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NEW MAGNET POLE SHAPE FOR ISOCHRONOUS CYCLOTRONS*

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ABSTRACT

A new design has been developed for shaping pole tips to produce the radially increasing fields required for isochronous cyclotrons. The conventional solid hill poles are replaced by poles mounted over a small secondary gap which tapers radially from maximum at the magnet edge to zero near the center. Field measurements with a model magnet and calculations with the code TRIM show an increase in field at the edge of the magnet without the usual corresponding large increase in fringing, and a radial field shape more nearly field independent than for conventional hills. The "flying hills" have several advantages for variable energy multiparticle cyclotrons: (1) a large reduction in the power dissipated by isochronizing trim coils, (2) a more constant shape and magnitude flutter factor, eliminating flutter coils and increasing the operating range, and (3) a sharper fall-off of the fringe field, simplifying beam extraction.

INTRODUCTION

The pole tips of a variable energy, multiparticle isochronous cyclotron can be shaped to provide a fixed isochronism and flutter at a specified central field. For this fixed pole tip design, the isochronism correction and the flutter will increase rapidly as the central field is decreased, and the required shapes must be obtained with various types of field trimming coils. It is desirable to minimize the demands on trim coils by stabilizing the shape of the main field against changes in central field for at least two reasons: (1) The power dissipation of these coils is large since they must be thin enough to be placed in the magnet gap. (2) If many coils are required, adjusting the field can be a difficult procedure. Since the permeability of iron decreases rapidly with increasing field, average trim coil power is minimized if the pole tips are shaped to provide at least half of the required isochronism and flutter at the highest operating field. For this design the required range of isochronism is $1.00 < \gamma < 1.16$. A desirable pole tip configuration must therefore produce a radially increasing field at the highest central field which changes relatively little as the central field is decreased. Various techniques have been proposed or implemented which exploit saturation effects to produce such stable fields.[2,3]

FIELD MEASUREMENTS

A model magnet with an 18" diameter pole (1/11 scale of the SREL pole) has been used to determine pole tip designs which provide stable flutter, minimum trim power consumption, and desirable edge fields for extraction. The radial profile of the magnetic field produced by constant gap hills and valleys is quite stable against changes in central field, but is at best radially flat, and at high fields decreases radially with a roughly parabolic shape[3] as a simple equipotential model predicts.[4] To produce a radially increasing field, it is possible to taper the hills and/or valleys to reduce the main gap at the edge. Wedge-shaped hills of this type provide the full equipotential rise only at low central fields; at high fields they saturate, fringing increases, and the field shape becomes radially decreasing. The measured ratio of fields from the center to the edge as a function of model magnet current is shown in Figure 1

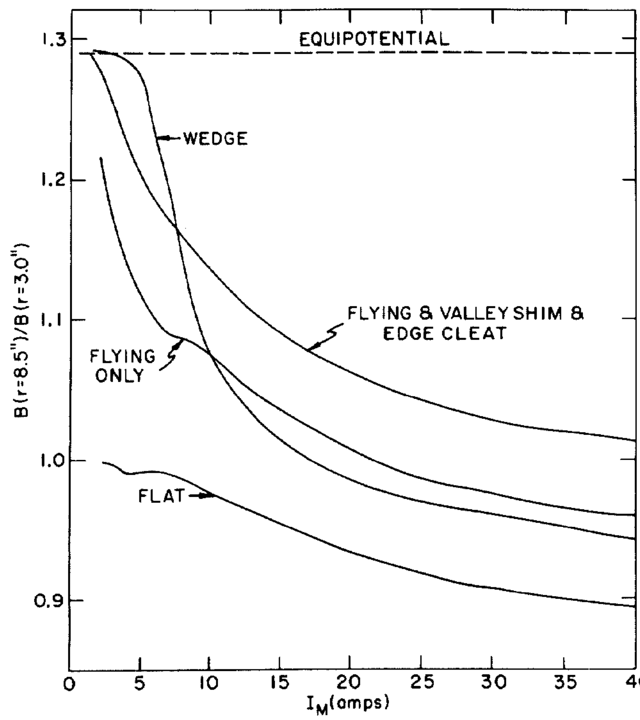

Figure 1. Measured ratio of magnetic field from 8.5" to 3.0" radius versus model main coil currents for four hill geometries. Curve B_z in Figure 4 gives excitation curve for model.

for flat and wedge-shaped hills. At low excitation (below 10 kG) the front surfaces of these two hill geomtries become equipotentials. At higher excitation (above 5 amps in Figure 1), the hills begin to saturate, edge fringing increases, and the field begins to fall well inside the magnet.

