

# Performance of an ISIS system using Compact Magnetic Quadrupoles

T. Kuo, L. Root, R. Laxdal, A. Altman, K. Jayamanna, D. Yuan,  
 M. McDonald, W. Uzat, P. Schmor, G. Dutto -- TRIUMF  
 and  
 M. Dehnel, K. Erdman -- Ebco Technologies/UBC

## Abstract

A short axial injection line using either four or two identical quadrupoles for phase space matching between an external  $H^-$  cusp source and the central region of a compact cyclotron has been tested, optimized and commissioned. The facility used for the tests consists of a  $H^-$  source and extraction system, a changeable axial injection column and an 1 MeV central region model cyclotron. 270  $\mu A$  of  $H^-$  at 1 MeV was obtained without bunching, for a 2 mA DC source output. The system is adopted for the injection into a 19 MeV cyclotron (TR13).

## 1. INTRODUCTION

Based on the experience with the TRIUMF's cusp source output and with the TR30 operating performance, a simpler, lower power rated and more compact ion source-injection system was selected for the new TR13 cyclotron. A 4-quadrupoles (4Q) system was chosen for injection matching over the larger solenoid plus doublet system. The requirement of 100  $\mu A$  protons on target demands that at least 120  $\mu A$  of  $H^-$  at 1 MeV should be available routinely. As the cyclotron is to be operated by complete automation, certain margin should be provided. The goal is 200  $\mu A$   $H^-$  obtainable at 1 MeV.

The 4Q system has been studied and designed by Dehnel et. al. [1]. Our effort was to test this system at the central region cyclotron and to achieve the 200  $\mu A$  goal. As shown in Fig. 1, it is of interest to recognize that the TRIUMF cusp source and extraction system has about ten folds of capability than the specification of the TR13, but at higher cost to build and more complex to facilitate. The imposed limitation on this compact system is in the source power (7 A arc maximum). The region of utilization is only the starting of a more powerful system. A great deal of details has been missing there and it is important to obtain magnified information in this area so that the small source output would be utilized efficiently.

## 2. SYSTEM DESCRIPTION

The central region cyclotron plus the ion source-injection system has been tested extensively as the model for the TR30 cyclotron. The system with the SQQ has produced 650  $\mu A$  RF beams at 1 MeV using a 7 mA  $H^-$  multicusp source, and most recently produced over 1 mA RF beams at 500 KeV by injecting 8 mA DC beam

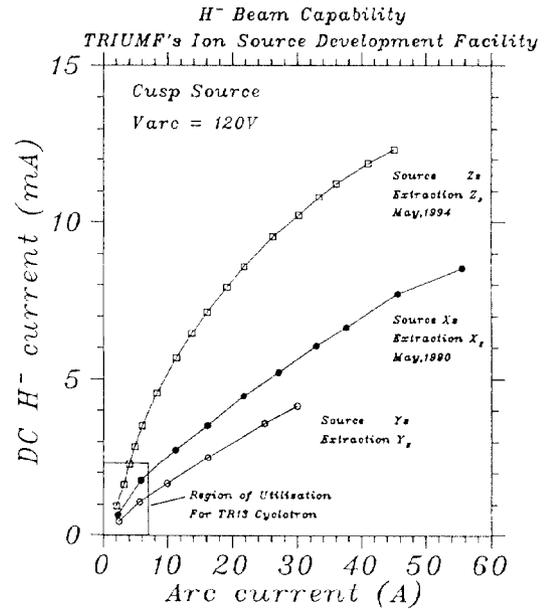


Fig. 1,  $H^-$  Beam capability at TRIUMF

through the spiral inflector. Fig. 2 shows the block diagram of the system emphasizing options in ion source, extraction region and the injection matching section. The options of source are two cusp housings, one 100 mm long, and the other 150 mm. The difference in  $H^-$  output will be discussed in the next section. The options for the extraction are the aperture of the plasma plate, the aperture

