Axial Focusing in the Acceleration Gaps of the Cyclotron

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Abstract

In this paper we compared analytical and numerical results of axial focusing in the acceleration gaps in the central region of the cyclotron. In the case of analytical method we considered only the electrical focusing properties of the acceleration gaps. In the case of numerical method we analysed the ion trajectories which include both the electric and magnetic fields data. The electrical field distribution in the four acceleration gaps has been numerically calculatied by program RELAX3D. The numerical orbit computations have been carried out by means of the computer code CYCLONE. The analytical and numerical calculation was done for protons and h=1 mode of acceleration.

1. INTRODUCTION

During electric gap_crossing, ions in the beam experience vertical focusing forces produced by the same RF field which is responsible for their acceleration. This electric focusing plays an important role near the center of most cyclotrons in a region where the magnetic focusing tends to be very weak.

As an application of the analytical and numerical method, we consider the central region of the cyclotron which is described in ref. [1,2,3].

2. THEORY OF ELECTRIC FOCUSING

In the paper [4] dealing with electric focusing, a fairly general dee geometry has been considered and the formula for the energy gain has been derived. The same formula will be used here. The assumed geometry contains a set of N_d identical dees which are symmetricaly arranged and uniformly separated in azimuth, so that $\Delta\theta=\theta_e=2\pi/N_d$ constitutes an electric ″sector″. In each of these sectors, the ions undergo one gap crossing when they enter the dee and another when exit. Each dee is assumed to have a constant angular width D, so that $\theta_2 - \theta_1 = D < \theta_e$ where θ_1 and θ_2 are the angles where the ions enter and exit the dee, respectively.

In [4] is shown that ν_z can be expressed by the following equation in the case when magnetic focusing is completly absent:

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

ν_z is the vertical oscillation frequency produced by the combined effect of both electric and magnetic focusing. In the above equation β_j is given by:

$$\beta_j = -\frac{h}{4nN_d}\left[\sin\phi - (-1)^j ctg\frac{hD}{2}\cos\phi\right] \qquad (2)$$

where j=1 or 2 specifies, respectively, whether the ion is entering or exiting the dee, h is harmonic number, ϕ is phase and n is ″turn number″, defined by:

$$n = \frac{T_0}{\eta V_1} = \frac{T_0}{\eta\, 2 N_d V_0 \sin\frac{hD}{2}} \qquad (3)$$

where T_0 is the average value of the energy before and after the ion completely traverses the gap, η is specific charge of the ions, ηV_1 is the peak energy-gain per turn and V_0 is the nominal dee voltage.

3. NUMERICAL STUDIES OF THE AXIAL FOCUSING

Equilibrium orbit properties are derived via the equilibrium orbit code GENSPEO. The median plane magnetic field map $B(r,\theta)$ is stored in a polar mesh with $\Delta\theta=1^0$ and $\Delta r=1$ cm. The electrical field distribution in the four acceleration gaps has been numerically calculated by program RELAX3D. For the analysis of the ion trajectories in the central region, which included both the electric and magnetic fields data, we used the code CYCLONE [5].

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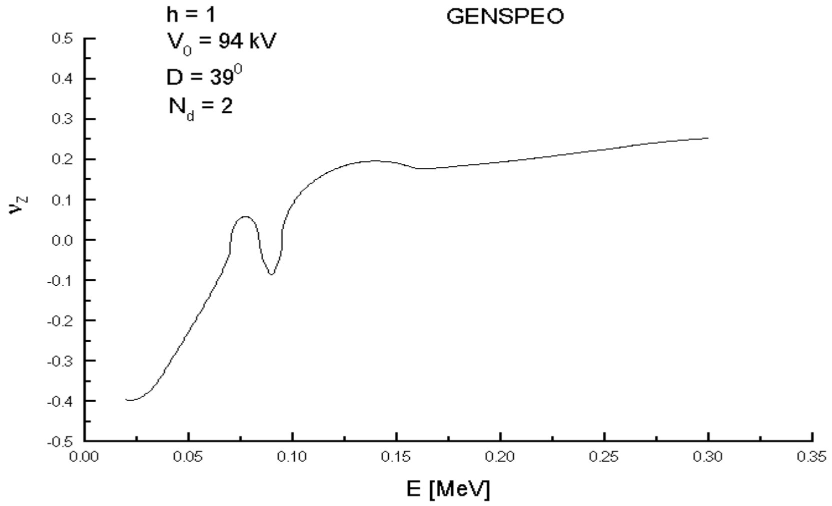
Fig. 1. Plot of the numerical calculated ν_z values using computer code GENSPEO as a function of the protons energy.



