Study of high-b plasma stability and transverse loses in the experiments on modern magnetic mirrors

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I Introduction

The paper reviews recent results obtained the experiments on the modern magnetic mirrors in Novosibirsk. An emphasis was made on studies of plasma transverse losses and stability in the regimes with maximal plasma beta. The experiments were carried out on the multiple mirror device GOL-3 and gas dynamic trap (GDT). Both devices are characterized by axial symmetry and improved axial confinement of plasma compared to conventional mirror machines [1-4]. Observed plasma activity in the GDT is thought to be related to both high anisotropy of fast ion component produced by 25keV, 5MW neutral beam injection and high plasma beta approaching 60%. This activity however does not result in considerable increase of plasma energy losses, which are dominated by axial collisional losses through the end mirrors. In the GOL-3 device, in which plasma is heated by axial injection of a relativistic electron beam, excitation of large amplitude plasma turbulence also does not considerably increase radial plasma losses, so that the axial ones are always dominate energy balance.

II GDT device

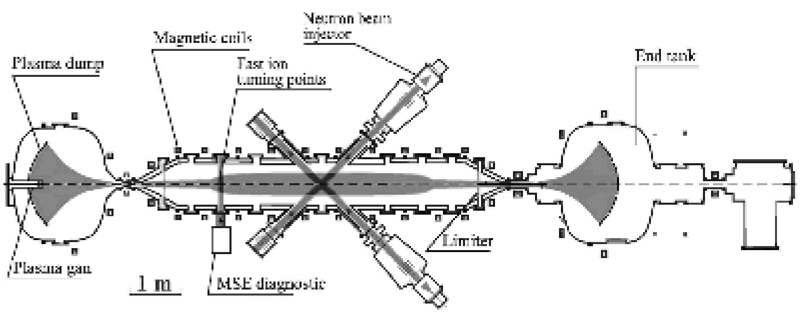

Fig.1. The gas dynamic trap layout.

Layout of the GDT device is shown in Fig. 1. A set of coils produce an axisymmetric magnetic field with a mirror ratio variable from 12.5 to 50 when the central magnetic field was set to maximally 0.3 T. Initial plasma with density $3\div6\times10^{19}m^{-3}$ and radius 6÷7 cm at the mid-plane was produced by a plasma gun located in the end tank. In the recent experiments [5], the plasma was heated and fast ions were produced by injection of a 5ms pulse of 20-25keV, 3.5-4.5MW neutral beams at the center of the device at 45^0 to the axis. The external min-B cells, which in a standard

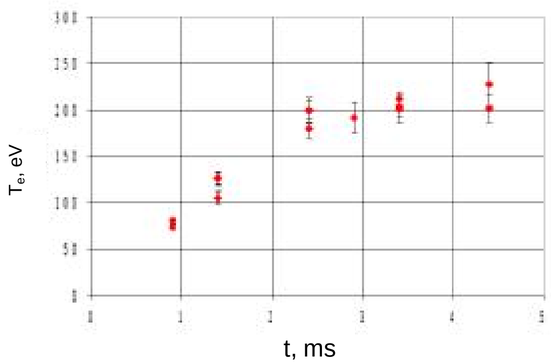

Fig.2. Electron temperature in GDT *vs.* time.

configuration are used to provide MHD stability of the plasma in the solenoid, were not engaged. Instead, the radial plasma transport was controlled by producing a sheared $E\times B$ flow at periphery with biased segments of end wall and radial plasma limiter in the solenoid. Then, the inherently unstable flute modes nonlinearly saturated due to the flow-enhanced line-tying mechanism and transverse currents generated in the vertex region [6] and plasma resides in the vortex interior without considerable radial losses. The electron temperature (see Fig.2) exceeded 200eV during a shot and on-axis plasma b approached 0.6 in the turning point region. Density of the fast ions with mean energy 10-12keV reached ≈ $5\times 10^{19}m^{-3}$ in the turning point regions and substantially exceeded that of the target plasma ($1.5\div3\times10^{19}m^{-3}$ at the mid-plane). In these high beta shots plasma exhibits some transverse oscillations with rather high amplitude, which were seen by different diagnostics including heating beam attenuation measurements (see Fig.3) and magnetic probes. The oscillations start at about 2ms after plasma beta exceeds certain limit. Studies of the oscillation structure indicate that their azimuthal mode number is m=2 and characteristic frequency is about 19kHz. Plasma radial losses are not considerably influenced by these oscillations and remain low compared to the axial losses through the mirrors. Axial structure of the oscillations was measured using an axial array of magnetic probes. Preliminary measurements indicate that axial wave length is comparable to the length of central solenoid. Measurements of radial component of magnetic field with magnetic probes located near the fast ion turning point and at the center of solenoid also indicate spontaneous axial redistribution of plasma pressure (Fig.4.). During plasma pressure build up it

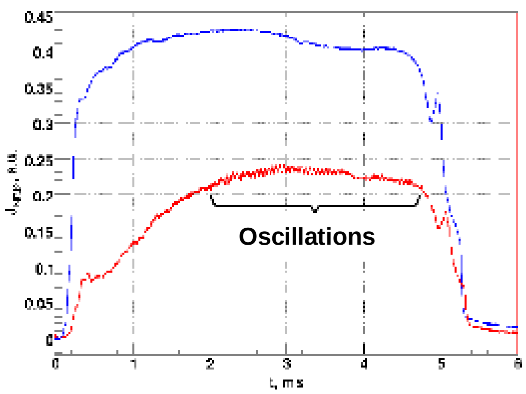

Fig.3. Oscillations of line plasma density.

