A COMPARISON OF TWO INJECTION LINE MATCHING SECTIONS FOR COMPACT CYCLOTRONS

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Two versions of injection line matching sections between the external ion source and the spiral inflector are used for the compact cyclotrons developed at TRIUMF in cooperation with Ebco Technologies. The 30 MeV model adopts a solenoid-doublet (SQQ) version while the 19 MeV unit takes a four quadrupole/two quadrupole (4Q/2Q) option. Both cyclotrons use a same type of H^- cusp source and an identical inflector-central region combination. A comparison has been made between these two systems, in terms of DC transmission and RF acceptance as a function of source's H^- current intensity and emittance. The design and optics characteristics for both systems are described and the results obtained are reported.

I. INTRODUCTION

The TRIUMF's TR30 central region model (CRM) is an exact 1 to 1 duplicate of the 30 MeV H^- cyclotron's central region in every respect and the highest beam energy can be up to 1.5 MeV. The system consists of a high output (7 mA) and low emittance (0.365 pi-mm-mrad) H^- cusp source, a low loss injection matching section from a SQQ design [1,2,3], and a large phase acceptance with good cantering inflector-central region. In 1990, up to 650-700 μA at 1 MeV RF beam with optimal beam quality has been achieved [4]. The normalized circulating beam emittance εr, εz are 1 π and 3 π mm-mrad respectively. The centering error is no more than 1.5 at 5th turn. All of these excellent design achievements resulted in a highly reliable, efficient cyclotron system for isotope production [5,6]. The efforts of many experts who worked on these systems with high degree of professionalism are duly recognized.

we report here about the recent study on further utilization and capability development of this system since 1993. The first is the development and tests for replacing just the high-power-source/ SQQ system with a simpler, lower-power and more compact injection system, for TR13 series cyclotrons suitable for hospital PET project installation. A 2mA source and a 4-quadrupole(4Q)/2-quadrupole(2Q) compact matching section was chosen. Up to 300 μA H^- at 1 MeV was achieved by May 1993 with this compact system[7,8]. Since Feb. 1994, more than 100 μA at 13 MeV has been obtained routinely from a TR13 cyclotron. The second is to explore the SQQ system's ultimate capability of handling large beams. In 1994, a new capability of 1.5 mA at 1 MeV has been achieved. The results of this being transferred to the engineering upgrade project for the Nordion/TRIUMF TR30 cyclotron. By April 1995, 2 mA at 1 MeV was reached.

II. SYSTEM DESCRIPTION

A. SQQ Injection Line

The SQQ injection line was designed by Baartman [1,2,3]. The method begins with setting the physical parameters the system has to deal with. A 25 KeV injection energy was selected and this define the $\beta\gamma$ value. The source parameters such as waist size, divergence, normalized emittance were chosen. A pair of cyclotron acceptance ellipses are calculated from an approximation in which a dipole magnet strength (1.2 T) and a field index (n=0.09) are defined. The εr from the up right ellipse approximation are given by $\beta\gamma\nu(r)((r)max)^{2}/\rho(cyc)$, same expression for εz. The (r) max and (z) max are the maximum half beam size over one betatron oscillation. $\nu(r)$, $\nu(z)$ are the betatron frequency at the first turn and $\rho(cyc)$ is the cyclotron parameter (20 cm). With half-size 4mm by 13 mrad at the source and a matched size of 1 mm radial and 1.7 mm vertical on the first turn, the matching system must provide a magnification of about 1/3. This defines initially the drift length from source waist to solenoid centre and the length from solenoid to the entrance of the inflector.

Beam matching at the first turn was studied for a number of inflectors with the electric bend radius A and tilt parameter k' as free design parameters. The normalized circulating emittance was minimized using the computer code TRANSOPTR [9], for each transverse plane and for the sum of the two, $\varepsilon r + \varepsilon z$. The transfer metrics for the inflector were obtained using the program CASINO [10].

By iterating matching calculations, a final system design is defined. More detailed studies are to minimize the emittance growth due to the transverse coupling in the inflector, and due to beam orbit off-cantering. The final reference tune was decided as the following [2]: Source waist to solenoid centr—1.3 meter; solenoid centre to Q1 cent— 20.3 cm; Q1 centre to Q2 centre — 11.3 cm; Q2 centre to median plane 21.4 cm. Solenoid field —1.4 kG nominal at 210 amperes; effective length—23 cm and beam rotatio—80xI (ampere) degrees. Q1/Q2 pole tip field =

-363/383 gauss nominal, effective length 6/10 cm and aperture diameter 5 cm.

