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INSTRUMENTS AND METHODS OF INVESTIGATION

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The ambipolar trap

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Contents

Abstract. Experimental studies between 1978 and 2004 on ambipolar (tandem) mirror traps are reviewed. Results on the formation of ambipolar ion-confining barriers and the formation of thermal barriers for thermally insulating electrons in ion barriers from plasma confined in a solenoid are discussed. Achievements on improving longitudinal plasma confinement and limiting transverse plasma losses in the trap are reviewed. The reasons for the limited density of solenoid plasma in TMX-U and GAMMA-10 machines are discussed. Some results on the MHD stabilization of plasma and on the suppression of plasma microinstabilities are reviewed. Prospects for constructing ambipolar fusion reactors are discussed

1. Introduction

The axially symmetric magnetic trap is the simplest magnetic system used for steady-state confinement of high-temperature plasma. However, the plasma in such a trap flows along the magnetic field, and it therefore becomes necessary to essentially slow its escape through the ends of the trap.

In 1954, G I Budker and, independently, R F Post proposed using magnetic mirrors to 'plug' the ends of such a trap. The time of longitudinal confinement of collisionless plasma with such mirrors is given by the formula [1]

$$\tau_{\parallel} \sim \tau_{\rm i} = \frac{1}{\pi\sqrt{2}} \frac{\sqrt{M_{\rm i}}}{e^4 \Lambda_{\rm i}} \frac{(kT_{\rm i})^{3/2}}{n} , \qquad (1)$$

where $\tau_{\rm i}$ is the ion scattering time, $T_{\rm i}$ is the ion temperature, n is the ion number density, and $\Lambda_{\rm i}$ is the Coulomb logarithm. The dependence of the time of longitudinal confinement of plasma on the ratio of the magnetic fields at the mirrors, $B_{\rm m}$, and in the trap, B, is weak: $\tau_{\parallel} \approx \tau_{\rm i} \lg (B_{\rm m}/B)$. Although this confinement time is many orders of magnitude longer than the ion passing time, it is still not long enough to confine high-temperature plasma in a steady-state fusion reactor. The attainable fusion power gain Q in such a simple magnetic mirror is less than unity [2].

In 1975, at the Institute of Nuclear Physics in Novosibirsk, the present author proposed a method to suppress plasma end-losses from a solenoidal trap by electric ambipolar barriers maintained in the double mirrors at the solenoid ends. If plasma with a density $n_{\rm p}$ higher than that in the solenoid, $n_{\rm s}$, is confined at the end mirror cells (between two mirrors), then ambipolar barriers of the height

$$e\varphi_{\rm c} = kT_{\rm e} \ln \frac{n_{\rm p}}{n_{\rm s}} , \qquad (2)$$

where $T_{\rm e}$ is the temperature of the plasma electrons, are formed (according to Boltzmann's law) at the ends of the long solenoid, and these barriers confine the ions. The time of longitudinal confinement of plasma in the solenoid of the ambipolar trap is given by

$$\tau_{\parallel} \sim \tau_{\rm i} \frac{e\varphi_{\rm c}}{kT_{\rm i}} \exp \frac{e\varphi_{\rm c}}{kT_{\rm i}} . \qquad (3)$$

For $e\varphi_{\rm c}$ much larger than $kT_{\rm i}$, the time of longitudinal confinement of plasma in the ambipolar trap is many times longer than that of confinement of plasma in a simple mirror cell.

Figure 1 illustrates the process of ambipolar confinement of plasma at the end of a solenoid. The high plasma density at the end mirror cells is sustained by ionizing the high-energy atoms injected into the magnetic field of the cells. In addition to ambipolar confinement, the proposal contained a means for ensuring MHD stability in an axially symmetric solenoid due to the minimum of the magnetic field in the end mirror cells.

The present author, together with colleagues, calculated the parameters of an ambipolar trap with double mirrors necessary for the confinement of fusion plasma. The calculation used Pastukhov's formula (see Ref. [3]). The results

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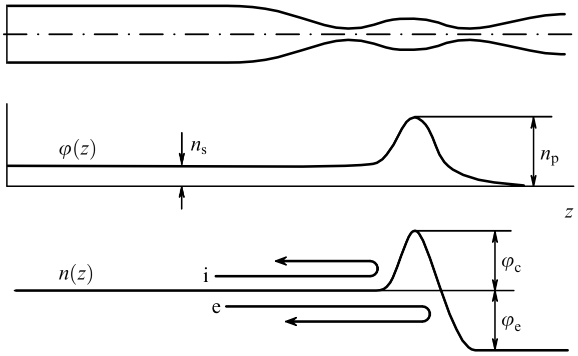

Figure 1. Ambipolar confinement of plasma in a solenoid.

showed that in a D–T reactor, the power gain Q could become much greater than unity [4].

A design of an ambipolar trap was also (independently) proposed in 1976 at the Lawrence Livermore National Laboratory (LLNL) by Fowler and Logan [5], who called their system a tandem mirror.

2. The main experiments

In the years that followed, the proposed concept of an ambipolar (tandem) trap was corroborated. In 1978, Miyoshi, Yatsu, Kawabe, and others used the GAMMA-6 trap (Tsukuba, Japan) in their experiments and formed ambipolar barriers about 20 V high in the end mirror cells in low-density low-temperature plasma. The researchers observed an increase in the time of longitudinal confinement of plasma in the solenoid [6].

At LLNL, a large group of physicists (Fowler, Logan, Coensgen, Simonen, and others) began to study the properties of ambipolar traps. In 1978, they initiated tandem mirror experiments (TMXs) involving a tandem trap, schematically displayed in Fig. 2. In 1979, this device was used to produce dense, hot, and MHD-stable plasma with the lifetime about 25 ms. Direct measurements revealed a substantial decrease in the longitudinal loss of ions from the solenoid through the end mirror cells. Here, the relative plasma pressure in the

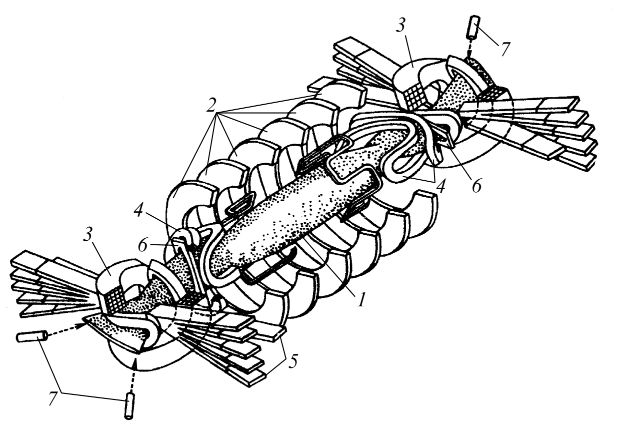

Figure 2. An ambipolar TMX trap: *1*, plasma; *2*, solenoid coils; *3*, baseball-type coils generating quadrupole magnetic fields with minima at the centers of the end mirror cells; *4*, interstage C-shaped coils; *5*, atomic injectors of the end mirror cells; *6*, gas 'boxes', or sources of controllable hydrogen inflow followed by ionization in the solenoid; and *7*, start plasma guns.

solenoid, $\beta_s = 8\pi nk(T_i + T_e)/B_s^2$, amounted to 5% and the electron temperature was estimated as being higher than 200 eV. In 1980, extensive research into the problems of plasma stability, the formation of ambipolar barriers, longitudinal and transverse plasma confinement, the energy balance, and other characteristics was conducted. The MHD stability of plasma in the solenoid was improved, and a maximum value of $\beta_s = 40\%$ was achieved. The plasma flowing from the solenoid at the end mirror cells was found to suppress a more serious microinstability, the drift-cone ion cyclotron instability (DCI). At increased plasma densities at the end mirror cells, the Alfven ion cyclotron instability (AICI) was observed. The measured ion barrier φ_c was found to reach 300 V.

The time of longitudinal confinement of plasma by ambipolar barriers in the solenoid of a TMX trap was found to exceed the time of confinement by magnetic mirrors by a factor greater than nine [7–9].

If electron cyclotron resonance (ECR) heating is sustained in confining barriers φ_c and the electron temperature T_{ep} higher than the electron temperature T_{es} in the solenoid is maintained in such barriers, then

$$e\varphi_c \approx kT_{ep} \ln \frac{n_p}{n_s} \tag{4}$$

and the necessary value of φ_c can be achieved at a smaller ratio n_p/n_s.

In 1979, Baldwin and Logan [10] suggested generating negative barriers of depth φ_b between the solenoid and the ambipolar barriers confining the ions in order to limit the electron heat flux from the barriers φ_c when $T_{ep} > T_{es}$; such negative barriers became known as thermal barriers. Figure 3 gives an idea of ambipolar plasma confinement in a solenoid in which thermal barriers have been introduced. In this case [11],

$$e\varphi_c = kT_{ep} \ln \left(\frac{n_p}{\gamma n_s} \sqrt{\frac{T_{es}}{T_{ep}}} \right) + e\varphi_b \left(\frac{T_{ep}}{T_{es}} - 1 \right) \tag{5}$$

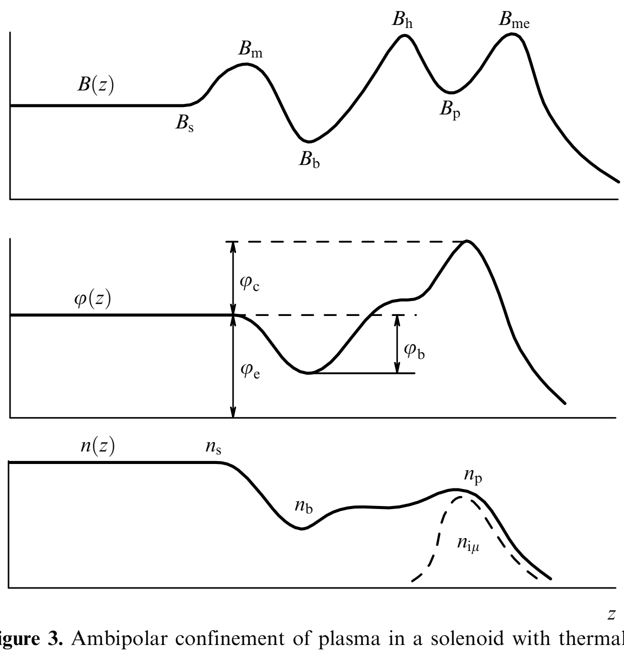

Figure 3. Ambipolar confinement of plasma in a solenoid with thermal barriers in twin end mirror cells according to Ref. [10].

and at $T_{ep} \gg T_{es}$ and $\varphi_b \sim \varphi_c$, the barriers that confine the ions can be formed if the plasma in them is of low density ($\gamma = 1$ in double mirror cells and $\gamma > 1$ in single mirror cells).

In 1981–1982, the TMX trap was remodeled into the TMX-U trap, which contained new end mirror cells with ECR heating and in which additional heating of the plasma in the solenoid was possible. In 1983, the new device was used in experiments in thermal barrier formation and plasma confinement. The thermal barriers in the TMX-U were formed in single end mirror cells with oblique atomic injection [12]. The ion barriers were formed at the extreme stopping points of the injected ions sloshing in the longitudinal direction; at these points, the ion number density was at its maximum and the ECR heating of electrons was performed. The thermal barriers were formed in the median plane of the end mirror cells, where the number density of the sloshing ions was at its maximum. Negative potentials were then generated because of the extended lifetime of the anisotropic population of the high-energy electrons (more than 80%), which formed as a result of ECR heating of electrons at a doubled frequency. Together with passing ions and ions captured by thermal barriers and isotropic and passing electrons from the solenoid in the end mirror cells, there are seven populations of charged particles. Nevertheless, the concept of barrier formation in such a multicomponent plasma contains no contradictions. There is a relatively rigid framework for the entire set of particles consisting of two populations confined by the magnetic field: the sloshing ions and the high-energy electrons in a thermal barrier. However, one could not have a priori expected such a complicated system to be stable. In the initial experiments with the number density $n_s \sim 0.5 \times 10^{12}$ cm^{-3}, thermal barriers were formed in which the observed increase in the time of longitudinal ion confinement in the solenoid was tenfold in the course of a time interval no longer than 10 ms with $n_s/n_p > 1-2$ [13]. The depth of the thermal barrier and the height of the ion barrier were measured in the case where atoms were ejected only into one end mirror cell, and the result was 0.45 and 1.5 kV, respectively. Later, various methods were developed for measuring the longitudinal potential profile in the plasma with both end mirror cells switched on. Subsequent experiments revealed that when the plasma density n_{sm} at the ends of the solenoid (at the magnetic mirrors) exceeded 10^{12} cm^{-3} ($n_s > (1-3) \times 10^{12}$ cm^{-3}), longitudinal confinement of plasma in the solenoid by ambipolar barriers was violated [14] (the reasons for this were unclear). The ion barriers and the longitudinal confinement times spontaneously decreased in the course of 1–3 ms. The threshold value of the density n_s depended, in particular, on the ion cyclotron resonance (ICR) heating in the solenoid. At $n_s \sim 10^{12}$ cm^{-3}, Allen et al. [14] were able to sustain thermal barriers φ_b at depths up to 0.7 kV in the course of 3–5 ms. For plasma densities $n_{sm} \leqslant 10^{12}$ cm^{-3}, the time of longitudinal plasma confinement by an ambipolar barrier was found to be close to its classical value within a broad range, $\tau_\parallel \approx 3-200$ ms [15]. The formation of thermal barriers made it possible to raise the ionic ambipolar barriers φ_c for $n_p < n_s$ and to increase the time of longitudinal plasma confinement compared to that of a classical mirror cell by a factor of 50 [13–15].

The TMX-U device has been used to study transverse plasma transfer and its effect on the disruption of ambipolar confinement. Radial sectioning of the end plasma receivers made it possible, by using the shapes of the calculated particle drift surfaces [16], to measure the nonambipolar ion losses as a function of the plasma radius and to analyze the dependence of these losses on a number of experimental parameters (see Panov's review article [17]). In most plasma confinement modes, transverse ion transfer proved to be much larger than neoclassical resonance diffusion. Apparently, the main fraction of nonambipolar transverse losses is produced by the asymmetry of the barrier surfaces with respect to the trap axis. The value of the time constant of neoclassical transverse ion transfer found analytically from the experimental data is in good agreement with the results following from the Ryutov–Stupakov resonance diffusion theory [18, 19]. Ambipolar transverse losses are smaller than those of nonambipolar and increase in the event of ICR heating in the solenoid. In modes with good longitudinal confinement, transverse losses are comparable to longitudinal losses.

Extensive investigations into plasma stability in a trap have been carried out, and plasma in the TMX-U proved to be much quieter than in the TMX. Studies of fluctuations in various frequency ranges revealed no dominating active instabilities, but such instabilities were found to limit the modes of operation. Low-frequency density fluctuations were observed in the solenoid, which were probably MHD perturbations. Fluctuations of the potential at approximately 130 kHz were observed in the end mirror cells. The sloshing ions together with the passing ions from the solenoid reflected from the barriers φ_c were found to substantially improve the microstability of the plasma in the end mirror cells of the trap: in their median plane, the DCI was suppressed, as was AICI. When high ion barriers φ_c were formed, development of vibrations at the local cyclotron frequency were observed in these areas, with the vibrations associated with DCI development. The spontaneous disruption of electrostatic longitudinal confinement is possibly associated with violation of the stability of ambipolar ion barriers due to insufficient ECR heating.

