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PROGRESS TOWARDS HIGHER INTENSITIES AND IMPROVED BEAM STABILITY AT TRIUMF

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Summary

The TRIUMF accelerator routinely delivers up to 120 µA of 500 MeV protons. For tests, 150 µA have been extracted in a cw mode, 225 µA equivalent in a 10% duty-cycle pulsed mode. Longitudinal space-charge effects are observed at these higher currents. A lead target, used as a beam dump and thermal neutron source, is being upgraded to allow extracted currents up to 375 µA cw. The reliability and performance of the cyclotron has significantly increased as the result of several recent developments. Improvements to the main magnet power supply (18,000 A) have resulted in a magnetic field stability better than ±0.8 ppm for periods of 2 h. The effect on beam phase, instability and separated turn operation is presented. A Lamb-shift polarized H$^-$ source provides up to 300 nA extracted. An ECR proton source has been tested as a replacement for the duoplasmatron on the polarized source. A gain in current of order 5 is expected. To satisfy the long-term needs, work has begun on developing an intense optically pumped, polarized source with the aim of increasing the current by a factor of 100.

Introduction

The TRIUMF H$^-$ cyclotron, in operation for seven years, has been gradually up-graded. 500 MeV proton beams with currents of up to 120 µA for meson production are available on demand during about two-thirds of the operating time. Simultaneously, proton beams of energy between 180 and 500 MeV with intensities between ~1 nA and 10 µA can be extracted for nucleon-nucleon experiments. In addition, a low energy beam of between 60 and 100 MeV with currents of several tens of microamperes can be extracted simultaneously for isotope research and production. The remaining one-third of the production time is dedicated to polarized protons, with currents up to 300 nA and polarization well in excess of 70% being delivered simultaneously along two external beam lines. The energy spread of the extracted beam can be reduced to $\Delta E/E \simeq 1/1000$ through sets of slits located in the centre region of the cyclotron. Time microstructures of 0.5 to 6 ns either every 43 ns or every 215 ns are available. Typical beam characteristics presently available are listed in Table I, together with future goals.

Table I
Beam properties

Property	Achieved	Future goal
Maximum energy	520 MeV	520 MeV
Intensity	150 µA cw	300 µA cw
(unpolarized)	225 µA(10% duty cycle)	
Intensity	300 nA	2 µA(with ECR)
(polarized)		30 µA(new source)
Polarization	75-82%	80-85%
Split ratio (line 4/line 1)	$1/10^4$	$1/10^5$~$1/10^6$
Phase width	0.5ns→6ns	11 ns
Pulse separation	43 ns, 217 ns	>23 µs
Transmission (5-500 MeV)	80%	86%
Fraction of dc beam to 500 MeV	50%	70%
Energy spread	10^{-3}(FWHM)	100 keV(3rd harm.RF)

The scheduling aspects related to the multiple simultaneous use of a facility of this type (typically seven to ten groups of users simultaneously utilize the various proton, meson and neutron beams) place a high demand on long-term machine reliability. Short-term machine reliability is an essential requirement when the machine is used for direct pion irradiation of cancer patients, which is presently done on a daily basis during high intensity operation. Although programs aimed at higher machine reliability, such as the improvement and replacement of the resonator system, receive very high priority, efforts aimed at increasing the beam capabilities, such as third harmonic RF operation for separated turns, new source capabilities and new experimental facilities, are proceeding.

High Intensity Performance and Developments

A summary of the beam charge delivered and the hours of operation over the past several years is illustrated in Fig. 1. Extracted beams of 100 µA and 120 µA have previously been reported.[1] Since then the current for high intensity beam production has been kept at about the same levels, but has been run for progressively longer periods, with a continual increase in the understanding and control of beam tunes, beam lines and induced radiation. The total beam charge delivered per year has increased by almost a factor of 10 from 25 mA h in 1978 to 220 mA h for 1982. At the same time, the residual radiation in the centre of the machine, measured during shutdowns with lead shields covering the tank wall,[2] has increased by less than a factor of 4 from 8 mrem/h to 30 mrem/h. Peak currents of 150 µA were demonstrated in the cw mode, 170 µA and 225 µA in a pulsed mode with duty cycle of 60% and 10%, respectively. The present limit of 150 µA for the maximum current in the cw mode is set by a lead target which acts as a thermal neutron source and which was designed for a maximum beam power of 50 kW.[3] A new lead target capable of handling 125 kW is being installed and will enable currents of up to 375 µA cw to be extracted. (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.)

