TOWARDS QUANTITATIVE PREDICTIONS OF HIGH POWER CYCLOTRONS *

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Abstract

The large and complex structure of cyclotrons poses great challenges in the precise simulation of high power beams. However, such simulation capabilities are mandatory in the design and operation of the next generation high power proton drivers. The powerful tool OPAL enables us to do large scale simulations including 3D space charge and particle matter interactions. We describe a large scale simulation effort, which leads to a better quantitative understanding of the existing PSI high power proton cyclotron facility and predicts the beam behaviour of CYCIAE-100 under construction at CIAE.

INTRODUCTION

High intensity problems in cyclotrons draw a lot of attention because of the widely use of high intensity proton beams for palliation neutron sources and accelerator driven transmutation technologies. The 1.3 MW CW proton beam at the Paul Scherrer Institute (PSI) poses great challenges for high intensity beam simulations in cyclotrons [1]. With the fast development of HPC (High Performance Computing), the powerful tool OPAL [2] which includes 3D space charge and particle matter interactions enables us to perform large scale simulations in complex high intensity accelerators.

The Beijing Radioactive Ion-beam Facility (BRIF) is now in the construction phase at the China Institute of Atomic Energy (CIAE). The driving accelerator of this project, CYCIAE-100, a high intensity proton cyclotron, is designed to provide a 75 MeV~100 MeV, 200 μA~500 μA proton beam [3].

In this paper, we report on precise beam dynamic simulations of the PSI Ring Cyclotron. We present a new particle matter interaction model taking into account energy loss, multiple Coulomb scattering and large angle Rutherford scattering together with the 3D space charge. This model is used to obtain the necessary beam loss statistics during the acceleration process in CYCIAE-100 Cyclotron This data is indispensable in the design of an efficient collimation system.

THE 1.3 MW PROTON CYCLOTRON

The high intensity accelerator complex at PSI generates a 1.3 MW proton beam in routine operation. This gives us the unique opportunity to study the beam behavior of high intensity proton beam based on the experience with MW beam powers.

The simulation in this paper starts at the beginning of the 72 MeV transfer line between the Injector 2 and Ring Cyclotron. There are 18 beam profile monitors in both x and y direction. The initial distribution is obtained using Transport [4,5] and fitting the profile monitor data.

For the start of the Ring simulation, the emittance acquired at the end of the transfer line is used. The length of the bunch is measured using the time-structure probes [6]. For a 2 mA beam, the non-normalized radial emittance is $1.5\pi\, mm \cdot mrad$, vertical emittance is $0.6\pi\, mm \cdot mrad$, and the standard deviation of bunch length is $\sigma = 23\, mm$. A six-dimensional Gaussian distribution is used as the initial distribution of the Ring Cyclotron.

The beam intensity of the Ring Cyclotron is mainly limited by the beam losses at the extraction. To keep the extraction loss lower than 0.02%, the following effects must be considered.

- The turn separation at the position of extraction septum must be as large as possible.
- The radial beam size at the extraction region should be smaller than the turn separation and large amount of halo particles must be avoided.
- Since a long "pencil " beam is used in the Ring Cyclotron, the space charge effect must be effectively compensated to avoid the formation of the S-shape beam which apparently increases the effective radial beam size.

In the original design of the Ring cyclotron, the beam will pass the coupling resonance $\nu_r = 2\nu_z$ four times at 490, 525, 535 and 585 MeV. A large horizontal oscillation is transformed into a large vertical one at the coupling resonances which can lead to beam losses. A trim coil TC15 was designed to avoid the resonance at 525 and 535 MeV. It provides an additional magnet field and field gradient in the radial direction. The effect is shown in Fig. 1. The trim coil provides a maximum magnetic field of 14 Gs. It has a long tail towards the smaller radii in order to make the integrated strength of the trim coil over the radius to zero.

A long beam with bunch length of $\sigma = 23\, mm$ is used in the Ring Cyclotron. To get a beam at the extraction turn with low losses, the flattop phase is adjusted to compensate the distortion caused by space charge forces. For an ideal flattop, the whole beam gains the same energy after one turn. In the case of high beam current, when the space charge force cannot be ignored, the head particle gains additional energy and the tail particle loses energy, so the beam will tend to show an s-shape in an isochronous cyclotron. Through the shift of the flattop phase, the tail particle gains more energy than the head one, which can compensate the linear part of the space charge force. Consequently there exists an optimum flattop phase for an given intensity.

