A POSSIBLE HIGH CURRENT H$^-$ INJECTOR FOR CYCLOTRON-BASED 'ENERGY AMPLIFIER' ACCELERATOR

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Abstract

In response to the beam intensity requirement of the high current H$^-$ injector cyclotron for a proposed cyclotron-based accelerator as an "energy amplifier" and for transmutation, a high intensity H$^-$ cyclotron beam is under development at TRIUMF using a central region model cyclotron and a high output d.c. H$^-$ ion source. At present, 2.5 mA RF beam current has been obtained at 1 MeV and a 3.3-4 mA capability is being investigated. The 3.3-4 mA is the space charge limit imposed by the design parameters of the existing system, such as injection energy, dee voltage, vertical betatron tune, source brightness and so on. A 10 mA, 120 MeV H$^-$ cyclotron (TR120) can be considered as a candidate for an intermediate stage accelerator. Preliminary parameters have been selected, some derived from the experimental results related to the scaling law for the space-charge effect.

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] 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, TR120, could be a preferred candidate as an intermediate stage. The main advantage of an H$^-$ cyclotron is the ease and low loss in extraction. TRIUMF's experience in high energy H$^-$ beam acceleration and extraction provides the theoretical and experimental confidence to build such a machine.

There are many critical issues in attaining currents in the 10 mA region. The most critical are those related to space-charge effects. The most pressing issues in the TR120 conceptual design stage are:

---to study a more accurate formulism of space-charge effects on the maximum intensity attainable,

---to develop a high-current high-brightness source to explore the space-charge phenomenon.

---to perform high- current injection studies to test the validity of the scaling law.

Table 1 shows the preliminary set of parameters for the TR120 cyclotron along with those of the upgraded TR30.

Table 1 Principal cyclotron parameters for TR30 and TR120

	TR30	TR120
Beam energy	30 MeV	120 MeV
Mean current	1.2 mA	10 mA
Magnet		
Average field	1.20 T	0.72 T
Hill field	1.90 T	1.16 T
Valley field	0.55 T	0.47 T
Hill Gap	4 cm	8 cm
Pole radius	76 cm	206 cm
Number of sectors	4	4
Spiral	No	Yes
Centering coils	No	option
Trim coils	No	option
RF		
Frequency	74 MHz	44 MHz
Dee Voltage	50 kV	100 kV
Harmonic	4	4
Number of dees	4	4 or 2
Gain/turn	200 kV	800/400 kV
Power	70 kW	1500 kW
Ion Source	H$^-$	H$^-$
DC current	12 mA	40 mA
Cesiated	No	Yes
Injection		
Energy	25 kV	50 kV
Focusing	SQQ	Skew Q+SQQ
Inflector	Spiral	Spiral
Bunching	Weak	Effective
Vacuum	Cryopump	Cryopump/ Cryopanel
Pressure	2x10^{-7} Torr	5x10^{-8} Torr

2 SPECIAL FEATURES OF TR120

First, we should point out that the hill field , average field and rf frequency are low because of electric Lorentz force stripping considerations. Although the beam energy is a factor of 4 lower than that of TRIUMF's 500 MeV cyclotron, the average field is similar. This is for the extremely low loss requirement. Second, to assure minimum gas stripping loss, the TR120 requires a factor of 4 better vacuum than TR30, essentially the same as TRIUMF's 500 MeV cyclotron.

A factor of 2 or 4 more in energy gain per turn further reduces the stripping loss. Detailed calculations of the Lorentz force stripping loss as a function of hill field, and so of magnet weight and coil power, will be carried out so that an economic factor can be obtained.

The 800 kV or 400 kV per turn energy gain depends on whether a 4-dee or a 2-dee system is used. A 4-dee system makes the beam loading (1.2 MW total) per each dee one half of the 2-dee system, from 0.6 MW to 0.3 MW. The skin loss power and the ratio of beam power to skin loss power will be substantially lower. The RF system should be more stable and reliable. However, the easy access of valley space for vacuum and diagnostic equipment would be lost. If we want to put the extraction mechanism, foil or jet, in the low field region the mechanism will have to be installed inside the dee. Remote handling would be more difficult but not impossible. The advantages and disadvantages will be carefully assessed. Assuming we use a 4-dee system, the low magnetic field and much higher energy gain per turn should give wider turn separation at extraction than a 2-dee system would. The advantage of single-turn extraction for H^- is not obvious. The requirement is imposed by the matching of the emittance to the acceptance of the accelerator downstream.

