SIMULATION CODE DEVELOPMENT FOR HIGH-POWER CYCLOTRON*

Chul Un Choi, Moses Chung†, UNIST, Ulsan, Korea
Seunghwan Shin‡, Jaeyu Lee, Tae-Yeon Lee, PAL, Pohang, Korea
Ga Ram Hahn, KIRAMS, Seoul, Korea

Abstract

A high power cyclotron is a good candidate as a driver of the accelerator driven system for the transmutation of long lived nuclear wastes. In this work, a simulation code has been developed for describing the beam dynamics in the high power cyclotron. By including higher order terms in transverse transfer matrix and space charge effects, we expect to describe the beam motion more accurately. The present code can describe equivalent orbit at each energy, calculate the tunes, and also perform multi-particle tracking. We report the initial results of the code for the simulation of a 13 MeV cyclotron. Lastly, an upgrade plan is discussed to add more features and to increase calculating efficiency.

INTRODUCTION

In Korea, nuclear energy occupies about 40 percent of the electric power production. It can be a solution to the energy problem that we are facing these days before commercializing nuclear fusion energy. But one of the difficulties is that expanding nuclear power plant as the nuclear power is dangerous when natural disaster occurs, thus, high-level radioactive waste that has a half-life of a few hundred thousand years is created. To transmute from high-level radioactive waste to short-lived radioisotope, development of high power cyclotron which is part of ADS (Accelerator Driven System) is very desirable.

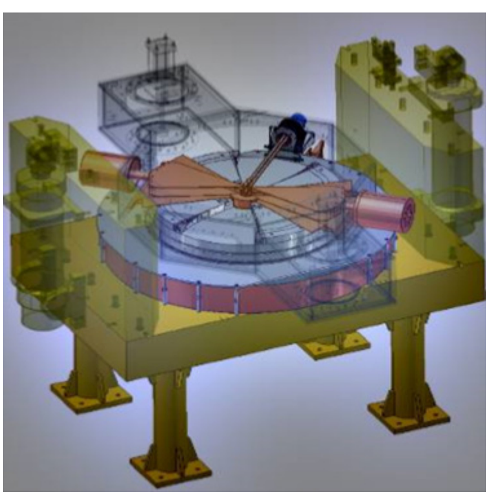

Figure 1: 13 MeV cyclotron.

As benchmark study for the simulation code, we simulate beam dynamics in KIRAMS 13 MeV Cyclotron (Fig. 1). The KIRAMS 13 MeV Cyclotron has four sector magnets and a RF cavity where it has its frequency of 77.3 MHz, Ion sources are producing proton beam and the beam current is 80 μA. The EO Code (Equilibrium Orbit Code) including beam tracking function is written by Matlab to demonstrate equilibrium orbit of multi-particle beam. This code uses Runge-Kutta Gill method to solve integration of the canonical equations of motion. This code does not yet include acceleration effect, but the conventional way of adding small energy is adopted. So the present code can describe equilibrium orbit at each energy level, and we can analyze various physical parameters such as equilibrium orbit, phase space, phase error, betatron tune, resonances and Twiss parameters.

In the future, we will add acceleration effect and algorithm of space charge effect in EO Code.

BEAM TRACKING

The magnetic field distribution (Fig. 2) is designed by OPERA-3D.

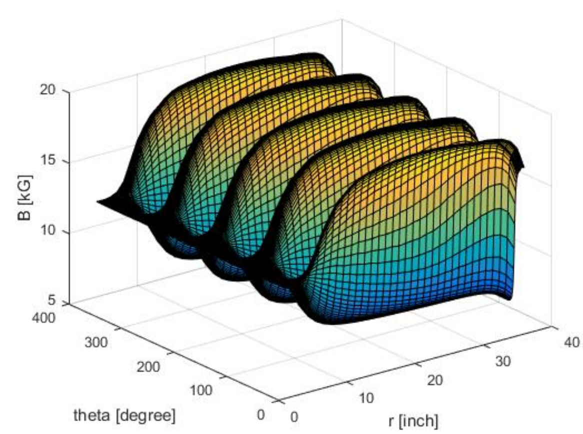

Figure 2: Magnetic field distribution with respect to r and θ.

