ICRH Experiments on the Spherical Tokamak Globus-M

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Abstract. The results of experiments on the RF heating of hydrogen-deuterium plasma at ion cyclotron frequencies in the Globus-M spherical tokamak are presented. RF power up to 200 kW at frequencies about 9 MHz fed via a single-loop antenna led to an increase in the ion temperature from 170 eV up to 300 eV in the best case. Characteristic times of the ion temperature buildup and decay corresponded to the ion energy confinement time. Simulation of processes of RF power absorption was performed.

The ICRF heating experiments on the Globus-M tokamak were started one year ago. Two possible scenarios of experiments have been considered for plasma heating [1, 2]. The one of them – to excite the FMS wave with frequency 4-5 times higher than the fundamental cyclotron frequency for deuterium. The RF power in this case should be absorbed by electrons by the TTMP and Landau damping. The FMS wave is not sensitive to the presence of higher ion cyclotron harmonics in the plasma. So ions can be heated through ion-electron collisions only.

The results obtained in the other scenario, which is known as the method of resonance minority ion heating, are presented in this report. In the “classical” version of this scenario a considerable part of the RF power should be absorbed by the light minority ions (hydrogen) at their fundamental resonance. Some power will be absorbed directly by deuterium at the second harmonic condition (at the same location). A part of power can be absorbed also by electrons (in a non-resonant way, by TTMP and Landau damping). Some fraction of the FMS wave will be converted into the Bernstein wave at ion-ion hybrid resonance.

In our case, this scenario looks somewhat different. One of the main features of the spherical tokamak plasmas (from the point of view of RF wave propagation) is a strong variation of magnetic field along the major radius. In the Globus-M tokamak [3], it changes almost 4 times on the way from the outer wall to the inner wall. It means that the resonance conditions for different harmonics of ion cyclotron frequency can be satisfied at the same time in different points of plasma cross-section. So besides two above mentioned resonances in the plasma cross-section there appear the second harmonic resonance for hydrogen on the LFS plasma periphery and the fundamental resonance for deuterium on the HFS plasma periphery. Some energy can be absorbed at the locations of the higher ion cyclotron harmonics for hydrogen and deuterium ions what is difficult to evaluate before the experiment. The role of RF energy absorption in these points is important for perspectives of developments of this scenario.

The second peculiarity of the Globus-M experiment consists in the fact that the amount of hydrogen in deuterium plasma is usually rather high. In a certain phase of the tokamak operation (just after the tokamak wall boronization) – even up to 50%. So in our case hydrogen is not a minority at all. Consequently, the cut-off barrier between fundamental resonances for deuterium and hydrogen may play an important role in FMS wave propagation.

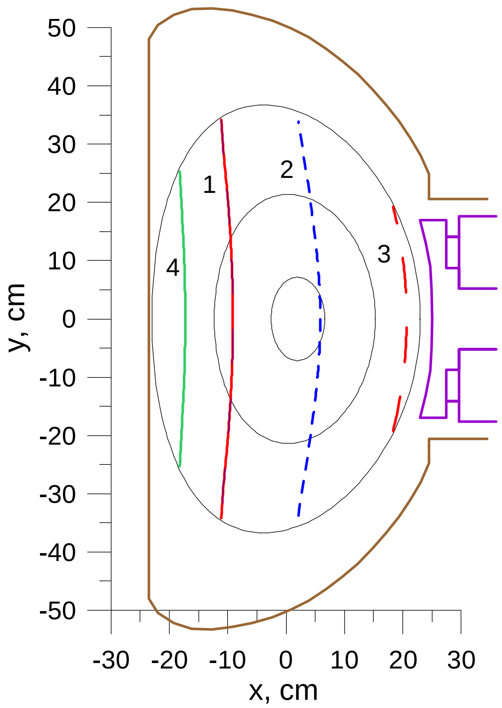

Fig.1. Resonance layers locations in Globus-M cross-section.

