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Experiments on Plasma Pressure Increase in the Solenoid of AMBAL-M

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Experiments on creation and studies of a high β plasma in a long solenoid of the axisymmetric mirror trap AMBAL-M are continued ($\beta=8\pi p/B^2$ is the ratio of the plasma pressure to the magnetic field pressure). For β increase without additional plasma heating we use the plasma pressure growth during additional hydrogen puffing through a gas-box and reduction of the magnetic field in the solenoid [1]. Another way of increasing β consists in forming a small local mirror trap in the solenoid where the plasma volume is much smaller than that in the whole solenoid, and it is easier to achieve high β values. In this report current experimental results on determination of the optimized gas-puffing regime and on study of the plasma behavior at reduced magnetic fields are presented.

The experiments are performed at the central solenoid of the ambipolar mirror machine AMBAL-M (Fig.1). The plasma in the solenoid is created by a gas-discharge source, located

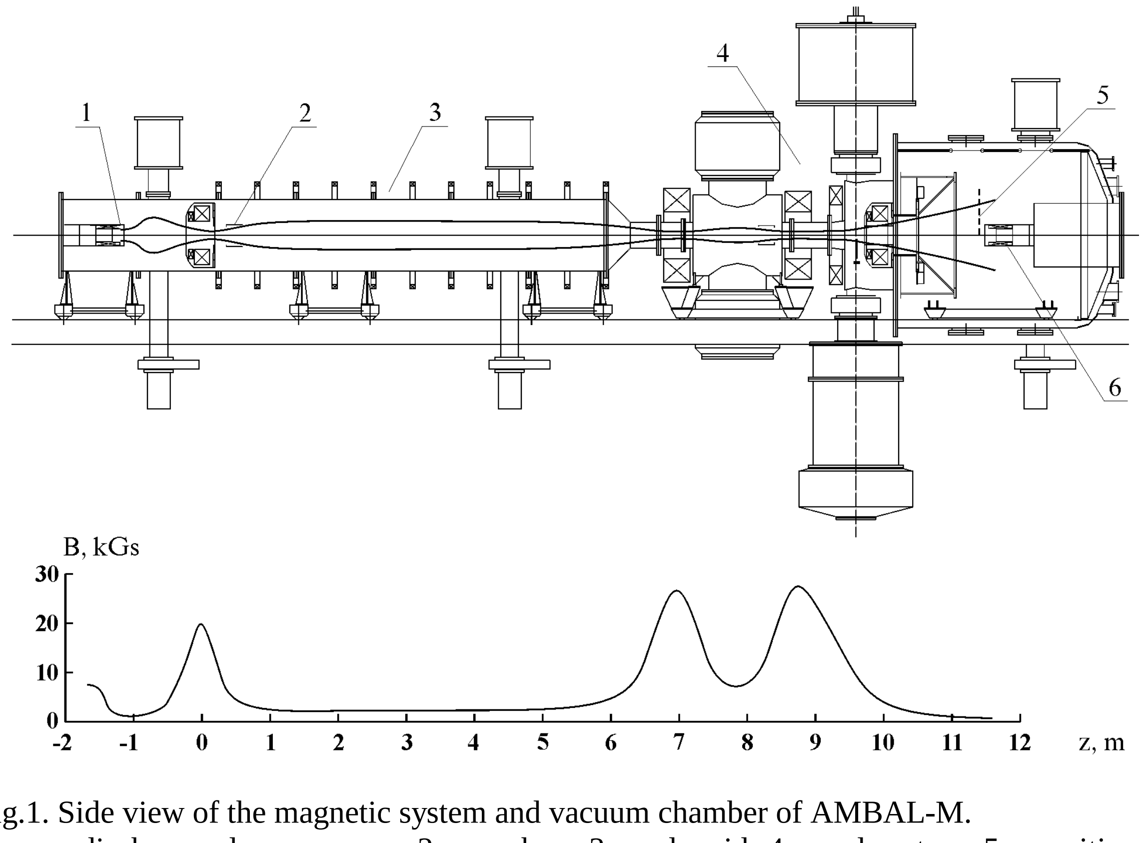

Fig.1. Side view of the magnetic system and vacuum chamber of AMBAL-M.
1 – gas-discharge plasma source, 2 – gas-box, 3 – solenoid, 4 – end system, 5 – position of end-loss analyzers, 6 – second plasma source. Magnetic field line starting from the plasma source ($z=-155$, $r=6$ cm) is shown. Below is given the magnetic field profile at the axis.

before a solenoid magnetic throat, which produces a turbulent plasma stream flowing along magnetic field lines. The plasma is heated by unstable nonuniform rotation in E×B field, and in the 7 m long solenoid is has diameter ~0.4 m, density $\sim 2 \cdot 10^{13}$ cm^{-3}, T_e ~45 eV and T_i ~200 eV.

