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The Development of the ICRF Plasma Production Scenarios in the URAGAN-3/URAGAN-3M Torsatrons

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Abstract

This paper gives an overview of the development of radio-frequency (RF) plasma production scenarios in the URAGAN-3/URAGAN-3M (U-3/U-3M) torsatrons and presents the results of experiments on plasma RF build up at the Ion Cyclotron Range of Frequencies (ICRF) with various types of antennae. The dependence of plasma production efficiency on device operation regimes, discharge parameters and antenna type is analysed. The experiments performed were aimed to find the efficient scenario of the plasma RF build up. These studies allowed to apply successfully the ICRF plasma production method for two purposes: 1) plasma RF discharge cleaning procedure, which was found to be effective for wall conditioning; 2) to produce dense target plasma for subsequent heating and sustainement.

Keywords:

torsatron, antenna, radio-frequency plasma production, ion cyclotron range of frequencies, plasma cleaning discharge

1. Introduction

The technology of plasma production in ICRF in stellarators, tokamaks and other fusion devices attracts considerable interest now, because it can be realized with the same equipment as ICRF heating. This technology, unlike others, has a number of advantages one of which is that can provide the spatial ionization of a neutral gas and the build up of dense plasma in a wide range of confining magnetic field.

The production of plasma can be realized in frequency range both below and higher than ion cyclotron (IC) frequency. The plasma production process below IC frequency is studied in details enough theoretically and in experiments (see, *e.g.* [1-5]). Theoretical results predict the applicability of this technology for large plasma devices up to reactor scale [6]. However, increase of device scale causes the decrease of heating frequency and, in a reactor scale device, it will be much lower than IC frequency.

Experiments showed the possibility to produce a plasma in the frequency range higher than IC frequency. Unlike plasma production at low frequencies, this case was not investigated enough theoretically.

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However, the possibility of use of the ICRF equipment normally planned as standard setup of every device gives an additional attractiveness to the ICRF method and fosters the continuous interest to the range of frequencies $\omega_0 > \omega_{ci}$.

This report presents the results obtained in the U-3/U-3M experiments on plasma production in both frequency range for two purposes: plasma RF discharge cleaning procedure and dense target plasma production for subsequent heating and sustainement.

2. RF Plasma Production Experiments: Results and Discussion

The U-3M device, the modification of U-3 machine, is an $l=3$, $m=9$ torsatron with major radius $R=1$ m, average plasma radius $a=12$ cm and range of magnetic field values $B_0=0.1-1.2$ T. A characteristic feature of the device is that its magnetic system (helical winding and 4 coils of vertical magnetic field) together with the supporting construction is enclosed into a large vacuum tank ($V\approx 70$ m^3) for ensureing the open helical divertor operation [1].

The results of the ICRF plasma production experiments in the U-3/U-3M torsatrons are presented in Fig. 1. These experiments were performed when the frequency of RF transmitter ω_0 was fixed and the value of confining magnetic field was varied in a wide range resulting the change of IC frequency ω_{ci}. Plasma production scenarios in wide frequency range ($0.3\ \omega_{ci} < \omega_0 < 20\ \omega_{ci}$) were realized with different antennae. At the frequency band below IC frequency ($\Omega \equiv \omega_0/\omega_{ci} < 1$, Fig. 1) the use of frame-type antenna (FTA)

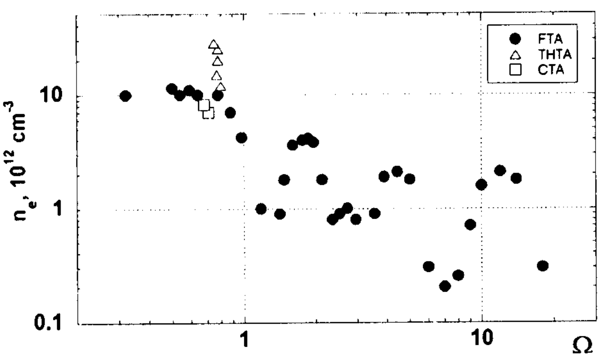

Fig. 1 The dependence of produced plasma density vs. dimensionless heating frequency $\Omega \equiv \omega_0/\omega_{ci}$. The data obtained in experiments with different type of RF antennae (FTA-circles, THTA-triangles, and CTA-squares) is summarized.

