Studies of Plasma Confinement and Stability in a Gas Dynamic Trap: Results of 2016 - 2018*)

Peter A. BAGRYANSKY, Egor D. GOSPODCHIKOV, Alexander A. IVANOV, Andrey A. LIZUNOV, Evgeny Yu. KOLESNIKOV, Zahar E. KONSHIN, Olga A. KOROBEYNIKOVA, Yury V. KOVALENKO, Vladimir V. MAXIMOV, Sergey V. MURAKHTIN, Egor I. PINZHENIN, Vadim V. PRIKHODKO, Valery Ya. SAVKIN, Alexander G. SHALASHOV, Dmitry I. SKOVORODIN, Elena I. SOLDATKINA, Alexander L. SOLOMAKHIN and Dmitry V. YAKOVLEV

Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences, Novosibirsk, Russia

(Received 28 September 2018 / Accepted 19 December 2018)

Paper presents a brief overview of the studies carried out in 2016-2018 at the Gas Dynamic Trap device at the Budker Institute. These studies were focused on the experimental substantiation of a new version of the Gas Dynamic Multi-mirror Trap project, which is aimed at developing the key technologies needed to implement a number of thermonuclear applications of linear magnetic traps. The paper reviews the work aimed at stable plasma confinement under auxiliary ECR heating. We showed that a value of on-axis electron temperature up to 450 eV at plasma density 1.2×10^{19} m^{-3} can be supported steadily. Studies on processes in expanders, which determine the axial thermal conductivity of the plasma, showed that the profile of the electric potential in the expander corresponds to a theory that gives favorable predictions regarding the thermal insulation properties of the expander. It was shown that the density of neutral gas in the expander in the range up to 10^{20} m^{-3} does not have a significant effect on energy confinement in the trap, despite an estimate of the critical density of 10^{18} m^{-3}.

Keywords: nuclear fusion, mirror trap, gas dynamic trap, plasma confinement, MHD stability, electron cyclotron resonance heating, axial electron conductivity

DOI: 10.1585/pfr.14.2402030

1. Introduction

This article provides a brief overview of the results of the studies obtained from 2016 to 2018 on the Gas Dynamic Trap (GDT) device [1] at the Budker Institute (Novosibirsk, Russia). These studies were mainly focused on the experimental substantiation of a new version of the Gas-Dynamic Multi-mirror Trap (GDMT) project, which is currently being developed at the Budker Institute in collaboration with a number of domestic and foreign organizations [2]. The project aims at developing the key technologies needed to implement a number of thermonuclear applications of open magnetic traps with a linear axisymmetric configuration. These possible applications include neutron sources for solving problems of thermonuclear material science, reprocessing spent nuclear fuel and control of fission reactors operating in a subcritical mode. The implementation of new ideas of plasma confinement: diamagnetic [2, 3] and helical [2, 4, 5] opens up in the project with the possibility of development on the basis of open-type traps relatively compact nuclear fusion reactors capable of working with alternative fuels that do not contain radioactive tritium (DD, D^3He), and possibly fuel that does not produce neutrons (p-^{11}B) [2].

The paper reviews the work aimed at stable plasma confinement under conditions of additional ECR heating combined with heating by neutral beam injection. We showed that a value of on-axis electron temperature up to 450 eV at plasma density 1.2×10^{19} m^{-3} can be supported steadily for 1.5 ms limited by the available heating and magnetic confinement systems. Stable high temperature discharge, no longer degraded by low-frequency instabilities, offered a unique opportunity to confirm quantitatively the gas dynamic plasma confinement model in a new range of parameters [6].

