TIME EVOLUTION OF PLASMA POTENTIAL IN PULSED OPERATION OF ECRIS*

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Abstract

The time evolution of plasma potential has been measured with a retarding field analyzer in pulsed operation mode with electron cyclotron resonance ion sources at JYFL and RIKEN. Three different ion sources with microwave frequencies ranging from 6.4 to 18 GHz were employed for the experiments. The plasma potential was observed to increase 10-75 % during the preglow and 10-30 % during the afterglow compared to steady state.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources (ECRIS) exhibit fast transient peaks of extracted ion beam currents at the leading and trailing edges of the applied microwave pulse [1,2]. The fundamental difference between these transients, called preglow and afterglow, is the charge state distribution (CSD) of extracted ion beams - low charge ions (LCI) exhibit preglow while the afterglow boosts the beam currents of highly charged ions (HCI). Studies [1,3,4] of the preglow are driven by the aim of creating a short-pulsed multi-charged ion source with high ionization efficiency. The afterglow mode is utilized e.g. for injection into circular accelerators [5] as it offers intensive beams of HCI.

In order to gain understanding on the plasma processes associated with these transients we measured the time evolution of plasma potential during the microwave pulse. Furthermore, the results allow us to estimate beam transport properties during the transients as the variations of the plasma potential are reflected to the beam energy spread.

EXPERIMENTAL PROCEDURE

The plasma potential of an ECRIS can be deduced by measuring the exact energy of extracted ion beams. The study presented in this article was performed with retarding field analyzers described in detail in references 6 (JYFL) and 7 (RIKEN). Three different ion sources, the JYFL 6.4 GHz ECRIS, the JYFL 14 GHz ECRIS, and a room temperature 18 GHz ECRIS at RIKEN, were employed for the experiments. The retarding field analyzer was located in the beam line downstream from the analyzing magnet to allow charge state dependent studies of the plasma potential. The output of the klystron was controlled by pulsing the input signal from a solid state oscillator with an rf-switch controlled by a pulse generator. The pulsing signal was also used as a trigger for the data acquisition. The klystron gain i.e. attenuator setting was kept constant. The voltage regulated power supply for the retarding electrode was floating on the high voltage of the ion source. This eliminates the error due to small fluctuations of the source bias, typically associated with the plasma breakdown. Signals from the retarding field analyzer and Faraday cup were measured across a resistor and stored with an oscilloscope. Schematic of the measurement setup is shown in Figure 1.

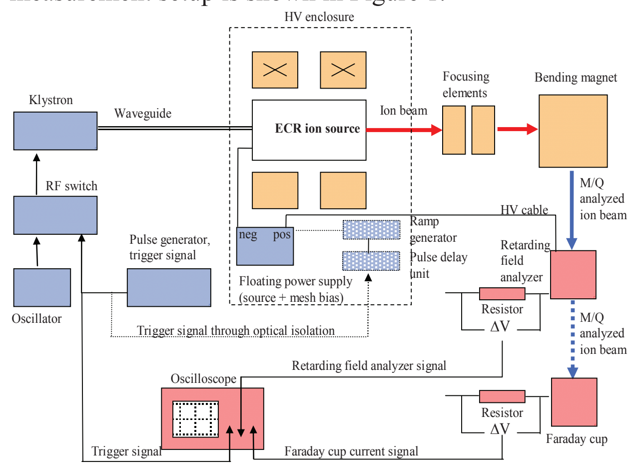

Figure 1: Schematic of the measurement setup.

Two slightly different methods were used for controlling the bias voltage of the retarding field analyzer. The more elegant method utilizes floating, optically isolated, pulse delay unit and voltage ramp generator. The trigger signal was fed into a pulse delay unit gating a fast (1 ms) linear voltage ramp from a signal generator. Adjustment of the pulse delay (measured from the leading edge of rf pulse) was used for selecting the time window for ramping the retarding voltage and acquiring the IV-curve for deducing the plasma potential as described in reference 6. This method was used always when possible i.e. when the variations of the plasma potential were found to be slower than the voltage ramp time of 1 ms, limited by the four-quadrant bias power supply.

Unfortunately, it was observed that this condition does not hold during the preglow and afterglow. For studying fast variations of the plasma potential (preglow and afterglow) the retarding voltage was fixed to a constant value for the duration of the microwave pulse. Increasing the retarding voltage in discrete steps between consecutive pulses makes it possible to deduce the plasma potential at arbitrary time within the microwave pulse after reconstructing IV-curves from the data.

The goal of the experiments was to compare the plasma potential during preglow and afterglow transient with the steady-state value with frequencies from 6.4 to 18 GHz.

