BEAM SIMULATION FOR IMPROVED OPERATION OF CYCLOTRON NIRS-930

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Abstract

A beam inside NIRS-930 cyclotron (Thomson-CSF, K_b=110 MeV, K_f=90 MeV) is diagnosed by such device as differential prove and phase prove, though the beam behavior is not well recognized. To understand the behavior of the beam, beam simulation is an effective method. The SNOP code is developed to simulate multiple particles in a cyclotron taking account of space charge effect using PIC method. Firstly, comparing the simulation results with actual measurement, we can ensure the correctness of simulation. The phase variation of 18 MeV proton beam of simulation was compared to that of the experiment. Both results show similar tendency. The beam loss point was also studied in simulation changing beam injected phase. We found that a lot of particles injected with early phase are lost at deflector. On the other hand, a lot of particles injected delayed phase is lost at inflector. The difference of the phase of maximum transmission ratio at inflector and deflector was 20°. Furthermore, space charge effect was found to decrease transmission efficiency if the injection beam current is more than ~1 mA. Considering the results of the simulation, actual operation of the NIRS-930 cyclotron can be improved.

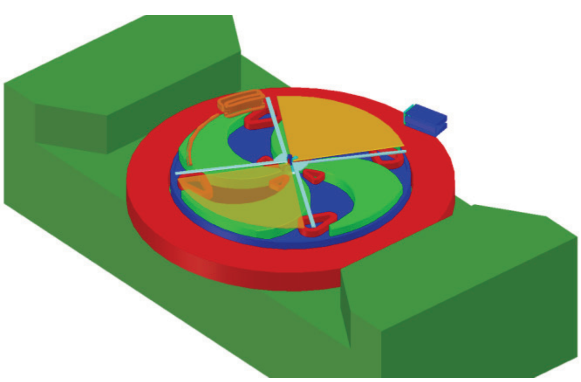

Figure 1: Half cut model of the cyclotron NIRS-930.

INTRODUCTION

Simulation of the beam of the cyclotron has been proceeded to analyze the beam aiming to develop the beam intensity and the quality at National Institute of Radiological Sciences. Cyclotron simulation code SNOP [1] is developed and applied for NIRS-930 [2] using 30 MeV protons [3]. Each electric field (Dee electrodes and inflector) and magnetic field (main coil, trim coils, harmonic coils, and magnetic channel) is calculated 3-dimensionally by Opera-3d (TOSCA) [4], and simulated injection, acceleration and extraction. In this study, 18 MeV protons accelerated with harmonics 2 were simulated. In this paper, we will show some suggestive simulation results which are useful to improve beam intensity and quality.

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BEAM TRACKING BY USE OF SNOP

Modeling of NIRS-930

The calculation model of NIRS-930 is shown in Fig. 1. The beam is guided by a bending magnet from ion source sit on the cyclotron and comes into the central part of cyclotron. The inflector injects the beam with the use of electric field. NIRS-930 has 4 spiral sectors. Main coil, 12 pairs of trim coils, 4 injection harmonic coils and 4 extraction harmonic coils are utilized to form magnetic field of the cyclotron. The angle of the dee electrode is 86°. The extraction radius is 920 mm and there are an electrostatic deflector, a magnetic channel and a gradient corrector for beam extraction.

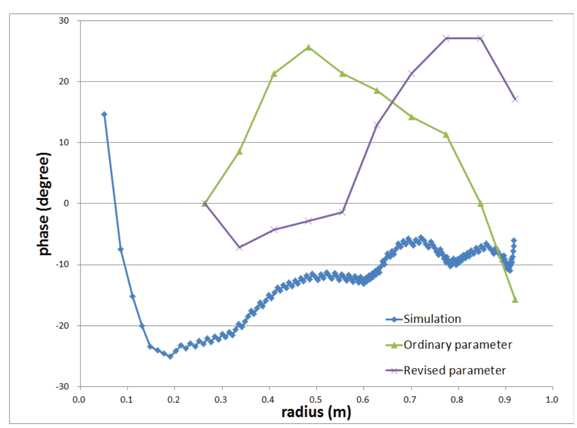

Figure 2: Comparison of the phase between the simulation and actual measurements. The phase of the innermost prove is defined as zero.

Simulation of Single Particle

At first, single particle simulation of 18 MeV proton was carried out. The first aim is to compare the variation of acceleration phase. In actual operation, each current of trim coils is adjusted so as to acceleration phase measured by the phase prove to be the designed one. Fine tuning in

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ordinary parameter (used in everyday operation) is made to maximize the extraction beam intensity. The comparison result is shown in Fig. 2. Simulation was optimized for the best phase agreement. Revised parameter used in the experiment is the one in the simulation except for the most outer 12th trim coil for fine tuning. The figure shows similar tendency of phase variation. The difference of simulation and experiment may come from the difference of B-H curves used in the calculation and real iron core.

