# Non-inductive Plasma Current Start-up and Drive by RF Power in the Globus-M Spherical Tokamak.

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**Abstract.** Plasma start-up and current ramp-up without the central solenoid is an important problem on the way to compact fusion reactors. There are several experiments demonstrating such possibility due to absorption of electromagnetic waves in vicinity of the electron cyclotron resonance for plasma formation and then current start-up [1, 2, 3]. In our case the non-resonant scenario of plasma and current generation by RF power at 900 MHz frequency was used in toroidal vessel at standard toroidal and weak poloidal magnetic fields. Plasma current up to 17 kA was achieved with average density (1–3)$10^{18}$ $m^{-3}$ and 10–20 eV electron temperature. Experimental data indicate that the plasma current could be determined by high energy “tail” in electron energy distribution function.

**Experiment.** An experiment on RF plasma start-up and current rump-up was carried out on the spherical tokamak Globus-M (R = 36 cm, a = 24 cm, A = 1.5) [4]. The RF generator with 900 MHz frequency and 100 kW power was used in the experiment. The pulse duration was up to 100 ms. The wave excitation was performed by a comb-like antenna oriented in poloidal direction which is shown in Fig.1. It was developed originally for CD experiments in the ohmic discharges in spherical tokamaks [5] and should excite waves in poloidal rather than toroidal direction. The RF power was fed through the one end of the antenna, whereas the other end was loaded by matching resistance. The gas puffing was programmed and optimized. Inductive toroidal electric field was not excited. Quasi-stationary toroidal magnetic field ($B_{t0}$ = 0.4T) and weak vertical magnetic field ($B_V \approx$ 2–2.5 mT) were applied before the RF pulse. The value of $B_V$ at the breakdown stage was chosen to obtain maximal rate of the current increase at the discharge start. The evolution of the plasma parameters during the discharge is shown in Fig.2. One can distinguish three stages of the discharge formation. At the RF start (3-4 ms) the ionization takes place (see the initial peak in $D_\alpha$ radiation), and the plasma fills all the volume of the torus (see video camera image at fig.3a, where the central column is seen on the left). Then after 3-5 ms time, the toroidal current arises up to the value of 4-5 kA with the 450-500 kA/s rate, which is comparable with traditional experiments on LHCD in tokamaks. The current direction was dependent on the direction of $B_V$. At the next stage of the discharge, the vertical magnetic field was enhanced fluently to increase the plasma current. The rate of current increase occurred to be proportional to the vertical field. But too fast increase led to the discharge termination. At achieving some optimal level the current ceased to increase and passed into saturation phase. There exists also some final stage of discharge: a long decay (more than 10 ms) of plasma after the RF end at constant magnetic fields. The achieved maximum of the current was 15-17 kA at plasma density (1-3)×$10^{18}$ $m^{-3}$ and electron temperature 15-20 eV which were measured by interferometer and Thomson scattering diagnostics. An attempt to increase the plasma density by intense gas puffing led to decrease of the current. Contamination of the plasma by impurities influenced negatively the current ramp-up phenomenon. RF current drive began from minimal RF power of 20 kW, but when the power exceeded the 40-50 kW value the RF current terminated due to impurity accumulation. The plasma column acquired vertical elongation near current maximum at $B_V \approx 8$ mT and adjoined closely to the central column, which is seen in video images (Fig.3b). The driven current was well controlled by external magnetic fields.

The current ramp-up was accompanied by increase of synchrotron and HXR radiation, which evidenced the generation of high energy electrons. The synchrotron radiation was observed in a broad frequency range 12-36 GHz with small delay after the current start. The radiation temperature can be evaluated as several keV. The HXR radiation was analyzed by a spectrometer in perpendicular direction to the current in the energy range higher 0.2 MeV. An averaged on 9 discharges spectrum is shown in Fig.4a. It extends up to $E_{мах} \approx 0.9$ MeV. This value can be taken as the upper limit of electron energy. Fig.4b shows that after 30 ms from the start (when registration of HXR began) some group of electrons managed to get $E_{мах} \approx$ 550 keV. Interesting is the fact that CX diagnostics observes the fluxes of high energy particles in these discharges (Fig.5a). Their “tails” outspread up to 1.5 keV, and “effective” temperature amounts 200-300 eV (Fig.5b). The frequency analysis of plasma radiation reveals the appearance of some satellites of pumping frequency at the level –(30-40) dB and shifted in low frequency side on ion cyclotron value for plasma outer edge. Essential increase of radiation was observed also in 400-500 MHz frequency range. Parametric decay instabilities takes place in current ramp-up stage only and vanishes in the stationary current phase.