In 1980, construction began at LLNL of a large tandem device, MFTF-B, with an axially symmetric solenoid with twin axially symmetric magnetic mirrors at the ends and quadrupole end mirror cells used for the confinement of high-temperature (15 keV) plasma with the density about 5×10^{13} cm^{-3} and the volume about 5 m^3 [20–22]. For a 30 kV rated ambipolar-barrier height, the expected value of the confinement parameter $n_s\tau_{\varepsilon s}$ was about 10^{13} cm^{-3} s (where $\tau_{\varepsilon s}$ is the energy lifetime) and that of the D–T fusion power was roughly 1 MW. After MFTF-B became operational in 1987 [23], experimental research into ambipolar traps in the United States was terminated due to a severe reduction in state financing of the magnetic fusion program. Work on all other open traps, MMX (Berkeley), LAMEX (Los Angeles), STM (TRW, Inc.), Phaedrus-B (Wisconsin), TARA (Massachusetts), and TMX-U (Livermore), was also terminated.

In Japan (PRC, University of Tsukuba), construction of the ambipolar trap GAMMA-10 began in 1981 and the first experimental results were obtained in 1984.

The MHD stability of plasma in the GAMMA-10 trap is ensured by the average minimum of the magnetic field, just as in the earlier tandem traps. However, this ambipolar trap differs in that the end mirror cells with plasma receivers are axially symmetric, and so is the solenoid. Quadrupole magnets with the field minimum (MHD anchors) are located between the end mirror cells and the solenoid. The area surrounding the plasma in the end mirror cells is vacuumed by cryogenic pumps with the pump rate up to

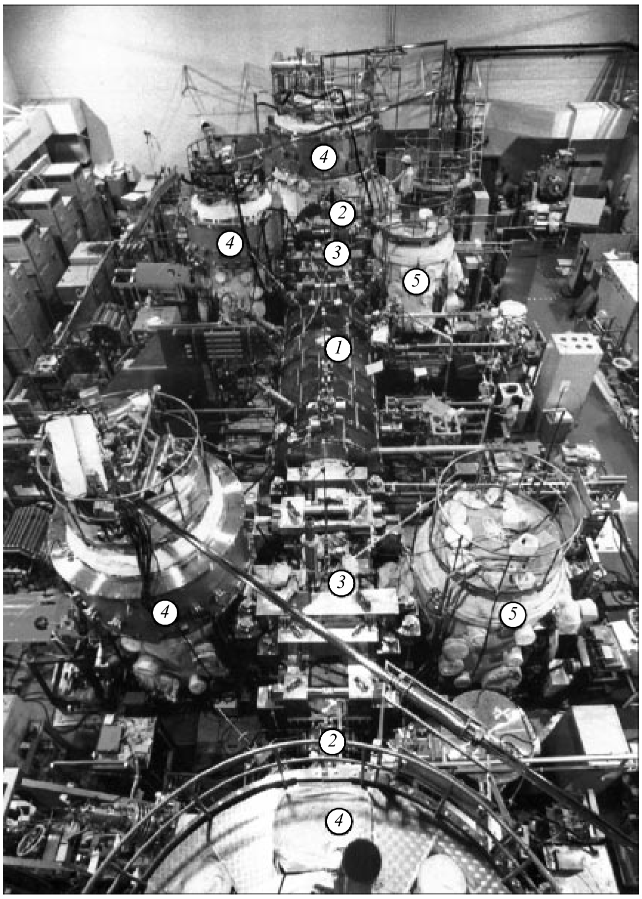

Figure 4. General view of the GAMMA-10 device: *1*, solenoid; *2*, end mirror cells; *3*, built-in MHD anchors; *4*, helium cryogenic pumps; *5*, detectors of MHD-anchor atomic beams.

$\sim 10^6$ liters per second. Figure 4 shows the general view of such a trap.

In 1984 – 1987, the GAMMA-1- device was used to obtain the main results concerning the formation of ion and thermal barriers and improvements in the confinement of hot plasma [24, 25]. Stable ion barriers with heights up to 1 kV and thermal barriers with depths up to 0.7 kV of durations $\tau_b \approx 10-3$ ms, accordingly, were formed in the solenoid containing plasma of the density $n_s \approx (0.5-2)\times 10^{12}$ cm^{-3}. In each thermal barrier, 140 kW ECR heating made it possible to generate a population of anisotropic electrons with the average energy 50 – 60 keV. The electron temperature in the ion barriers exceeded the temperature in the solenoid by a factor of approximately five and was as high as 500 eV.

The time of longitudinal ion confinement by ambipolar barriers for the main central part of the plasma column satisfactorily coincided with Pastukhov's scaling law and reached a value about 1 s.

The measured dependences of the time constant of transverse diffusion was found to correspond to the Ryutov – Stupakov theory of neoclassical transverse transport, and the symmetrized geometry of the trap is a favorable factor that contributes to this. All the investigated processes can be described in classical terms [17].

In 1988, the longitudinal confinement in the solenoid of the GAMMA-10 trap was improved by a factor greater than 10^3 compared to the confinement in a classical mirror cell, with the parameter $n\tau_\parallel$ of longitudinal plasma confinement amounting to $\sim 2\times 10^{12}$ cm^{-3} s [26].

By 1992, the ambipolar barriers in end mirror cells were raised to 2 kV, while the time during which they existed together with thermal barriers with depths up to 1.3 kV were increased to 60 ms [27]. However, this was achieved with the plasma density in the solenoid n_s less than 10^{12} cm^{-3}.

The following values of the parameters in the central solenoid were achieved in the mode with high ambipolar barriers $\varphi_c \leqslant 1.7$ kV (the high-potential mode): the plasma density $n \leqslant 2\times 10^{12}$ cm^{-3}, the electron temperature $T_e \leqslant 250$ eV, and the longitudinal and transverse ion temperatures $T_{i\parallel} \leqslant 0.45$ keV and $T_{i\perp} \leqslant 1.8$ keV [27, 28]. The lower limit of the maximum relative pressure of isotropic plasma, β, with the MHD stability in the solenoid at $\sim 0.5\%$, limited the density of the isotropic plasma (i.e., the plasma confined by ambipolar barriers). In the case of ICR heating of plasma in the solenoid, the limit in $\beta_\perp$ increased up to $\sim 2\%$ at $T_{i\perp}/T_{i\parallel} \sim 2.5$, and then increased linearly with the anisotropy [29]. However, the limit of the plasma density in MHD stability was found not to increase with the anisotropy because of the corresponding increase in the transverse ion temperature $T_{i\perp}$.

In the startup mode with high ambipolar barriers $\varphi_c \geqslant 1.2$ kV and with subsequent medium-power ICR heating in the central solenoid, the achieved time of transverse plasma confinement $\tau_\perp$ was 0.6 ± 0.4 s, with the plasma density on the solenoid axis $n_s \sim 10^{12}$ cm^{-3}, ion temperature $T_i = 0.5-0.8$ keV, electron temperature $T_e = 60-120$ eV, and $\beta_{\perp s} \leqslant 0.2\%$ [30, 31] with the ratio $\tau_{i\perp}/\tau_{Bohm} \sim 10^4$, where $\tau_{Bohm} = (8eB/3cT)a^2$, corresponding to a level reached in the best tokamaks. The measured energy time of confinement of the main population of electrons ($T_e \sim 100$ eV) $\tau_{e\varepsilon} > 0.1$ s exceeded $10^3\tau_{Bohm}$ [32, 33]. In this mode, plasma was generated in the solenoid with a broad profile of about 40 cm and the gradient size a about 12 cm. Because of the high value of φ_c, the potential Φ_s on the solenoid axis was no less than 2 kV and could be increased in the plasma core by a positive bias in the potential of the central ring segments of the ring plasma receivers compared to the floating value. The corresponding radial electric field E_r with a large shear at the plasma periphery suppressed the drift instability to the level of density fluctuations $\tilde{n}/n \sim 10^{-2}$ with a small positive bias in the potential mentioned above. As E_r was reduced, a negative bias in the potential increased the drift instability to $\tilde{n}/n \sim 10^{-1}$, and the longitudinal confinement time dropped to 10 ms [30]. For $E_r > 0$ and a real deviation of $\Phi_s(r)$ from the parabolic law ($\partial\omega_E/\partial r > 0$, where $\omega_E = -cE_r/Br$), the Kelvin – Helmholtz instability (KHI) cannot develop because the necessary condition for its development, $(\partial n/\partial r)\ \partial\omega_E/\partial r > 0$, does not hold. The centrifugal instability may develop if there is a large negative pressure gradient in the plasma. In the case of an increased gradient size, such an instability may not develop, and this has been observed in experiments ($a = 10$ cm $\rightarrow$ 12 cm) [30].

3. Subsequent experiments in Japan and the Republic of Korea

In 1992, the GAMMA-10 device was used to create conditions needed for operation without atomic injection into the end mirror cells with relatively low ambipolar barriers $\varphi_c = 300-500$ V, with the measured parameter of longitudinal confinement of isotropic ions dropping to

$n\tau_{\|} \sim 3 \times 10^{10}$ cm^{-3} s [34]. In the mode with low ambipolar barriers, the plasma potential in the central solenoid is moderate; accordingly, the radial electric field is close to zero and the centrifugal instability does not develop [30]. Drift instability at the plasma periphery may amount to a dramatic decrease in the potential in this region. Moreover, when longitudinal confinement is poor, anomalous transverse plasma losses may be unimportant. In 1994, this mode with low ambipolar barriers and powerful ICR heating (hot-ion mode) was used to raise the ion temperature to $T_{i\perp} = 10$ keV at $T_e = 130$ eV and $n_s = 2.2 \times 10^{12}$ cm^{-3}. At $T_{i\perp} = 5.3$ keV and a reduced magnetic field in the solenoid, the value of $\beta_{\perp}$ reached 5%. The time of transverse energy confinement $\tau_{\varepsilon\perp} \gg \tau_{\varepsilon\|} \sim \tau_{\varepsilon} \sim 8$ ms [35].

In the hot-ion mode, the plasma density in the solenoid did not exceed $n_s \sim 2 \times 10^{12}$ cm^{-3}. Hence, research was done with the aim of increasing the plasma density at $T_{i\perp} \sim 4$ keV, $T_{i\|} \sim 0.4$ keV, $T_e = 90$ eV, and $\varphi_c \sim 0.35$ kV. In this mode, the hot ions are confined to the central solenoids by magnetic mirrors ($n\tau_{\|\text{hot}} \sim 1.25 \times 10^{11}$ cm^{-3} s). The time needed for the electrons to slow down such ions $\tau_{\text{mod}} \ll \tau_{\|\text{hot}}$ [$n\tau_{\text{mod}} \approx n\tau_{\text{dr}} \ln (T_{i\perp}/T_{i\|}) \sim 4 \times 10^{10}$ cm^{-3} s, where τ_{dr} is the average time it takes the electrons to slow down the fast ions, or the electron drag time]. The measured parameter $n\tau_{\|} \sim 3 \times 10^{10}$ cm^{-3} s. Because $n\tau_{\|\text{hot}} \gg n\tau_{\text{mod}} \sim n\tau_{\|}$, the ratio of the total ion number density (n_s) to the number density of magnetized hot ions (n_{hot}) obeys the formula

$$\frac{n_s}{n_{\text{hot}}} \sim 1 + \frac{n\tau_{\|}}{n\tau_{\text{mod}}} \sim 2\,.$$

Switching off the ambipolar barriers (ECRH-pl/b), which confine only ions with a low temperature $T_{is} \sim T_{i\|}$, should reduce the total density by a factor of approximately two. This was demonstrated by Yatsu et al. [36–38] in 1997–1998. Symmetrizing the radial profile of the potential by symmetrizing ECR and ICR heating and optimizing this profile by adjusting the potentials of the ring segments of the plasma receivers led to a moderate increase in the density to $n_s = 2.5 \times 10^{12}$ cm^{-3} [39]. Installing an additional ICR heating system with a tenfold frequency and improving atomic injection into MHD anchors made it possible to raise the relative pressure in the MHD anchors to $\beta_{\perp A} \sim 1\%$ and, correspondingly, to increase the plasma density in the solenoid to $n_s = 4 \times 10^{12}$ cm^{-3} ($\beta_{\perp s} \sim 3\%$) [39].

One result that is most important for the prospects of a fusion reactor followed from the experiments with the GAMMA-10 device, and that is the production and sustainment of fairly stable (with a lifetime of about 150 ms) ambipolar barriers with heights up to 0.6 kV (with thermal barriers) and with a relatively low plasma density in these barriers, $n_{\text{pl}} \sim 0.1\, n_s$ [39–41].

Earlier, Cho and colleagues carried out X-ray studies on the GAMMA-10 device of the electron distribution function in an ion barrier with ECR heating [42, 43]. The researchers found that this function has a plateau with the energy maximum on the separatrix of the electrons in the ion barrier,

$$\varepsilon_{\text{sepm}} = \frac{e\varphi_c + e\varphi_b}{1 + B_b/B_p}\,.$$

Such an electron distribution corresponds to strong ECR heating, a case analyzed by Cohen [43]. ECR heating in the ion barrier prevails over scattering in the collision of the electrons captured by the electron barrier, while ECR heating at the second harmonic in thermal barriers dominates for other electrons, captured by the mirror cell. In weak ECR heating, the positive potential in the ion barrier is generated in order to confine the heated Maxwell electrons according to Boltzmann's law, but in strong ECR heating, the positive potential is generated in order to limit the escape of maximum heated electrons. In the velocity space, the ECR field at the top of the ion barrier causes diffusion in the transverse velocity, while the weak scattering of captured electrons leads to a plateau in the distribution function in the longitudinal velocity. In contrast to dependence (5) for weak ECR heating, the dependence of the height φ_c of the ion barrier on the number density n_{ep} of the electron captured in this barrier in the event of strong ECR heating obeys a power law (rather than a logarithmic law), while the dependence of the depth φ_b of the thermal barrier is an exponential one [44]:

$$e\varphi_c = kT_{\text{es}} \left[\frac{3\sqrt{\pi}}{4} \left(1 - \frac{B_b}{B_p} \right) \frac{n_{\text{ep}}}{n_s} \exp \frac{e\varphi_b}{kT_{\text{es}}} \frac{1}{1 - B_b/B_m} \right]^{2/3} - e\varphi_b\,. \quad (6)$$

This dependence holds on the resonance surface $\omega_{\text{ce}} = \omega_{\text{PECR}}$, on which the number density of the captured electrons n_{ep}, the energy of such electrons on the separatrix ε_{sep}, and the positive potential φ must have their maximum values in the distributions along the magnetic field. The captured electrons oscillate about the resonance surface along the magnetic field and 'heat up' the less energetic electrons in the entire space occupied by the ion barrier.

