COMPACT COMMERCIAL 9 MeV DEUTERON CYCLOTRON WITH PULSED BEAM

K.Erdman, D.Johnson, A.Papash, M.Dehnel, B.Gyles, B.Kovac, S.Medianu, I.Popa, V.Sabaiduc, R.Watt

EBCO Technologies Inc, 7851 Alderbridge Way, Richmond, BC, CANADA, V6X 2A4

Abstract

A Compact commercial Cyclotron to accelerate negative Deuteron ionsup to an energy of 9 MeV was built by EBCO Technologies Inc. The Injection line, Central region and Inflector have been designed to accept beam of 15 keV/A injection energy. A short pulse Buncher was provided to ensure acceleration of single beam bursts. Extensive computer simulations of beam injection and beam acceleration were made to find possible solutions for single turn extraction of high intensity beam. Special attention was paid to centre accelerated beam to better than 0.8mm, to minimize dispersion and to keep the radial emittance to less than 0.5 PI mm*mrad.

1 INTRODUCTION

It was proposed by TENSOR group to control spectrum of neutrons passing through the luggage in order to ensure safety of flight passengers and to check on-line baggage for explosive materials, drugs etc. Idea was experimentally proved on Tandem accelerator at Auburn University (Alabama, USA) with pulsed Deuteron beam of moderate intensity.

To enable reasonable time to check each piece of luggage it is very important to provide 2 nanoseconds deuteron beam pulses with repetition frequency of 1 MHz and average current of 25 – 50 micro-amperes. Pulse width equal to 27° of RF phase band for a cyclotron main RF frequency of 36.6 MHz, which would normally correspond to a transmission rate of 7.4% of the injected DC ion source beam. However, only one out of every 37 circulating pulses is permitted to be extracted. The transmission rate for the injected beam becomes 7.4% / 37 = 0.2%. Assuming a bunching factor B_f = 2 in the injection line the required D^- ion source DC output current should be no less than ((0.025mA/0.2%) x 100%)/(B_f = 2) = 6.25 mA.

2 ION SOURCE AND INJECTION

Ebco's existing D^- ion source technology prior to project commencement yielded output currents of approximately 1.5 milli-amperes. However, based on recent strides in negative ion volume cusp source development [1-2] and advice from Dr. T.Kuo followed up by further advice from Dr. Leung [3-5], Ebco felt confident to improve ion source technology to the appropriate levels. This has been achieved such that the D^- ion source DC output current is 7 mA. One of the key advances was to ensure that the Cusp filter field strength is suitably increased as arc power is increased.

Typical Ebco PET Cyclotrons with deuteron option inject D^- ions at 12.5 keV, however, in this application a 30 kV injection voltage was chosen. Since Cyclotron utilize axial injection, the Inflector, Central region and Dee tips have been completely redesigned to accommodate a higher injection energy beam. Cyclotron assembly including Injection line, Magnet and beam line is presented in Fig.1. ISIS layout is shown in Fig.2. A standard ion source body and lens design was used, however, filter and cusp magnets were adjusted experimentally, and ion source lens aperture inserts were used to facilitate experimentation. Additional vacuum pumping (roughing pump, two turbopumps and Cryo pump of 4000 l/min speed of Hydrogen) was utilized as per [1].

Figure 1. TR9D Assembly. Injection line, Magnet, Beam line.

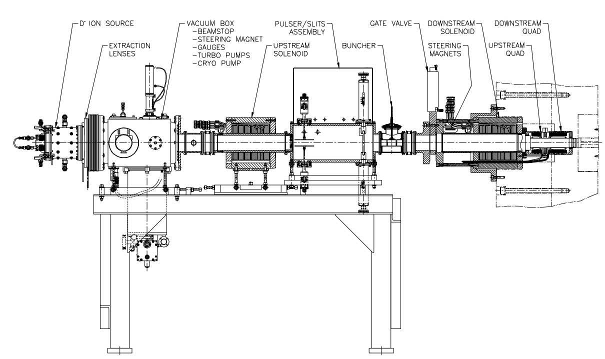

Figure 2. Layout of TR9DP Ion Source and Injection System.

CP600, *Cyclotrons and Their Applications 2001, Sixteenth International Conference*, edited by F. Marti

The ISIS ion-optics utilizes an SSQQ design (i.e. two solenoid magnets followed by two quadrupole magnets). With a normalized 4rms high-current source emittance of 0.7πmm·mrad the SSQQ leads to an injected beam profile as shown in Figure 3.