**Discussion.** The possibility of plasma formation by RF waves was demonstrated in a number of experiments in various frequency ranges [6,7,8]. The estimation shows that in our case at input power of 20-30 kW the RF electric fields can exist on the antenna elements with the field strength $E_{//} \approx$ 1kV/cm - along the magnetic field and $E_V \approx$ 0.5 kV/cm - in vertical direction. In such fields the primary electrons can easily gain the oscillation energy up to 100 eV, which is considerably greater than ionization potential of hydrogen, and form the cold plasma. The life time of such a plasma is rather small and is determined by drift processes.

It is remarkable that the initial current arose at stationary phase of the vertical field, when the toroidal inductive electric field is absent entirely. One can suggest two mechanisms for explaining the observed phenomena. The first of them can have RF wave nature. The antenna used in the experiments unlike the traditional multi-waveguide system is tricky for correct electrodynamic modeling, but the simple evaluation based on geometrical consideration gives for the wave spectrum $N_{pol} \approx 6 - 8$ and $N_{tor} \approx 1 - 15$. The excited spectrum is symmetrical in both directions from the antenna. The modeling shows that the waves with $N_{tor}$> 3-5 can easily enter the primary plasma. The most slowed components can be absorbed by Landau mechanism. The 2D simulation predicts the existence of RF fields up to several tens of V/cm at 40 kW of input power, which is much greater than Dreiser field ($E_{cr} \cong$ (5-7) $10^{-2}$ V/cm) and makes it possible to produce run-away electrons. In addition, the observation of low frequency satellites and ion "tails" evidences the developments of parametric decay processes, when the 'cold' lower hybrid resonance arises in the plasma at 300-400 MHz frequencies and resonant acceleration of electrons and ions could take place. The increasing vertical $B_V$ helps to confine the fast electrons and sustain the current.

The second possible mechanism is the direct electron acceleration in the fields on antenna elements (like described in [9]). But in our case the oscillation energy of electrons can not be greater than 500-1000 eV. The most probable is a hybrid scenario: RF fields on the antenna surface produce two groups of fast electrons running along and against the toroidal field. The vertical field $B_v$ saves only one of them, shifting it inside the chamber. Then they interact with less slowed waves and gain higher energy, sustaining plasma current.

**Conclusion.** The work presents the first use of "lower hybrid" waves for the double purpose - creating a target plasma and ramp-up and driving the plasma current in a spherical tokamak. The antenna with a broad wave spectrum produced the plasma current up to 17 kA. The further progress depends on understanding of electron acceleration mechanism.

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[1] V.F.Shevchenko, M.R.O'Brien, D.Taylor et al. Nucl. Fusion, **50** (2010), pp.1-5.

[2] A. Fjiri, Y.Takase, J.Sugiyama et al. Proc. of the 22 IAEA Conference, (2008), EX/P6-6.

[3] H.Tanaka, T.Maekama, M.Uchida et al. Proc. of the 22 IAEA Conference, 2008, EX/P6-8.

[4] V.K.Gusev *et al* 1999 *ZhTF* **69** 58-62. 1999 *Tech.Phys* **44** 1054

[5] O.N.Shcherbinin, E.Z.Gusakov, V.V.Dyachenko, M.A.Irzak and S.A.Khitrov, 2009 *18th Top.Conf. on RF Power in Plasmas (Gent, Belgium 2009)* AIP Conf.Proc. **1187** 427-430

[6] F.Jobes, J.Stevens, R.Bell et al. Phys. Rev. Let., (1984), **52**, #12, pp.1005-1007.

[7] V.N.Budnikov, V.V.Dyachenko et al. Proc. of the 19-th Conf. on CFPP, Insbruck, (1992), pp. 997-1000.

[8] M.Gryaznevich, V.Shevchenko, A.Sykes, Nucl. Fusion, **46** (2006) S573-S583

[9] V.Fuchs,Y.Demers, P.Jacquet et al. Plasma Phys. Control. Fusion**, (1999)** A495-A505.

