STRONG-FOCUSING CYCLOTRON - HIGH-CURRENT APPLICATIONS*

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Abstract

A superconducting strong-focusing cyclotron (SFC) is being developed for high-current applications. It incorporates four innovations. Superconducting quarter-wave cavities are used to provide >20 MV/turn acceleration. The orbit separation is thereby opened so that bunch-bunch interactions between successive orbits are eliminated. Quadrupole focusing channels 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.

Preliminary simulations indicate that each SFC should be capable of accelerating 10 mA CW to 800 MeV with very low loss and >50% energy efficiency.

INTRODUCTION

High average beam power is needed in >800 MeV accelerators for several applications: accelerator-driven subcritical (ADS) fission [1], spallation neutron sources, rare-isotope beams, intense neutrino beams, and muon sources for muon colliders. The present state of art for high power is 1.3 MW at 590 MeV at the isochronous cyclotron at PSI [2], and 920 kW at 910 MeV at the Spallation Neutron Source at ORNL [3]. The above applications could in several cases profitably use >5 MW average beam power, and various efforts have been proposed to improve the performance of both cyclotrons and linacs.

For cyclotrons the major limitations to beam current arise from losses at injection and extraction where each bunch must miss the preceding orbit [4], from the coupling among bunches on successive orbits which largely co-penetrate [5], and from resonance-crossing due to the migration of betatron tunes through most of an entire integer during acceleration. A final problem arises with the rf cavities for which it is problematic to flatten and symmetrize the accelerating fields and to suppress longitudinal modes that can propagate around the cyclotron [6].

We set out to remedy those problems in a sector cyclotron. The provisions for the magnetics [7], the rf acceleration [8], and the injection and extraction [9] are detailed in accompanying papers. Here we present an overview of the provisions designed for ~8 MW performance.

OVERVIEW OF THE SFC

Fig. 1 shows the layout of a 4-stack SFC capable of accelerating 4 proton beams to 800 MeV final energy. It consists of an injector cyclotron (TAMU100) and a main cyclotron (TAMU800). The main parameters are summarized in Table 1.

To fully separate orbits it is necessary to apply a maximum rf acceleration per turn and to choose a low dipole field strength. In the conventional design of a sector cyclotron the sectors are curved as spiral arcs so the fringe fields of each sector provide weak vertical focusing. Curving the arcs, however, seriously complicates the placement of rf cavities, which must be oriented along a radius of the orbits in the gap between sectors. We opted instead to configure the sectors as simple wedges and to

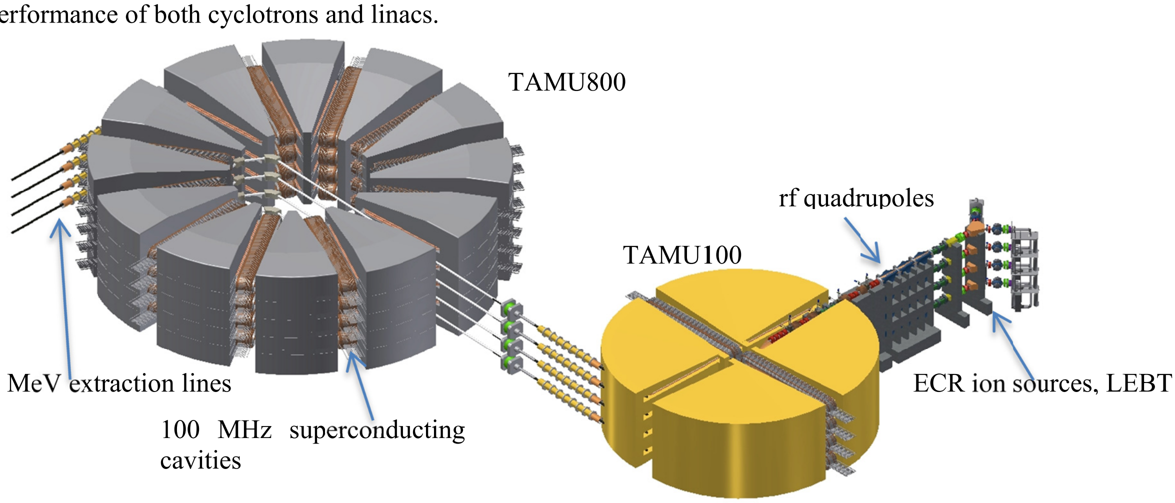

Figure 1: Strong-focusing cyclotron, showing injectors and main ring for a flux-coupled 4-stack.

