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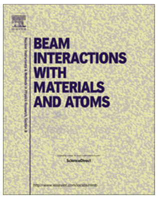

Approach to increase beam intensity extracted from a cyclotron

M. Nakao [a,*], S. Hojo [a], K. Katagiri [a], N. Miyahara [a], A. Noda [a], K. Noda [a], A. Sugiura [a], T. Wakui [a], V. Smirnov [b], S. Vorozhtsov [b], A. Goto [c]

[a] *National Institute of Radiological Sciences, National Institutes for Quantum and Radiological Science and Technology, Chiba 263-8555, Japan*
[b] *Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia*
[c] *Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198, Japan*

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ABSTRACT

To increase the beam intensity of cyclotrons used for producing radionuclides, beam loss during extraction must be reduced. Extraction efficiency is limited by the beam parameters in front of the deflector, especially angular distribution. Computer simulation of the second harmonic mode for 18 MeV protons, which is frequently used, has been carried out to understand beam behavior in a cyclotron. The extraction efficiency is determined by the width of the angular distribution of particles in the phase space plot at the deflector. An effective method to reduce the width is to shorten the bunch at injection. The simulation shows that the bunch phase length at injection must be $\leqslant 30^\circ$ to realize a 30 μA extraction beam current and satisfy the deflector heat limit of 200 W.

1. Introduction

The need for radionuclides for medical use is increasing. In particular, radionuclide production by accelerators is becoming essential because the use of fission reactors has become more difficult and accelerators are required to make more nuclear species. Radionuclides are used in nuclear medicine not only for diagnostic purposes such as positron emission tomography (PET) and single-photon emission computed tomography (SPECT), but also for targeted radionuclide therapy (TRT). Radioactive ^{11}C re-accelerated beam will be applied in cancer treatment [1], which enables simultaneous imaging of the irradiation field of the patient by the use of Open-PET [2] during treatment. A high-intensity beam for radionuclide production is necessary to realize such applications.

National Institute of Radiological Sciences (NIRS) has the NIRS-930 cyclotron (Thomson-CSF, bending limit $K_b = 110$ MeV, focusing limit $K_f = 90$ MeV) [3], and two small cyclotrons used exclusively for short-lived radionuclide production such as ^{11}C, ^{13}N, ^{15}O and ^{18}F. NIRS-930 is also used for physical and biological experiments. The beam quality is valued in experiments while the beam intensity is more cared in radionuclide production. If we wish to increase beam intensity to increase the radionuclide yield, it is necessary to understand the behavior of the beam and the causes of beam loss in the cyclotron. Because we can measure beam loss at only the limited positions where probe electrodes exist, we need to use computer simulations of the beam behavior in the cyclotron in order to get information related to beam loss. There are also time domain information which cannot to be measured by probes easily.

Simulation codes for cyclotron ion beams that include the space charge force have been developed [4–10]. In this research we utilized the SNOP code [9,10], developed at JINR, because it is superior for simulating a beam from injection to extraction. A simulation study at NIRS-930 using the SNOP code reproduced the beam parameters for the first harmonic [11]. Subsequently, we have started to simulate the second harmonic mode for 18 MeV proton, which is now one of the most commonly used beams for radionuclide production.

At NIRS-930, we are trying to increase the extraction current of 18 MeV proton beam to 30 μA. Because there are demands of 18 MeV proton beams both in NIRS-930 and the small cyclotron at the same time. Not building a new machine but using the existing cyclotron, we can use RI medicine synthesis equipment which already exists. The presently attained extraction efficiency and current of 18 MeV protons are 57% and 20 μA, respectively. Although such methods as cutting the beam by using a phase slit can increase extraction efficiency, they are unsuitable as they decrease beam current. On the other hand, an increase in extraction current without an increase in extraction efficiency will cause such troubles as melting and activation of the deflector electrodes, which

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[*] Corresponding author at: Research Center for Nuclear Physics, Osaka University, Japan.

E-mail address: nakaom@rcnp.osaka-u.ac.jp (M. Nakao).

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will increase the radiation exposure of the operators at maintenance time. In particular, the pre-septum electrode of the deflector, which is at ground potential, is bombarded the most by the beam. We assumed that an acceptable heat exposure of the electrode is $\leqslant$200 W to satisfy the conditions that deflector does not melt and is not excessively activated [12]. At the same time, the extraction beam current must be at least 30 μA to satisfy the demands of radionuclide production.

2. Simulation scheme utilizing SNOP

SNOP is software for simulating particles in a cyclotron taking into account the space charge force. SNOP uses calculated 3D electric and magnetic field values of each part of a cyclotron, such as the iron core, main coils, trim coils, harmonic coils, inflector electrodes, dee electrodes, deflector electrodes and magnetic channel, using OPERA-3D [13]. Key parameters of NIRS-930 are shown in Table 1. The calculation model of the NIRS-930 cyclotron is shown in Fig. 1.

