# THREEHALF-TURN ANTENNAS START-UP

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The start-up experiments were carried out at Uragan-2M stellarator with the Three-Half-Turn antenna (THT) without any pre-ionization. Conditions for optimal gas breakdown were found out through the variation of the neutral gas pressure, magnetic field strength and anode voltage of RF generator. The plasma parameters were measured with three Langmuir probes, optical spectroscopy and mutichord optical diagnostics.

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## INTRODUCTION

Plasma heating at the ion cyclotron range of frequency (ICRF) is not the most promising technique nowadays, and it is used for hot plasma studies. This means that devices with ICRF equipment can create plasma target for other heating methods. RF plasma start-up experiments were carried out at Uragan-3M [1]. Current work is devoted to Three-Half-Turn (THT) [2] antenna start-up experiments at Uragan-2M stellarator.

THT antenna has 3 straps oriented perpendicular to the magnetic field lines. Each strap is aligned to the form of the last closed magnetic surface and is placed at 2 cm distance from it. Straps are 8 cm wide and 90 cm long. The THT antenna is fed through the central strap. THT antennas routinely are used for plasma heating [3, 4]. The research task was to study independent RF plasma creation with THT antenna in Uragan-2M with use of Uragan-3M [5, 6] experience.

## EXPERIMENTAL SETUP

*Fig. 1. THT antenna was made from crankshaft one by replacing central crankshaft strap with the straight one*

Uragan-2M is a stellarator of the torsatron type ($l$=2, $m$=4) which has the additional toroidal and compensating vertical magnetic fields.

The crankshaft antenna was installed between toroidal coils along the longer plasma column side until 2017 experimental campaign. Then it was modified into THT antenna (Fig. 1) substituting the central crankshaft strap with the straight one.

## MEASUREMENTS

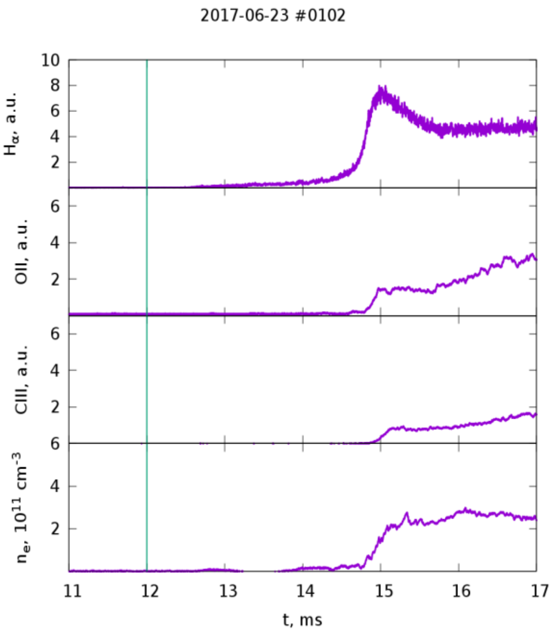

*Fig. 2. Typical THT Antenna Discharge. $H_\alpha$, OII and CIII emission lines were measured with 4-channel optical monochromator $n_e$ – with 2 mm interferometer. Kaskad-1 RF-generator start is shown with vertical line. $U_{K1}$=7 kV, $p_{H2}$=6.2·$10^{-6}$ Torr*

The experiments on ICRF discharge initiation were performed at variable RF power ($P$=50…100 kW, anode voltage at generator, $U_{k1}$=5…7 kV), confining magnetic field $B_0$=0.4 T, $k_\varphi$-0.32 to produce RF plasma in hydrogen at a continuous gas puff with pressure range $p_{H_2}$≈7.5·$10^{-6}$…1.5·$10^{-4}$ Torr. The density $n_e$ increased continuously from units $10^9$ cm$^{-3}$, passes (2…3)·$10^{12}$ cm$^{-3}$ in the $T_e$ maximum and achieved a "quasistationary" level of ~7·$10^{11}$cm$^{-3}$. Plasma was monitored with $H_\alpha$, OII and CIII optical emission lines during constant parameters change (Fig. 2). The optimal regimes were measured in details with Langmuir probes and multichord optical diagnostics.