Since $\nu_r \approx 1.7$ in the region of extraction, adjusting the injection position and angle, results in the betatron amplitude being almost equal to the radius gain per turn. This is a special turn pattern because the last turn is well separated from the overlapping second, third and fourth last turns (see Fig. 2). In this case, the turn separation at the extraction turn is much larger than a width of the beam, hence it allows the extraction of high intensity beam with low losses.

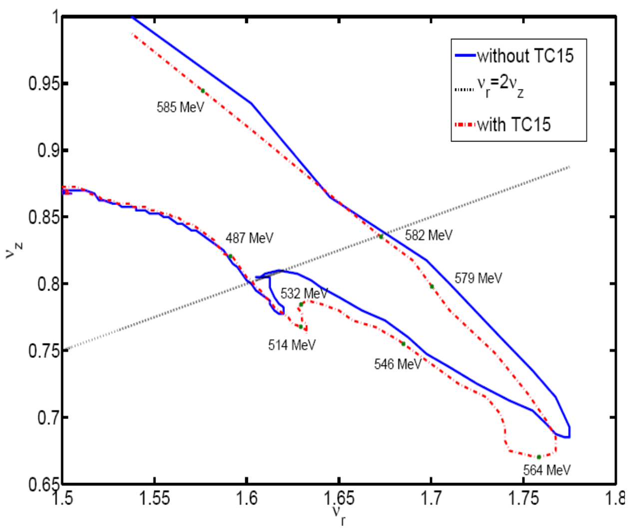

Figure 1: Tune diagram with and without TC15

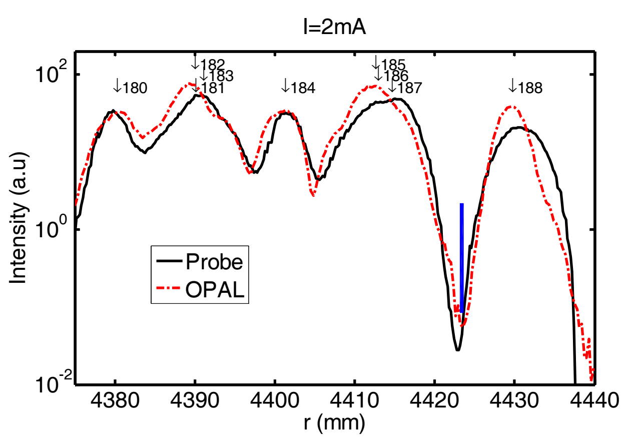

Figure 2: The formation of the turn pattern at extraction in the PSI Ring Cyclotron.

THE PARTICLE MATTER INTERACTION MODEL

General-purpose Monte Carlo codes, e.g. MCNPX [7], FLUKA [8,9], are developed to model the particle matter interaction, however, they have limited capabilities to track the particle in both complex external and space charge fields. We extend OPAL in order to handle efficient particle matter interactions, hence collimator systems in high intensity accelerators can be modeled together with space charge.

When the particle interacts with the matter, the energy loss is calculated using the Bethe-Bloch equation. Comparing the stopping power with the PSTAR program of National Institute of Standards and Technology (NIST), the error is found in the order of 10 % for copper, from several MeV to 10 GeV. For the application at PSI, the error is within 3% in the region from 50 MeV to 1 GeV. For relatively thick absorbers such that the number of collisions is large, the energy loss distribution is Gaussian [10]. If the energy of the particle is low enough to be absorbed after a certain distance, it is marked to be deleted and written to a file.

The Coulomb scattering is treated as two independent events: the multiple Coulomb scattering and the large angle Rutherford scattering, using the distribution given in [11].

As a benchmark of the collimator models in OPAL, the energy spectrum and angle deviation is compared against two general-purpose Monte Carlo codes, MCNPX and FLUKA, as shown in Fig. 3. A 72 MeV cold Gaussian beam with $\sigma_x = \sigma_y = 5\,mm$ is send through a copper elliptic collimator with the half aperture of 3 mm in both x and y direction from 0.01 m to 0.1 m. The deflected particles contribute to the energy spectrum and angle deviation after a collimator. These particles may be lost downstream.

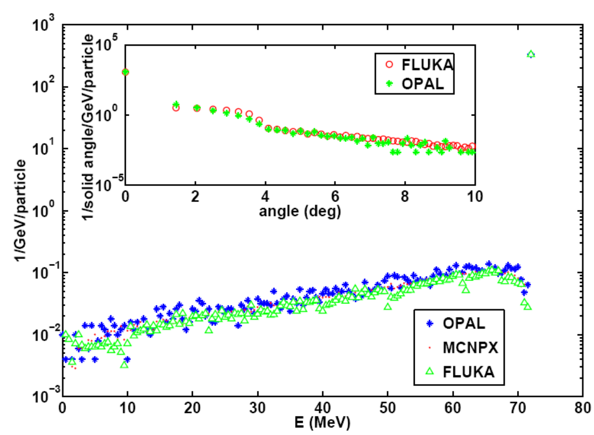

Figure 3: Energy spectrum and angle deviation (small plot).

