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ABSTRACT

Electron Cyclotron Resonance Ion Source (ECRIS) plasmas are prone to kinetic instabilities resulting in loss of electron and ion confinement. It is demonstrated that the biased disk of an ECRIS can be used as a probe to quantify such instability-induced electron and ion losses occurring in less than 10 μs. The qualitative interpretation of the data is supported by the measurement of the energy spread of the extracted ion beams implying a transient plasma potential >1.5 kV during the instability. A parametric study of the electron losses combined with electron tracking simulations allows for estimating the fraction of electrons expelled in each instability event to be on the order of 10% of the total electron population.

I. INTRODUCTION

Electron Cyclotron Resonance Ion Source (ECRIS) plasmas are prone to kinetic instabilities that often limit the parameter space available for optimizing the extracted currents of high charge state ions.[1] The instabilities are driven by the anisotropy of the electron velocity distribution, and the threshold of their appearance is strongly related to the strength of the magnetic field near the minimum-B. It has been demonstrated[2] that two-frequency heating is an effective method to suppress the instabilities at a given magnetic field or alternatively shift the instability threshold to higher B_{min}.

Various diagnostics methods including the detection of plasma microwave emission,[3] bremsstrahlung bursts,[4] and oscillation of the extracted beam current[4] have been applied in the past to observe the transition between stable and unstable discharge regimes. The kinetic instabilities are associated with electron and ion losses that are notoriously difficult to quantify using the above indirect diagnostics. Fortunately, the majority of modern ECR ion sources (with the exception of charge breeders) are equipped with a biased disk[5] located at the injection end of the discharge chamber where the flux of charged particles escaping the confinement intercepts with the axial wall of the vessel. In this article, we demonstrate that the biased disk can be used as a probe to quantify instability-induced electron and ion losses. The interpretation of the data is supported by the measurement of the corresponding transient of the extracted ion beam energy spread.

II. EXPERIMENTAL SETUP AND PROCEDURE

The experimental data were taken on the A-ECR-type JYFL 14 GHz ECRIS[6] at the accelerator laboratory of the University of Jyväskylä. Typical ranges of the adjustable source parameters in a

TABLE I. Typical operating parameters of the JYFL 14 GHz ECRIS.

14 GHz microwave power (W)	200–800
Neutral gas pressure (gauge reading) (mbar)	$\leq 10^{-6}$
B_{min}/B_{ECR}	0.65–0.75
Biased disk voltage (neg.) (V)	20–300
Extraction voltage (kV)	8–14

stable operating regime of the ion source producing high charge state ions in the single frequency heating mode are listed in Table I.

The 21 mm diameter circular biased disk of the ion source is normally connected directly to a −1 kV/10 mA power supply floating on the source potential and providing a voltage ranging typically from −20 V to −300 V. In order to measure the instability-induced electron and ion transients with appropriate time resolution, the setup was amended with a 4.7 μF capacitor and 1 MΩ resistor connected parallel to the power supply. The purpose of the capacitor is to act as an additional charge storage capable of managing the transient surge of current. The current flowing in the circuit was monitored by measuring the voltage across a 1 kΩ resistor connected in series with the disk. The electron and ion current transients were measured varying the ion source operational parameters, i.e., microwave power, neutral gas (oxygen) pressure, magnetic field strength, and biased disk voltage from 100 W to 600 W, 1.5 × 10^{-7} mbar to 4.5 × 10^{-7} mbar, B_{min}/B_{ECR} = 0.75 to B_{min}/B_{ECR} = 0.80, and 0 V to −200 V, respectively. The given range of magnetic field settings corresponds to the discharge regime plagued by periodic instabilities.

The instability-induced transient of the energy spread of the extracted ion beams was measured by recording the temporal m/q-analyzed beam current signals from a Faraday cup located downstream from a 90° bending magnet at different magnet current settings. The data were then reconstructed off-line to reveal the temporal variation of the beam current energy spread $\Delta E/E$ using the instability-induced bremsstrahlung emission peak as a trigger. The energy spread data were taken with 10 kV ion source potential for helium and oxygen.