Electrons land in the ion barrier of a single mirror cell as a result of the ionization of injected and Franck–Condon atoms and also as passing electrons from the solenoid and the mirror cell (thermal barrier) as a result of scattering and ECR deceleration.

The scattering of electrons in the ion barrier causes these electrons to diffuse in longitudinal velocity over the velocity surfaces similar to an ellipsoidal separatrix, not only inside it but also outside, in its vicinity. As a result, there forms an electron flux with an energy exceeding the limit energy on the separatrix, ε_{sep}, and directed into the space occupied by the thermal barrier and in the drift space. This electron flux intensifies because of reflection from a magnetic mirror, As a result of the electron reflection in the event of ECR heating, the electrons leave the resonance surface and head toward the center of the mirror cell, which causes a unidirectional drift accompanied by an increase in longitudinal velocity. In the thermal barrier, the electrons from this flux with energies close to $\varepsilon_{\text{sepm}}$ are scattered back into the ion barrier and into the solenoid. Electrons from the ion barrier that fly into the solenoid have energies within the range

$$e\varphi_b < \varepsilon < \frac{e\varphi_b}{1 - B_b/B_m}\,.$$

The electrons that land in the solenoid become thermalized. This population of hot electrons with the temperature of several kiloelectronvolts and the concentration of several percentage points was observed in the solenoid by Cho et al. [33]. In the high-potential mode [$n_s \approx (0.5-1) \times 10^{12}$ cm^{-3}, $T_{\text{es}} \sim 250$ eV, and $T_{\text{is}} \leqslant 2$ keV], the given population mainly heats the electrons confined in the solenoid [33]. In the hot-ion mode [$n_s = (1-4)\times 10^{12}$ cm^{-3}, $T_e \sim 100$ eV, and $T_i \leqslant 5$ keV], the electrons in the solenoid are heated mainly by ions.

The ions in the region of the confining barrier φ_c consist of sloshing ions and reflected (passing) ions from the solenoid. The number density of sloshing ions, most probably, decreases as the ions approach the resonance surface longitudinally because of the decelerating effect of the electric field [14]. The longitudinal distribution of the number density $n_{ipas}(B)$ of passing ions on the inner slope of the ion barrier is given by the formula [43]

$$\frac{n_{ipas}(B)}{n_{sm}} = \exp\left(-\frac{e\varphi(B)}{kT_{is}}\right) - \sqrt{1-\frac{B}{B_m}}\,\exp\left(-\frac{e\varphi(B)}{kT_{is}}\,\frac{1}{1-B/B_m}\right). \qquad (7)$$

Ratio (7) is at its maximum near the boundary separating the thermal barrier and ion barrier, B_1, for a positive potential $\varphi_{pasm} \ll \varphi_c$ and gradually decreases as we move up the slope, $\varphi < \varphi_c$. The number density of the passing ions at the maximum is

$$\max\frac{n_{ipas}}{n_{sm}} \approx \exp\left(-\frac{e\varphi_{pasm}}{kT_i}\right) - \sqrt{1-\frac{B_1}{B_m}}\,\exp\left(-\frac{e\varphi_{pasm}}{kT_i}\,\frac{1}{1-B_1/B_m}\right), \qquad (8)$$

where

$$\varphi_{pasm} \approx 2\varphi_c\,\frac{1-\sqrt{1-B_1/B_m}}{1+\sqrt{1-B_1/B_m}\,(2\varphi_c/T_i)/(B_m/B_1-1)}\,.$$

As a result, the number density of the ions and the compensating electrons on the slope of the ion barrier depends on the plasma density n_{sm} in the solenoid. Most energetic electrons captured by the ion barrier intersect with the fairly dense population of ions and electrons on this slope. The passing ions are compensated by the passing electrons from the solenoid with a moderate temperature T_{es}. The energetic electrons in the ion barrier lose an energy ε_{ep} to the electrons from the solenoid with the characteristic time constant

$$\tau_{\varepsilon l} = \frac{1}{2\pi\sqrt{2}}\,\frac{\sqrt{m}}{e^4\Lambda_e\langle n_{ipas}\rangle}\,\varepsilon_{ep}^{3/2}\,.$$

For $\varepsilon_{ep} \sim 1$ keV and $n_{pas} \sim 10^{11}$ cm^{-3}, we have $\tau_{\varepsilon l} \sim 3$ ms. As the ion number density in the ion barrier grows, the diffusion of electrons in longitudinal velocity increases due to electron scattering by ions, which weakens their drift because of the reflection from the magnetic field. When heating power the plasma density in the solenoid increases at a constant ECR, the energy of the electrons in the ion barrier decreases, their reflection weakens, and, accordingly, the barrier height φ_c diminishes. The lowering of the barrier leads to an increase in the number density of the passing ions in the barrier and a further spontaneous drop in the barrier height, observed in TMX-U experiments.

Cho et al. [41, 45–47] analyzed the results of experiments of many years in the formation of barriers with the GAMMA-10 device. They arrived at the following formula for the confining barrier φ_c (in kilovolts):

$$\varphi_c = 10^{-4}[1 + 5\times 10^{-3}P_{BECR}^{1.04}]\,P_{PECR}^{1.73}\left[c\left(\frac{n_p}{n_s}\right)^{2/3} - 1\right] \times \exp\left(-\frac{n_s}{3\times 10^{12}}\right),$$

where P_{BECR} and P_{PECR} are the ECR heating powers in the thermal barrier and the ion barrier (kW), respectively, and $c = 9-11$ for the hot-ion mode and $7-9$ for the high-potential mode.

An attractive feature is the growth of the ion barrier with the ECR heating power; the rapid drop in its height as the plasma density in the solenoid increases is another notable property. In recent years, attempts have been made to raise the ECR heating power in ion barriers in the hot-ion mode of the GAMMA-10 device [47, 49]. The barrier φ_c increases its height in accordance with the experimental dependence discussed earlier. At $P_{PECR} = 450$ kW, $P_{BECR} = 200$ kW, and a 20 A current of oblique atomic injection in the mirror cell, the ion barrier $\varphi_c = 2.1$ kV was formed in the hot-ion mode [49]. A two-temperature flux of energetic electrons from the drift space with the effective energy approximately proportional to P_{PECR} reached the plasma receiver [48].

Experiments involving the GAMMA-10 device did not reveal spontaneous disruption of the longitudinal confinement of the ions in the solenoid by ambipolar barriers caused by an increase in the ion number density. Possibly, this is due to the limitations imposed on this density by the conditions of MHD stability of the plasma in the solenoid. In their latest experiments in the formation of high ion barriers in the hot ion mode, Saito et al. [48] identified a lowering of these barriers by 10% in the course of roughly 30 ms as the linear plasma density in the solenoid increases.

Thus, the disruption of longitudinal plasma confinement in the solenoid by ambipolar barriers can be overcome and the plasma density threshold can be raised by increasing the ECR heating power. As regards the jumps in the Pekker potential in a mirror cell with a thermal barrier [50] (whose presence was illustrated by Cohen's numerical Fokker–Planck simulations [44]), when the field B_s in the solenoid is much weaker than B_m, the potential begins to decrease at the end of the solenoid before the field maximum (as shown in Section 2.4 in the review article in Ref. [51]), and the Pekker jump after the field maximum may not even occur.

In 1988–2002, experiments on the small axially symmetric ambipolar trap HIEI were conducted at Kyoto University [52–55]. The trap was 4.6 m long, with the solenoid 1.9 m long, and the magnetic field in the solenoid was as high as 1 kG, with the magnetic field in the magnetic mirrors as high as 7 kG. Production of plasma with the duration up to 10 ms, the plasma MHD stabilization, and barrier formation were done by a high-frequency field in the ion-cyclotron frequency range. The plasma parameters in the solenoid were $n_s = (1-3)\times 10^{12}$ cm^{-3}, $T_i = 100-200$ eV, and $T_e = 15-25$ eV. An ion barrier with $\varphi_c > 120$ V and thermal barriers with $\varphi_b = 30-35$ V were formed [35]. Also, researchers studied the suppression of turbulence and transverse losses of plasma by biasing the ring limiter in the solenoid up to +200 V. Here, substantial shear in the azimuthal plasma velocity was recorded and plasma density fluctuations were found to decrease by a factor of approximately ten, while the transverse plasma losses decreased by a factor of approximately three [54]. In their recent research, Yasaka et al. [55] implemented a magnetic divertor in the solenoid, which made it possible to substantially lower the MHD activity of the flute mode $m = 1$.

Plasma experiments involving the solenoid of the HANBIT device at the Korea Basic Science Institute are permanently performed since 1998 [56–59]. The parameters of the axially symmetric solenoid are as follows: the magnetic mirrors are 5 m apart, the diameter of the vacuum chamber is 0.6 m, the magnetic field is $B_s = 2.1-2.4$ kG, and the magnetic field in the mirrors is $B_m = 24$ kG. Plasma production, heating, and MHD stabilization were achieved by ICR heating with preionization of the gas by ECR heating. The researchers were able to produce plasma with the initial gas pressure in the chamber of approximately 10^{-5} Torr with additional puffing. ECR preionization was done by klystrons, whose power reached 2 kW. To achieve ICR heating, a slit antenna with the power up to 500 kW was installed in the median plane of the solenoid and a double-half-turn antenna with the power up to 100 kW was installed near a magnetic mirror. So far, the ICR heating has been about 200 kW. When heating is not sufficiently strong, MHD-stable plasma with the density $n_s = (2-3) \times 10^{12}$ cm^{-3} and a duration of roughly 150 ms forms at frequencies of the microwave field somewhat lower than the ion-cyclotron frequency. When the heating power is about 200 kW (higher than 150 kW), a fairly dense plasma is formed even if the frequency is equal to or somewhat higher than the ion-cyclotron frequency. The diameter of the produced plasma amounts to 25–35 cm, the ion temperature is 200–300 eV, and the electron temperature is about 25 eV.

4. Experiments in Novosibirsk

In 1977, the construction of an ambipolar trap with an average minimum B (with quadrupole end mirror cells), AMBAL, began at the Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences [60]. After the failure of one of the end mirror cells, it was decided that experiments should be continued with another mirror cell, which had already passed all tests (the AMBAL-Yu device). The experimenters studied the storage of hot plasma. Meanwhile, a new ambipolar trap, AMBAL-M, of axially symmetric geometry was to be set up in a special building whose construction was in its final stages. Experiments with the AMBAL-Yu device began in 1986 [61].

Figure 5 gives an idea of the AMBAL-Yu device. The magnetic field with its minimum at the center of the mirror cell (7–10 kG) is generated by a pair of coils of the male–female type. The magnetic mirrors are set apart by ± 0.5 m from the center along the axis and are formed in the fan-shaped end parts of the field with the magnetic-field ratio $B_{max}/B_0 = 2$. The fan-shaped fields 'rest' on the plasma receivers, on which the plasma guns are mounted. Jets of hydrogen plasma emitted by these guns pass through the magnetic well, where they are intersected by beams of high-energy hydrogen atoms. Fast ions, which form as a result of the ionization of, and exchange in, the atoms in the jet (target plasma), are captured by the magnetic well (trap). In their first experiments, Gilev et al. [62] were able to store a high-temperature population of ions with a low number density of only 1.5×10^{11} cm^{-3}, mainly due to the instability of the target plasma jets emitted by the ring guns. Replacing the ring guns with a specially designed slit gun

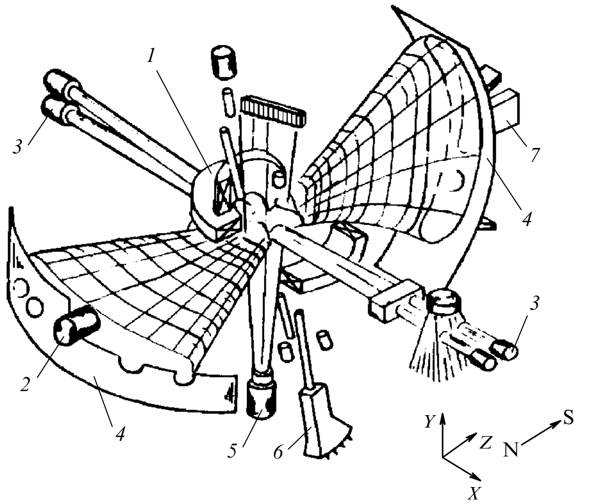

Figure 5. The AMBAL-Yu device: *1*, magnetic-mirror coils of the male–female type; *2*, plasma gun; *3*, START-2 atomic-beam injectors; *4*, end plasma receivers; *5*, diagnostic DINA-4A atomic injector; *6*, five-channel energy analyzer of the charge-exchange atoms; and *7*, end energy analyzer.

[63] made it possible to produce stable target plasma in a trap with a cross section close to a circular one, the density 2.4×10^{14} cm^{-3}, and the temperature about 10 eV. Atomic beams from four START-2 injectors [64] with the energy 17 keV and the total current 160 A were captured in this target by the trap in the form of ions (50%). A high-temperature population of ions with a number density greater than 10^{13} cm^{-3} was stored in a volume of 3 l with the average energy 6 keV ($T_e = 25$ eV) [62].

Earlier, in the plasma in a solenoid with a mirror cell, Kabantsev and Taskaev [65] detected and then studied a low-frequency (~ 30 kHz) drift instability of the flute type, identified as a drift Kelvin–Helmholtz instability (KHI). Generation of such an instability is related to the nonlinear distribution of the radial electric field 'ejected' into the plasma along the magnetic field by the ring plasma gun, whose plasma is a gas discharge in a diaphragmed ring channel placed in the solenoid [66]. The drift in crossed magnetic and nonlinear electric fields leads to a differentiated rotation of the plasma column. In certain conditions, this rotation is unstable and is accompanied by the generation of frequency modulation of the electric field. Experiments have shown that the development of the KHI is associated with the heating of ions in the solenoid plasma up to anomalously high temperatures of about 50 eV [67]. As a result of such instability, electrostatic waves are generated and the energy of plasma rotation transforms into the energy of wave packets. Such electrostatic waves are effectively absorbed by the ion component, with the mode of static heating of ions setting in. The attained temperature of the ions depends on the ratio of the strengths of ion stochastic heating and electron drag. Here, due to the high longitudinal specific heat, the temperature of the electrons in the entire plasma jet does not rise.

