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ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

FEASIBILITY STUDY OF 8 MeV H^- CYCLOTRON TO CHARGE THE ELECTRON COOLING SYSTEM FOR HESR

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

Рассматривается возможность использования компактного коммерческого циклотрона для ускорения отрицательных ионов водорода до энергии 8 МэВ в качестве зарядного устройства для высоковольтного терминала системы электронного охлаждения в накопительном кольце высоких энергий в GSI (Дармштадт, Германия). Проведена оценка физических и технических параметров ускорителя. Рассмотрены различные варианты использования коммерческих циклотронов. Проведено сравнение характеристик ускорителей с точки зрения их использования как источника пучка отрицательных ионов водорода интенсивностью более 1 мА. Предложен оригинальный проект, основанный на использовании систем и узлов существующих коммерческих ускорителей.

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INTRODUCTION

High Energy Storage Ring (HESR) [1] is under construction at GSI (Darmstadt, Germany) as a major part of the high energy upgrade project FAIR of the existing Heavy Ion Accelerator Complex UNILAC-ESR-SIS (Fig. 1). The fast electron cooling of antiprotons is to be employed to allow high brightness experiments with a stored antiproton beam (up to 10^{11} pps), as well as experiments with an internal target. The powerful cooling of antiprotons in the energy range from 0.8 to 14.5 GeV is mandatory to provide high resolution experiments to investigate hadron structure and interaction of quarks and gluons in the nuclear medium.

For spectroscopy of charmonium states between 5 and 8 GeV, an energy resolution of 100 keV is foreseen providing the upper limit for relative momentum spread of antiproton beam as low as 10^{-5}.

The HESR project aims at a luminosity of up to $3 \cdot 10^{32}$ $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ in antiproton–proton collisions employing an internal cluster jet or frozen pellets hydrogen targets with thickness of

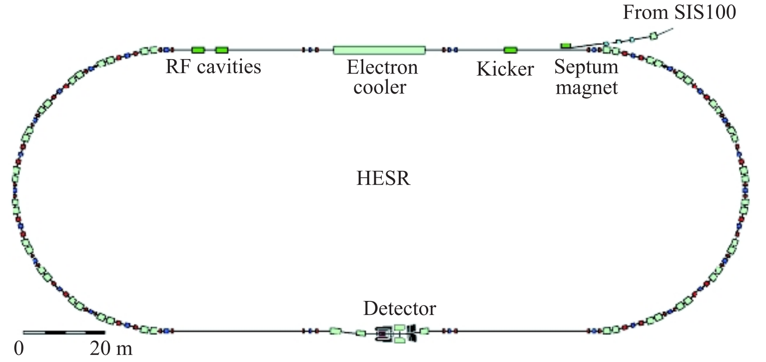

Fig. 1. Layout of the High Energy Storage Ring (HESR) for antiprotons [9]

$5 \cdot 10^{15}$ atoms/cm^2. The antiproton cooling rate should satisfy the required beam parameters. The beam heating due to intrabeam scattering, the fluctuations of ionization energy losses and multiple scattering of antiprotons on the target must be eliminated.

ELECTROSTATIC COLUMN

The electron cooling system for HESR consists of a charging device with electron gun, solenoid and recuperation line (Fig. 2). An electrostatic column is chosen as a high voltage device to accelerate 10 A beam of 8 MeV electrons. The acceleration column is 12 m high in order to restrict the electric field strength to 10 kV/cm (Fig. 3).

