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STATUS REPORT ON THE TRIUMF CYCLOTRON

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Summary

During the last two years TRIUMF has operated at currents of up to 150 μA, with 250,000 μAh/yr delivered for meson production, an increase of more than a factor of two over any previous year. Simultaneously, currents between 1 nA and ~10 μA were extracted stably to the proton area. Currents of 170 μA cw and 250 μA equivalent in a 30% pulsed mode have been demonstrated. The maximum polarized beam current was increased from 300 nA to 600 nA. Reliability, defined as the percentage of available beam time to the scheduled beam time, was around 85% for the various beam lines. Key factors in achieving these performance levels were the reliable operation of the RF system, resulting from improved alignment and diagnostics of the resonating cavity, the availability of bright ion sources with beam output exceeding requirements, the prompt reproducibility of the beam in the injection line and the stable operation of the main magnet. These improvements are described together with planned future improvements.

Introduction

During 1982 and 1983 reliable beam production has been the highest priority at TRIUMF. The effort has resulted in yearly beam production levels of 229 mAh/yr in 1982 and 241 mAh/yr in 1983, more than twice the production levels achieved in previous years and quite close to the initial design goal of 300 mAh/yr.[1] Monthly production, yearly production, hours per year of operation over the history of the cyclotron are shown in Fig.1, together with a few milestones achieved in the effort toward high peak currents. It is noteworthy that over the last two years there was more beam charge produced than in the entire previous operating history. Routine operating currents which were reported to be about 100 μA at the Caen conference were increased to 120 μA in 1982 and to 130-140μA in 1983. The yearly hours of beam operation were maintained between 4000 and 5000 h/yr over the last several years, the remaining hours per year being accounted for by shutdowns, weekly maintenance, overhead for beam set-up and tuning and downtime due to failures. In 1983 this latter was 14% of the total scheduled beam time. Polarized beam production accounted typically for about one third of the scheduled beam time. Polarized currents are now routinely of the order of 300 nA with 600 nA demonstrated; polarization of >75%. A few weeks of polarized beam are normally scheduled ahead of major shutdowns to reduce the exposure to personnel during maintenance. Typical exposure levels in the centre of the machine during shutdowns two or three weeks after high intensity production, with screening shields at the periphery of the tank, are about 38 mrem/h, up from 15 mrem/h in 1981, and are expected to converge to saturation levels of 54 mrem/hr if the total yearly extracted beam charge at 500 MeV is maintained at 300 mAh.

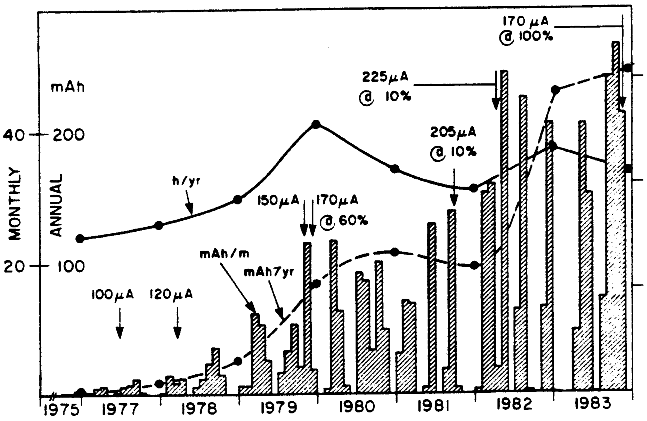

Fig. 1. History of beam production and major milestones in peak current.

A recent layout of the facility is given in Fig.2. Recent additions include on the south side an annex for the installation of a third ion source terminal and a new experimental hall. On the north side, near the chemistry annex, a commercial 42 MeV 200 μA variable energy H$^-$ cyclotron has been recently installed and is now operational for isotope production. Near the cyclotron vault an extension has been built for storage of remote handling equipment and for vault equipment servicing. The cyclotron is shown schematically at the centre of the layout. The beam can be extracted simultaneously from three extraction ports. Typically, during high intensity operation a 500 MeV proton beam of ~130/140 μA is extracted down Beam Line 1A through a thin target at T1, a thick target at T2, and is dumped into a molten lead target at the TNF (Thermal Neutron Facility). Simultaneously, a proton beam as low as ~1 nA is extracted on the opposite side down Beam Line 4B (maximum 1 μA) or 4A (maximum 10 μA) for nucleon experiments at energies between 180 and