The strength of the electron drag on ions is proportional to $T_e^{-3/2}$. Increasing the ion temperature requires increasing the electron temperature. This can be done by 'placing' a potential barrier for the electrons (a thermal barrier) between the plasma gun and the solenoid (trap). The thermal barrier

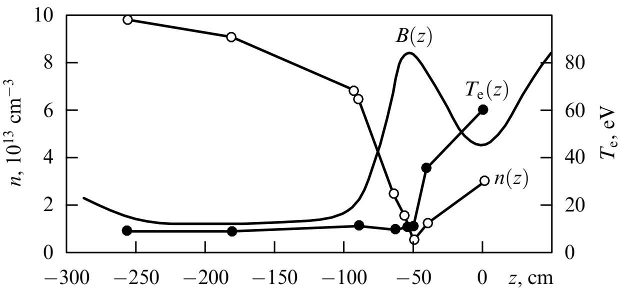

Figure 6. Distributions of the magnetic field $B(z)$, the plasma density $n(z)$, and the electron temperature $T_e(z)$ along the axis from the plasma gun to the center of the AMBAL-Yu device. In the median plane of the mirror cell, $z = 0$ and $B(0) = 7$ kG.

was implemented in the AMBAL-Yu device [68]. A slit plasma gun was replaced by a ring gun with a solenoid that supplied the plasma. Figure 6 shows the distributions of the measured magnetic field, plasma density, and electron temperature along the axis from the plasma gun to the mirror-cell center. Clearly, the plasma density at the entrance magnetic mirror has a minimum that is no greater than 10% of the density in the supply solenoid. Such reduction in the plasma density is caused by the reflection of the ions in the solenoid with the temperature about 50 eV from the magnetic mirror and the continuing pumping of energy from the KHI only into the transverse motion of the ions. Here, it is important to implement a minimum length of magnetic-field buildup from the solenoid to the mirror to guarantee an adiabatic mode close to the collisionless mode on this length. The plasma density increases to 3×10^{13} cm^{-3} towards the trap center.

To the left of the density minimum in Fig. 6, the electron temperature along the axis remains constant at the value about 10 eV, while on the right (in the trap), the electron temperature increases dramatically, up to roughly 50 eV. To the left of the density minimum, there must be a potential barrier for the electrons obeying the Boltzmann law

$$\Delta\phi(n) = \frac{kT_e}{e} \ln \frac{n}{n_{\min}} .$$

The measured height of the barrier to the left, $\geqslant 20$ eV, supports this supposition, The height of the barrier to the right, ~ 150 eV, is determined by the conditions needed for plasma confinement in the trap.

The appearance of a thermal barrier led to a dramatic reduction in the electron specific heat, a rise in the electron temperature in the trap, and a respective reduction of ion cooling in the medium of these electrons accompanied by a substantial rise in their temperature. The measured temperature of the ions from the hydrogen plasma proved to be 650 eV [69]. In experiments with deuterium plasma, the ion temperature 930 eV was reached under enhanced voltage across the ring discharge in the gun. This value was corroborated by the results of measurements of the yield of thermonuclear neutrons [69, 70]. The plasma density in the trap was 3×10^{13} cm^{-3}. Thus, a quasistationary source of low-temperature plasma ($T \leqslant 10$ eV) was produced in the mirror-cell high-temperature plasma ($T_i \sim 1$ keV and $T_e \geqslant 50$ eV) without any additional heating.

After Ryutov and Stupakov's [18, 71] discovery and analysis of substantial neoclassical transverse plasma losses in ambipolar traps with multipole components, the tendency to build fully axially symmetric traps only strengthened. Hence, simultaneously with experimental work on the AMBAL-Yu device, a fully axially symmetric ambipolar trap, AMBAL-M, was being designed.

The possibility of MHD stabilization of plasma in an axially symmetric magnetic field has been known for a long time. In particular, J Andreoletti and H P Furth in 1963 proposed a radial magnetic system with minimum B, but the magnetic well in such a system is very shallow. In 1982, Arsenin [72] suggested that the ends of a long trap be attached to ring mirror cells bent along the radius, which have no minimum B but lead to a favorable average curvature of the trap on the whole. The drawback of ring mirror cells is the small thickness of plasma in the gyroradii, which is an unfavorable factor in the plasma microstability.

To ensure MHD stability in the AMBAL-M trap, it was suggested adjoining the ends of the trap to semicusps containing hot-ion bell-shaped plasma in the region of adiabatic ion motion [73, 74]. (In semicusps, the physical thickness of plasma is much larger than that in ring mirror cells.) In the outer layer of plasma in the trap, MHD stability is ensured by the favorable average curvature in the semicusps. The outer layer is stable if a certain limit of the ratio of plasma pressure in the semicusps to plasma pressure in the trap is exceeded [74]. In the inner bell-shaped layer of plasma in a semicusp with an inverted density gradient, the field curvature is unfavorable. However, the magnetic field is then highly nonparaxial, and therefore, as the plasma pressure is slowly (almost linearly) reduced to zero, the plasma remains MHD stable [73]. Because the ion motion ceases to be adiabatic in the vicinity of the zero field, the plasma pressure suddenly drops. Nevertheless, in a trap with semicusps at its ends, the stability under transverse displacement of plasma is, on the whole (hard mode), retained, but the condition of such stability becomes more rigid [74]. However, MHD perturbations at higher radial and azimuthal modes remain unstable, and the inner regions of the plasma in the semicusps are the prevailing source of such perturbations. MHD stability of plasma in high small-scale permutational modes is ensured by the effect of a finite Larmor radius (FLR), mainly in the plasma in the trap. The stability condition in the higher modes amounts to imposing an upper bound on the ratio of the plasma pressure in the semicusps to the plasma pressure in the trap, with a sufficiently large ion gyroradius in the trap. For the complete MHD stability, the range of admissible values of the ratio of these pressures must be sufficiently wide [74].

Figure 7 gives an idea of the AMBAL-M device. The magnetic system consists of a 14 m long central solenoid, two end mirror cells with the mirror separation 1.75 m, and two MHD stabilizers (MHD anchors) in the form of semicusps, with the distance between the mirrors along the axis amounting to 0.26 m. The overall length of the magnetic system is 21 m. Here is the distribution of the magnetic field along the device. The magnetic fields generated in the solenoid can be as high as 4.5 kG, those in the mirror cells as high as 15 kG (in the mirrors, as high as 60 kG), and those in the semicusps up to 6.7 – 12 kG (in the mirrors, up to 23 kG). The solenoid was supposed to produce plasma with the following startup parameters: density $\hat{n} \approx 10^{13}$ cm^{-3}, volume about 1.5 m^3, and temperature $T \geqslant 100$ eV. Accordingly, in

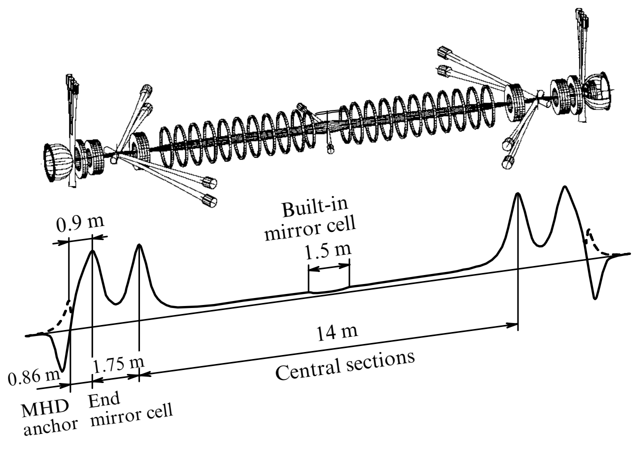

Figure 7. The AMBAL-M device.

the end mirror cells, $\hat{n} \approx 3 \times 10^{13}$ cm^{-3} and $\langle E_i \rangle \sim 12$ keV ($T_e \geqslant 100$ eV); in the semicusps, $\hat{n} \approx 10^{13}$ cm^{-3} and $\langle E_i \rangle \sim 5$ keV [75, 76]. The plasma radius in the mirror cells was to be about seven gyroradii of the D^+ ions. The radial thickness of the bell-shaped plasma in the 6 cm semicusps is equal to seven gyroradii of the H^+ ions [75].

Plasma is stored and sustained by injecting high-energy atoms: four beams of 25 keV deuterium atoms are injected into each end mirror cell for capture by ions, and four well-focused beams of 6 keV hydrogen atoms are injected into each semicusp [76].

To maintain a deep vacuum in the mirror cells, the injection of atomic beams is done through magnesium-vapor supersonic jets blocking the passage of gas from the sources of fast atoms [77]. The duration of an injection could be as long as 100 ms.

The vacuum system consists of the solenoid chamber ($L = 12$ m and $D = 1$ m), the end mirror cell chambers ($L = 1.3$ m and $D = 1.2$ m), the semicusp chambers ($L = 0.8$ m and $D = 1.6$ m), the end tanks with the volume 16 m^3, and the adapters. The overall length of the system is 27 m. Before being assembled, all vacuum units were degassed at 400 °C. To reduce gas recycling, the entire assembled vacuum system can be heated for long periods up to 250 °C, and a thin film of pure titanium is periodically sputtered onto the inner surface of the solenoid chamber. To absorb fast atoms from the plasma, the inner surfaces of the chambers of the mirror cells and semicusps are covered by 0.3 mm thick niobium warm-up liners. The main evacuation of the vacuum chambers is done by titanium-sputtered cooled panels [76, 77].

Simultaneously with work on the AMBAL-M project, a group of scientists from the United States developed a theory of MHD stabilization of anisotropic plasma with a high $\beta \geqslant 0.7$ via conducting walls and FLR effects in mirror cells [78, 79]. For large (in absolute value) $\nabla_{\parallel} \beta \propto \beta$, the diamagnetic circular current exhibits a distinct maximum in the mirror cell's median plane and generates a poloidal magnetic field, which locally amplifies the magnetic field in the region between the plasma and the conducting wall. This field, which is local along its length, keeps the plasma from performing rapid transverse large-scale displacements, because it is limited by the conducting surfaces. It was decided to use the AMBAL-M device to study MHD stabilization by the conducting walls in an end mirror cell via ECR heating of electrons to high temperatures [77]. Together with the Institute of Applied Physics of the USSR Academy of Sciences, a system of double-frequency cyclotron heating of electrons by two extraordinary microwaves fed to the plasma at a pitch angle of roughly 50° [80] was worked out. The plan was to heat the population of electrons with the number density about 10^{13} cm^{-3} in the volume of about 10 l to the transverse temperature of roughly 400 keV and to reach $\beta \sim 0.75$. With β increasing, stabilization was to be achieved by freezing the plasma into the ring gas-discharge cells built into the end plasma receivers (a description can be found in Ref. [74]).

Later plans included placing a local mirror cell with a reduced magnetic field at the center of the solenoid, as shown in Fig. 7. By using an atomic injector or ICR heating, an anisotropic population of ions with the number density $\sim 3 \times 10^{13}$ cm^{-3}, the transverse temperature ~ 10 keV, and $\beta \sim 1$ can be maintained in this mirror cell. Such a mirror cell with plasma stabilization can serve as an MHD anchor in the trap [81].

In addition to experimenting with MHD stabilization of plasma in an axially symmetric geometry, there were also plans to raise the temperature of the isotropic plasma in the solenoid of the AMBAL-M device to ~ 500 eV at the density $\hat{n} \approx 10^{13}$ cm^{-3} by improving the longitudinal confinement and additionally heating the plasma in the solenoid.

In 1993, one end system (the first phase in the development of the AMBAL-M device) became operational [82]. Figure 8 shows the plan of this phase. Here, instead of the solenoid, a second end tank with a plasma gun is attached from the left to the end mirror cell.

Hot startup plasma was produced in the end system (mirror cell plus semicusp) by a ring plasma gun, as in the AMBAL-Yu mirror cell. But in contrast to the AMBAL-Yu experiment, plasma was fed to the end mirror cell by a plasma gun not through a supply solenoid with a fairly uniform magnetic field of considerable strength but through an increased beyond-mirror magnetic field, which together with the solenoid's field of the plasma gun forms a deep mirror cell with a weak field in the median plane (Fig. 9). In such a transport mirror cell, the plasma jet from a gun of about 2 equiv. kA is mostly reflected by the mirror cell's exit magnetic mirror, is captured by the mirror cell, diffuses radially, and mainly leaves it and also goes inside to the central floating electrode of the ring gun. The ions in the transport channel are heated by KHI. Less than 10% of the plasma jet (heated to the ion temperature about 180 eV) from the gun enters the end mirror cell. Hence, the plasma produced in this mirror cell had a moderate average density 6×10^{12} cm^{-3} in a volume of about 20 l. The observed smoothing of the radial profile of the plasma potential over the magnetic flux reduces the stochastic heating of the ions in the end mirror cell, with the result that their temperature was no higher than 200 eV. Longitudinal confinement of ions under turbulent heating is close to classical confinement. The energy lifetime of plasma in the end mirror cell is roughly 0.5 ms, and the transverse energy losses are a hundred times smaller than the longitudinal losses [83, 84].

In the entrance magnetic mirror of the end mirror cell, the plasma density is observed to be at its minimum value, which is the same along the radius, $\sim 10^{12}$ cm^{-3}. The longitudinal potential distribution was found to depend on the radius, and in the large part of the cross section, there was a distinct minimum of the potential coinciding with the minimum of the

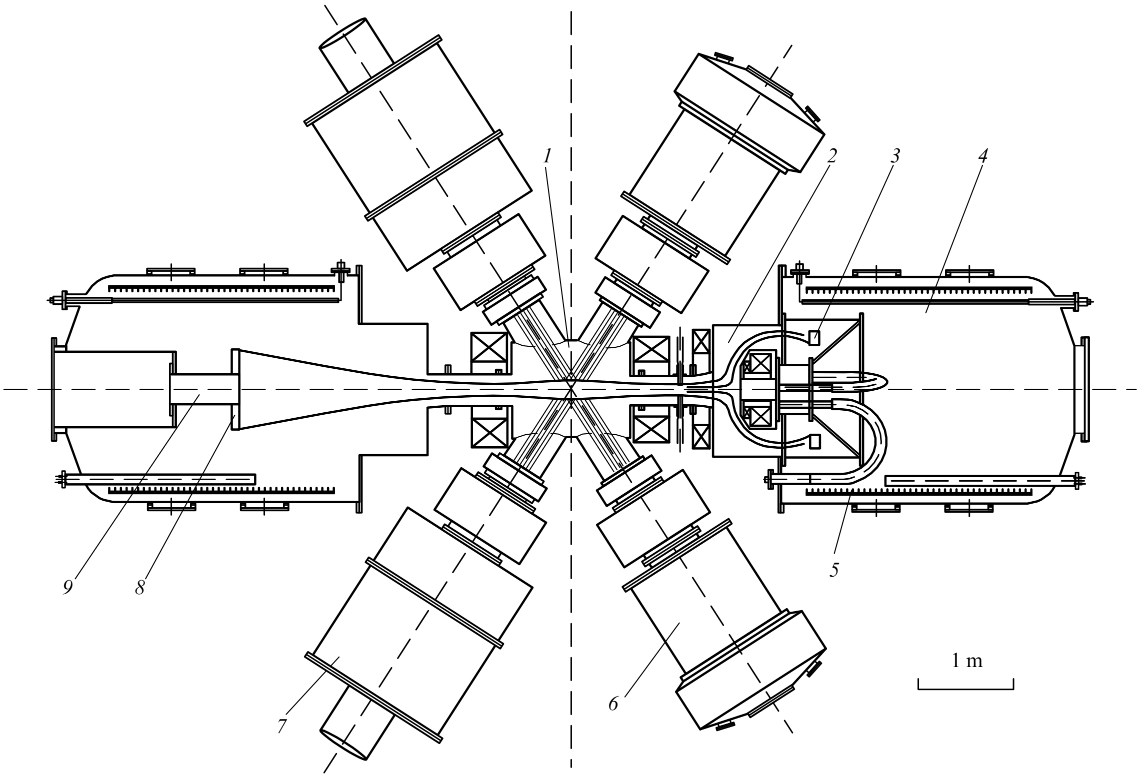

Figure 8. First phase in the development of the AMBAL-M device (bottom view): *1*, end mirror cell; *2*, semicusp; *3*, end receiver of plasma from the semicusp; *4*, left end tank; *5*, titanium panels for gas evacuation; *6*, absorbers of atomic beams; *7*, atomic injectors with two sources of fast atoms in each; *8*, receiver of plasma from the left mirror cell; and *9*, ring plasma gun.

