STUDIES ON A HIGH CURRENT INJECTOR CYCLOTRON

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Abstract

At VECC, we are developing a 2.45GHz microwave ion source, a low energy beam injection line and a 10 MeV, 5-10mA compact proton cyclotron to study problems associated with high beam intensities. In order to estimate the effect of beam density distribution on tune shift during injection we have used a truncated gaussian density distribution of various shapes and have evaluated the tune shifts due to the space charge force. We have described a method to maximize the limiting current by optimizing parameters of the compact cyclotron. Design of the low energy beam transport line is also described.

INTRODUCTION

Under the ADSS development program of the Department of Atomic Energy, the Variable Energy Cyclotron Centre at Kolkata is developing, a 2.45GHz microwave ion source, a low energy beam injection line and a 10 MeV, 5-10mA compact radial sector proton cyclotron. The aim is to study the injection, acceleration and extraction related problems associated with high beam intensities. In a low energy cyclotron the transverse space charge effects are strongest on the first few turns because the energy of the beam is low and focusing forces are small at the machine center. The motivation of our study is to improve the transverse space charge limiting current and to make projections as to how to achieve this in a low energy compact isochronous cyclotron. In order to estimate the effect of beam density distribution on tune shift we have used a truncated gaussian density distribution for the beam and have evaluated the tune shifts due to the linear and nonlinear part of the space charge force. To improve the limiting current, apart from using high injection energy, the general trend is to use the value of the betatron tune as high as possible, but this procedure generally does not yield the desired result. In this work we have described a method to maximize the limiting current by optimizing the parameters of the compact cyclotron. We have also studied the dependence of the limiting current on various machine and beam related parameters such as vertical betatron tune, average magnetic field, beam injection energy, emittance of the beam etc. The design of the low energy beam transport (LEBT) line which will be used to transport 100 keV, 30 mA proton beam from the ion source and eventually to match this beam into the central region of the 10 MeV compact cyclotron, is also described.

SPACE CHARGE TUNE SHIFT

In order to estimate the effect of the beam density distribution on tune shift during the injection, we have used a truncated gaussian density distribution and have evaluated the tune shifts due to the space charge. The form of density distribution is,

$$\rho(x,y) = \frac{q\lambda}{G(a,b,p)} . exp\left[-\frac{p^2 x^2}{2a^2} - \frac{p^2 y^2}{2b^2} \right] \qquad (1)$$

We have used a finite elliptical cross section for the beam having semi major and semi minor axes *a* and *b* respectively in the transverse planes. We have truncated the beam at $a=p\sigma_x$, and $b=p\sigma_y$, conserving the number of particles within the beam cross section. A uniform density distribution corresponds to *p* equal to zero in Eq. (1), keeping *a* and *b* constant. The parameter *G* can be evaluated from the normalization condition. Using the above form of density distribution we have evaluated the electric field due to the beam. The electric field so obtained is fitted with a function $Ax+Bx^3$ to evaluate the contribution of linear and nonlinear part. Figure 1 shows the effective betatron tune ν_s in the presence of space charge force as a function of the injection energy (for 5mA beam current). The vertical betatron tune ν_z available from the electromagnetic field in our 10 MeV cyclotron is equal to 0.84. As the value of *p* increases, beam becomes more and more dense near the centre. Results of study show that a nearly uniform beam density distribution in the transverse planes and the beam energy $T_{inj} \geq 100$keV are favourable for injection.

