BEAM DEVELOPMENT ON THE VARIABLE ENERGY CYCLOTRON AT CALCUTTA

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Abstract.- The VEC at Calcutta, with a K = 140 is now operational. Internal beam currents of about 15 μA for 30 MeV alpha beams have been initially achieved. About 5 μA has been successfully extracted. Beam development and our initial experience in tuning and setting up the first internal and external beams are described. The methods used in calculating the control settings for a given beam, based on orbit calculations with the aid of computer codes and scaling laws are discussed. A comparison between the calculated settings and the optimized settings which produced beam show good agreement, indicating the utility of computer codes and scaling laws in generating the control settings for the various light and heavy ion beams to be accelerated in future on the VEC.

1. Introduction.- The first internal beam of 50 MeV alphas was obtained by us in June 1977[1)] and the first external beam of 30 MeV alphas in July 1978[2,3)]. Continuous beam development on our VEC was, however, only possible from the January of 1981. We describe some of our experience in setting up the first internal and external beams on our cyclotron. A plan view of the cyclotron is shown in Fig. 1.

A set of about 50 parameters are required to be tuned on the control console of the VEC for the acceleration of a new beam specified by a final energy/nucleon and a charge to mass ratio q/m. A typical set of operating parameters for a beam of 30 MeV alphas is shown in Table I. These parameters include the centre region settings, the seventeen trim coil currents and the deflector shape and voltages. The first valley coil is sometimes used for beam centering and the fifth set for precessional extraction. Most of the parameters in Table I can be calculated in advance with the aid of the magnetic and electric field measurements using orbit codes.

2. Control setting calculations and Scaling Laws.- We use the following procedure for calculating the trim coil settings for a beam: i) the magnetic field measurements on the VEC were made at five main coil current levels and are stored on a tape in the form of polynomial coefficients in the main coil current I, with one set of coefficients for each grid point (R,Θ). A program interpolates and generates the magnetic field for an estimated main coil current,
ii) the equilibrium orbit code integrates the orbits in this field and computes the corrections ΔB to be made in the average iron magnetic field at about 70 successive values of the radii in order to produce constant time periods,
iii) this intermediate tape for the corrections ΔB (R) forms the input to a least square fitting routine. This code calls the input data tape containing the measured trim coil effects dB/dI, interpolates these effects for the specified current level and calculates the strength and polarity of the trim coil currents which will produce the required corrections in the magnetic field. This is done by solving a 18 x 70 matrix equation,

$$\left[\left(\sum_{j=1}^{18} \frac{dB}{dI_j} \cdot I_j \right) - \Delta B(R_i) \right] = 0 \quad \text{Eq. 1}$$

corresponding to the effect of the 18 variables (the 17 trim coils + the main coil) at each radius. This is done simultaneously for the 70 representative radii. Since the number of equations exceed the variables, the program obtains the best trim coil solution by the method of least squares, making the deviation in the magnetic field a minimum from the calculated isochronous field, at the specified number of radii.

Table 1 - A typical set of operating parameters for a beam of 30 MeV alphas

Element, Mass, Charge:He 04 + 02 Reference Date : 4.2.81 Time : 0400 hrs.

RESONANCE		TRIM COILS				DEFLECTOR		
1. Main Coil	714.3 A				Estimated			
2. Frequency	6.0098 MHz	12.	TC1	-250 A	-387 A	29. Counter	1. 5840	
3. Dee Voltage	36.2 kV	13.	2	-500	-391	30. settings of	2. 6423	
CENTRE REGION		14.	3	-160	-254	31. points 1-7	3. 4796	
Ion Source		15.	4	-82	0	32. in Fig.1.	4. 3343	
4. Radius	2.07 v	16.	5	0	0	33.	5. 4249	
5. Azimuth	3.9 v	17.	6	38	0	34.	6. 6145	
6. Rotation	5.14 v	18.	7	-33	0	35.	7. 2746	
Puller		19.	8	20	49	36. Septum jack	12.98 v	
7. Left/Right	7.43 v	20.	9	0	0			
8. In/Out	3.56 v	21.	10	207	223	37. Entry voltage	48.4 kV.	
9. Arc current	800 mA	22.	11	0	0	38. Exit voltage	0	
10. Arc voltage	250 v	23.	12	409	454	VALLEY COILS		
11. Filament current	317 A	24.	13	39	0	39,40 V.C.1	10 deg.	238
		25.	14	428	537	41,42 2	0	0
		26.	15	-635	-668	43,44 3	0	0
		27.	16	-680	-750	45,46 4	0	0
		28.	17	761	751	47,48 5	20.7	201