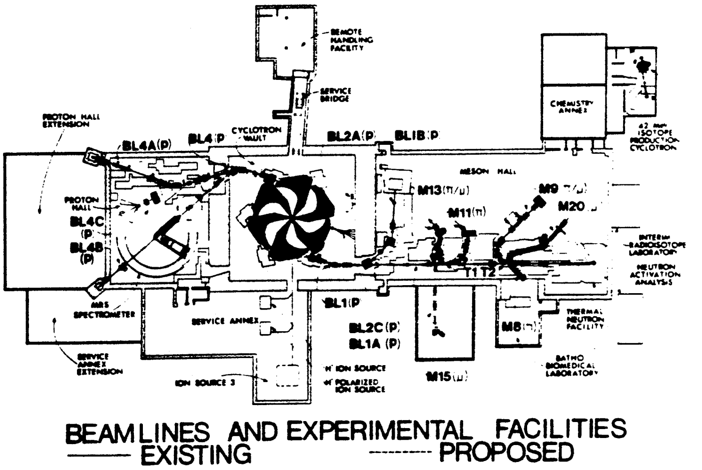

Fig. 2. Layout of the TRIUMF Facility.

500 MeV. A beam of 20-30 μA can also be extracted down Beam Line 2C for isotope research or production. Polarized beam operation is normally shared between Beam Line 4A or 4B and Beam Line 1B. Five secondary channels for meson beams are presently operational along Beam Line 1A. A sixth one, M15, is being installed in the new hall. One of the channels, M8, is being used for π^- therapy of cancer patients on a daily basis during high intensity operation, with typical treatments divided into as many as 15 consecutive daily fractions.

Typical cyclotron beam characteristics presently achieved are listed in Table 1 together with future goals. The progress toward these goals will be discussed below. A description of the experimental areas and typical proton and meson beam characteristics are given in Reference 2.

Table I
Beam Properties

Property	Achieved	Future Goal
Maximum energy	520 MEV	520 MeV
Intensity	170 μA	400 μA
(unpolarized)	250 μA(30% duty cycle)	
Intensity	600 nA	30 μA
(polarized)	(Lamb shift)	(optically pumped)
Polarization	75-82%	80-85%
Split ratio (line 4/line 1)	$1/10^5$	$\sim 1/10^6$
Phase width	0.5ns→6ns	
Pulse separation	43 ns, 217 ns	
Transmission	85%	88%
Fraction of dc beam to 500 MeV	50%	70%
Energy spread	3×10^{-3}(FWHM)	
(with slits)	10^{-3}(FWHM)	100 keV(3rd harm.RF)
Particles extr.	p	p,H^-

Progress Toward High Intensity

The maximum cw beam current extracted at 500 MeV from the machine was 170 μA (Fig. 1). Prior to 1983 the maximum current was limited to 150 μA by the beam power absorption of the original TNF lead target which had been designed for 50 kW.[3] (The beam power reaching the beam dump is normally less than two thirds of the power of the extracted beam because of absorption and losses at the meson producing targets.) During the first quarter of 1983 a new lead target, cooled by forced convection, was installed in the Thermal Neutron Facility. This is rated to absorb initially 125 kW and is capable of being upgraded to higher power absorption after a series of tests. It will be therefore compatible with an extracted current of ~400 μA.[1]

The limitation at 170 μA came from the vertical section of the 300 keV electrostatic injection line, where a set of uncooled protecting skimmers were monitoring excessive current loss. This was found to be caused by two consecutive defocussing quadrupoles upstream from the chopper slits.[4] Because of space charge and bunching, the higher intensity beam requires an alternating gradient sequence which has been implemented during the present shutdown. The diagnosis and correction of this problem was made difficult by the lack of access to the beam line in this region.

