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DEVELOPMENTS AT TRIUMF*

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Summary

The TRIUMF H⁻ cyclotron has been operating with 80% availability over the last year. Two proton beams are extracted simultaneously with energies which may be varied independently between 183 and 520 MeV, while the ratio of their intensities may be adjusted from unity to 1/5000. Beam intensities up to 10 μA are being scheduled for regular operation, and 50 μA have been achieved during tests. The intensity of the ±78% polarized beam from the 'Lamb shift' ion source is 30 nA (extracted). The external beams have an energy spread of 1.5 MeV and emittances of ∿3π mm-mrad; the microscopic and macroscopic duty factors are 11% (5/43 nsec) and 100%, respectively. The secondary beam lines operational include a muon channel, a slow and stopping pion line and a biomedical π⁻ line. Monokinetic fast neutrons, 40-70% polarized, are also available from a liquid deuterium target. It is planned to increase the extracted beam current in stages to 100 μA by the end of 1977. Work is also progressing on additional beam lines, a 180 kW beam dump and thermal neutron source, a medium resolution proton spectrometer, and adding third harmonic flat-topping to the RF to reduce the energy spread to 0.1 MeV.

Introduction

The successful acceleration of an H⁻ beam to 500 MeV in the TRIUMF sector-focusing cyclotron and the extraction by stripping of two simultaneous beams with energies independently variable between 183 and 520 MeV was first reported by Richardson *et al.* in 1975.[1] More details on the cyclotron performance and the beam properties during the first six months of operation were given at the 7th International Conference on Cyclotrons in Zürich.[2-4]

During the last two years the emphasis has been on (i) more reliable and efficient beam production for experiments with both the normal and the polarized beam, (ii) higher extracted beam currents at 500 MeV, (iii) beam dynamics and RF work toward separated turn acceleration and 100 keV resolution, and (iv) design and construction of new experimental facilities and beam lines.

The beam properties achieved are summarized in Table I and compared with their design values. The most significant recent value is the 50 μA 500 MeV beam which was achieved during a test in November 1976. The beam was dumped for a few minutes on the present temporary beam stop T2, originally designed for currents of the order of 10 μA. Thermal switches on the temporary dump prevented increasing the extracted current beyond 50 μA or extending its duration, but a 30 μA beam could be maintained for several hours.

Operation and Reliability

As shown in Fig. 1 the beam is extracted simultaneously at two extraction ports 180° apart and injected into the two beam lines, BL1 and BL4, which feed the meson area and the proton area, respectively. 10 μA beams are normally delivered down BL1, 1 μA down BL4A, 10-20 nA down BL4B.

The cyclotron is operated 24 hours per day, seven days a week. In a 14-day cycle there are usually two days of maintenance and one or two days for operator training and beam development. In the past 12 months the machine reliability, as defined by the ratio of hours of cyclotron operation to scheduled operating time, has been about 80%. The reproducibility of the system is quite satisfactory. Once the optical systems are set up by computer to a previously established master solution and the RF and the ion source are brought up, it usually takes less than an hour to bring the beam from the ion source to the T2 target. Special programs which check the status of systems and give warnings when abnormal conditions occur are normally on line.

Since first operation at the end of 1974 there have been six shutdowns, each lasting between three to six weeks, scheduled for machine improvements. Two unscheduled shutdowns during the winter 1975/76 were the result of overheating of components in the RF resonators. The most serious problem was the melting of the Al tips of the central region electrodes; calculations confirmed that this could have been caused by electrons trapped in the crossed electric and magnetic fields. After these tips were replaced with water-cooled copper electrodes and thermocouples were installed to monitor the temperature, the heating has been kept well under control. The RF voltage is now kept around 85 kV.

The vacuum has been gradually improving and is now around 6×10^{-8} Torr after a few weeks of beam operation.