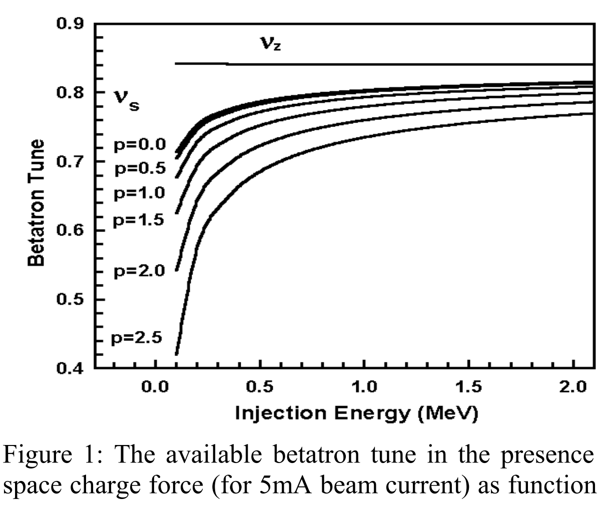

Figure 1: The available betatron tune in the presence of space charge force (for 5mA beam current) as function of injection energy. ($\nu_z = 0.84$)

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LIMITING CURRENT

In this section we describe a method to maximize the limit of the beam current that can be injected into a compact cyclotron. Let us assume that a beam with uniform particle distribution is injected into a cyclotron. We further assume that beam has a circular cross section and identical normalized transverse emittance $\pi\varepsilon_n$ in both the radial and vertical planes. The limit on the injected beam current can be easily obtained by solving the beam envelope equation [1,2] under the matched condition, and is given by

$$I = \frac{I_0}{2}\beta\gamma\frac{\Delta\phi}{2\pi}\left[\frac{q^2\overline{B}^2a^2\ \upsilon_0^2}{m^2c^2} - \frac{\varepsilon_n^2}{a^2}\right] \quad (2)$$

where a is the matched (allowed) beam radius and R is the average orbit radius at the injection, υ_0 is the transverse betatron tune (vertical betatron tune υ_z or radial betatron tune υ_r), and $\omega = q\overline{B}/\gamma m$ is the orbital angular frequency of a particle with charge to mass ratio q/m in an average magnetic field $\overline{B}$. $\Delta\phi$ is the accepted beam phase width in the central region. β and γ are the usual relativistic terms for the normalized particle velocity and energy respectively. $I_0 = 4\pi\varepsilon_0 mc^3/q$, is known as the characteristic current and for proton $I_0 = 31\ MA$.

We see from Eq. (2) that a high value of injection energy ($\beta\gamma$), a low beam emittance and a large beam phase width $\Delta\phi$ are the obvious choices to improve the limiting current. However, in a compact proton cyclotron short beam bunches are desirable to minimize the beam losses at the extraction. The limiting current can also be improved by increasing the beam size a, but the allowed beam size is severely restricted due to the limited space in the central region. Beam size should not exceed the available linear aperture to avoid the nonlinear effects. The other two choices are to use a high average magnetic field and to improve the betatron tune significantly. However, it is not possible to increase both $\overline{B}$ and υ_0 together in a compact isochronous cyclotron.

For a compact isochronous cyclotron having N symmetrical sectors with hill field B_H and valley field B_V, we have the following relations [3]:

$$\overline{B} = \frac{N\theta_H}{2\pi}(B_H - B_V) + B_V \quad (3)$$

$$\upsilon_z^2 = -\beta^2\gamma^2 + \frac{N^2}{N^2-1}\left[\frac{(B_H-\overline{B})\cdot(\overline{B}-B_V)}{\overline{B}^2}\right](1+2tan^2\xi) \quad (4)$$

$$\upsilon_r^2 = \gamma + \ldots \quad (5)$$

Here θ_H is the hill angle and ξ is the spiral angle at the injection radius R. It is to be noted here that these formulas are appropriate for sufficiently large injection radius. In an isochronous cyclotron the radial betatron tune is always greater than one in the region of the interest and is approximately independent of average magnetic field (up to the first order). One can easily calculate the limiting current using Eq. (2) and an increase in the value of υ_r will always increase the limiting current. However, the situation is not similar with the vertical betatron tune υ_z. Since υ_z and $\overline{B}$ are dependent on each other, choosing a high value of υ_z or $\overline{B}$ may not improve the limiting current. Maximum in the limiting current I will occur at a particular hill angle where $\upsilon_z\overline{B}$ will be maximum. It can be obtained by putting Eq. (3) and Eq. (4) into Eq. (2) and maximizing I as a function of θ_H. This occurs at a hill angle,

$$\theta_H = \frac{\pi}{N}\cdot\left[\frac{\left(\frac{N^2}{N^2-1}(B_H-B_V)(1+2\tan^2\xi) - 2B_V\beta^2\gamma^2\right)}{\left(\frac{N^2}{N^2-1}(1+2\tan^2\xi)+\beta^2\gamma^2\right)\cdot(B_H-B_V)}\right] .(6)$$