III. EXPERIMENTAL RESULTS

Figure 1 shows an example of the electron and ion bursts recorded from the biased disk. The leading edge of the negative (electron) current transient was used as a trigger signal for the data acquisition, i.e., $t = 0$ corresponds to the onset of the instability. The given example was recorded with −20 V disk voltage with 350 W power, 1.5 × 10^{-7} mbar oxygen pressure, and B_{min}/B_{ECR} = 0.78. The integrated negative and positive charges, i.e., $Q = \int I dt$, escaping the confinement and collected by the disk are also shown in the figure. The instability excites an electromagnetic wave interacting with the electrons and expels it into the loss cone, which is seen as a spike of (axial) electron current, followed by a drastic increase in the ambipolar potential resulting in an ion transient carrying an approximately equal positive charge, thus maintaining the plasma quasineutrality. The described sequence takes place in less than 10 μs, and the transient currents exceed the typical biased disk steady-state positive current of 1 mA by 1–2 orders of magnitude.

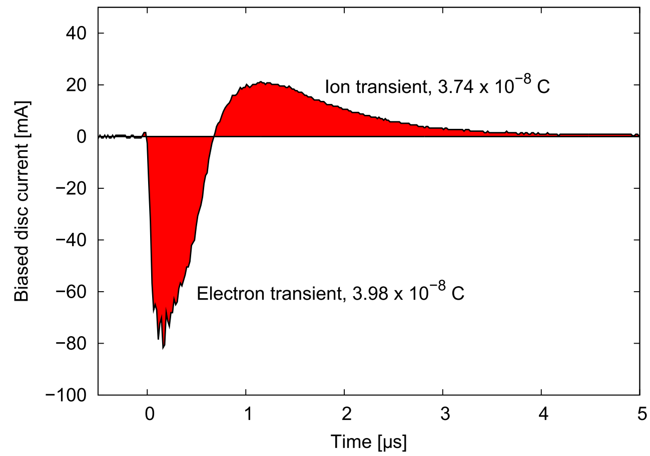

FIG. 1. An example of the instability-induced electron (negative) and ion (positive) current transients of the biased disk.

The above description is corroborated by the time-resolved energy spread $\Delta E/E$ of the extracted ion beams during the instability transient shown in Fig. 2. The He^{2+} and O^{6+} (used as reference beams) peaks of the m/q-spectra stretch in energy overlapping with the adjacent residual gas and impurity peaks for few microseconds

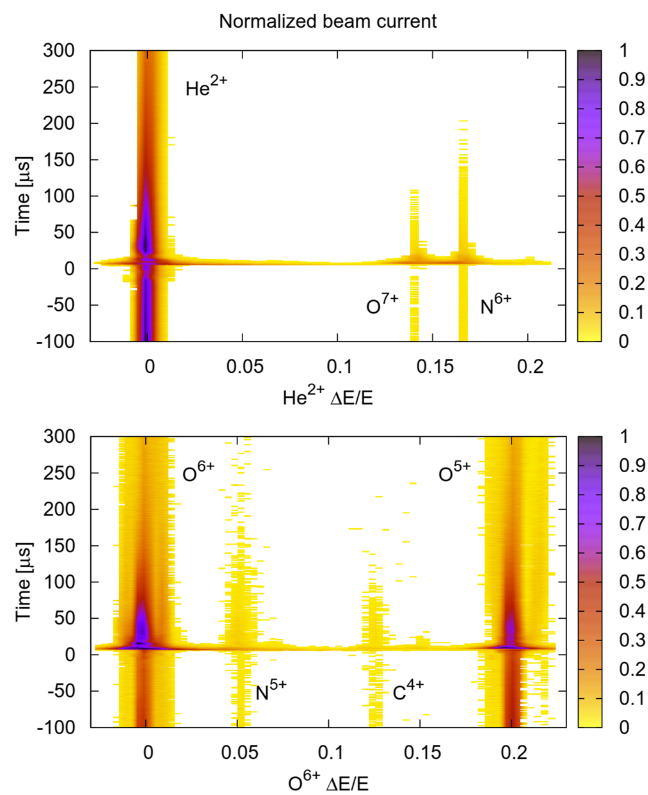

FIG. 2. Ion beam energy spread normalized to He^{2+} (top) and O^{6+} (bottom) at 10 kV source potential.

