NEW FACILITIES AND KAON FACTORY DESIGNS FOR TRIUMF

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ABSTRACT

The TRIUMF 520 MeV H^- cyclotron came into operation in December 1974 and first delivered a 100 μA beam in July 1977. Facilities recently commissioned include a second proton line for polarized and high resolution experiments (single turn extraction has been demonstrated at 200 MeV), a pion spectrometer, a 70/90 MeV proton beam for isotope production and a new slow (≤ 30 MeV/c) pion/muon channel. Major projects under way include a high-resolution fast pion channel, dc and rf separators to give purer stopping muon beams, and a time projection chamber.

Further in the future are the possibilities of building a third (simultaneous) 400-500 MeV proton beam and high-flux muon and biomedical π^- channels. More fascinating still is the possibility of elevating TRIUMF from a pion to a kaon factory, producing currents 100-1000 times more intense than those at present available in the GeV range. Two post-accelerator designs are being considered—a 30 μA rapid cycling 8-10 GeV proton synchrotron (which could in turn inject into a higher-energy machine)—and a 400 μA isochronous ring cyclotron built in two stages, the first to 3 GeV and the second to 8.5 GeV.

INTRODUCTION

Since the cyclotron was commissioned in December 1974 the regularly operated beam current has been gradually increased from a few nA to 20 μA . A 100 μA beam was first run in July 1977 and since the commissioning of the permanent beam stop and thermal neutron facility (TNF) with a 120 μA beam in February 1978 100 μA shifts have been scheduled with low but increasing frequency. (The status of the cyclotron has most recently been reviewed by K.L. Erdman.¹) During 1979 just over 10% of the high-current running is being scheduled at 100 μA . The integrated charge delivered will be $\sim 75,000 \mu A-h$, a factor 3 greater than that delivered in 1978 (27,000 $\mu A-h$ —itself a factor 3 greater than the figure for 1977).

The reason for not scheduling a greater percentage of 100 μA running is to keep the radiation levels in the cyclotron vacuum tank low while significant manual work remains to be done there. (This work includes installation of additional extraction systems and various improvements to the RF accelerating system, including full remote handling capability and the addition of third harmonic flat-topping.) Although the use of peripheral graphite absorbers, lead shields and other techniques has reduced the radiation level by a large factor,² we are now at a stage where the skilled workforce receives close to its permitted quarterly dose during a one-month

shutdown.

Besides its role as a meson factory, TRIUMF has a second important role to play as a source of variable energy proton beams between 180 and 520 MeV; indeed it is at present the only accelerator producing protons directly at these energies, without degradation. Experiments requiring unpolarized beam and regular energy spread (1 MeV FWHM) are of course mounted on lines 4A or 4B (see Fig. 1) and run simultaneously with pion or muon experiments fed from targets in line 1A. The fraction of beam delivered to line 4 can be varied between 1/1 and 1/10,000 by suitable choice of the shape and height of the extraction foil.

However, a polarized source is also available and still-selected beams of higher energy resolution are being developed. These beams are too weak to be useful for pion production, so the cyclotron is dedicated to their use for 20-30% of the time, depending on demand. The Lamb shift polarized source³ provides a 200 nA extracted proton beam with $>70\%$ polarization at all energies. Furthermore a beam of highly polarized monoenergetic neutrons can be obtained via the $d(p,n)2p$ reaction with a liquid deuterium target.⁴ The high value of the Wolfenstein R_t parameter results in neutron polarizations rising from $\sim 50\%$ near 500 MeV to 65% near 200 MeV; the intensity is 2×10^6 neutrons/sec through a 5 cm aperture.

Fig. 1. Beam lines and experimental areas.

BEAM LINES AND EXPERIMENTAL FACILITIES
— EXISTING
----- PROPOSED

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RECENTLY COMMISSIONED FACILITIES

Internal Cyclotron Slits (for reducing the proton beam energy spread)

Four pairs of internal slits, located in the 3 and 30 MeV regions, were commissioned during 1978. With these it has been possible to select beams of small emittance, narrow phase acceptance and small coherent betatron oscillations so that the turns remain separated out to 200 MeV. (Improvements in cyclotron stability have also been necessary.) That a single turn could be extracted was confirmed by observing the time-of-flight spectrum of the external beam.⁵ In this case the energy spread should be ≤ 320 keV; work is in hand to measure this directly.

Proton Line 1B

This "peanuts" line (so-called because of its supposed cost philosophy) was completed and commissioned in January 1979. It is intended for polarized or high resolution beams, allowing them to be used simultaneously on lines 1B and 4; beam intensity is limited to 10 nA. Beams of 200, 250, 300 and 350 MeV have so far been commissioned; the spot sizes are $< 5 \times 10$ mm.

