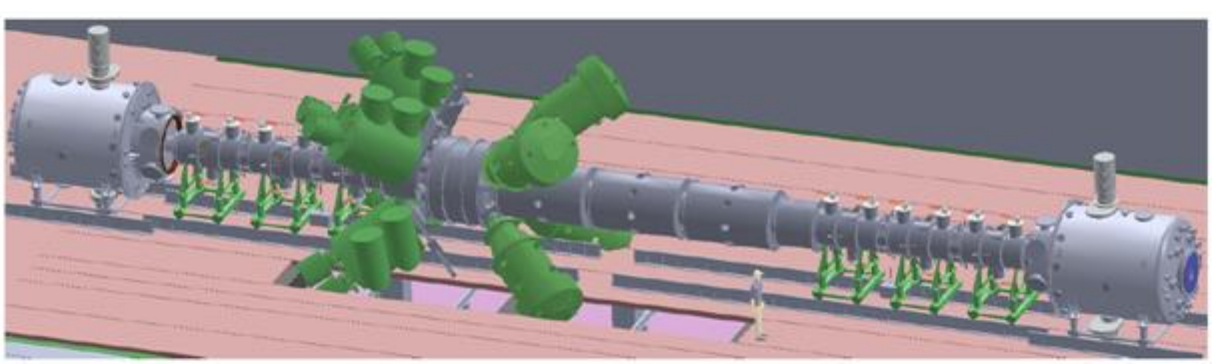

FIGURE 1. View of the GDMT device.

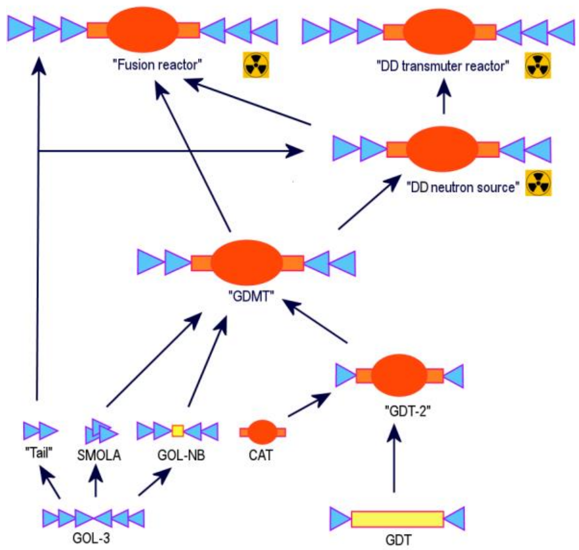

FIGURE 2. Baseline scenario for development of a fusion reactor based on magnetic mirror.

densities and temperatures relevant for a fusion reactor and with the end divertors providing suitable power and particle exhaust. Characteristic time scales range from energy confinement time (~100ms) and fast-ion slowing down time, which are in the order 20-100 ms, to the time for reaching an equilibrated magnetic field configuration, which is of the order of several seconds.

The main purpose of the GDMT device construction is to demonstrate the fusion technologies on a mirror-based device. The GDMT device features are

1. Equivalent Q~1 (compared to previous projects of the mirror-based neutron source with Q≈0.1), suggesting a reasonable scaling up from the current experiments);
2. Superconducting magnets;
3. The main methods for suppression of axial plasma losses: the very high mirror fields, multi-mirror end sections, plasma rotation in end sections with helical magnetic field induced by radial electric field, use extreme plasma pressure in the central cell, ambipolar effects, etc.

The main challenge for construction of the GDMT device is a lack of the experimental data for choosing the major stabilization method to be applied. After completion of the experiments on the GDMT device, assuming that the robust stabilization methods is developed, next steps critically depended whether the end plasma losses could be strongly suppressed or not.

We developed a road map (see Fig.6) to a pure reactor based on mirror machine. It suggests development of a robust stabilization methods for axisymmetric system and methods to diminish the end plasma losses. This is planned to be done in several steps enabling us to try the different conceivable approaches.

Before start of the GDMT device construction we are going to test different basic ideas in moderate scale experiments. These experiments are shown in the chart (see Fig.2) starting from the GOL-3 and GDT experiments to future fusion reactor. Along with the design of the GDMT we are going to construct several smaller scale experiments modeling its particular features.