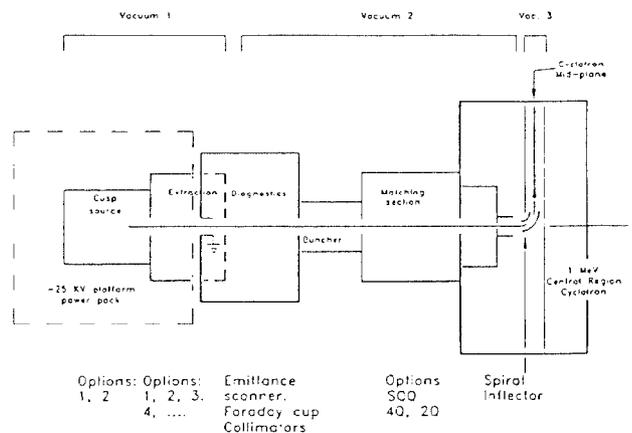


Fig. 2, Schematic of ISIS and CRM Arrangement

of the extraction electro, the extraction optics geometry, vacuum characteristics, electron filtering, etc.. Selecting a proper source-extraction combination is the first task we have to carry out in order to obtain higher beam currents and better beam brightness. To this end, the emittance scanner and an accurate Faraday cup become very important and necessary tools. The Faraday cup or beam stop should be capable of rejecting electrons, primary or secondary, for beam monitor accuracy. It should also be a tuning guide to obtain best beam quality possible. A three-electro device which serves these two functions has been designed and fabricated. The device works very well and becomes an indispensable equipment for our study.

The matching section has been made interchangeable from the SQQ system to a 4Q system which in turn can be used as 3Q or 2Q. Rotational adjustments about the injection axis is also facilitated. The spiral inflector following the model for the 500 MeV cyclotron at TRIUMF works well since it never causes any difficulty during the entire course of our study. The RF system of the 1 MeV cyclotron uses self-excited mode at 4th harmonics and at 74.5 MHz. When it is well-matched to its RF amplifier, 50 KV on dee can be obtained with 7KW forward and 0.05 KW reflected. However, there is no dee voltage monitor and feedback, nor automatic recovery from sparks. This makes our RF beam measurements difficult and not precisely reproducible.

Aside from a fixed beam probe for high beam currents measurement, two differential-integral probes are available, one with three fingers for axial profile measurement. A radial slit probe can also be used for centering error study and dee voltage study.

### 3. EXPERIMENTAL PROCEDURE and RESULTS

#### 3.1. Tests with SQQ System

The first stage of our study is to test the whole system using low arc power with the already installed SQQ matching section. The purposes of this stage of test are multiple. First, we need to establish a performance reference with which the 4Q system can compare. Secondly, we need to acquire as much information in the pre-injection section, to study the injection characteristics through the SQQ-Inflector section and to measure the post-injection RF beams in terms of intensity and real RF acceptance phase width. Thirdly, we need to acquire measurement techniques and develop diagnostic instrumentation. This systematic approach proves to be extremely fruitful as evidenced by the recent success of achieving 1 mA RF beams using the same SQQ-Inflector section.

To our surprise, the pre-injection beam preparation occupied most of our effort. The source-extraction system optimized for higher beam currents at higher arc power turns out to be very inefficient in the low arc current region. Furthermore, the beam divergence is very large resulting in

a beam of very low brightness. Large fraction of beams is lost before reaching the entrance of the SQQ section. The emittance measurements show that at 3 amp of arc, the total beam currents is 0.8 mA with 0.49 pi mm-mrad normalized emittance and 60 mrad full divergence. At 6.6 amp of arc, the corresponding values are 1.8 mA, 0.38 pi mm-mrad and 82 mrad. So the beam loss are either due to large divergence or due to large emittance. Various efforts were made to reduce the beam size but maintain the source-extraction at the same condition. At 7 amp arc, we obtained 1.05 mA DC beams through the inflector and 137  $\mu$ A RF beams at 1 MeV. The RF phase width is about 47° or acceptance of 13%. The H<sup>-</sup> beams through a 20 mm collimator 40 cm away from the source extractor is 1.5 mA. The results are shown in the Fig.3, marked by the data points with SQQ, Extraction 1 and Source 1.

