MAGNETIC FIELD DESIGN FOR A COMBINED FIXED FREQUENCY AND FREQUENCY MODULATED CYCLOTRON

Stig Holm and Per-Ulf Renberg

The Gustaf Werner Institute, University of Uppsala, Uppsala, Sweden

Abstract

A modification of the 185 MeV synchrocyclotron[1] at the Gustaf Werner Institute, Uppsala, is under way. The reconstructed cyclotron will operate with frequency modulation for protons in the upper energy range (110-200 MeV), while low energy protons and heavier particles will be accelerated in fixed frequency isochronous mode. Circular trim coils will be used to adjust the basic field in order to keep focusing properties and the phase-energy motion within required limits with frequency sweep as well as with constant frequency. Valley coils will be used for harmonic corrections at the centre and at the extraction radius, where they also will provide some gradient correction.

1. Introduction

A reconstruction of the magnetic field configuration and the RF-system of the old synchrocyclotron at the Gustaf Werner Institute will enable an operation of the cyclotron in a combined fixed frequency and frequency modulation mode. The RF-system will consist of an electronically modulated frequency source, an amplifier chain with a high power final stage and an accelerating electrode system of two 90^{o}-Dees. A change from broad-band f.m. operation to c.w. operation involves a disconnection of the damping resistors as well as a change of the driving electronic system. The final amplifier stage will be the same in both cases.

The design of the basic magnetic field is based on a band-width approaching 10 % for protons at maximum energy 200 MeV, the limiting factor for a further reduction being the vertical focusing at large radii. The required band-width decreases at lower magnet excitations for vertical focusing reasons and the limit for isochronous acceleration of protons will be about 110 MeV. For all other particles c.w. operation is possible at all field levels (except high energy ^{3}He-particles). The required field correction of the basic magnetic field will be done by means of trim coils.

2. Pole gap configuration

In order to obtain sufficient field variation and required magnetic rigidity the maximum useful radius of the old magnet has been increased. Thus the tapered poles of the magnet have been extended by iron rings to obtain straight edges with a radius of 1.4 m giving an extraction radius of 1.2 m at a maximum proton energy of 200 MeV.(Fig. 1.) The design of the iron sectors giving the 3-fold symmetry of the gradient field is based on field measurements in a 1:4 model magnet. The non-uniform saturation of the iron sectors was partly eliminated by holes in the sectors drilled from the pole side.

12 pairs of concentric trim coils and 6 pairs of valley coils will be used for the field correction. Tests in the model magnet of the concentric coils have shown that 900 ampereturns per cm radius will change the gradient of the mean field by 20-30 G/cm in the radial interval 20-120 cm. (Fig. 2.) Additional gradient corrections (≈ 5G/cm) near extraction can be obtained from 3 pairs of valley coils. Harmonic coils at small radii will be used to eliminate the first harmonic component of the basic field.

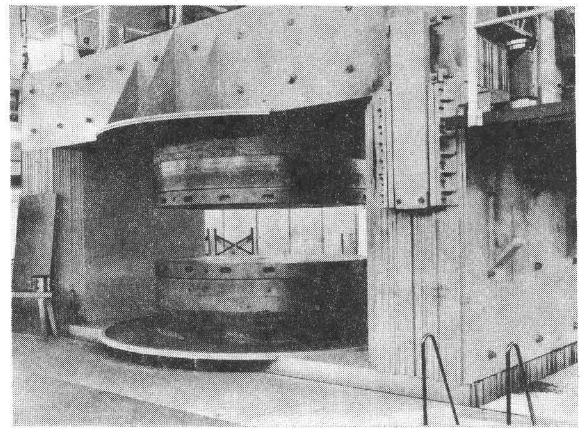

Fig. 1. Side view of the cyclotron magnet with the extended poles.

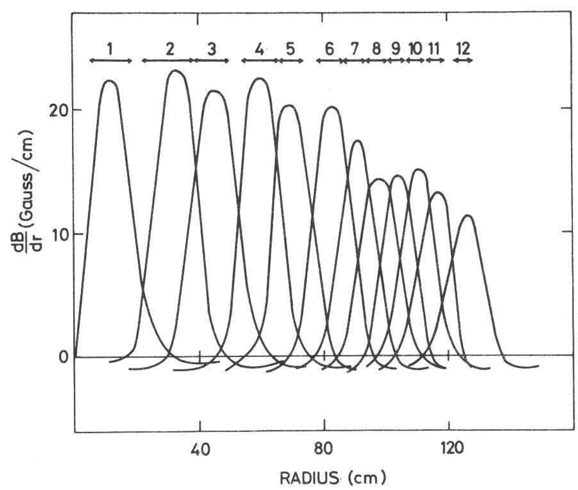

Fig. 2. Gradient correction capability from 12 sets of concentric trim coils. Arrows indicate the radial widths of each coil. Power consumption ∿ 6 kW/pair.