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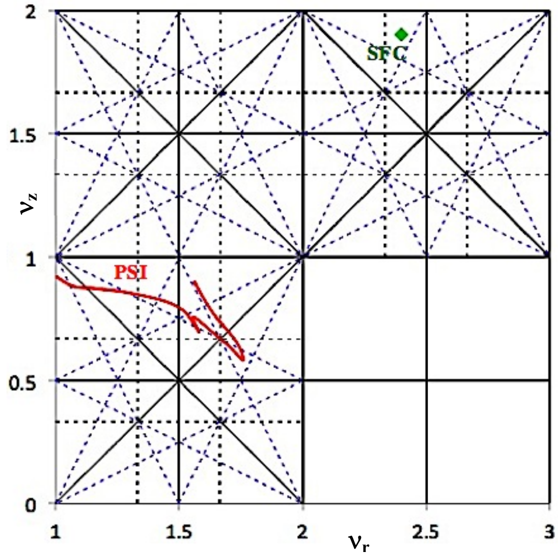

Figure 2: Tune plot showing the pattern of betatron resonances through 4th order.

provide focusing optics within the sectors themselves. The guide field in each sector has a nominal value of 1 Tesla, and the aperture is tapered to maintain isochronicity. With rf cavities located in 10 of the 12 sectors, an energy gain of 20 MV/turn is provided, and the closest turn-turn orbit separation is 4.6 cm at the extraction orbit.

The importance of orbit separation has long been appreciated by the PSI team, and has motivated their steady improvement of RF acceleration in their cyclotron [4]. They observed a cubic dependence of attainable beam current on the number of orbits in the cyclotron ($I \propto N^{-3}$), valid over a 10:1 range. Our choices of rf acceleration and dipole field yield a reduction in N from the 155 currently at PSI to 35 for our 800 MeV ring design.

STRONG FOCUSING CHANNELS

Cyclotrons have until now been limited to weak focusing, provided by hill/valley contouring of the poles for ring cyclotrons and by fringe fields between sector dipoles for sector cyclotrons. It has never been possible to control the betatron tune sufficiently to lock the tune to a favorable operating point; the tunes typically follow a trajectory that crosses both coupling and Walkinshaw resonances, as shown in Fig. 2 for the PSI cyclotron.

Fig. 3a shows the arrangement of 35 quadrupole focusing channels (QFC) on the flux plate that forms the lower boundary of one cyclotron in a sector magnet. Fig. 3b is a detail of the end of one QFC, showing the single-layer Panofsky quadrupole (gold) and window-frame dipole (blue) windings. It also shows the 4.6 dia. beam tube and the inlet and outlet flow channels for cryogen, which flows in the hermetic space between the round beam tube and square coil form. The wire placement in each winding is adjusted to cancel dominant higher multipoles. Figure 3c shows the calculated gradient map over the beam aperture, showing a maximum error of ~2%.

