HIGH CURRENT BEAM EXTRACTION FROM THE 88-INCH CYCLOTRON AT LBNL

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Abstract

The low energy beam transport system and the inflector of the 88-Inch Cyclotron have been improved to provide more intense heavy-ion beams, especially for experiments requiring ^{48}Ca beams. In addition to a new spiral inflector [1] and increased injection voltage, the injection line beam transport and beam orbit dynamics in the cyclotron have been analyzed, new diagnostics have been developed, and extensive measurements have been performed to improve the transmission efficiency. By coupling diagnostics, such as emittance scanners in the injection line and a radially-adjustable beam viewing scintillator within the cyclotron, with computer simulations we have been able to identify loss mechanisms. The diagnostics used and their findings will be presented. We will discuss the solutions we have employed to address losses, such as changing our approach to tuning VENUS and running the cyclotron's central trim coil asymmetrically.

INTRODUCTION

The majority of beams delivered by Lawrence Berkeley National Laboratory's 88-Inch Cyclotron go to users who can be separated into two groups with quite different needs. Users such as those in the National Security Space community perform microchip testing using the cyclotron's ion beams, and they typically require high-charge-state ion beams with relatively low currents. The addition of the fully-superconducting electron cyclotron resonance (ECR) ion source VENUS [2] has increased the variety of beams that can be delivered; for example, Xe^{43+} has recently been added to the 16 MeV/nucleon cocktail. The second group of users are those performing fundamental Nuclear Science research, and these users routinely require high-current, medium-charge-state ion beams. A beam of particular interest for heavy ion physics is ^{48}Ca, where researchers have requested beam currents of nearly 2 pμA. In order to deliver such high currents, a four-year upgrade project was undertaken to identify and correct beam loss mechanisms. Dedicated beam studies showed that there are two primary regions where beam losses occur: along the low energy beam transport (LEBT) system and the center region of the cyclotron.

LOW ENERGY BEAM TRANSPORT

For high current beams, only two of the 88-Inch Cyclotron's three ECR ion sources are typically used: VENUS and the AECR-U [3]. Unlike the fully-superconducting VENUS, the AECR-U is a normal conducting ion source which has been in operation in its upgraded form since 1995. Initial tests of the $^{48}Ca^{11+}$ production capabilities using the AECR-U showed that the cyclotron could only deliver approximately 0.5 pμA, and although the injected current could be increased, no more current could be extracted from the cyclotron [1]. During most of these runs with the AECR-U as the injector, the source extraction voltage was kept at approximately 12.5 kV, but when VENUS, with its higher available extraction voltages, was used as the injector it was found that beam transmission increased. As a result, it was decided to increase source extraction voltage to over 25 kV for both sources (VENUS is already capable of 30 kV) to reduce potential space charge effects along the LEBT and during injection. Additional work was also performed on the AECR-U line to improve the alignment of the transport system, in particular near beam extraction where poor alignment leads to significant beam loss.

The increase in source extraction voltages required upgrades to the cyclotron's axial beam line which is shared by all of the ion sources. In particular, the final solenoid lens that affects the beam trajectory as it nears the cyclotron had to have its maximum current increased. This increase in lens strength required additional water cooling capabilities for that lens. The increase in extraction voltage also led to increases in both the required chopper voltage (upgraded to ±1000 V) and buncher voltage. In order to reduce the necessary buncher voltages, both the fundamental and harmonic bunchers were moved upstream to increase the distance to the cyclotron. The fundamental buncher was moved from 2.54 to 3.1 m away from the cyclotron midplane, while the harmonic buncher was moved from 2.13 m to the former location of the fundamental buncher. These changes result in a nearly 20% reduction of the required bunching voltages for each buncher.

The failure of the VENUS 90° analyzing magnet's power supply during a long, high current run, and the performance of its temporary replacement, illustrated how important the current stability of this supply is. It was found that peak performance required a supply with current stability of at least one part in 10^4.

CENTER REGION

All three of the 88-Inch Cyclotron's ECR ion sources use the same axial line for approaching beams. These sources produce a varied range of beam species (protons to uranium) and beam energies, therefore a gridded mirror inflector is used to bend the approaching beam into the cyclotron's midplane. The mirror inflector is intended to act as a parallel plate capacitor tilted 45.7° above the cyclotron's midplane; the bottom plate may be biased positively while the upper plate is replaced by either grids

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or wires to allow beams to pass through. When not electrically biased, this inflector is used to measure beam current. Comparisons of the measured beam current on the inflector to that measured using a radially-adjustable current probe within the cyclotron, we find that on average only 30-50% of the beam current that reaches the inflector makes it out to 0.13 m radius. Therefore the center region was targeted as one where great current gains could be possible.

In order to reduce space charge effects, the LEBT was improved to allow for source extraction voltages in excess of 25 kV. The mirror inflector typically requires a positive voltage bias of approximately 70% of the extraction voltage, and it was found early on that with such a high bias the inflector was susceptible to sparking. Because of this, it was decided that a dedicated spiral inflector for these mid-mass, mid-charge, high-current beams would be designed and installed that would not only reduce the required voltages, but would have the added benefits of no beam losses due to grids and would better center the injected beam [1].

There had long been evidence that the beams in the center region were high relative to the cyclotron midplane; for example, beam marks were more prevalent on the upper halves of Dee inserts. To better understand the dynamics of the beam as it makes its way from the center region to cyclotron extraction, a radially-adjustable scintillator/camera probe was designed and installed [4]. This device clearly showed that the beam was approximately 5 mm above the midplane over the inner 250 mm, and outside of this radius it returned to the midplane.

