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

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Пархомчук В., Папаш А. E9-2006-69
Циклотрон H^--ионов на энергию 8 МэВ для подзарядки системы электронного охлаждения накопительного кольца высоких энергий

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). Оценены физические и технические параметры ускорителя. Рассмотрены различные варианты использования коммерческих циклотронов. Проведено сравнение характеристик ускорителей с точки зрения их использования как источника пучка отрицательных ионов водорода интенсивностью 1 мА. Проведена оценка различных вариантов. Предложен оригинальный проект, основанный на использовании систем и узлов существующих коммерческих ускорителей.

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Parkhomchuk V., Papash A. E9-2006-69
An 8 MeV H^- Cyclotron to Charge the Electron Cooling System for HESR

A compact cyclotron to accelerate negative hydrogen ions up to 8 MeV is considered the as optimal solution to the problem of charging 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 types of commercially available cyclotrons are compared as a possible source of a 1 mA H^- beam for the HESR. An original design based on the application of well-established technical solutions for commercial accelerators is proposed.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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INTRODUCTION

The High Energy Storage Ring [13] (HESR) is under construction at GSI (Darmshtadt, Germany) as a major part of the high energy upgrade of the existing heavy ion acceleration 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. A powerful cooling of antiprotons in the energy range from 0.8 to 14.5 GeV is mandatory to provide high resolution experiments to investigate hadrons 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 $3{\cdot}10^{32}$ cm^{-2} s^{-1} in antiproton–proton collisions employing an internal cluster jet or frozen pellets hydrogen targets with thickness of $5{\cdot}10^{15}$ atoms/cm^2. The antiprotons cooling rate should satisfy the required beam parameters. The beam heating due to intra-beam scattering, the fluctuations of ionization energy losses and multiple scattering of antiprotons on the target must be eliminated.

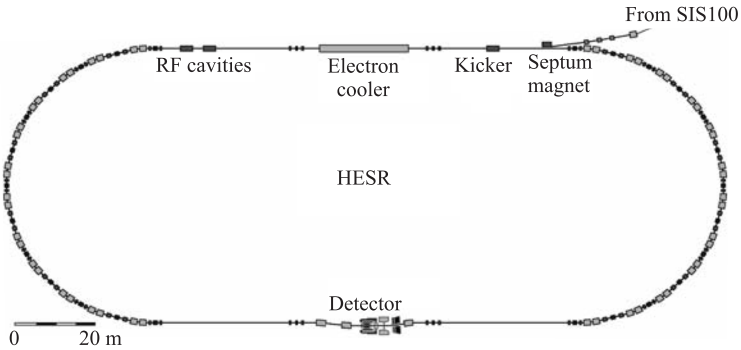


Fig. 1. Layout of the High Energy Storage Ring (HESR) for antiprotons [13]

1. ELECTROSTATIC COOLER

The electron cooling section of HESR consists of a charging device, solenoid and recuperation line (Fig. 2). An electrostatic column was 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).

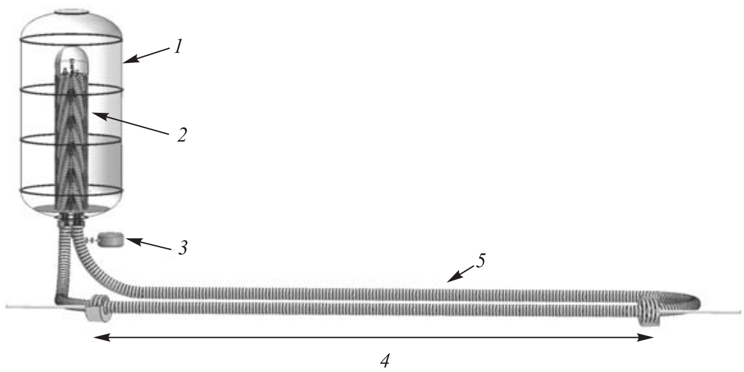


Fig. 2. The view of electron cooling system to accumulate 14 GeV antiprotons at HESR. *1* — high voltage tank; *2* — electrostatic column; *3* — cyclotron to charge head of electrostatic column; *4* — cooling section solenoid; *5* — reversal track (part of recuperation line)

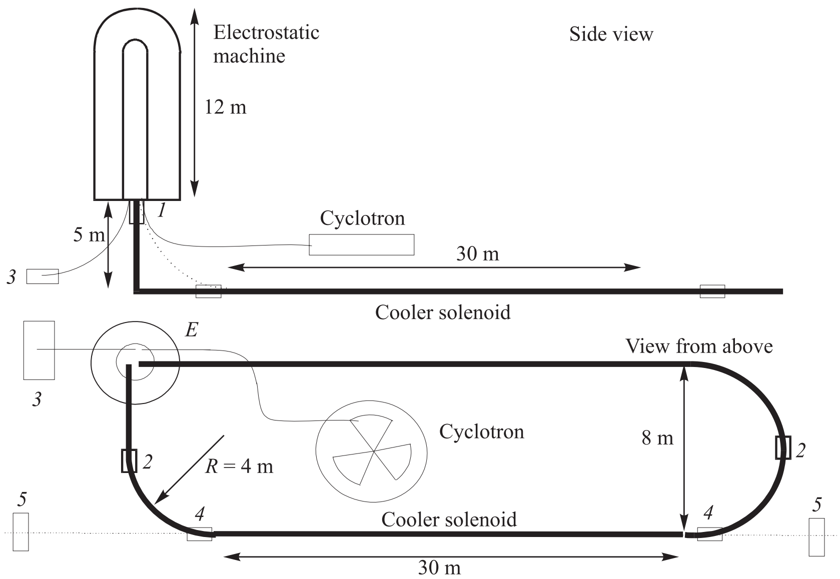


Fig. 3. High voltage cooler for the HESR. *1* — transformation section for the beam transfer from the low-magnetic field of the electrostatic column to the high magnetic field of the cooler; *2* — system of the electrostatic dipole corrections; *3* — energy analyzer of H^-beam for the precise voltage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

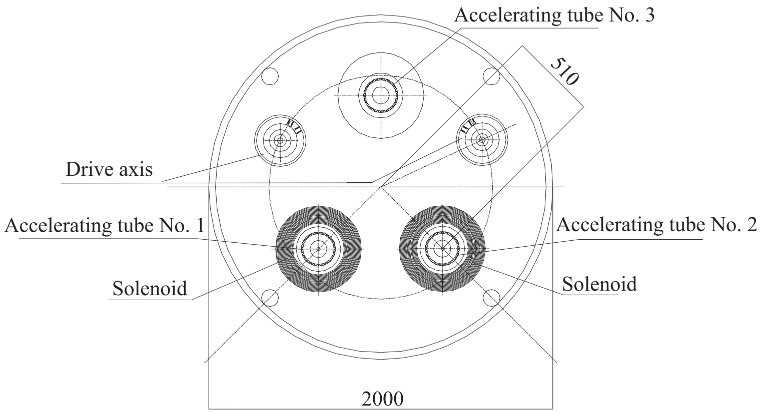


Fig. 4. Transverse cross section of the electrostatic column

The cooling solenoid and the recuperation line (30 m long each) are located in the horizontal plane. Three vertical optic channels are installed in the electrostatic column (Fig. 4). Two lines will be used to accelerate and decelerate electron beam on its way from the electron gun to the collector, the recuperation rate being 10^{-4}. Different charging systems are considered. Mechanical charging device like PELETRON or Van de Graaf belt cannot provide the required current of electron beam and voltage stability. An electron LINAC would produce a huge radiation background. Series of independent charging devices might be acceptable except any spark or discharge will destroy all elements in one section.

A cyclotron was chosen to charge the electrostatic column (Fig. 3). The third optic channel is designed to transport 1 mA beam of 8 MeV negative hydrogen ions to the head of the electrostatic column. The voltage of the column head is determined by the energy of H^- beam from the cyclotron. The electrostatic column is located in the center of the tank and consists of 80 sections with potential growing from the bottom section to the top. 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. 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. Shown in Fig. 4

are 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. The drive axes are made of a dielectric material and could withstand the potential difference between the sections. Accelerating tube No. 3 is 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.

2. COMMERCIAL CYCLOTRONS

The possibility to use commercial cyclotron is discussed in the following section. Commercial cyclotrons of the energy range from 10 to 30 MeV are widely used in isotope production and other medical applications. The experience gained for a few decades of exploiting of H^- cyclotrons should be considered in favor of a cyclotron based source of intense protons as well as negative hydrogen ions. As for today, the beam intensity from cyclotrons is limited by the extraction device.

It is worse to refer to the injector-II at PSI (Switzerland), where a 2 mA self-consistent proton beam is available. The TRIUMF 500 MeV cyclotron accelerates a 400 μA beam of H^- ions up to an energy of 500 MeV. A 30 MeV H^- beam of up to 1 mA current is available at cyclotron TR30. 3 mA beam of H^- ions was accelerated to 1 MeV at the central region model at TRIUMF [6]. The experience gained by TRIUMF scientists and engineers provides the theoretical and experimental confidence to increase the intensity of negative hydrogen beam [1, 2].

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.

2.1. 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 beam 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.

