RADIO-FREQUENCY PLASMA START-UP AT URAGAN-3M STELLARATOR

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A double frame antenna with a broad spectrum of parallel wavenumbers (with respect to the magnetic field) is used for radio-frequency (RF) plasma production in Uragan-3M stellarator type device. The delay between the start of RF pulse and the discharge development (breakdown (delay) time) is analyzed as functions of the magnetic field strength, neutral gas pressure and anode voltage of the RF generator. The reproducibility of the RF discharges is improved by the pre-ionization by the pulse of the three-half-turn antenna preceding the main RF pulse. The pre-ionization also results in shortening of the breakdown time for the frame antenna. The Langmuir probe measurements are made with two probes located at the plasma edge near and far from the double frame antenna. The measurements give rather high edge electron temperature, about 100 eV, at the initial stage of the frame antenna discharge both near and far from the antenna. The information on the plasma build-up is also given by the H_α chord measurements.

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INTRODUCTION

Plasma production at the ion cyclotron range of frequency (ICRF) is used at a number of tokamaks and stellarators to initiate wall conditioning discharges. At Uragan family of stellarators (see, e.g. [1]) the ICRF plasma production is a main tool to create target plasma at regular shots. Several previous studies [2-5], both theoretical and experimental, were focused on discovering the physical nature of the plasma creation. The points of the physical picture described in above mentioned papers are briefly the following.

- It is important that few initial charges exist in the plasma confinement volume. They naturally appear from the background radiation. The electrons oscillate in the antenna near-field and make an avalanche if the oscillating energy exceeds the ionization threshold.
- When the low density plasma is created, the process of plasma production proceeds owing to ionization of the neutral gas by electron impact in relatively hot plasma. The energy losses induced by inelastic collisions of the electrons with neutral gas are compensated by RF heating.
- At low plasma densities the RF heating is made by the slow wave, which should be propagating.
- After reaching some plasma density level, the fast wave comes to play. Alfvén resonances, which generate the slow wave inside the plasma core, are important for further plasma production.

Based on this, one can build a simplified physical picture for an atomic gas and ions in a single charged state. Hydrogen is a molecular gas, and presence of the molecular ions (H_2^+, H_3^+) in addition to atomic ion H^+ makes the process of wave propagations more complicated.

A number of experiments on plasma production were made at Uragan-3M (U-3M) stellarator type device, which has a huge vacuum tank. When it is filled by hydrogen with the continuous gas puff, this tank contributes to 'exchange' of generated in plasma atoms with molecules. This is confirmed by analysis of Balmer series [6], which has molecular origin. The 'exchange' promotes molecular ions formation in weakly ionized plasma. Anyway, plasma production is successful in U-3M device.

The present U-3M experimental campaign for plasma production studies is motivated by an insufficient understanding of the role of molecular plasma content in plasma production.

