CONCEPTUAL DESIGN OF A 240 MeV SUPERFERRIC SEPARATED ORBIT CYCLOTRON *

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Abstract
A conceptual design of the Separated Orbit Cyclotron (SOC) for the proton energy of 240 MeV based on the use of superferric magnets (dipoles and quadrupoles) is presented. Superconducting RF cavities are used as well. The beam intensity is determined by, but not limited to the 500μA available from the IBA "Cyclone-30" cyclotron to be used as the 30MeV injector. The electrical power draw of the helium refrigerator is 250kW.

1 INTRODUCTION

The separated orbit cyclotron (SOC) [1,2,3] has a number of attractive advantages over its classical analogues, the greater part of which are very high, close to 100%, coefficients of beam injection and extraction. This SOC's property allows one to deal with the acceleration of currents in the milliampere range at very small beam losses. In this way, the SOC more resembles a linear accelerator than a cyclotron.

By reason of the limited orbit separation determined by the achievable accelerating RF voltage, SOC-type accelerators can be practically constructed only by applying superconducting technology, namely, superferric magnets (dipoles and quadrupoles) of small outside transverse dimensions. Experience gained in the production and use of magnets of such a type [4], confirms their good operating quality. It is also reasonable to use superconducting cavities in the accelerating system.

This work was performed on contract from the HRIBF group at the Oak Ridge National Laboratory as part of their study for high-current drivers for the next generation radioactive beam facility. The conceptual design for the SOC has to meet requirements with the following main specifications: 1)The maximum proton energy should be between 200MeV and 250MeV depending on space. 2)Proton injection could be used with a 30MeV commercial cyclotron. The IBA model CYCLONE-30 at a maximum current of 500μA is accepted here. 3) The total internal beam loss and extraction beam losses must be less than 1.0%.

To research the conditions satisfying a stable motion of particles without losses, a simulation program was developed. In the program, all main conditions of longitudinal and transversal motion were taken into consideration. According to the evaluated errors in the dipole and quadrupole alignment, the beam envelope, including orbit distortions, was computed. Its size lies within the limits of 42mm x 34mm and determines the aperture and outside dimensions of the magnets, the latter of which are equal to 96mm x 96mm.

2 LATTICE AND BEAM DYNAMICS

The SOC magnet system contains 240 bending-focusing periods with 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.

An isochronous condition is insured by the required length of the periods, which is achieved by combining bending angles in dipole pairs and straight parts of the equilibrium particle trajectory. Sufficient turn separation to clear magnet yokes is achieved by means of 16 accelerating 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, consequently. The last turn separation is equal to 97 mm.

Synchrotron motion in (Δt, Δw) co-ordinates is presented in Fig.1 for a maximum energy spread Δw_m and bunch duration Δt_m at injection. The energy

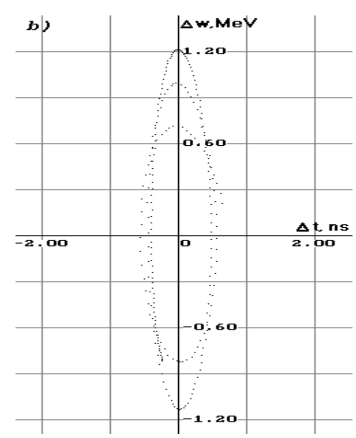

Figure 1: Synchrotron motion at k_2=0.002.

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spread, increasing by the end of acceleration, is equal to 1.2MeV. During the acceleration, there are 2.5 synchrotron oscillations of the particles, and the maximum amplitude of these oscillations is 2.5 mm.

The focusing system of the accelerator represents a symmetric 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 values of the gradients in the defocusing and focusing quadrupole lenses are similar in all sectors and equal to G_D= -57.5T/m and G_F=53.5T/m.

Figure 2 shows a diagram of betatron oscillation resonances to 1-st. 2-nd and 3-rd orders.

