The TRIUMF project

J. B. Warren
TRIUMF, University of British Columbia,
Vancouver 8, B.C., Canada

ABSTRACT

The engineering and construction of the 'Tri-University Meson Facility', by a group of four Western Canadian Universities–University of Alberta, Simon Fraser University, University of Victoria, University of British Columbia–commenced at the end of April 1968. This meson workshop and facility for intermediate energy nuclear physics and chemistry is based on a six-sector A.V.F. cyclotron designed to accelerate 100 μA of H^- ions to an energy of 500 MeV.[1,2] Virtually the whole beam may be extracted by stripping the two electrons from the negative hydrogen ions by passage through a thin foil so the resulting protons swerve out of the cyclotron. The energy of the extracted protons may be continuously varied from 150 to 500 MeV by altering the radial position of this foil. At the outset two beams will be extracted and fed to separate experimental areas; each will have 100% macroscopic duty factor, a microduty structure of 7 ns every 44 ns corresponding to a phase acceptance of 60°, and an energy resolution of ±650 keV.

1. H^- DISSOCIATION AND ACTIVATION

The fundamental limitation on the maximum current which may be usefully accelerated in a cyclotron is set by the beam which is lost into the vacuum tank and rf structure by the acceleration and extraction processes. This lost beam creates radioactivity, and the residual radiation fields even after a substantial cool-off period must not be so high as to render servicing of the machine impossible. In the case of an H^- cyclotron this directly limits the maximum magnetic field, B_{max}, which may be used, since in moving through the field the ions are subjected to an electric dissociating force E(MV/cm) = $0{\cdot}3\ \gamma\beta B$(kG), which tends to remove the second electron, bound only by 0·755 eV, and leave a neutral atom. For a given velocity β, or energy, this sets a limit on the B_{max} that can be used, since there is a limit to the number of neutrals that may be allowed to create radioactivity in the cyclotron components. The lifetime of the ions is an exponential funtion,[3,4]

$$\tau \simeq \frac{10^{-14}}{E} e^{49/E_s}$$

CYC69A08

so in our machine essentially all electric dissociation is expected to occur in the outer orbits where the kinetic energy of the ions lies between 450 and 500 MeV. The neutrals so produced then spill out tangentially to their orbit in a narrow fan shaped spray, modulated azimuthally by the azimuthal variation in B, and having 2 cm vertical width at the vacuum tank wall.

Some stripping of the ions will also be caused by collisions with residual gas atoms. Here theory and measurements indicate that double electron gas stripping is relatively negligible to single electron stripping. Theoretical estimates of the process based on Born[5,6] and impulse approximation[7,8] predict an inverse square law variation with the velocity. Measurements which have been made lie mostly at energies below 1 MeV, with some up to 45 MeV. The stripping cross-section of H^- in hydrogen follows a l/v^2 dependence from 0·06 to nearly 20 MeV, though the absolute value is in less fair accord. Data for air fit a $l/v^{3/2}$ law better. The estimated radiation fields and residual activity produced by these stripped ions thus depends essentially on the manner the extrapolation to high energies is performed.

If a total beam spill of 20 μA at 500 MeV is allowed, then the neutrals passing through a ¼ in thick vacuum wall of stainless steel produce radioactivity mainly by spallation, and the residual radiation field 24 h after shut-down following a prolonged run would amount to 2 rad/h at a distance of 1 m from the tank wall. At the centre of the cyclotron the residual radiation field would amount to 540 mrad/h.[9] The remainder of the primary proton range will be taken up in a 50 cm thick graphite shield ring, but this will only contribute 40 mrad/h at the centre of the cyclotron 24 h after shut-down. At other intermediate energy synchrocyclotrons the residual activities produced have been of similar order and servicing has been successfully accomplished. This residual activity in stainless steel will unfortunately decay rather slowly, for example, from 540 to 290 mrad/h after 30 days cool-off. However, with careful servicing procedures and remote handling devices, it may well prove possible to cope with higher levels of activation. No other practical fabrication material is any marked improvement on stainless steel it seems.

It is desired to accelerate and extract 100 μA at 500 MeV with a beam power loss of 20% or 10kW, or 20 μA approximate current loss.

