SEPARATED ORBIT CYCLOTRON – SEARCH FOR SIMPLIFICATIONS

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Abstract

A new version of bending magnets for the Separated Orbit Cyclotron for a proton energy of 240MeV (SOC-240), a superconducting cyclotron cooled with liquid helium, is proposed. It permits one to simplify magnet manufacturing considerably. The possibility of combining bending and focusing functions in such a kind of magnets is considered. Power consumption is evaluated in the case of using copper windings cooled with other coolants.

1 INTRODUCTION

Very high, close to 100%, coefficients of beam injection and extraction are one of the main attractive advantages of separated orbit cyclotrons [1,2,3] over their classical analogues. This SOC's property allows one to deal with the acceleration of currents in the milliampere range at very small beam losses. But the advantages of SOCs are connected with difficulties of their manufacturing. That is the reason of a limited approach to their use. Efforts to simplify the technology connected with the production of such a type of accelerators are undertaken in this paper.

2 SOC-240

The conceptual design for the SOC-240 was performed and shortly described in a report in 1999 [4]. This project contains a superferric cyclotron for a proton energy of 240 MeV with an IBA CYCLONE-30 30MeV commercial cyclotron as an injector, delivering a maximum current of 500μA.

The SOC magnet system comprises 240 bending-focusing periods with an increasing length divided into 16 sectors. At every turn, the beam traverses 16 periods, each consisting of two dipoles, defocusing and focusing quadrupoles and an accelerating RF cavity (Fig.1.).

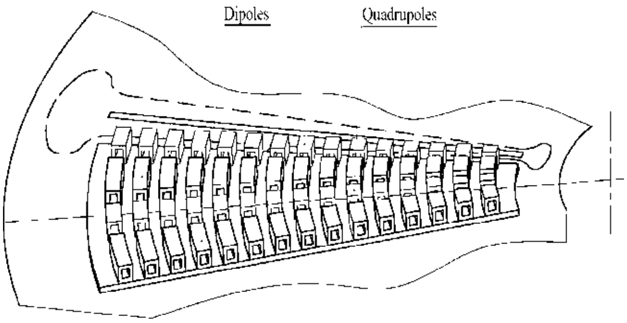

Figure 1: View of the SOC-240 sector.

An isochronous condition is insured by the required length of the periods, which is reached by combining bending angles in dipole pairs and straight parts of the equilibrium particle trajectory. A sufficient turn separation to clear magnet yokes is achieved by means of 16 accelerating superconducting cavities, each with a maximum amplitude of 1.2MV. The total number of turns is 15; the final energy and radius are 240.9MeV and 3.526m, respectively. The last turn separation is equal to 97 mm.

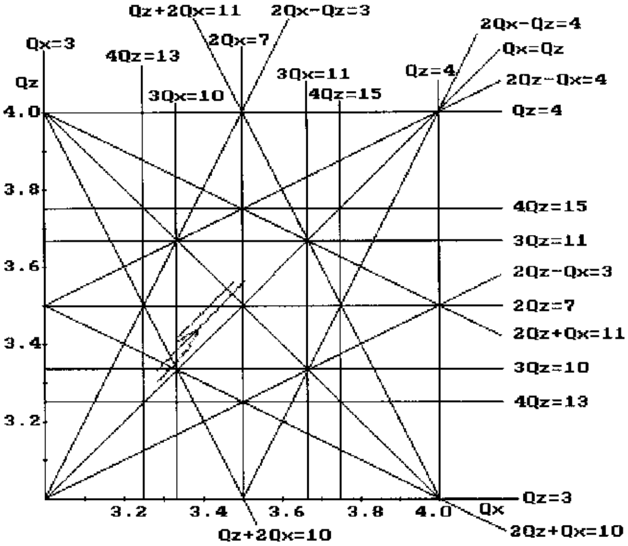

Figure 2: Diagram of betatron oscillation resonances.

The focusing system of the accelerator represents a D-O-F-O structure. The dipole magnets are sectored and have zero edge angles. The length of each magnet was chosen so that all magnets had identical fields equal to 1.4T. The gradients in the focusing and defocusing quadrupole lenses are similar in all sectors and equal to G_F=53.5T/m and G_D= -57.5T/m.

Figure 2 shows a SOC-240 diagram of betatron oscillation resonances of the 1-st, 2-nd and 3-rd orders.

