

# BEAM INSTABILITIES IN ELECTRON CYCLOTRON RESONANCE ION SOURCES\*

Bryan Isherwood<sup>†</sup>, Eduard Pozdeyev, Guillaume Machicoane, and Yoshi Yamazaki  
National Superconducting Cyclotron Laboratory, East Lansing, MI, USA  
Facility for Rare Isotope Beams, East Lansing, MI, USA

## Abstract

Accelerator facilities for radioactive beams and low energy nuclear physics such as FRIB require intense, stable ion beam currents in order to achieve required reaction rates for rare and undiscovered isotopes. Presently, the only way to produce intense continuous wave beams of highly-charged, medium to heavy-mass ions is with Electron Cyclotron Resonance Ion Sources (ECRIS). The complex nature of these devices causes temporal instabilities to occur, most notably: slow and fast instabilities. Slow instabilities and drifts, occurring over hours, decay the beam current intensity due to variations in ambient and hardware conditions. These drifts require beam operators to constantly monitor and tune ECRIS plasma parameters in order to maintain experimental beam requirements. Fast instabilities, in the form of ms oscillations, occur at operational parameters needed for high-intensity, high-charge state beams. These oscillations cause sudden drops in beam current of the order of 30%. We present here initial results of recent measurements to investigate these instabilities. Results for slow instabilities indicate a linear decay of beam intensity following a sharp current drop due to a brief source conditioning period. Results for fast instabilities show a relationship between the frequency and amplitude of beam oscillations and the electric potential of the plasma chamber bias disk.

## INTRODUCTION

ECR ion sources' are the principle devices used in accelerator facilities to generate high intensity, high charge state ion beams. However, instabilities within the system diminish the reliability of modern accelerator facilities by introducing unexpected beamline behaviors. We investigate two types of instabilities: slow intensity drifts and periodic beam instabilities. The slow intensity drift is characterized by a steady continuous change in beam current intensity, typically a decrease, occurring on the order of hours. This effect usually manifests itself following the initial ignition of the plasma but can also be seen when changing plasma parameters. Significant enough drifts lead to increased experimental uncertainty and dead time in beam applications as the constantly changing beam must be tuned regularly. Periodic beam oscillations caused by cyclotron instabilities within the ion source plasma cause catastrophic losses of beam intensity on the order of 30%. These instabilities are

characterized by emission of microwave, bremsstrahlung, and visual light radiation from the plasma and ultimately a drop in measured beam current [1]. Oscillations of this type also lead to experimental uncertainties within beamline systems by interfering with RF technologies. The remainder of this report is dedicated to an explanation to the beam current oscillation phenomenon as well as results from a recent measurement designed to explore the effects of different plasma parameters on both instabilities.

## THEORY BACKGROUND

While at this time a mathematical description for the slow drift of the ion beam is unknown, great strides have recently been made in understanding physical processes behind the instabilities responsible for the observed beam current oscillations. Cyclotron instabilities ignite within the system when the energy of slow quasi-longitudinal extraordinary wave modes undergo rapid growth [2]. This process can be represented by

$$\frac{dE_{\mu}}{dt} \approx < \gamma - \delta > E_{\mu} \quad (1)$$

where  $E_{\mu}$  is the energy of the emitted microwaves and  $\gamma$  and  $\delta$  are the growth and decay rates, respectively [1]. As the system enters a regime where  $\gamma > \delta$ , the plasma will begin to amplify the intensity of microwave emissions. Electrons with energies in the range of 10 - 100 keV interact with these microwaves and escape confinement. As a result the beam current is diminished while the electron population of the system recovers.

## MEASUREMENT

Measurements were taken using an AECR-U type source, known as ARTEMIS, powered by a 14.5 GHz klystron source [2]. A 90° analyzing magnet steered the beam to a faraday cup 14 feet downstream of the ion source (Figure 1).

### Slow Beam Drift

Several measurements using an argon beam were taken in order to evaluate this effect, each time the system was allowed to evolve for several hours following the plasma's ignition. A set of 5 semiconductor temperature sensors (DS1820) were placed on the source and return water coolant lines for both the plasma chamber and coils as well as the gas inlet line. These thermal sensors were connected to a wireless driver (Embedded Data Systems: OW-SERVER) which communicated with an external computer. The faraday cup

\* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661 and the National Science Foundation under Cooperative Agreement PHY-1102511.

