PHYSICAL DESIGN PROGRESS OF AN 800 MeV HIGH POWER PROTON DRIVER*

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Abstract

We presented the conceptual design of an 800 MeV high power proton ring cyclotron in the paper [1]. More detailed physical design was carried out since then. The 3D model of the main magnet is built and the magnetic field map is obtained which fulfils the requirement of isochronism. The most challenging issues regarding high power operation, including the space charge effects and beam losses during the extraction, are quantitatively studied by using state-of-the-art high performance computation technique. On that basis the layout of the cyclotron is adjusted.

INTRODUCTION

An 800MeV high power cyclotron was proposed to provide high power proton beam for ADS, neutron science, proton radiography, RI production and other applications [1]. After the systematic investigation and comparison of different candidates, a separated-sector, warm-magnet solution is adopted. In this solution, an 100 MeV proton beam is injected into the cyclotron and extracted at around 800MeV by using electrostatic deflection, which is proven to have high extraction efficiency. The current layout of this solution is shown in Fig. 1. It is worthy of note that accelerating cavities number is increased by one so as to increase the energy gain and radial gain per turn, since faster acceleration is advantageous to reduce space charge effects and larger turn separation is favorable for clean extraction. The expense we have to pay is the more crowded space, because one valley is occupied by both the injection line and cavity, but this shouldn't be big challenge since it is already realized in PSI 590 MeV Ring.

MAGNET MODELING

In the conceptual design, an ideal isochronous magnetic field map was constructed by using the scaling laws and the Enge's empirical model [2]. Based on that, the basic fundamental beam dynamics was studied and show the feasibility of this solution in paper [1]. Since then we managed to build a three-dimensional finite element model of the main magnet and to calculate the practical magnetic field by numerical methods. In order to reduce the numerical error, the 3D model is discretized by using hexahedron elements, as is shown in Fig.2-a. After several iterations, the isochronous magnetic field distribution is achieved, which can meet the beam dynamics requirements, such as differential phase slip restriction, horizontal and vertical focusing. Figure 2-b shows the magnetic flux intensity distribution on the magnet surface, in which the field is closing to saturation at the outer edge of the pole. The maximal field on the middle plane is about 2 Tesla and the average field increases from 0.52 Tesla at the injection radius to 0.92 Tesla at the extraction radius, as is shown in Fig. 3.

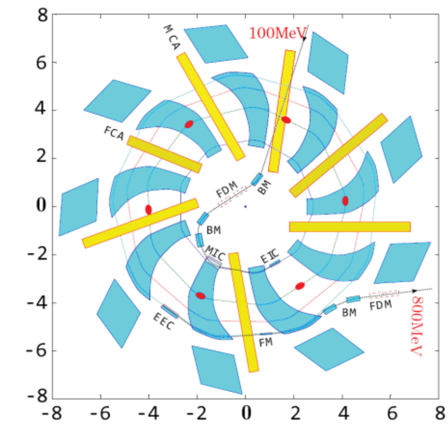

Figure 1: The updated layout sketch of the 800 MeV cyclotron solution, including injection and extraction elements (MCA: main cavity, FCA: flat-top cavity, FDM: focusing doublet, BM: bending magnet, MIC: magnetic injection channel, EIC: electric injection channel, FM: focusing magnet, EEC: electric extraction channel).

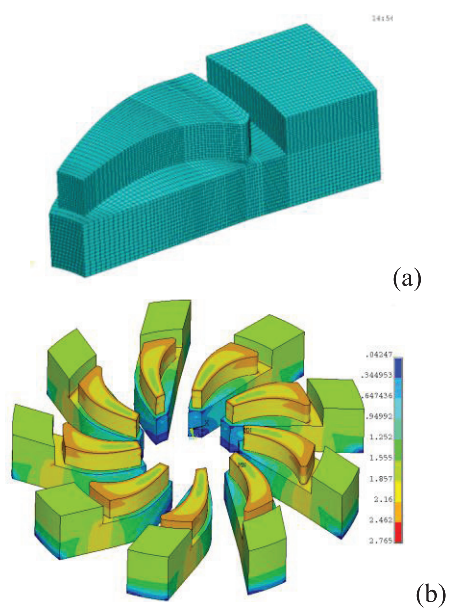

Figure 2: (a) The 1/8 model of the main magnet; (b) the magnetic flux intensity distribution on the main magnet.

