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BEAM DYNAMICS STUDIES FOR A STRONG-FOCUSING CYCLOTRON*

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Abstract

Results are presented from end-to-end simulation of a 100 MeV strong focusing cyclotron (SFC). The development of the high-current SFC is motivated by applications for production of medical isotopes and for a proton driver for subcritical fission.

It uses a novel superconducting cavity to provide sufficient energy gain to fully separate all turns. An arc-contour F-D doublet, trim dipole winding, and sextupole are located along each turn within the aperture of each sector dipole to control the betatron and synchrotron motion and to stabilize non-linear dynamics with high-current operation.

The phase space evolution of a proton bunch in the SFC was simulated using both the code OPAL and an *ad hoc* Runge-Kutta tracker.

Iterative optimization of the dipole, quadrupole, and sextupole fields was used to provide precise isochronicity, favorable betatron phase advance, and cancellation of dispersion in each cell.

INTRODUCTION

High-current CW proton drivers in the 100 MeV-1 GeV range are desired for a number of applications : spallation neutron sources, medical isotope production, and accelerator-driven fission. In each case CW currents of >10 mA are desired, and cost is a central challenge.

The only accelerator that is capable of the required performance is a superconducting linac, but it requires a large number of superconducting cavities, spanning several cavity topologies, and is typically very expensive.

A cyclotron provides a compact footprint and CW operation, and requires a modest number of identical cavities, but its beam current is limited by weak focusing and strongly overlapping orbits. The effects of space charge, bunch-bunch interactions, and wake fields are best managed using strong-focusing and dispersion correction, and full separation of neighboring orbits.

The strong-focusing cyclotron (SFC) was invented to build upon the benefits of the cylotron and eliminate its limitations [1]. The dipoles are configured as in a 6-sector cyclotron, with superconducting cavities in four of the sector gaps to produce sufficient energy gain/turn to fully separate all orbits (Figure 1). The cavities are designed with an r-ϕ wedge geometry and re-entrant ends (Figure 2), which produces an energy gain/cavity ΔE that increases from ~0.4 MeV at injection to 2.4 MeV at extraction.

The vertical gap between iron pole faces is symmetrically stepped between arcs so that the bunch sees a distinct,

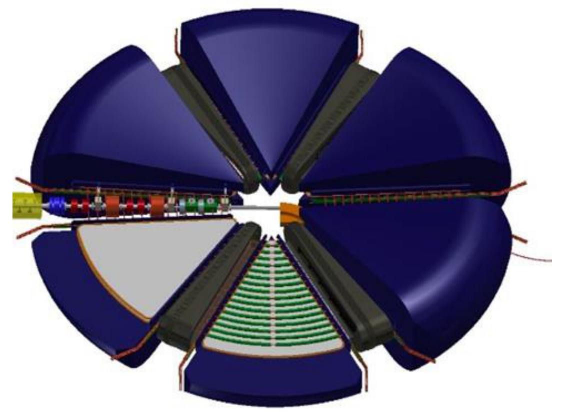

Figure 1: Cutaway view of a 100 MeV SFC, showing the 16-turn spiral trajectory, the superconducting slot cavities (dark grey), and the beam transport channels (green).

approximately homogeneous dipole field B_{mn} on the mth sector of the nth orbit [2]. The values $\{B_{mn}\}$ are chosen to make all cavity-to-cavity transit times equal (isochronicity). The modulation of ΔE produces nearly equal spacing of all turns in the isochronous spiral orbit (a unique attribute of the SFC), and makes it feasible to fully separate all orbits. An arc-contoured beam transport channel (BTC) is located along the reference trajectory as shown in Figure 1. It is important to note here that the arcs in each sector are *not* concentric in the optimized parameter set.

Each BTC contains an F-D doublet of wire-wound superconducting quadrupoles (using MgB_2 superconductor operating at ~10 K) to provide a strong-focusing lattice [3]. The BTC is fabricated as a wire-wound Panofsky quad and window-frame trim dipole, as shown in Figure 3, in which the MgB_2 windings operate at 10 K. A sextupole is located at the entrance to each BTC, and a beam profile monitor (BPM) is located at the exit from each BTC.

