Development of Experiment on Multiple-Mirror Trap for Fusion in Budker INP

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Abstract. In 2015, the existing GOL-3 multiple-mirror trap has been converted into three specialized devices, each dedicated to a specific scientific problem. Experiments on studies of plasma mechanisms of sub-THz radiation generation use the GOL-3T device. A device with a sub-ms electron beam was isolated for further studies of ITER-grade transient heat loads to tungsten. Research of multiple-mirror physics will continue in a new GOL-NB device that will consist of a central trap with 0.3 – 0.6 T field, 2.5 m length and 1 m diameter and two attached multiple-mirror sections with 4.5 T field. The plasma will be heated by 1.5 MW NBI. Operation of the first stage of GOL-NB started in 2015. It includes 6-m-long 4.5 T solenoid of variable configuration with a plasma gun. The $(1 - 4)\times10^{20}$ m^{-3} plasma stream transport through the system was studied. A new helical mirror confinement idea and the first concept exploration device SMOLA will be presented as well.

1. Introduction

The idea of multiple-mirror confinement was one of the first attempts to improve poor energy confinement time of classical mirror traps. The price for the confinement improvement was the requirement for high collisionality that transforms into the requirement of a very high plasma density. We will briefly overview the idea and first experiments in the next section. The most recent GOL-3 experiment in Novosibirsk demonstrated a significant growth of the energy confinement time at transition from a simple solenoidal magnetic field to a multiple-mirror configuration. It was the first open trap that reached a sub-fusion electron temperature. Later in the paper, we will discuss the main findings from GOL-3 experiments.

In current projects of reactor-grade open traps like GDMT [1], multiple-mirror sections are used as important elements that significantly improve confinement in a central gasdynamic trap. Plasma in GDMT is two-component with fast ions that provide fusion reactivity and background warm plasma that keeps stability of the system. Only warm plasma escapes through mirrors. This makes the requirements for multiple-mirror systems much more feasible than for a reactor with Maxwellian fusion plasma. New physical knowledge base for GDMT-relevant configurations and physics is required for a robust design of GDMT multiple-mirror sections. The same knowledge base is required for codes benchmarking. This task should be solved by a new GOL-NB device that is a deep modification of GOL-3. Physics and status of GOL-NB will be briefly discussed.

Recently a new idea of active plasma flow control with helical mirror system was proposed in [2]. In the proposed configuration, rotating plasma experience a force from the magnetic mirrors that are moving in the plasma reference frame. The first concept exploration device SMOLA with helical mirror configuration is introduced in the separate section.

2. Multiple-Mirror Confinement: Idea and First Experiments

The idea of multiple-mirror confinement was suggested in [3,4]. In the simplest configuration, a multiple-mirror system is a set of regularly-spaced coils with the common magnetic axis, see FIG. 1. Each pair of coils can be considered as an elementary mirror cell. The main technical parameters of this system are the mirror cell length l, the total number of mirrors N, the full system length $L = N \times l$, values of the magnetic field in maxima B_{max} and in minima B_{min} and the mirror ratio $R = B_{max} / B_{min}$.

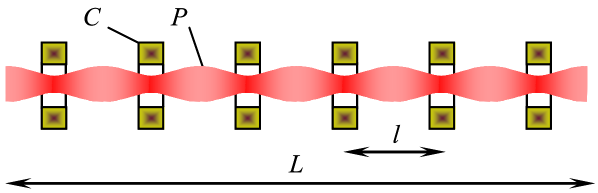


FIG. 1. A multiple-mirror confinement system. Designations are: C – magnetic coils, P – plasma, L – full system length, l – elementary mirror cell length (magnetic field corrugation period).

