A CENTER REGION UPGRADE OF THE LBNL 88-INCH CYCLOTRON

K. Yoshiki Franzen*, J. Benitez, A. Hodgkinson, M. Kireeff Covo, C. Lyneis, B. Ninemire,
L. Phair, P. Pipersky, M. Strohmeier, and D.S. Todd,
Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
D. Leitner, Michigan State University, East Lansing, MI 48824, USA

Abstract

The design and results of an upgraded cyclotron center region in which a mirror field type inflector was replaced by a spiral inflector is described. The main goals of the design were to facilitate injection at higher energies in order to improve transmission efficiency and to reduce down-time due to the need of replacing mirror inflector wires which rapidly break when exposed to high beam currents. The design was based on a detailed model of the spiral inflector and matching center region electrodes using AMaze, a 3D finite element suite of codes. The spiral inflector was used to extract a 2.0 pμA 250 MeV ^{48}Ca beam from the cyclotron thus meeting design goals. Furthermore, the inflector was utilized during an eight week experiment without any issues delivering around 1 pμA ^{48}Ca as requested by the users.

INTRODUCTION

The Lawrence Berkeley National Laboratory 88-Inch Cyclotron has a more than 50 years track record of producing beams to support the nuclear science community. The present mission of the cyclotron is two-fold: 1) to serve the National Space Security community and other users with beams for radiation tests of microcircuits, and 2) to serve the local nuclear science community with a focus on super-heavy element research. For the first of these users groups the beam intensity levels produced by the cyclotron is usually adequate. Instead it is the ability to produce ion species at higher charge states that is of main interest. On the other hand, for the second user group the beam intensity plays an important role. Especially of interest for the Berkeley Gas Separator (BGS) group is the availability of a high current ^{48}Ca ion beam in the ~250 MeV energy region [1,2]. Previous measurements have routinely utilized such a beam of currents up to 0.6 pμA with the ions produced by the Advanced Electron Cyclotron Resonance (AECR) ion source. However, as shown in Fig. 1 it was not possible to increase this maximum cyclotron output current above this value due to space charge effect causing beam losses along the beam lines and the cyclotron center region. Another limitation was that the maximum output current of ^{48}Ca^{10+} and ^{48}Ca^{11+} from the ion source was limited to around 50 μA. It was therefore decided to use the more powerful VENUS ECR ion source to obtain a higher current level and to improve the transport efficiency by increasing the extraction voltage from 14 kV to 25 kV or higher. Preparing VENUS required the development of a new low-temperature oven and has been reported elsewhere [3]. Increasing the source extraction voltage required an increase in maximum current of the final focusing element of the injection beam line, and a redesign of the cyclotron center region geometry in order to handle the increases in injected beam currents and energies. The goal was also to improve the transmission of the center region which is where the majority of losses occur between the source and the cyclotron extraction.

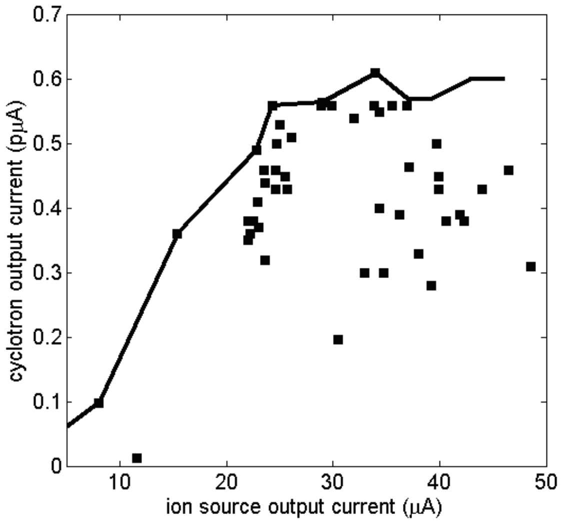

Figure 1: Each data point indicates an optimized tune of ^{48}Ca^{10+} or ^{48}Ca^{11+} in the 250-270 MeV region prior to the intensity upgrade (February 2011 and earlier).