At low injection energy of the beam in the range of 50keV to 200keV, $\beta\gamma$ is very small and numerical value of the term in the square bracket in Eq. (8) approaches to 1. Thus maximum of $\upsilon_z\overline{B}$ occurs at hill angle $\theta_H \approx \pi/N$. Substituting $\theta_H = \pi/N$ in Eq. (3) and Eq. (4) and using them in Eq. (2) we can easily get an expression for the maximum limiting current.

As mentioned earlier, at a low injection energy $\beta\gamma$ is very small and it is very difficult to provide any spiral angle at the injection radius. If emittance $\varepsilon = \varepsilon_n/(\beta\gamma)$ of the beam is small compared to the available acceptance $\alpha\,(=\upsilon_z a^2/R)$ at the injection radius, we have a simple expression for maximum limiting current for a straight sector ($\xi = 0$) compact isochronous cyclotron as,

$$I_{max} = \frac{I_0}{8}\beta\gamma\cdot\frac{q^2a^2}{m^2c^2}\cdot\frac{\Delta\phi}{2\pi}\cdot\frac{N^2}{N^2-1}(B_H - B_V)^2 . \quad (7)$$

The current that can be injected into a compact cyclotron can be increased substantially by increasing the difference between the hill and the valley fields.

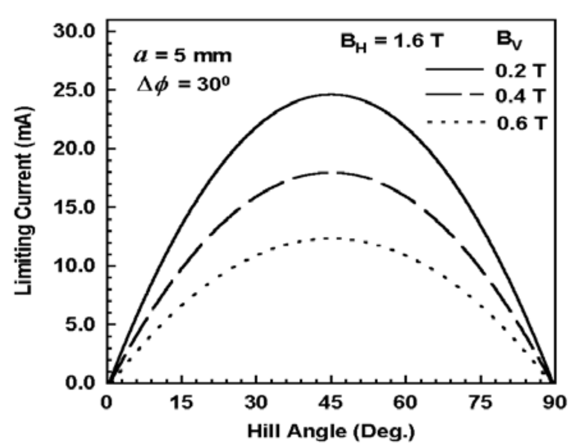

Figure 2: Variation of limiting current as a function of hill angle in a 4 sector compact cyclotron for proton beam with injection energy of 100keV and ε_n = 0.8 π mmmrad.

Figure 2 shows the variation of the limiting current with hill angle for various combinations of hill and valley fields. The limiting current has a broad maximum in the vicinity of the hill angle 45^0. The peak value of the limiting current as well as the sharpness of the peak both are seen to increase as (B_H -B_V) is increased. For small values of (B_H -B_V), the reduction in the limiting current is marginal when one chooses a hill angle slightly away from 45^0. When (B_H -B_V) is large, which is generally realized by making deep valleys, the choice of hill angle is very crucial. A hill angle slightly away from 45^0 results in a substantial decrease in the limiting current. The dependence of the peak value of limiting current on the normalized beam emittance at several values of injection energy of the proton beam is shown in Figure 3. As expected the current increases with the beam energy and reduces if the emittance is large. Clearly a beam with low emittance and high injection energy is desired.

