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RECENT DEVELOPMENTS AT THE TRIUMF MESON FACTORY

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Abstract

The TRIUMF meson factory, which is based on a 6-sector isochronous cyclotron accelerating H^- ions to 520 MeV, has been operating since December 1974. Two proton beams are extracted simultaneously to feed the two experimental areas. The energies of the two beams may be varied independently between 183 and 520 MeV, while the ratio of their intensities may be adjusted from unity to 1/5000. The intensity of the unpolarized beam is at present normally 1 μA, although operation at 10 μA has recently begun for one 12-hour shift each week; the intensity of the ±78% polarized beam from the 'Lamb shift' ion source is 30 nA (extracted). The external beams have an energy-resolution of 1.5 MeV and emittances of ∿3π mm-mrad; the microscopic and macroscopic duty factors are 11% (5/43 nsec) and 100%, respectively. The secondary beam lines operational include a muon channel and two pion lines, one of slow and stopping pions, the other of negative pions for biomedical applications; monokinetic fast neutrons are also available from a liquid deuterium target. It is planned to increase the extracted beam current in stages to 100 μA by the end of 1977. Work is also proceeding on (i) additional beam lines, (ii) a 180 kW beam dump and thermal neutron source, (iii) a medium resolution proton spectrometer, and (iv) adding third harmonic flat-topping to the RF to permit separation of the internal orbits and reduction of the energy spread of the extracted beam to 0.1 MeV.

Introduction

The TRIUMF meson factory is a joint project of four universities in Western Canada—the University of Alberta, the University of British Columbia, Simon Fraser University and the University of Victoria. The land, buildings and some administrative services have been provided by the universities; the accelerator and experimental equipment were funded by the Atomic Energy Control Board of Canada from 1968 to March 1976, when responsibility was transferred to the National Research Council of Canada. At Moscow in 1972 J.R. Richardson [1] described progress in construction of the project, which is based on his proposal [2] for a meson factory centred on a sector-focused cyclotron accelerating H^- ions. The chief advantages of this design for nuclear and particle physics experiments at intermediate energies are

(i) the energy is continuously variable from 183 to 520 MeV;
(ii) two or more beams may be extracted simultaneously at independently variable energies and intensities; and
(iii) the macroscopic duty factor of the beams is 100%.

Of course, any isochronous cyclotron provides 100% duty factor. It is the acceleration of H^- ions which is crucial to obtaining multiple beams and variable energy. Extraction—that notorious problem for circular accelerators—is made trivial by inserting a carbon or aluminum foil to strip the electrons from the ion.[3] In TRIUMF's case two foils are used, 180° apart in azimuth, to provide two external beams, and each may be adjusted in position to provide beams of continuously variable energy.

A price has to be paid for these advantages. The binding energy of the H^- ion is only 0.75 eV and an electron may easily be detached in a strong electric field or in collisions with residual gas molecules. Unfortunately, high motional electric fields $\gamma \underline{v} \times \underline{B}$ are experienced by relativistic ions of velocity $\underline{v}$ travelling in a magnetic field $\underline{B}$. To keep the beam loss to 7% in TRIUMF the magnetic field must not exceed 5.8 kG on the 'hills', so that the magnet diameter must be about 4 times larger than would be required for a proton cyclotron, the mean orbit radius at 500 MeV being 7.8 m. In spite of this record radius, the 6 separated-sector design results in the magnet weight (4000 t) being no greater than that of the Berkeley 184-inch synchrocyclotron. Indeed the weight has been no obstacle to creating a successful elevating system which raises the entire upper half of the cyclotron by 1.20 m for access to the vacuum tank.

To avoid beam loss by gas stripping a very good vacuum must be maintained—10^{-7} Torr air in TRIUMF to keep the loss to 11%. To achieve this the vacuum tank (17 m diam × 0.5 m high) is pumped by helium-cooled cryopanels at 20°K, backed up by four 25-cm oil diffusion pumps for hydrogen.

The accelerating system consists of two rows of quarter-wavelength cavities mounted 'mouth to mouth' above and below the beam plane. These operate at 23.055 MHz—the 5th harmonic of the ion frequency—with about 85 kV at the tips, giving a 170 keV impulse to the ions twice per revolution.

The H^- ions are injected axially at 300 keV by means of a 50 kV electrostatic deflector with spiralled electrodes. For each of maintenance the ion sources themselves are located away from the cyclotron, the ion beam being steered and focused along the 35 m injection line by a periodic system of electrostatic quadrupoles and deflectors. The unpolarized ion source is of the Ehlers type, giving 1 mA H^- ions at 12 keV within 60π mm-mrad.

