

*PLASMA HEATING AND CURRENT DRIVE*  
**RF HEATING BELOW ION-CYCLOTRON FREQUENCIES**  
**IN URAGAN TORSATRONS**

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The experiments on Uragan-3M torsatron (stellarator) on Alfvén resonance heating are presented. Usage of the three-halfturn antenna provides plasma density increase and heating of the electron plasma component.

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Uragan-3M is a small size torsatron with  $l=3$ ,  $m=9$ ,  $R_0=1$  m major radius,  $\bar{a} \approx 0.12$  m average plasma radius and toroidal magnetic field  $B_0 \leq 1$  T. The whole magnetic system is enclosed into a large 5 m diameter vacuum chamber. The Alfvén resonance heating in a high  $k_{\parallel}$  regime is used on this machine. This method of heating is advantageous for small size devices since the heating can be accomplished at lower plasma densities than the minority and second harmonic heating. Uragan-3M is equipped with two antennas. One is a frame-type antenna for low density plasma production. Another antenna in Uragan-3M is an unshielded THT (three-half-turn) antenna [1] that consists of 3 straps oriented in poloidal direction.

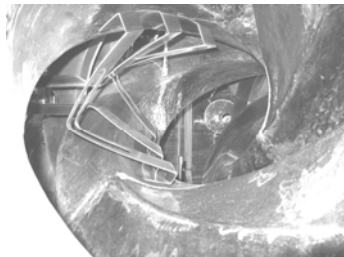
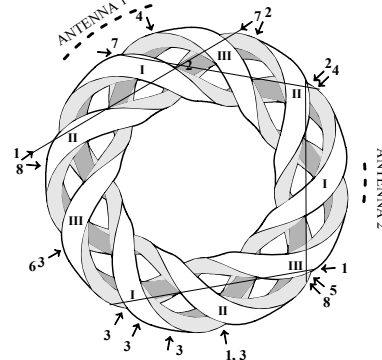


Fig. 1. THT antenna

The strategy of usage of the Alfvén resonance heating with compact strap antenna (see e.g. [2]) is a result of balance of the technological restriction to have a compact antenna which occupies one device port and necessity to suppress the excitation of low  $k_{\parallel}$  Alfvén resonances that reside at the plasma periphery and cause plasma edge heating. The experiments with the THT antenna were attempted earlier [3, 4]. They showed increase of plasma density from  $\langle n_e \rangle \approx (0.5 \dots 2) \times 10^{12} \text{ cm}^{-3}$  provided by a pulse of the frame antenna to  $\langle n_e \rangle \approx (0.5 \dots 1.5) \times 10^{13} \text{ cm}^{-3}$ . In that time Uragan-3M was not equipped with a diagnostic for measuring the electron temperature. Since the expected heating in Alfvén resonance conditions is the electron heating, the result of those experiments remains incomplete. Second experiment also suffered from huge radiation losses that resulted in low plasma temperature what is indicated by the light emission from low charged states of light impurities. In current series of experiments, the electron cyclotron emission (ECE) diagnostics is

employed. On-axis magnetic field value is  $B_0=0.72$  T. For this magnetic field the cut-off value of plasma density is  $n_c \approx 0.85 \times 10^{13} \text{ cm}^{-3}$ . This value is limiting for ECE diagnostics. Taking into account this fact, the experimental series is organized so that this level would be not exceeded despite the higher levels of plasma densities are achievable.



- 1 - optic spectroscopy
- 2 - microwave reflectometry and interferometry
- 3 - probe measurements
- 4 - ECE
- 5 - laser impurity injection
- 6 - SXR
- 7 - CX neutral energy analyzers
- 8 - magnetic diagnostics

Fig. 2. Scheme of Uragan-3M diagnostics

The diagnostics involved into these experiments are shown on Fig.2. The frequency of heating is chosen so, that the peaking  $k_{\parallel}$  value in the antenna spectrum satisfy the Alfvén resonance condition at the plasma core. Since the device is small and  $k_{\parallel}$  is high the frequency should be chosen quite close to the ion cyclotron. It is  $f_1 = 8.6$  MHz for the frame antenna and  $f_2 = 8.9$  MHz for the THT antenna. For these frequencies the ion cyclotron zone is present in plasma column. In regular discharges the frame antenna creates plasma with the density  $\langle n_e \rangle \approx (0.5 \dots 2) \times 10^{12} \text{ cm}^{-3}$  and temperature  $\langle T_e \rangle \approx 1$  keV. In the experiments the pulse of the frame antenna goes first. Immediately after the frame antenna pulse the THT antenna is switched on. The temporal evolution of the plasma parameters in such a shot is shown in Fig. 3.