The review also gives results of studies on physical processes that develop in the region of the expanding magnetic field behind magnetic mirrors and determine the longitudinal electron thermal conductivity of the plasma. It was shown that the behavior of the electric potential and the characteristic electron energy in the expander basically corresponds to a theory that gives favorable predictions regarding the thermal insulation properties of the expander [7]. Experiments to study the influence of neutral gas in the expander on plasma confinement in the central part of the GDT were carried out. It was shown that the key parameters of the plasma remain constant over a wide range of gas densities in the expander n = (10^{16} - 10^{20} m^{-3}) de-

author's e-mail: p.a.bagryansky@inp.nsk.su

*) This article is based on the presentation at the 12th International Conference on Open Magnetic Systems for Plasma Confinement (OS2018).

spite the estimate of the critical density of $10^{18}\,\mathrm{m}^{-3}$. It was shown also, that the hypothesis that the gas is extruded from plasma due to collisions with plasma particles has experimental basis.

2. Encouraging Results and New Ideas Underlying the Project of GDMT

The new version of the GDMT project differs from the previous version developed in 2012 [8] in that it is based on new results obtained over the last decade on the GDT device which demonstrated the possibility of overcoming key problems of plasma confinement in open magnetic traps with a linear axisymmetric configuration. In addition, the project is based on new ideas that open the possibility of drastically improving longitudinal plasma confinement in such systems in comparison with the classical mirror cell. This, in turn, gives the principal grounds for the development based on linear traps of relatively compact thermonuclear reactors capable of working with alternative fuels: DD, D^3He and even $p^{11}B$.

According to the authoritative expert opinion [9], the key problems of plasma confinement in open-type traps are the following:

- suppression of transverse transport caused by MHD instabilities for linear axisymmetric traps;
- overcoming the influence of micro-instabilities;
- achievement of the values of the electron temperature relevant for nuclear fusion applications.

The lack of obvious success in solving these problems has caused a drastic reduction in worldwide research activity in the field of mirror traps at the turn of the eighties and nineties of the last century.

These three problems were successfully solved. Experiments at the GDT device demonstrated that

- stable high energy density plasma can be confined with simple circular magnets [10];
- micro-instabilities can be suppressed [11];
- electron temperature reaching a keV values had been measured [12].

These three accomplishments provide a basis to reconsider the mirror concept as a neutron source for materials development, nuclear fuel production, spent fuel reprocessing, driver for hybrid fusion-fission reactors, and as pure fusion reactor for energy production [9].

As been mentioned above, the new version of the GDMT project is also based on two proposals that open the possibility to drastically reduce the longitudinal plasma losses in mirror traps – ideas of helical confinement [2,4,5] and diamagnetic confinement [2,3].

The idea of helical confinement is to realize a new type of axial confining system for linear plasma devices. It is based on $E \times B$ plasma rotation in a nonuniform helical magnetic field. In the rotating reference frame the helical ripples of the magnetic field look like traveling waves propagating along the system axis. Due to parallel plasma viscosity and/or collisions with locally trapped particles, the plasma as a whole will acquire axial momentum. Related processes have been observed in tokamaks as transformations between poloidal and toroidal rotation components. The main conclusion from the theoretical analysis of the effectiveness of suppressing the longitudinal flow of plasma that moves through the helical system is that the density of the axial flow of particles and energy from the mirror cell with the attached helical end sections decreases exponentially with the number of cells at the end section. For comparison, the density of the axial flow of particles and energy from the mirror cell with the attached multi-mirror systems decreases inversely proportional to the number of cells of the end system [2, 13].

The idea of diamagnetic confinement arose as a result of analysis of the plasma equilibrium with the maximum attainable relative pressure $\beta \approx 1$ [3]. The plasma equilibrium in a linear trap at $\beta \approx 1$ under the topology-conservation constraint evolves into a kind of diamagnetic "bubble". This can take two forms: either the plasma body greatly expands in radius while containing the same magnetic flux, or, if the plasma radius is limited, the plasma distribution across flux-tubes changes, so that the same cross-section contains a greatly reduced flux. If the magnetic field of the trap is quasi-uniform around its minimum, the bubble can be made roughly cylindrical, with radius much larger than the radius of the corresponding vacuum flux-tube, and with non-paraxial ends. Then the effective mirror ratio of the diamagnetic trap becomes very large, but the cross-field transport increases. The confinement time can be found from solution of the system of equilibrium and transport equations and is shown to be $\tau_E \approx (\tau_\parallel \cdot \tau_\perp)^{1/2}$, where $\tau_\parallel$, $\tau_\perp$ are characteristic axial and transverse confinement times. If the cross-field confinement is not too degraded by turbulence, this estimate in principle allows construction of relatively compact fusion reactors with lengths in the range of a few tens of meters [2]. In many ways, the described diamagnetic confinement and the corresponding reactor parameters are similar to those claimed by the field-reversed configurations.

