EFFECT OF ORBIT CENTERING AND MAGNET IMPERFECTIONS ON BEAM PROPERTIES IN A SUPERCONDUCTING CYCLOTRON*

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Abstract

An extensive set of orbit computations were used to study the role of orbit centering and magnetic field imperfections in determining overall beam transmission in the K500 cyclotron. Magnetic imperfections (from magnet construction and from centering coils), central region electrode imperfections, and the spread in starting times all contribute to beam offcenteredness. This can give phase space distortion as the beam traverses the $\nu_r=1$ resonance near the center of the machine and near the extraction region and axial loss at the $\nu_r=2\nu_z$ coupling resonance. The studies particularly examined the effect of magnetic imperfections on extraction efficiency in order to guide a decision on installing corrective shims in the magnet. Surprisingly, calculated extraction efficiency in the existing imperfect field is found to closely match that in a perfect field, provided the inner and outer first harmonic correction coils are optimally set.

Introduction

Beam extraction in the K500 cyclotron is carried out by introducing a first harmonic bump in the magnetic field in the edge region where $\nu_r= 1$, thereby off-centering the orbits and producing good separation between turns at the electrostatic deflector entrance. After the first few beams were extracted it became obvious that only a narrow range of first harmonic bumps could be used to extract the beam, and that the amplitudes of these bumps were much larger than had been expected from pre-operational orbit calculations which neglected fabrication errors. The discrepancy was such that computed perfect field orbits did not survive to the extraction energy when extraction bumps as large as the experimental bump were applied .

The pre-operational computations assumed negligeable construction errors and therefore the only harmonics used in the computations were the 3N harmonics and the centering coil plus extraction bump first harmonics. Noting the discrepancy between computed and experimental bump settings we decided to insert imperfection components as observed in the magnetic field measurements and thus work with more realistic fields in the computations[1].

When the measured magnetic field (including the imperfections) was used in the orbit codes, the agreement with the experimental settings for the extraction bump was remarkably good, showing also the small range of angles in the extraction bump which had been found experimentally to enable the beam to survive the vertical blow-up when traversing the $\nu_r= 2\nu_z$ resonance. We decided then to pursue a detailed study of the effect of the imperfections on the orbit dynamics and specifically on the beam extraction in order to assess the possible benefits which might be derived if the field were shimmed to reduce the imperfections. These studies then compare perfect field and real field orbit behavior, and indicate very little difference in the key figure of merit, extraction efficiency.

Orbit studies

We picked two different ions for the studies on orbit dynamics. We considered first $^{12}C^{4+}$ 30 MeV/nucleon in a B_o=3.45 Tesla field as a typical ion that is frequently run in the K500 cyclotron. The choice of the second ion was based on the ν_r behavior. We wanted to study a case where $|\nu_r-1|$ was small and therefore possibly more sensitive to imperfections in the magnetic field. For this purpose, we chose the ion $^{40}Ar^{6+}$ 11.5 MeV/nucleon in a magnetic field with B_o=4.82 T (close to the bending limit in the operating diagram) and with a low charge over mass ratio (Q/A=0.15). This ion lies in the low energy region of our first harmonic operation. For this ion, for R < 10 inches, we have $|\nu_r-1| < 0.01$.

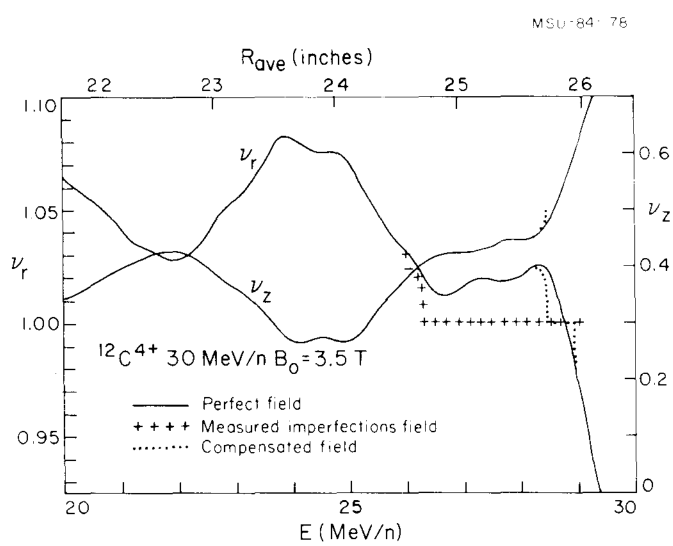

Fig. 1. ν_r and ν_z values for the Carbon field in the extraction region. The top scale gives the average radius of the equilibrium orbit (EO) corresponding to the energy given by the scale at the bottom.The solid line shows the values for the perfect field. The crosses show the behavior for the field with the permanent imperfections (no compensating trim coil harmonics included). The dots show the total field behavior.

