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

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Abstract. Non-inductive 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 920 MHz frequency was used in toroidal vessel at standard toroidal and weak poloidal magnetic fields. Experimental data indicate that the plasma current could be determined by high energy “tail” in electron energy distribution function.

Experiment. An experiment was carried out on the spherical tokamak Globus-M (R=36cm, a=24cm, A=1.5) [4]. The RF generator with 920 MHz frequency and 100 kW power was used in the experiment. The pulse duration was up to 100 ms. First results were published in [5]. The wave excitation was performed by two comb-like antennae: one of them excited mostly poloidally slowed waves (PSA) and the other – toroidally slowed waves (TSA) (Fig. 1). The RF power was fed through the one end of the antenna, whereas the other end was loaded by matching resistance. Two gas valves placed far from antennae were used in experiments. Gas puffing (H_2, D_2) 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. After gas ionization and plasma formation the toroidal current arises up to the value of 4-5 kA. The current direction was dependent on the direction of B_V. If B_V is kept to be constant the current is saved on this level. At the next stage of the discharge, the vertical magnetic field was enhanced 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 (up to 40 ms) of plasma after the RF end if confining magnetic fields were preserved. The achieved maximum of the current was 15-17 kA at plasma density (1-3)$\times 10^{18}$ m^{-3} and electron temperature 15-20 eV. An attempt to increase the plasma density by intense gas puffing led to decrease of the current. The RF plasma discharge was created in helium also but evidences of the current were not observed. 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 current ramp-up phenomenon exists at decreasing of B_{t0} down to 0.2 T. The TS antenna demonstrates smaller efficiency in electron beam and current generation. Variable Current Loop method (VCLM) [6] shows that LCFS appears beginning from (3-4) kA current (Fig.3) and then moves inward during the discharge. The plasma column acquired vertical elongation near current maximum at $B_V \approx 8$ mT and adjoined closely to the central column. Calculated displacement of LCFS during the discharges (for TSA and PSA) is shown on Fig. 5, where ΔR is a distance between antenna and the closed surface. Time evolution of peripheral density, which was measured by probe on equatorial plane on R=58,5 cm (Fig. 4), and behavior of RF power P_{rad} radiated into plasma (see Fig. 5) confirm this thesis. It is seen, that P_{rad} decreases at the pulse end. The fact can explain the current saturation.

As it was shown in [5] the current ramp-up was accompanied by appearance and increase of synchrotron and HXR radiation, which evidenced the generation of high energy electrons. Their energy extends up to $E_{Max} \approx 0.9$ MeV. In discharges with constant Bv the electron energy E_{max} didn't exceed 400 keV. Long duration of current after RF pulse (Fig.2) agrees with time of confinement of high energy electrons. CX diagnostics observes the fluxes of high energy particles in these discharges. Moreover the fluxes were essentially higher in RF discharges without current. Frequency spectra of plasma radiation can evidence developing of parametric decay instabilities (PDI) of pumping waves. PDI 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 [7,8]. The estimation shows that in our case at input power of 20-30 kW the RF electric fields which can exist on the antenna elements are sufficient for plasma formation. RF breakdown takes place in vicinity of antenna surface and then the plasma fills all the volume even if B_t exists only. The initial current arose at stationary phase of the B_V, 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 main pikes of the wave spectrum $N_{pol} \approx 6–8$ and $N_{tor} \approx 1–15$ for PSA and $N_{tor} \approx 6-8$, $N_{pol} \approx 1$ for TSA. The excited spectra are symmetrical in both directions from the antenna. The ray-tracing modeling shows that the waves with $N_{tor}>$ 3-5 can easily enter the primary plasma independently from value of N_{pol}. The most slowed components ($N_{tor} \cong 15$) can be absorbed by cold electrons due to Landau mechanism. The 2D wave 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" are typical for lower hybrid heating. The 'cold' lower hybrid resonance arises in the plasma at 100-200 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]). The RF field spectra arising on antenna surface are much more complicated than spectra excited in plasma. The strongly slowed field components contain power sufficient for acceleration of warm electrons up to high energies by Landau mechanism. Result of Fourier transformation of poloidal and toroidal field components excited by PSA is shown on Fig.6. The spectrum includes strongly slowed components up to $N_{tor} \approx 50$. In this condition the expected energy gain by electrons can amount several hundreds of eV. We believe that a hybrid scenario is most probable. RF fields on the antenna surface produce two groups of fast electrons with several hundreds eV energies 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 ($N_{tor} \geq 6$) and gain higher energy, sustaining plasma current.