To establish the lifetime of the negative hydrogen ion with precision at the $\bar{v} \wedge \bar{B}$ products of interest to TRIUMF, with the help of the Proton Linear Accelerator group at the Rutherford Laboratory, a quite direct measurement of the lifetime has been made. 50 MeV H^- ions were accelerated in the P.L.A., passed through an accurately surveyed magnet providing fields up to 20 kG, and the neutrals so produced detected in a spark chamber. From this work the value of B_{max} in our magnet has been set at 5·76 kG corresponding to a lifetime of 70 μs at an energy of 500 MeV. With a 400 keV gain per turn and a maximum radius of 312 in the integrated beam loss from electric dissociation amounts to 6½%.

Calculations made on the basis of a residual pressure of air of 1×10^{-7} torr show, of course, that the current loss occurs mainly at low energies and will amount to 10% and corresponds to an integrated power loss of 4·6%. Under running conditions the residual gas composition is more likely to be 8×10^{-8} torr of hydrogen and 2×10^{-8} torr water vapour, if the tank pressure be maintained at 1×10^{-7} torr, and such a mixture would result in only about one-fifth of the 4·6% power loss.

Thus both the electric dissociation and gas stripping and hence residual radioactivity should be rather less than the limiting values we have rather

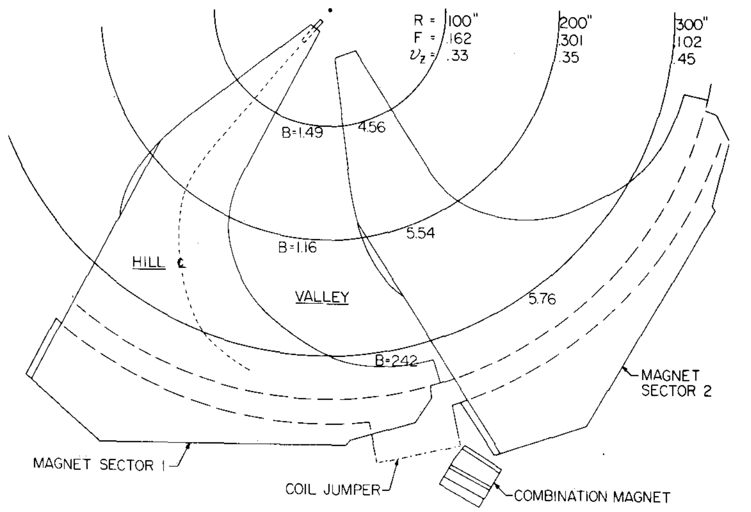
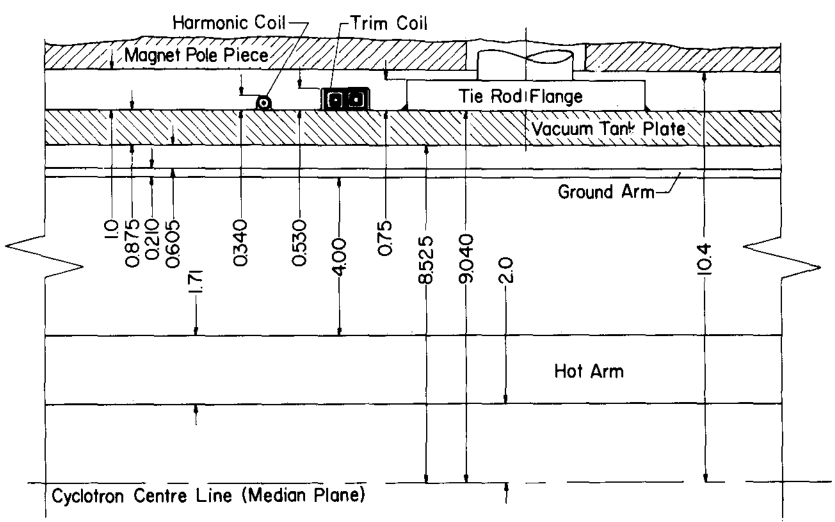


Fig. 1. TRIUMF pole shape and field parameters



Inside Tank:	℄ to Hot Arm:	2.000	
	Hot Arm:	1.710	
	Hot Arm to Cold Arm:	4.000	
	Cold Arm:	0.210	
	Cold Arm to Tank:	0.605	
		8.525 × 2 =	17.050
Tank Plates:			1.750
Gap between Tank and Pole Piece:			2.000
Total Gap between Pole Pieces:			20.800

Fig. 2. Disposition of magnet gap

arbitrarily set for servicing the cyclotron after a prolonged period of running at 100 μA extracted current at 500 MeV.