Table I. Beam Performance

Property	Achieved	Aim
Energy range	183-520 MeV	165-500 MeV
Current	10 μA (regular) 50 μA (once) 100 μA (pulsed 1%) 50 nA (pol)	100 μA (500 MeV) 300 μA (450 MeV) 60 nA (pol)
Polarization	78%	80%
Duty factor - max - min	11% (5/43 nsec) 4% (chopped)	11% 1% (slits)
Transmission	80% (5-500 MeV) 8% (dc-500 MeV) 30% (bunched)	86% (5-500 MeV) 10% (dc-500 MeV)
Vertical centring	±6 mm	±6 mm
Isochronism (sinϕ)	±0.4	±0.02
Energy spread (10% peak)	2.0 MeV 1.5 MeV chopped	1.8 MeV 0.5 MeV (slits) 0.1 MeV (3 harm)
Rad emittance (90%)	3π mm-mrad	3π mm-mrad
Vertical emittance (90% beam internal) (90% beam external)	 1π mm-mrad 3π mm-mrad	 1.2π mm-mrad 2.4π mm-mrad
Spot size at T2	3 × 14 mm²	2 × 10 mm²

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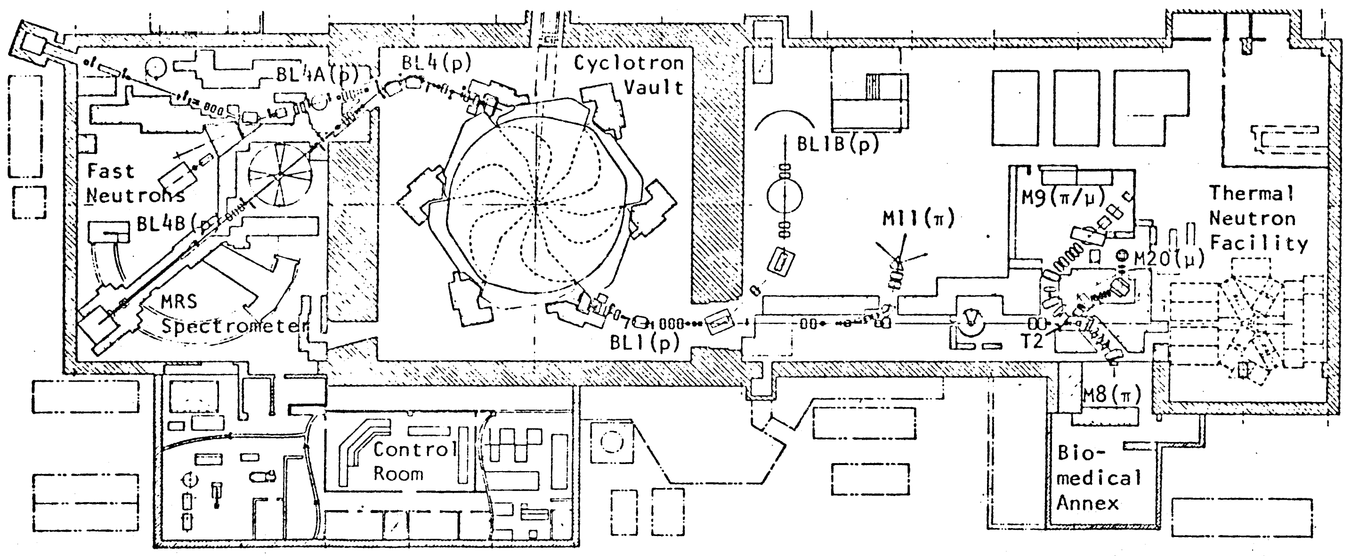

Fig. 1. Layout of the facility. Symbols and properties of the systems are described in the text.

At operating values of 1.5×10^{-7} Torr the beam loss due to vacuum, about 10% uniformly distributed with radius, is less harmful from the point of view of residual activity than the loss due to electromagnetic stripping, 7%, localized mainly at the higher energies (450-500 MeV). A few per cent vertical beam loss in the 200-230 MeV region is thought to be caused by the $\nu_r-\nu_z=1$ resonance for those initial phases for which the centring is more critical. Substantial improvements in the beam behaviour through the cyclotron, as described elsewhere at this conference,[5] have contributed to the reliability and ease of operation.
Foil scrapers have been mounted above and below the median plane to strip any beam which could otherwise hit the resonators. The stripped beam portion is sent onto two secondary emission monitors for monitoring and control.

A major improvement in the TRIUMF facility was the addition in February 1976 of the polarized H^- source, delivering about 250 nA of 75-80% polarized beam at injection and up to 50 nA of polarized beam at extraction. The source is of the Lamb shift type with a Sona zero-field crossing region to enhance polarization. The polarizations measured by pp scattering at various energies between 203 and 515 MeV are illustrated in Fig. 2; no substantial depolarization appears in the cyclotron or injection system. During 1976 40% of the time was scheduled for polarized beam.

