

THE TRIUMF 520 MeV CYCLOTRON: RECENT AND FUTURE DEVELOPMENTS

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ABSTRACT

The TRIUMF cyclotron is now routinely producing 150 μA protons at 500 MeV for meson production with a maximum available current of 200 μA and beam availability of 90%. A successful resonator upgrade program, the recent commissioning of a new 92 MHz rf booster cavity and a new compact CUSP ion source will allow the current to be increased to 225 μA routinely and 300 μA maximum, once an upgrade of the high radiation target areas is completed. Furthermore, the 300 μA maximum H^- internal current will allow, in parallel with 100-200 μA for meson production, the simultaneous extraction of 50-100 μA for a radioactive beam facility and of 50-100 μA for isotope production at 70-100 MeV. A proton therapy facility is also proposed. A new optically pumped H^- polarized source will allow a highly stable and reproducible 5 μA beam at $\sim 75\%$ polarization to be extracted. The feasibility of the extraction of an H^- beam with electrostatic and magnetic channels has also been demonstrated. Problems and plans for the extraction of 150 μA H^- for KAON will be discussed.

1. INTRODUCTION

The TRIUMF cyclotron has now been operating since 1975. The design goal of 100 μA proton beam extracted at energies between 200 and 500 MeV was achieved at the end of 1977. It is only since 1984 however, that the present level of high intensity beam production, based on routine extracted currents between 140 μA and 200 μA , for a total yearly integrated charge of about 300 mAh, has been attained. Beam availability has been maintained, over these last years, above 85%, with $>90\%$ achieved during 1991. A typical yearly schedule includes two shutdowns of six to eight weeks each, for maintenance and development; two periods of six to seven weeks of polarized beam before the shutdowns; and two periods of 12 to 13 weeks of high intensity beam after shutdowns. Typical simultaneously extracted beams during high intensity operation are: 140 μA at 500 MeV down BL1A, 40 to 50 μA at energies between 70 and 110 MeV down BL2C and up to 10 μA down beam line 4A or 1 to 100 nA down BL4B with variable energy between 180 and 520 MeV (Fig. 1).

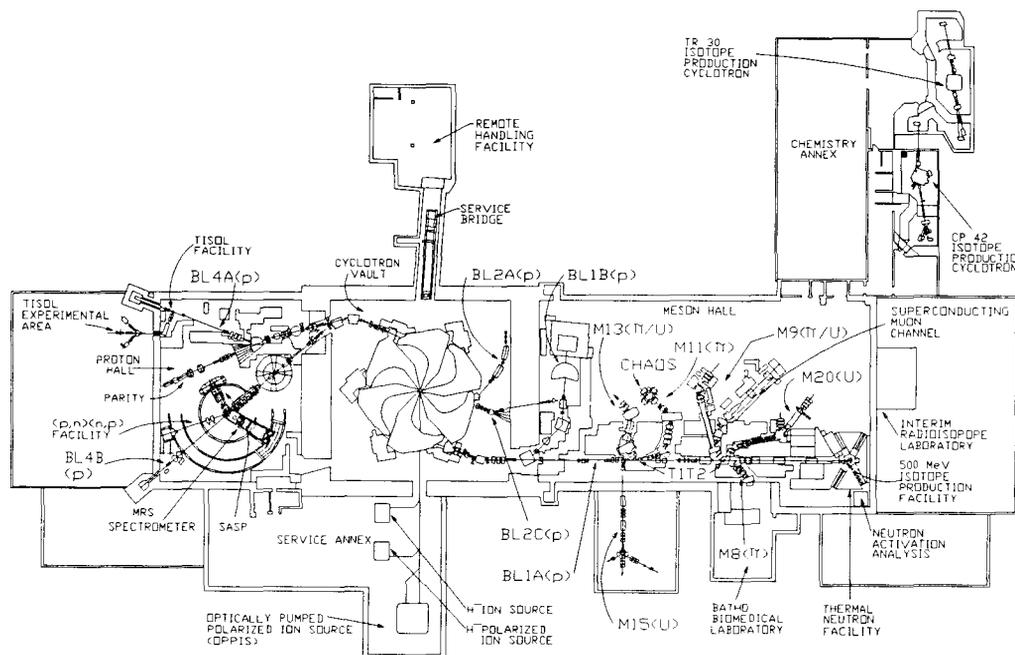


Fig 1. Layout of TRIUMF facility.

