# A SEPARATED SECTOR CYCLOTRON FOR THE PRODUCTION OF HIGH INTENSITY PROTONS*

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*Abstract*

We describe in this paper the design of a separated sector cyclotron (SSC) for the production of an intense beam of 230 MeV protons. The goal was an accelerator that could be used as the driver of an ISOL type Radioactive Ion Beam Facility.

## 1 INTRODUCTION

The purpose of this study is the conceptual design of an accelerator for the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL) to produce 200 μA of protons at energies of approximately 200-250 MeV, that would fit in room C110 at ORNL. The choice in this option of a separated sector cyclotron (SSC) is driven by the desire of minimizing the losses in the accelerator. Most of the losses in an isochronous cyclotron usually occur at the deflector septum during extraction. The radius gain between turns should be increased as much as possible to decrease these losses. The radius gain per turn due to the energy gain, in abscence of any other off-centering mechanism is given approximately by:

$$\Delta R = R \frac{\Delta E}{E} \frac{\gamma}{\gamma + 1} \frac{1}{\nu_r^2}$$

Where R is the extraction radius, E is the final energy, $\Delta E$ is the energy gain per turn, $\gamma$ is the relativistic factor and $\nu_r$ is the radial focusing frequency. Increasing the voltage of the RF system is the obvious way of increasing the energy gain, but it is limited by sparking and power limitations. Increasing the radius of the cyclotron is the other parameter that we have used in this design to increase the turn separation. One of the boundary conditions in this study was the desire to obtain a cyclotron design that would fit in room C110 at ORNL. Under this condition we estimated that 3.7 m is the maximum extraction radius compatible with fitting the cyclotron in that room. These decisions of increasing the cyclotron size and RF voltage come at a price, the accelerator cost increases. This SSC option then emphasizes reliability and lower technical risk over cost.

Our design has benefitted from past experience developed mainly at two laboratories: the National Accelerator Center (NAC) at Faure, South Africa [1], and the Paul Scherrer Institut (PSI) at Villigen in Switzerland [2]. Both laboratories operate large separated sector cyclotrons that accelerate protons in similar ranges of energies and intensities. The NAC cyclotron is a multi-ion, variable energy machine that accelerates protons up to 220 MeV, with currents of up to 200 μA at 66 MeV. The PSI accelerators are single ion, fixed energy. They accelerate protons to 72 MeV in their Injector II and to 590 MeV in their ring cyclotron with intensities above 1.5 mA. The PSI cyclotrons can be described as state of the art in high intensity operation. The extraction efficiency is 100 % even at 1.5 mA.

A companion paper describes a different option: a compact superconducting cyclotron [3].

## 2 SECTOR MAGNETS

One of the first decisions to be made in the design process is the number of sectors in the magnet and the angular width of each sector necessary to achieve the final energy of approximately 250 MeV. To avoid the effects of resonances like the $\nu_z = 1$ and the $\nu_r = N/2$ we have selected four sectors and a magnet sector angle of 34 degrees (f= 34/90=0.378).

The magnetic field of the sector magnets was studied with the finite element code TOSCA. We have adopted a minimum magnet gap of 3.8 cm with the assumption that the magnet surface close to the median plane will be part of the vacuum chamber. We expect to obtain an isochronous field by shaping the pole tip surface and thus eliminate the need for trim coils. We would like to have the magnetic field approximately constant inside the sector magnet along each orbit for a given energy, and change according to the isochronism requirements for different energies. With this purpose the TOSCA grid was designed with construction circles that followed the theoretical (hard edge approximation) closed orbits. The points along these circles have assigned to them a constant gap value. After obtaining a polar grid from the TOSCA

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model we isochronized the field and found the difference between the calculated field and the field required to maintain isochronism during acceleration. This difference was used to change the gap as a function of energy and a new model was calculated. After several iterations a reasonable approximation to the isochronous field was obtained with errors of less than 100 gauss and less than 50 over most of the radius. A top view of the whole SSC in Room C110 at ORNL is shown in Figure 1. A view of the sector magnets is shown in Figure 2.

## 3 BEAM DYNAMICS

The equilibrium orbit (closed orbit) properties were calculated in the polar grid obtained from TOSCA. These results confirmed the choice of sector angle maintaining the operating point away from deleterious resonances.

