SIMULATION OF BEAM DYNAMICS IN A STRONG FOCUSING CYCLOTRON*

K. E. Badgley†, Fermilab, Batavia, Illinois
J. Gerity, P. McIntyre, A. Sattarov, Texas A&M University, College Station, Texas
S. Assadi, HiTek ESE LLC, Madison, Wisconsin
N. Pogue, Lawrence Livermore National Lab, Livermore, California

Abstract

The strong-focusing cyclotron is an isochronous sector cyclotron in which slot geometry superconducting cavities are used to provide sufficient energy gain per turn to fully separate orbits. Each orbit travels through superconducting beam transport channels, located in the aperture of each sector dipole, to provide strong focusing and control betatron tune. The SFC offers the possibility to address several effects that limit beam current in a CW cyclotron: space charge, bunch-bunch interactions, resonance crossing, and wake-fields. Simulation of optical transport and beam dynamics entails several new challenges: the combined-function fields in the sectors must be properly treated in a strongly curving geometry, and the strong energy gain induces continuous mixing of horizontal betatron and synchrotron phase space. We present a systematic simulation of optical transport using modified versions of MAD-X and Synergia. We report progress in introducing further elements that will set the stage for studying dynamics of high-current bunches.

INTRODUCTION

Commercial facilities for medical isotope production, material irradiation by spallation neutrons, and accelerator driven subcritical core for spent nuclear fuel destruction or energy production [1-3] are a few examples where high beam current accelerators are required. The production of high current beams in cyclotrons has several challenges, including: space charge effects, turn to turn separation and total number of turns. It has been shown that the maximum achievable current increases as the inverse cube of the number of turns in the cyclotron [4]. To overcome the challenges of high intensity cyclotrons, The Accelerator Research Lab of Texas A&M University is developing a Strong Focusing Cyclotron (SFC) [5-7] that incorporates two technological innovations developed in the laboratory: low profile tapered superconducting RF-cavities, that are capable providing up to 3MV accelerating voltages, and superconducting strong focusing/defocusing (FD) beam transport channels (BTC) that should allow full control of the beam. Figure1a) shows the 6 sector 100 MeV SFC and its main components: 4 tapered low profile SRF cavities and BTCs along the design path. The arrangement of the BTC on the face of the pole piece of the sector magnet and the BTC quadrupole and window-frame correction dipole windings are shown in Figure 1 b)-c). Figure 1 d) shows an example cross section of BTC producing a 7.5 T/m quadrupole. The main parameters of the cyclotron are given in Table

Table 1: Main Parameters of the Cyclotron

Parameter	Value
Number of sectors	6
Sector Angle, degrees	54.42
Injection Energy, MeV	6.5
Injection Radius, m	1.1
Extraction Energy, MeV	100
Extraction radius, m	4.3
Harmonic number, h	25
Number of Turns	14
Cavity Frequency, MHz	117
Maximum Quad Strength, T/m	7.5
Correction dipole field, mT	20

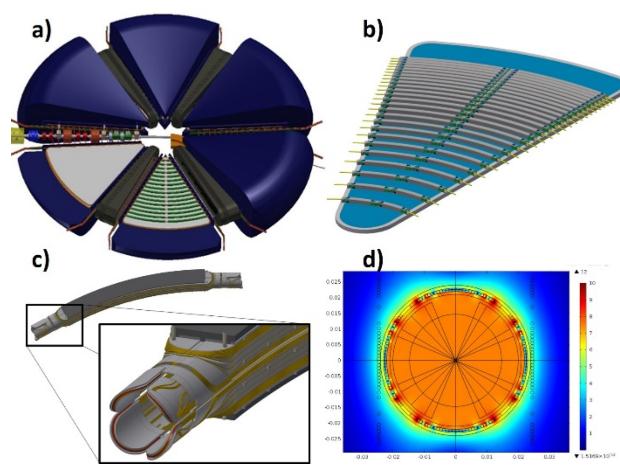

Figure 1: 100MeV SFC and its main elements.

