ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF036

A COMPACT CYCLOTRON FOR 35 MeV PROTONS AND 8 AMeV OF H_2^+

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Abstract

The design characteristics and parameters of a compact cyclotron able to accelerate H^- ions up to an energy of 35 MeV and H_2^+ ions up to an energy of 8 AMeV are presented. This cyclotron is a 4-sector machine and its special feature is the possibility to modify the profiles of the sector hills to allow for the acceleration of the two different species. When equipped with two RF cavities and operated in harmonic mode 4, it accelerates the H-beam, which is extracted by stripping. The resulting proton beam is used for the commercial goal of radioisotope production. On the other hand, when equipped with four RF cavities, also operated in harmonic mode 4, it accelerates a high intensity H_2^+ beam that is of interest for the IsoDAR* experiment. Here, the presented cyclotron takes on the role of a prototype for the central region design of the final IsoDAR* cyclotron (60 A MeV H_2^+). By increasing the number of cavities, the energy gain per turn as well as the vertical focusing along the first orbit are increased, thereby optimizing the acceptance. Moreover, to minimize space-charge effects, the injection energy of H_2^+ is raised to 70 keV compared to the H- injection energy of 40 keV.

INTRODUCTION

A Memorandum of Understanding established a partnership between Best Theratronics Ltd. and LNS-INFN to develop a new high-power machine for proton and H_2^+. The study of this machine is based on the design of the central part of a bigger cyclotron studied for the DAEδALUS and IsoDAR experiments, respectively investigating the CP-violation and the existence of sterile neutrinos [1,2,3].

The primary goal of the project is the production of 1 mA proton beam at 35 MeV with cyclotron. The cyclotron here described and labelled B35P, accelerates H^- ions, which are extracted by stripping to deliver the proton beam. An additional feature of the cyclotron presented is the capability to accelerate ions with q/A=0.5 (H_2^+ hydrogen ionized molecule, deuteron and He^{++}) up to the maximum energy of 8 AMeV.

This feature is worth investigating, especially because one of the goals of the agreement is to check experimentally the acceleration of H_2^+ beams with currents up to 5mA. This feature is also of interest of Best Theratronics Ltd. because fine adjustments of the cyclotron central field and/or of the pole shims, allows the acceleration of He^{++} beams up to a maximum energy of 32 MeV (8 MeV/amu) and or deuteron beams up to 16 MeV.

The present magnetic circuit of the cyclotron is an evolution of the previous design presented at the Cyclotrons2014 [3]. The main differences are:

- the hill gap has been reduced to 5.4 cm from 6 cm;
- the maximum energy of H^- that has been increased from 28 MeV to 35 MeV;
- The iron size that was increased too;
- the coil sizes and the current to feed them have been optimized to reduce significantly the power consumption, which now is 7 kW;
- The stray field was significantly reduced to less than 20 Gauss on the cyclotron axis at a distance of 1.5 m from median plane, that is the position where the H^- source will be installed.

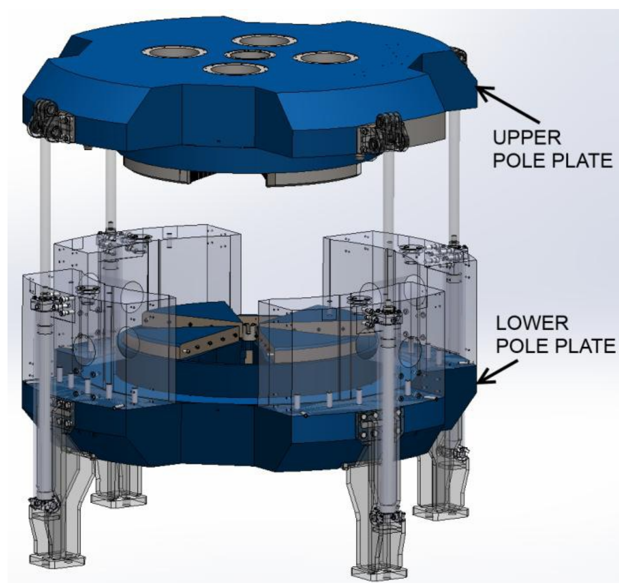

Figure 1: B35P layout.

These advantages have been achieved reducing the valley gap of the cyclotron from the previous value of 1400 mm to the present value of 1000 mm. The main change in respect to the September 2013 design is that the cyclotron here discussed is not a true dual machine for proton and H_2^+. That means, it is mandatory to open the cyclotron to switch from the proton operation mode to the H_2^+ mode.

