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INITIAL OPERATING EXPERIENCE WITH THE TRIUMF 300 keV H⁻ INJECTION SYSTEM

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Summary

The present TRIUMF injection system consists of a 12 keV Ehlers type unpolarized H^- ion source located in a 288 keV accelerator terminal, and connected to the cyclotron by a 35 m long injection line which contains two 90 deg electrostatic bends, three periodic quadrupole sections, and elements to pulse, bunch and chop the beam. The stray magnetic field from the cyclotron has been compensated in the source and along the beam line with passive shielding and ferrite permanent dipoles. The beam enters the cyclotron axially and is bent into the median plane by means of a spiral inflector. This system is now being commissioned and currents of 50 μA dc and 250 μA peak in a pulsed mode have been obtained with 90% transmission. Currents of 500 μA dc and a bunched beam of 1.5 mA peak have been obtained previously in the prototype injection system, and similar performance can be expected with the present system. A polarized H^- source is under construction.

Introduction

The TRIUMF ion source injection system has been commissioned up to dc currents of 50 μA and first delivered an H^- beam in October 1974. To date the system has operated for about 700 h at beam currents of a few microamperes, and has been operable almost continuously.

During the first year of operation the average cyclotron current will be limited to a few microamperes to keep the induced radioactivity low; in a 1% duty cycle pulsed mode a peak current of 250 μA has been obtained which, when increased by a factor of four by bunching, will allow a peak current of about 1 mA to be injected into the cyclotron. This, with a cyclotron phase acceptance of 10%, will allow the use of low long-term average currents to study the dynamical behaviour of a 100 μA short-term average beam (which is the cyclotron design objective).

In order to establish the capability of the injection system to provide the required currents to the cyclotron, tests were made on the full-scale central region model injection line.[1,2] These tests demonstrated a 500 μA 300 keV H^- dc beam transported with 90% transmission along a 22 m path, and after bunching a 1.3 mA peak current beam was injected into the model cyclotron. An average current of 120 μA was accelerated up to the 6th turn. Because of sparking problems in the model line caused by excessive beam power dissipation on beam line elements under fault conditions, the current will be increased above 50 μA in the TRIUMF injection line only once the system has been fully interlocked to avoid substantial beam losses. Apart from this sparking few difficulties were encountered in commissioning the central region model to design current levels.

In addition to the unpolarized beam, a polarized beam will be available to TRIUMF within the present year. The Lamb shift polarized ion source has already delivered 300 nA with 80% polarization.[3] The high-voltage terminal and the transport line to the main line are now under construction.

The Injection System

A schematic layout of the ion source injection line system is given in Fig. 1. The first terminal, now in operation, contains an Ehlers[4] type H^- source which is capable of producing a beam of 2 mA within an emittance of 0.32 π mm mrad. The second terminal houses the polarized Lamb shift source, the emittance of which is expected to be smaller than that of the unpolarized beam. Provision has been made for installing at a later date a third terminal (dotted line in Fig. 1). The 300 keV injection energy was chosen as a compromise between higher energies—desired to increase the cyclotron injection acceptance, to provide a large enough radius for the first turn to clear the centre post, and to reduce space charge effects—and lower energies which reduce the size, cost and the voltage holding requirements of the electrostatic elements in the injection system and give more convenient separation between the first and second turn in the cyclotron.

For a given source, a short-east-west horizontal section followed by a 90 deg horizontal bend section carries the beam into a common section consisting of a 16 m long north-south horizontal section, a 90 deg vertical bend section and a 13 m long axial line. The exceptional length of the injection line was dictated first by the necessity of having a long drift path following the buncher to permit small buncher voltages and hence avoid aberrations produced by the energy dispersion of the inflector, and secondly to allow the necessarily large and complex ion source terminals to be built and maintained in a radiation-free, low magnetic field region in a stable and accessible position outside the cyclotron shielding structure. In order to keep beam loss due to H^- stripping by the residual gas below 10%, the vacuum in the line is maintained in the 10^{-7} to 10^{-6} Torr range by liquid nitrogen trapped diffusion pumps and sublimation pumps.