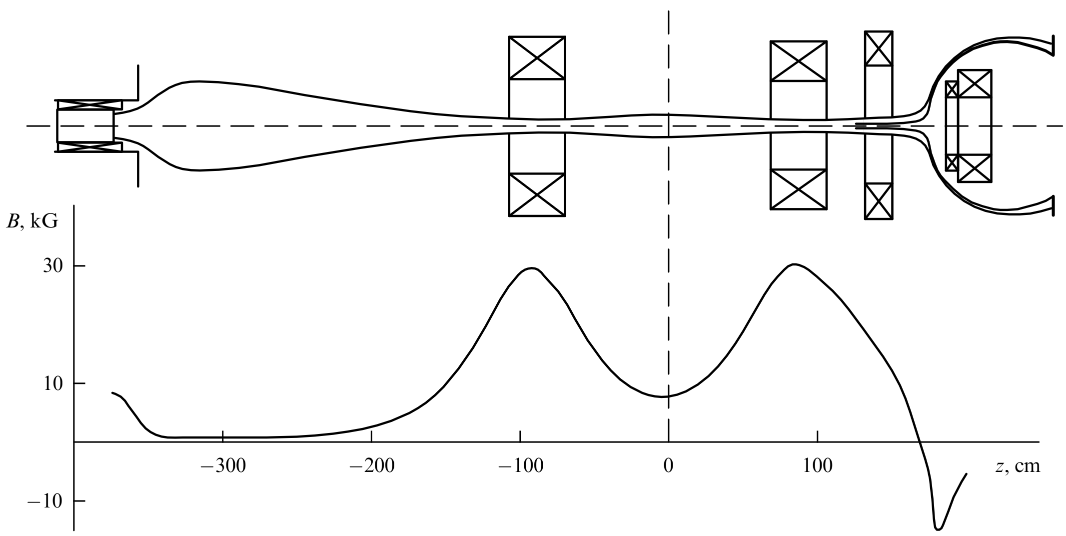

Figure 9. Geometry of plasma flow gun (to the left) to the end system; the longitudinal distribution of the magnetic field is shown in the lower part.

density. The electron temperature in the transport mirror cell did not exceed 10 eV, then gradually increased, reaching values of about 15 to 20 eV (depending on the value of the radius) in the entrance magnetic mirror, and finally rapidly grew. In the medium plane of the end mirror cell, the electron temperature increased to values no smaller than 50 eV [84].

The plasma jet contains a longitudinal electron current (earlier observed in the AMBAL-Yu device). A fraction of the current of the discharge electrons in the plasma gun spreads along the magnetic field lines. The larger fraction of this current enters the end plasma receiver and returns through the vacuum chamber. The smaller fraction of the ejected current moves across the magnetic field and then returns, forming current loops in the plasma. In the transport mirror cell, the current flowing from the chamber and the plasma periphery closes on the ungrounded anode through the radial diffuse (nonambipolar) ion flux. The gun emits a 1.6 kA electron current, a 1.2 kA current flows along the end mirror cell, and a current of 1 kA reaches the semicusp. Along the plasma periphery in the transport channel, there flows a back current of 0.3 – 0.4 kA [84]. The nature of the observed transverse electron-current losses is unknown; it is probably related to plasma turbulence. The electron current flowing from the gun retains its ring structure in the transport mirror cell, and as we move away from the gun, the inner cavity of the current fills up and the maximum in the radial distribution of the current moves inward, while at the entrance to the end mirror cell and farther, the maximum in the current density is reached on the axis. After the median end mirror cell's plane, the electron current concentrates within a region surrounding the axis with a radius that is approximately two times smaller than the plasma radius. The estimated coefficient of diffusion of the current to the axis, $D_{\perp j} \sim 10^5$ cm^2 s^{-1}, is close to the measured plasma diffusion coefficient $D_{\perp} \sim 2 \times 10^5$ cm^2 s^{-1}, but the longitudinal variation of the current's radial profile is not purely diffusive, because the maximum of the current density over the magnetic flux does not drop as long as the current is inside the end mirror cell [85]. As a result of smoothing the radial profile of the potential, the longitudinal acceleration of electrons increases in the region below the magnetic surface that passes through the ring cathode in the gun. This and the observed current contraction lead to a high flux velocity of the electrons, close to the thermal velocity ($\sim 0.6 v_{\mathrm{Te}}$ in the entrance magnetic mirror of the end mirror cell) [85], which severely limits the expulsion of heat from the end mirror cell by electrons and the thermal barrier.

It has been established that the electron current plays the main role in the heating of electrons in the end mirror cell due to the scattering and stopping of fast current electrons. The strength of this heating is approximately three times that of the heating of electrons by ions [84]. Later, the distribution functions of electrons in the end mirror cell was measured. In the near-axis region, where the longitudinal current is concentrated, a flux of fast current (beam) electrons with energies ranging from 150 to 350 eV and the density equal (according to rough estimates) to 10% of the total electron number density [86] was registered.

Experimental studies of KHI-generated plasma turbulence responsible for ion heating were continued on the end system of AMBAL-M. Here, electrostatic and magnetic vibrations with a broad spectrum of frequencies ranging from several dozen to several hundred kilohertz (with azimuthal modes up to the tenth) were recorded [84, 87]. In the high-frequency range, white noise dominates (noise up to several megahertz was detected) [88].

The plasma generated in the end system was found to be macroscopically stable, and no global plasma displacements were recorded. At the periphery of the plasma, in the decay stage, plasma density vibrations with the amplitude about 10% and the characteristic frequency about 5 kHz were discovered [84]. Also, the radial profiles of the plasma pressure in the semicusp and the mirror cell were measured. In the semicusp, in the vicinity of the zero field, where the adiabaticity of ion motion is violated, the plasma pressure proved not to be very low. On the basis of measurements of these profiles and plasma parameters, the researchers estimated the effectiveness of the semicusp as an MHD stabilizer by its contribution to the stability integral in the hard mode. The stabilizing contribution of the semicusp proved to be three to four times larger than the destabilizing contribution of the mirror cell [88, 89]. In an experiment in which the semicusp was switched off, the global stability of the plasma was found to be retained, and the level of oscillations in the plasma density at the plasma periphery and the size of the region of transverse motion in the decay stage were found to increase by a factor of approximately two. This experiment and the study of the behavior of the longitudinal electron current made it possible to draw a conclusion concerning the stabilization of large-scale MHD modes by the longitudinal coupling of plasma and the cathode (plasma) of the plasma gun at the end. Achieving MHD stability of the plasma in a completely axially symmetric geometry both in the period of turbulent heating and in the stage of plasma decay is an important result of experiments on the end system (cell) of the AMBAL-M device.

An experiment was conducted in which two hydrogen-atom beams with the energy 16 keV, the total equivalent current 100 A, and the duration 200 μs were injected into the end mirror cell. About 8% of the injected atoms were captured by ions in the mirror cell, and a population of hot ions with a density of roughly 5×10^{11} cm^{-3} in a volume of 20 l accumulated. A linear increase in the density of this population was observed, which holds out hope that dense high-temperature plasma can be produced in the end mirror cell by injecting atomic beams with a duration no shorter than 10 ms [84].

To be able to inject atomic beams into the end mirror cell, four ion IK-50 sources were designed and bench-tested for the production of deuterium ion beams with the energy up to 30 keV, the current amounting to 40 – 50 A, and the duration 80 – 100 ms [90]. After these sources were installed in the atomic injectors of the mirror cell, their synchronous operation involving hydrogen ions was tested. One hydrogen-atom beam with the energy 25 keV and the equivalent current 17 A was injected into the startup plasma [88].

Also launched and tested was a single gas-barrage wide-aperture magnesium-vapor target jet for atomic injectors.

Due to cuts in financing, further experiments in this project were conducted with half the central solenoid attached to the end system, as shown in Fig. 10. Suggestions concerning the transition to experiments involving the entire solenoid have been developed and are published in Refs [88, 91].

MHD stable hot plasma with the solenoidal length 6 m and the diameter about 0.4 m was produced in a solenoid with the magnetic field about 2 kG with a beyond-mirror source of cold plasma (gun) at one end (see Fig. 10). The transverse plasma distribution varies along the length of the solenoid. Far from the gun, the plasma density in the near-axis region amounted to 2×10^{13} cm^{-3} [92]. According to the results of precise measurements, the electron temperature amounted to 50 eV [93]. The ion temperature was estimated only by the energy spectrum of the ions, measured by an analyzer located beyond the exit magnetic mirror. The spectrum was found to resemble the Maxwellian one, and the ion temperature exceeded 200 eV [93].

While the solenoid is filled with plasma, which is turbulently heated by KHI, the coefficient of transverse diffusion caused by electrostatic vibrations remains large. According to the results of measurements of fluctuations of the azimuthal electrostatic field and plasma density, this coefficient attains values about 10^6 cm^2 s^{-1}. Nevertheless, transverse plasma losses in the solenoid are smaller than longitudinal losses.

When the discharge current in the plasma gun is suddenly switched off (this takes about 0.1 ms), the plasma decays with a drop in density by a factor of approximately three in the course of approximately 0.5 ms. During this time, the fluctuations of the electrostatic field decrease and reach an unobservable level, the plasma becomes quiet, and its lifetime

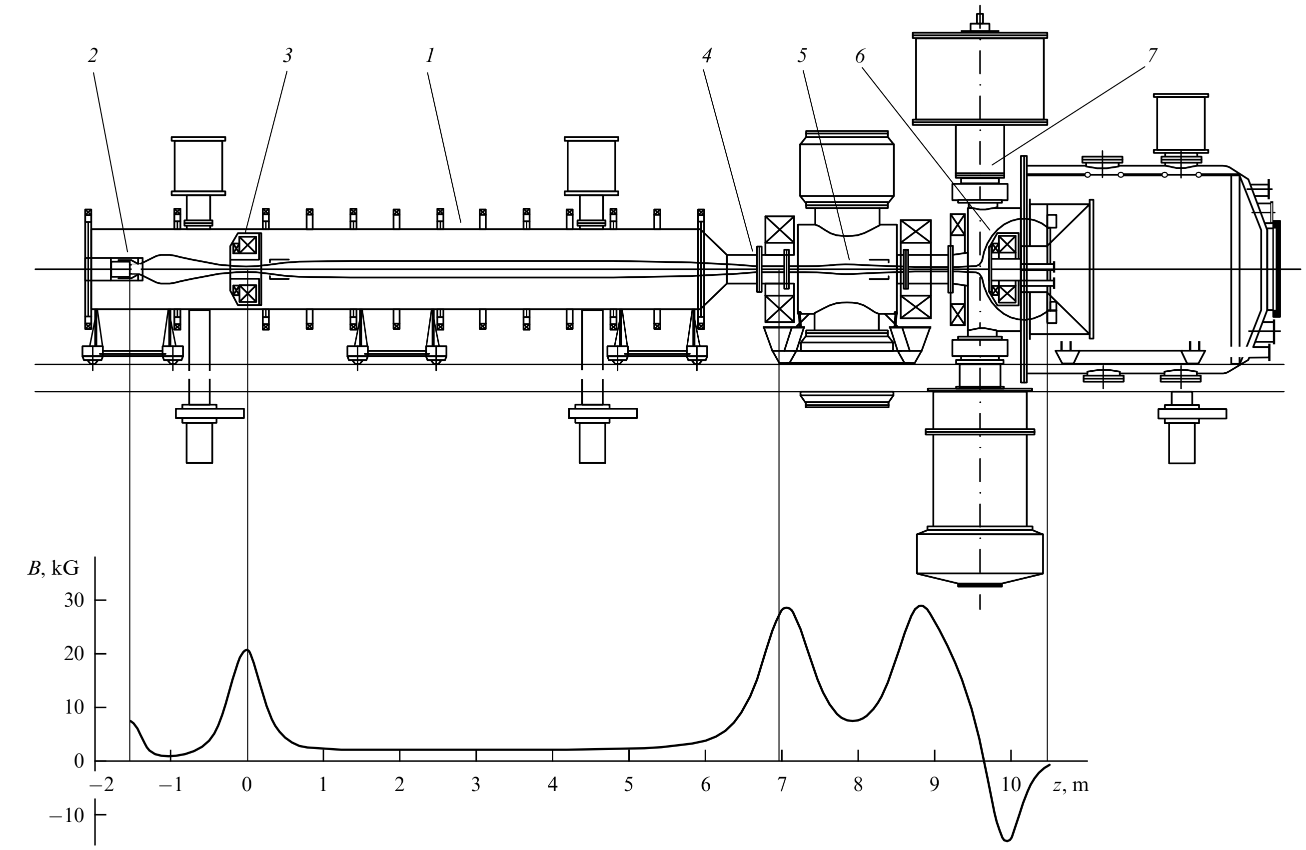

Figure 10. Half of the central solenoid with the end system (side view): *1*, solenoid; *2*, plasma gun; *3*, entrance magnetic mirror of the solenoid; *4*, exit magnetic mirror of the solenoid; *5*, end mirror cell; *6*, semicusp; and *7*, atomic injector of the semicusp.

increases more than threefold [92]. The transition of the plasma to the quiet state is accompanied by a strengthening of large-scale fluctuations, which are probably related to the emergence of MHD activity in the plasma due to the reduction of its stabilization by the effect of longitudinal coupling with the conducting end. After approximately two-thirds of the plasma is lost, another mechanism of MHD stabilization probably comes into play. Possibly, this mechanism is related to the replenishment of the halo with plasma and gas and to changes in the conditions at the plasma periphery [94]. In the transient period, transverse plasma losses do not prevail over longitudinal losses, because the transition (decay) time is close to the classical longitudinal plasma lifetime. An increase in the lifetime of plasma in the quiet state corresponds to a decrease in plasma density.

After the discharge in the gun is switched off, the transverse plasma losses decrease dramatically. Already in 0.2 ms, the radial plasma flux is reduced by a factor of approximately 30. After the turbulent state decays, the transverse losses decrease, at least to the level of measured radial variations of the transverse plasma transfer, by a factor of 10^3 [92]. The measured radial profile of the density of quiet plasma is in many respects similar to the profile of turbulent plasma prior to decay, and the radial density gradient reduces on the whole by a factor of approximately three. Accordingly, the diffusion coefficient of quiet plasma is estimated as approximately 3×10^3 cm^2 s^{-1}, which is only several times larger than the classical value.

