ON COMMERCIAL CYCLOTRON OF INTENSE PROTON BEAM OF 30 MEV ENERGY RANGE

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Abstract

Compact Cyclotron to accelerate negative Hydrogen ions up to intermediate energies still considered as favourable source of intense Proton beams. Experimental Data are being analyzed and might be considered in favour of high intensity design. It is likely that existing commercial machines are still not in the limit of high beam current. It is expected that even with physical restrictions like transverse and longitudinal Space Charge one would be able to inject high intensity H- beam into compact Cyclotron, accelerate beam of few mA intensity with minimum losses and extract it on target

INTRODUCTION

Cyclotrons of 30 MeV energy range being used for isotope production and other medical applications. There are few Projects of high power Cyclotrons for Accelerator Driven Pulsed sub-critical Reactor, energy transmutation Projects etc. The objective is to deliver 10 mA of CW beam from low energy Accelerator and inject into main Accelerator. High brightness Proton Source matched to RFQ plus DTL LINAC is considered as favourable configuration for commercial accelerators at intermediate energies of 20-30 MeV

Experience gained during few decades of operation of H- Cyclotrons should be considered in favour of Cyclotron based Source of intense Proton beam.

As for today the beam intensity from Cyclotrons is limited by extraction device. Commercial cyclotrons accelerating protons from internal PIG Source are delivering up to the 2–3 mA of beam to the internal target located inside the Vacuum Chamber. Targets are water cooled, tilted and spin in order to dissipate hit power up to 50 kW. 2 mA of proton beam have been extracted from Self-Extracted Cyclotron [5].

The principal advantage of H-cyclotron is the ease and low loss in extraction by stripping of negative Hydrogen into Protons on thin carbon foil. Commercial sources of intense Deuteron beams are based on similar design. Single particle, fixed RF frequency Cyclotron is relatively chip and robust in operation. The variation of beam energy might be done by radial movement of stripping mechanism. Beam stability is excellent. With proper design of vacuum system stripping losses of negative ions are kept at extremely low level. TRIUMF's experience in high energy H-beam acceleration and extraction provides the theoretical and experimental confidence to upgrade intensity of H-beam [1].

It is worth to refer to commercially available cyclotrons TR18/9 and TR30/15 produced by EBCO (CANADA) and CYCLONE-30 by IBA (Belgium). Both models present third generation of medical cyclotrons and in operation from 1986-1990. Some equipment has been modified and beam intensity was upgraded from 500 mkA to 1mA. Record level of 3mA of CW beam was measured at 1 MeV CRM Model in TRIUMF [2].

CUSP SOURCE

DC current of 15mA of H-ions (and recently – up to 30 mA) has been extracted from CUSP Source [3]. Also 6 mA beam of negative Deuteron ions was measured after CUSP Source at TRD-9 MeV Pulsed Cyclotron [4] Injection energy is 25 keV for H- ions and 15keV/amu for negative Deuterons.

4RMS normalized emittance is 0.35π mm.mrad for beam current up to 10 mA [3]. Slight growth of normalized emittance to 0.5π mm.mrad was observed when beam intensity is increased to 15-20 mA. It should be possible to increase DC H- current up to 25–30 mA while holding the normalized emittance below 0.65π mm.mrad. Upgrade of CUSP Source is under progress and Dr.K.Leung of LBNL mentioned possibility to boost DC H- current up to 50 mA. RF input, Cs rods inside of Plasma Chamber, modifications of extraction optics have been tested to improve performance.

2 mA to 3 mA of Deuterons beam out of 6mA have been transmitted through injection line of TRD9 cyclotron. 300 mkA of CW beam of D- ions was measured at 1 MeV probe. Due to safety restrictions it was not permitted to accelerate Deuteron beam of full intensity to the final energy. Reduced current was accelerated and extracted without losses. CUSP sources with brightness of $100\text{mA}/(\pi\text{mm*mrad})^2$ for H- and $20\text{mA}/(\pi\text{mm*mrad})^2$ for D- are available.

INJECTION LINE (ISIS)

Tests have been carried out at TRD9. Injection line is comprised from standard elements and was described earlier [4]. Einzel Lens immediately after Source and double steering are used to correct beam divergence and centre beam. Faraday Cup is used as Ion Beam Stop. Downstream is second pair of steering magnets and Solenoid to focus beam on Pulse Slits. Third pair of Steering magnets is desirable in order to correct beam on axis. Second Solenoid is provides beam focusing at Inflector entrance and two quads are match beam to Cyclotron acceptance. RF Buncher is located between Pulse Slits and second Solenoid. Total length of ISIS is approximately 2600 mm. In general it is simple optical scheme with extraction hole of CUSP Source as image point, intermediate beam focus at Pulse Slits and second focus on Inflector entrance. Beam shape versus intensity was measured at different sections of injection line and in the Cyclotron – from Source to IBS, from IBS to Pulsed Slits, from Slits to Inflector entrance, from Inflector to 1 MeV PopUp Probe, from Probe to extraction foil and Beam Line.