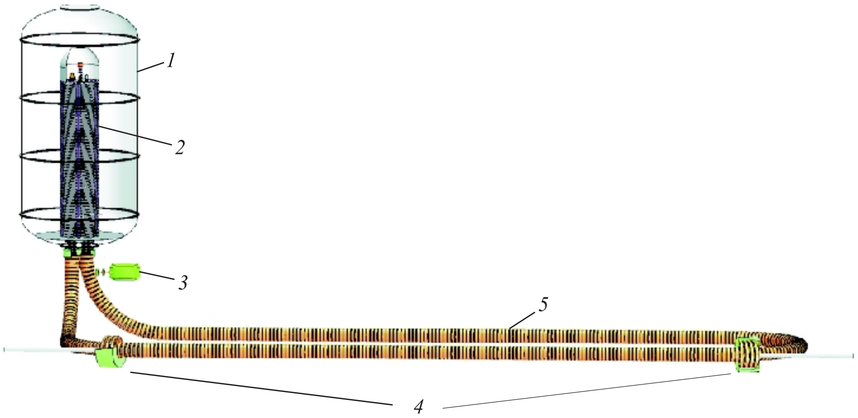

Fig. 2. The view of electron cooling system to accumulate 14 GeV antiprotons at HESR: *1* — high voltage tank; *2* — electrostatic column; *3* — cyclotron to charge head of electrostatic column; *4* — cooling section solenoid; *5* — reversal track (part of recuperation line)

The cooling solenoid and the recuperation line (30 m long each) are located in the horizontal plane (Fig. 3). Three vertical optic channels are installed in the electrostatic column (Fig. 4). Two lines will be used to accelerate and decelerate (recuperate) electron beam on its way from the electron gun to the collector, the recuperation rate being 10^{-4}.

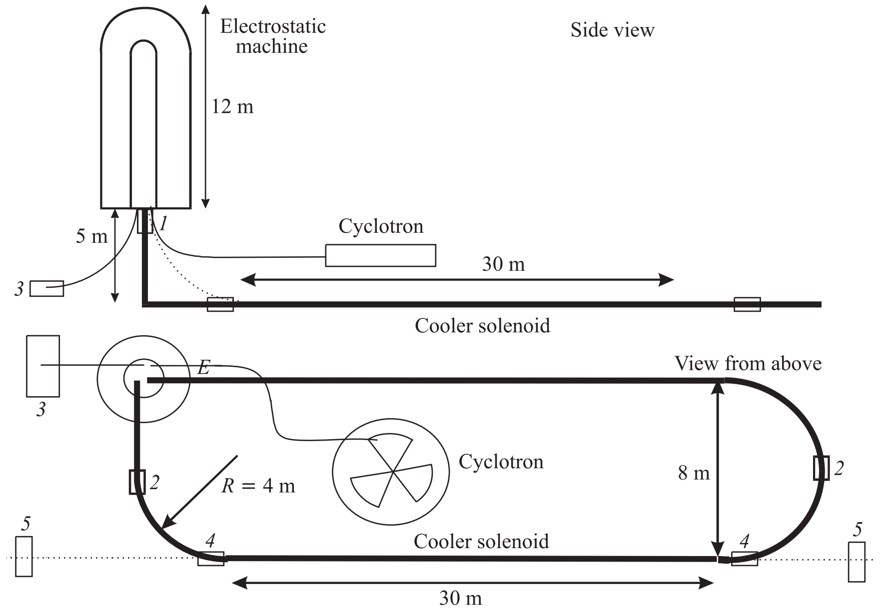

Fig. 3. High voltage cooler for HESR: *1* — transformation section for the beam transfer from the low-magnetic field of the electrostatic column to the high magnetic field of the cooler; *2* — system of the electrostatic dipole corrections; *3* — energy analyzer of H$^-$ beam for the precise voltage measurement; *4* — point of convergence of the $\bar{p}$ and electron beams; *5* — HESR triplets (TRIP_C1)

