Abstract—A flux-coupled stack of 800 MeV isochronous cyclotrons is being designed as a basis for accelerator-driven thorium-cycle fission power. The sector magnet consists of a stack of independently suspended cold-iron cores (each with its superconducting coil closely coupled), and a warm-iron flux return that contains and supports the stack of cores. This design makes it feasible to provide multiple independent cyclotrons within a common, compact structure.

Index Terms—superconducting dipole, cyclotron, nuclear fission, accelerator.

I. INTRODUCTION

The idea of accelerator-driven transmutation has a long and distinguished pedigree. In 1950 E. O. Lawrence first proposed to transmute thorium into $^{233}\text{U}$ and then induce fission using fast neutrons from spallation of a high-energy proton beam [1]. In 1993 C. Rubbia revived the idea and showed that an accelerator could directly drive a subcritical power reactor, and that the neutron spectrum from a lead moderator would sweep the capture resonances of transuranic isotopes and consume long-lived wastes [2].

Three difficulties have remained in developing a realistic embodiment of these concepts:

• A GW reactor with neutron gain $k \sim 0.98$ requires $\sim 15$ MW of $\sim 1$ GeV proton beam; such beam power has never been achieved.

• Accelerator systems typically lack the reliability that would be needed for power plant operation.

• In a coaxial drive geometry the absorption of neutrons by fission fragments causes a problematic variation of neutron gain $k$ during burn-up.

We have addressed all three difficulties by designing a flux-coupled isochronous cyclotron stack to provide a pattern of 7 drive beams [3]. An overview of the multi-beam driven thorium core and the neutronics in the reactor has been presented in a previous paper [4]. The present paper describes the design of the superconducting sector magnets for the 800 MeV isochronous cyclotron.

II. ISOCRONOUS CYCLOTRON DESIGN

We are developing a design for a flux-coupled stack of seven 800 MeV isochronous cyclotrons. Fig. 1 shows an overview of the isochronous cyclotron stack. The parameters of each cyclotron are summarized in Table I. The beam current is limited to 2 mA, which is consistent with space charge limits and is currently achieved routinely at the PSI cyclotron [5]. Each sector consists of a stack of pole pieces that produce the required field distribution for the cyclotron apertures. The stack of pole pieces is supported within a warm-iron flux return by means of low-heat-load tension supports. This approach follows closely the design of the ring cyclotron at RIKEN [6].
III. SECTOR MAGNETS

A. Magnetic Design

Each sector magnet must provide a dipole field integral Bρ(r) that scales with relativistic γ (to maintain isochronicity), fringe-field focusing to control betatron tune, and curvature to adjust the sharing of tune between horizontal and vertical motion. The sector design that optimizes these several conditions is shown in Fig. 2. It consists of a stack of 10 cold poles suspended within a common warm-iron flux return. The central 8 poles form 7 apertures that are used for cyclotrons. The outermost two poles are sacrificial: they serve to smooth the transition of field at the top and bottom of the stack so that out-of-plane field components can be suppressed in the 7 cyclotron apertures so that closed-orbit corrections are modest.

B. Cyclotron Performance

The cyclotron performance can be characterized by the variation over the acceleration range of horizontal and vertical tunes, departure of the revolution frequency from the reference value (32 MHz), and maximum deviations of the beam from reference closed orbit.

Fig. 3 shows the variation of tune over the acceleration cycle. Since the beam only stays in the cyclotron for ~200 cycles, the tune can pass through fractional resonances but must not pass through an integer resonance.

Fig. 4 shows the variation of revolution frequency from the reference value. A variation of ±0.1% is compatible with the design energy spread of the same amount.

C. Mechanical Design and Cryogenics

Each pole piece is constructed of a steel slab and a superconducting coil, as shown in Fig. 6. Table II summarizes the geometry and coil assembly on the each pole piece. The slab is contoured to produce the desired variation of Bρ from injection to extraction. The coil is constructed from NbTi cable, heavily stabilized (10:1) with Cu. The coil is wound onto the pole piece and vacuum impregnated in place. The coil is supported within a stainless steel housing. The housing is welded to stainless steel tension skins lining both faces of the pole piece, so that the coil is supported against the pole piece suffi-
sufficiently to overcome in-plane Lorentz repulsion.

A clear gap of 10 cm is provided for the beam within each cyclotron aperture. The cyclotron will be operated ‘cold bore’ – there is no room to accommodate a room-temperature lining, nor indeed is there any need for one.

The pole pieces are contoured at their side boundaries to achieve two effects: null force and betatron tunes. We designed the pole geometry in the stack to null the vertical Lorentz forces on each pole piece. The residual vertical Lorentz forces are listed in Table II. There is a residual horizontal Lorentz force, acting towards the back leg of the warm iron flux return. A pattern of low-heat-load tension supports is sufficient to provide for support of the (vertical) gravitational load and the horizontal back plane force on the pole pieces.

The fringe field pattern at the boundaries between sectors produces a quadrupole field that vertically focuses the beam as it passes from one sector to the next. The field taper for isochronism provides a natural horizontal focusing. It was necessary to contour the pole face near the sector boundaries in order to attain focusing that did not cause the betatron tune to cross an integer resonance.

Fig. 7 shows the profile of the pole pieces through a \((z, \theta)\) cross-section. The pole face contours and the coil positions are shown. Note that it was necessary to use a 2-section coil on the top/bottom poles, in order to cancel the vertical asymmetry in \(B_z\) and thereby minimize closed orbit error.

D. Sacrificial pole pieces

The termination of the stack of pole pieces at the warm-iron flux return produces out-of-plane fields that would displace the median orbit and produce significant beam growth. We found it impossible to suppress these field components without perturbing the fringe field focusing of the neighboring cyclotron aperture. So we elected instead to add an additional sacrificial pole piece, for which the neighboring aperture is not used for a cyclotron, and design its coil and pole geometry to suppress out-of-plane fields in the 7 cyclotron apertures. Fig. 5 shows that this technique was successful.

IV. Conclusion

We have shown that one can deliver 15 MW of continuous proton beam at 800 MeV, within the limits of demonstrated accelerator performance, by stacking 7 flux-coupled isochronous cyclotrons within a common warm-iron flux circuit. The overall system is only ~20% larger than a single such cyclotron. The apertures are spaced 20 cm apart in the stack, which places significant constraints on the RF acceleration system. We have devised a novel RF structure for this purpose, which will be reported in a future paper. The injection and extraction systems actually benefit from this close stacking.

We have designed the accelerator systems so that only magnetic flux is shared among the 7 cyclotrons. All other systems are independent, so that if a subsystem fails on one cyclotron the other 6 continue operating. This redundancy should provide the operating reliability for a power reactor.

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