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I.10. Study of the Central-Region Orbits of the CYRIC 680 Cyclotron

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Introduction

The CYRIC 680 cyclotron is a commercially-based variable-energy and 4-sector AVF machine. The accelerating system consists of two 60-deg. dees, which can be operated on push-pull or push-push mode over a frequency range of approximately 20 to 40 MHz, allowing for acceleration of particles on harmonic number h = 2, 3, 4 and so on. Maximum energies are for protons 40 MeV, and for other ion (with charge number q and atomic mass number A) $50*q^2/A$ MeV. Concerning the central region of the cyclotron, one should note that the machine had been designed to use a fixed puller, and to take a roughly the same orbit for the three harmonic acceleration modes. Keeping the above-mentioned facts in mind, an orbit calculation in the central region has been carried out in order to study a possibility of an axial injection method suitable for the cyclotron. Such studies are in progress under a condition, that the existing central region geometry be unchanged except for the shape of the puller. Therefore, the question is how to obtain the orbit of an axially injected beam that smoothly converges to the presently employed trajectory.

Orbit study

The orbit study has been made with a computer program developed at IPCR (The Institute of Physical and Chemical Research) for numerical orbit calculation[1].

A charged particle motion in the electric and magnetic fields is determined by the equation of motion ;

$$\vec{F} = \frac{d\vec{p}}{dt} = q\,(\vec{E} + \vec{v}\ x\ \vec{B}) \tag{1}$$

where $\vec{F}$ = total force, $\vec{p}$ = momentum, t = time, q = charge, $\vec{E}$ = electric field, $\vec{v}$ = velocity and $\vec{B}$ = magnetic field. If the cylindrical coordinate system (γ, ϕ, z) is used, eq.(1) can be represented as follows ;

$$\dot{r} = \frac{p_r}{m}, \quad \dot{\phi} = \frac{p_\phi}{mr}, \quad \dot{z} = \frac{p_z}{m},$$
$$\dot{p}_r = \frac{1}{m}\left(\frac{p_\phi^2}{r} - qp_\phi B_z + qp_z B_\phi\right) + qE_r,$$
$$\dot{p}_\phi = \frac{1}{m}\left(-\frac{p_r p_\phi}{r} - qp_z B_r + qp_r B_z\right) + qE_\phi,$$
$$\dot{p}_z = \frac{1}{m}\left(- qp_r B_\phi + qp_\phi B_r\right) + qE_z,$$
$$\dot{m} = \frac{q}{mc^2}\left(p_r E_r + p_\phi E_\phi + p_z E_z\right), \tag{2}$$

where p_r, p_ϕ, p_z ; E_r, E_ϕ, E_z ; B_r, B_ϕ, B_z are the radial, azimuthal and axial components of the momentum $\vec{p}$, electric field $\vec{E}$ and magnetic field $\vec{B}$, respectively, and m is the relativistic mass and c is the velocity of light. The dot (.) denotes d/dt, the derivative with respect to time. Eq.(2) is solved by a fourth-order Runge-Kutta-Gill method with time independent variable. The three magnetic field components, which can be calculated by using a first-order Taylor expansion near the cyclotron median plane (z=0) and relation from $rot\vec{B} = 0$ are represented as follows ;

$$B_r(r, \phi, z) = z\frac{\partial B_z}{\partial r}(r, \phi, 0,),$$
$$B_\phi(r, \phi, z) = \frac{z}{r}\frac{\partial B_z}{\partial \phi}(r, \phi, 0,),$$
$$B_z(r, \phi, z) = B_z(r, \phi, 0), \tag{3}$$

where $B_z(r, \phi, 0)$ is calculated by using the 4-point Lagrangian interpolation of the field data which was expressed in Fourier analysis as

$$B_z(r, \phi, 0) = \overline{B}(r)\left[1 + \sum_{i=1}^{m} A_i(r) \cos i(\phi - \psi_i(r))\right].$$