The beam divergence from Source exceeds 60mrad. 2mA of DC beam out of 4 mA was transmitted through 20 mm collimator located ahead of IBS Probe. Normalized emittance of D- was estimated as 1π mm*mrad while further studies have shown that beam of 0.5π mm*mrad is useful for injection into Cyclotron.

TRANSMISSION

Transmission from ISIS to Cyclotron was measured as ratio of DC current in Injection Line to CW Current at 1 MeV PoP-Up Probe Three Graphite diaphragms of different sizes have been fixed in position and holes dimensions on each diaphragm were adjusted to vary beam dimensions in the injection line. Two diaphragms have been located at drift space between Solenoid and Pulse Slits. Beam was focused on Pulse Slits. Cyclotron and Inflector have been tuned for maximum current at PopUp Probe. Due to safety regulations “Pepper Pot Probe” designed in TRIUMF was used to ensure full beam size for low intensity beam. With such Probe CUSP Source was tuned for maximum available beam and source parameters have been fixed. Measurements have been repeated without Pepper Pot Probe but for moderate current. It was no losses detected between Pulser Slits and inflector even for beam size corresponding normalized emittance of to 1π mm*mrad.

Degradation of transmitted current with increase of emittance of injected beam was fixed.

Table 1: Transmission Versus Beam Current

Emittance	Transmission	Remarks
0.2π mm*mrad	17%	
0.3π mm*mrad	15%	
0.4π mm*mrad	11%	
0.5π mm*mrad	10%	
0.7π mm*mrad	9%	
0.8π mm*mrad	7%	hit plates

Special Faraday Cup made up from circular rings of different diameter was located in place of Inflector. Almost 90% of DC beam was registered inside Faraday Cup collimator of 8 mm diameter. It was concluded that ISIS should accept at least 1π mm*mrad beam and limitations for injection could come from Inflector and Central region. Useful for further acceleration beam is included into 0.5π mm*mrad phase space area. Increase of beam intensity from CUSP Source without limiting of beam phase space area will not benefit high current mode of operation. Computer Code “PBO Lab3D” was used to estimate beam dimensions versus beam current. For high current Mode of operation ISIS should be redesigned.

More elements should be used to keep beam envelope inside of vacuum pipe. During experiments with negative beam Argon gas was injected into the region between source exit and IBS Probe to neutralize beam in the injection line. It was not detected essential difference between beam profile without Argon flow and with Argon flow.

PULSE WIDTH

Pick Up electrode, Fast Faraday Cup and 1 GHz fast oscilloscope have been used to measure beam pulse structure. Equipment was provided by TENSOR and tests have been carried out by TENSOR and author. The First location where beam pulse width was measured was chosen immediately after Pulse Slits. Duration of pulses have been adjusted by changing of Gap between Slits.

Pulse width of $\Delta\tau$ = 10-12 nsec was achieved by reducing of Slits gap to 4-5 mm. It was possible to reduce pulse width even to 5nsec but in expense of drop of beam intensity. Inflector was replaced by Fast Faraday Cup and beam pulses have been registered after flying from Pulse Slits to Inflector location 1100 mm downstream. Time of flight for 30 keV Deuterons was estimated as 700 nsec. Increasing of pulse width from 10 nsec to 16-20 nsec was registered on Fast Faraday Cup (60%). Longitudinal component of electric Fringe field between Pulse plates might be the reason of energy spread in beam pulse. Also beam size between Pulse plates has been not optimized. Increase in beam pulse width approximately 8 nsec might be caused by 400 V/cm longitudinal component of pulse electric field. If one would assume that all particles enter slits with one energy and beam size is almost half of aperture between plates then energy spread of 400 eV should be caused by longitudinal component of electric field. It was not detected growth of pulse width above 60% even for higher beam intensity. The attempt was done to worse vacuum in the injection line in order to see compensation of Space Charge but results are not clear.

One may conclude that for range of beam current available at experiment the Space Charge in longitudinal direction not yet playing essential role. Buncher efficiency of 1.5 to 2 times was measured during tests. At the same one should expect that fringe field of Buncher could increase pulse width. To minimize fringe field effect beam should be focused at the Buncher location to spot of 10 mm diameter even less. Optimization of Buncher position should be optimized by using of SPUNCH Computer Code from R.Baartman [6].

INFLECTOR

New Inflector was designed and tested. It worse to mention possible parameters if one would like to transmit 20-30 mA of DC beam through the Inflector – injection energy – 60 keV, tilt parameter $\boldsymbol{k' = 0.6}$, Gap at entrance = 8mm, voltage between plates – 20 kV.