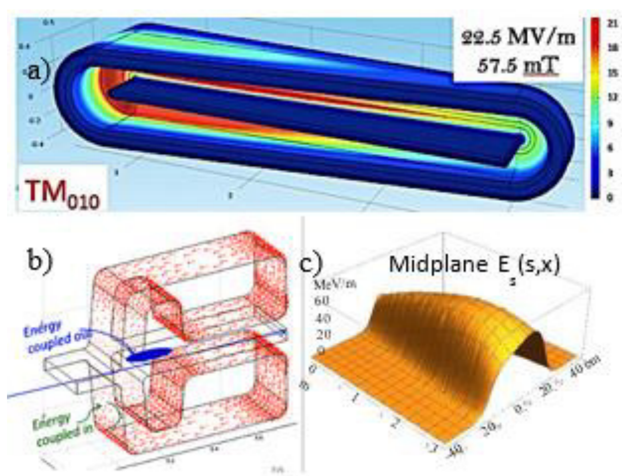

Figure 2: Superconducting cavity rf cavity, showing details of structure, location of couplers, midplane rf field.

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The above provisions enable optimization of isochronicity, betatron phase advance, and dispersion throughout the spiral orbit. They can be used to counteract the non-linear effects from space charge, coupled-bunch, and wake fields that often limit beam current in conventional machines.

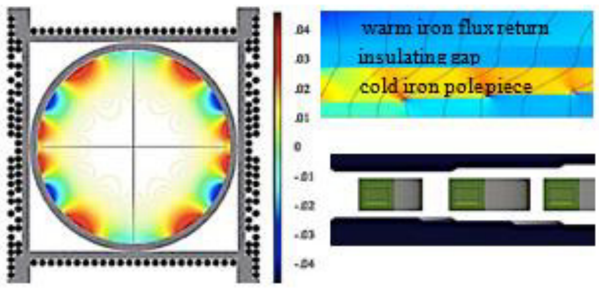

Figure 3: Left: Beam transport channel, showing detail of wire placement for quad and trim dipole windings; Upper right: cross-section of sector dipole, showing warm iron flux return, insulating gap, and cold iron pole plate; Lower right: positions of BTCs centered in each stair-step of the dipole aperture.

DESIGN OF THE SFC LATTICE

The configuration of magnetostatic and RF fields in the SFC creates challenges for simulation using conventional codes (*e.g.* MAD-X and Synergia) that are used for linacs and synchrotrons. Three attributes of the SFC fields are both important to its effectiveness and difficult to model:

- combined-function fields with strong curvature;
- strong acceleration distributed throughout the lattice;
- precise isochronicity to control coupled-bunch fields.

Conventional codes embody simplifying assumptions that do not accommodate all three of those attributes [4]. For that reason a more robust code basis is being developed for the design and simulation of SFC. It utilizes 3-D calculation of the d.c. magnetic fields using Vector Fields [5] and cavity RF fields using COMSOL [6]. A custom Runge-Kutta (R-K) tracker transports bunches through those fields, with benchmarking against OPAL [7] to implement the turn-by-turn field maps and support dynamics studies.

The R-K tracker is used to optimize the spiral geometry and the individual field values for all magnets and cavities. We have developed a set of Python tools [8] that extracts particle data from OPAL's simulation in the presence of space charge, wake fields, and bunch-bunch interactions. When complete the tools will enable us to study and optimize beam dynamics with high bunch current.

Following is the step-by-step process to design the SFC:

1) Define global parameters for the SFC: kinetic energy for injection (6.5 MeV) and extraction (100 MeV), target value for maximum dipole field (0.9 T, chosen to prevent saturation in the flux return), and target values for the vertical gap (h = 7 cm) and radial spacing between turns (g = 15 cm).
2) Define target values for the RF frequency and harmonic (116.4 MHz, h=25), Prepare a 3-D field model of the cavity and adjust its geometry (with a modest wedge angle) in which the cavity entrance edge is oriented so that bunches enter close to normal to the cavity edge.
3) Design a target geometry for the reference trajectory with approximately equally spaced turns and calculate the values dipole field B_{mn} for isochronism.
4) Prepare a 3-D field model of the sector dipole, in which the aperture between pole faces forms a staircase of parallel arc-shaped facets. Adjust the vertical gap h_{mn} between the facets for each arc to produce the field B_{mn} required for isochronicity [9].
5) Design all BTCs with a single common cross-section, and with the curvature of each BTC matching the bend radius ρ_{mn} for that segment of the spiral orbit.

