ON COMMERCIAL H^- CYCLOTRONS UP TO 30 MeV ENERGY RANGE FOR PRODUCTION OF MEDICINE ISOTOPES

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A 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 accelerators are compared. Measures to improve performance and to increase beam intensity are proposed.

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INTRODUCTION

Commercial cyclotrons of the energy range of 104 30 MeV are widely used in isotope production and other medical applications. An 1 mA beam is extracted from the TR30 H^- cyclotron. An 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. 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 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).

Table 1. *Cyclotrons to produce PET isotopes*

Cyclotron	Company	H^-/D^- Energy	H^-/D^- Current
CYCLONE10 “Light”	IBA Belgium	10 MeV	60 µA
CYCLONE 18/9	IBA Belgium	18/9	70/30
MINI-TRACE	GE /SCND USA	10/5	60/30
PET-TRACE	GE /SCND USA	18/9	65/30
RDS-111	CTI (USA)	11	100
HM-12	SUMIT (JPN)	12/6	60/30
HM-18	SUMIT (JPN)	18/9	60/30
TR18/9	EBCO (CND)	18/9	300/150

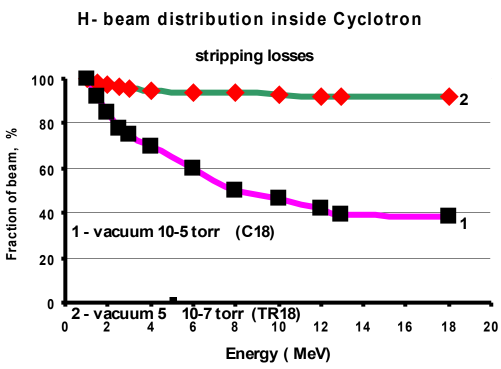

Fig.1. Beam losses during acceleration caused by a dissociation of H^- ions on residual gas in the vacuum chamber of a cyclotron

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). 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 is clearly indicates the stripping losses (Fig.2). Cold PIG ion source provides up to 200 µA of H^1 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).

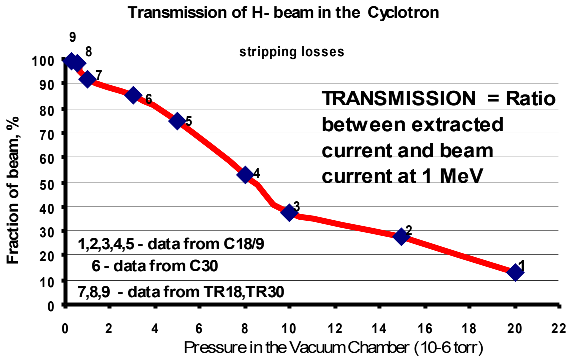

Fig.2. Transmission of H^- beam inside a cyclotron at different vacuum conditions

***Table 2**. Parameters of PET cyclotrons*

Cyclotron	C10 IBA	RDS 111	C18/9 IBA	TR18/9 EBCO
H^-/D^- Energy	10 MeV	USA 11	18/9	12…18/ 6…9
H^-/D^- current	60 µA	100	70/30	300/150
Sectors	4	4	4	4
Average field	10 kGs	12	10	12
Field in Hill	17 kGs	19	17	20
Fld in Valley	3 kGs	1.57	3	5
Pole radius	50 cm	45	75	60
Yoke diametr	150 cm	160	210	170×170
Hill gap	3 cm	1.5	3	3.5
Valley gap	67 cm	40	67	20
Sector angle	54°	56°	54°	32…45°
Trim coils	NO	NO	flaps	5 coils
Hole in Plug	NO	NO	NO	∅=5 cm
Coil, kA× turn		51	112	85
Coil PS	12 kW	22	24	24
Magnet weight	10 tons	10	20	25
RF freq	42 kHz	72	42	73/36
RF harmonic	2	4	2/4	4
Number of dee	2	4	2	2
Dee voltage	32 kV	30	32	50
Energy gain	60 kev	140	60	200
Dee ang. width	30°	30°	30°	45…32°
RF power	10 kW	10	10	20
Self-shield	Yes	Yes	No	No
Ion source	int.PIG	PIG	2 PIG	CUSP
Source current	1 mA	--	1	5…15
Injection vltg	--	1 kV	--	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

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…0.8π mm·mr) [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 3βλ/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 isochronous one is not exceeds ±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 the Table 3. The area in the phase space corresponding to the circulating radial emittance of 1π mm·mr 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 an H^- beam*

Norm.emittance	0.5 π	1 π	1.5 π	2 π
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·mr 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 in the TR18. The beam footprint on the stripping foil is (5×5) mm².

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 the 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.

