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FIRST EXPERIMENTS ON NEUTRAL INJECTION IN MULTIMIRROR TRAP GOL-3

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Multimirror plasma confinement is investigated at the GOL-3 facility in Budker Institute of Nuclear Physics as one of alternative concepts of magnetic nuclear fusion [1]. Plasma with density ~10^{21} m^{-3} is heated by a relativistic electron beam (1 MeV, 30 kA, 8 μs, ~120 kJ) up to temperature ~2 keV, confinement time in multimirror magnetic field reaches ~1 ms. Significant progress in physics of multimirror confinement, which was achieved in GOL-3 experiments, improves prospects for an axisymmetric linear fusion reactor with β ~ 1 and moderate (10^{22} m^{-3}) plasma density. Such approach requires development of new techniques of plasma heating in addition to existing high-power relativistic electron beam. High density, short lifetime, small plasma radius and high gas pressure near the wall are the challenges that complicate application of neutral beam injection for GOL-3. A supposed NBI system for GOL-3 should have ~10 MW at ~1 ms pulse in order to keep plasma parameters at a reasonable level during the confinement phase. First results of sub-MW NBI are presented in the paper.

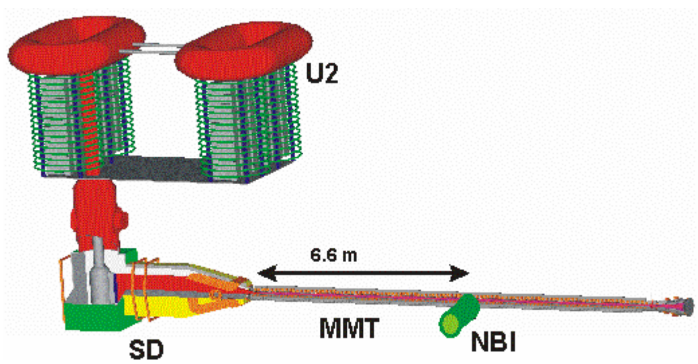

Fig.1. Layout of NBI system at GOL-3 facility; U2 - electron beam generator, SD – sheet electron beam diode, MMT – multimirror trap, NBI – neutral beam injector.

Layout of GOL-3 facility is presented in Fig. 1. Classical theory predicts optimal plasma confinement in a multimirror system at ion free path length roughly equal or few times larger than the corrugation period [2]. At ion temperature $T_i \sim 1$ keV this means the plasma density should be above 10^{22} m^{-3}. GOL-3 experiments [1] showed that high level of plasma turbulence reduces the free path length and enables effective confinement at densities below 10^{21} m^{-3}. This makes the idea of using NBI more feasible with a special care for vacuum conditions in injectors.

First technology demonstration experiments were done with a “START”-type injector [3]. It was mounted in a special section which forms a local mirror trap with B_{max}/B_{min}=4.8/3.4 T in the central part of the 12-meter-long multiple mirror (corrugated) solenoid. Deuterium beam with 15-18 keV energy, 0.45-0.55 MW power, and pulse duration 0.8 ms was injected into the trap normally to the axis. Beam neutralization efficiency in a gas-puffed target was 60%. In the discussed experiments the injector had a planar ion source, so the beam diameter of 14 cm was larger than the plasma one. No significant plasma heating by NBI was expected. Beam attenuation profile was measured by a set of secondary emission detectors in a beam dump. Energy density of the beam passed through plasma was measured by calorimeter.

The most evident problem of usage of NBI in multimirror confinement system is neutral beam transport to the hot plasma core through dense gas and plasma edge. Unlike tokamaks, in current GOL-3 experiments the edge plasma density can be higher than the core density. Gas concentration in the beamline should be less than 10^{20} m^{-3} for the lossless beam transport. The gas-puff system of GOL-3 was modified to comply with this requirement. In contrast to flat axial distribution of initial gas pressure used previously, two short density peaks at 3.5 and 9 m were created by pulse valves in the discussed experiments with neutral injection (Fig. 2). While at maximum gas concentration exceeds $1.8{\cdot}10^{21}$ m^{-3}, at the injection point it goes down to 10^{20} m^{-3} that allows achieving required pressure in NBI duct by differential pumping. The difference between two regimes in Fig. 2 is the delay of initiation of a foreplasma-creating linear discharge in respect to the gas-puff.