Tests at higher peak currents were performed in a 10% pulsed mode, which permits greater percentage beam losses. A maximum extracted current of 250 μA equivalent was achieved from ~500 μA injected. It is believed that at higher currents, even with the new alternating gradient quadrupole configuration, the current will be limited by space charge effects, the peak current inside the bunch being of the order of ~10 mA. Recent calculations[5] show that a new first harmonic buncher located about 2 m above the inflector in addition to the existing first and second harmonic bunchers (at 21 m and 16.5 m from the inflector) will allow an injected beam of 800 μA, presently available from the ion source, to be sufficient for 400 μA extracted.[5] One should note that other difficulties are expected on the path toward higher currents: RF loading, additional cyclotron beam spills, cooling problems at the targets T1 and T2, beam line spills, etc. Therefore, whereas operation at 200 μA is expected soon, operation at 400 μA will require further development.

Progress Toward Separated Turns and H^- Extraction

Separated turns have been demonstrated at 200 and 250 MeV[6]. Separated turns at higher energies are important for (1) high energy resolution (100 keV-FWHM) of the extracted beam[7] (2) for direct H^- cw extraction studies of TRIUMF as an injector for an accumulator-synchrotron combination.[8] These studies will be presented at this conference separately.[9]

The requirements for separated turns to full radius have been discussed previously.[7,10] Briefly, (i) the magnetic field has to be stable to within 0.7 ppm corresponding to 2° of phase jitter; (ii) the RF voltage has to be stable to within ±80 ppm and (iii) the third harmonic flattopping of the RF waveform is required, particularly at higher intensities. The fundamental and third harmonic components have to be synchronous so that their phase difference, measured in third harmonic degrees, is less than 0.12°. The progress toward the achievement of these goals can be summarized as follows.

The magnet stability has been demonstrated to meet the required tolerance. After the encouraging results reported at the Caen conference[10], where the required stability had been demonstrated for short (half an hour) periods of time (by improving the magnetic field feedback to the magnet power supplies), feedback to the RF frequency from an external capacitive beam phase probe for currents above 1 μA and from counter derived signals for currents above 0.5 nA have been successfully tested to maintain the beam phase within the required ±2°. In parallel, a special NMR probe with a resolution of <0.3 ppm has been developed[11] for direct feedback between magnet and power supply to meet the required tolerance.

The achievement of the third harmonic flattopping of the fundamental RF at TRIUMF is a unique problem, since it is based on both fundamental and third harmonic components being excited within the same large cavity which extends across the diameter of the machine (16 m) through a structure composed of eighty separate segments.[12,13,14] A fair amount of effort has recently been spent in this direction. A new 3:1 tuning mechanism and a control feedback circuit required for flattopping are being designed and will be tested at power in a two-segment resonating cavity installed in a test stand.[15] The fundamental and third harmonic voltage profiles along the dee gap have been measured using a set of 60 voltage probes installed this shutdown. The results are shown in Fig.3. As expected from previous 1:10 model studies, a decrease of the capacity between hot arm and ground arm at the centre segments will be required to improve the uniformity of the third harmonic voltage.

Measurements and studies have been performed to establish the relationship between the mechanical stability of the eighty 3 m-long cantilevered hot arm structures forming the dees and the stability of voltage and phase of the fundamental and third harmonic components. The important question to be answered is whether the RF cavity is modulated electrically as a whole so that a single amplitude or phase feedback circuit can be used for control (for both fundamental and third harmonic) or whether different segments can produce local, unrelated perturbations. A simple analysis based on incoherent summing of perturbations from the various segments leads to a tip vibration stability requirement of 5 μm or less. Coherent addition may reduce this requirement even to the present tip vibration amplitude which is of the order of 50 μm. Fig.4 shows the similarity between the RF fundamental voltage signal on one of the dee gap voltage probes and the signal giving the time of flight through the machine (proportional to $V \cos \phi$). Other results indicating a coherent behaviour of the perturbations are given separately at this conference, together with the criteria for mechanical stability.[16]

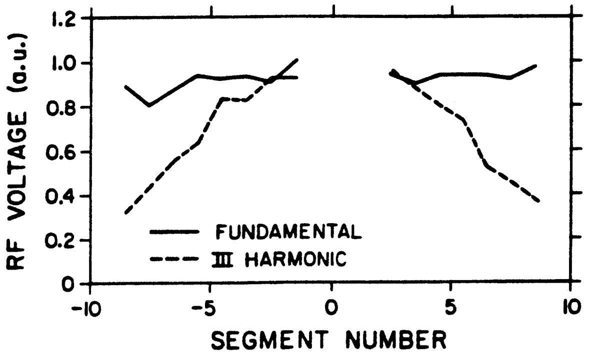

Fig. 3. RF voltage distribution along the dee-gap for fundamental and third harmonic measured on the lower north dee.

