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THE RELATIONSHIP BETWEEN THE DIFFUSION OF HOT ELECTRONS, PLASMA STABILITY, AND ECR ION SOURCE PERFORMANCE

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Abstract

The diffusion of electrons from ECRIS plasmas results in the emission of a continuous energy distribution of photons from the plasma chamber. Measurements ECRIS bremsstrahlung that are both time and energy resolved of the are often difficult to perform due to the 10's – 100's ms timescale that the plasma evolves over. However, the advancement of low-cost micro-controllers over the last decade makes timing and gating photon spectrometers easier. We present a proof of principle measurement which uses an Arduino micro-controller as a gate-and-delay generator for time resolved ECRIS bremsstrahlung measurements. An example plot of the time resolved spectrum, triggered by beam current variation induced by kinetic instabilities is shown.

INTRODUCTION

Accelerator facilities like the National Superconducting Cyclotron Laboratory (NSCL) and the Facility for Rare Isotope Beams (FRIB) require high intensity, high charge state ion beams for facility operations. These facilities rely on electron cyclotron resonance (ECR) ion sources (ECRISs) to produce stable ion beams for their operations. To that end, researchers have determined different ways to optimize the performance of the ion source [1–3]. In particular, the semi-empirical magnetic field scaling laws have proven to be reliable and important guides to optimizing the performance of ECR ion sources [4].

However, the ECR ion source plasma is prone to microinstabilities that cause quasi-periodic losses of high energy electrons and limit the ion source's performance on the high field and power range of the operating parameter space [5]. These instabilities result from the combination of loss-cone confinement and resonant heating mechanisms that create the ECR plasma. These combined mechanisms create steady-state electron populations that are anisotropic, with large transverse energies, $T_\perp >> T_\parallel$ [6]. These electrons can excite and amplify electromagnetic plasma modes within the plasma chamber and, in doing so, drive themselves into the loss cone [7, 8]. This instability is known as a kinetic cyclotron maser instability and is a type of inverse Landau damping [9, 10].

Electrons driven into the loss cone rapidly escape the plasma chamber, disrupt the plasma quasi-neutrality condition, and alter the confinement characteristics of ions within the system. These imbalances result in the quasi-periodic beam current variations that are characteristic of the instabilities in ECR ion sources [5]. Consequently, the average extracted current of highly charged ions decreases, limiting the ion source's performance, particularly on the high field side of the ion source's operating parameter space. It is difficult to suppress the instabilities as they are a natural consequence of the loss-cone and microwave heating mechanics [11]. Understanding when and how a plasma changes from stable to unstable is essential for optimizing ECRIS performance.

Measurements on AECR at the University of Jyväskylä (JYFL) show that large losses (50 – 90%) of highly charged beam currents occur when operating the ion source with large injected microwave powers and magnetic field strengths, in particular when $B_{min} > 0.7 – 0.8\ B_{RF}$ [5], where $B_{RF} = \omega_{RF}/(28\ \mathrm{GHz})$ (more commonly known as B_{ECR}), and ω_{RF} is the propogation frequency of microwave injected into the plasma chamber. Followup measurements on SuSI at the NSCL demonstrated that the instabilities could occur over a larger subset of the magnetic field parameter space, $B_{min} < 0.55\ B_{RF}$ [12]. The instabilities at lower field values tended to repeat more frequently and perturb the plasma less. However, those measurements focused on the stability characteristics of the magnetic field parameter space as a whole and revealed few details into the effect of the varying field strength on the beam current's transient characteristics.

We report the results of an investigation into the extracted beam current, from an unstable plasma while changing the ion source magnetic field when operating the ion source with magnetic fields lower than those prescribed by the semi-empirical scaling laws. In particular, we focus on the effect of changing magnetic field topologies (extraction side field maximum and global minimum) upon the transience state of extracted Ar^{8+} currents. These results demonstrate a connection between the amplitude and repetition frequency of the plasma instabilities and the longitudinal magnetic field's topology.

