INJECTION STUDY FOR HIGH CURRENT H^- CYCLOTRONS

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In the 14th Int. Conf. On Cyc. held at Cape Town, 1995, we reported a 2.5 mA H^- cyclotron beam capability using a 28 keV, 15 mA dc injection. Baartman pointed out that the upper limit should be about 3.3 mA for our model cyclotron. In order to test whether we can reach such a limit, a cesiated H^- source and a 5-electrode extraction system have been developed. More than 20 mA dc beam with a normalized 4 rms emittance of 0.5 π-mm-mrad has been obtained. As a result, 1.8 mA accelerated rf beam at 0.9 MeV is achieved using 50% duty factor but without injection bunching, equivalent to a 3.6 mA for the full power. The magnet profile of the model cyclotron and its effect on the bunching gain factor at energies 0.3, 0.5 and 0.9 MeV (resp. 1.5, 2.5 and 4.5 turns) were studied.

1 Introduction

Over the past few years, there has been a strong interest in the possibility of using high power accelerators for energy production and transmutation as proposed by C. Rubbia and his colleagues [1]. Such a system requires a beam power of 10 MW in the 1 GeV energy range. Experts in the cyclotron community, particularly from PSI [2] and from Laboratoire du Cyclotron CAL [3] have proposed 10-12 sector ring cyclotrons to meet this demand. In Dec. 1995, a workshop was held at Santa Fe [4,5] to address the critical beam-intensity issues in cyclotrons for this application. Craddock and Blosser summarized the various injection options for the final-stage ring cyclotron, the so-called "PSI dream machine". Among them a 120 MeV H^- cyclotron could be a candidate as an intermediate stage. Another alternative is H_2^+ cyclotron [6,7]. The main advantage of both H^- and H_2^+ cyclotrons is the ease and low loss in extraction.

In response to the beam intensity requirement of the high current H^- injector cyclotron, a high intensity H^- beam is under development at TRIUMF using a central region model (CRM) and a high output dc H^- ion source. At present, a 3.6 mA rf beam current has been obtained at 0.9-1 MeV (already completed one vertical betatron oscillation) and a higher current capability is being investigated. The motivation of our study is to explore the space charge limit and to make projection as to how to achieve 10 mA for a 120 MeV H^- cyclotron.

2 Space Charge Effect

At the 1995 ICC, Baartman [8] presented the H^- beam intensity limits based on space charge effect considerations. Using a tune shift model and Joho's separated turn model [9], the axial space charge limit gives $I_{max}(circ) \sim 10$ mA with estimated values of β and ν_z at the 2nd turn as well as the vertical aperture of the dees and the magnetic field of the model cyclotron. On the other hand, the extrapolation from the 1995 data gives only 3.3 mA. It was pointed out that the data suffered from the beam loading effect and from a larger emittance of the injected beam at higher source output. Thus the 3.3 mA was considered a conservative limit which may be moved up if the beam loading and emittance situation are improved. The present results reported in section 5 show that this is indeed the case. Longitudinal space charge effect considerations leads to a 5 mA maximum for a phase width of 36 degrees. However, this is also a conservative value because the image current effect was not included.

For a 10 mA H^- cyclotron, we can choose to scale up the injection energy and the acceleration voltage by a factor of 2 (β by a factor of 1.4) while maintaining ν_z about the same with respect to the same orbit turn. The product of dee aperture and the central magnetic field will have to be scaled up by a factor of 1.4 as well if we use 3.6 mA as our new experimental limit. The scaled up higher injection energy will improve the injection bunching from the situation that the buncher cannot be conveniently located at its ideal position as now for the CRM and TR30 cyclotrons. In addition, the magnetic field will be lower and the corresponding frequency is lower, hence λ is longer. The larger $\beta\lambda/R_{buncher}$ ratio will reduce the undesirable transit time effect for a high current non-grid buncher.

3 System Description

The design and performance of the TR30 and CRM cyclotrons have been reported by Milton [10], Baartman [11], Schneider [12] and Kleeven [13]. Since 1994, the injection system has progressively been improved and optimized [14] to achieve our new current capability. The upgraded injection system is shown in Fig. 1 and described in the following subsections.

