

FLUX-COUPLED STACKING OF CYCLOTRONS FOR A HIGH-POWER ADS FISSION DRIVER*

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Abstract

The sector magnets for an isochronous cyclotron are configured as a flux-coupled stack of apertures, each forming an independent cyclotron, separated sufficiently to accommodate independent superconducting RF cavities. The stack strategy makes it possible to deliver any amount of proton beam power consistent with the limitations of each individual cyclotron, and to deliver the aggregate power to a number of spallation targets as dictated by optimum coupling for accelerator-driven subcritical (ADS) fission and by limitations in target transfer.

INTRODUCTION

A half century of nuclear power production has produced a substantial inventory of spent nuclear fuel (SNF), high level radioactive waste, for which no comprehensive secure long term disposal plan has been established. Currently US SNF inventory is about 65,000 metric tons and is growing at a rate ~2000 metric tons per year [1] due to the operation of 104 commercial nuclear power plants that make ~20% of the US electricity. SNF is primarily composed of uranium and transuranic (TRU) elements – plutonium and minor actinides (MA). All TRU elements are fissionable, but an actinide burner needs a fast neutron spectrum in order to prevent further breeding of MA. Critical systems loaded with pure TRU and high MA content were found to have potential safety problems due to the low fraction of delayed neutrons.

An accelerator driven subcritical (ADS) system provides a safe way to drive a pure-TRU core [2]. Fissions in an ADS system are sustained by spallation neutrons created by an energetic proton beam striking a neutron-rich target. A system of flux-coupled stacked isochronous cyclotrons, capable of accelerating protons to 800 MeV, is being developed as the driver for ADS fission in a molten salt core. The injection line will deliver protons with energy of 2.5 MeV to the TAMU100 cyclotron. TAMU100 accelerates the protons to 100 MeV and transfers them to TAMU800 which will accelerate the protons to their final energy of 800 MeV. The overview of the ADS driver is shown in Fig. 1. The design goal for each cyclotron is 10 mA current at 800 MeV = 8 MW CW. This power is beyond any spallation target design, so we propose to chop and split the beam from TAMU800 into three beams, each delivering 2.7 MW beam power. Spallation for the molten salt core is done by delivering the spread beam through a window that is immersed in the fuel salt within the core, so that the fluid flow for the heat exchanger of

* Work supported by the grants from the Mitchell Family Foundation and by State of Texas ASE Fund.

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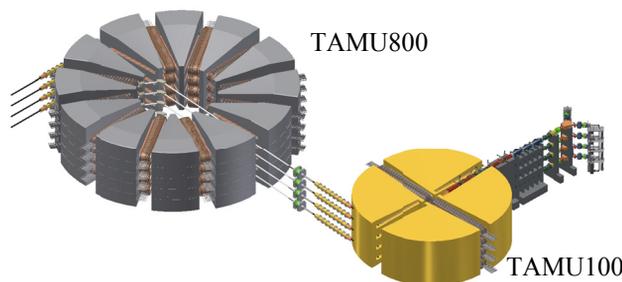


Figure 1: Accelerator system showing the four beam lines from injection through the booster and main cyclotrons.

the core is used to cool the target window. Preliminary simulations indicate that 2.7 MW should be a realistic parameter for that approach.

MAGNET DESIGN STRATEGY

In order to make room for the RF cavities and to operate in CW mode, TAMU100 and TAMU800 were both chosen to be isochronous separated-sector cyclotrons. To maximize the total beam current, both designs utilize a method for flux-coupled stacking of isochronous cyclotrons developed at the Accelerator Research Lab of Texas A&M University [3].

Sufficient orbit separation is needed to eliminate interactions among bunches on adjacent orbits and to minimize beam loss at injection and extraction. For this purpose we have developed a design for a strong-focusing cyclotron (SFC) [4] that incorporates four innovations. Superconducting quarter-wave cavities are used to provide >20 MV/turn acceleration [5]. The orbit separation is thereby opened so that bunches are completely isolated on successive orbits. Quadrupole focusing channels (QFC) are incorporated within the sectors so that alternating-gradient strong-focusing transport is maintained throughout. Dipole windings on the inner and outer orbits provide enhanced control for injection and extraction of bunches. Finally each sector magnet is configured as a flux-coupled stack of independent apertures, so that any desired number of independent cyclotrons can be integrated within a common footprint.

The size and number of sectors for the booster and main cyclotron were optimized from a cost/performance perspective. Since the quadrupole focusing channels [4] provide a strong-focusing FODO transport for all orbits, the sector dipoles can be configured as simple wedges (no spiral) which greatly accommodates efficient placement of rf cavities. The FODO transport allows us to lock the betatron tunes to a favorable working point from injection to extraction.