APPARATUS AND PROCEDURES

All measurements were taken using the Superconducting Source for Ions (SuSI) at the NSCL[13] (Fig. 1). The ion source's confining magnetic field is created with four superconducting solenoids and a superconducting hexapole coil. The four axial solenoid coils provide longitudinal confinement while allowing for control over the injection and extraction maxima and the field minimum. The system's

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design allows for each of the longitudinal field extrema to vary independently of one another.

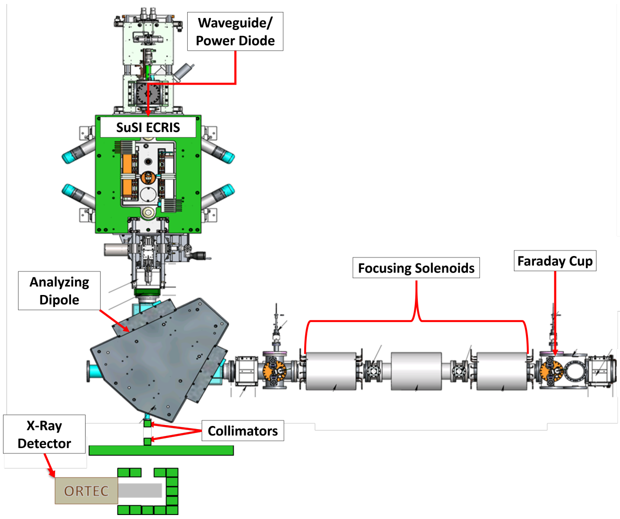

Figure 1: A schematic of the source-beamline configuration used for this measurement.

This measurement acted as a supplemental measurement to Isherwood et al. [14], except in this case, we measured extraction ion currents rather than the diffusing electrons. The dynamics of the diffusion electrons are complicated, however, and a direct 1-to-1 comparison would between these two measurements would be difficult at present. However, these same field parameters allow us to observe the effect of plasma instabilities at less than what is prescribed by the scaling laws. Those fields were based around a "control" magnetic field profile, which all other measurements could be compared against. For our purposes at the moment, the importance of the field profile is that it sets the global minimum and extraction side maximum lower than what is prescribed by the scaling laws (see Table 1).

Table 1: A comparison between the magnetic field topologies of the "standard" field configuration for facility operations and the "control" field configuration used in this study and Ref. [14].

	Standard	Control
B_{min}/B_{RF}	0.71	0.62
$B_{Inj,max}/B_{RF}$	3.96	3.68
$B_{Ext,max}/B_{RF}$	1.94	1.71

The extraction and einzel lens voltages were fixed at 20 kV for the duration of the measurement, with the puller electrode fixed at 0 V. Argon ions were extracted from the plasma chamber with a fixed neutral gas pressure of 213 nTorr, as measured by an ion gauge on the injection side of the plasma chamber. A 90° dipole was used for charge selection and guided the ions into a solenoid focusing lattice to guide the selected charge state current into a Faraday cup. Reflected/emitted microwaves from the plasma chamber were measured with an HP 8473C Low Barrier Schottky Diode connected to a bi-directional waveguide coupler connected to the microwave waveguide. The diode cannot measure the propogation frequency of the emitted microwaves, but does measure the instability repetition rate. The beam current and microwave power signals were measured simultaneously using a Tektronix MDO3054 oscilloscope. Bremsstrahlung measurements were taken on axis using a High Purity Germanium Detector (HPGe), placed in line with the longitudinal axis of the ion source's plasma chamber. Two lead bricks and a cylindrical piece of tungsten collimated the flux of bremsstrahlung radiation emitted from the ion source.

RESULTS

Varying the Extraction Side Field Maximum

We will start by looking at the effect of varying the extraction side field maximum on the extracted Ar^{8+} current. The extraction side field maximum appears to control several characteristics of the unstable plasma, such as the repetition rate and amplitude of individual instability events. Figures 2, 3, and 4 demonstrate these trends through measurements of extracted Ar^{8+} currents and emitted microwave power signals, in time and frequency domains. The increasing field strength correlates with an increasing instability repetition rate and decreasing current variation and microwave emission amplitudes. Furthermore, the higher frequency events tended to occur more randomly, with a larger spread over the frequency domain. Eventually, the microwave power signal beings to resemble electronic noise, albeit large amplitude noise. At this point, the extracted current reaches its minimum over the domain. Figure 5 quantifies these trends by looking at the averaged Ar^{8+} current extracted from the plasma chamber.

