FAST SPUTTERING MEASUREMENT STUDIES USING URANIUM WITH THE NSCL ECR ION SOURCES*

Derek Neben†, Jesse Fogleman, Daniela Leitner[1], Guillaume Machicoane, Guy Parsey, Alfonse Pham, Shane Renteria, Jeffry Stetson, Larry Tobos, and John Verboncoeur
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, USA
[1] Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

Existing heavy ion facilities such as the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University rely on Electron Cyclotron Resonance (ECR) ion sources as injectors of highly charged ion beams. Long ion confinement times are necessary to produce dense populations of highly charged ions because of steadily decreasing ionization cross sections with increasing charge state. To further understand ion extraction and confinement we are using a fast sputtering technique first developed at Argonne National Laboratory [1] to introduce a small amount of uranium metal into the plasma at a well-defined time. In addition we utilize an axial x-ray apparatus [2] to characterize the hot electron plasma population via its bremsstrahlung emission.

INTRODUCTION

The Coupled Cyclotron Facility (CCF) at the NSCL [5] can accelerate ion beams up to 160 MeV/u with a corresponding beam power on target ranging from a few hundred watts to up to a kilowatt. Heavy ions from oxygen to uranium are injected from two ECR ion sources: a 14.5 GHz normal conducting Advanced Room TEMperature Ion Source (ARTEMIS) and the Superconducting Source for Ions (SuSI) operating at 18 and 24 GHz [8,9]. Typically a Mass to Charge (M/Q) range between 8 and 5 is injected for CCF operations, and some typical beams are: $^{48}Ca^{8+}$, $^{76}Ge^{12+}$, $^{238}U^{30+}$, and $^{16}O^{3+}$. The medium charge state is necessary because the final magnetic rigidity needs to be reduced approximately by half to inject properly into the K1200 after charge stripping inside the cyclotron.

We aim to probe ion confinement time by introducing a plasma contaminant and measuring its breeding and decay time. The fast sputtering technique, pioneered by ANL [1], was employed on ARTEMIS and SuSI with an uranium sample. Sputtering is a process where plasma ions are pulled onto a cathode, typically negatively charged to a few hundred to a few thousand volts, and cathode material is ejected [10]. Because ionization is an endothermic process cathode material cools the plasma and supplies cold electrons that perturb the plasma energy balance, therefore the smallest measurable contaminant currents are used. The high negative voltage applied to the sputter probe might perturb the electron losses and therefore plasma confinement [3]. Fast sputtering using an axial and radial geometry was investigated on ARTEMIS. On SuSI only the axial method was available.

* Work supported by Michigan State University and the National Science Foundation: NSF Award Number PHY-1415462
† neben@nscl.msu.edu

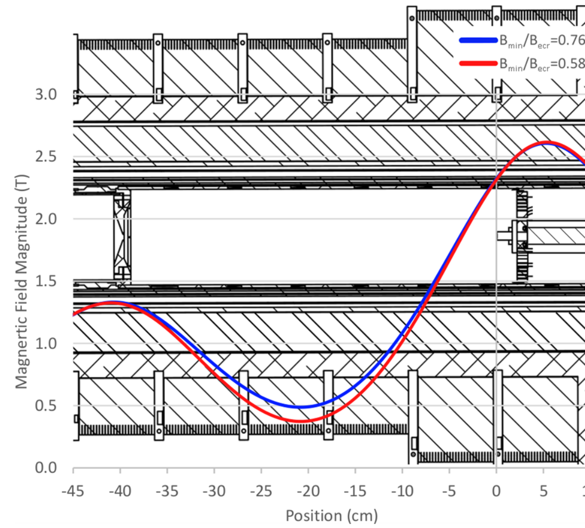

Figure 1: SuSI Magnetic field as simulated with Poisson Superfish overlaid with axial sputtering injection. The sputter probe was 55 mm forward of the peak at injection, and 10 mm forward of the bias ring.

