29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-4.104 (2002)

Runaway Electrons Acceleration in Globus-M Spherical Tokamak

V.K.Gusev[1], I.N. Chugunov[1], A.V. Dech[1], V.E. Golant[1], N.A. Khromov[2], R.G. Levin[1], V.B. Minaev[1], A.B. Mineev[3], A.N. Novokhatskii[1], M.I. Patrov[1], Yu.V.Petrov[1], K.A. Podushnikova[1], N.V.Sakharov[1], V.V. Rozhdestvenskii[1], A.E. Shevelev[1], N.I. Vinogradov[1]

[1] *A.F.Ioffe Physico-Technical Institute, St.Petersburg, Russia*
[2] *Ioffe Fusion Technology Ltd., St. Petersburg, Russia*
[3] *D.V. Efremov Institute of Electrophysical Apparatus, St. Petersburg, Russia*

Introduction. Study of runaway electrons behaviour was performed in Globus-M spherical tokamak (ST) in ohmic heating regime. Basic design parameters of the device are $R = 0.36$ m, $a= 0.24$ m, $B_T < 0.6$ T, $I_P <0.5$ MA. The interest to runaway electrons study in STs is justified by few reasons. First - they can supply data on magnetic field topology and turbulence. Second – their behaviour may differs from conventional tokamaks due to specific features of magnetic and electric field distributions across the plasma column. Experiments were performed with the goal to investigate marginal runaway dominating regimes in ST, with classical Dreicer mechanism of acceleration. Such regimes are commonly obtained in the conventional tokamaks, when $E/E_{\rm crit}$ > 0.03-0.04. Here E is toroidal electric field in V/m and $E_{\rm crit}$ is Dreicer field linearly depending on plasma density, effective charge and inversely on electron temperature. Preliminary experiments [1] didn't discover significant runaway production rate at such values of the $E/E_{\rm crit}$. Investigation of runaways production at higher values of $E/E_{\rm crit}$ was one of the experimental tasks. Also it was desirable to obtain regimes with knock-on-avalanche runaways acceleration. This mechanism, which is regarded as the main runaway production source in large fusion devices, is attainable in the discharges with runaway confinement time exceeding the avalanche time, $t_0 \sim 0.015\cdot(2+Z_{\rm eff})/E$, [sec, V/m], [2]. Here $Z_{\rm eff}$ is effective plasma charge. The decrease of t_0 by minimizing $Z_{\rm eff}$ and maximizing electric field with possible improvement of runaways confinement may give a chance to study such a regime. For this reason fresh boronization of vacuum vessel was made before experiments, resulting in decrease of discharge radiation losses more than factor of five [3], which is regarded as a significant decrease of $Z_{\rm eff}$. Another signature of low $Z_{\rm eff}$ is extremely low background plasma density (without gas puff), which doesn't exceed $1.5\cdot10^{18}$ m^{-3}. To make experimental data more comprehensive few new diagnostic instruments were used together with fast HXR spectrometer [1]. First is HXR detector operating in flux regime, which is sensitive to HXR in the energy range of 0.1-1 MeV. Two microwave radiation detectors were used for the recording of radiation on the wavelengths 0.8 cm and 3 cm. Those microwave tools were responsible for recording of synchrotron radiation produced by runaway electrons themselves and to thermal microwave collective radiation aroused from electron beam - wave interaction, occurring during instabilities.

Experimental results. The experiments were performed in OH discharge in wide range of parameters. The plasma current was changed from 0.1 MA to 0.3 MA and the plasma density was in the range of $(0.15 – 3)\cdot 10^{19}$ m^{-3}. Magnetic field strength at plasma axis was changed from 0.29 T to 0.55 T.