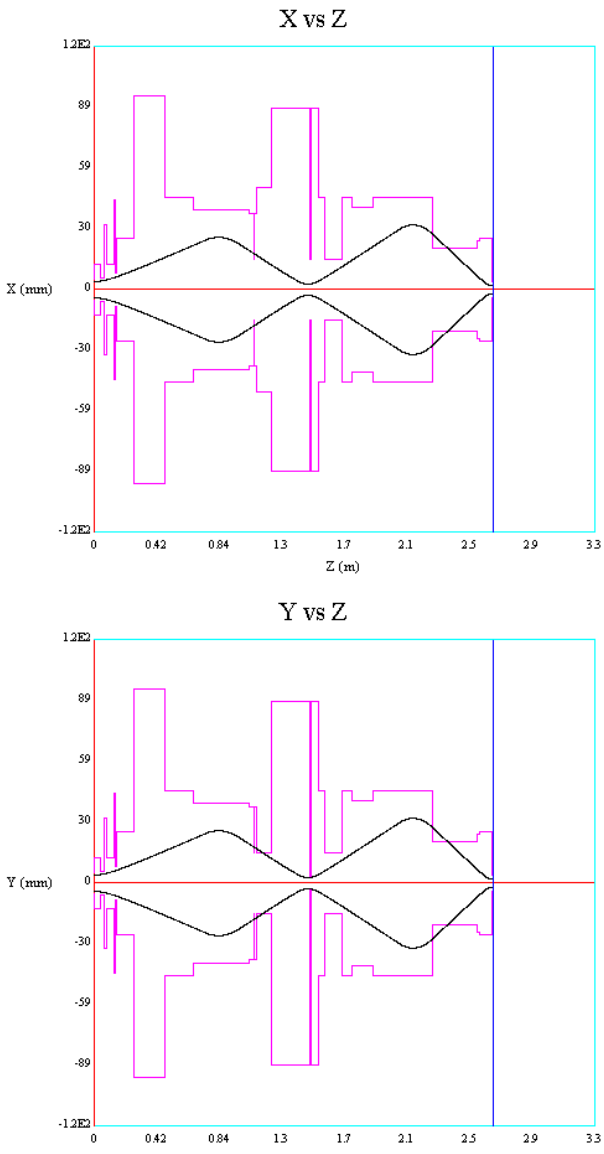

Figure 3. Horizontal and Vertical Beam Profiles in the TR9DP Injection System.

The injection line must first capture the divergent ion source beam, and this is done with a wide aperture (100 mm) upstream solenoid magnet. To center beam on axis two pares of steering magnets are installed between Ion Source and upstream solenoid. The upstream solenoid magnet focuses the beam through the Pulser plates (plate separation = 30 mm), and onto a Pulser slit with gap of 5 mm. Immediately after the slits the beam passes through a buncher. The buncher is followed by a gate valve, and a third set of steering magnets. Downstream of the Pulser slits the beam is again divergent, and is captured by the downstream solenoid. Rotate-able quadrupole magnets are the next items in the system, and they provide asymmetric focusing to provide match of source beam to cyclotron acceptance.

The RF pulser (1-2 kV voltage and 1 MHz frequency) synchronized with main RF will be chopping DC beam through 5 mm gap between Pulser plates.

3 INFLECTOR

Computer codes CASINO [6] (version for WINDOWS) and RELAX [7] (version for LINUX) from TRIUMF [10] as well as AUTOCAD, EXCEL and EBCO developed programs were used. 3D magnetic field distribution in the magnet yoke hole was simulated. Absolute values were scaled to measured magnetic field.

Coordinates of Inflector central ray calculated by analytical formula have been used to create input data for RELAX. Computer code to convert data from CASINO to electrode shape as well as BND subroutine to convert geometric values into integer numbers were written at EBCO. On the base of RELAX computed electric field and real magnetic field new Central trajectory was calculated. Inflector electrode voltage was fitted (about 1 kV less than designed value) to ensure that central particle will leave Inflector in the median plane (Z = 0) with vertical momentum equal zero (Pz = 0). New RELAX electric field was computed on base of second iteration geometry.

Inflector shape and central trajectory is fitted much better now. Radial and axial coordinates of exit are almost the same while exit angle is different on 2 – 3 degrees. Difference between designed and applied Electrode voltage is 100 V.

Special attention was paid to fit central ray from Inflector to Central region trajectory in radius, radial momentum and azimuth.

Inflector with electric radius of 30 mm and tilted parameter k' = - 0.84 was chosen as basic one for TENSOR cyclotron.