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IRON CONFIGURATION

The cyclotron has been optimized to accelerate H_2^+ (D, He^{++}) and H^-. To switch from one configuration to the other, the ion source, the shims of the hills, the RF cavities and the central region have to be replaced. Indeed:

- The ion sources to produce H_2^+ and H^- are different. The He^{++} source is different from both the previous ones, too. The installation of two or more ion sources prevents to put the ion sources in the axial direction, which could lead to a more complex and less efficient injection line.
- The central regions to accelerate high intensity H_2^+ and H^- beams are very different, because the injection energies are very different. To use a single central region, the injection energies of the heavier ions should be significantly lower than the injection energy of H^- and the injection efficiency for the other ions with q/A=0.5 should be lower too.

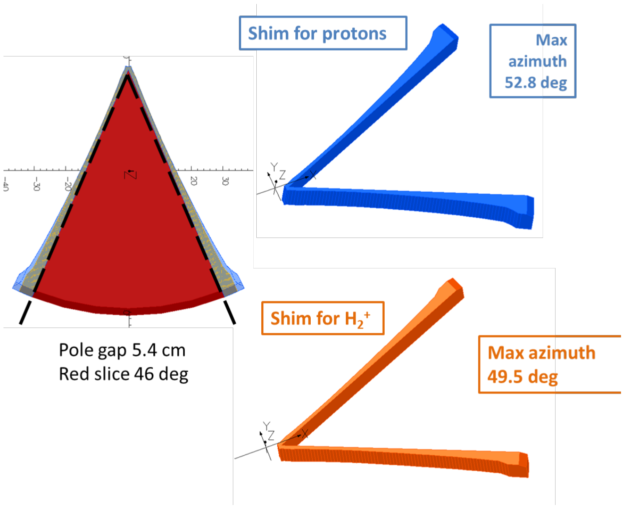

Figure 2: View of the tip of the hill and the two iron shims to adjust the field to be isochronous with H^- or H_2^+ respectively.

- To achieve the twofold goal of producing the 35 MeV proton beam and 8 MeV/amu of H_2^+ beam, the magnetic field has to be slightly changed. This can be easily obtained adding specific iron shims at the boundary of the hills. See Figure 2;
- The RF frequency could be the same for the two configurations and it could be the same even for the q/A=0.5 case, but in this perspective the harmonic number should vary for the two cases. In particular, for the proton beam the 2nd harmonic should be necessary, while the 4th harmonic mode has to be used when H_2^+ or He^{++} are accelerated. The use of the 2nd harmonic is not convenient for many reasons in an H^- commercial cyclotron, so for the present design beams are always accelerated in 4th harmonic. That means that different RF frequencies and different cavities are requested to accelerate H^- and H_2^+;
- 2 RF cavities are enough to accelerate the H^- beam up to 35 MeV. However, 4 RF cavities will be mandatory to perform the acceleration test of H_2^+ with beam current of 5 mA. Indeed, for this test we need a faster acceleration to reduce the beam size growth due to the space-charge effects and to check the true central region for the IsoDAR and DAEdALUS cyclotrons.
- The stripper extraction is the selected solution to get the proton beam out from the cyclotron, see Fig. 4. An electrostatic deflector is mandatory in the case of H_2^+ and He^{++} , D^+ extraction.

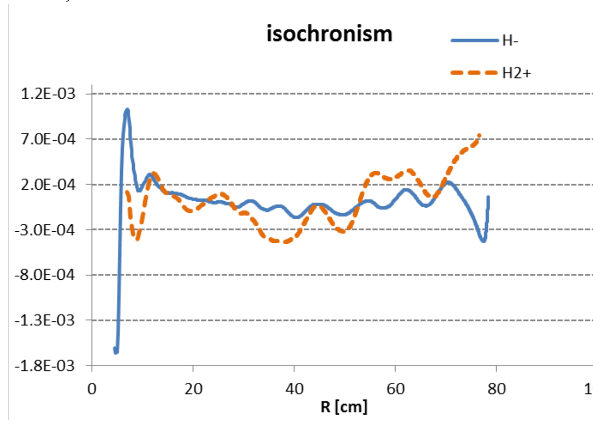

Figure 3: Ratio between the average field and the ideal isochronous field for H_2^+ and H^- vs.R. The R values are not the average radius but the orbit radius at centre of the hill.

SIMULATION DATA

The maximum difference between the average magnetic isochronous field for H_2^+ or H^- is 3%, this is due to the mass increase related to the relativistic effects. The expected Opera error is <0.3% everywhere on the median plan, so we believe our simulation are reliable. The ratio between the ideal isochronous field and the simulated magnetic field vs. radius for the H^- and H_2^+ acceleration are shown in Figure 3. In both cases, the magnetic field is isochronous within accuracy better than 0.05% along the whole acceleration path. The corresponding phase slip, respectively for H^- and H_2^+, stays inside +/- 6 deg. The behavior of ν_r e ν_z along all acceleration are perfectly acceptable too.

