Plasma Heating and Fuelling in the Globus-M Spherical Tokamak

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Abstract. The results of last two year plasma investigations in Globus-M are presented. Described are improvements helping to achieve high performance OH plasmas, which is used as the target for auxiliary heating and fuelling experiments. Increased energy content, high beta poloidal, good confinement are reported. Experiments on NBI plasma heating in the wide range of plasma parameters were performed. Some results are presented and analyzed. Experiments on RF plasma heating in the frequency range of fundamental ion cyclotron harmonics are described. In some experiments which were performed for the first time in spherical tokamaks promising result was achieved. Noticeable ion heating was recorded at low launched power and high concentration of hydrogen minority in deuterium plasma. Simulations of RF wave absorption are briefly discussed. Described also are modification of the plasma gun and test-stand experiments. Fuelling experiments performed at Globus-M are discussed.

1. Introduction

Globus-M operational limits and plasma parameters range obtained up to year 2002 in OH regime are described in [1]. Example of plasma discharge in non-boronized vessel is shown in Fig.1.

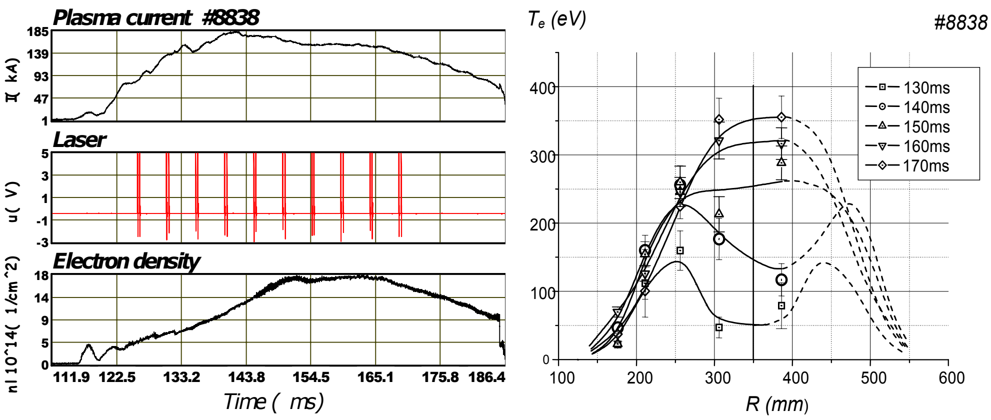

FIG. 1. Plasma current, laser pulse train and line integrated density (left). Electron temperature profile variation (right) in discharge #8838.

Vacuum vessel conditioning and boronization procedure together with magnetic coils program modification helped to achieve improved discharge performance. At relatively low toroidal magnetic field ~ 0.4 T, discharge duration was increased up to ~ 100 ms at the current amplitude 0.15 ~ 0.2 MA. Current flat top was well pronounced with the duration in excess of several confinement times and few current diffusion times. The densities up to 7 10^{19} cm^{-3} could be obtained. At the increased current 0.25-0.27 MA the discharge duration decreases to 70-80 ms. Some OH discharges demonstrated new features previously not observed. Recorded MHD activity behavior was typical for neoclassical tearing modes (NTM). NTM onset was correlated with increase of beta poloidal beyond critical value > 0.3 [2]. Obtained discharge contains less impurity concentration, which minimize plasma resistance and helps to save magnetic flux compensating resistive losses. Example of survey spectra picked up by optical multichannel analyzer (OMA) is shown at Fig. 2.

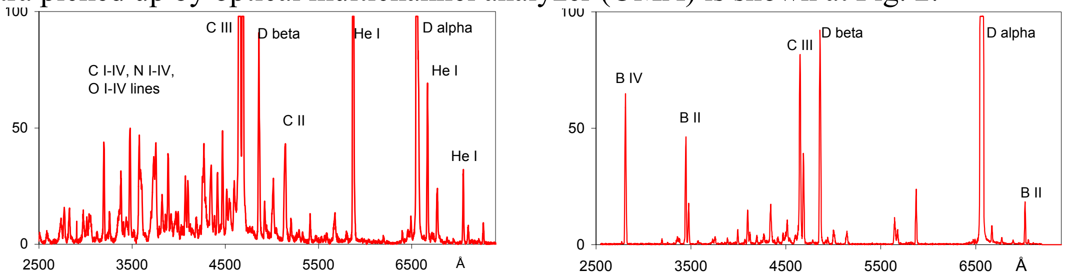

FIG. 2. OMA Spectra in Globus-M discharge before (left) and after boronization (right).