2. MAGNET DESIGN

The magnet design has proceeded through a number 20/1 scale models excited by two single coils linking all sectors carrying a current up to 3000 A. The field data, measured at $1^\circ \pm 0{\cdot}02^\circ$ intervals azimuthally and 0·125 in ±0·002 in radially to an accuracy of 1/2 G with a temperature stabilised Hall Probe (Siemens FC 33), has been analysed to yield field plots and orbits.[10] Early work with a 24 in gap showed it was not possible to get an economical magnet with adequate flutter in the outer region to achieve vertical focusing with the spiral angle not exceeding 70°. Reduction of the gap to 20·8 in has enabled an isochronous focused beam to be achieved out to the full energy radius of 312 in; the parameters at three typical radii are shown in Fig. 1. It is the huge size which provides the major challenge in the design of this cyclotron.

This gap is taken up by various cyclotron components as shown in Fig. 2. To achieve the precise field pattern 54 trim coil pairs are being provided together with 12 harmonic coil pairs at different radii for each of the six magnet sectors.

The magnet is to be constructed from mostly 3 in thick plates of 1006 killed silicon steel with 10 in thick pole tips. The main energising coils will be made in the form of 12 separate windings of aluminium bar 18 in × ¾ in cross-section linked together by welded joints, making complete top and bottom assemblies. The assembly is shown in Fig. 3; access to the resonators, etc., in the vacuum tank can be achieved by raising the complete top section a height of 42 in.

Adequate space exists next to the valley regions for recombination magnets to enable extracted beams of any energy to be passed down the beam pipes.[11]

It is hoped the final magnet field will be within 2% of that predicted by the 20/1 model. A 10/1 scale model is at present under construction to check the scaling, and also to determine the shimming procedure to be adopted.

3. RF SYSTEM

The radio frequency accelerating system adopted is an unusual one in that the dees are in the form of $\lambda/4$ resonant cavities, as originally proposed by K. R. MacKenzie. To keep down the size, the rf is run at the fifth harmonic of the ion rotation frequency, i.e. at 23MHz so that the quarter wavelength is nearly 10 ft. The structure is shown in Fig. 4.

The ions circulate in the 4 in gap between top and bottom resonators and the dee-to-dee voltage is required to be maintained at 200 kV ±200 V, while the required tolerance along the gap is 1% per metre. Model measurements have shown that the coupling between top and bottom resonators is very tight because of the filling in of the sides by the flux guides, and this also makes the voltage distribution along the edges very uniform. The coupling between the dees is also tight so that a single loop feed from the transmitter, by way of a 5 $\lambda/2$ long resonant line, appears to be all that is necessary. From a series of model tests, made with models up to half scale of one dee, we anticipate a Q of 6000, so requiring 1·2 MW of rf power.