2.2. H^- Cyclotrons with an Internal Ion Source. 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.

One may refer to CYCLONE-10/5, CYCLONE-18/9 manufactured by IBA (Belgium), PET Unit based on the RDS-111 cyclotron (CTI, USA), Mini-Trace and PET-Trace (GE/SCANDITRONIX, USA), HM-12, HM-18 (SUMITOMO, Japan), etc. Modern commercial PET units are equipped with the third generation of commercial medical cyclotrons (Table 1). Also cyclotrons CP42 of Cyclotron Corporation are still in use and provide H^- beams of up to 200μA current.

Table 1. Commercial cyclotrons for production of PET isotopes

Cyclotron	Company	Country	Energy H^-, MeV	Energy D^-, MeV	Current H^-, μA
CYCLONE 10/5	IBA	Belgium	10	5	60
CYCLONE 18/9	IBA	Belgium	18	9	70
CYC10 Light	IBA	Belgium	10	–	70
MINI-TRACE	GE/SCAND ITRONIX	USA Sweden	10	5	60
PET-TRACE	GE/SCAND ITRONIX	USA Sweden	18	9	65
RDS-111	CTI	USA	11	–	100
HM-12	SUMITO HI	Japan	12	6	60
HM-18	SUMITO HI	Japan	18	9	60
TR1/9*	EBCO	Canada	18	9	< 300

* External CUSP ion sourse.

Most commercial cyclotrons were designed specifically to be used for producing PET isotopes (^{11}C, ^{13}N, ^{15}O, ^{18}F). The proton beam current required for producing PET isotopes is quite moderate – up to 70 μA on the target. The four-fold symmetry magnetic structure of cyclotron is of a closed type. Four sectors and four deep valleys create the profile of an isochronous magnetic field as well as desired flutter in order to provide adequate axial focusing. Return yoke, upper and low disks create closed magnetic flux. Four holes in upper valleys and four holes in low valleys are used for pumping, RF cavity support, diagnostic equipment, etc. Two dees are installed in opposite valleys. The gap between hills can be reduced to 20–50 mm while in the valleys, gap is almost 600 mm, flutter is large and axial focusing is provided by straight sectors without spiral edges.

Negative ions are produced inside a cold PIG ion source located at the center of the vacuum chamber (this type of ion production is referred to as internal injection). Particles are extracted from the source by RF voltage applied to two dees mechanically connected with each other by a strap.

H^- ions are accelerated using the fourth or second harmonic of the RF frequency. The vacuum conditions are quite moderate due to the high gas flow to feed the ion source. Vacuum is $8{\cdot}10^{-6}$ Torr when gas flow rate exceeds 3 sccm. The beam transmission as a function of energy for different vacuum conditions was measured at CYCLONE18/9 (IBA) and TR18/9 (EBCO Techn., Vancouver, Canada) (Fig. 5).

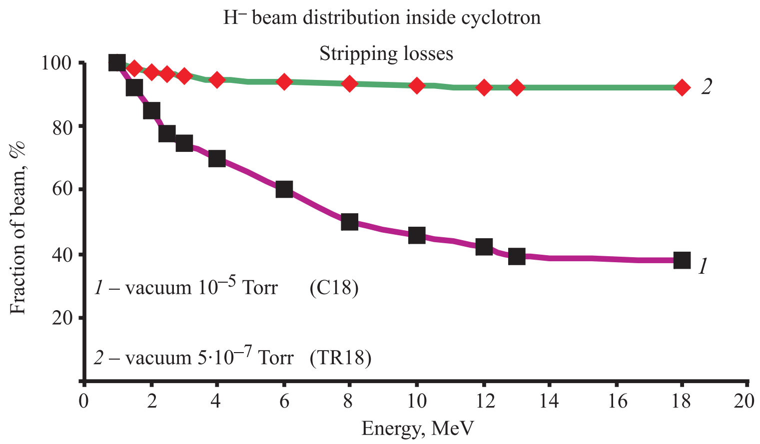


Fig. 5. H^- beam distribution inside of the cyclotron vacuum chamber

To distinguish the beam losses caused by non-isochronous motion from the losses of negative ions due to gas stripping, the polarity of the main magnet was reversed and a proton beam was accelerated. The magnet was tuned for an isochronous field. Part of the proton beam was lost due to the RF phase selection in the center of machine. No additional losses of the protons have been observed. Then polarity of the magnet was reversed and negative ions were accelerated. Cyclotron was tuned for isochronous motion. The degradation of the H^--beam intensity clearly indicates stripping losses inside the vacuum chamber. The beam losses due to the stripping of H^- ions were measured on many cyclotrons operating at different vacuum conditions (Table 2).

Some cyclotrons operate with internal ion source, others – with external injection from a CUSP source. Experimental data on H^- beam transmission versus vacuum are summarized in Fig. 6. Commercial cyclotrons CYCLONE10/5 and CYCLONE18/9 with an internal cold PIG ion source could provide up to 200 μA of H^- ions at 1 MeV – after the phase selection is done already. Nevertheless, the extracted beam is limited to 70 μA due to the poor vacuum conditions. By improving the vacuum inside the machine, the stripping losses can be reduced to an acceptable level and extracted current will be increased by a few times. Turbo-pumps (for example, two high speed turbo-pumps TPH-2301 from PFEIFFER with a pumping speed of 2000 l/s each) and cryo-pumps would

Table 2. Beam transmission versus vacuum conditions

Vacuum	Probe location	Transmission	Available current
10^{-5}	1 MeV pop up probe	100% (internal PIG)	200 μA
$2{\cdot}10^{-5}$	Extraction probe (18 MeV)	13% (internal PIG)	20 μA
$1.5{\cdot}10^{-5}$	Extraction probe (18 MeV)	28% (internal PIG)	40 μA
10^{-5}	Extraction probe (18 MeV)	37% (internal PIG)	40 μA
$8{\cdot}10^{-6}$	Extraction probe (18 MeV)	53% (internal PIG)	55 μA
$5{\cdot}10^{-6}$	Extraction probe (30 MeV)	75% (ext.CUSP+ ISIS)	350 μA
$3{\cdot}10^{-6}$	Extraction probe (30 MeV)	85% (ext.CUSP+ ISIS)	350 μA
10^{-6}	Extraction probe (18 MeV)	92% (ext.CUSP+ ISIS)	200 μA
$5{\cdot}10^{-7}$	Extraction probe (30 MeV)	$>$ 98% (ext.CUSP+ ISIS)	700–1000 μA

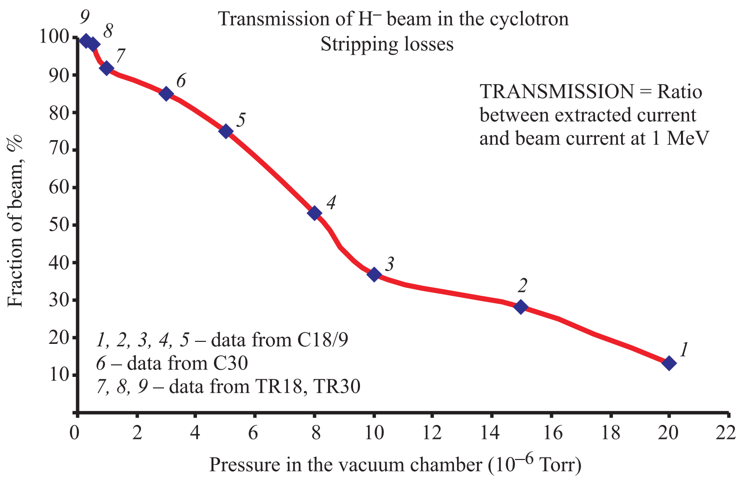


Fig. 6. Stripping losses of H^- beam during acceleration in the cyclotron

allow one to keep the average pressure inside the vacuum chamber at a level of 10^{-6} Torr even at a high gas flow from the ion source.

Two ion sources – one for H^- ions and the other – for D^- ions are installed in the vacuum chamber of CYCLONE18/9 as well as in CYCLONE10/5. Attempts were made to double the total beam current by running both ion sources with the same gas (hydrogen). The geometric position of the sources was not optimized to accelerate the two beams simultaneously. The results were negative presumably because the increased gas flow in the vacuum chamber caused a drop in the beam transmission. The installation of a few ion sources inside the cyclotron chamber could benefit the high intensity production of H^- ions only if one was able to provide vacuum conditions at a level of the $3{\cdot}10^{-7}$ Torr with 5÷8 sccm gas flow of hydrogen inside the cyclotron. The partial pumping speed for hydrogen should exceed 50000 l/s in order to maintain a high vacuum. At least four cryo-pumps with a pumping speed of 10000 l/s each should be installed into the free holes of the magnet yoke. *Commercial PET cyclotrons employing an internal PIG source are not acceptable for producing a 1 mA beam of H^- ions even with a modified vacuum system.*

2.3. Self-Extracted 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-extracted cyclotron [3]. The prototype machine is operating at IBA. 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 magnet. A proton beam of 6 mA intensity from an internal PIG source is accelerated to the final energy of 14 MeV. An extracted beam of up to 2 mA intensity is available. A few side effects might prevent from employing self-extraction. 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 extracted beam from a self-extracted cyclotron exceeds 10π mm·mrad while the designed value of the beam emittance for HESR is 2π mm·mrad.

