GENERATION OF WIDEBAND ELECTROMAGNETIC RADIATION ON A DECAY STAGE OF A MIRROR-CONFINED PLASMA PRODUCED BY ECR DISCHARGE

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A specific nonlinear regime of electron cyclotron instability is discussed aimed at explanation of complex temporal patterns of stimulated electromagnetic radiation from a mirror trap with non-equilibrium plasma typical of ECR discharge. This regime is characterized by self-modulation of a plasma cyclotron maser due to coherent interference of two counter-propagating unstable waves with degenerate frequencies. The proposed simple theoretical model allows reproducing multi-scale behavior of quasi-periodic pulses of electromagnetic radiation and precipitation of energetic electrons detected at a laboratory setup based on a mirror trap with plasma sustained by mm-wave gyrotron radiation.

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INTRODUCTION

Laboratory setups based on mirror traps are actively used to simulate nonlinear wave-particle interactions in space plasmas. In particular, we reported previously that a new regime of electron cyclotron (EC) instability has been revealed in a compact mirror trap during the plasma decay [1]. In these experiments plasma discharge with duration of ~1 ms was sustained by 37.5 GHz / 80 kW gyrotron under the EC resonance conditions. The ECR heating results in an electron distribution function that consists of two fractions, one of them being a small energetic addition to the other component which is much cooler and denser. In the reported experiments the bulk plasma density is about 10^{13} cm^{-3}, an electron temperature is 300 eV, a hot-electron density is 5×10^{10} cm^{-3}, and an effective hot-electron temperature (primarily the transverse energy) is 10 keV. Detailed description on this experiment is given in the accompanying paper [2] in this issue. Here we only mention that intense short-pulse (5 μs) emissions of fast (10…100 keV) electrons and synchronous bursts of electromagnetic radiation at the fundamental cyclotron harmonic have been observed with about 1 ms delay after the end of the microwave pulse supporting the initial non-equilibrium plasma. Observed bursts form rather complex temporal patterns – the interval between single spikes in a time series may become irregular, spikes may join in double-bursts, and a kind of stochastic generation regime is sometimes detected. Typical examples of such activity are shown in Fig. 1 (top). The important feature of this data is that different patterns were observed quite randomly for the same experimental conditions. In the present communication we discuss a possible simple mechanism responsible for such complex and random temporal behavior of the observed burst activity.

1. TWO-LEVEL MASER MODEL

Main features of the instability were reproduced by the model of simple two-level maser proposed in our previous paper [3]. The joint evolution of the hot-electron density N and the density of the electromagnetic energy W can be qualitatively described by the following equations

$$\begin{cases} dN/dt = -\kappa W N, & \kappa \approx h/T_h \\ dW/dt = (\gamma-\nu)W, & \gamma \approx hN \end{cases}. \qquad (1)$$

The first equation describes the rf-field-induced losses of hot electrons with effective temperature T_h, while the second equation describes the change of the wave energy in terms of the relation between the linear instability growth-rate γ and dissipation ν. The coefficients κ and h determine the losses of hot particles and the averaged growth-rate, respectively. The derivation of Eqs. (1) from the quasi-linear plasma theory and comprehensive discussion of its application limits can be found, e.g., in Ref. [4].

Quasi-linear interaction of hot resonant electrons with the electromagnetic wave exponentially increasing at the linear stage of instability reduces its transverse energy. As a result, some fast electrons fall within a loss cone and leave a trap. These losses reduce the instability growth rate and, finally, restrict the increase in the electromagnetic energy density in the system. Here the dissipation is governed by electron collisions with the background plasma thus $\nu(t)$ is assumed to be known function monotonically decreasing during the plasma decay after the gyrotron power switch-off. Decrease in the wave energy losses provides repeated recovery of the instability conditions and thus serves as an effective source of free energy. This particular feature is responsible for the operation of the cyclotron maser in absence of a direct pump at the plasma decay stage.