3. Recent Version of the GDMT Project

Below we list all possible requests for the realization of thermonuclear projects based on linear traps.

- ♦ Neutron sources (DT) for:
  - material testing (for this application, it is required to achieve a power density of neutron flux $j \sim 2\,\mathrm{MW/m^2}$ on the surface of the test area $S \sim 1\,\mathrm{m^2}$);
  - the reprocessing of minor actinides from spent nuclear fuel by the transmutation method (total neutron flux $J_\Sigma \geq 10^{18}\,\mathrm{s^{-1}}$ is required for this application);

- control of fission reactors operating in subcritical mode (total neutron flux $J_\Sigma \geq 10^{19}\,\mathrm{s}^{-1}$ is required).

♦ Relatively compact fusion reactors capable of operating with alternative types of fuels: those that do not contain tritium (DD, D^3He) and do not produce neutrons (p-^{11}B).

Based on these requests, we can formulate all possible goals for the implementation of the GDMT project.

♦ Development of technologies needed for neutron sources (DT):
  - material testing (the peaked distribution of the density of the neutron flux along the axis of the device is required. According to the results of numerical simulation, a peaked distribution of the axial density of the neutron flux can be formed with an oblique injection of neutral beams and an axial magnetic field profile with a minimum gradient size in the stopping region of hot ions);
  - transmutations and control of subcritical fission reactors (homogeneous neutron flux density is required).

♦ The development of technology and demonstration of the effectiveness of new confinement modes:
  - diamagnetic, the goal is to demonstrate the possibility of achieving an effective thermonuclear power gain in the case of the DT reaction $Q_{\mathrm{DT\_eff}} \approx 1$;
  - helical, the goal is to demonstrate that the density of the axial flow of particles and energy from the mirror cell with the attached helical end sections decreases exponentially with the number of cells;
  - multi-mirror with low level of plasma density, the goal is to demonstrate that the density of the axial flow of particles and energy from the mirror cell with the attached multi-mirror end sections decreases inversely proportional to the number of cells of the end system.

One of the main tasks of researches under the GDMT project is a comparison of multi-mirror and helical sections attached on both sides to a magnetic trap in terms of their ability to reduce effectively the axial flux of plasma particles and energy from the trap. According to the results of the comparison, the most effective system should be selected for its further use in future installations of the reactor class.

The recent version of the GDMT project assumes a modular construction principle that allows realizing all requests to the project, using all available developments and ideas. Figure 1 shows a schematic view of GDMT device. GDMT includes a central part – module of neutral beam injection (NBI), a solenoidal cell that together with the NBI module are part of a magnetic trap, as well as replaceable end sections, which, depending on the experimental program, can be multi-mirror or helical. On the ends of the installation are located expander tanks. The entire magnetic system is assumed superconducting.

The solenoidal cell also has a modular structure; it consists of identical three-coil modules having separate power supplies for each coil. Figure 2 gives schematic view of NBI module and solenoidal cell in configuration

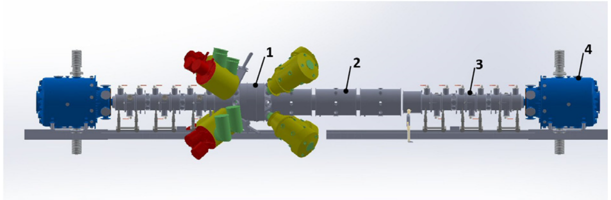

Fig. 1 Schematic view of GDMT device: 1 – NBI module; 2 – solenoidal cell (can be adapted for configurations corresponding to a neutron source prototype or a diamagnetic trap); 3 – end cell (multi-mirror or helical); 4 – expander/divertor.

