HIGH INTENSITY PROTON BEAMS FROM CYCLOTRONS FOR H_2^+

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Abstract

To deliver high intensity proton beams it is proposed to accelerate H_2^+ by cyclotrons and to use the stripping method to extract the beam. The high binding energy of the H_2^+ molecule allows to use very high magnetic fields produced by superconducting magnets even at energies as high as 1 GeV/n. High beam currents are achievable with these cyclotrons as extrapolated from the experimental results obtained by H^- cyclotrons. The main advantages, i.e. easy operation, high reliability and high conversion efficiency from electrical to beam power are presented.

1 INTRODUCTION

The interest for Accelerators Driven Systems (ADS), to be used for energy amplification or waste transmutation, has stimulated the study of cyclotrons able to deliver proton beams with current higher than 10 mAmp and energy as high as 1 GeV[1,2]. The main constraints required to ADS are: minimum beam losses, high reliability and high conversion efficiency from electrical to beam power. The cyclotron projects proposed as ADS are able to achieve low beam losses during the acceleration and extraction process by using large extraction radii (≥ 6 m) and high accelerating voltages (8 MV/turn). In this paper superconducting cyclotrons, able to accelerate H_2^+, and the related advantages are described. The extraction of the H_2^+ beam is accomplished by a stripper which produces two free protons breaking the molecule. Extraction by stripping does not require well separated turns at the extraction radius and allows to use a low energy gain per turn during the acceleration process, with a significant reduction of thermal power losses for the RF cavities. Extraction by stripping is a very powerful tool to increase the reliability and simplify the operation mode as demonstrated by the success of commercial cyclotrons. The magnetic rigidity of H_2^+ is twice that for protons with the same velocity, neverthless using superconducting magnets it is possible to maintain the size of cyclotrons for H_2^+ at reasonable values. Another important advantage of accelerating H_2^+ is the reduced space charge effect due to the lower q/A ratio as compared with protons, which is expecially advantageous during the early stages of acceleration.

Thereunder the feasibility of extraction by stripping of H_2^+ is demonstrated simulating the extracted trajectories in the measured magnetic field of our K800 compact superconducting cyclotrons (CSC). Moreover a preliminary study on the possible use CSC and/or ring superconducting cyclotron (RSC) to accelerate high beam currents at high energies is presented.

2 EXTRACTION BY STRIPPING

The stripping process has largely been used to extract H^- ions at energies as high as 520 MeV (200 kW) and in many commercial cyclotrons to extract H^- or D^- beams with a beam power up to 40 kW. The small binding energy (0.7 eV) of H^- ions forbids the use of high magnetic fields, which would cause high losses produced by electromagnetic stripping, while the 16.3 eV binding energy of the H_2^+ molecule allows to use a magnetic field as high as 10 T even at energies as high as 1 GeV per nucleon. There are also other differences between the stripping process for H^- and H_2^+. In the first case two electrons have to be removed to extract one proton and the foil has to be thick enough to guarantee stripping efficiency of 100%. If the H_2^+ is not stripped at first cross it turns inside the cyclotron and hits once again the stripper until it is stripped. Then for H_2^+ it is possible to use a stripper with thickness smaller than for H^- and then a longer mean life is expected. Strippers made of pyrolitic graphite are used at TRIUMF to extract the 520 MeV H^- beam. These strippers have a mean life of 3-5 mAh [3]. For a beam current of 5 mA of H_2^+ a mean life of 0.5-1 hour is expected, which is a conservative limit if we consider that thinner foils can be used and that just one electron has to be removed to produce 2 protons. Moreover stripping of H_2^+ produces electrons but while for H^- the electrons are bent towards the centre of the machine and hit the stripper foil after spiraling in the magnetic field, for H_2^+ the electrons are bent towards the outer radius, so an electron catcher can be installed to remove the electrons emerging from the stripper and strongly reduce the stripper damage and increase its life. For RSC at energies of 1 GeV/n, a group of 4 or more thin stripper foils in cascade could be used to further increase more the mean life time. Anyway experimental data in this field are necessary in order to propose a final design.

3 ACCELERATION OF H_2^+

3.1 Compact superconducting cyclotron

To check the feasibility of stripping extraction in compact superconducting Cyclotrons the trajectories of H_2^+ inside our K800 Cyclotron were studied. The simulations show that for an enough large angular range of the stripper position inside the hill the particles escape from the trajectories of H_2^+ inside cyclotron magnetic field in one turn. According to our simulations small variations of the extraction radius have negligible effects on the extraction