INJECTION LINE UPGRADE

Using a set of Allison scanners [4] positioned after VENUS' analyzing magnet, emittance data and Twiss parameters were obtained for a 25 kV ^{40}Ar^{9+} ion beam extracted at different currents. This particular beam was chosen since its mass-to-charge ratio is similar to that of ^{48}Ca^{11+}. Using TRACE 3-D [5] the phase-space ellipses were propagated through the system to a plane 1600 mm above the cyclotron mid-plane. All optical elements were tuned in the calculation such that the beam envelopes were well within each beam line aperture along the way. Starting from 1600 mm above the cyclotron mid-plane and onward the beam was represented by an ensemble of particles with Gaussian phase-space distributions of each transversal axis as $\psi(x,x') = \frac{1}{2\pi\varepsilon} e^{-\frac{\left(x^2+(\alpha x+\beta x')\right)^2}{2\beta\varepsilon}}$ in

---

*Correspondence address: Mevion medical systems, 300 Foster St., Littleton, MA 01460, USA

ISBN 978-3-95450-128-1

which ε is the 5σ emittance and α and β are the Twiss-parameters as calculated by TRACE 3-D. This ensemble was then launched into a 3D magnetic field map containing the final focusing element and the cyclotron main magnet. The trajectories and the 3D magnetic field were calculated by OmniTrak and Magnum respectively [6]. The current applied to the final focusing element (GA3), a solenoid embedded in the yoke of the main magnet, was optimized, while the current value applied to the main magnet was obtained from successful tunes. The results of these simulations defined the specifications of the new power supply necessary to drive solenoid GA3 to support the higher beam transport energies. However, it also became clear that the heat load on this element would be unacceptably high with the existing cooling system. Therefore a chiller system was added, decreasing the cooling water input temperature from ~23 ˚C down to ~5 ˚C which keeps the magnet temperature reasonably cool during high energy beam transport.

CYCLOTRON CENTER REGION

The 88-Inch Cyclotron has for several decades utilized a mirror type of inflector which is responsible for bending the approaching beam 90˚ into the cyclotron mid-plane. This kind of inflector consists of a flat surface electrode tilted at 45.7˚ angle against the cyclotron mid plane. A set of wires are positioned parallel to and 4.1 mm above the electrode's face. The mirror inflector is very versatile and will continue to support all low-intensity beams for microchip testing. However, a disadvantage is that the grid wires tend to break after being exposed to high beam currents which often makes it necessary to replace the assembly thus increasing the downtime during experiments. We therefore designed and tested an etched foil version of the grids, which offers longer life time by at least a factor two. Another problem is that at high beam injection energies it becomes difficult to hold the required voltage supplied to the electrode without sparking. A more fundamental problem is that the grids cause beam degradation and transmission loss. We therefore decided to design and test a spiral inflector [7] in order to study if transmission could be improved. However, since the 88-Inch cyclotron operates over a large range of beams it became clear that the design would only replace the mirror inflector during high intensity runs. The goal then was to quickly be able to switch between the two systems by utilizing the existing ion source mechanism which before the early 1990's was regularly used in a similar fashion when switching between an internal and an external ion source. Both inflectors are positioned on a removable shaft whose radial position can be changed several inches in all directions relative the cyclotron axis by using the ion source mechanism. However, using this mechanism puts a severe constraint on the maximum size of the spiral inflector including housing since it has to fit within the diameter of a shaft which is only 2.125" in diameter.

The design of the spiral inflector was based on a central ray trajectory obtained from the computer code CASINO [8]. This code produces a set of coordinates which describes the center ray trajectory of a particle with a given mass-over-charge ratio and kinetic energy traveling through a spiral inflector situated in a defined magnetic field. By stepping through the spiral inflector parameter space of height (A), magnetic radius (r_m) and tilt (k') it was possible to find a combination which defines a configuration which a) fits within the diameter of the shaft, b) provides a beam which clears the inflector during the first revolution and c) is centered enough to reach full acceleration. From the calculated trajectory data the next step was to define three-dimensional representations of electrodes that produce an electric field distribution which together with the magnetic field would steer the beam into the cyclotron mid plane. A code was developed in Matlab in order to define the surfaces in three dimensions. From the calculated surfaces a spiral inflector was designed, see Table 1 for a summary of specifications. The resulting electric field map of the inflector was calculated by using the HiPhi code where the geometry is represented in a finite element mesh obtained by the MetaMesh code [6].

The initial six-dimensional phase-space distribution of a beam starting 5 cm above the cyclotron mid-plane was thus obtained as explained above, and the optical properties of the spiral inflector were studied by launching more than 70000 particles entering from the injection line using the OmniTrak code. As mentioned the cyclotron magnetic field was obtained by the Magnum code and the result was compared to measured data. The transmission between the entrance and the exit of the spiral inflector was calculated to 89.3%.

