MEASUREMENT OF RADIAL OSCILLATION AND PHASE OF ACCELERATING BEAM IN KOLKATA SUPERCONDUCTING CYCLOTRON

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Abstract

This paper describes various measurements performed on the beam behaviour with the help of the main probes and the differential probe to have a clear insight of the accelerating beam and the difficulties of beam -extraction process in the K500 superconducting cyclotron at Kolkata. Beam shadow measurements with three probes at three sectors were done to get the information of beam-centering and radial oscillations. The radial oscillation amplitude is estimated from the measurements. A differential probe was used to measure the turn separation and its modulation due to radial oscillation. With the help of magnetic field detuning method, the beam phase history was also measured.

INTRODUCTION

The beam behaviour studies were carried out to have a clear insight of the accelerating beam and the difficulties of beam -extraction process in the superconducting cyclotron (SCC) at Kolkata. We have accelerated the beam of Ne^{4+} and N^{2+} under 2nd-harmonic operation and carried out different probe measurements. The probe is made of insulated copper electrode which collects beam current and conducted through a cable to be measured by electrometer. There are such three probes separated at nearly 120 degree apart were used to measures the current versus radius. One of the probe which we called main probe(Mp) moves on spiral path along the centre of hill whereas the other two probes (Bore probe, BP & Deflector probe, DP) moves straight radially. The convenience of three probes is that current can be collected on one probe and cut off from this probe by moving another probe in, to determine orbit centre. The main probe (mp) is attached with differential probe to measure turn separation. To obtain information on the coherent and incoherent radial oscillations we have used both differential probe and shadow measurement cast by one probe on another at different locations of the probes. Beam shadow measurements are well known technique and are performed at many radial position of cyclotron. The radial position of reference particle of the beam is assumed to be the location where the beam current drops to 50% during shadow measurement. The orbit-centre was obtained from such measurements by finding its deviation from equilibrium orbit which is calculated for three sector cyclotron using measured field data. It was found that a large off centering in the extraction region where ν_r =1 could not survive the beam upto extraction energy. Later it was clear from magnetic field measurement that significant first harmonic imperfections in the extraction region which accounts for the unexpected off centering. The radial motion of orbit centre under measured field imperfection was simulated and compared with observed data. An empirical relation was deduced to be used with beam shadowing measurement to obtain radial coherent oscillation in three sector cyclotrons. The present analysis being general unlike others [1] where we have included scalloped orbit with three dee system and decreasing radial gain per turn due to acceleration in order to apply in our system. The turn separation was measured by differential probe and its modulation due to radial oscillation was studied to estimate dee voltage. The shadow width which is the radial extent where the beam current is taken over by other probe is used to estimate the largest incoherent betatron amplitudes present in the beam. The paper also describes the measurement of particle phase history which also accounts for the loss of beam in the cyclotron.

METHOD OF MEASUREMENT AND ANALYSIS

Orbit Centre

A beam is centered when the geometrical centre of the cyclotron coincides with the orbit centre. A number of shadow measurements were performed for different radial positions of the probes. The first probe is fixed at some radius and the second probe is moved to obtain equal beam current density on both probes. The third probe is placed well outside during measurement. Similarly the third probe was moved and repeats the measurement while second probe was kept outside. The measurement sequence of the probes follows the direction of acceleration viz DP-BP-MP. The measured data are plotted as a function of the position of fixed probe (Fig. 1). The equilibrium orbit is computed in a perfect magnetic field where only 3N harmonic are present and shifted from geometric centre so that positions of three probes matches the measured values so obtain. The radial motion of orbit centre is calculated and compared with observed values.

Radial Coherent Oscillation

Particles displaced from the equilibrium orbit oscillate harmonically about it both vertically and radially. The radius of such particle performing coherent radial oscillation at the nth turn is given by:

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$$r = ra_0 + n\,\Delta ra + Ac\,Cos[\nu\,\theta + 2\,\pi\,n\,\nu + \varphi_0] + S(ra,\theta) \quad (1)$$

where

ra_0= Average radius at n=0

Δra= radius gain per turn due to acceleration

$$= \frac{6\,Q\,V_d\,Sin[h\frac{D}{2}]}{2\,E(ra)}\,ra$$

Vd=Dee voltage

h=harmonic number (our case h=2)

D=Dee angle = 60^0

E(ra)= Energy of particle as a function of radius

Ac=Coherent oscillation amplitude

Θ= azimuthal position

φ_0 = Phase of coherent oscillation

S(ra,θ) = scalloping due to varying azimuthal magnetic field.

The difference of radius at the two probes for the n^{th} turn due to coherent oscillation can be obtained from eq. 1 by choosing φ_0 =0 without ambiguity since ra_0 can be chosen at will and given by

$$r2 - r1 = \Delta r = Ac\,Cos[\nu\,\theta 2 + 2\,\pi\,n\,\nu] - Ac\,Cos[\nu\,\theta 1 + 2\,\pi\,n\,\nu] = -2\,Ac\,Sin[2\,\pi\,n\,\nu]\,Sin[0.5\,\nu\,\alpha]$$

Assuming for mathematical simplicity θ1=-θ2=-0.5 α so that α is the angle between two probes.