EXPERIMENTAL SET-UP

The extracted beam current was measured on a Faraday cup after the analyzing magnet the current was sampled using an oscilloscope as a voltage across a 100 kΩ resistor. A low-pass circuit with cutoff frequency at 109 kHz was attached in series to suppress noise in the MHz range, and oscilloscope waveforms were converted to real currents in post-processing. The sputter probe voltage was pulsed using a PVX-4140 high voltage switch and a DC high voltage supply. We could operate in DC mode by driving the switch to a constant on or off state. The timing and width of the high voltage pulse was controlled by a TTL signal sent to the high voltage switch from a signal generator located at ground through a TTL-to-fiber converter. The output voltage was monitored at the high voltage switch through a port allowing us to measure the rise and fall times of voltage applied to the probe. The microwave power was measured at the forward coupler on the klystron for both ARTEMIS and SuSI.

On SuSI an axial High Purity Germanium (HPGe) x-ray detector and collimation system was used similar to [2] for observation of the high energy electron tail. The HPGe detection efficiency was measured offline using a ^{152}Eu source

ISBN 978-3-95450-186-1

of known activity and allowed us to correct our spectra for efficiency. Collimation provides a maximum angle of about 10 minutes of arc as calculated using geometric optics, this angle when projected onto the extraction electrode produced a circle of 6.7 mm in diameter. Because the extraction electrode on SuSI was 8 mm we are detecting the plasma x-ray emission and backscattering from the sputter sample.

The axial sputtering apparatus on SuSI utilizes an electrically isolated probe that may be translated axially several centimeters relative to the injection baffle on axis. Our uranium slug was a cylinder 10 mm in diameter and was located 55 mm forward of the magnetic field peak at injection as shown in Fig. 1. The axial sputter probe passes through an isolated aluminum ring that can be independently tuned to preserve some bias disk function. The magnetic field at the sputter probe location on SuSI changed by 88 Gauss between the two different magnetic field configurations. Originally three different magnetic field configurations were chosen on SuSI but we found a $B_{min}/B_{ecr} = 0.9$ to be unstable. The sputter probe depth was chosen to achieve hundreds of nanoamperes of DC uranium current at modest neutral gas flows, and oxygen was used as a support gas.

On ARTEMIS the sputter depth was chosen with similar goals. However, the face of the axial uranium sample was protruding 6 mm outside of the iron plug at injection and places it at 5 mm behind the magnetic field peak as simulated using Poisson Superfish. The same axial sample was used on both sources, and we found there to be minimal surface degradation. The ARTEMIS radial uranium sample was made of a thin uranium strip 9 mm wide pressed into an aluminum holder. The face of the radial sample was protruding 2 mm into the plasma chamber inner diameter to ensure adequate DC uranium current.

AXIAL FAST SPUTTERING ON SUSI

The extracted uranium was peaked on U^{38+} shown in Fig. 3. The summed DC uranium spectra on SuSI when compared against the summed oxygen was 0.48% for the $B_{min}/B_{ecr} = 0.58$. The sputter pulse width was chosen by balancing the shortest pulse length possible while clearly being able to observe the waveform on the scope. Each current in Fig. 4 is averaged over 16 consecutive events. The averaging was necessary to produce a clear waveform. Two magnetic field configurations were probed in this measurement while keeping a constant injection pressure and microwave power. The plasma parameters used for the measurement are summarized in Table 1.

The sputter probe was driven at -500 V with a pulse width of 3.2 ms and repetition rate of 105 ms. For a $B_{min}/B_{ecr} = 0.58$ the bremsstrahlung spectra were sampled and fitted with an exponential function between 121 keV and 263 keV with a temperature of 39.7 keV and a highest measured energy of 271 keV. Similarly, with a $B_{min}/B_{ecr} = 0.76$ the temperature was 63.9 keV and a highest measured energy of 426 keV. The measurement angle is small, due to good collimation, so we were clearly able to observe in Fig. 2 the K edge, $K_{\beta 1}$, $K_{\alpha 1}$, and $K_{\alpha 2}$ in descending order from highest energy in both spectra with uranium. We observe a shift to higher charge states in Fig. 3 with a higher B_{min}/B_{ecr} ratio. We also observe a larger total xray emission and an emission at higher energies for a higher B_{min}/B_{ecr} ratio in Fig. 2.

