# A SUPERCONDUCTING RING CYCLOTRON TO DELIVER HIGH INTENSITY PROTON BEAMS

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*Abstract*

A superconducting ring cyclotron able to accelerate $H_2^+$ to 1 GeV/amu has been investigated. This ring consists of 12 magnetic sectors. Each sector is equipped with a pair of the so called S-coils. The magnetic field and the forces on the superconducting coils are evaluated using the 3-D code MAFIA. The acceleration of $H_2^+$ allows the extraction of the beam by a stripper. The extraction by stripping brings many advantages, i.e. increased reliability, higher beam current, lower energy gain per turn and higher conversion efficiency from electrical to beam power.

## 1 INTRODUCTION

Accelerator complexes consisting of two or three cyclotrons, one or more injector cyclotrons and a main ring cyclotron booster, have already been proposed as drivers for energy amplifier or waste transmutation plants[1,2]. The main constraints for these accelerator complexes are: current higher than 10 mA and energy as high as 1 GeV, minimum beam losses, high reliability and high conversion efficiency from electrical to beam power.

We believe that up to now accelerator driven systems (ADS) based on conventional cyclotrons accelerators are the more reliable and economical solution for a demonstrative plant which requires a beam power of 1-5 MW[3,4]. To deliver higher power, i.e. 10 or more MW, the key points for the ring cyclotrons are the space charge effects, the extraction devices and the power to be dissipated in each cavity. To overcome these problems a classical solution is to increase the radius of the cyclotron and the number of cavities.

An alternative solution based on the acceleration of $H_2^+$ molecule has been proposed[5,6]. In this case the extraction of the $H_2^+$ beam is accomplished by a stripper which produces two free protons breaking the molecule. Due to the different magnetic rigidity as compared to the $H_2^+$, the protons escape quite easily from the magnetic field of the cyclotron. Extraction by stripping does not require well separated turns at the extraction radius and allows to use lower energy gain per turn during the acceleration process, with a significant reduction of thermal power losses for the RF cavities. The extraction by stripper allows to extract beams with large energy spread (0.5÷1%) so the energy spread produced by space charge effect is non crucial in this kind of accelerator, and flattopping cavities are unnecessary. Hereunder the design of a superconducting ring cyclotron booster for $H_2^+$, the results of the magnetic field study and of the force acting on the superconducting coils are presented.

## 2 EXTRACTION BY STRIPPING

The extraction by stripping has been largely used to extract $H^- \rightarrow p + 2e$, at energies as high as 520 MeV at TRIUMF and in many commercial cyclotrons. The main limit of this kind of cyclotron is the small binding energy (0.7 eV) of $H^-$ ions which forbids the use of high magnetic fields, consequently the radius of a cyclotron able to accelerate $H^-$ up to 1 GeV is of about 20 m. The binding energy of the electron of the $H_2^+$ molecule is about 20 times stronger than the $H^-$ one, and consequently the use of magnetic field as high as 10 T even at energies as high as 1 GeV/amu is permitted. There are also other differences between the stripping process for $H^-$ and $H_2^+$. In the first case both the two electrons have to be removed to extract one proton and the foil has to be thick enough to guarantee the stripping efficiency of 100%, while for $H_2^+$ if the molecule is not stripped at first cross through the stripper, 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. According to the TRIUMF data [7] a mean life of 0.5-1 hour is expected for a beam current of 5 mA of $H_2^+$. This is a conservative limit because a thinner foils can be used and 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. Another important advantage to accelerate $H_2^+$ is the reduced space charge effect due to the lower q/A ratio as compared with protons and the better emittance and higher currents of $H_2^+$ sources as compared to the $H^-$ sources. The main disadvantage to accelerate $H_2^+$ is its magnetic rigidity which is twice that for protons with the same velocity, nevertheless using superconducting magnets it is possible to maintain the size of cyclotrons for $H_2^+$ at reasonable values.

