ASPECTS OF THE DESIGN OF AN 8 MeV CYCLOTRON AS INJECTOR FOR A 200 MeV SEPARATED-SECTOR CYCLOTRON

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Abstract.- Certain characteristics, design aspects and calculations for the magnet, dees, extraction system and central region of the injector cyclotron are reported.

1. Introduction.- A k = 8 MeV solid pole cyclotron (SPC1) is being designed and built by the NAC as an injector for a k = 200 MeV separated-sector cyclotron (SSC) which has an energy gain factor ranging from 25 for protons to ~20 for the heavier ions.[1] The beam requirements for the various fields of application are fairly diverse [2]. Good quality proton, deuteron, $^3He^{2+}$ and α- beams up to maximum energy and 10μA beam intensity as well as heavy ion beams up to Q/A ≈0.25 are required for nuclear physics and related experiments while 100μA beams must be supplied at intermediate energies for neutron therapy and isotope production.

2. Magnet.- In designing the SPC1 magnet, we aimed at a good efficiency by following the guidelines given by Howard et al[3]. Some of the parameters and considerations which had to be taken into account, are the following. The extraction radius of 47.6 cm and the maximum average magnetic field of 0.86 T at extraction are fixed by the matching conditions to the SSC. At least 140 mm clearance between the rf-liner plates is required for the radial insertion of an ion source for heavy ions. It must be possible to raise the upper yoke and pole assembly for easy access to components inside the vacuum chamber. Due to the relatively small pole diameter, the average pole gap should not be too large, otherwise excessive trim-coil power is required to obtain an isochronous field. There should be sufficient axial focussing to keep the beam height less than ~25 mm for the 100μA proton and deuteron beams. The injector will be used for medical applications, and down-time should be kept to a minimum. All components should therefore be easily accessible for maintenance.

Figure 1 shows the final dimensions of the 54.5 ton magnet which we believe to be a fair compromise between all the requirements that were laid down. The two 112-turn vacuum impregnated coils for the magnet were constructed from 16.5 mm x 16.5 mm OFHC copper conductor with a 9.2 mm diameter duct for cooling water, the total copper weight being ~1.85 tons. Eight layers of windings were used for each coil, and two adjacent layers form one cooling circuit. The excitation current is supplied by a 140 V 1000A power supply with a stability of 2 in 10^5.

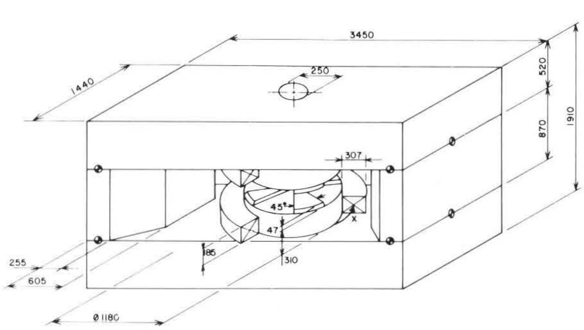

Fig. 1: Dimensions of injector magnet.

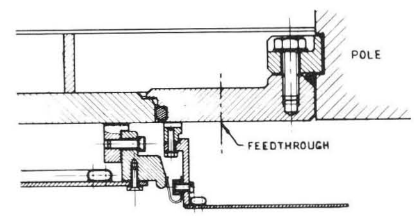

Fig. 2: Sealing between vacuum chamber and feedthrough ring.

To make the inside of the vacuum chamber relatively accessible, the upper yoke, pole and feedthrough ring can be lifted by means of two 100 mm diameter screw shafts positioned on either side of the magnet. Each screw is driven by a high-torque low-speed hydraulic motor and the screws are synchronised by means of a roller chain. The sealing between the vacuum chamber and the lid is shown in figure 2.

Although the originally specified maximum average field at extraction was 0.86 T, a value of 0.95 T was assumed for the design of the magnet. Due to a recent request for 320 MeV $^3He^{2+}$ and and 220 MeV α- beams from the SSC, it will now be necessary to push the magnetic field up to ~I T. This requires an excitation current of ~960 A and a total power of ~90 kW which is close to the limits of both the power supply and the cooling system. We are, however, fairly confident that this field can be generated.

