PLASMA INSTABILITY IN THE AFTERGLOW OF ECR DISCHARGE SUSTAINED IN A MIRROR TRAP

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Abstract

The investigations of plasma decay in ECR heated discharges confined in a mirror magnetic trap is actively studied subject for many years. The motivation of this work is to study plasma instabilities causing perturbations of ion current during the plasma decay.

Present work is devoted to time-resolved diagnostics of non-linear effects observed during the afterglow plasma decay of an 14 GHz Electron Cyclotron Resonance Ion Source (ECRIS) at JYFL operated in pulsed mode. Plasma instabilities causing perturbations of extracted ion current during the decay were observed and studied. It is shown that these perturbations are associated with precipitation of high energy electrons along the magnetic field lines and strong bursts of bremsstrahlung emission. The effect of ion source settings on the onset of the observed instabilities was investigated. Based on the experimental data and estimated plasma properties it is assumed that the instabilities are of cyclotron type. The conclusion is supported by a comparison to another type of plasma devices (SMIS 37, IAP RAS) exhibiting similar characteristics but operating in a different plasma confinement regime.

INTRODUCTION

A number of studies have been devoted to the investigations of plasma decay in ECR heated discharges confined in a mirror magnetic trap (e.g. refs. 1-4). The motivation of this work is to study plasma instabilities causing perturbations of ion current during the plasma decay. The initial transient peak observed during the afterglow plasma decay has been successfully utilized for injection to circular accelerators of heavy particles[5]. The ejection of multicharged ions during the plasma decay is related with its strong nonequilibrium state. ECR plasma heating results to complex non-equilibrium velocity distribution of electrons. In addition, the electron and ion components of plasma are confined in the magnetic trap differently due to significant difference of collision rates. Plasma non-equilibrium state continues to grow after switching off the microwave pulse due to loss cone scattering depending on electron energy, which in particular can cause instabilities described e.g. in Refs. 6-9. Strongly non-equilibrium velocity distribution of electrons confined in mirror magnetic trap can be found in Earth's magnetosphere10 as well as in plasma generators driven by high frequency microwave radiation. Thus, the investigations described in the present paper have rather wide range of applications. The main focus of this work is determining the reasons of apparent perturbations of ion current extracted from plasma during the afterglow of ECR discharge. It is obvious that these perturbations are related to plasma instabilities. The temporal correlation of these perturbations and peaks of bremsstrahlung emission was suggested in ref. 11. Bremsstrahlung and characteristic X-rays are produced by collisions of fast electrons in plasma and with vacuum chamber walls, the latter being the dominant process. Ejection of electrons from the plasma to the walls is evidently related with changes in confinement of fast electrons whose lifetime in quiescent plasma amounts to seconds. Ejection of fast electrons (> 100 keV) from a mirror trap in afterglow mode has been studied in refs. 7 and 12. It was demonstrated that as a result of development of cyclotron instability fast electrons interacting with electric field of plasma waves could enter the loss cone and abandon the trap. The instantaneous current of such electrons, expelled in bursts of less than 200 ns, can be substantial. It is hypothesized in this paper that ion current perturbations, peaks of bremsstrahlung radiation and ejection of fast electrons from the trap are consequences of a single phenomenon, and are related with the evolution of cyclotron instability in strongly non-equilibrium plasma in afterglow of ECR discharge. To confirm this hypothesis a detailed study of temporal behavior of extracted ion currents, bremsstrahlung emission and fast electrons expelled from afterglow plasma was carried out.

EXPERIMENTAL SETUP

The experimental data were taken using the JYFL 14 GHz ECRIS[13]. The source uses an Nd-Fe-B permanent magnet sextupole arrangement and solenoid coils forming a minimum-B structure for confinement of the plasma. The strength of the sextupole field on the wall of the plasma chamber is 0.95 T. Plasma electrons are heated by 50 - 800 W of microwave power at 14.085 GHz. Typical operating neutral pressures are in the 10^{-7} mbar range. The main parts of the setup are a 14 GHz klystron amplifier with a rise and fall times of < 10 μs and < 40 μs, a fast RF-switch with a rise time of 40 ns controlling the incident power, dedicated electron detector with attenuating foils mounted downstream from the plasma electrode, Germanium x-ray/gamma ray detector equipped with a lead collimator structure, TNT2 digital signal processing unit[14]. The Ge-detector arrangement is suitable for studying the temporal behavior of

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bremsstrahlung emission but does not yield direct information on the plasma electron energy distribution. At a later stage of experiments the electron detector was removed to allow extracting ions and recording the temporal evolution of the charge state distribution.