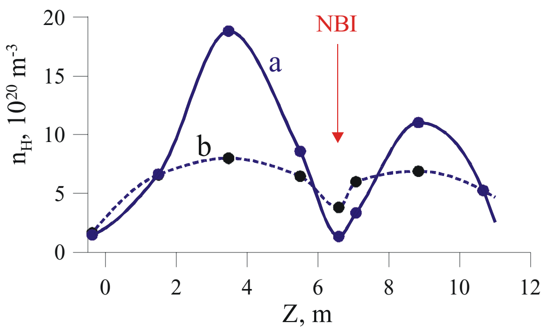

Fig. 2. Initial gas pressure distribution along the facility; a and b are two operation regimes studied in experiments.

Two initial gas profiles being used in experiments are shown in Fig. 2. Profile "a" with shorter pressure peaks is optimal for neutral beam transport. At the same time, this regime is near a plasma stability limit and disruption probability is about 50% in this case. Stable operation is realized for more shallow profile "b", but parasitic neutral beam losses in

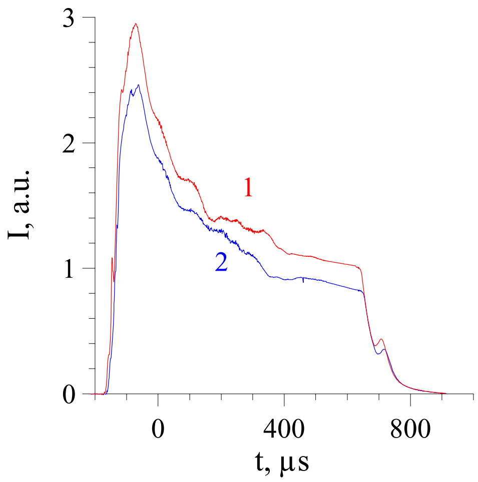

Fig. 3. Waveforms of the beam current at the beam dump: 1 – vacuum only, 2 - gas- filled chamber.

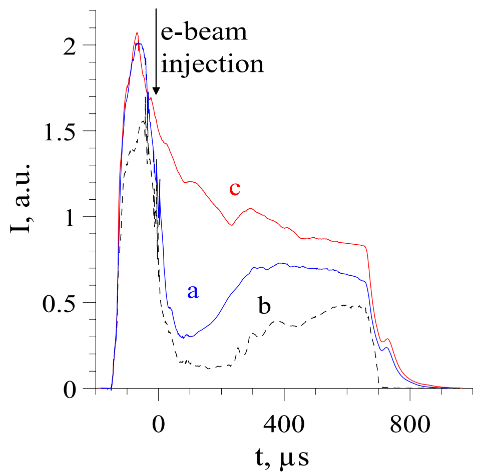

Fig. 4. Waveforms of the beam current at the beam dump: a, b – with plasma in two regimes similarly labeled in Fig. 2; c - vacuum only.

the beamline are doubled for this case.

Figure 3 shows the beam current loss due to gas in the beamline for the pressure profile "a". Curves 1 and 2 are the cases of beam transport through vacuum and gas, respectively. The difference about 15% corresponds to expected beam losses due to stripping in the beamline.