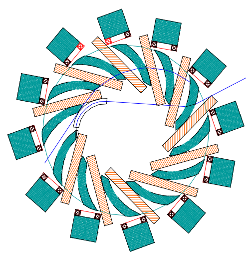

Figure 1: Layout of the 12 sectors RSC for 2 GeV $H_2^+$

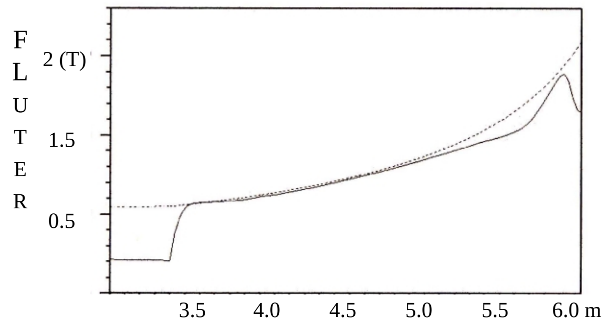


Figure 2: Comparison between the average isochronous magnetic field required and the average field achieved by Mafia simulations.

## 3 SUPERCONDUCTING CYCLOTRON

High energies as 1 GeV are achievable by Ring Cyclotrons which could produce large flutter values and enough axial focusing. As starting point to design the superconducting ring cyclotron we scaled up the 1 Gev Ring cyclotron proposed by PSI group. In particular we scaled magnetic field up to 4.3 T and the extraction radius to about 6 m. Our cyclotron design, like that of the PSI, is based on 12 magnetic sectors. Inside each valley, except one, an accelerating cavity is installed. The free valley is devoted to host the devices for injection and extraction of the beam.

In table 1 the main parameters of the superconducting cyclotron ring are presented. The preliminary study of the RSC shows that it is very difficult to achieve the required isochronous field using superconducting coils wrapped around the iron pole in the usual way. More easy, advantageous and elegant is the use of the so called S-coils [8]. These are a pair of superconducting coils wrapped around the pole/yoke and perpendicularly to the median plane, out of the extraction radius. This solution allows to have more free space among the sectors, and moreover the cryostat is now completely in the outer region, without any interference with the cavities and the accelerated beam. Preliminary evaluations by the 3D MAFIA code were done to evaluate the magnetic field and the forces on the coils. To simplify the simulation we assumed a straight sector, without spiral angle. Figure 2 shows the theoretical isochronous field and the average magnetic field vs. radius evaluated by the MAFIA code for the geometry simulated. As shown by Fig. 2, there is a quite good agreement between the required field and the field simulated by MAFIA even though there are large differences, up to 10%, in some regions. To reduce these differences it is sufficient to adjust properly the angular width of the sectors vs. radius and recalculate the magnetic field by the code. After five cycles of this procedure the differences between the theoretical and the simulated magnetic field were reduced to 0.1÷0.2% about at all radii, only at the two ends the differences reach values of 1÷1.5% yet. At the present stage of the design a lot of parameters are not yet fixed ( i.e. size and shape of the RF cavities), so it is not useful to achieve the exact fit of the isochronous magnetic field. The simulations show that with the present geometry the isochronous field is feasible. Another useful result obtained by the simulations is the value of the magnetic stray field in the valley, which is about 0.4 to 0.6 Tesla, higher than expected. The flutter of the magnetic field is then lower than expected, see figure 3. Due to this low flutter value, the cyclotron field is not able to focus the beam in the axial plane. It is then mandatory to spiral the shape of the sectors to introduce an extra axial focusing. The focusing forces produced by this spiral angle and by the flutter of the magnetic field are able to produce enough axial focusing to achieve a Qy=0.1. Of course it is important to minimise the spiral angle of the sectors because the useful space among the sectors, where the RF cavities have to be installed, is strongly reduced. The simulations by Mafia code allow us to evaluate the axial and radial forces acting on the superconducting coils.