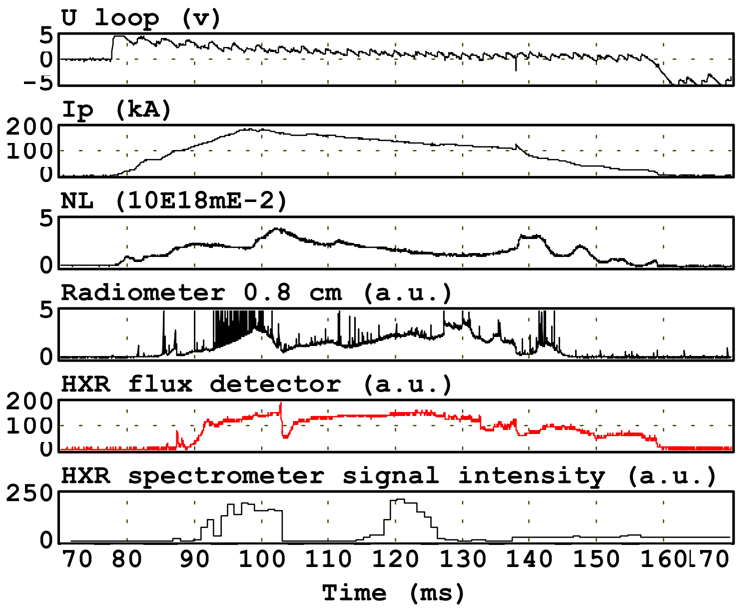

Fig.1 Experimental waveforms of plasma parameters in very low density discharge #3577. From top to bottom: loop voltage, plasma current, line-averaged density, intensity of 0.8cm radiation recorded by radiometer, HXR intensity by flux detector, integrated over energy spectrum HXR intensity

Fig.1 represents waveforms of plasma parameters in very low-density regime ($n_e < 5\cdot 10^{18}$ m^{-3}) with small gas puff at the initial stage, characterized with high E/E_{crit} ratio. In such discharges the density ramp-down starts after plasma current reached maximum value. During discharge density decreases down to very low background value, causing significant increase in E/E_{crit} ratio. Other waveforms are typical for very low-density discharges, even without gas puffing. The spectra of HXR originating from interaction of runaways with limiter were usually analysed during three distinct time intervals. The high-energy boarder energy spectrum represents the maximum energy of runaway electrons. First time interval is corresponding to current ramp-up phase (~ 15 ms). The energy limit of HXR usually doesn't exceed 0.5-1 MeV in this phase. The second time interval is more or less attributed to current plateau phase (~ 20 ms) and the current ramp-down of the discharge is covered with third time interval. Interestingly is that rather often highest energies of HXR up to 4 MeV or higher are recorded at the final stage of the discharge, where plasma current is decreasing. Another significant effect is freezing of HXR energy during the first time interval at the value below 1 MeV, in spite of highest electric field and rather long time intervals free of MHD activity, enough for electrons acceleration to higher energies. At the same time interval periodic bursts of synchrotron radiation are recorded by 0.8 cm wavelength radiometer. Such bursts are sometimes accompanied by characteristic plasma current and loop voltage spikes, witnessing for instability development. This type of instability is recognized as well-known fan instability. Maximum energies recorded in this experimental campaign didn't exceed 5 MeV. The dependence of maximum runaways energies on plasma current is shown on Fig. 2. Straight line represents so-called orbit shift limit with $E_R^{max}=\gamma^{max}\cdot m_{e0}c^2$. Here $\gamma^{max}=(1-v_e^2/c^2)^{-1/2} \approx 100\cdot I_P(1-R/r_l)R/r_l$, [MeV, MA, m], R – major radius, r_l – limiter radius.

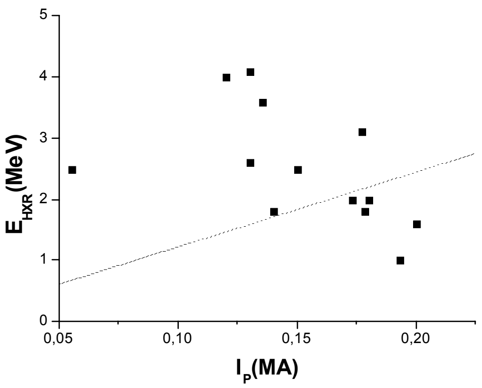

Fig.2 Maximum energy of runaways versus plasma current for very low density regime

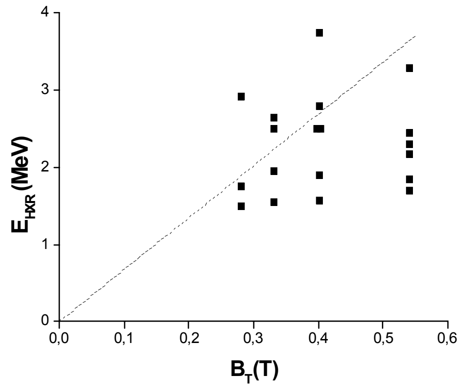

Fig.3 Dependence of maximum runaways energy on toroidal field strength for moderate densities