Dynamics of neutral beam attenuation in the plasma is presented in Fig. 4. Curves “a” and “b”, taken in one experimental campaign, correspond to beam current passed through the plasma with two initial density profiles shown in Fig. 2. Curve “c” is a reference waveform. At the moment t = -30 μs a special linear discharge which creates the preliminary plasma is initiated. Main relativistic electron beam is injected into this plasma in the moment t = 0 μs. Plasma density rapidly increases up to $6\cdot10^{20}$ m^{-3} that results in capturing of 72% of the neutral beam. Peak value of the plasma density significantly exceeds the initial gas-puffed density. Main reason for this is axial density redistribution after the electron beam pulse. Such redistribution includes mainly magnetized charged particles, so the gas density in the injector and in the duct remained tolerable.

Experiments with injection of neutral helium beam show 20% capture of 15 keV particles. In contrast to hydrogen, charge exchange process is negligible for helium and fast helium atoms are captured due to electron-impact ionization.

Shadow of plasma column on the beam profile was used as a chord diagnostic of plasma density evolution. A map of plasma density is shown in Fig. 5. Horizontal coordinate represents time, vertical is for chord radius. First 100 μs of plasma confinement stage the plasma density profile is non-stationary and peaked. Fast changes in plasma profile may be the result of “hot spots” in the beam-heated area which cause a difference in density

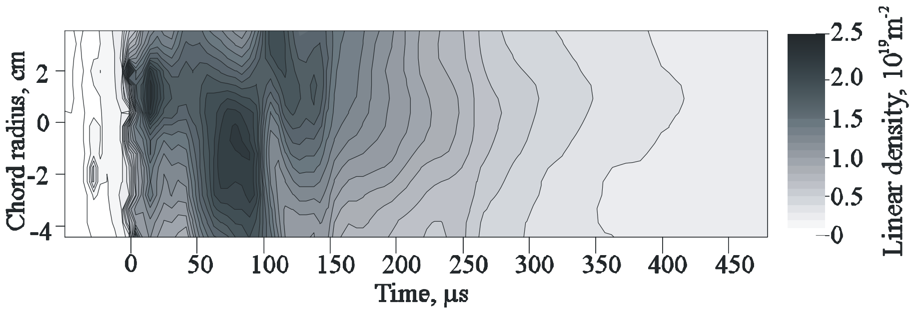

Fig. 5. Evolution of radial profile of line-integrated density.

redistribution time for different magnetic flux tubes. Then a quasi-stationary profile with half-width diameter about 6 cm is established. This profile exists till the plasma decay.

Figure 6 gives the comparison of the plasma density from the beam attenuation measurements with a diamagnetic plasma pressure measured near NBI port. Plasma pressure grows up to ~$2 \cdot 10^{20}$ keV·m^{-3} during the electron beam injection and then decreases to $0.5 \cdot 10^{20}$ keV·m^{-3} in ~200 µs. The density grows from $2 \cdot 10^{20}$ to $5 \cdot 10^{20}$ m^{-3} during some time after the beam injection and then stays constant during about 100 µs After that density slowly decreases to10^{20} m^{-3} in 300 µs. This means that energy loss from the plasma initially occurs due to its cooling and at latter confinement stage particle loss becomes dominant.

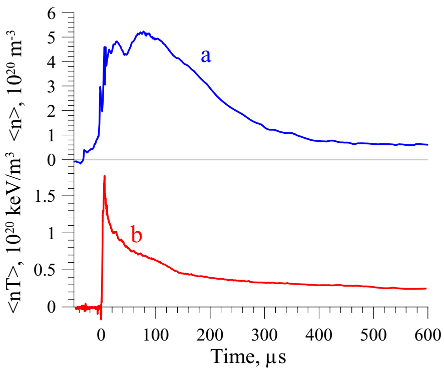

Fig. 6. Waveforms of plasma density (a) and diamagnetic pressure (b).

In general main result of this work is the achievement of a special regime of GOL-3 operation with a stable plasma ant stable operation of the NBI system. This gives a good prospect for a next planned step in the development of a 1 MW injector module with geometrical focusing of the beam into ~4 cm diameter. The pressure of fast captured ions should be significant in this case.

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