STRIVING FOR INTENSE BEAMS FROM THE TEXAS A&M K500 CYCLOTRON

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Recently, our efforts on increasing the extracted beam intensity from our K500 superconducting cyclotron at Texas A&M University have increased in the interest of supporting secondary radioactive beam experiments. We are pursuing plans to upgrade our ECR ion source, such as employing two frequency microwaves for plasma heating, and to clean up our injection line optics to get more beam into the cyclotron. However, the bottleneck will be the performance of the deflectors. In this report, we will describe our general beam tuning procedures and our current cyclotron performance. We will then focus on the properties of three recent beams, two with large beam currents and one with an exceptional extraction efficiency, in order to learn and to extend the performance of our cyclotron.

1. Introduction

With increased use of secondary radioactive beams in our laboratory, intense beams of more than 1 μA are desired from our K500 superconducting cyclotron at Texas A&M University. Recently we came close with two beams, namely 900 nA of 18.6 AMeV $^{7}Li^{2+}$ and 800 nA of 35 AMeV $^{20}Ne^{7+}$, and then finally, after removing a constriction in the injection line (a poorly designed beam chopper), we extracted 1.1 μA of 15 AMeV $^{84}Kr^{17+}$. We certainly expect to get over 1 μA of the lithium and neon beams with an increased transmission through the injection line. Developing the lithium beam has taken much effort; this beam runs at 33 kG, the lower end of our operating diagram, and has gone through several different tuning schemes to increase the beam intensity. The extraction efficiency has been inconsistent; on average it was only about 25%, but at various times it ranged anywhere from 15-35%. However, in our most recent effort with new tuning parameters, it improved to 47% for the 900 nA extraction measurement. The neon beam also went through a few iterations, and its extraction efficiency has improved from about 35% to 51% for the latest 800 nA measurement.

The improvement in extraction efficiency is important, not only because it obviously increases the extracted beam current, but it means that less of the beam is lost on the extraction elements. Our main concerns are the two, fragile, high-voltage electrostatic deflectors. As we inject more beam into the cyclotron, the critical issue will be how to protect the deflectors and keep them operating reliably. We need to answer questions such as: how much beam power can they safely handle and how much cooling do they need and how to cool them. Installing any cooling is very difficult because of limited space available in our compact cyclotron.

One approach is to run beams with high extraction efficiencies. The 41 AMeV $^{64}Zn^{21+}$ beam which we ran twice in 1997 had an extraction efficiency over 90%; the extracted current was about 140 nA. The specific reason behind the good extraction efficiency is not really understood. Although it is expected to be better than average because the beam trajectory should match well with the curvature of the deflectors, which were designed for 40 kG beams; however, that is not the only criterion as the 90% extraction efficiency is not duplicated by other beams running in the 38-42 kG region.

The recent improvements in beam intensities and extraction efficiencies have come from using new sets of main and trim coil settings. Examples are the already mentioned 18.6 AMeV $^{7}Li^{2+}$ (33 kG at extraction) and 35 AMeV $^{20}Ne^{7+}$ (37 kG) beams. The equilibrium orbit and extraction properties for the lithium and neon and also the 41 AMeV $^{64}Zn^{21+}$ (42.5 kG) beam are examined so that we can learn and increase the beam intensities for all beams.

2. Our General Tuning Procedures

A sample list of beams from our cyclotron is given in Table 1. As shown in Fig. 1, the K500 cyclotron is injected axially with ions from one of two ECR ion sources, ECR1 or ECR2. Ions from a source are analyzed in a 90° bending magnet. The injection line, consisting of dipoles and solenoids, and two electrostatic quadrupole triplets for ECR2, is tuned initially while peaking the beam on the bottom plate of the spiral inflector at the center of cyclotron. Before the removal of the beam chopper (all the numbers in Table 1 are with the beam chopper in place), the beam transmission ranged 25-50%. The

Table 1. Sample list of beams.

