BEAM DYNAMICS OF A COMPACT SC ISOCHRONOUS CYCLOTRON-PRELIMINARY STUDY OF CENTRAL REGION*

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Abstract

We are in the preliminary stages of beam studies for the Megatron, a compact high field superconducting (SC) isochronous cyclotron, K250-42, is designed as a proof-of-principle for a single stage high power proton accelerator. This cyclotron intended to accelerate protons to a final energy of 250 MeV with two 45° dees with a final radius ~ 40 cm. The ideal isochronous field for the cyclotron has been built and the general beam dynamics studies are to be performed. Different injecting conditions are simulated to find the qualified injecting particles for the acceleration.

INTRODUCTION

Multi-MeV to GeV proton primary beams at intensities beyond present technological limits are required in the fields of long range fissile materials sensing, medical isotopes, ADRS and other high intensity proton beam projects. With existing technology, none of these machines are compact or inexpensive. For significantly lower cost, schedule and risk, a 250 MeV prototype Compact SC Proton Cyclotron, which addresses all of the fundamental design and performance issues of a compact cyclotron for such applications, was proposed[1]. This compact high field SC isochronous cyclotron K250-42, which is called Megatron, is designed as a proof-of-principle for a single stage high power proton accelerator. This cyclotron is to accelerate proton to a final energy of 250 MeV with two 45° dees with a radius ~ 40 cm. By employing a 20 mA external ECR proton source, the injected proton beam currents at high brightness are foreseen. Using phase selection in the center, a fully magnetized pole, low energy gain per turn, then a precise relation between momentum and radius at large radius is expected. We are seeking for two goals, a) to use this relationship to develop multi-turn extraction with passive elements only, to achieve a high external proton beam intensity (~ 1 mA); and b) to see if it is possible to achieve a high extraction efficiency without single turn extraction, with an energy spread $|\frac{\Delta E}{E}| \sim 0.1\%$[2]. The RF acceleration is on the first harmonic with $f_{rf} = f_0 \sim 64$ MHz. Superconductor coils will provide a central field of $B_0 = 4.3$ T and a peak hill field of 6.6 T. This ambitious project involvs many studies. We report here on just the beam dynamics in the cyclotron central region (CR).

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ISOCHRONOUS MAGNETIC FIELD

For preliminary study, to iterate the circulation of the beams within the magnetic field, we built a basic magnet model based on three codes: POISSON, OPERA-3D, and SOLIDWORKS. In order to get a high enough flutter field to match the high isochronous field, we have investigated a new pole material, Holmium, and have found that the material performed much better ferro-magnetism than that of the steel, which is shown in fig. 1[3].

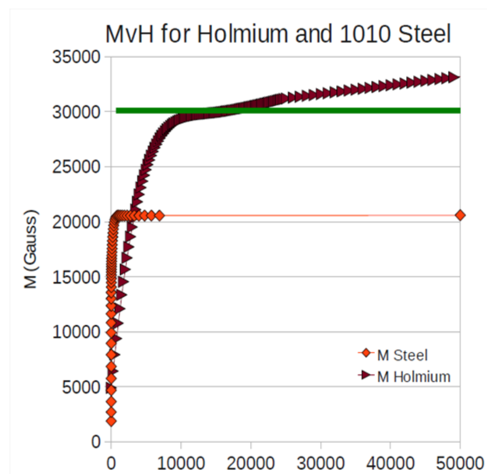

Figure 1: Magnetism comparison between Holmium and steel.

The uniform M approximation[4] says if the ferromagnetic material is saturated, the absolute difference between the magnetic fields in the hill regions and that in the valley is invariant. So the average field is only determined by the applied current in the superconducting coil plus the saturated ferromagnetic poles. Following Eq. 1 the simulated magnetic field data from OPERA-3D was manipulated to generate an ideal isochronous field for first-step beam dynamics iteration.

$$B_{ideal}(R, \theta) = B_{sim}(R, \theta) - B_{ave}(R) + B_{iso}(R) \quad (1)$$

Fig. 2 shows the averaged field matched the required isochronous field, which can minimize the phase error.
Fig. 3 shows a field map using an average isochronous field for one quarter of the median plan ($z = 0$). Fig. 3 tells that with Holmium we can reach a cyclotron that the peak magnetic field at around 6.5 Tesla which exceeds any existing proton isochronous cyclotron.
Fig. 4 generated from an Equilibrium Orbit Code GENSPEO, shows static equilibrium orbit properties over the entire acceleration. We can tell that the differential phase er-

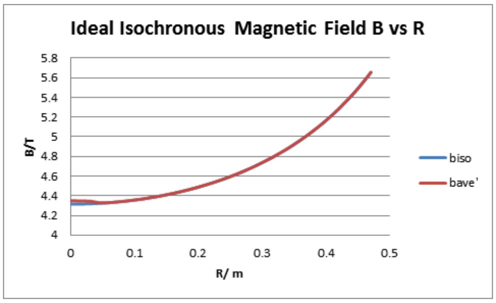

Figure 2: The average magnetic field and the ideal isochronous magnetic field.

