On the Development of 2 mA RF H⁻ Beams for Compact Cyclotrons

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A 2.5 mA RF H- beam has been achieved at 1 MeV in a central region model (CRM) cyclotron. Experience with a 30 MeV H cyclotron shows that only 4-5% is lost due to gas stripping when the 1 MeV beam is accelerated further to 30 MeV. Thus 2 mA or more H⁻ beams at 30 MeV and beyond becomes technically achievable. This new beam intensity is now possible due to the following contributions. Firstly, a 15 mA DC H⁻ source with good emittance has been successfully developed for H⁻ injection. Secondly, the DC transmission capability via a solenoid-doublet matching section designed by Baartman is fully utilized. Thirdly, the results of many improvements are successfully combined, such as the development of a 2-gap non-intercepting compact buncher, the optimization of the inflector, improvement on inflector cooling, the optimization of the first acceleration gap, the development of beam diagnostic and tuning techniques, and so on. At present, the new beam capability is being transferred to the TRIUMF operated TR30 H⁻ cyclotron through the 1 MeV upgrade project led by Milton.

1 - 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 and low emittance H⁻ cusp source, a low loss injection matching section from a SQQ design [1,2,3], and a large phase acceptance with good centering inflector-central region. The design parameters and performance of the TR30 cyclotron have been reported [3,4,5,6]. In 1990, up to 650μA at 1 MeV RF beam with optimal beam quality had been achieved [7]. Recent studies on further utilization and capability development of the CRM system were re-initiated since 1993. The first is the development and tests of replacing just the high -power source/SQQ system by a lower-power source and more compact injection system, a 4-quadrupole(4Q)/2-quadrupole(2Q) matching section, for TR13 cyclotrons suitable for hospital PET project installation. A 300 μA H⁻ beam at 1 MeV was achieved by May,1993 with this compact system [8,9]. The second is to explore the SQQ system's ultimate capability of handling large beams. In Nov.,1994, a new record of 1.5 mA at 1MeV had been achieved. The technical design of this new result had been transferred to the 1 mA upgrade for the Nordion/TRIUMF TR30 cyclotron.

Since then, the ion source output was further improved to 18 mA. By October 1995, 2.5 mA RF beams at 1 MeV was reached. Fig. 1 shows the RF H⁻ cyclotron beams achieved bunched and unbunched at 1 MeV as a function of dc H⁻ beams already through the inflector. A dc beam stop inserted into the first gap is used to make this measurement. For the unbunched beam the acceptance is highest between 4mA to 8mA dc where the source is also brightest. At high dc currents the emittance worsens and the high beam loading lowers the dee voltage. Consequently, a smaller acceptance resulted. For the bunched beams, a gain factor of 2 was obtained at lower dc injection. About 40% transmission can be achieved at 1 mA dc. Owing to the improperly located buncher position and space charge effect, the gain ratio falls off rapidly as dc currents increase. Baartman [10] provides a theoretical explanation for these phenomena.