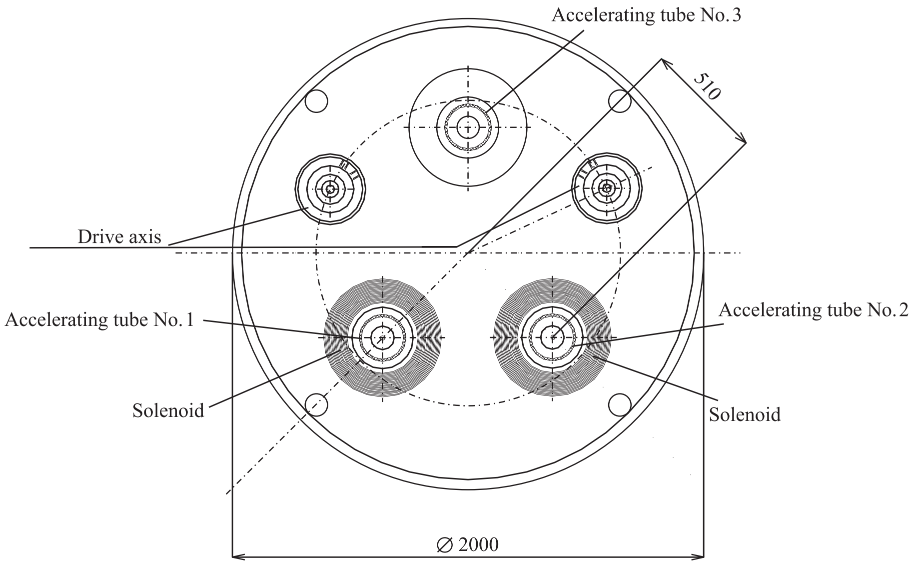

Fig. 4. Transverse cross section of the electrostatic column

Different charging systems are considered. Mechanical charging device like PELETRON or Van de Graaff belt cannot provide the required current of electron beam and voltage stability. An electron LINAC to charge high voltage platform would produce a huge radiation background. Series of independent charging devices might be acceptable, except any spark, or discharge will destroy all elements in the section where discharge has happened.

A cyclotron is proposed to charge the electrostatic column (Fig. 3). The third optic channel in the electrostatic column will be designed to transport 1 mA beam of 8 MeV negative hydrogen ions to the head of the electrostatic column (Fig. 4). The voltage of the column head is determined by the energy of the H^- beam from the cyclotron. The electrostatic column is located in the centre of the tank and consists of 80 sections with potential growing from the bottom section to the top one. Maximum negative potential of the head is 8 MV. The insulating gas is SF_6 under pressure. The top part of the electrostatic column is covered with an electrostatic shield.

The H^- ions bring double charge while colliding with walls inside the ion collector. The secondary emission of electrons from the ion collector may harm insulator stability of column. The problem of electric stability inside the column should be carefully studied and will be discussed in future presentations.

An electron gun is located at the high voltage terminal of the electrostatic column. Cathode of the electron gun is immersed in a magnetic field. The electron beam crosses the section of the growing magnetic field (from 500 Gs to 5 kGs) outside the electrostatic accelerator. Then, the electron beam is bent in the vertical and horizontal planes and injected into the cooling solenoid with a magnetic field of 5 kGs. The electron beam passes through the correction electrostatic dipoles at the matching point. After passing the main solenoid, the electron beam is guided back to the acceleration column where it is decelerated and dissipated inside the collector at the head of the electrostatic column with efficiency of 99.99% (the recuperation rate is 10^{-4}).

An accelerating tube No. 1 for accelerating the electron beam, an accelerating tube No. 2 for decelerating the electron beam, an accelerating tube No. 3 used for charging the column head (H^- beam), a drive axis for supplying power to the solenoid are shown in Fig. 4. The drive axes are made of a dielectric material and could withstand the potential difference between the sections. Accelerating tube No. 3 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, which is 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 (Fig. 3). 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

Different types of cyclotrons are available on the market. One should investigate the merit of the employing of commercial machines for the acceleration and extraction of high intensity beams of H^- ions in the energy range of 8 MeV. Commercial cyclotrons of the energy range of 10–30 MeV are widely used for isotope production and other applications.

Proton Cyclotrons with an Internal Target. CYCLONE14+ from IBA (Belgium) can be considered as the best example of a cyclotron with an internal target. An internal PIG source provides a proton current of up to 6 mA. A 14 MeV proton beam of 2 mA current hits a target disposed inside the vacuum chamber. The target is water cooled, tilted or spin off in order to dissipate 50 kW of the beam power. Beam extraction from CYCLONE14+ is not provided for.