[1,5] enabled the reliable build up of plasma with densities up to 10^{13} cm^{-3} and temperatures $T_{e,i} \leq 200$ eV. With increase of plasma density the RF power deposition profile is shifted onto plasma boundary making the heating efficiency of FTA worse. Unlike FTA, the efficiency of proposed later three-half-turn antenna (THTA) [7,8] has not been reduced with increase of density that allowed to produce the plasma with density up to 3×10^{13} cm^{-3}. However, THTA weakly excites slow wave (SW) which is responsible for low density plasma build up. Thus, it requires the initial low density plasma with values of order $n_e \geq 10^{11}$ cm^{-3} from an external source. To eliminate this disadvantage and to enable the reliable production without any assistance and heating of dense plasma the crankshaft antenna (CTA) was proposed, optimized numerically for the U-3M torsatron and successfully tested in experiments [9,10]. The meander modulation of the central strap which is pertinent to CTA improves SW excitation on plasma break-down stage. Therefore, CTA has the efficiency compared to FTA one at the low density and to the THTA's one in a dense plasma.

Figure 1 shows that the highest plasma density up to $n_e \approx 3\times10^{13}$ cm^{-3} was achieved at the frequency range below the ion cyclotron frequency. This fact can be explained by the higher plasma production efficiency in this frequency range for the U-3/U-3M experimental conditions.

The plasma generated at frequencies $6 \leq \Omega \leq 20$ was used for the plasma RF conditioning of the inner surfaces of devices [11]. Plasma production process was experimentally optimized on the confining magnetic field and neutral hydrogen pressure values in order to reach maximal outgasing from inner surfaces. The conditioning was carried out by periodical pulsed RF discharges: 1 pulse per 5 secs, RF input power was 50–80 kW, discharge duration was up to 50 ms, the stationary magnetic field was within 200–300 Gs. The typical values of plasma density and temperature in RF conditioning discharges are presented in Fig.1 (frequency band $6 \leq \Omega \leq 20$) and in Fig. 2. The removal of light impurities during RF plasma cleaning discharges (RF PCD) was investigated. Application of RF PDC allowed to achieve the significant improvement of plasma parameters in the U-3/U-3M torsatrons (Fig. 3). Since usual glow discharge cleaning is uncompatible to the conditions of U-3M/U-3, the RF PCD technique was established in Kharkov torsatrons as necessary procedure not only at the beginning stage of device operation, but also between series of experimental discharges ensuring the reproducibility of discharges.

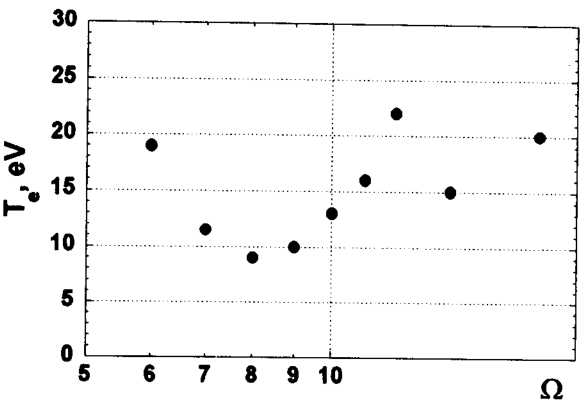

Fig. 2 The dependence of electron temperature vs dimensionless heating frequency $\Omega \equiv \omega_0/\omega_{ci}$ in RF PDC.

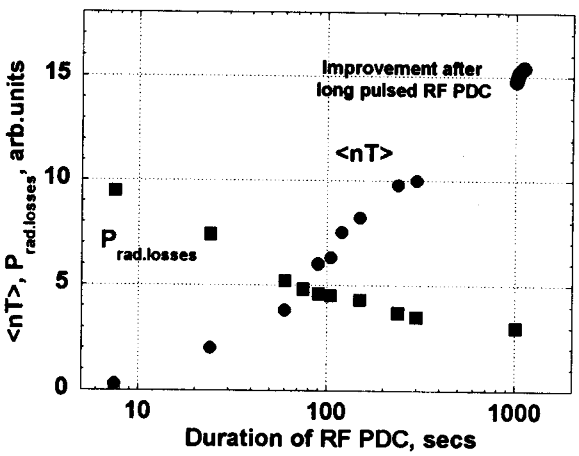

Fig. 3 The dependence of plasma energy (circles) and radiation losses due to light impurities (squares) *vs.* duration of RF PDC.

The futher improvement of plasma performance (see Fig. 3) was achieved after long pulsed RF PDC: the duration of RF discharges was extended up to 0.2–0.5 sec, confining magnetic field values within 0.4–0.5 T. In these experiments the heating frequency was below the IC frequency: $\Omega < 1$. Under this scenario of RF PDC the plasma density was significantly higher (up to $n_e \approx 10^{13}$ cm^{-3}) that allowed to increase plasma-wall interaction rate and, as a consequence, to realize more effective conditioning. During this stage of conditioning the significant reduction of recycling rate (about of factor 3) was observed. All types of antenna (FTA, THTA and CTA) were used in this RF PCD scenario.

