

A SUPERCONDUCTING ISOCHRONOUS CYCLOTRON STACK AS A DRIVER FOR A THORIUM-CYCLE POWER REACTOR*

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Abstract

Designs for thorium-cycle power reactors require a proton driver capable of 1 GeV energy and 10 MW total power. For this purpose we have prepared a preliminary design for the magnetic structure for a stack of 5 superconducting isochronous cyclotrons, each delivering 2 MW beam power. By achieving the required power with multiple independent apertures rather than pushing beyond currently achieved limits, we hope to arrive at a design that is cost-minimum and reliable.

Each sector magnet consists of a flux-coupled stack of cold-iron inserts supported within a single warm-iron, in a fashion inspired by the new Riken heavy-ion cyclotron. We have developed a preliminary field design in which in-plane fields are cancelled in all 5 apertures and the field-map is appropriate for the focusing optics of the sector cyclotron.

1 THORIUM-CYCLE POWER REACTOR

The concept of using thorium fuel for nuclear fission dates back 50 years. Until recently it was viewed as undesirable because it could not sustain a chain reaction, and because it required a neutron driver to transmute thorium up to U^{233} for fission. In the aftermath of Three Mile Island and Chernobyl it has been realized that these features are actually *benefits*: a TCPR cannot melt down, cannot make bomb-capable isotopes, and can be designed to consume its own waste (and more besides). Moreover thorium is plentiful; there are sufficient known reserves to power Earth's energy needs for the next millennium.

2 DRIVER REQUIREMENTS FOR TCPR

The neutron flux needed to transmute thorium can be provided by spallation of a high-energy proton beam on lead. Rubbia *et al.* [1] authored a conceptual design for a 1 GW TCPR which utilizes a 10 MW, 1 GeV proton driver. Since that time several authors have developed conceptual designs for accelerators that might meet this ambitious requirement: Alessi *et al.* [2] proposed a superconducting linac; Fietier *et al.* [3] and Stambach *et al.* [4] examined designs for high-power isochronous cyclotrons (IC). In both cases the 10 MW beam power places very ambitious demands upon the injection, acceleration dynamics, and extraction. To illustrate the reach that such performance represents, the current state of the art for ICs is the ring cyclotron at PSI [5], which

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produces 590 MeV with 1.8 mA beam current. No high-power superconducting linac for protons yet exists.

Reliability is of paramount importance for a proton driver for TCPR. In a reactor core (including that for TPCR) sudden interruptions in drive power can thermally shock the fuel rod assembly. If beam power were interrupted even for seconds, safety procedures would require that a scram be initiated, in which the entire complex is powered down, all systems are evaluated for proper function, and the system is powered up following a controlled procedure. A scram typically takes several days. Unscheduled interruptions place a major impact upon the electric supply grid. Typically it is required of power generation technologies that scrams do not occur more often than a few times per year. Such reliability is rare in accelerator systems.

3 THE FLUX-COUPLED IC STACK

Motivated by these considerations, we have developed a conceptual design of the magnetic structure for a flux-coupled *stack* of ICs. Since a single IC for GeV kinetic energy is a quite large system (~15 m diameter, 5 m high), we realized that one could provide for multiple independent IC's within a single flux circuit by bracketing multiple coil/pole piece subassemblies within a common flux return. The redundancy provided by such a stack of independent ICs would go far to address the requirement for reliability: if any one IC were to be lost (for example by an inflector arc), the core would continue receive 80% of its drive power – no scram would be initiated. If the outage were short term, the missing IC could be restored to operation without interruption. If a component were broken, the TCPR could continue in service at reduced power until a scheduled downtime could be arranged.

We were further motivated in stack concept by the

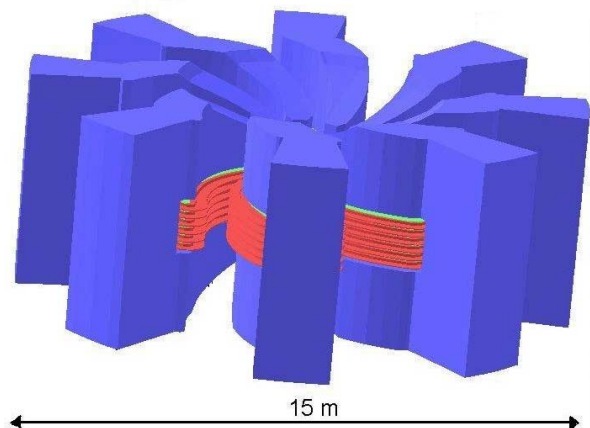


Figure 1: An 8-sector, 5-aperture flux-coupled IC stack.

design of the sector magnets for the Riken superconducting ring cyclotron[6]. In that design, each sector magnet consists of a pair of cryogenic subassemblies (superconducting coil supported on cold-iron pole piece) suspended within a warm-iron flux return yoke. The magnetics can be arranged so that the cryogenic subassemblies are approximately buoyant (forces in balance above and below), so that the supports of the subassemblies introduce only modest heat load.