A conceptual design of the injection system is similar to the injection system used at NAC [4]. The beam is injected at an energy of 8 along one of the two valleys not used for the main RF cavities. Two deflecting elements with fields of 12.0 kG and 1.15 kG are used to bend the beam into the accelerated orbit. As the turn separation between central rays at injection is large, 4.0 cm for an energy gain of 1 MeV, there is no problem in accommodating a septum between turns. The actual dee voltage profile may reduce this energy gain significantly.

A plan view of the extraction system is shown in Figure 3. The maximum radius of the 231 MeV internal beam ellipse is plotted as well as the central ray of the extracted beam.

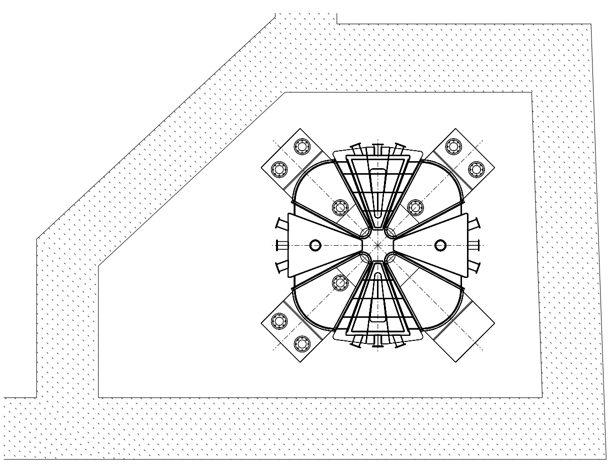

Figure 1 Plan view of the SSC installed in Room C110 at ORNL.

This system closely resembles the extraction system of the NAC SSC [4]. The beam extraction is started by increasing the separation between the final orbit and the internal beam with an electrostatic deflector (ED) with a relatively low field of 25 kV/cm extending from θ=-44 to θ=-32 degrees (l ≈0.64 m).

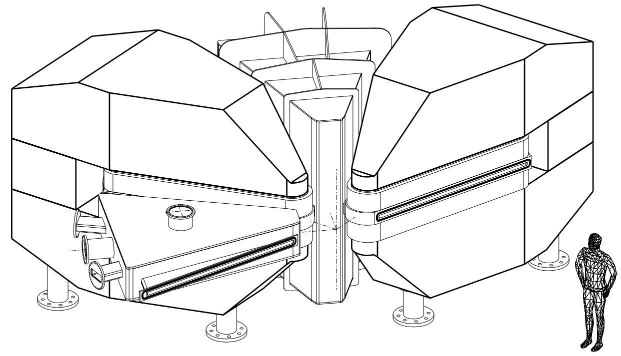

Figure 2 Partial view of the SSC showing two of the sector magnets and two of the valley vacuum chambers.

Approximately 90 degrees later, from θ=44 to θ=50 degrees (l ≈ 0.30 m) the turn separation is sufficient (1.5 cm) to insert a septum magnet (SM1) of low field (0.1 T), (see Figure 4). This septum magnet is located inside the dee. The next deflection is produced by a second septum magnet (SM2) located from θ=116 to θ=128 degrees (l ≈ 0.65 m). The separation here is 12 cm allowing a higher field (0.4 T) magnet. Finally a bending magnet (BM) with a field of 1.0 T is used to clear the next sector magnet.

The phase spread of the beam will produce an energy spread and a radial spread that will reduce the turn separation from the theoretical monoenergetic beam separation. To reduce this deleterious effect it is desirable to accelerate a narrow phase width**,** but space charge forces increase the energy gain of the ions in the leading edge of the bunch and decrease the energy gained by the ions in the tail of the bunch. This effect tilts the bunch effectively increasing the turn width and decreasing the separation between consecutive turns.

Analytic treatments of space charge effects in cyclotrons are not very detailed due to the complexity of the problem, and mostly give a qualitative idea of how the different parameters enter in the analysis. Numerical calculation of space charge effects in cyclotrons are still very primitive and no hard limits can be obtained from them. Instead we use approximate formulas to compare our design with cyclotrons running in the high intensity regime (PSI Injector II and Ring cyclotron). According to W. Joho [5] the voltage spread induced by the longitudinal space charge forces can be estimated from the formula:

$$\Delta U_{SC} = 2800\Omega \frac{< I > n^2}{\frac{\Delta\Phi}{2\pi}\beta_f}$$

A figure of merit is the ratio of the space charge induced voltage spread to the voltage gain per turn. This ratio for our design falls in between the corresponding values for the PSI cyclotrons. Both of these accelerators achieve 100 % extraction.

