CONCEPTUAL DESIGN OF A 100 MeV INJECTOR CYCLOTRON

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Abstract

This paper outlines the conceptual design work of a 100 MeV injector cyclotron for the 800 MeV ring cyclotron, which was proposed by the China Institute of Atomic Energy (CIAE) as a high power proton source of diverse application purpose. For high intensity operation, a straight-sector magnet structure and low magnetic field are preferable. This cyclotron is very similar to PSI Injector II cyclotron, but with higher extraction energy.

INTRODUCTION

In the BRIF-III proposal, an 800 MeV high power proton cyclotron complex was proposed to provide high power proton beam for ADS, neutron science, proton radiography, radioactive ion production and other applications [1]，[2]. In this solution, the ECR source will provide a 40~50 mA quasistatic proton beam for a Cockcroft-Walton high voltage generator or a RFQ, which can accelerate the proton to around 1 MeV. Then a low-energy beam line will transport and inject the beam into the injector cyclotron, in which the beam is accelerated to 100 MeV by two double-gap RF cavities and will extracted by electrostatic deflector at its final turn. A medium-energy beam line delivers the beam to the 800 MeV ring cyclotron. The block diagram of the facility is shown in Figure 1.

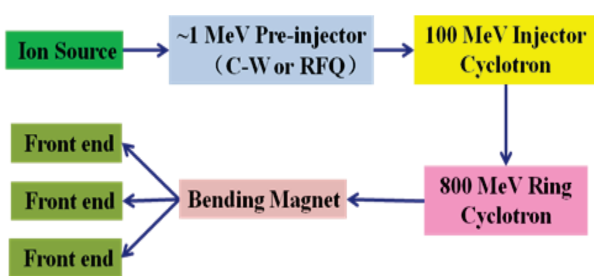

Figure 1: The block diagram of the BRIF-III proposal.

The choice of the energy relies on the feasibility within the BRIF project. This BRIF-III project is divided into two phases. For the first phase, it is proposed to construct the 800 MeV ring cyclotron and to utilize the 100 MeV, 200 µA compact H- cyclotron CYCIAE-100 of the BRIF-II project as its injector. The CYCIAE-100 is under construction at CIAE and is scheduled to start commissioning in 2014. Then in the second phase, in order to achieve a high beam current, the CYCIAE-100 will be superseded by a dedicated separated-sector injector cyclotron, which is described in this paper. The layout of the BRIF facility is shown in Figure 2.

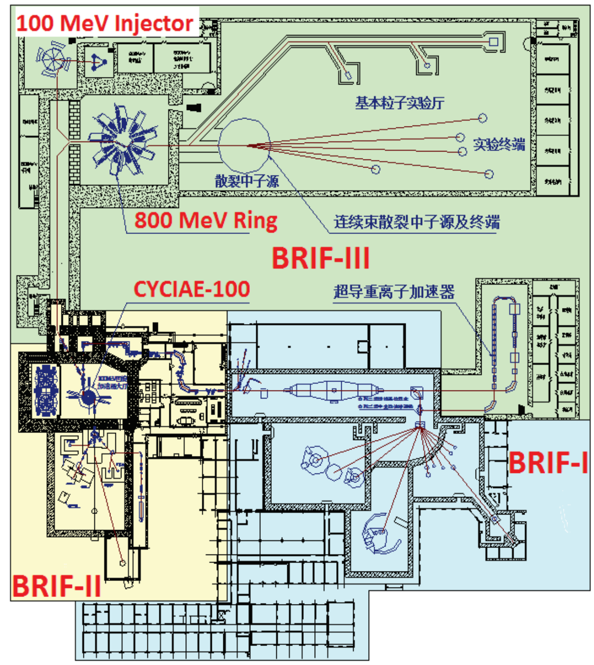

Figure 2: The layout of the BRIF facility.