Up to 15% of low intensity DC beam might be transmitted through Inflector and Central Region (we refer it as RF acceptance). If one would limit vertical aperture at the first turn inside the Cyclotron to 6 mm then 7% of beam will be accepted. Existing design provides 20 mm vertical gap inside Dees and small beam misalignment should not cause beam losses in the centre.

Computer simulations have been carried out to estimate RF Phase acceptance of Central Region. Particles of RF Phase band of 80^0 and normalized emittance of 0.5π mm*mrad should pass Inflector housing, Dee posts etc. Beam size in vertical direction was measured by 5 lamel vertical probe in the Centre. 300 mkA (90% of total intensity) was measured at central lamel of 3 mm height.

Foot-print of beam on Inflector housing is displaced 1.2mm above Median Plane. Reducing of vertical gap between electrodes in the Central Region forcing beam to exit inflector close to Median Plane. One should use designed value of voltage between inflector plates to transmit beam through narrow gap. For the best transmission operator should adjust Voltage between Inflector plates from designed value of 17.5 kV down to 16.9-17.1 kV. Visible size of beam footprint at Inflector housing is 4mm. Rotation of Inflector around axis, Correction of shape of electrodes should improve transmission.

Measurements of beam current have been carried out in side of accelerator. It was no losses detected between 1MeV Pop Up probe and extraction probe. Operating pressure was $5*10^{-7}$ torr. One Cryo-pump inside of free hole in the Magnet Yoke provides vacuum in Cyclotron Additional equipment might be installed if one would like improve vacuum conditions.

VACUUM

Beam transmission for different vacuum conditions have been measured. Proton beam was accelerated without losses from 1 MeV Pop Up probe to extraction.

Degradation of H- beam intensity in the region between 1 MeV and extraction radius clearly indicates stripping losses inside of cyclotron. Table 2 summarizes results which includes data from different cyclotrons – with internal Ion Source as well as from cyclotrons with external injection.

Table 2. Beam Transmission Versus Vacuum

Vacuum	**Probe location**	**Transmission**	**Current**
10^{-5}	1 MeV Pop Up probe	100% (intern.PIG)	200 mkA
$2*10^{-5}$	Extraction probe(18 MeV)	13% (intern.PIG)	20 mkA
$1.5*10^{-5}$	Extraction probe(18 MeV)	28% (intern.PIG)	40 mkA
10^{-5}	Extraction probe(18 MeV)	37% (intern.PIG)	40 mkA
$8*10^{-6}$	Extraction probe(18 MeV)	53% (intern.PIG)	55 mkA
$5*10^{-6}$	Extraction probe(30 MeV)	75% (CUSP)	350 mkA
$3*10^{-6}$	Extraction probe(30 MeV)	85% 8CUSP)	350 mkA
10^{-6}	Extraction probe(18 MeV)	92% (CUSP)	200 mkA
$5*10^{-7}$	Extraction probe(30 MeV)	>98% (CUSP)	500–700 mkA

Maximum available current from Cyclotron with internal PIG source might be increased in few times by improving of vacuum inside of machine. High speed turbo-pumps and cryo-pumps should limit pressure to $3*10^{-6}$ - $5*10^{-6}$ level with PIG source inside Cyclotron.

BEAM PARAMETERS

Measured off-centring of beam was less than 1 mm .
RF phase motion was studied by using of Garren-Smith curves. No deviations of RF phase from isochronous was detected. Magnetic field was shimmed to keep possible phase shift to less than 10deg RF [4]. Direct measurements have confirmed computer simulations. 37 MHz RF frequency which is 4th harmonic of orbital frequency have been used. Amplitude of Dee Voltage is 50 kV. Particles require approximately 60 turns to be accelerated to final energy.

Pulse width of beam bunches have been measured by Faraday Cup at the end of beam line and then measurements have been repeated - the Pick Up electrode was installed in the beam line and signal was fixed at fast oscilloscope while beam was stopped at Faraday Cup. Width of beam pulse is 4 nsec at half height and RF cycle corresponds to 27 nsec. RF phase band of 60^0 is considered as phase acceptance of Cyclotron.

CONCLUSION

Possible commercial source of high current proton beam of 30 MeV range might be based on existing TR30 design with some modifications:

- CUSP Ion Source of high brightness,
- injection energy 60 keV,
- two bunchers,
- ISIS redesigned for Space Charge beam with intermediate focus on first Buncher and second focus on inflector entrance,
- new Inflector, new Central Region,
- 4 Dees , 50 kV, 4^{th} harmonic RF.

Even with Space Charge limitations imposed on beam one should be able to accelerate at least 3 mA of H- ions.

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