SIMULATION OF THE SFC

OPAL provides an excellent basis for simulating particle and bunch motion in the spiral orbits of a cyclotron. It has however a significant limitation for use with SFC in the way it generates the magnetic field at the location of a particle at each time step.

The quadrupoles and trim dipoles of each BTC are configured as a wire-wound assembly in the geometry of a Panofsky quad and a window-frame dipole. The vertical wire-wound plane passes through the midplane of the SFC. OPAL uses a method of analytic continuation from a 2-D map $\bar{B}(x,s)$ in the mid-plane to calculate the vector field at each point on the trajectory of a particle. Thus it is important to generate a high-resolution 3-D map of $\bar{B}(r)$ in order to accurately resolve the magnetic field near the edge of the BTC aperture.

The R-K tracker has been used to develop a method for iteratively locking the synchronous phase advance/cell $\Delta\psi$ and similar methods are being developed to optimize the betatron phase advance/cell $\Delta\varphi$ and to correct dispersion η, in all cases progressing sector-by-sector through the entire spiral trajectory. The methods are described below.

LOCKING ISOCHRONICITY

It is important to lock exact isochronicity of the reference orbit, so that all bunches arrive at each cavity at precisely the same time. For this purpose a timing matrix M_{ij} is defined, which couples the change in the arrival RF phase $\{\psi_{ij}\}$ and the field values of the trim dipole $\{B_{tij}\}$ for each cavity in each turn. We calculate the pseudoinverse of this under-constrained system and use it to choose trim dipole settings that yield an isochronous solution (achieved within ~0.001°).

OPTIMIZING PHASE ADVANCE/CELL

It is important to optimize the phase advance per cell $\Delta\varphi_x$, $\Delta\varphi_y$ for maximum stability of betatron motion. Note that $\Delta\varphi$ is the variable of significance rather than betatron tune because the trajectories are spiral and not closed.

Following the same pseudoinverse method, a pseudoinverse matrix is formed of the values of $\Delta\varphi_x$ and

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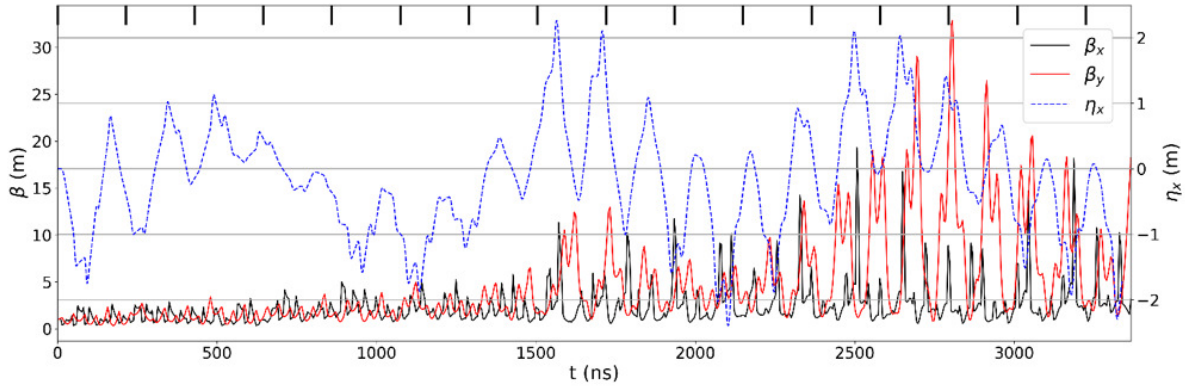

Figure 4: Lattice functions β_x, β_y, η_x for the entire SFC. The successive turns are indicated at the top.

