Analysis of a Beam Centering Error Measured with a Radial Main Probe

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Abstract

A method for estimating a beam centering error in a cyclotron has been developed to optimize a beam orbit during the early stages of acceleration. A series of actual beam positions measured with a single radial main probe was used for the estimation of the centering error amplitude. The estimation was formed by fitting the beam positions to the function representing radial betatron oscillation around an accelerated equilibrium orbit. A radial betatron frequency and an energy gain per turn were also obtained from the fitting calculation.

1 Introduction

Insufficient adjustment of cyclotron parameters for a center region, such as positions of an inflector and a puller in an axial injection system, brings an orbit center away from a center of symmetry which corresponds to a center of a cyclotron magnet. A first harmonic component of a magnetic field makes the orbit center move in a circle around the center of symmetry[1]. As a result of this displacement, we have precession of the orbit either in the direction of motion of a particle for a radial betatron oscillation frequency of $\nu_r < 1$ or opposite to the direction of motion of the particle for $\nu_r > 1$. The displacement of the orbit center just before extraction from the cyclotron may improve an extraction efficiency, but sometimes may worsen the final beam quality.

A large first harmonic in the magnetic field drives a linear resonance at $\nu_r = 1$ that makes the radial motion unstable. The crucial resonance will cause an increase in amplitude of radial oscillation that results in loss of a beam in a center region. On the other hand the resonance is helpful for increasing a turn separation just before the extraction, what is called precessional extraction.

For the optimum tune-up of the cyclotron beam, the beam centering error has to be reduced during the early stages of acceleration. The beam centering error can be measured precisely with multiple radial probes[2]. The JAERI AVF cyclotron[3] is, however, equipped with a single radial main probe covering a full radius. The centering error of the beam in the center region was estimated from a beam density distribution measured with the main probe only. The estimation of the centering error is based on the assumption that the centering error amplitudes, ν_r and the energy gain per turn are identical for the first several turns.

2 Method of the Centering Error Estimation

The radial motion of a cyclotron beam can be expressed as the betatron oscillation around the equilibrium orbit. A radial position of the equilibrium orbit is uniquely determined by the particle energy. The shift of the equilibrium orbit due to the change of the particle energy after acceleration depends on the energy gain per turn. The radial position of the particle is expressed as

$$R(\theta) = A\cos(\nu_r\theta) + B\sin(\nu_r\theta) + R_{eq}(\Delta E, \theta), \qquad (1)$$

where A and B are amplitudes of the radial betatron oscillation, that is the centering error, θ an azimuth integrated from the first acceleration, ΔE the energy gain per turn, R_{eq} the radial position of the equilibrium orbit. The ν_r and ΔE are assumed to be constant during the first several turns.

A relation between the particle energy and an average radius of the equilibrium orbit for a 10 MeV proton beam is shown in Fig. 1. The particle energy in the center region is expressed by a second order polynomial of the average radius, since a non-relativistic approach can be applied to this energy region. Here we approximate the average radius of the first turn as

$$\overline{R_0} = b_1\sqrt{E_0 + \Delta E + b_2} + b_3, \qquad (2)$$

where the constants b_1, b_2 and b_3 are determined by a fitting of the energy vs. average radius curve, and E_0 is an injection energy. The particle energy of the first turn observed by the main probe of the JAERI AVF cyclotron is $E_0 + \Delta E$, since particles are stopped by the main probe after having the first energy gain.

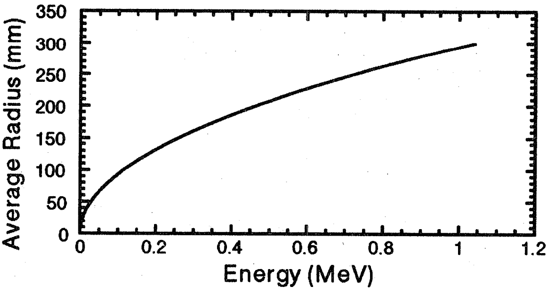

Fig. 1 The average radius of the equilibrium orbit as a function of the particle energy for a 10 MeV proton beam.

