

Plasma Formation and First OH Experiments in the Globus-M Tokamak

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Abstract. The paper reports results of experimental campaigns on plasma ohmic heating, performed during 1999-2000 on the spherical tokamak Globus-M. Later experimental results with tokamak fed by thyristor rectifiers are presented in detail. The toroidal magnetic field and plasma pulse duration in these experiments were significantly increased. The method of stray magnetic field compensation is described. The technology of vacuum vessel conditioning, including boronization of the vessel performed at the end of the experiments, is briefly discussed. Also discussed is the influence of ECR preionization on the breakdown conditions. Experimental data on plasma column formation and current ramp-up in different regimes of operation with the magnetic flux of the central solenoid (CS) limited to ~ 100 mV·s are presented. Ramp-up of the plasma current of 0.25 MA for the time interval ~ 0.03 s with about 0.02 s flat-top at the toroidal field (TF) strength of 0.35 T allows the conclusion that power supplies, control system and wall conditioning work well. The same conclusion can be drawn from observation of plasma density behavior – the density is completely controlled with external gas puff and the influence of the wall is negligible after boronization. The magnetic flux consumption efficiency is discussed. The results of magnetic equilibrium simulations are presented and compared with experiment.

1. Introduction

Globus-M is the first Russian spherical tokamak (ST), built at A.F. Ioffe Physico-Technical Institute in March 1999. The design description, operational principles and experimental program are described in [1,2]. The discharge in Globus-M starts, as usual, with an inductive voltage pulse applied to the secondary winding – a gas column of low pressure hydrogen prefills the vacuum vessel. The loop voltage must be sufficient both for breakdown and current ramp-up with required speed. Unfavorable factors influencing the initial discharge phase in Globus-M and other STs are: (i) the volt second capability of the CS limited by the lack of space, (ii) a low toroidal field and increased value of stray magnetic fields, created by machine parts closely placed to the inner plasma boundary and induced currents in the vacuum vessel. Also, it is impossible to use an iron core for magnetic induction increase in STs and high current air transformers (CS) wound from fat conductors are used – increasing stray magnetic fields in the closely adjacent plasma region. Favorable factors are low toroidal loop length ($\sim R$) which leads to higher inductive electric fields values and high toroidicity, increasing both toroidal magnetic and inductive electric fields towards the inner plasma border, $B_T, E \sim 1/R$. Townsend avalanche theory and inductive breakdown in conventional tokamaks are well described in the literature and a comprehensive review exists [3]. It is difficult to create an extended poloidal zero region in STs with residual field levels of a few mT. The effective radius a_{eff} of such a region is smaller in STs, which leads to the decrease of the connection length $L_{\text{eff}} \approx 0.25 \cdot a_{\text{eff}} \cdot B_T/B_S$, where B_S is the poloidal stray magnetic field

strength. The decrease of L_{eff} requires the increase of the inductive electric field, so STs usually operate at higher values of electric field. Another important issue of plasma formation in STs is current ramp-up. A low value of plasma inductance (smaller R) allows plasma current to be increased at a high rate. START demonstrated a ramp-up speed up to 50 MA/s [4] with an induction-compression method. This is possible in STs due to higher plasma stability to MHD perturbations. The plasma current ramp-up with optimally high speed is favorable for faster density increase and saving of resistive poloidal flux. Vacuum vessel wall conditioning is of great importance, especially for Globus-M, which has a close fitting vacuum vessel. The influx of hydrogen and impurities from the wall interacting with the plasma lowers conductivity, increases Z_{eff} and could prevent high current achievement, or even saturate the discharge at the impurity burnthrough phase. We hope that experimental data from this report will contribute to the ST database and will be helpful for scientists working in this new area of fusion research.

2. Preparation of experiments

The basic principles of machine preparation for the experiments are described in [5]. The principal difference in the 2000 experimental campaign preparation was the commissioning of the main power supplies, which permits a significant increase in toroidal field, plasma current and pulse duration. Now 5 of the 8 of thyristor rectifiers are commissioned. This allows 7 pairs of 9 poloidal field coils to be fed simultaneously with the TF coil and the CS. Another significant event was the commissioning of the plasma position control system. The executive modules of R and Z control systems are fast current invertors operating at 2 kHz frequency and currents of ± 1.6 kA. Significant changes in vacuum vessel conditioning were made. In addition to He glow discharge, Ar glow discharge was used. Finally two cycles of vessel boronization were carried out with the technology described in [5]. Additional experimental equipment was constructed: a mass-spectrometer for residual gas analysis, a pulsed vacuum-meter, and a third microwave interferometer channel were added. A new large aperture vacuum glass port of 380 mm diameter was installed which significantly improves the view angle of the video camera. Two SXR detectors equipped with Be foils of different thickness (100, 300 μm) were installed. An HXR monitor was put into operation.