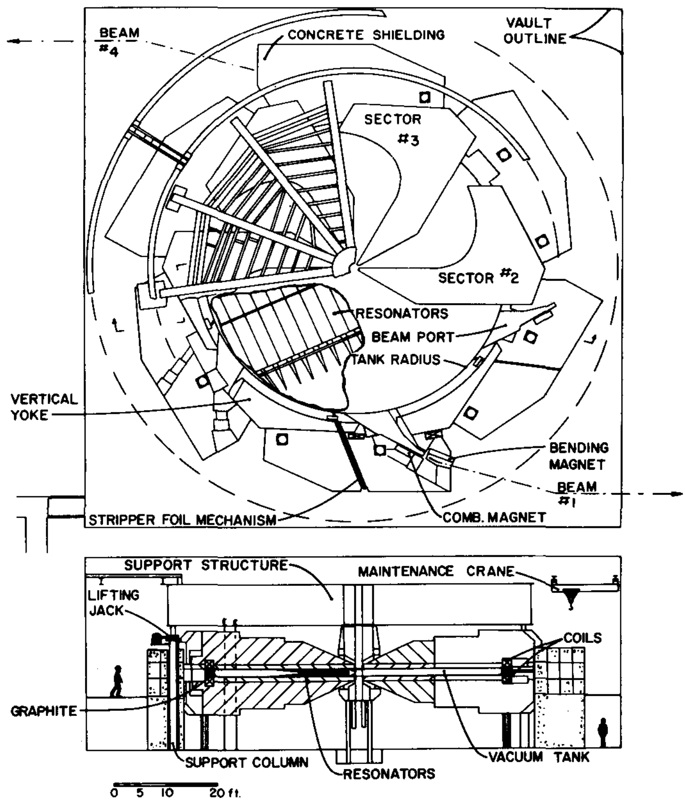


Fig. 3. TRIUMF cyclotron – cross-sections

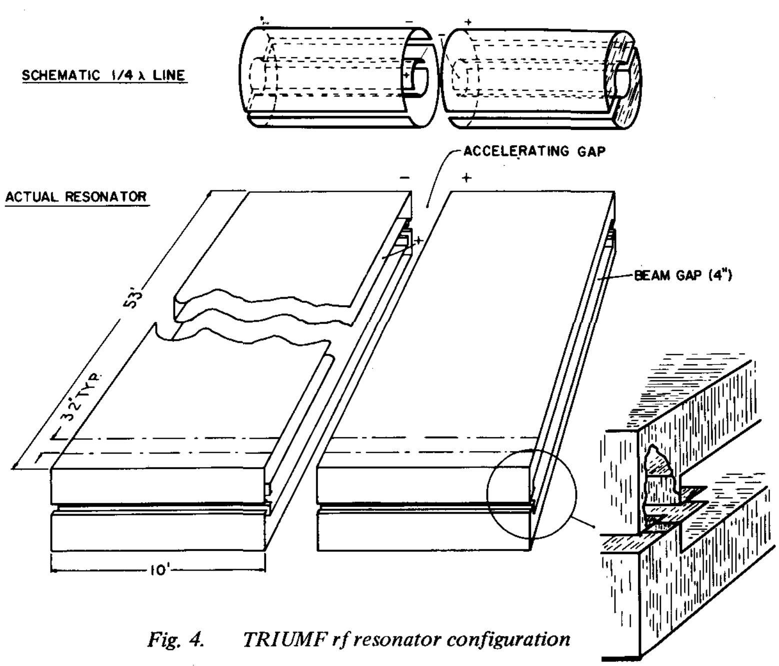


Fig. 4. TRIUMF rf resonator configuration

In view of the problems experienced with insulators in vacuum under the stress of high rf field, a mechanical structure has been sought which will provide the required rigidity with no insulating material. The resonators will be made in 32 in wide sections from a silver-aluminium roll-bond sheet in which water channels are formed. Units will be joined electrically only at the roots and tips. Tuning adjustment will be made by flaps on the ground plane side at the high voltage end[12] and the orientation of the dee structure in the magnet is such that the lines of adjusting devices lie in a valley region, so that only the end and central resonators are somewhat enclosed by the magnet. The ground planes of the resonators are mechanically fixed to the vacuum tank walls, and the hot arms are to have a cantilever adjustment for setting the 4 in gaps between ground plane and hot arms to the required tolerance of 0·1 in.

Model tests[12] have shown that it is relatively easy to introduce a third harmonic via a second loop suitably placed in a resonator. By introducing 16% amplitude of third harmonic the phase acceptance should increase from 60° to 90°. However, this also necessitates the gap tolerance being much tighter (~0·01 in) to achieve separated turn extraction and the high energy resolution then possible.

4. ION SOURCE, INJECTION AND CENTRAL REGION

Several kinds of ion source have been operated successfully with an output of H^- ions; Of the commercially developed sources, the Cyclotron Corporation version of Ehler's hot filament Penning arc source can provide 2 mA of H^- ions within the emittance, $\pi/4\ \Delta x \times \Delta\theta_x$ of 42 mm mrad at an energy of 300 keV, which is quite adequate for TRIUMF beam requirements. Hot filament sources operated at rather high hydrogen pressures are apt to have very limited filament life (~10 h) so that at least two sources have to be installed to ensure serviceability.

Injection energies from 150 to 500 keV have been considered, and a design figure of 300 keV chosen. The central support post can be cleared adequately on the first turn by suitable design at any energy in this range over a ±45° phase range of ions. Higher energy injection was strongly favoured as reducing the spread in orbit centre points which affects the energy resolution of the beam. Likewise, the vertical betatron oscillation situation is improved somewhat by using higher energies. In contrast the spiral electrostatic inflector requires rather higher fields, 100 kV/in for 500 keV ions, and bunching is easier at the lowest energy, though there is about 45 ft height available between the median plane to the ion source plane above the vault shielding. The estimated cost of the source and transport system is only a slowly rising function with energy.

