PHYSICS PROBLEM STUDY FOR A 100 MEV, 500 MICROAMP H$^-$ BEAM COMPACT CYCLOTRON *

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Abstract

A high intensity compact cyclotron, CYCIAE-100, is selected as the driving accelerator for Beijing Radioactive Ion-beam Facility (BRIF). At present the physics design of this machine has been accomplished. This paper gives a brief review of the general design of this machine. For further intensity upgrade of this compact machine in the future, it is crucial to carry out in-depth study on the self fields effects including the contributions of single bunch space charge and the interaction of many radially neighboring bunches. In order to include the neighboring bunch effects fully self-consistently in compact cyclotrons, a new physical model is established for the first time and implemented in the parallel PIC code OPAL-CYCL. After that, the impact of the single bunch space charge and neighboring bunches on the beam dynamics in CYCIAE-100 for different intensity levels are studied by the simulations using the new model.

INTRODUCTION

Since 2004 a new exotic beam project, Beijing Radioactive Ion-beam Facility (BRIF), has been started at CIAE. As a driving accelerator for BRIF[1], CYCIAE-100 adopts a compact structure with 4 straight sectors. The H$^-$ ions produced by the multi-cusp ion source are accelerated, and the high intensity proton beams are extracted through dual stripping. The extracted beam is 200–500μA featured with energy of 75–100 MeV, which is continuously adjustable. Figure 1 shows the overall structure of CYCIAE-100 and Table 1 lists its key parameters. From the view of beam dynamics, the physics problem of this machine is composed of several aspects, including axial injection, central region, acceleration, stripping extraction and beam lines, which have been described in several papers published formerly[2]–[5]. The basic physics design and current construction status of machine will be briefly reviewed in the following section.

Table 1: Key Parameters of CYCIAE-100

Item	value
ion source type	multi-cusp
injection current	> 5 mA
number of poles	4
angle of poles	~47^o
radius of poles	2000 mm
outer diameter of yoke	6160 mm
height of magnet	2820 mm
total iron weight	~415 t
field range	0.15–1.35 T
gap between hills	50–60 mm
injection energy	40 keV
rf frequency	44.32 MHz
Dee Voltage	60–120kV
number of cavities	2
harmonic number	4
extraction type	multi-turn stripping

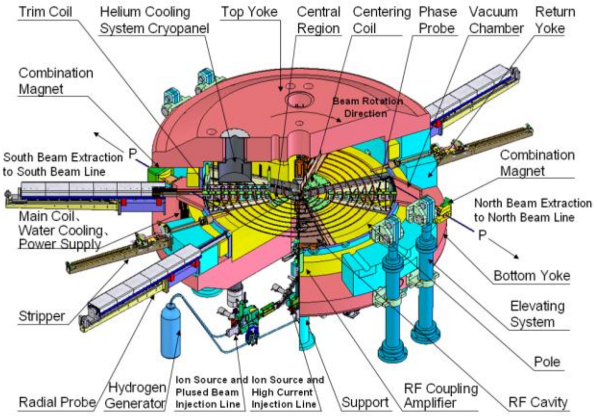

Figure 1: Sketch of the major parts of CYCIAE-100.

Beam loss is the key factor which limits the beam current of a high intensity cyclotron. Space charge effects, being one of the most significant collective effects, play an important role in high intensity cyclotron. Space charge may cause massive beam loss at the low- and middle-energy accelerator. In CYCIAE-100, the injection energy is only 40keV and the maximal energy is 100MeV (γ=1.106), and therefore, space charge can be remarkable under high current conditions. In addition, a common

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characteristic of high intensity compact cyclotron is that dozens of radially neighboring bunches overlap at large radii region (therefore multi-turn extraction is adopted). Simulation shows that the particles in the extracted proton bunch by the stripper come from about 30 injected bunches in CYCIAE-100. This is mainly caused by two factors. Firstly, limited by space, the Dee voltage of RF cavity is relative small, accordingly, the radial gain per turn, or turn separation, is small. Simulation shows that the turn separation is reduced to only 3mm at the extraction point. Secondly, in order to achieve high current, the RF phase acceptance in the central region reaches 40^{o}, and limited by space, no flat-top cavity is installed. Consequently, the particles at head and tail of the bunch gain quite different energy during each gap-crossing and energy spread is inevitably large, accordingly, the radial distribution range of a bunch is big. As a result, it is necessary to include the mutual interactions of radially neighboring bunches, or neighboring bunch effects for short, in space charge studies.