In Fig.1, the cross-section of the Globus-M chamber is shown for real experimental parametres (ellipticity – 1.6, triangularity – 4 cm, B_0 = 0.4 T, I_p= 250 kA.) and f=9MHz. Black ovals – magnetic flux surfaces ψ = 0.2, 0.6, 1.0. Resonance surfaces: 1 – deuterium second harmonic and hydrogen fundamental resonance, 2 – deuterium third harmonic, 3 – hydrogen second harmonic and deuterium fourth harmonic, 4 – ion-ion hybrid resonance for 50%H+50%D plasma. The fundamental resonance for deuterium is just outside of the magnetic surface ψ = 1.0. The locations of the resonance layers are calculated taking into account all tokamak magnetic field components. The position of the radiating part of the RF antenna is shown in the chamber port.

To evaluate the possible role of these features of the Globus-M experiment the modeling of wave absorption processes was performed with help of 1D “cylindrical” code developed in Ioffe institute [1] and by 3D full-wave “TORIC” code developed in Kurchatov institute by V.L.Vdovin. In both codes, the real parameters of experiments were taken into account including high hydrogen concentration. The distribution of the RF wave absorption intensity by different species of plasma was obtained by 1D code for equatorial Globus plane.

In Fig.2, the results are shown after integration over whole wave spectrum excited by the RF antenna placed at the LFS of the tokamak for the constant input power level. Green line denotes absorption by electrons, red line – by hydrogen and blue line – by deuterium. It is seen that both for C_H=10% and for C_H=50% total efficiency of wave absorption is approximately equal. The role of the cut-off barrier seems to be negligible (due to strong magnetic field non-uniformity). In addition, the role of second hydrogen harmonic appears to be very important. For the first thing, it provides direct energy absorption by hydrogen close to the nearest wall, what can decrease the heating efficiency. For the second thing, it creates condition for FW conversion into Bernstein wave.

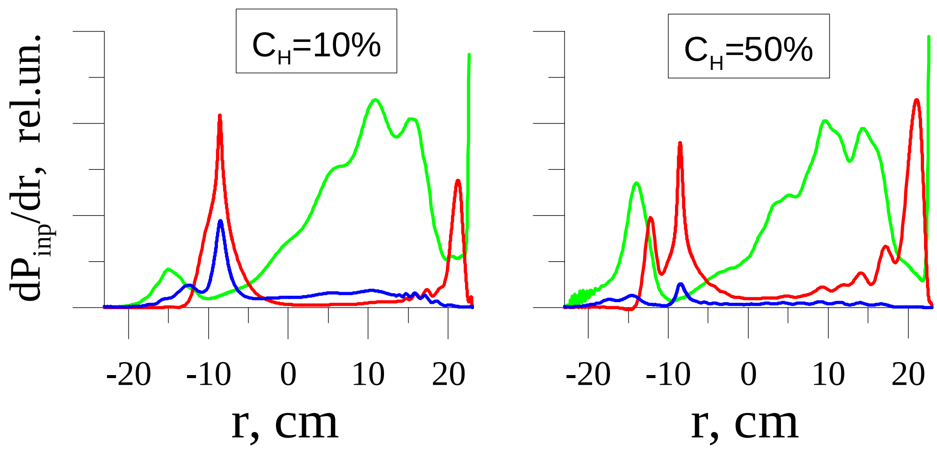

Fig.2.Distribution of RF power absorption over plasma diameter.

The Bernstein wave in turn will be absorbed partly by electrons and partly by deuterons in vicinity of second cyclotron deuterium harmonic in the central plasma region (and possibly, in vicinity of the third harmonic, what cannot be described by the codes working in FLR approximation). The modeling by 3D code is much more time consuming and for this reason, it was performed in limited range of parameters. Nevertheless, the 3D modeling confirmed the good RF absorption at high hydrogen concentration and positive role of Bernstein waves aroused in second hydrogen harmonic condition.

Distributions of RF energy absorption by various plasma components (similar to presented in Fig.2) calculated in broad range of plasma compositions were integrated over plasma diameter. Energy fraction absorbed directly by different plasma species is shown in Fig.3. Energy exchange between plasma particles was not taken into account. It should be noted that large fraction of energy goes into electrons. Fraction of energy coupled to protons changes only slightly in range of practically accessible hydrogen concentration, which is usually 20% - 50%. Direct energy absorption by deuterons expected to be not high. All calculations were made at parameters assumed for Fig.1 and $n_0 = 5{\cdot}10^{19}$ m^{-3}.

