MAGNETIC MIRRORS: HISTORY, RESULTS, AND FUTURE PROSPECTS

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The evolution of open traps brought them from simple solenoids to highly sophisticated and huge tandem mirrors with quadrupole magnetic stabilizers. They tried to compete with toroidal devices using ambipolar confinement and thermal barriers, but were too late and failed, and are almost extinct. A side branch of open traps went for simplicity and good fast-ion confinement inherent in axially symmetric mirrors. Since simplicity means lower cost of construction and servicing, and lower engineering and materials demands, such type of traps might still have an edge. Axially symmetric mirrors at the Budker Institute of Nuclear Physics in Novosibirsk currently represent the frontline of mirror research. We discuss recent experimental results from the multiple-mirror trap, GOL-3 [1], and the gas-dynamic trap, GDT [2]. The next step in this line of research is the GDMT program that will combine the GDT-style fast-ion-dominated central mirror with multiple-mirror end plugs. This superconducting device will be modular and built in stages. The first stage, GDMT-T, will be based on 5m, 7T superconducting solenoid (multiple-mirror plug of the full device). Its 3-year scientific program is oriented primarily on PMI studies.

PACS: 52.55.Dy, 52.55.Jd, 28.52.-s

HISTORY OF MIRROR RESEARCH

Early years of fusion research were covered by the shroud of secrecy, so that nothing was really published until 1955, when this science area was declassified. As a result, the idea to use adiabatic confinement of plasma particles for controlled fusion (Fig. 1) originated independently in US, where it is attributed to R.F. Post, and in USSR, where it was proposed by G.I. Budker (Fig. 2,3). According to Fowler [3], in 1952 Post experimented with confinement in ECH discharges in a solenoid with stronger coils at the ends. By that time, the magnetic mirror phenomenon itself was already known from cosmology, while the magnetic confinement for fusion was being explored for toroidal configurations. According to Dimov [4], Budker and Post proposed the mirror confinement concept independently in 1954.

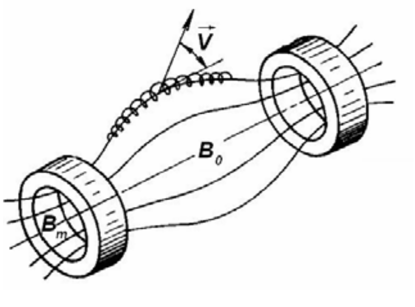

Fig.1. Confinement of particles in a magnetic field between stronger field areas, dubbed mirrors, is due to the adiabatic conservation of the magnetic moment and particle energy

The story of development of mirror traps for fusion is dramatic: there were periods of high hopes and booming growth, periods of innovation and sudden twists in construction, dark periods of disappointment and neglect. In 1957 Rosenbluth predicted that mirrors will be unstable to flute-interchange modes. However, in 1958, when first sizable mirror devices OGRA (in USSR) and DCX (in US) entered operation, no such instability was identified. It wasn't observed until 1961, when Ioffe confirmed its existence on PR-2 machine. The discovery caused significant disappointment, but it was quickly countered by Ioffe himself, who proposed to use quadrupolar field corrections to stabilize the flute modes. Since then the coils serving the purpose are dubbed the Ioffe rods.

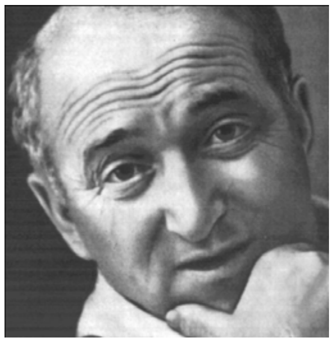

Fig. 2. G.I. Budker

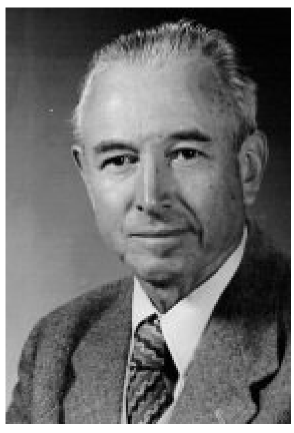

Fig.3. R.F. Post

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

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

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

In 1971 Budker et al., and Logan et al. independently proposed the idea of a multiple-mirror trap. It seeks to improve the axial confinement by considering plasma outflow through a sequence of mirrors, rather than through a single mirror throat. Unfortunately, it promised improvement only in very dense plasmas, which placed such traps in the domain of inertial machines rather than steady-state reactors. In 1974 Pastukhov derived his famous formula allowing evaluation of axial confinement in mirrors with axial ambipolar electric fields. In 1976 Dimov, Fowler, and Logan independently proposed the idea of a "tandem mirror" or an "ambipolar trap". In it the specially-produced populations of hot ions in small plugging mirrors at both ends of a solenoid produce ambipolar barriers, stifling the plasma outflow (Fig. 4).