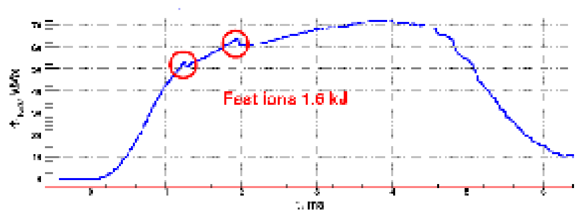

Fig.4. Plasma diamagnetic signal at fast ion turning point.

drops down within several tens of microsecond and than recovers. Comparison of the signals at the turning point and near mid-plane reveals that radial magnetic field, i.e. plasma pressure changes in these regions in an opposite way. Namely, pressure decrease near the turning point is accompanied by pressure increase near the midplane and vise versa.

III MULTI-MIRROR TRAP

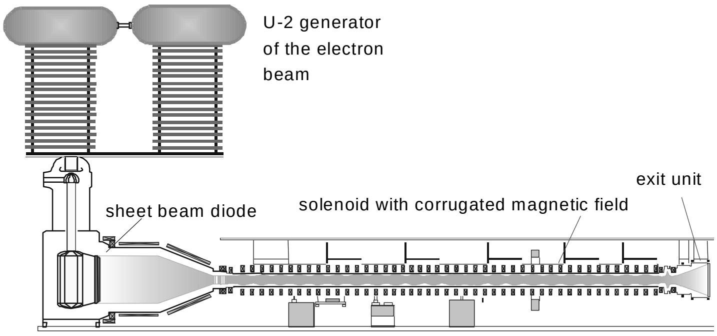

Fig.5. The multi-mirror trap GOL-3 layout.

In the multi-mirror GOL-3 device [7] plasma is confined in a 12-meter long solenoid composed of mirror cells (4.8T/3.2 T) with a spatial period of 22cm connecting to each other. To heat plasma a 1MeV, 30 kA, 1.5 kA/cm^2, 8-12µs electron beam was injected axially at one end. The beam left about 50% of its energy in plasma with density of ~ 10^{21}m^{-3} inducing strong and fast heating of both plasma electrons and ions. Recent findings in studies at the GOL-3 device enabled significant improvement in the multi-mirror reactor parameters in comparison with the original proposal [2]. It was found that during injection of the electron beam, axial electron heat conduction is suppressed by more than three orders of magnitude. Peak electron temperature reaches ≈ 2 keV. Under this condition, axial non-homogeneity of power deposition from the beam caused by variation of magnetic field result in development of very steep gradients of the electron temperature and plasma pressure along the device. Steep pressure gradients drive axial plasma flows, which in their collisions transfer plasma directed energy into ion temperature, so that it increases very fast to ≈ 2 keV. Plasma expansion along the mirror cells excited an instability, which

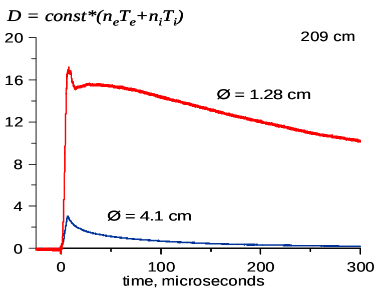

Fig. 6. Dynamics of plasma pressure from diamagnetic measurements for the cases of thin and standard electron beams at 209 cm distance from the input mirror.

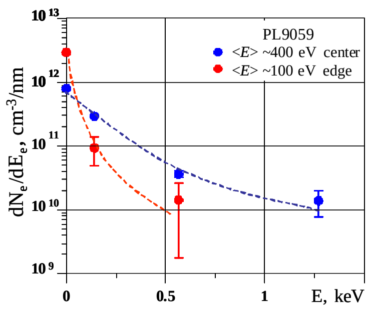

Fig. 7. Thomson scattering data for the point at the axis and 6 mm apart (at the expected edge of the beam-heated zone).

result in effective exchange between the passing and trapped ions in the cells. Therefore, an effective mean free path of ion scattering appears to be about a length of the cell even for rather small plasma densities in the range of 10^{21} – 10^{22}m^{-3} that corresponds to the longest time of plasma axial confinement.

At the same time, the turbulent fields in the plasma could enhance transverse losses. In the essentially new regime of the GOL-3 heating of the plasma was done with a reduced-cross-section electron beam of 13 mm diameter with the total current decreased tenfold comparing to the full-scale experiments (at the same current density of ~1 kA/cm^2) [8]. The plasma radius was close to that of the beam. Results of the first experiments with the thinner beam look quite interesting. The plasma heating in some region within the first two meters from the beam injection point appeared better, than straightforward recalculation (see Fig. 6). Here formally calculated plasma β value reaches 35% for the waveforms shown in Fig.6 with no specific signs of any fast instability. At the rest of the plasma column the beam relaxed as in the standard regime (see Fig.7 with Thomson scattering data). Role of transverse energy and particle losses increases comparing with the standard operation mode with a good confinement where transverse losses do not exceed 10% in global energy balance.

IV DISCUSSION

Large amplitude plasma oscillations and axial re- distributions of plasma pressure were observed at GDT device in the regimes with sufficiently high plasma beta and electron temperatures approaching 250eV. These phenomena, however, do not considerably increase radial plasma losses. GOL-3 experiments with tenfold reduced plasma cross-section in general confirmed existing understanding of underlying physics. The main plasma parameters were essentially the same as in the previous experiments. Excitation of large amplitude plasma turbulence also does not considerably increase transverse losses.

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