Recent Beam Developments with the LBNL 14GHz AECR-U Ion Source*

M. Galloway[1;1)] D. Leitner[1] C.M. Lyneis[1] W. Cornelius[2]

1 (Lawrence Berkeley National Laboratory, Berkeley, CA, 94705, USA)
2 (Scientific Solutions Inc., San Diego, CA, USA)

Abstract A radial sputter probe has been developed for the AECR-U as an additional method of producing metal ion beams. Negative voltage is applied to the probe to incite collisions with target atoms, thereby sputtering material into the plasma. The sputter probe is positioned through one of the 6 radial access slots between the permanent hexapole structure of the AECR-U. The probe position can be varied with respect to the inner edge of the hexapole magnet structure. Charge state distributions and peak beam intensities at bias voltages up to −5kV were obtained for gold samples at varying distances of the probe with respect to the plasma. For high charge states production the radial position with respect to the plasma was more sensitive than for the medium and lower charge states. For high charge state ion production the probe was optimized at a distance of 0.6cm inside the chamber wall (4.1cm from the center of the chamber). Stable beams with peak intensities of up to 28eμA of Au^{24+} and 1.42eμA of Au^{41+} have been produced using the sputter probe technique.

In addition, a solid state circuit under development by Scientific Solutions, Inc which provides a bandwidth up to 100MHz was used to drive the 14GHz klystron amplifier for the LBNL AECR-U ion source. Various broadband and discrete heating modes were tested and the results for high charge state ion production were compared with single frequency heating.

Key words ECR ion source, high charge state, metallic ions, broadband microwave

1 Introduction

The double frequency (10 and 14GHz) Advanced Electron Cyclotron Resonance ion source, AECR-U[1], is one of two ion sources providing ion beams for regular operation to the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory. During fiscal year 2005, approximately 30% of cyclotron beam time was dedicated to the acceleration of cocktail beams provided by the AECR-U for the space radiation effects testing program. Cocktail beam experiments[2] require several different ions at the same atomic mass over ion charge ratio to be extracted from the ion source simultaneously. This beam is injected into the cyclotron which mass separates the ions before they are delivered to the experiment. In this way the cyclotron ion beam species can be changed within minutes. Up to 12 ions are used in a typical cocktail, many of which can only be produced from solid material. Several methods can be applied simultaneously to produce beams from solid material: high and low temperature ovens[3], direct insertion, and the MIVOC method[4]. To meet increasing demands for the variety of ions available for

---

Received 20 April 2007

* Supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy under Contract DE AC03-76SF00098

1) E-mail: MLGalloway@lbl.gov

users in a cocktail beam, a sputter probe has been developed as an additional means to introduce solid materials into the plasma.

The sputter technique was originally developed at the ATLAS facility at Argonne National Laboratory[5]. To sputter material into the discharge plasma, a negatively biased target with respect to the plasma chamber is placed on the edge of the plasma region. The positively charged ions from the plasma are accelerated towards the metal target. If the kinetic energies of the bombarding ions exceed the molecular binding energy of the target material, atoms are dislodged from the surface of the sputter probe[6]. These atoms can then diffuse into the plasma region to be ionized. In comparison to the direct insertion method where the material is directly immersed into the plasma and vaporized, the biased sputter probe causes less disturbance to the plasma and the beam output can be more precisely controlled. On the present sputter probe up to three different target materials can be mounted at the end of a tantalum holder through a radial access port in the AECR-U.

As high charge states such as $^{209}\mathrm{Bi}^{41+}$ and $^{129}\mathrm{Xe}^{35+}$ are routinely used in the 88-Inch Cyclotron cocktail beams, it is advantageous to improve the performance of high charge state production from the AECR-U. It has been reported by other groups that the use of broadband microwave frequency in place of discrete frequencies for electron heating in an ECR ion source enhances source performance, especially for the high charge states[7]. By using a larger microwave bandwidth to heat the plasma, the ECR heating zone volume should increase as compared to single or multiple discrete frequency resonance zone volumes. An increase in ECR zone volume potentially allows a larger area in which electrons can become accelerated. This may result in an increase in electron temperature and density, thereby increasing high charge state production. Therefore, ion source performance for high charge state production was tested with broadband frequency heating in comparison to the single and double frequency heating typically used in the AECR-U ion source.

2 Preliminary results from ion sputtering for gold ions

2.1 Experimental set-up

The AECR-U hexapole structure has 6 radial access slots which allow for vacuum pumping, oven ports, and other feedthroughs (as shown in Fig. 1). The plasma chamber size is defined radially by the inner radius of this hexapole structure at 3.8cm from the axis of the source.

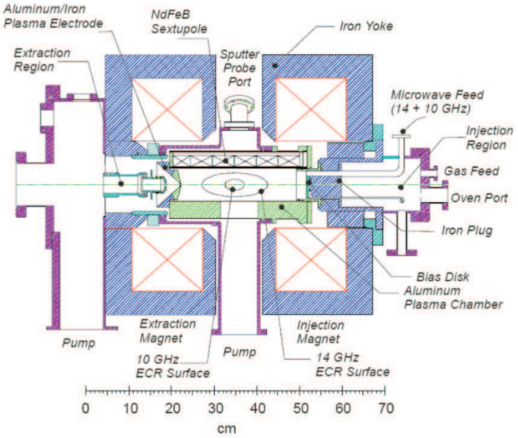

Fig. 1. Schematic of the AECR-U ion source.

