K150 Operations and Development

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Introduction

We had a very busy year operating the K150 cyclotron. For the reporting period we logged over 3770 hours of beam-on-target and 2900 hours for beam developments. Included in the beam-on-target time was 146 hours for the SEE testing.

As it was in previous years the 15 MeV proton beam was produced regularly throughout the year for the light ion guide (LIG) project. In the fall, the production of the radioactive gallium 64 isotope from a zinc 64 target and subsequent charge breeding using an ECR ion source (CB-ECR) progressed to a point where we sought to test the entire radioisotope production and re-acceleration process by accelerating $^{64}Ga^{12+}$ to 14 AMeV with the K500 cyclotron. We chose to use ever present and prominent $^{16}O^{3+}$ ions as a pilot beam to inject and to tune the K500 cyclotron, which in turn selected 12+ for the gallium 64. The oxygen beam was also used in beam transport to the MARS cave, where we sought to identify the radioactive beam. The beam on target was then switched from oxygen to gallium by shifting the K500 RF frequency by +8 kHz while keeping the same cyclotron field. This test is described in detail in a separate section.

Beside the 15 MeV protons, we have produced 40 to 45 MeV protons for the SEE testing for several groups. For the lower end of proton energies, we have developed 6 and 10 MeV proton beams. The 6 MeV beam at 330 amps on the main field marks the lowest operating cyclotron field to date.

The 7.22 AMeV (29 MeV total) alpha beam was accelerated twice during the year for the production test of the astatine 211 on a bismuth target. After the first test, the bismuth target was water-cooled to withstand the higher beam current, and on the second time almost 5 pμA of the beam current was extracted. It was then irradiated for about 8 hours and this resulted in producing about 30 MBq of activity from ^{211}At. Of this activity, about 30% could be extracted and separated from the bismuth target using chemical processing. Further testing for the production of ^{211}At is planned for the coming year.

The TIARA experiments have started after the installation of the target and the associated detector assembly at the front the MDM spectrometer. Beginning in the late summer five beams have been transported to the cave for their experiments; beams used were: 10 AMeV $^{19}F^{7+}$, $^{23}Na^{8+}$, and $^{25}Mg^{9+}$, and 7 AMeV $^{22}Ne^{7+}$ beam.

We have reported in the past of our struggles with 3rd harmonic beams. Last year, our attempt to accelerate 4 AMeV deuteron beam (using 1+ ions from ECR2) failed, the beam current simply died on the way out to the extraction radius. We tried next a slightly higher 4.5 AMeV deuteron beam here we at least were able to guide enough beam to the extraction radius and extract around 20 nA. However the extraction efficiency was poor and the beam proved to be too unstable to be useful. So this year, we tried using D^- ions from the H^- source, taking advantage of its lower emittance to inject more efficiently into the cyclotron. Also, using 50% higher dee voltage than the previous 4 AMeV tuning effort and plus the easier strip extraction, we were able to extract 70 nA out of 10 μA (~1% throughput). The resulting beam was stable enough that it was used in an experiment. So, why did the D^- beam work and not D^+?

Certainly the higher dee voltage helped. It would be interesting to see if the new D^- cyclotron tuning parameters would work with D^+ from ECR2.

Lastly, we tested a compact spiral inflector, see Fig. 1, in place of the mirror inflector for the axial injection into cyclotron. This was a quick test of the design and fabrication process for the inflector (the inflector was machined in-house on our NC machine). We ran a couple of 1st harmonic beams and a 3rd harmonic beam to test that the inflector inflected the beams into the cyclotron, and then we tried to optimize the beam current by varying the inflector rotation angle and the inflector height. For a few days we had for this test (before the inflector had to be removed due to a water leak on the inflector), we were able to achieve about 5% throughput for 6.3 AMeV $^{16}O^{5+}$ beam (as compared with about 10% with the mirror inflector). The inflector height adjustment was rather clumsy and we will need to revisit the spiral inflector. The design and the dimensions of our test spiral inflector are detailed below.