The frame antenna ionizes the neutral gas during 1...4 ms and heats low-density plasma. The power delivered to the antennas is about  $P_1 \sim 100$  kW for the frame antenna and  $P_2 \sim 150$  kW for the THT antenna.

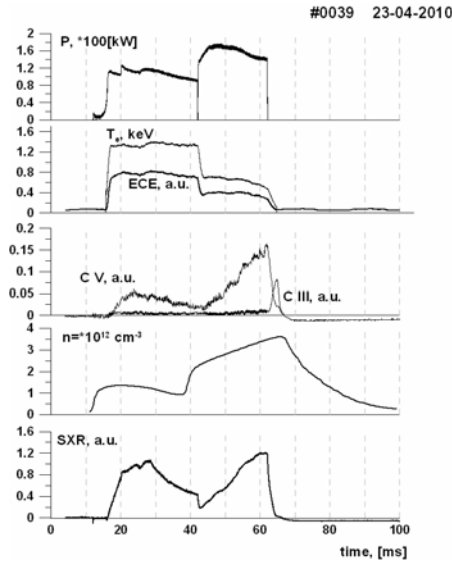


Fig. 3. Evolution of RF power, radiation and electron temperature, CV and CIII lines emission, plasma density and SXR intensity in a shot with continuous gas puff. Neutral gas pressure is  $9.3 \times 10^{-6}$  Torr

Plasma density is  $\langle n_e \rangle \sim 10^{12} \text{ cm}^{-3}$  during the frame antenna pulse. After it the plasma density grows rapidly to  $\langle n_e \rangle \approx 2.5 \times 10^{12} \text{ cm}^{-3}$  and, further is ramping up to  $\langle n_e \rangle \approx 3.5 \times 10^{12} \text{ cm}^{-3}$  at the end of the THT antenna pulse. Carbon CV line emission is higher during the THT antenna pulse. CIII line emission is small during the whole shot, but there is a huge recombination peak after the THT antenna pulse indicating that carbon is in highly ionized states in the plasma. Electron temperature is calculated from the radiation temperature using formula  $T_e = T_{rad} / (1 - e^{-\tau})$  using tokamak approximation formula for the optical thickness of the plasma  $\tau \approx 5.6 \times 10^{-14} \langle n_e \rangle T_e R_0 / B_0$  [5] (here the plasma density is in  $\text{cm}^{-3}$ , electron temperature is in eV, torus major radius  $R_0$  is in cm, and the magnetic field is in G).

During THT antenna pulse electron temperature is lower, but the electron energy content is almost the same as compared with the frame antenna plasma. It is difficult to increase plasma density with continuous gas puff. For this purpose a pulsed gas puff is used. An example of a pulse with gas puff is given in Fig. 4. The gas puff causes a splash on  $H_\alpha$  hydrogen spectral line emission. The plasma density, soft x-ray and CV emission signals grow substantially. The ECE signal also starts to grow at the beginning of the gas puff pulse, but then decreases. This behaviour could be explained by locking of ECE emission in dense plasma. Soft x-ray diagnostics and CV radiation intensity indicate that plasma is not cold. The plasma density comes close to the value  $\langle n_e \rangle \approx 8 \times 10^{12} \text{ cm}^{-3}$  demonstrating the THT antenna ability to increase plasma density to such values.

With more powerful gas puff the plasma density could be increased more, but the diagnostics indicate decrease

of the plasma energy content. Tuning the gas puff intensity, the maximum plasma density is decreased to values  $\langle n_e \rangle \approx (5 \dots 7) \times 10^{12} \text{ cm}^{-3}$  that allows one to enable electron temperature measurements. One of such pulses is shown in Fig. 5.

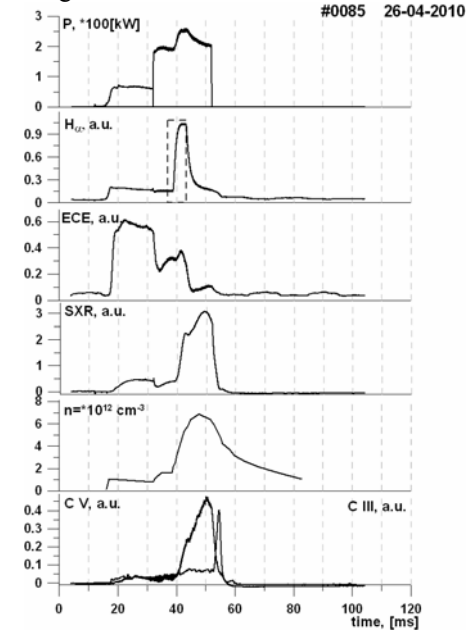


Fig. 4. Evolution of RF power,  $H_\alpha$  hydrogen line intensity, ECE signal, soft x-ray intensity, plasma density and CV and CIII lines emission in a shot with continuous and a strong pulsed gas puff.

