AMPLIFICATION OF THE RUNAWAY ELECTRONS FLOW IN THE URAGAN-3M TORSATRON

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In this work the results of amplification of the runaway electrons flow and interaction runaway electrons with RF-heating wave on the Uragan-3M torsatron are presented. Results described in the article confirm using runaway electrons for gas breakdown. The results allow making some recommendations for using of self-created flows of accelerated particles for stimulation of gas breakdown.

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INTRODUCTION

We have already presented the first results of experimental study of working gas discharge ignition due to runaway electrons (RE) in the Uragan-3M torsatron [1].

The detailed results on the temporal behavior of the RE dynamics are presented. The flow is formed due to toroidal electric field during rump-up phase of the magnetic field pulse. The detailed study of the RE flow intensity from several experimental plasma parameters such as: the working gas pressure, the magnetic field strength, the amplitude and length of the microwave pulse which additionally stimulated ionization processes was made.

For the driving RF pulse and microwave pulse the start up and length was optimized at the rump-up stage of the magnetic field.

Additional set of the experiments were done where the RE were amplified by the main RF plasma production generator "Kaskad-2".

1. EXPERIMENTAL SETUP AND DIAGNOSTIC ELEMENTS

Experiments were performed in U-3M device [1]. The U-3M is an l = 3, m = 9 torsatron with open helical divertor configuration. The major radius of the device is R=1 m, average minor radius of plasma confinement volume a = 0.12 m, working magnetic field B=0.72 T. Plasma is produced by absorption of a RF power (f = 8…8.6 MHz, $P\leq$200 kW) supplied by two antennas placed near the last closed magnetic surface.

The U-3M diagnostics used in the experiments: optical spectroscopy, microwave reflectometry, interferometry, Langmuir probes, Radiometry (measurements of Electron Cyclotron Emission), X-ray diagnostics, energy analyzis of charge exchange atoms, magnetic probes, toroidal loop, hard X-ray diagnostics.

Earlier, the question arose as to why soft X-ray radiation detectors fix the bremsstrahlung of RE. One of the reasons could be Compton scattering.

Compton scattering is the scattering by a free electron of an individual photon. A photon is scattered by an electron and transmits a part of its energy and momentum and also changes its direction of motion. After scattering the photon will have energy and frequency less than its energy and frequency before scattering. Accordingly, after scattering, the wavelength of the photon increases.

2. EXPERIMENTAL RESULTS

2.1. NEUTRAL GAS IONIZATION IN RUNAWAY ELECTRONS FLOW

The ability of ionization of working gas inside the confinement volume corresponds to the intensity of the ionizing particles flow [2, 3]. The estimation of the flow intensity could be done basing on observation of several secondary phenomena, which occur due to interaction of the RE flow with the confining magnetic fields and metal constructive elements. Here we talk about a wide spectrum of radiation (from microwave to X-ray). As one of the diagnostic tool in our experiments we used a set of electrostatic probes located at the edge of the plasma confinement volume.

We have found that the intensity of RE flow depends on the microwave power (2.45 GHz microwave generator) which is proportional to the pulse amplitude and its delay in relation to the magnetic field pulse start.

2.2. THE MAGNETIC FIELD VARIATION CAUSES THE RUNAWAY FLOW

An X-ray radiation output was observed in the absence of RF-heating at the rump-down phases of magnetic field pulse. At the same time the particles ejection on the probes situated at the edge of the torus was detected. Such ejection was also accompanied with the sufficient H_{α} and ECE radiation. Thus we have concluded that the flow of suprathermal particles is formed at the edges of magnetic field pulse (Fig. 1).

Such a "RE flow" is created by the toroidal electric field which is induced by the magnetic field intensity variation.

The flow intensity is sensitive to the working gas pressure value.

It was shown that at the low pressures the flow exists not only at the magnetic field pulse rump-down phases but also during the phase of stationary magnetic field [4].

