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PELLET INJECTION IN BEAM-HEATED PLASMA ON THE GOL-3-II FACILITY

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1. Introduction

Multimirror confinement of a dense plasma was proposed in [1] as one of alternative fusion concepts. The plasma is confined in a long solenoid with corrugated magnetic field. Free path length in such facility should be much less than length of the solenoid, therefore the plasma density should be ~10^{17}-10^{18} cm^{-3} to get reasonable length of the whole system. This gives β>1 with the existing magnetic technology. High density compensates expected short lifetime of the plasma in the multimirror trap.

Experimental activity at the GOL-3-II facility is mainly devoted to studies of a dense plasma heating and confinement in a 12-m-long solenoidal trap (description of the device can be found in [2]). Plasma of $10^{14}\div10^{17}$ cm^{-3} density is heated by high-power relativistic electron beam with total energy content of up to 200 kJ. The beam excites Langmuir microturbulence in the plasma due to two-stream instability and its energy is transferred to the plasma electrons. As a result the beam loses up to 30% of the initial energy. Electron temperature of the plasma is up to 2 keV at the density of 10^{15} cm^{-3} [3]. Increase of the plasma density above this value leads to worse efficiency of the beam-plasma interaction and, consequently, to fast decrease of the plasma temperature.

Higher plasma densities can be achieved in a two-stage scheme of heating of a dense plasma bunch. The beam releases energy in the main ~10^{15} cm^{-3} plasma due to collective mechanisms. Then this energy is transferred to a pre-formed $10^{16}\div10^{17}$ cm^{-3} bunch by binary collisions. Achieved peak pressure in the dense bunch triples pressure of the surrounding main plasma (see, e.g., [3]). Ion temperature reaches ~150 eV with ~500 eV peak electron temperature at ~$5\cdot10^{15}$ cm^{-3} density. Further thermalisation of the plasma and growth of the ion temperature are limited by longitudinal heat losses and fast expansion of the bunch.

Up to date the usual fueling technique at the GOL-3-II facility was fast gas-puff. Required initial density distribution over the length is formed by a set of fast valves. Studies of the two-stage heating of the dense plasma were done with this system. Further optimisation of the experiment leads to pellet injection as a tool for creation of the dense plasma bunches. Description of this new system and first experimental results are presented.

2. Pellet injection for the GOL-3-II experiment

Technique of pellet injection for diagnostics and fueling purposes is widely developed within toroidal fusion community (see, e.g., reviews [4,5]). Usually it turns to be costly cryogenic devices. Following features of the GOL-3-II experiment lead to considerably simplified technique. First of all, duration of the electron beam in our experiment is short enough (~10 μs) and the pellet can be positioned in the vacuum chamber just prior to the beam injection. Very high specific power of the beam results in a fast volumetric heating and explosion of the pellet, which forms consequently the dense plasma bunch. In our case pellets shouldn't move through the hot plasma and thus the high initial velocity of the pellet isn't required.

Short lifetime of the GOL-3-II plasma (typically ~100 μs) makes the plasma behaviour almost insensitive to radiative losses even at marked concentration of the impurities. Thus it is possible to apply pellets made of non-cryogenic solid materials with high fraction of hydrogen isotopes (plastics, LiD) in multimirror experiments. At the same time an additional energy loses to ionisation in that case.

Physics of transition from the solid pellet to the dense plasma bunch is following. The pellet with ~10^{19} atoms in a first microsecond forms the gas cloud under the volumetric energy release of hot plasma electrons. As this low-ionized cloud expands spherically, its periphery becomes less dense and more hot. Under GOL-3-II conditions at $n \cdot T^{-3/2} \sim 10^{16}\,\mathrm{cm}^{-3}\mathrm{eV}^{-3/2}$ the fast transition of the dense gas to magnetized plasma bunch occurs and it further expands along the magnetic force lines. After that the behaviour of the bunch is well described by the two-stage heating scheme.

Dense plasma fueling by the pellet injection, unlike the gas-puffing, delivers 100% of the atoms into the beam-plasma interaction region. This leads to following features of the method:
- no dense cold plasma exists outside the beam cross-section (enables accurate spectroscopy and charge-exchange neutral analysis, no extra charge-exchange losses of energy);
- better operation of the facility in respect to Shafranov-Kruskal instability;
- wider choice of impurities for diagnostic purposes.

3. Configuration of the experiment

The GOL-3-II facility is a long axially-symmetrical open trap. The magnetic system is 12-m-long solenoid with 4.7 T field and 9 T in end mirrors. The solenoid allows operation with uniform magnetic field along the axis or in multimirror mode with sections of corrugated field with 22 cm cell length and H_{min}/H_{max}~1.5. Initial plasma is created by linear discharge and then electron beam (~1 MeV, ~30 kA, ~8 μs) is injected for plasma heating (total energy content of the beam is up to 200 kJ). Diameter of the beam in the uniform part of the solenoid is ~6 cm.

