NONLINEAR BEAM DYNAMICS STUDIES OF HIGH-INTENSITY, HIGH-BRIGHTNESS PROTON DRIVERS *

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Abstract

Space charge effects, beam losses, wake fields, and orbital control are significant collective effects that affect beam dynamics. The strong-focusing cyclotron incorporates helical orbits with a strong-focusing lattice and high-gradient cavities. It makes it possible to fully separate orbits and suppress interaction between bunches on neighboring orbits. We simulate nonlinear synchro-betatron coupling and explore methods to use the tools of strong-focusing to suppress beam blowup mechanisms.

INTRODUCTION

The Accelerator Resarch Lab at Texas A&M University is developing designs for a strong-focusing cyclotron (SFC) as a high-current (12 mA CW) proton driver for ADS fission [1], production of medical isotopes, and neutron damage studies [2]. The purpose of this paper is to explore how the unique features of the SFC can be used to control nonlinear dynamical effects that limit beam current in accelerators.

Particle motion in the SFC is described in terms of six phase space coordinates (x,x',y,y',ΔE,Δϕ]. The lattice of the Strong Focusing Cyclotron (SFC) requires inclusion of longitudinal or synchrotron motion as one cannot decouple longitudinal and transverse planes past mid-plane analysis. In this case synchrotron motion causes modulations of the parameters or forces and sidebands appear as a result in the tune space. The effects of synchrobetatron couplings and resonance-crossing should become dominant as intensity increases or bunch length elongates.

The SFC lattice combines periodic quad-focusing elements [FD] with common sector magnets and RF cavities, and in this respect it is similar to a combined-function synchrotron. The orbits however are spirals, and dynamics is strongly dependent on initial conditions, and in this respect it is similar to linacs. This results in synchrotron sidebands [1] in the betatron motion with chromaticity as developed by Orlov [2] and synchrobetatron resonances caused by chromaticity as analyzed in a review by Suzuki [3]. The SFC lattice is highly regulated by the arrangement of superconducting beam transport channels (BTCs) [4], Mobius-geometry RF cavities [5], and low-field superconducting sector dipoles [6] to produce matched beta function [β_x, β_y], dispersion [D] and D' to manage emittances. We simulate the SFC as a spiral transmission line, and we include forces from error fields, wake fields, cavity-coupling of bunches, and space charge.

Designs have been developed for a 6-sector 100 MeV SFC (TAMU100, shown in Figure 1) and for a 12-sector 800 MeV SFC (TAMU800) for which TAMU100 would serve as injector. A key element of the SFC is its use of the beam transport channels (BTC), installed along the equilibrium trajectory or each orbit in each sector as shown in Figure 1b. Each BTC contains an FD doublet of Panovsky quadrupoles (up to 6 T/m, used to local tune) and a window-frame dipole (up to .02 T, used to control isochronicity).

Simulation of beam dynamics in both SFCs starts by tracking a 4D map of a bunch propagating through the lattice elements and interacting with EM fields, similarly to the kick codes COSY-INFINITY, Elegant, MADx, and CERN Mathematica. We have started with that framework and added complexity to the simulation as the design progresses. The framework utilizes a combination of mathematical scripts based on COSY-INFINITY fed by Madtomma. Tracking is made using CSRtrack. Figure 2 shows the elements of one cell of an SFC lattice.

We impose a shell on the kick code that operates a simultaneous quadratic optimization, in which we can optimize up to 48 variables that define the isochronous orbits. The framework has evolved to include space charge, chromatic effects, and evolution of bunch-length.