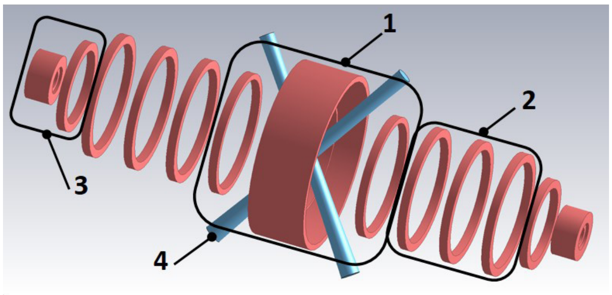

Fig. 2 Schematic view of GDMT central part in configuration of diamagnetic trap: 1 – NBI module; 2 – three-coil module; 3 – mirror plug; 4 – neutral beams.

Table 1 Parameters of the magnetic system of GDMT as well as plasma parameters predicted in the configuration of diamagnetic trap.

Parameters of GDMT magnetic system	
Length	~ 5m
Diameter of main coils	1.3 m
Diameter of the central coil	2 m
Magnetic field in the center	0.3 - 3 T
Field rise time	5 s
Field in mirror plugs	11/18 T
Basic plasma parameters	
Radius in the center	0.3 m
Length of plasma column	~ 4 m
Total power of NBI	10 MW
Energy of neutrals	40 keV
Time of NBI operation	5 s
Mean ion energy	~ 20 keV
Plasma density	10^{20} - 10^{21} m^{-3}

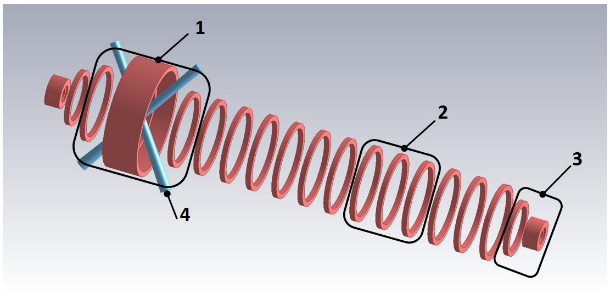

Fig. 3 Schematic view of GDMT central part in configuration of neutron source prototype: 1 – NBI module; 2 – three-coil module; 3 – mirror plug; 4 – neutral beams.

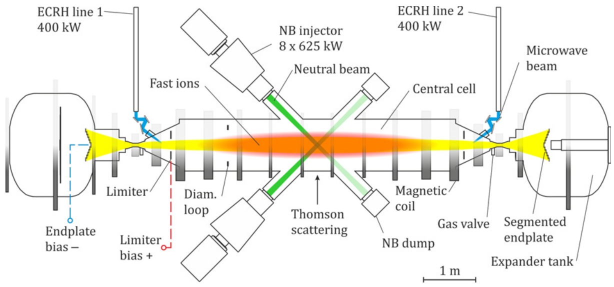

Fig. 4 Schematic of the experiment. At the both ends are shown the new plasma-facing endplates for tuning of the radial distribution of plasma potential in the axial region.

of diamagnetic trap.

Parameters of the magnetic system as well as plasma parameters predicted in this configuration are listed in Table 1.

Figure 3 demonstrates schematic view of GDMT central part in configuration of neutron source prototype. The length of the central part of the magnetic system in this configuration is 10 meters; the magnetic field in the central plane of the trap is up to 2 T. At the time of this writing, the development of the conceptual design of the superconducting magnetic system of GDMT central part has been completed.

4. Stable Confinement of High Electron Temperature Plasmas in the GDT Experiment

The increase of the electron temperature to keV-level along with the results of previous GDT experiments, which demonstrated plasma confinement with a high ratio of plasma pressure to magnetic pressure of $\beta \approx 60\%$ [10, 14], provide a basis for extrapolating the gas dynamic trap concept to fusion-relevant applications. These parameters are adequate for a neutron source to test and develop fusion materials [1, 15], or to initiate work on subcritical fission reactors and nuclear waste processing based on a fusion-driven burning of minor actinides [16].