The tandem-mirror idea proved to be extremely popular and successful. In 1978 GAMMA-6 in Japan provided evidence of formation of ambipolar barriers and improved confinement, and a much bigger machine, TMX, entered operation in Livermore. In 1979 it reached its peak parameters of β=40 %, T_e~250 eV, n_e~3x10^{19}m^{-3} with 7 MW NBI, which produced 1 keV-high ambipolar barriers. These plasma parameters are essentially still unsurpassed in other open traps. In the same year a further improvement on the idea of a tandem mirror, the thermal barriers, was proposed by Baldwin and Logan. Shaping of the profile of the ambipolar potential by heating electrons in an additional plugging mirror promised thermal insulation of the electron component from the end walls. The invention caused hasty mid-work corrections in the design of MFTF, which became MFTF-B, TMX was modified to become TMX-U.

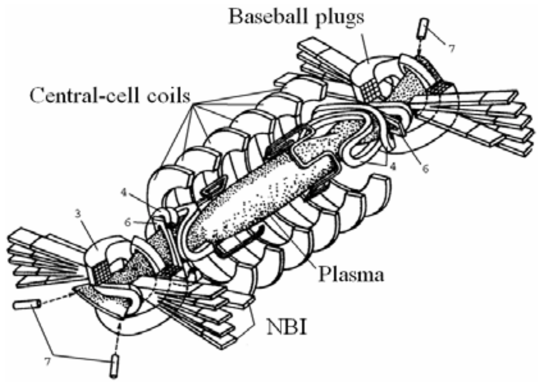

Fig. 4. Scheme of a tandem mirror (ambipolar trap) based on the TMX design

Ryutov and Stupakov showed that the large neoclassical-like resonant transport would be present in non-axisymmetric quadrupole fields. The problem could be addressed by making the main trap body symmetrized, while retaining quadrupole anchors at far ends of the device. New sophisticated facilities - TARA (in US), GAMMA-10 (Japan), AMBAL (USSR) entered the construction stage.

The period 1978-1987 can be called the Golden Age of mirror research. Besides tandem mirrors, flourishing in US, other confinement schemes emerged: in 1979 Mirnov and Ryutov proposed the gas-dynamic trap, in 1983 successful experiments on PSP-2 confirmed efficient centrifugal confinement in supersonically rotating plasma. In 1982-1984 a comprehensive analysis of fusion technologies and perspectives for tandem mirrors was completed by the TASKA team.

As the tandem-mirror design became more and more complex, the time and resources spent on each unit multiplied. Furthermore, complex plasma shape caused additional instabilities and transport. In particular, placing poorly-conducting thermal barriers between the main trap body and quadrupole anchors reduced their stabilizing efficiency. Thus, the early results of newly-constructed facilities were disappointing, especially in comparison with tokamaks. This led to a sudden and abrupt end of the open-traps program in US and of the Golden Age of mirrors. Faced by a choice of spending limited budget on tandem mirrors or on TFTR, the US DoE made the decision in favor of tokamaks. In 1987 the mirror research in US was terminated. MFTF-B was dismantled right after completion. Nevertheless, some die-hard activity in other countries persisted.

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

In 1988 the new generation of fully axisymmetric traps entered the scene. These were: the small-size ICRH-heated tandem mirror HIEI in Japan, the gas-dynamic trap GDT, and the multiple-mirror trap GOL-3 in Novosibirsk. By 1993 the main ideas behind stabilization of the gas-dynamic trap, the expander- and FLR-stabilization mechanisms were confirmed. HIEI reported promising results on suppression of radial transport by limiter biasing. Besides progress in theory, the last 20 years of mirror research were marked by steady progress in plasma parameters in Novosibirsk traps. By 2006 the GDT team reported β=60 %, T_e~200 eV, n_e~3x10^{19} m^{-3} by using limiter biasing for stabilization with turned-off expanders. The scheme of GDT is shown in Fig. 5.