Initial Operation

H^- ions were first accelerated to 500 MeV at 13:07 on 15 December 1974; the first proton beam was extracted an hour later. Early in 1975 the two external proton beams (Fig. 1) were commissioned and by April nuclear physics experiments were under way simultaneously on the two beam lines (BL1, BL4) on a 16 h/day, 7 d/week basis. By the summer of 1975 the primary beam intensity had been raised to 300 nA, the machine was being operated 24 h/day, 5 d/week, and the three secondary beam lines (M8, M9, M20) had been commissioned, allowing pion and muon experiments to begin.

Up to the autumn of 1975 machine reliability had been reasonably good; in July and August the cyclotron was fully operational for over 70% of the scheduled time. During the winter, however, the cyclotron was plagued by a number of problems with the RF system. First a series of water leaks developed in the resonator sections near the centre of the cyclotron, requiring their removal and repair. This was followed by arcing which melted the aluminum tips of these resonators. Calculations showed that electrons could be trapped near the centre and would be dumped close to where the damage occurred. The geometry of the resonator tips was consequently modified to prevent this dumping, the aluminum parts were replaced by copper and put into better thermal contact with the cooling, and thermocouples were installed to monitor the temperature.

These improvements were completed in February and the cyclotron has been in continuous operation since then except for a scheduled shutdown in June to install graphite shielding around the tank wall. Over this whole period the machine reliability has been quite satisfactory, the cyclotron being operational for an average of 81% of the scheduled time (3000 h). Since May the number of maintenance days has been reduced and the machine has been operated continuously for 12 days out of every 14. There have also been significant improvements in performance, particularly in intensity, emittance, and in the provision of polarized beam. The central activity during this period has been preparation of the machine for higher intensities. Regular operation at 1 μA began in February; this was the maximum current permitted by TRIUMF's radiation licence for the existing shielding. Recently, however, the licence restrictions have been relaxed, and 10 μA is being run for one 12-hour shift each week.

The major new facility commissioned this year has been the Lamb shift polarized ion source. This has provided a 30 nA extracted beam of polarized protons with 78% reversible polarization. A polarized beam of variable energy in the 200-500 MeV region is a unique facility and has been in such demand for experiments that it has been scheduled for almost 50% of the time since it became operational in February.

The major non-scientific event of the last year at TRIUMF was its official dedication by the Canadian Prime Minister in February. There were, however, powerful scientific implications, for he announced the government's decision to provide the further capital funds necessary to complete the project and bring the beam to its design intensity of 100 µA. This will involve the provision of extra shielding, the extension of beam line 1 and the building of a combined beam dump and thermal neutron facility (TNF). In addition, a new pion production target (T1) will be placed upstream of the present one (T2), and a beam line built there (M11) to collect fast pions. The medium resolution spectrometer (MRS) will also be completed and a low intensity line BL1B is being considered for experiments with polarized protons.

Beam Performance

The properties and behaviour of the beam up to July 1975 have been fully reported at the Washington [4] and Zurich [5,6] conferences, and will only be briefly reviewed here. The present performance is summarized in Table 1:

Table 1. Beam Performance

Property	Aim	Achieved
Energy range	165-500 MeV	183-520 MeV
Current (unpolarized)	100 µA (500 MeV) 300 µA (450 MeV)	1 µA (regular) 10 µA (12 h/week) 48 µA (pulsed test) 100 µA (CRC @ 2.5 MeV)
Current (polarized)	60 nA	50 nA
Polarization (reversible)	80%	78%
Split ratio (Line 4/Line 1)	1/1 to 1/2000	1/1 to 1/5000 (±25%)
Duty factor - maximum	11% 20% (3rd harmonic)	11% (5/43 nsec)
minimum	1% (slits)	4% (chopped)
Transmission (5-500 MeV)	86%	75%
Fraction of dc beam to 500 MeV	10%	8% 30% (buncher on)
Vertical centring	±6 mm	±4 mm
Isochronism ($\sin\phi$)	±0.02	±0.4
Energy spread (10% peak)	1.8 MeV 0.5 MeV (slits) 0.1 MeV (3rd harm^c)	2.0 MeV 1.5 MeV (chopped)
Radial emittance (90% beam)	3π mm-mrad	5π mm-mrad
Vertical emittance - internal (90% beam)	1.2π mm-mrad	1π mm-mrad
external	2.4π mm-mrad	3π mm-mrad
Spot size at T2	2 × 10 mm^2	3 × 14 mm^2