The plasma source has enough power to ionize and heat additional gas, which allows us to use hydrogen puffing for further increase of the plasma density. The gas is supplied to the periphery of the plasma column through a gas-box located near the entrance throat of the solenoid. Efficiency of the additional hydrogen puffing depends on the puffing rate and on the instant of the puffing start. In the experimentally found optimized gas-puffing regime the plasma density is increased to $5 \cdot 10^{13}$ cm^{-3} without substantial reduction of the ion temperature. Variation of the puffing rate and instant of gas puffing start show that the plasma density and diamagnetism reach maximum at the same amount of gas which has been puffed into the solenoid, regardless of the puffing rate and its instant, taken independently. In the optimum, the hydrogen density in the chamber before the plasma startup is $\sim 1.3 \times 10^{12}$ cm^{-3}. This is probably the maximum amount of additional gas, which can be ionized by the initial plasma. When the puffing rate strongly differs from the optimum one, the plasma density and diamagnetism become even lower than without gas puffing.

Next we studied the effect of magnetic field variation on β in the solenoid and performed series of experiments with hydrogen puffing and magnetic field variation in the solenoid and in the plasma source, made for better matching of magnetic surfaces. The optimization was aimed at achievement of maximum plasma pressure at the lowest magnetic field. Variation of the solenoid magnetic field from 2 to 0.3 kGs together with the gas-puffing and magnetic field matching, made it possible to study a wide range of the initial plasma generation regimes in the solenoid. The maximum obtained β~0.3 is limited by saturation of the plasma-source power which ionises the additional gas and heats the cold plasma, and by the increased charge-exchange losses caused by gas puffing. The results are presented in Fig.2 in the form of plasma density radial distributions, which show that for relatively small field decrease in the solenoid, the amount plasma is conserved despite substantial profile modification. It points to the conclusion that the plasma follows magnetic surfaces well. However, when the field is strongly reduced, the plasma falls beyond the limiter radius R_{lim}~30 cm at the uniform solenoid part, which leads to enhanced plasma losses. The stream becomes too wide and even annular, and the density maximum shifts outwards to the periphery.

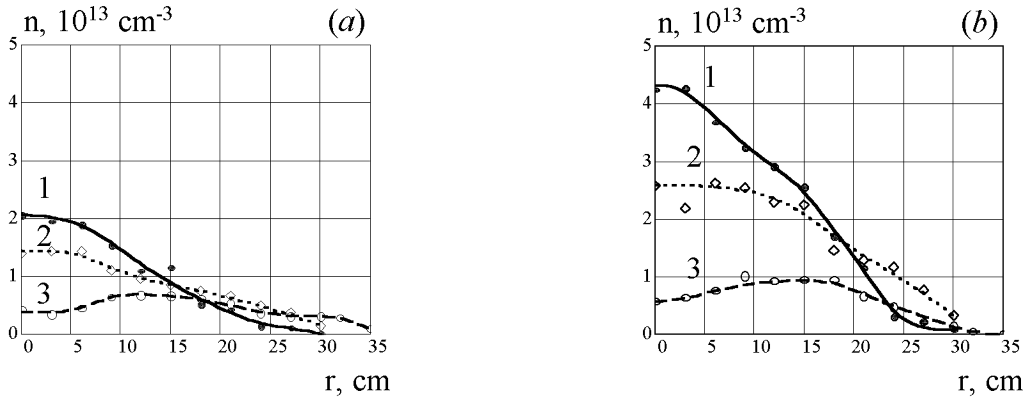

Fig.2. Radial profiles of the plasma density in the solenoid at decreased solenoid magnetic fields. *a* –without gas, *b* –with hydrogen puffing. 1 – nominal magnetic field B_0, 2 – reduced magnetic field $B_0/2$, 3 – $B_0/4$.