The major difference from a classical mirror trap is high enough plasma density that should provide small ion free path λ: $l \leq \lambda << L$. At this condition, particle exchange between locally-trapped and transiting populations occur. A test transiting particle becomes trapped soon into some elementary mirror cell, and then after a few oscillations it becomes transiting with random direction of movement. Therefore, instead of unidirectional movement towards one of the ends, this particle moves in a one-dimensional random walk manner with corresponding increase of the particle lifetime in the trap. The plasma confinement time scales as the square of the system length: $\tau \sim L/u \sim L^2/v_{\mathrm{Ti}}\lambda$. In a multiple-mirror system, free plasma expansion along the magnetic field transforms into a slow leak through the corrugated magnetic field. Theory predicts that the best conditions will be at $l \approx \lambda$. Then, the confinement improvement factor equals to the total number of corrugation cells: $K = \tau v_{Ti}/L \approx L/\lambda = N$. This value can be designed as large as required. The “loss cones” in particle distribution function are populated. This provides some immunity to microinstabilities.

The initial idea was soon tested in Q-machines with cesium plasma [5,6]. These experiments quantitatively confirmed the basic laws of multiple-mirror confinement. Than two significant attempts to build more advanced devices were done. The Berkeley Ten Meter Multiple-Mirror Device had nine 75-cm-long mirrors, used quadrupoles for interchanges stabilization and confined plasma created either by a theta-pinch or a plasma gun [7]. Finally, plasma with sub-fusion parameters was created and confined in the GOL-3 facility in Novosibirsk.

3. Highlights of GOL-3 Experiments

GOL-3 was built in the Budker Institute of Nuclear Physics in Novosibirsk under the leadership of D.D. Ryutov. It consisted of 12-m-long magnetic system, electron beam generator U-2, and an exit unit that contained a start plasma creation system and an expander with the beam receiver – see FIG. 2. The relativistic electron beam (<1 MeV, <30 kA, <12 μs, <180 kJ) was injected along the magnetic field for plasma heating.

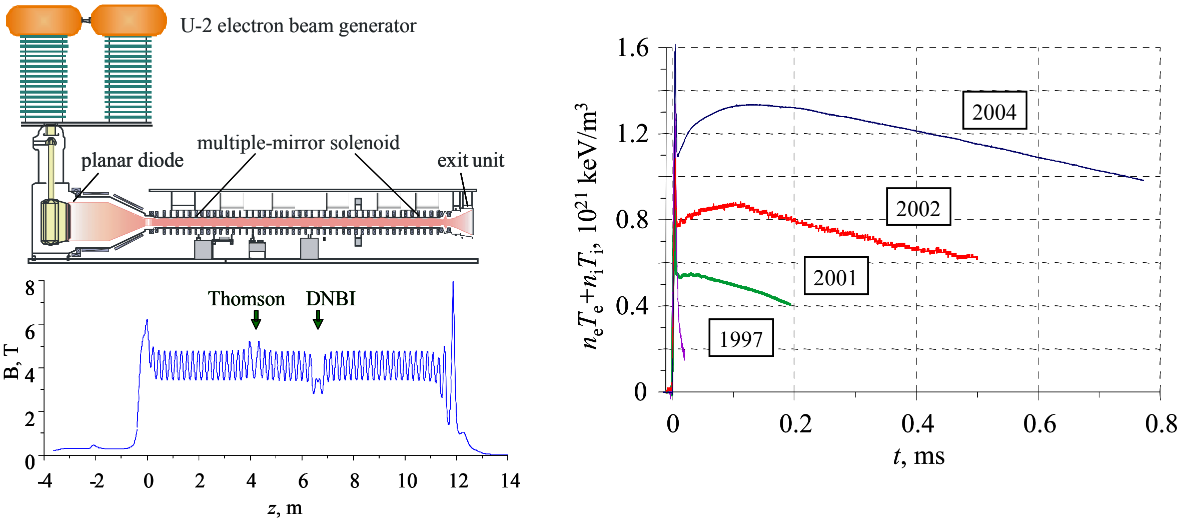


FIG. 2. Layout of the GOL-3 multiple-mirror trap (top left) and axial dependence of the magnetic field (bottom left). Axial coordinate z is measured from the center of the high-field coil at the beam input side. Right panel shows gradual improvement of diamagnetic energy lifetime with the step-by-step transition from a simple solenoidal (1997) to the full multiple-mirror configuration (2004) [8].