The present limit of 225 µA in the 10% duty cycle pulsed mode is due to the widening of the transverse beam size and to the greater energy dispersion produced by space charge forces in the radial and longitudinal direction along the 300 keV injection line. Although the current required in the injection line for extracting 225 µA is only about 450 µA (corresponding to 50% cyclotron beam acceptance to extraction), 275 µA of

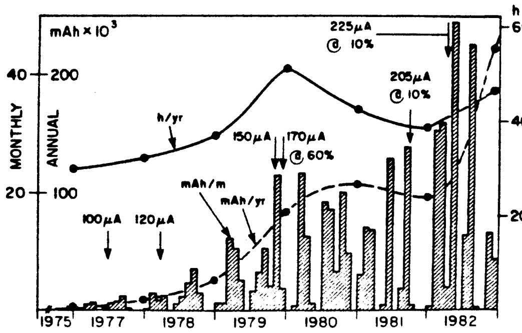

Fig. 1. Beam charge delivered and hours of operation over the past several years. Milestones in extracted peak currents are also indicated.

these are initially confined to the 40° wide phase acceptance at the centre of the cyclotron, resulting in a peak current of 2.5 mA at the entrance of the machine (spiral inflector). The beam transmission through the injection line at these high currents is only ~75% with most of the beam loss concentrated on cooled collimators (13 mm × 13 mm). The beam diameter should be small enough, even at these currents, to easily pass through the collimators were it not for the fact that there is insufficient beam steering capability to overcome the effects of misalignments and stray magnetic field. During February 1983 the beam line was accurately re-aligned and greater steering capability was introduced in a critical region.

For longitudinal matching to the cyclotron, the injection line contains a fundamental buncher and a downstream second harmonic buncher. A computer program, which uses a point-disk model similar to that of Agritellis and Chasman[4] was written to examine the effect of space charge on bunching. (Space charge effects are overestimated since the beam pipe image charges have not been included.) Calculated contours of the bunching efficiency are plotted in Fig. 2 as a function of buncher voltages for three injection line currents. A cyclotron phase acceptance of 40° and energy acceptance of ±0.4% was assumed. It can be seen that the existing buncher configuration is optimized for injection line currents of the order of 200 μA. An additional fundamental buncher located in the cyclotron downstream of the second harmonic buncher is planned in order to improve the cyclotron acceptance both for lower and higher current operation.

Operation at higher currents is important for various reasons, including the possibility of shorter sessions for patient irradiations and lower radiation in the machine, accomplished by using higher currents of lower energy proton beams to reduce electromagnetic stripping losses of the H^- ions while producing equivalent pion fluxes.[5] In addition the adequacy of the cyclotron as an injector for the kaon factory depends on the amount of beam which can be bunched in short phase intervals, preferably ~12°.

Reliability

The number of hours of beam operation and the total beam charge delivered declined in 1980 (see Fig. 1). This was primarily due to three unplanned shutdowns for repairs. During these shutdowns it was necessary to repair the 100 ton magnet jacks (used for raising the cyclotron tank lid and upper manget yoke for maintenance access) and to deal with damage in the cyclotron tank due to stray RF fields behind the resonator panels. The stray RF fields depend critically on misalignments and asymmetries between the upper and lower resonators. Resonator sagging due to RF heating of uncooled surfaces has been particularly difficult to prevent or correct. In the short term, the approach taken has been to closely monitor the resonator temperatures. The resonator alignment is adjusted whenever any of the strongback temperatures reach a critical limit (80° C above ambient). The results are evident in Fig. 1. The total integrated current delivered in 1982 was 229 mAh, nearly double the previous maximum. It is planned to replace all eighty resonator segments by 1986 with new resonators which will be properly cooled and mechanically more stable.

Magnet and Phase Stability

Medium energy resolution, $\Delta E/E = 1/1000$, has been achieved over the entire energy range by reducing the coherent and incoherent radial amplitudes with slits and flags near the cyclotron centre and at 30 MeV.[6] For high energy resolution, (separated turns to full energy), a beam phase stability of ±2° at 500 MeV is required and has been obtained through feedback from a capacitive beam phase detector to the RF frequency.[6] This approach, however, is not applicable for beam currents less than 300 nA (as is the case for most experiments requiring either high energy resolution or polarized beam) due to the limited sensitivity of the capacitive probe. Therefore, it was necessary to increase the stability of the main magnet directly to ±1.2 ppm in order to reach the required tolerance on the beam phase.

The previously reported stability of the TRIUMF main magnet field (±3 ppm for several hours) has been achieved by means of a NMR feedback loop.[6] Recently, the following improvements have been made to the main magnet power supply:

1) A differential amplifier was installed to isolate the error amplifier from the master/slave amplifiers.

2) The shunt was relocated and is now in parallel with the capacitor bank in order for the currents in the resonant circuit formed by the magnet inductance and the capacitor bank to be sensed by the shunt. The bandwidth of the current amplifier has been increased to ~2.3 Hz. The bandwidth of the voltage amplifier is ~2.5 kHz.

3) The temperature compensation circuit was changed with the selection of a new take-off point and the installation of a new compensation resistor. The sensitivity to shunt cooling water temperature was decreased from 30 ppm/degree to less than 0.5 ppm/degree.

