Письма в ЭЧАЯ. 2008. Т. 5, № 5(147). С. 787–792

ON BEAM INTENSITY UPGRADE IN THE COMMERCIAL CYCLOTRONS OF NEGATIVE HYDROGEN IONS

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Compact isochronous cyclotrons to accelerate negative hydrogen ions up to 30 MeV are widely used for production of medical isotopes and other applications. The physical and technical parameters of different accelerators are analyzed and compared. Measures to improve performance and to increase beam intensity are discussed.

Компактные изохронные циклотроны отрицательных ионов водорода при энергии до 30 МэВ широко используются для производства медицинских изотопов и других целей. В работе проведен анализ и сравнение физических и технических параметров различных моделей ускорителей. Обсуждаются способы повышения эффективности работы и увеличения интенсивности пучков.

PACS: 29.20.Hm; 29.25.Ni

INTRODUCTION

Commercial cyclotrons of the energy range of 10430 MeV are widely used in isotope production and other medical applications. A 1 mA beam is extracted from the TR30 H^- cyclotron. A 3 mA beam of H^- ions was accelerated to 1 MeV at the central region model at TRIUMF [1, 5]. Different types of cyclotrons are available on the market. The CYCLONE14+ (IBA) is an example of a cyclotron with an internal target. A 2 mA beam of 14 MeV protons hits the target disposed inside the vacuum chamber. Extraction is not foreseen.

The prototype of self-extracted cyclotron (proton beam up to 2 mA) is operating at IBA [4]. The field index drops rapidly in the extraction region. The radial stability is lost and particles escape magnet without any extraction device. 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. 30% of the beam spread out in the halo and should be dumped by the special beam stop.

H^- CYCLOTRONS FOR PET

The advantage of H^- cyclotron is easy and low loss extraction by stripping negative hydrogen ions to protons on carbon foil. 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 stripper. The CP42 cyclotrons are still in use and provide up to

Table 1. **Cyclotrons to produce PET isotopes**

Cyclotron	Company (country)	H^-/D^- energy, MeV	H^-/D^- current, μA
CYCLONE10 «Light»	IBA (Belgium)	10	60
CYCLONE 18/9	IBA (Belgium)	18/9	70/30
MINI-TRACE	GE/SCANDITRONIX (USA)	10/5	60/30
PET-TRACE	GE/SCANDITRONIX (USA)	18/9	65/30
RDS-111	CTI-SIEMENS (USA)	11	100
HM-12	SUMITOMO (Japan)	12/6	60/30
HM-18	SUMITOMO (Japan)	18/9	60/30
TR18/9	EBCO (Canada)	18/9	300/150

Table 2. **Parameters of PET cyclotrons**

Cyclotron	C10 (IBA)	RDS-111 (CTI-SIEMENS)	C18/9 (IBA)	TR18/9 (EBCO)
H^-/D^- energy, MeV	10	11	18/9	$12-18/6-9$
H^-/D^- current, μA	60	100	70/30	300/150
Sectors	4	4	4	4
Average field, kGs	10	12	10	12
Field in hill, kGs	17	19	17	20
Field in valley, kGs	3	1.57	3	5
Pole radius, cm	50	45	75	60
Yoke diameter, cm	150	160	210	170×170
Hill gap, cm	3	1.5	3	3.5
Valley gap, cm	67	40	67	20
Sector angle, $^\circ$	54	56	54	$32-45$
Trim coils	No	No	Flaps	5 coils
Hole in plug	No	No	No	$\varnothing = 5$ cm
Coil, kA$\times$ turn		51	112	85
Coil PS, kW	12	22	24	24
Magnet weight, t	10	10	20	25
RF freq., kHz	42	72	42	73/36
RF harmonic	2	4	2/4	4
Number of dee	2	4	2	2
Dee voltage, kV	32	30	32	50
Energy gain, kev	60	140	60	200
Dee ang. width, $^\circ$	30	30	30	$45-32$
RF power, kW	10	10	10	20
Self-shield	Yes	Yes	No	No
Ion source	Int. PIG	PIG	2 PIG	CUSP
Source current, mA	1	–	1	$5-15$
Injection voltage, kV	–	1	–	25/12.5
Vacuum, Torr	10^{-5}	10^{-5}	$8 \cdot 10^{-6}$	$4 \cdot 10^{-7}$
Pumps	Diff.	Diff.	Diff.	Cryo
H^- strip. losses, %	45		40	< 1
Extract. ports	4	1	8	2

200 μA of H^- beam. Commercial cyclotrons of third generation were designed specifically for producing PET isotopes (^{11}C, ^{13}N, ^{15}O, ^{18}F). Required beam current is quite moderate (Table 1). The four-fold symmetry magnetic structure of cyclotron is of a closed type (Table 2). Eight holes in upper and low valleys are used for pumping, support of RF cavities, diagnostic equipment, etc. Dees are installed in opposite valleys and mechanically connected by a strap. The gap between hills is reduced to 243 cm while the valley gap is pretty large. The axial focusing is provided for by straight sectors.