2. THE RESONATOR IMPROVEMENT PROGRAM FOR RELIABILITY AND BEAM STABILITY

Although all systems have been improved and made more reliable over the last ten years, the system which originally caused greatest concern and therefore received greater attention was the rf cavity. Conceptually, the system is simple. It can be seen as made of two $1/4$ wavelength coaxial stubs face to face and flattened to fit in the 16m diameter, 0.4m high, stainless steel vacuum chamber to form the two 180° dees of the accelerating structure.¹⁾

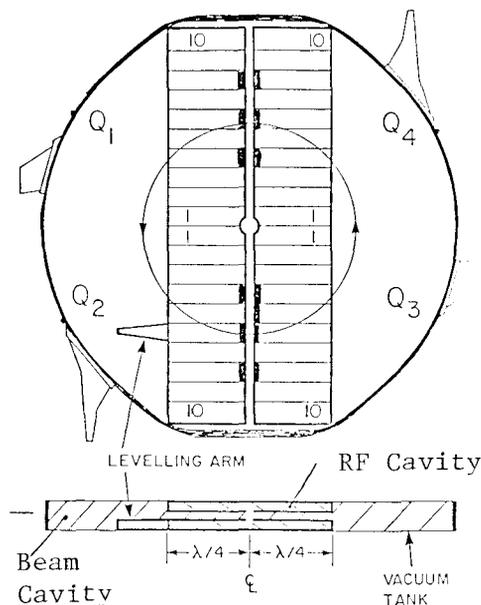


Fig. 2. Schematic view of main resonator cavity.

Mechanically, the system is made of eighty segments (Fig. 2), 10 upper and 10 lower segments in each quadrant. Mechanical tolerances for the 3m long cantilevered panels are very stringent: maximum deviation from the reference plane $\pm 0.5\text{mm}$ and tip vibrations below $\pm 25\ \mu\text{m}$ for a rf voltage stability in the order of $\sim 10^{-4}$. The original resonator panels were composed essentially of water-cooled copper panels facing the rf cavity with non-cooled aluminum strong-backs facing the beam. Soon after initial operation, it was found that small vertical electrical asymmetries in the cavity will excite substantial TM_{310} and TM_{410} parasitic modes in the beam volume.²⁾ Voltage differences, between upper and lower strong-backs, exceeding a few hundred volts resulted in multipactoring currents, transferring rf power to the non-cooled aluminum structures. Thermal deflections and serious panel distortions occurred, with structural rf damage. The problem has now been cured. Voltage probe and thermocouple diagnostics have been installed

to allow monitoring, reduction and control of parasitic voltages and temperatures.

To reduce parasitic amplitudes, hot arm to ground arm distances are adjusted at the tip of strategic segments with the intent of providing better electrical alignment and inducing additional perturbations of opposite sign to partially suppress in amplitude and phase the pre-existing perturbations. Reduction of stray voltages below multipactoring levels can normally be achieved over most of the volume. New type, more rigid, resonator segments with cooled copper surfaces on both sides of the aluminum strong-back have been constructed and installed in strategic positions (segments 4, 6, and 8) to bring tip alignment closer to the required tolerance and within tuning range. A factor of 2.5 improvement of the voltage stability was recently achieved with voltage stability better than 4×10^{-4} .

3. INTENSITY UPGRADE

Plans toward upgrading the intensity of the TRIUMF cyclotron to $500\ \mu\text{A}$ extracted at 500 MeV, have been previously reported.³⁾ In brief, they are based on the optimization and installation of a high brightness, more stable H⁺ Cusp source in the 300 kV terminal and on the addition, inside the existing vacuum chamber, of one or two fourth harmonic frequency Auxiliary Accelerating Cavities (AAC) to double or triple the energy gain per turn in the region between 400 and 500 MeV.⁴⁾ Electromagnetic stripping of the accelerated H⁺ ions is significant (8%) in this region and can be reduced by reducing the number of turns i.e. flight time of the ions through this region. Losses produced by residual gas in the $2\text{--}3 \times 10^{-8}$ Torr environment of the cryogenically pumped chamber are of minor significance compared with electromagnetic stripping losses.

The Cusp source which will be installed in the operational 300 kV terminal is a 10 cm diameter, 15 cm long copper cylinder volume source with its plasma contained by a system of SmCo_5 permanent magnets distributed around the volume.⁵⁾ Total extraction voltage across a well optimized system of electrodes is 25 keV. The normalized emittance of the beam is $0.12\ \pi\ \text{mm mrad}$ for 1 mA current from the source. This current is adequate for $500\ \mu\text{A}$ extracted since a combination of fundamental plus second harmonic buncher in the injection line provides a cyclotron acceptance of $\geq 50\%$ at these current levels.