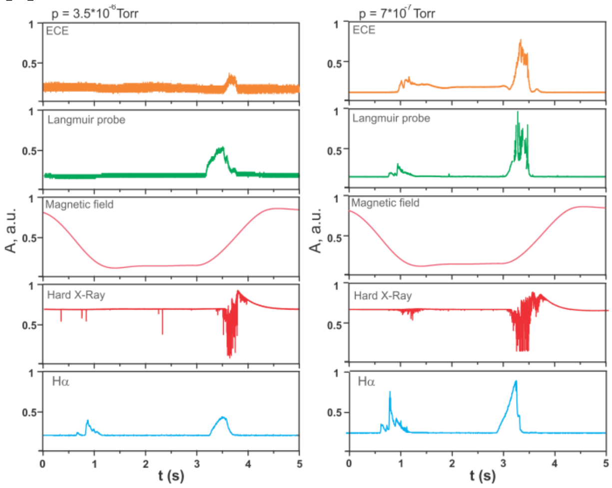

Fig. 1. The measurements carried out without applying the RF-heating at different working gas pressures

2.3. EXTERNAL STIMULATION OF THE RUNAWAY ELECTRONS FLOW

The signals from Langmuir probe, magnetic probe and X-Ray detector with and without the RE flow stimulation by the additional ionization were observed. The flow of RE was stimulated by the additional RF-ionization which was carried out at the magnetic field pulse front. Changes in the flow characteristics were observed through the measurements of current on the peripheral Langmuir probe together with the X-Ray output at the rump-down of the magnetic field pulse (Fig. 2).

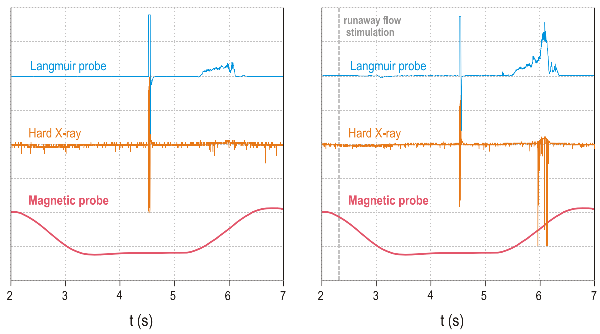

Fig. 2. The signals with and without the RE flow stimulation by the additional ionization (p =2·10^{-5} Torr)

In a spontaneous scenario of RE occurrence a plasma creation process takes place. This plasma becomes a source of accelerated particles – the source of RE.

Basing on these facts we have made an assumption that the increasing of number of plasma particles will cause increasing of the corresponding RE flow.

To create additional ionization we used a discharge created by microwave generator on the frequency of 2.45 GHz with the power of 0.5…1.5 kW. It was turned on when the magnetic field strength was 0.08 T (electron-cyclotron resonance) and it was working during 50…1000 ms (Fig. 3). The density of created plasma was about n_e=5·10^{10} cm^{-3}.

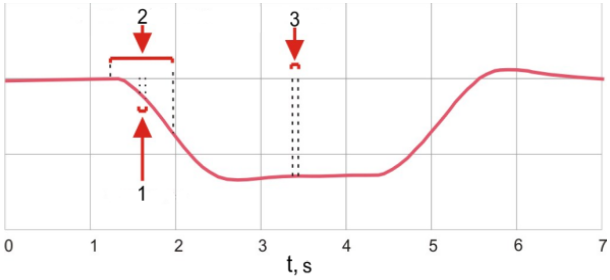

Fig. 3. Scenario of RE microwave stimulation.
1 – Microwave pulse; 2 – shift interval of microwave pulse; 3 – RF pulse

Also we were tried to use generator “Kaskad-2” to create plasma on rump-up stage of the magnetic field. “Kaskad-2” was worked on frequency about 5 MHz and output power about 100 kW (Fig. 4).

