NONSTATIONARY GENERATION OF ELECTROMAGNETIC RADIATION IN NONEQUILIBRIUM MIRROR-CONFINED PLASMA

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We demonstrate the use of a laboratory setup based on a magnetic mirror trap with plasma sustained by a gyrotron radiation under the electron cyclotron resonance conditions aimed at identifying the role of the background plasma as a trigger of the electron cyclotron instability. New regime of instability has been revealed during the plasma decay after the gyrotron switch-off when the plasma density becomes low enough, so that the electron plasma frequency is much less than the electron gyrofrequency. At this stage, we observe the excitation of electromagnetic waves which propagate nearly perpendicular to the magnetic field and cause precipitation of energetic electrons to the trap ends. The instability is detected as series of quasi-periodic broadband pulses of electromagnetic radiation (25…27 GHz frequency, typical pulse duration of 1…10 microseconds) and related precipitation of energetic (>10 keV) electrons. These emissions of the fast electrons can be attributed to the development of the kinetic instability of the extraordinary wave propagating quasiperpendicular to the magnetic field near the fundamental cyclotron harmonic.

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In the present paper we demonstrate the use of a laboratory setup [1] based on magnetic mirror trap with plasma sustained by gyrotron radiation under the electron cyclotron resonance (ECR) conditions aimed at identifying the role of the background plasma as a possible trigger of electron cyclotron instability. The generation of bursts of electromagnetic radiation associated with the explosive development of the cyclotron instability of a magnetized plasma, and accompanied by precipitations of energetic particles from a trap, has been observed in a wide range of plasma parameters in various conditions: in the magnetospheres of the Earth and other planets, in the Solar coronal loops, as well as in laboratory magnetic traps. In such systems variations of temporal and spatial structure of magnetic field may be of importance.

We performed our studies using a gas discharge in a magnetic mirror trap. Linearly polarized microwave radiation from gyrotron with a frequency of 37.5 GHz, a power of 80 kW, and pulse duration of 1 ms was focused by dielectric lens into the center of discharge chamber. The plasma was resonantly heated at the fundamental gyrofrequency harmonic. The ECR absorption region occupied an intermediate position between the magnetic mirror and the central cross section of the trap and corresponded to a magnetic field strength of 1.34 T. The discharge chamber 7 cm in diameter was located in an axisymmetric magnetic mirror configuration produced by two solenoids. The magnetic field pulse duration was ~13 ms, the maximum magnetic field strength in the mirror was 3.15 T, and the mirror ratio was 5. The separation between the magnetic field maxima in the mirrors (trap length) was 25 cm. The key feature of the experiment is the use of a pulsed gas puff, which makes it possible to control the plasma decay after the end of the microwave pulse. The working gas (nitrogen) was puffed into the discharge chamber through pulsed valve from flask with a controlled gas pressure. The flux of energetic electrons precipitated from the magnetic trap was measured with the help of p-i-n diode. The p-i-n diode used in our experiments is capable of detecting electrons with energies in the range from 10 to 500 keV. The measurements of plasma energy density were performed using the diamagnetic loop, placed normally to the magnetic field lines in the central cross-section of the trap. To record and analyze the spectrum of the plasma microwave emission, we used microwave receivers with different transmission bands. The receivers were mounted outside the vacuum chamber, near the system axis and perpendicularly to the axis above the quartz window.

Heating under the ECR conditions allows to create a two-component plasma containing cold dense component with an isotropic velocity distribution, and less dense component of hot electrons with anisotropic distribution function (with a predominance of the transversal to the magnetic field momentum as compared to the longitudinal one). Parameters of the initial plasma were $N_e \sim 10^{13}\,\mathrm{cm}^{-3}$, $N_h \sim 5\times10^{10}\,\mathrm{cm}^{-3}$, $T_e \sim 300$ eV, $T_h \geq 10$ keV.