The ion source room is located at the top level of the control and services building where the radiation level will be well below tolerance at all times. The transport system will use electrostatic quadrupoles and one 90° bending magnet to bring the beam vertically down the axis of the cyclotron. The solid centre post is 20 in diam.; the 90° inflector is outside the post, the beam entering off centre,[13] access to the inflector is from the underside of the vacuum tank. It is expected to install a rf sinusoidal buncher from the start; the exact parameters for this have not yet been fixed, but will allow the addition of third harmonic.

Focusing in the first few turns is dominated by the electric fields. The electric focusing in the first turn may be reduced by suitable pillars as shown in Fig. 5. In addition, as described in the paper given by E. G. Auld *et al*,[10] 'Design of the

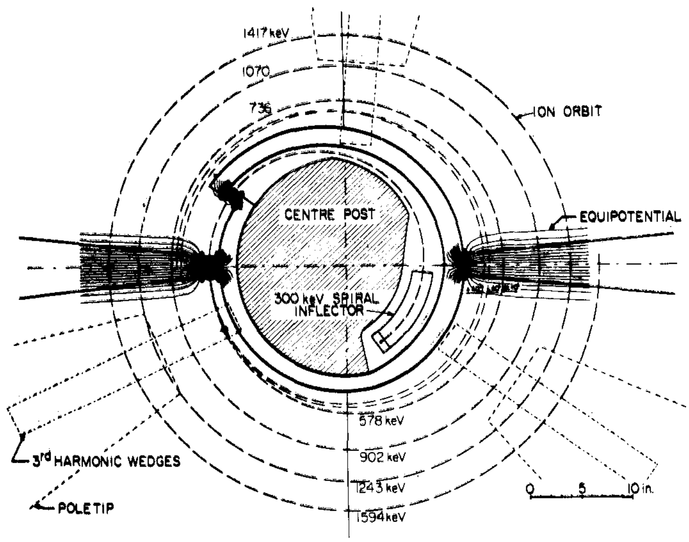


Fig. 5. Centre region configuration and orbits

4000 Ton Magnet for the TRIUMF Cyclotron', the magnetic focusing is maintained by the tapering of the magnetic poles from six- to threefold symmetry by using three wedges so that $\nu_z \sim 0{\cdot}2$. Quite extensive calculations are in progress and these show that a 60° wide phase band can be accepted.[13] However, in view of the great importance of the central region for achieving good beam quality, a full size central region model is being constructed–probably the largest lowest energy cyclotron ever–60 in diam. 2·5 MeV! It will enable the rf performance at full voltage on the central two resonator sections to be tested, and provide a full scale test of the beam optics and ion source automatic control and transport system. While this full size model is relatively costly, we hope to shorten the schedule of the project significantly by these early tests on key components and beam optics of the central region.

5. EXTRACTION

The recombination magnet and beam optics associated with the extraction system are discussed in the paper by L. P. Robertson.[11] The stripper foil itself will probably be of deposited carbon and can be relatively thick, >4 mg/cm,^{2} the maximum thickness being set by the multiple scattering which can be tolerated.

The two stripped electrons mostly go round back into the foil because of the magnetic field, so there is quite a significant heating of the foil. However, estimates of the power which may be radiated from such a foil, before the temperature is so high that evaporation of the foil becomes appreciable, amount to 250 W. This then is more than adequate remembering that each of the electrons carry away only 250 keV energy. There is also the problem of mechanical dislocation in the foil by proton bombardment; we hope to irradiate some specimens with several hundred MeV energy protons and examine them. The life of the stripper foil may well prove to be one of the limiting factors on the maximum current which can be achieved with this cyclotron.

VACUUM SYSTEM

The huge size of the vacuum pill-box (56 ft diam. $\times$ 20·8 in high) introduces mechanical problems both from the crushing force of 2700 tons and from the expansion which it undergoes when its temperature changes, the latter making the design of the vacuum seal a difficult problem.