Neutral gas pressure is  $9.3 \times 10^{-6}$  Torr

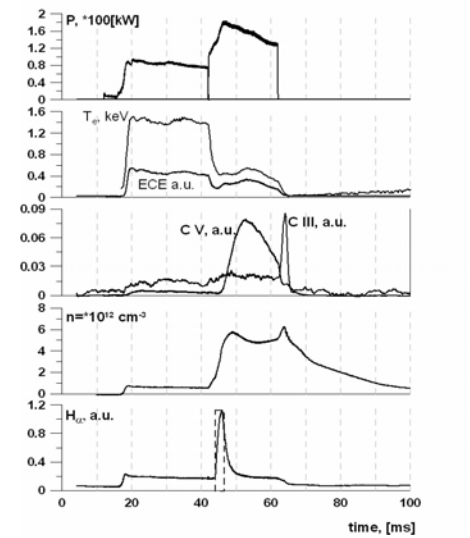


Fig. 5. Evolution of RF power, radiation and electron temperature, CV and CIII lines emission, plasma density and  $H_\alpha$  hydrogen line intensity in a shot with continuous and a moderate pulsed gas puff. Neutral gas pressure is  $4.9 \times 10^{-6}$  Torr

In this pulse during THT operation the density is  $\langle n_e \rangle \approx 5 \times 10^{12} \text{ cm}^{-3}$  and the electron temperature  $T_e = 0.5$  keV is achieved in the plasma column centre. The specific feature of plasma density behaviour is that after the gas puff the density does not return to the value which was before gas puff. The radial distribution of the CV intensity is calculated pulse by pulse chord measurements

(see Fig. 6). It is central at both stages of the discharge. The  $C^{4+}$  ion temperature is measured using Doppler spectrometry of a CV line. The estimates for Coulomb ion-ion collisions gives fast energy exchange between protons and  $C^{4+}$  ions. Thus their temperatures should be close to each other. The ion temperature is smaller than the electron one. It ramps up continuously during the THT antenna pulse and reaches the values close to  $T_i=100$  eV by the pulse end.

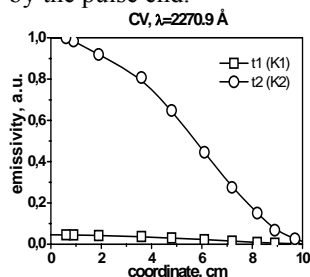


Fig. 6. Radial distributions of  $C^{4+}$  spectral line emissivity at time moments  $t_1=19$  ms (squares) and  $t_2=50$  ms (circles)

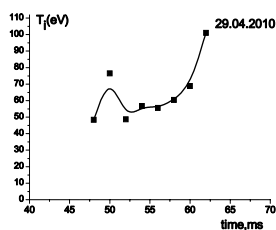


Fig. 7. Evolution of  $C^{4+}$  ion temperature in moderate pulsed gas puff shots

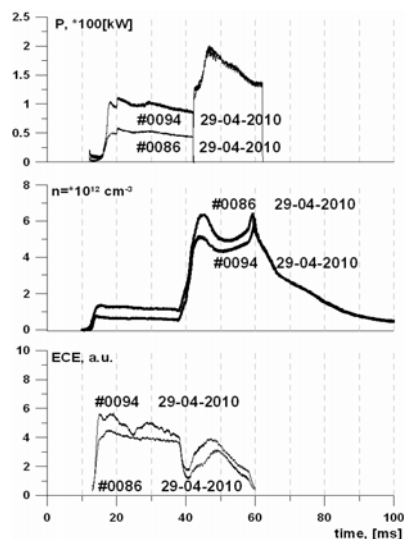


Fig. 8. RF power, plasma density and ECE intensity in two shots with continuous and a moderate pulsed gas puff that differ by the power delivered to the frame antenna

#### ACKNOWLEDGEMENT

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#### ВЧ-НАГРЕВ НИЖЕ ИОННОЙ ЦИКЛОТРОННОЙ ЧАСТОТЫ В ТОРСАТРОНАХ УРАГАН

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Представлены результаты экспериментов на торсатроне (стеллараторе) Ураган-3М по альфвеновскому нагреву плазмы. Использование трехполувитковой антенны позволило повысить плотность плазмы и нагреть ее электронный компонент.

#### ВЧ-НАГРІВ НИЖЧЕ ІОННОЇ ЦИКЛОТРОННОЇ ЧАСТОТИ В ТОРСАТРОНАХ УРАГАН

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Надано результати експериментів на торсатроні (стеллараторі) Ураган-3М з альфвенівського нагріву плазми. Використання трьохнапіввиткової антени дозволило підвистити густину плазми й нагріти її електронний компонент.