The H^- cyclotrons with an **internal cold-PIG ion source** are mostly used for PET isotope production. The advantage of H^- cyclotron is easy and low loss extraction by stripping negative hydrogen ions on carbon foil to produce protons. Single particle, fixed RF frequency commercial cyclotrons are relatively chip and robust in operation. The beam energy could be varied via the radial movement of the stripping foil. The beam stability is excellent. With proper design of the vacuum system, the stripping losses of H^- inside the vacuum chamber can be kept at an acceptable level. The H^- beam current from commercial PET cyclotrons is quite moderate (up to 100 μA).

Self-Extracting Cyclotron. A new method for extracting a beam without using extraction devices like electrostatic deflector, a magnetic channel or stripping foil was invented by Y. Jongen, W. Kleeven and tested at the self-extracting cyclotron [2]. The prototype machine is operating at the IBA headquarters in Fleurus (Belgium). The field index drops rapidly in the extraction region from $n > 1$ to $n < -1$. The stability of motion in the radial direction is lost and particles escape magnetic field. A proton beam of 6 mA intensity from an internal PIG ion source is accelerated to the final energy of 14 MeV. An extracted proton beam of up to 2 mA intensity is available.

A few side effects might prevent from employing self-extraction method for acceleration of H^- ions. Due to the loss of the radial stability, the beam is spread out in the radial direction and there is no clear separation between the last circulating turn and the extracted orbit, even so, the beam precession is employed in order to separate the orbits. Up to 25% of the beam current from the last turn should be intercepted and dumped in the special beam stop. As a consequence, the radiation background is very high. The normalized emittance of the extracting beam from a self-extracting cyclotron exceeds 10π mm · mrad, while the designed value of the H^- beam emittance for cooling section of HESR ring is 2π mm · mrad.

High Current H^- Commercial Cyclotrons of the 30 MeV Energy Range. Two commercial cyclotrons, CYCLONE-30 from IBA (Belgium) and TR30 from EBCO Technologies (Canada) are capable of accelerating H^- beam of more than 500 μA. The ion energy is varied from 15 to 30 MeV by the radial movement of the stripping foil mechanism. Using a modified version of the ion source, a new vacuum pumping system, modernized injection, one could expect an extracted beam of up to 700 μA from C30. The TR30 cyclotron is equipped with a modified version of the CUSP source [3, 4]. Proton beam of up to 1.3 mA current is extracted from the TR30 cyclotron. The 3 mA beam of H^- ions was accelerated to 1 MeV at the central region model at TRIUMF [5].

TR18/9 (EBCO Techn., Canada) can be considered as *a prototype* of a charger cyclotron for HESR high voltage platform providing some modifications to be done to extract H^- ions without charge exchange. The 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 $5 \cdot 10^{-8}$ Torr in order to prevent cold discharge inside the vacuum chamber and to minimize gas stripping of negative ions.

The beam injection transmission drops twice when the beam emittance increases from 0.3π to 0.8π mm · mrad [6, 7]. The beam of 15 mA should be injected into cyclotron in order to extract over 1 mA of 8 MeV H^- ions. The high performance version of external H^- CUSP ion source available on the market will be employed [3, 4].

VACUUM CONDITIONS

Main features of 8 MeV cyclotron and particular *vacuum conditions* are dictated by request to extract 1 mA high current beam of negative hydrogen ions without charge exchange. Electrostatic deflectors and a passive magnetic channel are employed to extract H^- ions. To deflect 8 MeV negative ions outwards from an equilibrium orbit, a positive DC voltage of up to 50 kV should be applied. In combination with poor vacuum conditions, positive potential might cause cold penning discharge (lightening) in the vacuum chamber. The top and bottom of the vacuum chamber play role of a cathode and anticathode, while the deflector plate under positive potential works as an anode. Electrons are spiralling along the magnetic field lines and produce avalanche.

Beam losses caused by vacuum dissociation at low energies up to 10 MeV and the energy gain per turn 200 keV/turn will be less than 1.2% of the total beam intensity if the vacuum is maintained at a level of 10^{-7} Torr. One should expect similar losses for 8 MeV H^- cyclotron because the cross sections are higher for low energies and main part of the stripping of H^- ions is produced at low energies. An operating pressure of $5 \cdot 10^{-8}$ Torr will be satisfactory to avoid DC positive discharge. Also, the H^- beam dissociation caused by the stripping of negative ions on the molecules of the residual gas will be reduced to less than 0.2% of total current.

