Proceedings of the 9th International Conference on Cyclotrons and their Applications
September 1981, Caen, France

DEVELOPMENTS TOWARD HIGHER BEAM INTENSITY AT TRIUMF

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Abstract.- TRIUMF has been operating at currents in excess of 100 μA for a substantial fraction of the time during the last few years. The reliability was adequate for the medical program to initiate π^- irradiations of human patients. 150 μA have been extracted at 500 MeV in a cw mode, 170 μA in a 60% duty cycle pulsed mode. The ion source and the injection line have been upgraded and 650 μA has been delivered to the cyclotron inflector entrance. A double buncher, which has been demonstrated to provide a cyclotron acceptance of 50% is expected to allow extracted currents of the order of 400 μA. Acceleration and extraction tests in the cyclotron to demonstrate this capability are under way. Peak currents in excess of 200 μA at 500 MeV have recently been achieved at 10% duty cycle. The total charge delivered during 1980 was 110 mA h. For 1981 the limit has been increased to 150 mA h. In order to further increase the yearly total charge to 300 mA h in the next few years a series of modifications aimed at extending the capability of the machine and at improving the reliability of components are being introduced. Detailed calculations and measurements taking into account the effect of both gas stripping by the various residual gases and electromagnetic stripping show that by extracting at 450 MeV the activation of the cyclotron can be reduced by a factor of two while maintaining the pion production rate. This will allow a further increase in the total yearly meson production by a similar factor.

1. Introduction.- It was reported in Bloomington [1] in 1978 that TRIUMF had reached its initial design goal of a 100 μA 500 MeV beam. Since then beam currents in excess of 100 μA have become increasingly easier to achieve and maintain, and the yearly integrated current has risen from 25 mAh in 1978 to 110 mAh in 1980. The charges delivered per month and per year over the past period are given in figure 1, together with a few milestones achieved in the effort toward high peak currents. The irradiation of cancer patients with π^-, which requires reliable 100 μA beam over periods of several weeks, was started in 1979 and is continuing. Higher peak currents and more extensive high intensity operation are requested by the oncologists and many of the physicists. The goals are a total yearly integrated current in excess of 300 mA h, so that most high intensity operation will be at 100 μA, and a maximum available current of 400 μA. This will allow (1) higher current at 500 MeV for short periods, (2) extraction at 450 MeV for increased pion production with equivalent cyclotron activation, and (3) high intensity 400 or 450 MeV beams available for injection into a possible post accelerator.

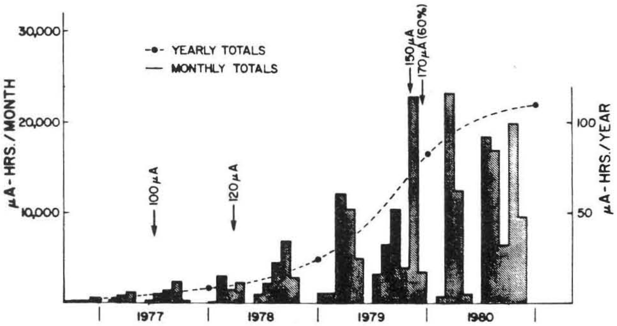

Fig. 1 : Beam charge delivered over the past four years and milestones in extracted peak currents.

During the last few years an average of 27% of the time was used for shutdown and weekly maintenance. About 6400 h were scheduled for production. Component failures reduced the scheduled beam time by 15%, whereas 13% was the overhead used for setting up different production modes. The actual beam production time was therefore about 4600 h per year and included periods of polarized or low intensity, high resolution beam [2], periods of 30 μA operation and periods of 100 μA operation.

The yearly total delivered charge is presently limited to 150 mAh in order to minimize the personnel dose during a major program of improvements for long-term reliability and reduced maintenance requirements in the cyclotron tank. The resonating cavity is being redesigned with improved cooling and alignment capabilities. The aim is to reduce the RF leakage in the beam gap, which has been responsible at various times in the past for the malfunctioning of probes, electrostatic correction plates, cryopanels, and heat damage to the resonators. Recent high intensity operational experience and future plans for various systems will be discussed below.