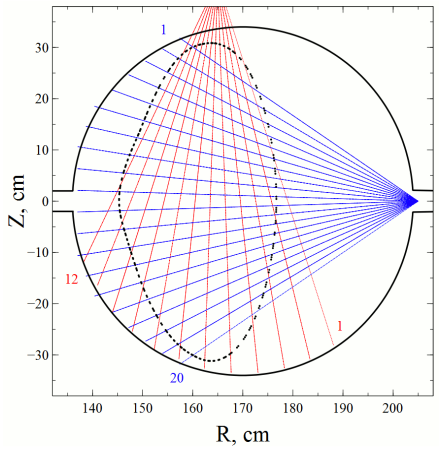

*Fig. 3. Chords (red – top, blue – side) overview for both bolometers of $H_\alpha$ multichannel diagnostics*

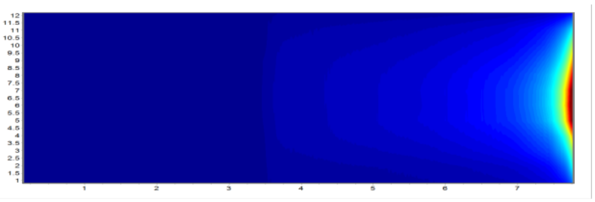

*Fig. 4. 12 $H_\alpha$ channels as seen with multichold diagnostics during startup. Magnetic field $B_0$=3700 Oe, $k_\varphi$=0.337, $p_{H_2}$=7.2·10$^{-6}$ Torr, Kaskad-1 T=12;25 ms, P=50…100 kW*

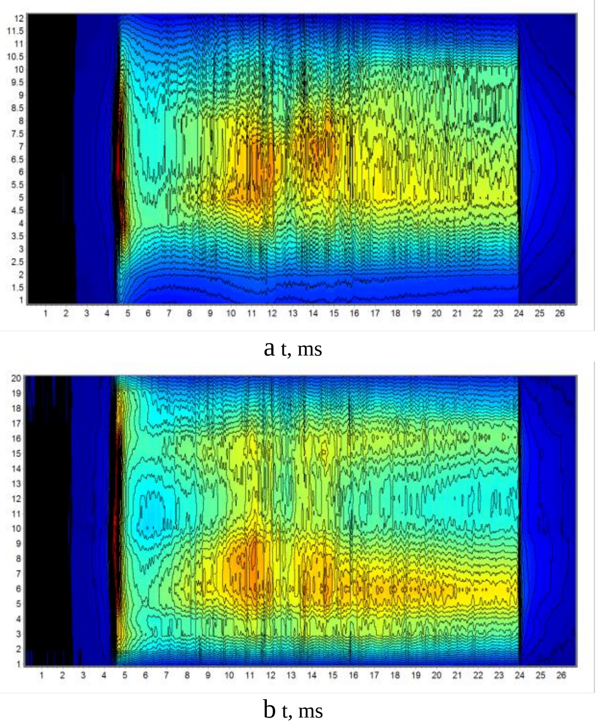

*Fig. 5. Total light emission for top (a) (red chords) and side (b) (blue chords) views*

Two multichannel pinhole cameras were installed in Uragan-2M for monitoring the distributions of visible light emission from two positions in the same plasma cross-section (Fig. 3). The plasma column $H_\alpha$ emission profile (Fig. 4) clearly shows the plasma creation in the camera centre. The luminous region splitting at the side view of total light emission (Fig. 5) is interpreted as the light reflection from vacuum chamber smooth metallic wall.