As a result, the stability of the field was improved to ±0.7 ppm for short periods, meeting the field stability requirement for separated turn operation. A comparison of the magnetic field stability before and after the modifications is shown in Fig. 3. By applying the NMR feedback loop, overall stability of ±1.5 ppm was maintained for periods of several hours.

Additional instabilities in the beam phase were monitored with a capacitive phase probe in beam line 1. These phase drifts have been reduced by means of a

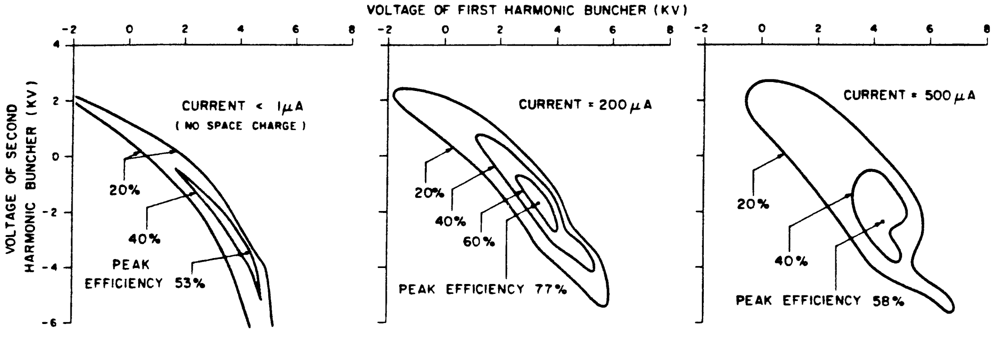

Fig. 2. Contours of the bunching efficiency at various buncher voltages for three injection line currents exhibiting the effects of space charge in three different regimes.

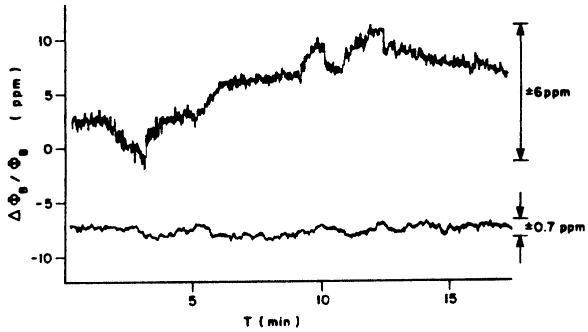

Fig. 3. Time variation of the cyclotron magnetic flux measured through an outer trim coil before (upper) and after (lower) the improvements to the magnet power supply.

feedback loop in which the RF frequency is adjusted to compensate for the phase drift. A resultant phase stability of ±0.7° was observed for periods of several hours.

For low current operation, the time relation between timing pulses from counters, detecting scattered protons in an external beam line, was measured with respect to the RF voltage peak, using a time-to-amplitude converter (TAC). The TAC output pulses were digitized with a peak sensing ADC. The centroid in the time distribution spectrum was determined by averaging the ADC values, using a local CAMAC microprocessor (TRIMAC) and was used as a measure of the relative beam phase. The update time (~1/20 s for 1 nA) for the averaging was varied according to the beam intensity. By using this beam phase to provide a compensating RF frequency shift, the resulting phase stability was improved to ±2° for extracted currents of less than 1 nA.

Polarized Source

Approximately 30% of the beam production time is scheduled for polarized operation. This is normally achieved in four time slots, each of two to three weeks in duration, prior to either a shutdown or a lengthy maintenance period. Although up to 300 nA of polarized protons have been accelerated up to full energy, the amount of current is still a limiting factor for a number of experiments using the polarized proton beam to produce a polarized neutron beam. Furthermore, experiments requiring high energy-resolution have found it necessary to compromise on either the current through the emittance-defining slits or the beam quality. Therefore development was begun on developing a more intense polarized H^- source. Two approaches are being pursued.

A short-term program is examining the gains that can be achieved by replacing the duoplasmatron of the Lamb-shift type source by an electron-cyclotron-resonance (ECR) type proton source. If the axial magnetic field is extended from the proton source over the cesium charge exchange region, then the proton beam can be neutralized without experiencing significant space charge effects. These space charge effects are presently limiting the H^- current from the polarized source. A gain in H^- current of a factor of five is expected with respect to the existing source. In order to achieve this gain it is essential to extract the proton beam with minimal divergence in the magnetic field. It is also important to remove the charged particles while maintaining space charge neutralization. A magnetic field profile which should allow this to be achieved has been described elsewhere.[7] An ECR-Lamb-shift type source has been constructed in the laboratory. The magnetic field profile and extraction geometry of the ECR source are being optimized.

A longer-term program is examining the feasability of an optically-pumped polarized H^- source. The scheme, as proposed by Anderson,[8] involves optical pumping to achieve electronic polarization in a sodium vapour. The polarization is them transferred to a proton beam by charge exchange. The predicted currents are substantially larger than what is possible from any of the existing sources. A sodium charge exchange cell has been built and the polarization of the sodium vapour is being tested.

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