REVIEW OF PHYSICAL DESIGN OF CYCIAE-100

The adoption of a compact structure for CYCIAE-100 can provide strong vertical focusing to meet the requirement of intensive beam acceleration. The carbon foils are used to strip the H^- with very small beam loss during the extraction, the efficiency of which can reach 99% from our calculation and test. In order to reduce the beam loss induced by the Lorentz stripping, the hill field at the outer region is less than 1.4T. The vacuum dissociation is the other reason inducing beam loss in this H^- machine, which requires the vacuum in the tank better than 5×10^{-6}Pa on average. For the RF system, it adopts double Dee structure, and the fourth harmonics w.r.t revolution period of accelerated particles. The resonant cavity of half wave length is completely installed and fixed in the valley of the magnet.

During the acceleration, the beam corresponding to different energy has fixed equilibrium orbit. The betatron oscillations around equilibrium orbits at different energies up to 100MeV are investigated in detail with many magnet structures and their fields. The vertical oscillation frequency is higher than 0.5 at most of the acceleration region and towards 0.7. This is of advantage to upgrade the beam intensity later on.

After the static study, the accelerating beam dynamics is also done in detail. The transverse ellipses along the AEO are matched step by step from the central region to final energy. The vertical beam profiles with different RF phases are simulated and multi-particle tracking is carried out to control the beam loss in this small hill gap machine. In practice, the imperfection magnetic field exists and the deviation of the orbit centre takes place. Under the influence of the 1st and 2nd harmonic fields, the beam will oscillate about the deviated orbit centre and thus result in its radial dimension growth. In order to obtain a good beam quality, the simulation results show that the magnetic field of the cyclotron should satisfy the following condition: the 1st harmonic is less than 2 gauss, the 2nd harmonic is less than 40 G, and the gradient of the 2nd harmonic is less than 8 G/cm. To comply with the requirement for being isochronous, it is demanded that the deviation between the measured field at medial plane and the idea field be approximately below 1.05×10^{-4}.

NEW PHYSICAL MODEL AND RELATIVE CODE DEVELOPMENT

In 2008, a 3D physical model was built to include neighboring bunch effects in the high intensity separated-sector cyclotrons using single turn extraction [6]. In this model, at the beginning only a single bunch is tracked until the turn separation is small enough, and then a new bunch is injected per revolution period. Two parameters M and N_B are introduced to set the time of starting injecting new bunches and the maximal bunch number respectively. The proper settings of these two parameters are crucial to precisely evaluate neighboring bunches effects. In this model N_B must be an odd number. Our study object is the central bunch and the other (N_B - 1) bunches are auxiliary. Therefore we call it "central bunch" model hereafter. This model was implemented in the code OPAL-CYCL[6], which is one of the flavours of OPAL framework[7] and tracks particles with 3D space charge including neighboring bunches effects in cyclotrons, with time as the independent variable. Simulation results using OPAL-CYCL shows that the setting with $N_B = 9$ and $M = 4.5$ gives convergent results for the PSI 590MeV Ring cyclotron with 3mA beam current[6].

However, it is quite difficult to study the neighboring bunch effects in CYCIAE-100 and other similar compact cyclotrons by using "central bunch" model, because in high intensity compact cyclotrons, all the radially neighboring bunches overlap heavily and there is no clear borderline between the central bunch and the others bunches. On top of this, the study on central bunch is worthless and insufficient, because in this type of machines, multi-turn stripping extraction is used and the extracted beam include the contributions of dozens of the neighboring bunches. From the view of extraction, study on the behaviour of the extracted bunch is more significant and valuable.

"Start-to-Stop" model

Recently a new physical model was established for compact cyclotrons such as CYCIAE-100. In this model the multi-bunch tracking is divided into three stages in sequence: startup-running-stop. This model imitates the stages of an accelerator's operation period and called "Start-to-Stop" model:

- Startup stage: with bunch injected and without bunch extracted

  A new bunch is generated in the injection point per revolution period. The existing bunches has not fill all the turns and the first bunch has not reached the stripper, so no particle is extracted.