EXPERIMENTAL SETUP

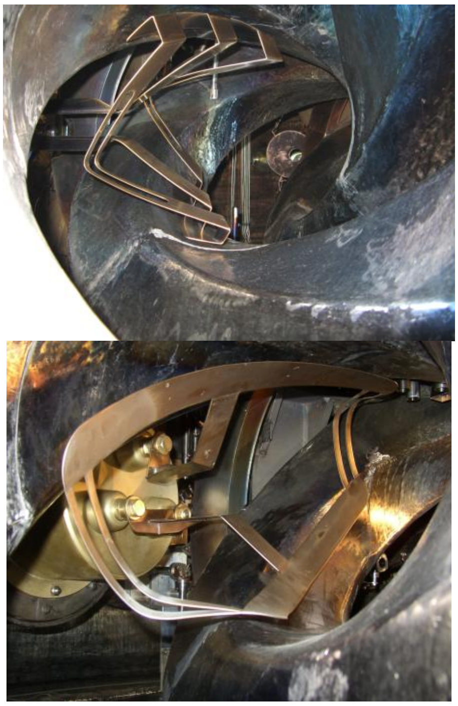

Fig. 1. Three-half-turn (THT, top) and double frame (bottom) antenna

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The experiments on ICRF discharge initiation were performed in frame of the EU (Belgium) – Ukrainian collaboration on ICRF plasma production studies. The double frame antenna with a broad spectrum of parallel wavenumbers (with respect to the magnetic field) [7] (Fig. 1) was operated at f= 8.6 MHz, variable RF power (P=15…130 kW, anode voltage of generator, U_{k1}=3…9 kV), confining magnetic field B_0=0.01…0.72 T to produce RF plasma in hydrogen at a continuous gas puff with pressure range $p_{H2}\approx7.5\cdot10^{-6}…1.5\cdot10^{-4}$ Torr. The three-half-turn (THT) antenna is used for pre-ionization to increase reproducibility of the discharges.

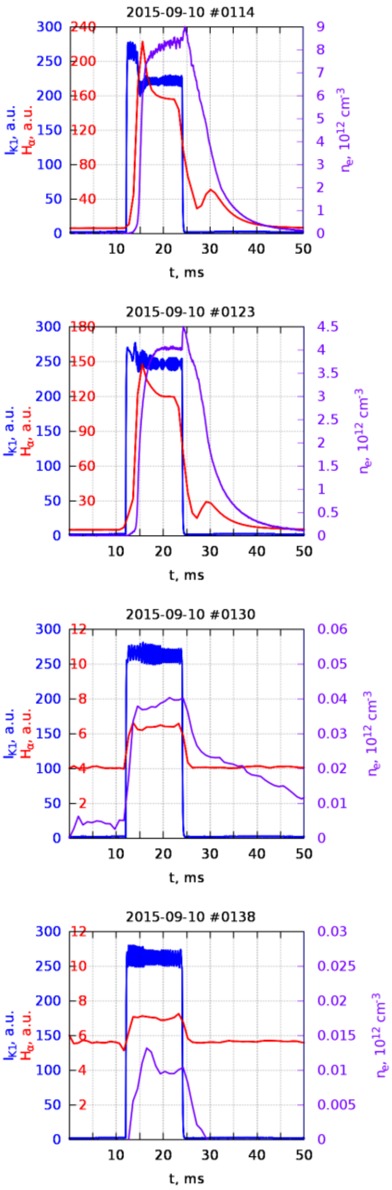

Fig. 2. Antenna current I_{k1}, H_α intensity and average plasma density evolutions given by interferometer for different steady magnetic field values (from up to down): 7.1, 6.5, 5 and 3 kG. t_{K1}=(10;25) ms, p_{H2}=4·10^{-5} Torr

It should be mentioned that sustaining a fully ionized hydrogen RF plasma takes place in the Alfvén wave range of frequencies ($\omega < \omega_{ci}$) for the given RF generator frequency at higher magnetic fields (B_0=0.72 T). The hydrogen gas RF breakdown moment is characterized by dominant concentration of the hydrogen molecular ions H_2^+ [8]. These result are in the breakdown performance in the U-3M in the frequency range $\omega>\omega_{ci}$, which allows existence of the LHR for all tested B values.

RF PLASMA PRODUCTION

The plasma of density up to 10^{19} m^{-3} is created when the frequency is in the range f=0.7-0.9 f_{ci}, where f_{ci} is the ion cyclotron resonance frequency. When f>0.9 f_{ci} the plasma is also produced, but with substantially lower density (Fig. 2). This could be explained by absence of the Alfvén resonances in the plasma column, which possibly are responsible for further plasma density increase. The range f<0.7 f_{ci} cannot be achieved without tuning down the generator frequency since reaching the upper technical limit of the confining magnetic field.