Beam position monitors are provided in a gap at the end of each sector for each orbit. In the planning for commissioning of TAMU100, we plan to inject low-power beam into the first two turns of the lattice with RF off and capture it on a retractable beam dump. That will enable us to verify injection matching and BTC alignment before

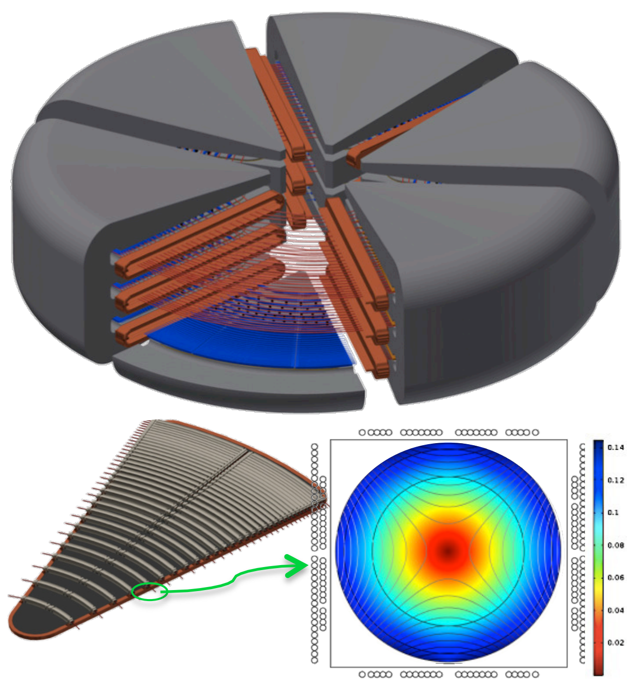

Figure 1. a) 3-stack of 100 MeV SFCs, with cutaway to show superconducting cavities, BTCs, and orbits; b) detail of a sector dipole flux plate and the arced BTCs.

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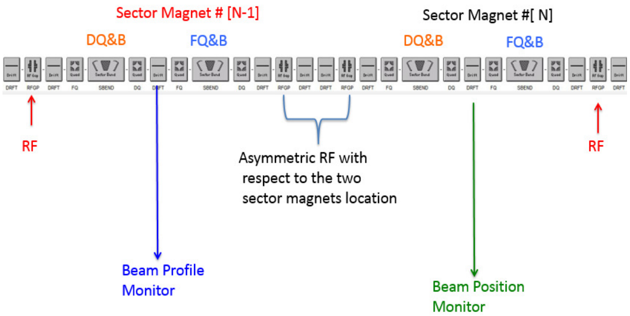

Figure 2. Lattice elements in the tracking simulation of one cell (sector dipoles) of the SFC lattice.

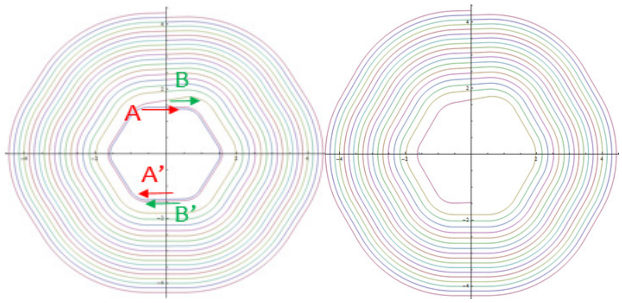

Figure 3, Reference orbits in the 6-sector TAMU100, before and after optimization of the injection orbit.

'threading the needle' of orbits with acceleration. The retractable beam dump can also be traversed to dump the beam after any desired orbit.

Figure 3 shows a first example of how the BTCs convey benefit in optimizing the SFC. Figure 3a shows a reference orbit for TAMU100 in which the orbit was launched from the extraction point and tracked back to injection, optimizing for isochronicity, maintaining stable phase advance in all cells, and holding constant betatron tunes from injection to extraction to a favorable operating point. Figure 3b shows a second optimization in which the optimization of the first two orbits was added to the optimizer criteria.

BEAM DYNAMICS STUDIES

We have studied beam dynamics using the tools described above. We established that the BTC quadrupoles can be grouped into 6 families (3x, 3y) and still provide excellent control with which to set tunes to any desired operating point and hold it there throughout acceleration.

We implemented a similarly grouped set of sextupoles at the exit from each sector to provide control of chromaticity, and a set of beam position monitors that will enable us to develop a correspondence between simulation and actual operation of the accelerator. With those tools, we proceeded to simulate the phase space dynamics of bunches, starting with low current and increasing to our design value.

Figure 4 shows Poincare plots for the 1σ-5σ contours of a bunch in a 3.5 mA 162 MHz SFC, tuned to hold (ν_x,ν_y) = (3.196, 3.241). The first three plots show that the phase space has very regular motion throughout acceleration with no particles reaching the BTC apertures.