The simultaneous extraction of two beams by stripping, conceptually simple, is complicated in practice by (i) the modulation of the beam envelope surface with respect to the geometric median plane due to small residual B_r components and to the strong six-sector azimuthal focusing; (ii) the operational need

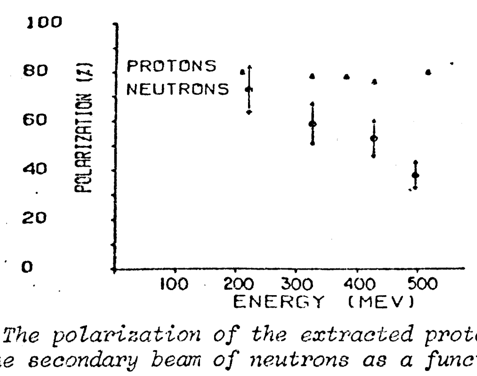

Fig. 2. The polarization of the extracted proton beam and of the secondary beam of neutrons as a function of energy.

to extract two beams differing in intensity by as much as a factor of 5000; and (iii) the limited vertical clearance (4 in. outside the dee, 3 in. inside) for the extraction probe. Up to 6 foils are usually stored in the extraction probe cartridge in a sequence determined by the experimental schedule. There are three main types (Fig. 3): type A for total extraction; type B for partial extraction at the lower energy with split ratio between 1/1000 to 1/3; and type C for split ratios down to 1/5000 and a stability of better than 25% for the low intensity beam. Materials are 0.001 in. Al or, for higher currents, 0.001 in. pyrolitic graphite.

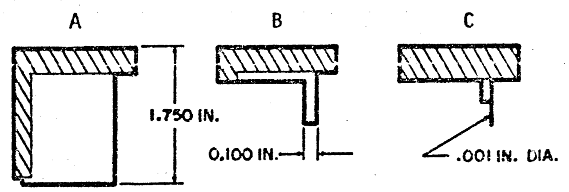

Fig. 3. Strippers for A) total extraction, B) partial extraction, C) extraction of 1 part in 5000.

Towards Higher Intensities

The performance of the cyclotron in terms of μA hours/month and the intensity milestones achieved in the last two years are shown in Fig. 4. During 1975, when a large part of the time was spent in commissioning the cyclotron and its systems, the current was kept

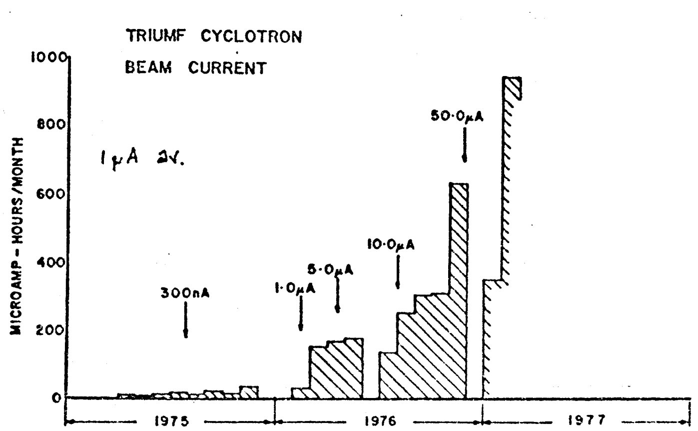

Fig. 4. Performance in terms of microampere-hours delivered.

below 300 nA, mainly due to initial shielding limitations along the beam lines. The removal of 0.001 in. thick Havar windows at the beam line front-ends, the replacement of Al stripping foils with lower density graphite, and improved beam line tuning allowed the operating current to be increased to 1 μA at the beginning of 1976. At this time a very welcome injection of funds specifically related to the 100 μA goal mobilized the laboratory. Additional shielding was immediately ordered and detailed designs were begun on the 400 μA beam dump, which will be used as a thermal neutron facility (TNF), and on the beam line extension required downstream T2.