GOL-NB EXPERIMENT

The proof-of-principle experiment named GOL-NB is now under construction. This device is designed to model the GDMT physics at lower plasma parameters and small pulse duration. The main purpose of this experiment is to study the scaling of the plasma end losses in a system with multi-mirror end sections at moderate plasma density. Essentially, this an extension of the GOL-3 experimental program to smaller plasma densities and longer pulse duration. The project was optimized given funding constraints that led to some important compromises in its technical and physical parameters. In particular, the device partly reuses infrastructure and hardware from the GOL-3 device. General view of the GOL-NB experiment is shown in Fig.3.

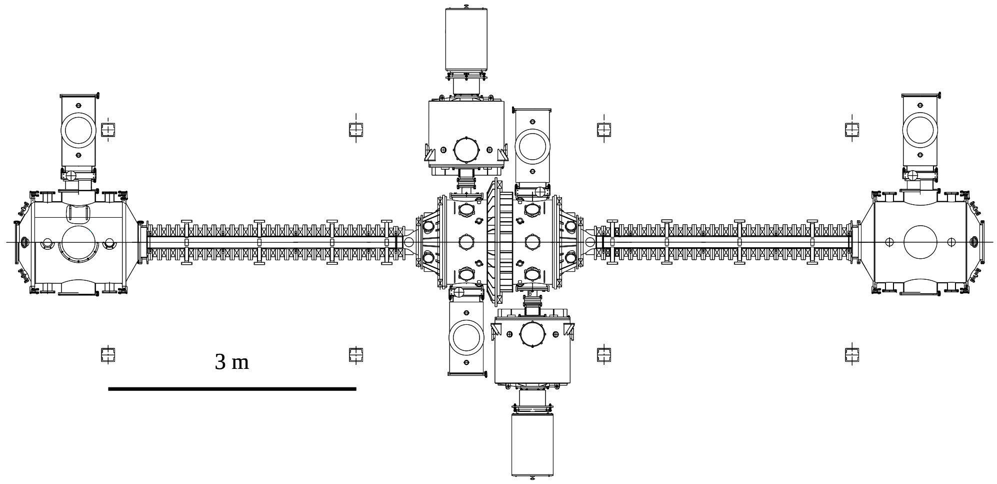

FIGURE 3. Layout of GOL-NB device (top view).

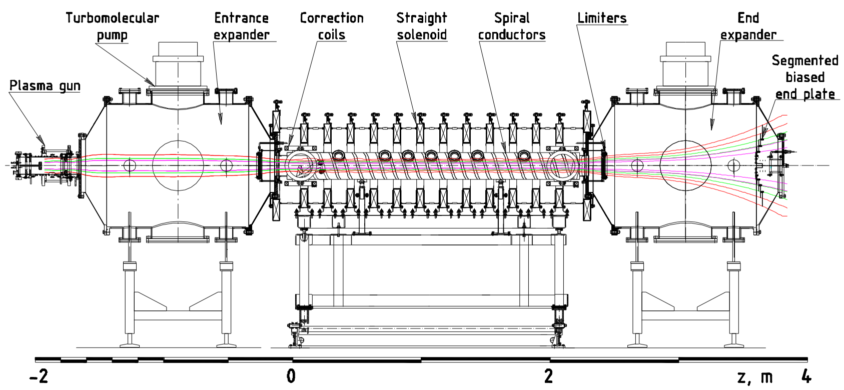

FIGURE 4. View of the helical mirror experiment.

The plasma is produced in a small size central cell by neutral beam injection and helicon plasma discharge. The plasma source is mounted on-axis in one of the end tanks. The central trap coils are designed to produce 0.6 T maximum field at the midplane. Multiple-mirror sections reuses 56 magnetic coils from GOL-3 device. Recently, plasma from a prototype source was successfully transported through ~3 m distance in the test experiments imitating the conditions of GOL-NB experiment. For powering of the GOL-NB magnetic system it will be used the former capacitor bank of GOL-3 device with only minor changes. The two 0.75 MW, 25 keV, 5ms neutral beams are used to heat the plasma in the central cell. They now in the final stage of commissioning. The baseline physical program at GOL-NB device suggests an accomplishment of the following Tasks.

Task 1: to demonstrate stable, GDT-like plasma confinement in the central cell.

Task 2: to demonstrate extended plasma lifetime in the central cell with the multiple-mirror end sections.

Task 3: to study the axial plasma end loss rate as a function of the value of the ion mean free path.

Task 4: to improve the plasma parameters with auxiliary plasma heating.

In parallel, a method of initial plasma build-up with a helicon discharge and gas puff into the central cell will be studied.