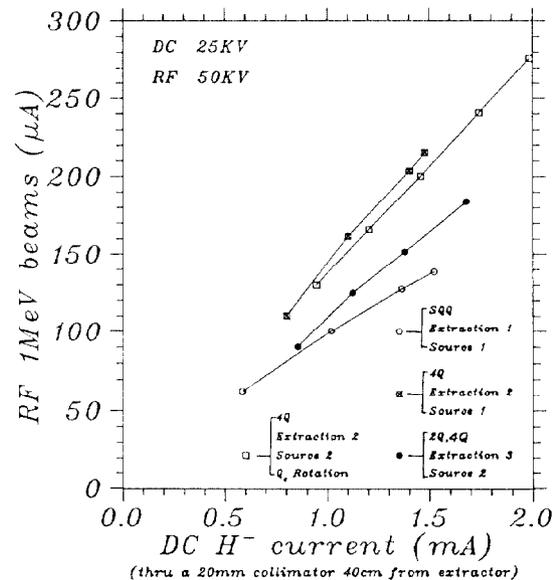


Fig. 3 1MeV RF beam obtained from different systems.

#### 3.2. Tests with 4Q system

The 4Q system replaced the SQQ after the 137  $\mu$ A RF beams has been obtained. The injection line was shortened by about 20 cm by design. The orientation of the 4Q with respect to the inflector and the cyclotron was set according to the design as well and the mounting was in such a way that the 4Q can be rotated as a whole, or one doublet rotates against the other, or the leading singlet rotates against the triplet. The source-extraction combination used for the SQQ tests remained for the initial tests for the 4Q system. The reason for that is to compare these two systems side by side although in reality it is not precisely true because the drift length was shortened from 80 cm to 60 cm. The beam size at the entrance of the first Q was already smaller or the beam density is higher for the same cross-section. The SQQ would have better beam current merit if the shorter drift length were used.

With the beam currents and quality from the source-extraction remained the same as those for the SQQ case, the 4Q system has been tested as 4Q, 3Q, 2Q, 4Q', 3Q' 2Q' ( ' designated as 90 degree rotation by reversing the electrical leads ) and quite a few other combinations. The actual quadrupole currents used agreed very well with the calculated values. A DC beam probe after the inflector was used to guide the system tuning. The best result is from the 4Q tune giving 1.32 mA. The corresponding RF beams is 177  $\mu$ A, about 30% improvement over the SQQ case. However, the readers are reminded that a shorter drift length was used for the 4Q case.

After these initial tests, we began to alter the extraction geometry by changing the plasma aperture, the extractor aperture and the electric field shape in the first extraction gap. A total of ten options were tested and for each hardware change, eight emittance measurements were done for different arc current settings and different tunes. Again, the 4Q results are the best and they are shown in the Fig. 3 marked by the data points with 4Q, Extraction 2 and Source 1. The total beam currents from the source were not improved but the emittance reduced from 0.38 to 0.34 pi mm-mrad, the divergence from 82 to 60 mrad for the 7 amp arc. In this condition, we obtained 216  $\mu$ A RF beams. In anticipating that the actual source-extraction-injection installed for the TR13 cyclotron might be different from those on the CRM, we proceeded to optimize the 4Q system further. The data points in Fig. 3 marked with 4Q, Extraction 2, Source 2 and Qs rotation show the final improvement. 276  $\mu$ A RF beams was achieved with about 14% transmission efficiency. The major contributors to this good result are from a new source (10 cm long, so called short source ) and from Qs rotation study [1].

