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DEVELOPMENTS AT TRIUMF

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Introduction

The first beam at TRIUMF was accelerated successfully to full energy just before Christmas of 1974. Dr. J.R. Richardson, who was the Director of the facility at that time reported on this initial operation at the International Cyclotron Conference in Zurich in 1974 [1]. The maximum energy of the beam, which is 525 MeV of protons was achieved at that particular time. This energy has not been increased in the machine; no magnet shimming has been carried on after the initial operation. Since that time the machine has been operated at a slowly increasing level of current into two different experimental areas. The energies of the beam are independently variable and the intensity ratios of the two beams are also independently variable up to a ratio of 1 in 10^4. Further progress was reported at Dubna in 1976 [2].

Operation

During the last year the machine has been operated in a program in which two thirds of the time has been directed to beam production and one third to machine study and technical improvements and modifications. Each year there have been two six week periods during which the machine has been shut down for modifications. Modifications to the experimental areas are done during the shutdown period.

Operating beam currents have been slowly increased from the initial 10 nA to 20 μA during the last three years, with short periods of high current operation. In July of 1977 the first beam of over 100 μA was extracted and since that time the stability and quality of the high current beam has been steadily improved as will be reported on by G. Dutto in another paper at this Conference. The operating current levels are shown in the first figure (Fig. 1) and the dates at which the maximum beam currents of 100 μA and 120 μA were achieved are also indicated in the same figure. The 100 μA beam necessitated the development of a high intensity beam stop [3]. It was decided to make this a versatile beam stop so that as well as just being a dump for the spent beam it also was designed in such a way as to become a source of both thermal and high energy neutrons.

The polarized ion source of the Lamb-shift type, which was put into operation shortly after the delivery of the first beam from the machine, has also been steadily improved. A dc beam of 1 μA of 70-80% polarized negative hydrogen ions is now regularly delivered at the exit of the ion source and a beam of 200 nA has been delivered to the experimental areas at full energy from the machine. The latter development has made possible a variable energy neutron beam which is created by charge exchange of the primary protons in a liquid deuterium target.

The transmission through the cyclotron has been steadily improved until with the buncher in operation a transmission of over 30% of the beam from the ion source through the cyclotron at a beam current of 20 μA has been achieved.

Beam Performance

A study has been made of the possible improvements to energy stability and to single turn extraction. The use of slits at the centre of the machine has allowed an impressive scan of the beam current as a function of the beam radius to be made. Separate turns are identified out to 200 MeV and then turn structure to full energy. The quality of the beam under these conditions is also discussed by G. Dutto in a paper at this Conference.

The next figure (Fig. 2) shows a chart recording of the 100 µA beam as delivered to the thermal neutron facility. The recording includes a short break during which a celebration was held to recognize the achievement of the beam current for which the machine was designed. The machine is usually tuned up in a pulsed mode so that the beamlines and the injection optics can be tuned under the space charge conditions which exist during high current operation. The tuning is achieved by pulsing the ion source at a 1 kHz rate, the duty factor being varied from 1% to 99% under these conditions. The machine is tuned at an average current of 10 µA, which represents a 10% duty factor. The beam can be very rapidly increased to full intensity simply by changing the duty factor in the ion source as can be seen in the figure. Under normal operating conditions a 10 µS hole is present in the beam every millisecond.

Non-intercepting beam monitors have been installed both in the injection line of the ion source and in the extracted beamline of the cyclotron. The beam monitors in the injection line are of the magnetic toroid type. The monitor in the high energy extracted beamline is of a capacitive pickup type. It is possible to measure the total flight time of the beam from the ion source through the cyclotron into the injection line and to minimize this flight time by using the trimming coils of the cyclotron. One is also able to use this time in a feedback circuit to stabilize the machine operation. Under this stabilized condition, very high ratios of extracted beam from one extraction channel to another extraction channel have been achieved. In the figure (Fig. 3) it is possible to see how the stability of the machine has been increased by the application of this feedback [4]. The magnetic field variations in the cyclotron can be measured by integrating the voltage induced in trim coil 54. This is a trim coil which goes around the entire magnetic field of the cyclotron and is normally used in a slow feedback circuit to stabilize the magnetic field to better than two parts in 10^6. This corresponds to a beam phase variation at 500 MeV of $\pm 5^{\circ}$. By feeding back the time signal one is able to modulate the frequency of the rf system to compensate for the changes in the magnetic field. In the diagram the magnetic field was purposely changed by 15 parts per million. This is the large bump on the trim coil reading. One can see how the feedback has smoothed out the variations and indeed the smoothing is sufficient to allow for single turn extraction from the machine. This also allows for a very stable split ratio between the two extracted beams from the cyclotron and the figure (Fig. 4) indicates how this ratio can be changed in a controlled way between the two beamlines up to a ratio of one part in 10^4.