Table 1: Main parameter of the RSC shown in fig.1)

| | | | |
|---|---|---|---|
| $E_{max}$ | 1 GeV/n | $E_{inj}$ | 150 MeV/n |
| $R_{ext}$ | 6.05 m | $R_{inj}$ | 3.48 m |
| N. Sectors | 12 | N. Cavities | 11 |
| RF | 41.4 MHz | harmonic | 6 |
| $V_{peack}$ | 700 kV | ΔE/n | 7.7 MeV |
| <B> at $R_{ext}$ | 1.86 Tesla | Bmax | 4.3 T |
| Sector width | 14°÷16° | $\xi_{spiral}$ | 56° |

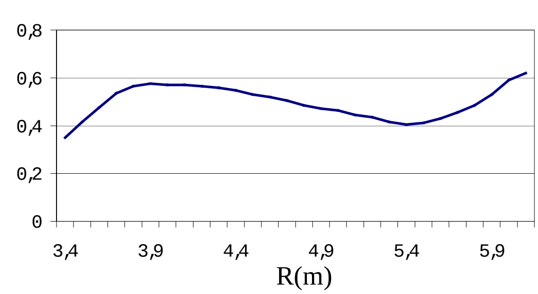


Figure 3: Flutter of magnetic field vs. radius

Table 2: Coil parameters and magnetic forces for the present proposal and for the SRC of RIKEN

| | SRC for $H_2^+$ | Riken |
|---|---|---|
| Max. Current | 7.2 MA t | 6 $mm^2$ |
| Current density | 36 $A/mm^2$ | 34 $mm^2$ |
| Coil size | 500×200 $mm^2$ | 284×310 $mm^2$ |
| Radial force | 500 t | 1800 |
| Axial force | -1400 t | -970 |
| Max. field on coils | 5 Tesla | 5.5 Tesla |
| Total energy stored | 32 MJ | 75 MJ |
| Flux through pole | 7.9 Weber | 28 Weber |
| Flux through yoke | 10 W | 13 W |

In table 2 the main parameters of the coils and of the values of magnetic forces acting on the coils are presented. The radial force is acceptable, while the axial force is a little high. The same table also shows the parameter values for the superconducting ring cyclotron under construction at RIKEN. Although the SRC of Riken is quite different from the SRC here presented, the sizes of the sectors and of the coils are quite similar and the comparison is useful to understand the feasibility of the present project.

## 4 VACUUM REQUIREMENTS

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 [9]:

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

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

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 is in a quite good agreement with experimental data. As shown in table 3, to maintain the losses during the acceleration at the same level as in the TRIUMF Cyclotron, the vacuum has to be of $10^{-8}$ torr. The proposed high energy cyclotron is more compact and smaller than the TRIUMF one, so to achieve a better vacuum should be feasible. Moreover to reach good values of vacuum is useful in order to increase the reliability of the RF cavities too.

Table 3: Beam losses due to interactions with residual Gas, along the acceleration path

| | $E_{max}$ MeV | $\Delta E/\Delta n$ MeV | $R_{ex}$ m | $I_{lmax}$ mA | Vac. torr | $I_{loss}$ % | $I_{loss}$ µA |
|---|---|---|---|---|---|---|---|
| TRIUMF | 520 | 0.34 | 7.8 | 0.4 | 2 $10^{-8}$ | 1.66 | 6.6 |
| RSC-$H_2^+$ | 2000 | 7.4 | 6 | 10 | $10^{-8}$ | 0.07 | 7 |

## 5 CONCLUSION

A lot of work has to be done to evaluate the feasibility of superconducting ring cyclotrons for $H_2^+$ of 1 GeV/amu. In particular the sector magnets able to produce magnetic fields of 4.3 T with the right magnetic field shape and the necessary coils to drive these sectors seem to be feasible even with the present technology, but the optimisation of the magnetic shape of the sectors to reduce the stray fields in the valleys and the magnetic forces on the superconducting coils must be completed. Significant reduction of these two problems could be achieved by increasing the extraction radius of about 10%. Maybe this is the best solution which allows also for more room between the sectors where the RF cavities have to be installed.

Up to now the most critical point is the optimum vacuum required inside the acceleration chamber. In despite of the good vacuum level achieved in the Triumf cyclotron, the use of RF cavities to be operated at high voltage and high power, like the PSI ones, could limit this goal if not properly designed [10].

Cyclotrons used as ADS have to guarantee a high level of reliability and easy operation as well as high conversion efficiency from electrical to beam power. According to the data of PSI the thermal losses for each copper cavity at 750 kV are of 280 kW, which gives an overall efficiency for ADS based on the proposed RSC of $\varepsilon_{tot}$=53%.

We believe that 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.

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