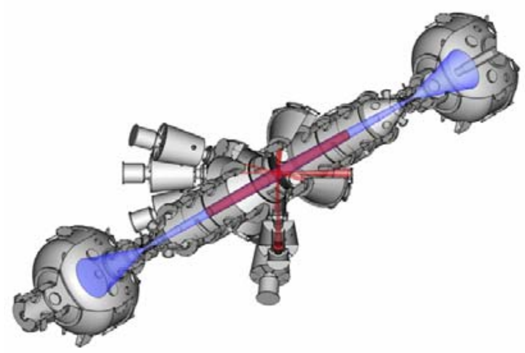

Fig. 5. GDT is a classical mirror with sloshing injected ions (red), stabilized by warm collisional plasma (blue). The plasma outflow is limited by the nozzle effect

The GOL-3 team observed plasma heating (of both, ions and electrons) up to 3 keV during turbulent heating by the relativistic electron beam. After the heating phase the multiple-mirror enhancement of confinement was found, which was even 10^2 times better than predicted at densities ~10^{20} m^{-3}. Many new stabilization schemes for axially symmetric mirrors were proposed by D.D. Ryutov, R.F. Post and others.

1. CURRENT STATUS

There are three relatively large traps (>10m long) in operation: GAMMA-10, GDT and GOL-3. Due to recent misfortunes, the team of GAMMA-10 is now oriented on PMI studies and seems to be out of the fusion race. This makes the axially symmetric traps in Novosibirsk the main representatives of the mirror community still aiming at fusion. However, one should also mention a medium-sized centrifugal trap MCX in US; it is still trying to improve on the PSP-2 legacy.

After several modifications the GDT parameters reached the record set by TMX, β=40 %, T_e~250 eV, n_e~3x10^{19} m^{-3}, in a transient state, while the electron temperature grows almost linearly during all 5ms of injection. Estimates show that tripling the injection time would increase the temperature by 50 %, but this would also exceed the β limit on confinement. Thus, GDT surpassed expectations of designers and reached its limits. The plasma parameters are in fact close to those set for the Hydrogen Prototype program, which was conceived as the final stage before construction of the actual neutron source. There was an important unexpected achievement of the GDT team in physics of confinement. It is the successful implementation of the vortex-confinement scheme for plasma stabilization by means of plasma biasing [5]. The influence of vortex confinement on radial transport also includes strong pinch effect in sloshing ions. The vortex confinement is cheap both in terms of spent power and in construction costs, and is predicted to be useable in fusion conditions.

GOL-3 also reached and outperformed most of its original aims (Fig. 6). The electron-beam heating technology works. It simultaneously provides fast ion heating up to 3 keV and suppression of axial electron heat conductivity by a factor of >10^3. Suppression of heat conductivity is interpreted as due to enhanced collision rate.

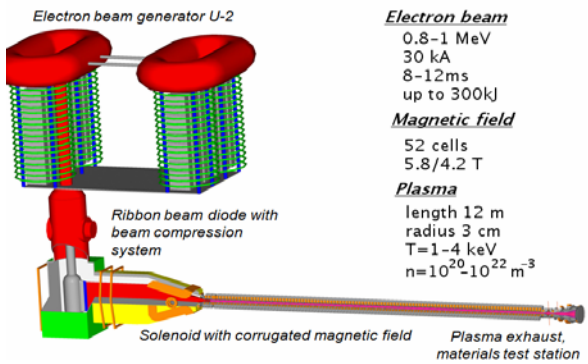

Fig. 6. Scheme and parameters of the GOL-3 device

The multiple-mirror confinement of ions in the corrugated field is also observed. However, the wall-confinement at β>1 was not achieved for unknown reasons. This makes the original pulsed-fusion scheme unlikely. Instead, the discovery of low-density anomalous multiple-mirror effect (Fig. 7) provides a new, unexpected way to make the multiple-mirror reactor stationary.

