

Overview of Results and Program Development in Globus-M Spherical Tokamak

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Globus-M is new Russian spherical tokamak built at the A.F. Ioffe Physico-Technical Institute in 1999. Technical characteristics and design details of the machine could be found in [1]. The principal machine mission is to investigate fundamental properties of low aspect ratio plasmas in the regimes with high toroidal beta and develop methods of auxiliary heating and current drive for spherical tokamaks.

The device is fed with the main power supplies (thyristor rectifiers) connected to national AC grid. During the last experimental campaign group of 5 thyristor rectifiers together with 2 fast current invertors was used to sustain currents in TF and PF coils. Main thyristor rectifiers are commissioned currently to half power limit, which is about 50 MW from 125 MW of total design value.

Overview of results in OH regime

Experimental study of ohmic heating (OH) regime was performed during 2000 –2001 experimental campaigns. Plasma current amplitude was limited by the power supplies capabilities and scheme of central solenoid (CS) feeding. Poloidal flux available from CS at single swing regime did not exceed 120 mWb. The highest value of plasma current achieved in the experiments was $I_p \leq 250$ kA, with the current ramp-up rate, $dI_p/dt \leq 13$ MA/s. Such current value corresponds to the Ejima – Wesley coefficient $C_{E-W} \approx 0.66$ (where $C_{E-W} = \Psi_S/\mu_0 I_p R$, with Ψ_S – poloidal flux change during current ramp-up, R – major plasma radius). The value of Ejima – Westley coefficient, which is the measure of magnetic flux consumption efficiency during plasma current ramp-up, is strongly dependent on the vacuum vessel conditioning, stray field compensation and discharge breakdown optimization, which are described in [2]. Significant flux consumption efficiency increase was recorded after vacuum vessel boronization. Another effect of boronization was in establishing of plasma density control. Plasma density is completely controlled with external gas puff. After the gas puff was off during the discharge plasma density exponentially decayed to the background level with the characteristic decay time of several milliseconds. Background plasma density became very low without external gas puffing ($n < 2 \times 10^{18} \text{ m}^{-3}$). Density limits achieved in OH regime of the Globus - M tokamak looks rather similar to those obtained in the START tokamak for the pure OH regime [3]. The existing Globus-M database is not enough to perform comprehensive analysis - it consists of 2700 shots totally. Preliminary results are: Greenwald limit is not overcome or achieved. Better results are obtained at lower currents, or at the phase of current damping phase ($\bar{n}_e n_{Green} > 0.6$). High density limit is easy to achieve at high q_{edge} values. During intensive gas puff at the current ramp-up phase the density rise usually accompanied by strong MHD activity which saturates the current rise and limit density at the level of $\bar{n}_e n_{Green} \approx 0.45$. The highest average density achieved so far in the OH experiments is $(3.5-4.0) \times 10^{19} \text{ m}^{-3}$. Fig.1a represents the achieved density limits in OH regime as the function

of plasma current density.