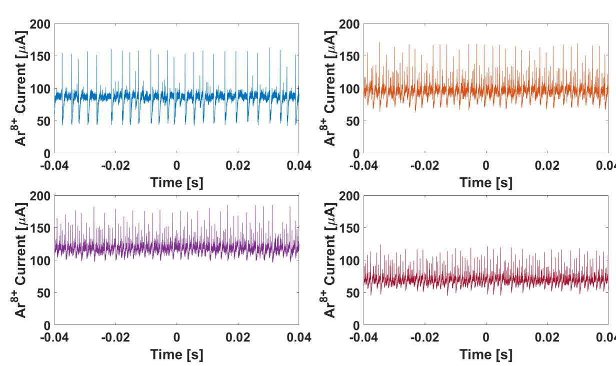

Figure 2: Ar^{8+} beam current for a varying extraction field maxima: (Top Left) $B_{Ext,max}$ = 0.99 T, (Top Right) $B_{Ext,max}$ = 1.07 T, (Bottom Left) $B_{Ext,max}$ = 1.15 T, (Bottom Right) $B_{Inj,max}$ = 1.23 T. B_{min} = 0.4 T, P_{μ} = 350 W, p_{Ar} = 213 nTorr.

Lastly, we find another noteworthy trend in Figs. 2 and 6. As we would expect, the average current increases to a maximum at $B_{Ext,max} = 1.15\,T \approx 1.79\,B_{RF}$, and then decreases as the field continues to increase. However, at this same point, the total number of high energy photons (E_{γ} > 80 keV) begins to decrease. We might expect the total photon intensity

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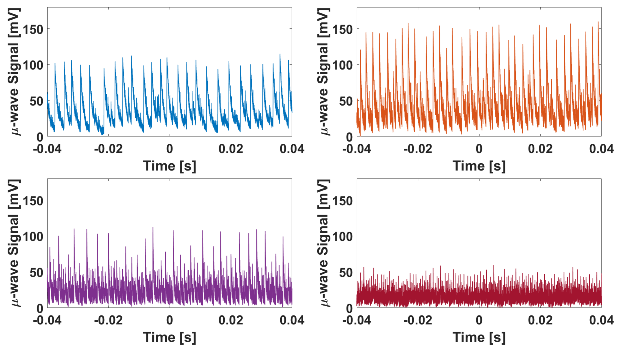

Figure 3: Microwave power signals for a varying extraction field maxima: (Top Left) $B_{Ext,max}$ = 0.99 T, (Top Right) $B_{Ext,max}$ = 1.07 T, (Bottom Left) $B_{Ext,max}$ = 1.15 T, (Bottom Right) $B_{Inj,max}$ = 1.23 T. B_{min} = 0.4 T, P_μ = 350 W, p_{Ar} = 213 nTorr. Microwave power has been offset by it's minimum value, over the entire 100 ms measurement period, to account for the AC coupling of the oscilloscope. Signals have been treated with a digital low pass filter using the Matlab signal processing toolkit, with a cutoff frequency of 333 kHz.

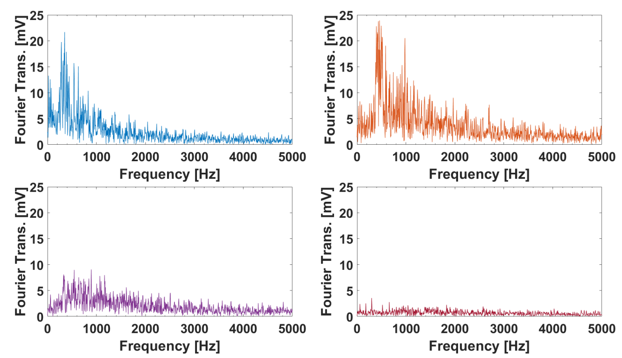

Figure 4: Fourier transform of the microwave power signals emitted from the ion source for a varying extraction field maxima: (Top Left) $B_{Ext,max}$ = 0.99 T, (Top Right) $B_{Ext,max}$ = 1.07 T, (Bottom Left) $B_{Ext,max}$ = 1.15 T, (Bottom Right) $B_{Ext,max}$ = 1.23 T. B_{min} = 0.4 T, P_μ = 350 W, p_{Ar} = 213 nTorr.