The emergence of quiet collisionless plasma with no significant turbulence and with no longitudinal currents in it, with the duration about 1 ms, in an axially symmetric magnetic field is extremely important for studies of transverse plasma transport in such a field. The results of experiments yield promising estimates of transverse plasma confinement in the central solenoid of an axially symmetric ambipolar trap.

To increase the plasma density even more, hydrogen was puffed into the solenoid plasma as the plasma was turbulently heated while traveling from the ring box near the entrance magnetic mirror. At the optimum rate of hydrogen puffing, the researchers were able to substantially increase the plasma density (in the near-axis region with the radius about 10 cm the density was 6×10^{13} cm^{-3} with a substantial drop in ion temperature) [93, 95]. The radial plasma distribution was found to change insignificantly, while the effective plasma radius increased because of gas puffing at the plasma periphery [95]. It was found that gas puffing increases not only the density but also the energy content of the plasma. The ions produced as a result of ionization of the gas rapidly accumulate energy from the electrostatic vibrations during stochastic heating, while the electrons accumulate energy because of the enhanced relaxation of the electron current in high-density plasma (a current of roughly 2 kA flows through the solenoid plasma in the near-axis region whose radius is about 10 cm). This means that with gas puffed into the plasma, the power released by the gun to the solenoid plasma increases. The average ion temperature in the near-axis region with the radius about 10 cm with hydrogen puffing dropped from 250 to 200 eV [95]. The electron temperature in experiments in 2003 (after the plasma gun was replaced) was found to decrease. With hydrogen puffing, this temperature on the axis decreases from 45 to 30 eV [95]. In the near-axis region of the solenoid with hydrogen puffing, the average value of the relative plasma pressure $\beta = 8\pi nk(T_i + T_e)/B^2$ amounted to about 14%.

The production of hot MHD-stable dense plasma of a large diameter in the solenoid opens the possibility of effectively heating such plasma via atomic beams and ICR heating by fast magnetoacoustic waves.

By reducing the magnetic field in the solenoid by a factor of two (down to 1 kG) and combining this process with hydrogen puffing, the researchers were able to produce MHD-stable plasma in the solenoid, with the density $\geqslant 60\%$ of the initial density [93, 95]. The ion temperature remained the same. In the near-axis region of the solenoid, the value of β was no smaller than 33%. The estimate given in Refs [93, 95] was $\beta \sim 40-50\%$.

Production in the solenoid of plasma with a high β in which large-scale MHD instability is suppressed by the line-tying of the plasma in the solenoid to the beyond-mirror ring cold plasma at the end opens the possibility of going over to MHD stabilization of plasma with a high β via the walls of the vacuum chamber and the FLR effect.

The developed method of producing hot MHD-stable axially symmetric plasma by using a ring plasma gun could be very useful in accumulating thermonuclear plasma in ambipolar traps.

5. Prospects of the ambipolar fusion reactor

A quasistationary high-power fusion reaction in a closed magnetic system of the tokamak type has become a reality. An experiment is in the works in which a self-sustained reaction (ignition of thermonuclear plasma) in the tokamak will be realized. Finally, there are plans to build a demonstration reactor based on the tokamak principle.

In a thermonuclear D – T reactor, radiation damage of the materials of the wall facing the plasma (the first wall) limit its service life to three to six years [96 – 98]. Replacing this wall in a tokamak reactor each three to six years is an extremely complicated and costly (not to mention the time factor) process. The development of materials for the wall with a resistance to radiation damage much higher than the current one is highly improbable. To build a low-radiation $D-{}^3He$ reactor based on the tokamak principle is hardly possible unless the average value of β in it is significantly increased. For these reasons, a project to develop an industrial fusion reactor based on the tokamak principle probably has no future.

Despite the possibility of igniting thermonuclear plasma and building a tokamak-based demonstration reactor, alternative thermonuclear systems, e.g., those based on an ambipolar trap, should also be developed.

The key issues of confinement and ignition of thermonuclear plasma in a tokamak are (a) keeping the plasma from leaving the system in directions perpendicular to the magnetic field, (b) eliminating impurities and reaction products in directions perpendicular to the field, (c) generating a steady longitudinal many-mega-ampere current, and (d) removal from the vacuum chamber of highly energetic particle streams leaving the fusion reaction zone for the divertor.

The key problems associated with an ambipolar trap amount to (a) longitudinal and transverse confinement of thermonuclear plasma, (b) MHD stabilization of the plasma in a completely axially symmetric trap, and (c) elimination of impurities and reaction products in directions perpendicular to the magnetic field.

The natural stationarity, the simple axially symmetric geometry, and the absence of any problem with local overload of the divertors by the energetic particles leaving the trap in naturally diverging magnetic fields at the ends facilitate the development of an ambipolar fusion reactor. An industrial ambipolar D – T reactor may prove to have certain advantages thanks to the simplicity, reduction of costs, and economy of time in replacing the first wall. In the MHD stabilization of plasma in the solenoid by the conducting walls of the vacuum chamber and the FLR effect, the expected average value of β is close to unity. Because of the substantial weakening of the magnetic field in the plasma, the cyclotron radiation emitted by the electrons carries away an insignificant amount of power, and therefore ignition of the $D-{}^3He$ thermonuclear plasma is possible.

Experiments have shown very good longitudinal confinement of plasma by ambipolar barriers, in accordance with classical predictions [7, 8, 13, 15, 26]. It has been proved through experiments that the formation and prolonged maintenance of thermal barriers is possible, which significantly reduces the power needed for sustaining ambipolar barriers [13, 14, 24, 27, 28, 39].

Experimental verification of the possibility of ion evacuation from stationary thermal barriers is needed. The main ions, D^+ and T^+, captured by thermal barriers can be evacuated back to the solenoid along the magnetic field, thus exciting the bounce vibrations of the captured ions at parametric resonances by using coaxial coils in the thermal-barrier planes. In the thermal barriers, the varying magnetic field generated by the current in these coils excites oscillations of the number density of the high-energy and equilibrium populations of electrons because the plasma is frozen into the magnetic field. As a result, the depth of the thermal barrier varies synchronously with the varying magnetic field. Accordingly, the frequency of the bounce vibrations becomes modulated. At double modulation frequency, there is resonant parametric buildup of the bounce vibrations of the ions in the thermal barrier (damping of the vibrations transforms into buildup at the bottom of the barrier), and the ions are ejected into the solenoid.

The complete axial symmetry of the trap leads to the reduction of neoclassical transverse plasma losses to an insignificant level. Actually, such losses are determined by the precision with which the magnetic system is assembled and can be limited. Transverse plasma transport is determined by the diffusion caused by plasma turbulence. With a long solenoid, the most detrimental factor is the low-frequency drift plasma instability [99], which may not even occur if β is large enough [100] and can be suppressed by the shear of the radial electric field. High-frequency instabilities are less detrimental. This has been shown to be true, in particular, of electromagnetic waves in the ion-cyclotron frequency range [101].

An encouraging factor in longitudinal plasma confinement is the ideal isometry of the axially symmetric trap [102], due to which no secondary plasma current flowing along magnetic field lines within the trap can occur and no magnetic islands and stochasticity regions of magnetic field lines can form. In view of this, it must be stressed that in the event of MHD stabilization of plasma in a magnetic field with an unfavorable curvature by any neighboring stabilizers (built-in or end MHD anchors, conducting ends, or plasma in the beyond-mirror expanders), plasma currents flowing along the magnetic field lines and leading to turbulence may be generated.

Hopes have been raised by the results of experiments in transverse plasma confinement in the long axially symmetric solenoid of the AMBAL-M device, in which researchers observed plasma with no significant turbulence, the duration of approximately 1 ms, and the diffusion coefficient $D_\perp \sim 3 \times 10^3$ cm^2 s^{-1}, which is only several times larger than the classical value [92]. The GAMMA-10 device was used to suppress the drift instability by the shear of the electric field and to achieve the value $\tau_{i\perp} \sim 10^4 \tau_{\rm Bohm}$ of the transverse ion lifetime in the plasma core in the solenoid [30, 31]. This relation corresponds to the level attained in the best tokamaks. The energy lifetime (including the transverse component) of the main population of electrons was also measured: $\tau_{e\varepsilon} \sim 10^4 \tau_{\rm Bohm}$ [32, 33].

The proposed main method of MHD stabilization of high-temperature plasma in an axially symmetric ambipolar trap is stabilization by the conducting walls of the vacuum chamber combined with the FLR effect with β close to unity (in particular, see Section 3 in review article [51]). We note that with such stabilization, there can be a sizable gap between the plasma and the conducting walls. Maintaining stable conditions in a thermonuclear plasma with a high β in the solenoid of an ambipolar reactor means considerable reduction of the vacuum magnetic field and simplification of the design of the solenoidal reactor zone, which makes it possible to speed up the process of replacing the first wall of the D–T reactor. A considerable advantage of the method being discussed is the possibility of avoiding the generation of longitudinal plasma currents during stabilization, which may lead to an enhancement of transverse diffusion.

The development of this method is closely related to studies of plasma stabilization by high-energy particles, mostly electron rings (see the review article by Berk [103]). Berk et al. [78] showed by theoretical means that for an axially symmetric magnetic trap, there can be regions of complete (strong) stabilization of plasma with hot ions and a value of β exceeding a high threshold value. In particular, for the global mode with $m = 1$, the stability condition with the plasma radius $r_{\rm p}$ equal to the wall radius $r_{\rm w}$ is given by (without an exact calculation of integrals over length)

$$G_{\rm wall}^{|1|} \approx \frac{1}{16} \frac{1}{\beta_\perp (1-\beta_\perp)^2} \left(\frac{4p_\perp}{p_\perp + p_\parallel} - \beta_\perp \right) \left\langle \left(\frac{\partial \beta_\perp}{\partial z} \right)^2 \right\rangle r_{\rm v} R_{\rm v} \approx \frac{1}{8} \frac{p_\perp}{p_\parallel} \left(\frac{4p_\perp}{p_\perp + p_\parallel} - \beta_\perp \right) \frac{\beta_\perp}{(1-\beta_\perp)^2} > 1 \,, \qquad (9)$$

where $\beta_\perp$ is the value of the transverse β in the inner region of the plasma, $p_\perp$ and $p_\parallel$ are the transverse and longitudinal plasma pressures, and $R_{\rm v}$ is the curvature radius of the vacuum magnetic field on radius $r_{\rm v}$ ($r_{\rm v} R_{\rm v} \approx$ const). This condition clearly shows that as the plasma anisotropy $p_\perp / p_\parallel$ increases, the value of $G_{\rm wall}$ rapidly grows, while the threshold value of β needed for stability decreases significantly. For $r_{\rm w} > r_{\rm p}$, the threshold value of β increases with the gap $r_{\rm w} - r_{\rm p}$.

To ensure complete (strong) stabilization, a second condition

$$G_{\rm FLR}^{|2|} \sim \frac{3}{2} \frac{\beta}{1-\beta_\perp} \frac{R_{\rm vs} \rho_{\perp \rm v}^2}{r_{\rm p}^2 \Delta} > 1 \qquad (10)$$

must be satisfied, where Δ is the radial range of the drop in plasma pressure ($\Delta \ll r_{\rm p}$), $R_{\rm vs}$ is the curvature radius of the vacuum field on the radius $r_{\rm w} = r_{\rm p}$, and $\rho_{\perp \rm v}$ is the transverse gyroradius of the hot ions in the vacuum magnetic field.

The results of a theoretical analysis in Ref. [78] suggest that the low-frequency electromagnetic turbulence is at a very low level when the stabilization of the plasma by the conducting walls and the FLR effect is complete (strong), i.e., when not only MHD-like and compressive drift instabilities are suppressed but also no waves with negative energy are generated.

Kaiser and Pearlstein [79] analyzed stabilization by the conducting walls of the ballooning mode with $m = 1$ of plasma with $\beta \sim 1$ in the central solenoid of an axially symmetric ambipolar trap. They derived a ballooning-mode equation that allows for FLR effects. A dispersion equation was derived for a stepped radial profile of the plasma pressure. For this equation, Li et al. [104] found an expression valid at $r_{\rm p} = r_{\rm w}$ for isotropic plasma:

$$\int_{-z_m}^{z_m} \left[\left(\frac{B_{\rm v}'}{B_{\rm v}} \right)^2 \frac{\beta}{(1-\beta)^2} \left(\frac{3}{2} - \beta \right) \left(\beta - \frac{1}{2} \right) - \frac{\omega^2 \rho}{B_{\rm v}^2} \right] {\rm d}z = 0 \,, \qquad (11)$$

where $B_{\rm v}' = \partial B_{\rm v} / \partial z$, ω is the natural frequency, and ρ is the plasma mass density.

In their paper [104], Li, Kesner, and LoDestro showed that it is possible to improve the MHD stability of plasma in the long solenoid of an ambipolar trap by corrugating the magnetic field on a small scale (an approach suggested by D E Baldwin). Equation (11) (taken from Ref. [104]) involves the factor $B_{\rm v}'^2$, whose value in the long solenoid with a corrugated magnetic field becomes large, $B_{\rm v}'^2 \propto B_{\rm r}^2 N^2$, where $B_{\rm r}$ is the amplitude of the rise of the magnetic field in its corrugated structure (limited by the condition that $\beta > 1/2$ at the maxima of the field) and N is the number of corrugations in the solenoid (limited by the geometry of the coils). Numerical calculations of the value of β as a function of corrugation were done for different magnetic-mirror ratios in the central solenoid and different gaps between the plasma and the wall. For magnetic-mirror ratios in the range from 5 to 10, $r_{\rm w} \sim 1.3 r_{\rm p}$, and $N \approx 20-30$, the threshold value of β was found to be ~ 0.7. The above conditions of plasma stabilization by conducting walls were calculated for plasma with a distinct boundary ($\Delta \ll r_{\rm p}$). When the plasma pressure at the plasma periphery gradually decreases with increasing radius, the stabilizing effect of the conducting walls weakens. Basing their reasoning on the results in Refs [79, 105] for a certain class of radial pressure profiles in a solenoid without magnetic mirrors, Arsenin and Kuyanov [105] derived formulas for the dependence of the threshold value of β for the stability of the $m = 1$ mode on the thickness of the peripheral transition layer for different values of $r_{\rm w}/r_{\rm p}$. As the peripheral pressure profile changes from a distinct boundary to a smooth transition with the thickness of the order of the plasma radius at $r_{\rm w} = 1.3 r_{\rm p}$, the threshold value of β increases from 0.6 to approximately 0.82.

Corrugation of the magnetic field may improve stabilization by the conducting walls of not only the $m = 1$ MHD mode but also azimuthal modes with $m \geqslant 2$, because for these modes, too,

$$G_{\rm wall}^{|m|} \propto \left(\frac{\partial \beta_\perp}{\partial z} \right)^2 = 4\beta^2 \left(\frac{B_{\rm v}'}{B_{\rm v}} \right)^2 .$$

For modes with $m \geqslant 2$, the contribution of the FLR effect also increases: $G_{\mathrm{FLR}}^{|m|} \propto m^2 - 1$.