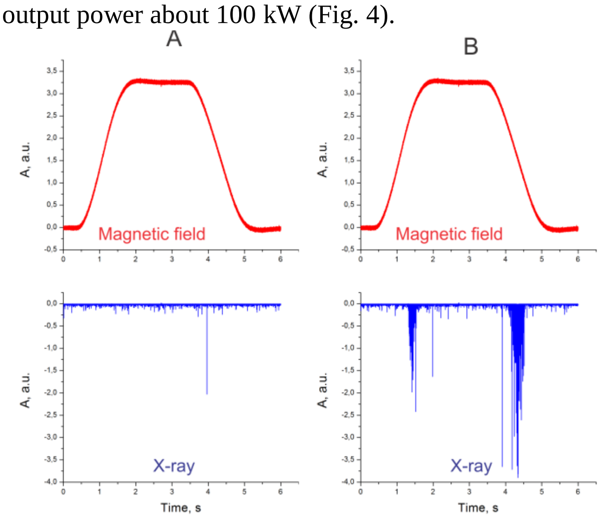

Fig. 4. RE behavior when RF-generator “Kaskad-2” works without additional microwave pumping.
A – “Kaskad-2” – OFF; B – “Kaskad-2” – ON; p= 2·10^{-5} Torr

The joint work of microwave generator (2.45 GHz) and “Kaskad-2” was also investigated (Fig. 5).

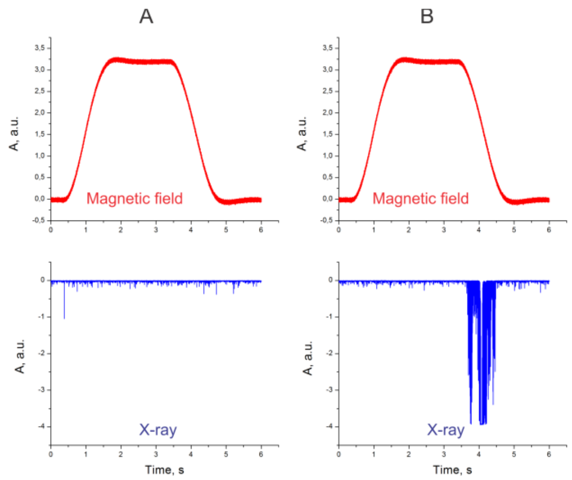

Fig. 5. RE dynamics when RF-generator “Kaskad-2” (100 kW) and microwave generator (1.5 kW) works together. A – “Kaskad-2” – OFF; B – “Kaskad-2” – ON; p = 2·10^{-5} Torr, B = 0.65 T

2.4. DEPENDENCE FROM LENGTH AND POWER MICROWAVE PULSE

As we already mentioned the RE flow affected the plasma discharge conditions during microwave pulse, which used for plasma production. The discharge performance has shown strong dependency on the RE flow intensity. Thus the flow is dependent on the amplitude and the length of the microwave pulse which is used to create plasma in the confinement volume. Optimization of the microwave pulse delay according to the magnetic field rump-up start is necessary condition for electron-cyclotron resonance on the frequency 2.45 GHz.

The dependence of RE flow on the stimulation pulse length for two different delays (200 and 400 ms) according to start of the magnetic field pulse is presented (Fig. 6). The estimates were made during comparison of the pulse parameters and its influence on the discharge performance.

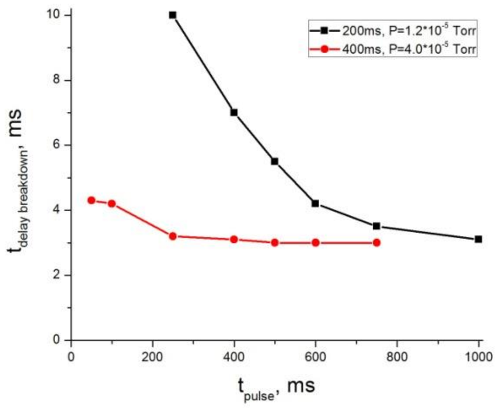

Fig. 6. Dependence temporal delay between RF-pulse start edge and the moment of discharge ($t_{delay\_breakdown}$). *p = 1.2·10*$^{-5}$ *Torr*

Dependence of RE flow intensity on the amplitude of the microwave stimulation pulse for two values of the pulse delay (200 and 400 ms) according to magnetic field pulse is shown on Fig. 7.