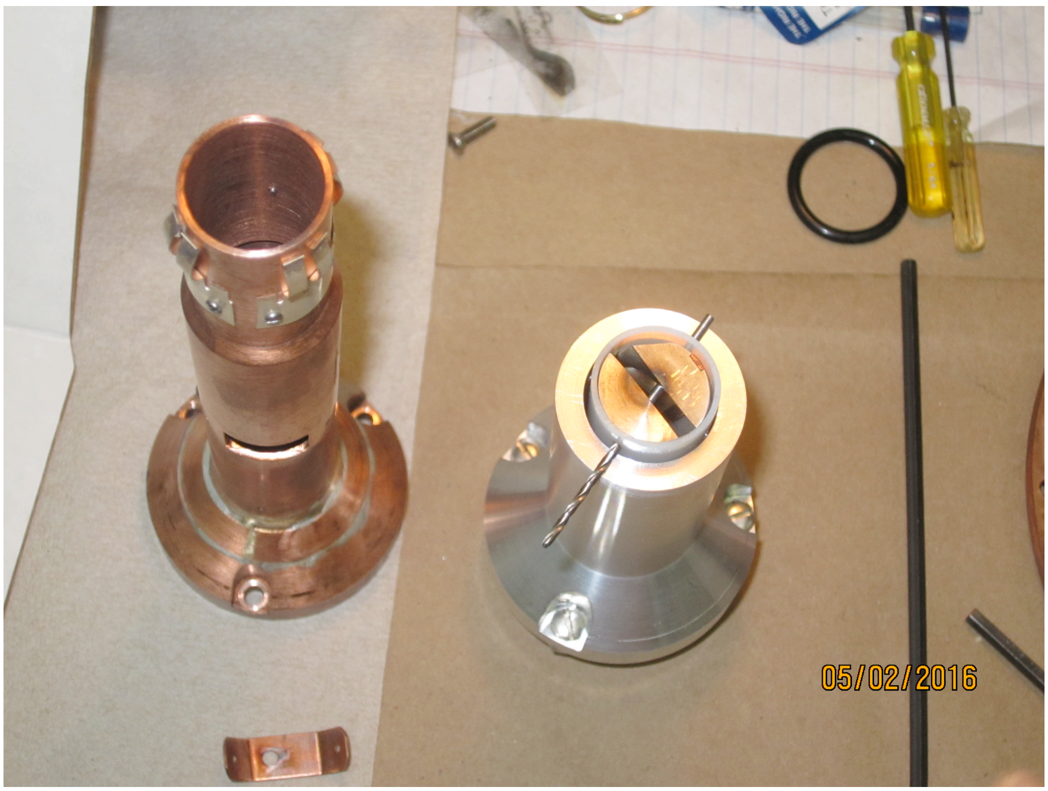

FIG. 1. Compact spiral inflector and its housing.

Compact Spiral Infector

A compact spiral inflector was designed and fabricated with the intent to simply replace the current mirror inflector which is surrounded by the RF dee tips (batwings) at the center of cyclotron. To fit inside the batwings the inflector housing was limited to 1" in diameter and the spiral electrode to ¾" in diameter, see Figs. 2 and 3. The housing was made of a 0.020" thin stainless steel tube and the spiral was machined from an Al rod. The spiral was designed with the well-known equations by Belmont and Pabot (of a particle trajectory in a constant axial magnetic field -$B_0\vec{z}$ with the initial electric field $\mathcal{E}$ alo ng +$\vec{x}$):

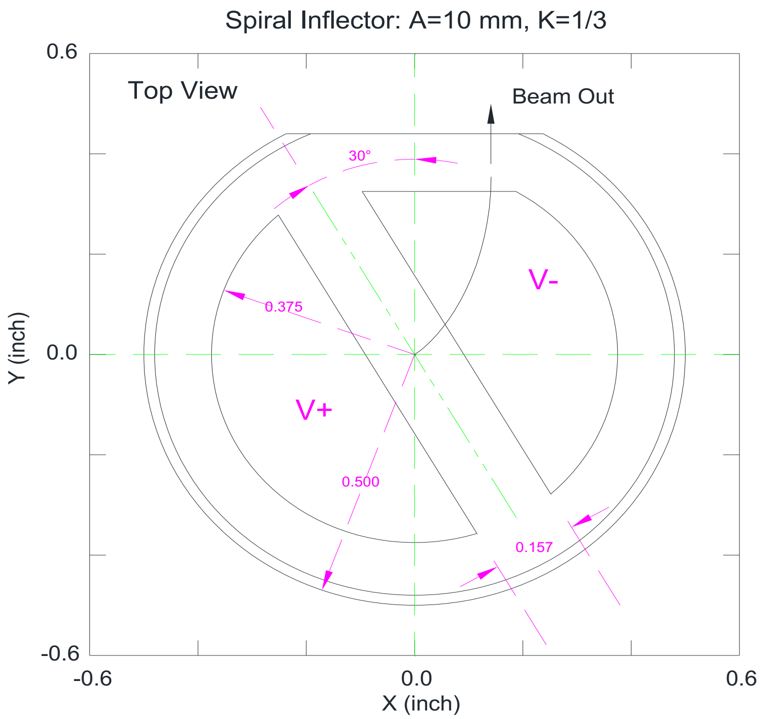

FIG. 2. Top view of our compact spiral inflector.