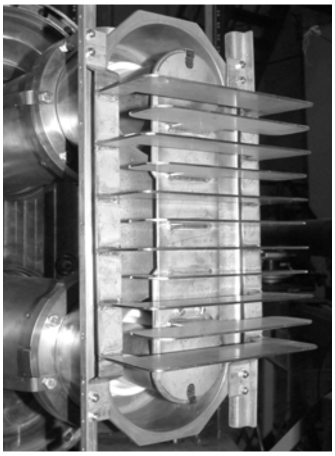


Fig. 1.RF antenna (the screen is removed)

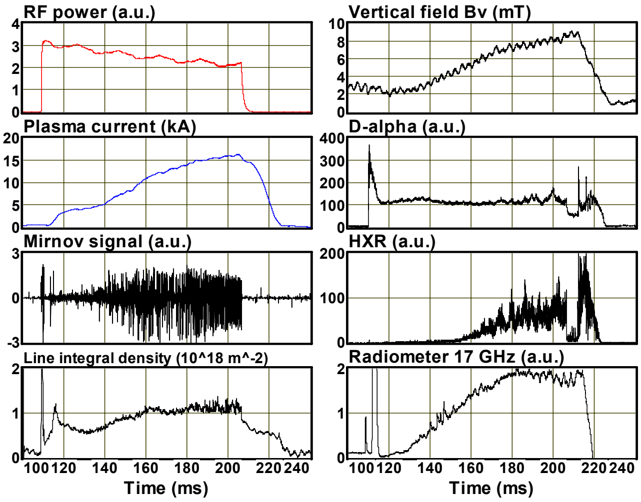



Fig. 2. Waveforms of plasma parameters ( sht#26715)

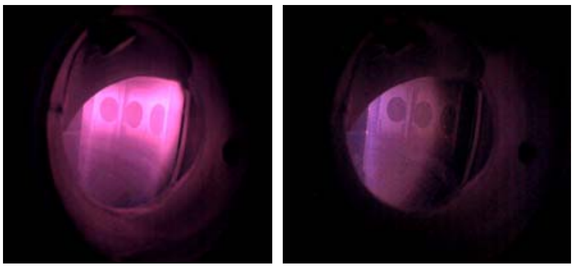


Fig. 3.Video camera images, a) t = 120 ms, b) t =190 ms

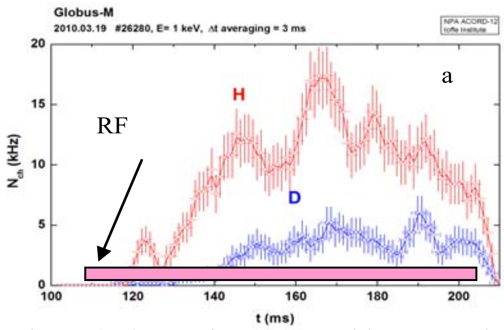
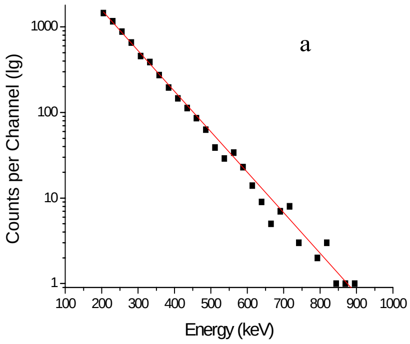
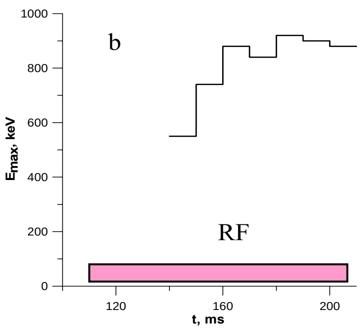



Fig. 5. a) Fluxes of CX atoms with energy 1 keV



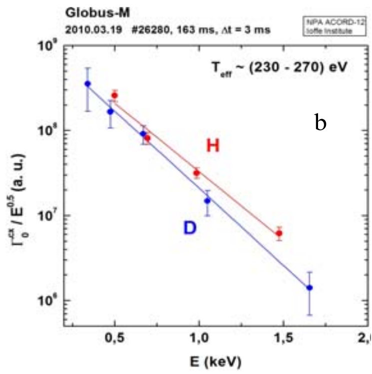




Fig. 4a. Spectrum of HXR Fig. 4b Maximal energy vs time Fig.5.b). Energy spectra of CX particles,