New Results from the Globus-M Spherical Tokamak

V.K. Gusev 1), V.M. Amoskov 2), A.S. Ananiev 1), E.A. Azizov 3), A.G. Barsukov 4), V.A. Belyakov 2), S.E. Bender 2), I.N. Chugunov 1), A.V. Dech 1), V.V. Dyachenko 1), V.E. Golant 1), M.A. Irzak 1), S.V. Krikunov 1), Yu.A. Kostsov 2), E.A. Kuznetsov 3), V.M. Leonov 4), R.G. Levin 1), S.Yu. Medvedev 5), V.B. Minaev 1), A.B. Mineev 2), O.A. Minyaev 1), E.E. Mukhin 1), A.N. Novokhatskii 1), M.I. Patrov 1), A.A. Petrov 3), V.G. Petrov 3), Yu.V. Petrov 1), K.A. Podushnikova 1), V.V. Rozhdestvenskii 1), N.V. Sakharov 1), O.N. Shcherbinin 1), V.N. Scherbitskii 3), E.I. Terukov 1), G.N. Tilinin 4), S.Yu. Tolstyakov 1), V.I. Vasiliev 2), M.I. Vildjunas 1), N.I. Vinogradov 1), A.V. Voronin 1), V.A. Yagnov 3)

1) A.F. Ioffe Physico-Technical Institute, St. Petersburg, Russia
2) D.V. Efremov Research Institute of Electrophysical Apparatus, St. Petersburg, Russia
3) TRINITI, Troitsk, Moscow Region, Russia
4) Nuclear Fusion Institute, RRC "Kurchatov Institute", Moscow, Russia
5) M.V. Keldysh Institute for Applied Mathematics, Moscow, Russia

e-mail contact of main author: Vasily.Gusev@mail.ioffe.ru

Abstract. New results from the Globus-M spherical tokamak are presented. High plasma current of 0.36 MA, high toroidal magnetic field of 0.55 T and other important plasma characteristics were achieved. Described are the operational space and plasma stability limits in the OH regime. The factors limiting operational space (MHD instabilities, runaway electrons, etc.) are discussed. New experiments on plasma fuelling are described. First results of experiments with a coaxial plasma gun injector are presented. Initial results of a plasma – wall interaction study are outlined. First results obtained with new diagnostic tools installed on the tokamak are presented. An auxiliary heating system test was performed. Preliminary results of simulations and experiments are given.

1. Introduction. Globus-M is the first Russian spherical tokamak (ST), commissioned in 1999 at the A.F. Ioffe Institute, St. Petersburg. Recently the achieved parameters in the OH regime were significantly improved through progress in vacuum technology, power supplies and control system modification. A plasma current value of 0.36 MA was obtained with a central solenoid poloidal flux of 0.23 Wb, both values being about 75% of the design value. The magnetic field strength reached 0.55 T (90%). The progress in plasma current amplitude and duration increase since 1999 is shown in Fig.1. The plasma current ramp-up rate reached 17 MA/s. The value of the Ejima-Wesley coefficient was $C_{E\text{-}W} \approx 0.66$ in discharges with optimized parameters. The parameters achieved in the last two years in the OH regime are adequate for transition to auxiliary heating and beta limit study. The properties of OH plasmas, with emphasis on operational limits and experimental tools for plasma performance increase, are described below in detail.

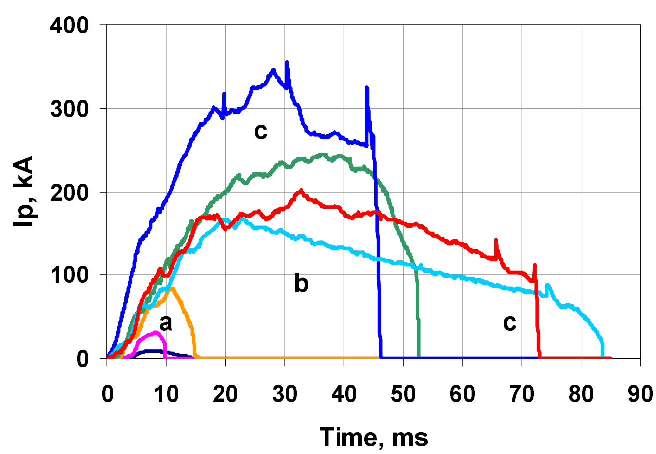

FIG.1. Plasma current evolution in the OH regime due to progress in vacuum conditioning and power supply technology. (a) capacitor batteries, (b) thyristor rectifiers in single swing and (c) in double swing regime.