The box itself is to be fabricated on site as a flat lid and tank of stainless steel. Sky and ground hooks together with a central pillar of high strength stainless steel hold the shape. There is the additional requirement of the relatively thin cylindrical wall to reduce residual radioactivity and to which the beam horns must be suitably welded. Many designs of seal have been examined and at present a simple polyurethane or viton O-ring is the choice, but such materials have limited life in the radiation field, estimated as about six months. Such a ring is ideal for the initial operation but a longer life solution still eludes us.

The pumping speeds[14] required to evacuate the chamber in a reasonably short time to below 1×10^{-7} torr depend on the magnitude and percentage composition of the gas load from the chamber, resonators, seal and mechanisms inside the chamber. Using a one-twentieth scaled model of the chamber and contents, which have undergone appropriate and realistic surface treatments, chamber pump-down performance is being simulated and the magnitude of the component gas loads are being obtained. It is intended to achieve 7×10^{-8} torr pressure in 15 h by means of a cryogenic pumping system using a helium cooled pipe at 20°K mounted inside a shield at liquid nitrogen temperature. The 20°K heat load depends greatly on the losses in such items as bayonet connectors and cryogenic taps, current designs of which seem to have large loss, and it may be that a simple welded up line may be much more efficient. Pessimistic estimates give a load of 100 W which would probably necessitate a turbine refrigerator, the long-term reliability of which is rather unknown. If the load can be reduced substantially Stirling engine refrigerators could be employed. The temperature of 20°K has been chosen because it is five times more economical than cryopumping at 4°K and also avoids build up of solid hydrogen on the cryo-array. De-icing of the 80°K shields of water vapour condensate will be required only once every two weeks. The hydrogen load will be taken by eight 10 in diffusion pumps, and likewise conventional pumping will be used on the ion transport line. For rapid evacuation of the tank, two parallel roughing lines using 500 cfm Rootes pumps are presently favoured for evacuation of the chamber from atmospheric pressure to 20 microns.

While heating coils are being provided on the tank through which steam at 140°C may be circulated for outgassing, it is hoped that by careful surface procedures in manufacture, the outgassing will be such that the cryogenic pumping will be adequate without such heating. The rf resonators can, of course, be heated *in situ* for outgassing.

6. THE FACILITY

(a) General plan

In order to achieve high cyclotron utilisation right from the start, it is planned to install two proton beam lines. One line will feed a meson area and terminate in a combined slow neutron facility, activation facility, and beam dump; the second line, restricted to 10 μA, will feed a Proton Area and end in a beam dump with a radiation chemistry rabbit facility.