- Running stage: with bunch injected and bunch extracted

  A new bunch is generated in the injection point per revolution period; meanwhile, the particles which have reached the stripper are extracted. When a macro-particle is extracted, its tracking is finished. Its phase space variables and the extraction time are written into disk and the memory blocks which stores its relative data are free. When the extracted particle number is equal to the injected particle number, the simulation is running under the steady state.

- Stop stage: without bunch injected, with bunch extracted

  No bunch is injected, which imitates the ion source stops providing particle and the accelerator is still working. During every revolution period, there are still particles reaching the stripper and being extracted. The total particle number is constantly reduced until all the existing particles are extracted, then the entire simulation is finished.

Comparing with the “central bunch” model, this model still holds the original meaning of the parameter M; meanwhile, the parameter N_B here means the total injected bunch number from start to stop. Its value is a much larger one, i.e. larger than the total turn number of a cyclotron at least.

When space charge field is solved using quasi-static approximation, one needs to assure the relative motion of particles is non-relativistic, i.e. in the beam rest frame, the formula

$$\eta \equiv \frac{\Delta p}{m_0 c} << 1 \tag{1}$$

should be fulfilled, where Δp is the momentum spread in the beam rest frame. In the PSI Ring and similar separated-sector cyclotrons with single turn extraction, the energy gain per turn is large and energy spread is small. To meet the requirement of formula (1), “central beam” model follows the rule that each energy bin corresponds one bunch. Whereas, in the CYCIAE-100 and similar compact cyclotrons, the energy gain per turn is relatively small and energy spread is relatively large. Therefore in the “Start-to-Stop” model, the adaptive energy binning technology, which is usually adopted to deal with a single beam with large momentum spread[8], is introduced in the multiple beams issue of compact cyclotrons. The momentum range of each energy bin η_{bin} to some value far smaller than 1, then the momentum of the kth energy bin is

$$p_{k,\text{bin}} = \sinh\left(k\eta_{\text{bin}} + \sinh^{-1} p_{\min}\right) \tag{2}$$

Where $p_{\min}$ is the lowest momentum of the all the existing particles and it defines the first energy bin. The bin index k of a given particle with momentum p_i is given by

$$k = \left\lfloor \frac{\sinh^{-1} p_i - \sinh^{-1} p_{\min}}{\eta_{\text{bin}}} \right\rfloor \tag{3}$$

After binning we perform the Lorentz transformation, calculate the space charge field using FFT based solver and perform back-transformation for each bin respectively. Finally the field data is summed up to give the total space charge force imposed on each particle.

Recent development of OPAL-CYCL

Recently we implemented above “Start-to-Stop” model in the code OPAL-CYCL, to make it applicable to high intensity compact cyclotrons such as CYCIAE-100.

In order to achieve the best balance between accuracy, stability and efficiency, recently a second order Leap-Frog integrator is implemented into OPAL-CYCL.

In addition, the computation load and memory load on computer nodes now are better balanced by taking advantages of the dynamic mesh grid repartition functionality of IP^{2}L[9]. Figure 2 shows the speedup at different repartition frequency for a production run setup. The timings were obtained on the Cray XT5 of the CSCS, Switzerland. Each of the computer nodes consists of 2 quad-core AMD Opteron 2.4 GHz Shanghai processors giving 8 cores in total per node with 16 GBytes of memory. We can see a significant gain of speedup when the repartition is performed once per 20 integration steps.

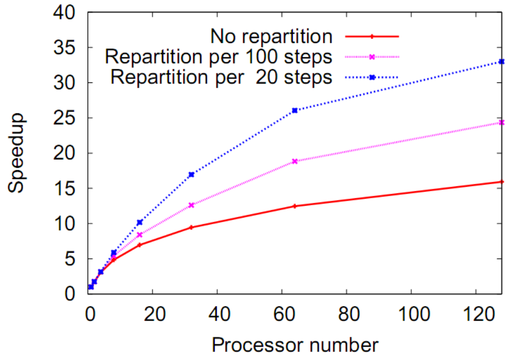


Figure 2: Speedup of OPAL-CYCL as a function of processors at different repartition frequency for a production run setup.