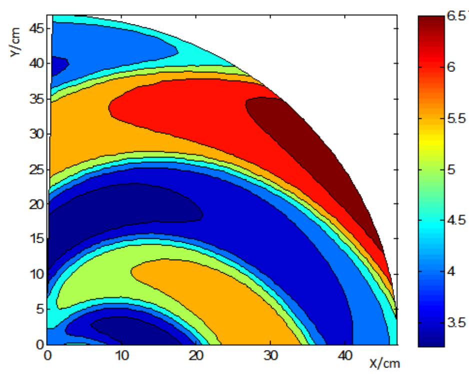

Figure 3: The total magnetic field map using an average isochronous field for one quarter of the median plan ($z = 0$).

ror is small, and just as important, particles see no disastrous resonances. Shown in Fig 2, a cone field, as a small perturbation on the isochronous field, is needed to meet the focus requirement in the center where the flutter is small. That makes a phase slip within the first gap of a few tens of degrees[5].

ION TRAJECTORIES IN SOURCE-TO-PULLER GAP

The first accelerating gap is between the ion source and the first dee tip, also called the "puller". The energy gain of the particle in the first gap is critical. Without enough energy gain, particles will be pulled back to the source or will hit the puller, leading huge particle loss at the very beginning. So it is very important to study the particle trajectories in the first gap for different injecting conditions. In addition, we should try to make the optimum injection time match the peak accelerating RF electric field. We are fortunate that the transit time effect is limited due to the high magnetic field[6]. So it is easier for us to perform precise study of the central region.

The software OPERA-3D was used to generate a simplified source-to-puller electric field map as showed in Fig. 5. The source-to-puller distance is 0.5 cm, the same as the accelerating spiral gap at $r \leq 5$ cm in the cyclotron. The amplitude of the accelerating field is about 86 KV.

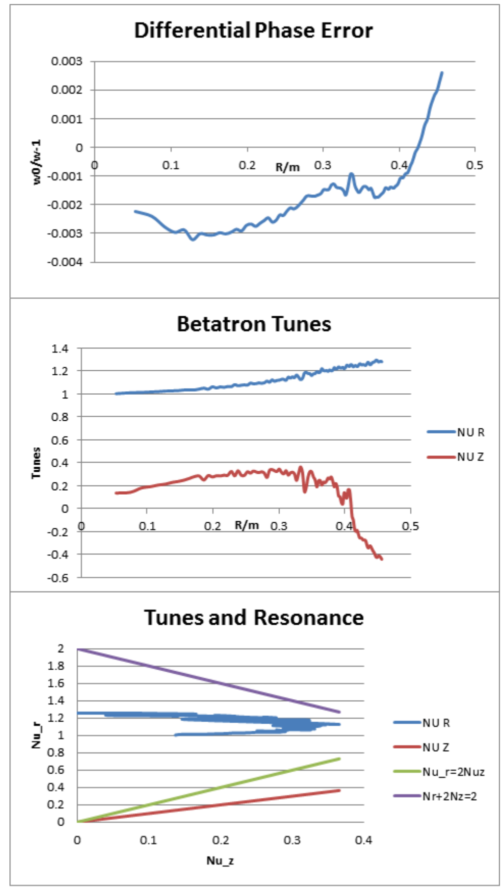

Figure 4: The general beam dynamics of the ideal magnetic field.

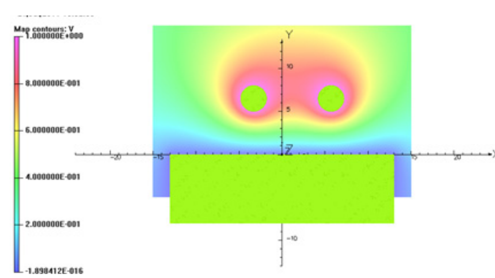

Figure 5: The source-to-puller electric field map.

