EXTRACTION STUDIES FOR A 250 MeV SUPERCONDUCTING SYNCHROCYCLOTRON*

M.M. Gordon and X.Y. Wu
National Superconducting Cyclotron Laboratory, Michigan State University,
East Lansing, MI 48824-1321

Abstract

A 250 MeV superconducting synchrocyclotron for use in cancer therapy is being designed here with a central field of 57 kG and a pole radius of 21 in. An iteration process that combines magnetic field and orbit computations is being used to design a suitable regenerator and magnetic channel system to extract the beam. Radial phase plots at a sequence of energies show that as the beam accelerates out to the regenerator, the stability region shrinks rapidly to zero spilling the orbits onto the outflowing asymptote along which their radius-gain per turn increases until they can clear the septum and enter the channel. Vertical stability is monitored with an orbit code that includes all nonlinear effects to fourth order in z. Our results show that strong coupling effects restrict the range of orbit-center displacements and vertical amplitudes that can be extracted successfully. In addition, we find that the regenerator strength decreases rapidly with increasing vertical amplitude.

1. Introduction

Beam extraction from synchrocyclotrons is based on the regenerative process invented by Tuck and Teng and developed by Le Couteur in the 1950's. Our choice of regenerator parameters was derived from an extrapolation of those used in the Harvard cyclotron.[1]

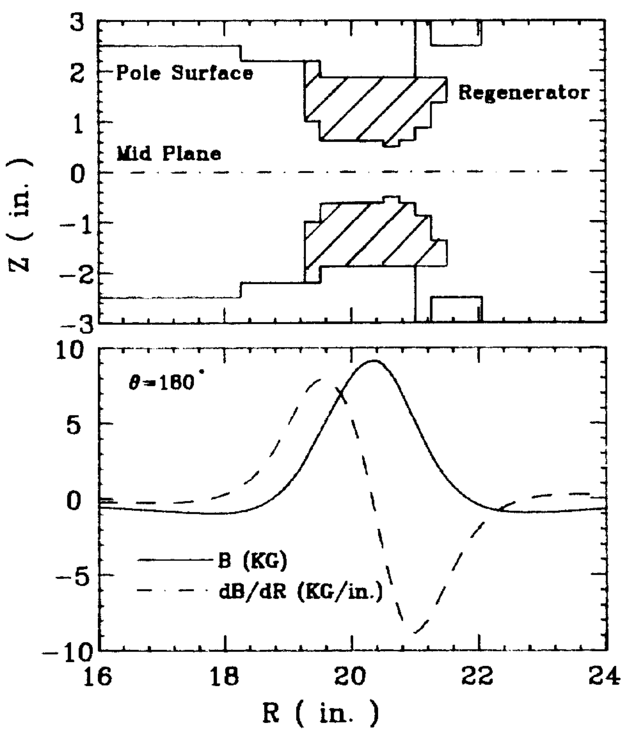

Fig. 1 -- At top, radial profile of regenerator situated on the edge of the magnet poles. At bottom, field B (solid curve) produced by regenerator, and its gradient dB/dr (broken curve) vs. radius. Plots are for $\theta = 180^{\circ}$, the center of the regenerator.

Before the regenerator is added, the ν_z values rise with increasing energy while the ν_r values fall. In the present design, these values cross the $\nu_r = 2\nu_z$ (n=0.2) resonance at 19.1 in., and this radius determines the approximate starting point for the regenerator.

The iron configuration of the proposed regenerator is shown schematically in Fig. 1 along with the field change and field gradient that it produces. This device has an average angular width of 30°, and has terraced edges to smooth out the azimuthal field variations.

The regenerator provides a powerful field bump whose strong gradient drives ν_r into the $\nu_r = 2/2$ stop-band while simultaneously depressing ν_z. This is shown in Fig. 2 where ν_r and $2\nu_z$ are plotted as a function of energy. The pair of curves for the unperturbed field come together and cross at 258.9 MeV, where n = 0.2 as noted above. With the regenerator present, the two curves diverge with ν_r rising sharply to $\nu_r = 1$ at 253.7 MeV, which becomes the peak energy of the extracted protons. At this point, $\nu_z = 0.29$.