A detector recording the current of electrons, escaping the magnetic confinement through the 8 mm extraction aperture, consists of an array of aluminum foils, each of them occupying a 10 mm aperture, suppression electrode and Faraday cup. The aluminum foils were assembled on a movable cradle whose position could be adjusted through a vacuum feedthrough. Foils of varying thickness were used for the experiments to provide a crude energy resolution for the detection of escaping electrons. The foil thicknesses and corresponding (approximate) energy thresholds for perpendicular angle of incidence are listed in Ref. 15.

The electron detector was positioned 205 mm downstream from the extraction aperture (location of the foil) where the magnetic field strength has decreased to approx. 4% compared to the extraction mirror. It can be assumed that the flux of magnetized electrons is reduced by a comparable factor. The effect of the magnetic field on electron trajectories and velocity components has been neglected when calculating the threshold energies. Consequently all the data were recorded using residual gas (mainly oxygen and nitrogen) mixed with a small amount of oxygen keeping the pressure constant at about $4{\cdot}10^{-7}$ mbar throughout the experiments. The bremsstrahlung radiation was measured radially from one of the magnetic poles of the sextupole structure. The detector line-of-sight was located between the solenoids. Thus, the bremsstrahlung observed by the Ge-detector is a mixture of thick target (wall) and plasma bremsstrahlung. Because the focus of the experiments was to study the temporal evolution of the bremsstrahlung, no special attention was paid in optimizing the collimator structure, which results to a significant contribution from Compton scattering. For this reason, only time-resolved (normalized) total count rates integrated over the energy range of the detected photons are presented in this article. During the analysis data from ~ 102 - 105 rf pulses were combined to gain statistics. The ion beam currents of different charge states of Oxygen were measured with a Faraday cup downstream from a bending magnet (M/Q analysis). An extraction voltage of 10 kV was applied. At the corresponding energy the ion time-of-flight from the ion source to the Faraday cup is on the order of 10^{-6}–10^{-5} s. The purpose of measuring the ion currents of various charge states was to study their (typical) temporal correlation with bremsstrahlung emission and escaping electron flux.

THE MAIN RESULTS

Figure 3 shows the temporal evolution of high charge state oxygen ion currents during the afterglow. Hereinafter t=0 corresponds to the end of microwave pulse. The given example was obtained with 500 W microwave power (2 Hz, 50 % duty factor), solenoid magnetic field profile (injection / minimum / extraction) of Binj = 1.95 T, Bmin = 0.32 T and Bext = 0.90 T and neutral oxygen pressure of $4.2{\cdot}10^{-7}$ mbar. Rather slow plasma decay with characteristic time of approximately 20 ms is interrupted by fast current drops with characteristic time less than 1 ms. Such temporal behavior of current could be related with a plasma instability resulting in abrupt change of lifetime and/or loss pattern of multicharged ions.

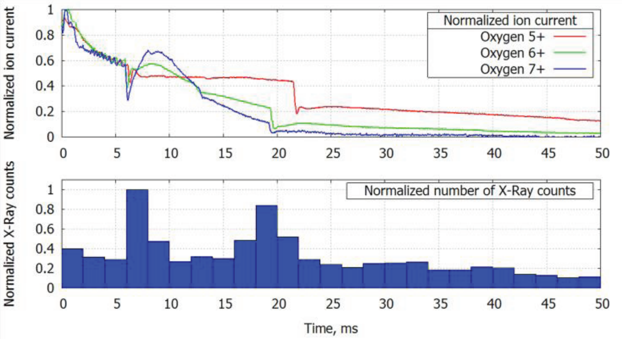

Figure 1. Ion currents of oxygen ions (upper curves) and normalized bremsstrahlung count rate (lower curve) during the afterglow plasma decay.

The figure also shows the temporal behavior of bremsstrahlung counts measured with the Ge-detector. The counts are summarized over 2 ms, averaged over 750 pulses in photon energy range from 30 keV to 1.2 MeV. It can be seen that significantly higher number of counts are detected during fast perturbation of ion beam current. Detected radiation is mainly related with collisions of fast electrons with vacuum chamber wall (wall bremsstrahlung). Formation of a fast electron population in magnetically confined ECR-heated plasma has been studied in number of articles (see, e.g., ref. 17) where it was demonstrated that under ECR heating energy of electrons may reach relativistic values. So, the abrupt peaks of bremsstrahlung are presumably related with pulsed ejection of energetic electrons as suggested in ref. 11.