3. H^- CYCLOTRON TR18/9 WITH EXTERNAL INJECTION

As for today, research and commercial cyclotrons accelerating a high current beam of negative hydrogen ions (up to 1 mA) were designed to inject H^- ions from an external ion source. Let us consider an example of cyclotron TR18/9 manufactured by the private company ADVANCED CYCLOTRONS (EBCO Technologies) from Vancouver, B.C., CANADA (Fig. 7). H^- ions are produced with a CUSP source which is biased to a negative potential of –25 kV. The three-electrode optics is adjusted to extract a low emittance beam from the plasma. A few versions of the CUSP source are available on the market. For producing PET isotopes, the TR18/9 cyclotron is equipped with a standard version of the ion source. The high performance version of CUSP also fits the injection system of TR18 and was tested on the modified version of TRD9 cyclotron. TR18/9 with some modifications can be considered as a *prototype* of a charger of HESR high voltage platform. The TR18 is oriented in vertical plane (Fig. 7).

The TR18 parameters are listed here:

• Accelerated beams — negative hydrogen ion (H^-), negative deuteron ions (D^-);

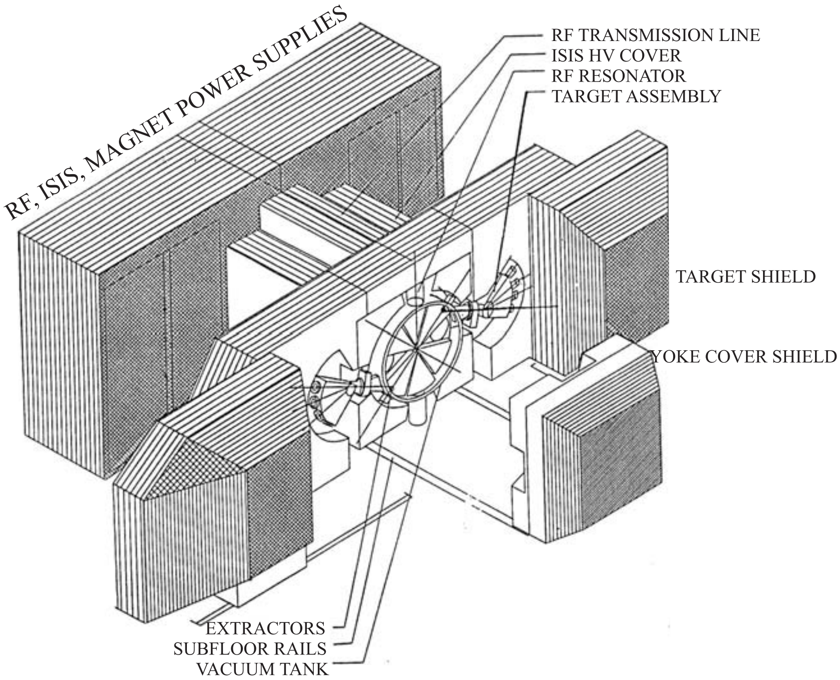


Fig. 7. General view of TR18/9 cyclotron. The self-shielding is shown

• Two extraction ports — simultaneous extraction in both directions (dual extraction);

• Two targets — located at the crossover points inside the return yoke of magnet;

• Two beam lines — with a switching magnet, quads and external targets;

• Beam energy — from 11 to 18 MeV, adjusted by the radial motion of the stripping foil;

• Extraction system — movable arm, pyrolytic carbon foil of 30 μg·cm^{-2} thick, 2 carousels, 5 foils per carousel;

• H^- extracted current — 200 μA (standard), 800μA (high performance ion source);

• D^- extracted current — 80 μA (standard), 300μA (high performance).

Magnet

• The median plane of the magnet is oriented in the vertical direction. Two sections (fixed and movable) are opened in the median plane, magnet weight — 25 t;

• Geometry — 4 sectors radial ridge, straight;

• 8 holes of 200 mm diameter in the valleys;

• Hill angle — variable from 32° in the center to 45° at the sector edge;

• Average field — 1.2 T, hill field — 2 T, valley field — 0.5 T;

• Hill gap — 35 mm, valley gap — 200 mm;

• Radius of sector — 560 mm, pole radius — 600 mm, yoke (square) — 1700×1700 mm^2;

• Magnet depth — 1080 mm, diameter of the injection hole in the magnet – 50 mm;

• Ampere turns — 85 kA × turns, coil cross section — 130×130 mm^2;

• Main magnet power supply — 500 A, 48 V, current stability of magnet PS — 10^{-5}.

RF system

• Number of dees — 2, angular width of dee (variable — 56÷42÷45°;

• RF frequency — 73 MHz (H^-), 36 MHz (D^-), RF harmonic of acceleration — 4 (H^-), 4 (D^-);

• Dee voltage — 50 kV, energy gain per turn — 200 keV, number of turns ≈ 90;

• Axial gap in the dee — 20 mm, axial gap in the puller — 10 mm;

• Power of RF amplifier — 20 kW (PET option), 30 kW (high beam current);

• RF voltage stability — 10^{-4}, RF frequency stability — 10^{-7}.

Vacuum system

• Pressure in the vacuum chamber — $2{\cdot}10^{-7}$ Torr (beam off), $4{\cdot}10^{-7}$Torr (beam on);

• Pressure in the source diagnostic box — $5{\cdot}10^{-7}$ Torr (beam on);

• Cryo-pump — 4,500 l/s (H_2O), 1,500 l/s (N_2) are installed inside of the hole in the magnet yoke;

• Cryo-pump and two turbopumps (200 l/s) are attached to the source diagnostic box;

• Vacuum chamber — an aluminum cylinder isolated by a pair of O rings between magnet poles.

Ion source

• External H^- MULTICUSP, injection energy (bias voltage) — 25 kV (H^-), 12.5 kV (D^-);

• Beam current / emittance (4 RMS, normalized) — 5 mA / 0.35 π mm·mrad (standard);

• Beam current / emittance (4 RMS, normalized) — 10 mA / 0.6π mm·mrad (modified);

• Beam current / emittance (4 RMS, norm.) — 20 mA / 0.8π mm·mrad (high performance);

• Diameter of extraction hole — 8÷10 mm, beam divergence at source exit - 15 ÷ 25 mrad;

• Arc current — up to 60 A, arc voltage — 100 V.

Injection line (ISIS)

• Einzel lens —- voltage 20 kV, displaced $\approx$ 100 mm downstream of source exit;

• Pipe diameter – variable from 100 mm inside solenoid to 50 mm in the yoke;

• Solenoid + axially rotated doublet of quads + two pairs of beam correctors;

• Beam diagnostic box — Faraday cup – ion beam stop (IBS), scanner, vacuum equipment.

Spiral inflector

• Electric radius $A_{\rm el}$ = 25 mm, tilt parameter of the modified central region $k' = -0.76$;

• Gap between the inflector plates — 8 mm at the entrance, 6.5 mm at the exit;

• Ratio between the plate width and the gap = 2, voltage between the plates = $\pm$ 7 kV;

Control system

• Computer system — Pentium PC, controllers — Allen–Bradley industrial PLC modules;

• Interface — Graphical user interface.

Beam parameters

• ISIS transmission (ion beam stop to inflector entrance) – 50% (20 mm collimator);

• ISIS transmission (ion beam stop to inflector entrance) – 80% (30 mm collimator);

• Out of 15 mA of H^- beam from the source 12 mA might be injected into the cyclotron;

• RF acceptance (DC : CW beam) — 10% buncher off, 20% buncher on;

• RF phase band accepted by the central region — 60° RF (standard), 90° RF (modified);

• Pulse width — 2.5 ns (60° RF), pulses period — 14 ns;

• Radial betatron tune ν_r = 1.06, axial betatron tune ν_z = 0.56;

• Circulating normalized emittance (4 RMS): radial — 1 π mm·mrad, vertical — 0.5 π mm·mrad;

• Beam axial width — 8 mm at injection, reduced to 5 mm at extraction;

• Extraction radius — 500 mm (18 MeV);

• Radius gain per turn (18 MeV) — 2.5 mm, beam radial width — 5 $\div$ 6 mm;

• Amplitude of the first harmonic $\sim$ 2 Gs; radial coherent oscillations $\sim$ 1 mm;

• Number of turns painting stripping foil — 3$\div$4, single turn extraction not available;

• Energy spread: in the circulating beam — 100 keV, in the extracted beam — 200 keV;

• Beam spot on the stripping foil — 5×5 mm^2.

The cross section of the TR18 cyclotron in the median plane is presented in Fig. 8. One can see the yoke, the four sectors, the two stripper foil mechanisms, the two extraction ports, etc. Dees are located in the free space of two opposite valleys. The cross-over points inside the return yoke are shown as well.