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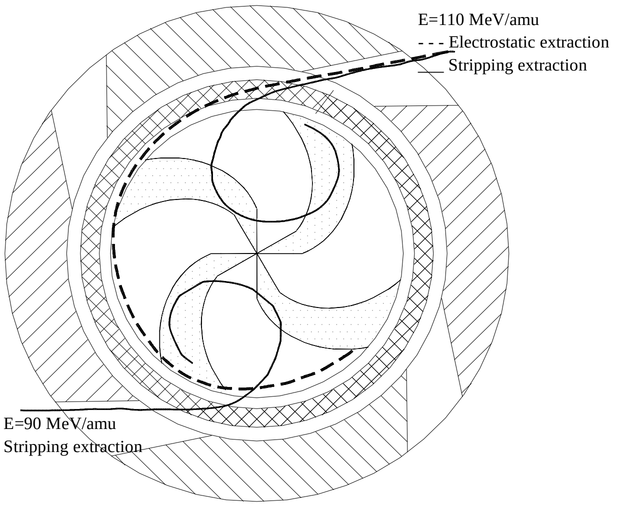

Figure 1: Layout of the 4 sectors CSC. The extraction trajectories for H_2^+ by stripping together with the trajectory for fully stripped ions q/A=0.5 extracted by electrostatic deflectors are shown

trajectory while the azimuth position has a strong effect on the size of the beam envelope. However a position which minimises the beam envelope in both the radial and axial plane along the whole trajectory was found too[4].

According to this evaluation and the positive experience of other laboratories [5] a design for a new CSC based on the design of our existing K800 cyclotron but with a lot of simplifications and some upgrading was started.

This cyclotron has been proposed as primary accelerator to produce radioactive ions beams at LNS[6]. In the framework of our upgrading program the new cyclotron have to accelerate a single kind of particle with q/A=0.5 at a fixed energy. The main simplifications are: single frequency, few trim coils with small size and power, fixed operation mode of the power supplies of the main coil, low liquid helium consumption, larger gap in the median plane and across the cryostat, more accessibility at the median plane.

Recently a design for a 4 sectors 110 MeV/amu CSC has been proposed by Mandrillon [7]. It presents some further advantages, i.e. a higher energy gain per turn and more space for RF cavities and vacuum pumps. This CSC can be used as a first acceleration step of an ADS [2]. In fig. 1 the simulated stripped trajectories for H_2^+ at 110 and 90 MeV/amu are shown. This CSC is also able to accelerate deuterons and fully stripped light ions (q/A=0.5, A≤32) up to the maximum energy. These beams could be extracted, obviously with a reduced power, by two electrostatic deflectors placed inside the valley.

The maximum current delivered by a CSC equipped with extraction by stripper is limited by the central region, due to space charge effects. According to the evaluation accomplished in [8], the TR30 compact cyclotron for H^- is able to accelerate a maximum of 3.3 mA. This experimental intensity limit is due both to the vertical space charge tune shift and to the longitudinal space charge effect. According to these considerations the TR30 compact cyclotron for H^- with a central region scaled up of a factor 1.44 should increase the current upper limit to 10 mAmp.

The beam dynamics features of H_2^+ in a CSC are similar to the case of H^- if the magnetic field, the accelerating voltage, injection energy are properly scaled. So we could extrapolate the space charge effect for the H_2^+ beam from corresponding figures for H^- Cyclotrons.

The intensity limit should be twice higher than the H^- case, as a consequence of the reduced charge to mass ratio q/A=0.5 of the H_2^+ ion. The selected values for the proposed CSC, of 60 keV for injection energy, 500 keV for the energy gain per turn and the 2 T magnetic field at the centre, allow to scale quite well the central region of the TR30. The expected maximum current, extrapolated according to [8] is then of 9 mA of accelerated H_2^+ and of 18 mA of extracted protons. A further significant advantage for injection of H_2^+ could be the higher injection energy and the better emittance and higher currents of H_2^+ sources as compared to the H^- sources.

3.2 A ring superconducting cyclotron

The spiral angle for a compact cyclotron has to be very large to produce enough axial focusing for energies higher than 200 MeV/amu. High energies as 1 GeV are achievable only by Ring Cyclotrons (RSC) which could produce large flutter values and enough axial focusing. A ring cyclotron similar to the PSI proposed cyclotron of 1 GeV [2], the so called “dream machine”, but with magnetic field of 4.3 T instead of 2.1 T, has been investigated to accelerate H_2^+ to 1 GeV/amu. The PSI cyclotron proposal is based on 12 sectors layout and allows for the installation of 8 accelerating cavities, two flattopping cavities, and of the injection and extraction systems. The cyclotron for H_2^+ ions does not need the flattopping cavities, so the number of sectors could be reduced to 10, and it becomes possible to increase the size of the valleys and have enough room to install straight cavities similar to the existing cavities of the PSI Ring.

Preliminary study of this RSC shows that it is very difficult to achieve the required isochronous field using superconducting coils wrapped around the iron pole. More easy, advantageous and elegant is the use of the so called S-coils [9]. These are a pair of superconducting coils wrapped, out of the extraction radius, around the pole/yoke and perpendicularly to the median plane. This solution allows to have free space among the sectors, and the cryostat is now completely in the outer region, without any interference with the cavities and the accelerated beam. Preliminary and approximate evaluations by Poisson were done, while simulations with a 3D code have to be developed to optimise the magnetic design. The installation of a stripper foil system in a valley allows for the beam extraction without electrostatic deflector and with an efficiency of 100%, see fig.2.