Facility Layout

The facility presently consists of two experimental areas, one dedicated primarily to nucleon-nucleon interaction and nuclear physics and the second to pion and muon reaction studies. The layout of the experimental halls and the extracted beamlines is illustrated in the figure (Fig. 5). During the summer of 1978 two additional extraction ports were installed on the machine at the side of extraction port II. The primary purpose of these ports is to provide beams for isotope production.

A bending magnet in beamline 1 allows for a second nucleon-nucleon interaction area in the meson hall and the extraction of two simultaneous, independently variable energy, polarized proton beams. A second target station has been constructed into beamline 1 for two additional secondary meson channels which are presently under construction. One of these channels is a backward going slow pion muon channel with an acceptance of 30 millisteradians and it should be completed by the end of 1978.

The beam stops at the end of beamline 4 are both carbon blocks in iron shields buried outside the building 12 meters below ground level. They are capable of stopping 10 µA in beamline 4A and

100 nA in beamline 4B. The roof of the area in which the MRS spectrometer is located is being totally shielded with 3.3 meters of concrete to allow the full freedom of movement for the spectrometer.

The beam stop at the end of beamline 1, which is labelled thermal neutron facility in the figure, is capable of handling beam currents of up to 150 μA. It has been provided with a D_2O moderator and four neutron channels to provide thermal neutron beams into the experimental area.

An internal beam dump has been added at the end of beamline 1B which is capable of handling 10 nA of beam. Thus two polarized beams will now be able to be extracted from the cyclotron simultaneously for nucleon-nucleon experiments.

The proton spectrometer in the nucleon-nucleon area has also been developed during the course of the last two years. With the stabilization of the beam in the machine an extracted beam having an energy spread of less than 600 keV at 500 MeV has been achieved and has been measured with the spectrometer. The figure (Fig. 6) shows the energy distribution of the scattered particles from a composite target as viewed by the spectrometer. The shielding of the roof of this MRS area with concrete will allow the full utilization of the spectrograph in experiments beginning in January 1979.

Thermal Neutron Facility

Since the stopping of the beam at the end of beamline 1 at high currents leads to usable neutron fluxes, it was decided to design a beam stop that would allow the stopping of up to 400 μA beams and optimize the neutron fluxes obtainable [3]. The thermal neutron facility is shown in the next figure (Fig. 7). The primary beam stop consists of a thin walled stainless steel flask filled with lead. This flask is connected to a vacuum system through pipes passing through an 8 meter water tank in which the flask is immersed. The lower half of the flask is in a separate compartment filled with D_2O to optimize the thermal neutron flux. Various ports for rabbit systems, slow neutron channels and fast neutron channels penetrate the 2 meter primary steel shield surrounding the double walled water tank. The performance of the lead beam stop during "beam on" periods has been measured up to beam currents of 125 μA. The lead in the flask becomes molten to its upper surface at beam currents of 20 μA. Cooling is achieved by convection in the lead and by conduction through the steel container near the upper surface of the lead where it is molten. As the current is increased to 100 μA the temperature in the centre of the lead where the beam is being stopped increases to 500 ^{o}C. At this current the bands of melted convecting lead contacting the stainless steel flask are 2 cm wide. This could be seen in tests simulating the action of the beam in the lead. The tests were carried on with electric heaters in the lead flask. The width of the molten lead contact area is a function of the beam current that is delivered to the stop.

After several runs of 100 μA the lead flask was removed from the water vessel and inspected for distortions or indications of thermally induced stress. No distortions of any kind were seen. It appears that the system will work as designed, as a high current beam stop. Neutron fluxes have been measured by foil irradiation techniques at the facility and neutron flux distribution for this geometry are now known.