TABLE 1. The parameters of the helical mirror experiment.

	Value	Comments
n, cm^{-3}	10^{13}	
T_e, eV	10-100	
E_r, V/cm	100	
Plasma radius, cm	5	
Number of periods	12	
Period, cm	18	
B_{max}, T	0.1-0.3	
R	1.5-2	Average mirror ratio

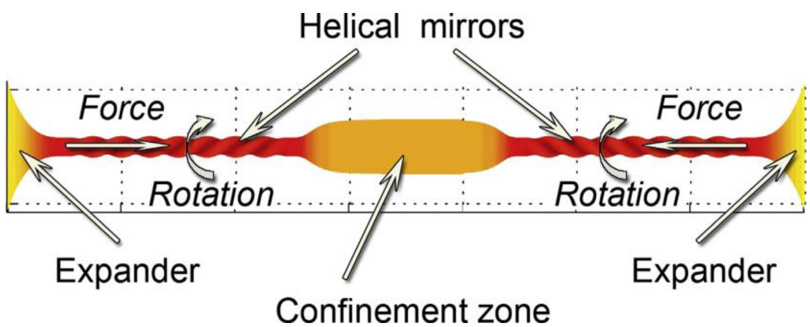

FIGURE 5. Scheme of the conceivable fusion reactor with helical multi-mirror end plugs.

HELICAL MIRROR EXPERIMENT – HEMEX

Recently, a novel method of stoppering of axial plasma flux in linear machines was proposed [5]. According to theory (see [26], superimposing of the helical magnetic field on to the axial field in the multi-mirror end plugs in combination with ExB plasma rotation would result in additional peristaltic end-stoppering of the axial plasma flow. In the reference frame rotating with plasma, the helically corrugated field looks like a series of axially moving mirrors (potential wells). Then, it is possible to choose the direction of the translation (inwards on both ends) and the sign of potential on axis (negative for radial pinch) simultaneously, so that the friction between the trapped and transiting ions would provide a force that is stoppering the axial plasma flow. In case of supersonic translation, the two-stream instability will guarantee sufficient friction between trapped and passing ions.

This idea will be proven in a small scale experiment named (SMOLA – HElical Mirror EXperiment – HEMEX). General view of this experiment shown in Fig.4. The parameters of the experiment are shown in Table 1.

Straight solenoid composed of 14 coils provides a uniform magnetic field upto 0.3T inside the 1.3m long operating volume. Special correction sections are used to match 3D magnetic axis with the geometrical axis of the expanders and to eliminate parasitic mirrors at the end of the helical sections. Plasma is produced by a plasma gun located inside the end tank. The plasma gun [27] with a plane LaB_6 cathode and magnetically insulated anode produces plasma with density $n \sim 2\times10^{19}$ m^{-3}, and temperature $T \sim 5$ eV . The anode and cathode are both electrically floating against the grounded vacuum chamber. A profile of the radial electric field in plasma can be varied by changing the anode bias relative to the radially segmented end-plate installed in the opposite end tank.

In case if the experiments prove the idea of confinement with the helical multi-mirror end plugs the fusion reactor based on this principle could be strongly shorten in length. Conceivable arrangement of such a reactor is shown in Fig.5.

EXPERIMENT ON BEAM–DRIVEN FIELD REVERSAL (CAT)

Injection of neutral beams is now the main method of hot ion plasma production in magnetic mirrors. Following the achievements of beta ~ 1 in quadrupole magnetic mirror experiments 2XIIB and BETA-II, it has been demonstrated that in axially symmetric GDT experiment plasma beta exceeded 0.6 at the fast ion turning points.

TABLE 2. The parameters of the CAT experiment.

	Value	Comments
n, cm-3	1-3×10^{13}	
Te, eV	3-150	
Beam energy, keV	15	
Plasma radius, cm	5	
Beam power, MW	3.5	In two beams
Impact parameter, cm	5	
B_{max}, T	0.45	
R	1.5	