The high energy gain per turn will make the first turn radius large, thus giving stronger vertical focusing, a key factor in overcoming the transverse space charge force.

A higher I_{max} limit is allowed. The 50 kV injection energy together with the lower RF frequency make the $\beta\lambda$ more than twice as large as that of TR30. The buncher can be located in the optimum position and effective phase compression can be obtained. The transit time effect will also be improved. We anticipate a much more effective injection bunching gain factor than we are getting now. Finally, a cesiated H^- source is under development. The new source would provide 30-40 mA with better emittance than we obtain at present. It seems to us that a 10 mA capability is attainable for the TR120 cyclotron.

3 SCALING LAW AND SPACE CHARGE EFFECTS

Transverse space charge effects are strongest at low energy, particularly on the first turn where the linear pulse length is shortest and the vertical tune is smallest.

The maximum current limit in the cyclotron central region can be deduced using the synchrotron vertical tune shift model [6], or Joho's separated turn model [5]. Both models give I(lim) in proportion to $\beta(\nu_z b_{max}/R_{inf})^2$. Baartman obtained I_{max}(circ) =10 mA for TR30 and the CRM test model, while the extrapolation from the experimental data gives 3.3 mA. As we shall discuss in the next section, the data suffer from beam loading effects and from dee voltage drop. Thus the real values might be higher. We will use 3.3 mA as a conservative limit for TR30 and demand 10 mA for the TR120. To achieve this we first scale up the central region in size but keep R_{inf} fixed, i.e. $R \propto \beta$. This leads to

$$I_{max} \propto \beta(b_{max})^2 \propto R^3 \text{ or } \propto \beta^3 \quad (1)$$

The three times higher current limit requires both b and R to be scaled up a factor of 1.44. The injection energy and dee voltage need to be scaled up by 2. In other words, if we make the magnetic field of TR120 the same as TR30, scale up the central region dimension by 1.44 in both R and z directions, raise the injection voltage and dee voltage to 50 kV and 100 kV respectively, then a conservative 10 mA limit would be attainable. However, the 19 kG hill field will result in excessive Lorentz stripping loss. Therefore we must lower the hill field to about 1.1 T. A flutter value of 2.4 gives an average field of 0.72 T. R_{inf} will then scale up by 1.68. The vertical opening for the 1st gap should be equal to that of TR30 times (1.44x1.68), which becomes 24 mm.

4 CRM MODEL TESTS

A 1 to 1 full scale central region model (CRM) was constructed to test the TR30 design concepts and critical components. In 1990, up to 0.650 mA of 1 MeV beam had been achieved [7]. Further utilization and capability development were re-initiated since 1994. In Nov. 1994, a new record of 1.5 mA at 1 MeV was obtained. The technical developments from this effort has since been transferred to the Nordion TR30 cyclotron.

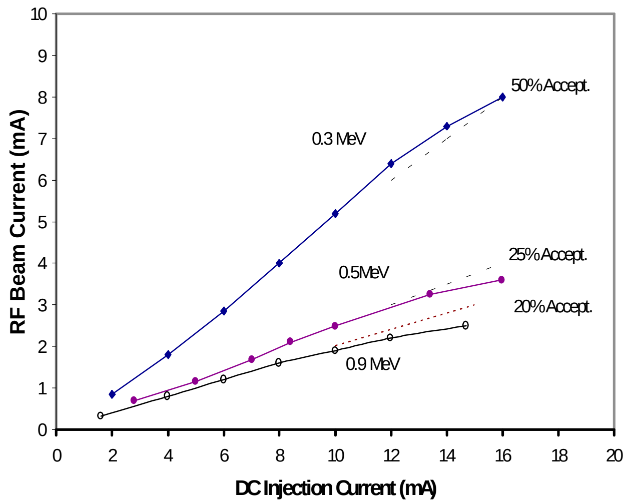

Fig.1 Unbunched beam current obtained at 3 discrete orbits.