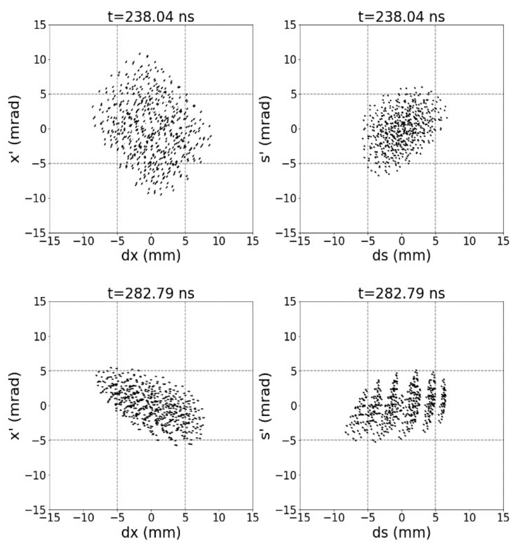

Figure 5: Poincaré sections from a single simulation of a bunch (N=14000) illustrating emittance exchange between the horizontal (left) and longitudinal (right) spaces, via a synchro-betatron mechanism.

the quad doublet settings for each cell. The matrix is inverted to obtain the quad settings that yield a constant $\Delta\varphi_{mn}$ for all sectors of all turns.

The linear motion of particle bunches was simulated with several choices of starting 6-D emittance :

- a pencil bunch with starting normalized emittances $\varepsilon_x = \varepsilon_y = 1\ \pi\ 10^{-6}$ m and $\varepsilon_\ell = 0.5\ \pi$ keV·ns;
- a bunch roughly corresponding to ~10 mA CW current, with $\varepsilon_x = \varepsilon_y = 16\ \pi\ 10^{-6}$ m, $\varepsilon_\ell = 2\ \pi$ keV·ns;
- a bunch roughly corresponding to ~20 mA CW current, with $\varepsilon_x = \varepsilon_y = 25\ \pi\ 10^{-6}$ m, $\varepsilon_\ell = 3\ \pi$ keV·ns.

The inversion method is still in development. A 'by-hand' equivalent method has been used to reduce the variance in φ_x, φ_y guided by stability of transport of the 10 mA-equivalent beam. The results of this process are shown in Figures 4 and 5.

Figure 6 shows the evolution of normalized emittances ε_x, ε_y through the 16 turns of acceleration, before and after optimizing $\Delta\varphi_x$ for all segments. It is noteable that there is no particle loss for the phase space equivalent to a 10 mA-equivalent beam, even though no correction of dispersion has yet been made.

CORRECTING DISPERSION @ CAVITIES

Dispersion at the entrance to each RF cavity is the driving term for synchro-betatron coupling (see Figure 5), and if un-corrected would pose a primary limit to beam current. Sextupole windings are located at the entrance gap of each sector and tuned to correct dispersion at the cavity entrances. We are working to implement the same pseudo-inverse matrix method to optimize the dispersion η_x and η_y

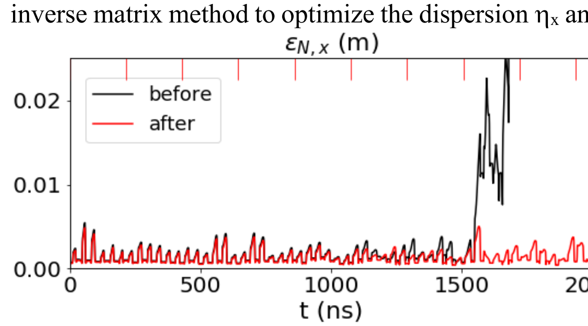

Figure 6: Evolution of the normalized horizontal emittance for roughly half of the SFC. Two cases are shown before and after optimization. Turn transitions are indicated at the top of the figure.

at each cavity entrance, using the sextupoles in each segment. Implementing this objective is a work in progress. It is to be expected that the dispersion-suppressed lattice will transport the 20 mA case without emittance growth, just as the previous optimization did for the 10 mA case.

CONCLUSIONS

The SFC has a unique combination of strong-focusing lattice, strong acceleration that fully separates all turns, and provisions for measurement and control of $\Delta\varphi_x$, $\Delta\varphi_y$, and η throughout the lattice. Methods for systematic optimization of 6-D phase space transport are under continuous development. The SFC has good prospects as a basis for low-loss acceleration of proton and ion beams of 10-20 mA.

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