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FIRST RESULTS ON THE GOL-3-II FACILITY

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ABSTRACT

First results of the GOL-3-II facility are presented. Transport of the high-power microsecond electron beam through the 12 m turbulent plasma column, beam relaxation in the plasma and plasma heating are investigated.

1. INTRODUCTION

The GOL-3 facility is intended for a study of interaction of a high-power microsecond relativistic electron beam with a plasma mainly applied to the problem of the fast heating and confinement of a dense plasma (10^{15} -10^{17} cm^{-3}) in a long open trap. The first stage of this device (see [1]) with a 7 m long plasma has been operated about six years at a beam energy content of up to 100 kJ. Main experimental results obtained for this period on GOL-3-I are the following:

- High level (up to 25-30%) of the collisionless energy losses of the microsecond electron beam in a plasma with a $\sim 10^{15}$ cm^{-3} density was obtained and an electron temperature of ~1 keV was achieved [2,3].
- At an intense interaction of an electron beam with a plasma, its longitudinal electron thermal conductivity was found to be in 2-3 orders of magnitude lower than classic one [3,4].
- Feasibility of heating a dense (10^{16} -10^{17} cm^{-3}) plasma with an electron beam by the "two-stage" scheme was demonstrated [5].
- Experiments on the interaction of an electron-hot plasma with various solid targets were carried out. This is important for the choice of ITER divertor material. The "target" plasma and the surface erosion which strongly dependent on the incident energy density were studied [6].
- First experiments on generation of a high-power ultraviolet "flash" from the dense plasma bunch at its various elemental compositions have been done [7].

In September, 1995 all experiments on the GOL-3-I device have been completed. The magnetic and plasma systems were disconnected from the beam generator U-3 (used up to this time) and disassembled. In a few months new magnetic, plasma and vacuum systems of the device have been assembled. Pair of new capacitor storage units for feeding the solenoid have been put into operation. A more capable beam generator U-2 was matched to the upgraded device. Thus, the second stage of the GOL-3 device has been assembled and got the name GOL-3-II. The first shots have been done in the end of 1995. This device is the next step in the study of the interaction of high-power electron beams with a plasma being carried out at the Budker Institute, Novosibirsk [8].

2. GOL-3-II FACILITY

Schematic of the device is given in Fig.1. The device consists of the beam generator U-2, plasma chamber, fore-plasma creating unit combined with an exit beam receiver, solenoid supplied by a 15 MJ capacitor storage.

One of the key improvements of the facility is a substantial increase in the energy content of the electron beam injected into the plasma. The beam generator U-2 enables one to obtain the beam with an energy content of up to 0.3 MJ. One-megavolt ten-microsecond pulse is produced by LC-generator and applied to the ribbon magnetically insulated diode [9]. The relativistic electron beam ($\gamma \sim 3$) with the cross section of 3.5x140 cm and current of up to 50 kA is produced by the fibrous graphite cathode and goes out through the anode slit into the vacuum slit channel of 1 m length with a guiding magnetic field of ~0.3 T. Next to this channel is the beam shape transformer where the beam changes its transverse cross section from the ribbon to the round one according to the magnetic force lines. Then the beam is compressed in a rising up to 4.5 T magnetic field and injected into the plasma through the graphite limiter with 5.5 cm aperture and thin foil. The waveforms of diode voltage and beam current after the limiter are given in Fig.2.

Another essential change in the new device is an extension of a plasma column of the GOL-3-II up to 12 m compared with 7 m of the first stage of the device. New foil replacement system enables up to 5 sequential shots to be done. The plasma chamber is a metal pipe made of stainless steel with the inside built-in limiters and in-chamber diagnostics - diamagnetic loops and Rogowsky coils. The chamber is placed inside the solenoid with mirrors spaced by 12.2 m. The solenoid is powered by the capacitor storage whose energy content was increased from 10 to 15 MJ. This provides the magnetic field in the uniform part of solenoid of up to 5 T, and in mirrors of up to 10 T (these values were 4.5 T and 9 T for the first experiments). Behind the exit mirror there is the fore-plasma production unit and beam receiver. With the use of this system a fore-plasma column of a $\sim 10^{15}$ cm^{-3} density was obtained in a metal chamber.