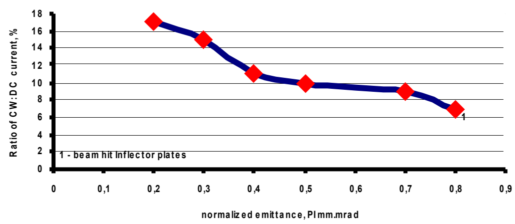

Fig.3. Dependence of the cyclotron acceptance on the emittance of injected beam. The buncher is off [6]

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·mr (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 to extract few mA of the H^- beam, if one would be able to inject over 20 mA of negative ions with an 4 RMS normalized emittance less than 0.6 π mm·mr.

30 MeV HIGH CURRENT CYCLOTRONS

Two commercial cyclotrons, CYCLONE-30 from IBA (Belgium) and TR30 (EBCO, CANADA) are capable of accelerating of more than 500 µA of H[1] beam (Table 4). Both machines are available in the H^- and H^-/D^- versions. The beam transmission in the C30 is improved due to an efficient RF buncher. The vacuum in the 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·mr. 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 an 1mA H^- beam in the CYCLONE30.

Table 4. *High current cyclotrons*

Parameter	CYCLONE30	TR30
Beam current	350…500 μA	1250 μA
Energy range (MeV)	15 4 30	15 4 30
Extracted emittance (normalized = $\beta\gamma\varepsilon$)	Rad/ax=10п/5п mm·mr	2п/1п mm·mr
Energy spread	2%	1%
Average field B_{av}	10 kGs	12 kGs
Hill field B_{hill}	17 kGs	19 kGs
Valley field B_{vall}	1.2 kGs	5.5 kGs
Pole radius	91 cm	76 cm
Hill gap	5 cm	4 cm
Valley gap	100 cm	18 cm
Sector angle	54…58°	32…45°
Coil power	7 kW	30 kW
RF frequency	65.5 MHz	74 MHz
Number of dees	2	2
RF harmonic	4	4
Dee voltage	50 kV	50 kV
Number of turns	180	150
Dee angular width	30°	45°
RF power	15 kW	35 kW
H^- ion source	multi-CUSP	multi-CUSP
Source current (DC)	5 mA	15 mA
Source emittance	0.8п mm·mr	0.8п mm·mr
H^- injection energy	30 keV	25 keV
Operating vacuum	$3\cdot10^{-6}$ Torr	$3\cdot10^{-7}$ Torr
Vacuum system	CRP + DP	2 CRP
Cycl. RF acceptance	30% bnch 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 the 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.

CONCLUSIONS

Private companies deliver a standard commercial cyclotron in a year from data 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 an 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 an 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.

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REFERENCES

1. T. Kuo, et al. Injection Study for high current H Cyclotron // *Proc. XV Cycl. Conf.* 1998.
2. T. Kuo, et al. Development of a 15 mA DC H Multi-CUSP Source // *Proc. XVI Cycl. Conf.* 2001.
3. K. Erdman, et al. Compact 9 MeV Deuteron Cyclotron with Pulsed Beam // *Proc. XVI Cycl. Conf.* 2001, p.383.
4. W. Kleeven, S. Zaremba, Y. Yongen. Self-extracted Cyclotron // *Proc. XVI Cycl. Conf.* 2001.
5. R. Baartman. Intensity limitations in Compact H^- cyclotrons // *Proc. XIV Cycl. Conf.* 1995.
6. A. Papash, T. Zhang. On Commercial Cyclotron of Intense Proton beam of 30 MeV Energy Range // *Proc. XVII Cycl. Conf.* 2004, Tokyo.
7. R. Laxdal, T. Kuo. *Beam tests on the TR13 Cyclotron "TRIUMF"*. Vancouver, Canada, 1994.

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КОММЕРЧЕСКИЕ ЦИКЛОТРОНЫ ОТРИЦАТЕЛЬНЫХ ИОНОВ ВОДОРОДА В ДИАПАЗОНЕ ЭНЕРГИЙ ДО 30 МэВ ДЛЯ ПРОИЗВОДСТВА МЕДИЦИНСКИХ ИЗОТОПОВ

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Компактные изохронные циклотроны отрицательных ионов водорода в диапазоне энергий до 30 МэВ широко используются для производства медицинских изотопов и других применений. Проведено сравнение и анализ различных моделей ускорителей. Предложены способы повышения эффективности работы и увеличения интенсивности пучков.

КОМЕРЦІЙНІ ЦИКЛОТРОНИ НЕГАТИВНИХ ІОНІВ ВОДНЮ В ДІАПАЗОНІ ЕНЕРГІЙ ДО 30 МеВ ДЛЯ ВИРОБНИЦТВА МЕДИЧНИХ ІЗОТОПІВ

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Компактні ізохронні циклотрони негативних іонів водню в діапазоні енергій до 30 МеВ широко використовуються для виробництва медичних ізотопів і інших застосувань. Проведено порівняння і аналіз різних моделей прискорювачів. Запропоновано способи підвищення ефективності роботи і збільшення інтенсивності пучків.