Around the cyclotron tank a special system of graphite absorbers surrounded by boriated gypsum sheets was installed to degrade the spilled beam, which is mainly lost horizontally through the special thin median plane portion (1/32 in.) of the tank wall. Being inserted between tank wall and magnet yokes they also partially shield the tank area from the activity induced on the yokes. A shielding factor of five was measured at the tank periphery and ten at the centre.[6]

The map of the residual activity in the tank—20 mrem/h at the outside, 2 mrem/h at the centre, in December 1976—is consistent with a peripheral distribution of the source and will be further reduced during shutdowns by inserting 2 in. thick lead shields everywhere inside the tank wall. This will be done by remote handling and is expected to allow hands-on maintenance on the tank components up to a 20-30 μA level. At higher levels complete remote handling will probably be required. An azimuthally moving service bridge carrying a radially moving trolley is available. Special types of trolleys and tools for various operations are being constructed. As soon as the TNF and the BL1 extension are ready, hopefully by the end of the year, beam tests and production at 100 μA will be started. Recently a 100 μA equivalent, 1% pulsed beam was extracted at 500 MeV. During this test the transmission between the injection line and the extraction radius was about 25%. Along the electrostatic injection line the 400 μA dc beam, adequate for 100 μA extraction, was transmitted in the dc mode and maintained for several hours.

Systems protecting the machine from thermal damage are being set up; they consist of non-intercepting transmission monitors and current-reading skimmer monitors along the electrostatic, 40 m long injection line, spill monitors in and around the cyclotron, and spill and halo monitors along the beam lines. Effort has still to be spent in order to make the Ehlers-type H^- source more stable and the injection line system more reliable at high currents.

Towards Separated Turns

An important feature of the TRIUMF resonator system is that a third harmonic RF can be added to the fundamental to flat-top the wave form and improve beam quality.[7] Recent tests of third harmonic operation at low power levels have been encouraging. The Q for the third harmonic (∿6400) is higher than for the fundamental (∿5500), and the 3:1 frequency ratio is within present tuning capability.[8] The amount of fundamental power (1 MW) being transmitted back along the third harmonic line is very low (∿50 W). Work is proceeding on the assembly of a 50 kW third harmonic amplifier. The stability requirements are $\pm3\times10^{-5}$ in RF voltage, $\pm5\times10^{-7}$ in frequency and $\pm4\times10^{-6}$ in magnet current. The latter two requirements have already been met for periods of ∿20 min. Although the isochronism achieved does not match that originally required, a technique has been found[5] by which separated turns and 100 keV energy resolution can still be obtained over limited energy ranges. In this technique slightly more than the nominal third harmonic is used and the irreducible phase oscillations are used to average out the imperfections in the RF flat-top.

Experimental Facilities

There are at present three meson channels installed around T2 (Fig. 1). The biomedical channel M8 provides π^- beams of up to 220 MeV/c with momentum resolution down to 1.5%, acceptance of 14% and fluxes between 10^5 and 10^6 π^-/μA-sec depending on the accepted momentum spread. Uniform distribution (within 10%) is available over irradiation surfaces of 10×10 cm^2 down to 1.5×2 cm^2. The slow and stopping π/μ channel M9 has produced π^+ beams from 60 MeV down as far as 15 MeV with momentum spread between 2% and 25% FWHM and intensities at 30 MeV of $\sim1.5\times10^6$ π^+/μA-sec with e^+ and μ^+ contamination of 13% each. Cloud muons formed near the target and target surface muons have been investigated and utilized at a rate of 10^5 μ^+/μA-sec and 2×10^4 μ^+/μA-sec, respectively, over a spot of a few centimetres in diameter. They are highly polarized. The third channel M20 has been constructed with borrowed magnets and is used primarily for muon spin relaxation and muonium chemistry.

A unique facility at TRIUMF is the variable energy beam of polarized fast neutrons produced on beam line 4A from a liquid deuterium target. At 325 MeV, for instance, this provides a flux of 1.5×10^5 n/sec per 30 nA protons. The neutron polarization rises from ∿40% at 500 MeV to ∿70% at 200 MeV[9] (see Fig. 2).

Several new beam lines and facilities are planned for installation during this year (Fig. 1). A high-energy and high-resolution pion line (M11) will deliver up to 350 MeV pions with better than 0.2% momentum resolution. The pions are emitted at zero angle from a 4 cm water target ($pp\to\pi^+d$) and 4×10^6 π^+/sec-μA are expected within a momentum acceptance of ±5%. A new proton beam line (BL1B) will accommodate polarized or low-intensity beam users in the meson area. A thermal neutron facility (TNF), besides constituting the beam dump for high currents, will generate thermal neutron fluxes of $\sim5\times10^{12}$ neutrons/cm^2-sec with a lead target in a D_2O moderator.[10] A medium resolution spectrometer (MRS), which initially will be of the QD type, will have an acceptance of ±5% in momentum, a solid angle of 2.3 msr and a resolving power of 350 keV at 500 MeV.

Acknowledgements

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