Improvement of discharge parameters helped to get rid of undesirable effect of energy confinement time saturation at relatively low density value specific for non boronized discharges. Fig. 3 represents part of confinement data base obtained during 2001-2004 years [3]. Maximum energy confinement time reached in non-boronized vessel in Globus-M doesn't exceed 4 ms, with maximum density below ~ $4{\cdot}10^{19}$ m^{-3}. Rectangles represent best shots achieved in the freshly boronized vessel. Most shots demonstrate features of improved confinement transition. D-alpha drops at constant or increased density rise rate, peripherial density profile pedestal build-up, SXR sawteeth amplitude and period drop indicate features of L-H transition previously reported [4, 5]. Data analysis gave opportunity to analyze conditions necessary for achievement of high performance OH regime (improved confinement transition) in Globus-M [3]. Those include achievement of quasistationary discharge conditions with relatively high current (~200-250 kA), minimization of radiation losses by boronization and increase of density together with peripherial power flux increase through the plasma boundary. The last remark means that the less is the plasma column surface area (smaller elongation) more likely plasma transits to H-mode at other equal conditions.

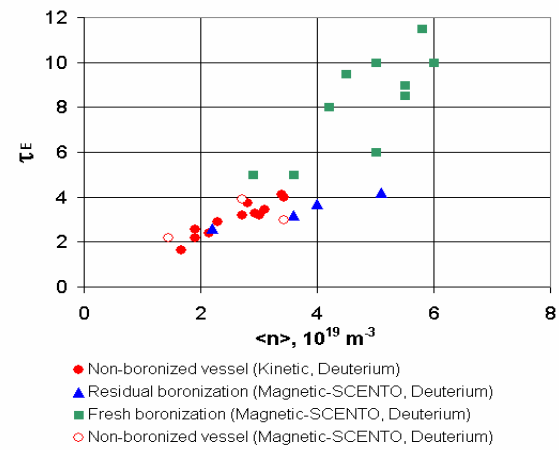

FIG. 3. Energy confinement time in boronized and non boronized vessel versus average density.

2. First results of neutral beam heating experiments

During 2003 – 2004 year experiments on the neutral beam plasma heating in Globus-M was continued. Experiments were started with two types of ion sources. One could operate at regular current of 45 A (70 A ultimate). The other one was optimized "normal" current source with the ion current up to 35 A. Both sources could operate at the voltage up to 30 kV. Comparison showed better (more sharp) beam focusing by "normal" current source. This one was further used in experiments. The neutral beam power density experimental profile is show in Fig. 4. The beam footprint dimensions measured at 1.45 m from the ion source at 1/e level of power was 3.5×15 cm^2, which is much better than expected. Experiments were performed in the range of plasma densities $(1.5 - 6)\cdot 10^{19} m^{-3}$, plasma currents 160 - 240 kA, toroidal magnetic field 0.4 T, or below. Neutral beam injector could produce both deuterium and hydrogen beams, which were injected into deuterium plasma in the co-current direction. Specific feature of the Globus-M vacuum vessel wall conditioning is use of glow discharge in mixture of gases He-Carborane for boronization. This technology permits decrease significantly Z_{eff} and vessel wall recycling coefficient. The side effect is increase of neutral hydrogen concentration in the bulk deuterium plasma, which could reach $n_H/(n_H+n_D) \sim 50\%$ in the first shots after boronization. Hydrogen is gradually released from the walls and after ~100 discharges the fraction $n_H/(n_H+n_D)$ usually doesn't increase 10%. Another specific feature of the experiments was different absolute concentration of neutrals in the discharges in the non-boronized vessel and freshly boronized ones. One of the reasons for this is minimization of impurity concentration after boronization and necessity to increase gas puff to sustain the same electron density. I.e. concentration of deuterium neutrals should increase in the discharge with boronized vessel walls.