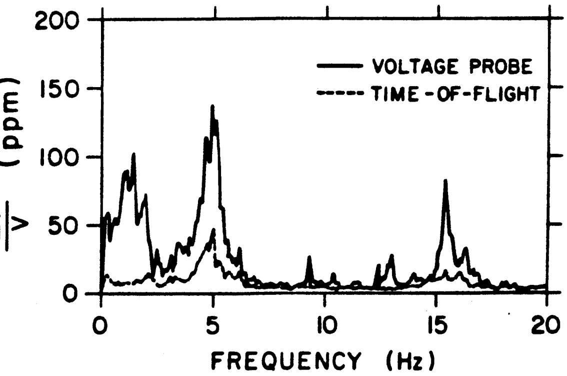

Fig. 4. Comparison between the voltage variation measured from a resonator probe (lower quadrant 2, segment 5) and the overall voltage variation inferred from the time-of-flight of the accelerated beam.

The Resonator Improvement Program

The TRIUMF resonator system has been previously described.[13,14] During the first years of operation it was realized that it was extremely difficult to maintain the resonator tips at the dee gap vertically aligned within the specified ±0.5 mm. Because of the size of the resonators and the 3-m-long, 4-cm-high cantilevered panels, the mechanical design has to take into account stresses, fatigue effects and RF thermal loads not only on the RF cavity side but also on the side facing the cyclotron median plane or the volume traversed by the beam. In fact, if the misalignment exceeds a certain amount, the vertical asymmetry between dee tips induces a substantial leakage field in the beam volume. If the surface is not conveniently cooled, heating due to RF leakage will increase the distortion and the process will lead to a runaway condition which eventually will result in thermal damage to resonator components or diagnostic devices. This actually occurred a few times, especially during the initial operational phase.

The resonator improvement program was conceived primarily to study and solve this reliability problem. Several results have already been achieved. The monitoring and stability of the existing resonators in the tank have been improved to a point where the alignment is being maintained under control and runaway conditions are being avoided; the major breakthrough occurred when the alignment could be optimized under RF-load conditions. Studies on a 1:10 model allowed an interpretation of the leakage field and the investigation of solutions toward its reduction. The major component of the field is the T_{310} mode in the semi-cylindrical volume of the tank. Methods of reducing the leakage by displacing the T_{310} resonating frequency from the main RF frequency have been proposed and are being investigated.[17] On the mechanical side a new resonator segment prototype was built, with cooling on the beam volume side (previously not provided) and in line with the alignment requirements. The prototype has been tested at full power in a test stand and is ready to be tested in the cyclotron tank. Preliminary measurements on the new prototype indicate a reduced tip vibration amplitude, probably as a result of an improved, less turbulent water cooling circuit on the RF panel. However, upgrading of the stiffness of the new prototype structure is being considered to further reduce the vibration amplitude. The finalization of the design for the replacement resonator segments is awaiting the results of the stability and third harmonic studies and measurements mentioned above.

Ion Sources

The TRIUMF operational Ehler's type PIG H^- ion source used for high intensity running has been described previously[18] and satisfies the present intensity requirements. However, filament lifetime and maximum current at the required brightness are limitations which we think can be overcome with a CUSP type volume H^- ion source. Measurements at LAMPF[19] on a pulsed system indicate that the source is already as bright as the TRIUMF H^- source.[18] Furthermore, it is large enough to house several filaments which could be used sequentially to increase the time between replacements.

Improved alignment and modifications to the Lamb-shift polarized H^- ion source has resulted in routinely extracted polarized currents increasing from 200 nA as reported in Caen[20] to 300 nA with 600 nA demonstrated during development periods. Research in the laboratory on an optically pumped polarized source has demonstrated that sodium vapour at practical densities can be polarized to better than 75% with a single 1 watt broadband dye laser.[21] A concentrated effort has begun to provide a proof-of-principle source by the fall of this year.