A new geometry for pole tips has been found which provides radially increasing fields that are much more stable than wedge hills. A cross section of a pole tip design incorporating these new "flying hills" is shown in Figure 2. The hills are attached to the root only near the center of the magnet. A gap

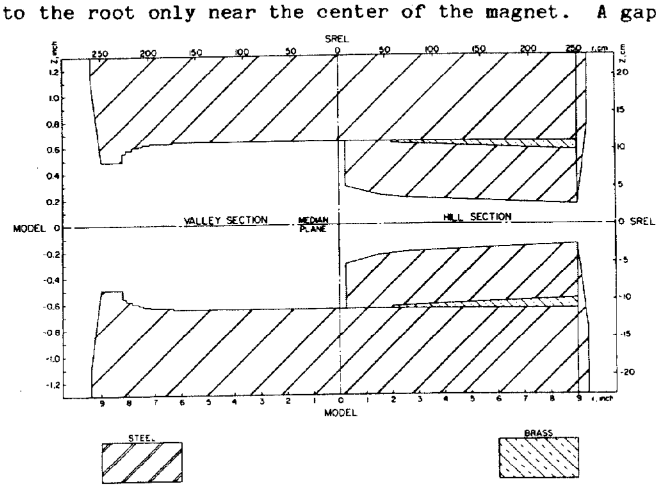

Figure 2. Cross section of pole tip design incorporating flying hills.

of radially increasing thickness separates the rest of the hill from the root. The thickness of the hill iron is constant except at small radii. The radial profile of the field for the flying hills varies much less with excitation than that of an equivalent wedge hill (hills of Figure 2 with the brass replaced with iron). The variation in the radial profile shown in Figure 1 for the flying hills is about 30% that for the wedge over the useful range (7 to 18 kG average field). At high fields (above 18 kG in the hills) the edge field is actually higher for the flying hill than for the wedge hill and as the excitation is decreased, the flying hill does not reach the equipotential limit until much smaller fields (about 2 kG). The increased edge field at high excitation is accompanied by decreased fringing of the field, as is indicated by the normalized radial contours of the field in Figure 3. This sharper magnetic edge has eased the extraction problem, so that a single electrostatic deflector should provide beam extraction in a fraction of a turn.[5]

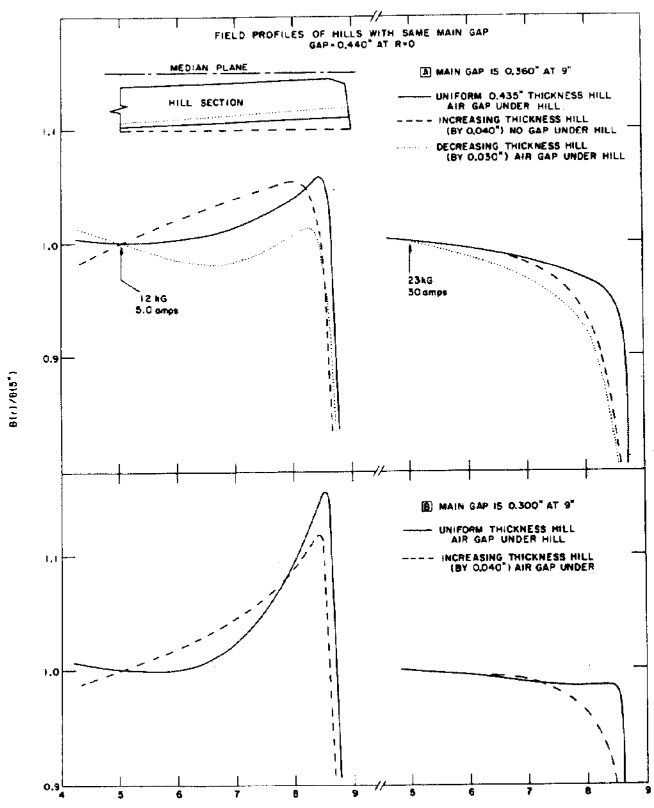

Figure 3. Radial profile of hill fields normalized to field at 5". Solid line is for flying hills.