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The density of seed electrons at the moment of microwave turn-on affects the characteristics of the preglow [3] and, thus, the effect of seed electrons on the time evolution of plasma potential was studied at JYFL. Seed electrons were produced by sustaining a low density plasma with low power cw microwaves from a TWTA. The power dependence of the plasma potential time evolution was studied at RIKEN. Helium and Argon plasmas were used for the experiments and the source settings, i.e. power, neutral gas pressure and magnetic field, were chosen to correspond to typical operational values of the ion sources.

EXPERIMENTAL RESULTS

He^{2+} ion beam was used for studying the plasma potential during the preglow with the JYFL ECR ion sources (6.4 and 14 GHz). The delay between plasma breakdown and first observation of extracted He^{2+} is less than 0.2 ms [3]. Microwave pulse pattern with on-time of 1.76 s and off-time of 5.9 s was used in order to assure that the plasma potential reaches a steady-state value and to drain the magnetic bottle from well-confined electrons between the pulses. The plasma potential and He^{2+} ion beam current following the microwave turn-on (at t = 0 ms) are presented in Figure 2. The plasma potential peaks immediately after the plasma breakdown being 30 – 50 % higher than the saturation value. The peak of the plasma potential coincides reasonably well with the preglow in the case of 14 GHz ion source. In the case of 6.4 GHz a similar peak of plasma potential was observed although the preglow is virtually non-existent.

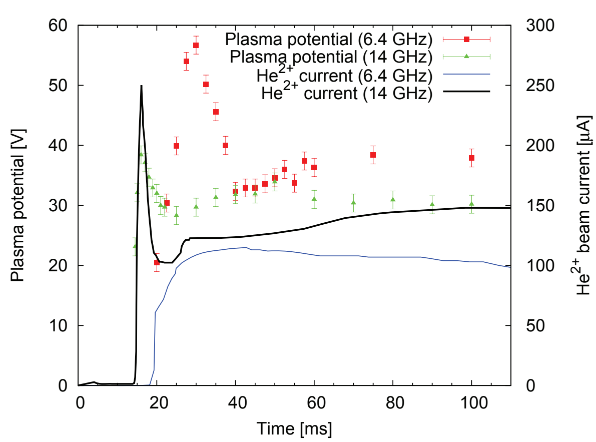

Figure 2: Preglow plasma potential and He^{2+} ion beam current of the JYFL ion sources.

It was observed with the JYFL 14 GHz ECRIS that while providing seed electrons clearly enhances the preglow ion beam current of He^{2+} and allows a faster plasma breakdown, the time evolution of plasma potential is unaffected as shown in Figure 3.

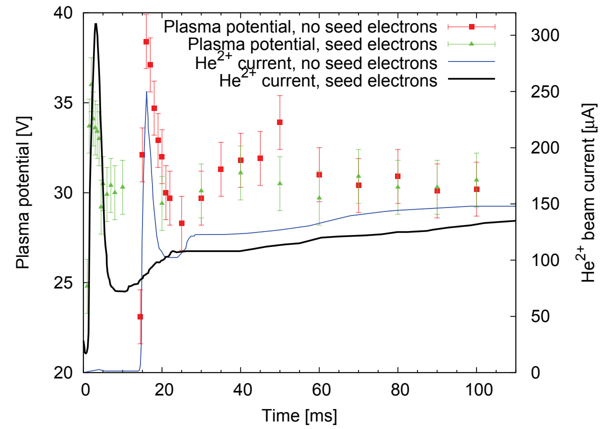

Figure 3: Preglow plasma potential and He^{2+} ion beam current with and without seed electrons (JYFL 14 GHz ECRIS).

Argon plasmas also exhibit similar transient behavior in the very beginning of the microwave pulse (confirmed at JYFL and RIKEN). Figure 4 shows a result from the 18 GHz ECRIS at RIKEN. Microwave pulse pattern with on- and off-times of 100 ms (i.e. duty factor of 50%), resulting into presence of notable amount of seed electrons, was used. The plasma potential was measured with Ar^{9+} ion beam.

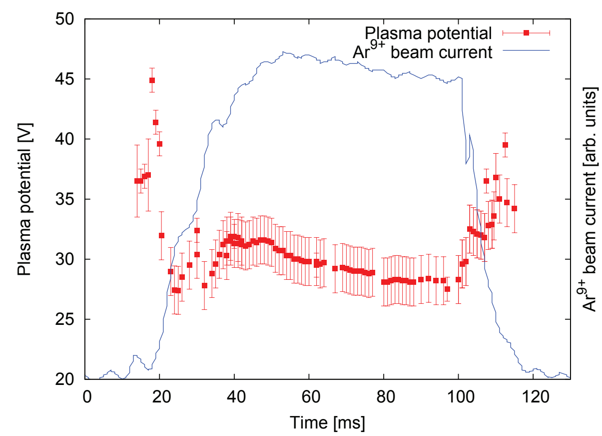

Figure 4: Plasma potential and Ar^{9+} ion beam current of the RIKEN 18 GHz ECRIS.

