SUPERCONDUCTING CYCLOTRONS FOR ACCELERATION OF H_2^+

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The acceleration of H_2^+ allows to extract the beam by breaking of the molecule crossing a stripper. The higher binding energy of the last electron in H_2^+ as compared to H allows the use of magnetic field so high as 10 T even at 1 GeV. The simulations of extraction by stripping from a compact superconducting Cyclotron are presented. The advantages, the current limits and the related technological problems of this alternative method are presented.

1 Introduction

Recent proposals for construction of reactors driven by accelerators, to be used as energy amplifier or waste transmutation, have stimulated the study of an accelerator complex based on Cyclotrons [1]. The main goals to be achieved by these accelerators complex are: energy of 1 GeV and current ≥10 mAmp. It is straightforward to reach these goals increasing the size of the Cyclotron and the energy gain per turn to obtain enough separation among the orbits at extraction radius, the growth of the longitudinal beam size due to the space charge effects it is also reduced. The cascade Cyclotron accelerator complex proposed up to date are a natural upgrading of the PSI accelerator complex [2,3]. In this paper an alternative method based on acceleration of H_2^+ using Cyclotrons and extraction by stripper is proposed. The H_2^+ molecule is broken in two free protons when crosses a stripper. These protons run along an inner circular trajectory with $R \approx R_{ex}/2$ and escape the region of magnetic pole of Cyclotron. The acceleration of H_2^+ molecule has the following advantages:

- beam extraction by stripper
- reduction of space charge effects
- lower voltages on the acceleration electrodes
- use of high magnetic field possible

The stripping process is normally used by some Cyclotrons laboratories [4] to extract light and medium ions, by TRIUMF Cyclotron to extract H^- at energies as high as 520 MeV and in many commercial Cyclotrons to extract H^- or D^- beams. Unfortunately the extremely low binding energy of H^- ion prevent the use of high magnetic field for high energies due to the high losses produced by electromagnetic stripping. The binding energy of H_2^+ ionised molecule is ≈16.3 eV, about 20 times higher than H^-, and allows to use very high magnetic field also at energies as high as 1 GeV per nucleon, see section 4. Of course the magnetic rigidity of H_2^+ is twice the magnetic rigidity of proton beam having the same velocity. So it is mandatory but feasible to use higher magnetic fields produced by superconducting magnets to accelerate this molecular beam. Up to now the Superconducting Cyclotrons have been dedicated to the acceleration of ion beams to be used for nuclear experiment and limited at low intensity beams. Although some projects like MSU and EXCYT [5,6] plan to increase the beam intensity of extracted beams, the expected upper limit is of some kW. This limit is mainly due to the poor separation between the orbits at the extraction radius and to the use of electrostatic deflectors in compact superconducting Cyclotrons. Moreover the use of superconducting magnet for high energies Cyclotrons, which use deflectors to extract the beam, is not convenient because the orbit separation at extraction radius is reduced. The extraction by stripping allows to extract longer beam bunch respect to the extraction by electrostatic deflectors and the condition of well separated turn at extraction is not strictly requested. So it is possible to use lower energy gain per turn during acceleration process. The reduction of the voltage on the DEES from typical values of 1 MV for single turn extraction of 1 GeV beam, down to 0.5 MV, gives a reduction of a factor 4 on the thermal power losses, making the design of the cooling system of the cavities a little less difficult task.

Thereunder to demonstrate the feasibility of extraction by stripper of H_2^+ a simulation, using the magnetic field of our K800 compact superconducting Cyclotron, is presented. Moreover some considerations on the possible use of larger compact and/or sector separated superconducting Cyclotron to accelerate high current beam at high energies, the main limits due to the interactions with the molecule of the residual gas and to the electromagnetic stripping of H_2^+ are presented.

