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NONLINEAR BEAM DYNAMICS STUDIES OF THE NEXT GENERATION STRONG FOCUSING CYCLOTRONS AS COMPACT HIGH BRIGHTNESS, LOW EMITTANCE DRIVERS*

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Abstract

The Strong Focusing Cyclotron development at Texas A&M University has evolved from stacks of cyclotrons to a single layer high brightness, low emittance device to produce greater than 10 mA of proton beam to a desired target at 800 MeV. The latest design has a major geometric design optimization of strong focusing quadrupoles and a modified algorithm of high gradient cavities. These optimizations address the turn separation and interaction of radially neighbouring bunches and produced a reduced the number of turns necessary to reach the desired final energy under control conditions. In this paper, we present the new design, the physics of nonlinear synchrobetatron coupling, mvh+nvv=p causing beam blow-up in other form of cyclotrons and how this work has resolved it. The cavity beam loading, and space charge effects of multi turns at low energies to reduce losses, are discussed.

INTRODUCTION

The Accelerator Research Lab at Texas A&M University is developing designs for a strong-focusing cyclotron (SFC) as a high-current (10 mA CW) proton driver for fundamental physics, ADS fission, production of medical isotopes, and as a spallation source for neutron damage studies. Challenges associated with high power, high brightness linear accelerators, such as minimizing particle losses, space charge and beam stability, are also obstacles from the SFC. Cyclotrons have additional degrees of complexity as the multi-bunches pass through the cavities and have coulomb and Wakefield interactions. We report on three studies in this paper: (1) better understanding of proposed cavity by modelling stiffened cavity after additional corrugations, (2) initial corona and multipacting studies of the new cavity, and lastly wakefield studies of uncoupled and coupled bunches traversing through SFC cavity with a realistic 6D initial bunch distribution.

BEAM DYNAMCIS

The world-record CW beam power for a proton accelerator today is the PSI isochronous cyclotron [1], which produces 2.2 mA CW at 590 MeV. Two issues pose the main limits to its beam current: succeeding orbits overlap strongly so the defocusing action of space charge is exacerbated; and it has only weak focusing so that the betatron tunes migrate throughout acceleration and cross multiple resonances. We solve both problems in the SFC, see Fig. 1, by incorporating two new elements:

- superconducting ó-wave slot-geometry cavities that provide sufficient energy gain per turn to fully separate the orbits;
- beam transport channels that provide alternating-gradient strong focusing to maintain constant betatron tunes throughout acceleration.

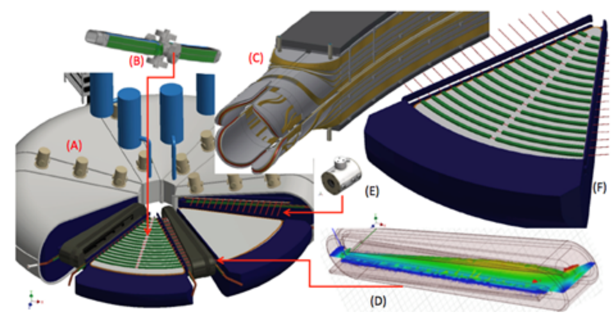

Figure 1: Strong-focusing cyclotron: a) cutaway showing the proton orbits, warm-iron flux return, (B) Beam Position Monitors between every two quad-channel. (C) quad channel composed of corrector and MgB2 4.2 cm bore magnet, (D) electric field distribution in the superconducting slot-geometry ½ wave cavity, (e) twenty five cm long 500 Watt instrumented beam dump at extraction channel, and (f) cold-iron flux plate with FD pairs of arc beam transport channels defining each equilibrium orbit.

Our initial simulations show that one such 800 MeV SFC could deliver > 10 mA continuously (cw) so that a high-current proton beam could be available for the above-mentioned purposes. In Ref. [2] we addressed the versatilities of quad focusing and added correctors allowing one to compensate for out of tolerance magnets by 100 times of other cyclotrons or 1% of main field. Additionally it has been shown the system can accept the loss of one of the ten cavities. In this paper we attempt to address the cavity and demonstrated a deep understanding of the self-field and beam coupling in the cavity.

SRF Cavity

The original straight cavity designed for SFC-800 MeV did not incorporate any corrugations in its calculations, although they were planned to be inserted based on the experience at BNL [3].

