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STATUS OF TRIUMF AND PLANS FOR DEVELOPMENT

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Introduction

The TRIUMF project has been previously reported to the All-Union Conferences in 1976(1) and 1978(2,3). The H$^-$ cyclotron has now been operating for seven years and has been gradually upgraded toward its final capabilities. 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 and intensity between ~1 nA and 10 μA can be extracted for proton beam experiments. In addition, a low energy beam between 60 and 100 MeV with currents of several tens of microamperes can be extracted at the same time for isotope research and production. About one-third of the production time is dedicated to polarized beam, with currents up to 300 nA and polarization well in excess of 70% being delivered simultaneously along two external proton beam lines. The energy spread of the extracted beam can be reduced to $\Delta E/E \simeq 1/1000$ through RF phase and phase space selection in the centre via a set of slits. Time microstructures of 0.5 to 6 ns every 43 ns or every 215 ns are available. Typical beam characteristics presently available are listed in Table I, together with future goals being aimed at. The layout of the facility, including the experimental areas, is presented in Fig. 1 and will be described below.

The scheduling aspects related to the multiple simultaneous use of a facility of this type (typically seven to ten groups of users are exploiting the various proton, meson and neutron beams at one time) 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. Therefore, after a first phase where the emphasis was on the machine construction and commissioning, under the leadership of J.B. Warren and J.R. Richardson, and a second phase under J.T. Sample where the emphasis was on upgrading the machine and the experimental areas to their present capabilities, we have recently begun a third phase under the directorship of E.W. Vogt where the highest emphasis is placed on maximizing the scientific output, which can greatly benefit from reliable conditions. Programs aimed at higher machine reliability, such as the improvement and replacement of the resonator system, are being given highest priority, while programs aimed at increasing the beam capabilities, such as third harmonic RF operation for separated turns, new source capabilities and new experimental facilities, are being brought ahead in parallel. The proposal for a kaon facility which aims at 15 GeV-100 μA beams and plans to use the cyclotron as an injector will be finalized during the coming year. The most significant aspects concerning production, developments and new facilities will be outlined below.

Cyclotron Performance

The cyclotron performance in terms of beam production is illustrated in Fig. 2. Extracted beams of 100 μA and 120 μA had already been reported at Dubna(2) in 1978. 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, while understanding and control of beam tunes, beam lines and induced radiation have been gradually improving. The total beam charge delivered per year has increased by almost a factor of 10 from 25 mA h in 1978 to 240 mA h predicted for 1982. Correspondingly, the residual radiation in the centre of the machine, measured during shutdowns with lead shields covering the tank wall,(4) increased 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

Table 1. Beam properties

CYCLOTRON

Property	Achieved	Future goal
Maximum energy	520 MeV	520 MeV
Intensity (unpolarized)	150 μA cw 225 μA (10% duty cycle)	300 μA cw
Intensity (polarized)	300 nA	2.5 μA (with ECR) 30 μA (new source)
Polarization	75–82%	80–85%
Split ratio (line 4/line 1)	$1/10^4$	$1/10^5 \sim 1/10^6$
Phase width	0.5 ns → 6 ns	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)

BEAM LINES

Beam line/ secondary channel	Particle	Energy (MeV)	Intensity	Spot size cm × cm	Momentum spread FWHM	Polarization
BL1A	p	180–520	120 μA (500 MeV)	0.2 × 0.5	0.2%	0
BL4/1B	$\vec{p}$	180–520	300 nA	0.2 × 0.5	0.2%	70–80%
BL4A	$\vec{n}$	160–500	10^8/s	6 × 6	1%	40–75%
BL2C	p	65–100	10 μA	1 × 2	0.2%	0
		Momentum (MeV/c)				
M8	π^-	0–220	1.3×10^8/s @ 180 MeV/c	1 × 2	13%	0
M9	μ^-	30–150	10^6/s @ 77 MeV/c	8 × 8	14%	50%
	π^+	30–250	2×10^8/s @ 120 MeV/c	10 × 2	14%	
M20	μ^+	30–200	6×10^5/s @ 30 MeV/c	3 × 4	5%	>90%
			1.1×10^6/s @ 180 MeV/c	8 × 8	5%	75%
M13	π^+	30–130	5×10^7/s @ 130 MeV/c	2 × 3	10%	
	μ^+	30 (surface)	1.3×10^6/s	2 × 3	10%	>90%
M11	π^+	90–470	5×10^6/s @ 200 MeV/c	2 × 3	3%	
M20 upgrade (in construction)	μ^+	30–200	3×10^6/s @ 30 MeV/c	3 × 4	5%	>90%
			6.0×10^6/s @ 180 MeV/c	8 × 8	5%	75%
M15 (in design)	μ^+	30 (surface)	1.6×10^6/s	2 × 1	12%	>90%