PROBE MEASUREMENTS

To measure local parameters of the boundary plasma (floating potential V_f, electron temperature T_e, electron density n_e), two movable arrays of electric (Langmuir) probes were used. Each array includes two single probes (diameter of probe collecting area 1 mm, length 2 mm, molybdenum) with the distance between the probes 3 mm. One probe is used to record the floating potential, another one – to get the I-V characteristic. One of the arrays (“vertical probes”, VP) is inserted into the vacuum chamber from the top in a poloidal cross-section close to A1 (Fig. 3) and can be moved vertically, passing at the distance of ~3 cm from the frame antenna edge. When making measurements, this array was fixed at the distance of 14.5 cm from the torus midplane, not reaching <0.5 cm the calculated last closed flux surface ([9], Fig. 4,a, position “near the antenna”). Another array (“horizontal probes”, HP) is inserted from the outboard side of the torus in the helical period 8 (see Fig. 1) in the poloidal cross-section 1.8 period-distant from the cross-section D1 in which the antenna feeding point is located.

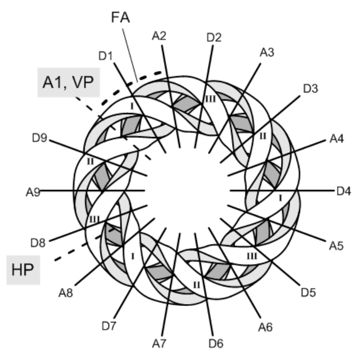

Fig. 3. Helical coils I, II, III of U-3M. Indicated are symmetric poloidal cross-sections A1, D1, A2, D2,…, A9, D9 in helical periods 1, 2, …, 9, respectively, disposition of the double frame antenna. Radial dashed lines indicate poloidal cross-sections where movable arrays of electric probes are inserted (VP in period 9, near A1; HP in period 8, between D8 and A8)

This array can move horizontally parallel to the major radius R at the distance of 2 cm over the midplane. During measurements HP were fixed at the distance of 9.25 cm from the vertical axis of the cross-section, corresponding to the distance <0.5 cm from the calculated plasma boundary (Fig. 4,b, position "far from the antenna").

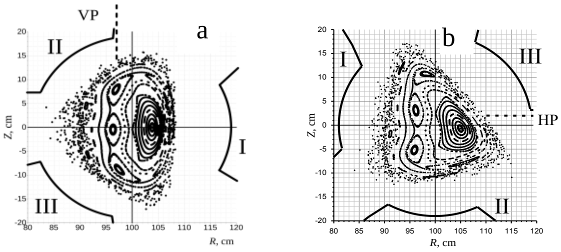

Fig. 4. Disposition of movable probe arrays VP (a) and HP (b) in poloidal cross-sections of the U-3M torus and lines of probe displacement (dashes) relative to the helical coils I, II, III and calculated Poincare plots of magnetic lines of force in these cross-sections [10]

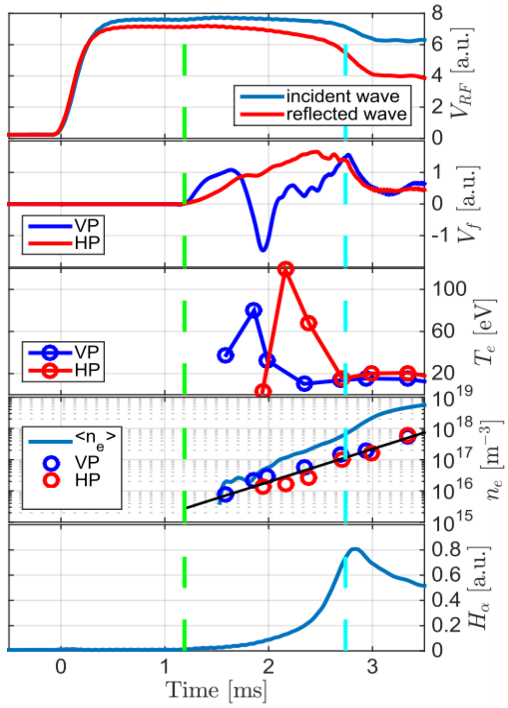

Fig. 5. Experimentally observed indications of gas breakdown (green vertical dashed line) during RF plasma start-up in U-3M for shot at U_{k1}=6 kV, p_{H2}=4.7·10^{-5} Torr and B_0=0.72 T. Time traces of forward (blue) and reflected (red) directional coupler signals, average electron density, and H_α signal, floating potential registered by the Langmuir probes, average plasma density by interferometer and electron temperature T_e and electron density n_e by LPs obtained in a series of identical shots