Since Sin [2 π n]=0 & Cos[2 π n]=1, we can write

$$\Delta r = -2\,Ac\,Sin[2\,\pi\,n\,\epsilon]\,Sin[0.5\,\nu\,\alpha], \text{ where } \epsilon = \nu - 1 \quad (2)$$

Hence maximum (and minimum) difference of radius due to coherence oscillation becomes

$$|\Delta r(max.)| = 2\,Ac\,Sin\,[0.5\,\nu\,\alpha] \quad (3)$$

The number of turns, dn between minimum and maximum of coherence oscillation is obtained by solving

$$2\,\pi\,n\,\epsilon = -\pi/2$$

$$2\,\pi\,(n + dn)\epsilon = \pi/2$$

So that,

$$dn = 1/(2\,\epsilon) \quad (4)$$

The difference of radius Δr plotted against the radial position of fixed probe will show oscillation. The difference of increasing radial position of fixed probe corresponding to minimum and next successive maximum of Δr are contributed by 1. Radial gain due to acceleration of dn number of turns 2. Peak coherence oscillation and 3. Correction due to scalloping of the orbit at the probe locations.

$$r(\Delta r_{max}) - r(\Delta r_{min}) = \Delta ra/2\,\epsilon + 2\,Ac\,Sin[0.5\,\nu\,\alpha] + \Delta S(ra,\theta) \quad (5)$$

Similarly between maximum and next successive minimum is given by

$$r(\Delta r_{min}) - r(\Delta r_{max}) = \Delta ra/2\,\epsilon - 2\,Ac\,Sin[0.5\,\nu\,\alpha] + \Delta S(ra,\theta) \quad (6)$$

where ΔS(ra,θ) is the correction term due to different scalloping at two probe position and is calculated for each positions of probes (ra,θ) from particle equilibrium orbit. The turn separation is obtained form equation (1) and is given by

$$\delta r = \Delta ra - 2\,Ac\,Sin[\nu\,\pi]\,Sin[\nu\,\theta + (2n+1)\,\pi\,\nu + \varphi_0] \quad (7)$$

This is fitted with measured δr(r) to estimate dee voltage as well as radial oscillation amplitude.

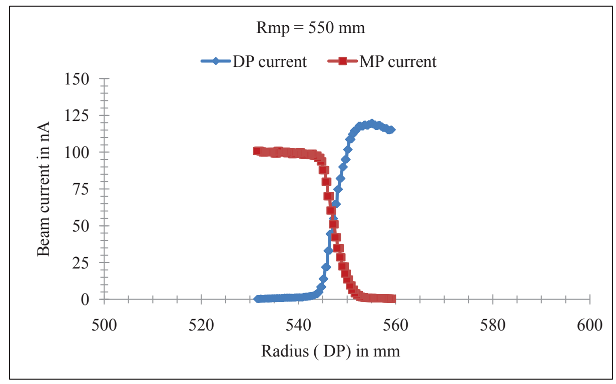

Figure 1: Shadow measurement with MP fixed at R=550 mm.

Incoherent Oscillation and Shadow Width

The maximum amplitude of the incoherent radial oscillation may be deduced from the measurement of shadow width. The edges of the beam of particles having largest incoherent oscillation manifest as the outermost and innermost particles in the shadow cast by one probe on another. The shadow width having maximum incoherent oscillation of A_{imax} is given by [1]

$$SW = 2\,A_{imax}\,Sin\,[0.5\,\nu\,\alpha]\,(1 + \chi) \quad (8)$$

where $\chi = \frac{1 - d\,\sin(\varphi 0 + 0.5\,\nu\,\alpha)}{1 - d\,\sin(\varphi 0 - 0.5\,\nu\,\alpha)}$

Here d is a dimensionless parameter dependent on coherence oscillation amplitude Ac and given by

$$d = 2\,Ac\,Sin\,[\epsilon\,\pi]/\Delta ra \quad (9)$$

The maximum and minimum of shadow width is obtained for the oscillation phase φ_0 where χ is maximum and minimum respectively. The value of φ_0 is assumed to be constant over the interval of shadow measurement. The normalized shadow may be obtained by dividing the shadow by 4 A_{imax} Sin [0.5 ν α] which is equal to the shadow width when Ac=0

The maximum incoherent radial oscillation, A_{imax} is obtained from the measured peak values of shadow width with radial position.