4. ANALYTICAL AND NUMERICAL RESULTS

In the case of our cyclotron we have N_d=2 and θ_e=2π/2=π for the period of one electric sector. The angular width of the dee is D=39°. The RF sistem is designed to operate with h=1, h=2 and h=4 harmonics modes. In each case the relative importance of AG focusing can be determined simply by examining the factor $ctg^2(hD/2)$ occuring in eq.(2). For h=1, h=2 and h=4, this factor takes on the values: 2.82; 1.23 and 0.21. We conclude that AG contribution to the electric focusing will be largest for h=1 and because of that we consider in this paper only h=1 mode of acceleration. Protons (η=Z/A=1) with an energy T_i=26.8 keV will be accelerated by the first harmonic of the RF field. The dee voltage is set at V_0=94 kV, so the peak energy_gain per turn is ηV_1=125.5 keV as determined from eq.(3). Using the computer code CYCLONE we have aproximately for T_0 the following values: 50, 80, 115 and 150 keV for four gaps respectively, for the first time that ion is crossing the gaps, and 190, 220, 250, and 290 keV for the second time.

Figure 1 presents a plot of the numerically calculated ν_z values using computer code GENSPEO as a function of the ion energy.

Figure 2 presents a plot of the analytical results for ν_z values as determined from eq. (1), as a function of the phase ϕ for h=1 and for the ion energy of 50, 80, 115, 150 keV (a) and for the ion energy of 190, 220, 250, 290 keV (b). The ion has these energies when it crosses first, second, third and fourth acceleration gaps for the first (a) and second time (b).

5. CONCLUSION

From Fig. 1. and Fig. 2. we can see that there is a good agreement between analytical and numerical results for ν_z for the given energy.

6. REFERENCES

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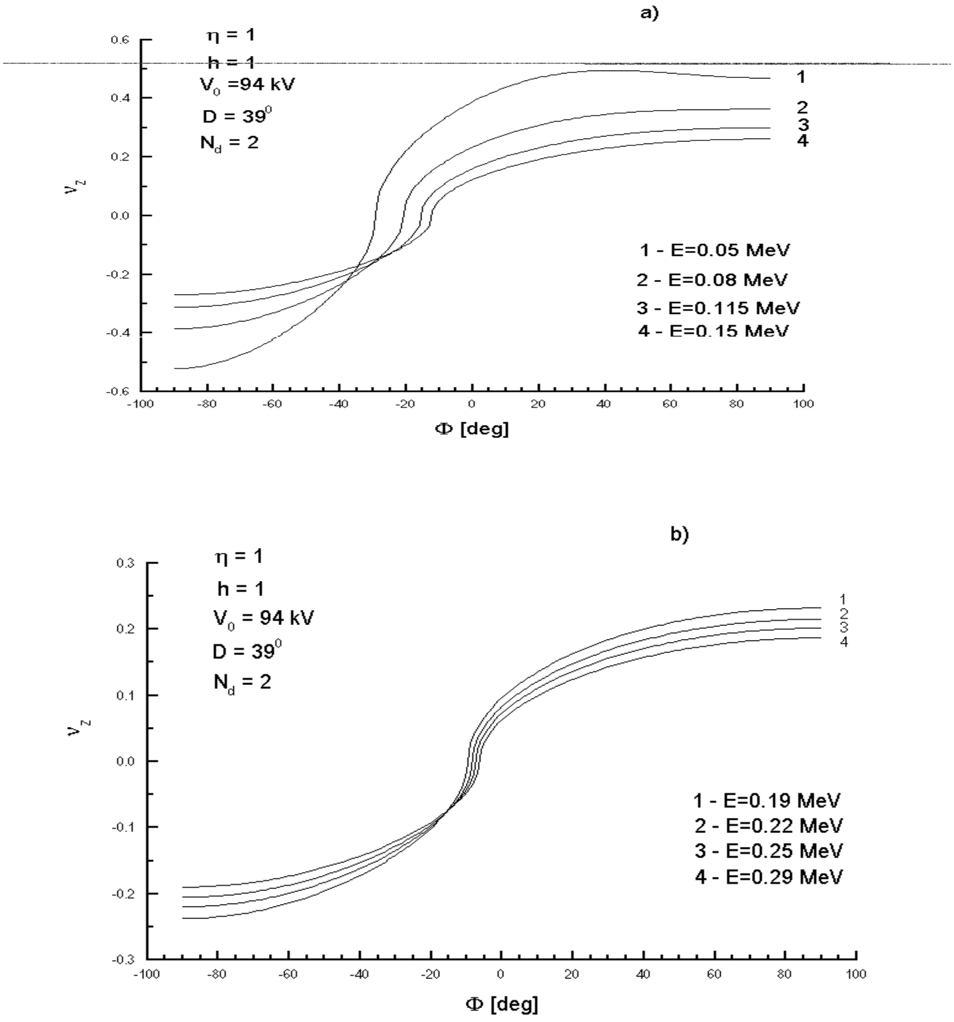

Fig. 2. Plot of the analytical results for ν_z values as a function of the phase ϕ for protons energy of 50, 80, 115,150 keV **-** (a), and for protons energy of 190, 220, 250, 290 keV **-** (b).