The shielding and compensation of the cyclotron fringe field along the beam path in the ion sources and horizontal beam line was done by using a combination of cylindrical steel shields and compensating ferrite dipoles; the details of their installation in various places are discussed in relevant sections below. The fringe field, which varies from about 50 G above the cyclotron to a few gauss in the ion source enclosures, was measured along the entire length of the beam line, and the shielding and compensation continued through successive iterations until the measurements showed that the desired field distribution had been achieved. For the unpolarized beam, the requirement was that $I_B(z)$ (the line integral of the component of the field transverse to the beam momentum) be less than the value which can be compensated by the electrostatic deflection plates. This is illustrated for the north-south horizontal section in Fig. 5, where curve 1 shows $I_B(z)$ due to the original fringe field, curve 2 shows the reduction due to cylindrical steel shields placed where possible, curve 3 shows the equivalent $I_B(z)$ which could be corrected by means of the electrostatic correction plates, and curve 4 shows $I_B(z)$ obtained by using an optimized distribution of small ferrite dipoles in conjunction with the shields.

For the polarized beam, magnetic field gradients can lead to polarization precession aberrations. However, calculations based on measurements of the residual compensated field indicate that the aberration is less than one degree. The longitudinal field, which is not compensated, leads to a total polarization precession of about 50 deg, which can be corrected by the Wien filter in the polarized beam injection line.

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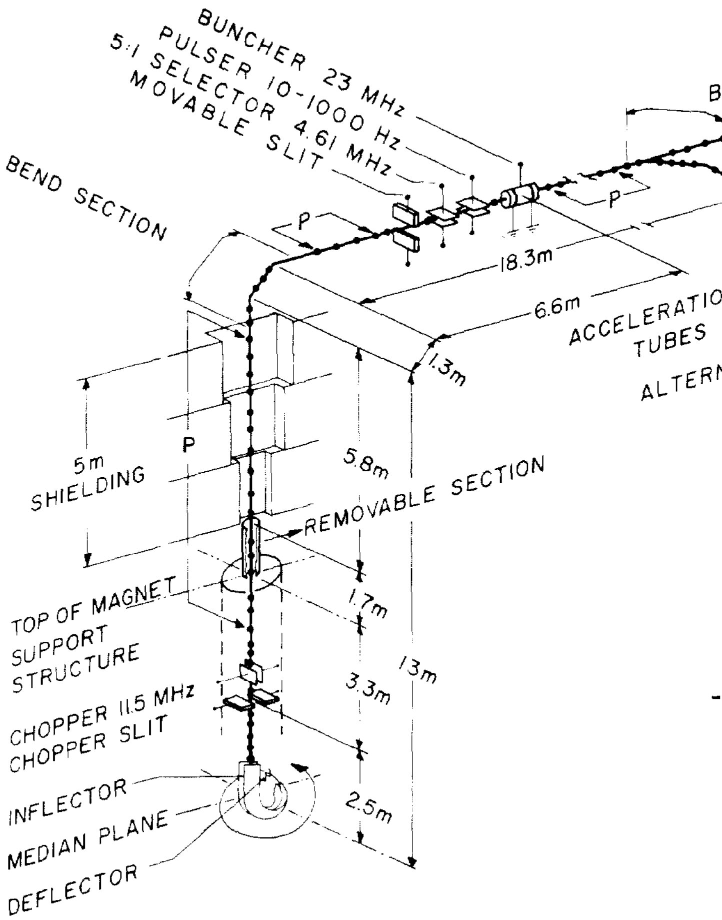
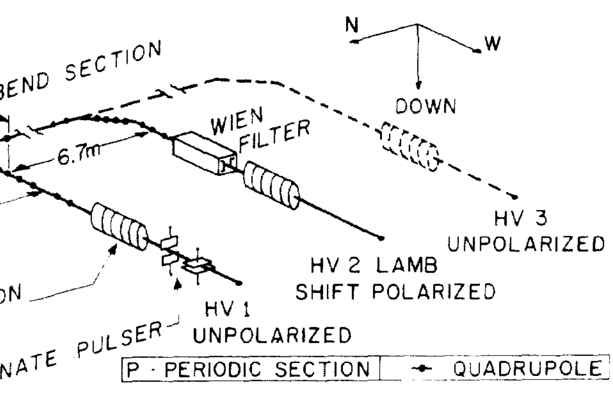

Fig. 1. Injection line layout.