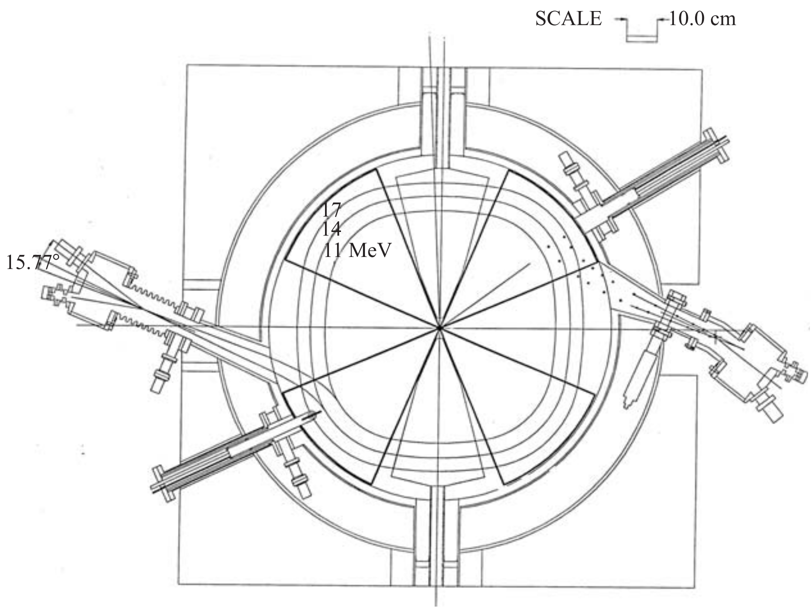


Fig. 8. Cross section of TR18 cyclotron in the median plane

The beam transmission from ISIS to the cyclotron (RF acceptance) depends on the transverse emittance of the injected beam (Fig. 9). Tests were performed on a commercial cyclotron designed by EBCO Technology [5]. The CW beam was measured with 1 MeV pop up probe as the ratio of the CW beam to the DC current in the injection line. The beam emittance was varied with collimators located in the drift section of ISIS. The transmission dropped by two times when the beam emittance was increased from 0.3 to 0.8 π mm·mrad [9]. Simple increasing the beam current from ion source cannot benefit the design goal to reach 1 mA because of the degradation of the beam transmission. In order to extract an 1 mA beam, one should inject over 12 mA of negative ions with an 4 RMS normalized emittance less than 0.6 π mm·mrad.

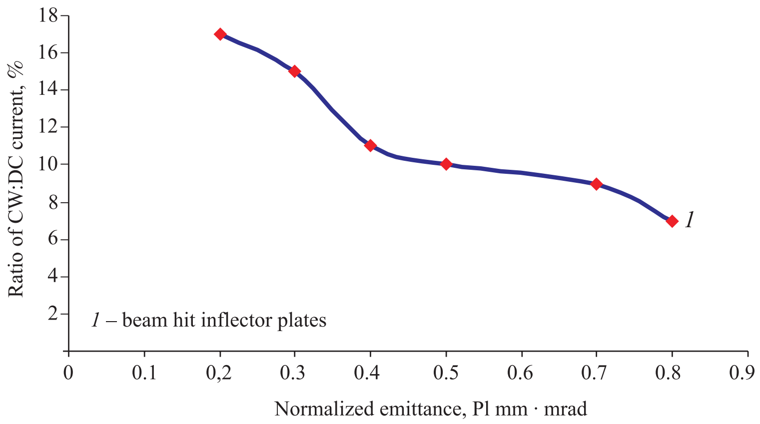


Fig. 9. Dependence of TRD9 cyclotron acceptance on emittance of injected beam. Buncher is off [9]

4. HIGH CURRENT COMMERCIAL CYCLOTRONS OF THE 30 MeV ENERGY RANGE

Two commercial cyclotrons, CYCLONE-30 from IBA (Belgium) and TR30 from EBCO Techn. (Canada) are capable of accelerating an H^- beam of more than 500 μA. Their main parameters are presented in Table 3. The original version of a CUSP ion source is installed at CYCLONE30. A 4 mA H^- beam of the 8 mA H^- beam supplied by the source is available for injection inside the cyclotron. The beam transmission is quite improved at C30 thanks to an RF buncher located in the injection line. About 30% of the injected DC beam are accelerated to the final energy. The vacuum in the CYCLONE30 vacuum chamber is moderate (Table 3), and up to 20% of the beam is lost during acceleration due to gas stripping (Table 2). The normalized emittance of the extracted beam exceeds 5 π mm·mrad. Using a high performance version of the ion source, a modified vacuum pumping system based on a high speed turbo-pumps and cryo-pump, modernized injection, one could expect an extracted beam of up to 700 μA from C30.

TR30 cyclotron is equipped with a high performance version of the CUSP source [4]. A few TR30 cyclotrons operate with a beam current of moire than 1 mA [6]. The beam transmission inside the TR30 is better than 99% thanks to the good vacuum conditions and external injection. The ion source, the injection line, the vacuum system, the RF, the extraction mechanism are pretty similar to those at TR18. The beam energy is varied from 15 to 30 MeV by the radial movement of the stripping foil mechanism.

Table 3. Parameters of the CYCLONE30 and TR30 commercial cyclotrons

Parameter	CYCLONE30	TR30
Beam current	$350 \div 500$ μA	$500 \div 1000$ μA
Energy (H^- ions)	15-30 MeV	15-30 MeV
Extracted emittance (normalized $= \beta\gamma\varepsilon$)	Radial $= 10\pi$ mm $\cdot$ mrad Axial $= 5\pi$ mm $\cdot$ mrad	2π mm $\cdot$ mrad 2π mm $\cdot$ mrad
Energy spread	2%	1%
Average field $B_{\rm av}$	10 kGs	12 kGs
Max. field in the Hill $B_{\rm hill}$	17 kGs	19 kGs
Min. field in the Valley $B_{\rm vall}$	1.2 kGs	5.5 kGs
Pole Radus	91 cm	76 cm
Hill gap	5 cm	4 cm
Valley gap	50 cm	18 cm
Sector angle	$54\div 58^\circ$	$32\div 45^\circ$
Coil power	7 kW	30 kW
RF frequency	65.5 MHz	74 MHz
Number of Dees (RF harmonic)	2 ($h_{\rm RF} = 4$)	2 ($h_{\rm RF} = 4$)
Amplitude of RF voltage	50 kV	50 kV
Number of turns	180	150
Dee angular width	30°	45°
RF power	15 kW	35 kW
Ion Source	H^- multi-CUSP	H^- multi-CUSP
DC Output current from Source	5 mA	10–15 mA
Source emitance (normalized $= \cdot\beta\gamma\varepsilon$)	0.8π mm $\cdot$ mrad	0.37π mm $\cdot$ mrad
H^- Injection energy	30 keV	25 keV
Vacuum (with beam)	$3{\cdot}10^{-6}$ Torr	$3\div5{\cdot}10^{-7}$ Torr
Vacuum system	Cr-Pmp + Diff.Pmp	2 Cr.Pmp (4,500 l/s)
RF Acceptance — CW to DC current	30 % Buncher on	12% Buncher off
H^- losses due to gas stripping	20%	Less than 1%
Type of extraction	Stripping on foil	Stripping on foil
Number of turns to paint foil	$5 \div 7$	$3 \div 5$

5. VACUUM CONDITIONS IN AN 8 MeV H^- CYCLOTRON

The cyclotron should supply the high-voltage terminal of the HESR electron cooling system with a beam of H^- ions of 8 MeV energy and a current of up to 1 mA. Particles will be extracted from the cyclotron 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). Electrons are spiralling along the magnetic field lines and produce avalanche conditions. 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. Computer simulations of the beam losses due to the stripping of H^- ions on the molecules of the residual gas as well as the beam losses due to Lorentz stripping were carried out for a 100 MeV H^- cyclotron C100. C100 is under construction as a part of radioactive ion beam facility of the China Institute for Atomic Energy [8]. An H^- beam of 500 μA intensity will be accelerated at C100.

5.1. Basic Process of Lorentz Stripping. At high energies, the magnetic field of a cyclotron produces strong electric field in the rest mass frame of the H^- ion which can strip the second electron from the negative ion, because of the additional electron is weakly bound in hydrogen by $E_0 = 0.755$ eV. The Lorentz transformation of a magnetic field B in the lab-frame to the electric field E in the rest frame is

$$E = \gamma\beta c B, \tag{1}$$

c is the speed of light, γ and β are the usual relativistic parameters. The relationship between the life time $\tau(E)$ of an H^- ion and the electric field E can be expressed as

$$\tau(E) = (A_1(E_0)/E)\exp{(A_2(E_0)/E)}, \tag{2}$$

where constants A_1 and A_2 are functions of the binding energy E_0 and for H^- were found experimentally and are equal to [8]

$$A_1 = 2.47 \cdot 10^{-6}\,\mathrm{V \cdot s/m} \tag{3}$$

and

$$A_2 = 4.49 \cdot 10^9 \ \text{V/m}. \tag{4}$$

The fraction of ions dissociated by the Lorentz field E after the beam travels a distance L is a function of the beam energy ($W^{1/2} \sim \beta$) and magnetic field B

$$f = 1 - \exp{(-t/\gamma\tau)} = 1 - \exp{(-L/\gamma\beta c\tau(B))}. \tag{5}$$

To simulate an acceleration process, expressions (2) and (5) were included into into the equations of motion and integrated in a real magnetic field [8]. Providing the maximum value of the magnetic field at the hill is 2 T and the energy gain per turn is 200 keV/turn, one should expect no more than 10^{-6} part of the beam will be lost due to Lorentz dissociation. In case of an 8 MeV cyclotron the electromagnetic losses should be negligible – less than 10^{-8} part of beam intensity.

