A LOW ENERGY CYCLOTRON INJECTOR FOR DAEDALUS EXPERIMENT

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Abstract

Multi Megawatt accelerators are today requested for different use. In particular the experiment DAEδALUS, recently proposed by MIT scientists to search for CP violation in the neutrino sector, needs three accelerators with energy of about 800 MeV, 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 main characteristics of the cyclotron injector able to accelerate a H_2^+ molecule beam up to 50 MeV/n is here presented. Due to the low duty cycle, the peak current is 6 mA. The problem related to the injection of a H_2^+ beam, delivered by a compact ion source, and to the space charge effects are shortly discussed. The main parameters of the magnet, RF cavities, the isochronous magnetic field and the beam dynamics along the acceleration and extraction path are presented.

INTRODUCTION

A new experiment called DAEδALUS (Decay At rest Experiment for δ_{cp} At Laboratory for Underground Science) to search for CP violation in the neutrino sector [1,2] has recently proposed. This experiment needs three neutrino sources produced by a proton beam with energy of about 800 MeV and average power of about 2 MW. According to the request of the experiment, the accelerators have to operate with a duty cycle of 20%, typically 100 ms beam on, 400 ms beam off. Due to this duty cycle, the peak power is 5 time higher than the average power. An accelerator complex consisting of two cyclotrons, one injector cyclotron and a superconducting ring cyclotron booster, has already proposed [3,4]. According to this proposal, the injector cyclotron, here described, is used to accelerate a peak current of about 6.2 mA of H_2^+ up to 50 MeV/amu. The beam extracted by an electrostatic deflector is then injected into a superconducting ring cyclotron which accelerates the H_2^+ beam up to 800 MeV/n, with peak power 10 MW and average power 2 MW.

The preliminary layout of the injector cyclotron is shown in Fig. 1. The extraction trajectory is also shown.

The reasons which lead us to choose the molecular beam H_2^+ to produce a final proton beam are:

- reducing the space charge effects;
- reducing the beam losses due to the extraction process using stripper foils.

The first problem is very serious at low energy and for the injector cyclotron. While the second is serious at higher energy, since at the extraction radius of the superconducting ring cyclotron it is difficult to have a good beam turn separation. For these reasons the beam extraction from the injector cyclotron will be performed by classical electrostatic deflector. Indeed the average beam power is of about 125 kW while the inter turns separation is of 14 mm and could be increased up to 20 mm, using the first harmonic precession method. The beam is then injected into an 8 sectors superconducting cyclotron ring. One or two stripper foils are then used to extract the proton beam from the ring cyclotron.

SPACE CHARGE EFFECTS

In this section we underline the different weight of the space charge effects for H_2^+ vs. proton beam. The space charge effects are serious for proton beam with current higher than 1 mA and mainly at low energy. The high charge density inside the beam bunches produces a repulsive force which generate detuning. To evaluate the strength of this effect the parameter called "generalized perveance" has been introduced [5] and it is defined by the following formula:

$$K = \frac{qI}{2 \cdot \pi \cdot \varepsilon_o \cdot m \cdot \gamma^3 \beta^3} \qquad [1]$$

Where: q, I, m, γ and β are respectively the charge, current, mass and the relativistic parameters of the particle beam. From formula [1] it is quite evident that proton beam has a perveance double as compared to the H_2^+ beam when the two particles have the same speed and the same current. But this is not a correct comparison. Indeed if protons and H_2^+ are accelerated by the same

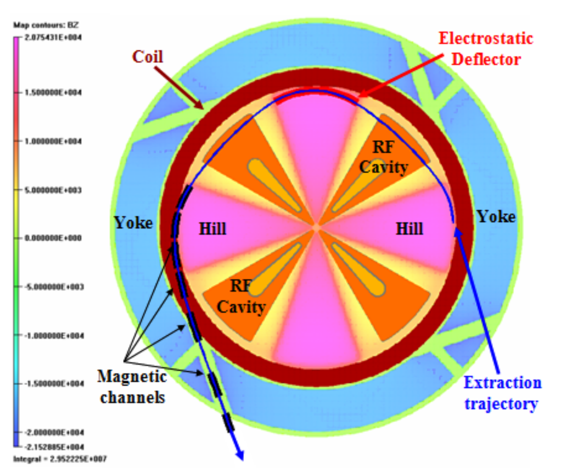

Figure 1: Layout or Patch of Cyclotron magnetic field. The extraction trajectory, with the magnetic channels, the electrostatic deflector and RF Cavities are also shown.

Table 1: Perveance Values of Proton and H_2^+ Beams at Different Currents and Energies

	$E_p=E_{H2}$ 30 keV	$E_p=E_{H2}$ 800 MeV	E_p=30 keV E_{H2}=70 keV
H_2^+, I=5 mA	0.881 10^{-3}	0.151 10^{-9}	0.247 10^{-3}
P, I=10 mA	1.245 10^{-3}	1.075 10^{-9}	1.245 10^{-3}
K_{H2}/K_p	0.707	0.141	0.198
P, I=2 mA	2.491 10^{-4}	2.15 10^{-10}	2.491 10^{-4}
K_{H2}/K_p	3.537	0.703	0.992

electric field, they have the same energy but not the same speed. On the other hand a beam of H_2^+ delivers a number of protons which is double as compared to a proton beam with the same current. So the right comparison has to be made for beam that produce the same proton current but which have the same total energy.