The characteristic of EO Code is based on the integration of the canonical equations of motion [1]. EO Code uses Runge-Kutta Gill method to calculate differential equations of motion. EO Code consists of several steps. First, this program calculates equations of motion which are r, p_r, x and p_x as a function of θ. Second, this program checks whether closed orbit is made or not. If closed orbit is not made, the program increases r and p_r of particle and iterates to find closed orbit of particle. If a closed orbit is made, the program then calculates the equations of mo-

* This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF-2015R1D1A1A01060049).
† mchung@unist.ac.kr
‡ tlssh@postech.ac.kr

ISBN 978-3-95450-167-0

tion in the z and p_z. Third, the program proceeds to the next orbit of the iteration process by increasing energy of particle. This process repeats until our target energy. Finally, we can calculate various physical parameters when this iteration process ends.

$$dr = \frac{rp_r}{p_\theta} d\theta, \tag{1}$$

$$dp_r = (p_\theta - q'rB) d\theta, \tag{2}$$

$$\frac{dx}{d\theta} = \frac{p_r}{p_\theta} x + \frac{rp^2}{{p_\theta}^3} p_x, \tag{3}$$

$$\frac{dp_x}{d\theta} = -\frac{p_r}{p_\theta} p_x - q\left[B + r\frac{\partial B}{\partial r}\right] x, \tag{4}$$

$$dz_z = \frac{rp_{z2}}{p_\theta} d\theta, \tag{5}$$

$$dp_z = \left(\frac{\partial B_r}{\partial r} - \frac{p_r}{p_\theta}\frac{\partial B_\theta}{\partial \theta}\right) d\theta. \tag{6}$$

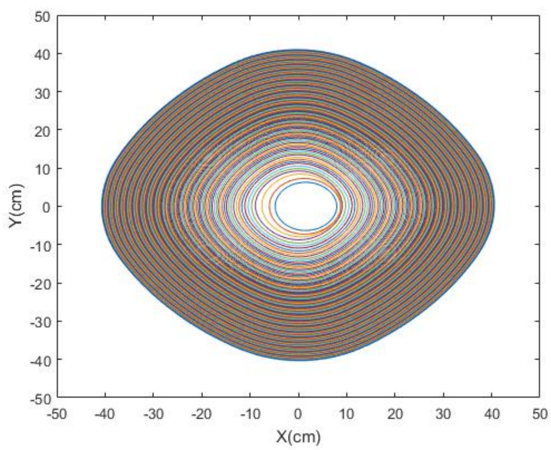

Figure 3: Equilibrium orbit of beam.

DATA ANALYSIS

Using the EO code, we can analyze a variety of physical parameters (i.e., equilibrium orbits, phase space distributions, betatron tunes and resonances, etc.)

Phase Space

We are tracking particle motion in phase space along degree and radial direction by the transfer matrices in Eqs. (7) and (8). The x coordinate represents radial direction, and z coordinate represents vertical direction. The EO Code distributes 2000 particles by Gaussian distribution. We can see how the particle distribution in phase space changes for each angular and radial position of the orbit.

$$\begin{pmatrix} x \\ p_x \end{pmatrix}_\theta = \begin{pmatrix} x_1 & x_2 \\ p_{x_1} & p_{x_2} \end{pmatrix} \begin{pmatrix} x \\ p_x \end{pmatrix}_i, \tag{7}$$

$$\begin{pmatrix} z \\ p_z \end{pmatrix}_\theta = \begin{pmatrix} z_1 & z_2 \\ p_{z_1} & p_{z_2} \end{pmatrix} \begin{pmatrix} z \\ p_z \end{pmatrix}_i. \tag{8}$$

Figure 4 shows the phase space particle motions in vertical plane at two different angles (blue dots at 2 degree and red dots at 300 degree) but same turn number (both in first turn).

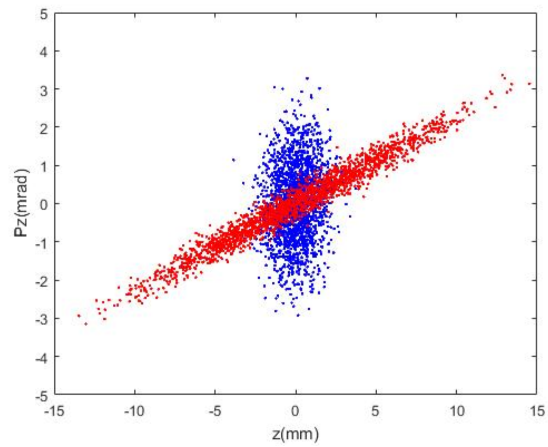

Figure 4: Distributions of particles in phase space for vertical direction.

Betatron Tune and Resonance

Betatron tune is defined as the number of the betatron oscillation during one closed orbit [2]. We can calculate betatron tune by transfer matrices in Eqs. (7) and (8). In Eqs. (9) and (10), ν_x and ν_z are betatron tunes of radial direction and vertical direction.

$$\cos v_x = \frac{1}{2}\left(x_1 + p_{x_2}\right), \tag{9}$$

$$\cos v_z = \frac{1}{2}\left(z_1 + p_{z_2}\right). \tag{10}$$

Figures 5 and 6 show turn excursions with respect to beam energy for radial plane and vertical plane, respectively.