The beam from the ion source on the cyclotron yoke is guided by a bending magnet over the center of the cyclotron and comes down perpendicularly. The main magnetic field of the cyclotron is calculated taking into account the iron core, iron yoke, main coils and 12 pairs of trim coils. The magnetic fields of the four injection harmonic coils and four extraction harmonic coils are added independently so that changes in the harmonic coil current can be made easily. Inflector electrodes consist of a positive electrode, a negative electrode and a housing, each of which is made of copper. Beam particles are deflected by the electric field. A physical model is used to calculate whether a particle collides with the inflector. The RF electric field of the dee electrode is derived as the product of the calculated electrical field and a sine function. This approximation agrees with the actual situation. In order to reduce computation time, the field of the deflector electrode and the magnetic channel are calculated independently from the magnetic field produced by the main coil.

The particle orbit was derived continuously from the initial point (35 mm above the inflector) to the point of loss or successful extraction. Each particle orbit was solved by the fourth-order Runge–Kutta method. The space charge effect was taken into account both by the particle-to-particle (PP) method (direct calculation of Coulomb force between macro particles) and by the particle-in-cell (PIC) method [14] using fast Fourier transform and Poisson boundary conditions. The results of both methods are compared and parameters, such as time step and cell division, are determined by considering the consistency of the two methods. The PIC method is much faster than PP method in case of more than 1000 macro particles so we use that in most cases.

Table 1
Key parameters of the NIRS-930 cyclotron.

	Parameter	Value
General parameters of NIRS-930	Injection	Axial injection with spiral inflector
	Bending limit (K_b), MeV	110
	Focusing limit (K_f), MeV	90
	Extraction radius, mm	920
Parameters of simulated proton beam	Injection energy, keV	5.9
	Central magnetic field, T	0.683
	RF frequency, MHz	10.00
	Dee voltage, kV	26.5
	Extraction energy, MeV	18
	Typical extraction beam current, μA	20

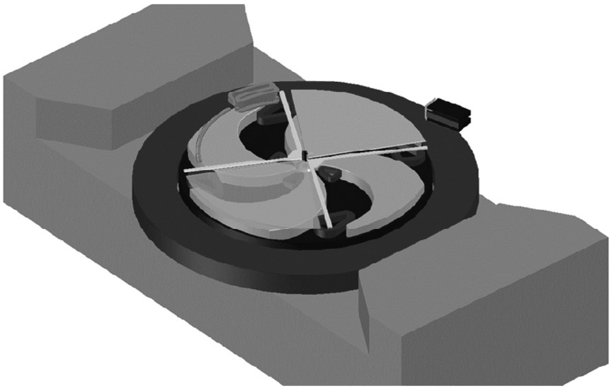

Fig. 1. 3D calculation model of NIRS-930.

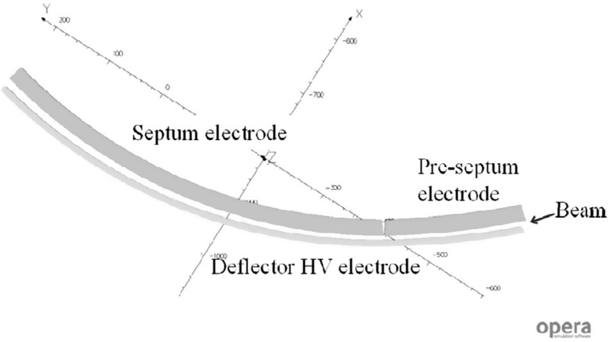

Fig. 2. Opera-3d model of deflector electrodes. A -24 kV voltage is applied to the deflector HV electrode. The septum and pre-septum electrodes are at ground level.

3. Simulation results

3.1. Visualizing the beam loss point and improving extraction efficiency

Many particles in the beam are lost at extraction; although causes of loss are varied. So we first focus on the beam condition at the deflector to investigate what kinds of particles are lost at the deflector. The names of electrodes in the deflector are shown in Fig. 2.

Fig. 3 shows a phase space plot in front of the deflector, plotting the destination (loss or extraction) of a particle at each position [15]. In Fig. 3, particle loss points are classified according to whether the loss is in the magnetic channel (indicated by cross), the deflector septum electrode (triangles) or the deflector high-voltage (HV) electrode (circles). For example, particles passing outside the deflector and moving outward are shown in the upper right of Fig. 3. Such a particle will be lost at the deflector HV electrode. In the central, nearly vertical region at a radius of 905 mm, the particles are lost at the deflector septum electrode. To the left of that region, particles pass inside the deflector and go around another turn. Such a particle is expected to be accelerated by the dee electrodes and then to return to the deflector with an increased revolution radius.

3.2. Horizontal particle distribution at the deflector

In the next step, we simulated the condition of the injected beam when it arrives at the deflector. The initial beam conditions of the simulation are as follows: the beam is composed of protons whose injection energy is 5.9 keV and the beam current is 105 μA.

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