Ion	E/A (MeV/u)	I extracted (nA)	Extraction efficiency
d	70	2	23%
7 Li 2+	19	900	47%
20 Ne 7+	35	800	51%
23 Na 7+	30	120	34%
31 P 9+	28	105	75%
64 Zn 21+	41	140	92%
84 Kr 17+	10	246	53%
84 Kr 23+	25	40	57%
84 Kr 23+	30	18	85%
209 Bi 35+	10	120	48%

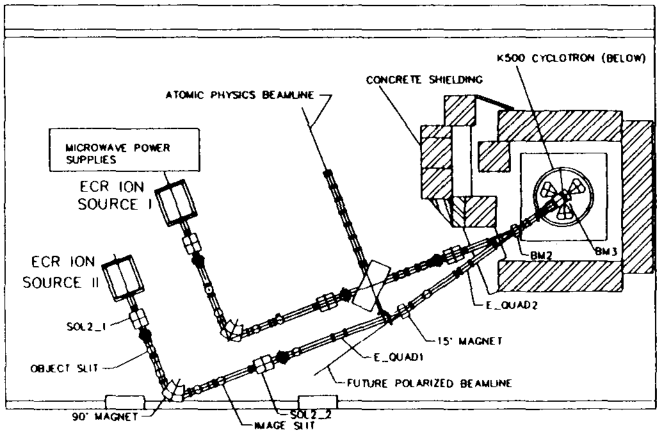

Fig. 1. Two ECR ion sources and the injection line above the cyclotron.

geometry of the spiral inflector and the cyclotron field at the center determine the source extraction voltage. However, it was discovered that this voltage requirement is not so strict and can be relaxed as much as 30%.

The beam current inside the cyclotron is monitored by a three-fingered beam probe, which can be positioned along on a spiraled track installed on the "C" hill, see Fig.2. The rf acceptance is about 5-10%. With a first and a second harmonic bunchers running, the beam current is boosted by 2 to 10 times depending on the ions. Except for beam losses at small radii where the beam probe can not be positioned to measure, the internal beam transmission from about 15 inches to the extraction radius at 26.5 inches is above 95% for many beams, with the vacuum obtained with the liquid helium cryopanels.

The first extraction elements are the two electrostatic deflectors E1 and E2 located at end of hills "A" and "B". They are followed by six magnetic channels M1 to M9; M4, M7, and M8 have been removed. The proper magnetic bump for resonant extraction and the radial positions for the extraction elements are found experimentally and rather simply by peaking the extracted beam. Also the dee voltages are not well calibrated, the voltages on the three dees and their relative phases are again tuned to peak the beam. In general, for beams running at 39-43 kG, the extraction efficiencies are usually better than 60%, but for the lower 30-35 kG beams they are 10-60%. Our overall beam transmission from source to extraction ranges from a few percent to a high of 10%. (Recently with the beam chopper removed from the injection line we obtained a new high of 12%.) Conditioning the deflectors is an important procedure in ensuring a reliable service from them. We condition slowly, first without and then with the magnetic field, while leaking in oxygen gas on the deflectors. Also, leaking small amounts of oxygen gas on the deflectors for high-voltage runs has made a big difference in our cyclotron operations. The oxygen gas seems to suppress

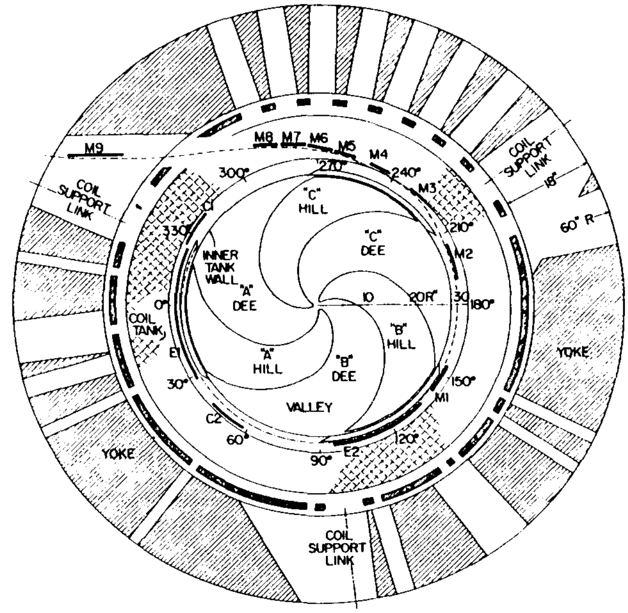

Fig. 2. Median plane of the K500 cyclotron.

sparking and sometimes even "cure" sick deflectors which show some drain currents.