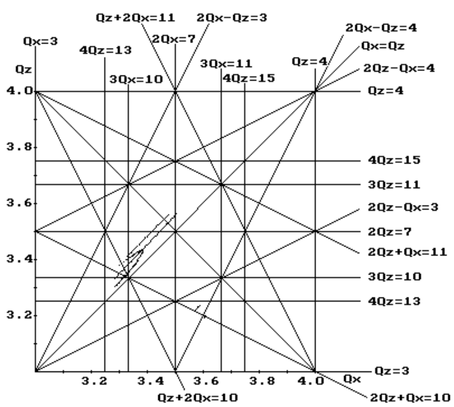

Figure 2: Diagram of betatron oscillation resonances.

A sextupole component of the dipole magnetic field with coefficient k_2=0.002cm^{-2} ($\Delta B=k_2Bx^2$) was taken into account. Nonlinearities in the quadrupole lenses were not considered because of their very high orders (fifth and more). In spite of crossing resonance lines, the motion is stable because the phase shift changes from sector to sector rather quickly.

Simulations including magnet alignment errors have been performed. Figure 3 shows 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. It is seen that beam is well contained within the designed aperture of the magnets.

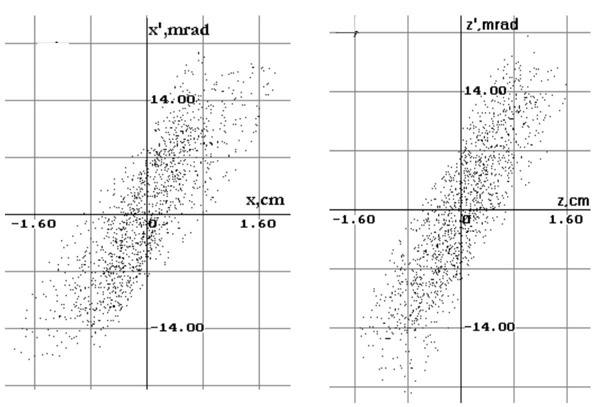

Figure 3: Phase diagram in the horizontal and vertical planes.

The acceleration of ions with q/A=1/2 in the SOC can be realised at a smaller ion acceleration rate (on the doubled harmonic) up to 46MeV/amu. In this case the injection energy should be 7.24MeV/amu.

3 SUPERFERRIC MAGNETS

The cross sections of the dipole and quadrupole magnets are presented in Figure 4. Their 2D magnetic fields have been calculated by the POISSON program for ARMCO steel. The investigations performed at the Laboratory of High Energies, JINR show a rather small difference of the saturation effects at helium and room temperature. The computed field distributions show a field inhomogeneity of about 1% in the dipoles and 3% in the quadrupoles.

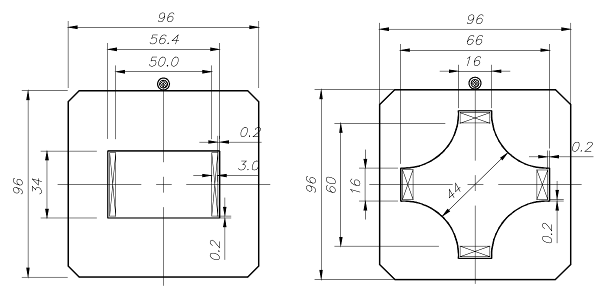

Figure 4: Cross section of the dipole and the quadrupole.

For quench protection reasons, the copper to superconductor ratio of the cable is chosen to be equal to 2:1. This helps to protect the magnet from small disturbances which can produce quenches. The width and thickness of the conductor containing 2970 NbTi filaments is 3.4mm and 1.4mm, respectively. It is insulated with double Capton and fiberglass epoxy layers for a total of 0.2mm thickness.

4 CRYOGENIC SYSTEM

The SOC cryogenic system consists of 16 sectors. Each sector contains 30 dipole and 30 quadrupole magnets with a cold iron yoke.

The equipment is mounted on the supporting sector platforms (Fig.5). Each of the platforms is fastened to the cryostat by suspension rods. The magnets are cooled in series by means of copper cooling tubes, which are soldered to a copper plate and mechanically attached to the iron yokes. Calculations show that the difference of temperatures between the cooling liquid and the s.c. winding is no larger than 0.2 K.