Simulation of Multiple Particles

In multiple particles simulation with SNOP, space charge effect is taken into account by the use of PIC (Particle-In-Cell) method. Calculated results of each particle were plotted in a phase space. The beam extracted from the cyclotron was shown in Fig. 3, which showed the emittance is 24.9 π mm mrad in the radial direction and 11.2 π mm mrad in the axial direction.

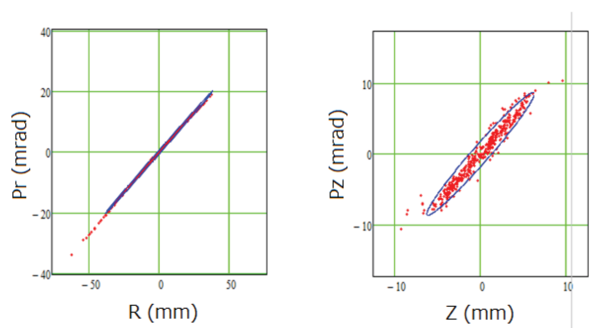

Figure 3: The phase space plot of the extracted beam in simulation.

BEAM TRANSMISSION EFFICIENCY

The injection beam in the simulation was Gaussian distribution in each transverse direction. It is also Gaussian distribution in longitudinal direction taking account of the buncher effect. The emittance of the injected beam is assumed to 100 π mm mrad in each direction. Beam bunch length is 280 mm corresponding to 60° of the RF phase. The injection beam intensity is assumed to 0.13 mA, which is the usual injection value measured by the inflector electrode. The simulation used 10000 particles.

The transmission efficiency of 18 MeV protons at each part of the cyclotron is given for both the experiment and the simulation in Table 1. ("R=10cm" means those particles are finally reached the point farther than 10 cm from center of the cyclotron.) The injection efficiency is better in simulation, while the extraction efficiency is better in experiment. Small change of deflector voltage and position makes large difference to the result, and there is such a possibility as to improve the transmission efficiency.

Table 1: Comparison of Beam Transmission Efficiency (survival ratio) (%)

Position	Experiment	Simulation
Entrance of the inflector	100	100
R=10cm	39	82
Before deflector	36	74
Extracted	23	24

BEAM PARTICLE LOSS POINT AND PHASE

The point of particle loss is studied for the purpose of improvement of the beam transmission efficiency. To compare the simulation and actual experiment, we have to estimate each kind of the initial particle losses at each part of the cyclotron. So we simulated the beam changing an injection phase, which means the relative time between RF phase and beam injection time. Zero point of phase is determined by the best timing of transmission efficiency from inflector to extraction.

(a)
(b)

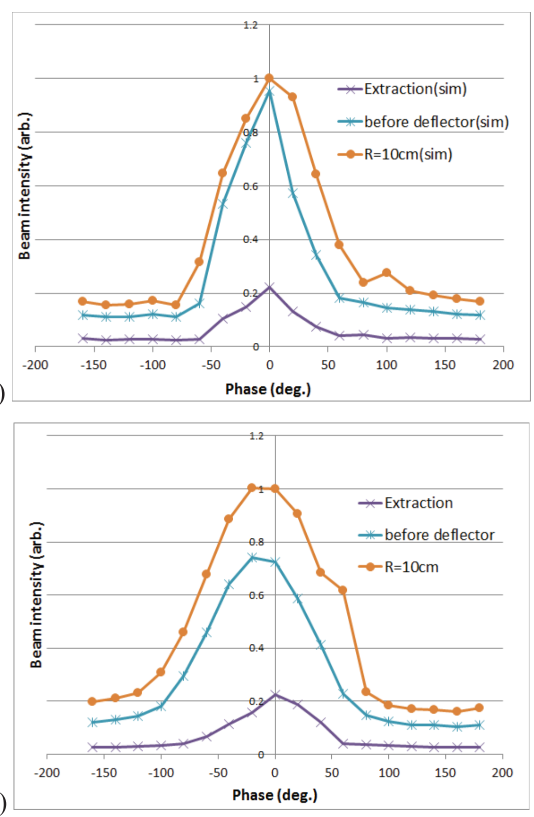

Figure 4: Beam intensity of each part of the cyclotron as functions of RF phase in the case of (a) simulation and (b) experiment. Ordinate is beam intensity of arbitrary unit where the intensity at R=10cm is defined as 1.