3. F.m. operation

Due to the reduced frequency band, the acceleration will have to be done with a weaker phase stability than previously, reflected in a lower phase oscillation frequency as well as a smaller tolerance level of the field. The important factor is the K-value of the field[2], which is proportional to the square of the phase oscillation frequency.

Requirements which govern the choice of a suitable field distribution permitting the acceleration of the ions to full radius without phase losses will be discussed below. Some considerations in the choice of acceleration parameters concern the radial beam quality.

Extraction studies have shown that, for radial amplitudes less than a few millimetres, an extraction rate of 95 % can be obtained with a regenerative system. In order to get this radial quality a central region of the same type as is used in isochronous cyclotrons will be used.

0018-9499/79/0400-2012$00.75 ©1979 IEEE

The initial orbit behaviour is expected to be the same as in c.w. cyclotrons although the dimensions are smaller as the dee voltage is lower than in most c.w. cyclotrons. A difference in phase motion will occur for particles starting in the beginning and at the end of the capture interval due to the difference in r.f.-frequency, but this will not result in appreciable differences in orbit pattern until after several turns. A computer study has shown very small spread in orbit centre locations for these extreme particles during the outward motion.

It is however clear that a deterioration of the beam quality is likely to occur if particles are swinging back close to the centre in the first phase oscillations.

3.1. Requirements for phase stability

With the adoption of broad-band rf systems the average voltage on the two dees is limited to about 12 kV. In order to increase the orbit clearence at the centre, the voltage can be boosted at the time for particle capture, in our case to about 16 kV for 50 μs, during which time the ions are captured and accelerated on the average to a radius of 0.5 m. When reducing the voltage adiabatically to the normal value, care must be taken to avoid phase loss of ions. The phase oscillation amplitude is determined by the adiabatic invariant

$$\frac{1}{\omega^2}\left(\frac{eVE_s}{K\pi}\right)\left[\oint F^{1/2}\,d\phi\right]^2 = \text{const.} \qquad (1)$$

where

$$F = \sin\phi_o + \sin\phi_s - (\phi_s+\phi_o)\cdot\cos\phi_s$$

The relation between frequency derivative, df/dt, and the equilibrium phase, ϕ_s, is given by

$$df/dt = -\frac{eVKf^2}{E}\cos\phi_s \qquad (2)$$

Denoting i = initial and f final or current values we define the ratio

$$C = \frac{df/dt_i}{df/dt_f} \qquad (3)$$

Inserting (1) and (2) into (3) we get

$$a_f\cos\phi_{sf} \geq \left(\frac{V_i}{V_f}\right)^2 \frac{1}{C}\,a_i\cos\phi_{si} \qquad (4)$$

where

$$a = \left[\oint F^{1/2}\,d\phi\right]^2 / \left[\oint F(o)^{1/2}d\phi\right]^2 \qquad (5)$$

The unequality sign denotes that an increase in phase stability region is permitted.

The function $a\cdot\cos\phi_s$ is plotted in Fig. 3. From this figure, using (2),(3) and (4) the required ratio K_f/K_i can be determined for different ratio V_i/V_f. Fig. 4 shows a plot of this ratio as a function of the initial equilibrium phase ϕ_{si} for two cases of voltage reduction neglecting the variation of E and f and assuming a constant df/dt. Our case corresponds to a ratio V_i/V_f of 1.33. As can be seen from this figure a voltage reduction always requires an increase in K-values with these assumptions. Thus the field should be shaped according to the voltage-time function or vice versa. It also appears that there is a minimum value of the initial $\cos\phi_s$ associated with the voltage reduction. From the relation (3) the required decrease in $\cos\phi_s$ is determined. In our case the decrease would be from $\cos\phi s_i = 0.7$ to $\cos\phi s_f = 0.6$ at constant df/dt.

