OPERATIONAL LIMITS AND PLASMA STABILITY IN OH DISCHARGE OF GLOBUS-M SPHERICAL TOKAMAK

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Spherical tokamaks (ST) and conventional tokamaks being topologically the same devices have a significant difference in plasma column toroidicity. One of the features of high toroidicity is the higher nominal value of the edge safety factor, q_{edge}, of ST compared to conventional tokamaks and the higher value of inductively generated toroidal electric field. The current paper deals with investigation of operational limits of the Globus-M tokamak (corresponding to existing performance of power supplies) with the emphasis of low q_{edge} regime. Also it is addressed to the problem of runaway electrons generation in spherical tokamaks. The main parameters of the Globus-M machine could be found in [1]. The experiments were performed in the range of plasma currents, I_p=0.1 MA-0.25 MA, toroidal fields, B_T= 0.08 T- 0.35 T, aspect ratios, $A= R/a$ = 1.5-1.6 (where R is the major plasma radius, usually 0.35m, a is the minor radius), plasma elongation, k=1-1.9, plasma triangularity < 0.45.

Density limits achieved in OH regime of the Globus- M tokamak looks rather similar to those obtained in the START for the pure OH regime [2]. The existing Globus-M data base is limited, consisting of 2700 shots totally. Preliminary results are: Greenwald limit is not overcame or achieved. Better results are obtained at lower currents, or at the phase of current damping phase ($\overline{n}_e/n_{Green}$ > 0.6). The high density limits are easily achieved at high q_{edge} values. The density rise during intensive gas puff at the current ramp-up phase is usually accompanied by strong MHD activity which saturates the current rise and limits density at the level of $\overline{n}_e/n_{Green}$ ≈ 0.45. The highest average density achieved so far in the OH experiments is ~ (3.5-4) 10^{19} m^{-3}. Plasma current amplitude was limited by poloidal flux available from central solenoid at single swing regime (<120mWb). The highest plasma current was 250 kA, current ramp-up rate achieved already is 13 MA/s. That gives the value of the Ejima – Wesley coefficient C_{E-W} ≈ 0.66 (where $C_{E-W} = \Psi_S/\mu_0 I_p R$, with Ψ_S –poloidal flux change during current ramp-up). The value of normalized plasma current, $I_N=I_p/aB_T$≈5, was reached.

Experiments with toroidal field ramp down were performed to investigate kink stability limit. Another purpose of this experiment was the achievement of the highest possible OH beta regime. Experiments with ramping down of B_T from the value of 0.3 T (R=0.35m) were performed. The rate of B_T ramp down was constant at the value of ~16.8 T/s. The minimum value of B_T, at which discharge was terminated, was 0.08-0.12 T. B_T ramp down was switched on at different moments either during of current ramp-up (I_P =120kA), or after the current reached maximum value of amplitude (I_P =170kA). All discharges demonstrated the

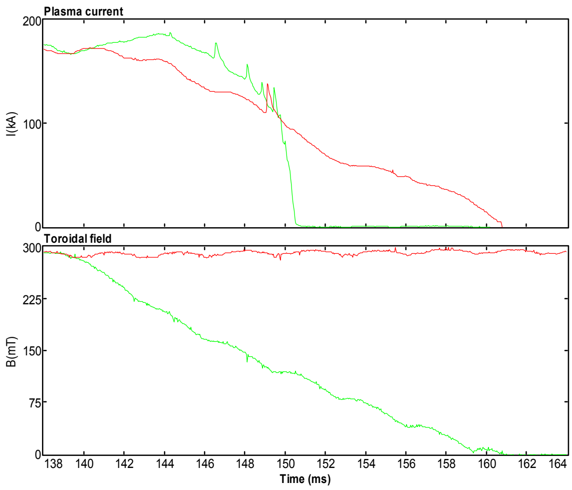

Fig.1 *The increase of the plasma current amplitude after the toroidal field ramp down. For comparison the plasma current trace with constant TF is shown.*