2. ISIS and injection line.- The tuning procedure and diagnostics for high intensities in the ion source and injection system [3] have been described previously [1]. A number of recent modifications have improved the performance of the system.

A second buncher, operating at twice the RF frequency, has been added to the beamline [2]. The separation between the two double-gap sinusoidal bunchers is 3.1 m; a distance which is ideally suited for a large (45°) cyclotron RF phase acceptance [4]. As a result the extracted current was increased by ~50% without increasing the ion source current. At extracted currents less than 30 μA up to 50% of the injected current has been accelerated through the cyclotron; whereas for 100 μA extracted the transmission is ~40%. Taking into account that the beam loss through the cyclotron is about 20% (see below) this corresponds to 60% and 48% acceptance through the central region. The difference between the 100 μA and the 30 μA situation is attributed to a longitudinal space charge effect [5].

After extended high intensity operation, the sparking rate of the 300 kV ion source terminal increased to a few sparks per hour. The sparking has now been eliminated. Permanent dipole magnets were used to accurately centre the beam at the entrance to the acceleration stack. In addition, the first three elements (7.6 cm) of the 91 cm long acceleration stack were shorted to the terminal in order to remove the electric field from the upstream 12 kV optics box. A system of apertures biased so as to stop stray electrons flowing into the acceleration tube is placed at its entrance.

A cooled slit located in the 300 keV injection line is used to quickly change the extracted current from 100 μA to 30 μA. It is useful for a mode in which the current is raised daily from 30 μA to 100 μA for a few hours for patient irradiation. With these slits the change in currents can be accomplished in less than one-half hour with minimal beam line tuning. Much more extensive tuning is required by altering the current at the ion source. A system of sublimation pumps has been replaced with cryopumps and the vacuum in the beamline is now maintained reliably around 10^{-7} Torr. Beam loss due to gas stripping has been substantially decreased.

3. Cyclotron.- Gas-stripping and electromagnetic losses have been measured [2] using secondary emission detectors placed between the outermost orbits and the vacuum tank wall. Stripped neutral atoms leave their orbits tangentially and each detector intercepts those atoms arising within a narrow azimuthal band. One detector was placed to measure gas and electromagnetically stripped atoms arising in a hill, the second accepts gas-stripped atoms from a valley. Measured electromagnetic losses agree well with those predicted from orbit codes (see figure 3 in Ref. 2). Measurements of beam transmission during deliberate changes in pressure have shown a 10% gas-stripping current loss for pressures equivalent to 1×10^{-7} Torr nitrogen, which agrees with calculations [6].

The beam losses in the cyclotron have been reassessed taking into account the measured partial pressures. During good running conditions the losses from 3 MeV to 500 MeV are about 20% of the circulating beam. These losses include electromagnetic stripping losses (~9%), gas-stripping losses (7-10%) and vertical beam losses (1-2%). The vertical beam losses are practically eliminated by careful matching of the injection line tune to the cyclotron and by proper alignment of the beam plane. If we assume that cyclotron activation is proportional to beam power losses then, for 500 MeV extraction, ~70% of the activation is due to electromagnetic dissociation, 25% to gas-scattering, and 5% to vertical beam losses. With this vacuum, by extracting at 450 MeV instead of 500 MeV, we can achieve a reduction in tank activation of almost 2 while maintaining the same π^- flux in the medical pion channel.

Typical spectra of the tank residual gases are shown in figure 2. The tenfold increase in the hydrogen partial pressure with the RF on is caused by dissociation of some of the water vapour adsorbed while the tank is vented for maintenance. The stripping cross-section for hydrogen is ~7 times [7] smaller than for air and thus the partial pressure of hydrogen is responsible for ~40% of the vacuum losses. A liquid helium cryopump has recently been tested in the vacuum tank and a reduction of the hydrogen partial pressure by a factor of three was attained. At 450 MeV and with