The extracted beam is focused on a pair of slits 3.5 m away from the cyclotron with a quadrupole doublet. The beam current is measured on a faraday cup located just after the slits. The slits are used as an object for beam optics to various experimental areas. An 18 mm diameter circular hole collimator placed 1.9 m upstream of the object slits is used to limit the beam emittance to 5π mm-mr. As part of the beam tuning the beam is optimized through the hole collimator. This and the object slits constrain the trajectory of the extracted beam, which makes repeaking of the beam, to correct for small drifts in the rf and the main field, more consistent and compatible with the beam optics.

3. Equilibrium Orbit Properties

The main cyclotron parameters are the rf frequency and the currents for the two main superconducting coils and the thirteen trim coils. These numbers are obtained with the MSU written program called TCFIT500. It builds up an isochronous field by interpolating among our measured maps at a number of reference coil currents, and then integrates over this field to find the equilibrium orbits. The orbit properties, such as the radial and vertical tunes, ν_r and ν_z, the phase angle ϕ of the particle to the rf, given as $\sin\phi$, are calculated as functions of energy.

The graphs of $\sin\phi$ and ν_r and ν_z for the three lithium, neon, and zinc beams are shown in Figs. 3(a)-(f). Figs. 3(a) and (b) are from an earlier solution of the lithium beam, and Figs. 3(c) and (d) are from the latest one. In comparing Figs. 3(a) and (b) with 3(c) and (d), the differences between the two solutions

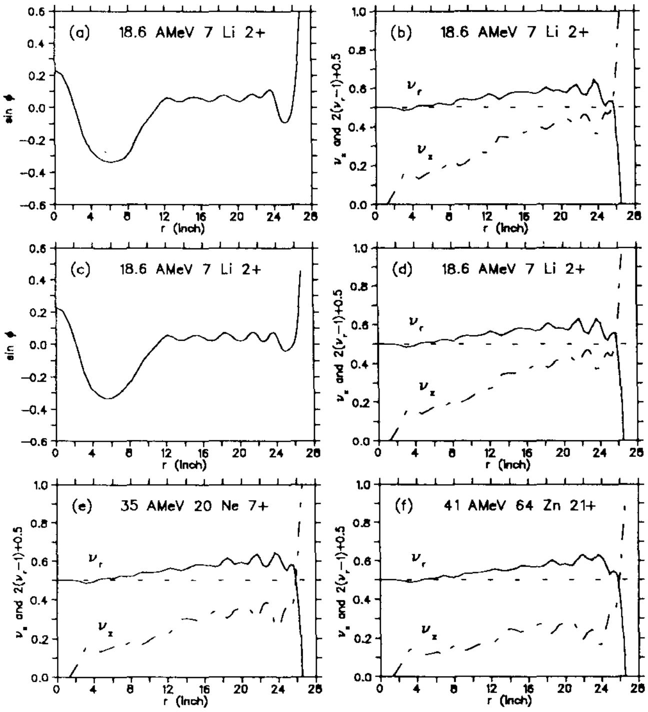

Fig. 3. Graphs of $\sin\phi$ and ν_r and ν_z versus radius for: (a)-(b) 18.6 AMeV $^{7}Li^{2+}$ (an earlier solution), (c)-(d) 18.6 AMeV $^{7}Li^{2+}$, (e) 35 AMeV $^{20}Ne^{7+}$, and (f) 41 AMeV $^{64}Zn^{21+}$ beam. Beams are extracted at about 26.5 inches.

appear to be very minor, and it is not clear why the new solution should produce a beam with a better extraction efficiency. The only real difference between the two is in the depth of the $\sin\phi$ dip at the extraction. The smaller dip in Fig. 3(c) gives a solution with the outside trim coils producing more fields in opposite direction to the main field outside 24 in, and this results in a smaller flutter for this region. Comparing Fig. 3(b) to 3(d), ν_z is reduced by 7% and ν_r is only slightly increased. The ν_r=2ν_z occurs about 4 turns before ν_r=1 resonance. The ν_r=1 and ν_r=0.8 crossing radii are further pushed outside by 1.5 mm and 1.0 mm, respectively, making extraction a little easier.