Correlation between the radial position of the equilibrium orbit in the direction of the main probe axis and the average radius for the 10 MeV proton is shown in Fig.2. Using a second order polynomial of the average radius, the radial position of the equilibrium orbit is expressed as

$$\overline{R_{eq}} = a_1 + a_2\overline{R} + a_3\overline{R}^2, \qquad (3)$$

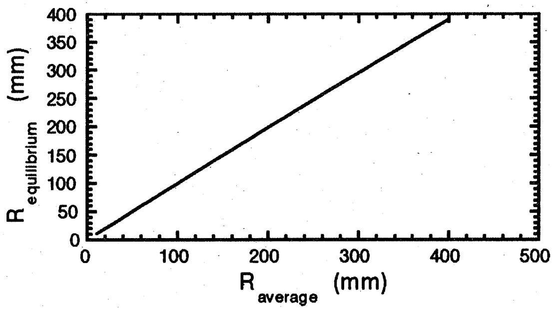

Fig. 2 Correlation between the radial position of the equilibrium orbit in the direction of the main probe axis and the average radius for the 10 MeV proton beam.

where the constants a_1, a_2 and a_3 are determined by a fitting.

By solving the equation of motion, the average radius of the equilibrium orbit is given by

$$\overline{R} = \overline{R_0}\left(\frac{E_0 + \Delta E + \frac{\theta}{360}\Delta E}{E_0 + \Delta E}\right)^{\frac{1}{2\nu_r^2}}, \qquad (4)$$

where $\overline{R_0}$ is the average radius of the first turn. From the equations (2), (3) and (4), the radial position of the equilibrium orbit can be expressed by the ν_r and energy gain.

The parameters of A, B, ΔE and ν_r are determined by a fitting of actual beam positions obtained from the beam density distribution using the equation (1).

3 Centering Error of 10 MeV Proton Beam

The beam density distribution of the 10 MeV proton beam measured with the main probe is shown in Fig. 3. Peaks corresponding to individual revolutions are clearly observed, but some peaks are duplicated. The duplicated peaks resulted from an error in signal processing. A centroid of the duplicated peaks was obtained by averaging the two peaks.

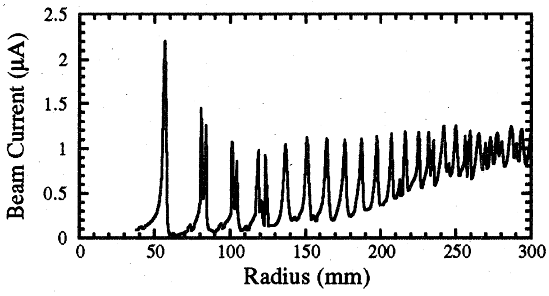

Fig. 3 Beam density distribution for the 10 MeV proton beam measured with the main probe.

The beam positions of the first thirteen revolutions are plotted in Fig. 4. The curve obtained by the fitting to the equation (1) is also plotted in the Fig. 4. The centering error amplitudes obtained by the fitting were A = -12 mm and B = +8 mm, which means that the orbit center was shifted by -12 mm in the main probe direction and by +8 mm in the direction perpendicular to the main probe axis.

The estimated energy gain and ν_r were ΔE = 0.052 MeV/turn and ν_r = 0.999. In the practical operation a nominal acceleration voltage was 11.39 kV, and thus the energy gain amounted to 0.045 MeV/turn. The energy gain estimated by the fitting is larger by 14 % than the nominal value.

In this preliminary analysis, errors of the fitted values were more than 50 %. The errors came from ambiguity of the peak position determination. More clearly separated peaks with a smaller width are required for precise analysis. Evaluation of this method for estimating the beam centering error is in progress.

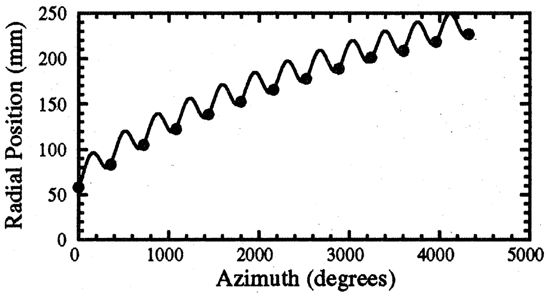

Fig. 4 Radial positions(dots) of the first thirteen revolutions for the 10 MeV proton. The curve accounts for a trace of the betatron oscillation estimated by the fitting.

References

[1] J.R.Richardson, "Sector Focusing Cyclotrons," Progress in Nuclear Techniques and Instrumentation (North-Holland Physics Publishing, 1965), vol. 1, pp. 29

[2] S. Adam and J.C. Collins, IEEE Trans. Nucl. Sci. **NS-26** (1979) 2362.

[3] K. Arakawa et al., Proc. 13th Int. Conf. on Cyclotron and Their Applications, Vancouver, Canada, (1992) 119.