The fraction of dc beam accelerated to 500 MeV depends on two factors—the phase acceptance of the central orbits and the losses due to gas and electric stripping. Consistent with the good centring and isochronism of the beam there are no localized losses due to vertical or phase excursions outside the central orbits. There is, however, a gradual decrease in beam intensity with radius, consistent with the gas stripping expected for the present residual vacuum (about 20% loss for 10^{-7} Torr air + 2 × 10^{-7} Torr hydrogen). Between 450 and 520 MeV there is a more rapid loss consistent with that expected for electric stripping (7% at 500 MeV). The azimuthal variation of activity around the tank wall has also revealed the characteristic signatures of the two H^- stripping processes. The phase acceptance is limited on the one hand by the vertical defocusing at the dee gaps for negative (leading) phase ions, and on the other hand by the energy gain required to clear the centre post on the first turn (≥60 keV, selecting phases <45° for 85 kV dee voltage). Of this 45° phase window only about 40° is expected to give good beam quality; i.e. an 11% microscopic duty factor. In practice such duty factors have been observed, both on internal and external beams. Consistent with this, an optimum fraction of 8% (≈11% × 75%) of the dc beam has been observed to reach 500 MeV. Under regular operating conditions the fraction is closer to 6%, due to our imperfect understanding of the beam behaviour at injection and in the central orbits. However, use of the buncher (a two-gap linac) in the injection line can raise the fraction of dc beam accelerated as high as 30%.

The emittances of the external beams have been reduced considerably over the last year by eliminating some foil windows and making others thinner, diminishing the amount of multiple scattering. The proton beams can be focused to spots <1 cm diam, and the beam spill from the halo is much reduced. The internal beam has incoherent radial and vertical betatron oscillation amplitudes of about 10 mm and 6 mm, respectively, depending on the exact local values of ν_r and ν_z, the radial and vertical tunes. There is some evidence for an increase in the vertical amplitude where the beam passes through the $\nu_r - \nu_z = 1$ coupling resonance near 150 MeV.

The techniques for providing two simultaneous beams have been improved in several respects. Firstly, a wider variety of foil shapes has been used to broaden the range of 'split-ratios' between the two beams. The most extreme ratio (1/5000 with 25% stability) is obtained with a 0.03 mm carbon filament. Continuous variation of the ratio is provided by adjusting the vertical position of the inner foil. Because of the limited range of movement this adjustment has benefited greatly from improvements to the vertical centring—now better than ±5 mm everywhere outside 70 MeV. (Direct transmission of probe measurements to the computer has reduced the time needed to measure, analyse and correct the centring from several hours to under 30 min.) An interesting feature that appears when beam is allowed to pass the outer foil is an extra component in between the regular beam pulses. This is beam that has gone out of phase at 530 MeV and is being decelerated back to the centre. [2]

The polarized H^- ion source has been delivering beam regularly almost every other week since February. It is of the Lamb shift type, with a Sona zero-field crossing region to enhance the polarization. Once the stray field of the cyclotron was properly compensated in this region, 75-80% polarization was achieved, as is typical of such sources. The polarizations measured by pp scattering at several energies between 203 and 515 MeV [7] are illustrated in Fig. 2; as expected, there is no significant depolarization over this energy region. The source delivers a maximum of 200 nA. With the buncher on a maximum of 50 nA has been extracted; more regularly, 30 nA is obtained.

Three secondary beams of pions and muons are currently produced at target T2 in the high intensity beam line BL1 (Fig. 1). A choice of six water-cooled targets of various lengths of beryllium, copper and water is available. The biomedical channel (M8), which is relatively short (7.2 m) to avoid decay loss, will transmit pions of up to 100 MeV with 1.5% momentum resolution and includes sextupole as well as quadrupole magnets in order to improve the beam optics. For irradiations the pions may be delivered uniformly over an area as large as 10 × 10 cm^2 or 4 × 15 cm^2. On the other hand, for pion scattering studies a beam of 10^5/sec-μA of 29 ± 1 MeV π^+ has been focused in a spot of only 1.2 × 1.8 cm. The time-of-flight spectrum in Fig. 3 illustrates the ease of separating these 29 MeV pions from muon and electron contamination.[8]

The slow and stopping π/μ channel (M9) also gives good quality pion beams at low energy, from 65 MeV down as far as 15 MeV, with momentum resolution variable between 2% and 15%. The electron contamination is low. For 30 MeV pions from the 10 cm beryllium target the π^+ flux is 1.5×10^6/sec-μA in a 3 cm diam spot with 13% each μ^+ and e^+ contamination; the π^- flux is 0.3×10^6/sec-μA with 13% μ^- and 50% e^-. The stopping density for π^+ is 5×10^5/sec-μA-g-cm^{-2} and for π^- a factor five less. Since funds have been insufficient to build the quadrupole muon collection section originally intended for M9, the properties of 'cloud' muons formed near the production target and 4.1 MeV 'Arizona' muons formed on its surface have been diligently investigated. An important discovery has been that the cloud muons are numerous (10^5/sec-μA), can be focused to a spot comparable to that of the pions, a few cm in diameter, and have at least 60% polarization. The 'Arizona' muons gave a stopping rate of 2×10^4 μ^+/sec-μA, with over 80% polarization.

The third channel (M20), dedicated to stopping muons, has been constructed at minimum expense from magnets loaned by other laboratories. The muon flux from forward-decaying pions is about 10^4/sec-μA, with a polarization of 60%, apparently due to contamination by cloud muons.