2. Radial Motion

The nature of the extraction process can best be understood by examining radial phase plots like the one shown in Fig. 3 for 252.5 MeV. Here values of p_x vs. x are plotted once per turn at $\theta = 180^{\circ}$ (the center of the regenerator) for three different orbits,

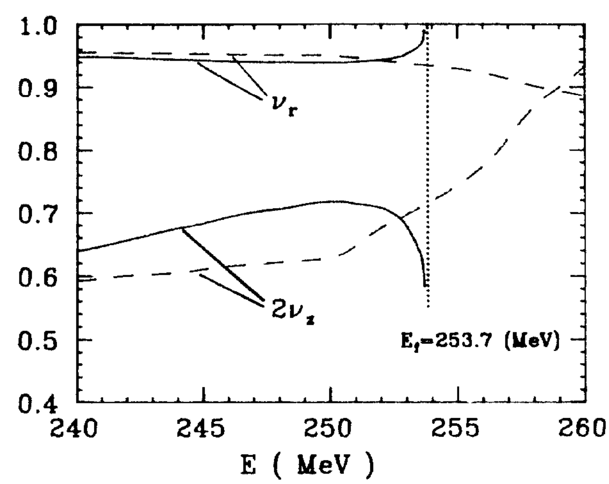

Fig. 2 -- Plots of ν_r and $2\nu_z$ vs. energy both without regenerator (broken curve) and with regenerator added (solid curve). $\nu_r = 1$ at 253.7 MeV, the peak extraction energy.

CH2387-9/87/0000-1255 $1.00 © IEEE
PAC 1987

one stable and two unstable, which clearly show the boundary of the stability region. This region shrinks to zero at 253.7 MeV where $\nu_r = 1$, and is sufficiently large at 252.0 MeV to encompass most of the internal beam that can survive the extraction process.

One can therefore see that as the protons accelerate outward, they encounter a rapidly shrinking stability region that eventually causes their orbits to spill over the boundary into the radially unstable region. As shown in Fig. 3, the phase points then move onto the outflowing asymptote along which their radius-gain per turn increases exponentially thereby enabling the protons to clear the septum and enter the magnetic channel.

Vertical stability ultimately limits the radius-gain per turn that can safely be achieved in the regenerative process. That is, as the orbits move progressively farther off center, strong coupling effects eventually cause the vertical height of the beam to expand beyond the allowed limits.

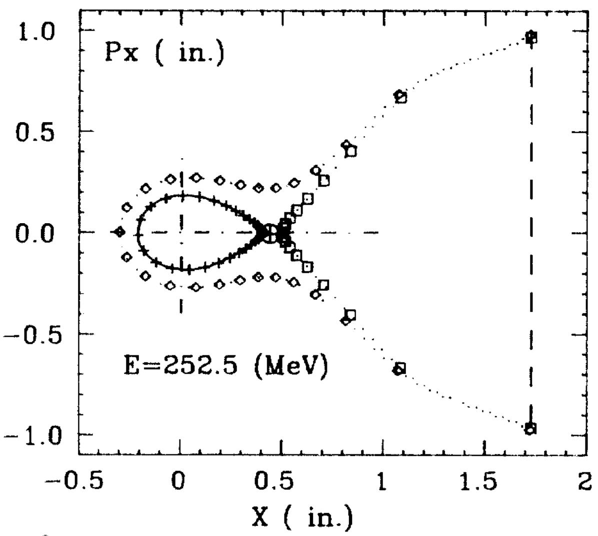

Fig. 3 -- Radial phase plots for three orbits at 252.5 MeV showing stability region and asymptotes produced by regenerator. The stability region shrinks to zero at 253.7 MeV.