increase of current amplitude, or its ramp up rate after B_T ramp down was switched on, which is the signature of the internal inductance decrease due to expanding of current channel. Fig.1 demonstrates the current amplitude increase after toroidal field ramp down is on. The ultimate characteristic time of current channel expanding estimated on the assumption of toroidal flux conservation (B_Ta^2=const, where a is the minor radius of plasma column) gives $a/(\mathrm{d}a/\mathrm{d}t) \approx 36$ ms. This is about twice higher compared to the current skin time. At such conditions only the central plasma region may be affected by expanding flux, thus removing the current density from plasma center towards periphery with decrease of l_i. The experimental traces of discharge #2370 with TF ramp down at the last stage of the discharge are shown in Fig.2. Vertical and horizontal positions of the plasma column are well controlled by feedback system and plasma column center deviation does not exceed ± 1.2 cm from equilibrium position. Successive bursts of MHD signal picked up by Mirnov coils are recorded at the moments when rational surfaces m/n = 4,3,2 are escaping the plasma column during TF ramp down. The EFIT code was used for the reconstruction of plasma magnetic configuration. EFIT data confirms that q_{95} values about 4,3 and 2 are reached shortly before MHD bursts recorded. Plasma current termination is due to loss of global column stability connected with m/n=2 kink mode development. The current accuracy of magnetic measurements does not provide confident data on stored plasma energy, W_p and $q(r)$ profile. Zero-dimensional transport code SCENTO [3] was used for the power balance analysis to evaluate behavior of $\beta_T=2\mu_0\langle p\rangle/B_T^2$ (where $\langle p\rangle$ is volume averaged plasma pressure). The input data plasma parameters (I_P^{exp}, U_{loop}^{exp}, nl^{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 experimental results (left four columns) and simulations are listed in the Table below. It's worth noting that plasma column with almost 100 kA current is still globally stable in weak toroidal field of ~ 800 Gs. The corresponding value of q_{cyl} (ITER definition) is below 0.9. Also in the experiment the magnetic field pressure decreased by one order of magnitude, permitting the toroidal beta to increase significantly.

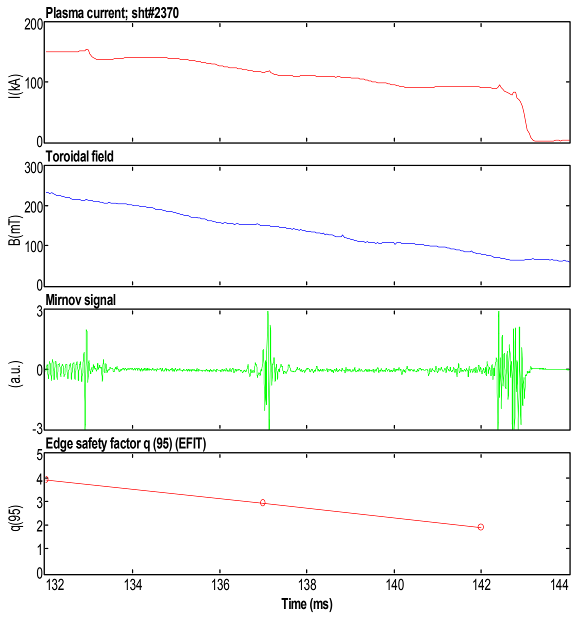

Fig.2 *Temporal evolution of discharge #2370 parameters with TF ramp down. Record low* q_{95}*~2.1 achieved at 141-142 ms.*

Table Results of experiment and simulation

t, ms	B_T, T	I_p, MA	n_e, 10^{20}	W_p, J	q_{95}	β_p	β_N	β_T, %
132	0.26	0.15	0.10	340	3.9	0.10	0.7	2.0
137	0.17	0.12	0.12	335	3.0	0.19	1.5	5.5
142	0.08	0.09	0.10	210	2.0	0.21	2.7	12.5

In the absence of detailed data on plasma parameter spatial distribution the flat current density profile, $I^*(\Psi) = dJ/dS = (1-\Psi^5)^2$ and flat $p(\Psi)$ and $q(\Psi)$ profiles were used in stability analysis with the KINX code [4]. Here Ψ is normalized poloidal flux. The results of the analysis for configuration of the plasma column at 137 ms showed that the equilibrium is stable against localized ballooning and external kink modes (n=1,2,3), if $q(0) > 1$; the peeling mode stability criterion is also satisfied. Plasma toroidal beta and normalized beta are even higher, than predicted by zero dimensional simulations (8.8% and 2.6 respectively). This preliminary result could be treated as indirect confirmation of plasma column stability improvement with flattening of current density profile at the condition $q(0)>1$.