2 - System Description

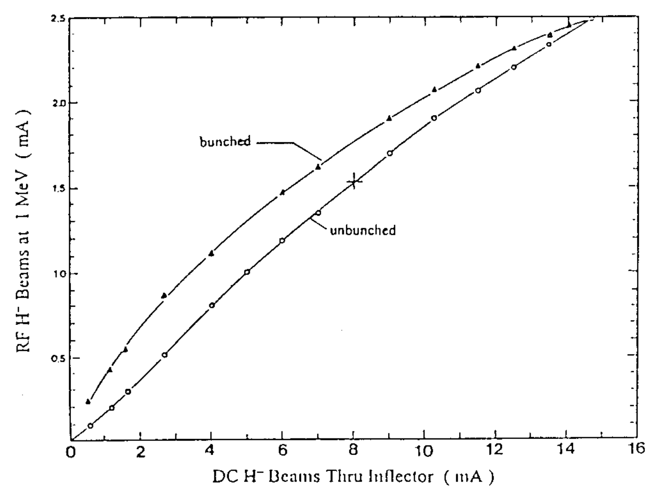

Fig. 1 - Cyclotron RF H⁻ beams capability at CRM

2.1 - Ion Source

The new H⁻ cusp source developed at TRIUMF can supply up to 18 mA dc beam with a normalized 4RMS emittance of 0.75 (π)mm-mr. The new capability corresponds to a factor of 3 increase in intensiy and only a factor of 2 increase in emittance compared to the older source's 6 mA with 0.37 (π)mm-mr. The brightness at the 6 mA dc level is about equal for both the newer and older sources. A collimated beam of 14.7 mA dc intensity with 0.65 (π) mm-mr was transported through the spiral inflector by the existing but optimized injection line. Out of this dc intensity, 17% or 2.5 mA is accepted into the cyclotron. The details of the new source development are presented in a companion paper of these proceedings [11].

2.2 - Injection line and Inflector

The solenoid-doublet (SQQ) based injection line and the spiral inflector were designed [1,2,3,12] to match an initial source normalized emittance of 0.37 (π)mm-mr through the axial magnetic field and the inflector to the 1st turn cyclotron acceptance ellipse. The major effort is to minimize the emittance growth during the passing of the inflector which imposes an additional acceptance limit. For the 4th harmonic spiral inflector design the acceptance for uncorrelated and correlated beams were calculated to be 0.16 and 0.24×10^6 $(\mu m)^2$ respectively [13,14]. These will give normalized acceptance emittance of 0.93 and 1.22 (π)mm-mr assuming that the emittance for two transverse planes were equal.

The factors contribute to a larger emittance growth through the inflector would be: a) only axially symmetric matching system (solenoids) are used, b) tall inflector height A and large tilt k' (strong transverse coupling), c) injection with small off-centering radius, d) purely uncorrelated beam before entering the inflector. For the injection line as a whole these would be: e) too good a vacuum for H^- thus lack of neutralization, f) use of electrostatic focusing elements for low energy H^- (destruction of neutralization) and g) high intensity and highly bunched beams [15]. These considerations lead to a system in which only magnetic focusing elements are used and a pair of quadrupoles are needed for proper matching in two transverse directions. The height and the tilt of the inflector are chosen to give a balance of tolerable emittance growth and injection orbit requirement.

The normalized cyclotron circulating emittance can be estimated using the dipole upright ellipse approximation, $\varepsilon_{nx} = (\pi)\,\beta\gamma\nu_x\,(x_{max1/2})^2/\rho(cyc)$. For the CRM cyclotron, $\beta\gamma/\rho = 0.383 \times 10^{-3}$ mm^{-1}, or R_{inf} = 2.607 meter. Taking $\nu_z = 0.3$, $\nu_r = 0.954$ and $z_{max1/2} = 2.5$ mm, $r_{max1/2} = 1.4$ mm, we obtained ε_{nz}, ε_{nr} to be ~0.71 $(\pi)\mu$m.

Beam matching was performed by tracking the σ matrix using computer code TRANSOPTR [16] which has the capability of ultilizing the infinitesimal transfer matrics approach while the transfer matrics for the inflector was obtained from the program CASINO [17]. For the optimal inflector matching with an uncorrelated input beam, the matched normalized cyclotron emittances for both transverse planes were 0.70 $(\pi)\mu$m [2]. This value showed about a factor of 2 in emittance growth but fitted well within the upright cyclotron emittance estimate. It was also smaller than the calculated inflector acceptance emittance for uncorrelated beam. Baartman pointed out that good matching will still be maintained as long as $\varepsilon_{nr} + \varepsilon_{nz} = 1.4$ $(\pi)\mu$m even if the $\varepsilon nr/\varepsilon nz$ ratio is deviated somewhat from 1. A correlated beam will yield a smaller emittance growth and this can be realized by adding a skew quad between the source and the solenoid.