$$x = \frac{A}{2}\{-\frac{2}{(2K+1)(2K-1)} - \frac{\cos(2K+1)b}{2K+1} + \frac{\cos(2K-1)b}{2K-1}\},$$

$$y = \frac{A}{2}\{-\frac{\sin(2K+1)b}{2K+1} + \frac{\sin(2K-1)b}{2K-1}\},$$

$$z = A\{1 - \sin b\},$$

where $A = 2T/(q\mathcal{E})$ is the electric radius of curvature and $K=A/(2\rho)$, $\rho = P/(qB_0)$ is the magnetic radius of curvature, and b is a dimensionless parameter ranging from 0 to $\pi/2$. (T, P, and q are the kinetic energy, the momentum, and the charge of the particle, respectively.) The equations describe the reference beam particle entering the inflector along the central axis (x=0, y=0) at the height of A and then inflected onto the median plane (z=0) and exiting at radius of $(A/|4K^2-1|)\sqrt{1+4K^2-4K\sin K\pi}$. We chose A=10 mm and ρ=15 mm, and so K=1/3 and the exit radius of 0.381" (9.69 mm), slightly larger than 3/8" (9.53 mm) (the radius of Al rod). (The fringe field would extend a little further out to cover this). Also we have squared up the inflector exit by trimming the Al rod and including a matching flat exit window on the inflector housing. The final momentum of the inflected beam is rotated 180K degrees, or 60

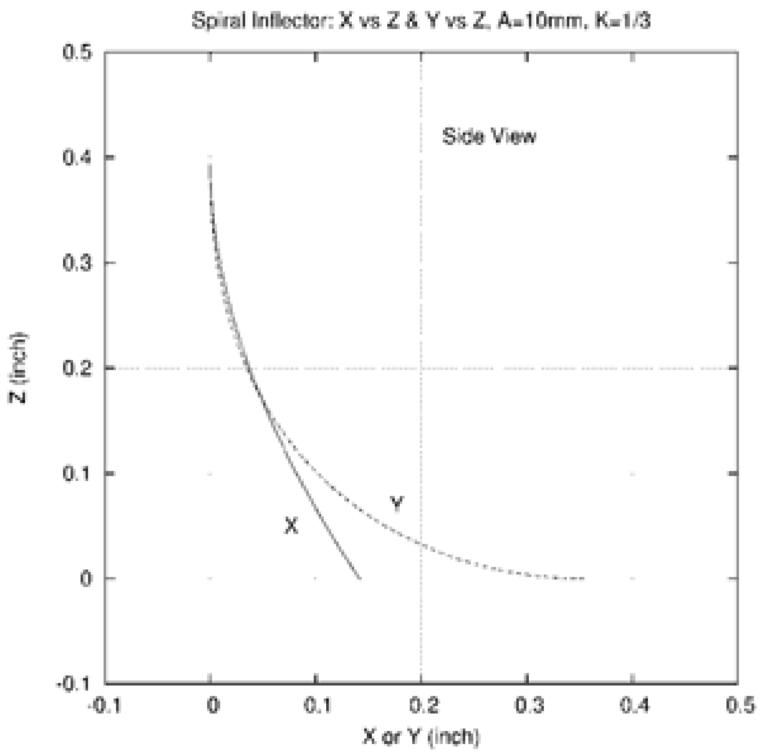

FIG. 3. Side views of X vs Z and Y vs Z of particle trajectory through the spiral inflector.

degrees about the z-axis, from the initial electric field direction (at the entrance of the inflector). So as seen on Fig. 2, by starting the electric field pointing +30 degrees with respect to the + $\vec{x}$ axis, the beam would inflect onto the median plane and exit along the + $\vec{y}$ axis, perpendicular to the notch on the inflector. The required electric field of the inflector is related to the source voltage and the value of A; with a typical value of 10 kV on the ion source, the electric field needed on the inflector is 20 kV/cm, or with a 4 mm gap it would be +4 and -4 kV on the inflector. From the particle trajectory equations, the particle velocity remains constant, and the velocity and the electric field are perpendicular to each other in going through the inflector. One can define the third vector perpendicular to the velocity and the electric field, and interestingly this vector is contained in the horizontal plane (without any z component). This third $\vec{\mathcal{E}} \times \vec{v}$ vector is then parallel with the inflector electrode surface. To machine this curved surface, one can imagine having an Al rod held fixed vertically and a thin, spinning cylindrical cutting tool in the horizontal plane starting at the top of the rod and advancing in small steps along the particle trajectory and at the same time rotating about the instantaneous trajectory point (following the $\vec{\mathcal{E}} \times \vec{v}$ vector), and then finally exiting out of the rod. From Fig. 2, the cutting tool would start at the top of the Al rod tilted -60 degrees with-respect-to the $\vec{x}$ axis and then would emerge 10 mm below the starting point rotated +60 degrees or in align with the $\vec{x}$ axis. In actual machining of the inflector, the spinning cutting tool was held vertically and an Al rod was held horizontally in a rotatable and x-y positioning jaw, and the rod was slowly fed into the cutting tool.