In order to increase the ion source serviceability, and hence reliability, a third 300 kV high voltage terminal is being constructed. Construction is scheduled for completion by December 1985. The terminal, at 300 kV, has been built large enough so that a high intensity H⁻ source and a polarized H⁻ source both can be installed and beams extracted through parallel acceleration tubes.

Controls

The control system philosophy and architecture described at the last Cyclotron Conference[22] has been considerably expanded during the past three years. The number of microprocessor based local control systems distributed throughout the central system has increased to more than twenty. Seven multiport memory ports are now in use, and the memory capacity of this device has been expanded from 16 kbytes to 64 kbytes. Using an active extender, the GEC Elliott Executive system has been further expanded into a third crate, allowing many more computer sources to be included[23] (see Fig. 5).

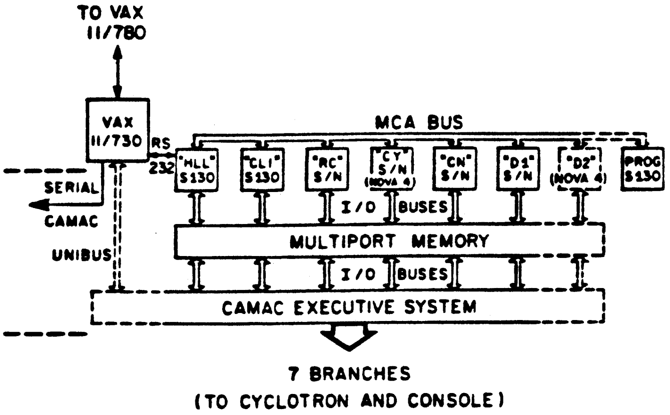

Fig. 5. Present configuration of the TRIUMF control system.

This last improvement will allow the recently installed control system VAX 11/730 direct access to cyclotron data bases. At present it communicates with the control system computer, using an asynchronous link. Already this configuration has permitted the implementation of sophisticated beam dynamics and general analysis programs, as well as the application of on-line graphical analysis to data acquired directly from the accelerator. A number of logging programs have also been implemented, allowing the study and correlation of parameter trends. A serial CAMAC bus permits acquisition of data not directly connected to the central control system (for example the RF 1:10 model); and an Ethernet link to the TRIUMF data analysis centre and public networks is under development.

Experimental Facilities

The development of both new and improved experimental facilities has continued at a high level over the past two years. In the Proton Hall a program to upgrade the medium-resolution spectrometer (MRS) to 100 keV resolution at 500 MeV is nearing completion. A six-quadrupole twister has been installed to rotate the horizontal dispersion of BL4B into the vertical bend plane of the spectrometer. Other improvements include a windowless scattering chamber and a new focal plane detection system using vertical drift chambers. The neutron beam facility has been upgraded with the liquid deuterium production target capable of handling a 1.5 μA proton beam. The present experiment in this area uses a large volume (55 cm^3) polarized target of the frozen spin type which was successfully commissioned in 1983.

In the Meson Hall the M20 secondary muon channel was upgraded to increase the flux by a factor 6, to provide two legs which can operate simultaneously with decay muon beams and by using a 3 m electrostatic separator to provide a transversely polarized surface muon beam. The muon flux on the M9 channel was improved by a factor 2 and the pion contamination reduced to 2 x 10^{-4} with the installation of a 1 m RF separator[24] with a crossed magnetic field. A novel surface muon channel M15 is presently being installed at the first meson production target position T1. This channel uses two samarium-cobalt quadrupoles located inside the target shield to provide a large solid angle acceptance. The channel extends vertically to ground level to the recently completed 250 m^2 experimental hall. The development of diamond production targets is underway to increase meson fluxes on the secondary channels. Both synthetic diamonds and natural diamonds are being used. A synthetic diamond matrix 3 mm thick, bonded to a water-cooled pyrolytic graphite backing has been tested successfully at 130 μA. A 10 cm long synthetic diamond target has been fabricated for tests at T2 in the next operating period.

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