2.3 - Central region

The central region geometry and the 1st few orbits plot have been presented at earlier accelerator conferences [3,4]. The design adopted high energy gain per turn so that the space charge effect at the 1st turn is minimized. The design also took advantage of large ν_z at early acceleration (0.2 at 0.1 MeV and 0.4 at 1 MeV) making a larger vertical acceptance possible. Longitudinal RF phase acceptance $\Delta\phi$ was designed for +/-20° while still maintained good centering without centering coils.

The first gap was 5 mm to reduce the transit time effect and the travel from the 1st gap center to the 2nd gap center was to obtain certain phase bunching. The $\Delta\tau/\Delta\phi$ ratio after 1 turn was calculated to be 1.5 to 2, leading to an apparent phase acceptance of 60° - 80° which agrees well with the observation of 2.5mA RF/14.7mA DC without injection bunching. For a smaller beam loading, the phase acceptance can be up to 48° [7] making the apparent acceptance to be ~72°. Again this seems to agree with the 0.8mA RF/ 4mA DC shown in Fig. 1.

3 - Beam Optimization

3.1 - Quadrupole Alignment

At some points of our study we observed that only 900 μA of RF beam could be obtained while the source dc beam before the inflector was 8.0 mA (9.3 mA dc total from the source). The dc beam burn pattern not far from the extraction indicated that the beam profile was no longer in a cylindrical symmetry at high beam current. The width in the source filter direction was about 2/3 of that in the beam bend (by the filter) direction. This led us to re-invesgate the rotational matching of the quadrupole and ion source orientation with the inflector's entrance direction. Fig. 2 shows the schematics of the angular relationship between the inflector, quadrupoles and ion source. Part (A) is self explanatory that ϕ should not deviate too far from 45° according to the spiral design for A = 25mm [1]. In part (B), θ indicates the angle between the ion source's elliptical beam orientation and the inflector entrance orientation, α is the beam rotation by the solenoid from a to a'. For solenoid current at 200 amperes, $\alpha \sim 0.8I = 160°$, we found $\theta \sim 20°$. Correction from the original -10° improved beam transmission ~ 9% for high beam but only ~ 3% for small beam.

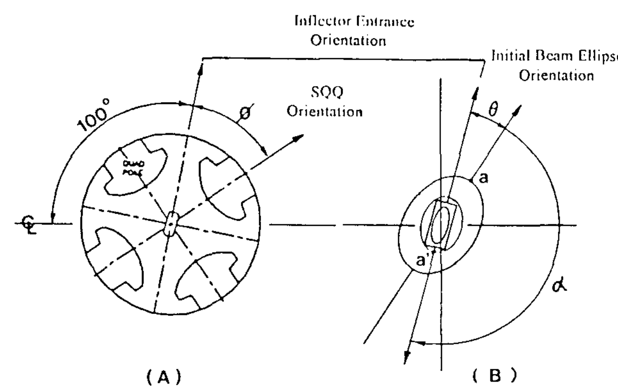

Fig. 2 - Schematics of angular relationship between quadrupole, inflector and ion source

The results of quadrupole rotation are shown in Fig. 3. The original angle ϕ_i was 100° and two representative RF beams at 0.5 MeV were 440 μA at 3.3 mA dc and 780 μA at 7 mA dc. As the quadrupoles were rotated to ϕ_f = 45°, the RF beams became 550 μA and 1100 μA. The improvement were 25% and 40% respectively, showing a larger improvement ratio for the transversely asymmetric dc beam at high intensity.

