EFFECT OF THE MAIN-COIL POSITION ON THE ACCELERATED BEAM OF THE K500 CYCLOTRON

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ABSTRACT

As a consequence of the failure of the development of several beams by the Texas A&M superconducting cyclotron, a program was initiated to find the cause. It was found that the vertical position of the main superconducting coil was the culprit. The vertical position has been substantially changed, and the operation of the cyclotron has improved dramatically.

1. INTRODUCTION

Soon after the first beams were accelerated by the Texas A&M K500 superconducting cyclotron in 1988, it was noticed that several of the beams had problems as they approached extraction. For example, when a reasonable phase function was used to calculate the trim-coil settings for 35 MeV/amu $^{14}N^{5+}$, the beam would fail to accelerate past a radius of 24.5 in., extraction radius being 26.5 in. The attenuation of the beam was fairly sharp, with a majority of the beam disappearing within 0.25 cm. Other beams, for example 30 MeV/amu $^{14}N^{5+}$, exhibited a sharp drop at the same radius, but with some of the beam surviving to extraction. In both cases, most of the beam could be brought to extraction radius by changing the outermost trim-coil, trim-coil 13. The current in this coil was changed in such a manner that it produced a large negative magnetic field gradient around R=24.5 in. Maximum extracted beam occurred for an intermediate value of trim-coil 13 with some of the beam still being lost at R=24.5 in.

With the installation of the ECR ion source in November of 1989, beam diagnostics became considerably easier, and a quick survey of beams became possible. Beams of 30 MeV/amu $^{16}O^{6+}$, $^{14}N^{5+}$, and $^{12}C^{4+}$ (Q/A = .375, .357, and .333, respectively) were developed, but a beam of 30 MeV/amu $^{16}O^{5+}$ (Q/A = .312) would not accelerate past R=24.5 in. even by changing the current in trim coil 13. A development attempt with 35 MeV/amu $^{40}Ar^{13+}$ (Q/A=.325) failed with the beam not accelerating past R=20 in. although 35 MeV/amu $^{14}N^{5+}$ (Q/A = .357) had been developed earlier. A beam of 53 MeV/amu alphas could be accelerated to extraction radius by changing trim coil 13, but with a large intensity drop at the outer radii, and the beam could not be extracted.

In general, the beams that could be extracted were confined to the lower left-hand side of the operating diagram shown in Fig. 1. The higher field, higher frequency (high γ) beams were inaccessible. To attack this problem, the field maps were re-examined and refined, the phase of the internal beam with respect to the rf voltage was measured for several beams, all the trim-coil connections were checked (each of the 13 coils has 12 separate leads external to the cyclotron) and even the elevations of the outer-radius steel were re-measured. Nothing of significance was found.

The first hint of what the problem might be came from examining plots of the intensity of the beam hitting

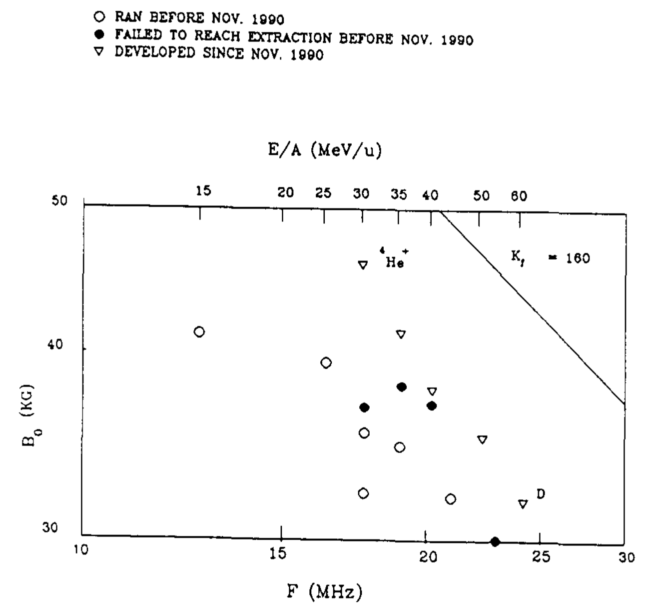

Fig. 1. Operating region for the K500. The positions of the higher-frequency, higher field beams are indicated. The line labeled Kf=160 represents the focusing limit (80 MeV/amu for Q/A=0.5).

the three-finger probe versus radius (I vs R). The three fingers of the beam probe are arrayed vertically, with each finger 5.7 mm high, separated by two 0.76 mm gaps. The data showed that for 30 MeV/amu $^{14}N^{5+}$, for example, all of the beam was intercepted either by the middle or by the bottom probe finger (Fig. 2). No beam was hitting the top finger of the probe from R=13 cm to R=67 cm except in the last 3 mm of the probe travel before the beam encounters the extraction system. This could be explained by an offset in the positioning of the probe tip which is not visible when the K500 is closed for operation. The probe is centered by the trim-coil covers, and such a light-weight device could easily be moved in the act of lowering the upper pole cap. In fact, the probe tip position is different depending upon whether the probe is moving towards or away from the center as shown by the difference between the I vs. R plots.