START-TO-STOP SIMULATION

In this section, we utilize the “Start-to-Stop” model to study the high intensity issues in CYCIAE-100. The motivation for this study is to predict the beam’s behavior at different current level so as to help the builders achieve the aim of the project. Since the aimed beam current of this cyclotron is 0.2–0.5 mA and it is planed to improve the current to 1mA during future upgrade，the simulation is done for 0mA, 0.2mA, 0.5mA and 1mA beam current respectively and the results are compared and analysis together.

In CYCIAE-100, the 40keV DC beam is transported from the ion source to the central region by the axial injection line and the spiral inflector. After the phase selection and acceleration during the first several turns in the central region, at the exit of central region we get a bunched beam with energy equal to 1.49MeV and initial position $R = 23.14\text{cm}$, $\theta = 0°$. The simulation starts from this position. Since it is hard to obtain the precise distribution of the beam at present, a 6D Gaussian ellipsoid distribution is assumed as the initial distribution. The initial phase width (6σ) is set to 6° and initial energy spread is zero. Both on the radial and vertical phase space, the particle distribitons match the eigen-ellipses and the rms emittances are 1.2π mm-mrad and 0.4π mm-mrad respectively. The beam sizes (6σ) on both directions are set to 12mm and the initial distribution is assumed uncorrelated in phase space.

In the simulation ten thousand macroparticles per bunch are employed and ultimately more than two million macroparticles are injected under the running stage. Considering all bunches should lie along the radial direction approximately, the mesh size along radial direction is set to 256 and on the two other directions is 32. Figure 3–Figure 6 shows the results given by the simulation.

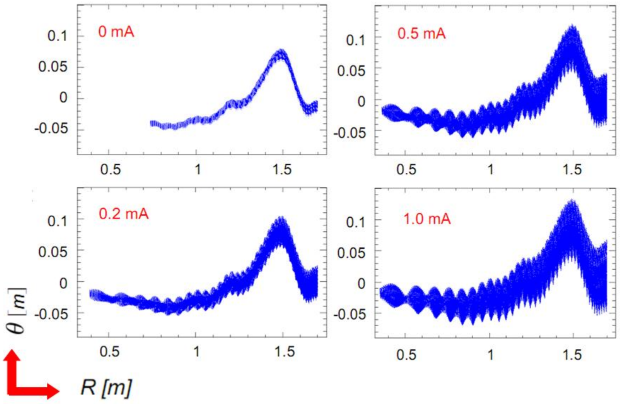
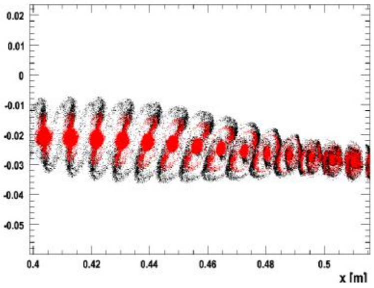


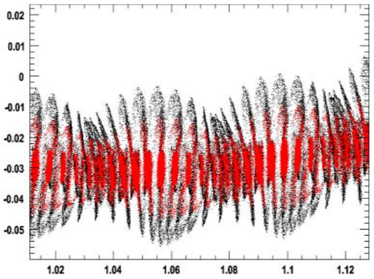
Figure 3: Top view snapshot at the time point bunches crossing 0° azimuth under the steady state

Figure 3 shows the top view snapshot at the time point bunches crossing 0° azimuth under the steady state of running stage. It is clear from the simulation that the phase width becomes larger along with the current increasing. In the final turn the phase width are 2.5°, 6.5°, 10.4° and 15.0° for 0mA, 0.2mA, 0.5mA and 1mA respectively. It is noted that despite the same value of *M*, the transition from single bunch simulation to multi-bunch simulation happens at earlier turn for higher current, because neighboring bunches effects rise up at earlier turn for high current.