<sup>†</sup> Isherwoo@nsl.msu.edu

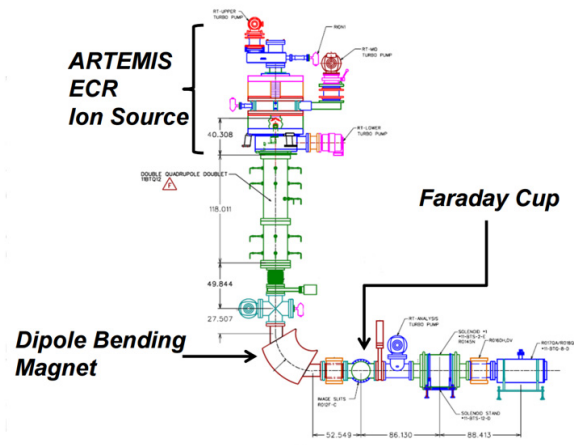


Figure 1: Sketch of ARTEMIS beam line up to the first Faraday cup

was connected to an EPICS controller that continuously recorded the value of the beam current. The systems extraction electrode's drain current was also measured to ensure that the extracted beam followed the same time evolution of the measured beam. The extraction voltage, biased disk voltage, solenoid coil currents, and injection gas pressure were varied in order to broadly scan the system's parameter space.

### Beam Current Oscillations

The ECR parameter space was set to force the plasma into the unstable regime with 500 A powering both injection and extraction coils, 20 kV potential at extraction aperture, -300 V biased disk potential, and 400 W input microwave power. An oxygen beam was chosen as previous measurements have shown oxygen to undergo cyclotron instabilities at lower field and power magnitudes [4]. The beam signal measured from the Faraday cup was measured through a 100 kHz low pass filter and recorded on a Tektronix TDS3014c oscilloscope operating in AC mode. Beginning from -300 V the biased disk voltage was increased in 10 V steps up to -150 V, where the oscillation amplitude became comparable to the signal noise. A second measurement followed the same procedure, except with 19 kV on the extraction aperture.

## RESULTS AND DISCUSSION

Our slow drift measurements showed an asymptotic decay after several hours (Figure 2). In all cases the beam ultimately decayed asymptotically to a lower current. The asymptotic current value was different for each of our parameter space values, although no correlation between how the beam will settle and the parameter space values has been determined. The drain current followed the extracted beam current over the same period. Our temperature sensors found no change in temperature of the return coolant during this time. In fact, most parameters remained constant throughout

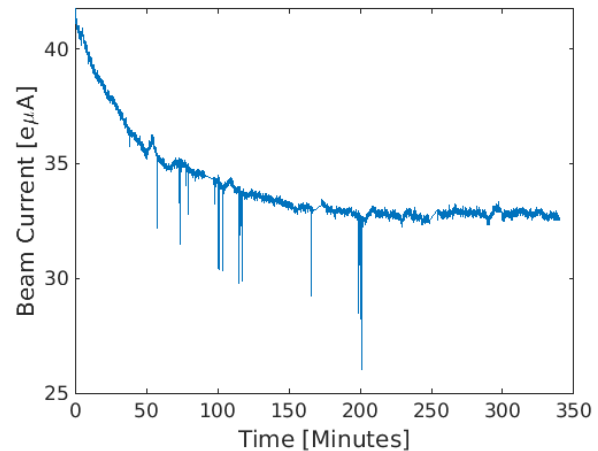


Figure 2: Beam current profile for  $\text{Ar}^{8+}$  over 5.5 hours. The downward fluctuations were a result of dead time due to supplementary measurements.

the process, including the pressure of the injected gas and the pressure of the gas that leaked out of the extraction aperture. Due to the complexity of the system a full analysis has yet to be completed. The periodic beam current profile observed

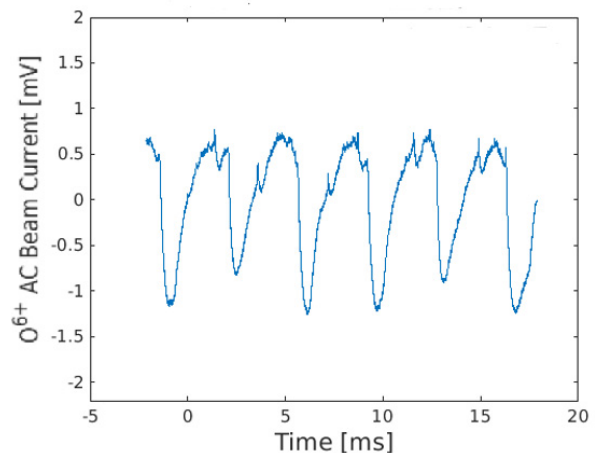


Figure 3: Beam current profile for  $\text{O}^{6+}$  with a frequency of 300 Hz.