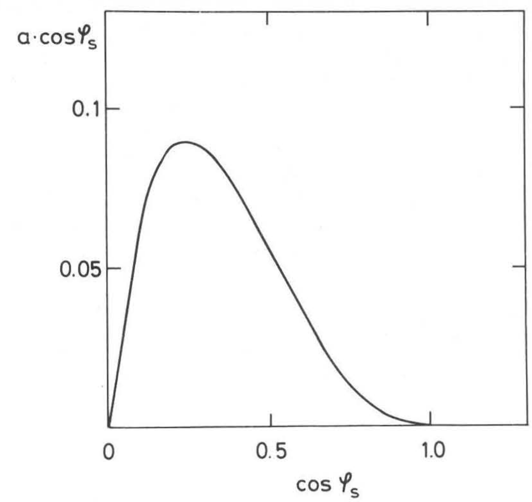

Fig. 3. The square of the normalized bucket area multiplied by $\cos\phi_s$ as a function of $\cos\phi_s$.

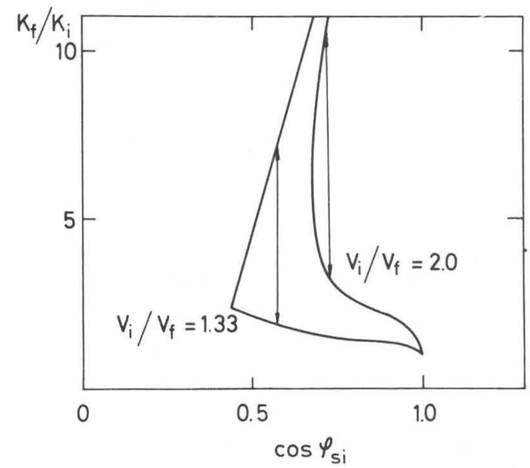

Fig. 4. Permitted ratios of the field constants K after and before a voltage reduction V_i/V_f as functions of $\cos\phi_s$. df/dt = constant.

Equation (4) can be used to determine $\cos\phi_s$ as a function of radius considering the effective voltage gain which in our design is reduced due to cut-backs of the dees to save capacity. By integrating eq. (1) the variation of K with energy and radius can be found. Alternatively, assuming a K-function within the above restrictions the field can be obtained using the relation

$$K = 1 - \frac{E}{B}\frac{dB}{dE}$$

The frequency derivative must then be used as a free parameter to obtain the required $\cos\phi_s$-function which is given by (1).

3.2. Capture efficiency and central region field shape

The reduced frequency band compared to conventional synchro-cyclotrons implies an increase in capture time at a given equilibrium phase due to the smaller K-value. However, requirement of a radial beam quality comparable to isochronous cyclotrons calls for a fast acceleration out from the central region to avoid quality deteriorations due to the closeness to the $\nu_r = 1$ resonance. Therefore the $\cos\phi_s$ value must be choosen to be much higher than what is optimum in a conventional SC, a condition which tends to counteract the gain in the capture time due to the K-value.

0018-9499/79/0400-2013$00.75 © 1979 IEEE

Another question concerns the usefulness of central field bump in such a machine. Earlier studies showed a net increase in capture time for the case of a positive df/dt which was used for heavier ions. In our present design these ions will be accelerated in c.w. mode. Recent calculations have also verified the results found in conversion studies for the SREL-cyclotron [3]), that a central field bump prevents the ingoing particles from hitting the center, thus acting to prolonge the capture time. However, the disadvantage of this scheme is due to the above-mentioned quality aspects.

In fig. 5 is shown the capture regions for a case studied using a field without field bump and with a steep field bump (shape as from model measurements) of 100 G. In the no-bump case the capture region is as expected nearly centered around t = 0 which corresponds to resonant frequency at r = 0.

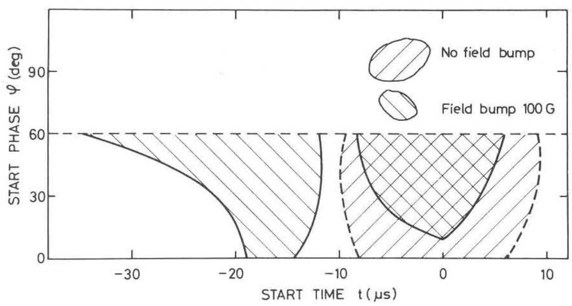

Fig. 5. Capture regions with and without field bump. df/dt = - 2.04 MHz/msec. The field shape in the no-bump case corresponds to K-values of 0.1 at r = 0 increasing to 0.35 at r = 0.78 m. $\cos\phi_{si}$ = 0.7 at r = 0. Maximum voltage gain/turn = 45 kV.

