# STUDY OF A SUPERCONDUCTING COMPACT CYCLOTRON FOR DELIVERING 20 MeV HIGH CURRENT PROTON BEAM

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*Abstract*

Compact cyclotrons which accelerate high current of negative hydrogen ions in the energy range 10–30 MeV have been widely used over the last 25 years for medical isotope production and other applications. For a number of applications, low weight, low power consumption, portability, or low radiation background are key design requirements. We have evaluated the feasibility of a compact superconducting cyclotron that would provide proton beams up to 20 MeV by accelerating negative hydrogen ions and extracting them by the stripping process with relatively high beam current of 100 µA. The study demonstrates that the survival of the H- ion under high magnetic field environment could be large enough to guarantee low beam losses as long as the RF voltage is high. The compact cyclotron is energized by a set of superconducting coils providing the needed magnetic field, while the azimuthal varying field is provided by four iron sectors. Additional superconducting coils are added to minimize the stray magnetic field, eliminating the need for a return iron yoke and reducing the total weight of the device. In order to assure adequate vacuum in the accelerating region, an external H- ion source is used.

## INTRODUCTION

Cyclotron technology has developed over many decades, and today it is considered a mature technology. The present approach for making cyclotrons includes the use of magnetic iron poles and iron return yokes to decrease the quantity of conductor needed to generate the magnetic field. In addition, magnetic iron sectors are used for shaping the field. The use of superconductivity in cyclotrons opens the potential for compact, high field devices. In this design the use of iron is minimized as both the main field and the return yoke flux are provided by a set of superconducting coils as shown in Fig. 1. The field shaping for the isochronous cyclotron was achieved using a combination of coils and iron pole tips in the bore of the coils, limiting the flexibility of field shaping by coils that are above/below the beam chamber (see Fig. 1). On the other side, the stray field is balanced by the contribute done by a set of superconducting shielding coils placed at outer radii. It results in a very fast decay of the magnetic field with distance away from cyclotron. The choice to operate with high magnetic field allows to maintain extremely compact the size of the machine as the extraction radius is 190 mm. Moreover, the elimination of the iron yoke allows for very large decrease in weight of the cyclotron, resulting in few tons weight machine.

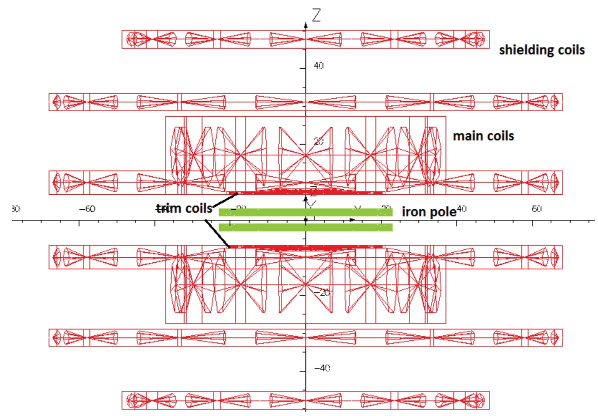


Figure 1: Coils configuration and iron poles location of the cyclotron magnetic system (units are cm).

## H-LOSSES AT HIGH FIELD

The beam current loss due to Lorentz stripping of H- is a matter of concern while designing high field cyclotron. Due to the relatively low final energy of 20 MeV, the beam fraction lost during the acceleration can be reduced in two way: by keeping within certain margins the magnetic field values and by decreasing the number of turns necessary to achieve the final energy. Moreover, in order to minimize the residual gas stripping the operational vacuum pressure has to set at $10^{-7}$ torr.

### *Beam Losses by Magnetic Lorentz Stripping*

When a H- ion is bent in a magnetic field, the electrons and proton are bent in opposite directions. If the magnetic field is strong enough, the slightly bound electron can be stripped.

The beam fraction lost per unit length in the laboratory frame depends on the lifetime τo given by Stinson [1], as

$$\frac{1}{L} = \frac{1}{\beta c \gamma \tau o} \tag{1}$$

Since the revolution time To of particles travelling into a cyclotron can be assumed constant:

$$To = \frac{2\pi \cdot Eo}{Bo \cdot q \cdot c^2} \tag{2}$$

with *Eo* rest energy and *Bo* magnetic field at center of the machine, it is possible to estimate the fraction of particle losses during the acceleration from the injection energy (30 keV) to the extraction one (20 MeV), by varying the confining magnetic field at center Bo. The calculations take into account of the magnetic field rise



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needed to compensate the relativistic mass increment. Figure 2 represents the fraction of particle losses for different magnetic fields, assuming the worst case of 1000 turns which means an energy gain of 20keV/turn.