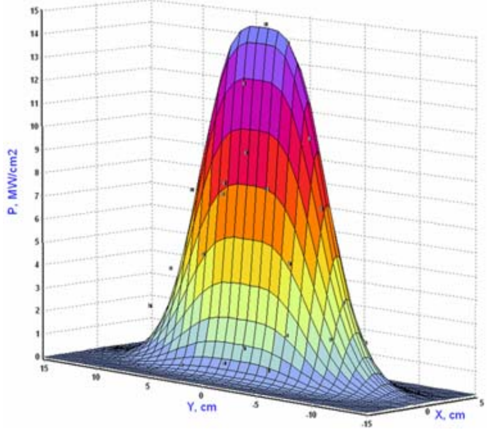

FIG. 4. Neutral beam power profile.
P_{out} = 0.6 MW, E_D = 30 keV.

The basic numerical simulations of Globus-M NBI heating, were made with the help of 1.5D transport code ASTRA by V.M. Leonov [6]. Simulations were made for equal electron and ion heat diffusivity coefficients which were normalized in such a way that resulted energy confinement time satisfies IPB98(y,2) scaling. Fig. 5 shows the dependence of absorbed by plasma fraction of beam power by different specie as the function of density. Here Pabs – total power fraction absorbed by plasma, Pbm_i fraction absorbed by ions, Pbm_e – fraction absorbed by electrons, Pc-x – charge –exchange losses.

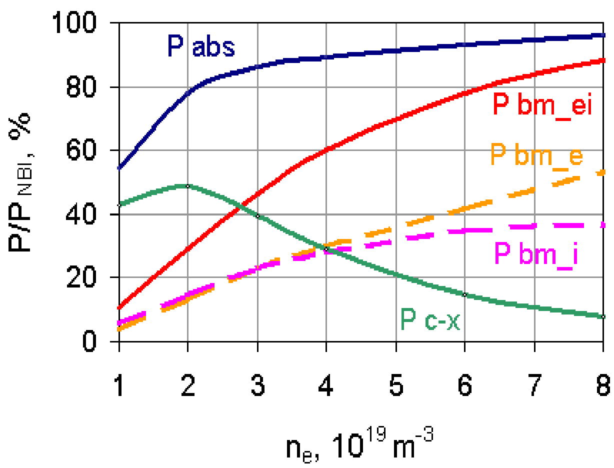

FIG. 5. Power balance simulated by ASTRA for NBI heating.

One should pay attention to the high level of charge-exchange beam power losses, P_{C-X}, especially at low density. Important that at moderate densities $\sim 3\cdot 10^{19} m^{-3}$ the power absorbed by electrons and ions doesn't exceed 50% of the beam total power. Also by simulation predictions deuterium beam is more effectively heats ions.

NBI experiments demonstrated effective ion heating. For comparison two discharges with similar conditions were chosen. One was with deuterium beam injection into deuterium plasma and another one with hydrogen beam injection into deuterium plasma. Plasma current and magnetic configuration was nearly the same ~ 180-190kA at inner wall limited discharge. The starting plasma density at which NBI is on was 1.2 and $1.4\cdot 10^{19}$ m^{-3}

respectively. During injection period average density rose up to 3 and $3.5{\cdot}10^{19}m^{-3}$ respectively. Electron temperature measured by Thomson scattering at the plasma column axis in boronized vessel in the discharge with I_P~200kA was T_{e0}~ 500-550 eV at plasma density, n_{e0}~$3{\cdot}10^{19}m^{-3}$. In non-boronized vessel it's usually higher at the same I_P and n_e. Ion temperature increase was recorded in NBI heating experiments. Fig.6 demonstrates ion temperature increase during injection of deuterium beam into deuterium plasma for the beam power ~0.6 MW (ohmic power ~ 0.25 MW), energy 30 keV-red curve.

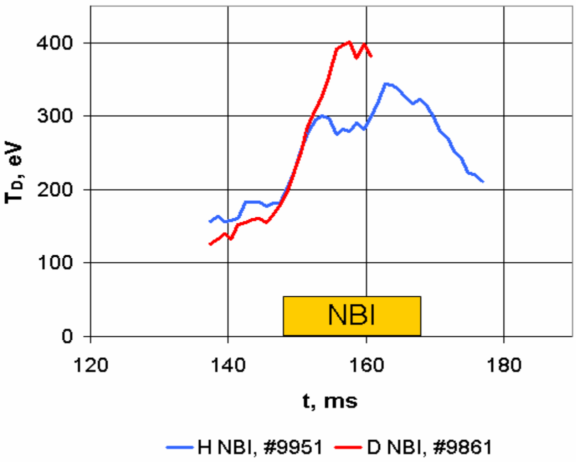

FIG.6. Ion temperature increase during NBI.