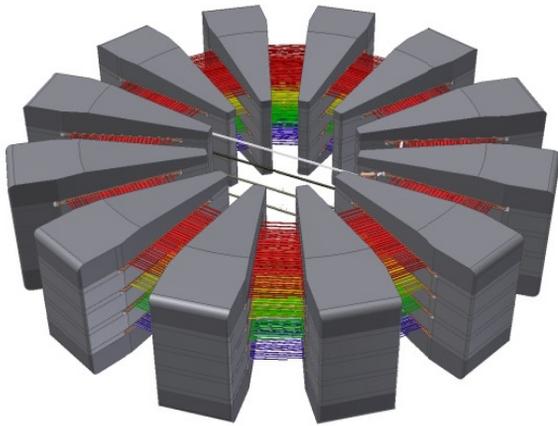


Figure 2: Layout of TAMU800 SFC.

Each QFC also has a dipole winding, which will be used for fine-control to maintain isochronicity on all orbits. On the injection and extraction orbits, the dipole winding will be made more robust and will provide a strong arc septum, integrated through succeeding sectors, which should improve low-loss injection and extraction.

Initial linear beam optics calculations set the vertical gap between pole faces to accommodate expected beam size at full energy, while the height of superconducting RF-cavities put constraints on the beam plane spacing between successive flux-coupled cyclotrons. To reduce the refrigerated cold mass we are following an idea based on the RIKEN ring cyclotron [6], where only pole pieces with coils are at cryogenic temperatures while flux returns are warm. Additional warm inserts between successive cyclotrons serve several purposes- they provide the necessary gap between beam planes, serve as a rigid support for suspended cold pole pieces, and provide proper coil mirroring to compensate the vertical forces between coils of each cyclotron. The use of superconducting RF-cavities requires proper shielding of the fringe fields. A set of simple L shaped brackets attached to the warm inserts can reduce the fringe fields to $<3 \mu\text{T}$. The residual fringe fields will be screened by a high μ material housing that encloses the RF-cavity [4].

Sector Magnet

Each sector consists of a flux-coupled stack of beam planes housed in one common warm iron return, as shown in Fig. 3. The number of stacked cyclotrons is defined by the total proton current needed to drive the ADS cores. Our current design of the ADS system requires 4 stacked cyclotrons each delivering a 10mA 800MeV proton beam. Fig. 3 shows a sector of the TAMU 800 with four stacks. In order to provide continuous focusing of the beam by strong focusing quads, gaps between sectors were minimized, leaving only enough space for RF-cavities and their mu-metal housing. Sectors are in the form of straight wedges with properly rounded corners and radial off set. The wedge angle is equal to $\frac{2\pi}{N}$, where N is a number of sectors in the cyclotron. Using wedge magnets allowed the main fields in both cyclotrons sector magnets to vary

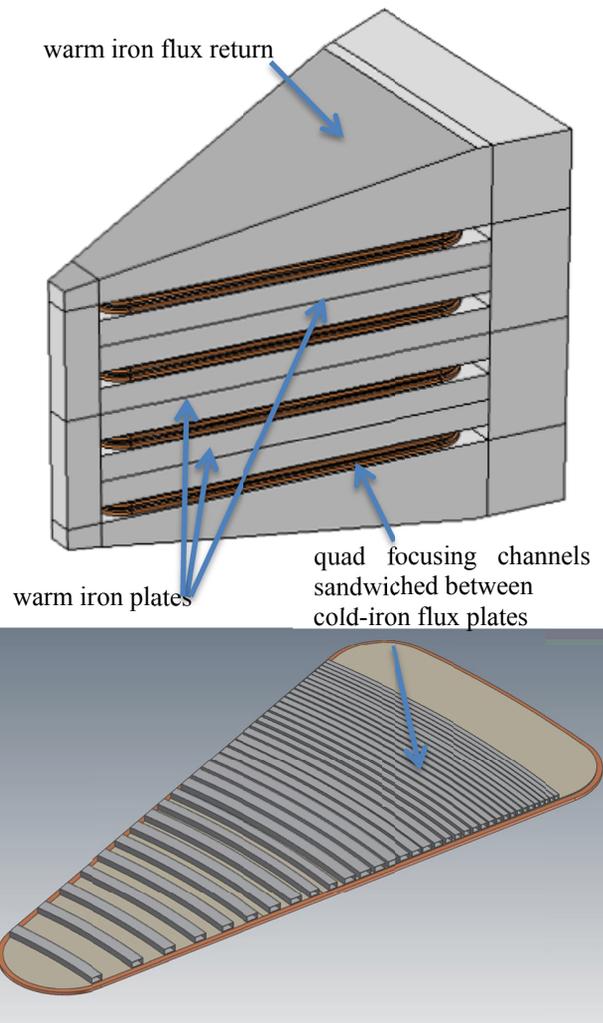


Figure 3: a) TAMU 800 sector containing apertures for 4 flux-coupled SFCs; b) detail view of one flux plate, showing the quad focusing channels and MgB_2 main winding.

little radially, $< 0.2\text{T}$, with the exception of the first few turns of the booster cyclotron. Two of the sector valleys will be reserved for injection, extraction and a possible 3rd harmonic cavity, leaving N-2 valleys for RF cavities. Table 1 summarizes the main magnet parameters for both TAMU100 and TAMU800.