Notes

1. M8, M9, M20 fluxes are quoted for full momentum acceptance, 100 μA protons on 10 cm Be target.
2. M13, M11, M15 fluxes are quoted for full momentum acceptance, 100 μA protons on 1 cm C target.
3. π^- and μ^- beams have same properties as π^+ and μ^+ beams except flux ~ 5 times lower.

mode is set by the lead thermal neutron target which acts as a beamstop and was designed for a maximum beam power of 50 kW.(5) A lead stop for 125 kW will be installed at the beginning of 1983 and 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 these are initially confined to the 45° wide phase acceptance at the centre of the cyclotron, resulting in a peak current of 2.2 mA at the entrance of the machine (spiral inflector). The large cyclotron beam acceptance is obtained using a fundamental plus a downstream second harmonic RF buncher.(6) An additional fundamental buncher, to partially correct the energy dispersion effects, and an increase in the effective beam line acceptance through improved geometrical alignment and compensation of stray magnetic fields are planned to overcome space charge limitations. Operation at higher currents is important for various reasons, ranging from the possibility of shorter sessions for patient irradiations to lower radiation in the machine, by producing equivalent pion fluxes using higher current lower energy proton beams to reduce electromagnetic stripping losses of the H^- ions.(7) In addition the adequacy of the cyclotron as an injector for the kaon factory will be dependent on the amount of beam which can be bunched in short phase intervals, say 20° or preferably 12°. The effort toward high peak intensities will be given highest priority, second only to the reliability improvement program.

It appears from Fig. 2 that both the number of hours of beam operation and the total beam charge produced declined in 1981. This was mainly due to three unplanned shutdowns which had to be called during 1980-81 for nonscheduled repairs. During one of these all 24 100-ton magnet jacks were removed and overhauled, and an original design fault in the ball-bearing guiding system was corrected. The other two shutdowns were required to deal with severe damage caused to diagnostic, beam-steering equipment or resonator structures by stray RF fields in the tank volume behind the resonator panels.(8) The critical behaviour of RF leakage in this "field-free" region and its close dependence upon misalignments and asymmetries between the upper and lower resonators had been observed since the first commissioning phase in 1975(8) and had been the object of further studies.(9) Resonator sagging due to RF heating of uncooled surfaces was found to be one of the most difficult phenomena to prevent or correct. Although the situation could be monitored closely with thermocouples and other diagnostics to minimize further RF damage (Fig. 2 shows that 1982 has been one of the best years for reliability), it was nevertheless decided to accelerate the resonator replacement program and replace all eighty resonator segments by 1986. The new segments will be supported by better cooled and more stable mechanical structures. Modifications advantageous for third harmonic and remote handling will be included. A new prototype resonator segment has been built and will shortly be tested at full RF power in a special test stand.

In parallel, a 1:10 scale metal model of the entire vacuum tank and resonator system has been built to study the nature and the possible reduction of RF leakage phenomena. The amount of leakage field as measured in the model with the resonators misaligned by various amounts is shown in Fig. 3. This agrees to within an order of magnitude with the amount of leakage observed in the cyclotron tank. With perfect symmetry in the model, the leakage can be reduced, in power, to 60 dB of the main field. An attempt to evaluate numerically the leakage in function of the misalignment was done using the two-dimensional program SUPERFISH.(10) The resulting curve, shown in Fig. 3, is surprisingly close to the measured values. A deeper analysis of the phenomenon is under way in an attempt at finding ways to reduce the effect.

Towards better beam energy resolution, the medium energy resolution mode, based on reducing the coherent and incoherent radial amplitudes with slits and flags in the centre and at 30 MeV, has been shown to give $\Delta E = 1/1000$ over the whole energy range and is available for experiments.(11) The effort toward higher energy resolution (100 keV) and separated turns to 500 MeV, which requires third harmonic flat-topping of the RF, has been slowed down as a result of the change in emphasis - toward reliability - of the resonator improvement program. Nevertheless, the third harmonic amplifier has been commissioned on a dummy load at full power and RF tests in the cyclotron will be performed shortly. It is doubtful, however, that the tuning mechanisms available on the present system (the original flexible tuning shorts out the resonator root failed and are not usable) will allow the 3:1 ratio between the two frequencies to be maintained stably. Sufficient tuning capability is built into the new resonator design.