The beam code Z3CYCLONE has been employed to calculate the ion trajectories in the first gap for different starting conditions. For all the cases, the field map is laid with a -30° rotation angle with respect to the magnetic field map due to the configuration of an ECR ion source and a spiral inflector. In Z3CYCLONE, two coordinate systems are overlapped. One is the absolute coordinate (x, y) matching the magnetic field and the other is the particle coordinate (ξ, η) based on the particle source. Four different cases with varied starting time phase, injecting angle, injecting ξ_0 and η_0 positions are showed in Fig. 6.

Fig. 7 shows the comparison of energy gains between dif-

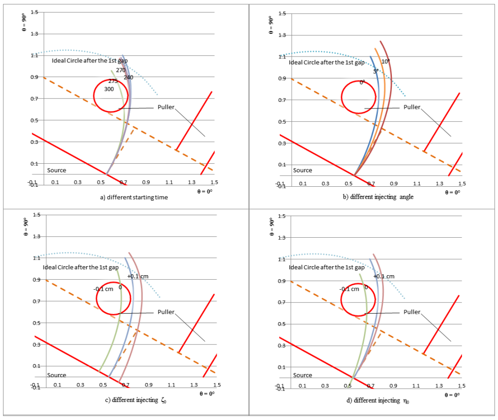

Figure 6: Ion trajectories with different injecting situations of a) starting time, b) injecting angle, c) injecting position ξ_0, d) injecting position η_0.

ferent injecting situations.

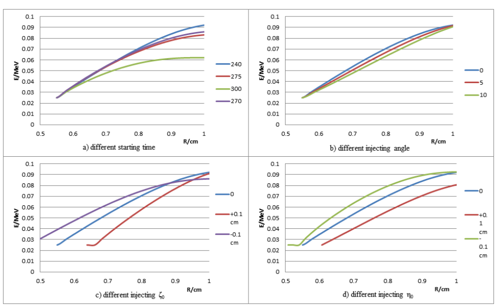

Figure 7: Energy gains in the source-to-puller gap with different injecting situations of a) starting time, b) injecting angle, c) injecting ξ_0, d) injecting η_0.

To be accelerated to the final energy, it requires particles not to hit the puller or to strike back to the source. In addition, we need particles to gain more energy and the system to be operated easily. Fig. 6 and fig. 7 show that to inject protons on the starting phase of $\tau = 240^o$ with respect to the RF electric field of the first dee, and setting the injecting angle to be 0^o, the injecting position to be $\xi_0 = 0, \eta_0 = 0$ is a best way. Also setting injecting angle to be 5^o or 10^o are good options.

CONCLUSIONS

The 250 MeV prototype isochronous sc proton cyclotron, Megatron, is in its initial study stage. The required strong magnetic field can be approached by employing the new ferromagnetic material, Holmium. Using Holmium as the magnetic pole tips, we can access a peak field around $B \sim 6.5$ T. Based on the magnet model built in OPERA-3D, an ideal isochronous field has been investigated to establish the required starting situation of the field. This field was utilized for the preliminary beam dynamics calculation of particle acceleration in the first gap. OPERA-3D was also used to generate the simplified electric field between the source and the puller for these simulations with the beam code Z3CYCLONE. The comparison of different injecting situations shows that injecting protons on the starting phase of $\tau = 240^o$ with respect to the RF electric field is the best option.

In the future, we will precisely investigate the acceleration from the first gap, further through the central region, and finally to full energy. A detailed central region electric model, now in development, is shown in fig. 8. The spiral inflector housing is in the center, with 2 dees (blue) and 4 hills (green). The overall diameter of this model is 10 cm, and the acceleration gaps are 5 mm. A dee voltage of 86 kV is assumed.

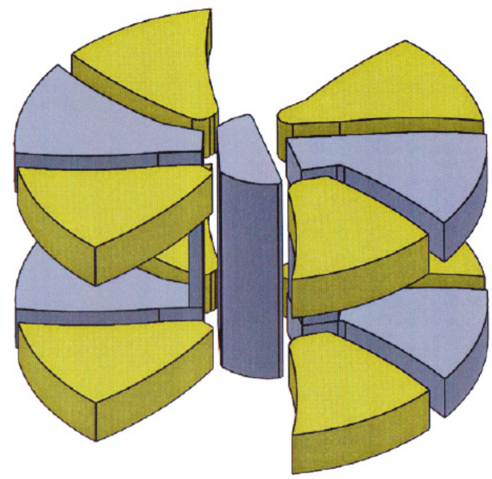

Figure 8: The full 3D CR electric field model for Megatron.

By iterate the calculation and the adjustment, we can adjust the basic magnet model in OPERA-3D and SOLIDWORKS carefully to prepare for the fabrication.

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