The Optimal Central Region Design of A Medical Compact Cyclotron

Dong Hyun An, In Su Jeong, Joonsun Kang, Seong-Seok Hong, Hong Suk Chang, Bong Hwan Hong, Min Yong Lee, Tae Keun Yang, Min Goo Hur, Won Taek Hwang, Jung Hwan Kim, Yu-Seok Kim, and Jong Seo Chai

Laboratory of Accelerator Development, Korea Institute of Radiological & Medical Sciences, Seoul, Korea

1. Introduction

The central region in compact cyclotron is important in beam matching between an ion source or an injection element and a cyclotron to minimize the beam loss at the first gap and the central region. The beam emittance of the internal PIG ion source is hard to define normally. Therefore the acceptance of the cyclotron, particularly in the central region, should maximize to minimize the amount of beam loss.

The beam acceptance of the central region of cyclotron can be defined by radial turn separation, hill gap, and RF phase acceptance. The radial turn separation is sufficient to accept the radial deviation by the energy variations and also the radial tune value of AVF cyclotron is about 1. But the vertical beam boundary is extremely limited by the hill gap and the vertical tune value from the magnetic field distribution is very small in the central region. And also the RF phase acceptance and the initial phase to extract ions from an internal ion source are limited by the cyclotron's fundamental parameters, harmonic number.

This paper is focused on investigation of the method to maximize the axial tune and the RF acceptance in the central region of compact cyclotron accelerator.

2. Methods and Results

2.1 RF Dee voltage

The PIG(penning ion gauge) ion source is a typical ion source of most of compact medical cyclotrons. The beam could be extracted from the PIG ion source by a puller where the RF Dee voltage is applied.

The extracted beam current is related with the dee voltage like below,

$$I_0 = A \cdot B \cdot V_{dee}^{3/2}$$

where B=0.4314 is the measured value with Arc current 0.2 A, hydrogen gas flow rate of 3 sccm, A is the multiplication factor for the higher Arc current and hydrogen gas. Figure 1 shows that the typical PIG ion source's extracted beam current with respect to DC Dee voltage with A=6. Empirically the extracted beam current from PIG ion source is influenced by the expansion gap size, gas flow rate, and Arc current. The maximum Dee voltage which applied on the puller is the first factor of beam current. The A value is estimated to apply the situation of Arc current 1.0 A, hydrogen gas flow rate of 5 sccm. When Dee voltage is about 40 kV, the DC beam current extracted from the PIG ion source is about 650 uA. Only 10% of the DC extracted beam can be accelerated with 50 degree of RF acceptance. If the RF acceptance is smaller, the accelerated beam current is smaller.

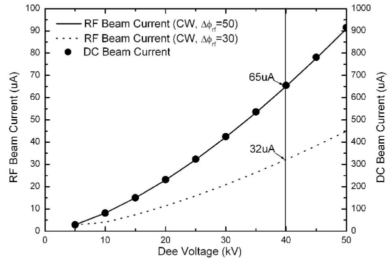

Figure 1. DC and RF beam current extracted from PIG ion source. $\Delta \phi$ is the estimated RF acceptance.

2.2 Magnetic field index and RF phase at the first gap and harmonic number

The axial tune [1] depends on the magnetic field index n=-rdB/Bdr, flutter funcion F of hill-valley structure, and the inclination angle δ at the magnet edges.

$$\nu_z = \sqrt{n + F(1 + 2\tan^2 \delta)}$$

In the central region of a compact cyclotron, F and δ is too small to contribute as an axial focusing effect. The isochronous magnetic field itself has much small negative magnetic field index. In order to get the finite axial tune in the central region by magnetic field distribution, it should make the radial magnetic field gradient negative, i.e., the magnetic field index be positive. Figure 2a shows the magnetic field distribution in the central region. But this modification of magnetic field distribution is limited by the isochronous condition and the amount of RF phase shift at the gaps.

The axial tune arising from the electric field can be expressed by the following equation in the case when magnetic focusing is completely absent [2].

$$\cos \nu_z \theta_e = 1 + \frac{1}{2}(\beta_1 + \beta_2)\theta_e + \frac{1}{2}\beta_1 \beta_2 (\theta_e - D)D$$

where $\theta_e = 2\pi / N_d$, D is the angular width of Dee, N_d is the number of Dee.

$$\beta_i = -\frac{\eta h V_0 \sin(hD/2)}{2T_0}(\sin\phi - (-1)^i \cot(hD/2)\cos\phi)$$

where h is harmonic number, T_0 is the average energy before and after the ion completely traverses the gap, η is the specific charge of the ions, V_0 is the nominal Dee Voltage, and ϕ is RF phase at the gap center. Figure 2b represents the dependence of the axial tune on the RF phase at the gap with the several harmonic number. The range of RF phase at the gap where the axial focusing is applied on the beam is dependent on harmonic number. The h=1 case shows that axial focusing is applied when the RF gap phase is above -20 deg. But the h=4 case represents that only the RF gap phase between -2 to 19 deg can be focused in vertical motion. The beam accelerated in the range of axial defocusing can be blown up because the magnetic axial focusing is too small to compress the beam during the acceleration.[3]

