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Stable operation regimes in the multi-mirror trap GOL-3

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1. Introduction.

The final aim of experiments carried out at the GOL-3 facility (Fig.1) is development of a multi-mirror fusion reactor concept [1,2]. Relativistic electron beam is used for deuterium plasma heating in the GOL-3 facility. In such a system, there are some specificities of the plasma heating and confinement [3].

The relativistic electron beam excites a high level turbulence in the plasma. At the plasma density of 10^{21} m^{-3}, the beam energy loss is up to 40%. The major part of electrons is heated up to average energies (temperature) of 1-2 keV.

The beam energy release is not uniform along the system length. The axial distribution of heating and plasma pressure depends on local ratio of beam density to plasma one. Within the first meter of the plasma column, a sharp maximum of plasma pressure is observed, then it has a steep descent and then the pressure continues to be decreased slower.

Another important fact is the following. As a result of the beam-plasma collective interaction, the efficient collision frequency of plasma electrons exceeds by a few orders the classical binary collision frequency. Consequences of this phenomenon are that the plasma longitudinal heat conductivity and its electron conductivity decreased substantially. All the mentioned above phenomena enable a possibility to form the high pressure gradients inside

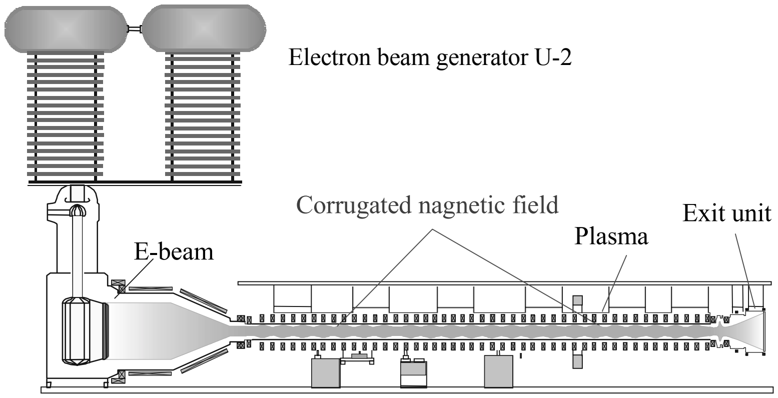

Fig.1. Layout of the GOL-3 facility. 12-meter-long solenoid consists of 55 cells of 22 cm length each with B_{max}/B_{min}=4.8/3.2 T. The plasma heating is provided by a high-power electron beam (~1 MeV, 30 kA, 8 μs) with total energy content of 120÷150 kJ.

mirror cells along the magnetic field and macroscopic motion of a plasma.

In the corrugated magnetic field all these peculiarities lead to occurrence of new phenomena and first of all, to the fast heating of plasma ions by the electron beam. With the injection of the electron beam into the multimirror trap the pressure gradients occur both in the trap cells and average on cells gradient along the whole trap. These gradients lead to two kinds of plasma macroscopic accelerations: local inside each cell and total on the system. Both these motions in a corrugated field lead to the electron energy transfer to ions much faster than the energy transfer due to binary collisions. As a result, electron and ion plasma temperatures up to 2 keV at density ~10^{21} m^{-3} are achieved and the value $n\tau T$ ~ (1.5÷3)·10^{18} m^{-3}s·keV at ion temperature ~1 keV is attained.