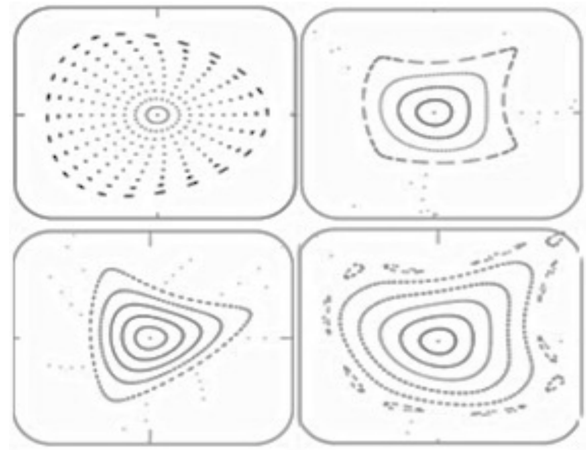

Figure 4. Poincare plots of a 3.5 mA 116 MHz bunch as it is accelerated in an optimized TAMU100 lattice.

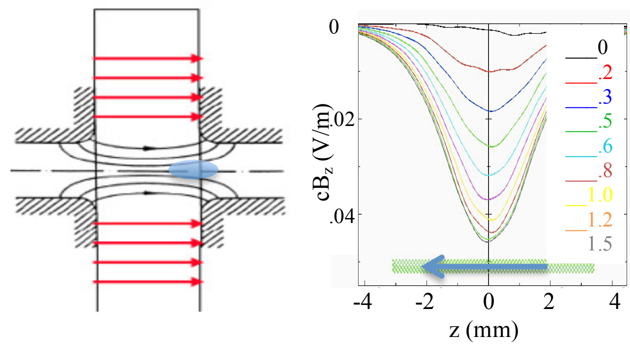

Figure 5. Effect of space charge on longitudinal bunch dynamics: a)bunch passing through cavity; b) longitudinal field inside bunch showing asymmetry from space charge.

For the last plot ν_x was moved near a 7th-order resonance. By the 9th orbit (40 MeV) beam breakup is evident on the 5σ plot. This result gives an example of the simulation at work, and it underscores the importance of controlling tune in a high-current cyclotron.

The nonlinearity and couplings are essentially due to two factors. First, off-momentum particles that go through cavity and then the edge of the sector magnet will go under a different chromatic affect. One aspect of this is shown in Figure 5b, where the space charge of the bunch produces asymmetric fields in the center of the bunch. Such chromatic effects result in synchrobetatron coupling.

We simulated the acceleration of the bunches in a 10 mA CW beam, for a favorable operating point and for tunes near 3rd- and 5th-order resonance. The favorable-tune case produced Poincare plots similar to those of Figure 4a-c; the cases near resonance are shown in Figure 6. When the tune is near a 3rd order resonance, clumping is evident by end of the 2nd orbit and the clumps can be seen driven apart. Similar clumping is evident when the tune is near a 5th order resonance, but clumps remain close. In both cases the beam was lost by 20 MeV. We conjecture that the clumps are driven apart in the 3rd order case by fringe fields of the sector dipoles and by cavity fields, both of which couple to 3rd order in the 6-sector lattice. For a favorable tune, clumping was not observed until near 100 MeV, and the beam profile remained intact.