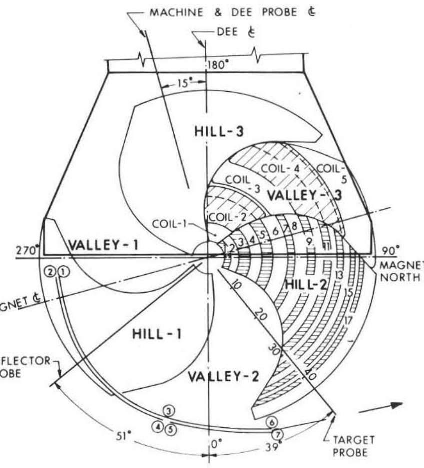

Fig. 1: A plan view of the pole face. The trim coils, valley coils and the dee, target and deflector area probes are indicated.

We use the code CYDE[4)] consisting of the chain of codes LESCO, DORO, and CYDEB, for the above computations. The equilibrium orbit properties and the expected phase history of the beam are also obtained as an aid to beam diagnostics. One of the flexible features of this code is the possibility of calculating the trim coil solution for an average field profile other than the isochronous field, i.e. $B(R)_{required}/B(R)_{isochronous}$ need not be equal to 1. Thus one can input the required central 'field bump' and the 'edge fall off' near the extraction radius, along with the main region of isochronism.

3. Centre region considerations.- The centre region parameters which require tuning on our cyclotron are, a) the central field bump, b) the ion source radius, azimuth and rotation and c) the ion source slit-puller spacing. An optimum value of these settings must provide a) the correct injection point (R,Θ) for a proper centering of the final orbits, b) a proper starting phase with respect to the peak of the RF for minimum energy and radial spreads consistent with a maximum phase acceptance and c) a shifting of the phase so that the ions reach the first half turn at a phase optimum for proper vertical electrical focussing.

The central field bump.- Below a radius of about 4 inches, there is appreciably no effect of flutter in our cyclotron. This is shown in Fig. 2. Vertical focussing in the central region is provided by the central field bump, and the electric fields of the dee . The fine details of the field bump required are such that there is a) sufficient vertical focussing and b) a rapid traversal of the $\nu_r = 1$ resonance which occurs, in the bump we use, between a radius of 5 and 6 inches. The bump, along with the azimuthal displacement of the ion source, is also helpful in shifting the phase of the beam in the first half turn. For 30 MeV alphas, the field bump due to the iron field of the main coil had to be reduced from 7% to about 3.9% with the aid of the first four trim coils. The optimum bump, found empirically, is shown in Fig. 2 .

As an approximation, the invariance of the bump labelled 'used' forms a useful scaling law for the centre region trim coils at the other field levels. In going upto a field level corresponding to a K = 104, we have found this to be generally true.

Due to the initial energy gained by the ions at the puller, the ion source has to be 'off centre' by an amount r_s, for a proper

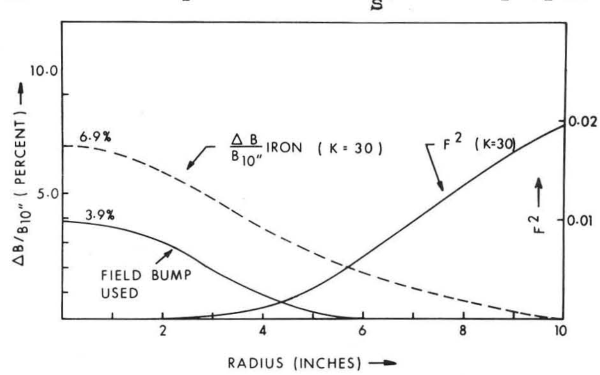

Fig. 2: The iron field bump in the centre region, and the final bump used. The flutter is also shown.

centering of the final orbits. In a single dee cyclotron,

$$r_s = 0.75\ r_o = c_k r_o \qquad \text{Eq. 2}$$

where r_o is the radius of the first turn.

Eq. 2 forms a useful scaling law for beams having a fixed turn pattern and we have used this to advantage for some beams. The electric gap crossing resonance plays a significant role in the centre region of our machine, and must be included in the calculations. For 30 MeV alphas, we observed a value of c_k = 0.35 instead of 0.75.