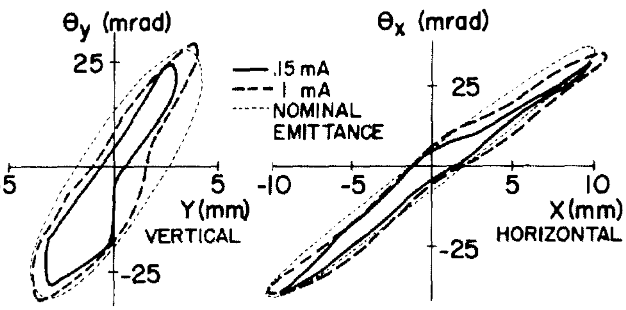

Fig. 2. Emittances at exit of 12 keV ion source.

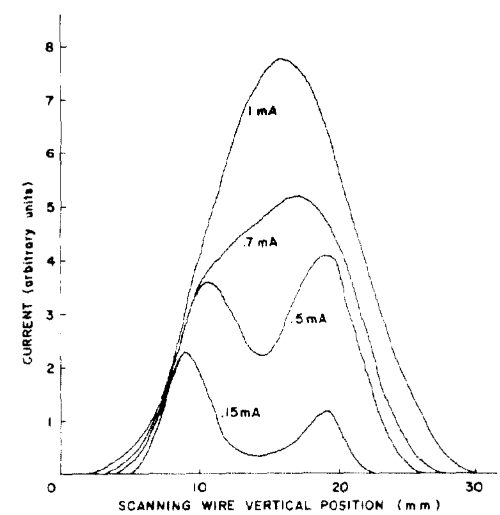

Fig. 3. Vertical beam profile at 12 keV ion source exit.

HV Terminal, Ion Source and Acceleration Tube

The 288 kV terminal voltage is supplied by an RF-driven air core cascade transformation power supply built by Delta-ray Corp. Its design specifies 0.01% stability with loads to 6 mA and 0.001% peak-to-peak ripple at its oscillator frequency, 50.4 kHz. The source and support devices within the terminal are CAMAC controlled and monitored via two light links which allow serial transmission each way between ground and the terminal.

The Cyclotron Corporation 12 keV H^- ion source is closely similar to the source for the central region model.[1] The beam stability has been significantly improved over that of the original commercial source. This has been done by controlling the ion source filament current by a servo-loop which seeks to stabilize the ion source arc current to within 1%. For currents between 150 μA and 1 mA the emittances, measured at the exit of the ion source magnet, lie within the specified values and increase with increasing current, as shown in Fig. 2. At low currents the vertical beam current distribution peaks in two locations (Fig. 3). The valley between the peaks progressively fills with increasing beam current until the double peak tends to disappear. This behaviour is believed to be connected to the space-charge-dependent curvature of the equipotentials near the ion source slit.

In the 1.3 m long 12 keV region which separates the ion source magnet from the acceleration tube entrance the 6 G transverse field has been reduced to less than 0.5 G by installing on the surface of the vacuum chamber an appropriate distribution of small 3 A m^2 barium ferrite dipoles. An optical bench in the chamber allows the position of the Einzel lens, two quadrupoles, slits, steering plates and scanning wires to be varied without loss of alignment. The beam envelope in this region has been measured as a function of the Einzel lens and quadrupole voltages and agrees with calculations (Fig. 4). However, a consistent discrepancy between theory and experiment appears when measurements of the accelerated beam are made. The accelerator tube appears to be stronger focusing than calculations (based on a potential distribution derived from a relaxation method) would indicate. This problem is presently being investigated.