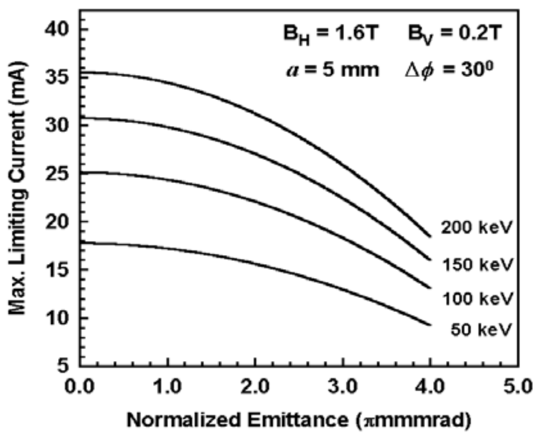

Figure 3: Variation of the peak value of the limiting current with normalized emittance in a 4 sector compact cyclotron at different injection energies of proton beam.

In the case of H^- ion acceleration, where turn separation at the extraction radius is not an important factor, it is advantageous to choose a hill angle $\theta_H \geq (\pi/4)$ for a four sector cyclotron. This choice reduces the size of the magnet (high $\bar{B}$) and is cost effective. In a proton cyclotron, a large turn separation at the extraction is mandatory to avoid the beam loss at extraction. In this case a better choice is to choose a hill angle $\theta_H \leq (\pi/4)$. This choice reduces the $\bar{B}$ and provides large turn separation at the extraction radius. However, the size of the magnet will be large and the cyclotron will be more costly. In both the cases the choice of the hill angle be such that the betatron tunes υ_r and υ_z are sufficiently away from the dangerous resonance.

We would like to point out here that the results presented above are valid when the injection energy is sufficiently high in the range of 100 keV to 200 keV and the average magnetic field is low. These results are not applicable for small injection radius (compared to the pole gap in the hill region). At the injection radius, the azimuthal separation between hill and valley should be quite large compared to the pole gap in the hill for the validity of the hard edge approximation.

LEBT

The LEBT will be used to transport proton beam from the ion source to the central region of the 10 MeV cyclotron. Microwave ion source (2.45 GHz) will produce I~30 mA of p beam at 100 keV with normalized rms emittance ~ 0.2πmm.mrad. Since beam from ion source contains a substantial fraction (~10 to 20 %) of molecular hydrogen ion, the LEBT designed here is aimed to fulfill the following; rejection of most of the molecular hydrogen beam as early as possible and transport of the beam through the strong hole lens of the cyclotron magnet to form a waist at the spiral inflector in the central region. We have used two magnetic solenoids one near the ion source (SOL1: 40cm, 3.6kG) and other near the cyclotron magnet (SOL2: 40cm, 3.3kG). The effect of the hole lens of the cyclotron magnet has been included by using a number of solenoid magnets of suitable strengths one after another. In the beam line there will be a buncher, a faraday cup and two beam steering magnets for horizontal and vertical directions.

Design of the LEBT including the space charge effects has been done using the computer code Graphic TRANSPORT of PSI [4]. Fig 4 shows the beam envelops in the x and y plane for an initial upright ellipse (beam size=2.5mm and beam divergence=21.33mrad). For initial beam with 80% of proton and 20% of molecular hydrogen, a slit of 5mm × 5mm improves the proton fraction to 99.3% after the slit without any loss in the proton beam.

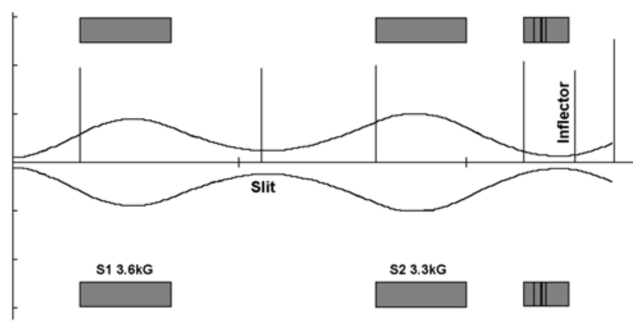

Figure 4: Beam envelop for 30 mA proton beam with normalised emittance 0.8π mmmrad.

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