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Typically in the K500 ν_r falls below 1.0 after reaching a peak near R=23 inches, and simultaneously ν_z increases (Fig. 1). The operating point thus crosses two resonances in the extraction region, namely $\nu_r=1$, and $\nu_r=2\nu_z$. The order of crossing theseresonances depends on the field level and on Q/A. The $\nu_r+2\nu_z=3$ resonance is beyond extraction, but we must be very careful because if the beam gets too close to this powerful resonance and is also very off-centered, the beam blows up vertically.

One of the first calculations we made was the determination of the range of first harmonic bumps in the extraction region (produced by the outer trim coil) which allowed us to accelerate the particle to the extraction energy without an excessive increase of the vertical height of the beam. We picked a factor of two growth in amplitude (with respect to the amplitude at the point with minimum ν_z) as the cutoff in determining whether there was vertical blow-up.

The particles were started in centered orbits approximately 150 turns before extraction (500 is the nominal total turn number for first harmonic operation). From these calculations we learned that the acceptable range of first harmonic bumps had amplitudes of 15 ± 5 gauss at phases of 270 ± 5 degrees. This result explains the difficulties we had during the first extraction experiment, that is we had to find this small "island", or else we could not compensate the imperfections properly. Actually, this compensation can be carried out only approximately because of the difference between the form factor and phase dependence of the imperfections and the compensating trim coils.

Up to now, the K500 cyclotron has operated without phase selection (we are in the process of designing phase slits that will limit the phase width of the beam[2]). The central region does not establish a narrow window, allowing instead beams as much as 60 degrees wide to accelerate past the first few turns. With the purpose of studying the effect of phase spread, we considered ions that started at the center of the ion source slit in a ±10 degree interval around the central starting phase. This central phase was taken as 30 degrees before peak voltage between source and puller. This starting phase has the maximum energy gain in that first gap. This total of 20 degrees in phase was populated with 41 particles equally distributed every half a degree in RF time.

In comparing extraction in the case with magnetic field imperfections to the perfect field case, we first found the magnitude and angle of the first (and accompanying second) harmonic from the centering coil which produced a central ray that was pretty well centered after 150 turns. We then found the extraction bump which would allow the particles to accelerate to the extraction energy (ν_r approximately 0.8) and give good turn separation at the entrance to the electrostatic deflector. In both cases, the RF frequency was tuned to obtain minimum turn number for a starting phase close to that of the central ray.

In Figs. 2a and 2b we show the first and second harmonic amplitudes and their phases. The solid line includes the imperfections introduced by optimized adjustment of the centering and bump coils, while the crosses indicate only the imperfections when no trim coils are excited. The first trim coil (centering) was excited to a peak first harmonic field of 16 G and a phase of 315 degrees. The bump coil peak first harmonic was also 16 G but at an angle of 275 degrees. We can see clearly that the main effect of the bump coil has been to decrease the first harmonic in the 25 to 26 inches radius region, but in doing so it also increased the imperfections in the region between 22 and 25 inches.