4. The edge fall off.- The extraction efficiency η is a strong function of the turn separation ΔR, given by

$$\eta = 1 - \sigma / \Delta R \qquad \text{Eq. 3}$$

where σ is the effective thickness of the septum, ΔR is given by[5)]

$$\Delta R = \Delta R(acc) + \Delta R(prec) \qquad \text{Eq. 4}$$

where $\Delta R(acc) = R(\Delta T/T)(\gamma/\gamma+1)(n+1)^{-1}$ Eq. 5

$$\Delta R(prec) = 2\pi A\ (1 - v_r) \qquad \text{Eq. 6}$$

R is the average radius of the orbit, ΔT the energy gain per turn, T the kinetic energy v_r the radial betatron frequency, A the amplitude of the coherent radial oscillations, and γ and n the total energy and field index respectively. $\Delta R(acc)$ and $\Delta R(prec)$ are the turn separation produced because of the dee voltage acceleration and precession of the betatron oscillations respectively. Conditions are therefore required to be created for a maximum turn separation at the radius of extraction. An edge fall off in the field profile helps in two ways, a) the momentum compaction is less as compared to a rising field and b) v_r can be made less than unity. At $v_r = 1$, coherent radial oscillations can be excited, and as v_r continues to fall below unity, the turn separation can be increased (Eq. 6). On the other hand, the falling field results in an excessive phase slip of the beam made worse by the high turn density in the extraction region. The Walkinshaw resonance $v_r = 2v_z$, which occurs in the falling field, can also lead to an 'axial blow up'. A compromise must therefore be made between the momentum compaction, coherent radial oscillations, the Walkinshaw resonance and the phase slip of the beam. We have found the phase loss to be the over-riding factor in bringing the beam upto the deflector entrance. Fig. 3 shows the edge fall off due to the iron field for 30 MeV alphas. The optimum field profile used in the extraction region is also shown. The $v_r = 1$ resonance in the field profile we have used occurs at about 38 inches and the average field index beyond this upto the deflector entrance varies between 0.1 and 0.2. For a similiar number of turns the invariance of the field profile labelled 'used' in Fig. 3 forms a useful scaling law for the outer trim coils at other field levels. The FWHM field positions of trim coils 14-17 are also shown. Due to the sensitivity of the resonance beyond 35 inches, a trial and error procedure for obtaining the outer trim coil currents for raising the 'iron' field profile to the 'required' profile was found undesirable. Precomputed settings, supplemented by a fine tuning was found more convenient.

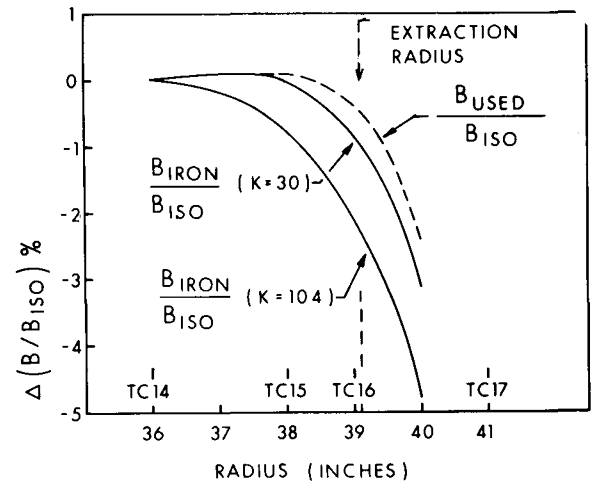

Fig. 3 : The ratio of the iron to isochronous field for 30 MeV He^{++} and 26 MeV He^{+} and the final ratio which was finally 'used'.

A comparison between the computed settings for the outer trim coil currents and the final optimized settings for the beam of 30 MeV alphas is made in Table I.

5. The deflector settings.- The azimuthal position where the deflector channel should start is governed by the azimuth where $\Delta R(\theta)$ is a maximum, usually the beginning of a hill or a valley depending on the direction of the spiral, although this has not found to be a very sensitive parameter. Since the channel lies in the fringing field region, the radial spread of the beam due to energy dispersion requires a flare in the channel defined by

$$d(\theta) = d_o + d_1(\theta-\theta_o) + d_2(\theta-\theta_o)^2 + . \qquad \text{Eq. 7}$$

Also, the minimum gap of the channel is decided by the radial amplitude of the betatron oscillations. The apparent length of the channel L can be obtained from

$$\delta = (q/2m) \left[E-Bv/C \right] (L^2/v^2) \qquad \text{Eq. 8}$$

where δ is the total radial deflection required, E the electric field, and v the velocity of the particle. The upper limit on E is decided by the sparking limit criteria, frequently called the 'VE' number. The VE number obtained by us is $1.25.10^4 (kV)^2/cm$.