Cold Pole Piece and Main Coils

Aside from serving pure magnetic purposes, the cold pole piece is a rigid mandrel onto which the superconducting coil will be wound and all supporting elements of main coils will be fastened. Although the sector magnets low field would allow the use of NbTi, recently emerged and commercially available MgB_2 with a higher critical temperature, 39 K [7], and sufficient engineering current densities $\sim 200 \text{ A/mm}^2$ at 1T [8] is a more attractive candidate for these coils. From a cryogenics point of view, it is also preferential to have the windings for the quadrupole focusing channels operating at the same temperature as the main dipole coils. For the SFC windings a wind/react fabrication is used.

Table 1: Magnet Parameters

	TAMU100	TAMU800
Injection energy	2.5 MeV	100 MeV
Extraction energy	100 MeV	800 MeV
Injection radius	0.66 m	3.8 m
Extraction radius	4.56 m	7.6 m
B (injection./extraction)	1.5/.37 T	.98/.93 T
Aperture between flux plates	7 cm	7 cm
# of sectors	4	12
# of RF cavities	2	10
Frequency	100 MHz	100 MHz
Harmonic	23	19
rf cavity azimuthal length	1.02 m	1.24 m
# of orbits	35	35

SIMULATION

Orbit separation and quad focusing channels require well-defined magnetic fields in the sector magnets. To achieve that goal, we used hard edge model for sector magnets to get fully analytical expressions for closed orbits. As a next step RF-cavities were added to determine design orbits, anticipated magnetic fields and injection parameters for each cyclotron. Feasibility of a strong quad focusing channels and range for available tunes over several energy ranges for given range of strength of quadrupoles was tested.

We started FEA modelling sector magnets for TAMU800 using COMSOL Multiphysics software [9]. Target operating currents for superconducting coils was determined. Currently we are in process of shaping the cold pole pieces to get design fields. Fig. 4 shows the radial dependence of dipole field that is required for isochronicity.

The magnetic design is currently being completed at the level required for the linear dynamics of transporting the beam through the SFC sequence. Thereafter we plan to use OPAL [10] developed at PSI specifically for cyclotron beam dynamics modelling, to simulate beam passage from injection to extraction with proper treatment of space charge effects and longitudinal dynamics.

The main dipole windings for TAMU800 each contain 500 turns of 1 mm² square MgB₂ conductor, bonded to a Cu stabilizing jacket, wound around a 5-cm-thick cold-iron flux plate (Fig. 3b). The main dipole windings will be fabricated using react-and-wind method due to its large size. A minimum bend radius of 0.5 m has been designed for the main windings to prevent strain degradation.

All coils will be operated on a 15-20K refrigeration circuit using cold He vapor.

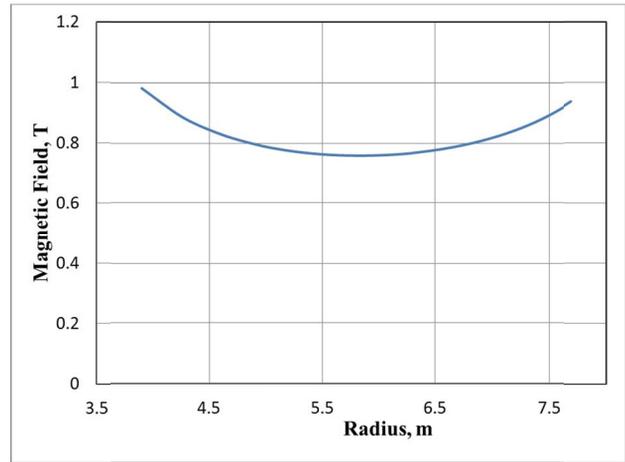


Figure 4: Magnetic field on two of the beam planes compared to isochronous field.

CONCLUSION

The magnetic designs for the superconducting booster and main cyclotron that will serve as the driver for an ADS system are presented. High beam power is achieved by stacking 4 identical flux-coupled cyclotrons, using novel high energy gain superconducting RF-cavities, and by separating and fully controlling orbits from injection to extraction. Each cyclotron is expected to be capable of low-loss delivery of 8 MW CW proton beam at 800 MeV.

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