Low Energy Extraction Ports

During the course of the last year it was decided to put two new ports on the cyclotron for low energy extracted beams. The positions of these ports on beamline 2 can be seen in the figure (Fig. 8). Extraction foils were positioned in the machine at the calculated radii and azimuth to extract beams through one of the new extraction ports. Profile monitors with 3 mm wire spacing were placed at the extraction port to measure the beams produced in this way. Beams having dimensions of approximately 1.5 cm at the extraction port were successfully extracted at 70 and

90 MeV by these foils. This successful extraction has now made TRIUMF the only cyclotron that has simultaneously extracted three beams of different energy and intensity. The TRIUMF cyclotron now has the capability of an energy variability of the extracted beam from 70 MeV to 525 MeV in a continuous fashion. External beamlines at this port to handle these beams will be installed in the next year.

Kaon Factories

The world's three meson factories are clearly in an unrivalled position to act as injectors to a future generation of high-current accelerators in the GeV range. These would perform the same functions for kaons and possibly antiprotons that the meson factories are doing so successfully for pions and muons. Preliminary studies have therefore been made of accelerator designs which would boost a beam from the TRIUMF cyclotron to several GeV. At the same time, TRIUMF would continue to deliver protons to the proton and meson halls, and in particular the biomedical facility would not be appreciably affected.

Both synchrotrons and cyclotrons have been considered for boosting the TRIUMF beam to higher energies. In the former case a fast-cycling synchrotron is proposed [5] to accelerate a 40 μA proton beam to 8 GeV for kaon production; this could eventually be followed by a 40 GeV second stage for the production of intense beams of antiprotons. The synchrotron design would be fairly conventional, except perhaps for the 20 Hz rapid-cycling; 60 Hz flat-topping would assist storage-ring action during the initial part of each cycle and improve the duty cycle during extraction. The major design challenges arise in matching the CW beam from TRIUMF to an essentially pulsed machine. Three extraction schemes from TRIUMF have been considered:

1. Resonant extraction of H^- at $\nu_r = 3/2$ (430 MeV); this would circumvent Liouvillean restrictions on filling the synchrotron phase space.
2. Conventional proton extraction by stripping foil (giving minimal interference with cyclotron operation).
3. Pulsed extraction of 100 turn 'stacks'; the longer time intervals between pulses would simplify the problem of directing them into different regions of synchrotron phase space.

The second proposal [6] is for a two stage isochronous ring cyclotron to accelerate a 100 μA proton beam to 8.5 GeV. 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. Superconducting magnets would be used, the weight of steel being estimated to be 2000 m tons for the first stage and 1800 m tons for the second. 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 help keep it hard and increase the flutter. Several integer and half-integer radial resonances would have to be crossed, but with a high energy gain per turn (3 MeV and 8 MeV respectively) this should cause no difficulty; certain resonances would in fact be used to assist in extraction. The accelerating system consists of SIN-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 to be used on successive stages. The ring configurations are shown in Figure 9.

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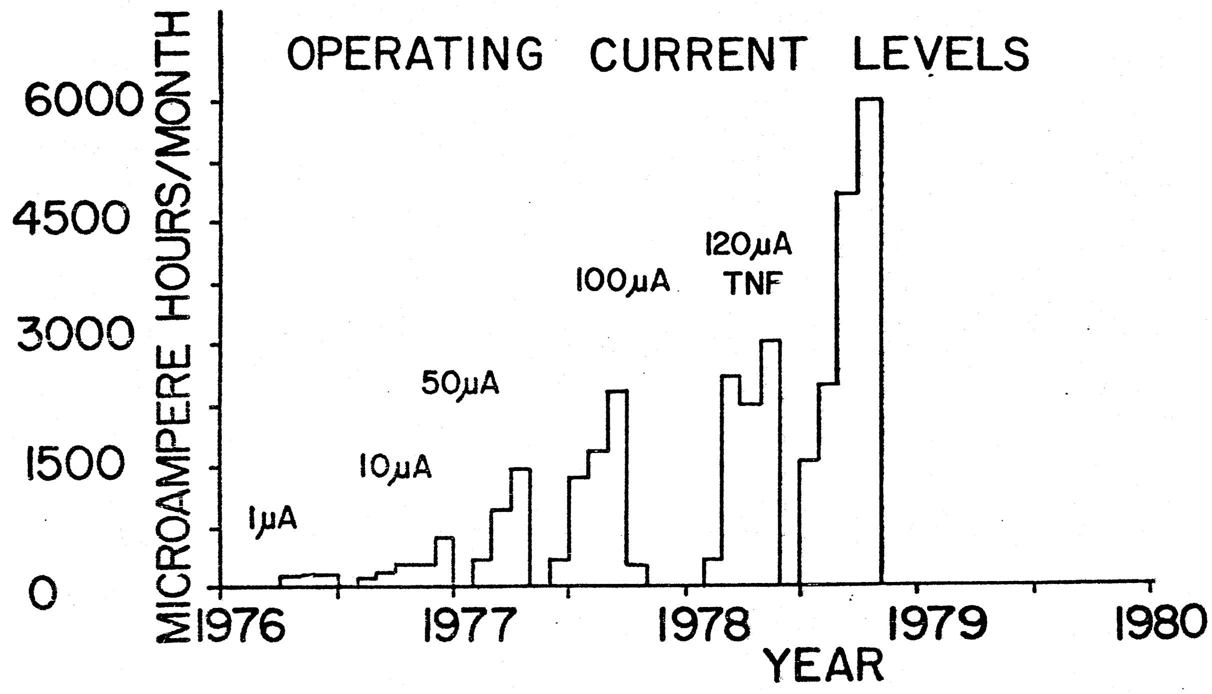