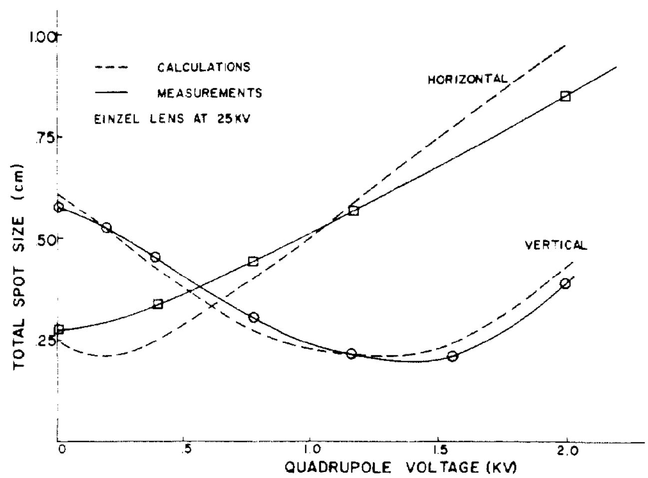

Fig. 4. Comparison of theoretical and measured 12 keV beam spot sizes.

The Injection Line

77 electrostatic quadrupoles about 10 cm long and 5 cm aperture, are distributed along the beam line. A majority are used in FODO repetitive sections, which when operating at their maximum voltage of 3 kV transmit a properly matched 10 mA beam with a maximum rms diameter of 20 mm. The remainder are used to match the repetitive sections to elements with individual optical properties, such as the accelerator tube, the bends, the chopping slits, and the inflector; they operate at voltages up to 10 kV. The mechanical alignment of the optical elements within a modular section was accurate to within ±0.2 mm. Steering plates placed at 1 m intervals each provide up to 4 mrad of beam steering and simplify the beam alignment procedure in the presence of residual magnetic fields or mechanical misalignments between the modular sections. The voltages are supplied to the elements by CPS power supplies with a stability of 0.01%. The overall stability of the system is very good, and a current which is steady to within 5% is routinely transmitted from the source and through the 1.2 mm chopper slit at the end of the line.

The East-West Horizontal Section

Four quadrupoles in this section provide matching between the acceleration tube exit and the horizontal bend section. Transport studies indicate that the horizontal and vertical beam waists created by the strongly focusing acceleration tube must both be brought beyond the acceleration tube exit in order to allow an optical solution with reasonable voltages and beam size. This emphasizes the importance of an accurate understanding of the beam in the 12 keV and acceleration tube regions. When the 6 G transverse magnetic field in this region was reduced to less than 0.5 G with compensating permanent magnets, no steering by the four independent quadrupoles was observed, indicating good beam centring. A slight discrepancy between calculated and experimental quadrupole voltages is attributed to the incomplete understanding of the acceleration tube optics referred to above.

The 90 deg Bend Section

The horizontal and vertical 90 deg bends have identical optical design. They consist of two 45 deg bend electrodes each placed between two quadrupoles to form a structure symmetric about the central 45 deg plane. When operated in a non-dispersive mode the section accepts a ±3 kV initial energy variation, which accommodates the ±1 keV energy modulation introduced by the buncher and also allows the injection energy to be varied slightly to help obtain well-centred orbits in the cyclotron. Such a non-dispersive solution has been experimentally realized in absence of the stray magnetic field, but cannot be implemented with cyclotron magnet on until further magnetic compensation is done in the bend regions.

The North-South Horizontal Section

The north-south horizontal section consists of a 9 m long periodic section, a 4 m long special section for beam pulsing and bunching, and another periodic section 3 m long. In the beam pulsing section, six quadrupoles, three on each side of the pulser slit, are symmetrically arranged to match a 2 mm waist at the slit to the two adjacent periodic sections.