5.2. Beam Losses due to Gas Stripping. A portion of H^- ions will collide with the molecules of the residual gas and will be stripped. One may estimate the ratio of beam losses *dI* per unit length *dl* by formula

$$dI/dl = \eta\sigma I_0, \tag{6}$$

where η is the number of gas molecules per unit volume; σ is the partial cross section of stripping between H^- and N_2, H^- and O_2, H^- and H_2O; I_0 is the initial beam current.

Formula (6) was included into the equations of motion and integrated for different vacuum conditions [8]. The 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 an 8 MeV H^- cyclotron because the cross sections are higher for low energies and most of the stripping of H^- ions is produced at low energies. An operating pressure $5{\cdot}10^{-8}$ Torr will be satisfactory to avoid DC positive discharge. Also the beam dissociation caused by the stripping of negative ions on the molecules of the residual gas will be reduced. Less than 0.2% of beam will be lost due to gas stripping. The beam intensity distribution versus vacuum was measured for TR18/9. While the residual gas pressure inside the TR18 vacuum chamber was maintained at a level of $3{\cdot}10^{-7}$ Torr, H^- ions were accelerated to the final energy without any measurable losses of intensity (Table 2). It would be difficult to maintain a high vacuum in the cyclotron if an ion source will be installed inside the vacuum chamber. With a gas flow in the source of 3 sccm, one should provide a pumping speed of over 50000 l/s to keep a pressure of $3{\cdot}10^{-7}$ Torr.

External injection should be used in order to minimize gas stripping and maintain high voltage on the deflector. Differential pumping will be used. Two high speed turbo-pumps (TPH2303 with a 2000 l/s pumping speed each) and one cryo-pump ($4500{\div}10000$ l/s for H_2O) can be attached to the ion source diagnostic box. Two cryo-pumps and two high speed turbo-pumps can be installed in the free holes of the magnet yoke. The turbo-pumps must be shielded from the residual magnetic field. The induction of the field at the external part of the hole in the yoke does not exceed 200 Gs. A protection cylinder made from 15 mm soft iron should restrict the residual magnetic field to 50 Gs close by to turbo-pump vanes. 70 Gs limit of transverse component of the residual magnetic field and and 100 Gs limit for longitudinal component being set by PFEIFFER as maximum allowable value for pump TPH2303.

6. ESTIMATION OF THE BEAM PARAMETERS OF AN 8 MeV H^- CYCLOTRON

It might be useful to estimate the beam parameters by using semi-empirical formulas, the results of measurements for similar cyclotrons. The RF acceptance of a high current H^- cyclotron like TR18, CYCLONE30, TR30, etc. is 40° RF. When the magnetic field is perfectly isochronized and no phase selection is applied, one should expect the RF phase band to be up to 60° RF. A large RF phase acceptance is considered as a positive feature for stripping extraction when number of turns to be extracted is not important. The orbits are not separated and overlapped in the extraction region. The energy of a particle in an isochronous cyclotron [7] is proportional to

$$E \approx 48\ B^2 R^2 (Z^2/A)[\text{MeV, T, m}], \tag{7}$$

where B is the value of the average magnetic field at radius R; Z is the charge of the particle; A is atomic number.

The number of turns to reach the energy E is

$$N = E/(\Delta E \cos\phi) = E/2N_{\rm dee}V_{\rm dee}\sin{(h_{\rm RF}\Delta\theta_{\rm dee}/2)}\cos{(\phi-\phi_0)}, \tag{8}$$

where ΔE is the energy gain per turn; $V_{\rm dee}$ — the peak RF voltage; $N_{\rm dee}$ — the number of the dees; $h_{\rm RF}$ — the harmonic of the RF; $\Delta\theta_{\rm dee}$ — the angular width of the dee; ϕ and ϕ_0 — RF phase of the particle and the initial RF phase. The amplitude of the dee voltage $V_{\rm dee}$ is a function of radius. For estimation purposes, one can use the value of the amplitude at the center of the cyclotron. The phase advance per turn of beam precession in the radial phase space is proportional to

$$\Delta\phi = 2\pi(\nu_R - 1). \tag{9}$$

Particles of different RF phases have a different energy gain per turn and will rotate different numbers of turns in order to reach the foil. The representation points will fill different positions in the phase space. For an 8 MeV cyclotron the radial betatron frequency is $\nu_R \approx 1.06$. The number of turns to fill in precession cycle is proportional to $2\pi/\Delta\phi$

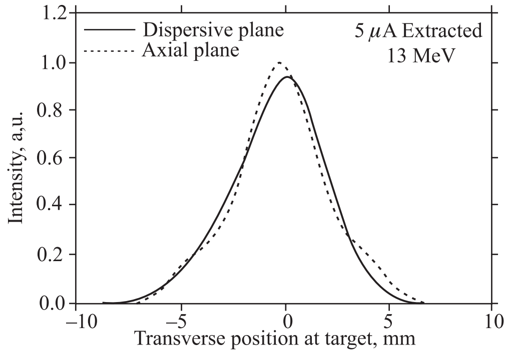
$$N_R = (\nu_R - 1)^{-1} \approx 16. \tag{10}$$

The central particles ($\phi_{\rm RF} \approx 0°$) receive the maximum energy gain per turn and will be accelerated at TR18 to the final energy for 90 turns. The off-phase particles ($\phi_{\rm RF} \approx +/-10{\div}20°$) need more turns (95÷97) to be at the same radius. At TR30, the central particles are accelerated for over 150 turns and the off-phased particles for 160÷165 turns. The effective area occupied by the representative points in the radial phase space will grow due to the precession mixture as

$$\varepsilon = \varepsilon_0(1 + A_{\rm coh}/X_0)^2, \tag{11}$$

where ε_0 — the emittance of the injected beam; $A_{\rm coh}$ — the amplitude of the coherent oscillations induced by the first harmonic h_1 of the magnetic field B

$$A_{\rm coh} = Rh_1/2B(\nu_R - 1). \tag{12}$$



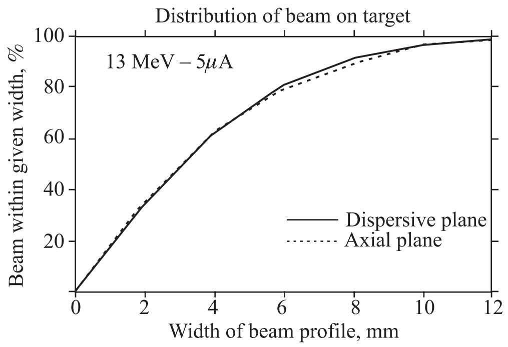


Fig. 10. Beam profile on target measured at TR13 (TR18 prototype)

The beam size (referred to as the incoherent amplitude of the radial oscillations) can be estimated from the following expression [10]:

$$\varepsilon^n = \pi\beta\gamma X_0\,(\mathrm{mm}) P_x\,(\mathrm{mrad}) = \pi\beta\gamma^2 \cdot X_0 \cdot X_0 \cdot 1000/R_\infty. \qquad (13)$$

Here, all the length units are in [mm], the emittance is in [π mm $\cdot$ mrad], β, γ — the relativistic parameters. The infinity radius $R_\infty = c/\omega$. During magnetic measurements and the shimming of cyclotrons TR18 and TR30, the first harmonic of the magnetic field was minimized to 2 Gs in order to keep the radial oscillations less than $A_{\mathrm{coh}} < 1$ mm. The energy spread for multiturn extraction is given by

$$\Delta E = dE/dr \cdot (2X_0 + dR/dn) = (\beta\gamma^3 E_0/R_\infty)(2X_0 + dR/dn). \qquad (14)$$

The radial width of the $\Delta\phi_{RF} \approx 40°$ RF phase band beam is $2\delta R = 5{\div}8$ mm for TR18 and TR30, coherent oscillations due to the imperfection first harmonic should add a few mm to the total width. The circulating radial emittance of the H^- beam for the TR13 cyclotron as well as the other beam parameters were measured by TRIUMF's scientists (Table 4). The shadow method was employed [10]. The beam profile on the target and the beam current within the given width are shown in Fig. 10.

The fraction of the beam included in the phase space area is given in Table 4. The area in the phase space corresponding to the circulating radial emittance $\beta\gamma\varepsilon_r = 2\ \pi$ mm · mrad covers almost 99% of the beam intensity. The beam density distribution is slightly different from Gaussian. The beam core, 2÷3 mm in diameter, is surrounded by tails (beam hallow). 90% of the beam is included into the phase area of $\beta\gamma\varepsilon_r = 1\ \pi$ mm · mrad. Beam collimation with moderate intensity losses can be used for an 8 MeV cyclotron. The beam shape can be tailored to satisfy the conditions for single turn extraction at 8 MeV even in the case of the high current operation mode.