External injection of H^- ions will be used in order to provide high vacuum and thereby to minimize stripping losses and maintain positive voltage on the deflector. Differential pumping of ion source and cyclotron vacuum chamber will be used. In order to maintain high vacuum, the two high speed turbo-pumps (TPH2303 with a 2000 l/s pumping speed each) and one cryo-pump (4.500–10.000 l/s for H_2O) will be attached to the ion source diagnostic box. Two cryo-pumps and two high-speed turbo-pumps will be installed in the free holes of the magnet yoke of 8 MeV magnet. The turbo-pumps must be shielded from the residual magnetic field.

BEAM EXTRACTION

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

- Protons are accelerated in the self-consistent mode at the 72 MeV cyclotron injector 2 (PSI, Switzerland). 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. Usually when turns are not separated 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 [2].
- Precession extraction. For the RF phase band of $\Delta\varphi \sim 20^\circ$ the extraction efficiency is 80%. The extraction efficiency may be as high as 96% if the RF phase band is restricted to (3°). No turn separation unless the flattop technique is applied.

Merit of Precession Extraction and Flattop. Precession extraction was invented by Prof. H. Blosser [8] and successfully employed at many cyclotrons. To create modulation of beam intensity in the extraction region the radial profile of the magnetic field is shaped in a special way. The radial betatron frequency drops from ν_r above unit to ν_r below unit. The first harmonic of magnetic field ($h_1 \sim 3$ Gs) is added in the region where radial betatron frequency is a crossing unit ($\nu_r = 1$). The coherent radial oscillations are excited. Following precession increases separation between turns by a few times — for example, from $dR/dN = 0.4$ mm to $dR/dN = 2$ mm. The phase of the first harmonic ψ_1 is adjusted to receive the maximum turn separation at the azimuth of the deflector entrance. The extraction efficiency is improved up to 98% for narrow RF phase band $\Delta\phi \sim 3°$ and up to 80% for wide RF phase band $\Delta\phi \sim 20°$.

In order to cross resonance and to excite precession in the extraction region, the magnetic field rises up above the isochronous, then drops below isochronous field and returns to isochronous value. The RF phase is shifted from $\phi = 0°$ RF to the phase $\phi \approx -40°$ and rises up to positive value $\phi \approx +40°$. Phase motion must be strictly controlled to avoid the deceleration. A combination of precession and flattop should improve the extraction efficiency for a wide RF phase band. Computer simulations of precession extraction [9] and experiments [10] were made at the TRIUMF 500 MeV H$^-$ cyclotron during the definition study of the KAON project. Orbits are overlapped in the TRIUMF cyclotron. There is no turn separation.