We wished to first explore the specifically magnetic design issues before proceeding with a serious cyclotron design for a GeV machine. We therefore elected to take as a model the exact 8-sector structure of the PSI IC, and design a magnetic structure that would produce 2.5 Tesla in a stack of 5 flux-coupled apertures.

Figure 1 shows our conceptual design. The size of the warm iron yoke is gauged by the aggregate flux that must be returned; it is clearly seen that it changes only slightly to accommodate five apertures compared to one. The curvature of the sectors is that of PSI, wrong of course for the isochronous condition for 1 GeV, but adopted nevertheless for this first exploratory magnetic design.

Figure 2 shows a detail of a sector magnet. The 6 pole pieces are suspended within the warm-iron yoke using a pattern of low-loss tension supports. Each cyclotron aperture has an 8 cm hill gap. Each coil is held to its pole piece by stainless steel skins 1 cm thick extending across the full pole surface. The skins support the coil's outer shell under tension around its entire circumference. The pole pieces are rigidly coupled to one another by stainless steel spacers located at the inner and outer bounds.

The main coil on each pole piece is a square coil (10x10 cm²) of heavily Al-stabilized NbTi cable, operating with an average current density 30 A/mm² (1% of the short-sample current in NbTi strand). The fringe field is shaped using a correction coil comprising two thin flat coils (15x1 cm², 10x1 cm²) flanking the main coil as shown. The currents in the main coils and the correction coils are chosen to suppress in-plane field components that are produced by the symmetry breaking of the return yoke.

We calculated the field distributions in the sector magnets using Opera 3D v8.0 [7]. Figure 3 shows the field distribution of the bending field B_z as a function of azimuth θ along three reference arcs in each IC aperture: injection ($r = 1.75$ m), middle orbit ($r = 3$ m), and extraction ($r = 4.25$ m). The 3 curves shift due to the isochronous spiral. There is a modest reverse-field overshoot in the fringe region, but the quadrupole component is within the usual range for optimizing cyclotron orbit dynamics.

Table 1 gives the coil currents and the net magnetic force on each of the 3 pole pieces in the upper half of each sector magnet (the lower half is of course symmetric). The forces are all much less than the weight of the poles.

Figure 4 shows the calculated in-plane field distribution $B_x(\theta)$ along each reference orbit, with and without correctors. In the topmost IC aperture, in-plane fields

without correction would be ~ 0.1 T, sufficient to drive the beam out of the aperture in a few turns. With the corrections shown, we are able to suppress in-plane fields to < 50 G (this level is about the limit of validity of our calculations due to finite mesh size in the 3D geometry). Further reduction could be accomplished with trim coils or shims.

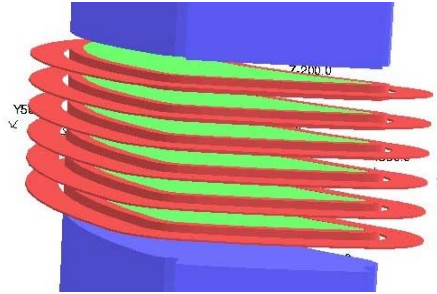


Figure 2: Detail of sector magnet, showing 6 pole piece subassemblies and superconducting coils.

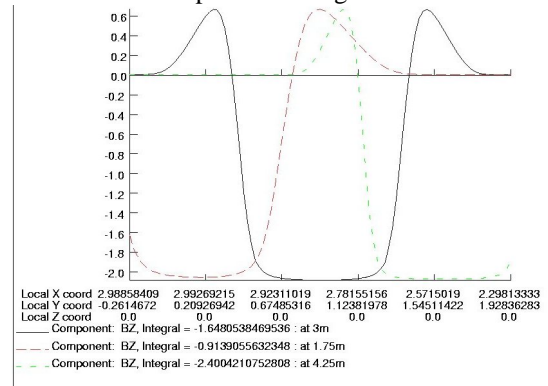


Figure 3: Calculated bending field distribution $B_z(\theta)$ along reference arcs in the sector magnets.