Direct measurement of fast electron flux from the JYFL 14 GHz ECRIS was carried out first time with the combination of Faraday cup and set of aluminum foils. An example of corresponding temporal plot is shown on Figure 2. In this case the microwave power of 200 W was pulsed with 20 Hz / 50 % duty factor. The magnetic field profile and neutral gas pressure were Binj = 1.95 T, Bmin = 0.32 T and Bext = 0.90 T and 4.0·10-7 mbar, respectively. The data represents the time-average of 100 microwave pulses. After the microwave power is switched off the detected electron current first falls rapidly - in less than 1 ms - and then exhibits slower decay. The abrupt fall of the fast electron flux is very different from the behavior exhibited by ions extracted from the afterglow plasma. Short and repeatable peaks of electron signal with significant magnitude can be observed superimposed on the "background" of slow decay. Similar qualitative behavior was observed

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independent of the ion source settings. Only the number of periodic instabilities and their temporal spacing were affected by the source parameters. A single peak of afterglow fast electron burst measured without any foil and with high temporal resolution (across a resistor) is presented in Figure 3. The duration of the burst (FWHM) is on the order of 100 ns. The magnitude of the electron current has been normalized with respect to the saturation value obtained during the microwave pulse. The fine structure of the peak cannot be resolved due to limited bandwidth of the oscilloscope (100 MHz) and stray capacitance of the cables. Thus, the given width of the peak (100 ns) represents the upper limit of the duration of the electron burst.

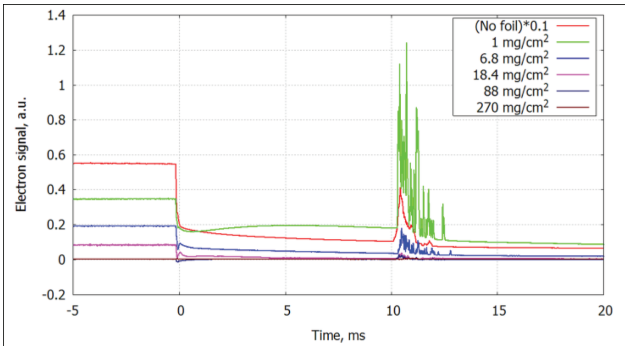

Figure 2: Electron current signal from the Faraday cup with different aluminum foils.

It can be observed that as the solenoid magnetic field strength is increased the first afterglow instability occurs closer to the trailing edge of the microwave pulse. Similar trend appears with increasing microwave power.

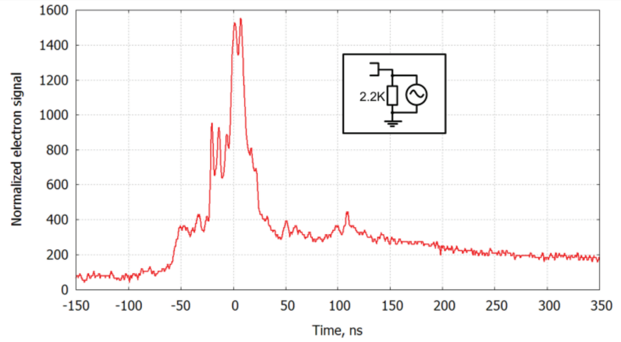

Figure 3: Afterglow electron burst signal with high temporal resolution. Acquisition method is shown in the figure schematically, t=0 corresponds to an oscilloscope trigger moment.

Escaping electron flux was also measured simultaneously with temporal behavior of bremsstrahlung radiation (count rate at energies ranging from 30 keV to 1 MeV). An example measured with 6.8 mg/cm^2 foil is presented in Figure 4. The electron signal has been normalized with respect to the value reached at the trailing edge of the microwave pulse. The corresponding ion source settings in this case were 200 W pulsed with 20 Hz, 50 % duty factor, $4.1 \cdot 10^{-7}$ mbar neutral gas pressure and magnetic field profile of Binj = 2.01 T, Bmin = 0.35 T and Bext = 0.95 T. Data in both plots were averaged over more than 105 pulses to gain statistics and achieve high temporal resolution. Due to a slight temporal shift of the onset of the instability from pulse to pulse, the duration of averaged pulse exceeds the actual duration of fast electron pulse. The figure highlights the coincidence of the bremsstrahlung and electron bursts.

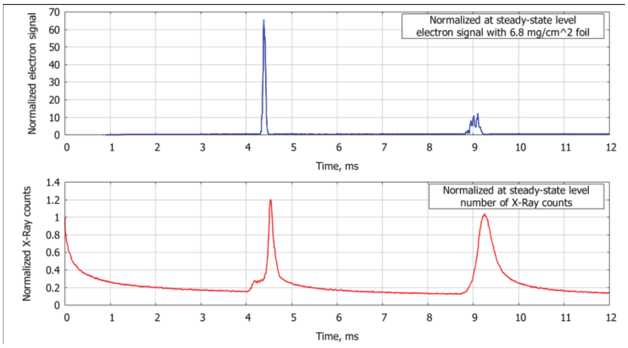

Figure 4: Temporal behavior of electron flux (upper curve) and bremsstrahlung (lower curve).