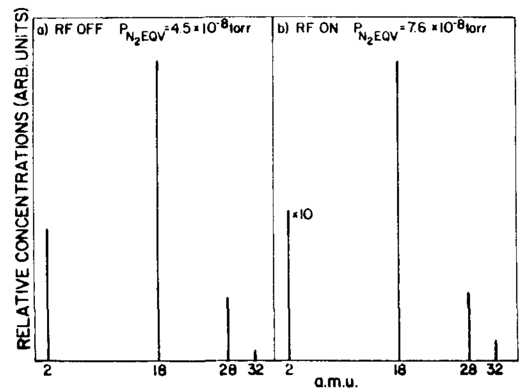

Fig. 2 : Cyclotron tank vacuum mass spectra with RF off and on. P_{N_2EQ} is the nitrogen equivalent stripping pressure.

these vacuum conditions this pump is expected to reduce the vault activation by 15%.

Figure 3 shows the total charge delivered, the magnitude of the residual radiation field at the centre of the cyclotron, and the residual field per unit charge delivered as a function of time. The decline of the latter shows that there have been substantial improvements in the total beam transmission in the cyclotron. These were primarily due to improved diagnostics, development of better tunes, and greater skills of the cyclotron operators.

4. Beamlines.- Since the Bloomington conference a thin target station, T1, has been installed upstream of T2 to serve channels M11 and M13 (figure 1 of Ref. 1). A 2 mm graphite target for 100 μA and a 10 mm graphite target for 30 μA was used. A 28 mm water target suitable for monoenergetic forward pions is being tested. A 10 cm Be target is usual at T2. Radiation-resistant elements, collimators and scrapers were originally installed downstream of T2 and immediately downstream of T1. The remaining beamline between T1 and T2 is being upgraded with remote handleable and radiation-resistant elements to allow thicker targets at T1. In the vault the 70 to 100 MeV line (2C) is being equipped to handle beams of 100 μA. A new high intensity extraction beamline, 2A, is being designed to deliver the beam to a third experimental hall, with the possibility of use as an injection line for the proposed kaon factory. The design of the vault section of 2A is complete and the front end is being constructed.

Beam spill monitors and software windows about beamline element settings provide protection against spill at high power. In regions of high loss, spill monitors using scintillators are being replaced by ion chambers.

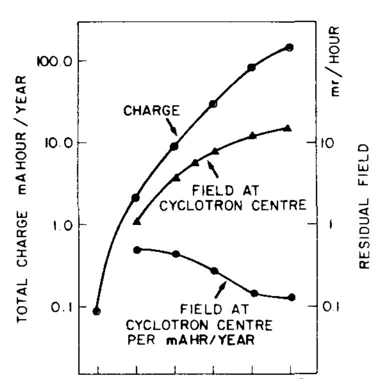

Fig. 3 : Total charge delivered and residual field at the centre of the cyclotron. Residual field measured with 50 mm lead shadow shields covcring tank periphery, three weeks after last beam.

Special attention had to be taken to protect the target system since spills are normally high and the critical dimensions small. The production targets may be water-cooled copper or beryllium blocks enclosed in 1 × 2 cm stainless steel cassettes or edge-cooled pyrolytic graphite. Damage results if more than 30 μA of beam hits the cassette edges or the graphite cooling interface. A plate or plates defining an aperture smaller than the critical edge is placed in front of each target. A trip is induced if the secondary emission current from the plate should exceed that associated with 20 μA. Targets, cassettes and windows may be damaged also if the beam density is too high. The density is estimated from the difference in the output of a solid foil and one with a hole at the centre. The calibration of the plates, done by deflecting a low current beam, changes by 30% or so during the first week of operation of a new monitor. Thereafter they are recalibrated once per year. These monitors have proven reliable during the past four years and have also been a valuable tuning aid.