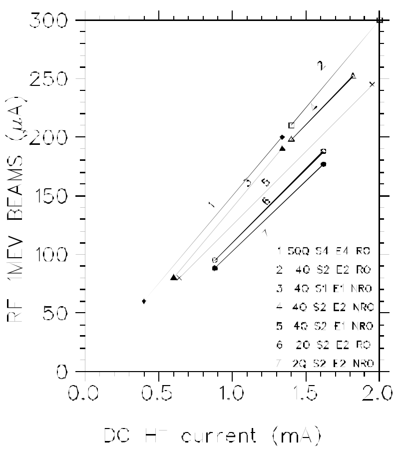

Fig. 1. Comparison of RF 1 MeV beam from different system

In addition to the beam rotation by the solenoid, the SQQ can be rotated with respect to the inflector axis as a whole without breaking vacuum. The ion source can also be rotated with respect to the injection line. The choice of 25 KeV beam energy makes the beam transport most easily in a magnetic only injection system. The tune of beam line is almost intensity-independent up to 14 mA DC. With proper control of vacuum, space charge neutralization is maintained and in turn emittance growth due to space charge effect is minimized.

B. 4Q/2Q Systems

The 4Q/2Q system was designed by Dehnel et. al. [7], following the matching technique established by Baartman. The SQQ is replaced by 4 identical compact quadrupole modules, while the injection energy, the cyclotron central region, tune frequency and the inflector parameters are remained the same. Assuming an initial source waist radius of 1.5 to 2.0 mm yielded the εcnr + εcnz sum between 1.4 and 1.8 π-mm-mrad. For 2Q (Q1+Q2) system, the optimized sum value is in 3.0 to 4.0 π-mm-mrad range.

The optimization results in a system using 50 cm source waist to 1st Q drift length; 21 cm from the 4th Q to the inflector and three equal spacing of 13.5 cm between Qs. The nominal pole face field strength for 4Q system are +290, -560 +560 and -530 gauss for Q1, Q2, Q3, and Q4 respectively. The effective length is 10 cm with bore diameter of 5 cm. Again, the whole 4Q/2Q can be rotated with respect to the inflector axis. The 1st Q can also be used as skew quadrupole.

III. TESTS and RESULTS

A. Tests with 4Q/2Q System

The performance of the 4Q/2Q system is summarized in Fig. 1 where the RF acceptance is plotted a function of DC current through a 20 mm collimator 40 cm from the extractor. Rotational optimization (RO) and non rotational optimization (NRO) are shown for S2E2 and for both 4Q and 2Q cases. We observed that the rotational optimization always improves the transmission. For 4Q case, curve 4 moves up to curve 2, while for 2Q case, curve 7 moves up to 6. The test results agree with the prediction that 4Q would yield smaller emittance than 2Q can. The S2E2 beam was tuncated to 20mm aperture. The DC intensity was 2mA and the corresponding normalized emittance was 0.27 π-mm-mrad. 300 μA RF beam was obtained with 15% RF acceptance. Larger Emittance beam resulted in lesser RF acceptance as curve 5 compared to curve 4.