In the experiments both the beam and plasma parameters are registered. The beam characteristics are measured with electrotechnical methods (voltages and currents at different points). The plasma pressure nT is measured by diamagnetic loops. The

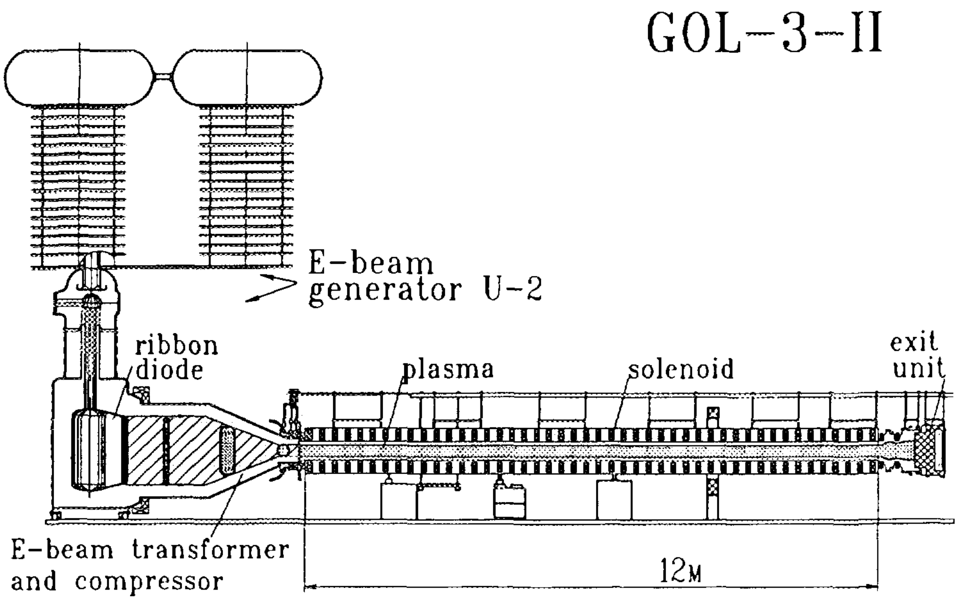

Fig.1 Schematic of the GOL-3-II device

density and temperature at 1.8 m distance from the input mirror is determined with a 90°-scattering of a ruby laser beam. At a 4 m distance from the input a 8° and 90° Thomson scattering with 2ω-Nd laser is placed. The spectral system based on the polychromator and framed photodiode array enables the registration of the plasma spectrum with high spectral (0.03 nm) and temporal (<100 ns) resolution. By the H_α line profile and its shift it is possible to determine an electron density, ion temperature and velocity of plasma motion. An electrostatic analyzer of charge exchange particles is used for finding out characteristics of the the plasma ion component. The analyzers of beam energy spectrum and plasma fast electrons are placed behind the output unit.

3. BEAM TRANSPORT THROUGH A 12 METER PLASMA COLUMN

During the injection of a high-power electron beam into a plasma of $\sim 10^{15}$ cm^{-3} density the beam-plasma collective interaction is observed. As a result, there is a high level of plasma turbulence in a plasma. This circumstance leads to the specificity of beam transport in such a system. The presence of oscillations causes the change of plasma properties compared to the classic ones. As is shown in the GOL-3-I experiments [3,4], an effective collision frequency of electrons changes substantially. In particular, this leads to a decrease in a plasma conductivity by a factor of 100-1000. Therefore, even at quite high plasma temperature (0.2-1 keV) its conduc-tivity is still insufficient for the beam current compensation. In addition, increase in the effective frequency of collisions can lead to an abnormally high transverse diffusion of beam electrons.

At the first stage of the GOL-3 device (7 m long) the net beam current achieved 10-20 kA at the injection current of 30-40 kA. With an increase in the system length up to 12 m on the GOL-3-II device one could expect the Kruskal-Shafranov macroscopic instability of the beam-plasma system caused by such currents. Actually, according to [10] the critical current is determined by:

$$J_{crit} = \frac{cB\pi a^2 b^2}{L(b^2 - a^2)},$$

where a is the beam radius, b is a radius of a conducting wall, B is the axial magnetic field, L is the system length.