The cross sections of the dipole and quadrupole magnets are presented in Figure 3. The computed field distribution showed a field inhomogeneity of about 1% in the dipoles and 3% in the quadrupoles. (The investigations performed at the Laboratory of High Energies, JINR show a rather a small difference of the saturation effects at helium and room temperature.)

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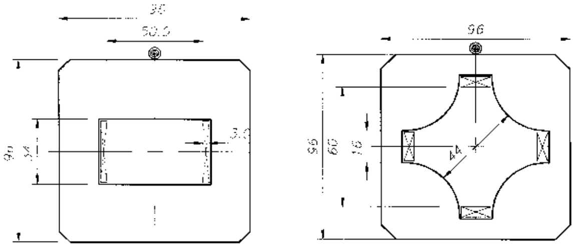

Figure 3: Cross section of the dipole and the quadrupole.

Simulations of accelerated particle motion taking into account magnet alignment errors were performed. Figure 4 gives tracking results in the horizontal (x,x′) and vertical (z,z′) planes including misalignment errors to ±0.4mm, the k_2=0.002cm^{-2} sextupole coefficients, and initial conditions corresponding to emittance at injection of E_x=30π·mm·mrad and E_z=20π·mm·mrad. Each point of the figures corresponds to the co-ordinates (x,x′) at the focusing lens input and (z,z′) at the defocusing lens input. During the acceleration, there are 2.5 synchrotron oscillations of particles, and the maximum amplitude of these oscillations is 2.5 mm. It is seen that the beam is well contained within the designed aperture of the magnets.

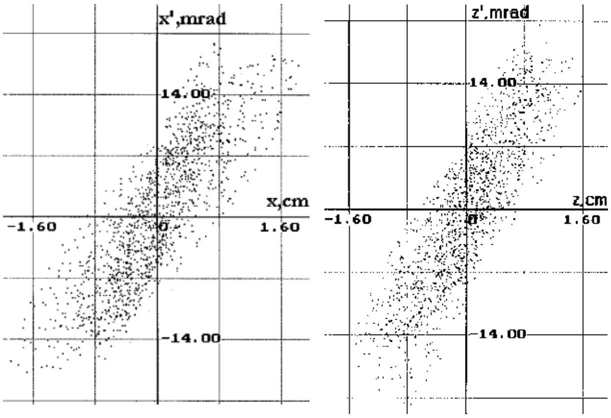

Figure 4: Phase diagram of the beam in the horizontal and vertical planes.

At the appropriate performance of the project requirements and obtaining proper gas pressure, particle losses should be very low. The first condition can be satisfied by introducing some reserves into such parameters, as clearance in apertures. The second one does not require special measures at cryogenic temperatures. For example, the operational pressure in the Nuclotron vacuum chamber [5] is lower than 10^{-9} Torr. At such low losses, a high, close to 100%, extraction coefficient can be measured by the method [6].

The SOC equipment is placed in the overall vacuum vessel. It is a bread-ring chamber with an outside horizontal diameter of 9m and an oval cross section 0.7m x 3.5m in size. The vacuum chamber is assembled in sections corresponding to the number of sectors. The sectors are fastened by eight suspension rods inside the cylindrical parts. The length of the rods is chosen so that the middle of the platform remains in the initial horizontal plane with a sufficient accuracy after cooling down. Indirect cooling of the windings is performed with a two-phase helium flow.

The cryogenic supply system is based on the TCF50 refrigerator with a 500W nominal capacity at 4.5 K. The compressor power supply for the cryogenic equipment is about 150kW.

Though the projected parameters and characteristics meet the required specifications, potential users' desire to simplify technology made the authors upgrade the project in order to reduce intricate works.

3 SERCH FOR SIMPLIFICATIONS

Rather laborious fabrication of the SOC-240 magnet cells, in particular dipole ones, is one of the difficulties of its magnet manufacturing. To decrease cooling losses during cyclotron operation, the number of cryogenic current leads for supplying the dipoles is reduced to a minimum. All the dipoles are supplied with their current in a series and so their magnetic field is the same one. In such a case, their length, determined by the synchronous conditions, and the curvature radius must be alternating.