A substantial improvement has recently been realized in the magnet stability. The tolerance in beam phase stability of ±2° at 500 MeV, required for separated turns, had been previously satisfied through feedback between a capacitive beam phase detector and the RF frequency.(11) This method, however, cannot be used at beam intensities of a few nA, which are normal for high resolution or polarized beam experiments because of the limited sensitivity of the capacitive probe (~0.3 μA). A direct improvement of the magnet stability was therefore attempted. First an NMR probe was used to generate a slow feedback on the main magnet supply and reduce the magnetic field oscillation from ±10 ppm to ±3 ppm. More recently a few critical modifications on the temperature compensation circuit of the shunt resistor in the main magnet power supply and other improvements in the power supply feedback circuit have allowed ±0.7 ppm, corresponding to ±2° tolerance, to be achieved directly for periods of half an hour. Magnetic field variations, measured by integrating the voltage in an outer trim coil before and after the recent power supply improvements, are compared in Fig. 4. Slow response phase detectors based on counter techniques will complement the feedback system to correct for slow drifts in power supply current. For separated turns the RF voltage must also be kept stable to $\pm 3\times10^{-5}$. A stability of $\pm 6\times10^{-4}$ was reported at Dubna,(3) while $\pm 1.5\times10^{-4}$ was measured after more rigid mechanical coupling between the 80 resonator segments had been introduced to make the structure stiffer.(12) A factor of five improvement in voltage stability is therefore still required.

Polarized beam operation is normally scheduled for two to three weeks before extended maintenance periods, three to four times per year. The polarization of the beam extracted from the cyclotron at full energies was improved by about 3% as a result of the correction of the depolarizing $3.796\gamma = 5$ resonance at 300 MeV via a set of harmonic coils.(13) Furthermore, careful attention to minimize betatron amplitudes allowed 82% polarization to be observed beyond the $3.796\gamma = 6-\nu_z$ resonance at 467 MeV. The Lamb shift polarized source was made more reliable and an RF spin filter was inserted in the source to allow rapid spin reversal up to 1 kHz.

A development program to increase the polarized beam current is being pursued through two different schemes.(14) A short-term program contemplates replacing the duoplasmatron in the Lamb shift source with an ECR type proton source to overcome the space charge limitation which is intrinsic to a traditional Lamb shift source equipped with a duoplasmatron. A gain by a factor of five (~5 μA) is expected with respect to the traditional source. An ECR-Lamb shift source is presently being optimized in the laboratory.

In a longer-term program an optically pumped H^- ion source is being studied and developed. A sodium cell has been built and laser polarization of the sodium vapour is being tested. Recent developments at KEK in Japan indicate that currents of 50 μA and 80% polarization should be possible with this type of source.

Facility Development (Experimental Facilities)

Since 1979 two new secondary channels M13 and M11 have been installed at the thin (<4 g/cm^2) meson production target T1 on beam line 1. The M13 channel(15) ($\Omega = 30$ msr) delivers high quality beams of pions and muons with energies from 4-50 MeV. A large acceptance ($\Omega = 22$ msr) QQD spectrometer with a resolution of $\Delta p/p = 2 \times 10^{-3}$ has recently been commissioned on this channel. The combination of the high luminosity channel and this spectrometer, which can also be operated in the dispersion matched mode, provides one of the best facilities in the world for low energy pion physics.

The M11 channel (Ω = 6 msr) is designed for pion production in the energy range from 50-350 MeV. Pions produced in the forward direction from the production target are separated from the high intensity proton beam by means of a radiation-hard magnetic septum.(16) The septum has a maximum pole tip field of 0.5 T with a current of 5000 A through the 18 turn, 3 cm wide, septum sheet. Some representative fluxes from this channel and the other secondary channels at TRIUMF are listed in Table I.

Another interesting development has been the design and installation of an RF separator (see Fig. 5) on the M9 channel, the other high flux π/μ channel. Previously a 3 m long, 60 kV/cm gradient dc separator was used to provide a clean muon beam on this channel. The RF separator with a length of 1.0 m and a gradient of 24 kV/cm transmits twice the muon flux with less pion and electron contamination. The separator utilizes the fact that the proton beam extracted from the cyclotron has a time structure of 5 ns pulse width every 43 ns, and this pulse structure is retained by the secondary particles. The pulses of electrons and pions arrive at the RF separator at different times than the muon pulses and are deflected away by the time-varying voltage in the separator which operates at the cyclotron frequency.