Table 4. Circulating radial emittance of an H^- beam measured by the shadow method at TR18

Norm. emittance $\beta\gamma\varepsilon_r$ [π mm · mrad]	0.5 π	1 π	1.5 π	2 π
Fraction of the beam included in the phase area	66%	90%	97%	99%

7. EXTRACTION OF H^- IONS FROM AN 8 MeV CYCLOTRON

There are few possible ways to extract a beam from the cyclotron.

• Existing commercial H^- cyclotrons utilize extraction by stripping H^- to protons on foil. The ions reverse the curvature of rotation in the magnetic field and escape the magnetic field of the cyclotron. The extraction efficiency is close to 100%. Up to 1 mA of the extracted beam is available in a routine operation at TR30.

• Protons are accelerated in the self-consistent mode at the 72 MeV cyclotron INJECTOR-2. Almost 2 mA of particles are accelerated to 560 MeV by combination space charge forces with magnetic focusing and the round beam. The pulse width is less than 2° RF. There are almost no tails in the bunch after collimation. Turns are separated. The extraction efficiency is as high as 99.98%.

• Precession extraction was invented by Prof. H. Blosser and used at the MSU NSCL superconducting cyclotrons K500 and K1200. The extraction efficiency depends on the beam quality and pulse width. For the RF phase band of ∼ 20° RF the extraction efficiency is 80%. Almost 96% of the beam is extracted when beam is collimated to the narrow phase band (3° RF). There is no turn separation unless the flattop technique is applied.

• Extraction from the radius where the magnetic field is close to the isochronous value. It is used at many scientific and commercial cyclotrons like C235 for proton therapy, etc. The extraction efficiency varies from 50 to 80% depending on the beam quality.

• Self-extraction. It was invented by IBA at the self-extracted cyclotron CYCLONE14+. Up to 30% of the unwanted beam must be dumped. The beam quality is moderate.

The separation of turns and combination with flattop and precession extraction can be used to extract an H^- beam from 8 MeV cyclotron.

The radius gain per turn of H^- ions at TR18 is $dR/dn = 2.8$ mm at 18 MeV and 3.3 mm at 13 MeV (Table 5). Phase ellipse paints stripping foil few times. For a single RF phase, the half-width of a turn is $X_0 = 2.1$ mm ($\beta\gamma\varepsilon_r = 2\ \pi$ mm $\cdot$ mrad). The radial size of the bunch exceeds the radial increment between turns. 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 turns. The size of the beam spot on an extraction foil or a totally intercepting probe or a post, will be given by

$$W = dR/dn + X_0 \sin\left[2\,\pi\nu_R\right] \approx dR/dn + X_0[2\,\pi\,(\nu_R - -1)]. \qquad (15)$$

Table 5. 8 MeV H^- cyclotron. Beam width and radius gain per turn

E, MeV	$f_{\rm orb}$	$h_{\rm RF}$, MHz	B, kGs	R_∞, mm	B$\gamma\varepsilon = \pi$ mm $\cdot$ mrad	$2X_0$, mm	$R_{\rm extr}$, mm	$N_{\rm dee}$	*dE/dN*, keV	N, turn	*dR/dN*, mm
18	18	4	12	2607	1 π	2.8	500	2	200	90	2.8
13	18	4	12	2607	2 π	4.2	430	2	200	65	3.3
8	18	4	12	2607	1.5 π	4	340	2	200	40	4.3
8	15	4	10	3180	1.5 π	4.4	400	2	200	40	5.1
8	**10.7**	**4**	**7**	**4460**	***1.5*** π	**5.2**	**570**	**2**	**200**	**40**	**7.2**
8	18	4	12	2607	1.5 π	4	340	4	400	20	8.5
8	15	4	10	3180	1.5 π	4.4	400	4	400	20	10
8	10.7	4	7	4460	1.5 π	5.2	570	4	400	20	14
8	18	4	12	2607	2 π	4.6	340	4	400	20	8.5
8	**15**	**4**	**10**	**3180**	***2*** π	**5**	**400**	**4**	**400**	**20**	**10**
8	10.7	4	7	4460	2 π	6	570	4	400	20	14

In case of multiturn 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*. For TR18 and TR30, the normalized radial emittance of the extracted beam is $\beta\gamma\varepsilon_{\rm extr} = 2\ \pi$ mm $\cdot$ mrad.

8. THE BEAM PULSE STRUCTURE

Commercial pulsed cyclotron TRD9, which is the modified version of TR18/9 was used as a source of deuterons to generate neutron pulses. A pulsed beam of D^- ions was accelerated at TRD9 to 9 MeV, extracted and directed to a Be target [5]. The total radial size of the deuteron beam was measured as $2\delta R = 5$ mm for the RF phase band of $\Delta\phi_{\rm RF} \approx 40°$. In the extraction region of TRD9, the radius gain per turn of D^- ions is $dR/dN = 5$ mm. The amplitude of the coherent oscillations was restricted to 0.8 mm. Investigations on the pulse structure of the TRD9 beam experimentally proved the multiturn nature of stripping extraction. A fast Faraday cup and pick up electrodes were installed in the beam line and the time structure of the beam pulses was measured. The orbital frequency of D^- ions in TRD9 is $f_{\rm orb} = 9$ MHz, the RF frequency is $f_{\rm RF} = 36$ MHz. D^- ions were injected into the cyclotron at the energy of 15 keV/A, were accelerated in the CW mode and extracted. Time structure of the extracted beam was measured by 2 GHz fast oscilloscope. The pulses in the CW mode were separated by 27.7 ns. The pulse width at the base of peak was $\tau_{cw} = 4$ ns ($\delta\varphi \sim 53°$ RF). In the pulsed mode, a DC beam was chopped in the injection line with a repetition rate $f_{\rm pulse} = 1$ MHz. Single pulses of D^- ions of the pulse width $\tau_{\rm pulse} = 10 \div 20$ ns were injected into TRD9, accelerated to the final energy of 9 MeV and extracted via stripping on foil. It was expected that the radial beam size in TRD9 is less than radius gain per turn $dR/dn = 5$ mm. Single bunches should be separated by $T_{\rm pulse} = 1\ \mu$s (single turn extraction). Thus every single pulse will paint foil and extracted in single turn mode. A fast Faraday cup was installed in the beam line and measurements of pulses were performed. It was found that two or three peaks follow with a frequency $f_{\rm cycl} = 9$ MHz. Pulses are extracted every period of the rotation of the ions in the cyclotron – $T_{\rm cycl} = 109$ ns (Fig. 11). The beam pulses paint extraction foil in few times which is a direct prove of multiturn extraction. Only 20% of pulse intensity at the injection was captured for further acceleration. The rest of the beam was cut off by the radial collimators in order to reduce the parasitic tails. The pulse width of each peak is $\tau_{\rm pulse} = 2$ ns ($\delta\varphi \sim 25°$). The only reason for the presence of satellite peaks could be that the radial beam size including the tails is larger than the radius gain per turn. Turns are overlapped in the CW mode of operation.

Two radial collimator flags were installed inside the vacuum chamber of TRD9 — one at the center and the other – at the middle radius. The radial position

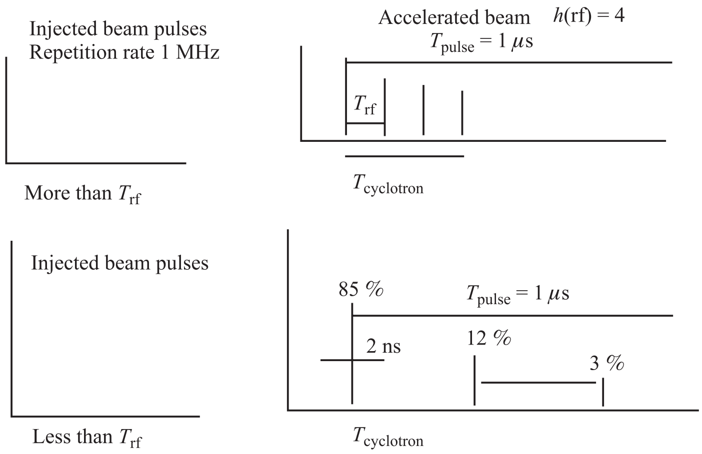


Fig. 11. Time structure of pulsed beam at the TRD9 cyclotron

of the flags, the dee voltage and the current of the magnet were optimized in order to reduce the unwanted beam. The cyclotron was tuned for a better ratio between main peak and the satellites. The diaphragms were installed in the injection line in order to reduce the beam emittance from 0.8 to 0.35 π mm $\cdot$ mrad. Two peaks were present even at the best tuning. The third peak was suppressed to a level of the RF noise. Without phase selection (collimators were out), the particles of the wide RF phase band of 40$\div$50° RF paint the stripping foil. The beam current distribution between peaks is $I_1 : I_2 : I_3 = 60 : 30 : 10\%$. By applying the phase selection the phase band was restricted to 20° RF. The current distribution between peaks is much better $I_1 : I_2 : I_3 = 80 : 15 : 3\%$. Almost 85 $\div$ 90% of the beam were extracted in one turn and rest during another turn.