Some understanding of the mode of operation of the flying hills has been obtained by measurements of the field components in the hill and by calculations with the computer code TRIM.[6] Coils would around the hill slab with their axis directed radially, and small coils under and over the hills with their axes oriented vertically were used with a voltage integrator to deduce the radial and axial components within the hill. Figure 4 shows the measured components of the field in the radial (B_r) and axial (B_z) directions. The field in the main gap is very nearly equal to B_z in the hill. At low excitation the radial component is very large, and field lines point along the hill slab: the hill forms a path of low

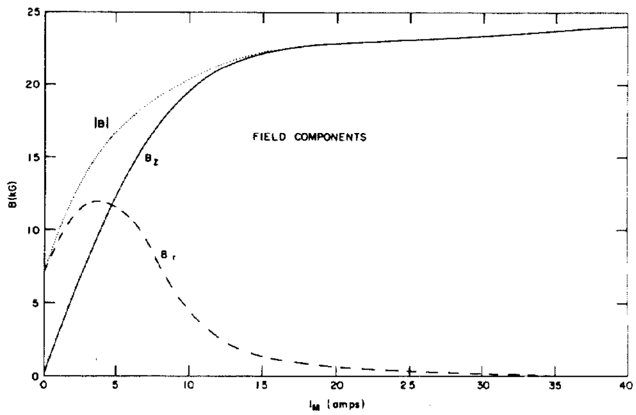

Figure 4. Radial and axial components and magnitude of magnetic field in the flying hill versus model main coil current.

magnetic reluctance from the center of the magnet to the edge. This "channeling" of flux through the hill causes the magnitude of the field (the curve B in Figure 4) to be much larger than that in a solid wedge hill, especially at lower excitation. This reduces the permeability of the flying hill relative to that for a solid hill at low excitation, and prevents the flying hill from reaching the equipotential limit until very low fields. Over the useful range of excitation the flying hill operates within a much narrower range of permeability than the wedge hill, which leads to the increased stability. Even at higher excitation (21 kG) the radial component persists, moving flux from the center toward the edge of the magnet. This redistribution of flux is clearly shown by the TRIM calculation in Figure 5. It is clear that the field lines within the root are diverted toward the center of the magnet, even relativey near the edge of the pole. This reduces the fringeing of field lines at the magnet edge and produces the sharper fall-off in field outside the pole, as indicated in Figure 3. Thus the distinction of the flying hill is that it produces stable edge-peaked fields.

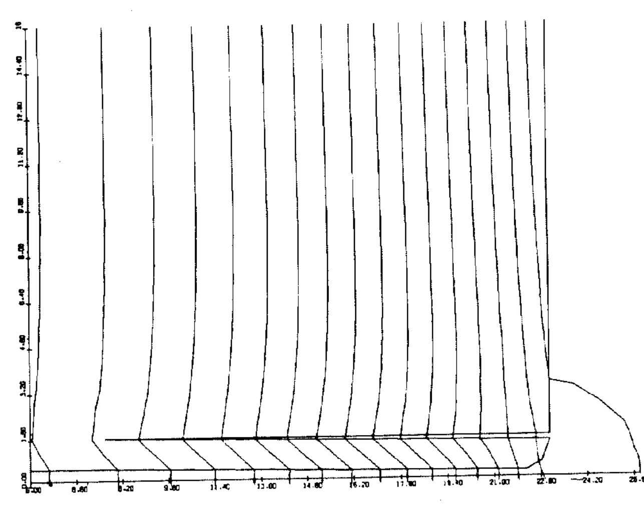

Figure 5. Magnetic field lines for pole and flying hill calculated with code TRIM.

The greater stability of the field shape for the flying hills results in a more nearly constant flutter factor compared to wedge hills. Below about 20 kG in the hills the permeability in the wedge begins to increase rapidly and the flutter rises sharply from 0.1 to 0.33. In contrast, the flying hills show a much more gradual charge in flutter, from 0.09 to 0.24, similar to that for flat hills. The more nearly constant flutter simplifies the design of the spiral shape [5] and eliminates the need for special coils to alter the flutter for different beams and energies.

