Design of an Axial Injection System for the Seattle MC50 Cyclotron

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Stimulated by requests by users to run high current alpha beams for isotope production, the University of Washington has requested that TRIUMF perform a design study of an axial injection system. The goals of the study include finding a relatively simple retrofit for the MC50 that will add the alpha beam capability while maintaining or improving the operation for proton and deuteron beams currently used. It must also be possible to install the new system with little or no disruption of the normal operation that includes regular neutron therapy treatments. In this paper the results of the study will be presented.

1 Introduction

The details of the MC50 cyclotron have been previously reported[1] so we will only repeat the basic parameters here. The MC50 cyclotron is a 3 sector, variable energy, positive ion cyclotron designed to operate in first harmonic mode for q/A=1, and in second harmonic for q/A=1/2. In first harmonic, protons can be extracted between 28 MeV and 51 MeV. Central field values range between 1.0 T and 1.7 Tesla. The RF system consists of 2 independent 90 degree dees, and can operate at voltages up to 40 kV.

The primary challenge of this design study is the need to retrofit the existing cyclotron with the minimum of disruption to the current operation. In particular for a solution to be attractive it must be possible to implement and test the various changes during the three day intervals each week between regular patient treatments. In practical terms this means making changes only to components that were designed to be removed quickly such as the dee tips and centre plug, and no changes to the magnet.

A second requirement is that the new axial injection system should be able to accommodate both first and second harmonic operation without changing hardware. This means a single central region for both harmonic modes. From a cost point of view, it would also be better to find a single ion source capable of generating sufficient currents of protons, deuterons, and alphas. The design study goals are for a system capable of 100 μA of protons and 50 μA of deuterons and alphas. (Present daily operation with the internal source is in the neighborhood of 70 μA of 50.5 MeV protons extracted.) For estimate purposes we set a nominal accelerated phase width of 10 degrees, and a bunching factor of 2, so that a beam of 1.8 mA DC from the source would be required for 100 μA of accelerated beam. Normal extraction efficiency from the cyclotron is about 80%.

2 Ion Source

Using the above numbers, and accounting for the extraction efficiency, the proton and deuteron modes require an injected current after emittance selection of 4.5 mA (no bunching). The α beam mode at 50 μA of extracted beam and the same RF phase acceptance and extraction efficiency requires approximately 2.2 mA injected.

While many ion sources are capable of producing protons and even deuterons in sufficient quantity to meet the 4 to 5 mA criteria, few are also capable of producing sufficient currents of α beams. The TRIUMF ISAC test stand CUSP source achieved 3 mA of $^4HE^+$, however no $^4HE^{++}$ was detected even at the nA level. Duoplasmatrons generate singly charged particles only, no data on doubly charged helium beam has been reported. ECR sources can provide medium intensity α beam output (approximately 1 mA from LBNL Super ECR Source[2]), however these are large and complex sources as well as expensive to build and operate. Almost all cyclotron α beams are produced by variations of the PIG source which has been used to produce multiply charged ions for many decades. An ultra high power density version of the PIG source was developed by Kuo and Laughlin[3] and has produced more than 4 mA DC of α beams. This technique has been used to reliably achieve 1.5 mA DC α beams for stable operation.

Figure 1 shows a simplified schematic of a PIG source. Two cathodes are located at either end a 2.5 cm long anode chamber within an axial magnetic field. Electrons

Particle	DC Intensity	Arc Power	Magnetic Field	Extraction Voltage
p_{ave}	7.5 mA	0.5 A @ 1 kV	7 kG	30 kV
d_{ave}	7.5 mA	0.5 A @ 1 kV	10 kG	30 kV
α_{ave}	1.5 mA	4.0 A @ 250 V	10 kG	30 kV

Table 1: Expected source output for sample source parameters

emitted from either cathode are accelerated into the anode. A large fraction of these electrons are trapped axially by the electrostatic well and radially by the magnetic field. The electron beam ionizes the injected gas to form a dense plasma (arc column) from which ion beams are extracted. The ion source position is adjustable in four independent coordinates, horizontally (puller to anode gap), radially (ion entrance angle to puller), vertically (extraction slit to median plane), and axial angle. The axial angle control tilts the ion source head such that the opposite edges of the upper and lower anode openings are used to limit the arc column size. Rotating the source head while increasing arc power density also causes the arc column to retreat from the extraction slit in either direction of rotation, the slit surface also becomes oblique with respect to the puller. The Kuo and Laughlin PIG source, as shown in figure 2, uses a modified 6° angle bore anode which allows the ion plasma column to be close to the extraction slit for any operating angle while increasing the calculated arc power density from a few kW/cm^3 at 0° axial angle (Penning mode) to greater than 140 kW/cm^3 at 5.5° (high thermionic mode) at a constant arc power of 1 kW. Total lifetime is in the order of 100 hours for continuous operation in the high thermionic mode with much longer lifetime for the Penning mode (protons and deuterons). Sample operating parameters for the source are given in table 1.