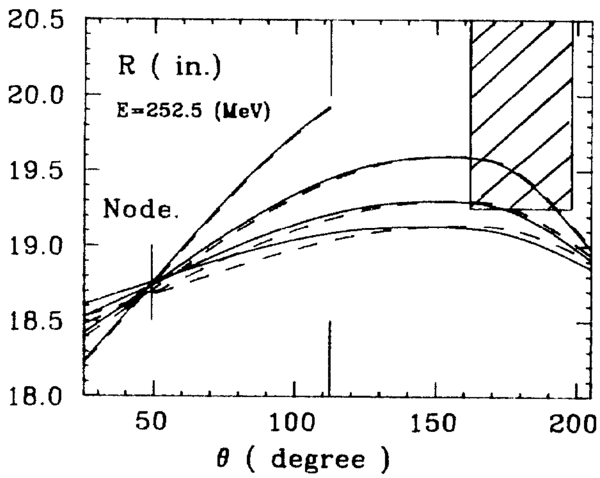

Fig. 4 -- Plots of r vs. θ for the last four turns of the two unstable orbits (depicted in Fig. 3) showing growth in turn separation at $\theta = 112^{\circ}$, the channel entrance. The regenerator shims lie within an area from $\theta = 162^{\circ}$ to 198° and from r = 19.25 to 21.5 in.

Figure 4 shows plots of r vs. θ between $\theta = 25^{\circ}$ and 205° corresponding to the last four turns of the two radially unstable orbits depicted in Fig. 3. These plots (and those in Fig. 3) have been terminated before the vertical motion becomes seriously unstable. In addition to showing the characteristic "node" near $\theta = 50^{\circ}$, these r vs. θ plots indicate that a radius-gain per turn of about 0.5 in. can be achieved near $\theta = 112^{\circ}$ where the channel septum would be inserted.

An examination of data like that in Fig. 4 for a range of energies indicates that the channel septum should be located at $r = 19.65 \pm 0.05$ in. Assuming that the channel aperture is 0.5 in. wide, the outer wall of this element would occupy 20.25 ± 0.05 in. For all of the orbits described below, it is assumed that the protons enter the channel when the r value of their orbits lies within these limits at $\theta = 112^{\circ}$, and this part of our extraction study stops at that point.

3. Vertical Motion

The impact of the vertical motion on the extraction process is investigated using the Z[4] Orbit Code which is based on exact equations of motion and magnetic field components that are correct to fourth order in z.[4] In addition to a given starting value for (r, p_r) at each energy investigated, the initial conditions consist of eight (z, p_z) points uniformly spaced around an eigenellipse having a given maximum height Δz_o. Actually, as a result of median plane symmetry, only four distinct (z, p_z) values are required.

Because of the shrinking stability region, protons with large orbit-center displacements begin extraction at lower energies than those with small displacements. The lower energy extraction orbits therefore suffer the largest growth in vertical height as a result of the coupling action. This is shown in Fig. 5 where the height Δz is plotted as a function of turn number for four different energies from 252.0 to 253.5 MeV. In each case, $\Delta z_o = 0.1$ in., a relatively small value, and the initial (r, p_r) point was chosen so that the protons reach the channel entrance in about 24 turns.

As can be seen, the maximum Δz value increases by a factor ranging from 3.4 at 252.0 MeV down to 1.3 at 253.5 MeV. Moreover, as Δz_o increases, the resultant growth factor at each energy also appears to increase, although the relevant orbit data become complicated because of other phenomena involving the radial motion.

Indeed, we find that the concurrent coupling of the vertical into the radial motion decreases the strength of the regenerator, and this weakening grows rapidly with increasing vertical amplitude. The net effect for a given (r, p_r) value is to increase the number of turns required to reach the channel entrance. Moreover, this increase in turn number is a complicated (seemingly discontinuous) function of both the phase and amplitude of the vertical oscillations. Such behavior is, of course, a consequence of the nonlinearities.

To show how this develops, we first note that the data on which Fig. 5 is based reveal that all of the orbits for 253.5 MeV enter the channel on turn 24. On the other hand, those for 252.0 MeV require between 22 and 28 turns although only 21 turns are required when $z = p_z = 0$. The corresponding data for 252.5 and

253.0 MeV show a smooth transition between these two cases.

The situation becomes much more complicated when Δz_o is increased from 0.1 in. to 0.2 in., assuming the same initial (r,p_r) values. For 253.5 MeV, the Δz growth factor increases slightly from 1.3 to 1.5, while the number of turns increases from 24 to 26-28. For 253.0 MeV, however, the growth factor is undefined since the turn numbers for the four orbits change (from 24-25) to a dispersed set: 26, 32, 74, and an undetermined number (>500). This type of behavior also occurs at 252.5 and 252.0 MeV.