POLE DESIGN

The flying hills have been incorporated into a pole tip design[7] (Figure 2) for converting the SREL synchrocyclotron into a variable energy heavy ion isochronous cyclotron. Two additional features have been added to help reduce the trim coil power consumption. The valleys have been shimmed near the edge to reduce the main gap to contribute to the desired isochronous shape. Since the valley field is always relatively low the iron in the poles remains linear, and the contribution to the average radial field shape from the valleys is stable. Unfortunately, the valley shims reduce the flutter, especially at high fields, and so only a limited amount of isochronism can be obtained by shimming the valleys. In addition, the radius of the pole in the hill sectors has been extended by adding "cleats" of iron to the pole tip edge along the hills. These cleats also increase the edge peaking of the field and cause the field to fall more rapidly just outside the magnet edge.

In order to provide realistic isochronized fields and to estmate power dissipation for the proposed cyclotron, measurements of fields produced by centered, circular trim coils have been made with the model magnet. Simple magnetic circuit calculations for the model and SREL magnets have been used to scale the measured trim coil fields to the full size magnet. A computer code was used to solve by iteration for the flux in each element which produced permeabilities, evaluated at the local H, consistent with the measured magnetization curves for the iron of the model and SREL magnets. The fringing and leakage reluctances were adjusted to fit measured excitation curves for the model and SREL magnets. A linear least squares procedure was used to adjust the trim currents to obtain a best fit of the measured main and trim field to the desired isochronous field. Twenty-seven trim coils are sufficient to provide isochronization to $\pm 5^{\circ}$ of phase slip for a 150 MeV/amu ^{16}O beam.

Main coil power was estimated by using the resistive model for the SREL magnet to scale from the computed fields to measurements of power vs. main field for the SREL synchrocyclotron.[8] Trim coil power was calculated using computed trim currents and assuming trim coils 4.0 cm high, 50% of which is copper. A computer code was used to search for minimum total power dissipation by varying the main coil current. The maximum main coil power over the operating range is about 240 kw.

Trim coil power dissipation has been computed for several different hill geometries. The trim power at maximum design energy as a function of ion mass is shown in Figure 6 for flat, wedge and flying hills alone and for flying hills with the edge shims and

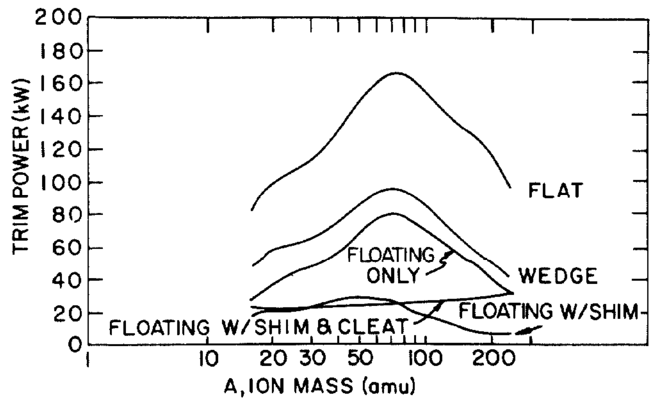

Figure 6. Trim power dissipation versus ion mass for maximum energy ions for several pole geometries. Typical maximum design energies are 150 MeV/amu ^{16}O, 100 MeV/amu ^{60}Ni, and 16 MeV/amu ^{238}U; see Reference 7 for the complete operating range of the proposed cyclotron.

cleats of Figure 2. The fields have been isochronized to 242 cm for these calculations. The use of the flying hill leads to lower trim coil dissipation than the corresponding wedge, and the addition of the valley shims makes a further substantial reduction. For fields which isochronized only to 242 cm the power dissipation is increased somewhat for high mass ions by adding an edge cleat around the hills. This is because the cleat increases the edge peaking even at high fields, and for the high mass beams, which require high fields but small isochronous corrections, the trim coils must reduce the field at the magnet edge. However, the edge cleats were added to permit the field to be isochronized to 245 cm and to improve the extraction characteristics.

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