Indirect cooling of the windings is performed by a two-phase helium flow. The mass vapour content of helium

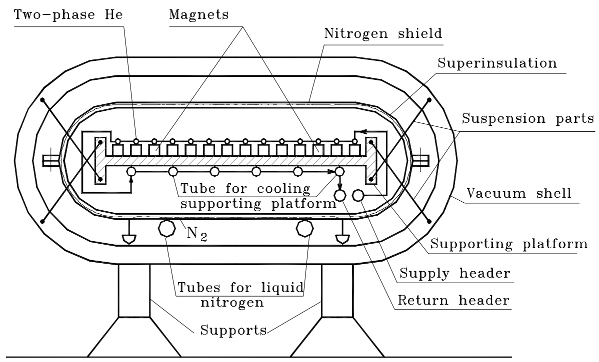

Figure 5: Cross section of the SOC

varies from 0 at the inlet of the sector to 0.9 at its outlet. Two-phase helium flow was chosen to cool the SOC on the basis of operating experience of the Nuclotron cryogenic system [4]. In comparison with two-phase helium, a single-phase coolant (liquid helium) leads to an increase of the helium flow through the magnet and to less efficient cooling. Experience has shown that instabilities in the flow distribution in parallel channels and large oscillations of vapour pressure and flow rate are not a problem with a two-phase helium system.

The cryogenic supply system is based on the TCF50 refrigerator with a 500W nominal capacity at 4.5 K.

The SOC has a common vacuum space for the beam and for cryogenic insulation. The operating pressure provided with cryosorbtion will be smaller than $1x10^{-7}$ Torr with hydrogen and helium being the major residual gases. No permanent pumps will be installed since none are required if helium leaks are kept small.

5 DESIGN OF THE ACCELERATOR FACILITIES

The SOC equipment is placed in the overall vacuum vessel. It is a ring chamber with an outside horizontal diameter of 9.0m and an oval cross section 0.7m x 3.5m in size (Fig.5). 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.

The operating position of the magnets at cryogenic temperature should be held within the limits from ±0.2mm to ±0.4mm relative to the equilibrium orbit. This problem could be solved in several ways: i) by defining the magnet positions through calculations of their expected displacement in the cold state; ii) by preliminary mapping of the footholds in the cold state of the support base on which the magnets are to be arranged afterwards; iii) by installing special windows for optical control of the magnet positions; iv) by adjusting the magnet position; v)by using beam diagnostics and correction systems.

To decrease cooling losses during SOC operation, the number of cryogenic current leads for supplying the magnets is reduced to a minimum: for instance all the dipoles are supplied with their current in series. In this case, the dipoles (formed in sector shape with different curvature radii) must have different lengths. To meet this requirement and to simplify fabrication, all the dipole magnet cores are made of identical stamped steel laminations. Steel laminations are welded or glued together on a mandril, the base dimensions of which correspond to the ones of the magnet gap (Fig.6). The mandril is flexible, and its curvature is adjusted for each dipole separately.

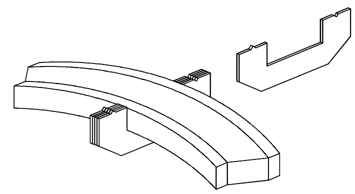

Figure 6: Steel laminations set on the mandril.

A similar mandril is used to fabricate the windings. This technology is used for quadrupole fabrication as well, with the difference of having no curvature and only four lengths.

6 CONCLUSION

From results of simulations, we can conclude that it is possible to accelerate beam with no additional corrections. In any case, provisions are made for horizontal and vertical correctors to compensate for coherent beam offsets.

In summary, the SOC concept is quite practical for high-current beam production in the few-hundred MeV range, and we strongly suggest that it should be further explored.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1]. F.M. Russell, ORNL. Nucl.Instr. and Meth., 23, 1963, p.229.
[2] U.Trinks. Proc. of the Int. Conf. on Cyclotron. Vancouver, Canada, May 1992.
[3] I.A.Shelaev. JINR Rapid Communications No.5[62]-93, p.16.
[4] A.M.Baldin et.al.,Proc.of the Cryog. Eng. Conf., Albuquerque, July 1993.