H^- ions are produced in a cold PIG ion source located inside the vacuum chamber of PET cyclotron. The vacuum is quite poor because of a high gas flow to feed the ion source. H^- losses due to gas stripping were measured at the CYCLONE18/9 and TR18/9 (Fig. 1).

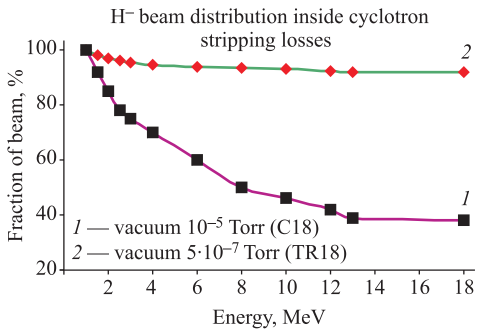

Fig. 1. Beam losses during acceleration caused by a dissociation of H^- ions on residual gas in the vacuum chamber of a cyclotron

To distinguish the beam losses due to the non-isochronous motion from the gas losses of negative ions, 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 during selection of the RF phases in the centre of machine. No additional losses of the protons have been observed. Then polarity of a magnet was reversed and H^- ions were accelerated. The degradation of the H^- beam in addition to the phase selection clearly indicates the stripping losses (Fig. 2).

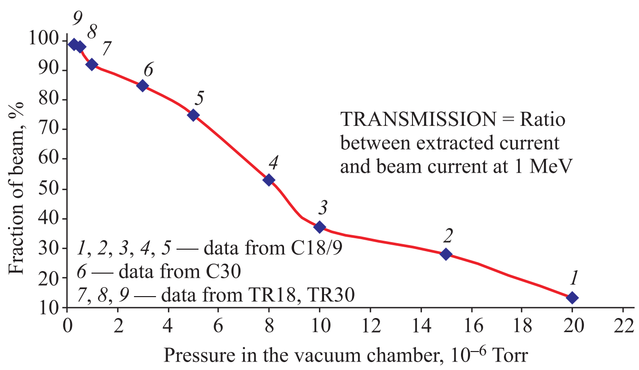

Fig. 2. Transmission of H^- beam inside a cyclotron at different vacuum conditions

Cold PIG ion source provides up to 200 μA of H^- ions at 1 MeV. Nevertheless the extracted beam from PET cyclotron is limited to 70 μA due to the poor vacuum conditions (Table 1). With proper design of the vacuum system of existing commercial cyclotrons employing internal ion source it can be possible to improve vacuum and double the H^- beam current (Fig. 2).

TR18/9 cyclotron (EBCO) with injection of H^- beam from the external CUSP ion source is used for PET isotopes production as well as in high current mode of operation. A few versions of CUSP source are available on a market — from 5 to 15 mA beam of H^- ions (4 RMS normalized emittance is $0.35 - 0.8\pi$ mm · mrad) [2]. The injection line (ISIS) consists of einzel lens, solenoid and two axially rotated quads to match the beam to the cyclotron acceptance. The electric radius of spiral inflector is 25 mm, the tilt parameter is $k' = -0.76$. The gap between inflector plates is 8 mm and the aspect ratio is 2. The beam transmission is improved by two times with $3\beta\lambda/2$ buncher. The beam centring is better than 1 mm thanks to the shimming of the first harmonic of magnetic field to less than 2 Gs. The deviation of central phase from the isochronous one does not exceed $\pm 10°$ RF.

The circulating radial emittance as well as other beam parameters of the TR18 cyclotron were measured by TRIUMF scientists [7]. The shadow method was applied. The fraction of beam included into the phase space area is given in Table 3. The area in the phase space corresponding to the circulating radial emittance of 1π mm · mrad covers almost 90% of the beam intensity. The beam density distribution is slightly different from gauss shape. The beam core of 3 mm in diameter is surrounded by halo (beam tails).

Table 3. **Circulating radial emittance of H^- beam**

Normalized emittance	0.5π	1π	1.5π	2π
Beam fraction, %	66	90	97	99

Particles of the 80° RF phase band pass between the TR18 central region electrodes. The RF acceptance of TR18 is 50° RF for the injected beam of 0.35π mm · mrad emittance [6]. Operating vacuum is better than $4 \cdot 10^{-7}$ Torr. No H^- beam losses (except one for the phase selection in the centre) have been detected at TR18. The beam footprint on the stripping foil is 5×5 mm.

