

An 8 MeV H^- CYCLOTRON TO CHARGE THE ELECTRON COOLING SYSTEM FOR HESR

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Abstract

A compact cyclotron to accelerate negative hydrogen ions up to 8 MeV is considered the optimal solution to the problem of charging the high voltage terminal of the electron cooling system for High Energy Storage Ring at GSI (HESR, Darmstadt). Physical as well as technical parameters of the accelerator are estimated. Different types of commercially available cyclotrons are compared as a possible source of a 1 mA H^- beam for HESR. An original design based on the application of well-established technical solutions for commercial accelerators is proposed

INTRODUCTION

High Energy Storage Ring (HESR) [9] is under construction at GSI as a major part of the high energy upgrade of the existing Heavy Ion Acceleration Complex UNILAC-ESR-SIS. The HESR project aims at a luminosity of up to $3 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ in antiproton proton collisions. The fast electron cooling of antiprotons in the energy range from 0.8 to 14.5 GeV is mandatory to allow high brightness experiments with a stored antiproton beam, as well as experiments with an internal target.

ELECTROSTATIC COOLER

The electron cooling section of HESR consists of a charging device, solenoid and recuperation line (Fig. 1). An electrostatic column was chosen as a high voltage device to accelerate 10 A beam of 8 MeV electrons.

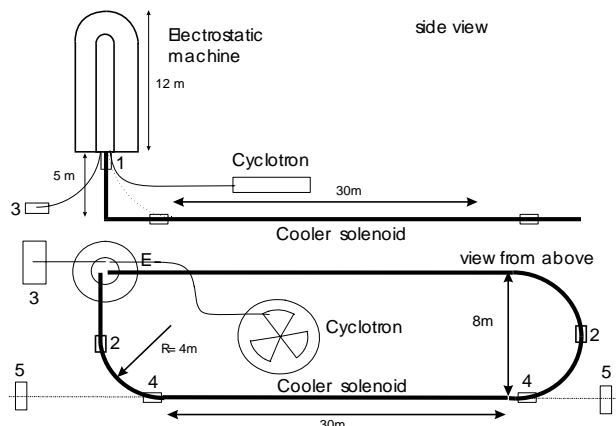


Figure 1. High voltage cooler for HESR. 1 – transformation section; 2 – electrostatic correctors, 3 – energy analyzer of H^- beam for the precise voltage measurement, 4 – point of convergence, 5 – HESR triplets.

Three vertical optic channels are installed in the electrostatic column. Two lines will be used to accelerate and recuperate electron beam. The third optic channel is designed to transport 1 mA beam of 8 MeV negative hydrogen ions to the head of column. A cyclotron is proposed to charge the electrostatic column. The voltage of the column head is determined by the energy of the H^- beam from the cyclotron. Third channel is also used for measuring the high voltage of the head of the electrostatic column. The low current control beam of H^- ions from an ion source, located at the head of the electrostatic column, will be accelerated and transported to the bottom of the tank where it will pass through the energy analyzer. The measured value of the control beam energy is to be used as feedback to adjust the voltage at the terminal top by tuning the cyclotron beam current.

COMMERCIAL CYCLOTRONS

Commercial cyclotrons of the energy range of 10430 MeV are widely used in isotope production and other applications. H^- cyclotrons with an internal ion source mostly used for PET isotope production. Beam current is moderate (704100 μA). A 30 MeV proton beam of up to 1 mA current is extracted from cyclotron TR30. 3 mA beam of H^- ions were accelerated to 1 MeV at the central region model at TRIUMF [4].

TR18/9 (EBCO Techn. Canada) can be considered as a prototype of a charger of HESR high voltage platform providing some modifications will be done. The high performance version of external H^- CUSP ion source is available on market [1,2]. To extract over 1 mA of 8 MeV H^- ions 15 mA of beam will be injected into cyclotron. The beam injection transmission drops twice when the beam emittance is increases from 0.3π to $0.8\pi \text{ mm}\cdot\text{mr}$ [3,5]. H^- ions will be extracted without charge exchange. Electrostatic deflectors and a passive magnetic channel are employed. A positive DC voltage of up to 50 kV will be applied. Operating gas pressure in the vacuum chamber should be better than $5 \cdot 10^{-8} \text{ Torr}$ in order to prevent cold discharge inside the vacuum chamber and to minimize gas stripping of negative ions.