A major project this year is the upgrade of the present M20 channel with the installation of a longer decay section, larger aperture quadrupoles and a 3 m dc separator. The channel will have two legs, capable of running simultaneously with backward decay muons in the 75° leg and backward decay muons in the 37.5° leg. The muon fluxes will be increased about a factor six with these improvements.

In the proton hall the MRS or medium resolution spectrometer with p_{max} = 1.5 GeV/c is being upgraded to achieve a resolution of $\Delta p/p = 10^{-4}$ over the full acceptance. The spectrometer, a QD system with vertical bend, will be dispersion matched to the energy spread of the proton beam using a 6-quadrupole twister which rotates the horizontal dispersed proton beam to the vertical plane. Other improvements involve a new scattering chamber which eliminates the need for vacuum foils in the beam and vertical drift chambers at the focal plane for better positional accuracy.

Several additions to the experimental facilities are presently at the design stage. One of these projects is the development of a second arm spectrometer at the same pivot as the MRS spectrometer. It will have a large acceptance, >20 msr, and a maximum momentum of 650 MeV/c, and be used as a pion spectrometer in (p,π) studies or in conjunction with the MRS spectrometer for (p,2p) studies.

Two secondary channel projects, one the upgrade of our present biomedical channel and the second the construction of a dedicated surface muon channel from the T1 target position, will utilize rare earth cobalt (REC) permanent magnet quadrupoles as the first element(s) in the channel. Their compact size and high field gradients allow them to be located close to the production target, increasing the solid angle of the channel. Calculations have shown that the flux of 180 MeV/c π^- from the biomedical channel M8 could be improved by a factor two with a 10 cm aperture × 20 cm long quadrupole located 23 cm from the production target. Measurements are under way to determine if the samarium cobalt magnets can withstand the radiation fields in this location.

The proposed surface muon channel M15 will have an increased luminosity over the present M13 channel. DC separators will be used to precess the muon spin by 90° thus producing beams of either transverse or longitudinal polarization, a significant new feature for μSR studies.

Kaon Factory Studies

A logical extension of TRIUMF's capabilities is to accelerate the intense proton current it produces at 500 MeV to even higher energies. A "kaon factory" accelerating the 100 μA proton beam to 10-15 GeV would produce beams of low and medium energy kaons and neutrinos and stopping hyperons 100-1000 times more intense than those currently available. Antiprotons would also be available and even the low energy pion and muon beams would be an order of magnitude more intense than at TRIUMF. Two design options - a fast-cycling synchrotron or an isochronous ring cyclotron - are open in the energy range of interest (Figs. 6 and 7); preliminary designs have been reported previously.(17-19)

A synchrotron reference design has been prepared based on a 30 Hz rapid-cycling 16 GeV machine; this would be capable of accepting 100 µA beams at 500 MeV without space charge or beam instability problems. The fast-extracted beam would be sharply pulsed ($1/10^4$) and very suitable for neutrino experiments; continuous (cw) beam could also be produced by the addition of a 16 GeV stretcher ring using dc superconducting magnets in the same tunnel (Fig. 8). The chief problem for a synchrotron is beam-matching with TRIUMF, because of the very different time structures. The TRIUMF beam is cw at 23 MHz, so that about 770,000 TRIUMF pulses have to be collected into one synchrotron pulse. The schemes which have been proposed to achieve this involve extraction of >100 turn pulses from TRIUMF followed by multiturn injection (via H^- or possibly H^0 stripping) into a dc accumulator ring in the synchrotron tunnel. Several novel features would be required in TRIUMF: an increase in the local turn density by an order of magnitude, extraction of H^- ions (rather than protons), and a pulsed extraction system. Both magnetic and RF turn compaction have been investigated but the RF method provides better matching to synchrotron phase space. H^- injection into the accumulator ring requires four kicker magnets at the megawatt level to avoid degrading the beam emittance by multiple scattering. To achieve the high repetition rate (30 kHz) and fast rise time (~100 ns) required, a novel kicker power supply design based on hard tubes is being explored.