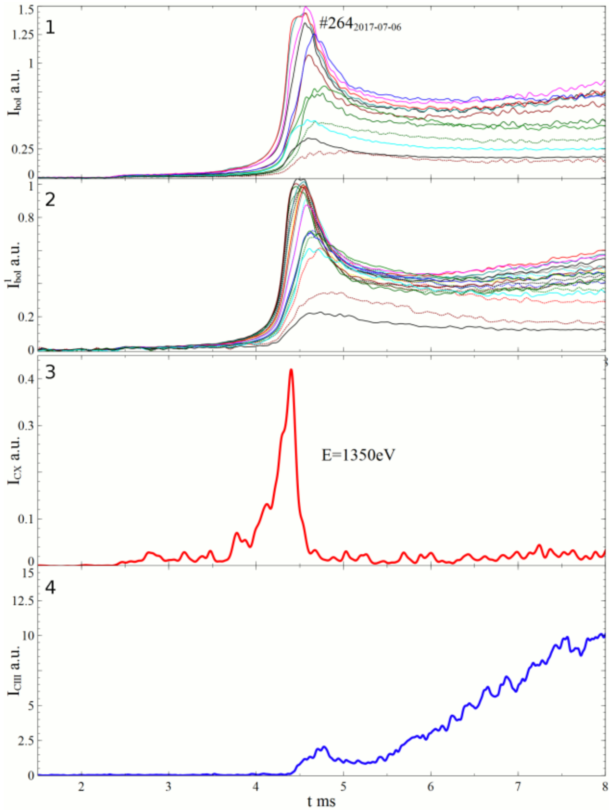

*Fig. 6. Startup evolution of total light emission from side view (1), top view (2), charge exchanged atoms flux with 1350 eV energy (3), and CIII emission (4)*

Neutral Particle Analyser (NPA) signals were measured with the same hardware used at Uragan-3M [7]. The peak of NPA signal coincided with the initial ionisation peak of the optical chords signals (Fig. 6). The signals of four different energies from NPA diagnostics (Fig. 7) were read during the sequential discharges with the same conditions. Uragan-2M device parameters are highly persistent which manifests itself in high reproducibility of discharges.

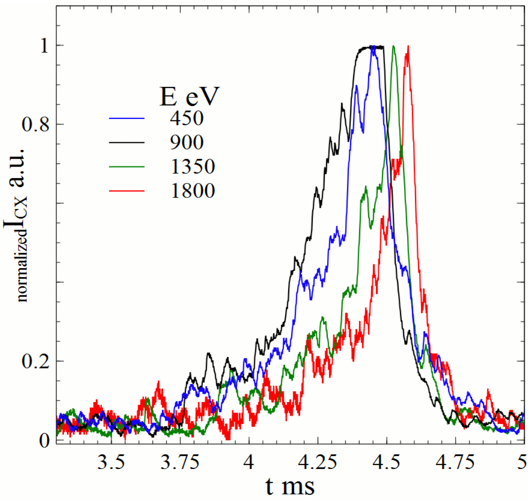

*Fig. 7. NPA signals in the set of similar discharges. CX flux with higher energy appears later*

## GAS BREAKDOWN DELAY DEPENDENCES

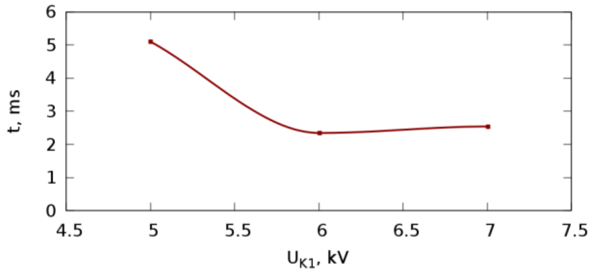

*Fig. 8. Gas breakdown delay dependence from voltage ($p_{H2}$=6.2·10$^{-6}$ Torr, $B_0$=0.37 T, $k_\varphi$=0.337)*