3. Experimental results

Figure 1 shows a video frame of the breakdown with an applied loop voltage of 4.5 V (without ECR assistance) and a simulated map of stray poloidal magnetic fields, $|B_p|$, at the moment corresponding to plasma breakdown. The discharge starts from the inner wall, where B_T and E are maximum. Simulations show that the corresponding L_{eff} providing development of a Townsend avalanche with an applied electric field is about 50 m, which correlates with $|B_p| \sim 0.01$ T at the border of the poloidal “zero” region. Application of an ECR RF pulse with 15 GHz frequency and 0.5 ms duration (power is about 10 kW) significantly reduces the breakdown voltage as in the experiments described in [5]. Interferometric data also confirm that the discharge starts from the inner plasma region. During the experimental campaign of summer 2000 the following plasma parameters were achieved: $B_T = 0.35$ T, $I_p = 80\text{--}180$ kA, $\langle n \rangle \sim 5 \cdot 10^{18}$ m^{-3} , pulse duration 40 ms, limited flat-top duration, current ramp-up speed ~ 5 MA/s. Most of the interesting results were obtained in the last experimental campaign (September 2000). Two discharges with equal loop voltage and plasma density, #1877 before boronization and #1901 after the first boronization of the vessel walls, were compared (see Fig. 2). The current ramp-up speed in discharge #1901 is about 10 MA/s and it has a longer flat-top. The magnetic flux consumption for the current ramp-up is about 85 mWb, including

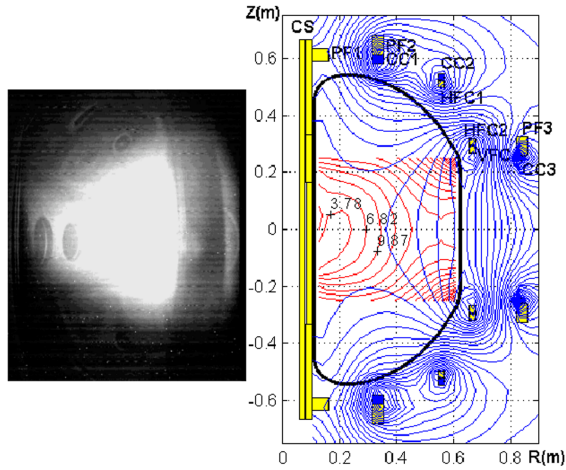


FIG. 1. Video frame of plasma breakdown (left). Magnetic flux (blue) and $|B|$ poloidal plot (red) in the phase of plasma breakdown (right).

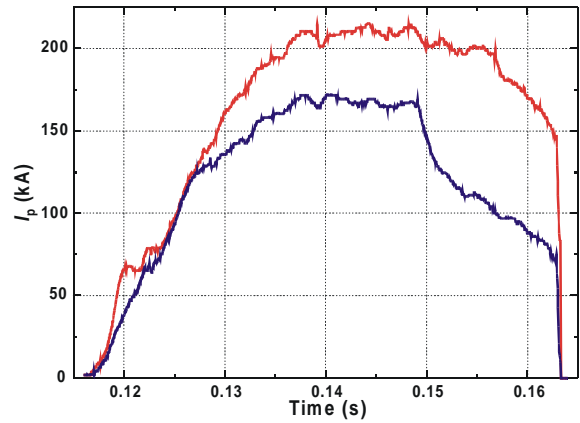


FIG. 2. Time evolution of plasma current before (lower trace, shot 1877) and after (upper trace, shot 1901) boronization.