to decrease with the increasing field (decreasing loss cone pitch angle), but we also see that the photon intensity is relatively insensitive to the field strength for the lower field strengths. In particular, the monotonic decrease appears to begin around a field strength of $B_{Ext,max}$ = 1.1 T, but accelerates beyond $B_{Ext,max}$ = 1.15 T. This trend is *not* reflected in the emitted microwave power, which peaked at $B_{Ext,max}$ = 1.07 T and showed no qualitative change around $B_{Ext,max} \approx$ 1.8 B_{RF}.

Varying the Magnetic Minimum

Varying the magnetic minimum caused a more abrupt change to the beam current's transient characteristics. Figure 7 shows four examples of the changing extracted beam current as the magnetic minimum is varied, as seen by an oscilloscope. For comparison, Figures 8 and 9 show how the

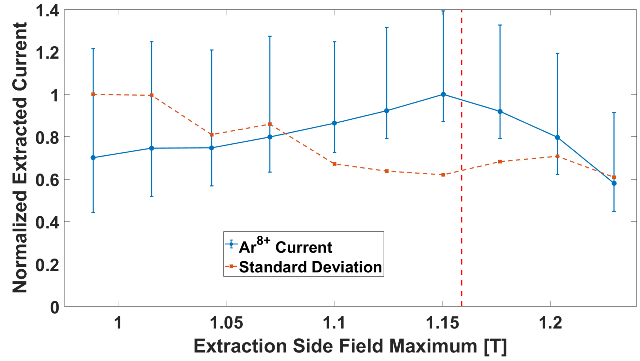

Figure 5: Trends in the average extracted Ar^{8+} beam currents, measured over a 200 ms period, and its standard deviation as the extraction side field maxima is varied. Both data sets are normalized by the largest values in their respective sets. Error bars represent the average positive and negative amplitudes away from the average measured current. B_{min} = 0.4 T, P_μ = 350 W, p_{Ar} = 213 nTorr. The vertical dashed lines show where $B_{Ext,max}/B_{RF}$ = 1.8

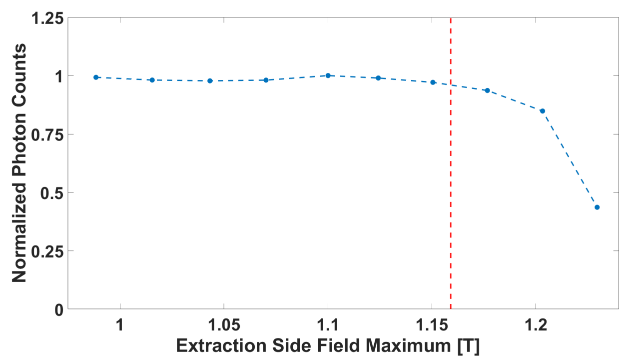

Figure 6: Total number of xray photons, with energies greater than 80 keV, measured while varying the extraction side maximum. B_{min} = 0.4 T, P_μ = 350 W, p_{Ar} = 213 nTorr. The dashed vertical line shows where $B_{Ext,max}/B_{RF}$ = 1.8. The data set is normalized by its largest value.

amplitude and frequency microwave signal change throughout this part of the measurement, in both time and frequency domains. At low fields, the amplitude and repetition frequency between subsequent instability events are similar. As the field increases, the amplitude between subsequent instability events becomes more random. The emission of microwave radiation begins spreading over the frequency domain. Eventually, we begin to see larger single instability events that occur less frequently. These events overshadow a set of smaller, but more frequent, instabilities events that do little to perturb the extracted current. At the end of our field domain, B_{min} = 0.47 T, the plasma appears to stabilize. The variations in the extracted current and emitted microwave power become indistinguishable from electronic noise. This does not mean that the plasma is stable, as it may exist in the so-called "CW" mode; however, without more sophisticated diagnostics, this operating point is almost indistinguishable from one that is stable [15].