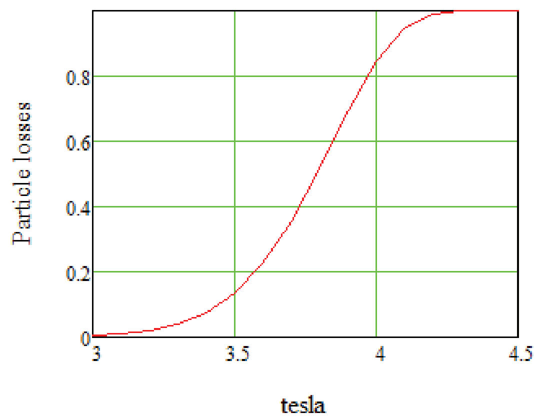


Figure 2: The plot represents the fraction of particle losses (unity corresponds to fully beam loss) for different magnetic fields at center, assuming the energy gain of 20keV/turn.

In order to maintain the particle losses due to the ion dissociation below the 10% and keeping a reasonable margin of safety, the cyclotron can operate by setting the magnetic field at center within 3 and 3.5 tesla

## MAGNETIC FIELD DESIGN

The main goal of such as cyclotron is to furnish protons at the energy of 20 MeV with a maximum extracted current of 100 µA. As mentioned above, the magnetic field is produced by a set of superconducting coils that provides both the isochronous filed and the return flux containment. The azimuthally varying field is provided by 4 sector thin poles placed above and below the median plane as shown in Fig. 1.

The extreme compactness of the machine and the ironless configuration make critical the field design for the confinement and focusing of the beam. Indeed the small thickness of the iron sectors implies a very low flutter value which, together with both the compact size and the related high field gradient, make necessary to use of spiralled sectors. In addition, a set of trim coils is also used to refine the main field. Moreover the relatively high beam current requirement suggests that we should have a good vertical focusing and a reasonable magnet gap to ensure low beam loss.

Taking into account of the above considerations, the main parameters of the machine are set as:

- The magnetic field at center is Bo=3.32 tesla
- The average radius of extraction Rext = 190 mm
- The magnetic gap is 20 mm
- The maximum spiral angle is 80 deg
- The sector width is 45 deg

The SC coils are supported by an aluminum cryostat for weight minimization (see Fig. 3), and these operate at the same current density of 135A/mm$^2$, achieving a peak field of 5.2 T. The total EM energy is estimated to be 1.95MJ.

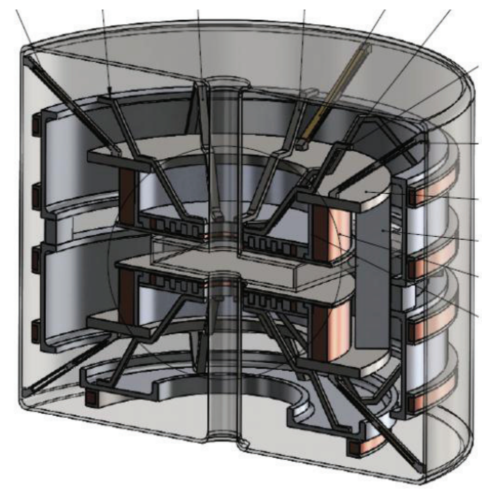

Figure 3: View of the cross section of the magnets and cryostat with coil supports and tension links.

In the ironless configuration all coils and electromagnetic forces are contained within the cryostat. Tension links made of high strength and low thermal conductivity structural material are used to support the cold mass off the outer wall of the cryostat.

The full dimension of the magnetic system is a cylinder with 1 m height and 1.5 m diameter.

## BEAM DYNAMIC STUDY

The beam dynamic analysis has been done by the dedicated code GENSPEO and SPIRALGAP in order to verify both the beam requirements at the equilibrium orbits and the accelerated trajectories.

### *Equilibrium and Accelerated Orbits Analysis*

The equilibrium orbit analysis shows that the magnetic field design provides the necessary beam stability on both transversal planes (Fig. 4) and a good isochronism is reached.

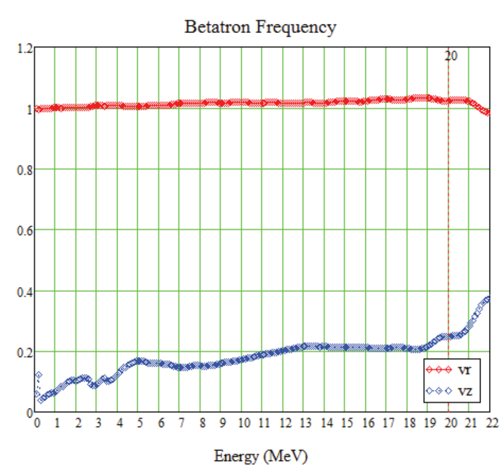


Figure 4: Vertical and horizontal betatron tunes are shown in the plot.