To better understand this effect, a magnetic model of the entire cyclotron was completed using Opera's Vector Fields [5]. Figure 1 shows the results of using particle tracking to locate the axial heights of the rotation planes of centered, constant-energy ions moving through the solved magnetic fields. It can be seen in this figure that these equilibrium orbits were high near the center of the magnet. It should be noted that the heights of the single particle equilibrium orbits were higher than those found on average using the scintillator. This disagreement is not unexpected as the height of the actual particles depends on where they are in their betatron oscillation, and the radial probe only intercepts the beam at one, fixed angle. Also there is evidence that the mirror inflector, which was used for those tests, is routinely run at a slightly lower than expected height and/or voltage which may being done to start the beam off low to correct for the fact the beam will be forced upwards during the first few turns

After creating the magnetic model, the reason for the high equilibrium rotation plane for ions was immediately obvious as the central plug for the lower half of the magnet has more iron than the upper half's central plug; the reduced iron in the upper plug is a result of iron being removed for lenses and the beam transport line itself.

The additional iron in the lower half of the magnet produces a greater magnetic field near the bottom pole when the main magnet and trim coils are run symmetrically. However, running one (or more) of these coils asymmetrically provides a method to lower the magnetic field near the center of the lower pole and improve the axial centering of the beam [6]. The effective radii of some of the inner three trim coils are shown in Figure 1. Using this as a guide, a circuit was designed that allowed for asymmetric operation of the innermost trim coil. When this capability was added it became routine to achieve increases in extracted beam current upwards of 50% simply through the adjustment of the amount of the central trim coil's unbalance.

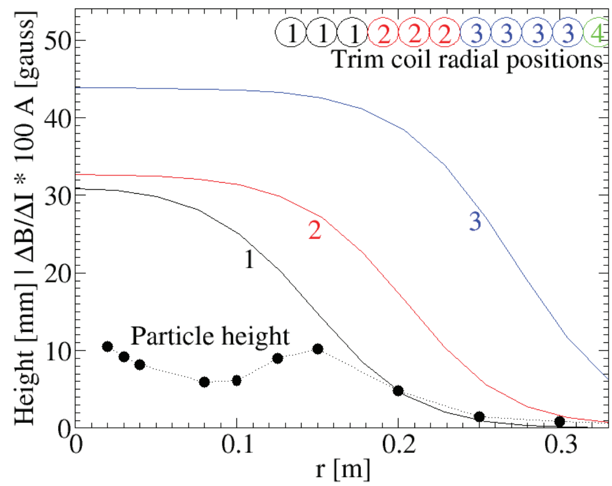

Figure 1: Equilibrium orbit heights for particle tracked through modelled magnetic fields are plotted as a function of radius with dots and a dashed line to guide the eye. The inner trim coil turns' radial positions are indicated at the top of the plot and the measured change in field per 100 A of current is plotted with the solid curves.

RESULTS

By upgrading both the low energy beam transport system and improving the center region, significantly more beam current was extracted from the cyclotron. As mentioned previously, initial transport testing of $^{48}Ca^{11+}$ from the AECR-U showed no increases in current extracted from the cyclotron past 0.5 pμA even when source extracted current was increased. Using VENUS during a eight-week-long $^{48}Ca^{11+}$ run, it was found that even with higher source extraction voltages, one could not simply increase the source beam current and expect to get more current out of the cyclotron; not surprisingly beam quality must be taken into account, too. The VENUS transport line is outfitted with two Allison-type emittance scanners. Source tuning coupled with regular checking of beam emittance, followed by additional cyclotron tuning provides a route, albeit slow, to increased extracted current. The fastest progression to high current transport was found by simply tuning the cyclotron on target for a relatively low current, then using the measured beam current on target as the sole diagnostic while iterating between source and cyclotron tuning. Following this straightforward tuning method, two interesting source

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tuning behaviors were found: transmission through the cyclotron was highest when only helium was used as a mixing gas (oxygen is typically also used for maximum calcium extraction from the source), and when the source was operated with little or no puller voltage. The reason that the removal of oxygen improved performance is not understood at present. As for the puller, it is a negatively biased electrode that both increases the source extracting electric field and prevents electrons along the axial line from streaming back into the source. The fact that this was kept near zero hints that allowing this backflow of electrons may have led to better beam neutralization near source extraction where the relatively slow-moving ion beam would be expected to develop much of its space-charge-related emittance.

By employing all of the changes to the beam line, center region, and source tuning practices, we were able to deliver 2.05 pμA of $^{48}Ca^{11+}$ on target. However this was more current than the target could tolerate for extended periods, so the average running current for the duration of the eight-week $^{48}Ca^{11+}$ run was kept in the range of 1.1-1.5 pμA. During this entire extended operation, the spiral inflector operated without any maintenance. This uninterrupted performance should be compared with previous high current runs using the gridded mirror inflector where wire replacements were typically required as frequently as daily even though beam currents were less than half of those used on this long run.

During the extended run, optimizing source efficiency resulted in an average consumption rate of 0.27 mg/hr over the two-month run with 16% of the consumed material ending up as extracted calcium from VENUS and 5% of the consumed material extracted from the source as 11+. The fraction of beam extracted from the source that ended up on target varied from 15-20% over the run.

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