Particle Phase History

The phase of the particles with respect to the rf is measured employing detuning of the magnetic field by

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using trim coils. The phase change with a small change ΔB of magnetic field is given by [2,3]

$$\Delta \mathrm{Sin}\Phi(r) = C \int_0^r \Delta B \, r \, dr \quad (10)$$

where C is a constant and given by $2\pi Q\, \omega_0 / E1$
E1- maximum energy gain per turn
ω_0- Orbital angular velocity

The beam will lost whenever $|\mathrm{Sin}\Phi(r)| \geq 1$ which indicates the particles start to decelerate and get lost. The beam current was made to zero with small perturbation of magnetic field using trim coils at different radius and phase was measured employing the above equation (10). The phase probe based on plastic scintillator is also used to measure the phase history and details are reported elsewhere [4].

RESULTS AND DISCUSSION

The shadow measurement was taken at various radius and the position of probe was obtained. It is assumed that the reference particle of the beam corresponds to the position where current drops to 50%. The orbit centre is obtained as deviation from its undisturbed equilibrium orbit and plotted against the average radius as shown in Fig. 2 along with calculated orbit shift. Three separate measurements correspond to individual set where each probe is fixed. The sharp rise of orbit shift near ν_r=1 was observed which could not survive the beam upto extraction radius.

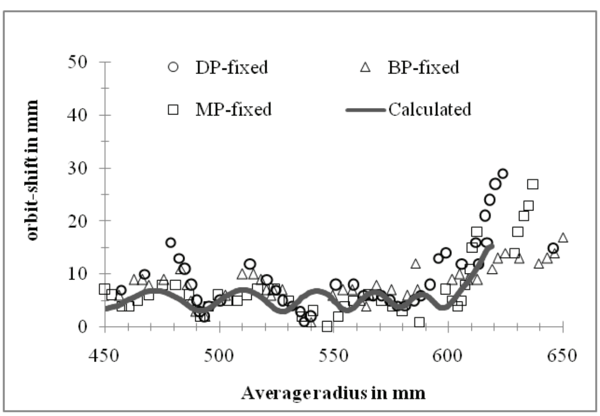

Figure 2: Orbit shift at different radius.

The coherence oscillation amplitude Ac is derived using equations 5 & 6. The dee voltage is obtained to be 33 kV from turn separation and used for calculating energy gain. The amplitude is fitted with cosine curve with a period same as Δr and plotted against radius as shown in Fig. 3. It is evident from the figure that oscillation increases sharply after 600 mm corresponds to ν_r=1 resonance. The incoherent oscillation amplitude $A_{imax.}$ is obtained from the maximum and minimum of the measured shadow width using equation 8 and plotted against radius in Fig. 3. The turn separation was measured using differential probe at lower radius below 300mm as the turns getting denser and becomes continuous with increase of radius. The dee voltage and radial oscillation amplitude was estimated from the turn separation.

The loss of the beam before the extraction radius is apparently due to phase loss and resonances. The increase number of particle turns from phase loss enhances the loss due to resonance. The particle phase with respect to rf voltage was measured by magnetic field de-tuning and using phase probe and are shown in Fig. 4. The continuous blue line in the figure corresponds to phase obtained from the magnetic field.

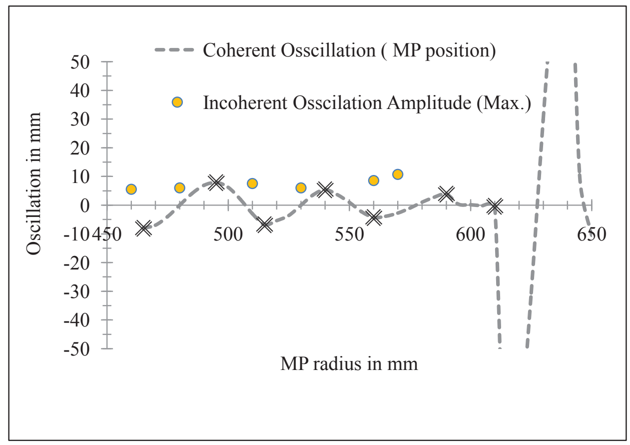

Figure 3: Radial betatron oscillation obtained from shadow measurement.

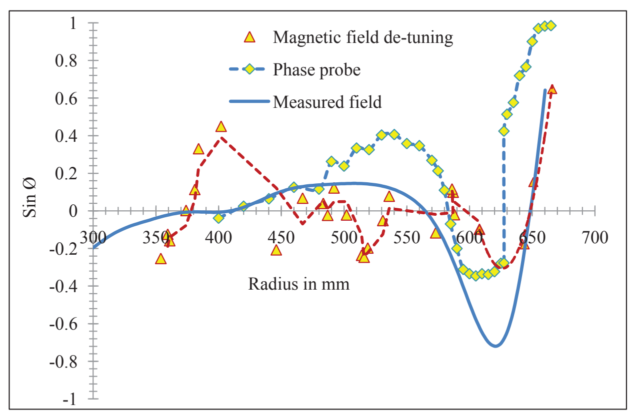

Figure 4: Particle phase history measured with two different methods.

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