ISBN: 978-3-95450-226-4 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2020-NACB03

DETERMINING THE FRACTION OF EXTRACTED ^{3}He IN THE $^3He^{2+}$ CHARGE STATE*

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Abstract

The parameter space of the TOF was explored using analytic methods as well as computer simulation to improve the design and functionality of a similar device that was constructed as a prototype for the Electron Beam Ion Source (EBIS) in 2019. A simulation of the beam line optics was produced in Opera-2D CAD software to show that other optical elements would not materially affect the operation of the TOF. This will allow for true measurements of the charge state ratios of helium for EBIS and extended EBIS operation in support of the Electron Ion Collider. EBIS operators will use the device to maximize the fraction of ^{3}He ions in the $^3He^{2+}$ state. Different geometries were explored as well to maximize the effectiveness of the device and to meet the performance criterion and physical constraints of the EBIS beam line.

INTRODUCTION

The Electron Beam Ion Source (EBIS) provides highly charged ions to the Relativistic Heavy Ion Collider (RHIC), and the NASA Space Radiation Laboratory (NSRL). It will also provide polarized ions for the future Electron Ion Collider (EIC). The ion with the correct charge-to-mass ratio and velocity is accelerated by the RFQ to high energy into the accelerator complex (LINAC, Booster, AGS ring, RHIC). It is therefore important for EBIS operators to be able to easily determine ion beam composition, specifically charge state ratios. Currently a magnetic, high resolution mass spectrometer is available to use. However, this takes on the order of several minutes to collect spectra, making it impractical due the many iterations it would take to properly tune the machine. An in-line time of flight spectrometer (TOF) allows for tuning on a pulse-to-pulse basis with lower resolution. The TOF consists of a Bradbury-Nielsen Gate (BNG), and a faraday cup. A BNG is a set of parallel equally spaced wires with alternating positive and negative voltages of the same magnitude. As an ion travels through the gate it is deflected and misses the faraday cup down the beam line. When the BNG wires are pulsed to 0 V the ions travel undeflected and are focused to the faraday cup [1]. The time savings allow EBIS operators to make many adjustments that would otherwise take several hours or days. A position monitor can also be affixed to the BNG about a centimeter away. It would be highly transparent so that gas injection and ion extraction can both be viewed. Last year, a BNG was tested at the Hollow Cathode Ion Source (HCIS). It was unable to deflect the entire beam. However, if one assumes homogeneity in the beam, it gave relative amounts of each ion by showing small changes on a DC background. Therefore, even a partially functioning BNG is sufficient to see desired effects. It would be beneficial to have the entire beam deflected. Simulations using Opera CAD 2D show that the entire beam can be deflected for true measurement of beam composition. These simulations further showed that other electrostatic elements in the beam line will not affect the functionality of the BNG as a chopper for TOF measurements, and established robust working conditions.

THEORETICAL REVIEW

Time of flight spectroscopy separates ions based on their charge-to-mass ratio by establishing a characteristic time to travel a specified distance. The characteristic time is given by

$$qV_0 = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{d}{t}\right)^2,$$

$$t = \sqrt{\frac{m}{q}}\frac{d}{\sqrt{2V_0}},$$

where V_0 is the voltage the ion of charge q and mass m is accelerated through, d is the distance traveled, and t is time. In this case, a BNG is used as a chopper to select a small sample of the beam to evaluate, so that each ion's trajectory along the specified distance starts at the same place and time. The average deflection is given by,

$$\tan\alpha = k\frac{V_p}{V_0},$$

with

$$k = \frac{\pi}{\ln\cot\frac{\pi R}{2D}},$$

where R is the radius of the wire and D is the is the distance between the centers of two adjacent wires. Here each parameter is as seen in Fig. 1.

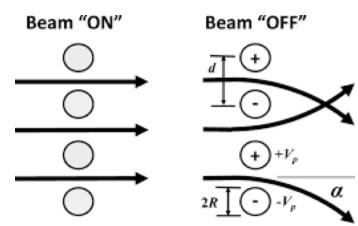

Figure 1: Schematic diagram of a Bradbury-Nielsen Gate [2].

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The average particle experiences this deflection [2]. We need for $\tan\alpha > \frac{d_{\mathrm{cup}}}{l}$ where d_{cup} is the radial distance that must be deflected over which in this case is about 20 mm, and l is the distance between the BNG and Faraday cup which is 1542 mm.

PRELIMINARY TEST

Last year, a prototype BNG was tested at the Hollow Cathode Ion Source, with gold on tungsten wire of radius 0.0254 mm, wire spacing 1 mm and $V_p = 300$ V. The BNG wires were at V_p and are pulsed to ground by positive and negative power supplies for 50 ns, through high pass filters (Fig. 2).