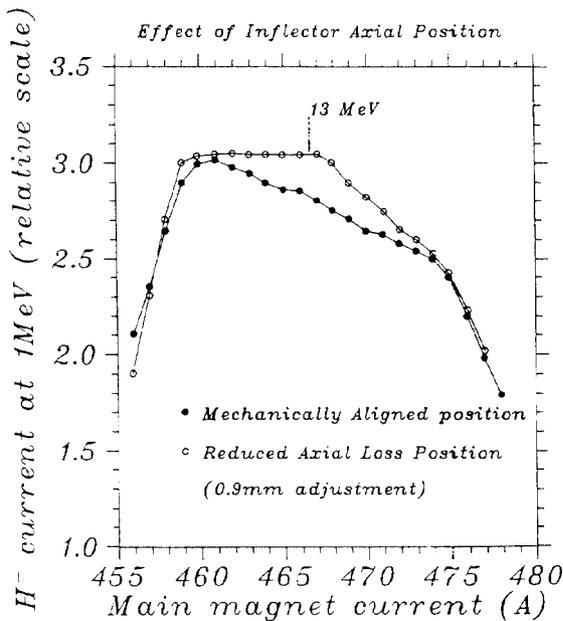


Fig. 4 H<sup>-</sup> RF currents affected by the axial alignment of the spiral inflector.

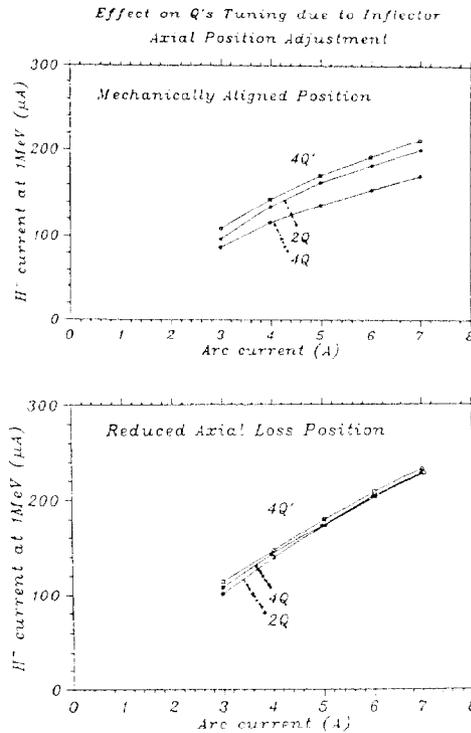


Fig. 5 Effects on Qs tuning due to inflector axial position adjustment

### 3.3. Tests with 4Q, 2Q on TR13 Cyclotron

The beam tests for the TR13 cyclotron followed the same procedures as exercised at CRM, but unusual results were obtained. We found that the 4Q performance was inferior to that from 2Q tuning by a large margin as shown in the upper graph of Fig. 5 while the 4Q' became the best. It was found that the differences come from a different extraction (extraction option 3) and a downsized pumping system. Also the drift length increases about 6 cm and the center magnet field ( not the resonance field ) decreases about 1 kG. However, when we tracked the 1MeV beams as the main magnet current varying ( magnetic phase profile ), the beams fell off monotonically before phase induced fall off occurred ( Fig. 4 ). Independent study shows that there should be no radial cut-off even at 480 amperes, thus the only reason for this is from axial loss which might come from a slight misalignment of the inflector. Indeed, a 0.9 mm adjustment brought the lost beams back so that no axial loss at 13 MeV. The consequence of this adjustment is that all 2Q, 4Q and 4Q' achieved the same good transmission (lower Fig. 5) indicating that the cyclotron acceptance is widen and the matching is improved.

## 4. REFERENCES

[1] M. Dehnel et al, " Injection System Design and Tests for the TR13 Cyclotron", (4th EPAC, 1994).