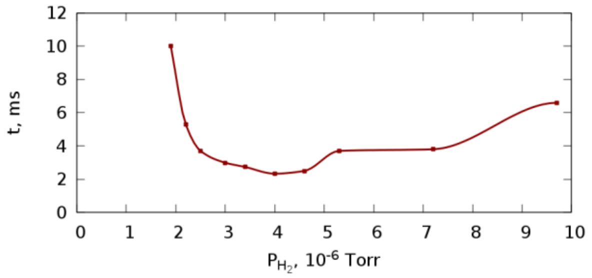

*Fig. 9. Gas breakdown delay dependence from neutral gas pressure ($U_{K1}$=6 kV)*

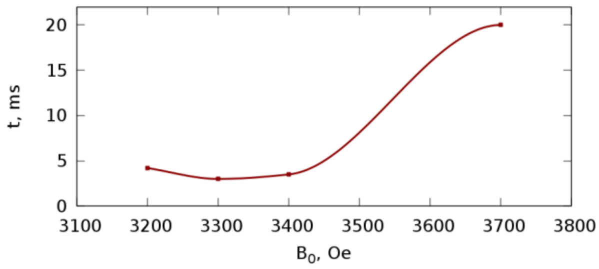

*Fig. 10. Gas breakdown delay dependence from magnetic field ($U_{K1}$=6 kV, $p_{H_2}$=6.2·10$^{-6}$ Torr)*

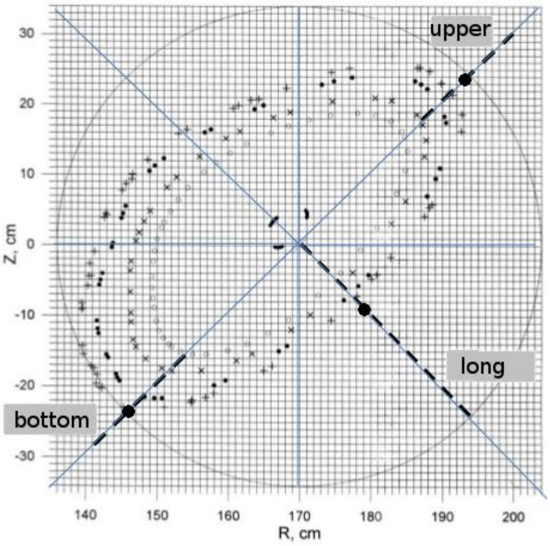

*Fig. 11. Langmuir probes positions (fat dots) in cross-section between toroidal coils. Closed magnetic surfaces are shown for $k_\varphi$=0.31, B/$B_0$=1.85 %*

The step by step change of discharge parameters allowed to summarize results as the gas breakdown dependencies of each parameter pass. Every pass parameter was changed until the boundaries of the discharge existence were found.

Dependencies are shown at Figs. 8-10. RF generator anode voltage dependency (see Fig. 8) shows the slump during RF-generator anode voltage change from 5 to 6 kV and stable values at higher voltages. The fnode voltage was bounded above with 7 kV for the safety reasons. The neutral gas pressure dependency measurements (see Fig. 9) were limited with safe RF-generator impulse duration and includes measured delay times less than 10 ms. The magnetic filed dependency (see Fig. 10) shows RF-discharge existence range. There was no gas breakdown at <3200 and >3700 Oe magnetic fields.

## LANGMUIR PROBE MEASUREMENTS

Three probes measured plasma properties in the same cross-section (Fig. 11). The upper and the bottom probe were aligned along the vacuum camera surface and the long probe was placed 15 cm far from the wall. Each measurement (Fig. 12) shows electron temperature and density measured with Langmuir probe during Kaskad-1 discharge. The measurement time range was limited with diagnostics sensitivity. Each signal time evolution shows electron temperature and density of already created plasma during the whole RF discharge. It is the evidence of plasma heating and close to working discharges density that was created even with the single THT antenna.