The values of V_f, T_e and n_e were determined as a result of processing the ion branch of the probe I-V characteristic where the "ideal" relation (see, e.g., [10]) $I(V) = I_s\{1\text{-}\exp[(V\text{-}V_f)/T_e]\}$ was fitted to the experimental characteristic. Here $I(V)$ is the current to the probe at the bias voltage V, I_s=0.5$An_ee(2k_BT_e/m_i)^{1/2}$ is the ion saturation current, A is the probe collecting area.

Fig. 5 shows the plots of the $V_f(t)$, $T_e(t)$ and $n_e(t)$ values derived from the I-V characteristics taken near and far from the antenna at different time moments after RF discharge ignition. In a qualitative consistence with the time evolution of signals in Fig. 5, the antenna-near floating potential V_f changes its polarity twice after ignition and finally attains the level of ~+15 V close to the "quasistationary" one in ~3.5 ms. The temperature T_e achives a maximum value of 80 eV (which is remarkably high for weakly ionized plasma), drops down to ~10 eV and stays at this level with minor variations later. The density n_e increases continuously from values order of 10^{15} m^{-3}, passes (2…3)·10^{16} m^{-3} in the T_e maximum and achieves a "quasistationary" level of ~7·10^{17} m^{-3}.

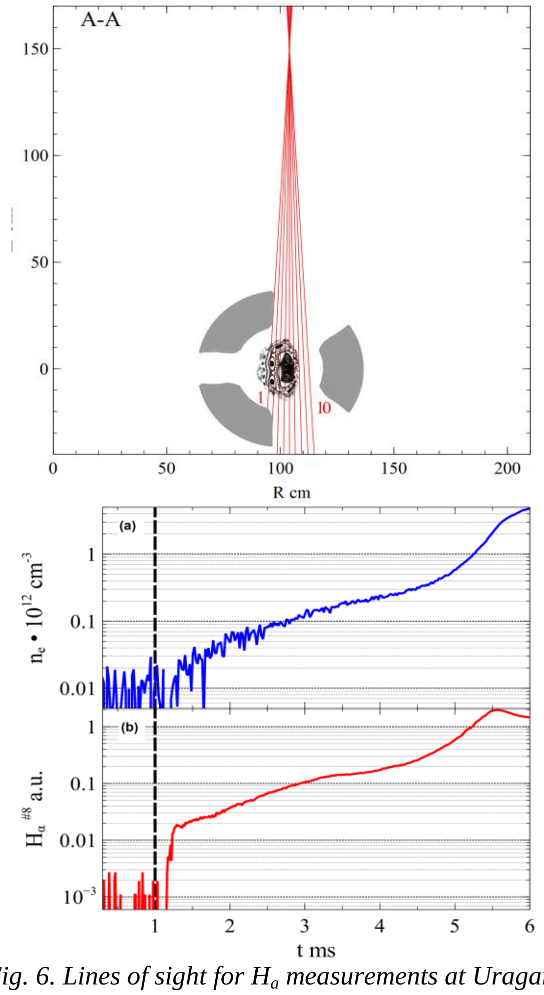

Fig. 6. Lines of sight for H_α measurements at Uragan-3M poloidal cross-section (top). Evolution of (a) line-averaged density and (b) H_α emission (bottom), dashed line marks the RF power switching-on time. U_{K1}=5.5 kV, p_{H2}=1·10^{-4} Torr, B_0=0.72 T

The potential V_f far from the antenna, contrary to its behavior near the antenna, does not change the polarity, all time is positive, attains a maximum of 80 V and then falls to ~10 V in the "quasistationary" phase. Similar to the $n_e(t)$ behavior near the antenna, the density increases continuously from ~10^{16} m^{-3} at t=1.8 ms, i.e. near the start of T_e rise, and reaches ~8·10^{17} m^{-3} in the "quasistationary" stage.