Figure 4 shows survival ratio at the R=10cm place, before reflector and extraction of each phase both simulation (a) and experiment (b). Both results of beam intensity as functions of phase agree globally. To see in detail, Fig. 4(a) shows the simulation result that the intensity of delayed phase (negative in abscissa) is higher than early phase (positive in abscissa) at before deflector. Such particles are lost largely after deflector. In other words, a lot of particles injected with early phase are lost at deflector. On the other hand, a lot of particles injected delayed phase is lost at the inflector. In actual cyclotron, Fig. 4(b) shows the same tendency. These results suggest particles of phase advance at injection are mainly lost at the deflector or the magnetic channel. In contrast, phase delayed particles are mainly lost at central region of the cyclotron.

If the phase of maximum injection efficiency (minimum loss in R<10cm) and the phase of maximum extraction efficiency is the same, the total transmission efficiency is the best. To realize this situation, beam phase advance from inside to outside must be reduced. Such an adjustment using trim coil may make cyclotron magnetic field slightly different from the ideal isochronous field, it would increase transmission efficiency. Figure 5 shows more detailed situation of beam loss point in each part of the cyclotron using shorter 10° duration bunch. The best extraction rate is 315°, while the best transport rate before deflector is 295°.

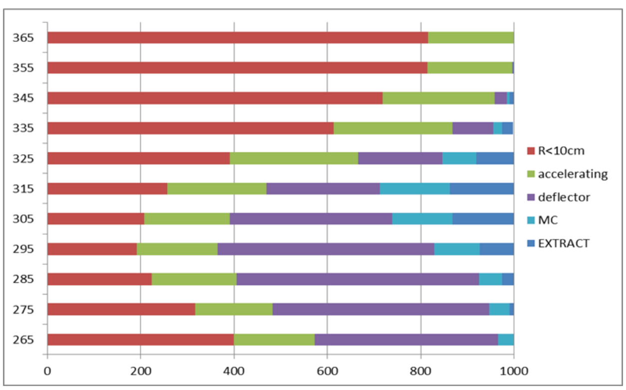

Figure 5: Particle numbers lost in each point or extracted, changing buncher phase in simulation.

SPACE CHARGE EFFECT IN CASE OF HIGH INTENSITY

Space charge effect makes the beam broader and the transmission efficiency worse. The maximum beam intensity which is limited by space charge was estimated by simulation. Figure 6 shows the beam intensity at each part of the cyclotron by changing injected beam intensity. That shows the situation that the ratio of beam intensity at each part was almost constant of injected beam intensity under 1300 μA. This situation is not actually applicable because beam collision at deflector damages the septum electrode. To increase the beam intensity, the increase of beam transmission efficiency is inevitable. The total transmission efficiency of the region was about 14%. If the intensity goes up above this value, the transmission efficiency drops sharply. This is due to the decline of the transmission efficiency from R=10cm to deflector (it means accelerating region). The space charge effect limits the transmission efficiency in this region with such a large intensity of the beam.

On the other hand, beam intensity cannot be increased over ~25 μA in the real NIRS-930. This may because space charge effect at injection line which is not simulated until now. To reduce the space charge effect, there is possible approach such as increasing of the injection voltage.

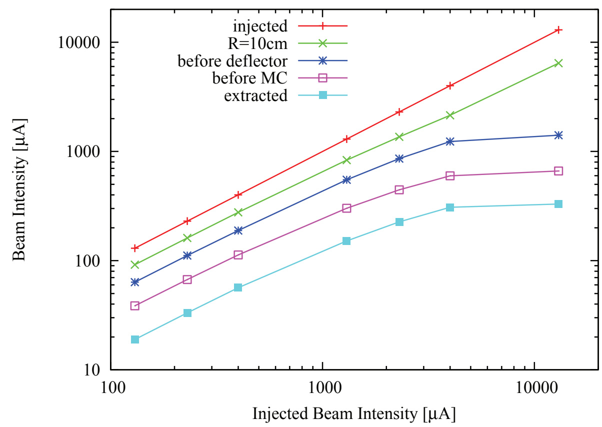

Figure 6: Beam intensity of each part by changing injected beam intensity.

CONCLUSION

We studied about the behavior of the beam in the cyclotron with the use of simulation and experiment. Improbable points were found such as RF phase matching of cyclotron. Simulating multiple particles with space charge effect found the places where the beam particles are lost. Then we can decrease beam loss and increase beam intensity in the actual cyclotron.

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