As is seen, with a 10-20 kA current in the 12 m system the Kruskal-Safranov instability can develop and the beam can be thrown to the wall of chamber or limiters as a result. In order to avoid this quite undesirab-le case practically complete beam current compensation is required.

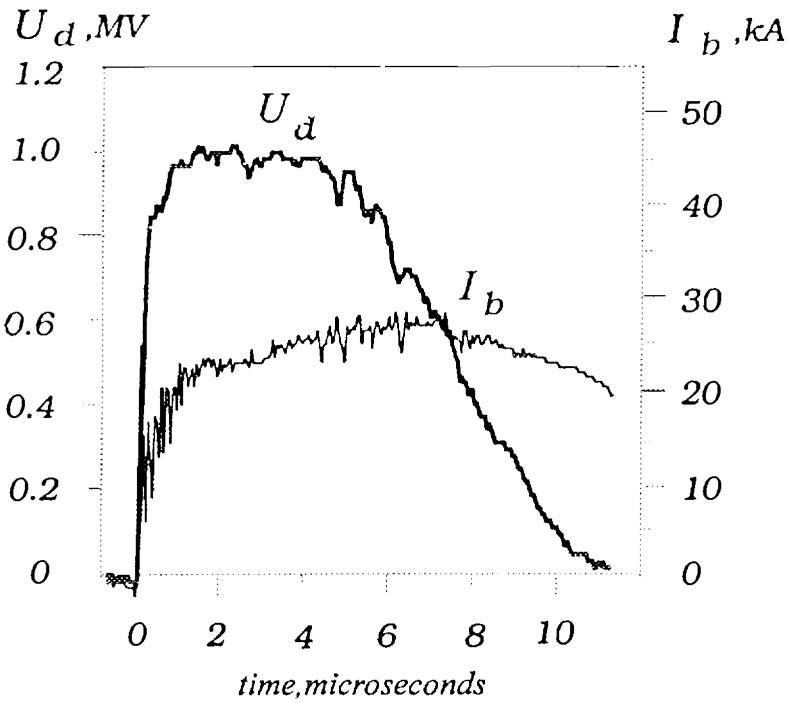

Fig.2 Electron beam parameters. U_d - diode voltage, I_b- input beam current. The energy content is 180 kJ.