3.2 - Inflector Alignment

Fig. 4 shows the current loss on the inflector as a function of RF beam at 1 MeV for 3 different situations. Curve (a) was the

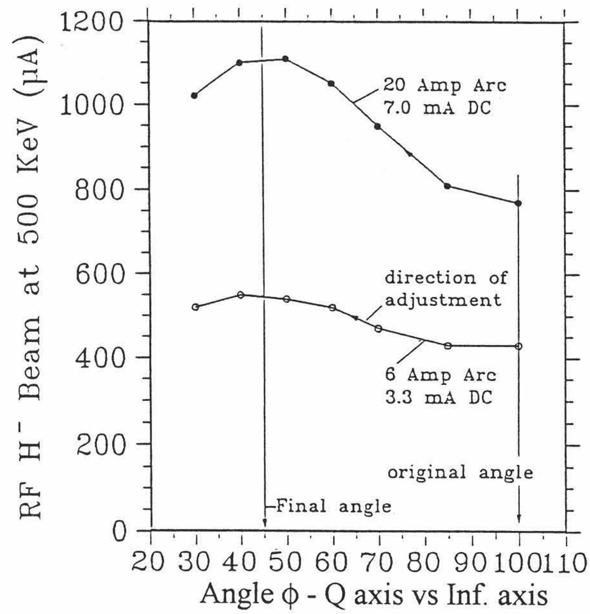

Fig.3 - Transmission and acceptance of fixed injection beam as Qs rotate

case for a maximum 9 mA injection before the Q orientation optimization. The RF beam was bottle necked at ~ 1 mA. Curve (b) was the case for a maximum 12 mA injection after the Qs and source orientations had been optimized. Curve (c) was the performance after the inflector gap had been "restored" to 8 mm as per the original design from a 7 mm previously set for the purpose of lowering the operating voltage. The transverse position of the inflector entrance was carefully aligned with the entrance collimator. The axial position of the inflector exit was aligned using flat topping of resonance curve technique. Cooling of the negative electrode made the high current (2.5 mA RF) operation very stable for long period of time.

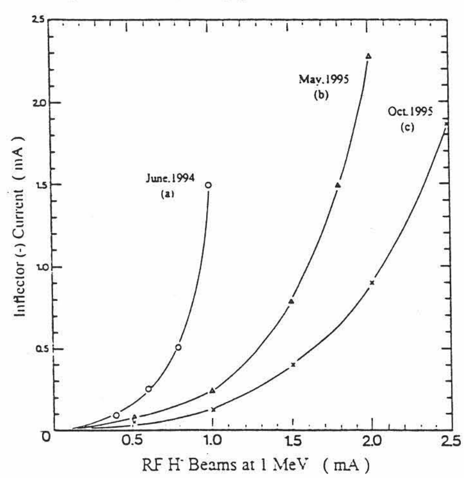

Fig.4 - Inflector currents as a function of RF currents at 3 different cases

3.3 - Central Region and Injection Energy

During the development of higher RF beam study, we found that injection tuning was critical and lengthy to achieve final peak beam currents. It was suspected that this may due to some problem in the central region. Close inspection on the central region led us to notice that the 1st gap geometry was not consistant with the design specification. Once this was remedied, not only did we obtain 10% more current, but the tuning for peak beam became easy and speedy.

As the DC injection current increases, space charge effect will worsen the emittance growth. One way to compensate somewhat is to use higher injection energy. The peak value was found to be ~ 28 kV, 3 kV higher than the original design. The inflector voltage increased accordingly, to +/- 9.4 kV. The improvement from source output was about 5%, from transmission was about 12% giving a total of ~18%.

3.4 - Injection Bunching

As shown in Fig. 1, RF beam amplification is obtained at lower dc injection currents by using a first harmonic non-intercepting 2-gap buncher positioned at a *convenient* (95 cm from inflector) but not *proper* (30 cm from inflector) location. The gap is 3 mm and the distance between 2 gaps is $3/2\beta\lambda$ (45 mm). The effective buncher radius is 10 mm formed by tungsten wires from a larger bore radius of 20 mm. The beam radius is also limited to 10 mm by a collimator installed immediately before the buncher.