THE COLLIMATOR SYSTEMS FOR CYCIAE-100

CYCIAE-100 is a compact isochronous cyclotron in which the vertical gap is limited. The half gap of magnet pole decreases from 30 to 24 mm with the radius. The two RF cavities with half gap of only 20 mm locate at the red line region as shown in Fig. 4. The revolution period is 90 ns and the bunch length is 2.5 ns.

The OPAL simulation including space charge effect and particle matter interaction starts with the initial energy of 1.49 MeV and normalized emittance of $4\pi\, mm \cdot mrad$.

The imperfect case is considered when simulating the vertical beam loss. Suppose the bunch is 3 mm off center in radial and vertical direction, and also a mismatch of the envelope is given as: $\sigma^*_{x,z} = 2\sigma_{x,z}, \sigma^*_{px,pz} = \sigma_{px,pz}/2$. When the beam intensity reaches 5 mA, the vertical beam loss is shown in Fig. 4. The lost beam concentrates at the position of RF cavity.

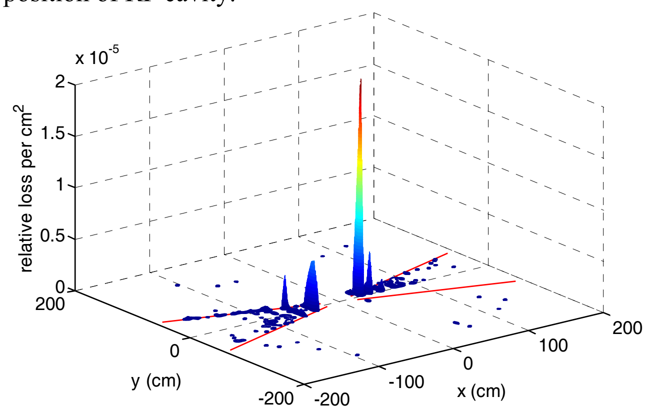

Figure 4: Vertical beam loss without collimator.

The collimator system is designed according to the following principle. Place the collimator at the low energy to minimize the radiation field. In general, collimation at high energies should be avoided, otherwise, large amount of additional radiation will be produced by the collimator itself. The simulations show that the best position for the collimator is at the entrance of the RF cavities, and the energy should limited up to 5 MeV. The material of the collimator is also carefully considered. The collimator material should not produce a large amount of neutrons when bombarded by protons. The release of gas in vacuum must keept to a minimum. Copper is selected as collimator material, also because of the good thermal conductance. The vertical beam loss with collimators is shown in Fig. 5. Comparing with Fig. 4, the losses are concentrated at the position of the collimators, and the RF cavities are well protected.

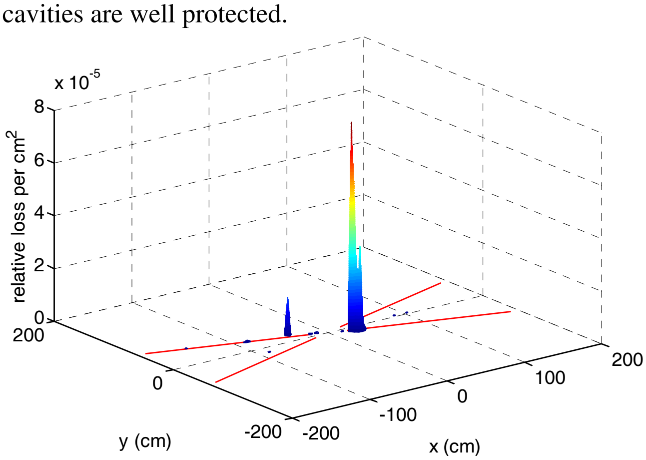

Figure 5: Vertical beam loss with collimator.

CONCLUSION

The beam power of 1.3 MW delivered by the PSI 590 MeV Ring Cyclotron together with stringent requirements regarding the controlled and uncontrolled beam losses poses great challenges with respect to predictive simulations. The comparisons with measurements show that OPAL can precisely predict the radial beam pattern at extraction with large dynamic range (3-4 orders of magnitude).

The ability of considering both space charge effect and the particle matter interaction in OPAL makes it a powerful and predictive tool for Cyclotron simulations. The design of the collimator system in CYCIAE-100 decreases the activity of the accelerator component and minimizes the radiation field inside the Cyclotron.

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