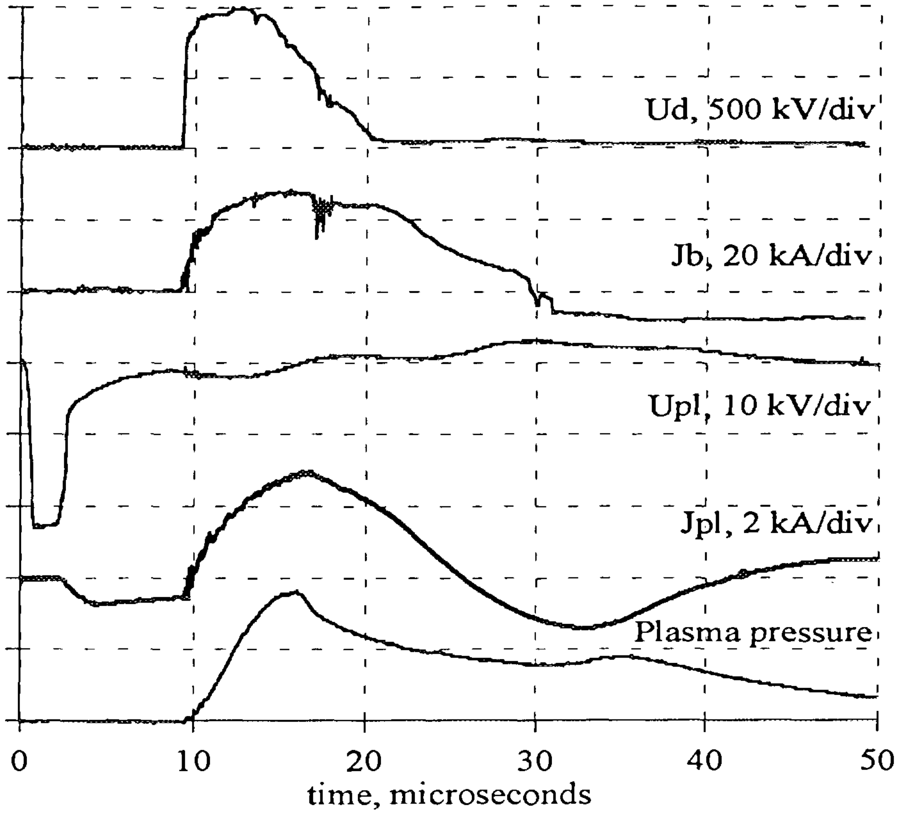

Fig.3 Typical waveforms: U_{pl} - voltage on the linear discharge, J_{pl} - total current in plasma. Plasma pressure - waveform of diamagnetic signal at 4.74 m from the input mirror.

Special efforts have been undertaken on the GOL-3-II device to reach this goal. First of all, prior to the beam injection in the vacuum chamber the plasma column is formed by the specific linear discharge. In this case, prior to beam injection an opposite current is flowing along the plasma. Secondly, the output beam receiver is initially under the flowing potential so, when the beam electrons reach it, an additional voltage occurs on the plasma column. This voltage facilitates an increase in the return current and consequently better compensation of the beam current. Some typical waveforms for the case of good compensation are shown in Fig.3. Prior to the beam injection the voltage U_{pl} is applied to the system for producing the foreplasma. In 3 μs after applying the voltage the break-down of the gas occurs through the whole system length and the current J_{pl} starts to flow along the plasma. Few microseconds later the electron beam injection begins. It is seen that the input beam current J_b reaches the amplitude of 30 kA. The net current in the plasma decreases first, reaches zero, and finally changes its direction following the initial beam current. In the case described, net current does not exceed 3 kA, and the substantial macroscopic beam motion across the magnetic field is not observed. It should be mentioned that during the beam injection into a gas net current exceeds substantially this value and the beam displacements are observed at the device output.

Another important factor for the beam transport is the electron transverse diffusion occured in a plasma with a high level of turbulence. This process is not yet studied in detail but it is probably manifested in the experiment by an increase in the transverse cross section of the electron beam at its propagation in a plasma.

4. PLASMA HEATING

In the first GOL-3-II experiments the beam was injected into the plasma with the density ranging from $5 \cdot 10^{14}$ to $2 \cdot 10^{15}$ cm^{-3} for different shots. According to scalings established at GOL-3-I, an energy content in a plasma column grows linearly with an increase in the energy content of a beam [3]. The main mechanism of an energy loss of the heated plasma bulk (the Maxwellian fraction) is the longitudinal electron thermal conductivity. In this case, the cooling characteristic time can be estimated as follows:

$$\tau = L^2 / \chi,$$

where L is the plasma column length, χ is a temperature conductivity coefficient.

Following this one can expect that on the new GOL-3-II device the total energy content in the plasma will 2-3 times increase according to an increase in the beam energy content. Energetic lifetime of the plasma will grow approximately 3-fold.

The first experiments have shown that the given scalings are met. Fig.4 shows the comparison of the plasma energy content profiles for the experiments on the first stage of the GOL-3 device and that for the first experiments on the GOL-3-II device. It is seen that with an increase of the beam energy content the energy store increases too, and the character of theplasma energy content distribution over the length is conserved.

Preliminary estimates of a plasma electron temperature from Thomson scattering data have shown that the temperature of a plasma with density $(0.3\text{-}1)\cdot 10^{15}$ cm^{-3} exceeds 0.5-1 keV. The correct comparison of the laser and diamagnetic measurements is not yet performed but up to an accuracy of factor 2 one can say that similarly to the first stage of the device, the diamagnetic signals are mainly determined by the Maxwellian fraction of heated plasma electrons.

The heated electrons have enough time to transmit a fraction of their energy to plasma ions. For our typical parameters the ions should be heated by binary collisions up to 30-50 eV. This temperature was measured by the Doppler broadening of the H_α line.