Resonance is an important factor in accelerator. Amplitude of betatron oscillation is increased when resonance is occurred and increase of the amplitude causes beam loss. Furthermore, cyclotron has serious damage when beam loss occurs. Therefore, betatron tune must avoid major resonance to decrease such damage. Calculated tunes are compared with the major resonance lines in Fig. 7. Around first few turns, the beam passes through the integer radial tune. This is due to the small field bump applied near the center in order to focus beam vertically. However, it is not so harmful to the beam because the beam passes through this resonance quickly due to the rather large turn separation. Excepting this region, calculated tunes in vertical and radial planes are between integer tune and half integer tune.

ISBN 978-3-95450-167-0

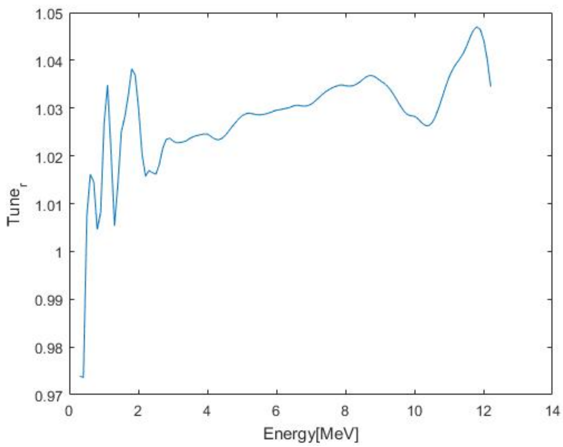

Figure 5: Radial tune variation with respect to beam energy.

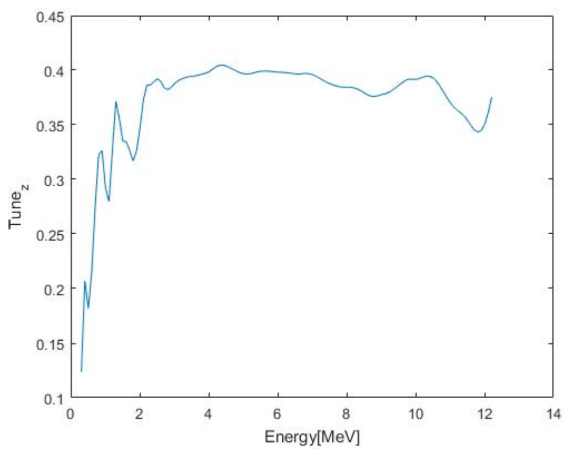

Figure 6: Vertical tune variation with respect to beam energy.

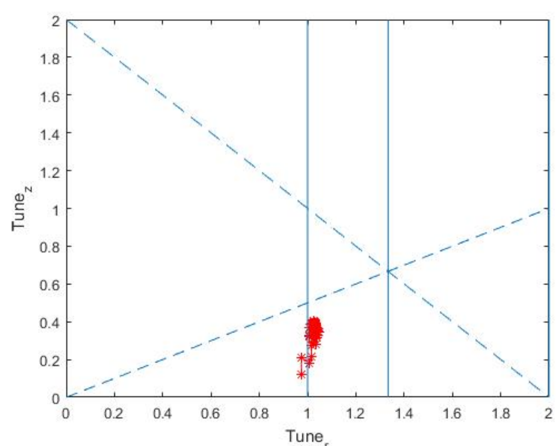

Figure 7: Operating point on tune diagram.

FUTURE PLANS

Now the interest of high power cyclotron is increasing in the world. In Korea, based on the success of 13 MeV and 30 MeV KIRAMS Cyclotrons [3], small project to develop simulation code is carrying out. Main purpose of simulation code is to describe beam dynamics on high power cyclotron.

Currently, we work including acceleration effect in EO Code. And we will add higher order term of beam physics in EO Code by the end of 2016. Space charge effect algorithm which must be considered to simulate high power cyclotron will be inserted in EO Code later. In 2018, we will design high power cyclotron using developed EO Code.

CONCLUSION

EO Code is beam tracking code using Runge-Kutta Gill method. This code doesn't include acceleration effect, but current program adds small energy when one closed orbit is formed. We can analyze various physical parameters by simulating EO Code. In the future, we will add various effect term which are acceleration effect, higher order term and space charge effect for simulating high power cyclotron.

REFERENCES

[1] M. M. Gordon *et al.*, "Computation of closed orbits and basic focusing properties for sector-focused cyclotrons and the design of 'CYCLOPS'", *Particle Accelerators.*, vol. 12, pp. 13-26, Nov. 1983.

[2] Mario Conte, William W Mackay, *An Introduction to the Physics of Particle Accelerators*. Genova, Texas, USA, 2008.

[3] J. Kang, B.H. Hong, D.H. An, H.S Chang, I.S. Jung, J.S. Chai, M.G. Hur, T.K. Yang, and Y.S. Kim, "Design study of the 30 MeV Cyclotron magnet", in *Proc. EPAC'06*, Edinburgh, UK, Jun. 2006, paper WEPLS078, p.2559.

ISBN 978-3-95450-167-0