The average field $\vec{B}(r)$, the coefficients A_i (r) and the phase $\psi_i(r)$ can be obtained from the measured magnetic fields. The field Bz(r, ϕ, 0) at radius r = 40, 60, and 100 mm for the three main-field excitations are shown in Fig.1. On the other hand, the electric rf-fields E_r and $E\phi$ are modeled from two kinds of method. In the first two acceleration gaps, the fields were obtained by first calculating the equipotential lines of the static field solution from the two-dimensional computer code PANDIRA simulation (as shown in Fig.2), and by modulating the field sinusoidally in time. To the electric rf-fields of the other accelerating gaps were applied the Gaussian distribution with the standard deviation $\sigma = 0.4$

W + 0.2 H, and also they were modulated sinusoidally in time, where W and H are the gap width and the aperture of the dee; in this case the values of W and H were 1.8 cm and 3.3 cm, respectively. In these electric field models, the z-compornents of the fields were assumed zero. In the beginning the orbits studies were performed with the existing internal ion source and the puller configuration. If the orbit takes the same trajectory in the central-region for the three modes of operation,i.e., the second-harmonic push-push (h = 2), the third-harmonic push-pull (h = 3) and the fourth-harmonic push-push (h = 4), the following relations should be satisfied:

1) The maximum energy gain per turn in the 60-deg. dee system with a peak dee voltage of V_0 is (θ is the rf-phase when the particle crosses the gap)

$$\Delta T = 4qV_0 \cos\theta , \tag{4}$$

where

$$\theta = \pm 30^o , \quad \cos q = 0.866, \quad for \quad h = 2 \; and \; 4 ,$$

and

$$\theta = 0^o , \quad \cos q = 1.0, \quad for \quad h = 3.$$

The central-region was designed for constant-orbit acceleration in mind with a total turn number approximately N=180 for each mode. Then from the relations,

$$\frac{q}{m}\frac{V_0 \cos\theta}{\omega^2} = const. , \qquad \omega = 2\pi\frac{f_{rf}}{h} , \tag{5}$$

the dee voltage V (=$V_0 \cos\theta$)is obtained as

$$V = 1.42 \times 10^{-4} \left(\frac{f_{rf}}{h}\right)^2 \frac{T + E_0}{z} , \tag{6}$$

where q = charge, m = mass of the particle, f_{rf} = radio frequency, T = final energy, E_0 = rest mass energy of the particle in MeV, h = harmonic number and z = charge number = q/e.

2) Magnetic field B and charge-to-mass ratio q/m of the particles must be changed in such a way that the radius r_0 given by

$$r_0 = \frac{1}{B}\left[\frac{2m_0 V}{q}\right]^{1/2}$$

remains constant, or, in a more conveniently form with B in kG, V in kV eq.(7) can be written as

$$r_0 = \frac{4.584}{B}\left[\frac{A}{z} V\right]^{1/2}$$

3) The ion source of the 680 cyclotron is introduced axially into the central-region and its position can be operated radially and azimuthally in the median-plane. Then this flexibility of positioning is necessary to make a good centering of the particle trajectory in the central-region.

4) Finally, in addition to discussions above, choice of an initial rf-phase, i.e., a starting phase of the particle, is a more important parameter to realize a successful orbit in such a calculation. The orbits under three acceleration modes of 2nd, 3rd, and 4th harmonics with final energies of 20, 12 and 3 MeV proton were calculated for the existing central-region geometry. Fig. 3 shows the computer simulated radial trajectory of the proton beam for each acceleration mode. 3. The present studies started with an investigation for the existing central region which utilizes the internal ion source for a single particle trajectory in the two-dimensional model of the rf-field. Based on this investigation, however, it is necessary to continue the studies of the phase-space behavior of a beam of particles starting with different initial conditions in a three-dimensional model of the rf-field, and to make an attempt to calculate also for an axially injected beam.

Reference

1) Goto A. et al., Scientific Paper of Institute of Physical and Chemical Research **74** (1980) 136.