Initial computations for the settings of the deflector shape were done with the aid of the code DFLKTR[6). This determines equilibrium orbit properties and traces the trajectory in the combined electric and magnetic field. The constants, L, V, D, d_o, d_1, d_2, etc. are varied untill the beam emerges at the desired radius and azimuth with the required radial deflection. In our case, we required these to be 1.841 m, at 150 deg. and 0.238 radians respectively. The channel shape was then optimized for maximum transmission. Using these settings to start with, the beam was extracted by fine adjustments of point No. 1 through 4 and 6. The external beam for 30 MeV alphas is at present about 5 μA., giving an extraction efficiency of about 35% at a dee voltage of 30-35 kV. Our calculated extraction efficiency was 45% at a dee voltage of 40 kV, a radial amplitude of about 6 mm, and a first harmonic of 1 gauss.

6. Beam tuning and diagnostics

a) The internal beam.- In tuning out the first internal beams, we found the 'shadowing' technique to be the most useful which gave us an indication of the true circulating beam in the presence of large spurious beams. Another very useful aid in beam tuning were the neutron monitors which made it easier to distinguish whether we were optimizing the true circulating beam or spurious beam. We observed that the centre region settings, namely the ion source radial position, azimuth, rotation, and the central field bump were very critical for the beam to cross the $v_r = 1$ resonance which occurs between 5 and 6 inches in our cyclotron, and for the orbits to be well centered beyond this radius, indicated by a 'sharp shadowing'. Further on, it was relatively easier to tune the beam. Another useful diagnostic aid was the 3 finger probe which could be put in the target area region which indicated that the beam was properly centered in the median plane, and also that there was no large vertical oscillations in the beam. In our cyclotron this probe is also replaceable with a DR probe. A typical plot of the beam current taken on the single finger dee probe is shown in Fig. 4.

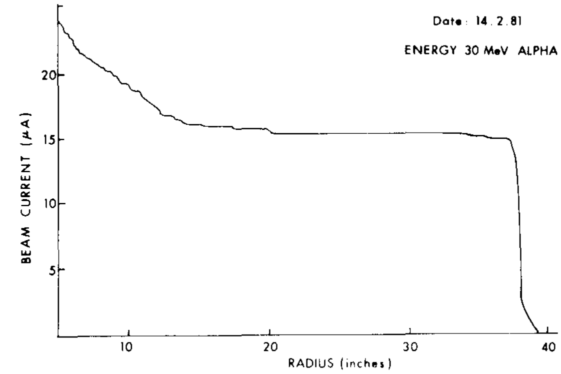

Fig. 4 : The internal beam current taken on the dee probe for 30 MeV alphas at V_D=40.4 kV.

d) The external beam.- While tuning out the first external beam of 30 MeV alphas, spurious signals from the faraday cup due to RF pick-up, made it difficult to 'lock-on' to an initial signal for true external beam which could be tuned. A Si(Li) detector was therefore installed in the external beam line to sample the external beam, and provide a signal in a count rate meter for initial tuning of the deflector. Initially, we could not get a signal corresponding to 30 MeV from the detector in a multichannel analyser (MCA). A careful shadowing between 37 and 39 inches indicated that there was no beam beyond this radius, due to excessive phase loss in the trial edge 'fall off' used. A recalculation of the last two trim coil currents for decreasing the phase slip using the previous phase history calculated with CYDE immediately resulted in an external beam.

7. Beam quality measurements.- Some initial beam quality measurements have been made for a beam of 30 MeV alphas at a dee voltage of about 30 kV.

a) Energy spread.- The energy spread of the beam was measured using a Si(Li) detector. The FWHM for 30 MeV alphas (at V_D = 30 kV) obtained is about 300 KeV i.e. $\Delta E/E$ = 1%. This includes the noise due to the detector and electronics.

b) Beam emittance.- An impression of the beam directly emerging from the cyclotron, taken on a paper placed in the beam line, showed a vertical spread of 1 cm. indicating that the Walkinshaw resonance did not pose a serious problem. The radial spread was large, filling the whole 4 inch diameter beam pipe. Radial emittance measurements done using the slotted plate method, gave an emittance of 90 mm mrad (V_D = 30 kV) as shown in fig. 5.