Pion Spectrometer

The UBC group studying (p,π) reactions⁶ have recently assembled a new magnetic spectrograph based on a 65 cm Browne-Buechner magnet, to replace their previous 50 cm spectrometer. The new magnet is designed to handle pions of up to 110 MeV along the central ray, with an angular range of 35° - 145° , momentum resolution of $\sim 0.1\%$, and acceptances of 30% in momentum and ~ 9 msr in solid angle. The spectrometer has been installed on line 1B and is currently being commissioned with beam.

70/90 MeV Proton Beams

Special ports for the extraction of 65-100 MeV and 100-180 MeV beams have been installed on extraction horn 2 (Fig. 2); 70 and 90 MeV beams were extracted in August 1978. These beams are intended for isotope production (in particular ^{125}I) and a short beam line is to be built in the cyclotron vault to bring them to the irradiation facility.

Target 1A1 and M13 Slow Pion/Muon Channel

A new thin pion production target (T1) has been installed in beam line 1A. Like T2 there are five targets mounted, but all ≤ 4 g/cm². T1 is designed to feed the M11 fast pion channel (see below) and the M13 slow pion/muon channel. M13 takes off at 135° in imitation of M9, which has very low electron and fast neutron contamination. The channel can operate up to 130 MeV/c (50 MeV pions) and is 9.5 m long with two 60° bends in opposite directions. Experiments

Fig. 2. Beams leaving exit horn 2.

with an α -source have shown the channel properties to be very much as predicted (solid angle acceptance 30 msr, momentum resolution 0.8% with slits closed and a small source). T1 is being commissioned with a proton beam during the week of this conference.

FACILITIES UNDER CONSTRUCTION OR DEVELOPMENT

Separated Turn Operation

To extend separated turn operation of the cyclotron from 200 MeV to 500 MeV it appears that the stability of the RF voltage is close to the required tolerance, but that the stability of the magnetic field has to be improved by about a factor 3. Third harmonic flattopping also has to be applied to the RF accelerating system to widen the phase acceptance and increase the beam intensity to ~ 1 μ A. Work on the RF system is proceeding satisfactorily. Separated turn operation should allow beams to be extracted with energy spreads as low as 100 keV.

M11 High Resolution Fast Pion Channel

This channel is designed to accept 30-350 MeV pions leaving the T1 target at 2.5° , and give $\pm 0.1\%$ momentum resolution with 6% momentum acceptance. Because of brazing problems with the septum magnet (which separates the pions from the proton beam) installation of the channel has been delayed and its design has been reconsidered. The first (60°) bending magnet is being modified to ensure a more constant field shape at different excitations. The second bending magnet will now bend 60° left for the achromatic and "normal"

dispersed modes, and 30° right for the "reversed" dispersed mode. Five sextupole magnets will be used to correct second-order aberrations.

M9 Channel Extension

The cloud and surface muon beams produced by the present M9 channel have good luminosity but suffer from high pion and electron contamination. To remedy this temporarily a crossed-field dc velocity-filter separator is being installed, lengthening the channel from 8.5 m to 20 m. With 40 kV/cm and 226 G fields the contamination is expected to drop to 1-2% for negative pions and zero for electrons. For 77 MeV/c muons (μ^-) the flux expected in a 10% momentum bite is $5 \times 10^5/\text{sec}/100 \mu\text{A}$ protons on a 10 cm Be target; the small vertical aperture (10 cm) and great length (3 m) of the separator plates unfortunately cut out 60% of the incident muons.

RF Separator

To improve the vertical acceptance of the extended M9 channel it is proposed to replace the dc velocity filter by an rf separator in 1980. This would be only 70 cm long and would consist of a resonant cavity excited at 23 MHz, the cyclotron rf and pulse repetition frequency. The separator would be located about 12 m downstream of the target so that 77 MeV/c pion and muon pulses would arrive about half a cycle apart and be deflected in opposite directions; a compensating magnetic field (~ 10 G) steers the muons back on target. With a 24 kV/cm fundamental field and 20% third harmonic flat-topping virtually all the muons ($\sim 10^5 \mu^-/\text{sec}/100 \mu\text{A}$) should be transmitted to the target, with <1% pion contamination.

Time Projection Chamber

To observe the rare decay modes of the pion or muon a detector is required having large solid angle, high resolution and good background rejection. The time projection chamber⁷ satisfies these requirements and one is being built for installation on the extended M9 channel. The chamber itself is complete and is undergoing initial tests. It measures 80 cm long $\times$ 100 cm diameter and runs on an 80:20 argon-methane mixture at 1 atmosphere in a 150 V/cm electric field. There are 12 endcap wires for each of the six 60° sectors. The cube magnet (on loan from the University of Chicago) provides a 9.2 kG field homogeneous to 0.5% over the chamber volume. The TPC will initially be used to search for the reactions $\mu^- Z \rightarrow e^- Z$ and $\mu^- Z \rightarrow e^+ (Z+2)$.