In GOL-3, electron temperatures of $T_e \geq 3$ keV at $n \approx 10^{21}$ m^{-3} were achieved for the first time in a linear system. Mean deceleration of beam electrons reached 40% in the 12-meter-long plasma [9]. Unexpectedly high value of electron temperature was explained in [10] with a suggestion of ~10^3 factor in anomalously high collisionality of plasma electrons during the beam injection time. Such collisionality leads to fast thermalization, fast escape of suprathermal electrons and suppression of electrical and thermal conductivity along the magnetic field. Anomalous collisionality within the beam-heated zone was also the cause for self-organization of radial structure of longitudinal currents that stabilized the system with Kruskal-Shafranov safety factor $q(r=0) \approx 0.3$ [11].

In beam-plasma experiments, usually a beam transfers its energy to plasma electrons and ions stay relatively cold. In the multiple-mirror configuration, the beam heated electrons as usual, but after a few microseconds electron temperature decreased rapidly from 2 – 3 keV down to 200 – 300 eV at (0.8 – 1)×10^{21} m^{-3} density. Simultaneously with this, ions acquired high temperature up to 2 – 4 keV [8] that evidenced for a new collective mechanism that exists in the corrugated magnetic field only. The key element of it [12] is a collective acceleration of ion flows by electron pressure directed from mirrors towards midplanes of mirror cells at anomalously suppressed thermal conductivity during the beam injection. Oppositely-directed ion flows mix in the centers of mirror cells. As the result, fast and effective energy transfer from electrons to ions occurs.

In the multiple-mirror configuration, energy confinement time dramatically increased and reached τ_E ~ 1 ms in best regimes (FIG. 2) [8]. The τ_E value was close to that predicted by theory [13], however physics turned out to be different and related to collective effects. Neutron measurements reveal an unexpected new feature. In regimes with the best parameters, neutron emission from high-axial-pressure-gradient parts of the plasma column experienced quasiperiodic oscillations like those shown in FIG. 3. Such oscillations were localized within separate corrugation cells, had typical frequency $\omega \approx v_{Ti}/2l$ and were caused by a small fraction of ions that oscillate in the cell [8]. Later, those oscillations were identified in theory [14] as electrostatic bounce instability of marginally-trapped ions.

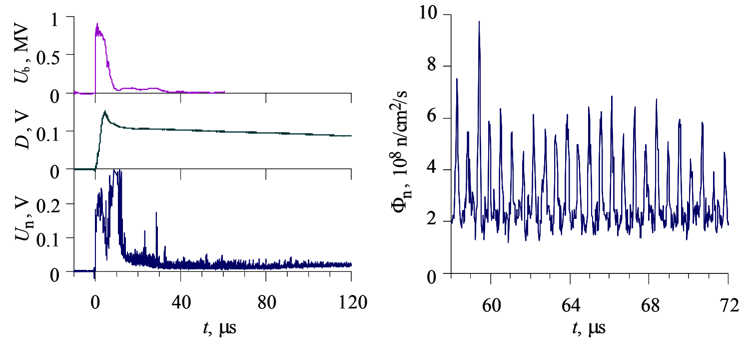


FIG. 3. Left, top to bottom: diode voltage U_d, raw diamagnetic signal D measured at coordinate z = 1.43 m, and raw signal U_n of local neutron flux detector. Right: fragment of the neutron signal recalculated to neutron flux Φ_n.

Action of the bounce instability of plasma is more important than just features of neutron signals. It increases particle exchange rate between populations of locally-trapped and transiting ions. This makes end sections of a finite-length multiple-mirror system effective even at lower density than required by the condition $l \approx \lambda$.

4. Separation of GOL-3 Research Programs

Apart from the multiple-mirror confinement physics, GOL-3 program included important parts that deal with generation of sub-THz electromagnetic waves from a beam-plasma system, plasma-facing components physics and long-pulse electron beams development. In order to optimize and accelerate research in all these directions, we have already divided GOL-3 into three independent devices. The first one will continue microwave generation program, it consists of the U-2 beam generator and 2-m-long plasma system GOL-3T [15]. Simulations of ITER-relevant transient power loads to plasma-facing materials will be done in the second device with a sub-ms, 10 MW, 80 keV electron beam. Finally, program on the multiple-mirror confinement will be continued with GOL-NB device.