REFERENCE ORBIT AND SECTOR MAGNETS FOR THE SFC

Beam dynamics and particle tracking require knowledge of the equilibrium orbit and elements of the accelerator. In a cyclotron, the equilibrium orbit and parameters of the accelerator elements are often found from a series of closed orbits. For the strong focusing cyclotron described here, the equilibrium orbit, and corresponding elements, must follow a spiral to stay within the BTCs, so the closed orbit method will not work. The remaining accelerator codes were designed for circular machines, or

* This work was supported by the Accelerator Stewardship Program of the US Dept. Energy, grant DE-SC0013543.
† email address karie.email@gmail.com

linacs, and do not have the capability to determine this spiral. This paper discusses modifications made to existing codes to model the SFC and initial results.

Reference orbit

A set of parametric equations were developed [7] to describe the spiral based on geometric constraints. Using Mathematica, an optimization on these equations was performed to find the isochronous path through our SFC. The script determines the strengths of the magnetic fields in the sectors and the phase and voltage gain of the RF cavities. Additional constraints in the optimization ensure the particle is perpendicular at the entrance of the cavity and maintains a turn to turn separation of 6 cm.

MAD-X

The MAD code, out of CERN [8], was chosen as it is a standard among accelerator design codes. With a complete description of the accelerator elements from the equilibrium orbit, a MAD input file was generated. Each sector dipole contains a focusing and defocusing quadrupole, so the sector is modelled as two combined function magnets. The strength of the dipole for the pair of magnets is the same and the strength of the quadrupole is left as a parameter to be optimized within MAD. There are two constraints placed on this optimization: the beta functions should be kept under a maximum value, and the phase advance, and tune, must be constant around a turn. One major drawback in using MAD, which was written for a ring, is that each element in a sequence file assumes the same energy. The 100 MeV SFC has 14 turns and 4 cavities and therefore requires a new sequence file each time a cavity was encountered, a minimum of 56 sequence files. Another issue is the optimization of the beta function and phase advance can only take place within a sequence. Initially the whole SFC was input in the same sequence file, this of course would be incorrect after the first cavity, but provides an idea on the strengths of the quadrupoles required. The next step was to break the inputs into 14 sequence files, one for each turn and using the correct starting energy for that turn. Again, this would be incorrect after the first cavity, but much closer to the actual quadrupole values needed to hold the beta and tune for that turn. The quadrupole strengths for the 14 turns are shown in Table 2. For symmetry reasons, the decision was made to break the sequence files at the midpoint between each sector producing 84 sequence files. The final step was to scale the quadrupole strengths to the energies after each cavity and enter these as 84 sequence files. The output of each sequence was fed into the next. At this stage, no optimization was performed, only a check that the tunes and beta functions were behaving as expected.

Sector Magnet

Following an approach described in [8], the feasibility of sector magnets that have desired field strength along spiral path was checked. For each sector magnet a TOSCA model of the cyclotron was created, and the gap size between adjacent pole-pieces was varied to achieve uniform integrated target fields in 4 cm wide stripe along the design trajectory. Less than 2% error between design and modelled field was achieved that can be corrected with dipole correction windings on BTC. Figure 2 shows B_z field in a mid-plane of the second sector of the cyclotron.

Table 2: Gradients that produce, $\beta_{x/y} \leq 10m$ and $\mu_x = 1.15, \mu_y = 1.183$

Turn	F-quad T/m	D-quad T/m
1	5.69	2.25
2	0.06	3.83
3	2.00	3.81
4	1.08	2.89
5	1.55	2.78
6	1.27	2.23
7	1.04	1.96
8	0.95	1.60
9	1.01	1.54
10	0.77	1.33
11	0.83	1.31
12	0.82	1.18
13	0.66	1.05
14	0.68	1.06

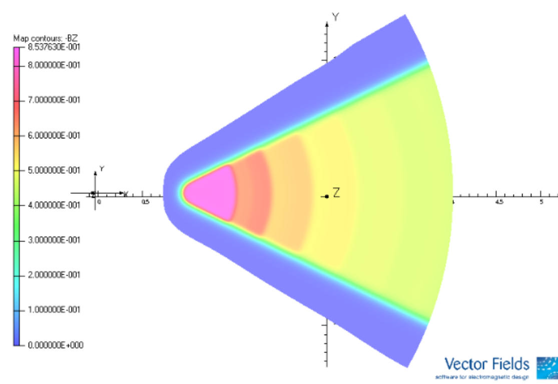

Figure 2: B_z Field map in one of the sectors of 100MeV cyclotron.