4 CENTRAL REGION

Time structure of neutron bursts require specific beam parameters. Energy gain per turn is 220 kV for central particle. Radius gain per turn in the center of machine is almost 20 mm and 5 mm in the extraction region.

In the CW mode beam pulses would follow every 27 nsec (4th harmonic of Cyclotron frequency which is 9.15 MHz). Rotation period is 109 nsec. Expected pulse width of injected beam after Pulser – 5 – 10 nsec.

With proper offset injected particles will occupy approximately 60 RF degrees of main RF voltage. In Pulsed mode only one bunch from 37 will be injected. We may hope for single turn extraction if the beam pulse duration is restricted to 10 RF degrees, injected beam emittance less than 0.3 PI mm*mrad, beam centering better than 0.5 mm (first harmonic of magnetic field less than 2 Gs), RF phase of central particle close to 0 RF deg (RF voltage stability 2 *10^{-4}).

Computer code "track" as well as special routines written at EBCO Technology were used to design TENSOR Central Region. 3D images of electrodes shape were prepared in AUTOCAD and converted into geometric values. Two electric field mesh were computed. Large grid with 1 mm mesh in X,Y,Z planes and fine grid covering Inflector housing – Puller region with mesh of 0.2 * 0.2 * 1 mm size. Cross-section of TENSOR Central Region in the median plane is presented in Fig.4. Hatched area represent Inflector housing, ground electrodes and Dee Posts.

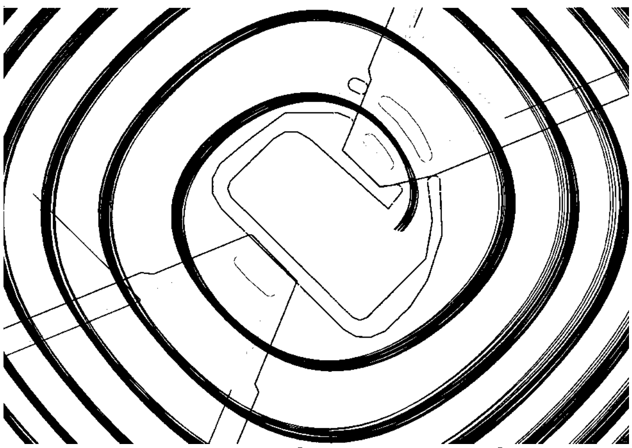

Figure 4. TENSOR Central region. Presented trajectories of 20 RF deg phase band and normalized emittance 0.5*PI mm*mrad.

As a first guess particles were tracked backward from Equilibrium Orbit to matching point. Then electrodes and posts were moved and shaped around backward orbit. On the base of this geometry RELAX fields were computed. Few accelerating runs were performed to find out radial oscillations and RF phase of central particle. Again central posts and electrodes have been slightly moved around accelerated orbit to minimize radial oscillations. Central particle cross Dee at the peak of Dee voltage. Beam is centered better than 0.8 mm (Fig. 5). Radial dispersion is low. RF phase of central particle almost zero

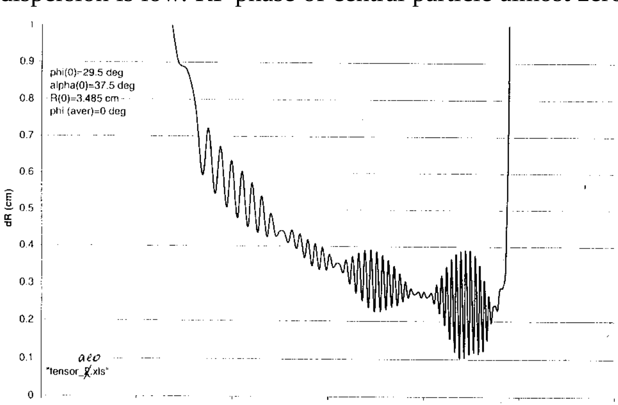

Figure 5. Radius gain per turn. TENSOR. Amplitude of radial oscillations 0.3 - 0.75 mm. Measured 360 deg magnetic field. RELAX electric field.

everywhere except center and end where it's deviate +/- 7 deg. Vertical beam size will depends on starting phase and for normalized emittance 0.5 PI mm*mrad will not exceed 10 mm.