The most complex protect monitor is that for the TNF and irradiation facility, shown schematically in figure 4. For this monitor hardwire logic signals insert a beam stop at the ion source should the difference between left and right, or up and down, signals exceed 15 μA beam. A trip also occurs if the beam density exceeds 6 μA/cm^2; on the other hand the spot should not be so large that more than 10 μA hits the halo ring protecting the cassette of the irradiation facility installed upstream of the TNF. The TNF beam dump has been operating reliably since its installation in 1978. The original lead target container was replaced after 50 mA hours in order to inspect the container for radiation damage or damage due to corrosion from the molten lead. The inspection showed that no damage had occurred. [8]

5. Development toward higher peak currents.- The maximum current which can be extracted from the cyclotron is presently limited to 150 μA by the TNF target which was originally designed and tested for a 100 μA 500 MeV beam. A new target, cooled by forced convection, and a new moderator tank are being designed to enable the cyclotron to produce 400 μA, 450 MeV beams. Protect monitors, meson production target and vacuum diaphragms presently designed for 200 μA, will have to be upgraded when the current is raised to 400 μA. The pyrolytic graphite stripping foil is predicted to be suitable at the 400 μA mark. The 150 μA limit was reached at the beginning of 1980. In order to explore higher currents, tests were continued in a pulsed mode. The major limitation was the inability to increase the source output within the small acceptance of 0.1π mm-mrad and 0.2π mm-mrad (vertical and horizontal phase space, respectively) found most suitable for reliable operation [1]. An ion source test stand was assembled and 1.2 mA within the desired acceptance was repeatedly observed in the model. This source is presently being tested with the cyclotron. A peak current of 205 μA, 10% duty cycle, has recently been extracted at 500 MeV. The new tune for the injection line at the higher intensity is being studied.

Space charge effects are substantial at these currents. In the inflector region the instantaneous current within the ~40° cyclotron phase acceptance was around 2.5 mA. Due to bunching, the longitudinal charge distribution is far from being uniform (see Ref. 5) and consequently there is a substantial variation of the energy distribution. There exists an optimum position along the line where the energy spread introduced by the bunchers is compensated by that introduced by longitudinal space charge. In view of the limited

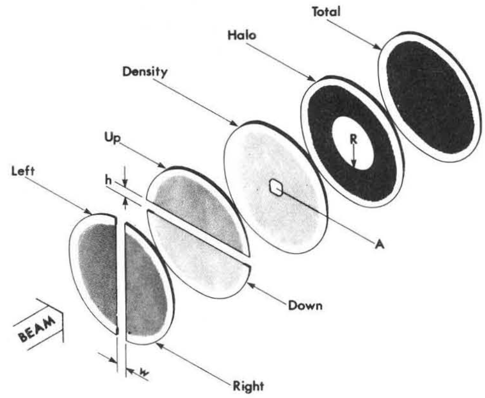

Fig. 4 : Schematic representation of the thermal neutron and irradiation facility protect monitor. Dimensions are h = w = 1 cm, A = 2 × 2 cm, R = 3.5 cm.

energy spread accepted by the inflector (±5%) this position should be as close to injection as possible, or else a compensating buncher has to be used a few meters above the inflector. For 400 μA extracted the instantaneous current in the inflector region will be 5 mA, which is close to the 10 mA limit for which the line was designed [5]. Misalignments or stray magnetic fields always tend to reduce in practice the theoretical acceptance of a system. However, the 70° phase acceptance achievable with third harmonic flat-topping of the RF would make the space charge effects less critical as a result of the lower instantaneous current.

6. Development toward higher delivered charge per year.- It is planned to increase the total yearly integrated current to 300 mAh in the next few years. Extrapolating present conditions would then result in an eventual five-fold increase in the residual radiation field in the cyclotron. We have performed a detailed, computer-assisted analysis of the man-dose to be expected at the higher intensities for all maintenance jobs and proposed improvements. Radiation levels have been extrapolated according to a realistic scenario of current increase. The study showed that the man-dose which would be received by maintenance personnel would be 60 man-rem per year with an additional 20 man-rem per year for the cyclotron improvement program. Seventy-five per cent of the maintenance man-dose was due to 20 jobs which led to exposures greater than 1 man-rem per year. By improving the procedures for these jobs in terms of reliability and remote handling ability, and by completing the improvement program as soon as possible, we are confident that we can keep the total yearly man-dose below 40 man-rem at the 300 mAh per year operating level. By extracting some of the time at an energy of 450 MeV to reduce electromagnetic stripping losses in the cyclotron, it will be possible to increase the average extracted beam intensity to an equivalent (in terms of pion production) 500 mA h per year.

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