PARTICLE TRACKING

The next step on our way to determining the amount of current the SFC can support is particle tracking. The main goal in particle tracking is to be able to turn on the effects due to space charge. MAD-X's space charge capabilities are still under development at this point, so two options for tracking high current beams were considered: Synergia- a tracking code developed at Fermilab and designed for high energy and large circumference rings [9] and OPAL [10]-developed at PSI. Both codes can take into account collective effects, such as space charge, and also can take the MAD-X sequence files as input.

Modified MAD-X-PTC

Tracking in MAD-X again required the same breakup of sequence files by energy. The strength of the accelerator elements are based on the reference momentum of an ideal particle. This ideal particle's time is also used as the zero point at the end of the sequence, with other particles given as a difference from the ideal time. In each new sequence, the momentum of each particle must be renormalized to the new reference momentum. The timing difference must also be renormalized.

There was an additional issue in the treatment of the RF cavities in MAD; they are treated as a single kick without taking into account the transit time factor. A Matlab script was written to save all the particle data at the output of each sequence file and apply an energy kick if a cavity was encountered. The resulting momentum and time would be renormalized to the next sequence file's momentum and that would be fed back into MAD.

Synergia

Similar to MAD-X, Synergia was designed for high energy machines, and so had the same assumptions through the RF cavities, which meant the transit time factor had not been included. Working with the Synergia group at Fermilab, a new RF module was developed to add this correction. Benchmarking of Synergia's single particle tracking capabilities versus the modified MAD-X-PTC module resulted in agreement both in energy gain and beam size through the SFC [11]. Initial space charge studies have begun with a 2 mm radius 7.5 mm long ellipsoid beam composed of 10,000 macroparticles and 10 mA. Using the same quadrupole strengths developed with MAD, all the particles make it through without space charge. When space charge is turned on, only ~60% make it through. The quadrupole strengths are being adjusted to compensate. Figure 3 shows the initial beam size and phase space, and the size and phase space after the first sector with and without space charge.

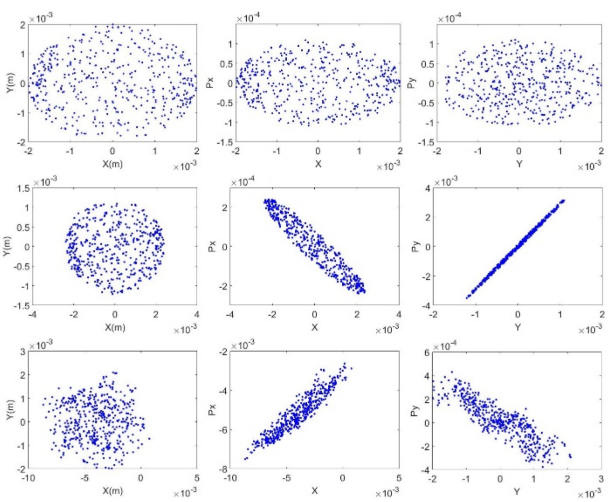

Figure 3: Beam size (left), x-phase space (middle) and y-phase space (right) for the initial beam (top), after first sector without space charge (middle), and after the first sector with space charge (bottom) in the 100MeV cyclotron

OPAL-T

OPAL, developed at PSI, was derived from MAD9P and OPAL-cyclotron was successfully used to describe the beam behaviour of the ring cyclotron. OPAL can take 3D electromagnetic field maps and model beam dynamics in the cyclotrons allowing a smooth transition from the simple optical element approximation to more realistic beam simulations.

Initial tracking was performed with OPAL-T since MAD-X and OPAL-T beam line element descriptions are almost identical. At this stage the hard edge approximation is still being used. A 32x32x32 grid and open boundary condition were used in field solver option of OPAL-T to account for space charge effects. A uniform, 2mm radius and 7.5mm long cylindrical para-axial 10mA beam with bunch spacing of 8.55ns was injected into the cyclotron. The RF cavities were modelled as a simple energy gain. Since the spiralling path slightly deviates from the isochronous one, the phase of each RF cavity was adjusted, so the center of the beam would always be at the design phase of 75°. Previously observed coupling effects between adjacent bunches through the cyclotron RF cavity [12] were excluded in this approximation. As is seen with Synergia, the quadrupole strengths without space charge will need to be modified. Figure 4 shows the rms beam size in x and y through the first three turns of the SFC modelled with 10,000 particles.