The new regime of cyclotron instability has been revealed during the plasma decay after ECR heating switch-off when the plasma density becomes low enough, so that the electron plasma frequency is much less than the electron gyrofrequency [2]. In such plasma, instability development is determined by the substantial difference in the lifetimes of the trapped hot and cold plasma components. Density of the cold plasma component decreases rapidly after the ECR heating switch-off, thus creating conditions for the excitation of waves propagating across the magnetic field. The experiment described in [2] showed the existence of quasi-periodic bursts of energetic electron flux precipitating from the trap ends and synchronous pulses of microwave radiation of plasma in a direction nearly perpendicular to the ambient magnetic field at a certain puff rate of molecular nitrogen.

Present research is aimed at direct observation of microwave radiation which causes precipitation of energetic electrons from the trap. A set of microwave receivers with different transmission bands was used for spectrum measurements. Every receiving channel includes two filters: band-pass filter and low-pass filter that provides good suppression of high frequencies. Filters were designed to exclude the light-striking of stray radiation of a gyrotron in the detection bandwidth. All receivers were calibrated such that allowed to measure an absolute value of a microwave intensity escaping from the plasma volume.

According to the theory of cyclotron instabilities [3] it is usually assumed that the resonant interaction of electromagnetic waves with anisotropic hot electrons occurs at the center of the magnetic trap where the magnetic field strength, and hence the electron gyrofrequency, are minimal. But the present experiment shows that the electromagnetic radiation is generated at frequencies significantly higher than the value of the electron gyrofrequency at the trap center. However the frequency of the detected electromagnetic radiation has increased following the confining magnetic field strength what proves the cyclotron mechanism of the instability development.

In experiments the electron gyrofrequency at the trap center was in frequency range of 10…15 GHz. At the same time the instability was detected as series of quasi-periodic broadband pulses of electromagnetic radiation in 25…27 GHz frequency range with typical pulse duration of 1…10 microseconds. Synchronously a precipitation of energetic (≥10 keV) electrons was observed. Typical signals are shown in Fig. 1 and 2. Bursts of microwave radiation of the plasma have a rich temporal structure with strictly defined typical periods which are discussed in the accompanying paper [4]. The maximum amplitude of the signal on microwave detectors has reached a value of 300 mV which corresponds to the radiation power of 5 mW. Taking into account the value of solid angle which is covered by the receiver and the distance to the trap center one can derive the total emitted power of 3 W. For this kind of signals it is a significant quantity to prove the stimulated nature of radiation.

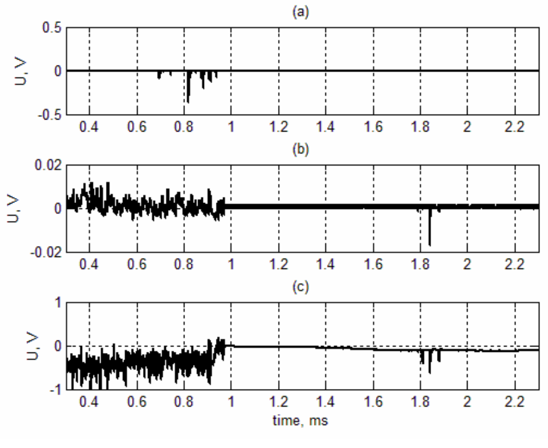

Fig. 1. Typical signals from receivers: a – microwave radiation in direction longitudinal to the ambient magnetic field at 6…18 GHz frequency range (the whistler mode); b – microwave radiation in direction perpendicular to the ambient magnetic field at 18…26 GHz frequency range (the fast extraordinary mode); c – signal of hot electrons precipitated from the trap. The gyrotron was switched-off at 1 ms