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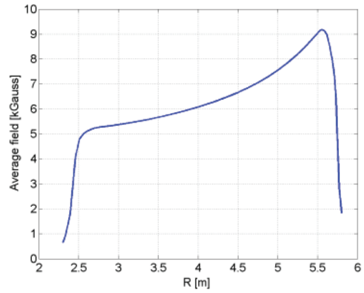

Figure 3: The average field on the middle plane.

BEAM DYNAMICS

Turn Diagram

The beam dynamics study is carried out based on the field map which is discussed above. Figure 4 shows the differential phase shift and the magnetic field error during the acceleration is restricted within ±0.5% during the acceleration. At the extraction region, a sharp filed drop is needed to increase the orbit curvature and to decrease ν_r to around 1.5, as is shown in Fig. 5. Because when ν_r=1.5, the betatron oscillation phase advance is 540^o and hence the turn separation of the coherently oscillating beam reaches maximal, which is favourable for single-turn extraction. In the ideal field map [1], no dangerous resonance line is crossed during acceleration, but for the practical magnetic field of current design, the ν_r=2ν_z and ν_z=1 resonance lines are crossed at the energy around 800 MeV. In PSI Ring, the ν_r=2ν_z line is crossed by 2 times but no beam loss is observed at these regions. The reason is that profiting from large energy-gain per-turn, the beam passed these dangerous regions very quickly. Therefore, no beam loss is anticipated in this cyclotron, neither. However, more study is needed to evaluate their influences and the restrictions of the first harmonic field error. The field structure should be optimized further to increase the vertical focusing and to avoid crossing dangerous resonance lines if possible.

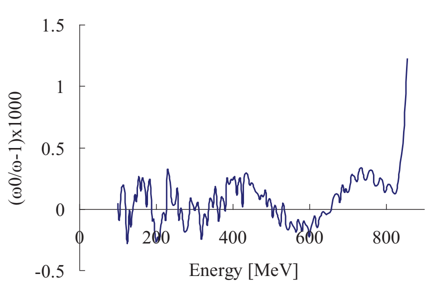

Figure 4: The differential phase shift.

Acceleration and Extraction

The Accelerating equilibrium orbit is tracked by using OPAL-CYCL code, in which the practical magnetic field map and the sinusoidal cavity voltage curves are used. Six single-gap cavities with a peak voltage of 1 MV and one flattop cavities with peak voltage standing at 11.5% of the main voltage accelerate the proton to 845 MeV in 149 turns, meanwhile, the rf phase slip is kept in -10~20^o.

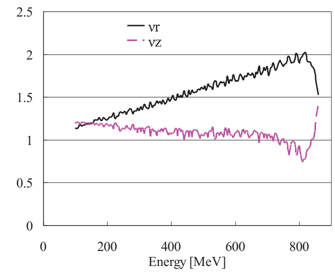

Figure 5: The tune diagram of the cyclotron.

Beam extraction is a critical issue for high power proton cyclotron. The total turn separation consists of two parts: acceleration and precession. Therefore, in the current solution, the accelerating cavities number is increased to 6, comparing with 5 in the conceptual design. On the other hand, the beam is eccentrically injected into the cyclotron. The injection radius and radial momentum are adjusted iteratively to achieve maximal value of the last turn separation. The optimized case of eccentric injection case is shown in Fig.6, which shows we can get a bonus of 20 mm from precession and the last turn separation be enlarged to as high as 24 mm. It shows that with this scheme, we can safely extract the beam from cyclotron by putting the deflector septum between the last two turns without beam loss. However, in this simulation we did not include the space charge force of the beam itself, which could distort the bunch distribution and enlarge beam's radial size for high current operation.

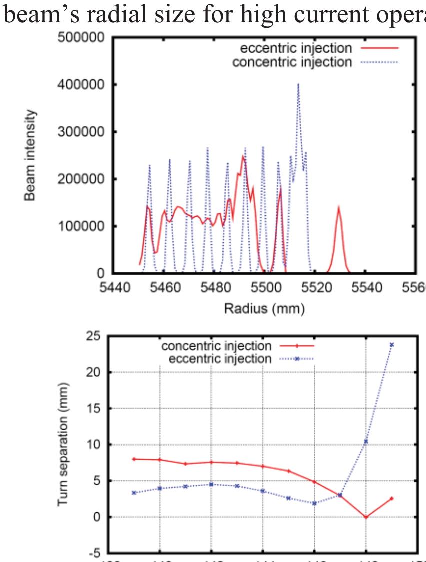

Figure 6: The radial beam profile (up) and center-to-center separations (down) of the last few turns for concentric and eccentric injection case.