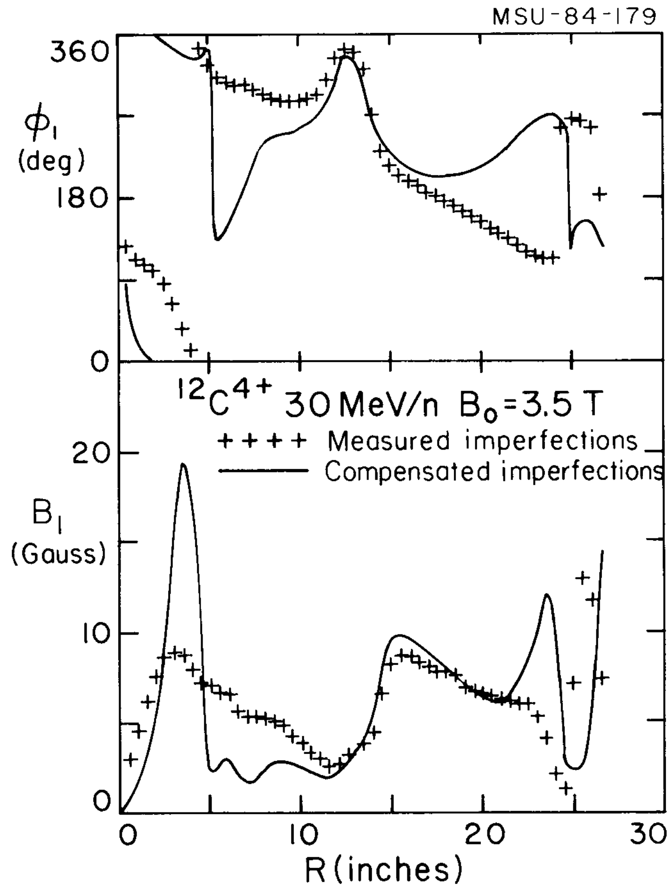

Fig. 2a. First harmonic amplitude and phase in the Carbon field. The effect of the trim coil near extraction is to decrease the resultant amplitude between 25 and 26 inches.

The effect of these compensating bumps on the equilibrium orbits can be seen in Fig.1. The equilibrium orbit does not exist in the field with the measured imperfections between 26.3 and 29 MeV/n. In the total field with the trim coil harmonics in it,this region is reduced to 28.5 to 29 MeV/n, making it much easier for the beam to traverse it without suffering major distortions or moving outside the region of stability once the equilibrium orbit reappears. We have plotted in Fig. 3 the static phase space diagram at 28 MeV/n for these three fields. Results are shown on the left for the perfect field (only 3N harmonics), in the middle the field with measured imperfections included, and finally on the right the field with the trim coils adjusted to optimally compensate the imperfections. We see that the area of the stable region is approximately the same in the compensated field and in the perfect field, while it does not exist in the field with uncompensated imperfections.

The original group of 41 rays that started at the ion source at different times were accelerated in the compensated field and in the perfect field up to the entrance to the deflector. The general behavior in both cases was very similar. The energy distribution, the time spread, and the (r, p_r) distribution were

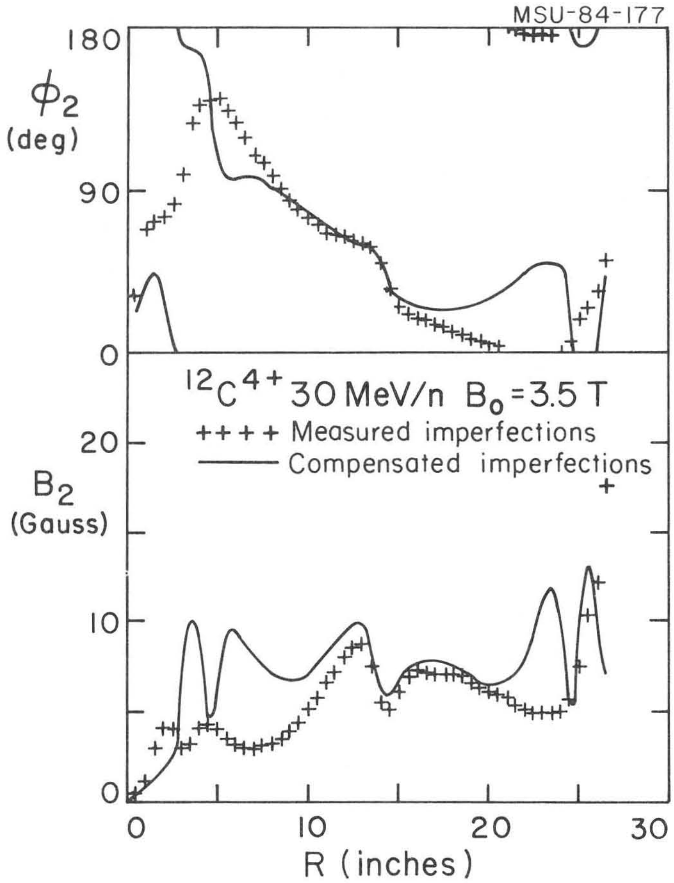

Fig. 2b. Second harmonic amplitude and phase in the Carbon field.

comparable. The case with the compensated imperfections did not show any detectable degradation of the beam relative to the perfect field orbits.