In discharges with moderate density $(1\text{-}3)\cdot 10^{19}$ m^{-3} the runaway energies and production rate go down. Runaways production rate in Globus-M become negligible for plasma density $n_e > 3\cdot 10^{19}$ m^{-3}. Significant experimental result, observed in the whole density range is that the runaway current, which usually dominats at low density regimes in conventional tokamaks, in Globus-M doesn't exceed 10-20% of total plasma current and doesn't play significant role in energy balance. Experiments demonstrated, that every time, when plasma lost runaway beam due to MHD instability, total current didn't decrease below 80-90 % of initial (before instability) value. Important result observed in [1], that in major disruption event during current quench phase no runaways are generated, was again confirmed for wider operational parameters range.

Discussion. Experimental results obtained in very low density regime, showed that in spite of low Z_{eff} in Globus-M it was not possible to achieve total runaway discharge. Also we failed to obtain knock-on-avalanche regime of runaway acceleration. This may be due to specific some mechanism limiting runaways production rate and confinement time (or energy limit of runaways) in spherical tokamaks. The value of E/E_{crit}, derived from SXR temperature estimate at the initial stage of the discharge, exceeds 20% during most discharge time, with maximum value at the beginning stage, exceeding 50%. One could see from Fig. 2 that well-known energy limits couldn't be straightforwardly applied to runaways in spherical tokamaks. At very low densities the limit energy of runaways seems to decrease with plasma current, rather than increase. This may be explained with increase of boundary q value, with corresponding suppression of magnetic fluctuation level and hence runaways confinement improvement at lower currents. At higher electron densities the maximum HXR energy fell down to ~ 1-3 MeV depending on toroidal field strength. Fig. 3 represents the dependence of HXR energy limit on toroidal field strength for the density interval of $(1.2 - 3)\cdot 10^{19}$ m^{-3}. The straight line represents the toroidal field ripple limit for runaway electron energy [4], $E_R^{max} < 300\cdot B_T R/N_{TF}$, [MeV, T, m], where N_{TF} – the number of toroidal field turns. This runaway energy limit mostly holds on in such discharges. Possible reason influencing the energy and production rate of runaways may be connected with high toroidal (geometrical) effects causing strong variation in toroidal electric field radial distribution, $E \sim R^{-1}$. According to simulations, the production rate variation across the Globus-M plasma column can be four times higher at the periphery than in the plasma centre, see Fig. 4. Here the production rate, $\Gamma \approx 0.43\cdot n_e \nu_{ei}(E/E_{\mathrm{crit}})^{3/2(1+Z_{eff})}\times$ $\times\exp\{-[E/4E_{\mathrm{crit}}+\sqrt{(1+Z_{eff})}E_{\mathrm{crit}}/E]\}$, [$10^{20}$ m^{-3}, s^{-1}] is plotted as a function of normalised minor radius, r/a for parabolic temperature and density distributions. Reduced production rate ~ $n_e^2(r/a)$, and enhanced losses of a hollow type runaway beam from plasma column periphery due to radial shift of orbits significantly modifies runaways behaviour in spherical tokamaks.

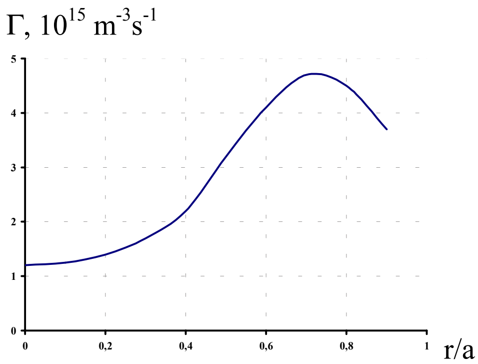

Fig.4 Radial dependence of runaways production rate for the low density discharge #2657

This work was supported by RF Ministry of Science, IAEA and RFBR grants 00-02-16934, 01-02-17882. Also support was from RAS grant #12 for young scientists.

[1] V.K. Gusev et al., Proc. of 28th EPS Conf. on Contr. Fus. and Plasma Phys., Funchal, ECA Vol. **25A** (2001) 93-9

[2] I.M. Pankratov et al., Nuclear Fusion, **38**, (1998) 279

[3] N.V. Sakharov et al., This conference

[4] G.Martin et al., ITER Workshop on Disruptions (1991)