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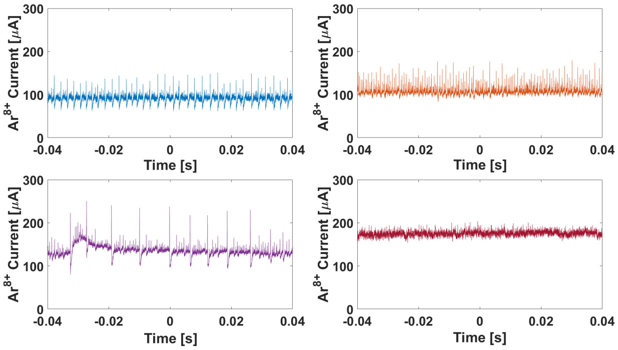

Figure 7: Fourier transform of the microwave power signals emitted from the ion source for a varying magnetic minimum: (Top Left) B_{min} = 0.34 T, (Top Right) B_{min} = 0.40 T, (Bottom Left) B_{min} = 0.44 T, (Bottom Right) B_{min} = 0.47 T. $B_{Ext,max}$ = 1.1 T, P_{μ} = 350 W, p_{Ar} = 213 nTorr.

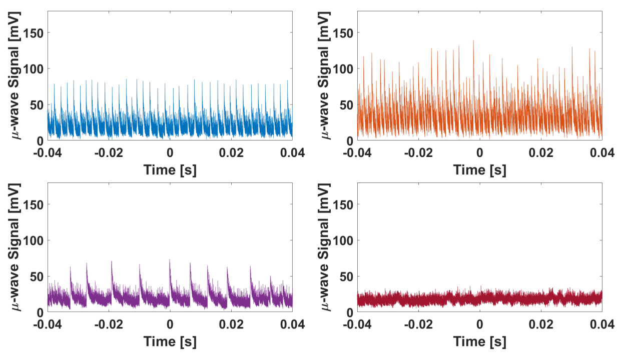

Figure 8: Fourier transform of the microwave power signals emitted from the ion source for a varying magnetic minimum: (Top Left) B_{min} = 0.34 T, (Top Right) B_{min} = 0.40 T, (Bottom Left) B_{min} = 0.44 T, (Bottom Right) B_{min} = 0.47 T. $B_{Ext,max}$ = 1.1 T, P_{μ} = 350 W, p_{Ar} = 213 nTorr.

The average extracted beam current increases over the measured domain (see Fig. 10). At B_{min} = 0.47 T ≈ 0.73 B_{RF}, the beam current reaches its maximum while also minimizing its upward and downward deviations. The field domain was not large enough to determine if the current would continue to increase or begin to decrease beyond 0.47 T, although previous measurements suggest an eventual decrease [5]. In this case, the maximum current correlates with a minimum in the emitted microwave power. Lastly, we can see that intensity of photons emitted from the plasma chamber increased monotonically with the increasing magnetic field strength. In this case, we do not see any qualitative change in the diffusion rate of electrons out of the system.

DISCUSSION

The results of these measurements demonstrated how the ECRIS magnetic field topology affects the stability of its plasma. Figures 2 and 7 show that more frequent instability events tend to correlate with larger amplitude beam current variations, in particular, larger losses. A longer time between instability events may indicate that a larger population of