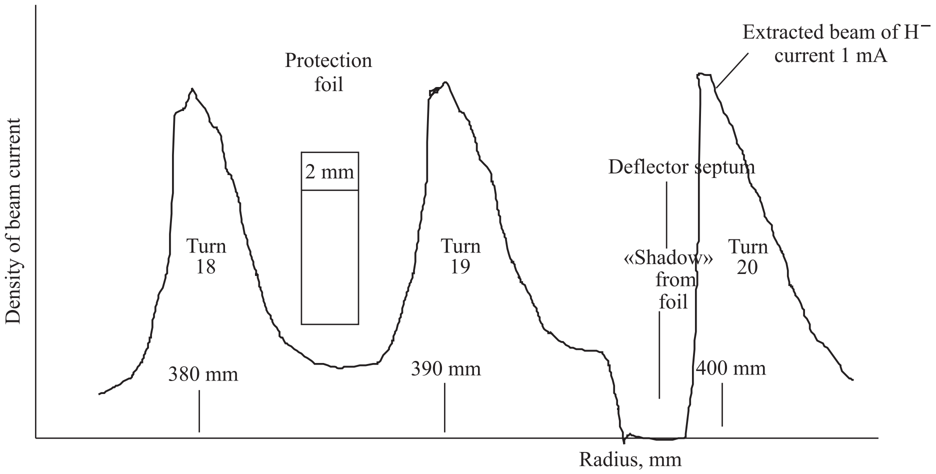

Fig. 5. Radial profile of 8 MeV H$^-$ beam at extraction

A special device — a radio frequency deflector (RFD) — was employed to excite radial oscillations during the crossing of half-integer resonance $\nu_R = 3/2$ at energy $E = 418$ MeV. The radial component of the electric field of RFD pushes ions inward each odd turn and outward each even turn. Due to the following precession the beam density pattern is painted with the maxima and minima. A typical ratio of the beam density was 80% at the precession maximum and 20% at the precession minimum (Fig. 5). Carbon foil of 1 mm width was placed between the precession maxima where the beam density is minimal. The foil intercepts unwanted H$^-$ beam. Up to 70 μA of 430 MeV H$^-$ ion were extracted by the deflector without hitting the deflector septum or the ground electrode. The 10 μA H$^-$ ion beam tails were stripped and directed to a special dump area. The septum of the deflector was shadowed by the protection foil.

Computer simulations and following experiments were performed to estimate the merits of flattop [9]. An RF voltage with a frequency corresponding to the third harmonic of main RF was applied to a special device — a radio frequency booster. Device is located in the extraction region of the TRIUMF cyclotron. The phase of the third harmonic voltage was opposite to the phase of the main RF. The amplitude of the flat-topping voltage was optimized to 15% of the main RF. With flattop turned on, particles of different RF phases, after exciting radial oscillations, follow exactly the same pattern as central phase particles. The radial position of the precession maxima was stabilized.

To check the stability of the radial position of the precession maxima, experiments were performed at the TRIUMF cyclotron. The RF phase of the beam was changed from 0 to $\pm 20^\circ$ RF by detuning the main RF frequency $f_{\rm RF} = 23$ MHz in the range of ± 100 Hz. A radial probe scanned in the region of interest and the distribution of the beam density were measured. The radial position of the precession maxima moved by a few mm, when the RF phase was changed from 0 to 20°, and no flattop was applied. Also, the radial position of the precession maxima was drifted in time due to the different factors like change of the dee voltage, drift of the cooling water temperature, etc.

When flattop was turned on, the radial position of precession maxima did not move even if the RF frequency was detuned on 100 Hz, i.e., RF phase was shifted from 0 to $\pm 10^\circ$ (RF phase band is $\Delta\phi_{\rm RF} \approx 20^\circ$). The radial position of precession maxima is stable in time and drift is reduced to acceptable level. The beam density distribution between precession maximum and minimum was improved to 90 and 10%.

BEAM PARAMETERS

In the extraction region of existing H^- cyclotron orbits are overlapped. 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). The circulating radial emittance of the H^- beam for the TR18 cyclotron was measured by the TRIUMF scientists [11]. Almost 99% of the beam intensity included in the phase space area corresponding to the circulating radial emittance $\beta\gamma\varepsilon_r = 2\pi$ mm · mrad and 90% of beam — 1π mm · mrad [11]. For a single RF phase and normalized emittance $\beta\gamma\varepsilon_r = 2\pi$ mm · mrad the half-width of a turn is $X_0 = 2.1$ mm. The radial size of the bunch exceeds the radial increment between turns in the extraction region.

Table 1. **Beam width and radius gain per turn**

E, MeV	B, kG	$\beta\gamma\varepsilon$, mm · mrad	$2X_0$, mm	$N_{\rm dees}$	dE/dN, keV	$N_{\rm turns}$	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**	$\mathbf{1.5\pi}$	**5.2**	**2**	**200**	**40**	**7.2**
8	12	2π	4.6	4	400	20	8.5
8	**10**	$\mathbf{2\pi}$	**5**	**4**	**400**	**20**	**10**
8	7	2π	6	4	400	20	14

The precession of the phase ellipses in the radial phase space will cause the overlapping of extracted turns. The particles of the narrow phase band will be extracted in 2 turns and a beam of the 40° phase band — in 3–4 turns. The size of the beam spot on an extraction foil or a totally intercepting probe or a post might be given by

$$W = \frac{dR}{dn} + X_0 \sin(2\pi\nu_R) \approx \frac{dR}{dn} + X_0[2\pi(\nu_R - 1)]. \tag{1}$$

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 W, i.e., to the radius gain per turn dR/dn. During extraction the phase ellipse paints stripping foil a few times (multi-turn extraction).