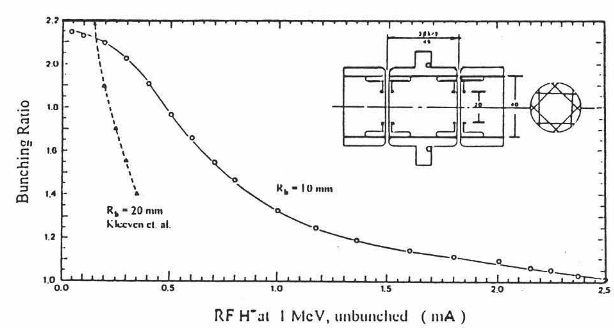

Fig.5 - Bunching gain ratio from an improperly located buncher

Fig. 5 shows the gain ratio as a function of unbunched RF beams up to 2.5 mA. There is a good gain of better than 1.6 for unbunched beam less than 650 μA at 3.5 mA dc and at this current the bunched beam already reaches 1 mA. For this reason the 1 mA operation with the TR30 cyclotron experienced no stress at all from the source-injection system. At 1mA unbunched, the gain factor is only 1.3, precisely predicted by Baartman's calculation including longitudinal space charge force. As a comparison, we plot Kleeven's result [7] from $R_{buncher}$ = 20mm, r_{beam} = 15mm for the same experimental system. The difference of these two curves came from the transit time effect due to different R_b values and r_{beam} to R_b ratios [18].

We were concerned about the emittance growth due to bunching [15,18]. The result of buncher test with the TR30 cyclotron is quite interesting. At the beginning 100 μA at 29 MeV was extracted on target and 20 μA distributed evenly to a 4-jaw collimator. When the buncher was turned on target currents jumped to 250 μA while the collimator currents increased only to 30 μA, also evenly distributed. No retuning of injection line and beam line was necessary. It is believed that the emitttance growth was there but the growth was washed out by the further acceleration process. The buncher puts higher longitudinal beam density into the good phase window, thus improves the transverse beam profile. In other words, for the same truncated percentage, say 90%, of the beam particles, the transverse emittance of the extracted beam is actually improved with bunching.

3.5 - Circulating Emittance

The circulating emittance at high RF beam currents (2.5 mA) from a source emittance of 0.65 (π)mm-mrad has not yet been measured. However, an upper limit can be estimated from previous measurement [19]. For $\nu_z = 0.6$ at 13 MeV and source emittance 0.6(π)mm-mr at very low beam current, Laxdal obtained ε_{nz}, ε_{nr} to be (3.5,1.3)(π)mm-mr using vertical half height measurement to obtain $z_{max1/2}$ and shadow block method for $r_{max1/2}$. The sum $\varepsilon_{nz} + \varepsilon_{nr}$ of 4.8 (π)mm-mrad would translate to 1.9 (π)mm-mrad with source emittance 0.36(π)μm and $\nu_z = 0.4$. This agrees well with Baartman's estimate of 1.4 πμm at $\nu_z = 0.3$ and 1.86 πμm at $\nu_z = 0.4$. Kleeven obtained (1.8, 1.7)(π)mm-mrad for (ε_{nz},ε_{nr}) with $(z_{1/2})_{rms}$ and $(r_{1/2})_{rms}$ to be 2.5 mm and 1.5 mm. Kleeven's result was about a factor of 2 higher and may be due to the use of *rms* definition. We estimate that for 14.7 mA 0.65 (π)μm DC injection, the sum of two transverse circulating emittance would be about 4.0 (π)μm for 2.5 mA RF beam at 1 MeV with $\nu_z = 0.4$.

4 - Summary and Discussion

At present, the CRM of the TR series cyclotron has a beam capability of about a factor of 4 than the highest beam available five years ago. The increase of beam capability was obtained without major change of injection line and central region, but only by source and RF upgrade as well as restoration and optimization of the original design. The reasons for making the new capability possible may come from the fact that the magnetic vertical betatron frequency is enhanced by the strong electric focusing, the maximum betatron amplitudes can be larger than designed and the DC beams may be correlated in some degree. However, the system seems to approach the space charge limit imposed by these parameters. Baartman predicted a 3.3 mA limit for the unbunched beams.