breakdown losses (~ 5 mWb), which is significantly better than before boronization. The saved magnetic flux could be used either for-flat top creation or for current amplitude increase. One could bear in mind that all experiments were performed with single swing CS regime operation, which allows the use of no more than 110 mWb of flux. Even better results were obtained after the second boronization. The record value of plasma current of 0.25 MA was achieved in discharges #1985 and #1997. This is close to the practical capability of the CS. Figure 3 shows the trace of 0.25 MA current, shot #1997. Remarkable is the fact that the discharge lasts with very low loop voltage ~ 1 V. Plasma density control is also changed significantly after boronization. Figure 4 shows the traces of line averaged density in shot #1919. The density increase during the discharge is due to the gas puff. After the gas puff is turned off the density decays to the background level with the time constant ~ 8 – 9 ms. This indicates a dramatic decrease of the neutral gas and impurity wall influxes. With the help of constant gas puffing a permanent density increase during the pulse was achieved. An example of permanent density increase is shown in Fig. 5. It is worth noting that line averaged density on the peripheral chords (24 and 50 cm), which corresponds to $-a/2$ and $+a/3.5$ chord positions with respect to the center of the vacuum vessel, is also rather high. This may be a feature of a relatively “broad” density profile. The average density could be as high as $3 \cdot 10^{19} \text{ m}^{-3}$ in such types of shots. The feedback stabilization provides position control of the column within 1 cm, which is also confirmed by video camera.

4. Discussion and Summary

During 1999 the first experimental data were taken. The low capabilities of the provisional power supplies did not permit high values of plasma parameters to be achieved. One of the important results was the development of the method of stray field compensation. The method, which is based on a 2-D dynamic numerical model of poloidal field simulation, takes real waveforms of coil currents and vessel induced currents account. The model was accurately calibrated in the experiment with the help of a 2-D coordinate magnetic probe array, measuring B_r and B_z poloidal field components. The simulated current distributions in CC1–CC3 and PF3 coils provide the necessary conditions for poloidal “zero” region creation. The lines of equal magnetic flux from the energized coils are also shown in Fig. 1. Adequate stray field compensation simplifies breakdown conditions to provide reliable breakdown in the hydrogen pressure range $3 \cdot 10^{-5}$ – $6 \cdot 10^{-5}$ torr. The loop voltage of about 4.5 V is sufficient

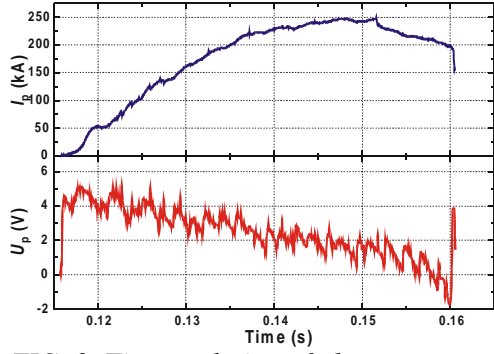


FIG. 3. Time evolution of plasma current and plasma voltage in shot 1997.

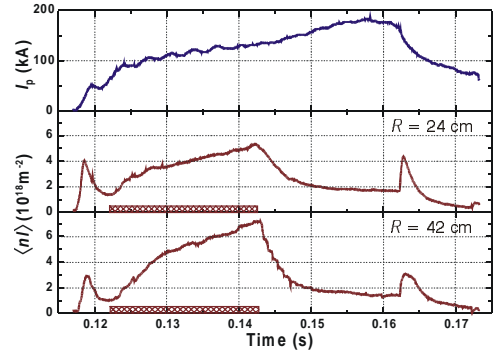


FIG. 4. Evolution of plasma line averaged density measured along vertical chords ($R=24\text{cm}$, $R=42\text{cm}$) in shot 1919. The gas puff pulse is shown by the hatched rectangles.

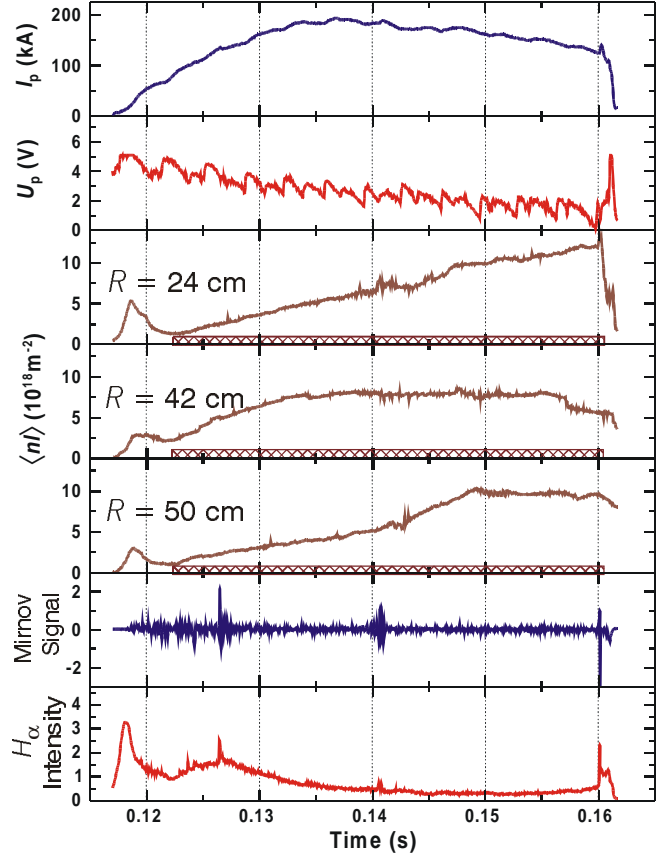


FIG. 5. Evolution of plasma parameters in shot 1945 with permanent density increase. The gas puff pulse is shown by hatched rectangles.