The estimated normalized emittance at 30 kV with a source slit opening of 2mm x 4mm is 0.30 π mm-mrad in both planes. Emittance selection reduction through collimation, beam transport losses, and deceleration is estimated to be about 25%. For protons and deuterons this reduction is of little consequence whereas for α beams this reduces the available injected current to 1.1 mA. A factor of two in the intensity required can be achieved through a buncher.

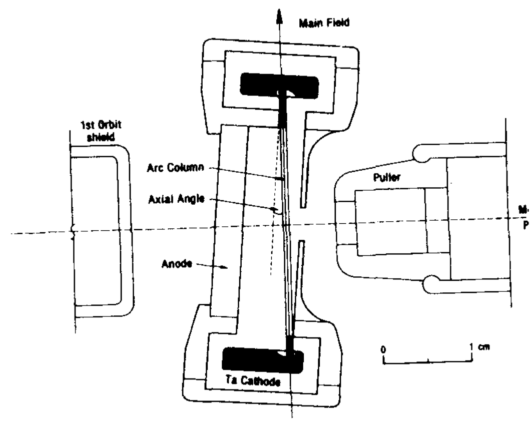

Figure 1: Simplified section view of a normal PIG source

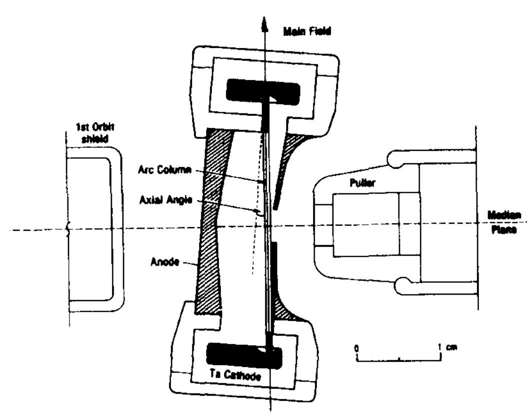

Figure 2: section view of PIG source designed to achieve high plasma densities

3 Central Region

As is normally done in variable energy positive ion cyclotrons, the proposal is to operate in constant orbit geometry (i.e. the dee voltage is scaled as the magnetic field is changed to keep the orbit radii unchanged). In

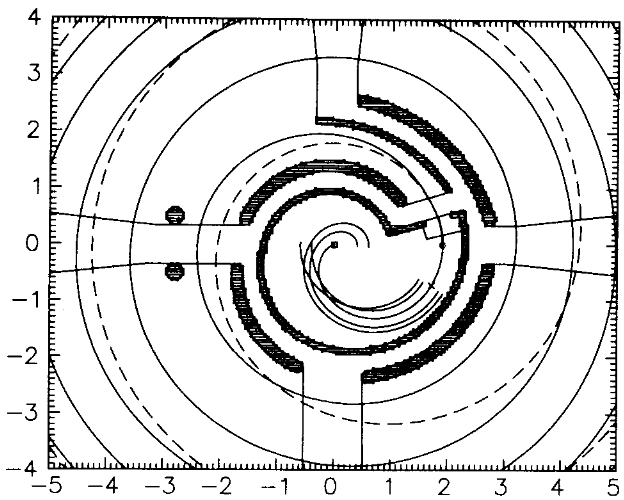

Figure 3: Median plane section view of the central region showing central rays for first (solid) and second (dashed) harmonic modes. Also shown are the edges of the inflector electrodes and the central trajectory through the inflector.

this cyclotron the flutter contribution to the magnetic field at the centre is small, so the orbit variation as a function of average field will be quite small. Therefore it is possible to design the central region for the maximum average field and dee voltage. Simple scaling rules can then be used to determine the dee and inflector voltage as the average field is varied to change the extraction energy.

Somewhat less typical is the desire to use the same central region to accelerate ions in both the first and second harmonic modes. Various systems have been employed in the past to do this. We have chosen to use a first dee "puller", that has an electric length of 120° so that the energy gain is the same in both harmonics. This option has the benefit of substantially greater energy gain on the first turn for the first harmonic mode, than using a straight 90° dee. Figure 3 shows the proposed electrode shapes along with a central trajectory. A first harmonic particle was tracked backwards from a centred starting position 7 turns out, to determine the centring conditions required at the matching point (shown as a cross in figure 3). The inflector design program CASINO [4] was then used to find inflectors that would produce the desired centring. This search was also constrained to inflectors that were short enough to fit in the existing vertical space, and had inflector plate voltages in neighborhood of 8 kV maximum. The inflector shown in the figure has an electric bend radius of 3.2 cm and an electrode tilt (k') of 0.49.