As an example of the waveforms observed, U^{32+}, U^{35+}, and U^{38+} are shown in Fig. 4 for $B_{min}/B_{ecr} = 0.58$. The beam current decay after the high voltage pulse was fitted with an exponential function between 97% of the peak current and when the current returns to its prepulse value. The decay times from the fitting of U^{32+}, U^{35+}, and U^{38+} waveforms were 2.4 ms, 2.9 ms, and 2.4 ms respectively. We found that increasing the B_{min}/B_{ecr} ratio to 0.76 did not change significantly the observed waveform or decay time.

Table 1: Key SuSI Parameters for Two Different Magnetic Field Configurations

Parameter	$B_{min}/B_{ecr} = 0.58$	$B_{min}/B_{ecr} = 0.76$
Injection Pressure	$7 * 10^{-8}$ mbar	$7 * 10^{-8}$ mbar
Extraction Pressure	$5 * 10^{-9}$ mbar	$7 * 10^{-9}$ mbar
Total Current	729 eμA	885 eμA
Microwave Power	700 W	700 W
Sputter Voltage	-500 V	-500 V
Bias Ring	-10 V	-50 V

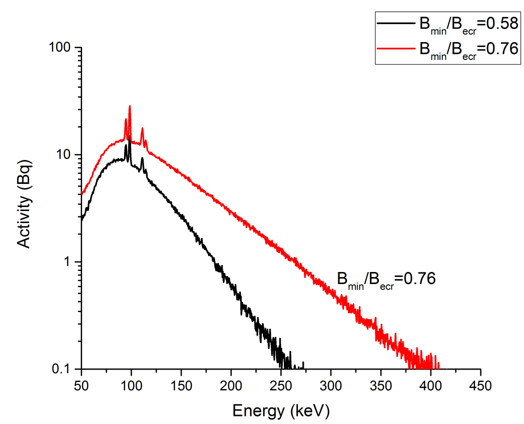

Figure 2: Axial bremsstrahlung spectra measured through the extraction electrode. With the magnetic field minimum closer to the ECR resonant field, the electron heating is more efficient for the same gas pressure and microwave power.

ISBN 978-3-95450-186-1

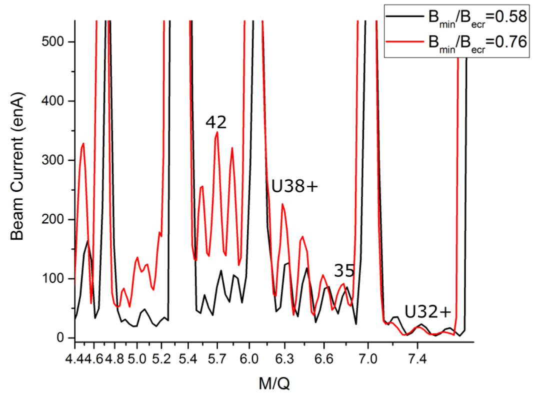

Figure 3: Beam current and mass to charge ratio on SuSI with two different magnetic fields characterized by their B_{min}/B_{ecr} ratios.