The field calculations were performed with a 3-dimensional relaxation program which does not take saturation effects into account. An estimate of the saturation effects could however be made with a 2-dimensional relaxation program and it showed that, as could be expected at these relatively low fields, saturation does not play an important role.

An interesting feature of our design is that the sectors are shifted radially outwards by ~60 mm so as to obtain an azimuthally averaged field which is almost flat in the radial direction. By doing this and by adding shims 5 mm thick and 50 mm wide on each sector at the extraction radius, the amount of trim-coil power required to produce an 8 MeV isochronous proton field was reduced from several kilowatts to merely 40 W. For

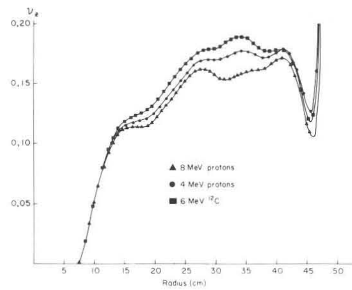

Fig.3: ν_z-values as a function of radius for three reference particles.

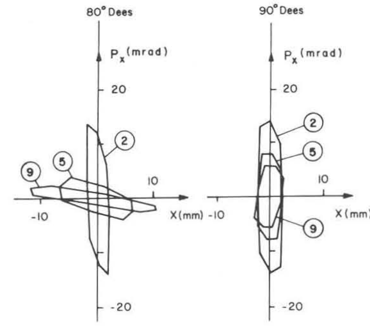

Fig.4: Radial phase ellipses at 180° on 2nd, 5th and 9th orbits for $^{12}C^{3+}$ beam accelerated in 80° (left) and 90° (right) dee systems with CP-phase corrections and having an emittance of 12π mm. mrad at the extraction energy of 6 MeV.

the 4 MeV isochronous proton field, almost no excitation current was required through the trim-coils. The degree of isochronism obtained, is illustrated by the fact that the phase of a proton, accelerated in the trim-coil field, never deviated by more than 2°rf from the phase curve obtained in an ideal isochronous field[4]. The ν_z - values for three reference particles are shown in fig. 3. It must be stressed, however, that the trim-coil fields are based on fields calculated for the given pole geometry. The real field measurements are due to start this month and we hope to be able to confirm these results soon.

By moving the sectors radially outwards instead of giving them a radial profile, we also gained the following: The ν_z-values were increased (up to 50%) in the central region[5], machining costs were reduced and more space was made available in the valleys. The azimuthal length of the harmonic coils, especially the inner set, could therefore be increased making them more effective.

3. Dee-angle and beam behaviour in radial phase space.- In SPC1 the rf-frequency ranges from 8.6 MHz to 26 MHz and the 2nd and 6th harmonic modes are being used for the acceleration of particles. With 90°-dees acceleration occurs at peak voltage. The use of 80°dees, however would allow a decrease in distance between the electrostatic channel and the first magnetic channel which is better for extraction. Furthermore, the smaller dee capacity would permit the high-frequency position of the short-circuiting plate to be further away from the magnet, which is desirable from a mechanical design point of view, and the bigger dummy-dees would allow more space for the installation of diagnostic equipment.

The work of Schulte[6], however, indicates that due to coupling between the longitudinal and radial phase space, a radial broadening of the beam can be expected if off-peak acceleration is used under the following conditions: acceleration on high harmonic numbers, low beam energies and acceleration near the ν_r = 1 resonance. If 80° - dees are used in SPC1, all these factors exist when particles such as ^{12}C, ^{20}Ne or low energy α-particles are accelerated. A study of the radial phase space behaviour of various beams of particles was therefore undertaken.