To obtain magnetic fields on the median plane in the machine centre and along the axial bore, a three dimensional magnetic model of the MC50 has been assembled

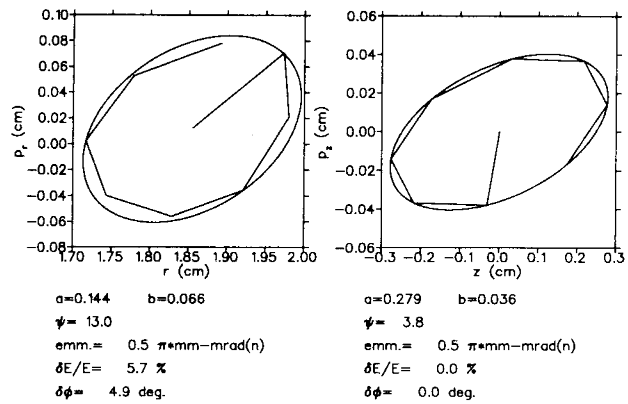

Figure 4: Results at the matching point for a horizontal (left) and vertical (right) eigen-ellipse that was started on turn 7 and tracked backwards to the matching point.

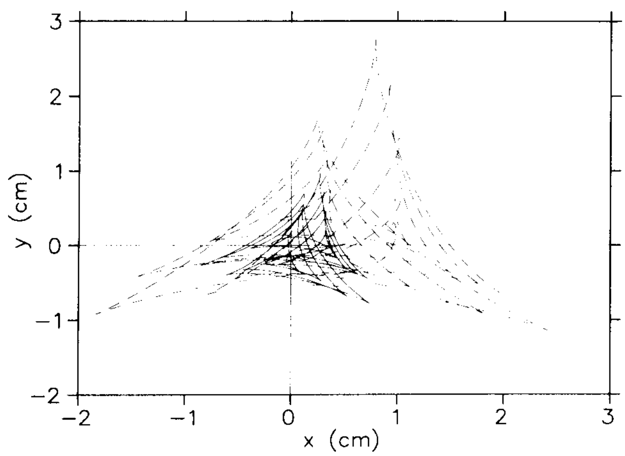

Figure 5: Beam centres for first and second harmonic central rays during the first 5 turns.

using TOSCA. Results for the average field agree well with the measured data at full field. This model is also being used to evaluate the effect of making changes to the iron section of the centre plug. This is important since the holes in the existing centre plug are in fact off centre to accommodate the source cathodes, while for axial injection we will want an on axis hole.

Vertical and horizontal eigen-ellipses for 0.5π mm-mrad normalized emittances were tracked backwards and the results at the matching point are shown in figure 4. These results show little distortion of the beam indicating clean passage through the electric lens of the central region. Figure 5 shows the orbit centre for first and second harmonic beams over the first 5 turns. The beam moves well onto the centre by this point, and what centring error remains can easily be removed using the harmonic coils provided in the MC50.

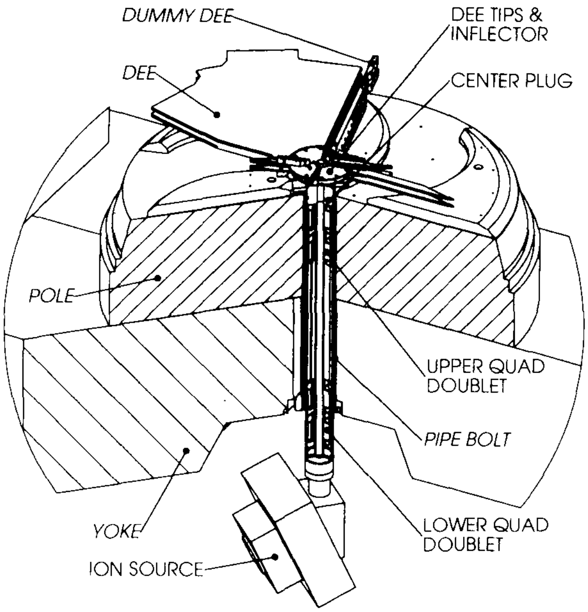

Figure 6: Section view of the of the MC50 showing a possible layout for the injection line including a quadrupole doublet in the magnet bore

4 Injection Line

At present the injection line calculations are not complete. However we have developed a design based on the TR30[5] injection quadrupole magnets, for a quad doublet that will fit in the space in the axial bore created when the existing centre plug is removed. These are shown in figure 6. Preliminary calculations show that these magnets should be capable of producing the focusing conditions at the entrance of the inflector necessary to match into the cyclotron. In order to reduce the α current required from the ion source a buncher will be included in the injection line. At these beam currents longitudinal space charge should be manageable, however because of the relatively low beam energy the transverse beam size and the buncher will have to be carefully matched.

In order to keep the inflector orbit geometry constant, the injection energy will have to be scaled in the same manner as the dee voltage for the constant orbit mode. At low extraction energies (at present used infrequently) this results in very low source extraction voltages. This in turn will most likely reduce the source output current and increase the emittance. It therefore may be necessary to extract from the source at a higher energy and use the buncher to decelerate the beam to achieve high intensity α beams at low final energies.

5 Conclusions

A preliminary design of a central region for the MC50 cyclotron capable of accelerating beams on both the first and second harmonics has been assembled. All parameters appear to be within the ranges defined by existing cyclotrons. There is however a difficult clearance between the inflector electrode and the second dee tip which requires the inflector aspect ratio to be held to a minimum. Past ion source experience also suggests that a PIG ion source operated with a very dense small plasma column should be capable of generating sufficient currents of protons, deuterons, and alphas.

References

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