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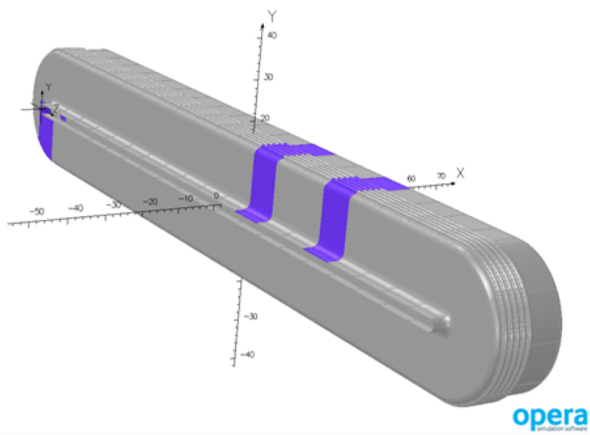

Figure 2: SFC straight cavity is designed from many sections. E&M calculations are made of parts for meshing. Matching of meshes initially introduced larger than normal corona at the seams. We fixed these problems as shown in Figure 4a.

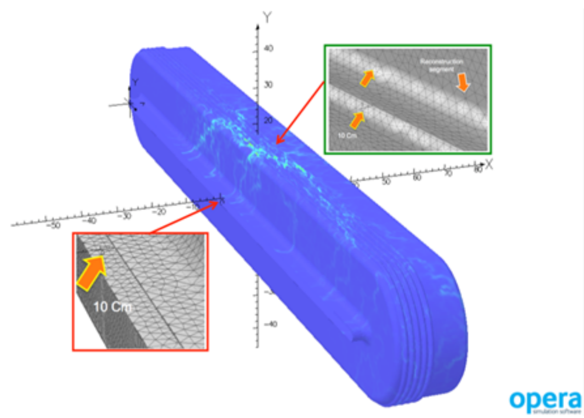

Figure 3: SFC straight cavity shows corona and not multipacting after further studies of E&M. The rate of Corona and its signature does not match the multipacting of 4a at high power due to primitive coupler design. The location of the coupler will be altered to determine its effects in future calculations.

The corrugations were to not only added as stiffeners for pondromotive forces, but based on BNL's calculations take advantage of increasing the path-length for the electron to reduce multipacting via secondary electron emission by the mechanical corrugations. The other element introduce to our calculations was corona. Corona is a surface condition phenomenon, but FEA method analysis for a cavity of this size, with additional mechanical stability, can be difficult. The simulation is difficult because small, hard to detect, mesh issues which can numerically introduce performance degradation. The cavity simulated is made of Niobium and operates at 4.2 K. We sweep a fan of electrons at the surfaces and scan for emission and multiplication based on $Y=\delta^N$, where N electrons are exponentially grown with secondary emission of δ.

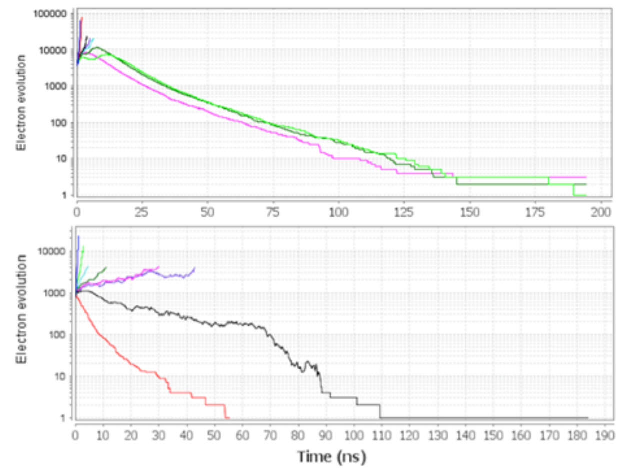

Figure 4: The surface phenomenon on the Bellows, or corrugations, is purely corona as the electron multiplication does not meet multipacting signature. As the electron count is doubled, the electrons impacted with increasing power insertion does not scale appropriately to indicate multipacting. The above shows multipacting at 40 dB at a simplified port-coupler location. Coupler is not centred correctly in the design.

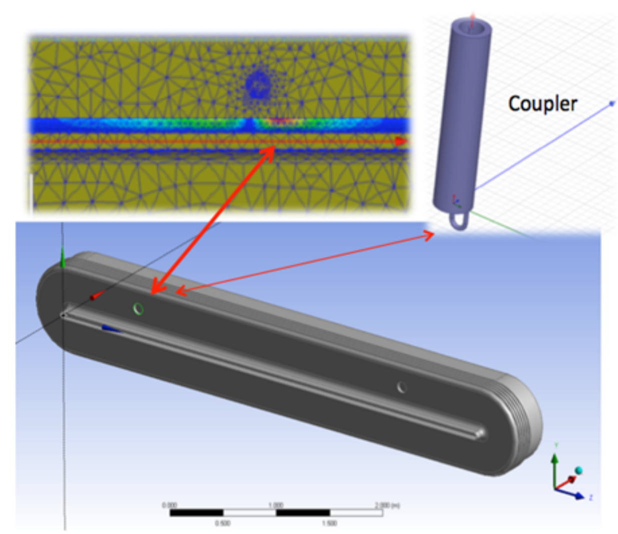

Figure 5: SFC cavity has shown resilience to pondromotive forces by producing clean S12 transfer function. Further studies of next generation cavity for a 100 MeV SFC require more rigorous work as reshaping the cavity produces RF field leakage and asymmetry which are not present in this cavity.