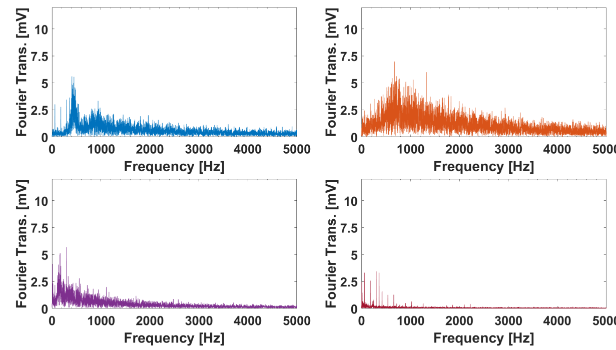

Figure 9: Fourier transform of the microwave power signals emitted from the ion source for a varying magnetic minimum: (Top Left) B_{min} = 0.34 T, (Top Right) B_{min} = 0.40 T, (Bottom Left) B_{min} = 0.44 T, (Bottom Right) B_{min} = 0.47 T. $B_{Ext,max}$ = 1.1 T, P_{μ} = 350 W, p_{Ar} = 213 nTorr. The peaks in the lower right plot are the result of electronic noise that is persistent throughout the facility.

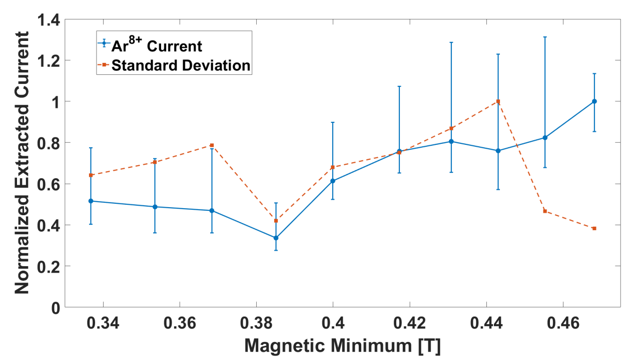

Figure 10: Average, maximum, and minimum Ar^{8+} beam currents, measured over a 100 ms period, for a varying magnetic minimum.

electrons builds up before the instability event. This buildup would result in a larger loss of electrons from confinement per event and perturb the plasma to a greater degree. On the other hand, this hypothesis would also imply a larger release of microwave energy from the plasma per event. However, confirming this hypothesis is difficult, as we cannot measure the propagation frequencies of the emitted microwaves. Without this information, we cannot correct Figs. 3 and 8 for waveguide losses.

Figures 6 seem to suggest that the decreasing extracted ion current above $B_{Ext,max}$ = 1.8 B_{RF} is correlated with a decreasing electron diffusion rate. The more frequent instability events may suppress the accumulation of electrons within the system, effectively suppression the production of highly charged ions. However, the increasing instability rate does not appear to affect the diffusion rate of electrons while the magnetic minimum is increased (Fig. 11). Alternatively, the changing electron diffusion rate may result from the varying pitch angle of the magnetic field's loss cone. However, if that were the case, we would expect to see a change in

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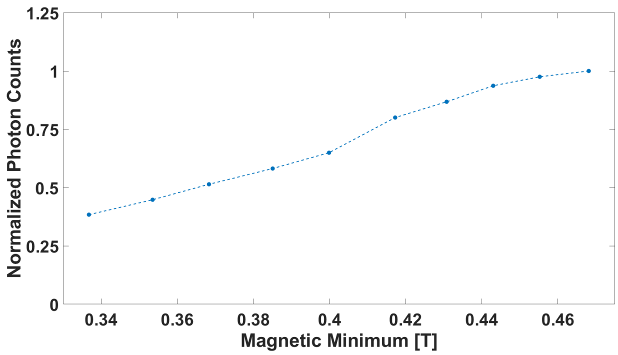

Figure 11: Total number of xray photons, with energies greater than 80 keV, measured while varying the magnetic minimum. $B_{Ext,max}$ = 1.1 T, P_{μ} = 350 W, p_{Ar} = 213 nTorr. The data set is normalized by its largest value.

the electron diffusion rate for lower extraction field maxima, which is not the case.

More work is necessary in order to understand the relationship between ECR ion source performance and the kinetic instabilities within the ion source plasma. The results shown here indicate that the ECRIS performance is not necessarily correlated with the presence of kinetic instabilities. Rather, a more complicated interaction between the magnetic field topology and the electron population appears to limit the extracted ion current. However, these results are limited to the low power regime, and may not represent performance at higher powers. Further studies of the electron diffusion rate, particularly beyond the B_{min}/B_{RF} = 0.8 performance limit, may provide greater insight into the scaling laws.

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