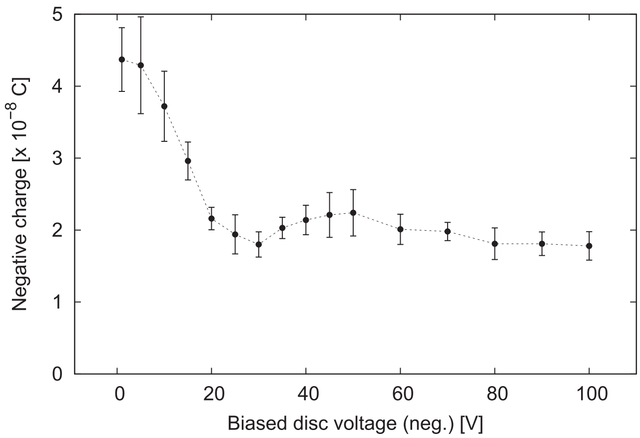

FIG. 3. Magnitude of the instability-induced negative charge burst collected at the biased disk as a function of its voltage.

following the onset of the instability at $t = 0$. This corresponds to $\Delta E/E$ of 10%–15% and implies that the plasma potential reaches a transient value up to 1.5 kV during the ion transient. The "negative energy" spread associated with the instability is due to a droop of the power supply providing the 10 kV ion source potential incapable of handling the drain current surge. The transient bursts of the ions are clearly visible up to 50 μs, including residual gas and impurity ions being released from the plasma chamber walls.

Figure 3 shows an example of the negative charge (electrons) collected by the biased disk during the instability transient as a function of its voltage with 300 W power, 3.0×10^{-7} mbar oxygen pressure, and $B_{min}/B_{ECR} = 0.75$. The negative charge decreases with increasing (negative) bias voltage up to ~20 V and then plateaus at higher voltages. It is believed that the increased signal at low disk voltages is due to the 20–40 eV "cold" electron population,[7] retarded by the positive plasma potential and the negative bias voltage, being able to reach the disk. The observation implies that although the kinetic instabilities are caused by the "hot" ~200 keV electron population,[8] they result in electron losses across the whole electron energy range.

The parametric sweep data are displayed in Fig. 4 showing the negative charge (electrons) collected by the biased disk during the periodic instability transient as a function of the microwave power at various neutral gas pressures, magnetic fields, and disk voltages corresponding to instability repetition rates from 500 Hz to 1.5 Hz.

Two clear trends were observed; the biased disk voltage affects the integrated charge as discussed above, and the electron burst becomes weaker as the microwave power is increased. The latter is presumably due to the fact that the instability repetition rate increases with power,[4] hence allowing fewer electrons to accumulate in the discharge between the periodic bursts and be subsequently expelled during the transient. The effects of the neutral gas pressure and the B_{min}/B_{ECR}-ratio on the expelled charge are much weaker and cannot be distinguished. This is consistent with previously published results[4] demonstrating that the magnetic field strength and neutral gas pressure define the threshold between the stable and unstable regimes, whereas varying the microwave power (≥200 W) only affects the repetition rate of the periodic instability onsets.

IV. DISCUSSION

The reported experiments have demonstrated the usefulness of the biased disk as a probe of instability-induced electron and ion losses. One of the possible applications of the technique is to study the statistical correlation between the magnitude of the electron and ion bursts and the repetition interval of consecutive instability onsets. Such an experiment could provide evidence supporting a theoretical model[8] connecting the released energy to the period between consecutive instability events. Furthermore, the observed peak of