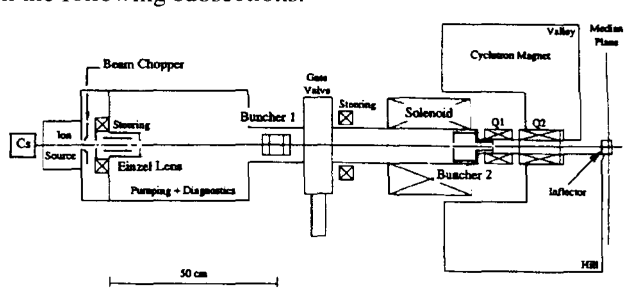

Fig. 1. Schematic of injection line layout

3.1 Cesiated H$^-$ Source

The non-cesiated H$^-$ source has been improved over the last several years. It can provide 20 mA dc with a normalized emittance of 0.75 π-mm-mrad. However, the maximum dc transmission through the inflector was limited to 16 mA. The limitation is most likely due to the larger emittance and divergence than those the injection system can accept. In order to reduce the emittance and on the other hand to increase the peak beam current, the technique of Cs injection into the source plasma has been developed.

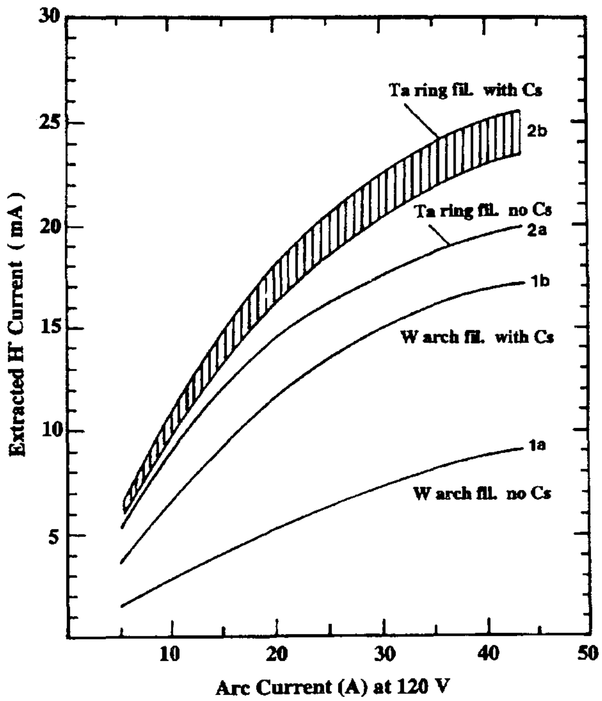

Fig. 2. H$^-$ dc beam current achievable using a cesium assisted source.

The measured H$^-$ dc beam current as a function of arc power for two filament options with and without Cs are shown in Fig. 2. Curve 1a represents the result for the commonly used arch shape tungsten filament without Cs, while 1b with Cs. We observe the usual factor of two improvement -- evidence that Cs injection does work well for our source. Similarly, curves 2a and 2b represent results for tantalum ring filament, without and with Cs injection respectively. The use of Ta rings without Cs already shows better results than the use of a W arch with Cs, indicating that the ring arrangement is having the same desirable effect as that of Cs – lowering the temperature of the plasma electrons in the H$^-$ production region. For this reason it is natural that Cs injection does not improve the H$^-$ intensity very much for the 2b case particularly at lower arc power.

3.2 Extraction Lenses

The emittance and beam profile of the H$^-$ beam from Cs operation are of great interest. At the beginning of Cs injection when the Cs delivery is extremely small, we observed that without any adjustment of optical devices the portion of beam going through a 20 mm collimator increased from 85% to 100% while the portion landing on the collimator decreases from 15% to 0. Stopping the Cs delivery reverses this process. Thus we observed for the first time an amazing beam size breathing phenomenon due to the Cs effect. As the Cs delivery rate increases to a point the total extracted H$^-$ beam increases, the source plasma potential drops dramatically. This leads to a big change in extraction optics settings. For the highest total beam current extraction at 5 kW, 20% of the extracted beam was stopped by the 20 mm collimator. Emittance measurement shows that this beam has a larger divergence but smaller emittance than those of the non-Cs assisted beam at the same power using the same extraction system. We concluded that the existing extraction optics (3-electrode configuration) would not be able to handle the change of source plasma with Cs injection.

An einzel lens was then designed and added immediately after the ground potential electrode making the new system a unique 5-electrode configuration. It provides the optimal condition for beam current extraction, electron suppression and matching for the injection system downstream. At lower arc power the beam transmission is almost 100% and at high power up to 96%. More than 21mA dc H$^-$ can be transported through the inflector using the new Cs-source and 5-electrode optics system.

3.3 Beam Chopper

With a limited peak rf power from the CRM rf amplifier the rf beam at 1 MeV vs. injected dc beam displays a trend of saturation as the accelerated beam approaches 2mA and beyond. This was attributed to several reasons such as beam dump after initial acceleration, rf beam loading and the worsening of injection beam emittance. In order to lessen the first two effects a beam chopper using extraction voltage gating has been added. Duty factor can be continuously adjusted from 1% to 100%. As can be seen from Fig. 5 in section 5, the RF beam shows only a slight degree of saturation at 21mA dc injected current when 50% duty factor is used. Measurement will be made to determine the saturation dependence on the emittance of the injected beam by the use of a small duty factor.