We also came across the unfavorable scaling $\beta \propto 1/B$ instead of $\beta \propto 1/B^2$, as it should have been for collisionless confined plasma. The reason for this discrepancy is that in the plasma, flowing like a stream, the quantity $\int ndS$ is conserved. Therefore, mere reduction of the field does not result in the desired large increase of β.

If along with the solenoid field reduction, the field in the plasma gun is reduced by the same factor, magnetic surfaces will coincide with the initial ones. Matching of the solenoid and gun fields improves the plasma density profile, and similarity with the nominal field surfaces. However, strong reduction of the magnetic field in the source hampers effective plasma generation due to increasing ion Larmor radius and related enhanced plasma losses on the channel walls of the plasma source. Thus, we have to restrict ourselves to modest source field decrease.

Numerical analysis of the small-scale MHD fluctuation equation in the solenoid shows that the threshold β value when the ballooning instability develops, is close to unity and is poorly defined, because it strongly depends both on line-tying conditions at the plasma receiving end plates and on the transverse plasma pressure profile. In order to achieve the limiting β value and experimentally observe development of the ballooning instability, the magnetic field profile in the solenoid can be modified locally producing the unfavorable field-line curvature. One may reduce the field not in the entire solenoid, which leads to increased plasma size and enhanced transverse losses, but locally, by switching off of several solenoid coils. Thus, switching off two coils, we obtain a short local trap with mirror ratio R=2.7 (Fig.3(a)), where it is possible to achieve higher local β values. First experimental results are presented in Fig.3(b). The plasma density in the local trap remains at the same

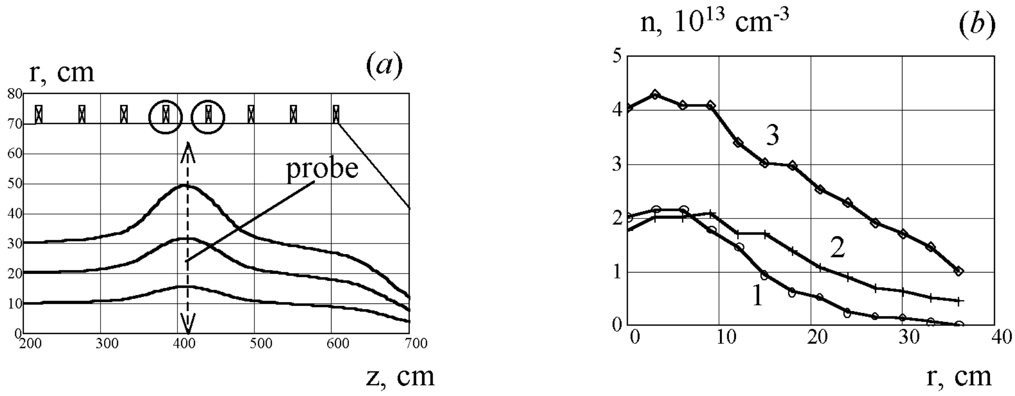

Fig.3 Schematic layout of the local mirror trap in the solenoid (*a*), and plasma density profiles in the middle of this trap. 1 – uniform magnetic field, 2 – with the local trap, 3 – local trap and gas puffing.

level as in the uniform field, hence, β must be several times higher due to magnetic field decrease. At present, the ion temperature should be precisely measured to estimate the plasma pressure correctly.

In conclusion, the plasma in the solenoid was obtained with the following parameters: length ~6 m, radius $R_{1/e}$~17 cm, n~$2\cdot10^{13}$ cm^{-3}, T_e~45 eV, E_i~200 eV, and β~0.06. With hydrogen puffing into the solenoid, the plasma density was increased to $5\cdot10^{13}$ cm^{-3}. Optimization of gas puffing rate and its timing was performed, which together with magnetic field variation provided max β~0.3 in the solenoid. This is probably the limit of the plasma density and β increase in the solenoid, when it is filled by the stream from the source, without additional plasma heating. Experiments with the local mirror trap in the solenoid were started, and β increase was observed in this trap. Further β increase is possible using additional plasma heating.

1. T.D.Akhmetov, V.S.Belkin, I.O.Bespamyatnov et al., Operation with a High Pressure Plasma in the Central Solenoid of AMBAL-M, 30th EPS Conference on Contr. Fusion and Plasma Phys., St. Petersburg, 7-11 July 2003 ECA Vol. 27A, P-2.191.