The pellet injector is placed at ~6.5 m from the beam input in a short section with lowered to 3.8 T magnetic field. Layout of the injector and diagnostics is shown in Fig.1. The injector itself consists of a pulsed flat coil which induces current in a disk pellet holder and thus accelerates it with the pellet on top. Five shots can be done without breaking the vacuum. Power source supplies injector with ~1.5 kA, ~40 μs FWHM current pulse. Initial velocity of the pellet is ~20 m/s. Injector is switched on simultaneously with the main magnetic field. Time-of-flight was checked with removable piezoelectric probe for the pellets made from materials with different density and masses from 0.1 to 10 mg.

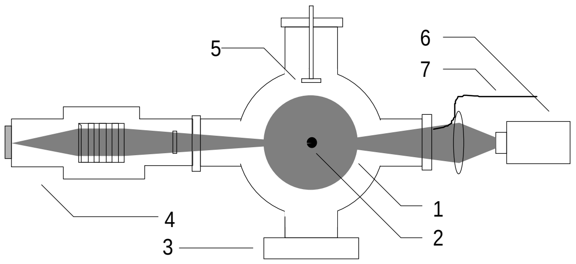

Fig.1. Experimental configuration: 1- main plasma, 2- injected pellet, 3- pellet injector, 4- imaging VUV spectrometer, 5- movable piezoelectric probe, 6- CCD camera, 7- lightguide to spectral system

Several diagnostics were used to study parameters of the pellet plasma. Initial pellet position and expansion is imaged in visible light by CCD camera and digital VUV pinhole (~1 μs frame). Visible spectrum is measured with imaging digital spectrometer. Density measurements by H_α broadening is done with digital spectral system, which consists of two parts: high precision detector with ~1 μs frame and system with ~5 μs repetitive spectral scans of moderate resolution. Lightguides to this system can be placed at the different distances from the injector.

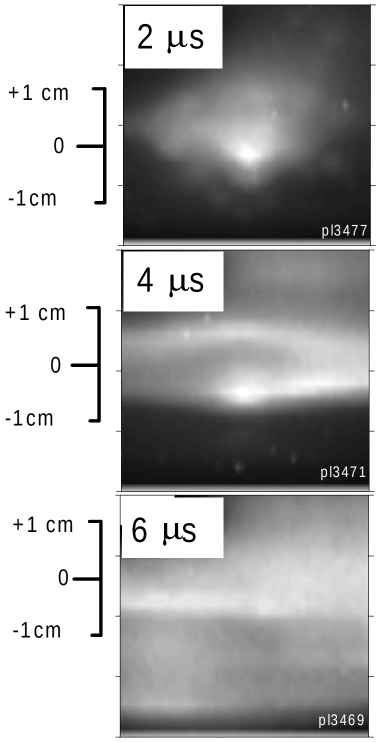

Fig.2. VUV images of expansion of the pellet plasma. Frame duration is 1 us

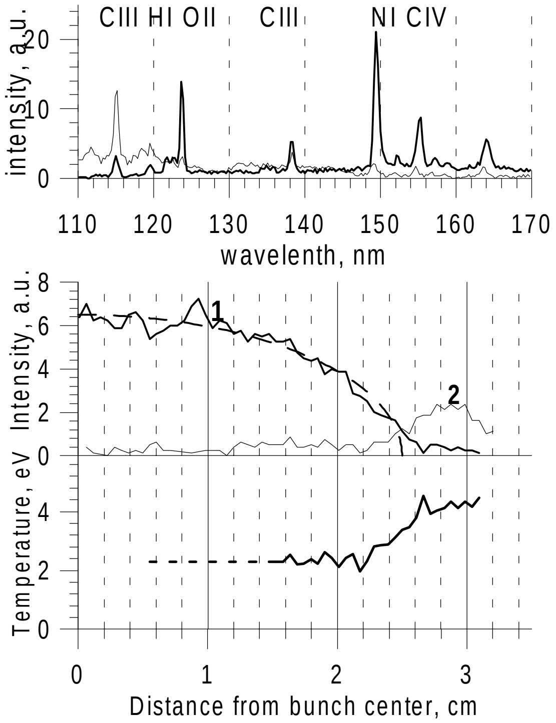

Fig.3. Beginning of expansion of 1 mg CH_2 pellet. Top: VUV emission spectra for 1.8 cm (thick) and 2.8 cm (thin) from center. Middle: radial dependence of intensity 1-CIII 57.4 nm, 2 - CIV 154.8 nm, dashed line- calculation for spherical cloud. Bottom - radial dependence of temperature.

Density of the plasma at ~1.9 m from the injector is measured with 1.15 μm Michelson interferometer (second one monitors density of the main plasma at ~0.8 m from the beam input). Temperature profile across the dense cloud can be found from intensity ratio of spectral lines of ions of different ionization state. Seya-Namioka imaging VUV spectrometer with ~1 μs frame is used in this method. Time evolution of VUV emission from the plasma is measured with several vacuum photodiodes at different distances from the injector. All other standard diagnostics of the facility are also active.