2 Extraction by stripping

In the near future upon the installation of the axial injection system the LNS superconducting Cyclotron will accelerate H_2^+ up to 100 MeV/amu : the beam will be extracted by electrostatic deflectors and magnetic channel with a typical extraction efficiency of 30÷70%. To extract H_2^+ by stripping a new extraction path across the cryostat and the yoke is mandatory. So it will not be possible to upgrade our Cyclotron, but we can use its measured magnetic field and characteristics for extrapolation on new projects.

To check the feasibility of stripping extraction in compact superconducting Cyclotrons the trajectories of H_2^+ inside our K800 Cyclotron were studied. The magnetic field was interpolated from the measured magnetic field maps. The stripper foil, simulated by a sudden change of charge state, was placed at different angles inside a hill. We found that for an enough large angular range of stripper positions the stripped particles escape from the Cyclotron magnetic field

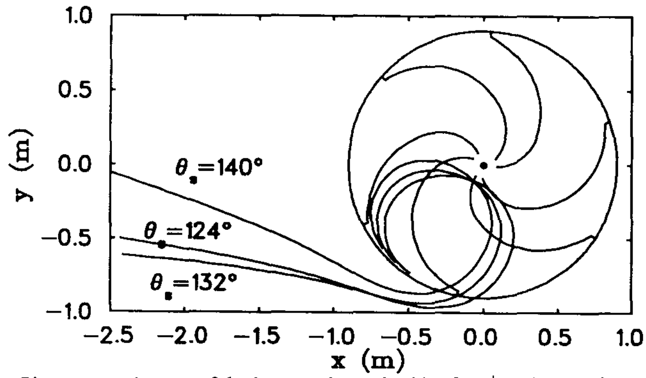

Figure 1: Trajectory of the last accelerated orbit of H_2^+ and extraction trajectory of the proton beam produced by the stripper.

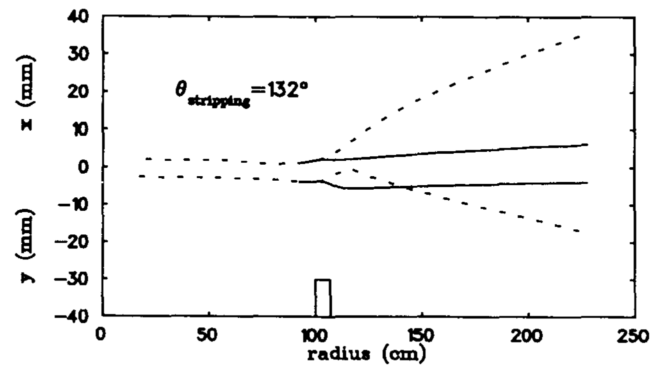

Figure 2: Beam envelope along the extraction trajectory without and with the magnetic channel, dotted and continuous line respectively.

in one turn. In figure 1 three different trajectories for three different stripper positions are shown. According to our simulations small variations of the extraction radius have negligeable effects on the extraction trajectory. The stripper position has a strong effect on the size of the beam envelope. This is mainly due to the different strength of focusing field crossed by the different trajectories. However a position which minimises the beam envelope in both the radial and axial plane along the whole trajectory was found. The radial and axial beam envelopes along the better extraction trajectory is shown in figure 2. The beam envelope has a maximum in the region where the trajectory crosses the cryostat. The insertion of a small magnetic channel at R=100 cm, quite far from the last accelerated orbit is sufficient to focus the beam and maintain its size below 10 mm in both the transversal directions up to the outer radii. Although for each Cyclotron the extraction trajectories are different, the present simulation confirms the experience of other laboratories [4], proving the feasibility of this process.

3 Acceleration of H_2^+ with Cyclotrons

3.1 Compact superconducting Cyclotron for H_2^+

A complex consisting of a Cyclotron cascade has been proposed to drive subcritical reactors. A compact superconducting Cyclotron (CSC) without any pre-injector and intermediate Cyclotrons, to produce high intensity proton beams with an energy of 400 MeV/amu, based on acceleration of H_2^+, could be a more convenient option.