Polarized Hydrogen Target

The principal components of a 4 cm³ polarized proton target have been purchased from the University of Liverpool. The target consists of frozen butanol and the components include the superconducting magnet, cryostat, and ³He gas handling system. The target is now being reassembled for use in p-p scattering studies.

FUTURE POSSIBILITIES

A number of additional projects are under consideration. They may be classified broadly as proton beams, secondary channels, spectrometers and post-accelerators. The latter we leave for the next section. For spectrometers there are proposals for a more powerful (645 MeV/c) pion spectrometer, and for upgrading the MRS (medium resolution spectrometer). Interest in new channels has centered on proposals for high flux channels, both of muons and of negative pions for cancer therapy. Besides designs similar to those at other laboratories, Lobb⁸ has proposed an axi-symmetric channel with an annular solid angle acceptance of 1 sr; pions or muons are selected with the help of an annular degrader. Any high flux channel would probably have to be fed from a new proton line. Work will start this year on installing the extraction system and combination magnet for an eventual line 2A (400-500 MeV, see Fig. 2) before the radiation levels around the cyclotron become too high. Finally there remains the possibility of extracting 100-180 MeV beams from the same exit horn; TRIUMF would then be providing beams of continuously variable energy from 70 to 520 MeV.

KAON FACTORIES

The present meson factories accelerate currents of the order of 100 μA (6×10^{14} protons/sec) to energies of 500-800 MeV. These currents are several hundred times larger than those being accelerated into the GeV range by the present generation of proton synchrotrons, whose intensities are limited by their injectors and the problems of injection. It is therefore tempting to consider the possibility of using the meson factories themselves as injectors to higher energy machines which would accelerate 10 or 100 μA to many GeV with the aim of producing kaon or even antiproton beams orders of magnitude more intense than available at present.

The uses to which intense kaon beams might be put (and some methods by which they might be produced) were discussed in 1976 at the Brookhaven Summer Study Meeting on "Kaon Physics and Facilities".⁹ Intense non-strange beams would also be available—nucleons, pions, muons and neutrinos—kaon decay providing a possibly unique source of electron-neutrinos of moderate energy. Some experimental topics of particular interest are:

- 1) K⁻-N interaction - the phase shift analysis is "still very confused" and unconfirmed resonances abound.¹⁰
- 2) K⁺-nucleus scattering - the K⁺ is the only strongly interacting probe weakly absorbed by the nucleus.
- 3) Hypernuclei - intense beams permit counter experiments and spectroscopy of hypernuclear excited states.
- 4) (K⁻, K⁺) reactions - could give stable baryonic systems with strangeness -2 such as (ΔE^-) and $^9\text{He}_{\Lambda}$.
- 5) Kaonic and hyperonic atom X-rays - give information on K⁻ and Σ^- -nucleus interactions.
- 6) K, Σ , Λ -decays - several possible channels involving neutral

- currents have yet to be observed.
- 7) Neutrino-induced reactions at intermediate energies.
 - 8) K^0 regeneration on nuclei.
 - 9) $p\bar{p}$ scattering - polarized beam would allow spin-dependent effects to be explored.
 - 10) π -N and π -nuclear scattering and reactions.
 - 11) Electromagnetic breeding of nuclear fuel by spallation neutrons - a possible practical application.

To produce intense and clean kaon beams energies well above threshold are needed. Berkeley has analysed various kaon beams, showing that their intensities rise very strongly with incident proton energy at first, but flatten off at ~ 7 GeV for K^+ and ~ 9 GeV for K^- . At TRIUMF, two options are being considered to accelerate intense proton beams to 8-10 GeV—a fast-cycling synchrotron and a two-stage isochronous ring cyclotron.

PROTON SYNCHROTRON

J.R. Richardson¹¹ has proposed building a fast-cycling synchrotron to accelerate a 32 μ A proton beam from TRIUMF to 8-10 GeV. In this case the chief design problem is in matching the time structure of the two machines, the synchrotron being pulsed at 20 Hz, while the 500 MeV cyclotron operates cw at 23 MHz. Three extraction schemes from TRIUMF have been considered:

- conventional proton extraction by stripping foil (giving minimal interference with cyclotron operation)
- resonant extraction of H^- ions at the $\nu_r = 3/2$ resonance (430 MeV); this would circumvent Liouvillean restrictions on filling the synchrotron phase space
- pulsed extraction of "100 turn stacks".