4. Experiments and discussion

Experiments were performed with pellets made of CH_2 (0.1÷1 mg mass range) and LiD (~20 μg mass). Density of the background plasma was $\sim 1 \cdot 10^{15}$ cm^{-3}. In general the behaviour of the pellet plasma is well described by simple model discussed in Section 2. Dynamics of the dense plasma is seen from VUV images in Fig.2 (0.15 mg CH_2 pellet). Transition from the spherical dense gas to magnetized plasma occurs in a few microseconds from the beam start (at relatively low temperature of the background plasma). Transverse diameter of the bunch reaches ~1.5 cm, that is in a good agreement with the expected value.

For a while the temperature of a dense core of this formation remains cold. VUV emission spectrum (taken with large 1 mg CH_2 pellet for 4÷6 μs interval from the beam start) shows abundance of CIII ions near the center of the bunch and CIV ions on the periphery (Fig.3). Ratio of intencities of the lines gives ~2.5 eV at the central part of the bunch for this case. Estimate of plasma density gives $3 \cdot 10^{18}$ cm^{-3} for ions and about twice for electrons. Dense plasma is still not magnetized and its final diameter is larger than for Fig.2 (~3 cm for this case).

After the pellet plasma density falls down to critical value, it becomes magnetized and the one-dimensional expansion starts. Dynamics of the plasma density is found from

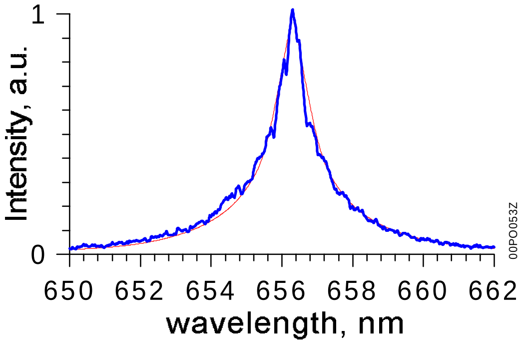

Fig.4. Profile of H_α emission from 0.3 mg CH_2 pellet (frame 7-37 us from start). Thin line calculated for 1.7 10^{17} cm^{-3}, 4 eV.

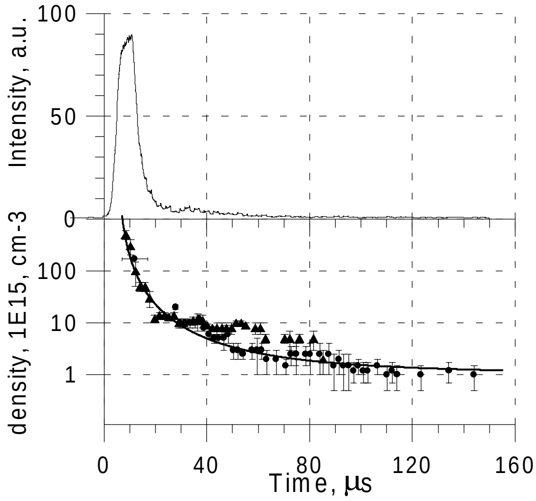

Fig.5. Expansion of light pellet: top - waveform of H_α intensity; bottom - calculated electron density, dots - spectroscopy, line - model.

H_α spectroscopy (surrounding rare main plasma doesn't affect the line profile). Typical line profile for the beginning of expansion of the pellet plasma is shown in Fig.4. Features on the profile corresponds to first few harmonics of double hyrofrequency (Δ~0.31 nm) and possibly to CII lines.

Plasma density decreases fast during the 1-D expansion - see Fig.5. This dependence can be compared with prediction of simple 1-D gas-dynamical model of expansion of a dense plasma bunch [6]. Assumed in the model are the typical for the GOL-3-II experiments energy deposition over bunch depth and linear growth of heating power during the beam injection. The model predicts transformation of heating power into longitudinal kinetic energy. Comparison with the experiment gives expansion rate (double velocity of the front boundary of the bunch) of ~$6.2{\cdot}10^7$ cm/s. This corresponds to ~500 eV kinetic energy of hydrogen ions and much more than temperature in the point of initial pellet position. High kinetic energy of ions can in principle be utilised into plasma temperature with pellet injection re-positioned in section of corrugated magnetic field.

5. Conclusion and acknowledgements

First experiments with pellet injection into the beam-heated plasma were done at the GOL-3-II facility. Dynamics of plasma density was measured. The pellets in beam heated plasma are evaporated and magnetized in a few microseconds after beam injection and then expanse along magnetic field. The dense bunch with the diameter about 2 cm is formed in the main plasma. An expansion of this bunch describes satisfactory by simple 1-D gas-dynamics model. A value $3{\cdot}10^7$cm/s for bunch expansion velocity is defined from measurements that corresponds to kinetic energy of hydrogen ions 500 eV.

The experiments shown the energy is transferred effectively from the electron beam to expanded pellet. The pellet injection method can be exploited for dense plasma bunch creation in multimirror confiment experiments as well for impurity input for diagnostics aims.

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