Therefore, small-scale corrugation provides an enhanced contribution of the local values $\beta > 1/2$ to the stability integral and may ensure independent MHD stabilization of plasma in the central solenoid of an ambipolar trap. At the magnetic-field minimum in each ripple, the linear density of the diamagnetic current increases in inverse proportion to the field strength; this current is used for transverse confinement of plasma with a constant pressure over the entire length. The poloidal fields of locally enhanced diamagnetic currents limit rapid transverse displacements of plasma toward the conducting walls of the vacuum chamber.

Even if the condition of strong stabilization $G_{\mathrm{FLR}}^{|2|} > 1$ is not satisfied in each ripple, the FLR effect in the corrugated solenoid as a whole may be sufficiently strong to suppress the higher modes and to stiffen the spatial structure of the first mode. Rosenbluth et al. [106] showed that according to the hydrodynamic theory, the increment of flute-like instability ω in weakly unstable plasma may be much smaller than the ion-cyclotron frequency ω_{ci} and, therefore, complete plasma stabilization by the FLR effect for $k\rho_{\mathrm{i}} < 1$ is possible because the condition $(k\rho_{\mathrm{i}})^2 > \omega/\omega_{\mathrm{ci}}$ can be satisfied (here, k is the wave number of the instability). However, the researchers studied weakly unstable plasma with a small β in an ordinary mirror cell, and therefore the question of whether strong stabilization of plasma with a large β in a long corrugated solenoid by FLR effects is possible remains unanswered.

Although plasma is stabilized within each ripple, longitudinal plasma currents between ripples do not appear because of the favorable curvature of the fields between the ripples. The results in Ref. [105] suggest that longitudinal currents at the ends of a corrugated solenoid with magnetic mirrors may also be absent.

Because plasma stabilization by conducting walls occurs only when β is larger than its threshold value, we must be able to accumulate plasma up to the threshold value of β without developing plasma instabilities. Although there may exist a band of stability in β at values below the threshold, we move into an instability band as we approach the threshold value [78]. As the plasma in the central solenoid accumulates, it may be stabilized by the plasma in the end mirror cells. This is accompanied by the generation of longitudinal plasma currents, which may increase transverse plasma losses. However, during the accumulation period, such elevated transverse plasma losses are admissible. There are several methods by which stable plasma can be accumulated in the end mirror cells with values of β above the threshold value. In 1987, Berk et al. [78] suggested short-term generation of multipole magnetic fields in mirror cells. Owing to the FLR effect, plasma stabilization allows a large number of poles, with the result that the violation of the cylindrical geometry of the plasma is small during the accumulation period when the current in the pulsed multipole winding is switched on.

Another method consists in using kinetic stabilizers, as suggested in Refs [107, 108]. These stabilizers ensure dynamic maintenance of the population of heavy ions in the region with a favorable curvature of the beyond-mirror magnetic field in an expander. The ions are injected into the outer end of the expander along conically steep converging magnetic field lines, which then transform into the less steep section of the magnetic lines (still conical, however), and finally 'enter' the last magnetic mirror. In the intermediate region between the conical sections, the magnetic field has a larger, favorable curvature. The ion beams are pinched and decelerated by the converging magnetic field and are then reflected into the region with the favorable curvature, where their density reaches its maximum. This density may be many orders of magnitude lower than the plasma density in the end mirror cells, and yet it may be high enough for suppressing MHD instabilities in the mirror cells [108]. The kinetic-stabilizer concept is based on Mirnov and Ryutov's proposal [109] to stabilize flute-like instabilities in a gasdynamic trap (GDT) by a dense flow of plasma from the trap in the beyond-mirror magnetic field with a favorable curvature [109], and on the results of subsequent GDT experiments in which the proposition was successfully implemented [110, 111].

The stability of the plasma during its accumulation up to the threshold value of β in an axially symmetric trap can be sustained by line-tying to ring sources of low-temperature plasma at the end plasma receivers (these ring sources must be turned on for short periods). This method has been tested in the AMBAL-M experiments in Novosibirsk [84, 93, 95].

Due to a finite conductivity of the walls, the decay of the currents induced in them leads to a gradual transverse drift of the plasma column. The increment of this slow instability $\gamma_{\mathrm{sl}} \sim c^2/4\pi\sigma d_{\mathrm{w}} r_{\mathrm{w}}$ (where σ and d_{w} are conductivity and wall thickness) is much smaller than the characteristic MHD frequencies [112]. Stabilization of this instability may be achieved, e.g., by line-tying to the ring gas-discharge cells with a closed Hall current in the beyond-mirror plasma receivers [74] (the longitudinal plasma current may then be small).

Several variants of a D−T fusion reactor based on an ambipolar trap have been suggested [113], and the differences are mainly in the design of the end mirror cells for longitudinal plasma confinement and in the ways in which MHD stabilization is implemented. The end mirror cells may be either of the single or of the tandem type. In the simplest case of a single mirror cell, the confinement potential φ_{c} is formed by the elevated ion density in such a mirror cell (Fig. 11). The power needed for sustaining this plugging ion population

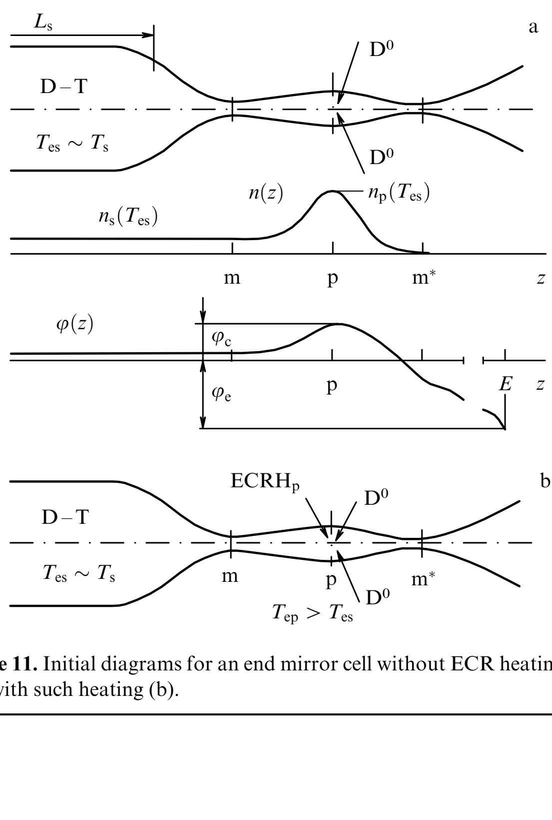

Figure 11. Initial diagrams for an end mirror cell without ECR heating (a) and with such heating (b).

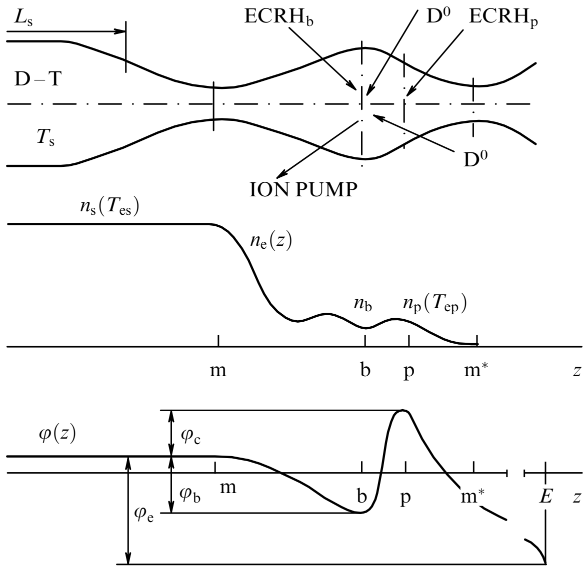

Figure 12. Diagrams for a single mirror cell with a thermal barrier.

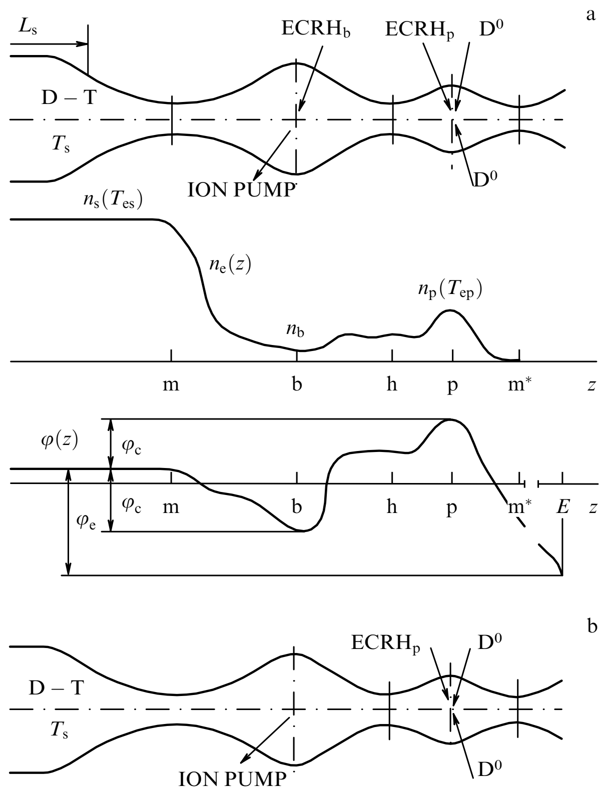

Figure 13. Diagrams for a double end mirror cell with a thermal barrier and ECR heating in it (a) and without such heating (b).

(and plasma on the whole) is proportional to the population density. In the single mirror cells with thermal barriers (Fig. 12) developed in the TMX-U and GAMMA-10 experiments, the necessary plasma density in the confining ion barriers decreases by a large factor, and so do the power inputs. The density of sloshing ions in the thermal barriers is close to their density in the ion barriers, with the result that the density of high-energy electrons in the thermal barriers becomes of the order of, or even higher than the plasma density in the ion barriers. In double mirror cells (Fig. 13), the thermal barriers with evacuation of the captured ions and the ion barriers are formed in separate mirror cells. Hence, any ratio of the plasma densities in the thermal and ion barriers is possible in such a scheme.

The advantage of single mirror cells with thermal barriers over double mirror cells amounts to the reduced length of the ion barriers and the end parts of the trap as a whole.

The ion barriers and thermal barriers in double mirror cells are separated by an intermediate magnetic mirror, and the electrons in the ion barriers with an effective temperature $T_{\mathrm{ep\,eff}} > T_{\mathrm{es}}$ are confined not only to an electric well but also to a symmetric magnetic well. ECR heating of these electrons in the resonance median plane is not accompanied by their displacement along the magnetic field lines by the Lorentz force; the electrons acquire a longitudinal velocity only because of angular scattering. Hence, with double mirror cells, we can expect an increase in the lifetime of electrons in ion barriers and more effective heating of these electrons. The average number density of the passing electrons, which cool the energetic electrons in the ion barriers, may decrease. The ambipolar ion barriers in double mirror cells will be more stable. With tandem end mirror cells, there is the possibility of optimizing the longitudinal distribution of sloshing ions in the ion barrier in order to avoid cyclotron instabilities in the median plane of the mirror cells and in the edge regions where the ions stop. The number density of high-energy electrons in the thermal barriers can be lowered to its minimum value, while the plasma density in the ion barriers may be optimized independently to increase the capture of ions from the injecting atomic beams. In contrast to single mirror cells, in double mirror cells, the high-energy electrons from the thermal barriers are not scattered into the ion barriers and do not increase the power consumed by the ion barriers [11]. As a result, in traps with thermal barriers, the energy consumption by double mirror cells is lower than that by single mirror cells, despite the double length. If we were able to sustain the sloshing ions with energies up to ~ 0.5 MeV by ICR heating, it would also be possible to lower the plasma density to its minimum in ion barriers, and therefore to reduce power consumption.

The fusion power gain Q, equal to the ratio of the nuclear power released by the reactor to the power consumed by the end mirror cells, must exceed the minimum value $Q_{\min}$ (the plasma power gain in the solenoid $Q_{\mathrm{pl}} \gg Q$). At $Q = Q_{\min}$, the fusion reactor generates only thermal energy, and all electric energy generated by it is used to sustain the operation of the reactor. The value of $Q_{\min}$ depends on the efficiency of the reactor and plant systems, without direct conversion of the energy of the flowing plasma into electric energy, $Q_{\min} = 2.6-3.6$. The power carried away by the flux of high-energy plasma particles from the trap ends in a D–T reactor amounts to about 15% of the thermonuclear power. Accordingly, in a reactor with direct converters, $Q_{\min} = 2.3-3.1$. The necessary power gain is determined by the admissible fraction $\varkappa$ of the produced electric power spent on sustaining the reactor operation: $Q = Q_{\min}/\varkappa$. It is profitable to ensure that $\varkappa \ll 1$, with the possible value of Q varying from 15 to 20.

Calculations of an ambipolar trap with the simplest single mirror cells without additional heating of the electrons and with such heating [4, 60] have shown that if the length of the trap is limited to 200 m and the magnetic field in the mirror cells to 15 T, the value of Q may be as high as 5. To raise Q above 5, the length of the solenoid should be increased substantially and the magnetic field in the mirror cells should be made stronger. Recently, Post [108] proposed using the simplest end mirror cells (without thermal barriers) with much higher magnetic fields (up to about 30 T) in completely axially symmetric traps [108]. This substantially reduces the volumes of the dense blocking plasma, and the power used to sustain this plasma becomes relatively small, despite the very high plasma density. The high magnetic-mirror ratio of the solenoid is ensured without choke coils by the high field of the mirror cells. A significantly large value of Q is attained when the trap length is about 100 m.

In 1986, the construction of the MINIMARS ambipolar D–T reactor with a fusion power of 1200 MW was completed at LLNL [114]. The reactor consists of a 95 m long solenoid with choke coils at the ends and two single 7 m long octupole mirror cells with thermal barriers. The strength of the vacuum magnetic fields is about 3 T in the solenoid, 26 T in the choke coils, and 1.5 T at the centers of the end mirror cells. MHD stabilization of plasma in the trap is achieved by using end mirror cells with octupole magnetic fields with a mantle of high-energy electrons and by employing the FLR effect. Plans are to study the possibility of raising the pressure ratio β and strengthening the MHD stability by the conducting walls. Because of the octupole geometry, the end mirror cells are sufficiently compact, and the shape of the main plasma in them is close to cylindrical. The main parameters of the plasma in the solenoid are as follows: the density $n_s \geqslant 2 \times 10^{14}$ cm^{-3}, the ion temperature $T_{is} = 29$ keV, the parameter $\langle \beta_s \rangle = 0.6$, the radius $r_{ps} = 0.42$ m, the neutron load on walls 2.7 MW m^{-1}, and the fusion power per unit length 13.7 MW m^{-1}. The small plasma radius in the solenoid (0.42 m) implies that the coefficient of transverse diffusion of plasma in the solenoid is many times smaller than in a tokamak reactor. The main mechanism of plasma loss from the solenoid is the capture by thermal barriers of the ions that fly toward the ion barriers. The captured ions are evacuated transversely to the magnetic field lines into the halo. Thanks to choke coils, the plasma density at the mirror cell centers is low ($\sim 5 \times 10^{12}$ cm^{-3}); accordingly, the power absorbed by the mirror cells is small and has been estimated at 20 MW. However, dozens of megawatts are spent on supplying electricity to the copper insertion coils in the choke coils to increase the magnetic field strength. The halo is used to limit the penetration of the low-density barrier plasma by gas.

