CONCEPTUAL DESIGN OF A HIGH FIELD ULTRA-COMPACT CYCLOTRON FOR NUCLEAR PHYSICS RESEARCH

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Abstract

We have studied the feasibility of using an existing wide-bore 8 T magnet as a component of an ultra-high-field cyclotron. Such a machine would use the highest magnetic field of any cyclotron to date, viz. 7.6 T averaged azimuthally with 8.5 T in the hills. The K95 `Eight Tesla Cyclotron' would have roughly the same magnetic rigidity (Bρ) as the Oak Ridge Isochronous Cyclotron in a package of only one fourth the radius, with a corresponding reduction in cost. Such a cyclotron could accelerate particles with a charge state Q/A = 1/4 to a final energy of 5 to 6 MeV/nucleon, the energy range currently being used to study superdeformed, high angular momentum nuclei that result from glancing collisions. Studies have stressed achieving sufficient vertical focusing (ν_z) despite the high magnetic field level, and finding a central region geometry that fits comfortably in the limited space available while providing centering and early-turn focusing properties that are similar to those of less compact machines.

1 INTRODUCTION

The Eight Tesla Cyclotron is conceived as a two stage project. The first stage of the project will be to build an internal beam cyclotron to accelerate He^+ from a PIG ion source to an internal beam stop. The design parameters for this stage are listed in Table 1. In this configuration the miniature cyclotron would demonstrate the ability of a high field magnet to provide adequate focusing to deliver a beam from the center of the machine to the extraction radius, and the current available for extraction could be measured. At a later time the accelerator could be converted from a test stand to a nuclear physics tool by replacing the internal ion source with an axial injection system and installing an extraction system. The cyclotron would then accelerate heavy ion beams of any species capable of producing a charge state near Q/A = 1/4.

2 THE MAGNETIC FIELD

The Eight Tesla Magnet has been in operation with flat poletips since 1994[1]. The magnet excitation reported in Table 1 was chosen because this is the highest current at which the magnet has operated reliably to date. Further development work on the magnet should make it possible to raise the average field with sectored pole tips to 7.8 T. This would place the RF frequency comfortably inside the FM band, allowing us to use a commercially available transmitter intended for FM radio stations, rather than a more expensive custom built transmitter.

Table 1. Internal beam cyclotron parameters

ORBIT PARAMETERS	
Charge state	0.250
Final energy	5.93 MeV
Final radius	18.9 cm
Turn number	178
MAGNET	
Magnet bending limit	95 MeV
Rigidity	1.42 Tm
Ampere-turns	3.1×10^6
Central magnetic field	7.58 T
Maximum hill field	8.47 T
Minimum valley field	6.75 T
Iron weight	8 tons
Pole radius	19.9 cm
Hill gap	2.54 cm
Valley gap	29.8 cm
Sector number	3
Sector spiral	7.46^{o}/cm
Sector width at max radius	62.1^{o}
RF SYSTEM	
Harmonic number	3
RF frequency	87.1 MHz
Peak dee voltage	28.5 kV

The poletips are small enough that we plan to machine sectors out of a single piece of iron for each pole. The equilibrium orbit properties for the calculated magnetic field are shown in Fig. 1. The iron in the pole tips is saturated, so raising the overall field level $<B>$ has little effect on the third harmonic component, B_3. Our B_3 peaks at 8 kG which is almost identical to the case for the 4.6 T Harper medical cyclotron. Flutter focusing depends on the ratio of $B_3/<B>$, so the higher the field, the smaller the contribution of flutter focusing to the total ν_z. Although ν_z is sufficient at middle energies, it rises slowly near the center so that the central focusing cone and electrostatic focusing are more important to the early turns in the high field machine than in its low field predecessors.

In this design it was necessary to incorporate iron into the ion source in order to shape the central field cone. Otherwise the poletip design is very similar to the three previous superconducting cyclotrons built at the NSCL. Because this is a fixed energy single charge state machine we may accomplish all needed field shaping with hill and valley shims so no trim coils are needed.