The above model describes relatively well some essential features of the measured data, but it does not reproduce the essential features of the latest data in which quite different patterns of the burst activity were observed randomly for the same experimental conditions [2]. This random switching between different nonlinear regimes of instability may be explained as a result of self-modulation of a plasma cyclotron maser due to coherent interference of two (or more) unstable waves with degenerate frequencies resulting in spatial modulation of amplification. Let us consider a simplest case of two counter-propagating modes with complex amplitudes a_+ and a_- such that the wave field may be represented as follows

$$\delta E \propto a_+(t)\exp(ik\xi - i\omega t) + a_-(t)\exp(-ik\xi - i\omega t).$$

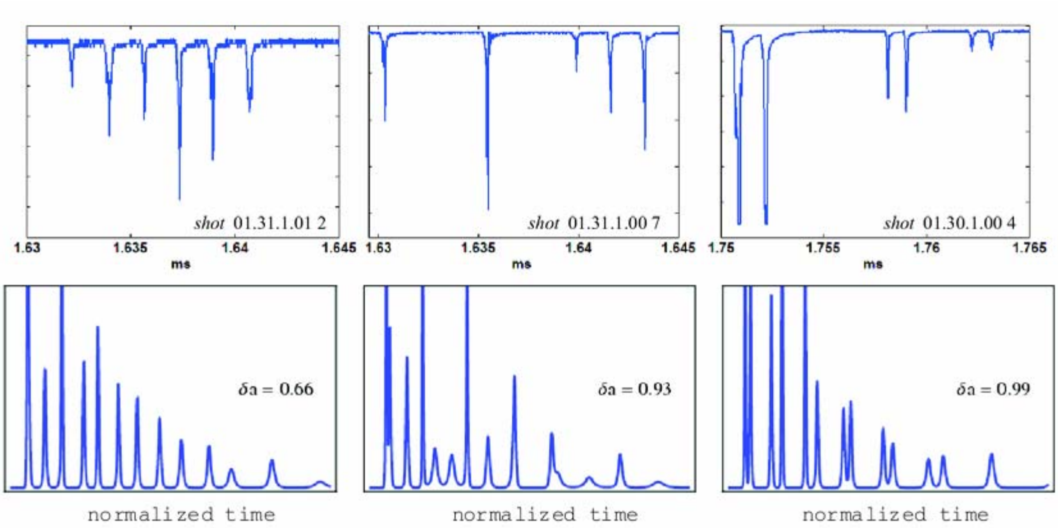

Fig. 1. Top: oscillograms of the signals from the pin diode measured precipitations of hot electrons from the trap after the gyrotron power is switched-off. Bottom: precipitation of hot electrons (dn/dt) calculated from equations (2) for different ratios δa between the initial amplitudes of two competing modes. One can see quasi-periodic (left), chaotic (center) and double-burst (right) regimes similar to those observed experimentally. Time is normalized over initial growth-rate (γ_0). Initial conditions: $a_+=10^{-2}\,\nu_1/\gamma_0$, $a_-=10^{-2}\,\delta a\,\nu_1/\gamma_0$, $n=1$, $n_\sim=0$. Plasma decay is modeled by exponent with $\nu_0/\gamma_0=1.05$, $\nu_1/\gamma_0=0.0003$

Note that in an axisymmetric trap spatial coordinate ξ stands most likely for the azimuthal direction. A standing wave formed by two coherent counter-propagating modes result in modulation $n_\sim$ of the hot electron density at the second spatial harmonic, such that

$$N=\left\{n(t)+\mathrm{Re}[n_\sim(t)\exp(2ik\xi)]\right\}N_0 .$$

In turn this results in the same modulation of the growth-rate and in the Bragg scattering that couples the counter-propagating modes. Taking all these effects into account, one obtains the following modification of the basic maser equations (1):

$$\begin{cases} dn/dt=-(|a_+^2|+|a_-^2|)\,n-a_+a_-^*n_\sim^*-a_+^*a_-n_\sim \\ dn_\sim/dt=-(|a_+^2|+|a_-^2|)\,n_\sim-a_+a_-^*n \\ da_+/dt=\tfrac{1}{2}(n-\nu)\,a_++\tfrac{1}{2}a_-n_\sim \\ da_-/dt=\tfrac{1}{2}(n-\nu)\,a_-+\tfrac{1}{2}a_+n_\sim^* \end{cases} . \qquad (2)$$