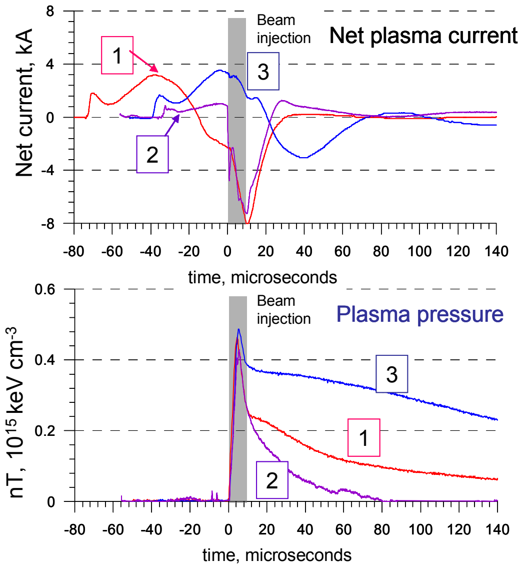

Fig.2. Dependence of plasma heating efficiency and energy confinement time on direction of discharge plasma current: 1 – plasma current is parallel to beam current; 3 – plasma current is opposite to beam one; 2- is an intermediate case.

2. Formation of helical structure of the magnetic field and its influence on the plasma confinement.

Necessary conditions for achievement of high performance regimes are obtaining of macroscopically stability of plasma. A special experimental campaign was devoted to studies of mechanisms for the stability. In the GOL-3 conditions the magnetic shear was shown to be the important factor for good plasma confinement. Sheared structure of the magnetic field is formed by axial guiding magnetic field of the solenoid and by azimuthal magnetic field, which is generated by axial currents in the plasma. Radial profile of local current density is created by three main sources of current, two of which are external (current of relativistic electron beam and current of the preliminary linear discharge) and the third internal source is the return current to the beam generator which also runs through the plasma.

An influence of helical structure of magnetic field on plasma heating and confinement of hot (T_i ~ 1 keV) plasma was demonstrated in special experiments shown in Fig.2. A preliminary plasma was created by high-current discharge pulse generated by pulse source. At the begin the discharge current is directed opposite to beam current. Then it changes its direction after ~80 μs. Thus, if we change a delay time between start of discharge current and start of beam pulse, we can vary configuration of asimuthal magnetic fields and shear of the total magnetic field. In the experiment indicated as 1 on Fig.2, direction of the discharge current (3 kA) coincides with the beam current (30 kA). The net current is – 8 kA with the same direction. In this case an energy confinement time of plasma is respectively small ($\tau \sim$ 10-30 μs). In the case of opposite current < 2 kA (case 2 on Fig.2) the net current and confinement time are changed insufficiently.

The stable regime of plasma is reached if discharge current value exceeds 3 kA and is directed opposite to the beam current (case 3 on Fig.2). In this case the net current is directed opposite to the beam current too and its value must exceed some specific value, ~2 kA for the regime under consideration.

3. Measurements of rotation transformation factor.

Helicity of the magnetic field may be described with the safety factor $q=(H_z/H_\varphi)\cdot(2\pi r/L)$ (where H_z and H_φ are longitudinal and azimuthal components of magnetic fields, r and L are plasma radius and column length). In the case of non-compensated beam current (up to 30 kA) it is in the range 0.3-0.5, that may lead to the perturbation of the external helical modes and the stability loss of the beam-plasma system. First experimental proof of formation of helical magnetic field was providing by the X-ray footprint of the relativistic electron beam on the collector [4]. In new experiment a time evolution of beam and net current density on axis of plasma column was carried out (Fig. 3). A Rogovsky coil of 3 cm diameter is placed at the axis of the collector for measurement of the net current density. Beam current density inside the coil is measured with collimated X-ray detector. Carbon foil covers coil entry in order to cutoff plasma current. As Fig.3a shows, X-ray signal corresponds to beam current density rather well. When foil is removed (Fig.3b), net current density signal remains practically the same, but a bit longer. This means that during the beam injection its current density on axis is not compensated (that is due to turbulent decreasing of conductivity) and corresponding rotational transformation factor $\mu=1/q$ equals to 2-3. Plasma current possibly induced at the beam switch off,