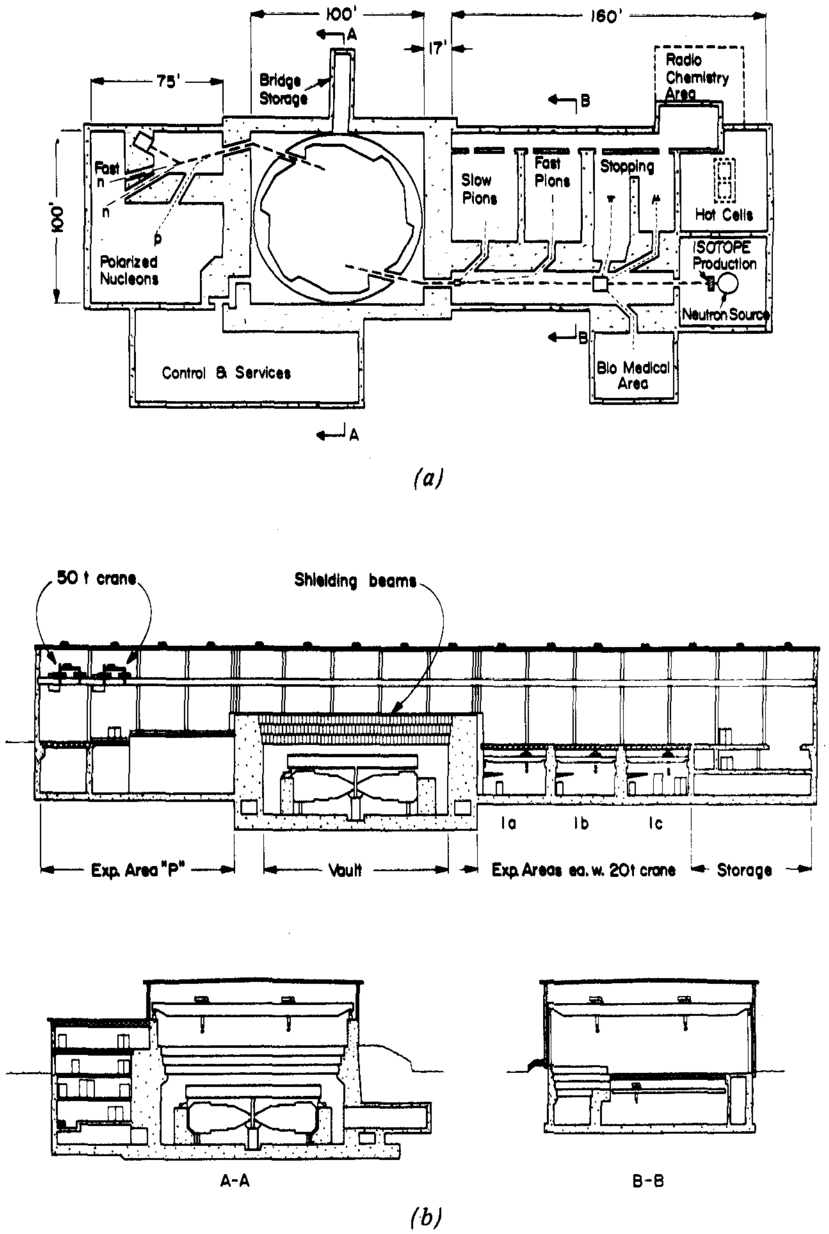


Fig. 6. (a) Plan of TRIUMF facility; (b) elevations of TRIUMF facility

Fig. 6 shows the plan currently envisaged for start-up, but since practically all the shielding is 'flexible', i.e. blocks of concrete or iron, it will be possible to change the layout of secondary beam lines and associated experimental areas without much trouble. The experimental floor is set 20 ft below grade, so as to use as much earth shielding as possible, and the beam height is set 4 ft 6 in above this. The set-up area for local control rooms is at grade level above the experimental floor instead of to one side as is more usual. Two 50-ton cranes each with two 25-ton hooks, which can be synchronised to lift 100 tons, will cover the whole area, and in addition each experimental region may have as part of its experimental equipment a small crane for local work eliminating the need for removing roof members for most purposes.

All the experimental floor area is needed for the cyclotron assembly.

(b) The cyclotron vault

The cyclotron will rest on its own concrete pad in a skeletal concrete box, the majority of the concrete being removed from the beam plane regions. The 17 ft of concrete shielding on the two sides through which the beams emerge will be on a separate pad. The shielding thickness is dictated by the fast neutron attenuation, the half thickness in concrete at energies of several hundred MeV being 18 in. The primary protons spilled from the cyclotron will be stopped in a 50 cm graphite ring and the cascade products further attenuated by the iron yokes or heavy concrete shields placed in the valley regions. Provision has been made for roof shielding of up to 21 ft as well as for local shields above the cyclotron valleys in the stripping region.

The top tie rods of the vacuum box lid are restrained by a steel support structure which rests on the centre post and on support columns outside the magnet yokes (Fig. 3). The whole of this, together with the upper poles of the magnet, may be lifted up 3 ft 6 in by a set of jacks for access to the components in the vacuum box, for servicing of the vacuum seal, etc. The ultimate residual activity levels should not preclude a student or cyclotron engineer working from a platform supported in this region for an hour! The bottom tie rods are set into the concrete pad below the cyclotron; these are, of course, provided with adjustments which reflect directly into the mechanical setting of the resonators, so this concrete pad is being designed to be rigid and stable. The complete box and support arrangements for the magnet have been designed to withstand a moderate earthquake.

Procedures for the rapid extraction and handling of large, highly radioactive items, such as resonator sections and flux guide end plates, have been examined; after insertion in lead flasks such components will be transferred to hot cells or storage cells by use of the main crane.

(c) Meson area

As shown in Fig. 6 the full beam will be delivered down a tunnel first to a 'thin' (4 g/cm) target probably of circulating water which will feed two π meson channels both designed for a momentum resolution of 10^{-3} (i.e. ±100 keV in energy) but optimised for 200 MeV and 50 MeV mesons respectively. The second thick (20 g/cm^2) target, probably of dense graphite, will be the source of stopping π mesons, of 30-100 MeV π minus mesons in a relatively pure beam of large aperture and flux for a radiobiological and medical therapy area, and of π mesons to feed a muon channel. Both the stopping π and μ meson channels will be optimised to give the maximum flux in a small sample of isotopically pure material. While it is anticipated that when any area is receiving its maximum flux of secondary particles that area will be closed off, it is intended that the local shielding and shielding between areas will be continuous and complete so that experimenters may set up equipment in a neighbouring experimental area.