Cylindrical mild steel shields 4 mm thick and 25 cm diam were mounted along the beam line wherever possible, and barium ferrite dipoles were mounted inside the shield ends, where their efficiency is enhanced by a factor of 10 due to the return flux guides provided by the shields. The optimal distribution of the permanent magnets gave the compensated $I_B(z)$ shown in Fig. 5, which shows only the vertical component since the horizontal one is much lower.

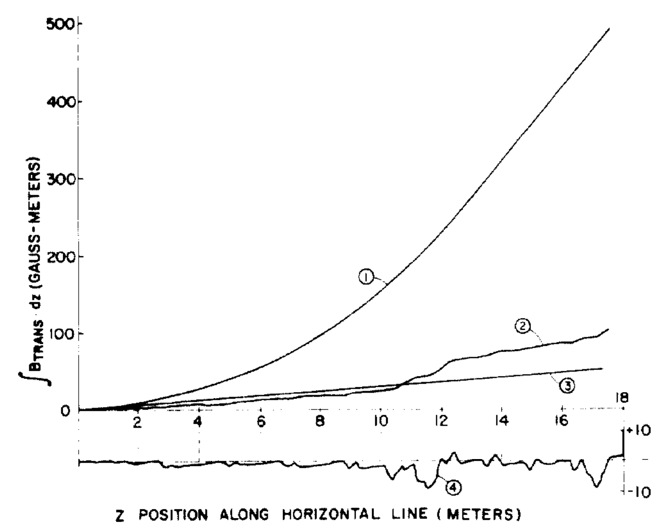

Fig. 5. Magnetic fringe field compensation. 1) Uncompensated field; 2) Field with mild steel shields; 3) Equivalent correcting power of electrostatic steering; 4) Field with mild steel shields plus optimized distribution of dipoles.

The behaviour of the optics along this section was studied and faults detected and corrected by comparing the beam displacement produced by known steering plate voltages with the predictions of a transport program displayed interactively on a Tektronix 4023 terminal.

The Axial Section

In the 13 m axial injection line an 8 m long periodic section is followed by four quadrupoles which focus the beam at the chopper slit. The lower six quadrupoles match the beam to the inflector and cyclotron central region acceptance.

Fig. 6a shows the axial magnetic component along the last part of the line; the field rises from 50 G 4.5 m above the inflector to 3 kG at the centre of the cyclotron. The abrupt dip at 0.3 m is due to the presence of a cyclotron field shaping iron plug. A special computer code BLINE was written to do beam optical calculations in this region. The calculated effect of the magnetic field on the beam envelope in the north-south direction is shown in Fig. 6b. At the chopper slit the magnetic

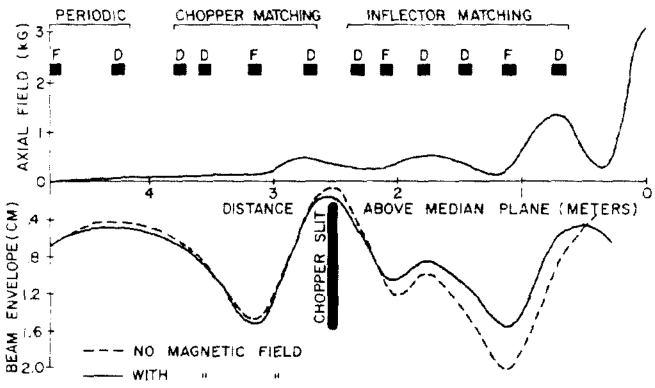

Fig. 6. Effect of cyclotron fringe field on beam envelope near chopper slit.

field increases the beam size from 1 mm to 4 mm, due mainly to a 15 deg solenoidal rotation of the beam cross-section in the x-y plane. However, the coupling introduced between the transverse x-y co-ordinates by the strong fields and gradients below the chopper slit substantially affects the quadrupole settings required for optimum matching to the inflector.

Due to the symmetry of the magnet structure the transverse magnetic field is less than 1 or 2 G over most of the axial line. This field has not yet been compensated, which leads to some beam misalignment in the matching regions so that complete optical optimization has not yet been achieved. At present, 90% transmission through 1.2 mm wide chopper slits is obtained by reducing the beam emittance at the ion source and by empirically adjusting the quadrupoles above the slits.