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The same analysis has been done by considering the accelerated particles by means of two spiral electrodes placed into the valleys. The electrodes width is fixed to 30 deg and the applied voltage at 20 kV. The harmonic mode operation is h= 2. It implies an energy gain of 40keV/turn.

In particular in the accelerating mode, it was necessary to set a starting phase offset of 40 deg in order to compensate the large phase excursion at the inner radii due to the de-isochronization necessary for the vertical focusing of the beam.

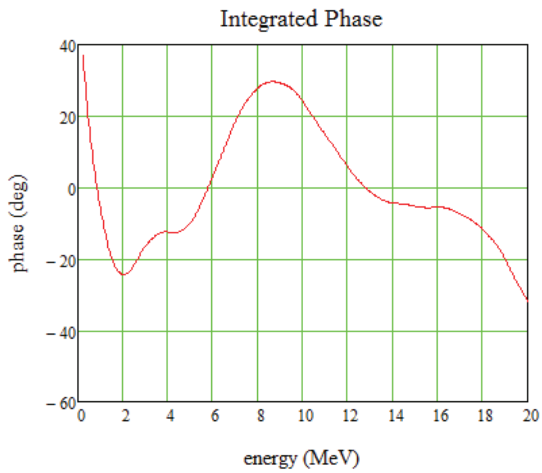


Figure 5: The plot shows the phase excursion of the accelerated reference particle.

Keeping within the narrow range of ±30 deg the phase slip (Fig. 5), the effective energy gain per turn during the most part of acceleration remains at the maximum level. This allows the beam to get the maximum energy in less than 550 turns.

### *Injection and Extraction*

The H- beam is provided by an high current multi-cusp ion source [2] placed externally able to give 15 mA current at 30 kV voltage. The injection beam line follows the standard design [3] in order to optimize the matching with the central region acceptance of the cyclotron.

The study of the central region of such cyclotron has emphasized some critical aspects: the low injection energy (30 keV) and the high value of the magnetic field (3.3 tesla) make challenge the central region design. In fact, the small vertical gap of the inflector and the tight distance between the accelerating electrodes limit the size of the beam injected from the inflector. Moreover, due to the limited focusing effect of the magnetic field in the central region, the vertical dimension of the accepted beam is only few mm, resulting in a limited injected current. The increase of the injection energy up to 60 keV should be decisive for solving different problems of the beam dynamic.

Finally, the extraction of the protons is done by the stripping of the H- ion that permits to minimize the beam losses.

## ACCELERATING CAVITIES LAYOUT

Due to the particular configuration of the cyclotron, the available space to place the accelerating structure is very limited. The main dimensions characterizing the hill/valley-vacuum chamber complex are an hill gap size of 20 mm, the valley depth of 30 mm (half gap) and a vacuum chamber diameter of 500mm.

Since the valley gap is very tight, the so-called stems which give the impedance contribute to the resonator design will be connected to the outer radius of the dees and will extend radially and not vertically. About the cavity layout we consider two options:

- Two 90 deg straight dees
- Two 30 deg spiralled dees

The first allows to operate in harmonic mode 2 and 10 kV voltage applied to get 40 keV/turn energy gain. The drawback is the high capacitance (370 pF) due to the very tight distance between electrodes and hill surface. On the other hand the spiralled shape allows to decrease substantially the total electrical capacitance (70 pF) but it needs to apply double voltage to achieve the suitable energy gain. The RF system study has to be accomplished out in order to evaluate the best solution to be adopted in terms of RF power needed and high voltage performance.

## CONCLUSIONS

In this paper we have presented a new concept design for a low energy and high current compact cyclotron for protons based on superconducting coils. In order to make extremely compact the machine, magnetic fields higher than 3 T have been considered for confining H- ion. It has been demonstrated that by means of high vacuum conditions and high values of energy gain per turn, it is possible to keep within 10% the beam losses due to the Lorentz stripping. It allows to achieve the current value of 100μA of extracted beam by using both an external ion source and the stripping extraction. The ironless magnet configuration has also been presented: it consists of a set of superconducting coils providing the main field, while both the azimuthal variation and the vertical focusing are done by small spiralled sectors. In addition the SC coils are used to magnetically shield the device eliminating the need for a ferromagnetic return yoke, resulting in a drastic reduction of total weight down to 2 tons.

## REFERENCES

[1] Stinson et al. NIM 74 333 (1969).
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[3] T. Kuo et al, Proc. of 15th ICCA, Caen, France 1998, p381