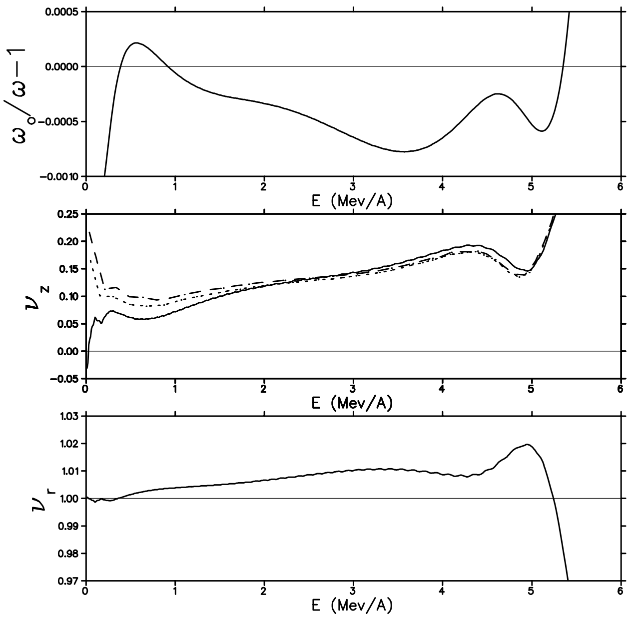

Fig. 1: Equilibrium orbit properties as a function of energy. Top: orbital frequency relative to isochronous frequency. Middle and Bottom: axial and radial focusing frequencies calculated by the E.O. code. Also plotted are the total axial focusing frequencies for accelerated orbits leaving the ion source at RF times τ_o = 207°(dashed line) and 201°(dotted line.) Peak dee voltage occurs at τ= 270°.

3 THE CENTRAL REGION

The central region was initially scaled from that of the Harper medical cyclotron[2] using the Reiser formula[3], which describes the geometrical enlargement or reduction of ion orbits for changes of the magnetic field, charge-to-mass ratio, and dee voltage. The Harper geometry is reduced by a factor of 0.80.

Electric fields in the central region are computed by RELAX3D[4] and then orbits are tracked by the NSCL code, CYCLONE[5]. Initial conditions for orbit simulations were chosen by running a variety of orbits in the scaled central region. Particles that left the chimney at an RF time τ_o = 204° were found to be the best centered (relative to other starting times) and were presumed to best characterize the beam in the actual Harper cyclotron.

The scaled geometry was then modified to further optimize beam centering in preparation for extraction studies. The design was also improved in several ways to compensate for the magnetic focusing that is lost due to the higher field. The optimized central region layout can be seen in Fig. 2. The first accelerating gap (from the chimney to the field free region at the center of the puller) has been shifted 4^{o} clockwise by the orbit code to simulate lengthening the puller gap in order to shift all phases in the positive direction. Fig. 3 shows the average phase per turn calculated from the time that a particle arrives at the electrical center of each gap.

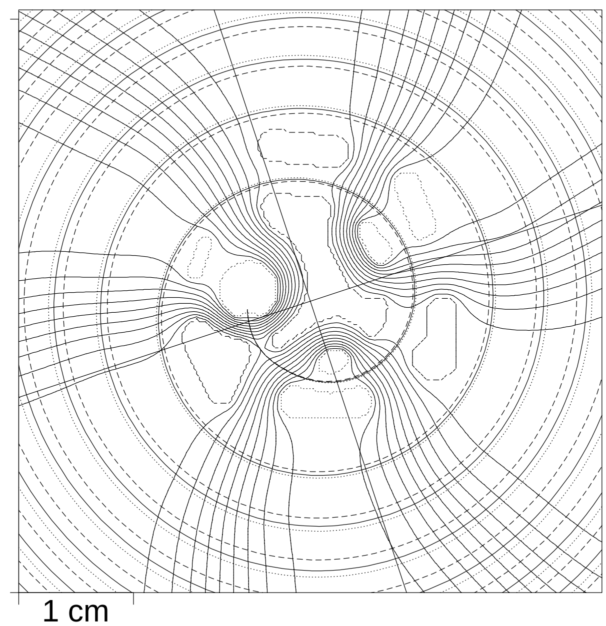

Fig. 2: Central region equipotential field map, and the first few orbits for beam leaving the ion source at RF times τ_o = 201°, (dotted line) 204°, (solid line) and 207° (dashed line).

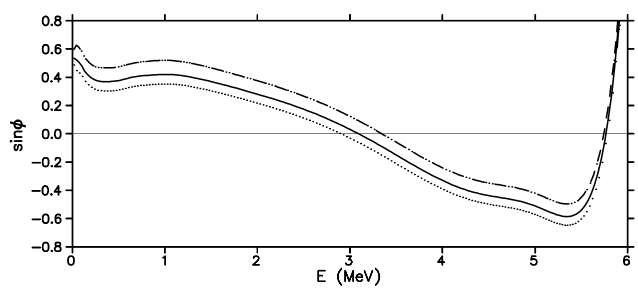

Fig. 3: Turn average phase for the three orbits of Fig. 2.