The experiments on sub-THz wave emission from the area of relativistic electron beam-plasma interaction are devoted to measure the spatial and spectral properties of the plasma emission in dependence on plasma and beam parameters. A plasma column with the diameter of 6 cm, length of 2.5 m and electron density $(0.2 - 2)\times10^{21}$ m^{-3} is confined by multiple-mirror magnetic field with the mean value of 4 T. The relativistic electron beam had the current density $j_b \sim 2$ kA/cm^2.

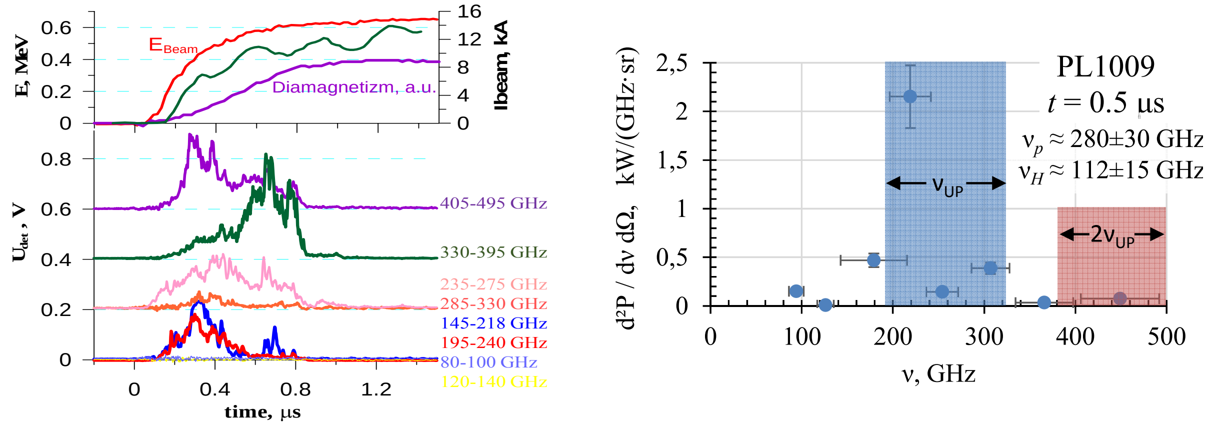
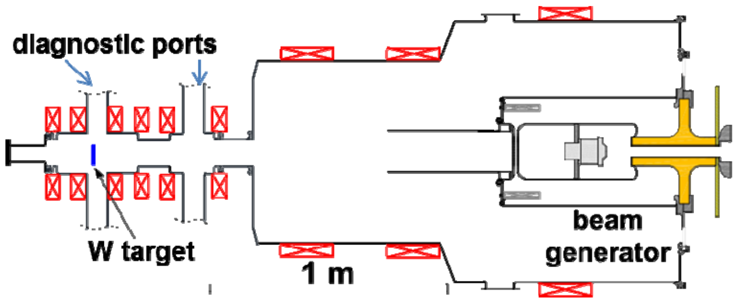


FIG. 4. Typical experimental data from GOL-3T. Left: typical waveforms of the beam energy and current and of plasma diamagnetism (top) and signals from THz detectors (bottom); right: spectrum of sub-THz waves propagating along the system axis.

In FIG. 4, the typical experimental data and measured emission spectrum are presented. The studies have shown that the beam pumps the plasma electron oscillations in a vicinity of the upper hybrid wave branch. These plasma oscillations can be converted in electromagnetic waves on regular or artificial plasma density gradients in a vicinity of upper hybrid frequency. The electromagnetic waves with the double upper hybrid frequency are also generated in the beam-plasma system due to coalescence of the plasma oscillations in case of high level of the oscillation energy density. As results, the wave emission with the specific power concentrated in the direction along the axis of the plasma column, in the frequency interval 0.25-0.5 THz has been obtained.

