# A SUPERCONDUCTING RING CYCLOTRON TO SEARCH FOR CP VIOLATION IN THE NEUTRINO SECTOR

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*Abstract*

Multi Megawatt accelerators are today requested for different use. In particular the experiment DAEδALUS, recently proposed by MIT scientist to search for CP violation in the neutrino sector, needs three accelerators with energy of about 800 MeVand average power of some MW and duty cycle of 20%. To reduce the cost of the accelerators a cyclotron complex consisting of an injector and of a booster ring cyclotron has been proposed.

The booster Superconducting Ring Cyclotron, able to accelerate $H_2^+$ molecule beam up to 800 MeV/amu and average power of 2 MW, is described. Although the average power is 2 MW, due to the duty cycle, the peak power will be 10 MW. The main advantages to accelerate $H_2^+$ are the reduction of space charge effects, the simple extraction process by stripper, the extraction of two beams at the same time from each booster cyclotron, which increase the beam life of the strippers. The main features of the magnetic sector, of the superconducting coils and the magnetic forces are evaluated with the code TOSCA. A solution to balance the high forces involved is presented. The state-of-art of the study of RF cavities, extraction system and beam dynamics are presented, too.

## INTRODUCTION

The experiment DAEδALUS (Decay At rest Experiment for $\delta_{cp}$ At Laboratory for Underground Science), to search for CP violation in the neutrino sector, has recently proposed [1,2]. This experiment needs three neutrino sources, produced by proton beams with energy of about 800 MeV, the neutrino flux will be detected by a large underground detector. The three sites are located at 1.5, 8 and 20 km far from the detector. Each site has to be driven with a proton beam power of 1, 2 and 5 MW respectively. A further constraints requested to the accelerators is to operate with a duty cycle of 20%, typically 100 ms. beam on, 400 ms. beam off properly synchronised. Due to this duty cycle the peak power is 5 time higher than the average power. Accelerator complex consisting of two cyclotrons, one injector cyclotron and a main ring cyclotron booster, have already proposed as drivers for energy amplifier or waste transmutation plants [3]. According to our proposal [4,5], a Superconducting Ring Cyclotron (SRC) able to accelerate a beam of $H_2^+$ up to 800 MeV/n with a peak current of 6 mA of $H_2^+$, peak power 10 MW, average power 2 MW, is here presented. The cyclotron to be used as injector of the present SRC is presented also at this conference [6].

The acceleration of $H_2^+$ molecule allows extracting the beam by insertion of a thin carbon foil at the radius where the beam reaches the maximum energy. The stripper foil breaks the $H_2^+$ molecule and produces two free protons. The stripper extraction is easier and more efficient respect to the extraction by electrostatic deflector, this helps in reducing constraints and costs on the RF cavities. The energy spread produced by space charge effect due to the longitudinal size of the beam is not serious in this kind of accelerator, and flattopping cavities are unnecessary.

The Fig.1 shows the proposed Superconducting Ring Cyclotron (SRC) layout, the injection and extraction trajectory with their magnetic and electrostatic channels, and the Rf cavities. The main parameters of the SRC are presented in Table.1

Looking at Fig. 1, it is evident that the most critical part is the inner region which is mainly filled by the RF cavities protrusion. The insertion of two double gap cavities is proposed mainly to increase the inter turns separation at the injection and to reduce beam losses due to the interaction of the $H_2^+$ beam with the residual gases.

## THE MAGNET SECTOR

The isochronous field is produced by 8 magnet sectors; each sector is powered by a couple of superconducting coils. The coils shape is shown in Fig. 2. Each coil is NbTi made. The coils do not stay on a plane but they are tilted as shown in Fig.2. The first part of the coils, from R=1.6 m up to R=2.6 m, is parallel to the median plane. In the range R=2.6 to 5.4 m the coils are tilted with an angle of about 6° respect to the median plane. The minimum and maximum distances between the coils are

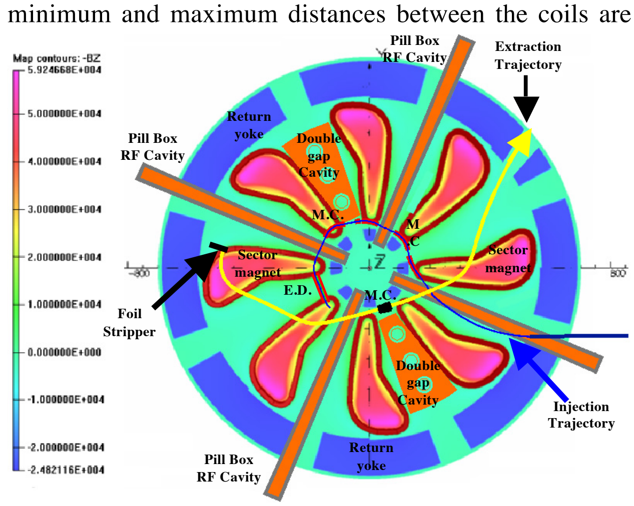


Figure 1: Layout of the Superconducting Ring Cyclotron. The injection and extraction trajectory, with their magnetic channels (M.C.) and the electrostatic deflector (E.D.) for the injection are also shown.