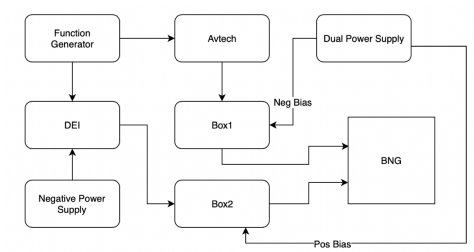

Figure 2: Box Diagram of the supporting electronics to the BNG.

Before each signal reached its set of wires, it passed through a resistor and capacitor in series to control rise times. Quadrupoles are tuned to increase beam intensity on the cup. Here a problem occurs. The rise time of the signal is not fast enough to resolve different peaks, as seen in Fig. 3. It is

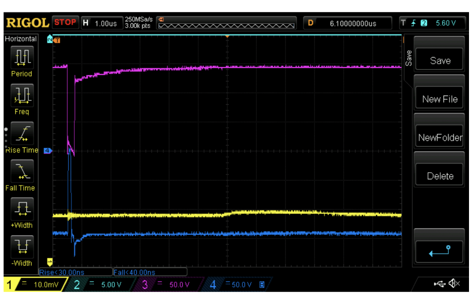

Figure 3: Voltage on the sets of BNG wires in magenta and blue, are normally held at $+V_p$ and $-V_p$, respectively, and pulsed to common during a 50ns gating pulse. The yellow trace shows the poorly resolved Faraday Cup signal, without the use of a pre-amp to drive the long signal cable capacitance.

evident that the signal increases after a few microseconds, but this does not give us any useful information about the contents of the beam. The problem is that we are terminating the scope in 1 MΩ, and therefore the RC time is large. Instead we put the Faraday Cup signal through a pre-amp, and terminate it in 50 Ω. After we add the pre-amp we get the desired spectrum, as seen in Fig. 4. We can see that the first peak is helium, then we have Nitrogen, Oxygen, and water, followed by Copper 63 and 65. These are expected

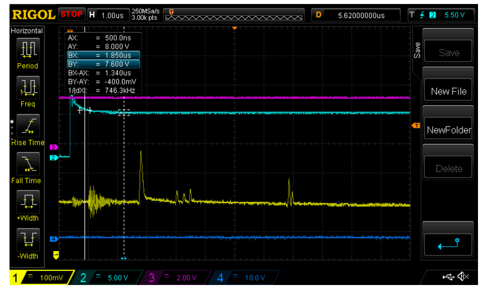

Figure 4: Time of flight data for ^{4}He, followed by C, N, O, and, ^{63}Cu and ^{65}Cu. Note that the relative abundances of ^{63}Cu and ^{65}Cu are are 69.2% and 30.8% respectively.

contaminants. We can know that the TOF is working at least partially, since the peaks have a width equal to the pulse time, and since Copper 63 and 65 appear in their relative abundances. Since, we do not deflect the entire beam this signal comes over a DC background. If we assume homogeneity in the beam, these are the proportions of the ion species.

Also, in this preliminary study, another set of parallel wires was on the same frame about 6 mm. This did not evidently alter the effects of the BNG, since this set of wires was at common, and the fields from the BNG decay to approximately 0, 1 wire spacing away from the device axially.

SIMULATION STUDIES

Opera-2D CAD was used to simulate beam optics. First, we did a study of just the BNG. Previously, we explored the ratio of R/D. It is desirable for this ratio to be such that $k > 1$. We have chosen $R = 0.2$ mm and $D = 1$ mm so that $k = 1.40$. The required voltage V_p is therefore 312 V. We start with $V_p = 500$ V.

BNG

First, we can see the BNG isopotential lines in Fig. 5.

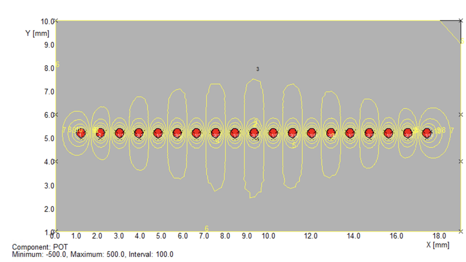

Figure 5: Isopotentials of the Bradbury-Nielsen Gate

An ion extracted at 25 kV can be sufficiently deflected by the this BNG. However, we can achieve better results by increasing V_p. We increased V_p to 850 V. It is likely that the beam will be expanding as it enters the BNG. Therefore the BNG needs to be robust in response to an expanding beam. We calculated ion trajectories entering the BNG at a variety of angles. As seen in Fig. 6, the BNG is robust to expanding beams.