Beam bunching will introduce energy spread and emittance distortions causing beam halos which, if not skimmed in the centre region through slits, will cause vertical losses at higher energies. Ideally one would like to operate without bunching, and with higher injection intensity, up to $\sim 7\ \text{mA}$, so that $\sim 500\ \mu\text{A}$ can be

transmitted say in a $\sim 25^\circ$ cyclotron phase acceptance. However, the normalized injected beam emittance for a 7 mA beam is higher, $\sim 0.35\pi$ mm mrad in both directions, and the advantage of avoiding bunchers is therefore questionable, specifically in light of the non-trivial problem of dissipating several kW of beam power through the beam defining central region electrodes.

4. AUXILIARY ACCELERATING CAVITY

Schematically, the cavity is made of two trapezoidal structures, placed symmetrically above and below the mid-plane, vertically separated by a 64 mm horizontal gap (Fig. 3). Hot arms and ground arms define electric accelerating fields at the periphery of the structure. The cavity operates at the fourth harmonic (92.24 MHz) of the main rf frequency and is $\lambda/4$ long radially, $\beta\lambda/2$ wide azimuthally so that orbiting ions can receive acceleration impulses both entering and exiting the cavity. The peak accelerating voltage rises sinusoidally with radius, covering the energy range from 370 to 520 MeV. Operational voltages of 150–160 kV have been achieved with 50–60 kW of power up to routine high intensity beam current. When tested during beam production the cavity behaved well for an extensive period of time and the corresponding new extracted beam characteristics were acceptable to experimenters. Beam intensity from cavity off to cavity on increased by 4%, a substantial fraction of the $\sim 10\%$ beam loss at high energy. The observed phase compression of the extracted beam (slightly less than a factor two) is shown in another paper to this conference; Ref. 6, Fig. 4. The same paper shows, Fig. 10, the longitudinal beam splitting phenomena which can be produced by using the cavity with opposite phase to locally reduce the total energy gain per turn to zero. Possible uses of this cavity are discussed in Ref. 6-7.)

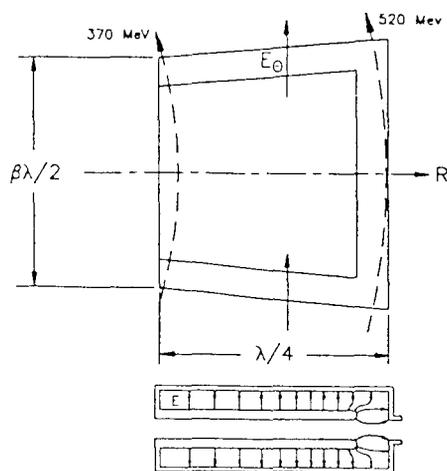


Fig. 3. Schematic view of auxiliary accelerating cavity.

The implementation of new levels of high intensity beam production on a continuous basis requires an upgrade of diagnostics and of the corresponding remote handling systems around the thin (1 cm C) and thick (10 cm Be) meson production targets. This has been delayed pending the decision for KAON, since in the latter case most beam would be extracted down BL2A and the present 200 μ A limit in 1A would be adequate. Operation with AAC cavities will still be important, however, because of the reduction in tank activation for the remaining 500 MeV experimental program and the improvement of beam quality H^- extraction from 4th harmonic flattopping.⁷⁾

5. EXPERIMENTAL FACILITIES

In the meson area, six secondary channels have been organized to collect pions and muons for experiments. On the M8 channel π^- are collected and transported to the medical cancer treatment area, where so far about 300 patients have been treated mostly for brain tumours or for deep-seated pelvic tumours. Results to date have been very encouraging. A clinical randomized trial is underway to establish through statistical analysis the effectiveness of the method. Results will be presented to this conference by Dr. George Goodman.⁸⁾

Recent secondary lines include M15 for high quality, polarized surface muons, with two high gradient electrostatic separators with compensating magnets providing the capability of transverse spin directions. The second arm of M9 operates with a large solid angle acceptance superconducting muon channel delivering an intensity of negative muons of $\sim 5 \times 10^5$ at 40 MeV/c.