The fourth secondary beam, of polarized fast neutrons, is produced on beam line 4A from a liquid deuterium target. At 325 MeV, for instance, this provides a flux of 1.5×10^5/sec neutrons per 30 nA protons. With the incoming proton spin rotated into the plane of scattering by a superconducting solenoid a high polarization transfer $R_t = 0.78$ is obtained.

Towards Higher Intensities

The problems of raising the beam intensity lie in three general areas: (i) the ion source, (ii) radiation, and (iii) heating. That the ion source and injection system are capable of delivering enough current to the cyclotron was confirmed when 100 μA was injected into our full-scale central region cyclotron [2] and accelerated successfully to 2.5 MeV. Space charge effects were not important at 100 μA, and are not expected to limit the current below 500 μA.

The radiation problem is the most crucial and has two aspects: (a) keeping the radiation below the permissible level in working areas during operation, (b) keeping the residual activity in the cyclotron and beam lines at a level where essential repairs and development can be performed. Point (a) can be satisfied now that funds are available for extra shielding. Point (b), however, requires a little more finesse. Inside the cyclotron, foil 'scrapers' have been mounted above and below the median plane to strip any beam which might otherwise hit the resonators. The scrapers are shaped so that beam spilt accidentally at any radius ends up in the same region on the vacuum tank wall, localizing the activity as much as possible. Furthermore, graphite blocks surrounded by boriated gypsum sheets have been installed all around the tank wall on the outside to provide a more sanitary degrader for the spilt beam than magnet steel and to shield the interior from the activity it induces. On installation the activity induced by 3 months of running at 1 μA was reduced by a factor 5 at the periphery to 2.5 mrem/h, and 10 at the centre to 0.5 mrem/h. Next, it is planned to install a temporary lead shield inside the tank wall each time the tank is opened; this will be handled remotely from the rotating service bridge and is expected to reduce the activity by a further factor 20. (Remote handling is also being developed for a number of other components, particularly targets in the beam line.) Finally, to reduce the spill due to H⁻ stripping by residual hydrogen gas two 25000 ℓ/sec liquid helium cooled cryopumps are being installed.

Monitoring of beam spill outside the tank and along the beam lines is provided by 'heliax' monitors (sections of helium-filled coax cable) and by standard radiation monitors. As mentioned above, the spill in the lines was considerably reduced by removing some of the foil windows and reducing the thicknesses of others. Magnetic shielding of the beam lines in the cyclotron vault also contributed through improvement of the beam tune.

Thermal damage due to beam being accidentally dumped in the cyclotron or beam lines should be prevented by the spill monitors tripping the machine off. In the case of the injection line non-intercepting current monitors have been developed (for pulsed beam at 99% duty factor) and have similarly been hardwired into the safety interlock system to protect against excessive beam spill.

If these developments take place on schedule, it is planned to begin continuous operation at 10 μA in January 1977 and part-time operation at 100 μA in January 1978.

Separated Turns

The $\lambda/4$-cavity form of TRIUMF's dees immediately suggests the possibility of exciting higher harmonics to flat-top the RF waveform, thus reducing the phase dependence of the orbital motion and permitting improvement of either the beam quality or the phase acceptance.[10] The simplest possibility is to add about 11% third harmonic in antiphase. In this case separated turns could be achieved, and hence the energy spread ΔE in the external beams reduced to ∿100 keV, for a phase acceptance $\Delta\phi$ of 14° rather than only 1° for purely fundamental RF. Furthermore, the stability requirements are relaxed to achievable levels: $\pm 3 \times 10^{-5}$ in RF voltage, $\pm 5 \times 10^{-7}$ in frequency and $\pm 4 \times 10^{-6}$ in magnet current. The latter two requirements are already met under normal operating conditions for periods of ∿20 min. Considerable testing of RF third harmonic has also taken place, a satisfactory Q (80% of that of the fundamental) being observed at signal level; the power amplifier and transmission line are under construction.

The other important requirement concerns the isochronism of the cyclotron. To achieve $\pm 10^{-4}$ energy spread at all energies the phase wander must not exceed ±1.1°. During the shimming of the magnet the field errors were reduced from ∿100 G to ∿0.3 G on average; at the largest radii, however, field oscillations of ±1.1 G resisted all efforts at smoothing and have resulted in ±20° oscillations in phase, as can be seen in our latest phase measurement (Fig. 4). In spite of this enormous violation of the isochronous tolerance a method has been found [11] by which the low energy spread of the isochronous case can be recovered over limited energy regions. The method requires balancing the positive and negative phase swings for a phase spread of comparable amplitude. Some results are shown in Fig. 5 (where the 50 keV contribution of instabilities to ΔE has been omitted). Above 450 MeV the non-isochronous ΔE is within 10 keV of that for perfect isochronism.