B. Tests with 4Q/2Q on TR13 Cyclotron

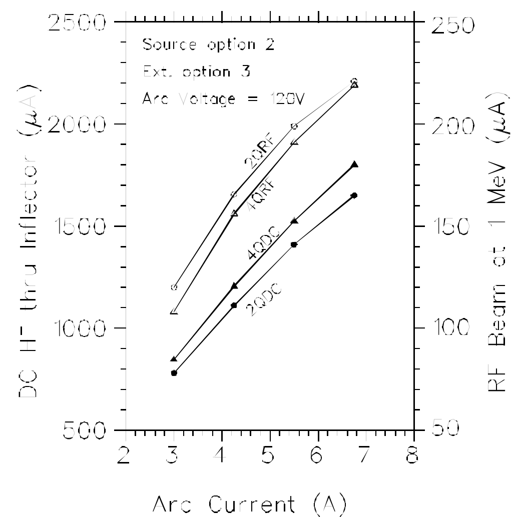

Fig. 2. DC transmission and RF acceptance of TR13 cyclotron

The beam tests for the TR13 cyclotron followed the same procedures as exercised at CRM, but unusual results were obtained. We found the 4Q performance was inferior to that from 2Q tuning as shown in Fig. 2. It was found that the differences came from a different extraction (E3) and a downsized pumping system. Also the drift length increase about 6 cm and the center magnetic field decreased about 1 kG. Optimizations with Q rotation and axial position of the inflector exit were performed. The graphic illustration for the improvement has been presented in a previous paper [8].

C. Tests With the SQQ System

The SQQ system has been vigorously studied since April 1994. After a few iterating cycles of source output and injection line optimization, a high power source-extraction S4E4 was finally developed to obtain 14mA DC beams through the inflector. This is shown in Fig. 3. The corresponding unbunched RF beam at 1.1 MeV reach 2 mA. The source normalized emittance for beam size tuncated to a 20 mm circle and 40 cm from the source exit are also shown as a function of transmitted beam. From 5 mA on the emittance increases from 0.37 π-mm-mrad to o.65 π-mm-mrad at 14 mA. The cyclotron acceptance falls off from 16% to 14.2%.

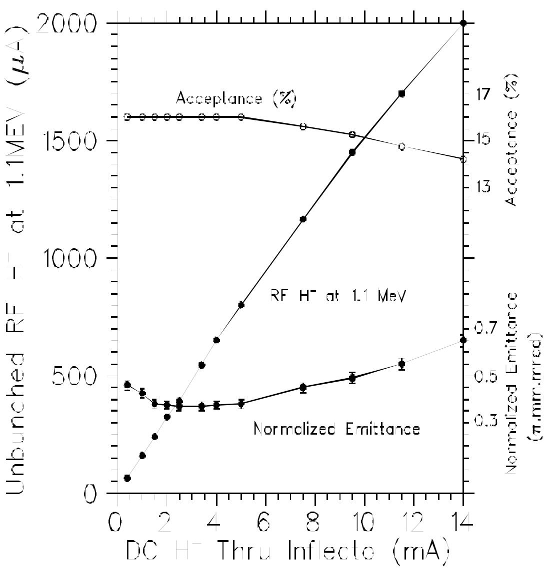

Fig. 3. DC H^- Thru inflector obtainable and H^- obtainable at 1.1 MeV from SQQ system of CRM

On the other hand, when the beam intensity is small the emittance value is also high (0.46 π-mm-mrad at 0.4 mA). But the transmission is still maintained at 16% revealing that space charge effect causes emittance growth at high beam. The RF system at CRM does not have enough power to hold 50kV and 2.2 kW of RF beams at 1.1 MeV at the same time, the dee voltage is believed to be less than 50 kV, which in turn contributes to the fall-off of acceptance.

IV. DISCUSSION

From the 4Q/2Q tests with the TR13 cyclotron, sufficient beam current of 220 μA at 1 MeV (210 at 13 MeV) has been achieved at only 7 amp arc power. For normal factory procedure and routine operation, 150 μA has been obtained without test optimization. The 2Q option met all the requirements for the TR13 and it was the most cost effective solution for 100 μA only specification. As a result, it becomes the TR13 designated injection line.

For RF beam current exceeding 1 mA, the SQQ system is the one of choice. The SQQ system possesses certain optical capability that the 4Q/2Q would not have, i.e., a larger bore diameter in the solenoid, a stronger focusing lens and the beam rotation when passing through the solenoid field. The beam shape from the source-extraction system has been assumed a cylindrical symmetry. This is true only if the beam intensity is small. At high ion source power and high extracted beam current, the beam shape appears to be elliptical. The solenoid rotates this beam about 160 degree at 200 amperes, matching the transverse plane to those of the doublet. Thus the source axis rotation, the SQQ rotation with respect to the inflector entrance axis and the beam rotation in the solenoid give a optimal matching capability.

In conclusion, the compact 4Q/2Q systems perform well with smaller beam intensity, while the SQQ system has a higher beam handling capability.

V. REFERENCE

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