The investigation of a long-pulse electron beam impact on tungsten target was done for studies of dynamics of tungsten erosion. Good angular characteristics permit compressing the beam in converging magnetic field and delivering a heat load ~10 GW/m^2 on the target with an area of ~1 cm^2. The ablation plume created by the heat load of tungsten target emits only spectral lines of neutral and single ionized tungsten according to spectral measurements. Relatively weak WI and WII spectral lines in the near infrared (NIR) region above 865 nm permits imaging of the tungsten target in the NIR spectral range during process of it heating and cooling.

Fast CCD cameras with minimal exposure time of 7 μs are used for visualization of dynamics of target erosion in the near infrared as well as in the light of 532 nm CW laser during the heating process and after it. Additionally, tungsten microparticles ejected from the target are analyzed experimentally. Images of these particles are recorded by fast CCD cameras. Besides, we use scattering of light of continuous laser (532 nm, 0.8 W) for the observation of dust particles in the size range of 2-30 microns, emitted from the surface of tungsten under the influence of transient heat load. The scheme of experiments and the CCD-image of droplet ejection from the tungsten surface are shown in the Fig. 5.



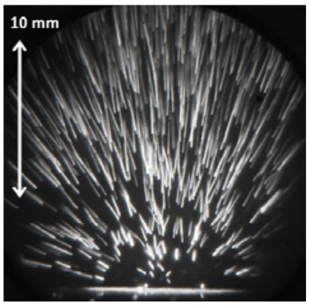


FIG. 5. Left: layout of experiments; right: fast imaging of droplet ejection.

5. GOL-NB Project

A conceptual design GDMT project revealed the need for new data on multiple-mirror confinement in the relevant regimes. The program of GOL-3 transformation into GOL-NB was introduced in [16]. GOL-NB has a GDMT-like magnetic configuration with a central trap, two solenoids attached to it and two end expander tanks, see FIG. 6. Plasma will be confined in the central trap with R = 15 for $B(z=0)$ = 0.3 T in the gasdynamic regime. Two neutral beam injectors [17] of 25 keV, 750 kW each will provide plasma heating. We expect that all physics known from GDT experiments [18] will work for the central trap too. The main processes we rely to are the following: fast ions from NBI will decelerate due to drag on target plasma electrons; main power losses will be through mirrors along the magnetic field; mean energy of escaping e-i pair $\varepsilon \approx 8T_e$ will be defined by the ambipolar potential; and vortex confinement technique with plasma biasing by annular electrodes will be used for the stabilization. Depending on the required configuration, each solenoid can create either a uniform magnetic field of 4.5 T or a multiple-mirror configuration with 13 elementary mirrors, B_{max} = 4.5 T and $R \approx 1.4$ (i.e. the same profile as in GOL-3 except the length).