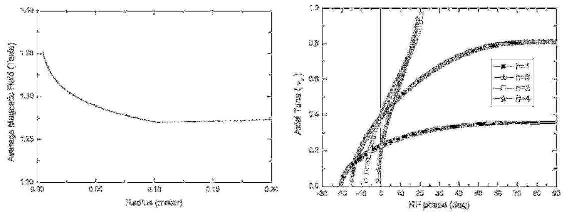

Figure 2. a) Average magnetic field distribution with radius. h=2, n=0.02, and v_z=0.14. b) Axial tune with respect to the RF phase at the gap center with h=1,2,3,4. V_0=40kV, η =1, T_0=35kV, N_d=2, D=39deg.

Table 1. Cyclotron's fundamental parameters

Type of Ion	Negative Hydrogen
Ion Source	Internal PIG type
RF frequency	38.65 MHz
Harmonic Number	2
Number of Dee	2
Dee Angular width	40 deg
Dee voltage	40 kV
Axial tune by magnetic field	0.14

Although the optimal vertical tune has been achieved, turn separation decreases with increasing the ion's energy. When the orbit centering doesn't consider, the overlap effect between adjacent turns and smaller turn separation makes beam loss. In order to minimize beam loss at higher energy, the orbit centering must be converged into the cyclotron's center in a few turns. The position of ion source have to be seek for the optimal orbit centering iteratively.

3. Beam trajectory simulation

Beam trajectory calculation has been carried out by solving the equation of motions numerically with the analytic electric field at the acceleration gaps and the given magnetic field distributions. The analytic electric field can be written like below [4]

$$V_x = \frac{V_0}{2}(1+\tan(\frac{r\sin x}{d}))$$

$$E_x = -\frac{V_0}{2d} r\cos x \sec h^2(\frac{r\sin x}{d})$$

$$E_y = 0.0$$

$$E_z \approx -z\frac{V_0 r^2}{d^2}\sec h^2(\frac{r\sin x}{d})\tanh(\frac{r\sin x}{d})$$

where V_x is the Dee voltage distribution along the beam direction. x direction is the beam direction at the gap. d is the gap width, z is a vertical position. r= $2d(1+z/h_g)/h_g$, where h_g is the height of Dee electrodes.

In the compact cyclotron flutter function in the central region is almost zero, so hill-valley effect is neglected in this calculation.

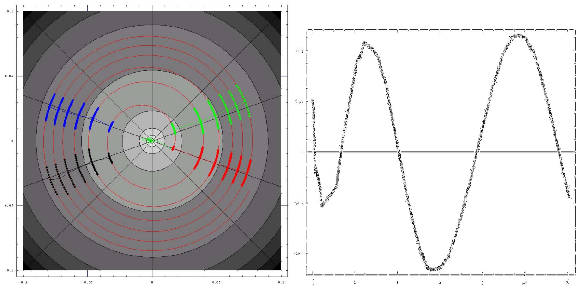

Figure 3. a) Horizontal beam trajectories with 6 turns b) Vertical beam trajectory. The x axis is the radian divided by . y-axis denotes the vertical position of the accelerated ion.

4. Results and Discussion

Beam trajectory calculation during 6 turns has been carried out with the fundamental parameters in Table 1. Figure 3a shows radial beam trajectory and dee gap positions. The circular line is the horizontal beam trajectory in the central region of cyclotron. The positions of 4 RF gaps are located at the colored dots. The green lines in the center of cyclotron is the trajectories of orbit centers which shows great convergence in a few turns. From the results the initial position of ion source and the RF gap positions for acceleration can be obtained by analytic calculations. The initial beam energy is about 20 eV and the starting RF phase is -10 deg. The initial position of ions is the point which can be obtained from the rotation of (0.017 m,0.002 m,0.002 m) by 30 degree about z axis. Normally the vertical slit size is about 4 mm. The z-position 2 mm is the maximum displacement from the median plane.

Figure 3b represents vertical beam trajectory. Using the harmonic number, we can focus the beam in the acceleration gap in low energy states. In addition, the magnetic field gradient is sufficient to focus the beam in the central region. The average axial tune of about 0.3 in the central region can be approximately obtained from the vertical beam trajectory.

5. Conclusion

In order to minimize the beam loss and to optimize the vertical tune in the central region, harmonic number and magnetic field gradient can be optimized by the analytic calculations. The obtained primary factors of h=2, n=0.02 has been found to has a good performance in vertical focusing in the central region. This procedure is just for the determination of the primary factors of new cyclotron.

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