Accounting for a not very high accuracy of probe measurements, one may state that the maximum values of T_e and n_e obtained near and far from the antenna, as well as the values of these parameters at the start of the "quasistationary" stage, are close by the order of magnitude. It seems important to note that the T_e maximum far from the antenna is ~0.2 ms delayed relative to the maximum near the antenna.

Floating potential of VP is most sensitive to a dense plasma appearance, and the gas breakdown time can be calculated as a time delay between the antenna RF voltage apply and its first (weak) reaction on the plasma loading appearance due to SW excitation in weakly ionized plasma, $\omega>\omega_{ci}$, (see the green dashed vertical line in Fig. 5, also the first burst in the H_α signal clearly seen in Fig. 6 than in Fig. 5 due to larger scale). Other indication of the start-up could be antenna load (blue vertical dashed line) or H_α burst. The blue vertical dashed line in Fig. 5 indicates the second and more prominent reaction on plasma loading by the antenna RF signals and plasma parameters due to AW excitation ($\omega < \omega_{ci}$) in a denser and fully ionized plasma. The latter is confirmed by achieving a maximum in the H_α signal in a more developed phase of the RF discharge (see Figs. 5 and 6).

In Fig. 5 the difference between the average plasma density, which is evaluated from the interferometer measurements, and the edge densities is smaller at start and larger at the end of plasma build-up. This indicates the fact that after ignition the density radial distribution is becoming more peaked towards the plasma core. The radial plasma expansion from the LFS (ICRF antenna side) towards HFS just after gas breakdown was earlier discovered in JET with high-resolution fast CCD camera [11].

H_α CHORD DISTRIBUTION

H_α chord distribution is measured by multi-chord H_α detector array [12]. The scheme of measurements is presented in Fig. 6.

Bottom part of this figure shows integral H_α and average plasma density evolutions.

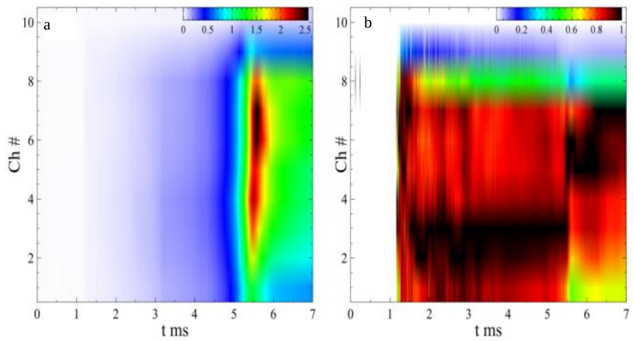

Fig. 7. Evolution of (a) H_α profile and (b) H_α profile normalized to its maximum in every discharge instant

As it is seen in Fig. 7, the H_α emission profile looks more hollow at the beginning than after plasma build-up. However, the emission is volumetric what indicates that plasma fills in the whole plasma volume.

PARAMETER SCAN

In the series of experiments dense plasma build-up delay time is investigated as a function of hydrogen gas pressure (Fig. 8).

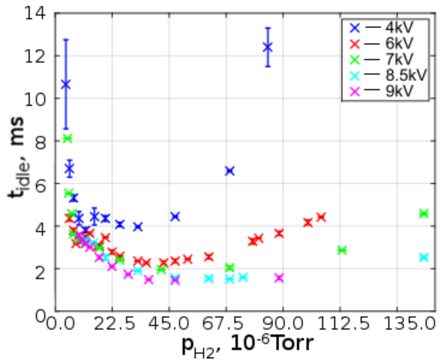

Fig. 8. The dense plasma build-up delay time dependence on the varying neutral gas pressure for different generator anode voltages

The results show the existence of an optimal value for the pressure which provides the lowest breakdown time for each antenna voltage. This optimal pressure is shifting towards higher pressures with the increasing antenna load. The delay time increases before reaching the highest and lowest pressure for each anode voltage value. For high pressures there is a threshold anode voltage. As it is seen from Fig. 8, e.g. for p_{H2}=8.25·10^{-5} Torr the threshold voltage is U_{k1}=4 kV.