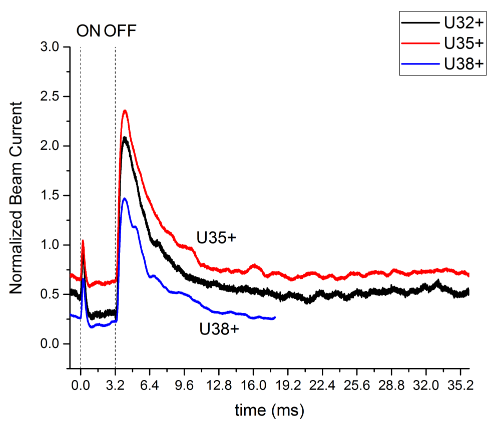

Figure 4: Beam current during and after a high voltage pulse event using an axial sputter probe on SuSI, the pulse began at time zero and was applied for 3.2 ms. The beam current has been normalized to the steady state sputtering value.

The plasma seems to collapse during the sputter pulse, but material is sputtered into the source as clearly observed in the decay after the sputter pulse. The decay time does not correlate with the confinement time or ionization time reported elsewhere and was surprisingly short for the measurements on SuSI.

The placement of the injection baffle with respect to the magnetic field in conjunction with the constant beam current DC offset at low repetition rates, may indicate the uranium was direct feeding into the plasma for this experiment. It is probable that the beam current waveforms represent the effect of high voltage modulation on the plasma. The afterglow-like waveform preceding the high voltage pulse that rose up to twice the DC beam current and the invariance in decay times across U^{32+} and U^{38+} support this idea. More studies will follow on the SuSI source to further investigate these experimental results.

Table 2: Key ARTEMIS Parameters Used for Both the Axial and Radial Sputtering Methods

Parameter	Axial Method	Radial Method
Injection Pressure	$1.3 * 10^{-7}$ mbar	$1.2 * 10^{-7}$ mbar
Extraction Pressure	$1.2 * 10^{-7}$ mbar	$1.3 * 10^{-7}$ mbar
Total Current	2.03 emA	2.09 emA
Microwave Power	200 W	200 W
Sputter Voltage	-400 V	-600 V

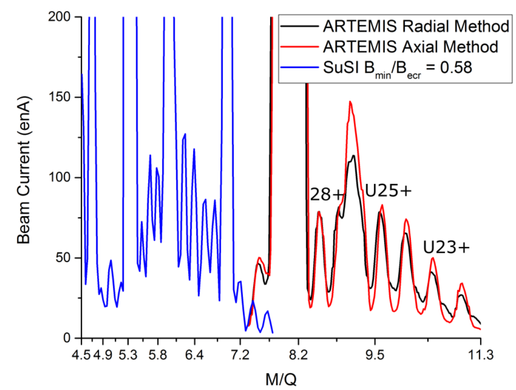

Figure 5: Charge state distribution of uranium on ARTEMIS and SuSI with an oxygen support gas.

AXIAL AND RADIAL FAST SPUTTERING ON ARTEMIS

In order to investigate the difference between radial and axial sputtering a series of measurements were done on ARTEMIS which allows for radial access as well as axial access to the plasma chamber. Similarly to SuSI, the ARTEMIS axial sputter probe was mounted directly on axis but in this case no bias disk or ring were used. The extracted uranium was peaked on U^{27+} shown in Fig. 5. The sum of measured uranium currents was 0.41% of the extracted beam when compared to the sum of oxygen and nitrogen peaks. Some important parameters are presented in Table 2 that compares axial and radial methods. For both methods nitrogen on ARTEMIS was 26% of the extracted oxygen beam was caused by a small vacuum leak. For Fig. 6 A duty cycle of 20% was used for 118.9 ms and 248.6 ms pulse widths because the use of a different signal generator was required. At lower microwave powers no averaging of the oscilloscope

ISBN 978-3-95450-186-1

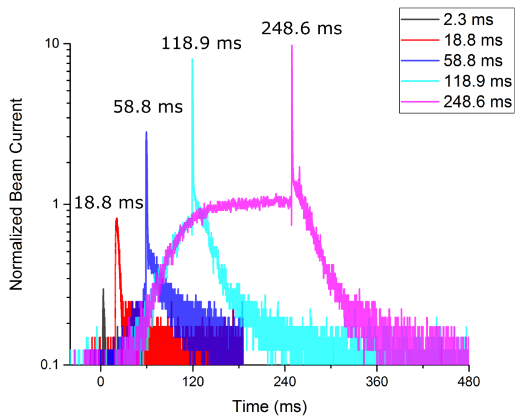

Figure 6: U^{25+} beam current for different high voltage pulse widths all starting at time zero using an axial sputter probe on ARTEMIS charged to a -400 V potential.