Merit of flattop was studied by adding the RF voltage to the third harmonic of the main RF. With flattop on the radial position of each turn was stabilized and turns were separated [9]. The beam shape in the cyclotron can be tailored by radial and vertical collimation to satisfy the conditions for single-turn extraction at 8 MeV even for the high current mode of operation. *The turn separation due to high energy gain per turn in combination with flattop can be used to extract an H^- beam from 8 MeV H^- cyclotron.*

Almost 50 μA of 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. *Protection carbon foil* of 1 mm width will be installed between the last circulating turns. The deflector septum will be shadowed from a direct hit by an incident beam [8]. Proper combination of magnetic field, the RF voltage and dee structure should be found in order to allow turn separation of 8 MeV H$^-$ ions.

To find the conditions for single-turn extraction at 8 MeV, 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 used, but sparks may harm the stable operation of the machine. The radial size of circulating beam $2X_0$ was estimated from expression

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

The beam radial width at 8 MeV exceeds 5 mm. The turn separation must be more than 7 mm in order to clear peaks at extraction. In the 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 up to 4 MeV and turn overlapping at the higher energies [7]. Turn separation for 8 MeV cyclotron is presented in Table 2.

The radial gain per turn at 8 MeV should be $dR/dn \approx 5-7$ mm in the standard mode of acceleration with two dees. When four dees are employed the radial increment is $dR/dn >$ 10 mm and total turn width will not exceed $\delta R \approx 8-9$ mm for the limited RF phase band of $\delta\varphi = 20-30^\circ$. In 8 MeV cyclotron, the energy gain per turn is $dE/dN = 400$ keV/turn and particles are accelerated in 20 turns. Protection foil, located between 18th and 19th turns, intercepts the unwanted beam and creates shadow for the deflector septum. To optimize extraction efficiency the width of protection foil is varied from 1 to 3 mm. One may come to the following conclusions:

Table 2. **Radial dispersion versus RF phase band**

RF phase band, °	dE/dN, keV	N_{dees}	N_{turns}	dR/dN, mm	Width, mm	B, kGs
0	200	2	40	5	—	10
±10	197	2	40		3	10
±15	193	2	40		7	10
0	200	2	40	7	—	7
±10	197	2	40		4	7
±15	193	2	40		10	7
0	**400**	**4**	**20**	**10**	—	**10**
±10	**394**	**4**	**20**		**3**	**10**
±15	**386**	**4**	**20**		**7**	**10**

- Amplitude of dee voltage of 50 kV should be chosen as an optimum one. The commercial power supply for TR30 or a similar RF amplifier can be purchased. The increasing of the dee voltage to a higher amplitude would create problems like sparks, etc.
- Combination of two dees and 10 kGs magnetic field cannot be used if one would like to separate turns. Even the applying of flattop voltage will not guarantee turn separation for the RF phase band of $\delta\varphi = 20{-}30°$.
- Combination of two dees and a low magnetic field of 7 kGs will not guarantee turn separation even for the restricted RF phase band of $\delta\varphi = \pm 10°$. The total width of the beam pulse could reach 9 mm, while the expected turn separation is only 7 mm.
- Reducing of the magnetic field to 7 kGs will span magnet yoke to an unacceptable value.
- Tails between circulating and extracted beams will be intercepted by the foil, stripped and dumped. The expected intensity of halo should be less than 5% of the total current. 50 μA of 8 MeV halo protons (beam power 400 W) must be dissipated. A combination of phase selection in the centre of the cyclotron and after 10 turns could help to 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. Position of turns will be stabilized for the phase band of $\delta\phi = 30°$ RF. The merit of the flattop will be verified in experiment.
- To reduce required electric field strength two electrostatic deflectors might be installed inside dees. Positive voltage less than 30 kV can be applied to the deflector plates, while a high vacuum of $5 \cdot 10^{-8}$ Torr will be maintained.
- Energy spread of the extracted beam is to be expected in the range of $\Delta E \sim 200{-}300$ keV.