In the bump case the capture is surprisingly enough divided into two distinct regions. One region is centered around t = 0 but considerably smaller than for the no-bump situation. The other capture occurs earlier i.e. when the frequency is higher.

A distinct difference between the motion of these two groups of particles is their minimum return radius. In the 'normal' group (centered) the ions return to a minimum radius of more than 24 cm for a 40° starting phase, while the corresponding radius is about 10 cm for the same starting phase in the early group. Due to the presence of the ν_r = 1 resonance at about 11-12 cm radius these ions will most likely be strongly decentered and therefore not so useful for acceleration and extraction. This decentering effect has not yet been quantitatively verified, but will be studied in connection with detailed central region design. If this effect turns out to be essential, the question of any net gain in using a field bump will depend upon if a gain in vertical focusing can compensate the reduced capture time for the useful group.

4. Trim coil requirements

While circular trim coils obviously are unavoidable in a cyclotron in which isochronous operation is foreseen for different ions and energies, they were initially considered to be unnecessary in a cyclotron solely devoted to f.m. operation. However, considering the requirement of variable energy f.m. operation and the necessity to adopt the average field to the vertical focusing and band-width limitations as well as to the phase stability conditions, circular gradient coils are also in this operation desirable.

The required gradient corrections for a high magnet excitation is shown in fig. 6. The basic field has been measured in a 1:4 scale model magnet and corrections from the trim coils (Fig. 2) have been added to the field in an equilibrium orbit program to obtain the 9 % band-width situation. The ν_z = 0 curve is the limit above which the beam is vertically unstable.

The theoretical curve for 7.3 % band-width shown was used for capture efficiency studies with a K-function that varied from 0.1 at r = 0 to 0.6 at r = 1.2 cm.

This band-width can obviously not be used at this energy with the present sector shape. However, by a lowering of the magnet excitation the ν_z-limit increases due to saturation effects in the sectors and at the same time the dB/dr requirements decrease (∿ as B^{-3}) for a given K-function. Therefore a 7 % band-width which might be required for continuous f.m.-operation will be attained a few tenths of MeV lower. At maximum energy the RF power consumptions can be kept within required limits by a reduction of the repetition rate and using the extra time for beam stretching.

Fig. 7 shows the situation at a reduced magnet excitation. The field requires here only slight trimming to obtain the isochronous shape for 110 MeV protons.

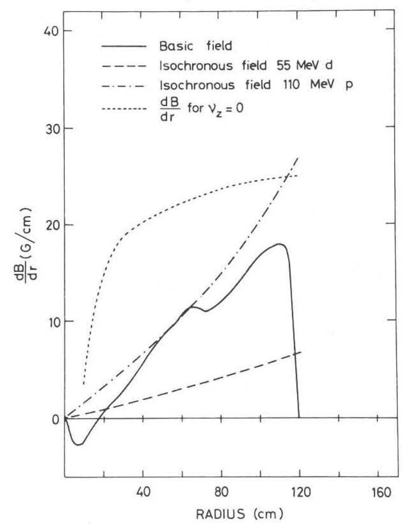

Fig. 6. Radial gradients of mean magnetic fields at an intermediate magnet excitation.

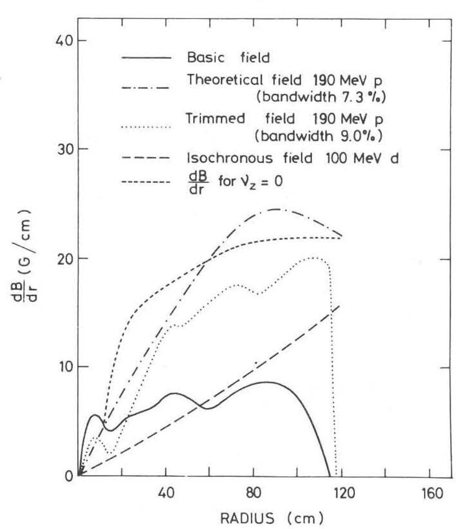

Fig. 7. Radial gradients of mean magnetic fields at a high magnet excitation.

0018-9499/79/0400-2014$00.75 ©1979 IEEE

The axial focusing conditions shown in fig. 8 for three different situations have been obtained from model data. The proton curve corresponds to 9 % band-width while the other curves are calculated for fixed frequency. The corresponding radial focusing conditions are shown in fig. 9.