The sputter probe is positioned through one of the radial access slots in the plasma chamber. Negative voltages of up to −5kV relative to the 12.5kV nominal plasma chamber extraction voltage are applied to the probe for sputtering. Initial testing utilized a movable single probe with a 3mm diameter gold target mounted at the end of a stainless steel rod. The probe distance was varied from a position flush with the chamber wall to about 1cm beyond the wall, into the hexapole structure (4.8cm from the center of the chamber).

2.2 High charge state ion production

Figure 2 shows the dependence of the Au^{40+} current on increasing sputter probe voltages at various distances. When positioned at or near the wall of the chamber the intensity of the high charge state ions decreases sharply with increasing probe bias voltage. This effect can be mitigated by increasing the flow of mixing gas however the resulting pressure increase

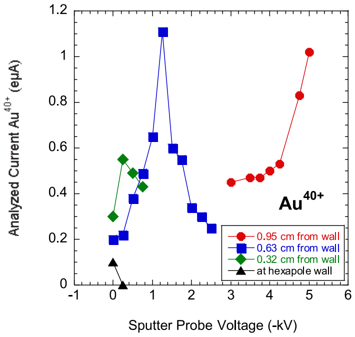

Fig. 2. Au^{40+} beam current extracted from the AECR-U ion source at varying distances from the wall of the hexapole magnet structure.

consequently reduces the intensity of the high charge states. As the probe bias voltage is increased, the charge state distribution shifts to lower charge states as a result of the increased flux of target material entering the plasma. The medium and lower charge state intensities are not as dramatically affected by increases of the probe bias voltage throughout the range of distances tested.

As the probe is moved further away from the plasma, higher bias voltages on the sputter probe are required. A peak in beam intensity for high charge state production of gold is seen at both 0.3cm and 0.6cm positions. Beyond this distance, it may be possible to reach a similar peak, but the power supply is limited to −5kV. Because the applied program at the 88-Inch Cyclotron requires very high charge states, a position of 0.6cm from the plasma chamber wall was chosen for optimum high charge state production.

2.3 Beam intensities from sputtering

Table 1 shows the achieved beam intensities of gold produced through the use of the sputter probe method.

Table 1. Sputter probe intensities for gold.

Q	41+	40+	39+	*	32+	31+	30+	*	27+	26+	*	24+
I/eμA	1.42	2.15	2.79	*	9.2	13.3	17.2	*	23.6	23	*	28

In order to get a quantitative number of the total particle flux that can be produced by sputtering, the sum of particles in a charge state distribution was measured as a function of sputter probe voltage (Fig. 3). The total particle current is given by the sum of particle currents for each charge state (see Eq. (1)).

$$I_{\text{total}} = \sum \frac{I_{\text{Q}}(\text{eμA})}{Q} \ . \tag{1}$$

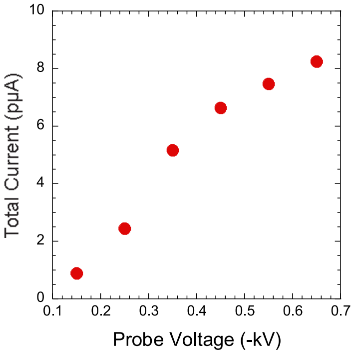

Fig. 3. Example of particle current of gold as a result of probe voltage. Probe is 0.4cm inside hexapole wall.

The probe was positioned at a distance of 0.4cm from the chamber wall to optimize for production of medium to low charge states. Magnetic confinement and 14GHz power at 700W were kept constant as the probe voltage was increased. The charge state distribution shifted during this test from higher to lower charge states as the sputter voltage was increased.

3 Testing of 14GHz broadband microwave circuit

To test the effectiveness of broadband electron heating, the single frequency oscillator used to drive the 2kW, 14GHz CPI klystron amplifier was replaced by a solid state circuit under development by Scientific Solutions, Inc. The computer controlled circuit is capable of providing a bandwidth of up to 100MHz centered over a nominal frequency of 14GHz which can be varied in increments on the order of a few MHz. The spectral density of the broadband can be varied by changing the number of discrete frequencies present within the broadband, up to 1024 frequencies. The source performance for high charge state production was compared between the single frequency heating mode and various broadband heating modes at similar RF power levels. Additionally, the absorption spectrum of the RF power was observed and optimized while changing the single peak frequency and the center frequency of the broadband.