The Inflector Deflector System

The inflector is similar to the one tested in the central region cyclotron[2] and consists of two spiral electrodes, with a 25.4 mm gap and operating at ±28.5 kV, which bend the beam onto the median plane. The cylindrical deflector, which provides the additional median plane deflection required to centre the beam in the cyclotron, consists of two 11 cm long electrodes, with a 2.5 cm gap, operated at ±18 kV.

Strong coupling terms in the 6×6 beam transport matrix introduced by the spiral shape of the inflector make optimization of the beam matching between injection line and central region rather complicated. Using a special version of BLINE, settings for the six inflector matching quadrupoles were found which placed 100% of the beam within the vertical acceptance and 83% within the horizontal acceptance of the cyclotron.

The transmission through the inflector-deflector is greater than 90%, and the losses during the first few accelerated turns are compatible with theoretical expectations, as described in these proceedings.[5]

Beam Time Structure

The elements which establish the beam time structure are distributed along the line, as indicated in Fig. 1. The pulser unit which provides the low duty cycle beam with high peak currents is presently located in the 12 keV region in the ion source terminal. Rectangular pulses of the order of 1 kV and of a duration between 10 μsec and 1 msec are applied to steering plates located before a 7 mm diam collimator. If excessive pulse modulation is induced on the HV terminal voltage by the pulsed beam load when we operate at high beam currents, the pulser will be relocated in the horizontal line, as shown in Fig. 1.

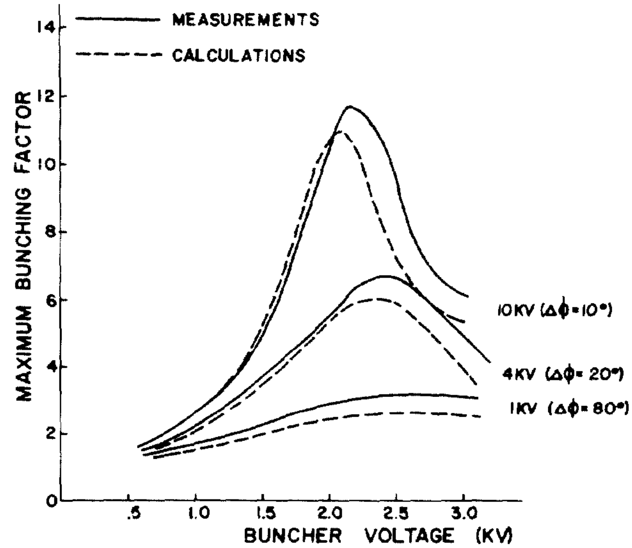

Fig. 7. Effects of bunching on beam transmitted through chopper slits, with phase acceptance and chopper peak voltage as parameter.

The 23 MHz double gap sinusoidal buncher, the 11.5 MHz sinusoidal chopper and the 1:5 pulse selector are similar to those used in the central region cyclotron, and are positioned so that narrow phase widths and maximum bunching efficiency can be obtained, as described by Duelli *et al.*[1]

Fig. 7 shows measured and calculated maximum bunching factors after the chopper slits as a function of buncher voltage for three different phase acceptances. Here the bunching factor is defined as the maximum increase in transmission through the slits produced by the buncher. The results are in good agreement with calculations. When the cyclotron acceptance was approximately 15-20 deg, the buncher increased the extracted beam intensity by a factor of 10, and when the cyclotron was optimized to accept a 50 deg phase interval, the bunching factor was found to be about 4, both measurements being in agreement with theory.

The chopped beam phase interval has been estimated both from transmission experiments and from the behaviour of the beam within the cyclotron. With the chopper slit width of 1.2 mm a phase width as narrow as 7 deg at full width half maximum could be injected into the cyclotron.

We wish to acknowledge the contributions made to the design and construction of this system by E. Page and W.J. Lester.

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