3.4 Injection Buncher

In Fig. 1, two bunchers are shown. The performance of Buncher 1 has been reported previously [8,14]. It was pointed out by Baartman that this buncher is located in a convenient (90 cm from the inflector) but not an ideal (32 cm from the inflector) position according to the results of his SPUNCH code calculation. The bunched beams begin to get unbunched beyond this optimal position when a higher buncher gap voltage is used. Unfortunately the proper location is occupied by the quadrupole buried inside the cyclotron magnet yoke.

A compromise is found that buncher 2 can be fitted partially inside the first quadrupole. The resonator circuit encompassed by 2 concentric grounded cylinders and end plates can be installed inside the 9 cm diameter bore. The center line position will be 40 cm from the inflector. RF power and frequency tuning will be sent through the vacuum feed-through. Buncher 1 will be 50 cm from buncher 2. It can be used as a prebuncher for the latter. Buncher 2 is in the fabrication stage and the whole system will be completed by the end of 1998. The system will be tested and its capability evaluated using foundamental mode rf drive first. Adding a 2^{nd} harmonic component or a saw-tooth wave form drive will be considered later.

4 Beam Phase and Injection Bunching

Previous beam tests had concentrated on the study at the 5^{th} turn (1 MeV). As the injection capability increases and the accelerated beam current is approaching the space charge limit it seems to be important to examine the beam property at earlier turns. For the TR30 type central region the ratio of unbunched ef beam to dc injection beam does not represent the phase acceptance, since there is a strong internal bunching (phase compacting) effect during the first half turn acceleration. Actual phase width and the internal bunching gain factor can be obtained from a Smith-Garren plot. An analog of such a plot using magnetic field variation was made for the 0.3, 0.5 and 0.9 MeV orbits (resp. 1.5, 2.5 and 4.5 turns) at a fixed injection current of 5 mA. This is shown in Fig. 3.

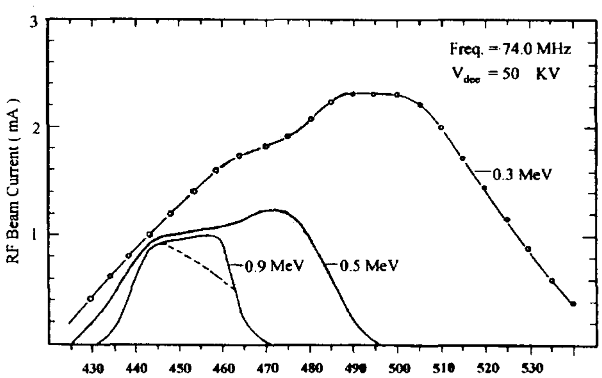

Fig. 3. Magnetic analog Smith-Garren plot for 0.3,0.5 and 0.9 MeV orbits. The dash curve shows profile before injection optimization.

We observe that there is a very large phase excursion and more than a factor of two in current reduction between the inner and the outer turns. The large rf phase slip (orbit phase slip times four) toward lower magnet current indicates that instead of having a desirable cone the central field increases as radius increases. The ν_z value could have been higher if a slight cone field were present.

The large intensity drop from 0.3 to 0.9 MeV comes from several reasons. First, since there is a large dc offset to the rf voltage at injection a large phase width is accepted at the earliest turn. Then there is strong phase clipping on the extreme lagging edge due to excessive phase excursion. Finally, the lack of cone field worsens the axial loss. It is worth mentioning that before the injection system is optimized, one must set the magnet current at 445A to obtain the peak 1.1 MeV beam current The radial profile at this setting was almost flat [13] from 1.1 to 0.3 MeV, giving the impression that the CRM magnet is perfect, which can now be explained differently. Although one could use this method to obtain phase selection the success occured accidentally rather than in a controlled manner.

4.1 Injection Bunching

Fig. 4 shows the injection bunching gain ratio as a function of unbunched beams at 0.3, 0.5 and 0.9 MeV obtained at their individual optimal magnetic field using buncher 1 alone. A different curve results when the 0.3 MeV beam is tuned at the 0.5 MeV magnet setting. At first glance the gain factor seems to be phase history dependent or magnet profile dependent. However, a closer examination reveals that these variations can be generated from a curve of bunching gain factor as a function of injected dc beam current [8] and from the analog Smith-Garren plot as shown in Fig. 3. It is of interest to note that the gain factor for the 0.5 MeV beam (at 475A) is not much better than the 0.9 MeV beam (at 455A). If the buncher system is not upgraded , the 0.5 MeV curve appears to be the upper limit for the 0.9 MeV beam even when the magnet profile is eventually corrected. Substantial improvement in bunching gain ratio must come from the upgrade of buncher system described in section 3.4.