For the 35 AMeV neon beam, an improvement in beam extraction was also obtained using the same $\sin\phi$ curve used for the lithium beam. The neon beam runs at a higher field (37 kG at extraction) than the lithium, both ν_r=1 and ν_r=0.8 crossing radii occur further outside than that for the lithium beam. The ν_r=2ν_z resonance occurs only one turn before the ν_r=1 for the neon beam.

For the zinc beam, the field at extraction is 42.5 kG and the flutter is weak, and consequently the ν_z values are smaller than that for the lithium and neon beams, see Fig. 3(f). In fact, it is interesting to note that we observed no obvious beam loss in going through the ν_z dip of 0.16 near 24 in. (There is also another problem related to small ν_z and that is if there is any error in the vertical position of the main

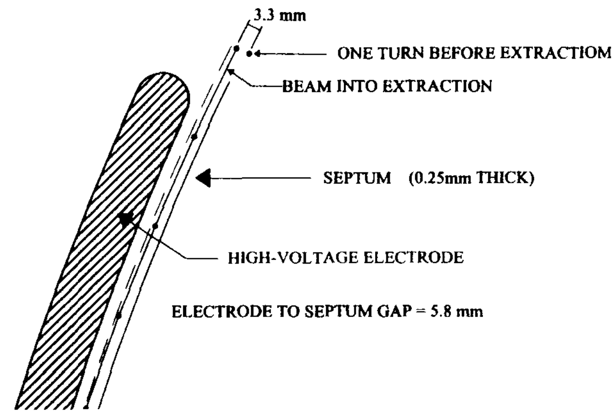

Fig. 4. Beam at extraction showing the turn separation and the trajectory into the deflector. The dashed line represents the midline through the electrode to septum gap.

coils, as we had in the past, there is an overall vertical displacement of the beam which is proportional to the positioning error and inversely proportional to ν_z^2.[1]) For this zinc beam, the ν_r=2ν_z resonance follows the ν_r=1 crossing by about 3 turns.

4. Beam Trajectories through the Deflectors

The curvature on the deflectors were designed for 40 kG beams, and so the trajectory for the 42.5 kG zinc beam should match the deflector curvatures better than that for the lithium and neon beams. This was verified by using MSU written programs SPRGAPX and DEFINXEX.[2] These programs are used to select the proper extraction radius and to track the beam through the extraction channel. Using ν_r=0.8 as the starting point for extraction, the orbit is bumped from the center until an adequate turn-to-turn separation is obtained for the last turn at the entrance angle of the E1 deflector. A typical value for the last turn separation is 3.3 mm, see Fig. 4. Using the bumped orbit data from SPRGAPX, including the energy, radius, and radial momentum, DEFINXEX then calculates the beam trajectory through the deflectors and the passive magnetic channels. The electric field intensities on the E1 and E2 deflectors (call them e_1 and e_2) are adjusted to make the beam go through a predefined point outside the cyclotron yoke. A range of e_1 and e_2 values is possible in DEFINXEX; three sets of e_1 and e_2 values were chosen, starting with a set where e_1 is only slightly bigger than e_2 and then two sets with larger e_1 values, to compare with the experimental numbers. Table 2 lists the three sets of e_1 and e_2 values for each of the three beams along with the experimentally found values.

In order to compare the DEFINXEX beam trajectories with experiment, the corresponding radial positions for the extraction elements are needed. The radial positions of the magnetic channels are not well calibrated, and so we compare

Table 2. Comparison of the deflector electric field intensities and the entrance and exit radii for the calculated beam trajectories with experiment. The difference between the beam trajectory and the deflector curvature is evaluated by examining $\Delta r_{E1} = r_{beam} - r_{def.\ midline}$ at several points along the 66 cm-long E1 deflector.