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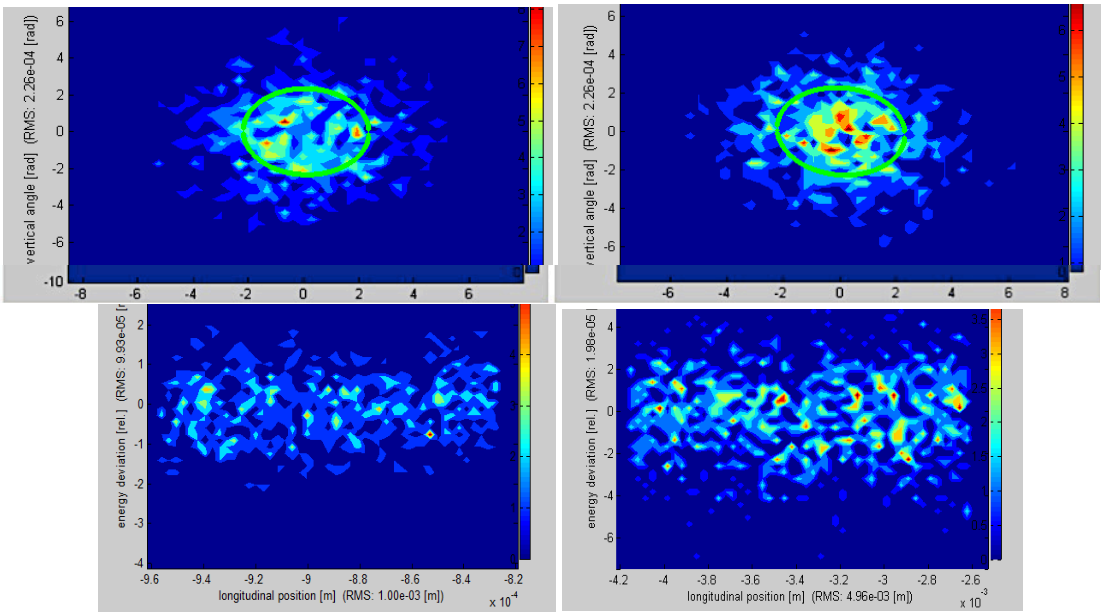

Figure 6. a) Beam breakup in transverse phase space after 2nd orbit when tune is near 3rd order and 5th-order resonances; b) beam breakup in longitudinal phase space when tune is near 5th order resonance.

Figure 7 shows similar dynamics for the longitudinal phase space of bunches in a 10 mA beam with favorable tune. ΔE grew from ±5° at injection to ±6° at extraction; Δϕ increased by 30%; the bunch was accelerated without loss from the 20 MV bucket.

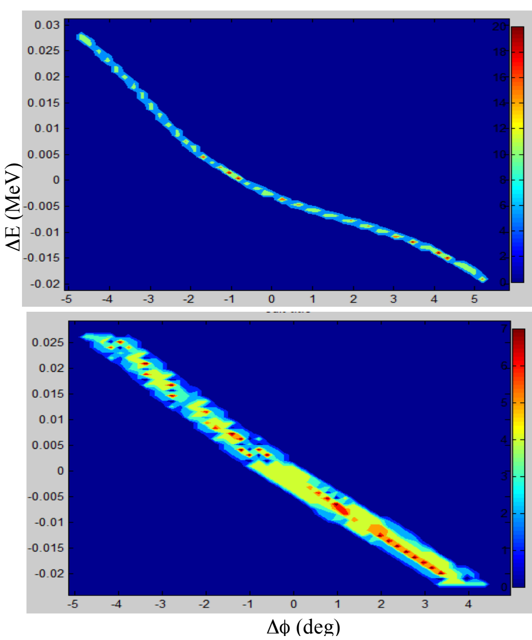

Figure 7. Longitudinal phase space of a bunch in a 10 mA beam: a) after first half-turn; b) 100 MeV.

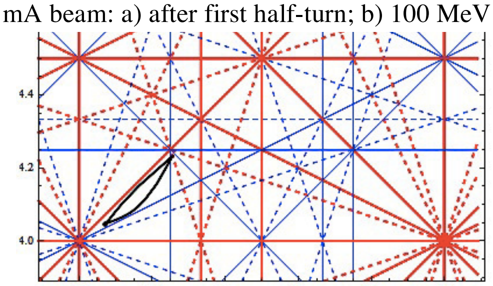

Figure 8. Tune distribution of points on the 5σ trajectory for a favorable tune.

Figure 8 shows a map of the tunes of individual particles on the 5σ contour of a bunch in 10 mA beam, accelerated using a favorable operating point. The tune can be positioned so no resonance crossing occurs, even at 5σ.

CONCLUSIONS

The above results are the beginning stages of a systematic investigation of non-linear dynamics in our strong-focusing cyclotron as it accelerates >10 mA of proton beam to 800 MeV for ADS fission and other applications.

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