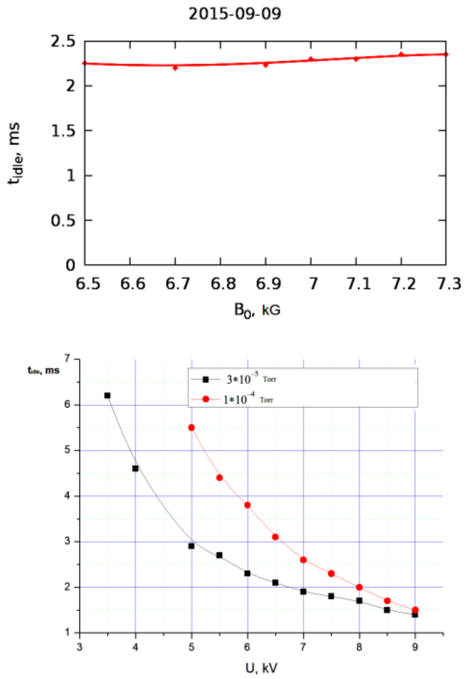

Fig. 9. The dense plasma build-up delay time dependence on the magnetic field (top, p_{H2}=2.5·10^{-5} Torr) and the anode voltage (bottom, B=7.2 kG)

The delay time is almost independent on the magnetic field value (Fig. 9). It is decreasing with increasing magnitude of the RF voltage at antenna.

ROLE OF PRE-IONIZATION

The reproducibility of the discharges is improved by a pre-ionization which is made by the pulse of the three-half-turn antenna preceding the main RF pulse. This antenna creates the plasma of the density $n_e \geq 10^{16}\,\mathrm{m}^{-3}$. The time between the THT antenna pulse end and the double frame antenna start, t_{gap}, (Fig. 10) is varied in the experiments.

The pre-ionization results in shortening of the plasma creation time (Fig. 11). It effects on the double frame antenna discharge even if t_{gap} is long.

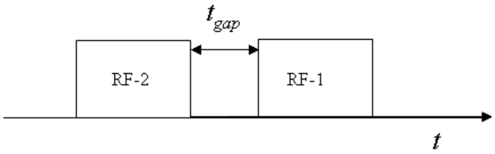

Fig. 10. Sequence of RF pulses of THT antenna (RF-2) and double frame antenna (RF-1)

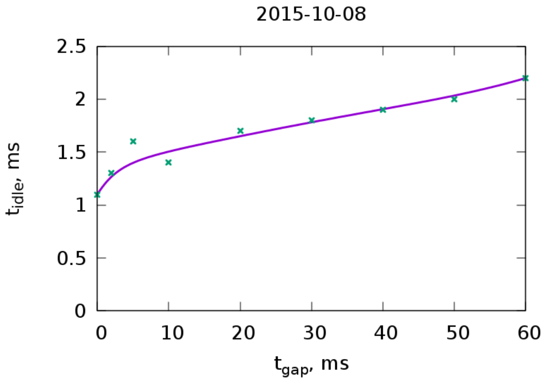

Fig. 11. Dense plasma build-up delay time as a function of time between RF pulses. B_0=7.2 kG, $p_{H2}=2\cdot10^{-5}$ Torr, U_{K1}=6 kV, U_{K2}=5 kV

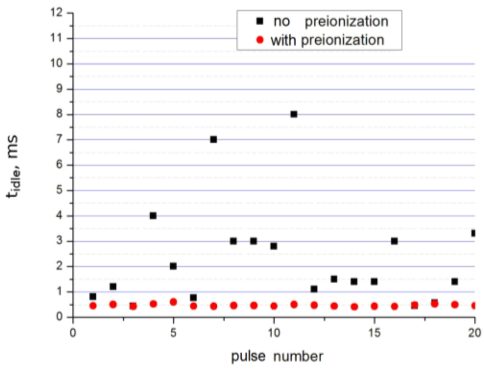

Fig. 12. Breakdown delay time for repetitive pulses with and without pre-ionization

Fig. 12 illustrates both shortening of the breakdown time effect and substantial increase of discharge repeatability.