These 41 rays are of course "central rays" for a radial phase space area that will be accelerated. We therefore studied the behavior of a circular phase space area in the (r,p_r) plane, corresponding to a final emittance of 7.5 mm mrad. The result for the 30 MeV/n Carbon field showed no significant deterioration of the beam when the imperfections were present. The 11.5 MeV/n Argon field on the other hand showed some distortions in the vicinity of the ν_r=1 stop bands between 1.0 and 1.5 MeV/n and between 9.8 and 10.2 MeV/n. When the beam traverses the first of these two regions, Fig. 4, the phase space area becomes very elongated, and as a result, when the beam traverses the second region, this area becomes distorted. The difference in behavior here is due to the Ar field having much smaller values of $|\nu_r-1|$ than the Carbon field.

Conclusion

Our studies have shown that in magnetic fields similar to the Carbon case where ν_r does not remain close to ν_r=1 for a significant fraction of the acceleration, the presence of imperfections in the magnetic field does not affect very significantly the beam extraction. On the other hand, for fields similar to the Ar case, it seems worthwhile to reduce the first harmonic imperfections in the region where ν_r is close to one.

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References

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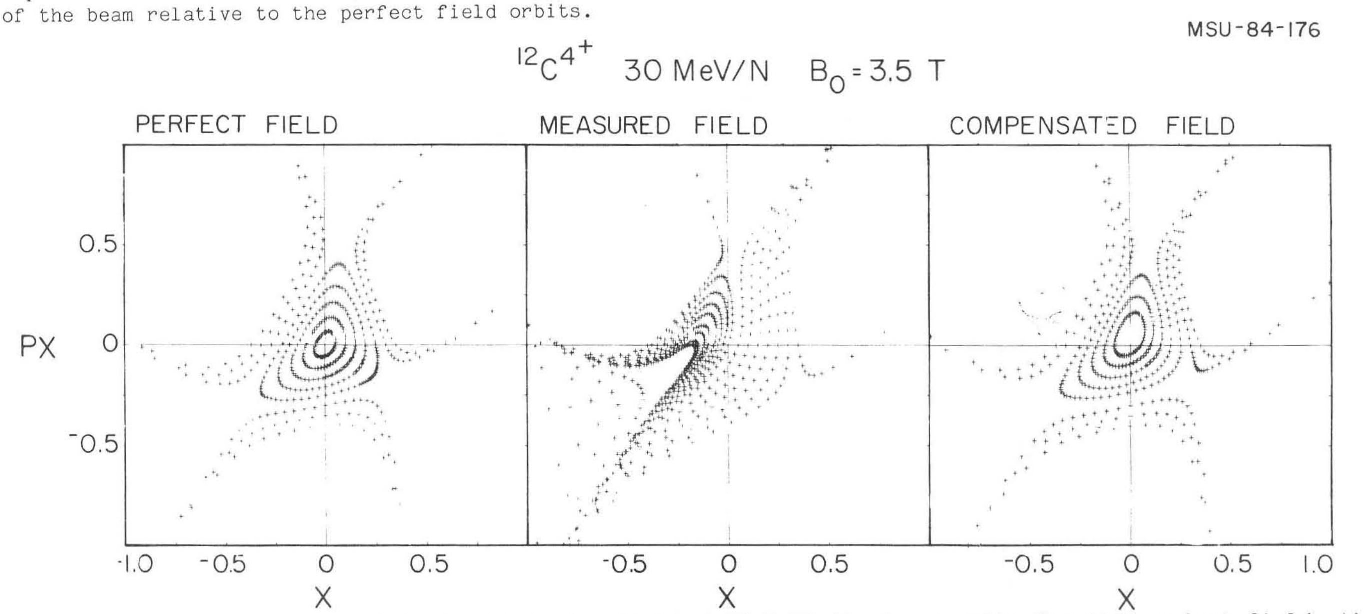

Fig. 3. Static phase space plots for the Carbon field at 28 MeV/n. We show results for the perfect field, the field with the permanent imperfections, and the field that includes the trim coil harmonics. The crosses are plotted once per turn along the spiral θ = 30° - (4.4 deg/inch) r, which corresponds to the linear spiral of the magnet sectors. The dimensions are in inches. P_x has been divided by the momentum unit $m\omega_0$ to express it in inches. Observe that the stability region area has been almost completely recovered after adding the trim coil harmonics.