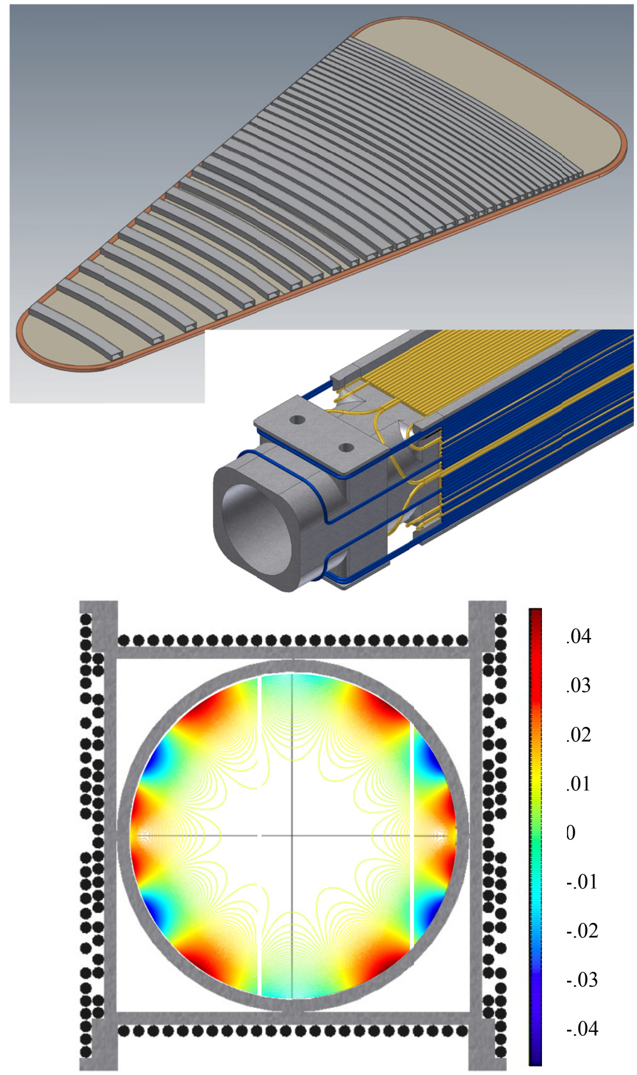

Figure 3:. Quadrupole focusing channels for the SFC: a) array of 35 channels on a flux plate; b) detail of one QFC; c) fractional gradient homogeneity over 4.6 cm aperture.

The main dipole windings on the flux plates and the QFC windings utilize Cu-stabilized MgB_2 superconducting wire. The windings are fabricated using the wind-and-react method for the QFC, and react-and-wind method for the main dipoles. All windings operate in the temperature window 15-20 K. 100 A in the QFC windings can generate 3 T/m gradient and 0.03 T dipole correction.

The QFC for each orbit in each sector magnet is actually wound in two equal sections, and the quad windings are powered in opposite senses in the two sections to make an FD transport channel.

The benefits of the QFCs for beam transport through the SFC are dramatic. Bunches in successive orbits are totally decoupled from one another. The betatron tunes can be controlled to maintain any desired operating point from injection to extraction. The green point in Fig. 2 is an example tune, for which Fig. 4 shows the lattice functions in one sector of the extraction orbit.

A room-temperature Cu absorber mask is located upstream of each sector magnet. It presents the most limit-

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Table 1: Parameters of the Two Cyclotrons

	TAMU 100		TAMU 800		
	inject	ex-tract	inject	ex-tract	
Energy	2.5	100	100	800	MeV
Orbit radius	0.66	4.6	3.8	7.6	m
Dipole field in sectors	1.5	.37	.98	.93	T
Beam aperture	4.6		4.6		cm
# rf cavities	2		10		
Frequency	100		100		MHz
rf harmonic	23		19		
# orbits	35		35		

ing aperture to each orbit and prevents direct losses on QFCs and cavities.

The QFC dipole windings are used to trim for isochronicity, and also to provide a strong septum at both injection and extraction so that both can be accomplished without interception of beam tails.

QUARTER-WAVE RF CAVITIES

The rf cavities for a high-current, high-energy cyclotron pose a particular challenge, because the entire structure must fit within the 95 cm vertical spacing between cyclotrons in the flux-coupled stack, and it must operate with high power efficiency both for economics and because it would be problematic to remove large structure power from such a confined space.

Fig. 5 shows the superconducting quarter-wave slot cavity that we have designed for use in both the injector and high-energy cyclotrons. The top and bottom lobes of the structure are end-coupled, which stabilizes the accelerating mode with modest in/out extent. Each lobe is driven by a linear array of loop couplers, each driven by a high-efficiency isolated solid-state rf power source.