Experimental Programme

An active programme of experiments is under way, covering a broad range of fields, including solid state physics, nuclear and radio-chemistry and biomedicine as well as nuclear and particle physics. The first experiment completed utilised the variable energy capability to show that pion production from carbon and copper obeyed a smoothly rising excitation function, contrary to previous isolated measurements. The primary proton beam has also been used to study scattering and reactions from various nuclei. In the case of (p,2p) reactions induced by 200 MeV polarized protons, asymmetries have been observed consistent with theoretical suggestions that spin-orbit coupling and nuclear absorption together effectively polarize the nuclear protons. The spin dependence of pp and np scattering is being studied by measuring the Wolfenstein parameters; the fast neutron beam allows the np process to be studied directly rather than extracted from pd scattering. New results have been obtained in scattering low energy pions from light nuclei, and stopped pions have provided the first observation of the $\pi^- d \rightarrow \pi^0 nn$ reaction. Muon spin rotation studies have revealed new features of μ^+ diffusion and the interstitial magnetic fields in solids; in a single crystal of iron measurements have been taken down to 23°K, much lower than before. Proton induced fission of uranium and spallation of iodine have provided neutron-rich and neutron-deficient isotopes for nuclear spectroscopy; a gas jet system is used to collect the isotopes. Proton irradiations are also being used in the study of electromagnetic breeding. In a medical application ^{123}I is produced by proton bombardment of a liquid caesium target and has been tested successfully on human patients. The negative pion radiotherapy programme is also progressing satisfactorily. Cell irradiations began in March, showing the expected reduction in survival rate at the end of the pion range (Fig. 6);[12] animal irradiations, which require a 10 μA proton beam, will begin shortly.

Acknowledgements

The progress reported here is the responsibility of numerous TRIUMF and university staff members. I particularly wish to thank my beam physicist colleagues J. Beveridge, E.W. Blackmore, G. Dutto, D. Gurd, C. Kost, G.H. Mackenzie, P.A. Reeve, P. Schmor and M. Zach. I should also like to acknowledge the encouragement of the past and present directors of TRIUMF, J.R. Richardson and J.T. Sample.

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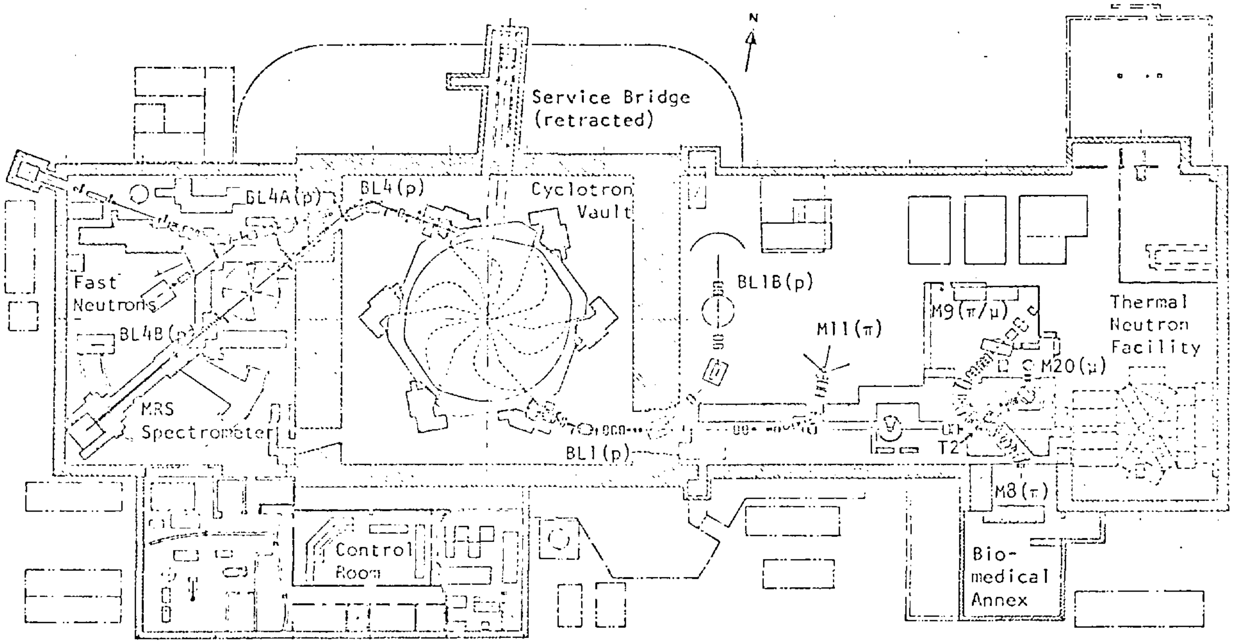


Fig. 1. Existing and proposed beam lines and experimental facilities.