Table 1: Spiral Inflector Parameters

Height (A)	25 mm
Magnetic radius (R_m)	32 mm
Tilt (k')	0
Electrode gap	10 mm
Electric field	2.0 kV/mm

In addition to the inflector the 88-Inch cyclotron center region also consists of the Dee and Dummy Dee inserts. The function of the inserts is to provide vertical focusing and decrease the transit time in the center region. In order to fit in the new spiral inflector onto the 2.125" shaft the entrance has to be positioned off the shaft axial center. The shaft itself thus has to sit off center of the cyclotron axis and hence the inserts have to be modified. Therefore, the original (mirror) center region design was adapted to accommodate the geometry of the spiral inflector. By propagating the beam distribution from the exit of the inflectors and accelerating it through the center region of the cyclotron it became clear that the original design could be improved. While strong vertical focusing is necessary to contain the beam during the first gap, the second gap was too narrow thus clipping part of the beam

ISBN 978-3-95450-128-1

and focusing the transmitted beam too early. Therefore we increased the vertical aperture in the second and subsequent gaps.

A simulated 25 kV $^{48}Ca^{11+}$ beam exiting the spiral inflector as preciously described, was tracked through the center region using the OmniTrak code. The magnetic field map was calculated from main and trim coil current values obtained from successful tunes of the beam in question. The frequency of Dee voltage was also set from experimental data and the electric field map of the center region was calculated with the HiPhi code. The starting phase of the Dee voltage field was optimized for maximum transmission. A majority (59.6%) of the trajectories clears the center region and reaches a radius larger than 250 mm. The losses experienced in the first couple of turns are due to particles hitting the inserts. The expected transmission from the entrance of the spiral inflector out to a radius of 250 mm is thus around 53%.

Based on the simulations a matched set of spiral inflector and center region electrodes were manufactured, of which the former can be seen in Fig. 2.

Figure 2: The LBNL 88-Inch Cyclotron spiral inflector with cover removed.

RESULTS

With most of the beam lines and center region upgrades commissioned we proceeded with testing. It was demonstrated to deliver a 2.2 pμA beam of 200 MeV $^{40}Ar^{9+}$ ion beam with a 25 kV 12.2 pμA output beam from VENUS giving an efficiency of 18%. Additionally, it was demonstrated to extract a 2.0 pμA beam of 250 MeV ^{48}Ca as was the goal of the upgrade. The transmission efficiency during this test was 11.5%. Observe that it seems feasible to reach even higher output currents by further increasing VENUS output current and decreasing emittance. Furthermore, the robustness of the inflector was tested when approximately 1.0 pμA ^{48}Ca beam was delivered for much of the experiment during an eight week run with an average consumption rate 0.27 mg/hour [9]. The design performed as required without any issues.

CONCLUSIONS

An upgrade of the injection beam line and the center region was designed and implemented. The design was based on detailed calculations. The upgrade included a spiral inflector with matching inserts replacing a mirror type inflector. It has been demonstrated that after the upgrade the 88-Inch cyclotron is able to provide a 2.0 pμA 250 MeV ^{48}Ca ion beam together with a reduction in down time.

AKNOWLEDGMENTS

This work is supported by the American Recovery and Reinvestment Act (ARRA). The authors would like to thank the operations and technical staff of the 88-Inch Cyclotron for their invaluable support.

REFERENCES

[1] L. Stavsetra, K. E. Gregorich, J. Dvorak, P. A. Ellison, I. Dragojevic´, M. A. Garcia, and H. Nitsche, Phys. Rev. Lett. 103 (2009) 132502

[2] P. A. Ellison, K. E. Gregorich, J. S. Berryman, D. L. Bleuel, R. M. Clark, I. Dragojevic´, J. Dvorak, P. Fallon, C. Fineman-Sotomayor, J. M. Gates, O. R. Gothe, I.Y. Lee, W. D. Loveland, J. P. McLaughlin, S. Paschalis, M. Petri, J. Qian, L. Stavsetra, M. Wiedeking, and H. Nitsche, Phys. Rev. Lett. 105 (2010) 182701

[3] J. Y. Benitez, K. Y. Franzen, A. Hodgkinson, T. Loew, C. M. Lyneis, L. Phair, J. Saba, M. Strohmeier, and O. Tarvainen, Rev. Sci. Instrum. 83 (2012) 02A311

[4] D. Wutte, M. A. Leitner and C. M. Lyneis, Physica Scripta T92 (2001) 247

[5] D. P. Rusthoi, W. P. Lysenko and K. R. Crandall, Proceedings of the 1997 Particle Accelerator Conference (1997) 2574

[6] Field Precision LLC, P.O. Box 13595, Albuquerque, NM 87192, www.fieldp.com

[7] J. L. Belmont and J. L. Pabot, IEEE Trans. Nucl. Sci. NS-13 (1966) 191

[8] B. F. Milton and J. B. Pearson, CASINO User's Guide and Reference Manual, TRI-DN-89-19, Vancouver (1989)

[9] D. Todd et al., "High Current Beam Extraction from the 88-Inch Cyclotron at LBNL", Cyclotrons 2013, Vancouver, Canada, MO2PB02, these proceedings.