The cyclotron option would involve two isochronous rings, the first stage (15 sectors) going to 3.5 GeV, the second (42 sectors) to 15 GeV (Fig. 9). The use of superconducting magnets significantly reduces the size and cost of these machines. Their time structures would be completely compatible with the TRIUMF isochronous cyclotron so that the 100 µA proton beam could be injected straightforwardly and with 100% efficiency. The magnet designs are proceeding satisfactorily. Orbit tracking through numerically computed magnetic fields shows good isochronism and real axial focusing up to the highest energies. The design of the superconducting coils for the cyclotron magnets is being investigated, the force-cooled option being favoured; stress computations are also under way. The crossing of both imperfection and intrinsic resonances in the cyclotrons has been studied. The former require field tolerances similar to those for TRIUMF. The latter could give rise to significant emittance distortion; however, the possibility of avoiding this by suitable changes in the field gradient appears promising. Studies of beam extraction from the cyclotrons have made encouraging progress. By suitable excitation of an imperfection resonance it appears possible to provide a clear separation between turns of 1 mm, sufficient for installation of an extraction septum.

Present accelerator studies are being concentrated on a critical comparison of the two options with regard to their potential beam properties, technical problems and costs, to enable the most suitable choice to be made. Studies are also in progress on appropriate experiments, experimental facilities and beam lines so that a complete proposal for a kaon factory can be prepared in the near future.

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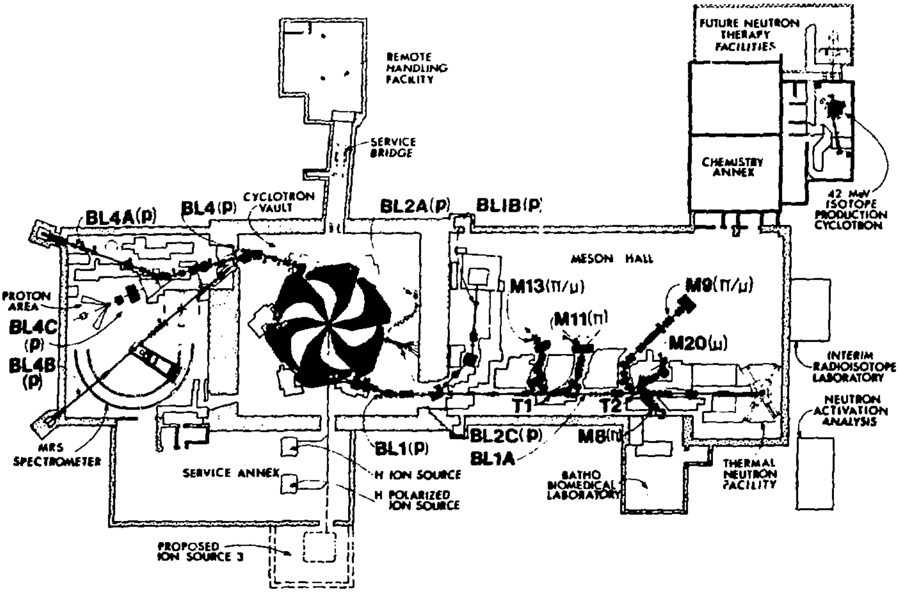


Fig. 1. Layout of the TRIUMF facility.

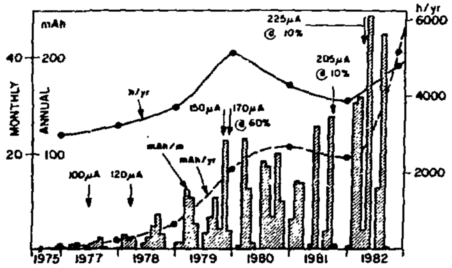


Fig. 2. Beam charge delivered and hours of operation over the past several years. Milestones in extracted peak currents are also indicated.

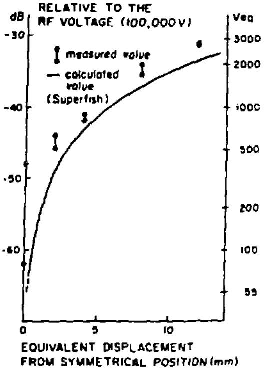


Fig. 3. Stray electric field measured in the 1:10 RF model of the cyclotron tank. Voltage and displacement are scaled up to corresponding cyclotron values.

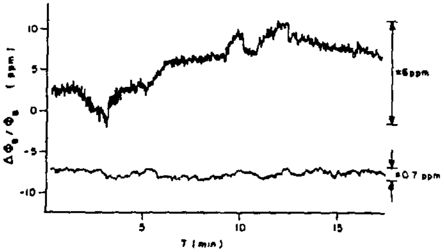
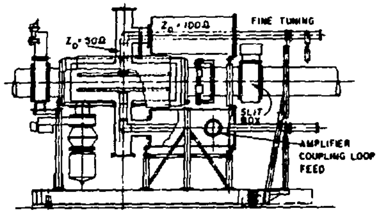


Fig. 4. Time variations of the cyclotron magnetic flux measured through an outer trim coil.