Fig. 1. Operating current levels at the TRIUMF cyclotron.

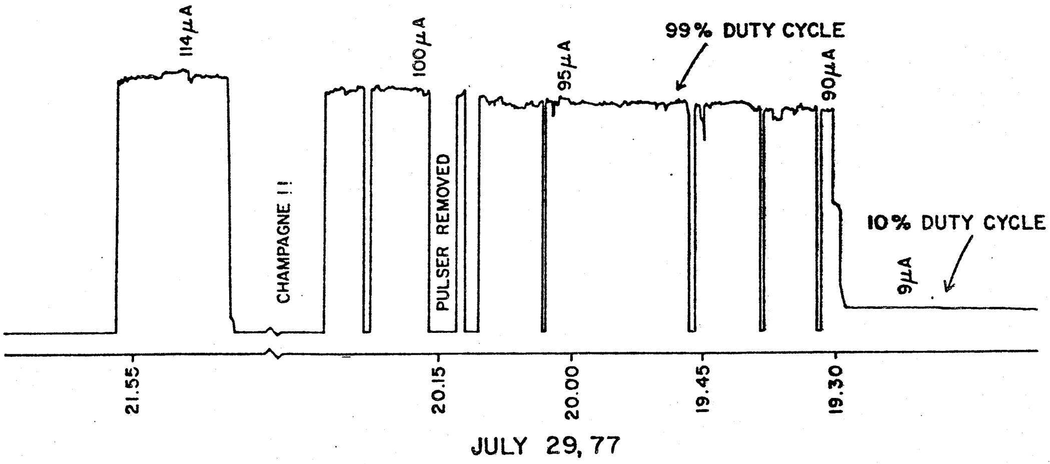

Fig. 2. Extraction of 100 μA from the cyclotron.

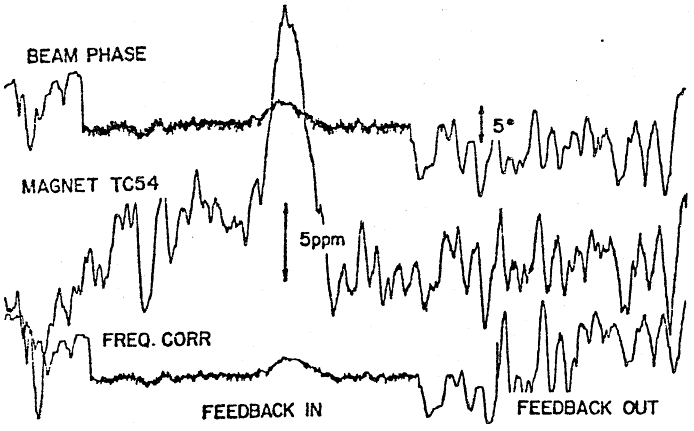

Fig. 3. Improvement of beam stability by the addition of time of flight feedback.

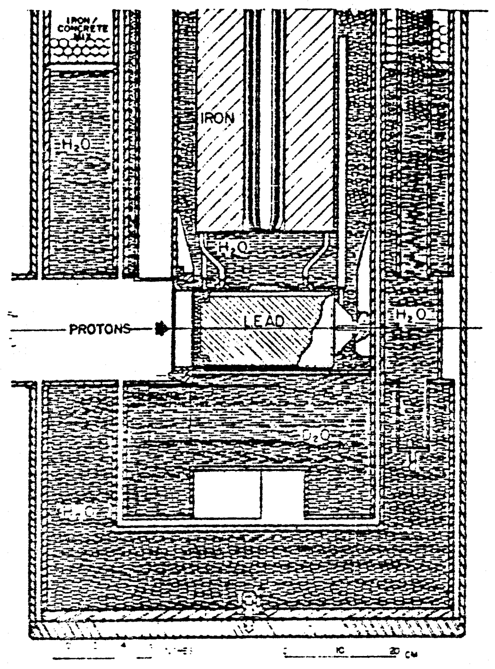

Fig. 7. Beam stop in the Thermal Neutron Facility.