Table 1 compares the perveance of H_2^+ and proton beams with a current of 5 mA and 10 mA, respectively, at the same and at different energies. The ratio of perveance values shows that, with respect to the space charge effects, accelerating a H_2^+ beam is less difficult than accelerating a proton beam with double the current. This advantage increases with higher beam energy. The last two rows of Table 1 show the perveance values of a proton beam with a current of 2 mA and the ratio vs. the perveance of a H_2^+ beam with 5 mA. Although the perveance of the 2 mA proton beam is lower than the same-energy H_2^+ beam (30 keV), if the energy of the H_2^+ beam is increased up to 70 keV, then the H_2^+ beam has the same perveance of the proton beam at 30 keV. Therefore a H_2^+ beam with energy of 70 keV and with current of 5 mA suffers the same space charge effects as a proton beam with energy of 30 keV and 2 mA.

INJECTOR CYCLOTRON

The injector II of the PSI and the commercial compact cyclotron designed by EBCO, IBA and SHI companies are able to deliver more than 1.5 mA of proton beam. The injector II of PSI is a conservative solution which is able to supply up to 3 mA of proton beam. Despite low injection (25-30 keV) voltage and moderate energy gain per turn (<200 keV/turn), the compact commercial cyclotrons are able to accelerate proton beams with current up to 1.5-2.2 mA [6].

For the reasons presented in the previous section, we propose a design which is a mixing between the PSI injector II and the compact commercial cyclotron. The central region of the proposed injector will be similar to the central region of the commercial cyclotron but with larger size, the study is yet in progress. To take account of the higher magnetic rigidity and to maintain the perveance of the H_2^+ beam similar to the perveance of the proton beam accelerated by the commercial cyclotron, both the energy of injection and the energy gain per turn are doubled. Moreover, the energy gain per turn increases along the radius up to the value of 1.8 MeV/turn at the extraction radius. This value is higher than the energy gain per turn in the PSI injector II to compensate both for the smaller extraction radius and for the higher magnetic rigidity. According to our simulation, the turn separation at extraction radius is 14 mm. This value could be increased using the so called first harmonic precession method, thus a turn separation of about 18-20 mm could be achieved. This turn separation, according to the experience of PSI injector II, allows to reduce the beam losses at less than 0.2%. So, for a delivered average beam power of 125 kW beam losses at the extraction should be lower than 200 W.

Table 2: Main Parameters of the Injector Cyclotron

E_{max}	50 MeV/n	E_{inj}	35 keV/n
$<R_{ext}>$	1.81 m	R_{inj}	55 mm
<B> at $R_{ext.}$	1.15 T	<B> at R_{in}	0.97 T
N. Sectors	4	Hill width	36°
Valley gap	1800 mm	Pole gap	100 mm
Diameter	5.7 m	Full height	2.7 m
N. Cavities	4	Cavities λ/2	Double gap
harmonic	6th	RF frequency	49.2 MHz
Acc. Voltage	70÷240 kV	Power/cavity	<110 kW
<ΔE/turn>	1.3 MeV	Number of turns	95
ΔR/turn at R_{ext}	>14 mm	ΔR/turn at R_{inj}	>56 mm
Coil size	200x250 mm^2	Current density	3 A/mm^2

The main parameters of the injector cyclotron are presented in table 1.

In Fig. 2 the design of 1/8 of the cyclotron magnet is presented. The magnet was simulated using the computer code TOSCA and the magnetic field on the median plane, produced by the simulation, is shown in Fig. 1. The estimated full weight of the cyclotron is about 410 Tons. The hills of the pole are practically straight and have a maximum width of about 36°. The central hole for the beam injection is generally 140 mm in diameter except the latest 200 mm near the median plane where it is 70 mm. The isochronous magnetic field was achieved by a smooth adjustment of the angular hill width vs. radius. Despite the design of the magnet is not yet finished, the isochronous field magnet, calculated using the code GENSPE [7], is satisfactory, see Fig. 3. The evaluated variation of the phase slip of the beam is of about ±9° RF in the acceleration range from 1 to 50 MeV/amu.

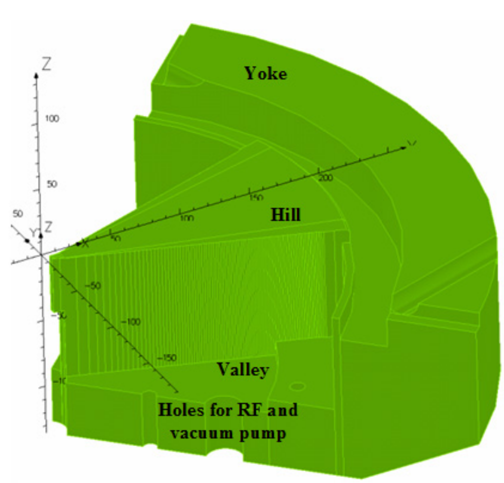

Figure 2: Lower half part of one sector, angular width 90°.