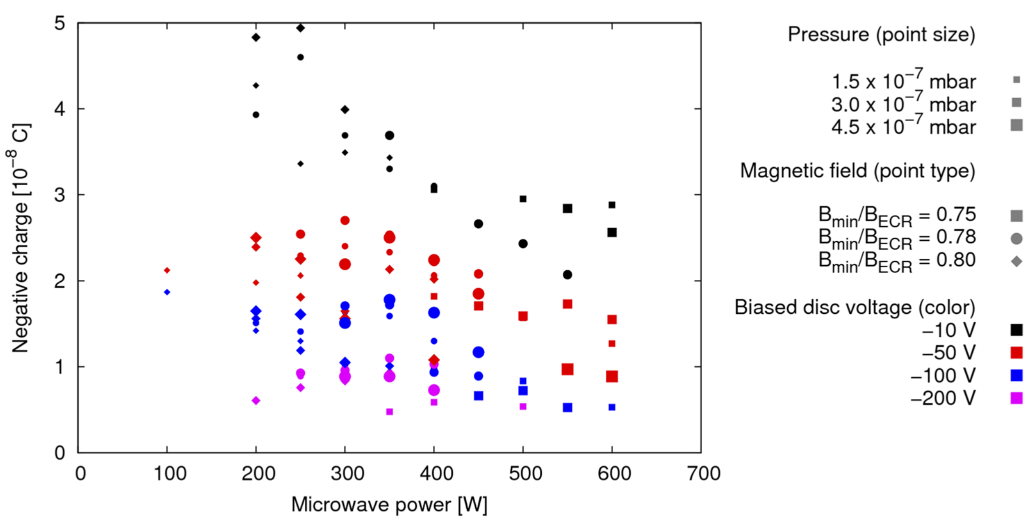

FIG. 4. Magnitude of the instability-induced negative charge burst collected at the biased disk as a function of the microwave power at various neutral gas pressures, magnetic fields, and disk voltages.

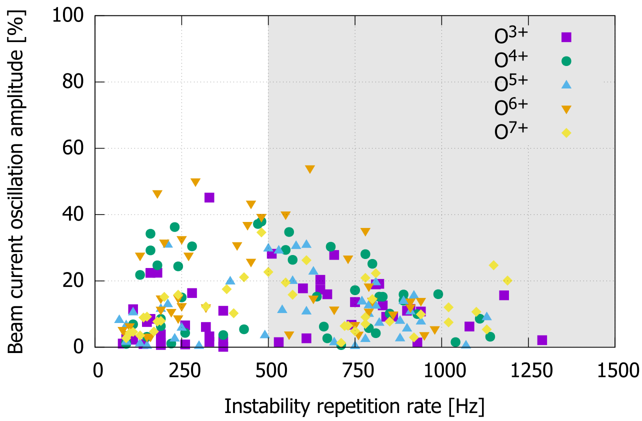

FIG. 5. The range of instability-induced beam current oscillation repetition rates and amplitudes of oxygen ion beams extracted from the JYFL 14 GHz ECRIS. The shaded area indicates the parameter space corresponding to the experiments with the biased disk. The data are taken from Ref. 11.

plasma potential inferred from the energy spread of the extracted ion beams and the ion current transient collected by the biased disk provides further evidence for the origin of increased impurity background of the extracted beams in the unstable operating regime, being especially relevant for charge breeder ECR ion sources.[9]

The electron burst collected by the biased disk can be used for estimating the order of magnitude of the total electron losses, both absolute and the fraction of the confined electrons. It is assumed that the electron density in the 100–130 cm^3 volume enclosed by the ECR zone (estimated for the range of B_{min}/B_{ECR} of 0.75–0.80) is 10^{11}–10^{12} cm^{-3}, which translates to the total negative charge of 1.6–21 μC, i.e., on the order of 10 μC. The distribution of the instability-induced electron losses is unknown, but recent experiments with the GTS ECRIS at GANIL, utilizing two x-ray scintillators with varied positions around the ion source, have revealed that the electron losses are not strongly localized, but the instabilities rather expel electrons "globally." The conclusion is based on the comparison of relative strengths of the signals recorded from the two detectors at each instability event displaying a constant ratio, which speaks against localized electron losses. It is therefore assumed that the electron loss distribution is similar to that found in the stable regime and modeled by electron tracking simulations[10] implying that approximately 5% of electrons are lost to the biased disk. As the instability is presumably driven by the "hot" electrons confined near the source axis and escaping preferentially along the axial flux, the total electron losses derived from this estimate represent the upper limit. With these assumptions, the 5–50 nC range shown in Fig. 4 corresponds to absolute electron losses of 0.1–1 μC with the upper bound being more representative of the losses integrated over the entire electron energy distribution as discussed above. Hence, it is concluded that the fraction of electrons expelled by each periodic instability event is on the order of 10% of the total electron population.

The above fraction is consistent with the 2%–30% periodic ripple of the beam current at instability repetition rates above 500 Hz, as shown in Fig. 5, for different charge states of oxygen. It is worth noting that also the beam current oscillation amplitude decreases on average with the instability repetition rate similar to the magnitude of the burst of the negative charge collected at the biased disk. The effect of the instabilities on the extracted current of different charge states, i.e., the average beam current oscillation amplitude and the temporal characteristics of the instability response, is discussed in detail elsewhere.[4,11]

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