A difference in I vs. R plots was also noticed when examining a plot made for a 30 MeV/amu $^{14}N^{5+}$ beam after raising the superconducting main coil approximately 0.75 mm above the median plane nominal position. The coil can be raised and lowered by means of tightening and loosening nuts on the six vertical links, and this had been done to examine the effect on the vertical behavior of the extracted beam. The ratio of beam intercepted by the bottom probe finger to beam intercepted by the middle finger increased slightly by elevating the coil, so it was decided to lower the coil and examine the plots. The coil was first lowered by approximately 0.75 mm, and it was directly confirmed by plots taken under the same conditions of beam tuning that a slightly greater percentage of the beam was intercepting the middle finger. More dramatically a beam with a trim-coil solution calculated with a standard phase history was able to bring more of the internal beam to extraction radius, and as the coil was lowered further, even more beam came to extraction radius.

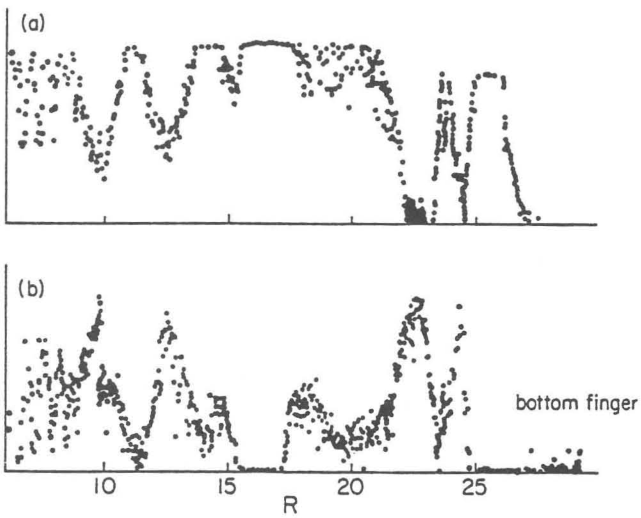

Fig. 2. Intensity versus radius for the top (a) and bottom (b) fingers of the beam probe. The main coil position was 0.8 mm below the position for which the magnetic fields were mapped.

To date, the main coil has been lowered by approximately 3.4 mm (0.135 in.) in 0.2 mm increments. After lowering the coil by 1.6 mm, a 30 MeV/amu $^{16}O^{5+}$ beam came to extraction with a standard phase solution. After lowering the coil another 0.4 mm, a 53 MeV/amu alpha beam could be extracted. With the coil lowered by 2.7 mm a 60 MeV/amu alpha beam could not be extracted. After lowering the coil by another 0.4 mm the beam was extracted. After the last lowering, a 65 MeV/amu alpha beam was extracted. Figure 1 indicates the beams developed after the lowering process began.

2. MECHANICS OF COIL LOWERING

The coil was lowered to its present position over a nine month period. Changing the coil position is fairly simple to accomplish, but it must be done with caution. The horizontal centering of the coil can give rise to large unstable horizontal forces when the field is high.[1] As described in Ref. [2], the K500 coil is an array of four coils wound on a single stainless steel bobbin. An outer stainless steel jacket is welded to the bobbin to form the liquid helium vessel. This vessel is suspended in a vacuum vessel by means of links which include low heat conductance fiberglass straps. There are no coil windings at the median-plane level, and the whole coil-cryostat assembly is penetrated at this level by a number of channels for the insertion of the extraction system devices and beam probes. If the coil is centered about these channels, there is at most 6.3 mm of vertical space above and below the channels into which the coil can be either lowered or raised. It is imperative that these channels, which are formed by tubes welded to the vacuum vessel walls, not support any of the weight of the coil. After lowering the coil by each 0.2 mm increment, the link strains were checked to make sure the links were still supporting the entire weight. The first indication of the coil approaching the channels might be excessive LHe consumption by the cryostat as the super-insulation between the coil and the channels is crushed, causing a heat leak. After each 0.8 mm increment, the coil was run at full field and the horizontal links were adjusted to balance their strains. No cold spots have been observed on the outer cryostat wall, and the LHe consumption has remained low.

3. RESULTS AND ANALYSIS

Since the performance of the cyclotron has improved with each incremental lowering of the main coil, the observation is that the magnetic mid-plane of the coil must have been at least 3.4 mm above the magnetic mid-plane of the steel poles. In this case there is a sufficient downward force on the beam at many radii to move it to the level of the lower probe finger. This force is due to the off-mid-plane, radial component of the coil magnetic field. The radial component of the coil field and the radial field components of the pole fields tend to cancel one another at a vertical displacement from the pole mid-plane of

$$Z = -\frac{R}{B_T}\,\frac{\partial B_c/\partial r}{\nu_z^2}\,\delta \qquad (1)$$

Here R is the radius, B_T is the total field strength at R, $\partial Be/\partial r$ is the radial gradient of the mid-plane magnetic field of the coil, ν_z is the vertical betatron frequency, and δ is the vertical distance the coil is offset from the steel. The quantity Z/δ is plotted vs. R in Fig. 3, along with ν_z and the phase of the beam for the 30 MeV/amu $^{14}N^{5+}$ beam.