Central Particles of 20 RF deg phase band will follow almost same precession pattern as central one up to 30 cm radius (corresponds to 5 MeV energy). Further out central and offset particles will be split in radius and two - three consequent turns will hit extraction foil. Beam time structure will look like central peak and few "tail" peaks withstanding out of central one at 106 nsec. Particles starting at the same time but occupying area in radial phase space soon will be distributed in phase as well as in energy.

Special routine of Monte-Carlo type was written to generate random point distribution in Radial Phase Space (uniform or Gaussian distribution of intensity). Program is based on Hamiltonian equations of motion rather than matrix approach.

Multi - particle tracking (1000 particles) in real magnetic and RELAX made electric fields have been performed to estimate intensity distribution between extracted beam pulses. Phase definition probes were provided in the center of machine and further out to cut unwanted RF phases. For standard conditions we expect that no more than 50% of beam intensity will be extracted in one turn with "tails" intensity distribution of 15% - 4% - 2% for one probe and 6% - 2% -1% for two probes. Statistic calculations were verified by tracking of particles on the boundary of radial phase ellipse.

5 FLATTOP STUDY

Merit of flattopping was investigated. Additional third harmonic Dee (111 MHz) was placed in free valley. Geometric dimensions, location and Dee voltage were adjusted to minimize beam off-centering. Flattop Dee starting at the center toward extraction would destroy beam quality. Radial extension of additional electrode was chosen from 30 cm to 60 cm. Dee voltage - 22% of main RF. Dee azimuthal extension – 12 degree. FLATTOP is not supposed to extend useful RF phase band. FLATTOP would be useful to keep same track (passage) for particles with different RF phases and avoid of overlapping of few turns at extraction. 80% of intensity would be extracted in ONE TURN.

6 COMMISSIONING

Deuterons in energy range from 5.8 to 9 MeV were accelerated and extracted into beam line (Fig.6). Injected beam spot on RF pulser slits is varying from 2 mm for DC current 2.6 mA to 5-6mm for DC current of 7 mA.

For beam of 0.18*PI mm*mrad normalized emittance transmission in CW mode (Ratio between DC current on Pulser slits when they are closed and current at extraction probe) was varied from 16% to 19%. It is corresponds to RF phase acceptance of 60-70deg. No losses were observed inside of cyclotron while accelerating beam of finite emittance.

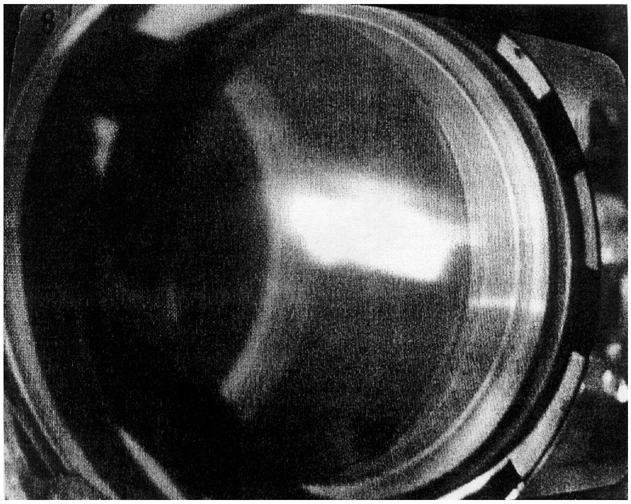

Figure 6. Extracted beam after Combination Magnet. Foto made from Quartz window.

REFERENCES

[1] T. Kuo *et al*, “Development of a 15 mA DC H^- Multicusp Source for Cyclotrons”. *Proc.14 Int Conf. On Cyc.and their Appl.*, Capetown,1995

[2] T. Kuo *et al*, “On the Development of 2 mA RF H^- Beams for Compact Cyclotrons”, *Proc. 14th Int’l Conf. on Cyclotrons and their Applications*, Capetown, 1995. *Proc.15 Int.Conf. on Cyclotrons, pp.381-384*, Caen,1998.

[3] K.N. Leung *et al*, “Small Multicusp H^- Source”, *Rev. Sci. Instrum. 59 (3)*, pp. 453-456, March 1988.

[4] K.N. Leung *et al*, “Optimization of H^- Production from a Small Multicusp Ion Source”, *Rev. Sci. Instrum. 60 (4)*, pp. 531-538, April 1989.

[5] K.N. Leung *et al*, “Electron Suppression Experiments in a Small Multicusp H^- Source”, *Rev. Sci. Instrum. 61 (3)*, pp. 1110-1116, March 1990.

[6] CASINO. B.Milton. TRIUMF, 1989.

[7] RELAX3D. K.Kost,TRIUMF, 1999.