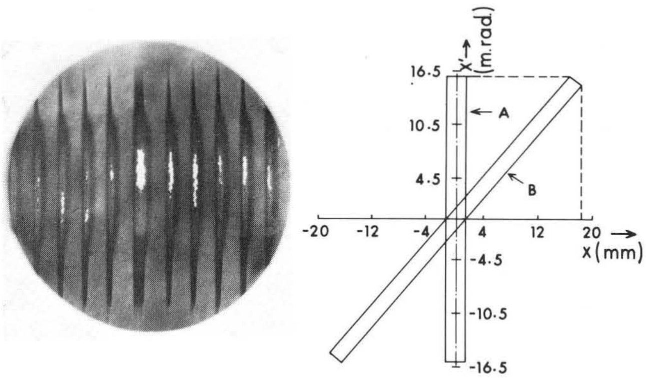

Fig. 5 : a) an image of the slits on a photographic paper 1.6 m away, b) radial phase plot(A) at the virtual source (B) at the position of the slotted plate.

c) Time structure of the beam.- The time structure of the beam was measured by using a start signal from a prompt gamma ray from the experimental cave, and a stop signal from the RF fed through constant fraction timers to a time to amplitude converter (TAC). The TAC spectrum in the MCA reproduces the beam structure in time, shown in Fig. 6. The beam pulse was found to be about 15 nsec. corresponding to an external phase width of 32.5°.

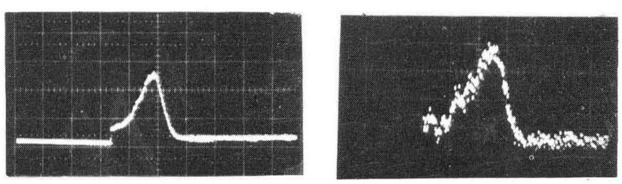

Fig. 6 : Time spectra of the gamma rays from the MCA.

8. The external ion optics.- The external beam transport system in our laboratory will ultimately consist of three high intensity channels and six high resolution lines. We have presently made only two of the high intensity lines operational. The first order ion optics and the optimum parameters of the quadrupole settings were calculated by using the code TRANSPORT[7]. Fig. 7 shows a schematic of the various elements and their sequence in the high intensity channels. Most of these elements were fabricated by us in the laboratory. Using the computed settings, about 1.5 µA beam was transported to the experimental area about 20 m away. A beam size of about 5 mm at target positions is obtained, as measured by a beam profile monitor.

9. Conclusions.- Our initial experience in tuning out the first internal and external beams on our cyclotron have been described. Beams of 30 to 60 MeV alphas have been accelerated. For the case of 30 MeV alphas, the present internal beam currents are on the order of 15 µA with an arc of about 0.8 A. About 5 µA beam has been extracted and 2 µA transported to the experimental areas. Our probes have a maximum dissipation of 3 KW. Filament lives are on the order of 50 hours.

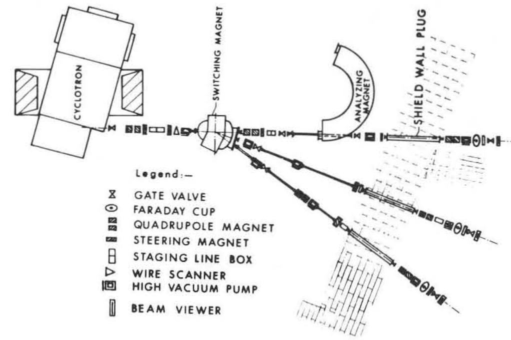

Fig. 7 : The sequence of elements in the high intensity beam lines.

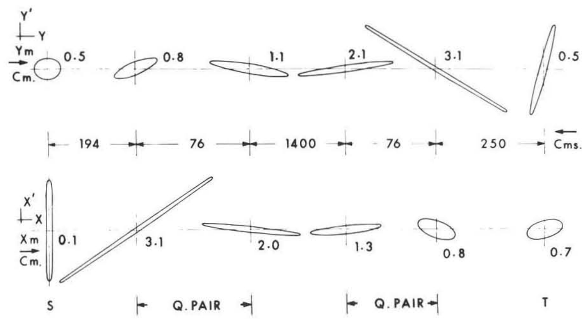

Fig. 8 : The vertical and radial phase space ellipse, at various positions in the zero degree beam line.

A beam of He^{+} has also been accelerated corresponding to a field level of K=104, to explore the higher field levels and serve as an analogue beam for the heavy ions C^{3+}, and O^{4+}

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