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

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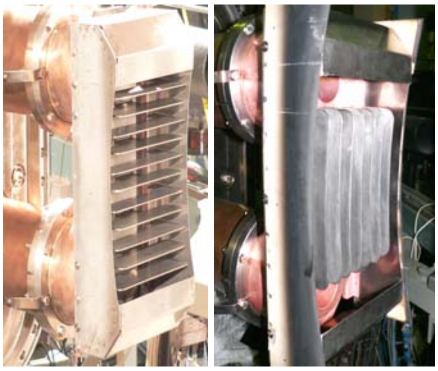

Fig. 1. Photo of PS (left) and TS (right) antennae

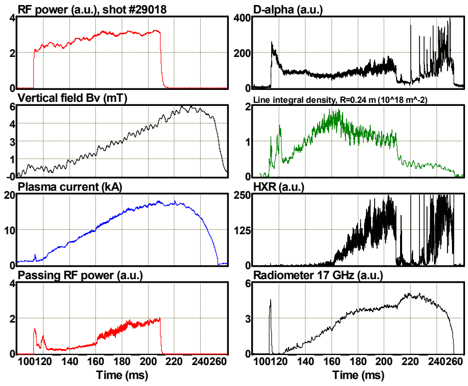

Fig.2. Waveforms of plasma parameters

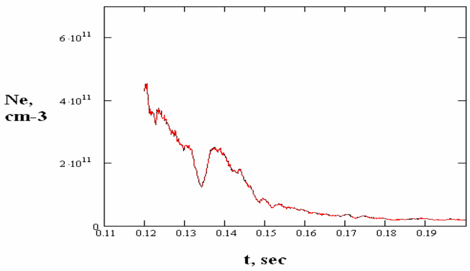

Fig.4. Behavior of peripheral density vs time

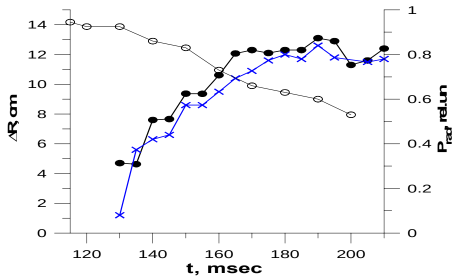

Fig.5. Behavior of distance ΔR (cross and fill circles) and P_{rad} (empty circles) vs time

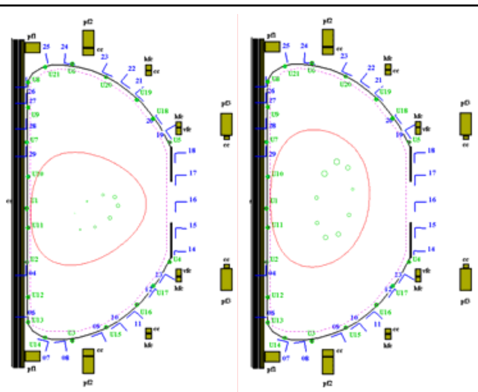

Fig.3. Reconstraction of LSCF: t=120ms (left); t=200 ms (right)

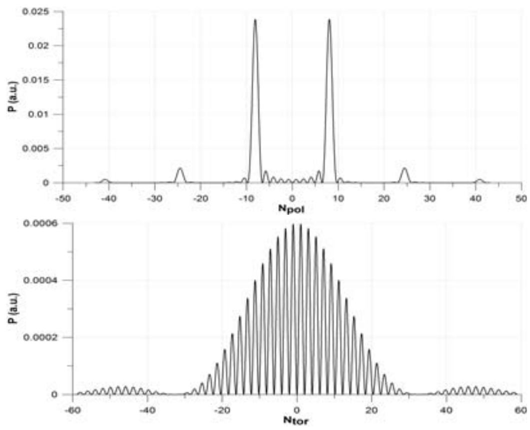

Fig.6. Fourier spectra of electric fields on PS antenna surface