Here all densities are normalized over the initial density of hot electrons N_0, time $\tau=\gamma_0 t$ and dissipation rate ν/γ_0 are normalized over the initial growth-rate $\gamma_0=hN_0$, the wave amplitudes are chosen such that the wave energy is scaled in terms of initial hot-electron energy, $W/N_0T_h=|a_+^2|+|a_-^2|$, and the superscript star denotes a complex conjugate.

Particular regimes that are of interest in context of the present paper are related to the initial conditions

$$n(0)=1,\quad n_\sim(0)=0,\quad a_+(0)=a_+^{th},\quad a_-(0)=a_-^{th}.$$

Here initial wave amplitudes are defined by thermal fluctuations in a hot plasma; their level in our experiments may be estimated as [5]

$$|a_\pm^{th}|^2=\frac{<|\delta E|^2/8\pi>}{N_0T_h}\sim\frac{\omega^2\Delta\omega}{\pi c^2N_0}\le 10^{-8},$$

where $\omega\sim 2\pi\cdot 30$ GHz and $\Delta\omega<\omega$ are, correspondingly, the frequency and the spectral width of the excited mode, and $N_0\sim 2\cdot 10^{10}$ cm^{-3}. Zero initial condition for the density modulation $n_\sim$ reflects the fact that in our case the initial density fluctuations (before the excitation of the maser) may be ignored since the modulation of inversion is over-pumped by the exciting waves during the burst formation. In this case solutions of equations (2) conserve the phase of wave amplitudes. Therefore, without loss of generality one can consider only real valued initial conditions for the wave amplitudes. Some interesting qualitative properties of maser dynamics in this regime have been identified in our early paper [6].

2. TOWARDS EXPLANATION OF THE EXPERIMENTAL DATA

The dynamics of the background plasma component is very essential for the proposed model since decreasing wave losses in the background plasma actually pump the maser instability. Unfortunately, measurements of the background plasma parameters have been possible only for the steady state ECR discharge and no reliable data are available describing the decay phase. So we reconstruct the electron density and temperature during the plasma decay basing on the particle and energy balance equations solved with initial conditions corresponded to the measured parameters of the ECR discharge. As applied to the discussed experiment, this technique was implemented earlier in [1, 6]. In our experiment the wave losses were mainly defined by the electron-ion collisions in the background plasma, so the loss rate is approximately equal to the effective collisional rate $\nu\approx\nu_{ei}\propto N_eT_e^{-3/2}$ [7].

Example of evolution of the loss rate is shown in Fig. 2. Maser generation typically starts at $t_*\approx 0.6$ ms, what corresponds to the characteristic growth rate of

$$\gamma_0=\nu(t_*)\approx 4.4\cdot 10^7\,\mathrm{s}^{-1}. \qquad (3)$$

While the instability was observed, the collisional loss rate can be approximated as exponential decay $\nu(t)=\nu_0\exp[\nu_1(t-t_*)]$, $\nu_0\approx 5.5\cdot 10^7$ s^{-1}, $\nu_1\approx 3.8\cdot 10^3$ s^{-1}.

At time t_* the electron temperature T_e is about 0.1 eV and the typical background density is $N_e\sim 10^{11}$ cm^{-3}, the density and pressure ratios between hot and bulk plasma fractions are $N_h / N_e \sim 0.1$ and $N_hT_h / N_eT_e \sim 10^4 \ldots 10^5$. This data agrees to the previously published results [1].