The EULIMA project, proposed by P. Mandrillon [7] some years ago, was designed to accelerate light ions with q/A=0.5. Of course it is able to accelerate H_2^+ too, and the beam could be extracted by stripper, in similar way as shown in figure 1.

The intensity limitation due to the electrostatic extraction is then overcome. A realistic evaluation on the upper intensity limits for H_2^+ compact Cyclotrons can be extrapolated from corresponding figures for H^- Cyclotrons. The acceleration of H_2^+ in a compact Cyclotron is similar to the acceleration process of H^-: in both cases the space charge effects are strongest in the first turns. According to the evaluation accomplished in [8], the TR30 compact Cyclotrons 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. Both these effects give quite similar upper limits. Moreover both the longitudinal and vertical limits scale as the cube of size of the central region. According to these considerations the TR30 compact Cyclotron for H^- with central region scaled up of a factor 1.44 should have a current upper limit of 6.6 mAmp. If the central region of H^- compact Cyclotron is scaled up to the magnetic rigidity of H_2^+ ions, doubling the magnetic field, the injection energy and the RF Voltage, see table 1, the intensity limit should be twice times 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 injection and RF voltage are quite close to the parameters of EULIMA project, while there is a serious difference in the magnetic field at center (3 vs. 3.8 Tesla). A proper central region should be designed. However a significant advantage for injection of H_2^+ could be a higher injection energy (about 150 KeV) and the better emittance and higher currents of H_2^+ source as compared to the H^- source. To deliver a good beam quality for next acceleration step inside a booster, ring Cyclotron or linac, a two stage phase selection, to reduce the natural large 70° acceptance phase to 20° RF, should be performed. The first phase selection, to reduce the accepted phases down to 40° RF have to be done at early turns using the posts of central region. Here about 80% of the beam intensity should be stopped. Assuming an injected d.c. beam current of 50 mAmp with an injection energy of 0.15 MeV a beam power of about 20 kW has to be removed. A proper shape of magnetic field could produce a correlation between the phase of the particle and

Table 1: Expected upper current limit, due to the space charge and central region effects for compact Cyclotrons

	Einj. keV	DEE kVolts	Bo Tesla	Imax mA
TR-30	25	52	1.9	3.3
TR-30 scaled up	50	104	1.9	6.6
CSC-H_2^+	100	208	3.8	13/26*

*Proton beam current after the stripper

its radial position. So a second stage of phase selection using movable slit should be able to define a final beam phase width of 15° RF. To prevent activation of Cyclotron components this second stage has to be installed at a radius where the beam energy is lower than 6 MeV/n. The expected beam reduction at this location should be 50% and to obtain a H_2^+ beam current of 5mAmp, 50 kW beam power should be removed. The gain per turn, after the phase selection, has to be increased up to the extraction radius to allows a phase compression down to 10° RF. The previous considerations are based on unbunched beam. The use of a buncher togheter with a higher injection voltage should reduce the required injected current and the power loss at the phase selection positions.

The most serious problems to use superconducting compact Cyclotrons is the transfer of the 4 MW power at beam. In a 4 sectors CSC with two accelerating cavities more than 2 MW have to be transfered to each cavity by a proper coupler. Moreover large cryo-panels have to be installed in the two empty valleys to reach a good vacuum of the order of 10^{-8} Torr, to minimise the beam loss for interaction with the residual gas, see Table 3.

3.2 Ring superconducting Cyclotron for H_2^+

The spiral angle for a compact Cyclotron has to be increased enormously to produce enough axial focusing for energies beam higher than 400 MeV/n. These higher energies are achievable only by Ring Superconducting Cyclotrons (RSC). A ring superconducting Cyclotron able to accelerate deuteron beam up to 1600 MeV has already been proposed [9] (Injection energy 100 MeV, Extraction radius 3.21 m, energy gain 4.6 MeV/turn, 8 sectors/cavities, weight 150x8=1200 tons). This accelerator needs the sophisticated orbit expansion process to obtain enough separation at extraction. This ring Cyclotron could be used to accelerate H_2^+ up to energy of 800 MeV/n using a lower voltage of 500 KV and the simpler and safer extraction by stripper method. The main doubt about this ring superconducting Cyclotron is the feasibility of the high magnetic field inside the sectors, about 8 T, while none loss due to electromagnetic stripping is expected. The losses due to the interaction with the residual gas for the TRIUMF Cyclotron, for the Compact and Ring Superconducting Cyclotrons are evaluated in section 4.