A very important parameter for ADS is the conversion efficiency from electrical to beam power. For the so called “dream machine”, the expected conversion efficiency is 44% [2].

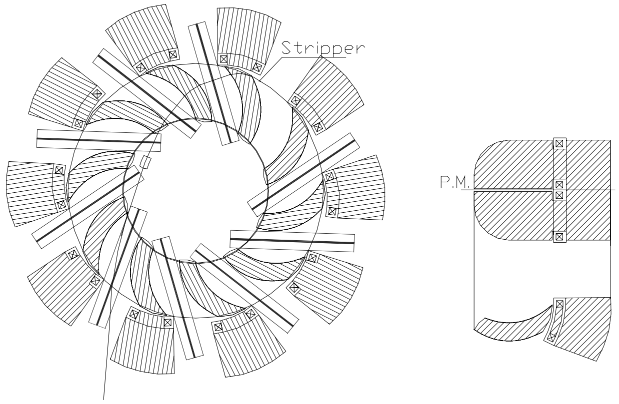

Figure 2: Layout of the 10 sectors RSC for 2 GeV H_2^+

According to the following formula:

$$\varepsilon_{tot} = P_{bt} / [(P_b + P_{loss})/\varepsilon_{ac} + P_{other}]$$

where:
ε_{ac}=75% is the AC/RF optimised conversion efficiency
P_{bt}=10 MW is the total beam power
P_b=9 MW beam power transferred by the Cyclotron
P_{other}= 3.5 MW for injector, pre-injector, magnets etc...
According to the data of PSI the thermal losses for each copper cavity at 750 kV should be 280 kW which gives a P_{loss}= 0.280*8 MW and an overall efficiency for ADS based on the proposed RSC of ε_{tot}=53%.

Table 1: Main parameter of the RSC shown in figure 2

E_f (MeV/n)	1000	$R_{ext.}$	5.5 m	$\langle B_{hill}\rangle$	4.3 T
E_i (MeV/n)	130	$R_{inj.}$	3 m	$\langle B_{val}\rangle$	0.9 T
N. Sectors	10	θ_{hill}	13°	ξ_{spiral}	56°
N. Cavities	8	V_{peack}	750 kV	$f_{cyc.}$	7.7 MHz

4 VACUUM REQUIREMENTS

As well known, due to the interactions with the residual gas, ions could lose the orbital electron along the acceleration path. The fraction of particles which survives is [10]:

$$T = N/N_0 = \exp(-3.35\ 10^{16} \int \sigma_l(E)\ P\ dl\ )$$

$$\sigma_l(E) \approx 4\pi a_0^2\ (v_o/v)^2 (Z_t^2 + Z_t)/Z_i$$

Where: P is the pressure (torr), L is the path length in cm. $\sigma_l(E)$ is the cross section of electron loss, v_0 and a_0 are the velocity and the radius of the orbit of Bohr respectively, and Z_t and Z_i are the atomic number of the residual gas and of the incident ion respectively. This formula gives a result in quite good agreement with experimental data. Anyway it is very important to have some measured values of the cross section for electron stripping of H_2^+ across residual gas. We plan to measure these cross sections next fall when at our laboratory an H_2^+ beam of 70 MeV/amu will be available. As shown in table 3, to maintain the amount of loss during the acceleration at the same level as the TRIUMF Cyclotron, the vacuum has to be 10^{-8} torr, twice better than the vacuum of TRIUMF Cyclotron. The proposed high energy cyclotrons here discussed are more compact and smaller than the TRIUMF one, so to achieve a better vacuum seems feasible. Moreover to reach good values of vacuum is useful to increase the reliability of the RF cavities too.

Table 2: Beam losses due to interactions with residual gas for TRIUMF and for the cyclotrons here considered

	E_{max} MeV	$\Delta E/\Delta n$ MeV	R_{ex} m	I_{lmax} mA	Vac. torr	T %	I_{loss} µA
TRIUMF	520	0.34	7.8	0.4	2 10^{-8}	1.66	6.6
CSC(H_2^+)	220	1	1.3	10	10^{-8}	0.02	2.
RSC(H_2^+)	2000	6	5.5	10	10^{-8}	0.08	8.

5 CONCLUSION

A lot of work has to be done to evaluate the difficulties related to the construction of H_2^+ Cyclotrons to achieve energies as high as 1 GeV, in particular the design of sector magnets able to produce magnetic fields of 4.5 T. However as here presented, now it is possible to construct superconducting cyclotron able to deliver high intensity proton beams with energy of 100-150 MeV. Cyclotrons used as ADS have to guarantee a high level of reliability and easy operation mode independent of the skilness of the operators, as well as high conversion efficiency from electrical to beam power. We believe that all these requirements are achievable by cyclotrons when designed to accelerate H_2^+ ions to be extracted by stripping.

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