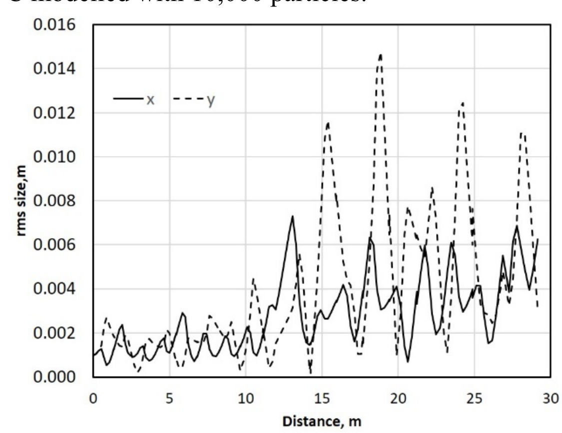

Figure 4: Rms beam size through the first 3 turns in OPAL-T showing beam blow-up when using the quadrupole strengths from MAD-X-PTC.

COUNCLUSION & FUTURE WORK

This work builds on earlier efforts to develop a realistic model of the SFC. Benchmarking of OPAL-T against the MAD-X-PTC results and Synergia results still needs to be performed. Adjustment of the quadrupole strengths to account for space charge is ongoing in both Synergia and OPAL-T. OPAL-cyclotron will eventually be used with full field maps of the sector and beam transport channels.

ACKNOWLEDGEMENT

The authors would like to thank Eric Stern and Leo Michelotti for their generous help with Synergia.

REFERENCES

[1] Isotopes for Nation's Future. A long range plan, https://www.isotopes.gov/outreach/reports/NSACI_II_Report.pdf

[2] N. Pogue, P. McIntyre, A. Sattarov, "Accelerator-based neutron damage facility using LEDA", in *Proc. PAC'13*, Pasadena, CA, USA, Sep. 2013, paper THODA2, pp. 1128-1130.

[3] S.Assadi *et al.*, "Strong-focusing cyclotron – high current applications", in *Proc. PAC'12*, New Orleans, LA, USA, May 2012, paper MOPPD033, pp. 436-438.

[4] W. Joho, 'The cyclotron facilities at PSI: an overview', http://gfa.web.psi.ch/publications/presentations/WernerJoho/Cyclotrons_PSI.pdf

[5] N. Pogue, P. McIntyre, A. Sattarov, "Superconducting RF cavity for high-current cyclotrons", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper WEPP063, pp. 2354-2356.

[5] S. Assadi, K. Melconian, P. McIntyre, "Nonlinear beam dynamics studies of high-intensity, high-brightness proton drivers", in *Proc. PAC'13*, Pasadena, CA, USA, Sep. 2013, paper TUPAC26, pp. 505-507.

[6] K. Melconian *et al.*, "Optimization of orbits, SRF acceleration, and focusing lattice for a strong-focusing cyclotron", in *Proc. PAC'15*, Newport News, VA, USA, paper THPF135, pp. 4038-4041.

[7] J. Kellams *et al.*, "Superconducting Sector dipole for a strong focusing cyclotron", in *Proc. ASC'14*, Charlotte, NC, USA, August 2014, paper 4003904.

[8] MAD-X, http://mad.web.cern.ch/mad/.

[9] Synergia, https://web.fnal.gov/sites/Synergia/SitePages/Synergia%20Home.aspx

[10] OPAL (Object Oriented Particle Accelerator Library), http://amas.web.psi.ch/.

[11] K. Badgley, "Design of a superconducting beam transport channel and beam dynamics for a strong focusing cyclotron", PhD. thesis, Phys. & Astron. Dept., Texas A&M University, USA, 2016.

[12] S. Assadi *et al.*, "Nonlinear beam dynamics studies of the next generation strong focusing cyclotrons as compact high brightness, low emittance drivers", in *Proc. PAC'15*, Richmond, VA, USA, May 2015, paper MOPMA047, pp. 656-658.