SPACE CHARGE EFFECTS

The maximum beam power delivered by the cyclotron is determined mainly by space charge effects. Space

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charge forces can increase the beam emittance and consequently reduce the extraction efficiency and result in beam losses during acceleration and extraction, which could be a serious limitation of beam current. Therefore, the massive particle simulation is carried out to investigate space charge effects.

The space charge effects are quantitatively studied by using the OPAL-CYCL [3, 4], a flavour of OPAL framework [5]. Since the injector cyclotron and transfer line is not designed yet, in the simulation we assume a typical gaussian distribution with conservative values for the normalized rms emittances of 0.2π mm-mrad in both the transverse directions, full phase width of $\pm 10^{o}$ and energy spread of zero. The beam is injected eccentrically with the optimized settings to enlarge the turn separation at extraction. In the simulation, $5\text{x}10^{5}$ macro-particles are tracked simultaneously and a co-moving 64x64x32 grid is utilized to solve space charge fields. The simulation for 0 mA, 1 mA and 5 mA beam current scenarios are carried out for comparison. The result shows the space charge have significant influence on the beam's behaviour. Along with the beam current increases, the longitudinal rms size is shorten, which is helpful for repressing energy spread increase during acceleration; Nevertheless, the radial size is lengthen, which is unfavourable for single-turn extraction. The beam's radial profiles of the last few turns is shown in Fig. 7, which shows for 0 mA and 1 mA case, the beam profile of extracting turn is clearly separated with the circulating turns, but they totally overlap for 5 mA case. Therefore, it is concluded that for the current design, the beam can be extracted cleanly when the beam power is less than 0.8 MW; but for higher beam power operation, more structure optimization and space-charge compensation methods are required with the aim of clean extraction. Figure 8 shows a snapshot from the top of cyclotron when the bunch reach the 0^{o} azimuth of turn 50. It worth to noting that for 5 mA case, the space charge induces longitudinal instability and the bunch divided into many sub-bunches, which was first observed in MSU SIR[6].

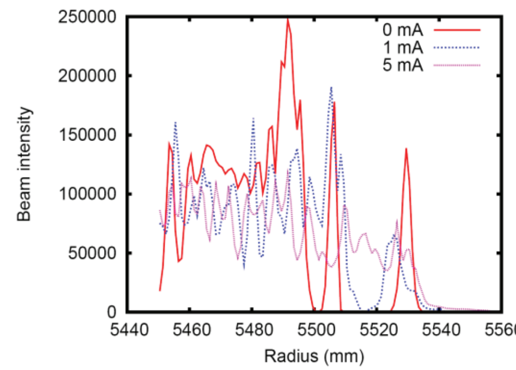

Figure 7: The beam intensity along radius of the last few turns for 0, 1 and 5 mA beam current.

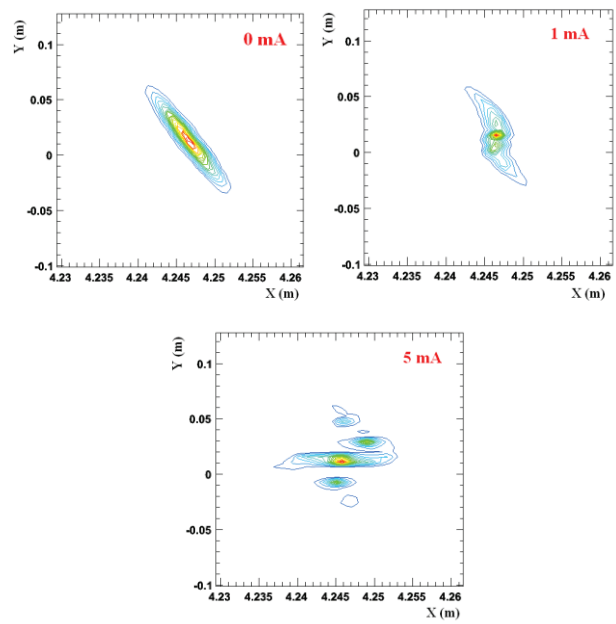

Figure 8: Top view of the bunch distribution at 0º azimuth of turn 50 in global coordinates for 0, 1 and 5 mA beam current scenarios.

OUTLOOK

The cyclotron magnet structure will be optimized further to increase the vertical focusing and to avoid crossing dangerous resonance lines if possible. More solutions should be explored to repress space charge effects and to enlarge the turn separation further. For example, flattop cavity phase can be adjusted to partially compensate the linear part of space charge force. Meanwhile, this physical design will be reviewed from the engineer's views to make it more feasible.

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