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We can see that as long as the magnitude of the exit angle is greater than 1°, the ion is sufficiently deflected. When

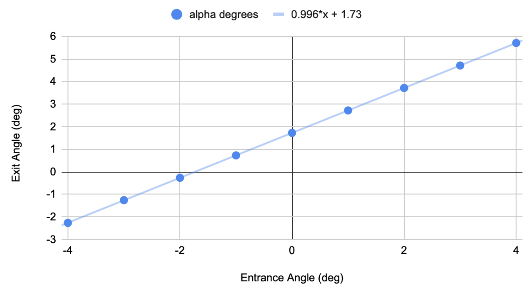

Figure 6: Exit angle vs. Entrance angle for an ion extracted at 25 kV.

modelling the BNG in opera by itself we use an X-Y symmetry so that we are viewing a cross section of the wire going into and out of the page. However, the other beam optics are cylindrically symmetric. Because the software is only 2D we must pick one symmetry system. We pick cylindrical symmetry. In this case the BNG is no longer modelled by a set of parallel wires, but by concentric circles. This does not give exactly the same deflection as the original case. However, it is nearly the same and without loss of applicability and in the interest simplicity, during the simulation, we used the cylindrically symmetric model.

Gridded Lens

The gridded lens was modeled as a transparent plane at the lens voltage with rings at common near the periphery to reduce spherical aberrations, to reflect the actual construction. We work with a gridded lens at −2 kV. A diagram of the gridded lens can be viewed in Fig. 7.

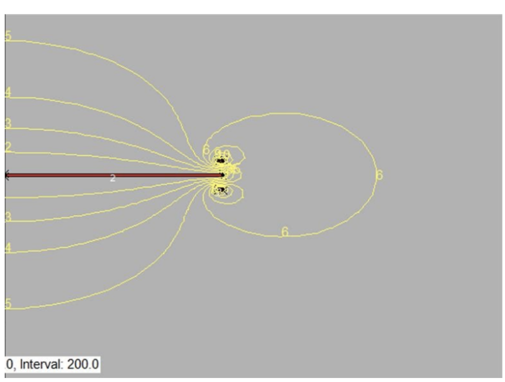

Figure 7: Iso potentials of the gridded lens gridded lens at −2 kV. Two rings on the right edge of the lens are at common to reduce spherical aberrations.

Acceleration Break

For ions to be properly accelerated by the RFQ they need to have an energy of 17 keV/nucleon. For $^{3}He^{2+}$, each ion needs to have 51 keV. Therefore it needs to drop through 25.5 kV, which can be achieved by using only internal EBIS electrodes during the extraction process. For $^{197}Au^{32+}$ each ion requires approximately 105 kV. This is achieved by biasing the entire EBIS source to HV during ion extraction, resulting in an additional voltage of approximately 80 kV across the acceleration break. A drawing of this element can be see in Fig. 8.

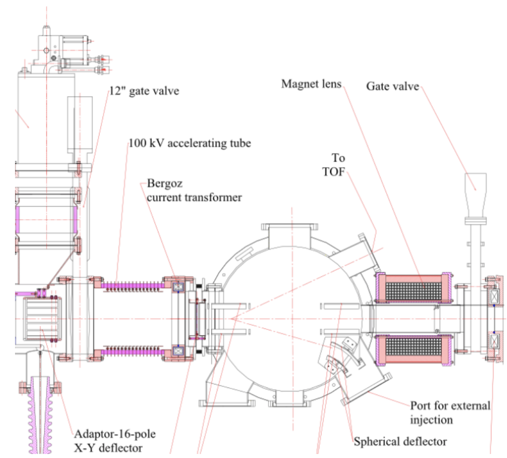

Figure 8: The 100 kV accelerating tube can be see on the left-hand side. We model the electrodes which are attached to the ceramic shown here in magenta.

If there is an 80 kV drop across the acceleration break then the total drop is divided linearly among the electrodes, with the first two electrodes being at EBIS common. Also note that if there is an 80 kV drop then the gridded lens is at −2 kV relative to this drop or at −82 kV relative to EBIS common. We only model the electrodes as thin conductors whose size and spacing are faithful to the drawing in Fig. 6.

Modelling the Entire Beam Line

Next, we calculate ion trajectories through the entire relevant beam line. Success is defined by being able to focus a beam onto the Faraday cup when the BNG is off, and preventing the beam from hitting the Faraday cup when the BNG is on. The first case we will study is the simplest, $^{3}He^{2+}$, because it does not require any voltage drop over the acceleration break. With −3.75 kV on the lens we are able to focus $^{3}He^{2+}$ to the Faraday cup when the BNG is off and deflect the beam from hitting the cup when the BNG is on, as can be seen in Figs. 9 and 10.