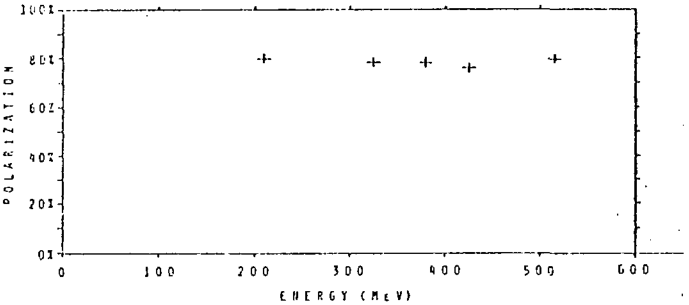


Fig. 2. Polarization of the extracted beam at various energies, measured by pp scattering. There is $\sim$6% uncertainty in the normalization; the statistical errors are smaller than the thickness of the lines.

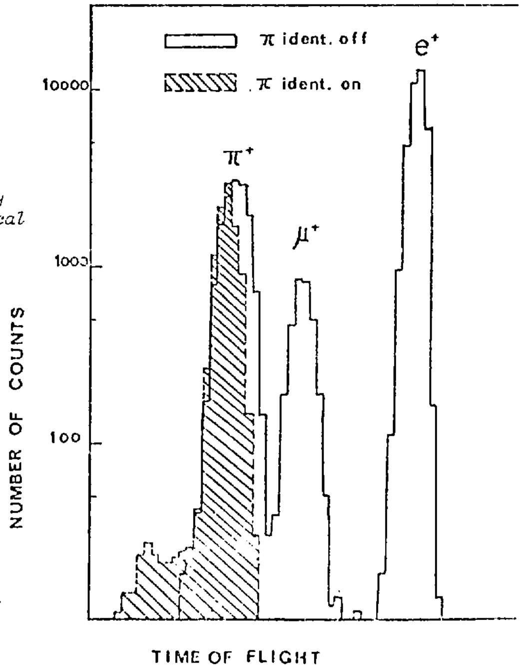


Fig. 3. Time-of-flight spectrum for positive particles in M8, showing the good π^+-μ^+ separation (note the logarithmic scale). The hatched peak was taken with π identification circuitry operating.

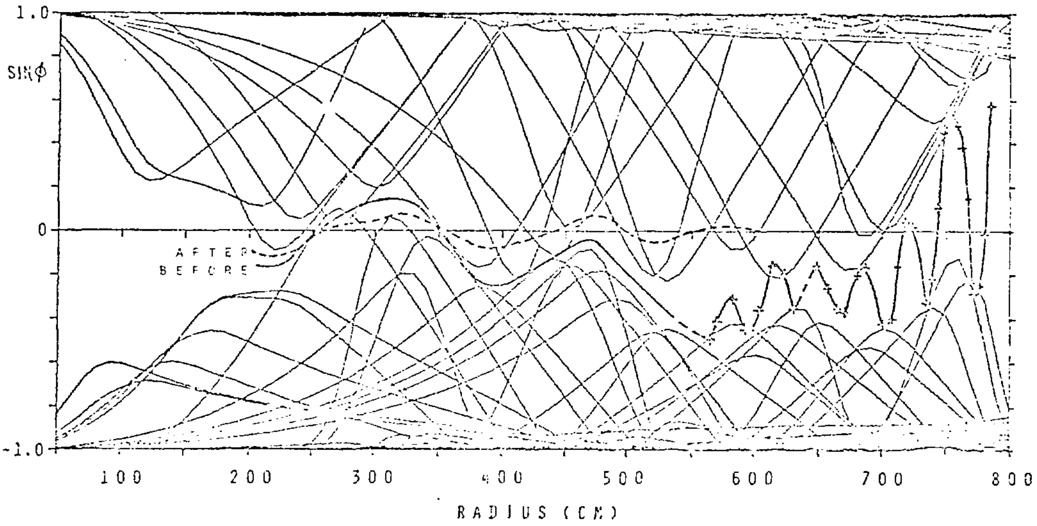


Fig. 4. Phase history sin $\phi(R)$ before (——) and after (---) the most recent adjustment of the 30 trim coils. The points (+) were obtained by timing external beams of different energies. The thinner peaked curves represent the phase changes induced by triplets of neighbouring trim coils needed to lose half the beam; the median phase curve should just touch them all.

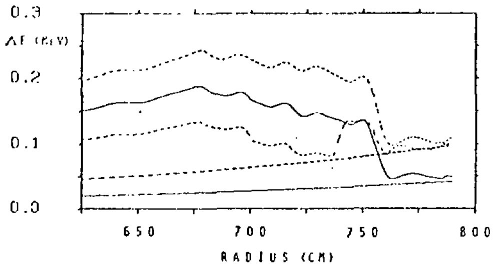


Fig. 5. Energy spread for separated turn operation (neglecting a 50 keV contribution by instabilities). The smooth and sinuous curves represent the cases of isochronous and measured magnetic field, respectively. The full curves are for 12% third harmonic, the dashed ones for 1% greater and less.