By October 1995, a 2.5 mA beam at 1 MeV was reached [8]. Fig. 1 shows the H^- cyclotron beam current achieved unbunched at 0.3, 0.5 and 0.9 MeV as a function of dc beam current already through the inflector. At 0.3 MeV 50% apparent acceptance is obtained even at the high injection current of 16 mA. It seems that the phase compacting factor is greater at higher injected current. The central region calculations show that about 90 degrees of phase can clear the radial electrodes, so the phase compacting factor is about 2. For the 0.5 and 0.9 MeV beams, the phase widths extracted from Smith-Garren plot are 54 and 48 degrees respectively. The phase compacting factors are 1.7 and 1.5. The CRM RF power is limited to 8 kW, of which 6.5 kW is needed for 50 kV. When the beam loading at high injection currents and high circulating currents exceeds 1.5 kW, the dee voltage is reduced, resulting lower apparent acceptance. This argument is supported by measurement using a pulser. At 50% duty cycle, the measured beam current is half of the dashed line shown in figure 1.

5 INJECTION BUNCHING

For a 2.5 mA unbunched circulating beam, 25 kV injection energy, h = 4 and R_{inf} = 2.6 m, Baartman found that the optimum position for the injection buncher is 0.32 m from the inflector. But this is also the required location for the quadrupoles. We then proceeded to install a double gap buncher at a convenient location (0.95 m from the inflector) to study the bunching phenomenon. The buncher gap is 3 mm and the distance between 2 gaps is 3/2 $\beta\lambda$ (45 mm). The effective buncher radius of 10 mm is formed by tungstem 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.

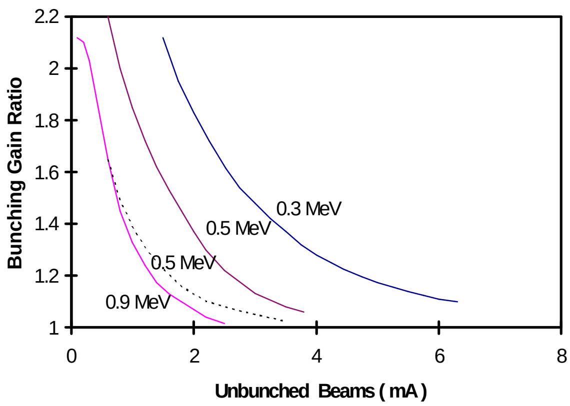

Fig.2. Injection bunching gain factor as a function of unbunched beam current and orbit energy.

Fig. 2 shows the gain ratio as a function of unbunched beams at 0.3, 0.5 and 0.9 MeV, obtained at their individual optimum magnetic field. As orbit energy increases the gain factor decreases and at each energy the gain factor decreases rapidly as the unbunched current increases. In addition, the gain factor seems to be phase history dependent. Two distinct curves results when the 0.5 MeV beam is tuned at two magnet current settings. Using a space-charge force code (SPUNCH), Baartman obtained a set of bunch phase width as a function of distance downstream, intensity and buncher voltage for a $\beta\lambda$ value. If $\beta\lambda$ increases, the buncher to inflector distance will increase in $\beta(\beta\lambda)$ scale, making an improved bunching gain factor possible. The transit time effect consideration also leads to an improved bunching gain if a larger $\beta\lambda/R_b$ ratio is used.

6 CONCULSION

As higher dc cw mode H^- beam current with high brightness begins to be available for cyclotron injection, an H^- cyclotron capable of delivering more than 1 mA external beam current has become a reality**.** Recent resuts from the model test at TRIUMF also demonstrate that beam current of 3 mA at medium energy can be achievable within the space charge limit imposed by the existing design. Using the scaling law governed by space charge effects, initial parameters for an H^- cyclotron capable of extracting 10 mA external beam current in the 120 MeV range has been conceived. Such a cyclotron could be considered as an intermediate stage injector for the proposed “energy amplifier” accelerator.

Detailed design study of this injector cyclotron and further model test will be carried out in the near future.

7 REFERENCE

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