2. Operational space and stability limits. The operational space of Globus-M in the OH regime is presented in Fig.2. There are three well-known borders limiting the operational space: the low q, low density (runaways) and high density (Greenwald) borders. The two density borders are shown in the figure as straight lines. The high density limit behavior in the OH regime looks similar to that of other STs, e.g. START [1]. In the experiments with plasma fuelling by gas puff from the low field side, it was possible to come close to the Greenwald limit ($n/n_{Gr} \approx 0.8$) at lower plasma current and at the current ramp-down phase. Further density increase was limited, presumably, by resistive, low n MHD modes. However, due to the higher magnetic field in Globus-M, the absolute value of achieved average density was high enough, $(7–8)\cdot 10^{19}$ m^{-3}. The low density border of operational space is defined by runaway behavior. The behavior of runaways in STs differs from conventional tokamaks due to strong toroidal electric field variation across the plasma column ($E_{//}$~$1/R$) and higher values of $E_{//}$. It is described in [2]. The main features of runaway behavior in Globus-M are as follows: (i) plasma current carried by runaways at low densities is not significant, $I_{run}/I_{Pl} \approx 10–15\%$, (ii) the spatial distribution of runaway production rate and runaway beam shape is hollow, with the maximum shifted to the periphery. This feature broadens the operational space beyond the runaway border, and limits the maximum energy of runaways (< 5 MeV) and their lifetime (< 5 ms). Also, runaway generation during a major disruption is not recorded, in spite of the rather high parallel electric field induced during the disruption, $E_{//} \geq 15$ V/m. Plasma current amplitude was limited by the lowest safety factor ($q_{cyl} \leq 0.9$, $q_{95} = 2$) that could be achieved in toroidal field ramp-down experiments. The increase of plasma stability to kink (n=1,2,3) and ballooning modes is explained by broadening of the plasma pressure profile in the configuration with $q(0) > 1$ [3]. Fig.3 represents the plasma parameter behavior in the toroidal field ramp-down experiment, during which the toroidal beta $\beta_T \approx 10\%$ was achieved.

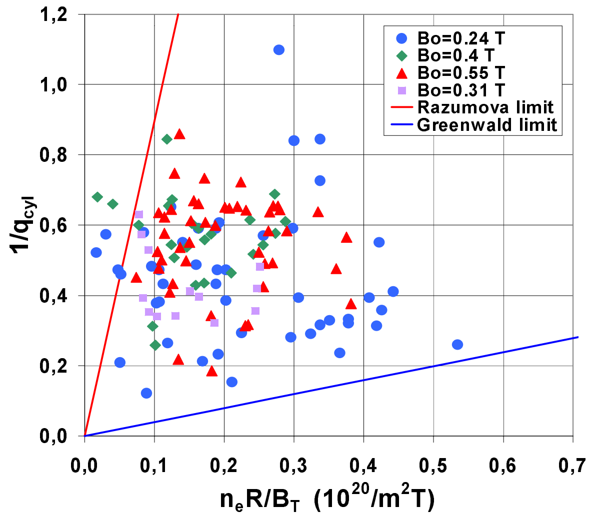

FIG.2. Operational space (Hugill diagram) of OH regime in Globus-M.

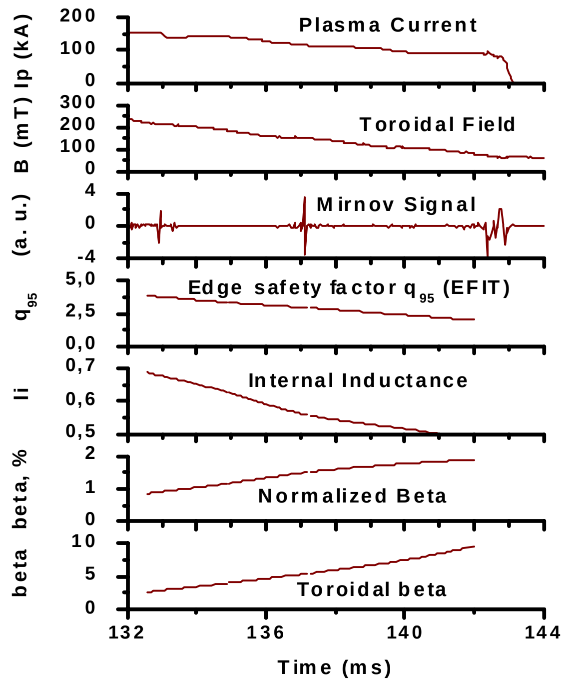

FIG.3. Time evolution of safety factor, normalized and toroidal β during toroidal field ramp-dawn experiment.