The absolute increase of ion temperature was ΔT_i ~ 220 eV. The injection was performed into discharge with non-boronized vessel walls. According to estimate of charge-exchange losses in OH regimes it was found, that in non-boronized vessel charge-exchange losses are lower than in freshly boronized one. Higher concentration of neutrals should increase charge-exchange losses and decrease the net heating power. The blue curve on the same figure demonstrates ion temperature increase during injection of hydrogen beam into deuterium discharge in the vessel with freshly boronized walls. The beam power is ~ 0.7 MW (ohmic power ~ 0.3 MW) and beam energy is 30 keV. In spite of higher injected power absolute increase of temperature is a bit less than in 9861. Few reasons could explain poor heating with higher power. First is charge-exchange losses which are higher after boronization. Second - the density profile could become more flat during injection and shift the absorption zone to plasma periphery. Fig. 7, where the ratio of two peripherial chords interferometer signals to the central one are shown, demonstrates how density profile begins to flatten after injection is on in boronized vessel. There is no such effect in the discharge # 9861, where density profile seems to keep unchanged. Third, according to ASTRA simulations deuterium beam more effective in heating ions. If so, there should be a sensitive difference in absorbed power by ions in two comparative discharges. The rate of ion temperature increase could provide estimate of the absorbed power P_i~$\Delta W_i/\Delta t$, where ΔW_i ~ $<\Delta n{\cdot}\Delta T_i>$ is averaged over the short time interval Δt, when confinement properties of plasma couldn't change significantly.

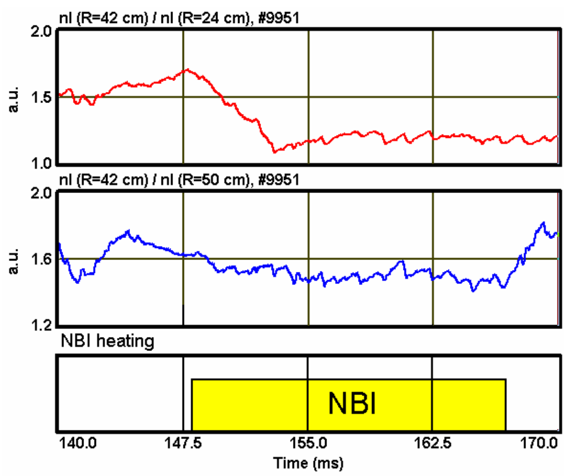

FIG. 7. Density profile flattening in the # 9951.

In the case of deuterium injection into non-boronized vessel P_i ~70kW contrary to P_i ~50 kW in the case of hydrogen beam injected in the boronized vessel. There is no big difference in the absorbed power, keeping in mind approximate value of estimated parameters. Other reasons, e.g. energy confinement degradation and sawtooth activity, which were not taken into account in simulations, are important too. Integrated analysis of experimental data with transport code is necessary to have all i dotted to optimize experimental conditions for NBI heating. As the final stage of experiment, when OH target plasma parameters degrade we tried to increase the plasma energy content combining 0.7 MW hydrogen injection with additional gas puffing. Fig. 8 shows equilibrium parameter, $\beta_P + l_i/2$ increase during NBI heating in shot # 10091.

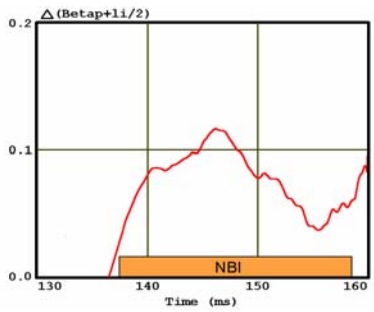

FIG. 8 Equilibrium parameter increase during NBI heating.

It was picked up by radial position feedback control system, automatically increasing current in the position control coils with plasma beta increase. Keeping in mind that profiles become flat during injection in boronized vessel, we cold attribute all increase of equilibrium parameter to beta poloidal increase. The corresponding increase in the energy content of plasma column is $\Delta W_P \sim 250$J. SCENTO simulation of energy balance gives nearly the same value. The basic OH energy content before the beam start is about 800J. 30% increase of plasma energy content was recorded during NBI.