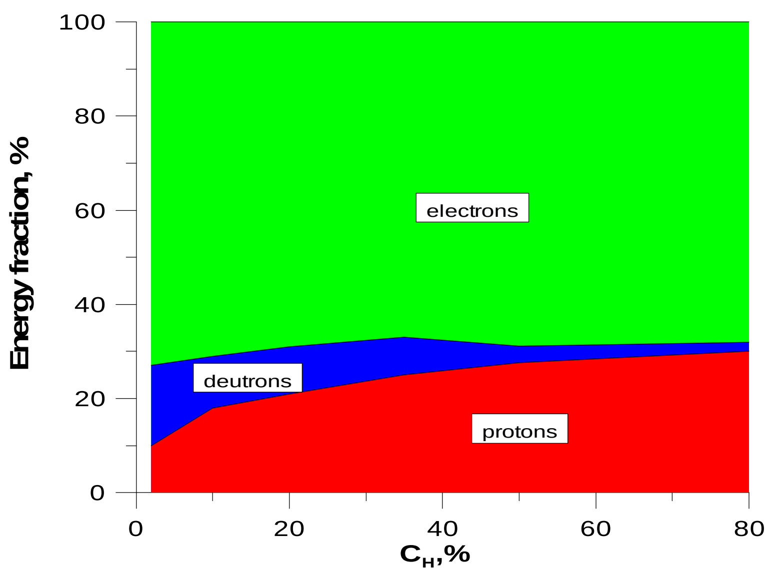

Fig.3. RF energy absorption distribution between various plasma components.

Experimental setup consists of tunable RF generator (ultimate power 1.5MW, frequency range 8-40 MHz). The usual single-loop antenna coated by NB ceramic was installed in the chamber port for FMS wave excitation. The coupling resistance of such an antenna calculated by 1D code for optimal experimental conditions is about 1 Ohm. The use of a coaxial resonator helped to arrange the optimal matching of the antenna and the generator. The resonator serves as a transformer, it converts the low resistance of plasma load to 50 Ohm at points of transmission lines connections. The length of the resonator is determined by the operating frequency. The full length of the resonator between two short-circuiting stubs should be equal to wave length. To shorten its length, special capacitors were placed inside the antenna coaxials as close as possible to the antenna strap. The RF power was delivered to the antenna by two transmission lines operating out-of-phase. The antenna input impedance is matched with transmission line by right choice of the stub position and the generator frequency.

The experiments were carried out at B_0 = 0.4 T. Plasma currents in various shots differed from 120 kA up to 240 kA, axial plasma density changed from $2{\cdot}10^{19}$ m^{-3} to $5{\cdot}10^{19}$ m^{-3} and operating frequency changed in the range 8.8 MHz - 9.2 MHz. The maximum input power was about 200 kW, pulse duration was up to 20 ms. Frequency deviation was connected with requirement of antenna tuning. After the conditioning procedure, no influx of impurity iones was seen during the RF pulse. The plasma density increased in small degree. The ion temperature behaviour was observed by 12-channel NPA analyzer, which measured simulteniously hydrogen and deuterium fluxes [4]. The line of observation was perpendicular to the plasma boundary, in the equatorial plane of the installation. Electron temperature was evaluated by SXR technique.

The experiments were organized in rather short experimental sessions, in which vacuum status of the chamber walls and antenna could be different. This circumstance can be one of the reasons of observed instability in plasma ion heating. As a rule, the essential hydrogen heating was registered during the RF pulse. The distribution function of protons was strongly distorted. Arising of energetic “tails” in proton spectra was found in every RF pulse. As to the deuterium heating the situaion is different.