BEAM PARAMETERS

Main features of 8 MeV cyclotron are dictated by request to extract high intensity H^- beam without charge exchange. In the extraction region of existing H^- cyclotrons orbits are overlapped. The circulating radial emittance of the H^- beam for the TR18 cyclotron was measured by TRIUMF scientists [6]. Almost 99% (90%) of the beam intensity included in the phase space area

corresponding to the circulating radial emittance $\beta\gamma\epsilon_r = 2\pi$ (1 π) mm-mrad. The beam shape can be tailored by collimation to satisfy the conditions for single turn extraction at 8 MeV even for the high current operation.

There are few possible ways to extract beam from a cyclotron without charge exchange

- Protons are accelerated in the self-consistent mode on the 72 MeV cyclotron injector 2 (PSI). Almost 2 mA of beam are extracted with 99.98% efficiency.
- Extraction from the radius where the magnetic field is close to the isochronous value. The extraction efficiency varies from 50 to 80% depending on the beam quality, turn separation etc.
- Self-extraction. There are no extraction devices but up to 30% of the beam must be dumped. The beam quality is moderate [10]
- Precession extraction. For the RF phase band of $\sim 20^\circ$ (3°) the extraction efficiency is 80% (96%). No turn separation unless the flattop technique is applied.

The turn separation due to high energy gain per turn in combination with flattop can be used to extract an H^- beam from an 8 MeV H^- cyclotron. The radius gain per turn of H^- ions in TR18 is $dR/dn=2.8$ mm at 18 MeV and 3.3 mm at 13 MeV (Table 1). Phase ellipse paints extraction foil few times (multi-turn extraction). For a single RF phase, the half-width of a phase ellipse is $X_0 = 2.1$ mm ($\beta\gamma\epsilon_r=2\pi$ mm-mrad). The radial size of the bunch exceeds the radial increment between last turns. In case of multi-turn extraction, the radial emittance of the extracted beam is proportional to the dimension of the beam footprint on the foil i.e. to the radius gain per turn dR/dn . Merit of flattop was simulated by adding the RF voltage to the 3rd harmonic of the main RF. With flattop on the radial position of each turn was stabilized. The turns were separated [7].

Almost 50 mA of an 8 MeV H^- beam can hit the deflector septum if tails between turns are not removed. There is a possibility to protect the deflector septum from an incident beam of negative ions. The carbon foil of 1mm width could be installed between the last circulating turns. The deflector septum will be shadowed from a direct hit by an incident beam [8]. The magnetic structure and RF should allow turn separation. To find the conditions for single turn extraction, one should compare the beam size with the radius gain per turn (Table 1). The magnetic field, the energy gain per turn were varied to find the conditions for single turn extraction. A dee voltage amplitude of 50 kV was chosen as reasonable for a commercial power supply. The option of four dees was compared with that of two dees. Higher dee voltage might be applied but sparks may harm the stable operation of the machine. The size of circulating beam $2X_0$ was estimated from expression

$$\epsilon^n = \pi\beta\gamma X_0(\text{mm})P_s(\text{mrad}) = \pi\beta\gamma^2 X_0 X_0 \cdot 1000/R_\infty$$

The beam radial width at 8 MeV exceeds 5 mm. The turn separation must be more than 7 mm in order to clear

Table 1. Beam width and radial gain per turn

| E MeV | B , kG | $\beta\gamma\epsilon$ mm mrad | $2X_0$ mm | Dees | dE/dN , keV | turns s | dR/dN mm |
|------------|-------------|-------------------------------------|--------------|------|------------------|------------|---------------|
| 18 | 12 | 1π | 2.8 | 2 | 200 | 90 | 2.8 |
| 13 | 12 | 2π | 4.2 | 2 | 200 | 65 | 3.3 |
| 8 | 12 | 1.5π | 4 | 2 | 200 | 40 | 4.3 |
| 8 | 10 | 1.5π | 4.4 | 2 | 200 | 40 | 5.1 |
| 8 | 7 | 1.5π | 5.2 | 2 | 200 | 40 | 7.2 |
| 8 | 12 | 2π | 4.6 | 4 | 400 | 20 | 8.5 |
| 8 | 10 | 2π | 5 | 4 | 400 | 20 | 10 |
| 8 | 7 | 2π | 6 | 4 | 400 | 20 | 14 |

peaks at extraction. In standard mode (2 dees) the magnetic field must be reduced to 7 kGs in order to separate turns at extraction. Majority of the beam will be cut off by collimators. The radial dispersion due to the RF phase dependence of the energy gain will add to the beam size in the radial direction and might cause a mixture of turns. Computer simulations as well as beam tests at the TDR9 cyclotron, where D^- ions were accelerated to 9 MeV in 50 turns gave an evidence of the turn separation in centre and turn overlapping at the end [7]. Turn separation for 8 MeV cyclotron is presented in Table 2.