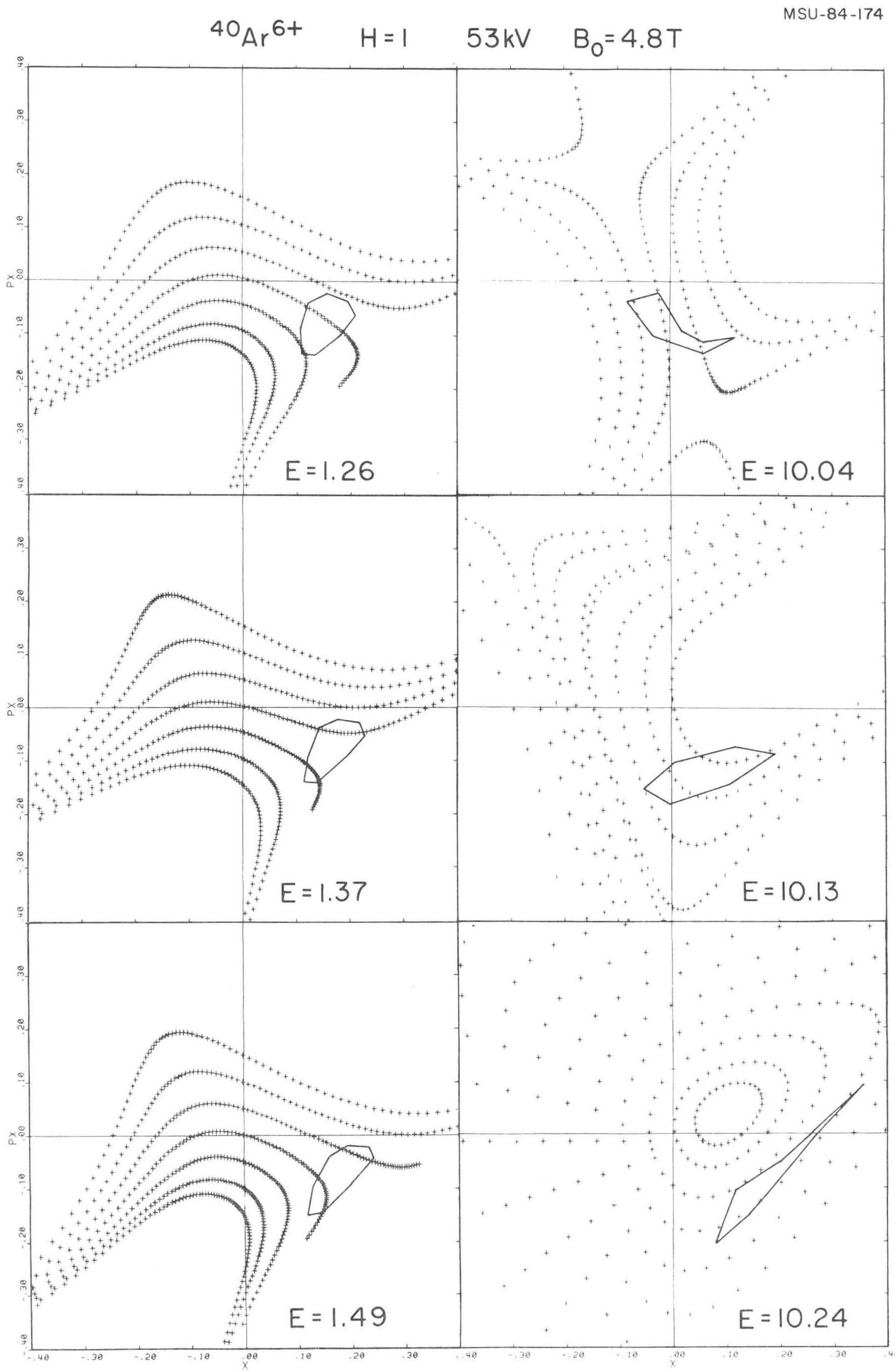

Fig. 4. Static phase space plots for the Argon field at the energies indicated in each of the six panels. We have used the field with the trim coil harmonics in it. See Fig. 3 caption for explanation of units.