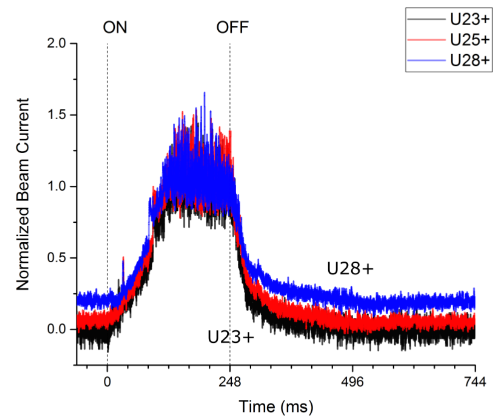

Figure 8: Beam current normalized to the steady state for three different charge states of uranium using a radial sputter probe on ARTEMIS. The pulse began at time zero and was applied for 248 ms at -600V potential.

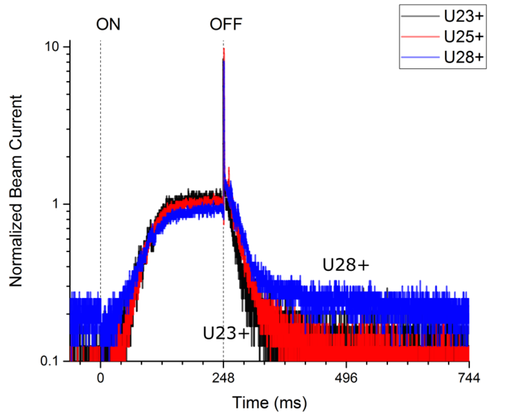

Figure 7: Beam current normalized to the DC value for three different charge states of uranium using an axial sputter probe on ARTEMIS. The pulse began at time zero and was applied for 248 ms at -400 V potential.

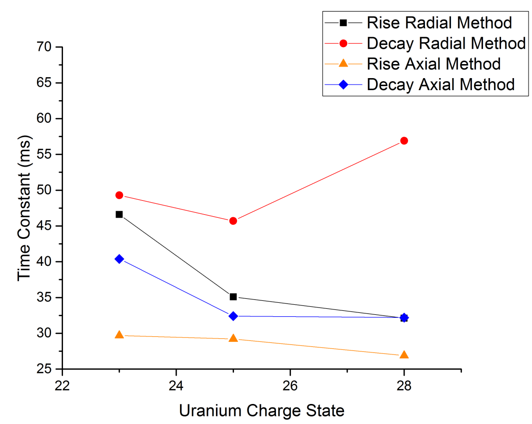

Figure 9: Time constants extracted from exponential fitting of beam current waveforms on ARTEMIS.

waveforms were necessary for all measurements conducted on ARTEMIS because the plasma was very stable.

The beam current waveforms in Figs. 7, 8 were fitted with an exponential function and the results of the fits are plotted in Fig. 9 for similar plasma conditions. For the decay fit all data was masked proceeding the 266 ms time mark, similarly for the rise time, data was masked after the 100 ms time mark. In all cases time zero marked the start of the high voltage pulse. Absolute times were used for fitting on ARTEMIS because the beam current waveform did not undershoot the prepulse value like it did on SuSI in Fig. 4. The steady state uranium currents for both axial and radial methods may be found in Fig. 5 and the charge state distributions were similar between methods. The fitting in Fig. 9 shows no clear trend with charge state and may have been caused by an unstable plasma with large variation between shots.