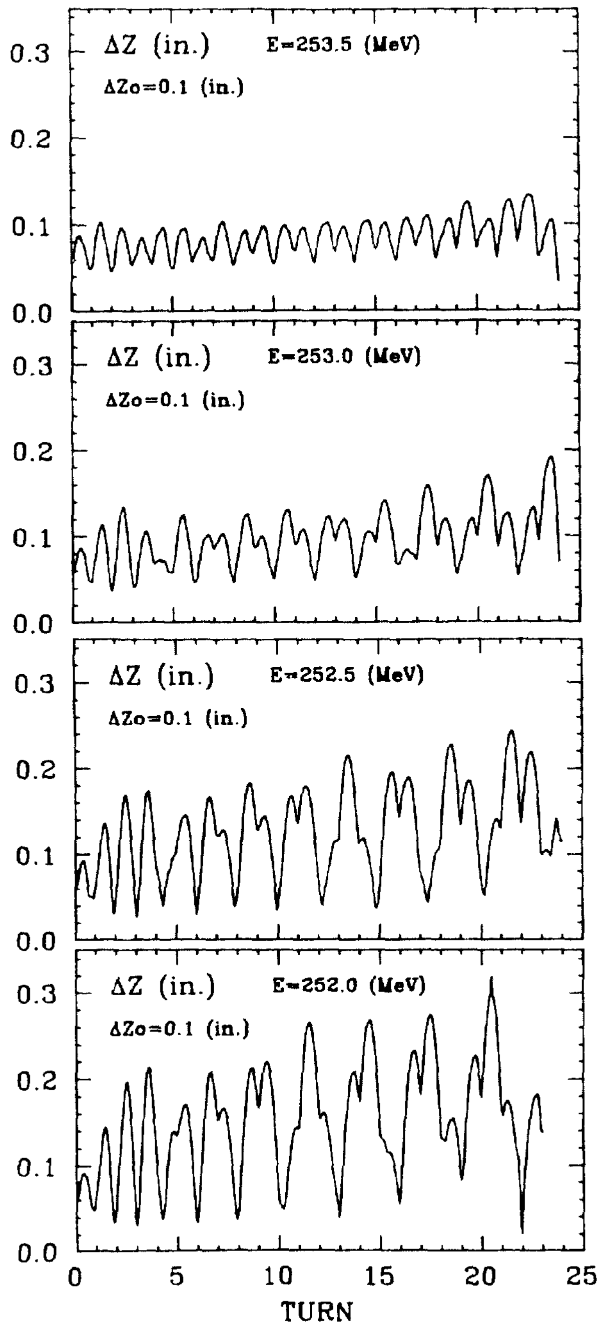

Fig. 5 -- Plots of height Δz vs. turn number for a group of orbits having an initial height Δz_o = 0.1 in. and energies from 252.0 MeV (bottom) to 253.5 MeV (top). All orbits run for about 24 turns to reach the channel entrance.

What happens here is that some of the orbits do not proceed directly to extraction, but instead return to the stability region where they execute one or more precession cycles before exiting again. When the value of Δz_o is increased still further, this behavior becomes very prevalent and corresponds, in effect, to a growth in the stability region.

We should note that the damping factor $(B\nu_z)^{-1/2}$ will cause the beam height to shrink by a factor of two between r = 1.0 in. and r = 18 in. Assuming the beam fills the vertical aperture in the central region, some beam loss will therefore occur whenever the growth factor for Δz (described above) exceeds about two. As indicated by our data thus far, severe beam loss will occur for the part of the beam that begins extraction below about 252 MeV, while only a small loss will occur for the part above 253 MeV. As a result, the energy spread within the extracted beam should be about 1.5 MeV.

Our results also suggest that it might be advantageous to purposely restrict the beam height in the central region since even though this would reduce the current reaching the regenerator, it would also reduce the machine activation due to vertical blow-up, *and might even improve the net extraction efficiency* to the point where the loss in extracted current would *not be significant*.

References

*Work supported by the National Science Foundation under Grant NO. PHY-86-11210.

1. G. Calame, et.al., Nucl. Instr. and Meth. 1(1957) 169.
2. M.M. Gordon and V. Taivassalo, Nucl. Instr. and Meth. A247(1986)423.