for inductive breakdown assisted only by a mercury lamp. With ECR RF preionization it decreases to 1–2 V and applied loop voltage amplitude is defined by current ramp-up requirements. Vacuum vessel conditioning during a long period of He glow discharge with successive boronization significantly improved the wall conditions, minimizing wall fluxes of neutral hydrogen and impurities. This led to some important consequences. First, the magnetic flux consumption necessary for plasma current formation was decreased. This made it possible either to increase current amplitude or to extend the current flat-top. It was proved that magnetic flux consumption could be effective in an ST with a close fitting vessel. The corresponding Ejima-Westley coefficient, defining full magnetic flux consumption during current ramp-up, $\Psi_S = C_{E-W} \cdot \mu_0 \cdot I_p \cdot R$, is about 0.8. This value is significantly lower than in conventional tokamaks and is close to the values referred to in [4] for STs. This helps to achieve 0.25 MA plasma current amplitude with limited voltsecond capability ~ 110 mWb of CS. Figure 6 illustrates the plasma column shape taken by video camera and those obtained from magnetic simulations. Double X-point plasma column ($A = 1.55$, $k \approx 1.5$, triangularity $\delta \approx 0.3$) with $q_{95} \approx 5.5$ was recorded. Remarkable is the fact that the separatrix touches the vessel at the same position in simulations and experiment. Second, the significant improvement of density control made it possible to achieve shots with permanent density increase, with minimum contributions from the wall fluxes. Third, the reproducibility of plasma current waveforms was achieved within ~ 10 – 12% accuracy for the same loop voltage applied. Figure 7 illustrates the reproducibility of plasma current waveforms in the succession of shots ##1957–1968 without current feedback stabilization (the position feedback control is on). The results of experiments discussed in this paper make realistic the achievement of the

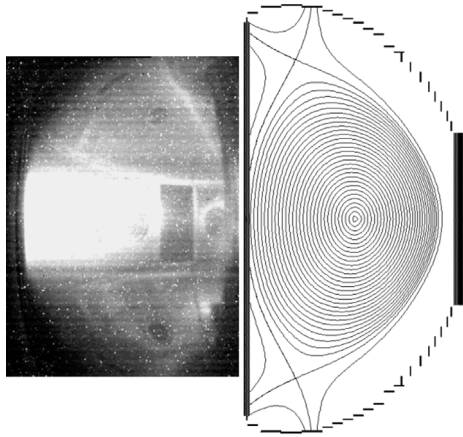


FIG. 6. Poloidal magnetic flux plot (right) simulated for the plasma column recorded by the videocamera (left). Shot 1968, $t=145\text{ms}$, $q=5.5$, $k=1.54$, $A=1.55$, $\delta=0.29$.

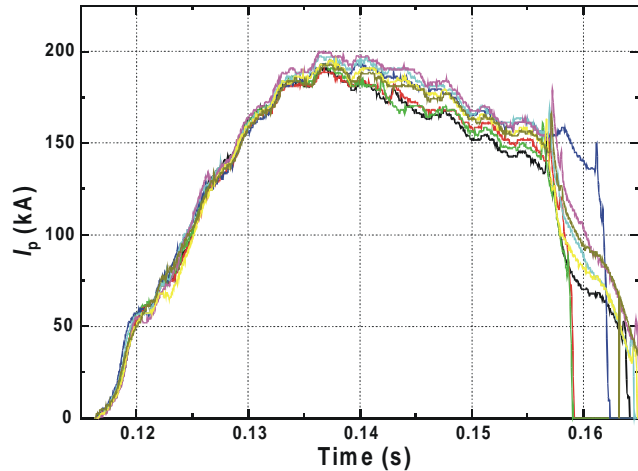


FIG. 7. Traces of plasma current in shots 1957 – 1968. High reproducibility is achieved after boronization without plasma current feedback stabilization.

full design value of plasma current, 0.5 MA, with pure inductive CD in a double swing regime.

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