The present author has studied the possibility of building an ambipolar D–T reactor with a corrugated solenoid without choke coils and with axially symmetric tandem end mirror cells [113, 115]. In the steady-state regime, the confinement of plasma with a high $\beta_\perp$ and its MHD stabilization by the conducting walls of the vacuum chamber and FLR effects may be achieved in both the solenoid and the end mirror cells. The magnetic field in the magnetic-mirror coils is limited to 14–15 T. The vacuum magnetic field is $B_{bv} = 1.67$ T in the thermal barriers, and $B_{pv} = 4.3$ T in the ion barriers. Reverse pumping of the ions captured by thermal barriers into the solenoid is also implemented. The average vacuum magnetic field in the solenoid is $B_{vs} = 2$ T. The main parameters of the plasma in the solenoid are as follows: the density $n_s = 1.5 \times 10^{14}$ cm^{-3}, the temperature $T_s = 25$ keV, $\langle \beta_s \rangle \geqslant 0.8$, $r_{ps} = 1$ m, $r_{ws} = 1.3 r_{ps}$, the neutron load on the walls 1.8 MW m^{-2}, and the fusion power combined with the nuclear energy in the blanket per unit length 24 MW m^{-1} [115]. The end mirror cells serve only to achieve longitudinal confinement of the fusion plasma in the solenoid. To ignite this plasma with the transverse plasma losses varying from insignificant values to longitudinal losses, the parameter of longitudinal confinement $n\tau_{\varepsilon\parallel}$ must be $(1.8-3.5) \times 10^{14}$ cm^{-3} s, with the generation of confining barriers of height $\varphi_c = (3.7-4.2)T_{is}$ in the mirror cells.

The energy balance of the trap depends on the geometry of the trap's magnetic system. Hence, a technology was developed for fabricating compact superconducting magnetic-mirror coils for the reactor [113]. In fabricating the sectioned coils from superconducting $(NbTi)_3Sn$ and NbTi wires for operation at 4.4 K, the overall length of the double mirror cell could be 12.5 m, with the size of the neutron shielding taken into account. For plasma densities $n_b \leqslant 10^{13}$ cm^{-3} in the thermal barriers and $n_p \geqslant 5 \times 10^{13}$ cm^{-3} in ion barrier, the power consumed by the end mirror cells is estimated as $P_{END} \leqslant 2 \times 90 = 180$ MW (almost all power is consumed by ECR heating mainly at a frequency near 40 GHz) [115]. Raising the plasma density in the ion barriers made it possible to increase the capture of the deuterons injected into the barriers by 30%.

The power gain $Q = 15-20$ is achieved with a solenoid of the length $L_s \leqslant 112-150$ m. The corresponding fusion reactor power is $P_{FUS} \leqslant 2700-3600$ MW. The reactor power can be decreased by reducing the radius of the plasma, but the tolerances on the transverse plasma energy losses are then closer. Raising the magnetic fields in the end double mirror cells makes it possible to substantially reduce the power consumed by the mirror cells, to shorten the reactor, and to generate thermal barriers in the mirror cells solely by passing ions without any ECR heating, i.e., spontaneously [81, 113].

A natural way to demonstrate the feasibility of an ambipolar D–T reactor with ignition of the fusion plasma is to build an experimental reactor with a shortened central solenoid and a power of approximately 700 MW ($Q \approx 4$) [116]. The reactor can be used to conduct prolonged studies of self-sustained nuclear fusion reactions and to test materials and units of the reactor without consuming electric power from an external source solely by using the nuclear power generated by the reactor. Figure 14 schematically shows the design of a superconducting magnetic system and the

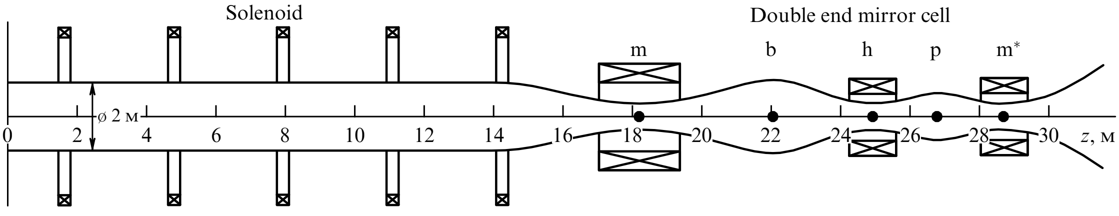

Figure 14. The magnetic system and the plasma geometry of a fusion reactor (right half).

geometry of the plasma in the reactor. The length of the solenoid is $L_s = 34$ m and the length of the trap is about 60 m. The overall mass of the superconducting coils with the straining rings is about 300 tons, which is less than in the LHD stellarator operating at NIFS (Japan).

It appears only natural that the first experiments should involve a long corrugated solenoid used to produce hot axially symmetric plasma with a β higher than the threshold value needed for its MHD stabilization by conducting walls and the FLR effect. If this succeeds, i.e., stabilized plasma with a high β is produced, the next step is to study its turbulence and transverse transport and conduct experiments in minimizing transverse losses.

Thermonuclear reactors that use the reaction

$$D + {}^3He \rightarrow {}^4He\,(3.6\ \text{MeV}) + p\,(14.7\ \text{MeV})$$

have important advantages. Such reactors can be profitably used for direct conversion of the energy of protons and alpha particles into electricity, which raises the efficiency of electric power plants. The main advantage is that the D$-{}^3$He reaction is accompanied by neutrons from associated reactions with partially reduced energy, whose number is 30 times smaller than that accompanying the D$-$T reaction. Therefore, the service life of the first wall with regard to radiation damage is one century or even longer. Assuming that the resistance to radiation damage is smaller, materials with minimum induced radioactivity can be used in the reactor, which makes a radiation-safe fusion reactor feasible [98]. The main drawback of D$-{}^3$He reactors is that the helium reserves on earth are not sufficiently large to satisfy all the energy needs. In 1986, Kulcinski and colleagues published the results of studies done in the United States that dealt with the possibility of extracting ^{3}He on the moon and bringing it to earth in quantities needed for the development of thermonuclear power production. Estimates show that economically, ^{3}He from the Moon is more profitable than coal from the earth (in energy equivalent) [117].

The confinement to a trap and the ignition of D$-{}^3$He plasma constitute a more complicated problem than in the case of D$-$T plasma. The main reasons are the higher operating temperature (60 – 70 keV instead of 25 keV) and the fact that the rate of the fusion D$-{}^3$He reaction is approximately five times lower than that of the D$-$T reaction. At such temperatures, bremsstrahlung and cyclotron radiation of electrons play an important role. The power of the cyclotron radiation can be lowered by reducing the magnetic field in the plasma without a sizable weakening of the confining (vacuum) magnetic field, i.e., increasing β in the main part of the plasma. A self-sustained D$-{}^3$He reaction is possible only if $\langle\beta\rangle \geqslant 20\%$ [97].

For almost a decade, from 1986 on, Golovin and colleagues developed the concept of an exceptionally clean fusion D$-{}^3$He reactor [96 – 98, 118 – 120], including the concept of an ambipolar D$-{}^3$He reactor. The researchers proposed a variant of such a reactor in the form of a corrugated solenoid with the length about 100 m with the vacuum field 6 T and 10-m long single end mirror cells with thermal barriers [120]. The magnetic field is 20 T in the magnetic mirrors and 5 T at the center of the mirror cells. The possible parameters of the plasma in the solenoid were as follows: the ion number density $n_{iD} = n_{i\,{}^3He} = 1.75 \times 10^{14}$ cm^{-3}, the electron number density $n_e > 3n_{iD^+}$, the ion temperature 70 keV, the electron temperature 60 keV, the relative pressure of decelerating alpha particles and protons $\beta_{ash} = 0.3$, the total $\langle\beta\rangle = 0.9$, the radius of dense plasma $r_p = 1$ m, the vacuum chamber radius $r_w = 1.25$ m, and the fusion power per unit length 34 MW m^{-1}. The population of sloshing protons with an energy $\geqslant 500$ keV is sustained in the end mirror cells. The relative pressure of electrons heated in a thermal barrier together with protons is $\beta_b \approx 1$. MHD stabilization is achieved by the conducting walls and the FLR effect. The height of the ion barriers is $\varphi_c \approx 280$ keV and the depth of the thermal barriers is $\varphi_b \approx 260$ keV. The power consumed by the end mirror cells is estimated as $P_{END} \approx 2 \times 100 = 200$ MW. Finally, the reactor power gain is $Q \geqslant 15$ and the thermonuclear power generated by the reactor is $P_{FUS} = 3400$ MW.

An ambipolar D$-{}^3$He reactor is of interest for future interplanetary flights as a source of energy and a plasma reaction – propulsion engine [121]. In a corrugated solenoid, the coils may occupy only about 10% of the solenoid's entire length, and a considerable fraction of radiation and neutrons from the thermonuclear zone may escape through the thin conducting shell into outer space, while the remaining part can be reradiated by the shell. The possibility of directly converting almost all kinetic fusion energy into electric energy allows considerably reducing heat emission. The problem of releasing thermal energy from a spaceship into outer space is considerably simplified. However, for an expedition to Mars, a reactor with the mass about 200 tons and the power output less than 100 MW could be used. This requires reducing the radius of the plasma in the solenoid, lowering the gain Q, and building a fairly light-weight superconducting magnetic system (provided this is possible). It is improbable that the reactor mass can be limited.

6. Conclusion

To conclude, we note that building an ambipolar D$-$T reactor will require a large amount of complicated experimental work in drastically increasing the values of the parameters of the plasma in the ambipolar trap to the level of reactor values. In experiments, we must raise the density of the plasma confined by ambipolar barriers in the solenoid by a factor of about 50, the electron temperature by a factor of about 100, and the energy lifetime of the plasma in the solenoid by a factor no smaller than 10. There will also be the task of experimentally verifying the possibility of MHD stabilization of axially symmetric plasma by the conducting walls and the possibility of reversing the pumping of the ions from the thermal barriers into the solenoid.

We must also bear in mind that the problem of building a fusion reactor based on the tokamak principle required nearly 50 years of intensive studies in high-temperature plasma physics. Experimenters had to 'travel' a long and difficult journey, beginning with the construction of small devices and finally building huge and complicated modern machines [122]. The results are glorious, and the physics of confinement of plasma in tokamaks is indeed very rich. All we need to do if we want to ignite thermonuclear plasma is to increase the time of plasma energy confinement by a factor of at least ten. This step in solving the problem of controlled fusion is planned for the first experimental reactor ITER based on a tokamak with a very large volume of thermonuclear plasma [122].

The scope of the plasma studies done so far (and the results obtained) in the physics of confining plasma to an ambipolar trap is much smaller than that for tokamaks. Nevertheless, using the huge volume of experimental data gathered on tokamaks and the investigation methods developed in the process, ignition and sustained burning of D–T plasma in a simple experimental ambipolar reactor can be realized in a shorter time. The means of solving all the key issues in realizing this project are obvious.

The observed limitation on the density of plasma in the solenoid was discussed in Section 3. Basically, it is related to the effect that the passing flow of plasma from the solenoid has on the energetic electrons in the ion barriers. The latter transfer a great amount of energy to the passing electrons (in Refs [113, 115], the power spent in the reactor on the ECR heating of passing electrons in the ion barriers is estimated as 2×9 MW). As a result, when the plasma density in the magnetic mirrors of the solenoid increases, the ion barriers diminish. To increase the limit of this density, we must increase the power of ECR heating in the ion barriers. The limit in density must not depend on the solenoid length and must increase with the temperature of the electrons in the solenoid.

In open traps, the region of confinement of hot plasma along the magnetic field is directly related to the cold plasma receivers at the trap ends. Sometimes, a conclusion is drawn that electrons of the confined plasma are sure to cool down very rapidly due to high longitudinal electron thermal conductivity. Actually, longitudinal thermal losses of electrons are limited very strongly by the electrostatic potential barriers at the ends of the trap, provided that secondary electron emission from the plasma receivers is low [123]. These electron barriers are formed automatically by plasma polarization and ensure that the number of escaping electrons is equal to the number of ions leaving the trap. In an ambipolar trap, the electron barriers formed in the beyond-mirror magnetic fields in front of the plasma receivers may be almost three times higher than the ion barriers (because $m \ll M_{\rm i}$ and the confinement of particles by an electrostatic barrier is worse in a diverging magnetic field). When an ion leaves the solenoid for a plasma receiver, it carries away an energy of approximately $5kT_{\rm i}$, while an electron carries away an energy of approximately $12kT_{\rm e}$ [51]. This facilitates the reduction of the electron temperature with respect to the ion temperature. In high-temperature plasma, the cyclotron radiation emitted by the electrons amplifies this tendency. However, in D–T plasma, the alpha particles give more than half their energy to the electrons [60], and the electron temperature may be higher than the ion temperature. As the time of plasma confinement in the solenoid increases, the electron and ion temperatures converge in all cases.

Secondary emission of electrons from the plasma receivers may leads to a dramatic increase in the longitudinal energy losses of electrons [123]. In secondary emission with $\eta \geqslant 1$, the cold secondary electrons replace the hot electrons and may accumulate in the solenoid and gradually lower the electron barriers. On a clear metal surface (Be, Ti, or Al), the total coefficient (per ion–electron pair) of secondary electron and ion–electron emission may be as high as 2. Among the known methods of suppressing secondary electron emission, the best one (in my opinion) amounts to building the plasma receivers from segments strongly slanted in relation to the magnetic field (like Venetian blinds). Electrons with an average energy of several electronvolts emitted almost at right angles to the magnetic field immediately return to the segments or are reflected back by the growing magnetic field. In the region before the Debye layer on the plasma receiver, a flattened longitudinal distribution of the potential sets in due to the accumulation of captured electrons from scattered passing electrons [123]. The absence in this region of a strong electric field repulsing the secondary ions from the plasma receiver facilitates the suppression of electron emission.

In experiments that used the TMX device with additional heating of the plasma in the solenoid, the plasma electron temperature was no lower than the ion temperature [7]. With the GAMMA-10 device in the mode with ion barriers $\varphi_{\rm c} \sim 1.1$ kV and weak ICR heating, the electron temperature observed on the axis of the solenoid was 250 eV, with the temperature of the main population of ions being 450 eV [28]. The maximum electron temperature in the solenoid, 280 eV, was obtained on the TMX-U device [14, 15]. In many open traps, when electrons were confined by magnetic mirrors, a very high electron temperature was attained. In the end mirror cells of the TMX-U device, ECR heating made it possible to maintain the electron temperature at the level of 50 keV with the density 10^{11} cm^{-3}. In the end mirror cells of the GAMMA-10 device, the temperature of most electrons on the axis was observed at the level of 60 keV (this value sets in during several dozen milliseconds), with the electron number density being 2×10^{11} cm^{-3} [124]. Thus, the high longitudinal electron thermal conductivity is not an obstacle for the development of a fusion reactor based on an ambipolar trap.

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