Acceleration of ions on the fourth harmonic of RF in combination with four 42–45° dees of 50 kV voltage amplitude and an average magnetic field of 10 kGs can be solution for the Single-turn extraction of 8 MeV H^- *ions. The total beam size should be less than 8 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 20–30° but stabilizes the orbit positions.

SPECIFICATIONS FOR 8 MeV H^- CYCLOTRON

Providing the parameters of the magnet and RF structure have been chosen to satisfy the conditions for single-turn extraction, one could propose the following parameters for 8 MeV H^- cyclotron (Table 3).

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

Energy, MeV	4–8
Beam current, μA	1
Beam to be removed, %	< 10
Energy range (H^- ions), MeV	4–8
Norm. emittance ($\beta\gamma\varepsilon$), mm · mrad	Rad./axial $= 1.5/2\pi$
Energy spread, %	1
Magnet geometry	4 sectors radial ridge, straight
Average field B_{av}, kGs	10
Field at the hill B_{hill}, kGs	16
Valley field B_{vall}, kGs	4
Pole radius, mm	450
Hill gap, mm	50
Valley gap, mm	250
Sector angle, °	43
Coil power supply	500 A, 48 V, stability $= 10^{-5}$
RF frequency, MHz	61 (RF harmonic $h_{\mathrm{RF}} = 4$)
Number of dees	$2 + 2$
RF voltage amplitude, kV	50
Energy gain per turn, keV/turn	400
Number of turns to reach 8 MeV	20
Dee angular width, °	45
RF power supplies, kW	2×20
Flattop	Optional, 12 kV 3rd harm RF
External ion source	H^- CUSP high performance
Ion source current/emittance, mA/mm · mrad	15/0.8π (4 RMS)
Injection line	Einzel lens + SSQQ + 2 bunchers
Injection line voltage, kV	40
Bunchers — linear $+ 3/2\beta\lambda$ drift	Linear — one gap, drift — 2 gaps, $d_{\mathrm{holes}} = 15-20$ mm
Spiral inflector	$A^{\mathrm{el}} = 45$ mm, $k' = -0.7$, gap $= 10$ mm
Operating vacuum (with beam), Torr	$5 \cdot 10^{-8}$
Vacuum system	2CRP (each 4500 l/s) + 2TP (each 2000 l/s)
RF beam transmission, %	10 (bnch OFF), 15–20 (bnch ON)
Beam losses (gas stripping of H^- ions), %	< 0.5
Extraction elements	ES deflector + magnetic channel + protection foil
Type of extraction	Separated single turns
Useful RF phase band, %	20–30 RF
Pulse width, ns	1.5–2
Turn separation at extraction, mm	10

End of Table 3

Bunch radial width at extraction, mm	8
First harmonic h_1, Gs	< 2
Beam off-centering A_{coh}, mm	< 1
Trim/harmonic coils, sets/sets	4/2
RF phase collimators — two	Position — at the 3rd turn and the 10th turn

As an option, one can use precession extraction in combination with flattop in order to separate turns for the RF phase band of $\Delta\phi = 30^\circ$ RF. Two main dees and two flattop cavities will be installed. The second pair of dees can be used as flattop cavities. Technically, precession is more complicated than the high energy gain per turn. The special shape of the magnetic field in the extraction region will be required. In addition one should use the high precision stabilization of the RF phase of the second pair of the cavities. Flattop does not increase the useful RF phase band over 20–30°, but stabilizes the position of the precession maximum. A tight tolerance is set on the RF phase drift $\delta\omega < \pm 1^\circ$ if the flattop is not used. With flattop on the RF phases might fluctuate in the range of $\delta\omega = \pm 3^\circ$. The two dee options could be considered as well if the amplitude of the dee voltage will be increased from 50 to 80 kV. The RF power supply is to be more expensive. Spark problems may harm the stable operation of the machine.

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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