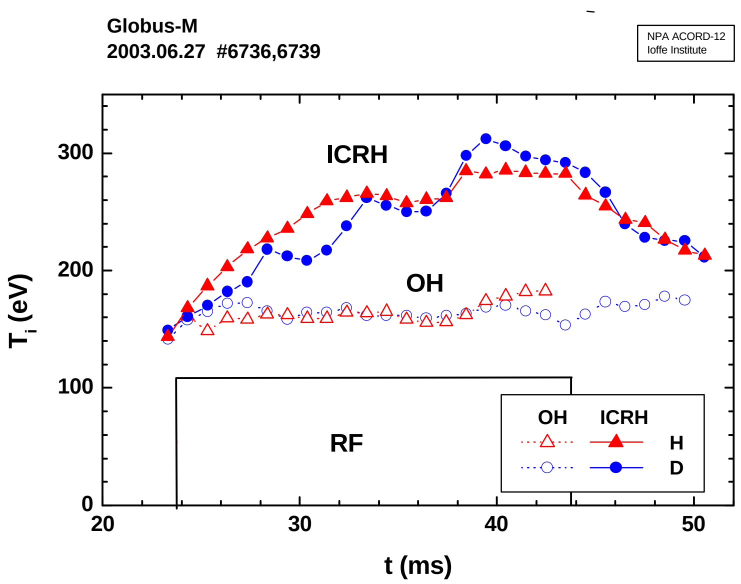

Fig.4. Evolution of ion temperature in shots #6736 and #6739.

In the best cases (2003 year experimental campaign) the ion temperature was almost doubled due to RF energy absorption (shot #6736, June 2003). Temperature evolution for this shot is presented in Fig.4 by solid lines. It is worth to note that time dependencies of deuterium and hydrogen temperature were very close. The temperature rised from 170 eV up to 300 eV. The characteristic time of temperature rise at the beginning of the RF pulse and its decay after the pulse was off corresponded to the plasma energy life time for both ion components. Experimental facts say about good energy exchange between deuterium and hydrogen population. As to the electron heating, the reliable results were not obtained. This shot was made after boronization procedure of the vacuum chamber, so the hydrogen/deuterium ratio was 1:1 at plasma current 240 kA , central density $4.5{\cdot}10^{19}$ m^{-3} and input RF power 150 kW, f = 9.2 MHz. Comparison is made with shot #6739 without RF heating.

The energy spectra of hydrogen and deuterium iones are shown in Fig.5 for the end of the RF pulse (solid lines). They reveal the existence of energetic "tail" in hydrogen spectra unlike the deuterium ones. It agrees with results of numerical modeling presented in Fig.3. The analysis shows that in this tail there is confined no more than 5% of all proton population. The energy of registered tail ions does not exceed 4-6 keV, what is favorable for ion confinement and thermalization. The hydrogen temperature is determined by points lying below the bifurcation energy. The spectra obtained in the shot #6739 without RF pulse coincide completely for both ion species (see dashed blue line, empty circles and triangles).