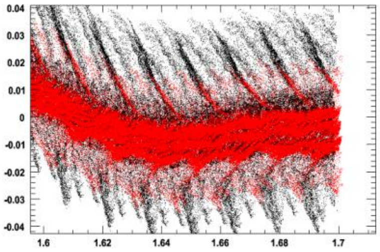
In Figure 4 three typical local regions of Figure 3 are zoomed in and the distribution for 0.2mA and 0.5mA are shown together for comparison. The "vortex" motion can be observed clearly at the low energy region. Looking into Figure 3 and Figure 4, we can find an interesting phenomenon that the beam phase width oscillates along the radius when the current is larger than 0.2mA, which is believed by the mismatch caused by space charge and neighboring bunch effects. This will be studied in detail in the future.



(a) 4~8MeV



(b) 31~40MeV



(c) 86~100MeV

Figure 4: Zoom-in plot (using the same scales) of Figure 3 for 0.2mA (red) and 0.5mA (black) beam currents

In CYCIAE-100, the stripping probe is placed at the position $R = 187.55\text{cm}$, $\theta = 59.6°$ for 100MeV beam extraction. Two electrons of a H^- particle are stripped by the carbon foil and the resultant proton beam is transported out of cyclotron. The distribution of extracted beam is crucial for the beam line design. Therefore the influence of space charge on the extracted beam is an interesting problem. Figure 5 shows the simulation result of the *R-Z* distribution of the extracted beam for different beam currents and Figure 6 shows its histograms along the radial and axial directions respectively. The beam sizes on both directions are expanded along with the current increase. On the axial directions more and more halo particles are generated along with the current increase. So the extraction beam line designer should take the beam current into account during beam upgrade so as to improve the transmission efficiency and reduce beam loss. Fortunately, up to 1mA, the axial beam size is less than 1.5cm, still smaller than the gap between hills (5cm) and the vertical distance of RF linear (4cm) at this region. Therefore, during the acceleration and extraction no massive beam loss is caused by the space charge and neighboring bunch effects under 1mA current.

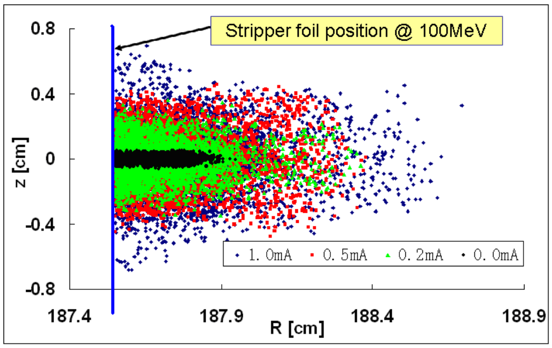


Figure 5: *R-Z* distribution of the extracted beam for different beam currents under the steady state.

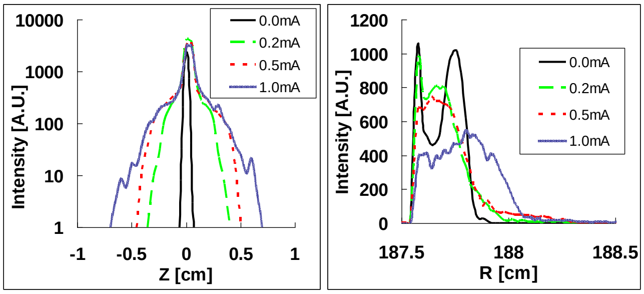


Figure 6: Comparisons of the histograms along the *Z* and *R* directions for the extracted beam for different beam currents under the steady state.

CONCLUSION AND FUTURE WORKS

The physics design for CYCIAE-100 has been accomplished. A brief review of the physics design on this cyclotron is presented. Then a new established "Start-to-Stop" model, which was recently implemented in OPAL-CYCL, is depicted. The "Start-to-Stop" simulation results of CYCIAE-100 shows that space charge and neighboring bunch effects will lengthen the phase width during acceleration and expand the beam sizes of the extracted beam both in the axial and radial directions, However, no massive beam loss is caused under 1mA current.

To improve the accuracy of the simulation, further investigation will be performed on the beam evolution at the central region to obtain the more practical initial conditions. In addition, limited by the computer resource, only 10 thousand macroparticles per bunch were employed to do the above simulation, and the mesh size is $256\times32\times32$. A larger scale simulation is planned to improve the precision of the simulation. After that, the current limit of CYCIAE-100 will be also studied by the simulations.

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Some of the computations were performed on the Cray XT5 at CSCS, Switzerland and some were performed on the cluster PANDA which was just finished at CIAE, China.

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