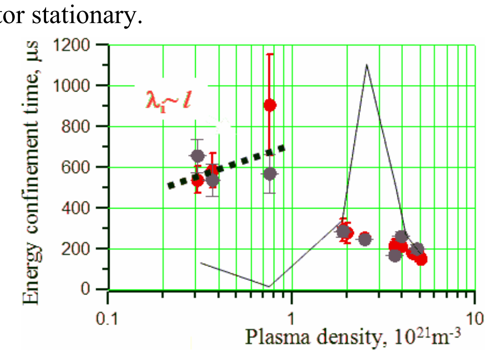

Fig.7. Energy confinement time in GOL-3 (after beam turn-off) vs. Coulomb and collective scattering models. The ion temperature is a function of density. It is much higher than the electron temperature at this stage

Performance of GOL-3 and GDT has been exceptional. In fusion parameters they are on par with tokamaks of similar age, like T-10 (Fig. 8). However, since GOL-3 and GDT are in operation for around 20 years already, it is hard to expect from them any further breakthroughs.

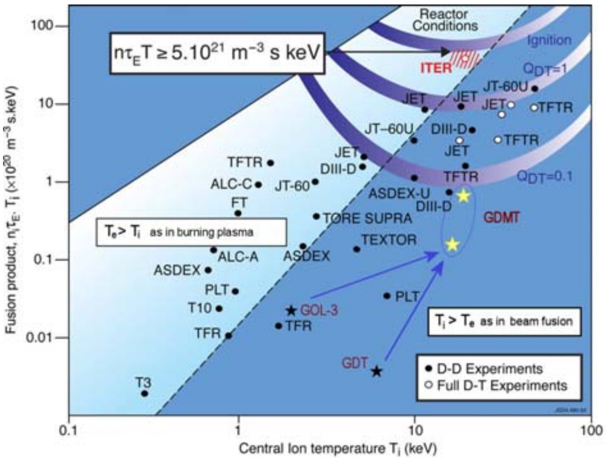

Fig. 8. Fusion-relevant parameters of traps in Novosibirsk in the context of tokamak database

2. ANALYSIS

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

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

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

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

$$n_e = Zn_i,\; j_{\|e} + j_{\|i} = B\int div\vec{j}_{\perp}\frac{d\ell}{B}. \qquad (1)$$

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

3. PROSPECTS

The viability of mirror traps as alternative fusion devices depends on their ability to be cheaper in construction and operation as compared to tokamaks. It would be also very useful to work with advanced fuels like d-d or d-He^3. While there are many obvious engineering advantages to mirror traps, like inherent steady-state operation, lower requirements on divertor materials, modular design, the most important feature is the high energy density (beta). The worst drawback is the poor axial confinement causing the stigma of low electron temperature. Thus, all future traps should aim at improved axial confinement while maintaining stable high-beta regimes at all costs.

Currently there are two advanced designs for next-generation mirrors. The first one is advocated by Agren and Moiseenko [6]. It is based on an innovative variant of quadrupole mirror with straight field lines and omnigeneous ion drifts. The other builds upon the new results of GOL-3 and GDT, aiming to improve the axial confinement of GDT scheme with multiple-mirror plugs in collective-scattering mode (Fig. 9). The Gas-Dynamic Multiple-mirror Trap (GDMT) is under design in Novosibirsk. It will be axisymmetric. For stabilization it will depend on the vortex confinement scheme aided by biased end-plates, momentum injection by NBI, and charge-injection via the electron-beam. The primary aim of the project is to prove the concept of the steady-state multiple-mirror fusion reactor, and obtain confinement scaling, while going to longer pulses and higher electron temperatures than available in GOL-3 and GDT. In particular, the magnetic and heating systems should be able to support 1s-long discharges, as compared to current duration of a few milliseconds. The secondary aim of GDMT is being a prototype energy-effective neutron source to replace the unrealized project of the Budker institute – the “Hydrogen Prototype” (HyP). Both aims require optimization of the device to yield high overall fusion efficiency, Q_{DT}, rather than high and localized neutron flux, as in GDT or HyP. Still, it is utilizing the beam-beam fusion within the sloshing-ion population, but the localized reflection points are replaced by an extended “active zone”.