OPERATING PARAMETERS

FREQ	23.1 MHz	GAP DIMENSIONS	15cm x 100cm	MOMENTUM RANGE	40 - 90 MeV/c
POWER	100 kW	ELECTRIC FIELD	24 kV/cm	PION REJECTION	10^{-3} } 74 MeV/c
Q	5000	MAGNETIC FIELD	113 gauss	ELECTRON REJECTION	10^{-2} } 74 MeV/c

Fig. 5. Schematic of the TRIUMF RF separator.

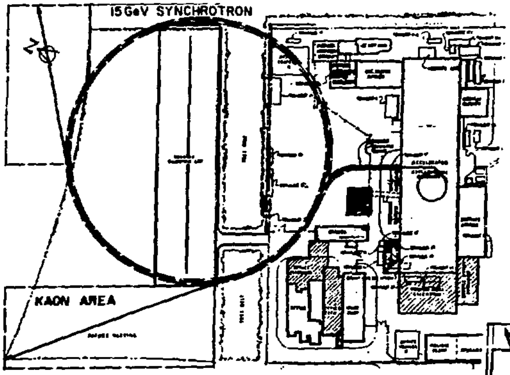


Fig. 6. Possible site layout for a 15 GeV synchrotron at TRIUMF.

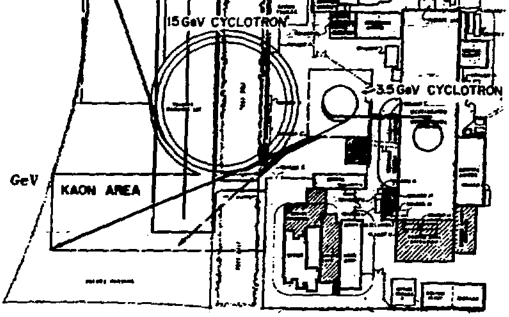


Fig. 7. Possible site layout for 3.5 GeV and 15 GeV cyclotrons at TRIUMF.

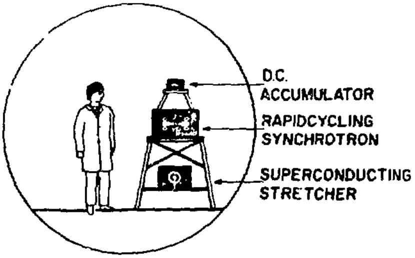


Fig. 8. Cross-section of the synchrotron tunnel.

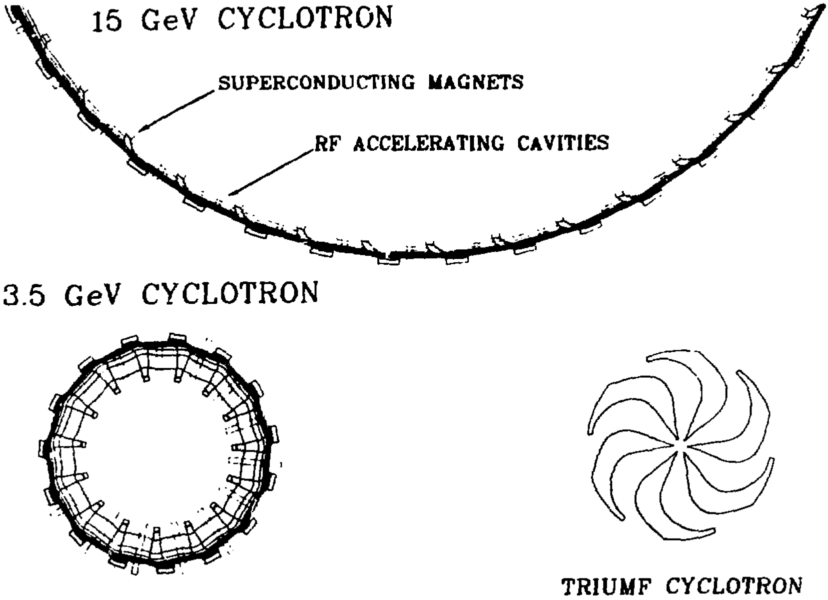


Fig. 9. The 3.5 GeV and 15 GeV superconducting cyclotrons, showing magnets, accelerating cavities and proton orbits, drawn to the same scale as the TRIUMF 0.5 GeV cyclotron.