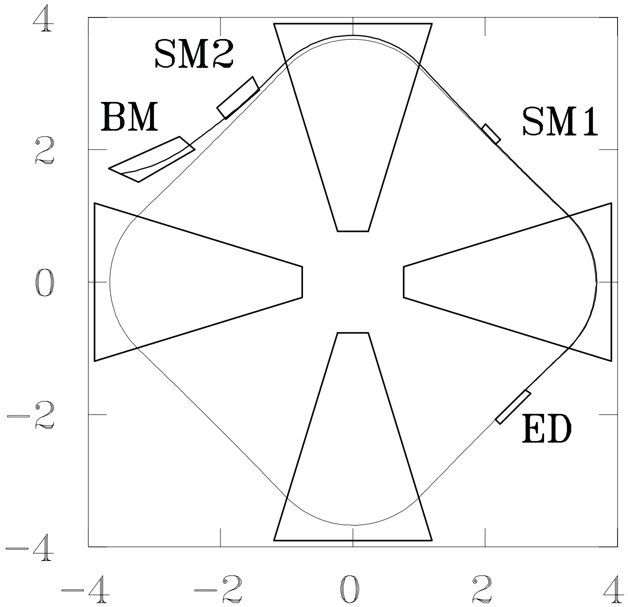

Figure 3 Top view of the extraction system.

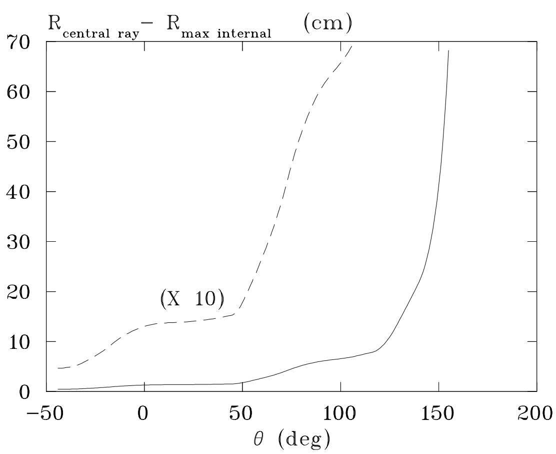


Figure 4 Difference in radius between the central ray of the extracted orbit and the maximum radius of the internal beam.

A solution to the turn broadening produced by a large beam phase width is obtained by using a flat-topping RF system. Additional electrodes are utilized that are excited with the third and ninth harmonic of the fundamental RF frequency. The result of particle tracking in the actual magnetic field with fundamental and higher harmonics showed that the addition of a third harmonic energy gain of 23.5 % of the fundamental is optimum. This additional voltage increased the phase interval corresponding to an energy spread less than 10 % of the energy gain per turn from just a few degrees to 25 degrees. If a ninth harmonic component is included the acceptable phase width is 43 degrees. The ninth harmonic cavity would certainly be a challenging project, running at 300 MHz. Serious design work should be done to determine its feasibility.

## 4 RF AND VACUUM

The main accelerating system consists of two dees placed in opposite valleys. The ion orbital frequency is 8.3 MHz giving RF in fourth harmonic of 33.2 MHz.. The cavity has been calculated using the program WAC [6]. For a peak voltage of 250 kV on the dees the estimated total power is 150 kW.

The beam chamber consists of the valley sections and sector magnet sections. The steel surfaces in the sector magnets constitute the beam chamber itself. Plating of the steel is necessary to avoid corrosion problems. The valley sections are of two kinds depending if the RF resonators fill the valley or if it is a valley used for injection, extraction or diagnostics. The design adopted for the vacuum seals has been copied from the PSI Injector II seals. It consists of metallic inflatable seals of toroidal shape that are deflated to disassemble the beam chamber and inflated when assembled. This mechanism allows radial motion of the four valley sections with respect to the sector magnets for fast assembly-disassembly.

## CONCLUSIONS

The present study showed that it is posible to design a SSC that would fit in Room C110 at ORNL to produce 200 μA of 230 MeV protons. Preliminary injection and extraction systems have been designed. Flattopping cavities are needed to decrease the energy spread and reduce the losses on the extraction septum.

## ACKNOWLEDGEMENTS

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