A large angular spectrometer, called CHAOS, is being constructed for pion physics. This will detect pions within $\pm 8^\circ$ of the horizontal plane, over an angular range approaching 360° . Four concentric wire chambers and a ring of scintillators and Cerenkov counters will be used for trajectory measurement and particle identification. The purpose is to study low energy pion-pion and pion-nucleon scattering at M11 and M13.

In the proton area on BL4B, a Medium Resolution Spectrometer (MRS, 1 MeV resolution) of the qd type is being joined by a Second Arm Spectrometer (SASP), designed to have a much larger angular acceptance. Improved energy resolutions (250 keV) are envisaged.

A facility of interest to this conference is the TISOL facility on BL4A. Here a thick target station is connected to an ECR source producing a wide range of radioisotopic ion beams. A 90° mass analyzing magnet is followed by an electrostatic transport line bringing the low energy (20 keV) radio-isotopes to an experimental area at

ground level. This installation is important since it is the prototype of the front end of the 10 MeV/n ISAC facility, being proposed for radioactive beam studies at TRIUMF.⁹⁾

The polarized beam has recently been upgraded to satisfy the demands for several experiments including π production from polarized neutrons on a proton target, charge symmetry breaking and parity violation. The new optically pumped H^- polarized source has been upgraded with more powerful titanium sapphire lasers for optical pumping of Rubidium instead of Sodium vapour in the polarized cell. Intensities of $2 \mu A$ with 78% polarization have been extracted at several energies from the cyclotron. It is believed that $5 \mu A$ extracted with 78% polarization is within reach with further source optimization.¹⁰⁾ For the experiments above, both source and cyclotron have to satisfy very stringent requirements: short pulse time structure (< 500 ps), 10^{-3} polarization stability during spin reversal, $< 10^{-4}$ (or better) intensity or energy variation between spin up and down and other challenging features. The optically pumped source is believed to be superior in this regard compared with atomic or Lamb-shift sources.

The low energy beams of beam line 2C are used for isotope research and production. Recently a metallic rubidium target has been tested which can safely be operated at 50 to 100 μA current without reduction in yield. Rubidium targets producing 2 Ci of ^{82}Sr have been realized. Two papers to this conference describe BL2C and its control.¹¹⁻¹²⁾

Finally, a proton therapy facility is being planned in the BL1B area. Two beam lines will be used: BL2C for eye melanoma with available proton energies between 60 and 100 MeV, and the existing BL1B (180 to 520 MeV) or a proposed BL2B (140 to 280 MeV) for brain tumours or other deep seated tumours and AVMs treatment. A scheme providing room for a gantry system and involving substantial building modifications is also being considered. A treatment facility plan has now been prepared by the B.C. Cancer Agency and has been submitted for funding.

6. H^- EXTRACTION FOR KAON

The scheme for direct extraction of an H^- beam (Fig. 4) has been reported previously.¹³⁾ A 11.5 MHz rf cavity (RFD) oscillating at 1/2 the fundamental rf frequency generates a radial coherent oscillation downstream of $\nu_r \sim 3/2$ at 428 MeV. In one of the minima of the precession pattern (see Fig. 6 in Ref. 6), where the radial beam density has been reduced by a factor of 5, a 1 mm wide stripping foil is used to extract about 10% of the internal circulating H^- beam through an existing port into one of the existing beam lines. This will create a gap in

the radial beam density at the location of the septum of the first electrostatic deflector. The other 90% of beam will then be extracted through the first and second electrostatic deflectors and through the five following magnetic channels. The first two channels, of moderate strength around 85 mTm, are iron free. The three channels downstream have iron cores. A separate iron free quadrupole and a gradient on channel five will provide vertical and radial beam focussing. The magnetic channels have to be designed so that the perturbations in the radial field gradient dB_z/dr in the region of the internal beam are kept below a maximum of 0.15 G/cm, on average over one turn.

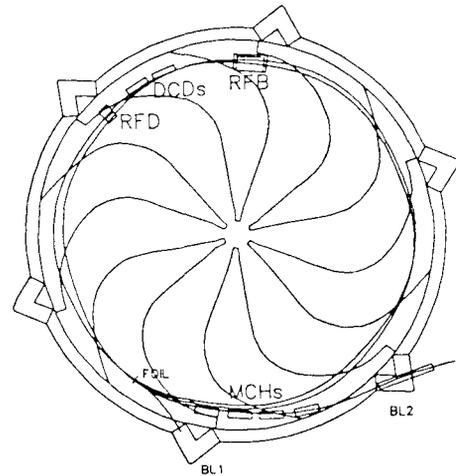


Fig. 4. H^- extraction layout

RFB - auxiliary accelerating cavity; RFD - rf deflector; DCDs - electrostatic deflectors; MCHs - magnetic channels.