On ARTEMIS we found pulse widths of 2.3 ms were practically undetectable in either radial or axial geometries and led us to 248 ms pulses that produced clear waveforms including the saturation curve to the steady state current values. In order to probe the build up time of the steady state plasma containing uranium we increased the pulse lengths and found a time constant of about 120 ms to reach steady state. The time constants were bounded between 26.9 ms and 56.9 ms which is consistent with timescales observed in [1] for gold. However, in order to observe waveforms on ARTEMIS with uranium we needed to drive our high voltage pulses for in excess of 20 ms which is a factor of 40 longer than what was applied in [1].

SUMMARY AND DISCUSSION

On SuSI we observe a net shift to higher charge states when increasing the B_{min}/B_{ecr} ratio. The measured axial bremsstrahlung spectra increases in the high energy component and temperature when increasing the magnetic field B_{min}/B_{ecr} ratio while maintaining the injection and extraction magnetic field constant. We investigated axial fast sput-

ISBN 978-3-95450-186-1

tering with a uranium sample and found that the high voltage probe needed to be driven on the order of milliseconds to clearly observe a beam current response on the Faraday cup. The waveform would exceed the steady state uranium current by up to 2.5 times for a short time after the high voltage pulse ended indicating that we were driving a plasma instability. The decay times when fitted with an exponential function were on average 2.6 ms and exhibited no scaling with charge state or B_{min}/B_{ecr} ratio.

For the fast sputtering data on ARTEMIS with a radial uranium probe, we found the need to drive the high voltage for 250 ms to observe the beam current saturation at the DC value. The rise and decay across three charge states of uranium was on average 37.9 ms and 50.6 ms respectively when fit with an exponential function. In addition, using the fast axial sputtering method with a uranium sputter probe there was an afterglow-like pulse that could reach amplitudes between 5 and 10 times the steady state current for 1 ms. The afterglow amplitude increases with pulse width approximately linearly (or a weak higher order function) until saturation is reached. We are planning to investigate both methods further to gain a better understanding of the observed time constants in the plasma. We are also planning to investigate the role of plasma instabilities in effecting the sampled beam current waveforms resulting from a high voltage pulse event.

REFERENCES

[1] R. Vondrasek *et al.*, *Rev. Sci. Instrum.* **73**, 548-551 (2002).

[2] T. Ropponen *et al.*, "Bremsstrahlung and Ion Beam Current Measurements With SuSI ECR Ion Source", in *Proc. ECRIS'10*, Grenoble, France, paper WECOAK04, (2010).

[3] V. Mirinov *et al.*, *Rev. Sci. Instrum.* **73**, 623-625 (2002).

[4] G. Shirkov, *Plasma Sources Sci. Technol.* **2** 250-257 (1993).

[5] R. C. York *et al.*, "The NSCL Coupled Cyclotron Project–Overview and Status", in *Proc. Cyclotrons'98*, Caen, France, 14 - 19 Jun 1998, paper K-01, pp.687-691 (1998).

[6] G. Douysset *et al.*, *Phys. Rev. E* **61** 3015-3022 (2000).

[7] D. H. Edgell *et al.*, "Modeling of Electron Cyclotron Resonance Ion Source Plasmas", in *Proc. PAC'01*, Chicago, USA, paper WPAH026 (2001).

[8] G. Machicoane *et al.*, "First Results at 24 GHz with the Superconducting Source for Ions (SuSI)", in *Proc. ECRIS'14*, Nizhny Novgorod, paper MOOMMH03, Russia (2014).

[9] G. Machicoane *et al.*, *Rev. Sci. Instrum.* **77**, 03A322 (2006).

[10] R. Behrisch *et al.*, "Sputtering by Particle Bombardment", ISBN 987-3-540-44500-5, Springer (2006).

ISBN 978-3-95450-186-1