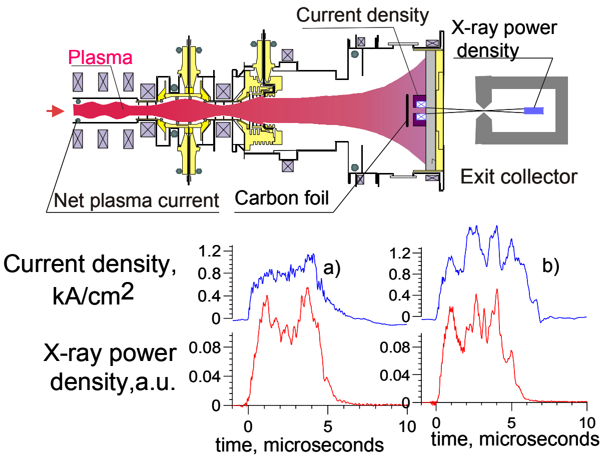

Fig.3. Layout of the experiment for current density measurement on exit unit and waveforms of signals: a) with carbon foil; b) without foil.

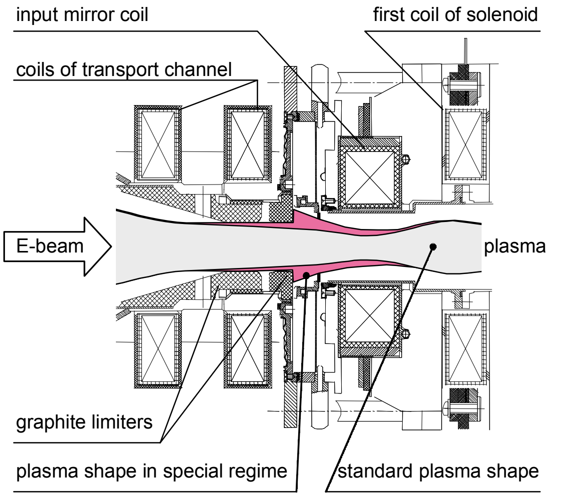

Fig.4. Layout of experiment for measurement of the radial distribution of plasma current in input mirror.

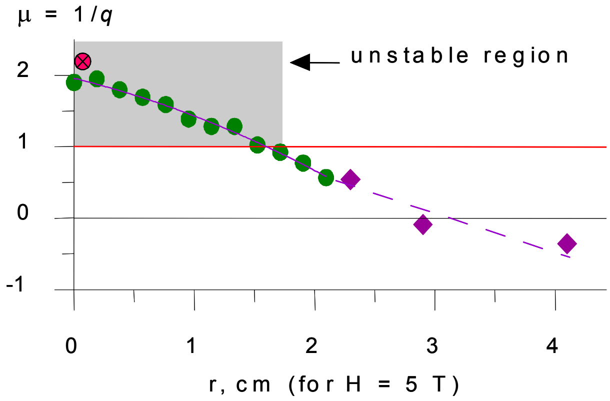

Fig.5. Results of measurements of rotary transformation factor at time moment of 3.5 microseconds after beam injection start. Points- X-ray footprint, cross-current density on exit, rectangles-currents measurements on entrance.

damps rather quick.

For registration of current density distribution on a plasma periphery a special experiment was provided (see Fig.4). In this experiment the magnetic field in the transport channel was varied from shot to shot, so the plasma diameter was changed too. Graphite limiter cuts off some part of plasma current corresponded to limiter diameter. Net current before and after the graphite limiter was measured. From relationship between currents the current density distribution was determined.

Results of all these experiments (as at the entrance and also at the exit of plasma column) in Fig.5 are summarized. Profile of rotary transformation factor on figure corresponds to stable operation regime of GOL-3. Features of this regime are appearance of sheared helical magnetic field and formation of magnetic surface with poloidal field equal to zero inside the plasma column.

4. Conclusion

Conditions for plasma macroscopic stability in the axisymetric configuration of corrugated solenoid were found. Direct measurements of the safety factor q within the core plasma show the existence of strongly sheared magnetic field, which has $q(0)<1$ and different sign of $q(a)$.

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