3.3 Compact room temperature Cyclotron for H_2^+

The above proposed CSC and the RSC are both big project which need to solve many technical problems to be executed. To check the feasibility and the limits of the proposed method, the design for a more conservative compact room temperature Cyclotron is in progress. In Table 2 preliminary parameters of this compact Cyclotron are presented. An accelerator complex based on this compact Cyclotron intended as injector for a ring Cyclotron, able to produce 2-6 mAmp 600 MeV protons beam, should be a realistic driver for a "Demo Plant" to investigate the

Table 2: Main parameters for the proposed H_2^+ Compact Cyclotron

Emax (MeV/n)	100	Sector width	44°
Einj (MeV)	0.150	Spiral angle	45°
Sectors N.	4	q/A	0.5
R_{ex}	1.64 m	Cavities	4
R_{inj}	0.05 m	frequency	50 MHz
<B>	1.8 T	Harmonic	4
B_{hill}	2.85 T	Voltage	160 KV
B_v	0.8 T	Weight	450 t

problems related to a full scale waste transmutation plant based on accelerators. Moreover this compact Cyclotron for 100 MeV/n H_2^+ is a very appealing accelerator to produce exotic ions. This Cyclotron should be able to accelerate deuterons and fully stripped light ions (q/A=0.5, A≤32) at fixed energy of 100 MeV/n. If a beam power up to 10÷20 kWatts is required, these beams could be extracted by electrostatic deflectors placed inside the free valley. This Cyclotron is proposed as primary accelerator of our upgrading program of the EXCYT project to produce exotic ions beams.

4 Limits

Of crucial importance for the design of the above Cyclotrons is the surviving probability of the H_2^+ molecule in the high magnetic field. The binding energy of the last electron is of 16.3 eV, about 20 times larger than the binding energy in the H^- case. This bind can be broken by the electric field which results from the motion of the ion in the magnetic field. The equivalent electric field in the rest frame of the H_2^+ molecule, due to the magnetic field B is given by the relativistic transformation of the electromagnetic field [10]:

$$\varepsilon = 3\cdot\beta\cdot(1-\beta^2)^{-1/2}\cdot B\cdot 10^{-2} \text{ MV/cm}$$

where β=v/c, and B is the magnetic field in Tesla.

The probability D to remove the electron which binds the two protons of the H_2^+ molecule depends upon the binding energy W of the electron and by the applied electric field ε. A useful formula suggested in [11] is:

$$D=\exp(-\alpha)/2\alpha\,, \quad \alpha=\frac{4}{3}\sqrt{2m/h^2}\, W^{3/2}/e\varepsilon$$

where m and e are the mass and the charge of the electron respectively, and h is the Plank constant. According to this equation the probability of removing the electron scales according to $W^{3/2}/\varepsilon$. Since the binding energy of H_2^+ is about 20 times the binding energy of H^-, the electric field should be 90 times higher than for H^- ion of same velocity. This means that to accelerate H_2^+ up to an energy of 2 GeV it will be possible to use a magnetic field as high as 10 Tesla without significant dissociation.

Another serious problem in the acceleration of the H_2^+ is the interaction with the residual gases. As well known, due to the interactions with the molecule of the residual gas, ions could lose the orbital electron along the acceleration

Table 3: Extimated current loss due to interactions with residual gas for TRIUMF and other ciclotrons projects.