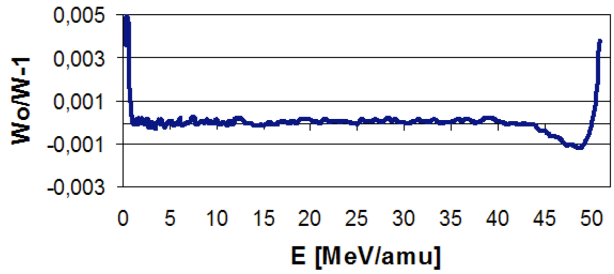

Figure 3: Relative difference between the RF frequency and the revolution frequency of the particles vs. energy.

RF CAVITIES

The four accelerating cavities are placed inside the large valleys of the cyclotron. The preliminary design of the resonator consists of a like triangular stem with a flat Dee, Fig. 1. The angular width of the Dee is 30°, to maximize the energy gain across the two accelerating gap. The height of the stem was fixed to achieve the resonance frequency of about 49.8 MHz, harmonic 6^{th} . The shape of the stem was adjusted to achieve an accelerating voltage of 70 kV at the injection radii and which increase up to the maximum value of 240 kV at the extraction radius, Fig. 4. The estimated thermal losses are 110 kW per cavity, but we expect a significant reduction of this value after the optimization process of Dee and stem shape's.

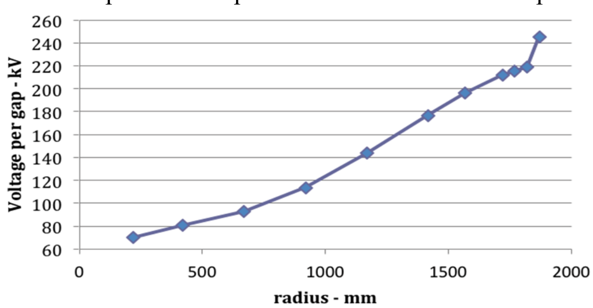

Figure 4: Effective voltage across each gap of the cavities.

BEAM DYNAMIC AND EXTRACTION

The path of the beam acceleration in the working diagram νz vs. νr shows that the two resonances νz=0.5 and νr=2νz are crossed at low energy while the other two resonances, νr=1 and νz=1 are crossed at the highest energies. The acceleration simulations, using the voltage acceleration profile of Fig. 4, show a regular beam envelope.

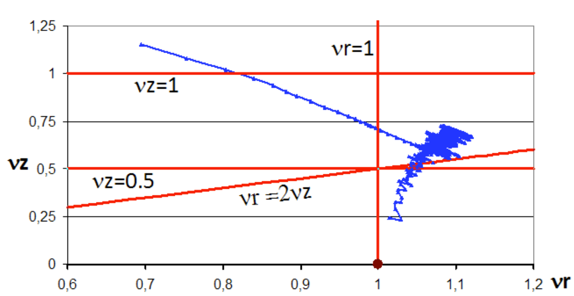

Figure 5: Axial focusing frequencies vs. Radial focusing (blue line), the main resonances are also shown.

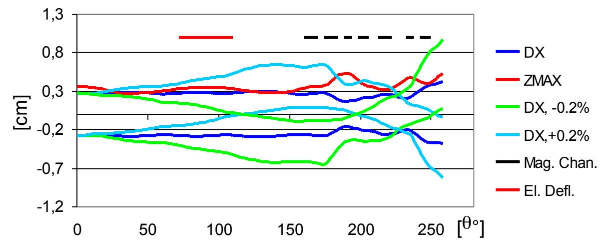

Figure 6: Beam envelope in radial (blue line) and axial plane (red line) along the extraction trajectory. Larger beam envelope, due to the energy spread (±0.2% green and cyclamen lines) is acceptable.

The extraction trajectory shown in Fig. 1, was achieved simulating an electrostatic deflector, placed in a hill, with an electric field of 35 kV/cm. The beam envelopes for the extraction trajectories are presented in Fig. 6. For all the beam simulations we assume a normalized emittance of 2.0 π mm. mrad. This value, about 10 times the beam emittance of the ion source [8], takes account of non linear effects along the inflector injection and due to space charge effects which produce a broadening of the beam emittance. The beam envelope is quite small in both the radial and axial plane. Also the energy dispersion along the extraction path is acceptable.

CONCLUSION

The present preliminary study demonstrates that a compact cyclotron able to accelerate H_2^+ beam up to an energy of 50 MeV/amu and average beam current of about 6 mA is feasible. The future studies will be addressed to the design a central region and to simulate the charge effects on the beam dynamic.

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