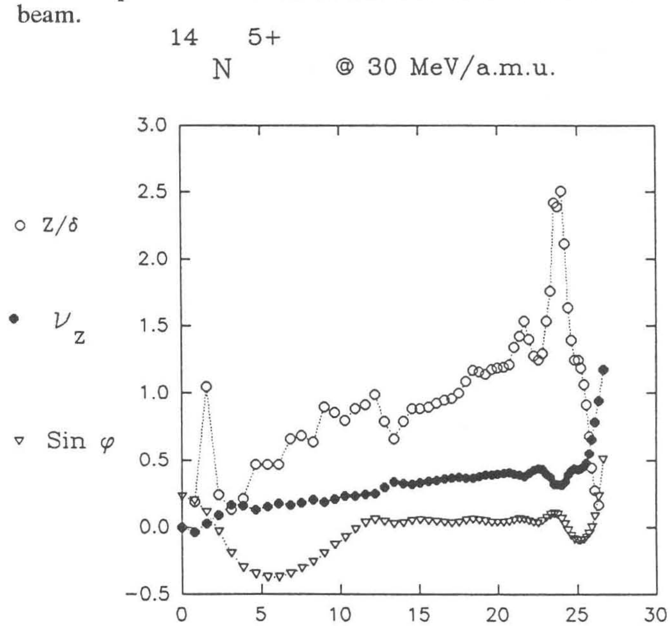

Fig. 3. Beam properties for a 30 MeV/amu $^{14}N^{5+}$ beam. Using field maps the vertical betatron frequency (ν_z) and the vertical median plane offset (Z/δ) are calculated using the sine of the beam phase (sin ϕ) as input.

The sudden increase in Z/δ near R=24 in. matches well with the abrupt disappearance of the beam near the same radius. For beams with higher fields ν_z decreases as the hill-to-valley field difference decreases. Thus Z/δ increases for both higher γ and for higher B_T. Near R=24.5 cm, ν_z experiences a decrease for all beams since at this radius a gap occurs between the hill steel and its continuation in the inner cryostat wall.

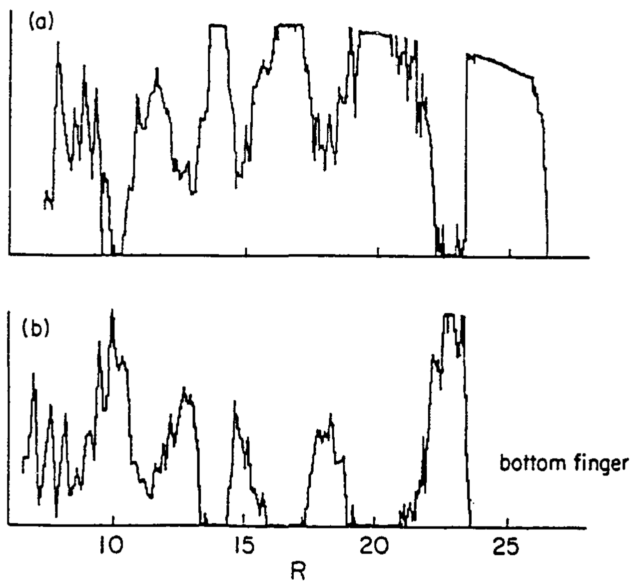

Fig. 4. Intensity versus radius for the top (a) and bottom (b) fingers of the beam probe. The main coil position was 2.7 mm below the position for which the magnetic fields were mapped.

Figure 4 shows plots of I vs. R taken with the three-finger probe for the preceding beam after the coil had been lowered by approximately 2.7 mm. The appearance of the beam on the bottom finger can be roughly, but not entirely, correlated with Z/δ. The large amount of beam hitting the bottom probe finger at R=23 in. corresponds to a local increase in Z/δ, but the beam is seen to hit the bottom finger at R=24.5 in. only for a much higher coil position.

Another effect observed with the coil lowering is the lowering of the deflector voltage required to extract such beams as 35 MeV/amu $^{14}N^{5+}$. Originally, a first deflector voltage of 65-67 kV was necessary. At present, the voltage is approximately 10% lower since the deflector is able to be positioned at a larger radius and at a less steep angle. The field maps have been largely unaffected, and indeed are more predictive now that the beam is closer to the median plane. Overall, the coil lowering has been a major success with the subsequent development of beams such as 65 MeV/amu deuterons, 50 MeV/amu $^{12}C^{5+}$ and 40 MeV/amu $^{63}Cu^{21+}$, and it has represented a major step in approaching the 80 MeV/amu focusing limit of the Texas A&M K500.

4. REFERENCES

1) Blosser, H. G., **Proceedings of the Eight International Conference on Cyclotrons and Their Applications** (IEEE, Bloomington, 1978), p. 2040.
2) Miller, P., **Proceedings of the Tenth International Conference on Cyclotrons and Their Applications** (IEEE, East Lansing, 1984), p. 11.