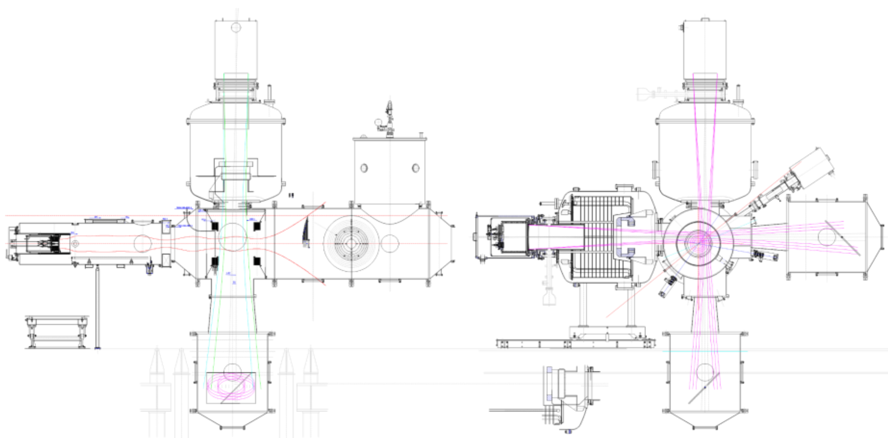

FIGURE 6. Experiment on field reversal in magnetic mirror.

Further increase of plasma pressure with higher neutral beam injection power may significantly improve the plasma confinement by increasing the effective mirror ratio or even form a reversed field configuration with transition to plasma confinement at the closed field lines.

The experiments on the beam reversal will be done at CAT device (Compact Axisymmetric Torus). The CAT magnet and neutral beam systems are shown in Fig. 6. The vacuum chamber consists of a cylindrical central cell 3.5 m long and 1 m in diameter and an expander tank attached to the central cell at the end. A set of coils mounted inside and on the vacuum chambers produce an axisymmetric magnetic field with a mirror ratio of 1.5 when the central magnetic field is set to 0.3 T. The initial plasma is produced by a washer stack hydrogen-fed plasma gun. The gun is located in one of the end tanks beyond the mirror throat. The two neutral beams are injected perpendicularly to the plasma axis. The beam duration of each injector is set to 5 ms. Neutral beam currents in excess of 250 equivalent atomic amperes will be injected with an accelerating voltage 15 keV. An NBI injected power of 3.5MW yields a fast ion pressure with $\beta > 1$ in several hundred microseconds after its start. Partial line tying on to the gun would provide stability to plasma column during accumulation of the fast ions. In between the plasma gun muzzle and the entrance mirror coil the magnetic field has a special profile with local minimum near the mirror coil which produces the effect of thermal barrier [23]. This effect was previously observed in the AMBAL experiment and was attributed to development of Kelvin-Helmholtz instability, which made the ion distribution to be strongly anisotropic in the region right at the entrance mirror coil. In the opposite end tank the magnetic field gradually decreases beyond the exit mirror thereby forming the thermal insulation from the end wall. The effect of suppression of electron thermal conduction was studies in the GDT experiments. We expect that this lead to decrease of the electron heat conduction to the both ends thus providing the conditions to self consistent increase of the electron temperature during the neutral beam injection. So, it is expected that the electron temperature of the gun-produced plasma should considerably increase from the initial value of 3–10 eV. The parameters of the CAT experiment are shown in TABLE 2. According to the results of the numerical simulations, the field reversal would become possible on an early stage of the beam injection. However, there are several open questions. The first one is a behavior of the electrons during the field reversal, which cannot be the fully modeled by the existing code. To

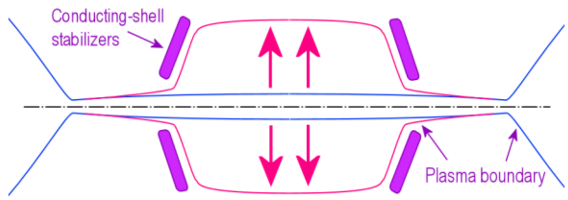

FIGURE 7. Scheme of diamagnetic confinement.

control the electron collisionality, which would be playing the critical role during the reversal, the electron gun would be installed on-axis in the tank opposite to the plasma gun. Another problem would be development of the plasma instabilities during the reversal which would deteriorate plasma confinement. To stabilize the unstable tilts it is foreseen to vary the plasma axial extent by slight changing of injection angle or by changing the axial positions of the internal mirrors coils. The remaining unstable azimuthal mode n=1,2 would be stabilized by the line tying to the gun. To ensure this stability, a sufficiently high density plasma is to be maintained in between the central cell and the gun.