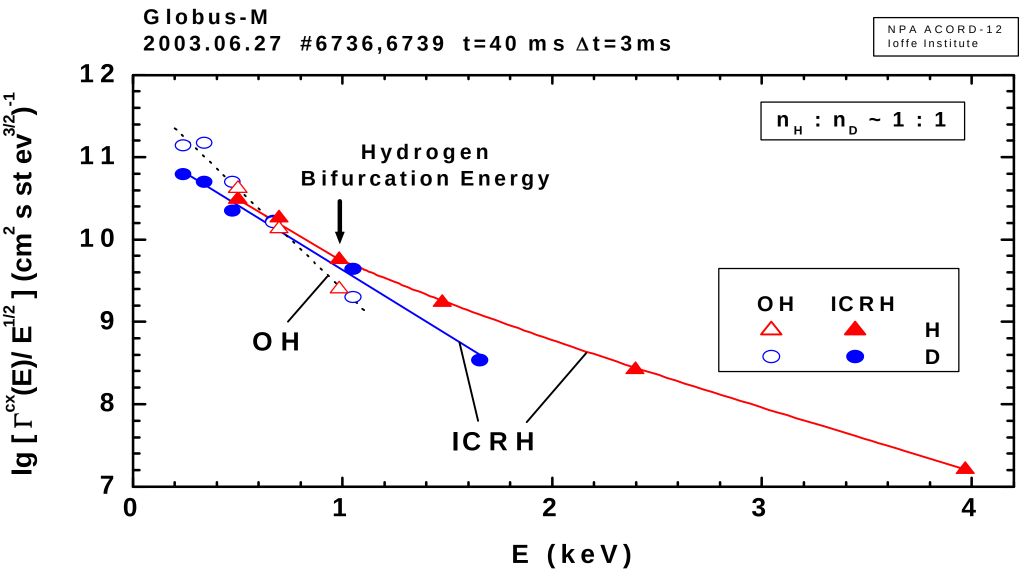

Fig.5. Energy spectra of iones with/without RF heating.

Fig.6 illustrates the other experimental situation, when one can see the explicit hydrogen heating (shot #9287, June 2004). The rise of deuterium temperature is much lower. Thermal equilibrium between ion plasma components is not reached. It should be noted that experimental conditions in this case were somewhat different: the chamber boronization was not performed, hydrogen concentration was much lower (20% – 30%), plasma current was 195 kA, P_{inp}= 150 kW, f = 8.8 MHz. Comparison is made with shot #9293 without RF pulse (dashed lines).

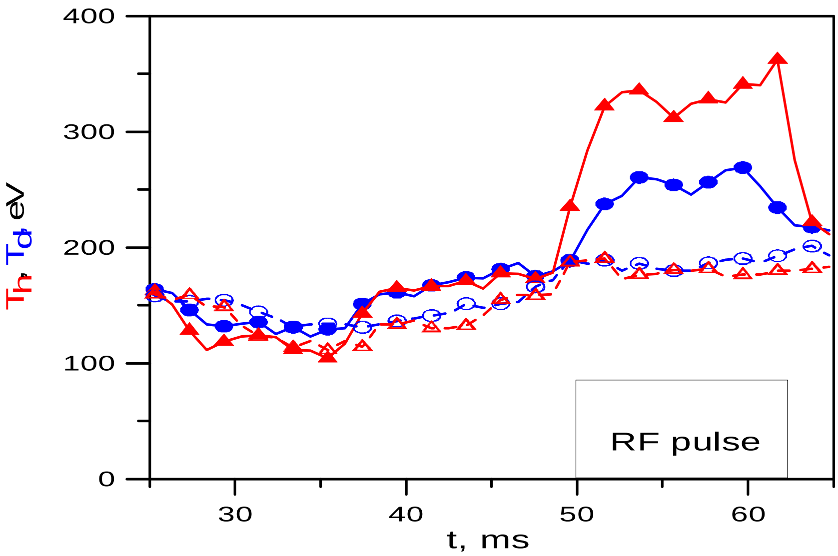

Fig.6. Evolution of ion temperature in shots #9287 and #9293.

Electron heating was not registered reliably, since RF power possibly absorbed by electrons is much lower than ohmic heating power (400 - 500 kW).

Unstable reproducibility of ion heating can be accounted for by the position of the second hydrogen harmonic. If it is located at the LFS plasma periphery, just in front of the antenna, energetic hydrogen iones can get out of the plasma very fast without energy exchange with the bulk plasma. If the resonance layer is placed deeper in the plasma, the situation should be getting better. The energetic iones are confined more effective, and larger part of RF power dissipates in inner regions of the plasma. However, the position of the resonance layer is very sensitive to a lot of discharge parameters: value and profile of plasma current, shift of magnetic surfaces, operating frequency and so on. In future experiments more attention should be paid to control of plasma parameters.

Conclusion 1.The ICRF heating experiments were started on the spherical Globus-M tokamak where conditions for several cyclotron harmonics were fulfilled simultaneously.
2.The experiments were performed with hydrogen-deuterium plasma with various ratios of ion components (with hydrogen fraction from 20% to 50%).
3. In some condition the ion temperature was almost doubled. But role of different absorption mechanisms and their dependence on discharge parameters is not clear yet

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