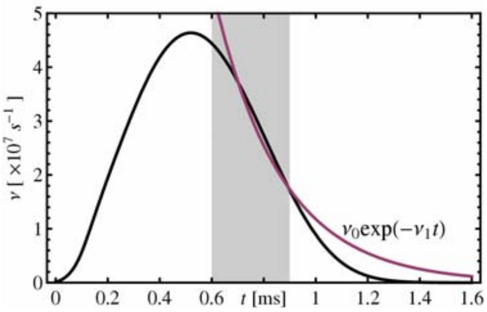

Fig. 2. Evolution of the collisional loss rate during the plasma decay and its analytical approximation at the instability stage. The time interval where the instability was observed is shown in gray

Peculiar feature of the proposed model is its sensitivity to small variations of initial conditions in the parameter range typical of described experiments. In particular, essentially different temporal patterns may be obtained for slightly different initial amplitudes of the counter-propagating waves while all other parameters of the system remain the same, see Fig. 1 (lower plots). Note that a random spread in the initial wave amplitudes is very natural due to its thermal origin. Once excited, both modes described above compete for the same resources, namely a free energy stored in hot electrons, so one mode typically dominates over another. The resulted maser dynamics show rather complex behavior similar to what was observed in the experiment. Note that in the theoretical plots time is normalized over the initial growth-rate γ_0 which is a free parameter here. In order to match the experimental data one should assume $\nu_1 / \gamma_0 \approx 3 \cdot 10^{-4}$ what corresponds to $\gamma_0 \approx 1.3 \cdot 10^7$ s^{-1}. This fits well to the estimate (3) obtained from the plasma decay modeling. Note that $\gamma_0 \sim 10^7$ is in a good agreement with the kinetic cyclotron instability of the extraor dinary wave propagating quasi-perpendicular to the magnetic field near the fundamental cyclotron harmonic that may be attributed to explain our experiment [1].

CONCLUSIONS

The self-modulation of the cyclotron maser may explain qualitatively the variety and randomness of the observed data. The proposed model is very simple so it does not require knowledge of the details such as particular type and characteristics of the unstable modes. Matching of the model to the experimental data results in a realistic estimation for the growth rate typical of the extraordinary wave instability at the fundamental cyclotron resonance. However, quantitative modeling requires more elaborate study which accounts for the wave traveling outside the generation region as well as plasma inhomogeneity in the radial direction across the magnetic trap.

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ГЕНЕРАЦИЯ ШИРОКОПОЛОСНОГО ЭЛЕКТРОМАГНИТНОГО ИЗЛУЧЕНИЯ ПРИ РАСПАДЕ ПЛАЗМЫ ЭЦР-РАЗРЯДА В ПРЯМОЙ МАГНИТНОЙ ЛОВУШКЕ

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Обсуждается новый нелинейный режим электронно-циклотронной неустойчивости, объясняющий сложную временную динамику импульсов электромагнитного излучения сильнонеравновесной плазмы ЭЦР-разряда в прямой магнитной ловушке. Режим реализуется при самомодуляции циклотронного мазера полем биений двух встречных неустойчивых волн с вырожденными частотами. Предложенная простая теоретическая модель позволяет воспроизвести многомасштабную структуру импульсов электромагнитного излучения и высыпания энергичных электронов, зарегистрированных в лабораторном эксперименте с использованием прямой ловушки с плазмой, поддерживаемой излучением гиротрона миллиметрового диапазона.

ГЕНЕРАЦІЯ ШИРОКОСМУГОВОГО ЕЛЕКТРОМАГНІТНОГО ВИПРОМІНЮВАННЯ ПРИ РОЗПАДІ ПЛАЗМИ ЕЦР-РОЗРЯДУ В ПРЯМІЙ МАГНІТНІЙ ПАСТЦІ

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Обговорюється новий нелінійний режим електронно-циклотронної нестійкості, що пояснює складну часову динаміку імпульсів електромагнітного випромінювання сильнонеравномірної плазми ЕЦР-розряду в прямій магнітній пастці. Режим реалізується при самомодуляції циклотронного мазера полем биття двох зустрічних нестійких хвиль з виродженими частотами. Запропонована проста теоретична модель дозволяє відтворити багатомасштабну структуру імпульсів електромагнітного випромінювання та висипання енергійних електронів, зареєстрованих у лабораторному експерименті з використанням прямої пастки з плазмою, що підтримується випромінюванням гіротрона миллиметрового діапазону.