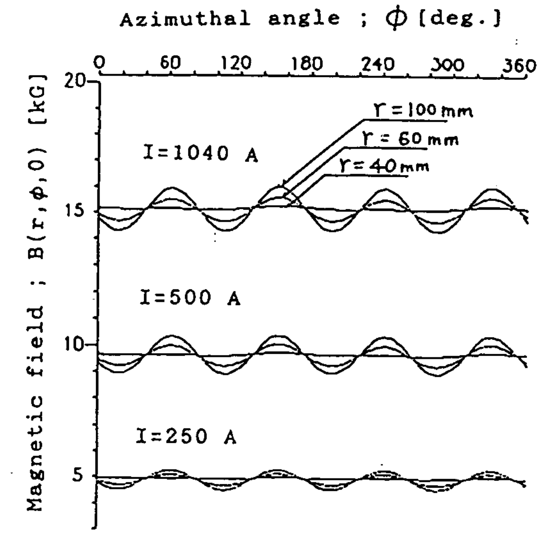


Fig. 1. Magnetic fields B(r, ϕ, 0) for the three main field in the central region.

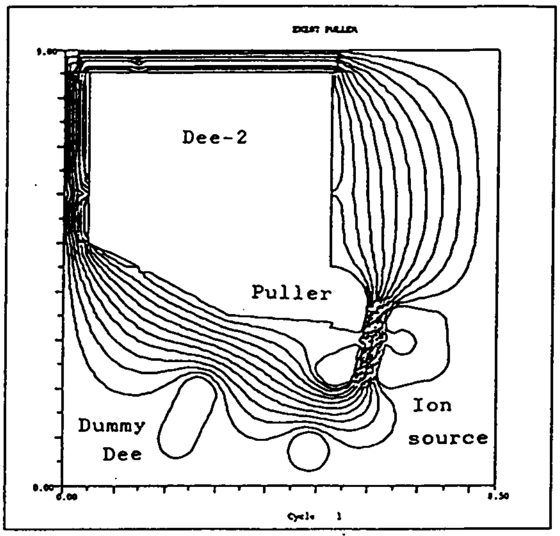
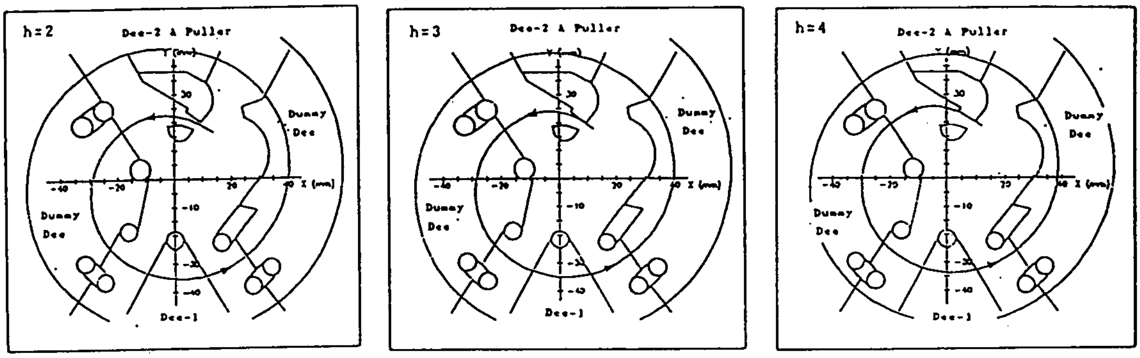


Fig. 2. Equipotential contours of the first tow gaps in the central region simulated by PANDIRA.



(a) (b) (c)

Fig. 3. Calculated trajectory performed by a proton particle for the existing central-region geometry. (a) Second harmonic mode for T_{final} = 20 MeV; V_0 = 32 kV; Ion source position R_{ion} = 21.5 mm, ϕ_{ion} = 50 deg.; Initial rf-phase θ_0 = 50 deg.. (b) Third harmonic mode for Tfinal = 12 MeV; V_0 = 19 kV; r_{ion} = 22.0 mm, ϕ_{ion} = 56 deg.; θ_0 = 50 deg. (c) Fourth harmonic mode for T_{final}= 3 MeV; V_0 = 7 kV; r_{ion} = 22.0 mm, ϕ_{ion} = 57 deg.; θ = 0 deg.