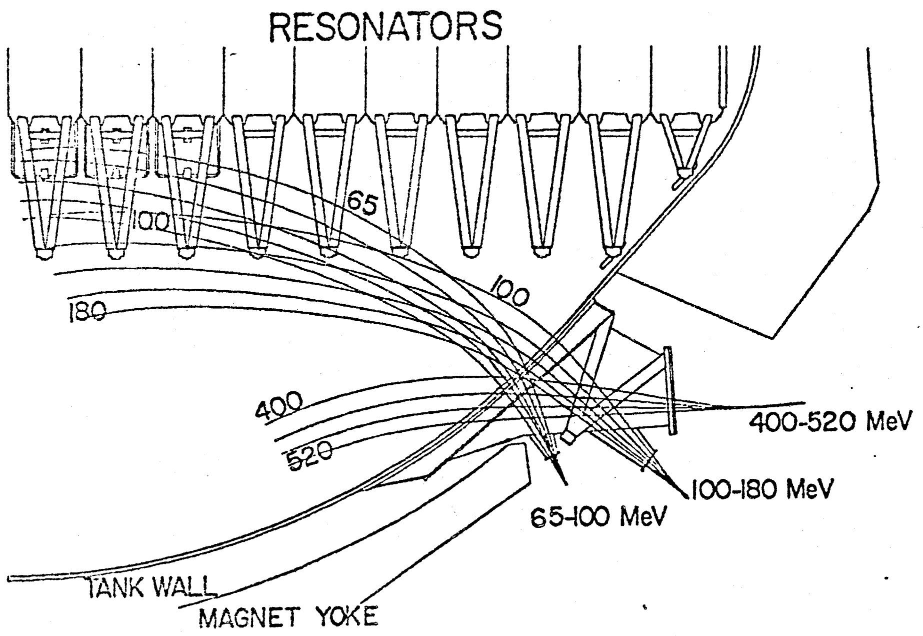

Fig. 8. Low energy extraction ports and beam trajectories.

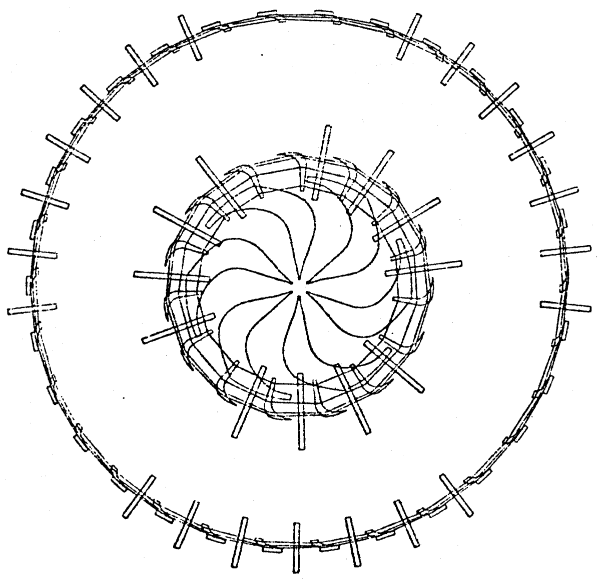

Fig. 9. 3 GeV and 8 GeV (20.7 m radius) ring cyclotron with superconducting magnets and SIN-style RF cavities. (TRIUMF magnet poles drawn to the same scale.)