3.1 High charge state production

The AECR-U was tuned to optimize production of $^{209}\mathrm{Bi}^{41+}$. Single frequency (14GHz), single and double discrete frequencies (14GHz and 10GHz), and a multiple mode broadband frequency were compared at similar power levels. The single frequency and peak of the broadband frequencies were set at 14.304GHz, which is the typical working frequency for the AECR-U. At the time of the first tests, the ion source had not been adequately conditioned to tune for high charge states; changes in power or magnet settings caused small bursts of vacuum pressure and instability. It was observed that the use of broadband frequency increased the stability of the source, allowing increased magnetic field settings and shifting the charge state production to higher states as seen in Fig. 4. The intensity for $\mathrm{Bi}^{41+}$for a 7 mode bandwidth (7 discrete frequencies over a bandwidth of 10MHz) reflected a 50% increase over single mode production.

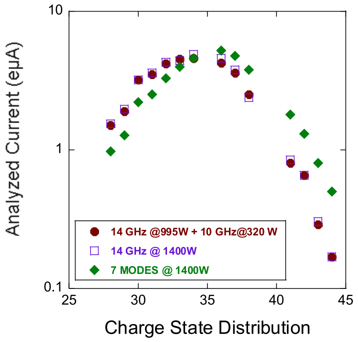

Fig. 4. First test of bismuth ionization using discrete vs. broadband microwave frequencies. All data was obtained at similar power levels. The plasma pressure was the same for all three test modes.

As the source conditions improved after 24 hours of operation, the plasma became more stable and less reactive to changes in power and magnetic fields. The difference between Bi^{41+} production using single frequency and multiple mode bandwidths decreased significantly as seen in Fig. 5. A bandwidth of 10MHz with 32 discrete frequencies yielded only 2.3% higher beam intensity of Bi^{41+} compared to single frequency production. The test was repeated for both xenon and oxygen high charge states. The results again did not reflect any substantial differences between single frequency heating and broadband heating.

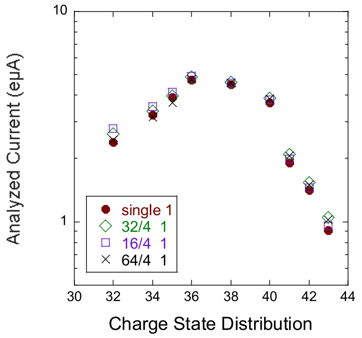

Fig. 5. Bismuth charge state distribution for single and multiple mode frequencies. RF power and magnetic fields were kept constant.

3.2 Microwave power absorption

During the broadband heating tests the reflected power was observed using a spectrum analyzer. As can be seen by comparing the spectrums of forward power with reflected power (Fig. 6(a) and 6(b), respectively), the lower and higher sidebands of a 100MHz broadband signal were not absorbed. A bandwidth of 20MHz yielded optimal absorption by the plasma, as seen in Fig. 6(b).

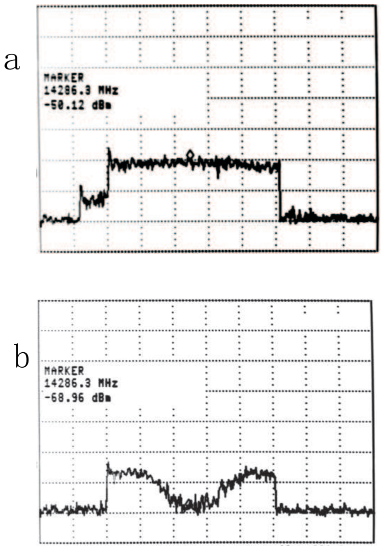

Fig. 6. Spectrums of forward power into the ion source (a) and reflected power from the source (b). The peak frequency is 14.286GHz.

Finally we used the ability of the solid state circuit to tune accurately and easily to a particular frequency to optimize for single frequency operation. The frequency was scanned from 14.2520GHz to 14.3043GHz while optimizing the beam intensity of high charge state xenon. As seen in Fig. 7 the peak beam intensity of $^{129}\mathrm{Xe}^{31+}$ changes very slightly. Based on these results, the working single frequency of the klystron was readjusted to 14.2713GHz for peak high charge state production.

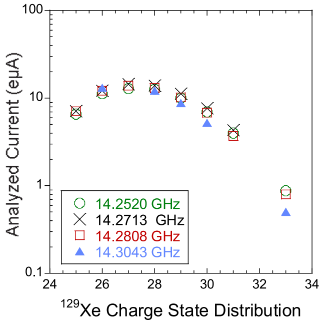

Fig. 7. Xenon charge state distribution as a function of single frequency microwave heating.

References

1 XIE Z Q. Review of Scientific Instruments, 1998, **69**: 625

2 Leitner D et al. Heavy Ion Cocktail Beam at the 88-Inch Cyclotron, http://www.phys.jyu.fi/ecris02/programme.htm

3 Clark D J, Lyneis C M. The Production of Beams from Solid Materials at the LBL ECR Source, Journal De Physique, 1989

4 Koivisto H, Ärje J, Nurmia M. Nucl. Instr. and Meth., 1994, **B94**: 291

5 Harkewicz R, Billquist P J, Greene J P et al. Rev. Sci. Instrum., 1995, **66**: 2883

6 Maissel, Glang, Handbook of Thin Film Technology, The Nature of Physical Sputtering, McGraw-Hill, chpt. 3-2, 1983

7 Gammino S, Ciavola G, Celona L. Nuclear Instruments and Methods, 2002, **A491**: 342