3. Plasma fuelling experiments. First experiments on plasma fuelling with a novel fuelling source were performed. The method is directed injection of plasma jet into the tokamak. To penetrate deep into the magnetic field, the plasma jet has to have high plasma density and high directed velocity. This means that the particle collision frequency in the jet plasma must be higher than the cyclotron frequency. Also, the specific kinetic energy must be high as compared with the magnetic field pressure. For the experiments in Globus-M ($B_T \approx 0.4$ T), the density of the injected plasma must be higher than 10^{21} m^{-3} and a velocity of ~70 km/s must be achieved.

A double stage source (plasma gun) [4] was used in the experiment. The source generates a jet of plasma with density exceeding 10^{22} m^{-3} with a total number of charged particles in the range of 10^{18}–10^{19}. The pulse duration is 0.04 ms and the ionization efficiency reaches 90%. The jet velocity of the hydrogen plasma varied between 10 and 40 km/s. Although this was lower than necessary for penetration, the experimental results showed a significant difference from conventional fuelling methods. Fig.4 demonstrates plasma initiation with the help of the injector. Instead of the gas puff used in the conventional scenario (also shown in Fig.4), a plasma jet was injected into the empty vacuum vessel shortly before inductive voltage was applied. One can see that the plasma

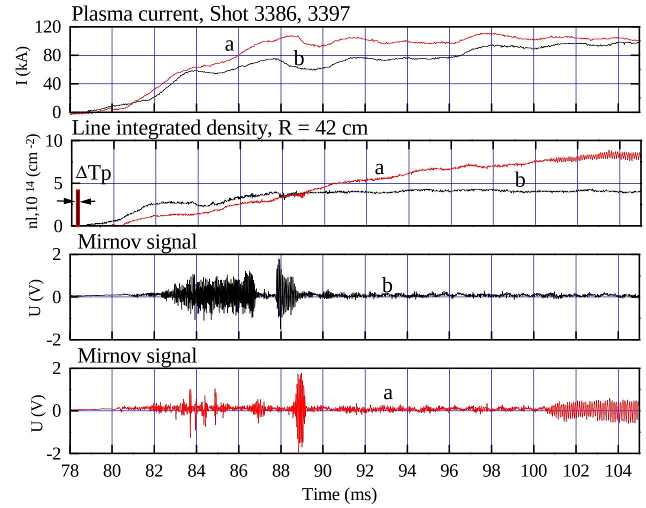

FIG.4. Inductive plasma initiation with different fuelling methods: a - with plasma injection (ΔT_p - time of the plasma gun shot), b - with gas puffing prefill.

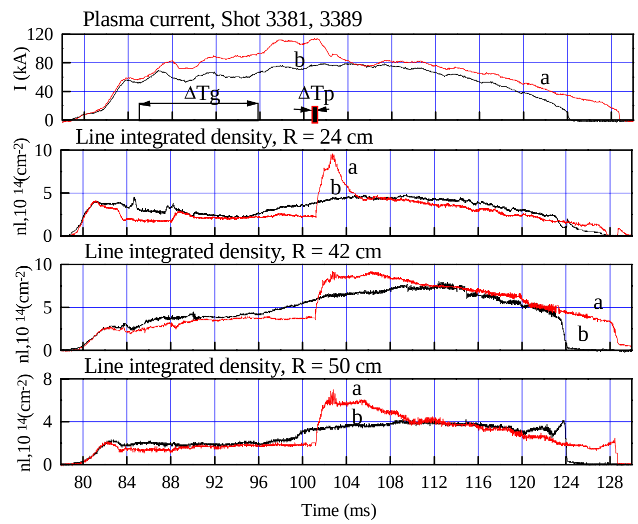

FIG.5. Comparison of the plasma injection (a) to the gas puff (b) fuelling methods. ΔT_g - gas puff interval, ΔT_p - plasma gun shot.