Computer simulations were carried out to estimate the beam intensity distribution in the extraction region of TRD9. The central orbits were tracked from the source to the extraction. The total number of turns in the TRD9 D^- cyclotron to reach 9 MeV is to be about 55. In the center of machine where the turn separation is 20 to 15 mm the position of central phase particle (0°) and particle with RF phases of (±15°) is close enough. The orbits are not overlapped. Due to the dependence of the energy gain per turn on the RF phase, the particles spread out in radius and the turns are overlapped. Without radial collimators, the distribution of the beam intensity between extracted turns is to be 50 : 40 : 10%. With collimators adjusted to cut tails, two turns hit the foil. The intensity distribution between peaks is 85% to 12%. About 3% of beam intensity was considered as a noise. The results of experimental tests well agreed with a computer analysis.

Benefit of flattop was simulated by adding the RF voltage to the 3rd harmonic of the main RF. The particles of 30° RF phase band were tracked to the stripping foil. The radial position of each turn was stabilized. The turns were separated.

Almost 150 μA of an 8 MeV H^- beam might hit the deflector septum if the turns are not separated. The power of 1.2 kW must be dissipated by the deflector septum of 0.25 mm thickness. No direct water cooling of the deflector septum is possible, only the radiation losses. It is known from cyclotron operation experience that a 0.5 mm tungsten septum can dissipate no more than 250 W of power of an incident beam. The radiation background in the region of the septum exceeds 200 Roe. There is a possibility to protect the deflector septum from an incident beam of negative ions. The carbon foil of 2 mm width could be installed between the last circulating turn and the extracted turn. So far the hallow between last circulating orbit and extracted beam will be removed. The deflector septum will be shadowed from a direct hit by an incident beam. The radial betatron tune of 8 MeV H^- cyclotron is $\nu_R \sim 1.06$. The azimuth and radial position of the protection foil should be optimized in order to shadow the septum. The stripped protons will be directed to the dump target with water cooling and radiation protection.

9. PRECESSION EXTRACTION AND FLAT-TOP

Precession extraction was invented by Prof. H. Blosser and successfully employed at many cyclotrons. The radial profile of the magnetic field is shaped in a special way in the extraction region. 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 crossing unit ($\nu_r =$ 1). The coherent radial oscillations are excited. Following precession increases separation between turns in a few times – for example from $dR/dN = 0.4$ to 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 $\Delta\phi \sim 3^\circ$ and up to 80% for wide RF phase band $\Delta\phi \sim 20^\circ$. 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 $\phi = 0^\circ$ RF to the phase $\phi \approx -\ 40^\circ$ and rised up to positive value $\phi \approx +\ 40^\circ$. Phase motion must be strictly controlled to avoid the deceleration. A combination of precession and flat-top should improve the extraction efficiency for a wide RF phase band. Computer simulations of precession extraction [11] and experiments [12] 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. 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 maximums and minimums. A typical ratio of the beam density was 80% at the precession maximum and 20% at the precession minimum (Fig. 12). A wide carbon foil of 1 mm was placed between the precession maximums where the beam density is minimal. The foil intercepts unwanted beam. Up to 70 μA of 430 MeV H^- ions were extracted by the deflector without hitting the deflector septum or the potential electrode. The H^- ions of 10 μA were stripped and directed to a special dump area. The septum of the deflector was shadowed by the protection foil.

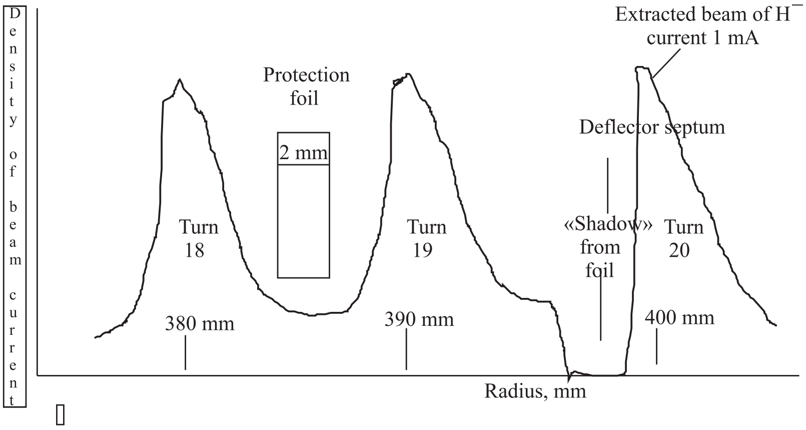


Fig. 12. Radial profile of 8 MeV H^- beam at extraction

Computer simulations and following experiments were performed by R. Laxdal, G. Mackenzie, L. Root and one of the authors [11, 12] to estimate the merits of flat-top. 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 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 flat-top 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° RF by detuning the main RF frequency $f_{RF} = 23$ MHz in the range of $\pm$ 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 flat-top was applied. Also the radial position of the precession maximums was drifted in time due to the different factors like change of the dee voltage, drift of the cooling water temperature, etc. When flat-top was turned on, the radial position of precession maximums does not moved even if the RF phases was detuned on 100 Hz, i. e. RF phase was shifted from 0 to $\pm$ 10° (RF phase band is $\Delta\phi_{\rm RF} \approx 20°$). The radial position of precession maximums 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%. In an 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 $18^{\rm th}$ and $19^{\rm th}$ turns, intercepts the unwanted beam and creates shadow for the deflector septum. The width of protection foil can be varied from 1 to 3 mm to optimize extraction efficiency.

10. TURN SEPARATION AT AN 8 MeV H^- CYCLOTRON

Modifications are required to adapt TR18 cyclotron to be used for accelerating and extracting 8 MeV H^- ions. The magnetic structure, the RF system should be redesigned in order to provide turn separation. The stripping mechanism should be substituted with deflector and magnetic channels. To find the conditions for single turn extraction, one should compare the beam size with the radius gain per turn. 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 design. The option of four dees was compared with that of two dees. As an alternative solution, higher dee voltage might be applied but the design of the machine will be much more complicate and expensive. The possible options are presented in Table 5. The beam size $2X_0$ was estimated from expression (13). The precession mixture due to the uncontrolled first harmonic should be taken into account. The radius gain per turn *dR/dn* can be estimated as the ratio between the energy gain per turn and the radial gain per turn

$$(2/R)dR/dn = (1/E)dE/dn. \quad (16)$$

In the absence of coherent radial oscillations and precession, the radial gain per turn can be expressed as the difference between the radial position of two successive orbits [7]

$$dR/dn = R_1[n^{1/2} - (n-1)^{1/2}] = (4.567/B)(dE/dn)^{1/2}[n^{1/2} - (n-1)^{1/2}]. \quad (17)$$

The energy gain per unit radial increment is given by

$$dE/dr = \beta\gamma^3 E_0/R_\infty \quad (18)$$

and the radius gain per turn can be expressed as

$$dR/dn = dE/dn/dE/dr. \quad (19)$$

Estimations by different formulae provide similar results. For comparison, the turn separation in the TR18 cyclotron at 13 and 18 MeV is included in Table 5.

Table 6. Radial dispersion versus RF phases. 8 MeV H^- cyclotron

RF phase, ϕ^0	*dE/dN*, keV	$N_{\rm dee}$	Number of turns	E_n, MeV	Radius turn n R_n, mm	Radius turn $n-1$ R_{N-1}, mm	Gain $dR/dn =$ $R_N - R_{N-1}$, mm	Beam width $\delta R =$ $R(0^\circ)-$ $R(\phi^0)$, mm	Field B, kGs
0	200	2	40	8	404	399	5	–	10
±10	197	2	40	7.9	401			3	10
±15	193	2	40	7.7	397			7	10
±20	188	2	40	7.5	392			12	10
0	200	2	40	8	577	570	7	–	7
±10	197	2	40	7.9	573			4	7
±15	193	2	40	7.7	567			10	7
±20	188	2	40	7.5	560			17	7
0	**400**	**4**	**20**	**8**	**404**	**394**	**10**	–	**10**
± 10	**394**	**4**	**20**	**7.9**	**401**			**3**	**10**
± 15	**386**	**4**	**20**	**7.7**	**397**			**7**	**10**
±20	376	4	20	7.5	392			12	10
0	400	4	20	8	577	562.4	14	–	7
±10	394	4	20	7.9	573			4	7
±15	386	4	20	7.7	567			10	7
±20	376	4	20	7.5	560			17	7

For an 8 MeV H^- cyclotron one should expect the value of the circulating radial emittance between 1.5 π and 2 π mm $\cdot$ mrad. The beam radial width exceeds 5 mm. The turn separation at 8 MeV must be more than 7 mm in order to clear peaks at extraction. We recall the standard mode of operation case where *two dees* are used for acceleration. From the data presented in Table 6, one should come to the conclusion that in the standard mode, the magnetic field of an 8 MeV cyclotron must be reduced to level of $B = 7$ kGs in order to barely satisfy the requirement of a 7 mm turn separation. A low emittance beam is also required in the standard mode and significant part of the beam intensity will be lost on the collimators.