These results encourage expectations that higher temperatures needed for fusion power are indeed possible in open traps [9]. While the reported experiments confirmed the core principles of longitudinal electron heat flux suppression in a carefully selected open field line geometry [17, 18], it faced difficulties with mitigation of anomalous transport related to the development of magnetohydrodynamic (MHD) instability of the plasma column. In particular, when the microwave power was focused in a narrow near-axial plasma region thereby leading to a highly peaked electron temperature radial profile, the duration of effective heating was always limited to about 0.6 ms; later on, a flute instability with azimuthal wavenumber $m = 1$ and a frequency of several kHz developed preventing further absorption of microwaves [12].

Owing to the fact that ECRH with intentionally broad power deposition and less steep temperature gradient does not lead to instability [12], it was proposed that T_e is in some way related to the issue. Similar problems were faced in the GAMMA 10 experiment [19]. We develop and experimentally investigate a technique to stabilize plasma during the whole microwave heating stage in an axially symmetric mirror trap. This technique based on radially sectioned biasing end plates (target plates), installed at both ends of the GDT device, to reduce the radial gradient of the plasma potential by means of biasing external electrodes (see Fig. 4).

At GDT, we demonstrated plasma discharges with parameters close to the reported record ones [12], but characterized by low MHD activity level and duration limited only by the available heating and magnetic confinement systems.

We have shown experimentally that a local modification of the radial distribution of the plasma potential allows for a complete suppression of the MHD-instability caused by strong ECR heating and enables to maintain a high-electron-temperature plasma in a large mirror trap. In particular, a stable electron heating up to 450 eV during 1.5 ms period with ECRH power of 400 kW was demonstrated for the first time at GDT facility. Concerning the absolute values of electron temperature, we note that these results are completely in line with previously reported values, considering the increased plasma density and halved microwave power of current experiment. Therefore, there is virtually no overhead cost to applying the developed stabilization technique. By performing a dedicated experiment with a stable high-temperature plasma, we were able to delve deeper into the basic plasma confinement physics. The longitudinal gas-dynamic energy loss rate was found to be in agreement with available theoretical and experimental data. More elaborate analysis based on new data will follow. The minimum value of the external potential sufficient for stabilizing the plasma is quite modest, so likely our technique may be extrapolated to even higher temperatures and to larger devices without overwhelming engineering difficulties. A detailed description of this experiment is given in [6]. Note that in our opinion, the observed effect of MHD-stabilization during ECR heating cannot be associated with the effect of line-tying when bias are applied to end plates. The argument for this conclusion is the fact, that there is no stable confinement in the presence of bias on the end plates and at the same time the absence of bias on the radial limiters, that ensure the vortex confinement.

5. Study of Physical Processes in the Expander

The main objectives of today's research on physical processes that determine the longitudinal thermal insulation of plasma in a GDT device are as follows:

- reliable scaling that will allow us to extrapolate today's experimental data on longitudinal confinement to the parameters of thermonuclear class facilities;
- adequate design of GDMT expander/divertor units.

These objectives determine the primary key issues important for development of new facilities based on magnetic mirror trap.

1) What is the minimum expansion ratio R_{min} of magnetic flux lines behind the mirror throat in which electron emission from target plate affects insignificantly on longitudinal heat losses in the mirror trap?
2) What is the value of ambipolar potential drop in Debye layer at the vicinity of target plate surface installed in position with $R \geq R_{min}$?
3) How the vacuum conditions in the expander affect the confinement of energy in the trap?