Further in the experiments it is planned to prove the idea of the diamagnetic plasma confinement [25], which would be realized if the magnetic field inside plasma is decreased, so that the effective mirror ratio grows significantly. The idea is illustrated in Fig.7, which shows distortion of the field lines during the increase of the plasma pressure in an axisymmetric magnetic mirror. During the accumulation of the fast ions and growing of the plasma diamagnetism, the plasma equilibrium evolves into a bubble-shaped form. The plasma would be roughly cylindrical in shape and is stabilized by conducting shell as shown in Fig.7. In the case of classic diffusion and under assumption that the end losses corresponds to collisional plasma flow through the end mirrors, as in the GDT, the conceivable parameters for $L = 30$ m, $B_0 = 10$ T, and initial mirror ratio of $R = 2$, would correspond to $n\tau_E \approx 1.4\times10^{15}\ cm^{-3}s$ at $T = 9$ keV, i.e. as in *D-T* fusion reactor.

CONCEIVABLE GDT-2 EXPERIMENT

The GDT device is being operated since its construction in 1986. It passed thought several upgrades, but nevertheless the main disadvantage still persists – the plasma in GDT can only be confined in the transient regimes. Especially it true after achieving of ~1 keV electron temperature with auxiliary ECR heating. Therefore, the next step in GDT modernization would be the installing of the superconducting coils and considerable extension of the neutral beam injection pulse to 20-30ms. That would enable to study plasma steady state that would of critical importance for prospects of the GDMT project. In turn this will require to develop specific methods of plasma fueling and handling of the neutral gas loads which is applicable in GDMT device .

The assumed bulk plasma parameters are close to those established in present-day GDT experiments. In particular, note the relatively low values for the field at the magnets. The bulk thermal plasma is assumed to be hydrogen or deuterium. To maximize the beta value, the neutral beam source energy is to be 40-60 keV for the magnetic field is 0.5-0.6 T at the midplane. The fast ions are assumed to slow down classically as in the conditions of GDT, yielding a neutron rate that depends principally on the electron temperature. The assumed thermal energy confinement time is comparable to the values obtained in the current experiments in the transient regimes.

DEVELOPMENT OF NB INJECTION SYSTEM FOR GDMT

To develop an injector module for the GDMT device a special conceptual design study has been initiated. The result of the conceptual design of the module is shown in Fig.8. In fact, the main features of the injector module design was chosen based on studies of the several prototypes. In basic version, the ion optical system with 3 slotted grids is used. The ion source grids are actively cooled enabling the source to operate in long a pulse mode with duration of ~ 100s. The beam parameters are given in Table 3.

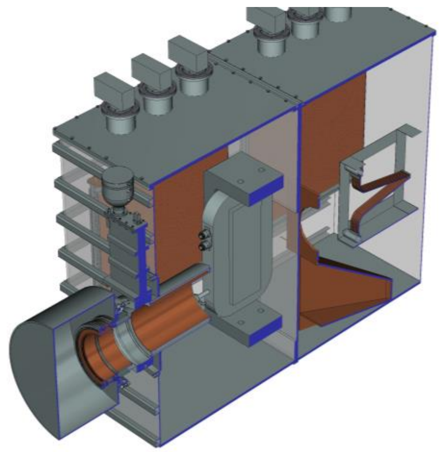

FIGURE 8. View of injector module: 1 –ion source, 2-neutralizer, 3 – magnetic separator, 4-residual ion dump, 5 – retractable calorimeter, 6 – cryopanels.

TABLE 3. The beam parameters

Parameter	Value	Comments
Beam energy, keV	40-100	Switchable
Ion current, A	100	
Pulse duration, sec	upto100	

CONCLUSION

At the moment, the linear systems for plasma confinement, which are studied at the Budker BINP, have demonstrated their advantages and, at the same time, certain problems are revealed that should be resolved if the fusion prospects of these systems are considered. These problems are the following. First, so far the linear machines are operated with relatively short pulse length. That means that the plasma can only be studied in transient regimes with limited performance. Secondly, the problem of too high end losses in the linear systems still persists. In the meantime, many ideas have emerged how to suppress the end losses, but still there no more or less universal recipe, which would be recommended for fusion grade devices of this type. In the Budker Institute, we developed a road map for addressing these problems in the next generation of the experimental devices. The future device at the Budker Instutite should operate in steady-state or in a long pulse operation mode. In order to solve the problem of high end losses we are considering several projects, in which we could prove the different methods. We believe that the development of the axisymmetric linear traps are a commercially viable path to fusion. In particular, these traps are looking very attractive for advanced fuels, like tritium-less D-D, or even in the future for neutron-free p-11B fuel.

ACKNOWLEDGMENTS

This work was supported by Russian Science Foundation (project 14-50-00080).

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