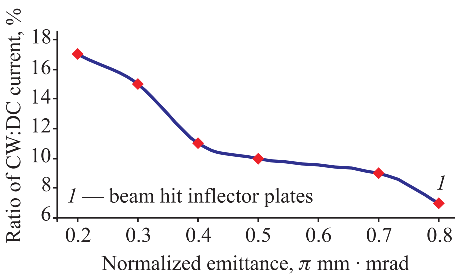

Fig. 3. Dependence of the cyclotron acceptance on emittance of injected beam. Buncher is off [6]

Dependence of the beam transmission from ISIS to the cyclotron on the transverse emittance of injected beam was studied at the commercial cyclotron TRD9 which is a modified version of TR18 [3]. The cyclotron RF acceptance is a ratio of CW beam after the phase selection is completed to DC current in the injection line.

The beam emittance was varied with collimators located in the drift section of ISIS [6]. The transmission from ISIS to cyclotron drops in by two times when the beam emittance grows from 0.3π to 0.8π mm · mrad (Fig. 3).

Simple increasing of beam current from the ion source cannot benefit the goal to increase accelerated beam to few mA because of the degradation of the beam transmission. Existing commercial cyclotrons would allow one to extract few mA of the H^- beam, if one would be able to inject over 20 mA of negative ions with a 4 RMS normalized emittance less than 0.6π mm · mrad.

30 MeV HIGH CURRENT H^- CYCLOTRONS

Two commercial cyclotrons, CYCLONE 30 from IBA (Belgium) and TR30 (EBCO, Canada) are capable of accelerating of more than 500 μA of H^- beam (Table 4). Both machines are available in the H^- and H^-/D^- versions. The beam transmission in C30 is improved due to an efficient RF buncher. The vacuum in C30 is moderate. Up to 20% of beam is lost inside the vacuum chamber because of the gas stripping. The normalized emittance of the C30 extracted beam exceeds 5π mm · mrad. Using a high performance version of CUSP ion source, modified vacuum pumping system (high speed turbo-pumps instead of diffusion pumps), one can hope to accelerate up to 1 mA of H^- beam in CYCLONE30.

Table 4. **High current cyclotrons**

Parameter	CYCLONE30	TR30
Beam current, μA	350–500	1250
Energy range, MeV	15 4 30	15 4 30
Extracted emittance, mm · mrad (normalized = $\beta\gamma\varepsilon$)	Rad/ax = $10\pi/5\pi$	$2\pi/1\pi$
Energy spread, %	2	1
Average field $B_{\rm av}$, kGs	10	12
Hill field $B_{\rm hill}$, kGs	17	19
Valley field $B_{\rm vall}$, kGs	1.2	5.5
Pole radius, cm	91	76
Hill gap, cm	5	4
Valley gap, cm	100	18
Sector angle, °	54–58	32–45
Coil power, kW	7	30
RF frequency, MHz	65.5	74
Number of dees	2	2
RF harmonic	4	4
Dee voltage, kV	50	50
Number of turns	180	150
Dee angular width, °	30	45
RF power, kW	15	35
H^- ion source	multi-CUSP	multi-CUSP
Source current (DC), mA	5	15
Source emittance, mm · mrad	0.8π	0.8π
H^- injection energy, keV	30	25
Operating vacuum, Torr	$3 \cdot 10^{-6}$	$3 \cdot 10^{-7}$
Vacuum system	CRP + DP	2 CRP
Cycl. RF acceptance, %	30 bunch ON	20
H^- strip. losses, %	20	< 1
Type of extraction	Strip. foil	Strip. foil

The TR30 cyclotron is equipped with high performance version of the CUSP source [2]. Two TR30 operate with a beam current of more than 1 mA. The H^- beam transmission in TR30 is better than 99% thanks to the good vacuum and perfect isochronous field. The ion source, the injection line, the vacuum system, the RF, the extraction mechanism of TR30 and TR18 are pretty similar. The beam energy is varied from 15 to 30 MeV by the radial movement of the stripping foil mechanism.

CONCLUSION

Private companies deliver a standard commercial cyclotron in a year from the date the contract is signed. Few months will be required to bring a cyclotron into a stable operation. The price of a commercial PET unit is varying from company to company. A very basic 10 MeV unit can be purchased for 0.8–1.2 MUSD. The PET cyclotron with external injection can be purchased for 2 MUSD. The price of a 30 MeV high current cyclotron is close to 5 MUSD. It is a policy of private companies to buy as many subsystems and spare parts as possible rather than to manufacture itself. Most private companies use storage facilities and assembly halls. Cyclotron to accelerate a 3 mA H^- beam can be fabricated based on elements and equipment used in commercially available machines. An original design of the injection system, inflector and central region in combination with well-developed standard equipment will ensure that the design goals can be achieved.

Acknowledgements. The author is grateful to Prof. R. Johnson from EBCO for warm reception and supervision during the job term under TRD9 project, to Dr. R. Laxdal for supervision during beam tests at TRIUMF, to Y. Jongen (IBA) for useful discussions at the time of experiments at C18 and to Dr. T. Kuo from TRIUMF for useful advice on the performance of CUSP ion source.

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Received on March 28, 2007.