Calculations with a computer code were carried out for a proton beam having an energy and radial emittance of 4 MeV and 50π mm.mrad respectively at extraction (2nd harmonic) and a 6 MeV $^{12}C^{3+}$ beam having a radial emittance of (a) 12π mm.mrad and (b) 57π mm.mrad (6th harmonic). For each case eight particles, lying on an eigen-ellipse, were accelerated from near the ion source up to extraction. In the case of the 4 MeV proton beam no apparent difference between the phase-space diagrams for 80°- and 90°-dees was observed. In the case of the phase-space diagrams for the 6 MeV $^{12}C^{3+}$ beam, however, a distortion of the phase-space diagram as well as a pronounced broadening of the beam could be seen when 80°-dees were used. The distortion disappeared after a correction for central particle phase was applied. Figure 4 shows the phase diagrams for 80°- and 90°-dees at an azimuthal angle of 180° for the 2nd, 5th and 9th orbits. It is clear that the beam accelerated in the 80°-dee system spreads during acceleration to more than five times the size of the beam of the 90° system in the extraction region (i.e. the 9th orbit). Even with an emittance of 57π mm.mrad, no signs of instability could be detected in the case of 90°-dees.

These results clearly show that an 80°-dee geometry is not acceptable for acceleration in the h=6 mode and as a result, SPC1 is now being designed with 90°-dees.

4. Extraction.- The extraction system for SPC1 consists of one electrostatic channel (EC) extending from 177° to 219° and two focussing magnetic channels MC1 and MC2 (figure 2 of reference 1). A maximum field strength of 90 kV/cm on the EC is required to extract the 8 MeV proton beam. If the outer set of harmonic coils is used for extraction, the fieldstrength can be decreased by ~1.3 kV/cm per gauss of first harmonic component. Thus, in principle, the fieldstrength could be reduced to 60 kV/cm for 8 MeV protons. For the least favourable case (i.e. 4 MeV, 100μA proton and deuteron beams), the calculated extraction efficiency is more than 90%.

Extraction starts before ν_r = 1. During subsequent transit through the fringe field, the particles experience a very strong axial focussing force and the beam crosses over sharply inside the dee (fig. 5.) The dee is cut away at this point to allow the use of an active magnetic focussing channel ~10 cm. long. The required gradient in this channel is 24 T/m for the 8 MeV proton beam and 16 T/m for the 4 MeV beam. When

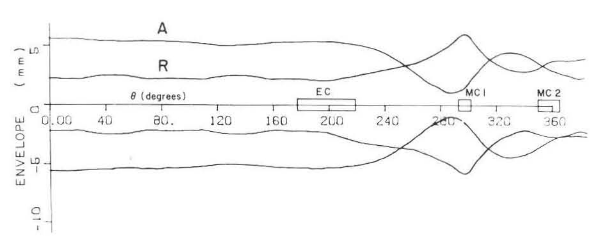

Fig. 5: Axial (A) and radial (R) envelopes for an 8 MeV, 12π mm.mrad deflected proton beam.