	E1					Δr_{E1}				E2		
		entr	exit	entr					exit		entr	exit
Beams	(kV/cm)	(inch)	(inch)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(kV/cm)	(inch)	(inch)
19 AMeV	40.0	26.46	26.83	-1.4	0.1	1.3	1.5	0.6	-1.4	37.0	26.93	27.50
7 Li 2+	42.0	26.46	26.85	-1.4	0.0	1.2	1.5	0.6	-1.3	32.3	26.96	27.53
(33 kG)	44.0	26.46	26.86	-1.4	0.0	1.2	1.4	0.6	-1.2	27.4	26.99	27.55
Expt:	76.8	26.40	26.87							46.1	27.09	27.66
35 AMeV	61.0	26.55	26.85	-1.4	-0.6	0.3	0.7	0.4	-0.6	59.4	27.00	27.55
20 Ne 7+	63.0	26.55	26.86	-1.4	-0.6	0.3	0.6	0.4	-0.5	54.5	27.02	27.56
(37 kG)	65.0	26.55	26.87	-1.4	-0.7	0.2	0.6	0.3	-0.5	49.4	27.04	27.58
Expt:	86.7	26.50	26.93							72.7	27.09	27.66
41 AMeV	83.0	26.53	26.83	-1.4	-1.0	-0.3	0.1	0.2	-0.2	81.2	27.04	27.58
64 Zn 21+	85.0	26.53	26.84	-1.4	-1.1	-0.3	0.1	0.1	-0.1	76.2	27.06	27.59
(42.5 kG)	87.0	26.53	26.84	-1.4	-1.1	-0.4	0.1	0.1	-0.1	71.0	27.07	27.60
Expt:	97.1	26.53	26.93							78.1	27.17	27.65

the trajectory only for the deflectors. Each deflector is positioned by two radial drives near the two ends. The two drives give radial as well as angular adjustments. Using measured deflector electrode curvature and electrode-to-septum gap values (for E1: ρ=25.55 in and gap of 5.8±0.15 mm; for E2: ρ=26.58 in and gap of 5.8±0.1 mm), the best fit deflector positions for each DEFINXEX calculated beam trajectory are determined. In Table 2, for our three beams and for three settings of e_1 and e_2 values, the entrance and the exit radii (of the midline between the electrode and the septum, see Fig. 4) of the best fit deflector positions, and the deviation in curvature between the beam and the E1 deflector as determined by the differences in radius between the beam and the deflector midline at several points along the deflector are listed. The experimental e_1 and e_2 values and the deflector entrance and exit radii for the three beams are listed below the DEFINXEX numbers. As expected the zinc beam at 42.5 kG has the best fit to the E1 curvature, as can be seen from columns 5-10 in Table 2. The neon beam at 37 kG is acceptable, but for the low field lithium beam, the large scalloping of the trajectory through E1 is troubling. The curvature errors through the E2 deflector for all three beams are under ±0.5 mm. Comparing the deflector electric field intensities, the experimental numbers are always larger, especially for the lithium beam. Looking at the deflector radial positions, experimentally the beams are radially pushed out more through E1 than the calculated trajectory; this perhaps accounts partly for the higher numbers. More studies are needed to understand the differences.

5. Conclusions

The 35 AMeV neon beam ran for almost three weeks with 80 watts of extracted beam power and an equal amount lost in extraction with no deflector deterioration. Naively this means that over 700 watts of extracted beam power could be achieved with a 90% extraction efficiency. However, to handle high intensity beams over the entire operating region, some changes to the deflectors will be necessary. These could be minor, such as modifying the deflector gaps or thinning the septum, or could be major, such as installing water cooling or designing a variable curvature deflector. Iterations in the beam tune calculations have helped to increase the beam intensities, and with improvements in the ion source and in the injection line, more studies will be needed to help guide us toward achieving an even higher beam power.

References

[1] D.P. May, et al., Proc. of the 14th International Conf. on Cyclotrons and their Applications, Cape Town, South Africa 1995, p. 381, World Scientific (1996).

[2] Felix Marti, private communication.