It is unnecessary to achieve better isochronous fields considering the indetermination of the OPERA code. To optimize the isochronous fields the thickness of the borders of the hills is shimmed as shown in Figure 2. Two different sets of shimming are used, one for proton (blue in Fig.2) and another for H2+ (orange). Only the top side of the hill boundary, over a height of 10.1 cm, has to be shimmed. The red part of the hill represents the unchanged part over these 10.1 cm height.

Table 1 summarizes the main B35P parameters.

EXTRACTION

The extraction studies have been performed using the magnetic field map produced by OPERA code. The used map extends:

- from R= 1 to R=180 cm and step of 1 cm ;

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- from teta=0° to teta=90° and step of 0.5° and symmetry 4. We evaluated the extraction trajectories and the beam envelope for the proton beam at three energies, 15, 25 and 35 MeV. The stripper positions for these 3 trajectories are:
- 15 MeV, R=508.1 mm, teta= 11° 30';
- 25 MeV, R=650.4 mm, teta= 11° 55';
- 35 MeV, R=762.17 mm, teta= 12° 30';

The cross over point of the three trajectories is at R=1699 mm and at teta= 58° 20', see Figure 4.

Table 1: Main Parameters of B35P

Common parameters			
N. Sectors	4	B_0	0.982 [T]
R axial hole	28.8 mm	R pole	830 mm
Valley gap	1000 [mm]	Pole gap	54 [mm]
Diameter	3000 [mm]	Full height	1500 [mm]
Iron weight	48.3 [tons]	Vacuum	10-5 Pa
Cavities λ/2	Double gap	Voltage	60 [kV]
Coil size	230x200 [mm^2]	Current	<1.04 A/mm^2
Parameters for ions with q/A=0.5, H2+			
E_{inj}	70 [keV]	E_{max}	8 [MeV/amu]
Hill width	H2+→ 26.5°÷51.4°	Bmax	1.709 [T]
harmonic	4th	Freq.	33.6 [MHz]
Parameters for proton beam q/A=1			
E_{inj}	40 [keV]	E_{max}	35 [MeV]
Hill width	H-→ 27.5°÷54.8°	Bmax	1.725 [T]
harmonic	4th	Freq.	67.2 [MHz]

The beam envelope was evaluated assuming a normalized beam emittance of 2π mm.mrad. The expected full beam sizes at the stripper position at the energies 15, 25 and 35 MeV are in the range 6÷4.5 mm and 7÷6 mm in radial and axial directions respectively. The beam sizes at the common extraction point are a little bit larger, in the range 15÷12 mm and 9÷7 mm in radial and axial directions respectively.

The beam envelope along the extraction trajectories have been evaluated using the computer code EXTRAZ developed at MSU and used in Catania and Milan to simulate the beam dynamic of the superconducting cyclotron. An excellent agreement between the results of this code and the integration trajectories achieved by the OPERA code has been already achieved.

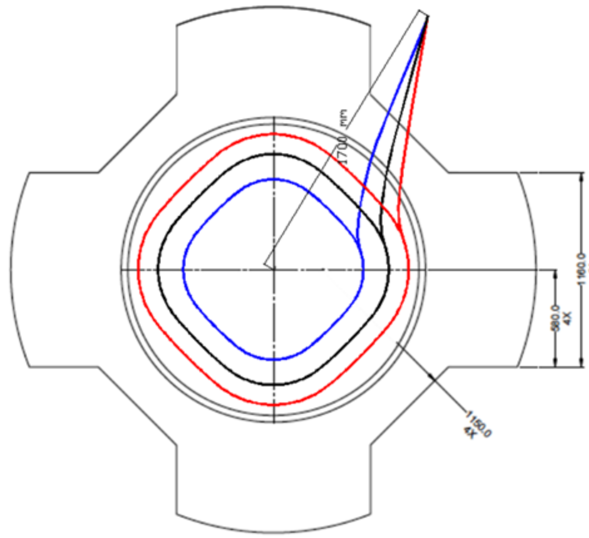

Figure 4: Equilibrium orbits and extraction trajectories for three proton beams at energies 15, 25 and 35 MeV respectively

CONCLUSION

Computer modelling of the B35P cyclotron able to accelerate H_2^+ and H^- beams has been performed. This cyclotron responds to a specific research request as well as commercial interests. A detailed explanation on how the same cyclotron can be used in these different scenarios has been given. Possible upgrades have been described too.

The design is the result of a balance between the requests of the IsoDAR project and the needs of the Best Theratronics Ltd. engineering to achieve a performing commercial cyclotron for protons All the results regarding the design such as the machine parameters, the simulation data, the beam dynamics, the vacuum and extraction study have been reported.

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