When four dees are employed the radial increment is $dR/dn > 10$ mm. The total turn width should not exceed $\delta R \approx 849$ mm for the RF phase band of $\delta\phi = 20430^\circ$.

Table 2. Radial dispersion versus RF phases

| RF phas | dE/dn keV | N_{dee} | turns rns | dR/dN mm | Beam width mm | B kGs |
|----------------|----------------|------------------|--------------|---------------|---------------------|------------|
| 0° | 200 | 2 | 40 | 5 | — | 10 |
| $\pm 10^\circ$ | 197 | 2 | 40 | | 3 | 10 |
| $\pm 15^\circ$ | 193 | 2 | 40 | | 7 | 10 |
| 0° | 200 | 2 | 40 | 7 | — | 7 |
| $\pm 10^\circ$ | 197 | 2 | 40 | | 4 | 7 |
| $\pm 15^\circ$ | 193 | 2 | 40 | | 10 | 7 |
| 0° | 400 | 4 | 20 | 10 | — | 10 |
| $\pm 10^\circ$ | 394 | 4 | 20 | | 3 | 10 |
| $\pm 15^\circ$ | 386 | 4 | 20 | | 7 | 10 |

Combination of four dees and an average magnetic field of 10 kGs can be solution for the SINGLE turn extraction of 8 MeV H^- ions. The beam size should be less than 9 mm while the turn separation is 10 mm.

Tails between circulated and extracted orbits will be cut off by the protection foil. The expected intensity of halo should be less than 5% of the total current. Multiple phase selection should limit losses and clean up the turns at extraction. The radiation load will be limited.

RF system, central region, inflector can be designed in such a way that a flattop voltage of up to 15 kV could be applied to the second pair of dees. Flattop does not increase the useful RF phase band over 20430° but stabilizes the orbits position.

SPECIFICATIONS OF CYCLOTRON

Providing the parameters of the magnet and the RF structure satisfy the conditions for single turn extraction, one could propose the following specifications for an 8 MeV H^- cyclotron (Table 3):

Table 3. Parameters of 1 mA 8 MeV H^- cyclotron

| | |
|--|--|
| beam to be removed | <10% |
| Energy range (H^- ions) | 4 ÷ 8 MeV |
| norm.emittance - $\beta\gamma\epsilon$ | Rad /axial = 1.5 / 2π mm·mrad |
| Energy spread | 1% |
| Magnet geometry | 4 sectors radial ridge, straight |
| Average field B_{av} | 10 kGs |
| Field at the hill B_{hill} | 16 kGs |
| Valley field B_{vall} | 4 kGs |
| Pole radius | 450 mm |
| Hill gap | 50 mm |
| Valley gap | 250 mm |
| Sector angle | 43° |
| Coil power supply | 500 A, 48V, stability = 10^{-5} |
| RF frequency | 61 MHz (RF harmonic $h_{RF}=4$) |
| Number of dees | 2 + 2 |
| RF voltage | 50 kV |
| Energy gain per turn | 400 keV |
| Number of turns | 20 |
| Dee angular width | 45° |
| RF power supplies | 2 3 20 kW |
| Flattop | Optional , 12 kV 3 rd harm RF |
| Ion Source | H^- CUSP high performance |
| Source current /emit | 15mA/0.8 π mm·mrad (4 RMS) |
| Injection line/voltage | Einzel lens + SSQQ / 40 keV |
| Bunchers–linear+3/2 $\beta\lambda$ | 2 gaps, $d_{holes} = 15\div 20$ mm |
| Spiral inflector | $A^{el}=45$ mm, $k=-0.7$, gap=10 mm |
| Operating vacuum | 5·10 ⁻⁸ Torr |
| Vacuum system | 2CRP(4500 l/s)+2TP(2000 l/s) |
| RF Beam transmission | 10%(bnch off), 15% (bnch on) |
| Beam losses (gas strp) | < 0.5% |
| Extraction elements | ESD+mgn chn+protection foil |
| Useful RF phase band | 20430°RF-single turn extract. |

| | |
|-------------------------|------------------------------------|
| Pulse width | 1.5 ÷ 2 ns |
| Turn separation at extr | 10 mm |
| Radial width of bunch | 8 mm |
| First harmonic | $h_1 < 2$ Gs |
| Radial oscillations | $A_{coh} < 1$ mm |
| Trim/harmonic coils | 4 / 2 sets |
| Phase collimators - two | 3rd turn and 10 th turn |

SUMMARY

A cyclotron for accelerating a beam of 1 mA H^- ions up to 8 MeV can be built from the equipment used in the commercial cyclotrons. An original design of the magnet, the RF and the extraction system in combination with well developed standard solutions will ensure that the designing goals can be achieved.

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