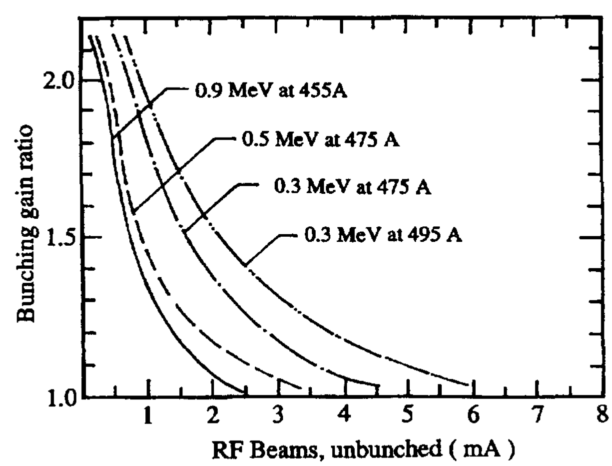

Fig. 4. Bunching gain factor as a function of unbunched beam.

5 Recent Results

The rf beam currents at 0.3, 0.5 and 0.9 MeV as a function of dc current through the inflector are illustrated in Fig. 5. Since buncher 1 does not help in achieving more current than the unbunched beam at high limit, only the unbunched beam characteristics are shown. At 21 mA injection we obtained 1.8 mA at 0.9 MeV with 50% duty factor, equivalent to 3.6 mA at full power for the same injection and space charge conditions. The acceptance is 17% , about the same as the older 2.5 mA rf beam out of 14.7 mA dc injection.

At lower injection current, the acceptance for 0.5 and 0.9 MeV are 25% and 20% respectively. The average phase widths extracted from several Smith-Garren plots are 48 and 40 degrees. The internal phase compacting factor is 1.8 for both cases. For the 0.3 MeV, 6.8 mA was achievable with 16 mA injection corresponding to an acceptance value of 0.42, a phase compacting factor of 1.8 and a 90 degree phase width.

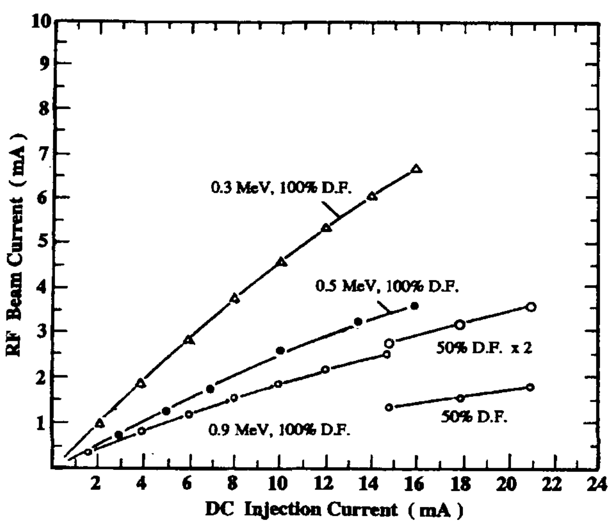

Fig. 5. Unbunched rf beam current obtained at 0.3, 0.5 and 0.9 MeV.

6 Summary and Discussion

Using a cesium assisted H^- source and a 5-electrode extraction system including an einzel lens, a 25 mA dc H^- beam at 28 keV with 0.6 π-mm-mrad normalized 4rms emittance for cyclotron injection has been developed. A new record of 3.6 mA H^- RF beam at 0.9 MeV was obtained without the use of an injection buncher. Further development of a brighter dc beam and of an effective bunching system may push the peak rf beam current even higher. The development of the cesiated source took up more time and effort than anticipated leaving the new buncher system unfinished at this time. The system will be completed by the end of this year.

The analog Smith-Garren plot reveals that the magnet profile of the model cyclotron is not ideal. A correction for such a profile should be made to restore a proper cone field so as to recover the reduction of ν_z. With phase trapezoids centered or slightly shifted toward higher magnet current from 1.5 turns to 4.5 turns, one can have the option of setting the magnetic field leaning toward the lagging phase to gain better electric focusing. It is anticipated that some improvement in axial acceptance should be attainable.

When the forementioned problem is resolved and development is completed, a new current limit will be explored and the new scaling factors for a 10 mA H^- cyclotron can be established. At present, the cesiated source and the matching extraction technology is being transferred to the Nordion/TRIUMF TR30 cyclotron. If the 2-buncher system is proven to be successful it will also be transferred. Together, the TR30 peak current capability may have the potential to be up graded from 1.2 to 2 mA.

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