Since the total number of dipoles is 480in this case, their fabrication requires intricate work. But the fact that the field in all the dipole magnets is alike, prompts one to unite a set of all radial situated dipoles in one stretched magnet capturing a beam from the first to the last turn. This "unidipole" must have the same field and consequently a vertical gap size as in the previously designed magnets but a common space in the radial direction. Such a version of dipoles decreases their number by a factor of 15 though overall dimensions increase accordingly. A growing path of the particle trajectories inside each unidipole is provided with the wedge form of its yoke (Fig.5). Such a decision permits one not only to reduce expenses of dipole fabrication but also to soften requirements for the radial position of magnets at their installation and support during operation.

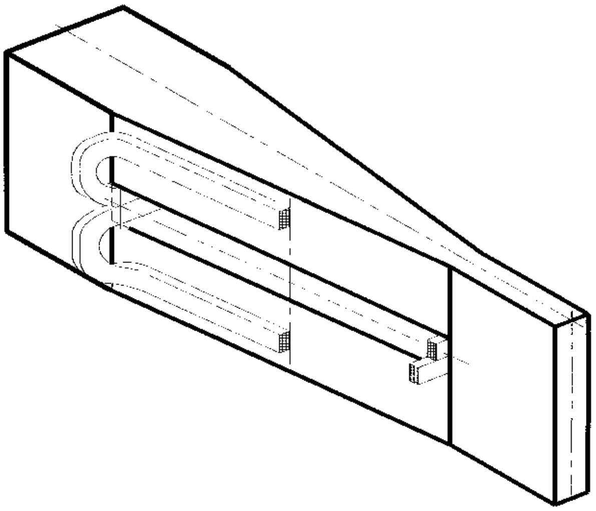

Figure 5: View of the "unidipole".

To simplify fabrication and adjustment, unidipole yokes should be made of stamped steel laminations. In this case, an exact adjustment of the required magnet length passed by the beam can be done by adding or removing steel sheets at the place of trajectory position.

The next step is to decrease a load on the quadrupoles and to transmit part of their function to the unidipoles. (In principle, it is possible to exclude quadrupoles completely.) So, the function of unidipoles becomes combined. Figure 6 illustrates the form of the pole profile of such a magnet. This form inside the region of the beam position is defined by the formula:

$$\mathbf{y = y(o)/[1+Gx(1-x/2R)/B(o)],}$$

where y is the gap height, y(o) is a constant gap height at the beam orbit position always lying in the centers of the unidipole steps, x is the radial co-ordinate, G=dB/dx, R is the curvature radius and B(o) is induction in the step centre.

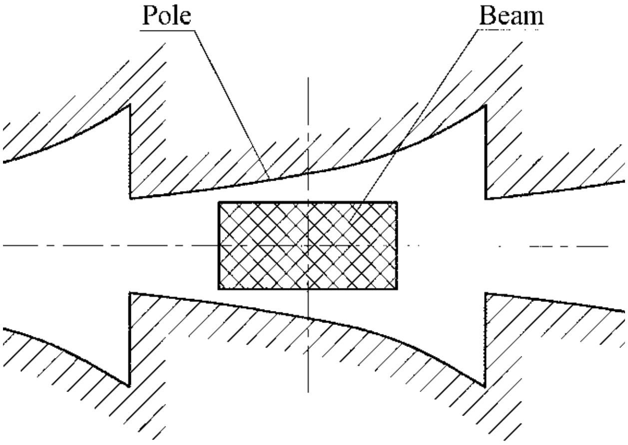

Figure 6: Pole profile of the magnet with combined functions.

To reduce the accelerator cost and to bring it nearer to the commercial one, an attempt of replacing s.c. windings by copper ones operating at cryogenic temperatures was made. A 100MeV cyclotron with pure copper windings cooled with liquid nitrogen and liquid neon was considered as an example. The calculations showed a real possibility of such an operation at a magnet compressor consumption of about 160 kW and 17kW, respectively.

4 CONCLUSION

The performed research of improving one of the versions of the separated orbit cyclotron has led to useful rationalisazion of its magnet system. A big gain from cooling SOC magnets with liquid nitrogen must not be assumed as significant one, but using liquid neon and pure copper windings may be considered as a competitive version. Preference remains to the superconductivity, as before. Simplifications concerning the service of refrigerators and helium consumption may be achieved taking into account rapid development of the helium refrigerator technology.

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