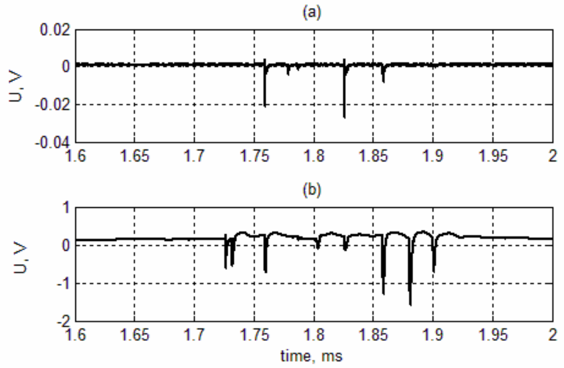

Fig. 2. Bursts of microwave radiation of the plasma have a rich temporal structure with strictly defined typical periods: a – microwave radiation in direction perpendicular to the ambient magnetic field at 18…26 GHz frequency range; b – signal of hot electrons precipitated from the trap

In all experiments bursts of microwave radiation and precipitations of hot electrons under cyclotron instability were observed approximately after 800 μs next to gyrotron switch-off. The emissions of the fast electrons that are observed at a noticeable delay after the end of the microwave pulse can be attributed to the development of the kinetic instability of the extraordinary wave propagating quasiperpendicular to the magnetic field near the fundamental cyclotron harmonic. A significant feature of such a scenario is that the instability threshold is determined not only by the absorption of waves in the background plasma but also by the transparency of the plasma layer. During the microwave pulse and at an initial stage of the plasma decay, such instabilities are suppressed due to depression of cyclotron radiation in the evanescence region of the overdense plasma.

In addition to the diagnostics described above, a diamagnetic probe was used for measurement of the plasma pressure variation during the burst activity. Data from the diamagnetic probe allowed estimations of the total energy losses accompanying the instability development. Such analysis shows that about 2/3 of the initial energy stored in the hot plasma component is taken away by hot precipitating electrons. Thus, the cyclotron instability plays a major role in energy balance of the decaying plasma providing much faster losses of the hot component as compared to those due to the Coulomb collisions.

The setup has been upgraded and the system for spectrum analysis has been developed. The frequency and the emitted power of observed microwave emission of the plasma have been measured. In this sense our laboratory setup can be used for modeling much wider range of fundamental processes in the plasma, e.g. processes in pulsating auroral plasma cavities and related systems.

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НЕСТАЦИОНАРНАЯ ГЕНЕРАЦИЯ ЭЛЕКТРОМАГНИТНОГО ИЗЛУЧЕНИЯ В НЕРАВНОВЕСНОЙ ПЛАЗМЕ, УДЕРЖИВАЕМОЙ В МАГНИТНОЙ ЛОВУШКЕ

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Исследованы временные и частотные характеристики квазипериодических импульсов электромагнитного излучения в распадающейся плазме импульсного ЭЦР-разряда в прямой аксиально-симметричной магнитной ловушке. Зарегистрированы серии квазипериодических импульсов электромагнитного излучения на частоте 25...27 ГГц с типичной длительностью импульса 1...10 мкс и связанные с ними высыпания энергичных (> 10 кэВ) электронов. Наблюдаемое излучение интерпретировано как результат резонансного взаимодействия горячих электронов с быстрой необыкновенной волной, распространяющейся в разреженной плазме поперек внешнего магнитного поля.

НЕСТАЦІОНАРНА ГЕНЕРАЦІЯ ЕЛЕКТРОМАГНІТНОГО ВИПРОМІНЮВАННЯ В НЕРІВНОВІСНІЙ ПЛАЗМІ, ЯКА УТРИМУЄТЬСЯ В МАГНІТНІЙ ПАСТЦІ

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Досліджено часові та частотні характеристики квазіперіодичних імпульсів електромагнітного випромінювання в плазмі, що розпадається, імпульсного ЕЦР-розряду в прямій аксіально-симетричній магнітній пастці. Зареєстровані серії квазіперіодичних імпульсів електромагнітного випромінювання на частоті 25...27 ГГц з типовою тривалістю імпульсу 1...10 мкс та пов'язані з ними висипання енергійних (> 10 кеВ) електронів. Випромінювання, що спостерігається, інтерпретовано як результат резонансної взаємодії гарячих електронів з швидкою незвичайною хвилею, що розповсюджується в розрідженій плазмі поперек зовнішнього магнітного поля.