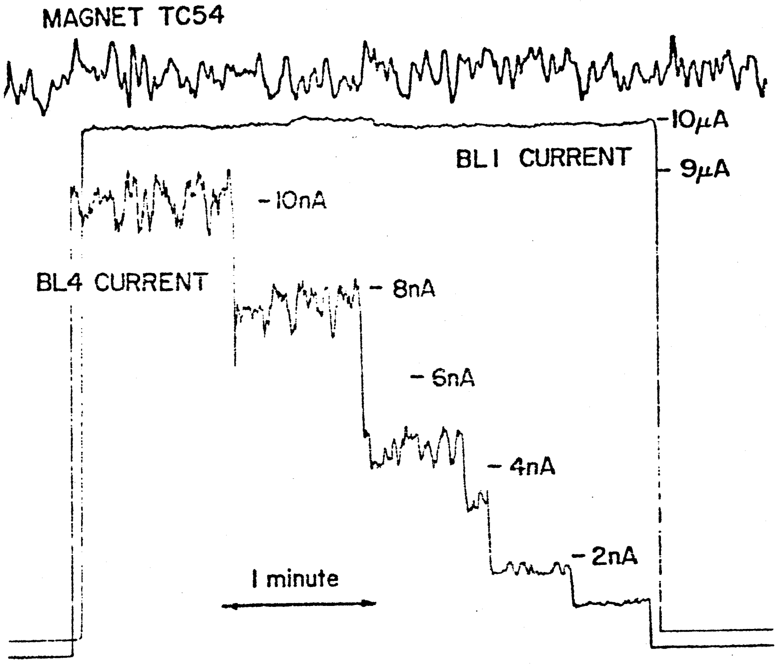

Fig. 4. Variation of the beam split ratio in the region 1:10^4.

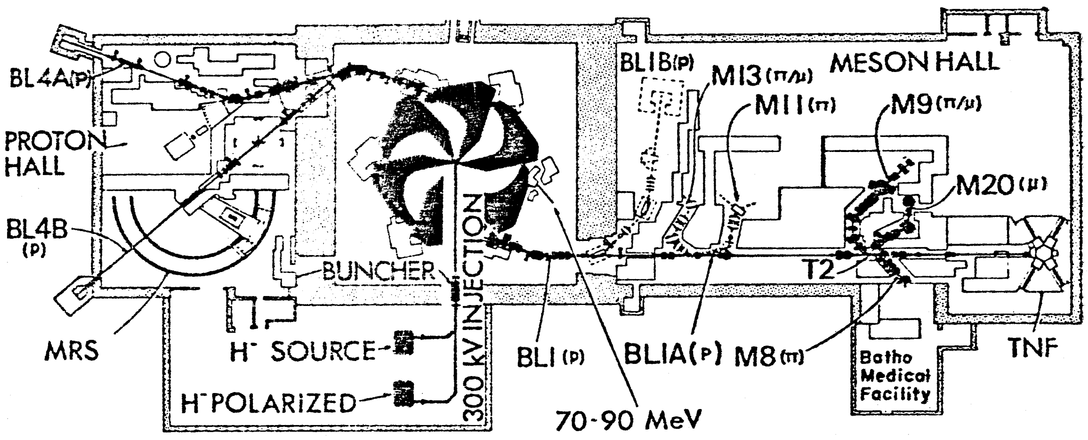

Fig. 5. TRIUMF facility overall layout

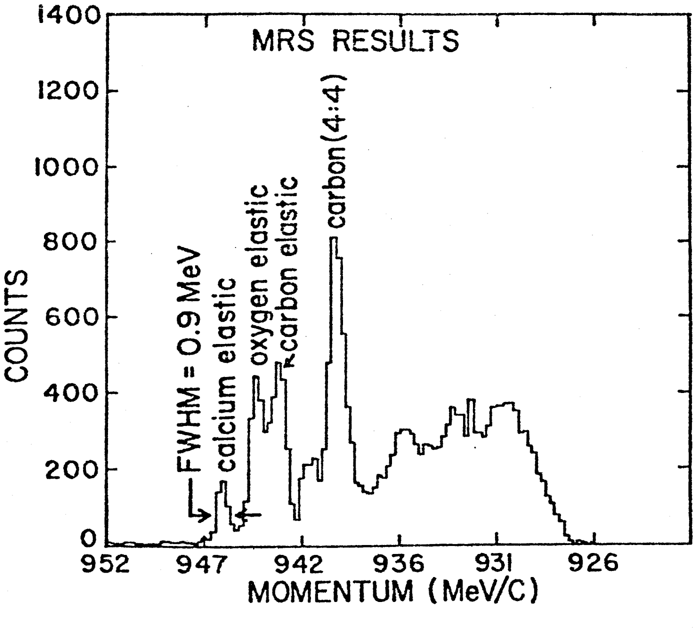

Fig. 6. Energy spectrum of scattered 500 MeV protons in the MRS.