Current theoretical understanding of expander/divertor physics is summarized in [18]. The main conclusions are:

1) main feature of the expander is existence of a fraction of electrons trapped in a well of effective potential between the magnetic mirrors and the negatively biased target plate;
2) the theory predicts monotonic decay of potential in the whole expander region from mirror throat to the Debye layer at the vicinity of the target plate;
3) in the case of expansion ratio $R \geq (m_i/m_e)^{1/2}$ theory predicts that the value of potential drops in Debye layer becomes much less than T_e;
4) characteristic energy of electrons at the vicinity of target plate becomes also much less than T_e;
5) for the case $R \geq (m_i/m_e)^{1/2}$ theory predicts negligible influence of electron emission from target plates on energy confinement in mirror trap.

The current state of experimental studies of processes in the expander, which determine the longitudinal thermal insulation, is summarized in [7, 20]. The main conclusions of these works are as follows:

1) plasma parameters in the central cell remain constant in the range of expansion ratio $30 < R < 200$;
2) potential drop in Debye layer near the end plate for expansion ratios $R > 30$ appeared to be much lower than electron temperature in the center of the trap;
3) characteristic energy of electrons in the vicinity of end plate at $R > 30$ is also much lower than electron temperature at corresponding magnetic force line inside the mirror cell. That indicates the presence of electrons population confined in expander by effective Yushmanov's potential [21];
4) the key parameters of the plasma remain constant over a wide range of gas densities in the expander $n = (10^{16}$ - 10^{20} m$^{-3})$ despite the estimate of the critical density of 10^{18} m^{-3}. It was shown, that the hypothesis, that the gas is extruded from plasma due to elastic collisions with plasma particles, has experimental basis.

Acknowledgments

The works included in this review were carried out with the support of Russian Science Foundation: project #14-50-00080 – Section 2; project #14-12-01007 – Section 4; project #18-72-10084 – Section 5. The results presented in Sec. 3 were obtained under auspices Russian Federal Agency for Scientific Organizations.

[1] A. Ivanov and V. Prikhodko, Plasma Phys. Control. Fusion **55**, 063001 (2013).
[2] P.A. Bagryansky, A.D. Beklemishev and V.V. Postupaev, J. Fusion Energy **38**, 162 (2019). https://doi.org/10.1007/s10894-018-0174-1
[3] A. Beklemishev, Phys. Plasmas **23**, 082506 (2016).
[4] A.D. Beklemishev, Fusion Sci. Technol. **63**, (No. 1T), 355 (2013).
[5] A.D. Beklemishev, AIP Conf. Proc. **1771**, 040006 (2016).
[6] D.V. Yakovlev *et al.*, Nucl. Fusion **58**, 094001 (2018).
[7] E. Soldatkina *et al.*, Phys. Plasmas **24**, 022505 (2017).
[8] A. Beklemishev *et al.*, Fusion Sci Technol, **63** (No. 1T), 46 (2013).
[9] T.C. Simonen, J. Fusion Energy **35**, 63 (2016).
[10] T.C. Simonen *et al.*, J. Fusion Energy **29**, 558 (2010).
[11] K.V. Zaytsev *et al.*, Physica Scripta **2014** (No. T161), 014004 (2014).
[12] P.A. Bagryansky *et al.*, Phys. Rev. Lett. **114**, 205001 (2015).
[13] I.A. Kotelnikov, Fusion Sci. Technol. **51** (No. 2T), 186 (2007).
[14] P.A. Bagryansky *et al.*, Fusion Sci. Technol. **59** (No. 1T), 31 (2011).
[15] P.A. Bagryansky *et al.*, Fusion Eng. Des. **70**, 13 (2004).
[16] D.V. Yurov and V.V. Prikhodko, Phys.-Usp. **57**, 1118 (2014).
[17] I.K. Konkashbaev *et al.*, J. Exp. Theor. Phys. **47**, 501 (1978).
[18] D.D. Ryutov, Fusion Sci. Technol. **47**, 148 (2005).
[19] T. Imai *et al.*, Trans. Fusion Sci. Technol. **63**, 8 (2013).
[20] E. Soldatkina *et al.*, Plasma Fusion Res. **14**, 2402006 (2019).
[21] E.E. Yushmanov, Sov. Phys. JETP **22**, 409 (1966).