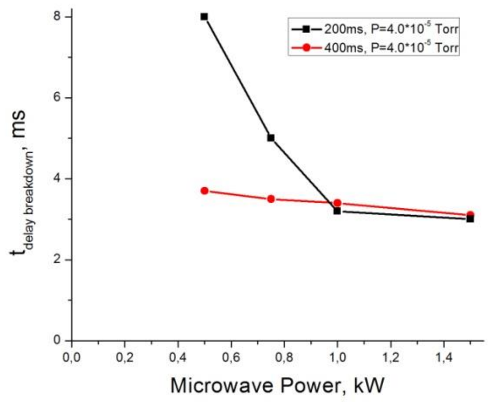

Fig. 7. Dependence from power of microwave pulse. $t_{delay\_breakdown}$ *– temporal delay between RF-pulse start edge and the moment of discharge. p=1.2·10*$^{-5}$ *Torr*

2.5. DEPENDENCE FROM THE WORKING GAS PRESSURE

In all experiments on U-3M is observed the dependence of intensity of RE flow from working gas pressure. The maximum of intensity of RE flow is in range $3·10^{-5}…5·10^{-6}$ Torr (defined by ECE and hard X-Ray).

To create the RE flow exist an optimum working gas pressure. Also the pressure has to satisfy the condition of the plasma formation at the fronts of the magnetic field pulse, which is the main source of RE.

The dynamics of synchrotron radiation and bremsstrahlung from working gas pressure is shown on Fig. 8.

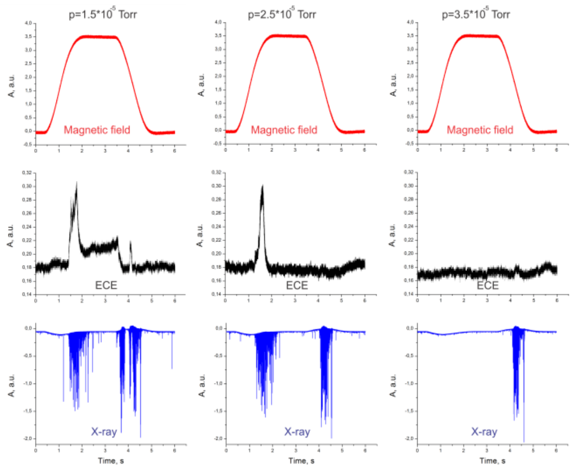

Fig .8. Bremsstrahlung (X-ray) and synchrotron radiation ~40 GHz frequency during the variation of magnetic field strength for different pressures of working gas

CONCLUSIONS

The effect of the amplification of RE in Uragan-3M experiments is carried out by stimulation of plasma creation on phase of charged particles acceleration . This stage corresponds to the magnetic field pulse rump up phase.

The RE flow intensity depends on plasma startup parameters and initial plasma breakdown time. This could be indirectly determined using of the amplitude and length of pulses of the RF and microwave pumping.

The RE flow intensity depends on the offset between the magnetic field pulse startup and the RF pulse startup.

Comparison of RF and microwave pumping has shown that 100 kW of RF power affect (“Kaskad-2”) in the same way as 1.5 kW of microwave power.

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УСИЛЕНИЕ ПОТОКА УБЕГАЮЩИХ ЭЛЕКТРОНОВ В ТОРСАТРОНЕ УРАГАН-3М

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Приведены результаты экспериментальных исследований по усилению потока убегающих электронов, а также взаимодействию потока убегающих электронов с электромагнитным полем волны, возбуждаемой высокочастотным импульсом в торсатроне Ураган-3М. Полученные результаты подтверждают возможность пробоя газа убегающими электронами. Это позволяет представить ряд рекомендаций по использованию самопроизвольно формирующихся потоков ускоренных частиц для стимуляции высокочастотного пробоя.

ПОСИЛЕННЯ ПОТОКУ УТІКАЮЧИХ ЕЛЕКТРОНІВ У ТОРСАТРОНІ УРАГАН-3М

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Наведено результати експериментальних досліджень щодо посилення потоку утікаючих електронів, а також взаємодії потоку утікаючих електронів з електромагнітним полем хвилі, що збуджується високочастотним імпульсом у торсатроні Ураган-3М. Отримані результати підтверджують можливість пробою газу утікаючими електронами. Це дозволяє представити ряд рекомендацій по використанню потоків прискорених частинок для стимуляції високочастотного пробою.