At the moment the last option appears to be the most promising, since it would provide an intermediate pulse frequency. The beam would be allowed to drift 90° out of phase at 450 MeV, after which it would begin decelerating back towards the centre (this behaviour has already been observed experimentally). The outermost 50 accelerating and 50 decelerating turns, which would be located in a 25 mm wide radial interval, could then be extracted in one bunch 0.44 μ sec long by pulsing an axial electric field. The repetition period would be 22 μ sec, corresponding to 14 synchrotron turns. Fast bumper magnets and rf acceleration would be used to move the equilibrium orbit away from the injection system. 200 macropulses per synchrotron cycle would be adequate to achieve an intensity of 2×10^{14} p sec⁻¹ (32 μ A), assuming 400 μ A in the present cyclotron. To accommodate the long injection time (9% duty factor) the magnet cycle would be flat-bottomed using 60 Hz third harmonic. This machine in turn could act as injector to a high intensity 40 GeV synchrotron.

Table I. TRIUMF $\rightarrow$ fast cycling synchrotron.

Number of stacked turns - TRIUMF	~ 100
Energy spread of extracted beam	450 ± 2.5 MeV
Injected beam microstructure	10 each pulses of 14 nsec
macrostructure	0.4 μ sec every 21 μ sec
Beam loss - stacking in TRIUMF	$< 2\%$
Phase space ratio	$\sim 10^5$
Synchrotron frequency	20 Hz
Space charge limit	8×10^{14} p sec ⁻¹
Phase space limit	10^{15} p sec ⁻¹
Synchrotron orbit time	1.5-1.14 μ sec
Macropulses per synchrotron cycle	200
Injection time	4.4 msec
Mean synchrotron radius	50 m
Average energy gain per turn	0.45 MeV
Radio frequency	0.67-0.93 MHz
Beam loss - extraction, injection and capture	$< 5\%$
Final energy	8-10 GeV

ISOCRONOUS RING CYCLOTRONS

The alternative proposal¹² is for a two-stage isochronous ring cyclotron to accelerate protons to 8.5 GeV. (Isochronous cyclotron designs for several GeV have previously been considered by Sarkisyan¹³ and Gordon.¹⁴) There being no incompatibility in time structure the full beam current from the present cyclotron (eventually 400 μ A) could in principle be injected into the ring machines. The first stage of 15 sectors and 10 m radius would take a 450 MeV beam from TRIUMF to 3 GeV, the acceleration being completed by a second stage of 30 sectors and 20 m radius (Fig. 4). Superconducting magnets would

Fig. 3. Superconducting magnet design for second stage 3 to 8.5 GeV 30 sector cyclotron.

Fig. 4. A possible kaon factory design for TRIUMF, utilizing 3 GeV and 8 GeV (20.6 m radius) isochronous ring cyclotrons with superconducting magnets and SLN-style cavities (the 520 MeV cyclotron magnet poles are shown to scale for comparison).

be used, the weight of steel being estimated to be 2000 tonnes for the first stage and 1800 tonnes for the second, less in total than in the present 500 MeV machine. Numerical orbit tracking through simulated magnetic fields has confirmed that the focusing properties of the design are satisfactory and has emphasized the importance of using small pole-gaps to prevent fringing field effects weakening the edge focusing. Steel is provided outside the coils on the focusing edge to provide a reverse field (see Fig. 3), keeping the edge hard and increasing the flutter. Several integer and half-integer radial resonances have to be crossed, but with a high energy gain per turn (3 MeV and 8 MeV, respectively) this should cause no difficulty. The most difficult technical problem will be that of extracting the beam efficiently. Here again the high energy gain per turn will be important; resonances will also be of assistance in exciting coherent radial oscillations. The accelerating system consists of SLN-style cavities, with flat-topping provided by operating some at the second harmonic (first stage) or third harmonic (second stage). The phase

compression effect is also utilized to allow higher fundamental frequencies (and hence smaller cavities) to be used on successive stages.

Table II. Ring cyclotron kaon factory.

	First Stage	Second Stage
Injection energy (MeV)	450	3000
Extraction energy (MeV)	3000	8500
Cyclotron radius c/wp (m)	10.3	20.6
Number of sectors	15	30
Primary cavities	8 at 46 MHz	15 at 69 MHz
Harmonic cavities	4 at 92 MHz	6 at 207 MHz
Cavity dimensions: primary (m ²)	5.9 × 3.6	4 × 2.6
secondary (m ²)	5.9 × 1.6	4 × 1.5
Total rf power (MW)	2.0	1.7
Energy gain/turn: (MeV)	1.2	7.9
ΔE/Δr (MeV/mm): injection	3.6	7.9
extraction	0.23	1.9
Radius gain/turn (mm): injection	5.6	30
extraction	5.3	4.2
Magnet weight (tonnes)	0.64	0.26
Approx. number of turns	2000	1800
	900	700

Both designs are very much in their preliminary stages; during the coming year they will have to be looked at in more depth and the feasibility assessed of submitting a formal proposal for one or the other. The author thanks all his colleagues at TRIUMF and the participating universities whose work he has had the privilege of reporting.

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