3. Fundamental IC harmonic hydrogen minority heating

Plasma heating experiments in the range of fundamental harmonic of the ion cyclotron resonance were continued in Globus-M. Such experiments were started for the first time in spherical tokamak configuration. RF heating experimental equipment consists of single loop antennae, RF generator, RF transmission line. All the system was tuned with the help of matching elements the frequency of 9 MHz. For conditions of Globus-M (B_{Tor}=0.4T, I_P=0.25 MA) IC resonance position locations are shown in Fig.9.

Numerical modeling of wave absorption processes was performed with help of 1D "cylindrical" code developed at the Ioffe institute [7] and by 3D full-wave "TORIC" code developed at the Kurchatov institute by V.L.Vdovin. In both codes, the real parameters of experiments were taken into account including high hydrogen concentration. The distribution of the RF wave absorption intensity by different species of plasma was obtained by 1D code for equatorial Globus-M plane. Results of simulations are discussed in detail in [8]. The most straightforward result is independence of totally absorbed power on hydrogen minority concentration. Both for C_H=10% and for C_H=50% total efficiency of wave absorption is approximately equal. The absorbed power goes mostly to electrons and the fraction of power input into deuterons and protons doesn't exceed 30% of the totally absorbed power. Different mechanisms are responsible for wave absorption. The role of the cut-off barrier seems to be negligible (due to strong magnetic field non-uniformity). In addition, the role of second hydrogen harmonic appears to be very important. For the first thing, it provides direct energy absorption by hydrogen close to the nearest wall, what can decrease

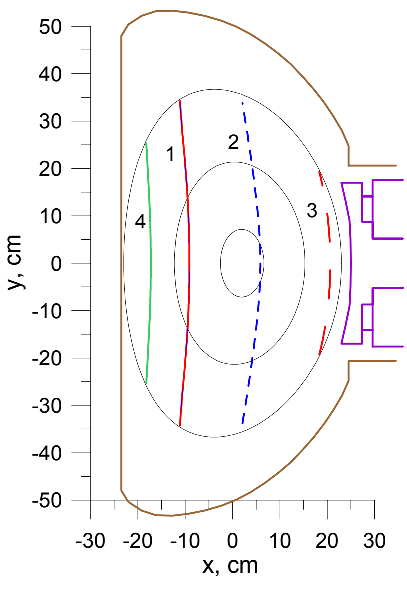

FIG. 9. Resonance layers location in Globus-M cross-section.
1 - deuterium second and hydrogen fundamental harmonics, 2 - deuterium third harmonic, 3 - hydrogen second harmonic and deuterium fourth harmonics, 4 - ion-ion hybrid resonance for 50%H+50%D plasma.

the heating efficiency. For the second thing, it creates condition for FW conversion into Bernstein wave.

During ICR heating experiments performed in 2003 year the launched power doesn't exceed 200 kW. Plasma current was 240 kA and the vessel was boronized. At isotope concentration ratio n_D/n_H=1 in the best case significant (up to two fold) ion temperature increase was recorded. Fig. 10 shows the ion temperature evolution during RF pulse for hydrogen and deuterium as well as in OH regime.

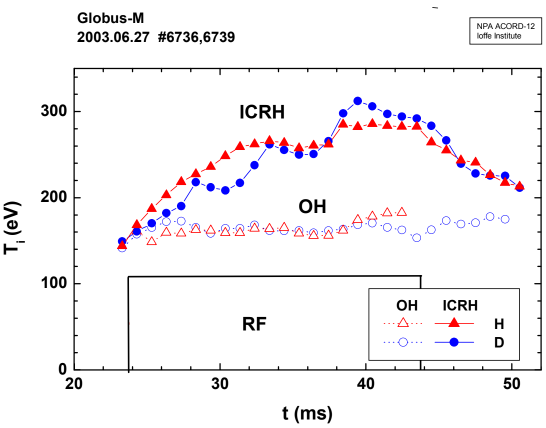

FIG. 10. Evolution of ion temperature in # 6736.

The temperature rose from 170 eV up to 300 eV. The characteristic time of temperature rise at the beginning of the RF pulse and its decay after the pulse was off corresponded to the plasma energy confinement time. There is experimental evidence of good energy exchange between deuterium and hydrogen population. As to the electron heating, the reliable results were not obtained. The energy spectra of protons and deuterons are shown in Fig.11 for the end of the RF pulse (solid lines).