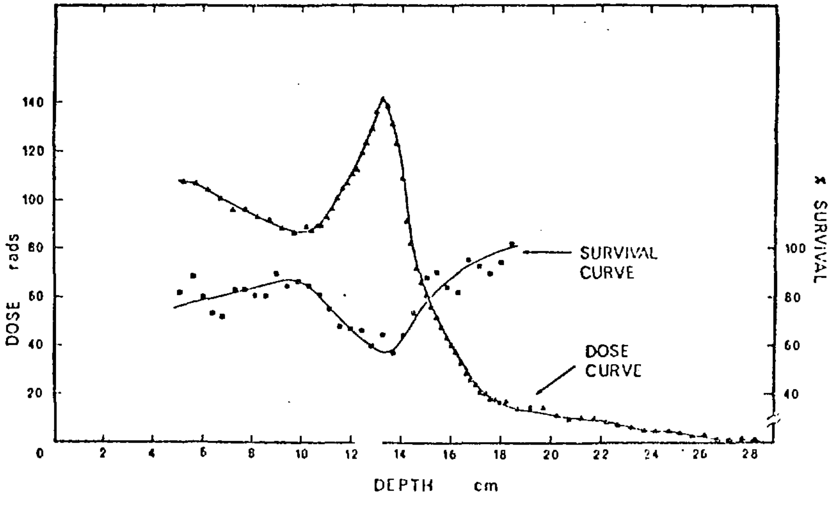
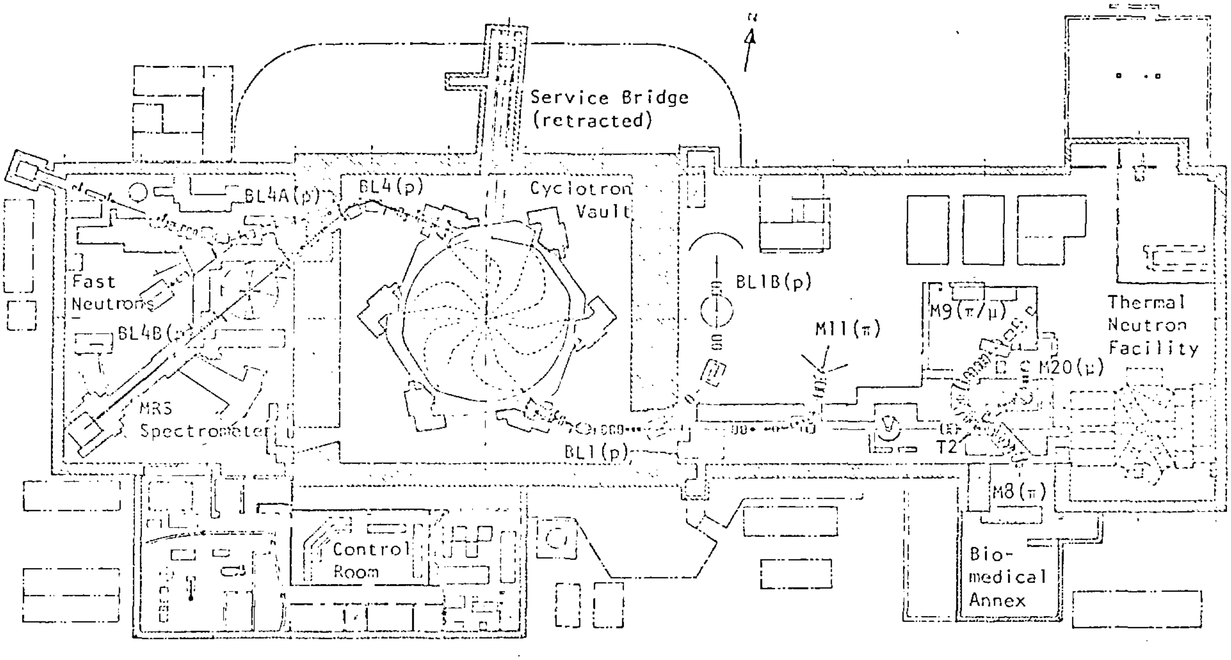


Fig. 6. π^- irradiation [illegible] expressed as a function of depth in water.



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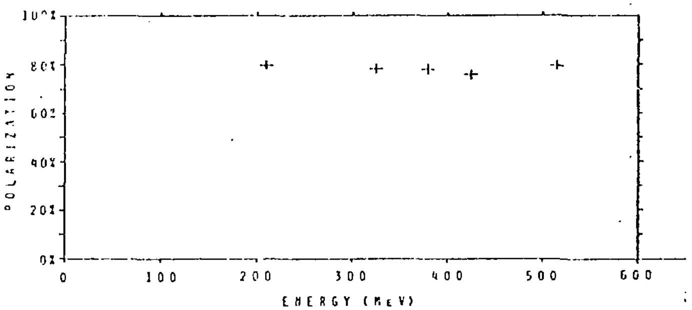