Our objective in the near future is to develop an H^- source using cesium, aiming at 25-30 mA with a normalized emittance smaller than 0.6 (π)mm-mrad. A new buncher located close to the predicted optimal position will be designed and installed. At that time we shall test the beam capability predicted by the space charge theory. Further down the road, moderate injection energy increase to 40 kV and dee voltage increase to 65 kV may be feasible, but the central region and the inflector will have to be redesigned.

The 1 mA upgrade program for the TRIUMF/Nordion TR30 cyclotron is practically completed. A 12 mA DC source and a buncher have been installed and used for some time. The new RF amplifiier capable of delivering 70 kW has also been in use. On August 8 this year, 1 mA at 30 MeV was extracted. Due to the waiting for the licence to operate two 500μA beams the new beam capability is not yet used in routine operation. Since the new system is more stable and reliable, ion source maintenance effort has reduced about a factor of 4. For a while the operation crew and the older control system is actually having difficulty in handling beams smaller than 300μA..

Acknowledgement

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References

[1] R. Baartman, "Matching of Ion Source to Cyclotron Inflector", Proc. 1st EPAC, p947, Rome, 1988.
[2] R. Baartman, "TR30 Injection Line Optics", TRIUMF Design Note, TRI-DN-89-25, 1989.
[3] R.Baartman et.al. "A 30MeV H^- Cyc. for Isotope Production" ,Proc. IEEE PAC Conference, p1623, Chicago, 1989.
[4] H. Schneider et. al. "A Compact H^- Cyclotron for Isotope Production", Proc. 1st EPAC, p1502, Rome, 1988.
[5] B. F. Milton et. al. "First Beam in a New Compact 30 MeV H^- Cyc. for Isotope Production", Proc.2nd EPAC, p1812,1990.
[6] B.F.Milton et. al." Commissioning and First Operation of a 500μA, 30 MeV, H^- Cyclotron", Proc. IEEE PAC 1991,p65.
[7] W. Kleeven et.al. "Status and Results from the TR30 CRM Cyc.", Proc. 2nd EPAC, p434, Nice,1990.
[8] M. Dehnel et.al. "Injection System Design and Tests for TR13 Cyclotron", Proc. 4th EPAC, p2367, London,1994.
[9] T. Kuo et. al. "Performance of an ISIS System using Compact Magnetic Quadrupole", Proc. 4th EPAC, p2364, 1994.
[10] R. Baartman, "Intensity Limitations for Cyclotron Injection", these Proceedings.
[11] T. Kuo et. al. " A 15 mA DC H^- Multicusp Source for Cyclotron Injection", these Proceedings
[12] L. Root, "Design of an Inflector for the TRIUMF Cyclotron", M.Sc Thesis.1972, UBC, Vancouver.
[13] R. Balden et. al. "Aspects of Phase Space Dynamics in Spiral Inflector", Proc. of the 12th Cyc. Conf. , Berlin, 1989.
[14] W. Kleeven & J. Pearson," Acceptance Calculation for Spiral Inflector", TRIUMF Design Note, TR30-DN-30, 1989.
[15] P. Heikkinen et. al. " Ion Optics in the Jyvaskyla K130 Cyc.", Proc. of the 13th Cyc. Conf., Vancouver, 1992.
[16] E.A. Heighway & R.M. Hutcheon, Nucl. Instrum. Method, Vol. 187, p89, 1981.
[17] B.F. Milton & J.B.Pearson, "CASINO: Calculation of Spiral Inflector Orbits", TRIUMF Design Note, TRI-DN-89-19.
[18] R. Baartman, " Spunch - A Space Charge Bunching Computer Code", Proc. of the 11th Cyc. Conf. p238,1987.
[19] R. Laxdal et. al., "Beam Measurements on a Small Cyclotron", Proc. 4th EPAC, p545, London, 1994.