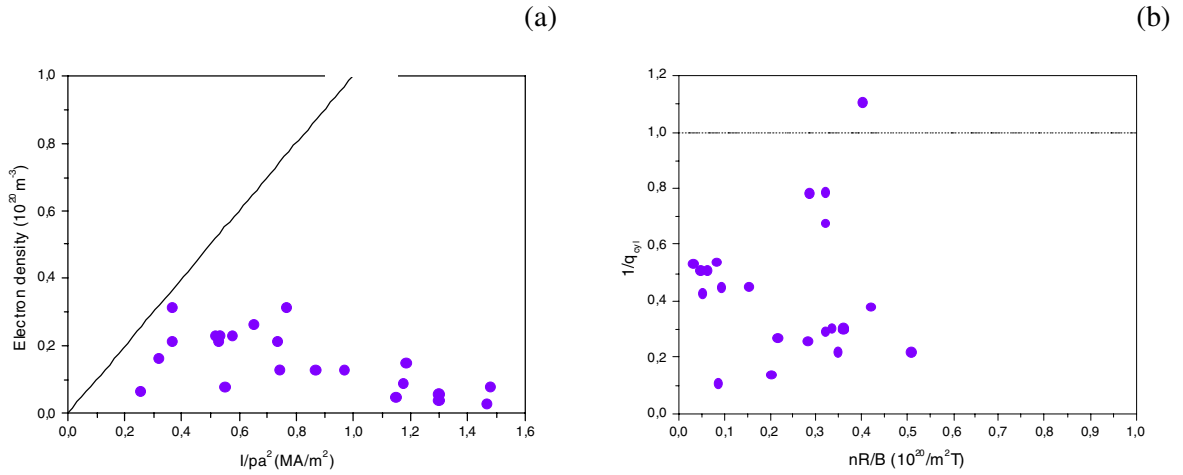


Fig. 1 Average electron density versus current density dependence (a) and Hugil diagram (b).

To investigate operational limits of OH regime the experiments were performed in wide range of toroidal magnetic fields, $0.08 \text{ T} < B_T < 0.35 \text{ T}$. In the experiments with ramping down of B_T from the initial value of 0.3 T ($R=0.35 \text{ m}$) the MHD stability limit was studied. Another purpose of this experiment was the achievement of highest possible OH beta regime. The toroidal field was ramped down to 0.08 T with the constant rate of $\sim 16.8 \text{ T/s}$. The increase of current amplitude, or current ramp up rate, after B_T ramp down was switched on, were recorded in all discharges. This effect is the signature of internal inductance decrease due to expanding of the current channel. The details of the experiment are published in [4]. The experimental traces of the discharge #2370 with TF ramp down are shown in Fig.2.

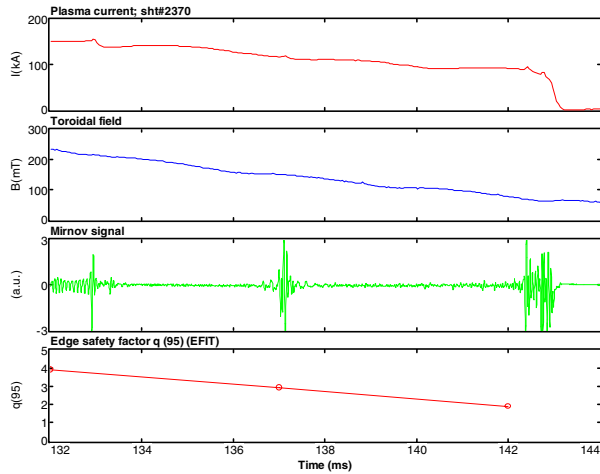


Fig. 2 Temporal evolution of discharge #2370 parameters with TF ramp down. Record low $q_{95} \sim 2.1$ achieved at 141-142 ms.

$\beta_T = 2\mu_0 \langle p \rangle / B_T^2$ (where $\langle p \rangle$ is volume averaged plasma pressure, B_T is vacuum magnetic field at plasma column axis). The experimental input data plasma parameters (I_P^{exp} , U_{loop}^{exp} , nI^{exp} , $Z_{eff}=1.5-1.9$) and plasma column geometry reconstructed by EFIT were used. The best fit of simulated U_{loop} to the experimental one was achieved when Lackner-Gottardi scaling for energy confinement time was taken. The flat current density profile, $I^*(\Psi) = dJ/dS = (1-\Psi^\delta)^2$ and flat $p(\Psi)$ and $q(\Psi)$ profiles were used in stability analysis with KINX code. Here Ψ is normalized poloidal flux. The results of the #2370 shot analysis for plasma configuration at 137 ms showed that the equilibrium is stable against localized ballooning and external kink