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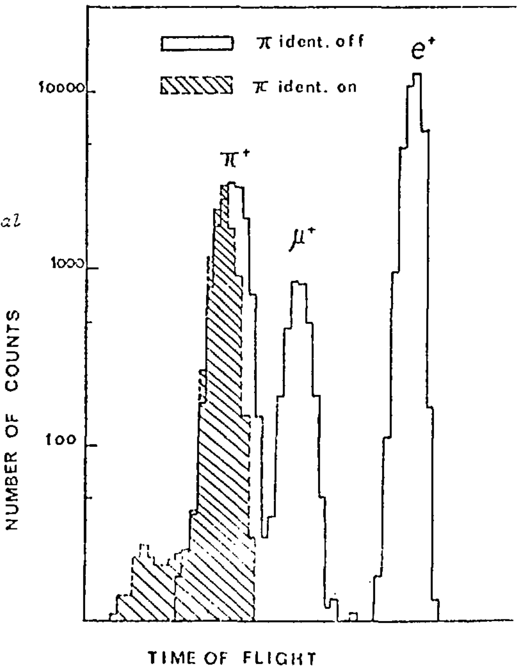

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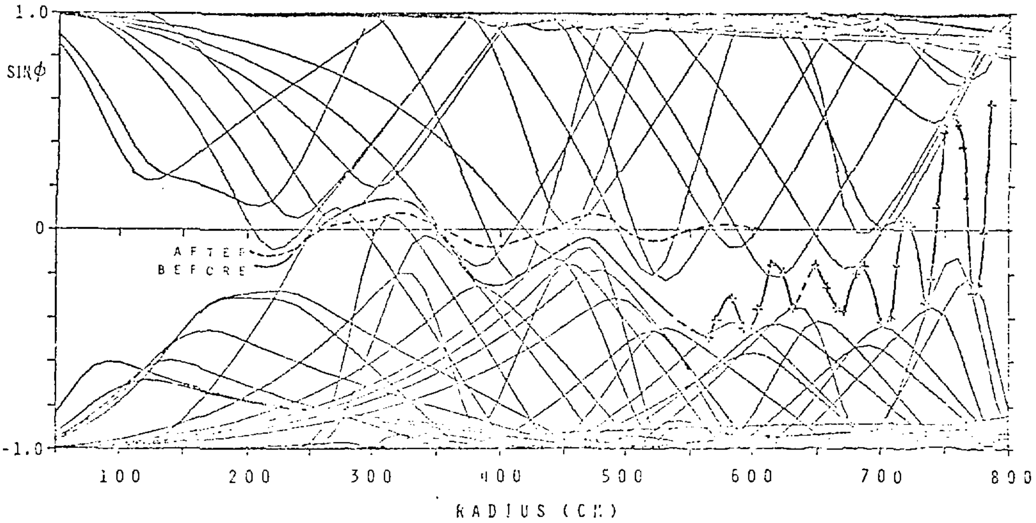

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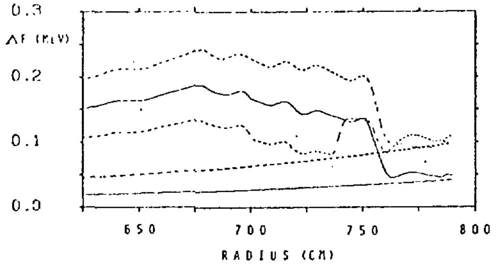

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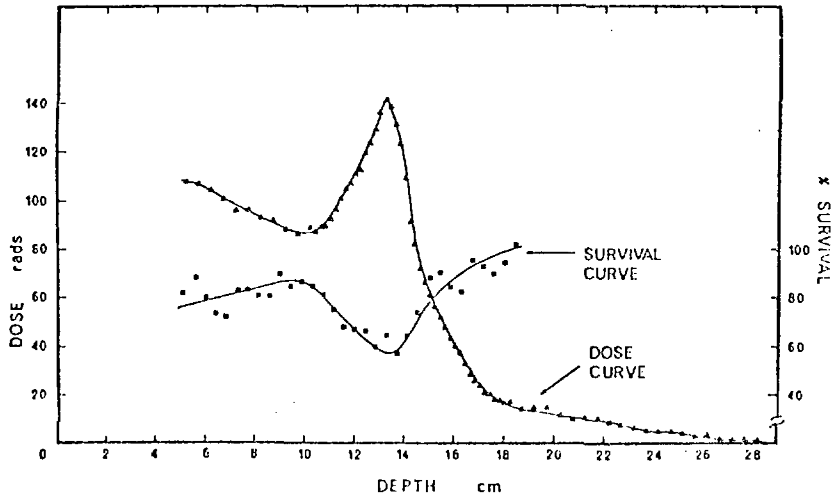

Fig. 6. π^- irradiation [illegible] and cell survival expressed as a function of depth in water.