We have now shown that we can focus or deflect a beam of $^{3}He^{2+}$ ions as desired. Next we will show that we can do the same with $^{197}Au^{32+}$. This requires us to have an 80 kV drop across the acceleration break, so that $^{197}Au^{32+}$ will have 17 keV/nucleon entering the RFQ. In this case the gridded lens is at −2 kV relative to the acceleration break (i.e. −82 kV relative to EBIS common). Although this is not the main focus of the study, it is important that the TOF detector is functional in all modes of EBIS operation. The TOF will not be able to discriminate individual peaks for $^{197}Au^{31+}$ and $^{197}Au^{32+}$. This is because the difference in travel time is less than the time the chopper is off. However, it will be able to see the envelope of the set of Au peaks.

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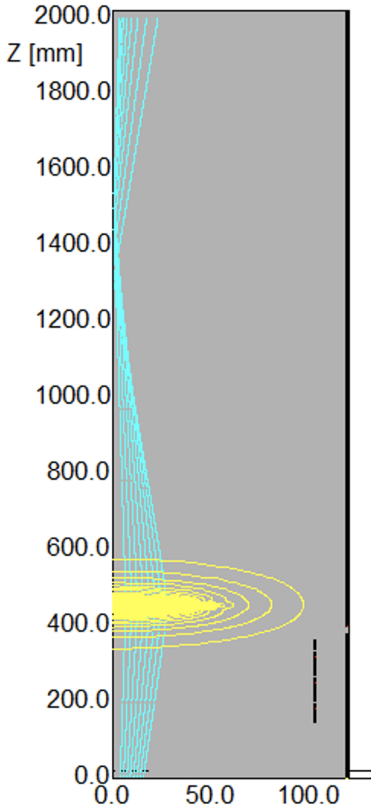

Figure 9: $^3He^{2+}$ focused to the 13 mm diameter Faraday Cup at axial position 1542 mm , with the BNG off.

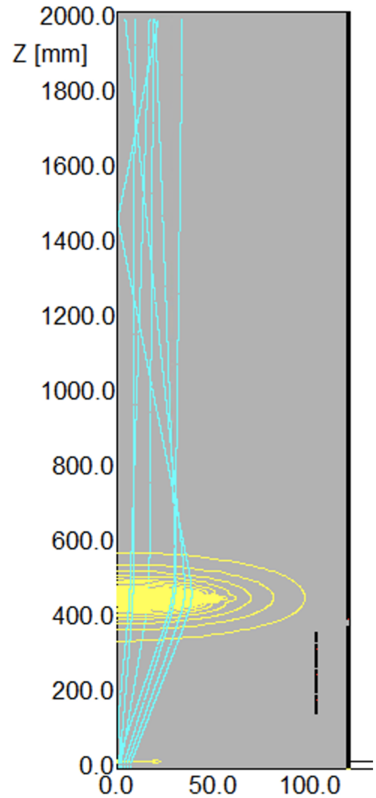

Figure 10: $^3He^{2+}$ deflected from the Faraday cup by the BNG. The ions were extracted at 25.5 kV with 0 V over the acceleration break, −3.75 kV on the gridded lens, and V_p = 850 V. The Faraday cup is located at Z = 1542 mm and has radius 6.5 mm

Simulations show that the BNG successfully deflects Au as well, with slight adjustments to the gridded lens, necessary to account for focusing due to acceleration.

Other Considerations

We intend to eventually install a harp style position/profile monitor about 1 cm axially from the BNG. Simulations have shown that it would not significantly affect the trajectories. The same considerations must be taken into account when the BNG or position monitor is inserted or removed from the beam line.

This also does not significantly affect the trajectories of the ions. The time of flight detector makes measurements use to the normal operational EBIS extraction optics except for the solenoidal lens focusing into the RFQ, which will be off during the TOF measurements.

CONCLUSION

We have now demonstrated that a Bradbury-Nielsen Gate can successfully deflect a slightly diverging beam from hitting a Faraday cup. After a suite of simulations, it is evident that the BNG can function properly with a variety of ions. We are now in the final design and construction process of the BNG for installation at the to EBIS. As previously stated, the TOF offers significant time savings to EBIS operators to see $^3He^{2+}$/ $^3He^{1+}$ ratio for the Electron Ion Collider-and other charge state ratios for RHIC and NSRL- with only minor and easily pre-programmed changes to the EBIS operating conditions.

ACKNOWLEDGMENTS

This work was supports by Brookhaven National Laboratory and the Department of Energy Office of Science.

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