Table 1: Main Parameters of the Proposed SRC

| | | | |
|---|---|---|---|
| $E_{max}$ | 800 MeV/n | $E_{inj}$ | 50 MeV/n |
| $R_{ext}$ | 4.90 m | $R_{inj}$ | 1.9 m |
| <B> at $R_{ext.}$ | 1.86 T | <B> at $R_{in}$ | 1.04 T |
| Bmax | <5.9 T | Flutter | 1.1÷1.8 |
| Outer radius | ≤7 m | Pole gap | 80 mm |
| N. Sectors | 8 | N. Cavities | 6 |
| Sector height | 5.6 m | Sector weight | < 480 tons |
| 4 Cavities | Single gap | 2 Cavities λ/2 | Double gap |
| <ΔE/turn> | 3.6 MeV | Number of turn | 380 |
| ΔR/turn at $R_{ext}$ | 5 mm | ΔR/turn at $R_{inj}$ | > 10 mm |
| Coil size | 15 x 30 $cm^2$ | Icoil | 5000 A/$cm^2$ |

70 cm and 10 cm at radii 2.6 and 5.4 m respectively. This solution is useful to produce higher field at outer radii and lower field at the inner radii. The large distance of the coil, at the inner radii, allows to have more room for the insertion of RF cavities and for the injection devices. The goals of our optimization process are:

- To achieve an isochronous magnetic field for the beam acceleration with good focusing properties;
- To leave enough room in the valley between the sectors to install the RF cavities;
- To minimize the volume of the Ring cyclotron to reduce the construction cost and the magnetic forces;
- A low gradient field in the valley area to allow the crossing of the injected beam without strong focusing/defocusing effects.

For sake of simplicity we divided each coil in four parts, the inner arc, the quasi straight section right side of the coil, outer arc of the coil, and the left side of the coil with a concave shape, see fig 2. This shape is not usual for the superconducting coil because the coil winding is more difficult.

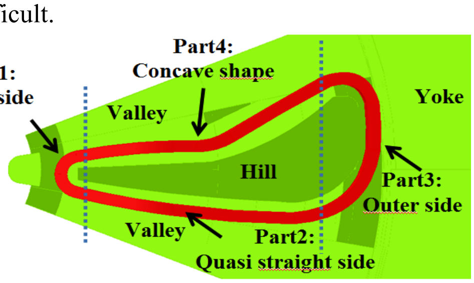


Figure 2: Upper view of a cyclotron sector, with the hill and superconducting coils.

The components of the forces are along the axis x, y and z of a canonical frame system with origin in the median plane and at centre of cyclotron. The x axis is direct perpendicular at the outer part of the coil. The z axis is perpendicular at cyclotron median plane. The strong magnetic forces which act on the two radial sides of the coils have opposite direction. To balance these forces and to reinforce the structure of the Liquid Helium [LHe] vessel we use a connecting plate (2.2 m long and 9 cm thick) to join together the parts 2 and 4 of the coil. This solution has already been used in the Riken superconducting ring cyclotron [7]. The connecting plate will be part of the LHe vessel. To have a robust LHe vessel a thickness of 4 cm for the inner wall and for the plate near the median plane is assumed, while for the outer wall and plate far from the median plane a thickness of 7 cm is fixed. This structure is enough strong to support also the vertical attractive force between the pair of coils. The LHe vessels of the upper and lower coils will be connected across the inner and outer part of the coil to sustain the huge vertical attractive force. The average pressure on these parts will be less than 13 $N/mm^2$.

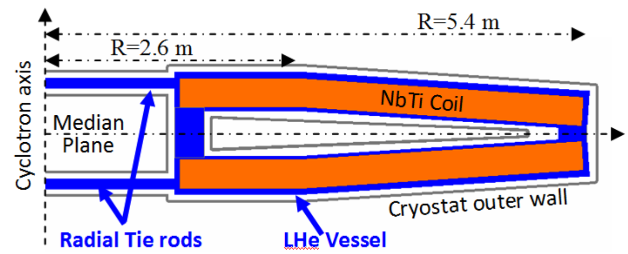


Figure 3: Vertical cross section of a couple of superconducting coils. The pair of radial Tie rods is connected to the 180° symmetric coil to balance the large radial force.

To minimize the magnetic forces the shape of the hill, pole and yoke has been changed since our previous paper [5]. The obtained values for Fx and Fy are still high. We succeeded in lowing them by 30% and we are confident that this percentage will increase as well as the optimization process advances. We expect that this process will not be enough to bring Fx to value below 500 kN and for that we are investigating a solution like Riken SRC [7]. An alternative solution could be to connect each pair of coil of one sector with the coil pair of the opposite sector placed at 180°. Each pair of coils is pushed out, connecting two opposite pairs through a couple of Tie rods, the force is counterbalanced. These Tie rods and their insulation cryostat are far enough from the median plane to not compromise the installation of the devices for beam injection.