FIG.6. Penetration of the plasma jet with 40 km/s speed into toroidal magnetic fields of different strength (from left to right $B_T(0)$ = 0 T, 0.05 T, 0.12 T, 0.25 T).

current ramps up faster and to a higher value at the same loop voltage (same magnetic flux consumption). It is also seen that magnetic turbulence during current ramp-up is lower in the case of injection. Fig.5 shows plasma density waveforms during gas-puff fuelling and plasma jet injection into an OH discharge. It is seen that density increases in ~0.5 ms after injection compared to ~10 ms during gas puff. Fig.6 shows video frames of plasma jet injection into the empty vessel of Globus-M with only toroidal magnetic field applied. One can see the deeper penetration of plasma jet with equal velocities into the lower toroidal field. The effect of plasma jet current interaction with a nonhomogeneous magnetic field (the plasma beam is pushed to the lower B_T region) is also seen in the photos.

4. Plasma – wall interaction study. Experiments are aimed to optimize the choice of material for the in-vessel protection plates (carbon or tungsten) and increase the effectiveness of the boronization technology. For this purpose, the investigation of the fundamental properties of films deposited onto vessel walls during boronization and study of in-vessel material redeposition has started. First results are presented in [5]. It was found that an amorphous film structure is created after boronization. It contains boron, carbon and hydrogen. The hydrogen content goes down with baking. The physical properties of the film are like those of semiconductors. The next analysis will be done after a few hundred plasma shots. Essential changes of the initial film structure are expected. Preliminary data (need to be confirmed) showed the creation of a diamond-like film at the surface of silicon probes placed in the X-point region.

5. Plasma diagnostics development. New diagnostic systems have been installed, including a poloidal array of Mirnov coils (28 units); four channel pyroelectric bolometer for radiation loss recording; time of flight (radar) reflectometer for edge density profile recording in the range of 4.5×10^{18} – 4.5×10^{19} m^{-3}. A paper on new diagnostic tools is under preparation. Fig.7 shows the density profile variation recorded by radar reflectometer during injection of a plasma jet. One can see a dramatic change in peripherial density behavior following the injection pulse. The density gradient recorded by the device increased ~3.5–4 times during 1 ms. The Thomson scattering system is under final assembly. A laser pulse train from the probing laser output is shown in Fig.8.

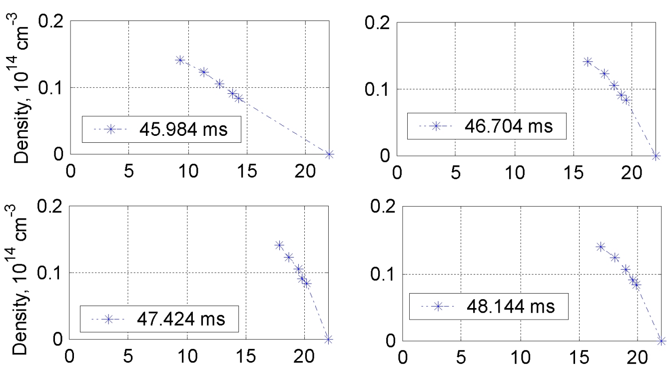

FIG.7. Density profile variation in shot # 3567 recorded by radar reflectometer during injection of plasma jet at 46.2 ms.

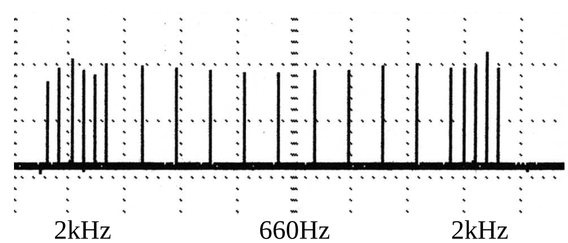

FIG.8. Thomson scattering probing laser pulse train of 20 pulses with variable repetition rate. Average output energy ~4 J/pulse.

6. Auxiliary plasma heating. One of the RF plasma heating scenarios of Globus-M is non-resonant transit time magnetic pumping (TTMP) absorption of a fast magnetosonic wave at $\omega/\omega_{ci} \approx 8$-10 (HHFW heating). To simulate the propagation and absorption of the plasma waves in the higher ion cyclotron harmonic frequency range in STs, a full-wave electromagnetic code is under development. A simulation model is described in [6]. As a result of simulations, the RF field distribution in the plasma volume and RF power absorption can be computed. Fig.9 represents the absorbed RF power density averaged on each magnetic surface for the Globus-M conditions.