The energy of fast electrons was estimated from the difference of currents measured with the Faraday cup through various foils. Unfortunately, the signals associated with the electron bursts were strong enough to saturate the data acquisition system for the majority of the pulses. Thus, the lack of data at low electron energies prohibits plotting an energy spectrum. However, it can be estimated that the upper limit for the average electron energy within the instability peaks is in the range from 49 to 60 keV. The existence of relativistic electrons was observed as the Faraday cup current even with the thickest foil i.e. 270 mg/cm^2 / 570 keV threshold energy.

DISCUSSION

The observed particle ejections from the trap have much in common with pulsed precipitations of hot electrons from the decaying plasma of ECR discharge in a mirror magnetic trap described in previous studies (refs. 6-9). These experiments were carried out using 37 GHz 100 kW pulsed gyrotron with pulse duration up to 1 ms and simple mirror magnetic trap with maximum field Bmax=1.8 T and mirror ratio of 5, confining plasma in gas-dynamic (collisional) regime. Precipitations of hot electrons from the magnetic trap detected by pin-diode appeared 600 µs after MW trailing edge. Basically, the electron distribution function formed by ECR discharge can be considered to be comprised of at least two fractions: (1) less dense "hot" component with strongly anisotropic velocity distribution function, i.e. significantly higher transverse electron energy in comparison to longitudinal energy, and (2) dense "cold" component with lower level of anisotropy (or even isotropic, depending on plasma parameters). The dense plasma component determines dispersion relation and damping of propagating waves, which can resonantly interact with energetic electrons. The anisotropy of the hot component ensures the growth of electron cyclotron plasma instabilities. The precipitations of hot electrons, observed in ref. 9, were identified to be a consequence of cyclotron instability of a slow extraordinary wave propagating across the magnetic field. Interaction of hot resonant electrons with this electromagnetic wave, exponentially increasing at the linear stage of instability, reduces their transverse energy[18]. As a result, some hot electrons enter the loss cone and leave the trap. During ECR discharge these instabilities are suppressed by phenomenon referred in the literature as depression of cyclotron radiation at gyro-frequency in dense plasma (see e.g. ref. 19). After switching off the microwave pulse the density of the "cold" electron fraction decreases rapidly in the decaying plasma due to Coulomb collision induced loss cone scattering, while the hot electrons with an anisotropic velocity distribution function are confined in the magnetic trap much longer. Therefore, starting from a certain time, the density of the hot component can become equal to or even higher than the density of the cold component. The growth of instabilities becomes possible in rarefied plasma when the plasma density becomes low enough, so that the electron plasma frequency is much less than the electron gyro-frequency. The periodic excitation of electromagnetic waves at frequencies near the electron gyro-frequency which propagate perpendicularly to the magnetic field and cause precipitation of energetic electrons have been observed recently[9]. It seems logical to argue that pulsed electron precipitations described in refs. 6-9 and those observed in the present work are of the same origin as the characteristics of the oscillograms are similar: (i) electron precipitations are generated as pulses (bursts) with a duration of ~ 10^{-7} s, (ii) the delay between the trailing edge of the microwave pulse and the first electron burst exceeds the cold plasma confinement time, (iii) amplitude of the electron (and bremsstrahlung) signal during the instability often overcomes the steady-state value. It is of note that the experimental conditions in the two experiments (this paper and ref. 9) are significantly different, the most important distinction being the operational regime i.e. classical (collisionless) vs. gas-dynamic confinement. Thus, it has been experimentally shown that the nature of the described instability mechanism is rather universal. These facts let us assume that observed phenomena is the result of resonant interaction between hot electrons and electromagnetic waves in rarefied plasma.

Temporal coincidence of electron and X-ray bursts as well as ion current perturbations during the afterglow plasma decay indicates that all of them are driven by the same mechanism. The number of electrons, i.e. amount of negative charge, expelled by the instability-driven plasma waves could be sufficient to affect the ambipolar potential. It is straightforward to assume that as a result of the cyclotron instability this imbalance is momentarily amplified causing perturbations of ion currents. Identifying the exact mechanism of ion current fluctuation requires further research. However, it has been clearly demonstrated that the driving mechanism of afterglow plasma perturbations is the onset of cyclotron type electron instabilities resulting to transient peaks of electron flow from the trap, bremsstrahlung emission and fluctuation of ion current.

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