Besides that and the reduction of the forces, the new shape of the coil helps in achieving the strong variation of the field vs. radius, from 3 T, at injection radii, to about 6 T at outer radii of the pole. The modulation of the angular width of the iron pole is not enough to produce the request variation. For this reason the coils had been tilted. Moreover, the hill and the coil have now a more spiralled shape than in the previous design just to achieve a stronger vertical focusing. According to the recent simulation, the νz is now ever larger than 0.6, see Fig. 4.

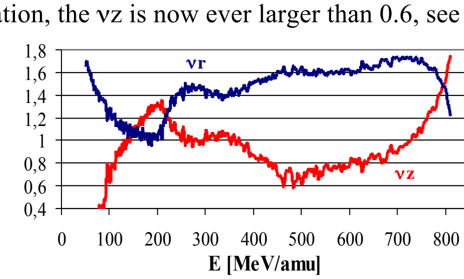


Figure 4: Radial and axial focusing frequencies vs. energy

## RF CAVITIES

The most efficient cavities for cyclotrons are the single gap cavities developed at PSI. These pillbox cavities are able to produce a high electric field on the accelerating gap up to 1 MV, but the drawback of these cavities is that they need extra space both at the inner radii and at the outer radii as shown in the layout of Fig.1. Unfortunately it is not practical to install more than four single-gap RF cavities in an 8-sector cyclotron. For this reason, the RF system of the DAEδALUS SRC consists of 4 RF single gap cavities (like the one developed at PSI) which are able to produce an energy gain of ~4 MeV per turn, plus 2

Table 2: Main Parameters of the RF Cavities

| RF | 49.2 MHz | harmonic | $6^{th}$ |
|---|---|---|---|
| RF parameters | | Single gap Cavity | Double Gap Cavity |
| Q factor | | 29000 | 13500 |
| Power losses | | 450 kW | 250 kW |
| Max Surface Current | | 6 A/cm | 250 A/cm |
| Max Electric field | | 5.5 MV/m | 20 MV/m |
| Voltage at injection | | 450 kV | 200 kV |
| Voltage at extraction | | 1000 kV | 300 kV |

RF double gap cavities (the λ/2 cavities) to increase the maximum beam power by about 20%. The single-gap cavity was designed with two sections along the radius to fit into the valley space, reduced due to the presence of the cryostat. The cavity wall consists of an 8 mm copper sheet on which a large number of cooling channels are directly TIG brazed. The preliminary design of the λ/2 resonator consists of a like triangular stem with a flat Dee. The angular width of the Dee is about 16°, to maximize the energy gain across the two accelerating gap. The height of the stem was fixed to achieve the resonance frequency of about 49.2 MHz, harmonic $6^{th}$ . The shape of the stem was adjusted to achieve an accelerating voltage that ranges from 200 kV at the injection radii to 300 kV at the extraction radius. The estimated thermal losses are 250 kW per cavity, and we expect a significant reduction of this value after the optimization process of the Dee and stem shapes.

## BEAM DYNAMIC

The iron of the hill was shaped to match the required ideal isochronous field with an accuracy of ±1%.

Although this value is not enough to guarantee the acceleration of the beam, we verified that the further small corrections on the magnetic field, to achieve isochronisms with accuracy of about $10^{-4}$, do not change significantly the focusing properties of the field. A serious effort is necessary to maintain the νz higher than 0.6. In Fig.4 both the νz and νr vs. energy are presented.

Unfortunately the crossing of the Walkinshaw resonance νr=2νz produces a significant grow of the beam size. So our next goal is to avoid the crossing of this resonance.

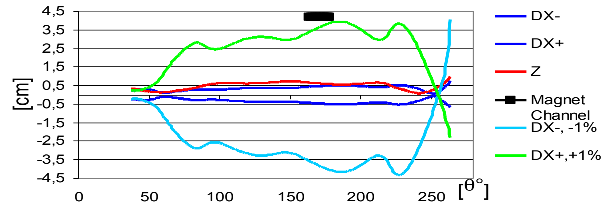


Figure 5: Beam envelope in radial and axial plane along the extraction trajectory. Effects due to the energy spread (±1%) are acceptable.

The beam envelope for the extraction trajectory is presented in Fig. 5. The normalized emittance of the beam envelopes shown in Fig. 5 is 3.35 π mm. mrad. This large value, about 15 times the emittance of the beam delivered by the ion source [8], takes account of non linear effect along the injection, acceleration and extraction from the cyclotron injector and of space charge effects which produce broadening of the beam emittance. Despite the large emittance the beam envelope is quite small in both the radial and axial plane, also if a large energy dispersion is assumed.

## CONCLUSION

The present study shows that an isochronous magnetic field with good focusing property is feasible with the coil configuration here presented. We are working to reduce the current density from 50 to 45 A/mm$^2$, while the maximum field value on the coil is already below 6 T. To have more room for the RF cavities at the inner radii, we are designing a coil with variable shape, 20 x 30 cm at the outer radii and 15 x 40 cm at the inner radii, but with constant cross section. In this way both the current density and the total current are constant. This solution will needs a special winding procedure of the superconducting coil.

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