The first gap position and cone field size have been chosen to keep the average phase near +30° for the first 1 MeV of acceleration (about 30 turns) in order to maximize electrostatic axial focusing in the region where the magnetic contribution to ν_z is below 0.1. The total focusing plotted in Fig. 1 is measured from half cycles of vertical oscillations of a ray that is displaced 2 mm vertically at the puller and then accelerated to full energy.

Axial confinement was investigated for starting times from τ_o = 201°-207°. The maximum displacements in axial position and momentum (at the puller) which remain within the beam aperture approximate an ellipse corresponding to a total (normalized) acceptance of 1.0π mm-mrad for the range of starting times studied.

Similar studies of orbits that are displaced radially at the puller indicate a normalized radial acceptance of at least 0.15π mm-mrad for the same range of starting times.

4 FEASIBILITY OF AXIAL INJECTION

In order to produce heavy ion beams the cyclotron would need an external ion source and an axial injection system. A spiral inflector geometry can be scaled from the design used in the K500 and K1200 cyclotrons[6] by holding the tilt parameter k′ constant[7]. The height and width of the inflector are inversely proportional to the magnetic field, so the scaled inflector is 0.81 cm tall and 1.25 cm in diameter. If a new central region were scaled from the K1200[8] the resulting first turn diameter would be 2.5 cm. The scaled inflector is too large to perfectly match the scaled central region, but the discrepancy is only 15% so the needed adjustments should be minor.

The electric field in the inflector gap increases in proportion to the magnetic field. The scaled inflector would have a 2 mm gap with a 24 kV/cm electric field, which is comfortably within the operating range of such devices.

The primary difficulty appears to be machining and properly positioning the miniature inflector electrodes. More detailed studies may be necessary to investigate increasing the gap height and the corresponding electrode voltage.

5 FEASIBILITY OF EXTRACTION

We plan a resonant extraction system where the first harmonic field perturbation is produced by a set of iron rods (1" in diameter) similar to the Chalk River trim rods[9]. The rods eliminate all space and cooling issues associated with trim coils and they can be centered at the radius where ν_r = 1, so that only a small displacement is needed to produce a sufficient first harmonic.

The turn separation produced by a 5 gauss field perturbation can be seen in Fig. 4. Here the τ_o = 204° central ray from the internal ion source central region has been tracked from the ion source to the likely position of an electrostatic extraction channel. The septum would be located near a radius of 18.5 cm. A phase space is defined by eight rays displaced from the central ray at the puller to form a 1 mm diameter circle. Each of the eight rays' starting phase has been adjusted so that its energy gain is similar to that of the central ray. The first harmonic perturbation causes little distortion of the phase space while providing a turn-center to turn-center separation of 2 mm.

The low first harmonic used for the initial off centering helps to minimize the axial expansion of the beam which occurs at the $\nu_r = 2\nu_z$ resonance roughly ten turns after the ν_r = 1 resonance. A beam which fills the 7.5 mm puller aperture has a height of roughly 5 mm at the entrance to the electrostatic deflector.

From this point a pair of 56° long electrostatic deflectors in successive hills, followed by a 64° electrostatic deflector located behind a dee, can extract the beam with an electric field of 130 kV/cm in a gap 2.5-3.5 mm wide, which is within the range of electric fields used successfully at the NSCL[10].

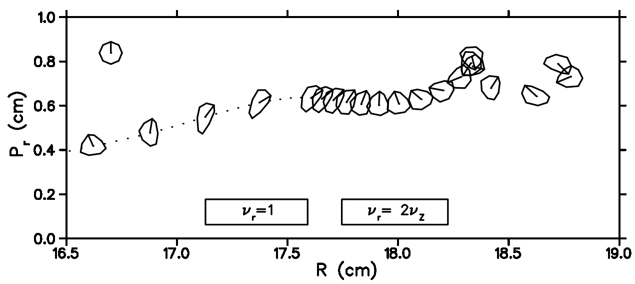

Fig. 4: Radial phase space behavior of a family of accelerated rays plotted at the azimuth of the electrostatic deflector entrance. The shape of the initial phase space (at the puller) relative to the central ray is indicated at the upper left. Radial momentum p_r is divided by $\omega_o m$ to yield units in cm.

6 CONCLUSION

The miniaturization of cyclotron components for an 8 T magnetic field poses no critical problems for the energy and charge-to-mass ratio studied. Such a machine would be a natural extension of the development work already performed for super-conducting cyclotrons.

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