The experiments with different antennae showed that antenna features on plasma production were in a good qualitative agreement with those predicted in numerical calculations [12,13]. However, experiments (Fig. 4) allowed to find a fairly significant quantitative difference between experimental and calculated values of plasma loading resistance for non-shielded antennas (see also [14]). This effect is explained in [14] by the presence of additional loading owing to rectified currents from plasma sheath onto the antenna being under high RF voltage.

It was experimentally found that floating (direct current (DC) disconnected from the electrical ground) RF antenna is being charged negatively and becomes as a source of impurities due to bombardment of antenna surface by ions accelerated in a plasma sheath. Meanwhile, the increase of impurities was not observed when antenna was DC grounded. The dependence of the rectified current and potential (DC voltage) of antenna vs RF current in the antenna (*i.e.* RF voltage applied to the antenna) is presented in Fig. 5. These measurements were done to study a possible way to control of the plasma particle fluxes interaction with the antenna surfaces. It was possible to drive the flux of electrons or ions on the antenna surfaces by DC grounding or disgrounding of the antenna externally using simple switching electrical scheme. The better plasma performance was achieved with DC grounded antenna, while RF PDC was carried out with disgrounded antenna in order to increase the outgasing rate. This result shows that ion fluxes on the antenna surfaces are responsible

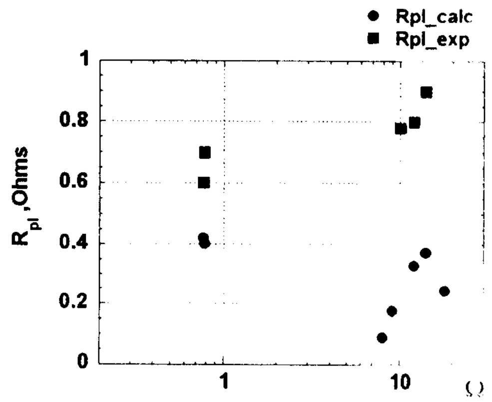

Fig. 4 The comparison of calculated plasma loading resistance values (Rpl calc – circles) to experimental ones (Rpl–exp – squares) at the different frequencies.

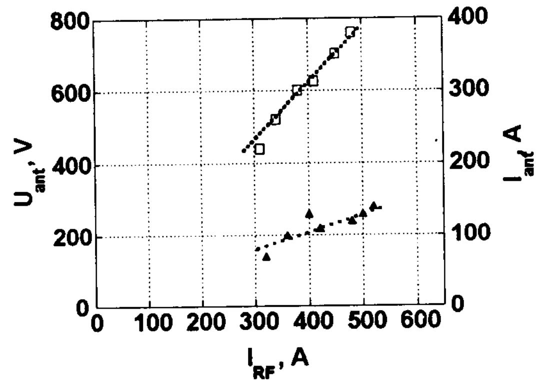

Fig. 5 The dependencies of antenna potential (squares) and rectified current (triangles) onto the RF antenna as a function of RF current in the antenna.

for the sputtering processes at the antenna and impurity release [15].

The impurity flux from the antenna surfaces during RF PDC can be substituted by a flux of appropriate atom species, for example, B_4C, if antenna is covered by plates of this material. Such a technique of external control of plasma particle fluxes is under studying now.

3. Conclusions

The results obtained can be summarized as follows:

1. The plasma with moderate density can be generated in a wide frequency range: $0.3\omega_{ci} < \omega_0 < 20\omega_{ci}$. The most efficient plasma production was realized with newly developed compact antennae in a frequency range below IC frequency. The plasma production scenario developed for this frequency range can be applied to the reactor scale devices.

2. The studies of RF Plasma Discharge Cleaning showed efficient removal of light impurities and reduction of neutral hydrogen recycling in the URAGAN-3/URAGAN-3M torsatrons. The optimal combination of the RF PDC scenarios enabled the effective conditioning in these devices and the significant improvement of plasma parameters.

The scenario of RF PDC in a low frequency range could be applied at the next generation superconductiong devices (LHD, W-7X, and ITER, as well).

3. The technique of external control of interaction between plasma particle fluxes and antenna surfaces seems very promising in order to carry out the boronization with hard source in RF plasma discharges during RF PDC.

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