Runaway electron behavior was studied in the OH experiments. The process of electron runaway usually accompanies the tokamak plasma pulse with maximum generation rate at the beginning and the end of the discharge. At the current quench phase, during inductive loop voltage increase, significant part of plasma current is sometimes converted to the current driven by runaway beam of high energy [5]. The situation in ST differs from conventional one due to a few reasons. Firstly, the value of inductively driven toroidal electric field at the discharge start–up is higher. In Globus-M it is usually in the range of $E_{Tor}(R_{0.16m}) \approx$ 4-6 V/m, depending on the required current ramp-up speed [1]. Experiments do not show significant runaway production, in spite of high ratio of electric field to Dreicer one. May be an uninvestigated mechanism of runaway population self-regulation is important. Change in local heating power $J^2\eta$ (with η - plasma resistivity), and associated change of plasma parameters (mostly T_e) may deplete the source of runaways due to strong negative feedback. According to experiments and simulations the beam current never exceeded 10-15% value of total plasma current. When the density reaches the maximum value the beam is dissipated, usually by MHD event. Fig.3 demonstrates the temporal behavior of main plasma parameters together with total HXR intensity picked up by spectrometer. Also E/E_{dr} value temporal variation is shown. Secondly, in ST $E(\rho) \neq$ const (with ρ - normalized plasma minor radius), contrary to conventional tokamaks.

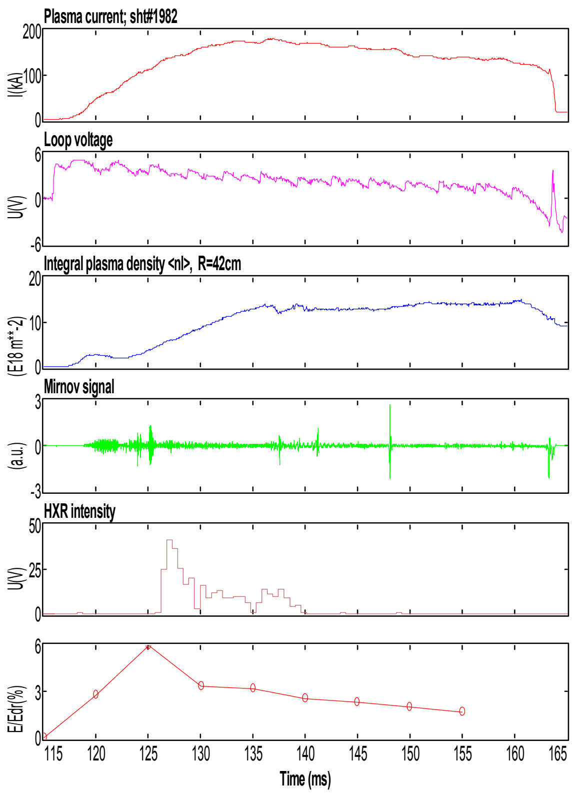

Fig.3 *Behavior of runaway electrons and other plasma parameters in the discharge #1982. No runaways are recorded at the current quench time.*

The big number of field line transits at the inner plasma boarder region (higher E region) may shift the maximum averaged $E(\rho)$ value to the plasma periphery. That, together with rapid inward motion of the disrupting plasma column, may be the reason of no HXR signal detected in post disruption phase, in spite of well pronounced inductive loop voltage spike at the current quench time, sometimes reaching $U_{loop,R0.11m} \approx$ 5-7 V. 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 runaway energy, $E_{run} \approx$ 2.2 MeV. For the design values of plasma current and toroidal field (the energy limit is linealy dependent on both) it will reach 3.5 MeV, before runaways interact with limiter, or field ripples. The energy spectrum of HXR representing energy spectrum of runaway electrons is shown in Fig.4.

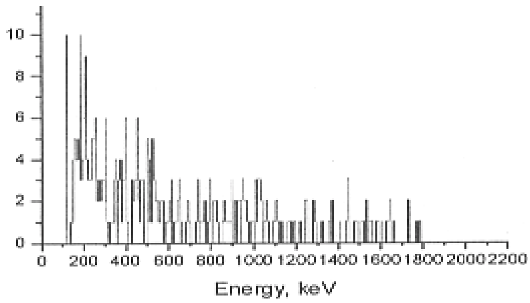

Fig.4 *Runaway electron (gamma photon) spectrum, recorded by HXR spectrometer.*

As a result the operational limits of Globus-M OH plasma were established. They are defined now by geometrical conditions: R = 0.35m, a = 0.23m, $k \leq 1.9$, $\delta \leq 0.45$ and performance of the existing power supplies: $I_p \leq 0.25$ MA, $B_T \leq 0.35$ T. Plasma parameters, $q_{edge} \geq 2$, $n_e/n_{Green} \leq 0.6$ and $\beta_N \leq 2.7$, $\beta_T \leq 12.5\%$ which were obtained in transient regime are limited by plasma stability, which is improving with l_i decrease and $q(0) > 1$. Runaway electron evolution on the stage of current ramp-up and current quench were investigated. Important differences in runaway electron generation and behavior between conventional tokamaks and STs are outlined.

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