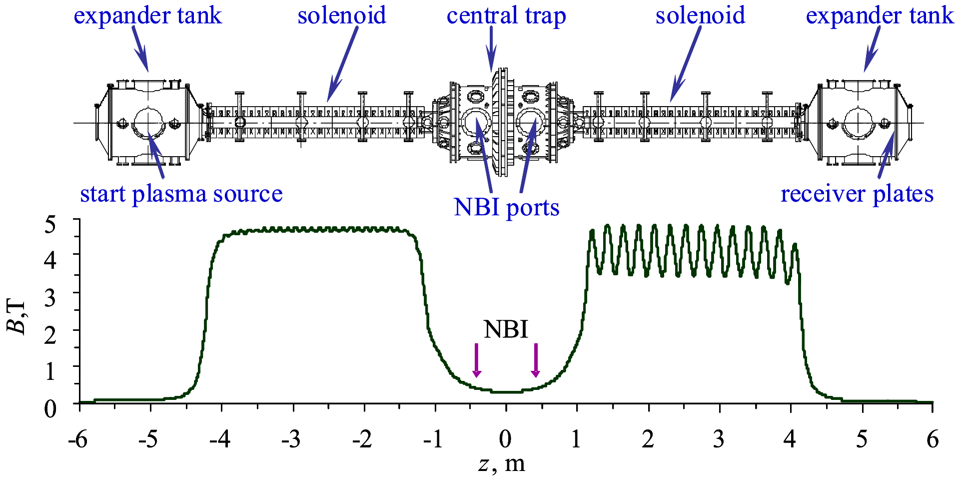


FIG. 6. Top: layout of GOL-NB. Bottom: the magnetic field profile at the axis. The right solenoid is shown in the standard multiple-mirror mode, the left one is with the uniform field.

End tanks are units in which plasma stream expands in decreasing magnetic field prior to be absorbed by endplates. The expansion ratio must be high enough with $R > 30$ in order to prevent central plasma cooling by a return flux of cold electrons (see [18] for details). An arc plasma source that will create start plasma in GOL-NB will be mounted in one of the expander tanks. A simplified prototype of the plasma source was tested in the existing part of GOL-3. It provided $(1 - 4)\times10^{20}$ m^{-3} density at 3 m distance from the source in relevant magnetic configurations [19].

The main physical task for GOL-NB is the multiple-mirror suppression of losses along the magnetic field. This dictated the choice of the parameter space. In GOL-NB, ion free path length should be comparable with the corrugation period, one-component plasma is preferred, and no requirement for long-living fast ions exists. Fast thermalization of beam ions means dense and reasonably warm plasma. The magnetic system provides a short gasdynamic particle lifetime. Large particle losses along the axis limit the achievable plasma parameters but make all other plasma processes less important that easies multiple-mirror physics studies.

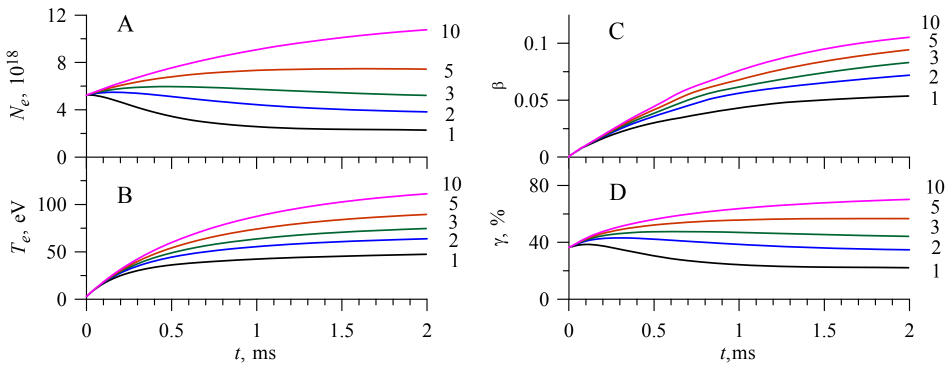


FIG. 7. Dynamics of plasma parameters at different suppression of plasma flow by multiple-mirror field (indicated by numbers near curves, unity corresponds to no confinement improvement): A - total number of electrons in the trap, B - electron temperature, C - relative pressure and D - beam capture efficiency. The particle source of the density control system was 1000 equivalent amperes.

Simulations of the baseline scenario were done in [20] with the 1D kinetic code DOL. The code allows simulations of pure gasdynamic systems with NBI heating. The confinement improvement was introduced phenomenologically. The initial plasma density was 3×10^{19} m^{-3}.

For a finite number of corrugation periods in the multiple-mirror configuration and the fixed length of an elementary mirror, we expect that only part of the solenoid will effectively restrict the plasma flow. However, FIG. 7 shows that even at modest suppression factors the plasma parameters improvement should be measured.

Currently different components and susbsystems of GOL-NB are in the design and manufacturing stages.