Successive bursts of MHD signal picked up by Mirnov coils are recorded at the moments when rational surfaces $m/n = 4, 3, 2$ are moving through the plasma column boarder, during TF ramp down. The EFIT code was used for the reconstruction of plasma magnetic configuration. EFIT data confirms that q_{edge} values about 4, 3 and 2 are reached shortly before MHD bursts recorded. Plasma current termination due to loss of global column stability is connected with $m/n = 2$ kink mode development. In the absence of kinetic data on stored plasma energy 0-D transport code SCENTO [5] was used for the power balance analysis to evaluate behavior of

modes ($n=1,2,3$), if $q(0) > 1$; the peeling mode stability criterion is also satisfied. 0-D simulations gave the value of toroidal beta for 142 ms about 12.5%. During the experiment the magnetic field pressure decreased one order of magnitude, permitting the toroidal beta to increase significantly. Stability analysis showed that theoretical beta limit could be even higher than predicted by 0-D simulations for flat current density distribution and $q(0) > 1$.

It's worth noting that in the TF ramp down experiment plasma column with almost 100 kA of plasma current is still globally stable in weak toroidal field of ~ 800 Gs. The corresponding value of q_{cyl} (ITER definition) is below 0.9. Globus-M operational space in I/q_{cyl} and normalized density units is shown on Hugil diagram, Fig.1b. The normalized plasma current, $I_N = I_p/aB_T \approx 5$ (where a is the minor plasma radius) was reached.

Runaway electrons behavior was studied in the OH experiments. Usually in STs the value of inductively driven toroidal electric field at the discharge start-up is high. In Globus-M it's in the range of $E_{Tor}(R=0.16m) \approx 4-6$ V/m, depending on the required current ramp-up speed. Experiments do not show significant runaway production, in spite of high ratio of electric field to Dreicer one (see Fig.3). It demonstrates the temporal behavior of main

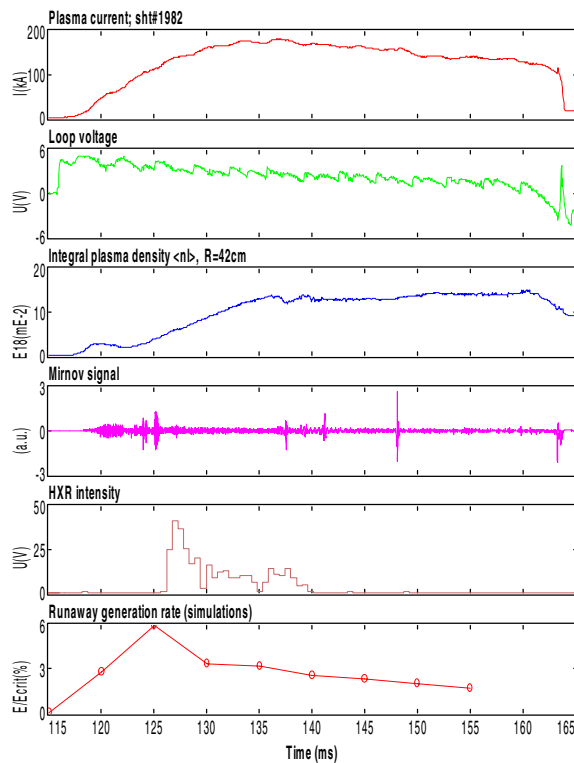


Fig. 3 Behavior of runaway electrons and other plasma parameters in the discharge #1982. No runaways are recorded at the current quench time.

plasma parameters together with radiation, picked up with HXR spectrometer. Also $E/E_{Dreicer}$ value temporal variation is shown. Experimentally observed production rate of runaways is small, when $E/E_{Dreicer} < 3\%$. According to experiments and simulations the beam current does not exceeded 10-15% value of total plasma current. When the density increases the beam is dissipated, usually by MHD event. Well pronounced loop voltage inductive spike at the disruption stage (Fig.3) is observed. Corresponding value of the electric field is quit high, $E_{Tor}(R=0.11m) \approx 7-10$ V/m. In spite of this in Globus-M the runaway production at the disruption stage was never observed. This may be caused by short duration of inductive voltage spike (typical duration is fractions of millisecond), which is less than acceleration time, or other reasons mentioned in [4]. Important issue also is the energy limit of runaways. According to [6] the most probable limiting factors for conditions of Globus-M are "orbit shift limit" and "toroidal field ripple limit", both giving approximately the same limits of runaways energy,

$E_{run} \approx 2.2$ MeV, which coincide with the measurements of maximum gamma photons energy.