OVERALL DESIGN

For high beam intensity operation, one must take beam loss control into account at the very beginning of the design. A large pole diameter is preferable for achieving low beam loss. There are two reasons. Firstly, in cyclotrons which accelerate bare proton particle, a large inter-turn separation for the last two turns is required to insert the septum of electrostatic deflector in between. The inter-turn separation is proportional to the orbit radius. Along with the increase of the beam current, the beam's radial size will be enlarged because of the large emittance of injected beam and space charge effects during accelerating. Secondly, we have more space in the valley to insert the auxiliary elements to do fine adjustment for the beam, such as collimators, dipole and quadruple magnets. In the preliminary design, the key parameters are given out for the dedicated injector cyclotron, which is listed in Table 1 and the layout is sketched in Figure 3. Two 3rd harmonic cavities are kept in the baseline design. But according to PSI Injector II experience, most probably they are not required for high current operation because a compact stationary beam will develop during the accelerating because of the strong vortex motion in the horizontal-longitudinal plane, which is introduced by the strong space charge force and the intrinsic coupling between the horizontal and longitudinal directions. In that case, all the four valleys can be used to install the accelerating cavities to enlarge energy gain per turn. Accordingly the total turn number can be reduced by half

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and the inter-turn separation at extraction can be doubled, which is quite favourable for controlling the beam loss during extraction.

Table 1: Key Parameters of the Injector Cyclotron

Item	Value
cyclotron type	Separate sector
cyclotron diameter (mm)	6100
cyclotron height (mm)	4000
Max. hill field (T)	1.15
Average field (T)	0.36~0.41
Sector Number	4
Sector radius (mm)	4134
Sector width (˚)	22~30
Hill gap (mm)	40
Main cavity number	2
Flat-top number	2
RF frequency (MHz)	44.4
Harmonic number	4
Cavity type	Double gap
Cavity angle(˚)	22.5

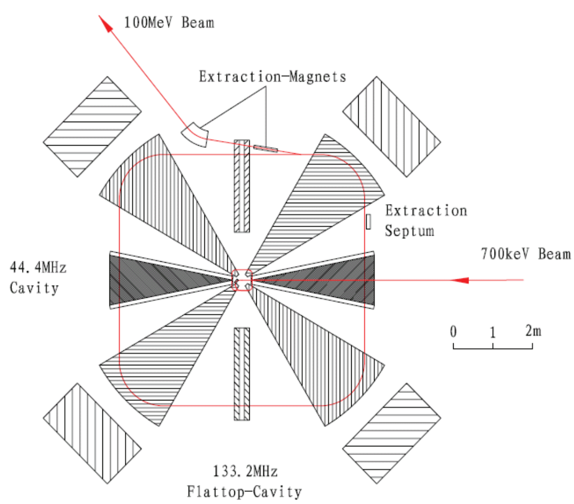

Figure 3: Layout sketch of the 100 MeV injector cyclotron.

BEAM DYNAMIC DESIGN

Isochronism and Tune Diagram

For the conceptual design stage, the Enge's empirical model is used to generate the fringe fields on the median plane, which is similar with the conceptual design of the main field for the 800 MeV main ring [1]. The resultant field map on the median plane is illustrated in Figure 4. Based on the calculation of the equilibrium orbits, the phase slip and transverse focusing characteristic for the injector is calculated. Figure 5 illustrates the phase slip history with the assumption of a energy gain per turn of 2 MeV, which shows the phase could be controlled within ±30o. The tune diagram for the injector is shown in Figure 6. These results indicate the good isochronism of the field is well achieved and the vertical focusing is strong enough for high intensity beam operation.

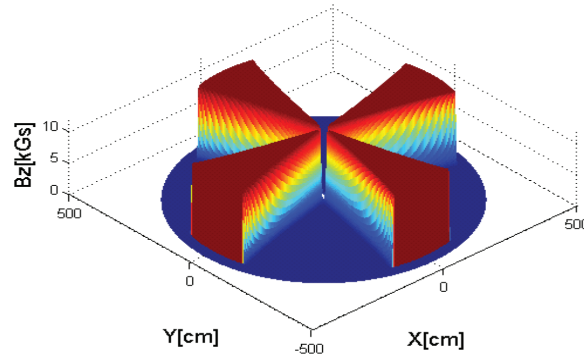

Figure 4: Field map for the 100 MeV Injector cyclotron.

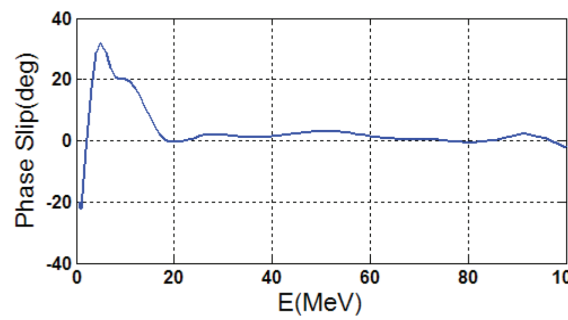

Figure 5: Phase slip of the 100 MeV injector cyclotron with the energy gain per-turn of 2 MeV.