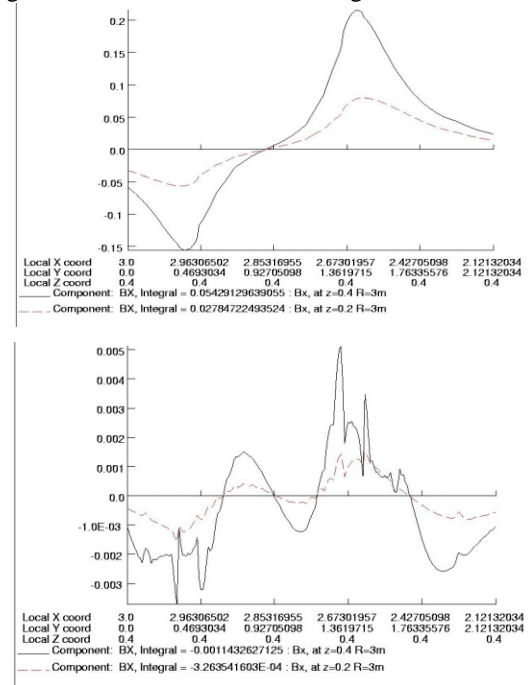


Figure 4: Calculated in-plane field distribution $B_x(\theta)$ along the middle reference arc in the two top apertures, a) without correction coils, b) with optimized correctors.

Table 2 gives the field integrals along the middle reference arc ($r = 3$ m) in each of the 3 upper apertures:

$$\frac{B_z \rho}{r} = \int B_z d\theta \text{ is the bending strength;}$$

$$\frac{G\rho}{r} = \int B_z' d\theta \text{ is the quadrupole strength (half-gap);}$$

$$\frac{B_x \rho}{r} = \int B_x d\theta \text{ is the out-of-plane deflection.}$$

Table 1: Coil currents in each pole piece of the top half of a sector magnet.

Pole piece	Main coil current (kA)	Trim 1 (A)	Trim 2 (A)	Net magnetic Force (kN)
1 (top)	300	58.5	43.9	36
2	300	58.5	43.9	25
3 (center)	300	58.5	43.9	8

Table 2: Field integrals along the middle reference arc in each of the top 3 apertures.

Aperture	$\int B_z d\theta$ (T)	$\int B_z' d\theta$ (T/m)	$\int B_x d\theta$ (mT)
Top	1.65	0.71	0.66
Next	1.65	0.71	0.20
Center	1.65	0.71	0

4 DESIGN CONSIDERATIONS FOR OVERALL IC AND TCPR

The present work was limited to establishing whether it was possible to design a flux-coupled stack of ICs using superconducting coils. From the point of view of magnetic requirements, it would seem that we have established at least a provisional *YES* to this question. The fringe field gradients are within range for appropriate beam dynamics, and the in-plane fields can be suppressed to very small levels. It remains to proceed to a design that has the appropriate curvature and field integral for acceleration to 1 GeV.

One attractive feature of a multi-cyclotron driver is that the protons could be delivered to the core in a distribution that could be optimized for the neutronics. This may prove important, because recent studies suggest that as fission products accumulate in the fuel rods during the life of a core, they absorb enough neutrons to degrade the further transmutation of remaining thorium so that fission yields decline. By tailoring the pattern of drive beams, it may be possible to reduce this parasitic effect.

It is appropriate at this juncture to discuss a few of the other important issues (RF cavities and extraction strategy) that also must be addressed to reach a real design for an IC driver stack. We will only frame a few issues in each case, as these designs are beyond the scope of the present paper.

We must drive the largest possible accelerating voltage in order to achieve good orbit separation in the ICs. For this reason much thought must go into how to maximize RF voltage, following the experience at PSI [8]. The superconducting correction coils that are needed to suppress in-plane fields and shape the gradient in the sector magnets extend ~ 20 cm out from the boundary of each side of each sector. This extension occupies a valuable fraction of the gap between sectors that is needed for RF. We note that it may prove advantageous to consider making each entire IC a *cold-bore* device, and operate the RF cavities at liquid nitrogen temperature to reduce ohmic losses in high-power operation. A cryogenic cavity could be integrated closely within the space between sectors, since insulation between 4 K and 77 K would be a minimal requirement.

Extraction is a major challenge with 2 MW beam power. It would be highly desirable to minimize losses to the greatest degree, most importantly to limit radiation damage to and activation of the accelerator components. It may be appropriate to consider designing the ring accelerator for H_2^+ , permitting efficient extraction after a stripping foil as discussed by Calabretta and Rifuggiato [9]. This of course would require twice the $B\rho$ in the sectors, and must be weighed carefully in overall design optimization.

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