FEASIBILITY STUDY OF 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) [1] 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 $3{\cdot}10^{32}\,cm^{-2}\,s^{-1}$ 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. Three vertical optic channels are installed in the

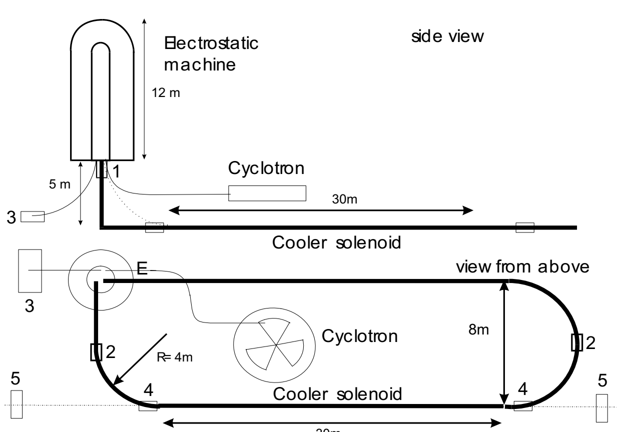

Figure 1.High voltage cooler for HESR.
1–transformation section; **2**– electrostatic correctors, **3** – energy analyzer of H^- beam for the precise voltage measurement, **4** – point of convergence, **5** –HESR triplets

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 $10 \div 30$ 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 ($70 \div 100$ μA). A 30 MeV protons of 1.3 mA are extracted from cyclotron TR30. 3 mA beam of H^- ions were accelerated to 1 MeV in the central region model cyclotron at TRIUMF [2].

TR18/9 cyclotron (“Adanced Cyclotrons” – former EBCO, 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 [3,4]. 15 mA of H^- ions will be injected into cyclotron in order to extract 1mA of 8 MeV H^- beam. Injection transmission drops twice when the beam emittance is increases from 0.3π to 0.8π mm·mrad [5,6].

BEAM PARAMETERS

Main features of 8 MeV cyclotron are dictated by request to extract high intensity H^- beam without charge exchange. Electrostatic deflector and passive magnetic channel are employed. A positive DC voltage of up to 50 kV should be applied. Vacuum in the acceleration chamber should be better than $5{\cdot}10^{-8}$ Torr while operating with high intensity beam in order to prevent cold discharge inside the vacuum chamber and to minimize gas stripping of negative ions. 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 [7].

Almost 99% (90%) of the beam intensity included in the phase space area corresponding to the circulating radial emittance $\beta\gamma\varepsilon_r = 2\pi$ (1π) mm·mrad The beam shape can be tailored by collimators to satisfy the conditions for single turn extraction at 8 MeV even for the high current operation mode. 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). 2 mA of proton 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 beam should be dumped. The beam quality is moderate [8]
- Precession extraction. For the RF phase band of ~ 20^o (3^o) 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 ($\beta\gamma\varepsilon_r$=2π 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 foot-print 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 [9].

Almost 100 μA 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 [10]. 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 The beam radial width at 8 MeV exceeds 5 mm. Turn separation must be more than 7 mm in order to clear peaks at extraction

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

Table 1. Beam width and radial gain per turn

E MeV	B, kG	$\beta\gamma\varepsilon$ mm mrad	$2X_o$ mm	Dees	dE/dN, keV	turns	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

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 [5]. Turn separation for different extraction conditions is presented in Table 2.

When four Dees are employed the radial increment is dR/dn > 10 mm. The total width of peak will not exceed $\delta R \approx 8 \div 9$ mm for the RF phase band of $\delta\varphi = 20 \div 30^o$. Tails between circulated and extracted orbits will be cut off by the protection foil. The expected intensity of halo

Table 2. Radial dispersion versus RF phases.

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

should be less than 5% of the total current. Multiple phase selection will limit losses and clean up the turns at extraction. The radiation load will be limited .

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 $\geq$ 10 mm.

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 $20 \div 30^o$ 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)	$4 \div 8$ MeV
norm.emittance - $\beta\gamma\varepsilon$	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^o
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^o
RF power supplies	2×20 kW
Flattop	Optional , 12 kV 3rd harm RF
Ion Source	H^- CUSP high performance
Source current /emit	15mA/0.8πmm·mrad (4 RMS)
Injection line/voltage	Einzel lens + SSQQ / 40 keV
Bunchers–linear+3/2βλ	2 gaps, d_{holes} = 15÷20 mm
Spiral inflector	A^{el}=45mm, k'=-0.7,gap=10 mm
Operating vacuum	$5 \cdot 10^{-8}$ 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	$20 \div 30^o$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 10th turn

SUMMARY

A cyclotron for accelerating a beam of 1 mA H^- ions up to 8 MeV can be built from the commercial equipment purchased for 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 design goals can be achieved.

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