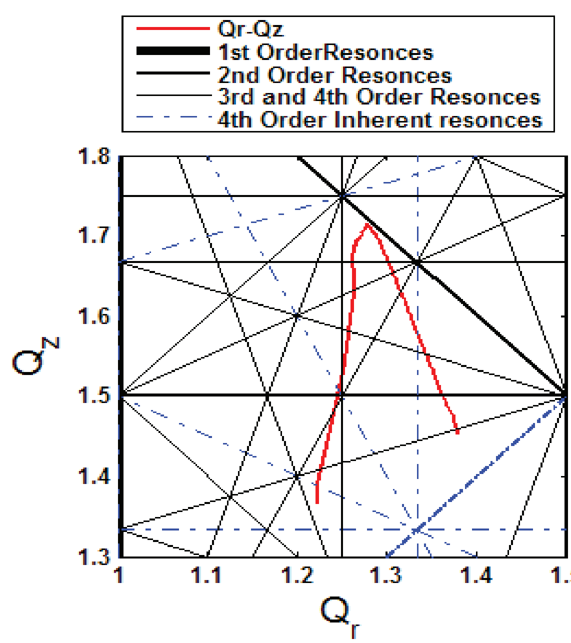

Figure 6: Tune diagram for the 100 MeV injector cyclotron.

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Resonances

The tune diagram in Figure 6 indicates that several resonances are crossed in the process of acceleration. Table 2 illustrates the major resonances crossed in the cyclotron. The second order resonance 2Qz=3 is crossed for two times, which may lead to the growth of the vertical beam emittance. The third order resonances 2Qr+Qz=4 and 3Qr=4 can neither be avoided by field shimming as they are driven by the main field. In order to investigate the influence to the beam quality brought by these resonances, two initially off-centered particles are tracked numerically. Both of the two particles have an initial offset of 5 mm vertically, meanwhile, in the radial direction there are off-centered by +5 and -5 mm respectively. Figure 7 records their radial and vertical oscillation amplitude at 0o azimuth respectively. Profiting from the high cavity voltage, the particles are fast accelerated and the major resonances did not bring evident influence on the beam quality. Further study indicates that a significant distortion of the beam quality could happen only when the voltage of the RF cavities decreases to 10% of the designed value.

Table 2: Major Resonances Crossed in the Injector

Resonance Order	**Resonance** expression	**Energy** E/MeV	**Driving** Term	**Effect**
2	2Qz=3	1.6, 84.5	dB_{z3}/dr	ε_z growth
3	$2Qr+Q_z=4$	1.7	B_{z4}	ε_z growth
	$3Q_r=4$	60.0	B_{z4}	ε_r growth

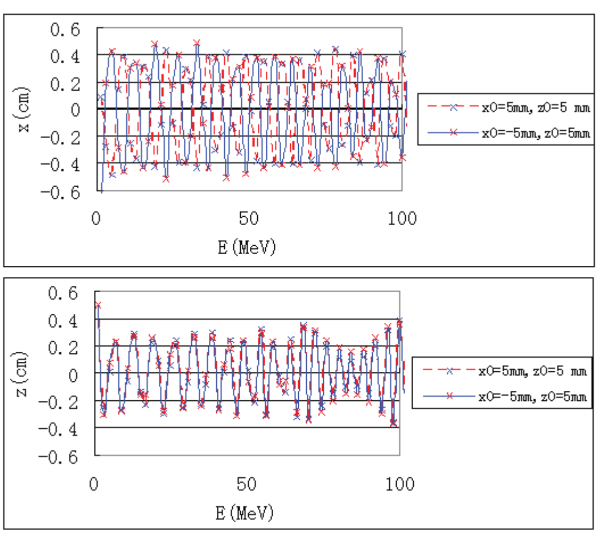

Figure 7: The radial (up) and vertical (down) oscillations of two off-centered particles.

CONCLUSION

The conceptual design work for a 100 MeV injector cyclotron has shown in this paper. Results indicate that the designed parameters are reasonable and could meet the requirements for basic beam dynamics. In the next step, the three-dimensional magnet model will be built by using finite element method and the quantitative beam dynamics simulation including space charge will be carried out by using the OPAL-CYCL code [3]. After that, the median-energy beam transport line and beam matching scheme between the injector to the main ring will be studied.

AKNOWLEDGEMENTS

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