Program development

Full power supply commissioning with the following increase of plasma current amplitude and pulse duration is planned for the fall 2001. The end of the year will be devoted to the optimization of ohmic heating regime and creation of target plasma for the high beta experiments. More details are in the report by N. Sakharov (this conference).

To reach collisionless regimes with high toroidal beta two auxiliary heating systems are under construction now. Systems commissioning is planned for the end of 2001, beginning of 2002.

First system comprises RF generator (ion cyclotron range of frequencies), transmission lines, coupling elements and antennae, which could be tuned to the frequency range of 6-50 MHz. Generator consists of oscillator tunable in the same frequency range and transmitter with power 1.5 MW. The system is manufactured and under test now. Heating scenarios are dependent on chosen frequency range and based on fast magnetosonic waves – plasma interaction in two distinct cases. One is hydrogen minority heating scenario in deuterium plasmas at the ion cyclotron fundamental frequency (6-15 MHz, depending on magnetic field strength). The other one is high harmonic fast wave heating (HHFW) scenario. For the second one the higher frequency range will be used (30-50 MHz). Preliminary 1-D simulations performed in quasitoroidal geometry showed high efficiency of single pass absorption in both cases with energy input into ion and electron plasma components respectively [1]. Now 2-D simulation code is under development to evaluate full 3-D picture of waves propagation and absorption. The preliminary results on electric field distribution and absorption region location in poloidal cross-section of Globus - M tokamak for single toroidal mode excited is shown in Fig.4.

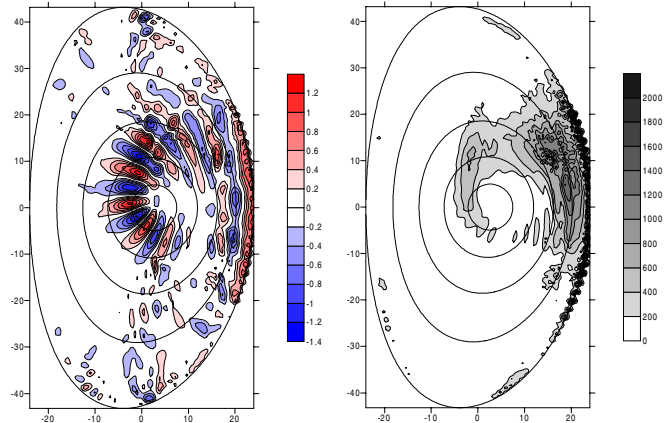


Fig. 4 *Electric field distribution (left) and absorption region location (right) in Globus - M tokamak for single toroidal mode, $N_z=22$.*

Second system is neutral beam injector (NBI). NBI is capable of acceleration hydrogen, (H) or deuterium, (D) species up to the energies of 35 keV, with output power about 1MW. The injector parts are constructed and under test now, power supplies are assembled. Preliminary simulations of the beam absorption, based on transport code ASTRA were performed. Simulations showed that: (i) beam shine through losses are low for the density range higher $2-3 \times 10^{19} \text{ m}^{-3}$, (ii) D beam injection into H plasmas increased power absorbed by ions, (iii) variation of atomic species (H – D) of the injected beam and their energy could alter the power deposition from one plasma component (e.g. electrons) to another. Fine physical experiments using flexibility of NBI scenario could be useful for studies of fundamental properties of low aspect ratio plasmas.

Other auxiliary heating and current drive (CD) systems are planned for Globus-M. Lower hybrid CD system, based on 2.45 MHz klystron with the power level 0.3-0.5 MW is under design now. EBW system simulations started recently.

At the end of the year significant increase of diagnostic equipment planned (more details in the report by Yu. Petrov, this conference).

Acknowledgement

Financial support of the work provided by RF Minatom, Ministry of Industry, Science and Technology, RFBR grants # 000216934, 010217882, 010217924 and IAEA grant.

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