Cavities are configured in 10 of the 12 gaps between sectors (1.24 m gap space). One gap is reserved for a 3rd harmonic cavity. The cavities operate at 4.5 K. Fringe dipole field is suppressed by shield plates so that the field at the Nb cavity is <3 μT.

APPLICATION FOR ADS FISSION

Our primary motivation in developing the SFC is for its use as a proton driver for ADS fission [1]. The 10 mA beam of each cyclotron is chopped as it is injected into TAMU100, and then separated into three beams after extraction from TAMU800, so that a 4-stack of cyclotrons can produce 12 2.7 MW beams. Each 2.7 MW proton beam can drive an 80 MW_{th} ADS molten salt core, fuelled entirely from the transuranics extracted from spent nuclear fuel (SNF). The 12 cores, totalling 1 GW_{th}, would burn all of the transuranics and long-lived fission products in

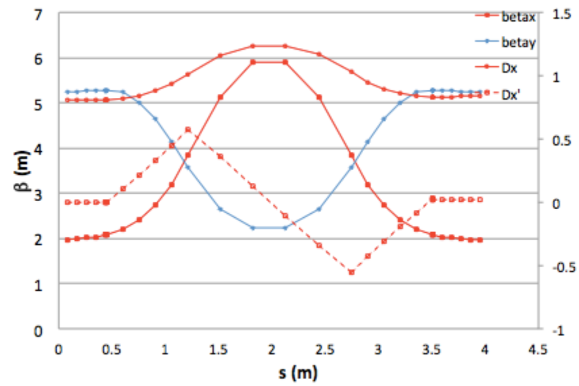

Figure 4: Lattice functions for the extraction orbit for the example tune are shown in Figure 2.

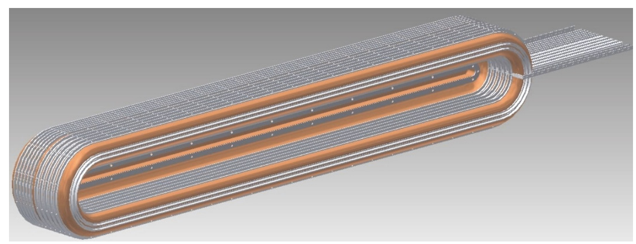

Figure 5: Half-section of the 100 MHz quarter-wave slot cavity for SFC.

the SNF from a conventional GW_e power reactor [1]. This capability, unique among the many methods for fission, offers the opportunity to close the nuclear fuel cycle and provide a path to green nuclear energy.

REFERENCES

[1] P. McIntyre, 'Accelerator-driven subcritical fission in a molten salt core: closing the fuel cycle for green nuclear power', submitted to Nature, May 2012, http://arl.physics.tamu.edu/ads

[2] W. Wegner *et al.*, 'PSI status 2008—Developments at the 590 MeV proton accelerator facility', Nucl. Instr. & Meth. A600, 5 (2009).

[3] S. Henderson, 'Experience with recently commissioned high-power proton accelerators and prospects for the future', 2011 Part. Accel. Conf.

[4] M. Seidel, 'Experience with the production of a 1.3 MW proton beam in a cyclotron-based facility', Proc. IPAC 2010.

[5] J.J. Yang *et al.*, 'Beam dynamics in high intensity cyclotrons including neighboring bunch effects: Model, implementation, and application', Phys. Rev. Lett. ST: Accel. and Beams 13, 064201 (2010).

[6] A. Adelmann *et al.*, 'On start to end simulation and modeling issues of the megawatt proton beam facility at PSI', 2005 Part. Accel. Conf., Knoxville, p. 3319.

[7] K. Badgley *et al.*, 'Flux-coupled stacking of cyclotrons for a high-power ADS driver, this conference.

[8] N. Pogue *et al.*, 'Superconducting rf cavity for high-current cyclotrons', this conference.

[9] S. Assadi *et al.*, 'Injection sequence high-power isochronous cyclotrons for ADS', this conference.