They reveal the existence of energetic "tail" in hydrogen spectra unlike the deuterium ones. The analysis shows that in this tail there is confined no more than 5% of all proton population. The energy of registered tail ions does not exceed 4-6 keV. It is favorable circumstance for ion confinement and thermalization. The hydrogen temperature is determined by points lying below the bifurcation energy. The spectra obtained in the shots without any RF pulse coincide completely for both ion species (see dashed blue line, empty circles and triangles).

The attempt to repeat this experiment was performed in 2004 year experimental campaign. Fig.12 illustrates situation, when one can see the explicit hydrogen heating (shot # 9287).

The rise of deuterium temperature is much lower. Thermal equilibrium between ion plasma components is not reached. It should be noted that experimental conditions in this case were somewhat different: the vacuum vessel boronization was not performed, hydrogen concentration was much lower (~20%), plasma current doesn't exceed 190 kA, P_{inp}= 150 kW, f=8.8 MHz. Comparison is made with shot #9293 (dashed lines). Unstable reproducibility of ion heating can be accounted for different experimental and fundamental reasons. One of them is the location of the second harmonic hydrogen resonance. If it is

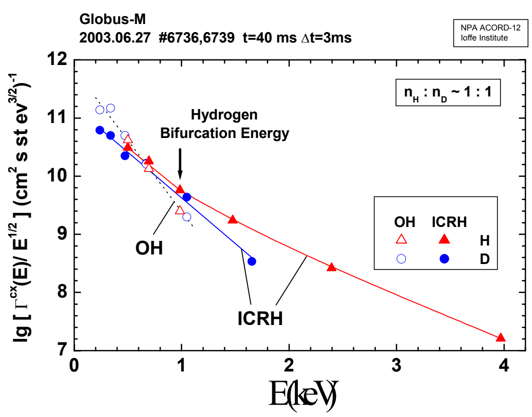

FIG. 11. Energy spectra of ions with / without RF heating.

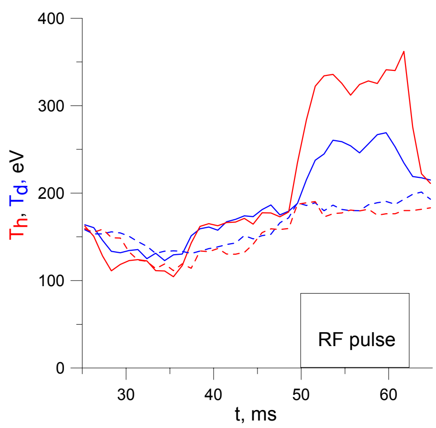

FIG. 12. Evolution of ion temperature in shot # 9287.

located at the plasma periphery, just in front of the antenna, energetic hydrogen ions can get out of the plasma very fast without energy exchange with the bulk plasma, but hit the wall and produce influx of neutrals and impurities into discharge. In future experiments more attention should be paid to control of plasma parameters.

4. Plasma fuelling with coaxial plasma gun

Last year studies of special fuelling source based on double stage coaxial plasma gun and initial successful experiments with plasma injection into the tokamak Globus-M are described in [9,10]. Optimization of the plasma fuelling source was performed by optimization of electrical parameters of power supply and device configuration. By numerical simulations we analysed the constant mass acceleration in coaxial source with capacitor battery at condition of energy conservation (2 kJ) without losses. The result is described in [10], but main conclusion is that the highest velocity can be achieved with highest capacitance and enough long muzzle length. The electrical parameters of optimized gun were: muzzle length 0.6 m, capacitance of accelerating stage C_p = 40 μF, charged voltage 4 ÷ 10 kV. Experimental test-stand for investigation of plasma gun parameters was equipped with a set of diagnostics to measure plasma density, impurity contents, speed of accelerated plasma jet, and its kinetic energy. All the equipment was installed inside a big vacuum tank, permitting quick access inside and providing background pressure less than 10^{-5} torr. As was measured optimised source generated during ≤ 50 μs clean highly ionised hydrogen plasma jet with density 10^{22} m $^{-3}$, total number of the accelerated particles 1 - $5\cdot 10^{19}$ and flow velocity 50 - 150 km / s, total kinetic energy 100 - 500 kJ. Fig. 13 represents the video frame of jet inside test stand. The bright spot at the right part represents pressure gauge luminescence under jet influence and indicates its position.