Wakefield Studies

The original linear and nonlinear beam dynamics of high intensity SFC-800 MeV was only concerned with the cavity as being loaded by the traversing beam travelling through it. When we considered low energy, nonrelativistic, beam of highly charged particles, we observed bunchlength sensitivity to injection, 6D emittances, RF voltage, injection energy, and momentum. In this studies, we tried systematically to take into account a bunched beam with the condition that they

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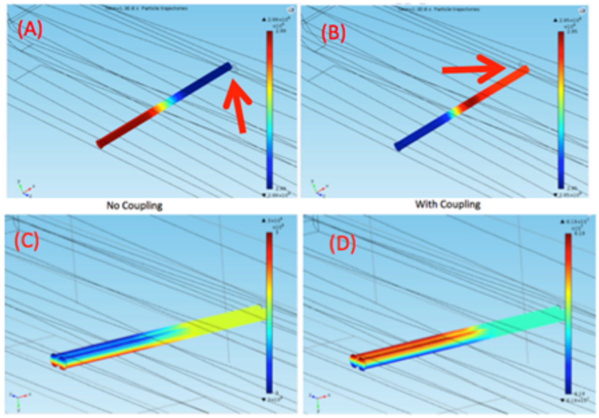

Figure 6: (A) Turn N injected bunch to the RF cavity, (B) turn N+1 bunch, (C) two bunches do not couple in the cavity, (D) two bunches couple via Wakefield.

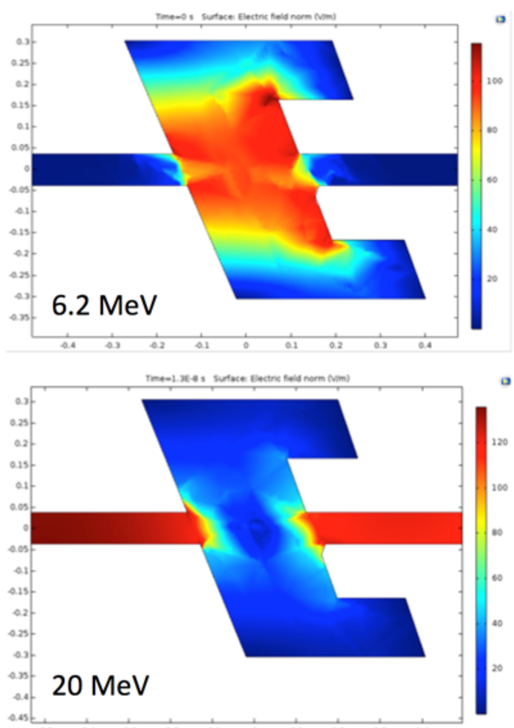

Figure 7: Wakefield effect of leading turn bunch is on trailing one is shown.

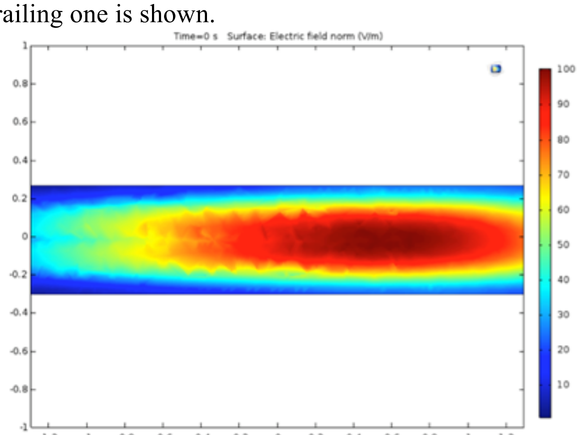

Figure 8: slower bunches is going into faster bunch Wakefield in slotted RF cavity.

arrive to the cavity for the specified turn with the appropriate energy, and the two seeds parallel to each other will be identical. The only variable are the realistic cavity, coulomb collisions, losses, beam cavity interaction, particle-particle interaction within the PIC space, secondary emission, radiation losses, and all positions and momentums at the arrival to the cavity associated with the turn. We can artificially allow both particles to have the same initial momentum but their energy gain is given by the cavity gain curve. At very low energy and very low intensity, we do not see any effect. At very low energy and high intensity, we see a clear effect from the wake of the higher energy beam on the lower injected bunch. However, at higher energies, above 20 MeV, no significant effect detected.

CONCLUSION

Wakefields are significant at very low energies. Further studies are underway to quantify time scales.

ACKNOWLEDGMENT

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