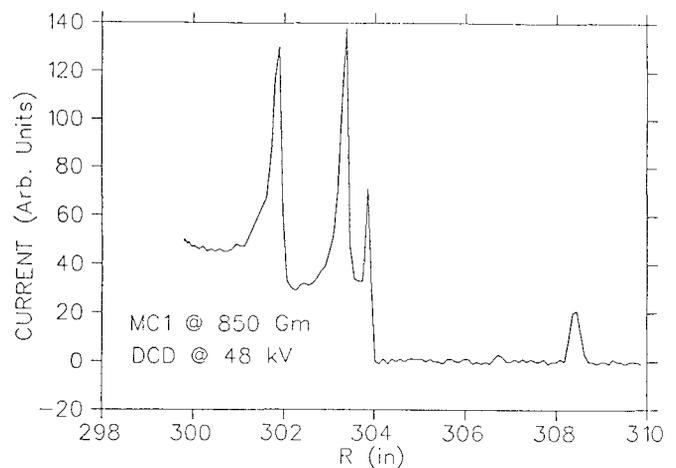


Fig 5. Radial H^- beam profile showing deflected 90% beam 6 m downstream magnetic channel 1.

A prototype of channel 1 was tested on the cyclotron with beam. Figure 5 shows the profile of the H^- beam radially separated by 10 cm from the internal cyclotron beam, 6 m downstream the channel: no beam losses on the magnetic channel were observed. The cross-section of the iron core current compensated channel to be used for channel 3 is given in Fig. 6. The channel has been designed so that it will produce a field reduction of 540 mT over a distance of 0.9 m with a useful aperture of 3.8 cm high by 3.0 cm wide. Model measurements in a rather uniform 4 Tesla test magnet show good agreement between calculated and measured field inside and outside the channel. However, beam measurements with a prototype channel installed in the highly non-uniform field of the cyclotron are planned for verification.

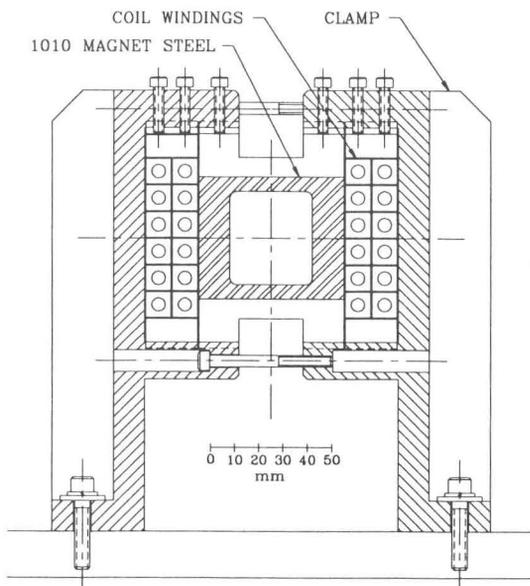


Fig. 6. Schematic section of magnetic channel 3.

The DCD has been shown to hold 80 kV positive voltage at low extraction intensities. However, during recent tests, voltage holding became marginal at extracted currents of approximately $30 \mu A$, 25% duty cycle. The reason for this is attributed to a larger than expected vertical beam size at extraction caused, inter alia, by emittance growth in the region of the rf deflector. In addition, the beam was vertically misaligned, with respect to the median plane of the electrostatic channel, by approximately 1.5 cm, thereby occupying a channel region where electric field gradients start being significant. Finally, the larger vertical emittance and halo distortions caused problems with spills down beam line 1 where the $30 \mu A$ beam was being channelled.

Obtaining and maintaining a high quality, stable beam at extraction is therefore essential at high intensity, even if the traditional requirement of separated turns is in

our case not necessary because of the septum prestripper protection. Beam studies with simulations and measurements are being carried out to achieve the necessary quality and stability. It has been found that phase dependent vertical emittance stretching occurring at $v_z = 0.25$ due to gradients in the RFD field, could result in 50% vertical emittance growth. The Auxiliary Accelerating Cavity (AAC) can be used to locally flattop the accelerating voltage during the precession so that all particles spend the same time between the start of the precession and extraction and phase dependence is cancelled.⁷⁾

7. REFERENCES

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