FIG. 13. Plasma jet side view.

A series of experiments was performed with DC magnetic field directed inside the stand across jet propagation. At the close position of the magnet with 0.3T magnetic field to the gun output the pressure gauge doesn't record any pressure signal. But when it was moved to the very end of path close to the gauge the pressure signal was nearly the same as recorded without magnet. That means practically full recombination of highly ionized jet during time-of-flight to the gauge position. So at the end of path we have very fast neutral flux instead of ionized plasma jet. Estimated recombination time and path (for plasma temperature 1 eV, velocity 50 - 100 km / s and density 10^{22} m $^{-3}$) are 20 - 40 μs and 0.5 - 1 m accordingly. It means that the plasma flow transforms into neutral particle flow on distance of ~1 m.

Several important experiments were also done with plasma gun on Globus-M. First set of experiments was done with optimized first (gas producing) stage of the gun. The measurements of neutral gas stream velocity produced by the first stage showed the velocities 6-20 km/s. Fig.14 demonstrates time traces of line integrated density in Globus-M during supersonic gas stream injection.

Rather effective penetration of the neutral gas stream into toroidal magnetic field up to 0.4 T is demonstrated. The characteristic density rise time was about 1 ms. During injection only tolerable changes of radiation monitored by bolometer and spectrometer were recorded.

Another set of experiments were devoted to plasma break down and current start-up. Unlike experiments described in [1] Globus-M operates in double swing regime of central solenoid. In such a scenario the break down is most difficult due to high value of stray magnetic field at the moment close to maximum of solenoid current. Fig. 15 represents comparison of

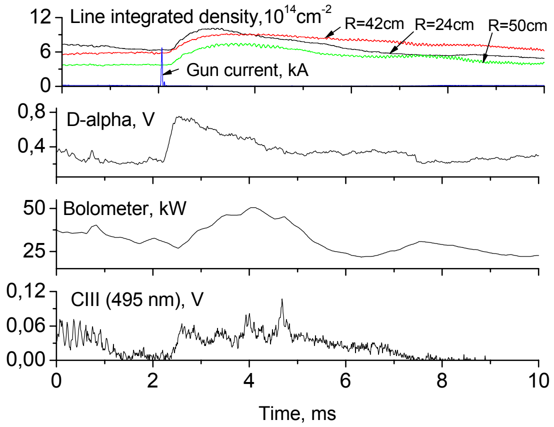

FIG. 14. Evolution of plasma parameters in Globus-M at supersonic gas injection (# 10130).

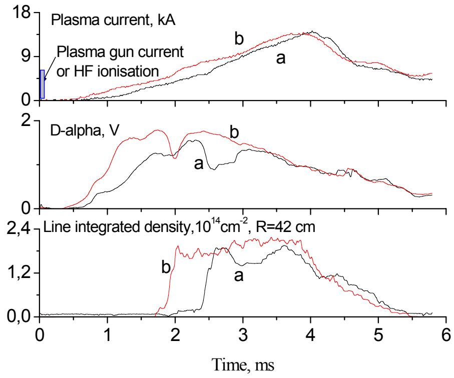

FIG. 15. Plasma discharge initiation; a-with plasma gun (#10167); b-with gas prefil and pre-ionisation (#10165).

conventional break down by means of neutral gas prefilling and ECR preionozation (10 kW magnetron radiation) with plasma gun shot into evacuated vessel (magnetron and gas prefill is off). The loop voltage applied was equal in both shots. One could see only minor difference in plasma behavior.

5. Brief summary

Three main experimental programs are currently under development at Globus-M spherical tokamak. For the last two year period first successful results were obtained in plasma auxiliary heating experiments with NBI. Promising, but requiring confirmation are results obtained in the RF heating of plasma in the fundamental IC range of frequencies. Very interesting, sometimes intriguing are results of plasma gun optimization and utilization. It is possible to develop hybrid scenarios based on different combinations of methods described in the report. The importance of such programs for international fusion community is great in spite of relatively moderate degree of programs developing. Success in Globus-M programs will open prospects for resolving important controlled fusion problems. Among main are fuelling and density control in fusion reactor of any magnetic configuration, creation of cheap, reliable and less disturbing plasma RF heating methods for ST tokamaks, optimization of plasma start-up in tokamaks and stellarators.

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