First antenna-plasma matching experiments were performed in Globus-M utilizing a set of equipment developed for the RF heating program. It consists of an RF generator of ion cyclotron frequency range, 7–40 MHz, with ultimate power up to 1.5 MW. Pulse duration is up to 100 ms. The single strip antenna is supplied with a Faraday screen, protected by boron nitride and installed into the vacuum vessel. In the first experiments, input RF power through one antenna will not exceed 500 kW. Two stubs produce antenna matching with the plasma and the generator mechanically step by step. The results of one of the first, low power (50 kW) shots are shown in Fig.10.

Assembly of the NB injector for the energy of 25–35 keV and 1.5 MW power has been completed. Numerical simulations of neutral beam absorption by the Globus-M plasma were performed. The first beam of deuterium neutrals with power level of ~0.25 MW was obtained.

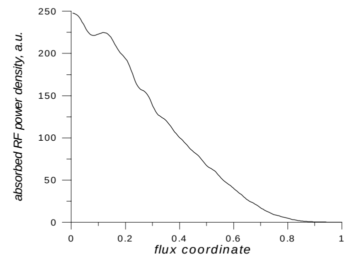

FIG.9. Absorbed RF power density averaged on each magnetic surfaces for B_T=0.56 T, I_P=0.3 MA, $n_e(0)=10^{20}$ m^{-3}, $T_e(0)$=0.5 keV, k=1.8, δ=0.16, f=30 MHz.

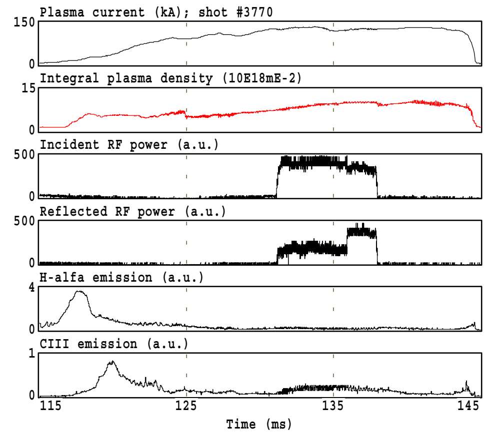

FIG.10. Evolution of plasma parameters during the antenna-plasma matching experiment. $B_T(0)$=0.4 T, f=24 MHz, P_{RF}=50 kW.

7. Conclusions. The Globus-M ST could stably operate in a wide range of densities and safety factor values. The plasma created during an ohmic heating discharge has all the necessary features for the target plasma to be used in auxiliary heating, high beta experiments. A possible way to increase OH plasma performance is connected with development of plasma fuelling methods and deeper investigation of plasma-wall interaction processes. The first results on plasma fuelling showed the necessity to increase plasma jet velocity to 70–120 km/s and the number of particles to 10^{20}, which will be done soon. Unlike the compact toroid injection method, plasma jet does not contain noticeable impurities, which results in lower plasma impurity flux. New diagnostic tools have been commissioned and first data are encouraging. Auxiliary heating experiments have begun.
The work is supported by the Ministry of Industry, Science and Technology and the Ministry of Atomic Energy of the Russian Federation, as well as by RFBR grants 00-02-16934, 01-02-17882, 01-02-17924 and 02-02-17693.

[1] A. Sykes, Tech. Physics, **44** (1999) 1047.

[2] V.K. Gusev, et al., Proc. of 29th EPS Conf. on Plasma Phys. and Contr. Fusion, Montreux, P4.104 (2002).

[3] V.K. Gusev, et al., Proc. of 28th EPS Conf. on Contr. Fusion and Plasma Phys., Funchal, ECA, vol.25A (2001) 1317.

[4] A.V. Voronin, K.G. Hellblom, Plasma Phys. and Contr. Fusion, **43** (2001) 1583.

[5] N.V. Sakharov, et al., Proc. of 29th EPS Conf. on Plasma Phys. and Contr. Fusion, Montreux, P5.078 (2002).

[6] V.K. Gusev, et al., Proc. of 2nd IAEA-TCM on Spherical Tori and 17th Int. Spherical Torus Workshop, São José dos Campos, SP, Brazil (2001).