5. PROSPECTS OF THE GOL-3-II FACILITY

The first experimental results obtained on the GOL-3-II device are the good base for the successful development of the GOL-3 program. By present, the capability of the beam generator U-2 is not yet fully applied. An increase in the energy content of the beam injected into the plasma in a factor of 1.5-2 is possible. This should lead to the corresponding growth of the energy content of the plasma. Nevertheless with already available parameters of the injected beam the following experiments can be conducted.

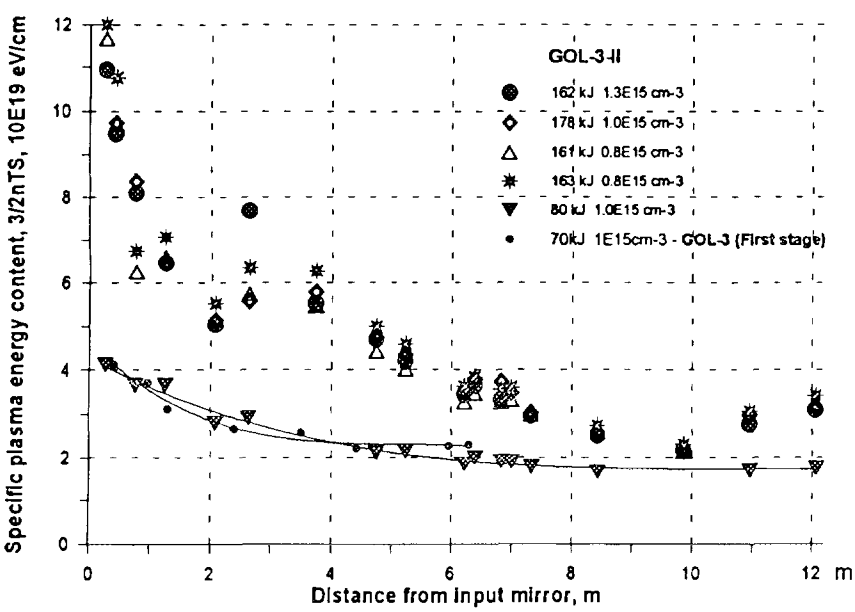

Fig.4 Distribution of specific plasma energy content over the device length at first stage of GOL-3 and at GOL-3-II.

First of all, these are experiments on a "two-stage" heating of a dense plasma bunches (see [5]). In this case, the bunch of a dense plasma ($\sim 10^{16}\text{-}10^{17}$ cm^{-3}) is produced in the plasma chamber and the electrons heated in the region with a $\sim 10^{15}$ cm^{-3} density should transfer their energy to the bunch. Such experiments have been started on the first stage of the device. It was shown that the energy content of the dense bunch is ~10% of the beam energy content. These experiments are planned to be continued at a new energy level on the GOL-3-II device.

Further, of special interest are the experiments with two bunches being heated and then collided. At the place of collision, the ion temperature could reach sub-keV range. Then, the obtained hot plasma bunch could be confined in a local "magnetic pit", i.e. in the short part of solenoid with weakened magnetic field. In this case it is possible to obtain a plasma with local $\beta > 1$ and to study a "wall" confinement of such a plasma.

Finally, existing magnetic system enables us to do inexpensive reconstruction of the GOL-3-II into a multimirror trap. The multimirror trap enables one to obtain a plasma with the density of $\sim 10^{16}$-10^{17} cm^{-3}, temperature ~1 keV, lifetime ~0.1 ms. The experiments with the multimirror confinement of hot plasma is one of the most important goals of the GOL-3 program.

6. CONCLUSION

The first GOL-3-II experiments on injection of 8 μs, 200 kJ electron beam into a plasma of 12 m length were carried out. The possibility of macroscopically stable beam transport through the 12 m long plasma column has shown under the conditions of the developed plasma microturbulence. As a result of collective interaction of the beam with the plasma the effective heating of the plasma with density $\sim 10^{15}$ cm^{-3} is observed. Putting the facility into operation opens up a prospect to carry out the experiments with dense ($\sim 10^{16}$ -10^{17} cm^{-3}) and hot (~1 keV) plasma in the multimirror trap.

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