displayed a sawtooth profile consisting of a brief emission period and slower electron recovery period. Figure 3 shows the beam current profile for a beam of  $\text{O}^{6+}$ , with an extraction voltage of 20 kV, over a 20 ms window. Figure 4 shows the frequency domain spectrum of this profile. As the biased disk voltage increases from -300 to -150 V the frequency of beam oscillations followed the set voltage (Figure 5). The voltages in Figure 5 represent the voltage measured on the biased disk and the frequencies were determined by fast Fourier transform through MATLAB and our uncertainty was determined by the FWHM on either side of our peaks in frequency space. It should be noted that between -220 V and

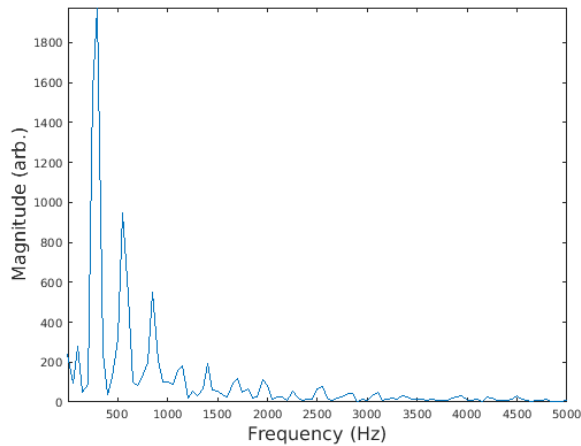


Figure 4: Fourier spectrum of beam current oscillation at 300 Hz for O<sup>6+</sup> beam.

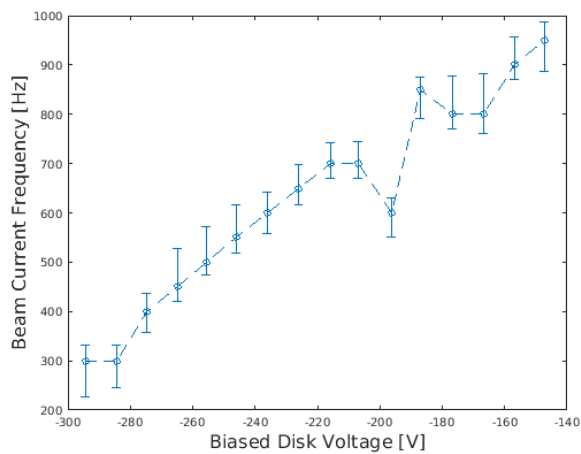


Figure 5: Relationship between beam oscillation frequency for O<sup>6+</sup> beam and the biased disk voltage.

-170 V this linear relationship breaks. Further investigation is needed in order to determine the cause of this observation. Despite this pattern, changing the extraction voltage to 19 kV diminished this effect. The oscillation frequency remained centered around 175 Hz regardless of biased disk voltage.

Fluctuations of  $\pm 5$  Hz were observed, but the frequency remained in this range throughout the measurement. In both of these cases the magnitude of oscillations decreased as the biased disk voltage decreased, but whether or not this is a direct effect of the plasma instability is unknown at this time.

## CONCLUSIONS

Our measurements have allowed us to observe and characterize our two limiting instabilities with our ECR ion source. While further investigation is necessary to determine the most efficient method of mitigating beam drifts our beam current oscillation measurements were incredibly insightful. Changing the biased disk voltage while the plasma underwent cyclotron instabilities showed a nearly linear relationship between the instability repetition rate and the biased disk voltage. Further investigation will involve using a super-conduction source with multiple axial coils in order to fully investigate the properties of the cyclotron instabilities.

## ACKNOWLEDGMENT

This research was made possible by the NSCL/FRIB Ion Source group staff Jesse Fogleman, Derek Neben, Alfonse Pham, Jeff Stetson, and Larry Tobos.

## REFERENCES

- [1] O. Tarvainen *et al.*, "Beam current oscillations driven by cyclotron instabilities in a minimum-B electron cyclotron resonance ion source plasma", *Plasma Sources Sci. Technol.* 23 (2014).
- [2] I. Izotov *et al.*, "Microwave emission related to cyclotron instabilities in a minimum-B electron cyclotron resonance ion source plasma", *Plasma Sources Sci. Technol.* 24 (2015).
- [3] G. Machicoane *et al.*, "ARTEMIS-B: A room temperature test electron cyclotron resonance ion source for the National Superconducting Cyclotron Laboratory at Michigan State University", *Rev. Sci. Instrum.* 77, 03A322 (2006).
- [4] O. Tarvainen *et al.*, "Periodic beam current oscillations driven by Electron Cyclotron Instabilities in ECRIS Plasmas", in *Proc. ECRIS'14*, paper MOOBMH01 (2014).