The radial dispersion caused by the dependence of the energy gain per turn on the RF phase 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 center and turn overlapping overlapped at the edge. Turns from 30 to 50 are not separated. Estimations of the turn separation for 8 MeV H^- cyclotron are presented in Table 6. The radial gain per turn at 8 MeV could be $dR/dn \approx 5$ mm in the standard mode of acceleration (two dees) and radial increment is $dR/dn > 10$ mm with four dees. The turn width should not exceed $\delta R \approx 8$ mm for the limited RF phase band of $\delta\varphi = 20°$.

One may come into following conclusions:

• Amplitude of dee voltage of 50 kV was considered as an optimum one. The commercial power supply for TR30 or similar RF amplifier can be purchased. The increasing of the dee voltage to a higher amplitude would create a problems lik sparks, expensive RF equipment, etc.

• Combination of two dees and a 10 kGs magnetic field cannot be used if one would like to separate turns. Even the applying of flat-top voltage will not guarantee turn separation for the required 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 dimensions.

• ***Combination of four dees and an average magnetic field of 10 kGs can be a possible solution for the extraction of 8 MeV H^- ions. The beam size should be less than 8 mm while the turn separation dR/dN = 10 mm will create conditions for the*** **single** ***turn extraction of a high intensity beam of the wide RF phase acceptance of $\delta\phi = 30°$ RF.***

• Tails between circulating and extracted beam will be intercepted by the foil, stripped and dumped. The expected intensity of halo should be less than 5% of the total current. The 8 MeV halo proton of 50 μA (beam power 400 W) must be dissipated. A combination of phase selection in the center 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 flat-top voltage of up to 15 kV could be applied to the second pair of dees. Turns will be stabilize in space for the phase band of $\delta\phi$ = 20÷30° RF. The merit of the flat-top will be verified in experiment.

• As an option – two electrostatic deflectors can be installed inside dees. A low positive voltage of +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 can be estimated by the expression used for single-turn extraction and is to be expected in the range of $\Delta E \sim$ 200÷300 keV.

11. TECHNICAL SPECIFICATIONS FOR AN 8 MeV H^- 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 cyclotron as a charger for the high-voltage platform of the electron cooling section of HESR (Table 7).

These parameters of the 8 MeV H^- cyclotron should be considered as preliminary and can be modified or reconsidered. The shape of the magnet, design and position of some subsystems — the source, the injection line, the RF cavities, vacuum system, etc., can be similar to TR18 (Fig. 8). The extraction probe will be removed. The deflectors and the magnetic channels should be installed inside the dees and hills if the four dee option will be chosen. The central region is pretty similar to that of TR18. The trajectories of particles for the RF phase band of $\delta\phi = 20°$ RF and emittance of $\varepsilon_{\rm norm} = 0.5\ \pi$ mm · mrad are shown in Fig. 13.

As an option, one can employ precession extraction in combination with flat-top in order to separate turns for the RF phase band of $\Delta\phi = 30°$ RF. Two main dees and two flat-top cavities will be installed. The second pair of dees

Table 7. Parameters of an 8 MeV H^- cyclotron

Accelerated particle	H^- ions
Beam current	1 mA (CW)
Fraction of the beam to be removed	$< 10\%$
Energy range (H^- ions)	$4 \div 8$ MeV
Trim coils (option)	4 pairs: adjust isochronous field for 4 MeV
Extracted emittance (normalized $= \beta\gamma\varepsilon$)	Rad $= 1.5\ \pi$ mm·mrad (95% of beam) Axial $= 2\ \pi$ mm·mrad (99% of beam)
Energy spread	1%
Magnet geometry	4 sectors radial ridge, straight
Average field $B_{\rm av}$	10 kGs
Max. field at the hill $B_{\rm hill}$	16 kGs
Min. field at the valley $B_{\rm vall}$	4 kGs
Pole radius	450 mm
Hill gap	50 mm
Valley gap	250 mm
Sector angle	43°
Coil power	20 kW

Table 7 (continue)

RF frequency	61 MHz
Number of dees (RF harmonic)	4 ($h_{\mathrm{RF}} = 4$)
Amplitude of RF voltage	50 kV
Energy gain per turn	400 keV
Number of turns	20
Dee angular width	45°
RF power supply - two	Each for 2 dees. 30 kW
Flattop (the 3$^{\mathrm{rd}}$ harmonic of RF)	15 kV, combined with 2 dees
Ion source	H^- multi-CUSP high performance
Output DC current from the source	20 mA
Normalized source emittance ($\beta\gamma\varepsilon$)	0.6 π mm·mrad (4 RMS)
Vacuum system of ISIS	2 TPH +1 Cryo
Injection energy of H^- ions	40÷50 keV
Injection line	Einzel lens + SSQQ
Bunchers – linear$\beta\lambda$ and sin 3/2$\beta\lambda$	2 gaps each, $d_{\mathrm{holes}} = 15{\div}20$ mm
Inflector	Spiral, $A^{\mathrm{el}} \sim 45$ mm, k$\sim$ –0.7, $h_{\mathrm{plates}} = 10$ mm
Vacuum (with the beam)	$5{\cdot}10^{-8}$ Torr
Vacuum system of cyclotron	2 cryo-pumps (4,500 l/s) 2 TPH2301 (2,000 l/s)
DC to CW RF acceptance	12% (buncher off), 20% (buncher on)
Gas stripping losses	Less than 0.5%
Extraction elements	two ESD + MgnChn + protection foil
Turn separation	10 mm at the extraction
RF transmission inside cyclotron	60°RF (20° useful for single turn extraction)
Type of extraction	Single turn ($\delta\phi < 20{\div}$ 30° RF)
Pulse width	1.5 ÷2 ns
Radial width of the bunch	7÷8 mm
Imperfection first harmonic	$h_1 < 2$ Gs
Radial oscillations	$A_{\mathrm{coh}} < 1$ mm
Harmonic coils	Two sets – the center, extraction region
Phase collimators — two	One at the third turn, the second – 10$^{\mathrm{th}}$ turn
Radial probes	Two: movable. 180° (in opposite hills)

can be used as a flat-top 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 recquired. In addition one should use the high precision stabilization of the RF phase of the second pair of the cavities. Flat-top does not increase the useful RF phase band over 30° but stabilizes the position of the precession maximum. A tight tolerance is set on the RF phase drift $\delta\phi < \pm1°$ RF if the flat-top is not used. With flat-top on the RF phases it might fluctuate in the range of $\delta\omega = \pm5°$ RF. The two dees option could be considered as well if

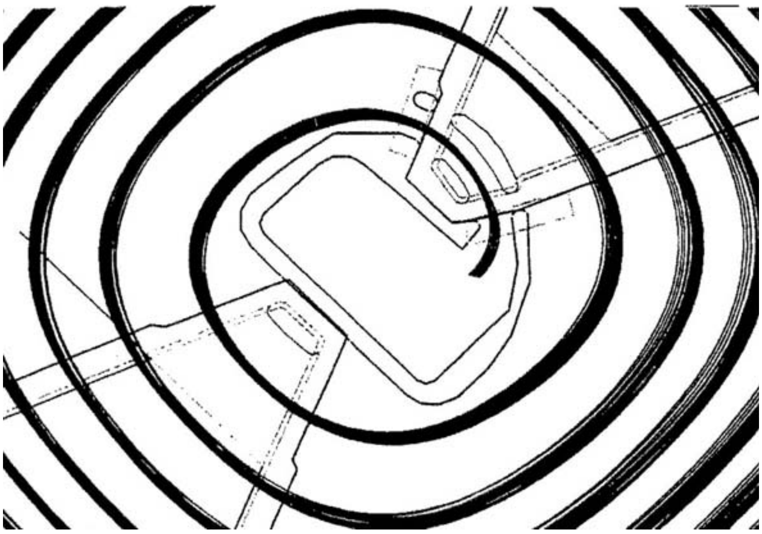


Fig. 13. Central region of the 8 MeV H^- cyclotron. Standard mode with 2 dees is shown

the amplitude of the dee voltage will be increased from 50 to 80 kV. The design of the RF system, the RF power supply as well as RF cavities are to be more complicated and expensive. Spark problems may harm the stable operation of the machine.

SUMMARY

One could roughly estimate the price and the period required to design, fabricate and test 8 MeV H^- machine. Private companies deliver a standard commercial cyclotron for isotope production after one year from the data the contract is signed. It is considered as good practise to run the first beam in one and a half year from the start of a project. At least a few months will be required to bring a commercial cyclotron into stable operation.

The price of a commercial standard cyclotron is varying from company to company and a very basic modification of a 10 MeV machine can be purchased for US$ 1.2 million. The PET cyclotron with external injection can be purchased for US$ 2 million. The price of a 30 MeV high current cyclotron is almost US$ 5 million. Many systems and subsystems of the proposed 8 MeV H^- cyclotron can be found on the market. It is a policy of private companies to buy as many subsystems and spare parts as possible rather than to design them. Most private companies use storage facilities and assembly halls. A cyclotron for accelerating a beam of 1 mA H^- ions up to 8 MeV can be designed and manufactured based on elements and equipment used in commercially available cyclotrons. An original design of the magnet, the RF and the extraction system in combination with well-developed standard equipment will ensure that the designing goals can be achieved.

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