6. SMOLA Helical Mirror Experiment

All multiple-mirror projects that were discussed earlier in this paper rely on fixed magnetic configurations produced by fixed magnetic coils. Such systems provide a passive plasma flow control. The idea of an active plasma flow control was revived in the recent proposal of helical mirrors [2]. In this proposal, plasma flows through helicoidal magnetic field. If plasma experiences rotation due to externally-applied radial electric field, then in the rotating reference frame the magnetic hills of the helical field transform into moving multiple-mirrors. By use of different helicities for both sides of a magnetic system one can always create a trap that will pump plasma flow back to the central section. Theory predicts exponential dependence of the flow suppression on the magnetic structure length, that is more favorable then the power dependence in passive systems.

The first concept exploration device SMOLA (from Russian Spiral Magnetic Open Trap) is now in the construction stage in BINP [21]. This device will be a fast low-cost effort to model a half of a trap with helical mirrors. It will consist of a tank with a plasma source that will create a plasma stream imitating a steady plasma flow from a central section of a long open trap, a solenoid that has two independent windings for uniform and helical field components, a set of biasing electrodes that serves for plasma rotation, and an exit tank with plasma receiver (see FIG. 8). The helical winding is made of two spiral conductors with the opposite currents that create a helical field with azimuthal mode number $m = 1$.

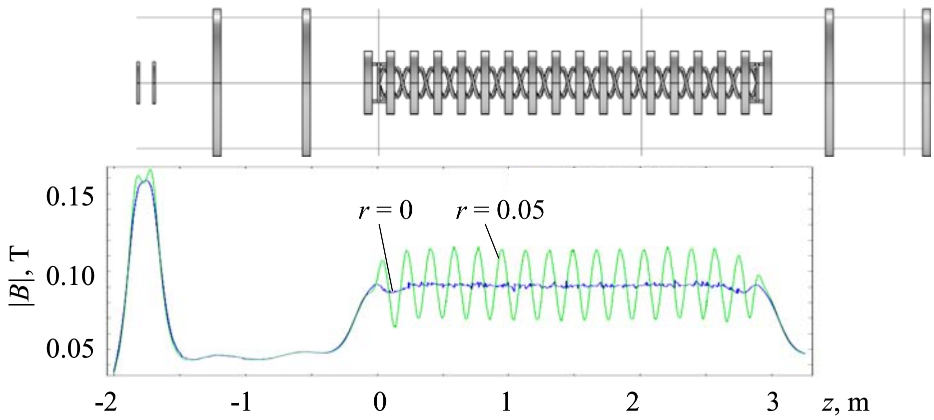


FIG. 8. Structure of the SMOLA magnetic system (top) and profiles of the magnetic field strength at the magnetic axis and at r = 0.05 m. Two coils of the plasma source at z ≈ -1.7 m are shown at the maximum field.

The flow suppression will depend on radius with more efficient plugging of the periphery. Moreover, the most important neoclassical effect for this type of magnetic configuration with properly biased plasma will be an inwards particle pinch [22] that will counteract usual diffusive processes. The central "hole" in the confinement properties weakens prospects of helical mirrors as the only additional systems for confinement improvement in open-trap-based reactors with collisional plasma. However such sections can be combined with more convenient multiple-mirrors.

7. Discussion and Summary

Recent advances in physics and technology of open confinement systems demonstrated solutions for all major problems like MHD stability, microinstabilities and large axial losses in stable operation regimes at sub-fusion plasma parameters. Novel concepts of fusion-grade open systems include two-component plasma and a composite magnetic system that consists of a central gasdynamic trap and attached multiple-mirror sections for confinement improvement. In such systems, multiple-mirrors will deal only with a stream of sub-fusion warm plasma that will have lower temperature and produce almost no neutrons.

During the previous 20 years the GOL-3 experiment was the only source that provided experimental data on hot plasma behavior in the corrugated magnetic field. GOL-3 operated with very unusual turbulent plasma heated by the high-power relativistic electron beam. Scalings for more reactor-relevant plasma with low turbuence level will be found from experiments in the GOL-NB multiple-mirror trap that will be build in BINP. Simultaneously, new SMOLA device will be built for studies of newly-proposed helical mirror confinement.

Acknowledgments

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