DISCUSSIONS

The mechanism of plasma production is not fully clear so far. The difficulties in understanding related to existence of the molecular ions which cyclotron frequency is lower than the heating frequency. If the molecular ions dominate the Lower Hybrid Resonance (LHR) appears in the plasma column at low plasma density, $\sim10^{15}\,\mathrm{m}^{-3}$ in our case. With increase of atomic ion content, this density value increases. The slow wave launched by an antenna travels to LHR position and is absorbed there without reflections (see, e.g. [13]). Since there are no heating behind the LHR location, the plasma density profile should be strongly hollow or peaked at the LFS. Following this, H_α chord profile should also be hollow or maximized at the LFS. In experiment we see no more than proximity of the periphery plasma density value to the average plasma density at the early stages of the discharge. These witnesses rather for the volumetric plasma generation than for plasma production only at the plasma edge with further diffusion of it inside the confinement volume. Similar could be concluded from the H_α emission profile.

An important moment is that the measured electron temperature is high when plasma density is low. For high parallel wavenumbers in hot plasma, for the slow wave the wave cut-off and propagation zones swap if the parallel phase velocity of the wave is lower than the electron thermal velocity. In such a case, a wave, being excited by the antenna, penetrates through the cut-off region at the plasma periphery, passes through LHR layer with only partial damping and propagates to the plasma core where it could be absorbed. The transition margin to this regime is established by a certain electron temperature, and for U-3M it is 100 eV [5]. In such a way, the volumetric plasma production is possible. However, more experiments are needed to clarify whether this effect is important.

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РАДИОЧАСТОТНОЕ СОЗДАНИЕ ПЛАЗМЫ В СТЕЛЛАРАТОРЕ УРАГАН-3М

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Рамочная антенна с широким спектром параллельных волновых чисел (по отношению к магнитному полю) используется для высокочастотного (ВЧ) создания плазмы в установке стеллараторного типа УРАГАН-3М. Задержка между началом ВЧ-импульса и моментом развития разряда (время (задержки) пробоя) анализируется как функции величины магнитного поля, давления нейтрального газа и анодного напряжения ВЧ-генератора. Воспроизводимость ВЧ-разрядов повышается за счёт предварительной ионизации с помощью трёхполувитковой антенны, которая запускается перед основным ВЧ-импульсом. Предварительная ионизация также приводит к уменьшению времени пробоя. Измерения температуры и плотности плазмы выполнены двумя Ленгмюровскими зондами, расположенными на краю плазмы вблизи и вдали от рамочной антенны. Измерения дают достаточно высокую температуру электронов, около 100 эВ, на начальном этапе разряда как вблизи, так и вдали от антенны. Информация о создании плазмы также дают хордовые измерения линии H_{α}.

РАДІОЧАСТОТНЕ СТВОРЕННЯ ПЛАЗМИ В СТЕЛАРАТОРІ УРАГАН-3М

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Рамкова антена з широким спектром паралельних хвильових чисел (по відношенню до магнітного поля) використовується для високочастотного (ВЧ) створення плазми в установці стелараторного типу УРАГАН-3М. Затримка між початком ВЧ-імпульсу і моментом розвитку розряду (час (затримки) пробою) аналізується як функції величини магнітного поля, тиску нейтрального газу і анодної напруги ВЧ-генератора. Відтворюваність ВЧ-розрядів підвищується за рахунок попередньої іонізації за допомогою тринапіввиткової антени, яка запускається перед основним ВЧ-імпульсом. Попередня іонізація також призводить до зменшення часу пробою. Вимірювання температури і густини плазми виконані двома Ленгмюрівськими зондами, розташованими на краю плазми поблизу і на віддаленні від рамкової антени. Вимірювання дають досить високу температуру електронів, близько 100 еВ, на початковому етапі розряду як поблизу, так і на віддаленні від антени. Інформацію про створення плазми також дають хордові вимірювання лінії H_{α}.