The peak of the plasma potential in the beginning of the microwave pulse is reached far before the beam current of Ar^{9+} reaches steady-state. The behavior highlights the fact that during the preglow the plasma is populated by low charge state ions increasing the plasma potential. The RIKEN 18 GHz ECRIS was also used for studying the time evolution of plasma potential at different microwave powers. The results are displayed in Figure 5.

The peak value of the plasma potential remains practically constant while the steady-state value increases at higher power (plasma density). The relaxation time decreases with increasing power. Saturation was not reached with 100 ms pulses for 100 W of power (indicated by the arrow associated with the data point).

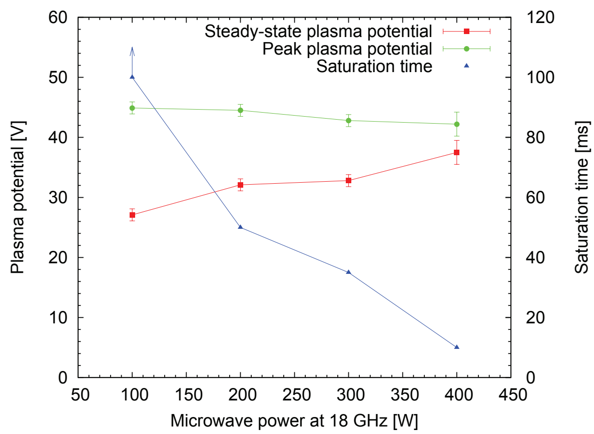

Figure 5: The effect of microwave power on the behaviour of the plasma potential (18 GHz).

Figure 4 shows also that the plasma potential increases momentarily during the plasma decay (afterglow). Similar behavior during the afterglow was observed with the JYFL ion sources. The magnitude of the afterglow fluctuation of the plasma potential was less pronounced at lower frequencies. i.e. lower magnetic field affecting the plasma confinement. The relative increase of the plasma potential during the preglow and afterglow transients for the three ion sources are listed in Table 1. The range of the values corresponds to varying ion source settings (however, a full parametric study is still desirable).

Table 1. Comparison of the relative increase of plasma potential (argon) during the preglow and afterglow.

Ion Source	Preglow / Steady-state plasma potential	Afterglow / Steady-state plasma potential
JYFL 6.4 GHz	1.06 – 1.12	1.09 – 1.14
JYFL 14 GHz	1.13 – 1.47	1.17 – 1.28
RIKEN 18 GHz	1.13 – 1.66	1.04 – 1.34

DISCUSSION

The conclusion of our studies can be summarized as follows: the plasma potential is higher during the plasma build-up and decay compared to steady-state conditions. However, the processes explaining the potential fluctuations are different for preglow and afterglow.

It is believed that the preglow peak of low charge state ion currents is caused by abrupt change in plasma energy content (electron energy distribution function, EEDF) [4]. At low ionization degree, the microwave power is sufficient to heat the electron population to high energies corresponding to so-called superadiabatic EEDF. The average electron energy collapses with exponentially increasing plasma density, which results to burst of electron losses from the plasma. Due to lower mobility, the loss rate of ions cannot match the loss rate of electrons. The difference in particle fluxes is compensated by the formation of plasma potential. High electron loss rate associated with the transition from superadiabatic EEDF to bi-Maxwellian one forces the plasma potential to peak in the process. The effect is presumably amplified by the fact that the preglow CSD is concentrated on LCI. High plasma potential is required to retard electrons and, on the other hand, supply LCI with enough velocity to balance the fluxes of negative and positive charge. As the mean charge of ions increases, the potential drops and reaches steady-state value. The damping of the plasma potential fluctuations seems to be faster with increasing microwave power and frequency i.e. increasing plasma density in steady-state. This is most likely due to increased rate of ionization pushing the CSD towards equilibrium in reduced time.

Plasma potential peaking during the preglow implies that any application, relying on running an ECRIS in pulsed mode and utilizing the preglow transient, must take into account the increased energy spread of the ion beam causing the bending and focusing properties of the ion beam differ from those of a cw beam. It is plausible to claim that the space charge compensation degree of the ion beams in pulsed mode is lower than cw beams, which could deteriorate the beam quality even further. This has been noted in experiments at JYFL [3] in which the bending magnet (energy spread) and solenoids (space charge compensation / beam particle distribution) had to be tuned differently when switching from cw beams to pulsed beams (preglow).

According to the prevailing understanding afterglow peak of HCI is initiated by a burst of cold electrons escaping the plasma [2]. As the microwave power is turned off, growing number of cold electrons populate the loss cone of the magnetic bottle in velocity space because they are not being heated perpendicular to the magnetic field anymore. It has been argued [8] that this process changes the magnitude and spatial distribution of the plasma potential reducing the confinement of ions. Our experiments suggest that the ion confinement is indeed reduced during the afterglow due to increased plasma potential, which results to a fast transient peak of HCI expelled from the plasma, followed by diffusive decay.

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