	E_{max} MeV/n	$\Delta E/\Delta n$ MeV	R_{ex} m	I_{lmax} mA	Vac. torr	T %	I_{loss} μA
TRIUMF	520	0.34	7.8	0.4	$2\ 10^{-8}$	1.64	6.6
CR-Cyc	100	1	1.65	5	10^{-8}	0.07	3.5
Eulima	400	2	2.2	10	10^{-8}	0.08	8
Dubna	800	4	3.21	10	10^{-8}	0.07	7
RS-Cyc	1000	4	3.65	10	10^{-8}	0.09	9.3

path. The fraction of particles which survives is [12]:

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

Where: P is the pressure (torr), L is the path length in cm . The cross section of electron loss [12] is:

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

where: v_0 and a_0 are the velocity and the radius of the orbit of Bohr respectively, and Z_t is the atomic number of the residual gas. This formula gives a result in quite good agreement with experimental data and is anyway useful to exstimate the expected beam loss in comparison with the parameters of the TRIUMF Cyclotron. 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, five times better than the vacuum of TRIUMF Cyclotron. The proposed high energies Cyclotrons here discussed are more compact and smaller than TRIUMF one, so achieve a better vacuum seems feasible.

5 Power conversion efficiency

A very important parameter for high current accelerators is their conversion efficiency from electrical power to beam power. For a Ring Cyclotron based on the PSI proposed "Dream Machine", the expected overall conversion efficiency is 44% [2], according to the following formula:

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

where:

- ε_{ac}=75% is the AC/RF conversion efficiency optimised
- P_{bt}=10 MW is the total beam power
- P_b=9 MW beam power transferred by the Cyclotron
- P_{fl}= 1 MW, power absorbed by the flat-top cavity
- P_{loss}= 4 MW thermal loss on walls of the 8 cavities, 1 MV peak Voltage, 1 MΩ shunt impedance
- P_{other}= 4 MW for injector, preinjector, magnets etc...

A Cyclotron for H_2^+ can be operate with a lower voltage than a Cyclotron with needs well separate turn. To maintain the residual gas beam losses at an acceptable level, a ring Cyclotron for 1 GeV beam could be equipped with 8 cavities, peak voltage 500 kV, see Table 3. According to the present data of PSI the wall losses are then of 150 kW for each cavity. The reduced wall losses have a strong influence on the overall efficiency of the complex that became of ε_{tot}=53%. The conversion efficiency could be increased up to 57% if the flat-top cavity is not necessary.

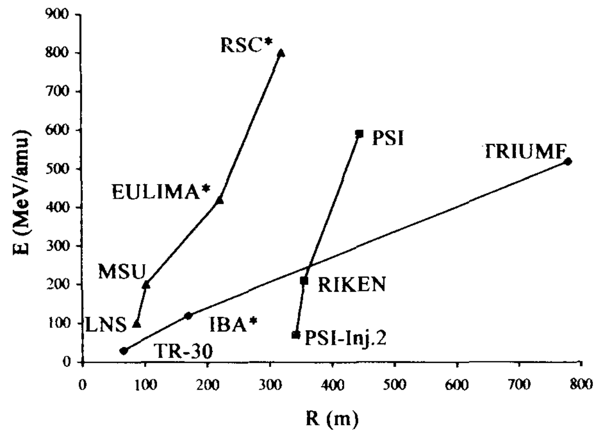

Figure 3: Energy vs. extraction radius for large Cyclotrons in the world, and for some proposed Cyclotron project, labelled by *.

6 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. However as here presented, this goal is possible. In figure 3 is shown the final energy of three families of Cyclotrons: Rings for protons, Cyclotrons for H^- and superconducting Cyclotrons for H_2^+ (constructed and proposals). The advantages related to the use of H_2^+ ions are evident. Moreover the reasons of the success of H^- commercial Cyclotrons are their reliability and easy operation mode. Also for the Cyclotrons dedicated to drive more or less complex plant it is necessary to guarantee a high level of reliability and easy operation mode independent of the skilness of the operators. We believe these goals are also achievable for large Cyclotrons when designed to accelerate H_2^+ ions to be extracted by stripping.

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