The degraded beam is then passed into a beam stop target of lead-bismuth eutectic cooled by light water, surrounded with heavy water and graphite moderator to provide a useful source of slow neutrons. Suitable holes for four sets of diffraction apparatus in the shielding around this target are being provided and provision is being made for a neutron guide pipe. There will also be rabbits and thimbles for neutron activation. A particularly important function in this area will be the preparation of proton rich isotopes of high specific activity by spallation reactions using the primary beam. Two hot cells and a radiochemistry wing are integrated into this end of the building.

(d) Proton area

In this region the configuration is again flexible and easily changed. Owing to the great cost and size of shielding, at the outset an area of 40 ft × 24 ft will be shielded, for experiments in nuclear structure physics and π production measurements for example. In addition provision will be made for secondary beams of polarised protons and neutrons and of unpolarised fast neutrons, to emerge into the experimental area outside this heavily shielded section.

7. DEVELOPMENT OF THE CYCLOTRON AND FACILITIES

Provision has been made in the design for the extraction of six external beams, but as maximum beam can only be provided to a single beam line at one time, the use of more of the pions from the single thick target may well be an early development. The cyclotron also seems capable[15] of providing a very highly resolved beam ±25 keV in 500 MeV, of lower intensity, and this is of great interest for intermediate energy nuclear structure physics. The tolerances which must be achieved in magnetic and rf fields for such energy resolution are not beyond the state of the art now.[13]

Again the current which might be achieved by bunching, flat topping the rf, reducing the pressure to 10^{-8} torr, without exceeding the limitation imposed by residual activation, and assuming a suitable stripper can be developed, is of the order of 330 μA at 500 MeV or 900 μA at 450 MeV. These exciting figures are something for TRIUMF to aim for in the nineteen seventies!

REFERENCES

1. TRIUMF proposal and cost estimate.
2. Vogt, E. W., and Richardson, J. Reginald, 'An H^- Meson Facility', *I.E.E.E. Trans. on Nuclear Science* **NS-13**, **4**, 262, (1966).
3. Hiskes, J. R., private communication.
4. Judd, D. L., *Nucl. Instr. & Methods* **18**, 70, (1962).
5. Wright, B. T., *Arch. Math. Naturvidenskab* **54**, 2, 9, (1957).
6. McDowell, M. R., and Peach, G., *Proc. Phys. Soc.* **74**, 463, (1959).
7. Dmitriev, I. S., and Nikolaev, V. S., *Sov. Phys. JETP* **17**, 447, (1963).
8. Bates, D. R., and Walker, J. C. G., *Proc. Phys. Soc.* **90**, 333, (1967).
9. Thorson, I. M., 'Shielding and Activation in a 500 MeV H^- Cyclotron Facility', TRI–68–4.
10. Auld, E. G., Orras, S., Otter, A. J., Mackenzie, G. H., Richardson, J. R., and Burgerjon, J. J., Design of the 4000 Ton Magnet for the TRIUMF Cyclotron, Proceedings of this Conference (1969), p. 111.
11. Robertson, L. P., Auld, E. G., Mackenzie, G. H., and Otter, A., Extraction of Multiple Beams of Various Energies from the TRIUMF Negative Ion Isochronous Cyclotron, Proceedings of this Conference (1969), p. 245.
12. Erdman, K. L., Prochazka, A., Fredriksson, O. K., Thomas, R., and Grundmann, W., A 'Square Wave' RF System Design for the TRIUMF Cyclotron, Proceedings of this Conference (1969), p. 105.
13. Craddock, M. K., Louis, R. J., and Reiser, M., H^- Ion Injection into the Central Region of the TRIUMF Cyclotron, Proceedings of this Conference (1969), p. 666.
14. Harwood, V. J., *et al,* TRI–69–9.

15.(a) Richardson, J. R., TRI–69–6.

(b) Richardson, J. R., and Craddock, M. K., Beam Quality and Expected Resolution from the TRIUMF Cyclotron, Proceedings of this Conference (1969), p. 85.