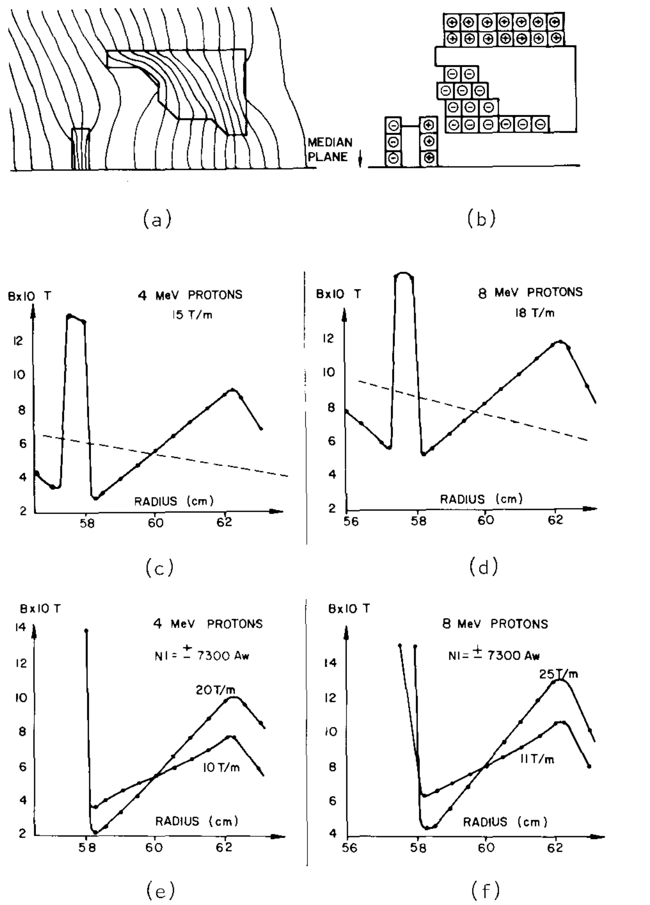

Fig.6: The geometry of the magnetic channel MC1 as a passive channel (a) and an active channel (b). The resulting flux densities for 4 and 8 MeV passive channels (c and d) are contrasted with the active channel results (e and f).

used as a passive element with a cross section as shown in figure 6, the desired gradient for the 4 MeV beam is obtained, but the corresponding gradient for the 8 MeV case is only 18 T/m.[4] Activating coils will therefore be used to increase the gradient. Figure 6 shows the calculated maximum and minimum gradients obtained in the two fields under consideration when 14 600 ampére-turns are used. The first harmonic component caused by the field perturbation due to this channel is small. At 40 cm we calculated 10^{-4}T and at 45 cm 7×10^{-4}T.

In the second focussing channel, extending from 350^{o} to 365^{o}, an average gradient of ~4 T/m is needed to produce the required beam properties at the first dipole in the beamline. As we want this channel to provide horizontal steering as well, we are presently designing a C-magnet for this purpose.

5. Axial acceptance calculations.- Preliminary calculations have been initiated to determine the possible influence of the acceleration gap height (H) and the inclusion of a magnetic cone field on the axial acceptance of SPC1 central region. The electric field in the acceleration gaps was approximated by a Gaussian distribution and the vertical acceptance was determined by calculating the transmission matrix by means of an orbit code and projecting the acceleration gaps on axial phase space at 90^{o} behind the puller slit. In figure 7

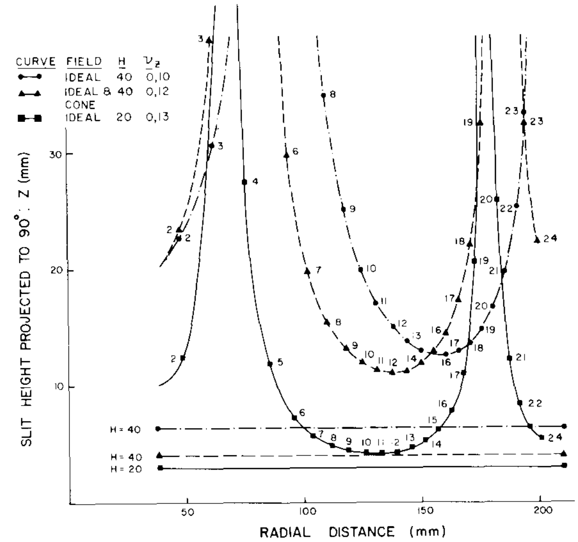

Fig. 7: Axial co-ordinate of gap lips as projected onto phase space at θ = 90^{o} (behind the puller) for 8 MeV protons.

the z intercepts in phase space of the projected gaps are plotted as a function of radial distance with the gap numbers indicated on each curve. Also plotted as horizontal straight lines are the maxima along z of the projected eigen-ellipses.

The three sets of curves were obtained for a gap height of 40 mm with and without a cone field of 80 G, and a gap height of 20 mm. Similar curves were obtained for $\dot{z}$[4].

We found this representation very useful to evaluate the effect of different parameters on the axial acceptance. Noting that the curves show singularities at those positions where the ions cross the median plane one may deduce an average ν_z-value from these graphs. The results yield ν_z-values of 0.1, 0.12 and 0.13 respectively. Increased focussing, i.e. greater ν_z is indicated by a shift of the whole pattern towards smaller radii (lower gap numbers) while increased acceptance is indicated by a raising of the minima.

Another parameter to be studied by this method is the starting phase. We also intend using these curves to determine the optimum position for the axial slits.

References

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