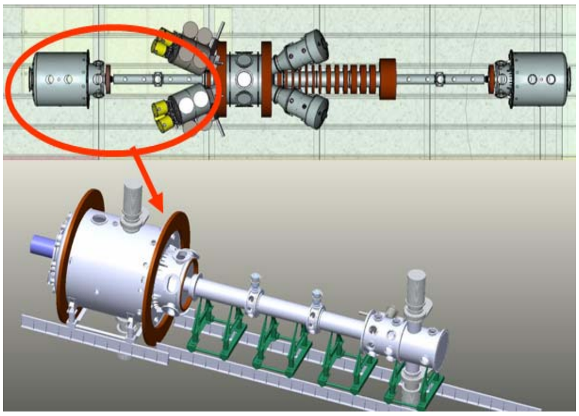

Fig. 9. GDMT trap and its first stage, the GDMT-T, superconducting high-field device for PMI studies

CONCLUSIONS

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

ACKNOWLEDGEMENTS

This work was financially supported by the Ministry of Education and Science of the Russian Federation, by the Russian Government project no. 11.G34.31.0033, the Presidium of the Russian Academy of Sciences program no. 30, the Council of the Russian Presidential Grants project no. NSh-7792.2010.2, the RFBR projects 10-02-01317-a, 11-01-00249-a, 11-02-00563-a.

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Article received 19.09.12

ЗЕРКАЛЬНЫЕ ЛОВУШКИ: ИСТОРИЯ, РЕЗУЛЬТАТЫ И ПЕРСПЕКТИВЫ

А.Д. Беклемишев, А.В. Бурдаков, А.А. Иванов, Э.П. Кругляков

Эволюция открытых ловушек привела их от простых соленоидов к сложнейшим тандемным ловушкам с квадрупольными стабилизаторами. Они вступили в конкуренцию с токамаками, используя амбиполярное удержание и термобарьеры, но проиграли, и сейчас близки к полному исчезновению. Боковая ветвь открытых ловушек осталась осесимметричной и сохранила простоту и хорошее удержание быстрых ионов. Поскольку простота конструкции означает меньшую стоимость строительства и обслуживания, и меньшие требования к конструкционным материалам, такие ловушки по-прежнему жизнеспособны. Осесимметричные ловушки Института ядерной физики им. Будкера в настоящее время являются наиболее передовыми в мире. Мы обсуждаем свежие экспериментальные результаты многопробочной ловушки ГОЛ-3 [1] и газодинамической ловушки ГДЛ [2]. Следующий шаг на этом пути – программа ГДМЛ, которая совместит центральный пробкотрон с плещущимися ионами в стиле ГДЛ с многопробочными секциями для подавления продольных потерь. Эта сверхпроводящая установка будет модульной и будет строиться поэтапно. Первый этап, ГДМЛ-Т, основан на пятиметровом сверхпроводящем соленоиде концевой многопробочной секции с полем 7 Тл. Трёхлетняя научная программа ГДМЛ-Т нацелена на исследование взаимодействия диверторной плазмы с металлами.

ДЗЕРКАЛЬНІ ПАСТКИ: ІСТОРІЯ, РЕЗУЛЬТАТИ І ПЕРСПЕКТИВИ

А.Д. Беклемішев, А.В. Бурдаков, А.А. Іванов, Є.П. Кругляков

Еволюція відкритих пасток привела їх від простих соленоїдів до найскладніших тандемних пасток з квадрупольними стабілізаторами. Вони вступили в конкуренцію з токамаками, використовуючи амбіполярне утримання та термобар'єри, але програли і зараз близькі до повного зникнення. Бічна гілка відкритих пасток залишилася осесиметричною і зберегла простоту і гарне утримання швидких іонів. Оскільки простота конструкції означає меншу вартість будівництва і обслуговування, і менші вимоги до конструкційних матеріалів, такі пастки, як і раніше, життєздатні. Осесиметричні пастки Інституту ядерної фізики ім. Будкера в даний час є найбільш передовими в світі. Ми обговорюємо свіжі експериментальні результати багатопробочної пастки ГОЛ-3 [1] і газодинамічної пастки ГДЛ [2]. Наступний крок на цьому шляху – програма ГДМЛ, яка поєднає центральний пробкотрон з іонами, що плескаються, у стилі ГДЛ багатопробочними секціями для придушення поздовжніх втрат. Ця надпровідна установка буде модульною і буде будуватися поетапно. Перший етап, ГДМЛ-Т, заснований на п'ятиметровому надпровідному соленоїді кінцевої багатопробочної секції з полем 7 Тл. Трирічна наукова програма ГДМЛ-Т націлена на дослідження взаємодії диверторної плазми з металами.