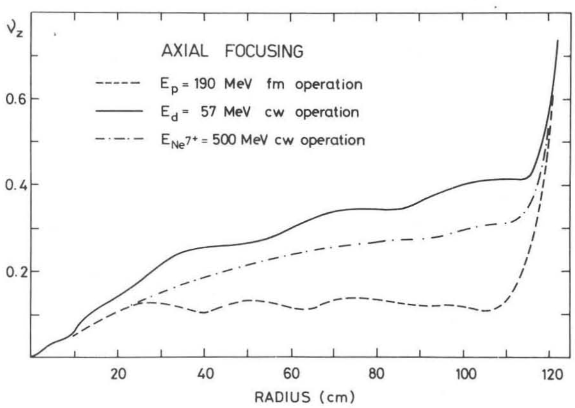

Fig. 8. Axial focusing at high and intermediate magnet excitation.

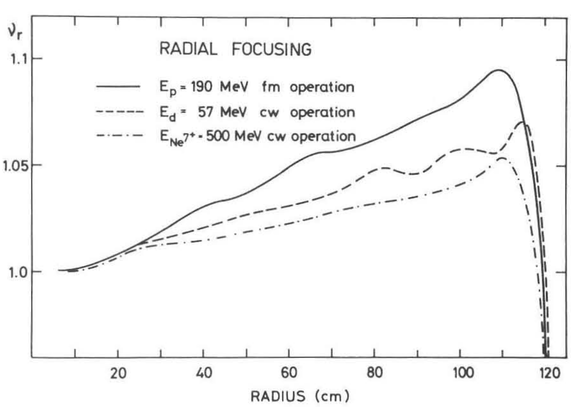

Fig. 9. Radial focusing at high and intermediate magnet excitations.

The degree of isochronisation which can be obtained with the present arrangement of trim coils on top of the hills is demonstrated in fig. 10.

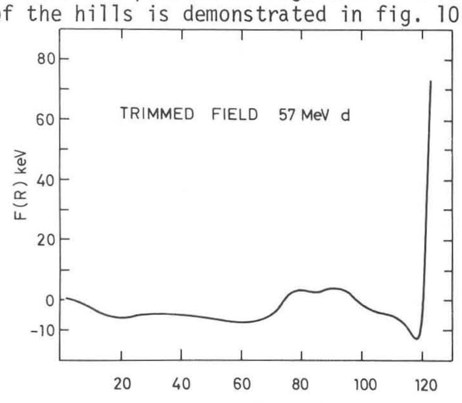

Fig.10. Phase slip integral F(R) for c.w.-acceleration of deuterons on second harmonic at an intermediate field level. R.f.-frequency=18.898 MHz.

The phase slip integral obtained for the 57 MeV deuteron case is plotted versus radius for a preliminary optimization. At this field level the anticipated dee voltage is 22 kV, which leads to a phase shift less than ± 5° during the acceleration out to the extraction radius.

5. Concluding remarks

The model field measurements and the orbit studies made so far have verified that a combined operation in c.w. - and f.m. modes is feasible from the orbit dynamic point of view. A wide variety of ions could be accelerated to different energies. Table I summarizes the expected performance. In the realization of such a combined system an important technical aspect is the requirement of flexibility in the RF-system so that the operational possibilities can be fully utilized.

Table 1

Expected performance of the reconstructed GWI cyclotron

Particle	Energy (MeV)	Acceleration mode	Maximum beam current (μA)
p^+	185-200	f.m.	10-1
p^+	110-185	f.m.	10
p^+	40-110	c.w.	40
d^+	25-100	c.w.	40
$^3He^{++}$	250-280	f.m.	2
$^3He^{++}$	75-250	c.w.	20
$^4He^{++}$	50-200	c.w.	20
Hevier ions	-200 Q^2/M	c.w.	0-1

References

1) S. Dahlgren, A. Ingemarsson, S. Kullander, B. Lundström, P.U. Renberg, K. Ståhl, H. Tyrén, and A. Åsberg:
Conversion studies for the Uppsala synchrocyclotron. Proc. 7th Int. Conf. on Cyclotrons and their Applications (Zurich, 1975) 127.

2) S. Kullander:
Studies on capture efficiences of synchrocyclotrons. Nucl. Instr. Meth. 81 (1970) 61.

3) M. Reiser, H. Kim and D. Le Vine:
Conversion studies for the SREL 600-MeV synchrocyclotron.
Proc. 5th International Cyclotron Conference (Oxford 1969) 749.