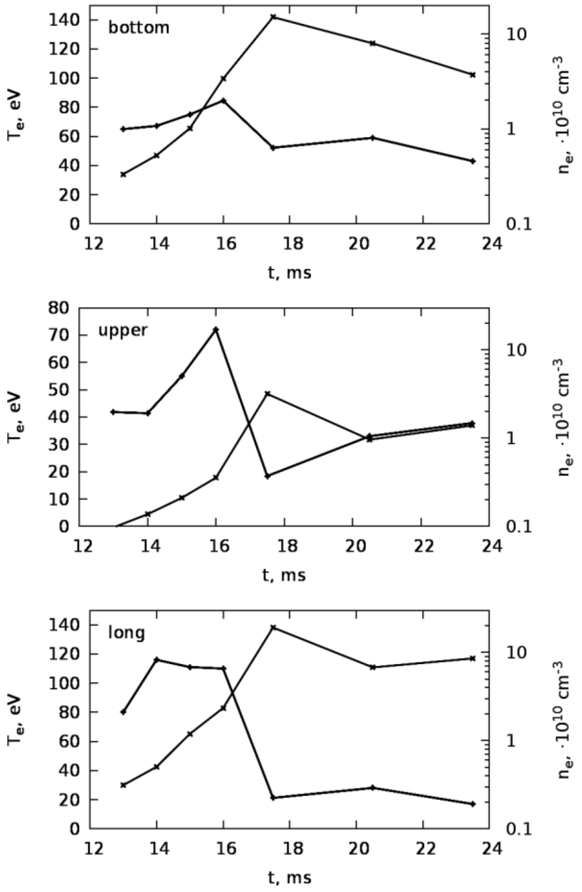

*Fig. 12. Values based on bottom, upper and long Langmuir probe measurements. Consecutive Langmuir probe measurements of electron temperature and density at one cross-section*

## CONCLUSIONS

The experimental conditions at Uragan-2M were changed through the variation of magnetic field, pressure and RF-generator parameters in order to find the optimal regime of THT antenna start-up. The optimum magnetic field was 0.37…0.38 T while standard field was 0.4…0.42 T.

THT antennas was capable of creating dense plasma at decreased compared to the regular regime magnetic fields, but with long idle time what is dangerous for antenna insulators because of high voltage at the antenna elements.

The electron plasma density and temperature were measured with Langmuir probe, the electron temperature was observed in real time with the separate spectral lines, the electron plasma density was measured in real time with microwave interferometer and multi-chord visible light diagnostics showed the shape and position of the plasma column.

The existence of cyclotron zone that crosses the closed magnetic surface creates conditions for Alfven resonance at low plasma density where the relay race occurs. The success of THT antenna startup experiments showed fullfillment of these conditions in the range of experimental parameters.

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## СТАРТ ТРЁХПОЛУВИТКОВОЙ АНТЕННЫ

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На стеллараторе Ураган-2М были проведены моделирующие эксперименты по старту трёхполувитковой (ТПВ) антенны без предионизации. Подбором давления нейтрального газа, напряжённости магнитного поля и анодного напряжения ВЧ-генератора были найдены оптимальные условия пробоя газа. Параметры плазмы измерялись тремя ленгмюровскими зондами, оптической спектроскопией и многохордовой оптической диагностикой.

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## СТАРТ ТРЬОХНАПІВВИТКОВОЇ АНТЕНИ

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На стелараторі Ураган-2М було проведено модельні експерименти зі старту трьохнапіввиткової (ТНВ) антени без предіонізації. Підбором тиску нейтрального газу, напруженості магнітного поля й анодної напруги ВЧ-генератора було знайдено оптимальні умови пробою газу. Параметри плазми вимірювались трьома ленгмюрівськими зондами, оптичною спектроскопією та багатохордовою оптичною діагностикою.