Physics 2405 Problem Set #1
21 January 2013

Complete set due back 13 February

1. Read the attached paper (very old) on the TRIUMF cyclotron. Just skim through the paper…you don't have to understand all the details. Even though it's old, TRIUMF is still the highest energy cyclotron in the world, and is the injector for the TRIUMF radioactive beam facility. TRIUMF was designed by Reg Richardson, a student of Lawrence (see second attachment). It is a sector focused cyclotron, where as I have sometimes called it a "spiral ridge" cyclotron. As I said in class, these sectors give the magnetic field a radial dependence, in order to allow for the relativistic effect on the orbital frequency during acceleration. Some parameters of the cyclotron are.

Injection energy:	300 keV
Final Energy:	520 MeV
Maximum Radius:	310 inches (built in 1970, before Canada went metric)
Injection Radius:	12 inches
Particles accelerated:	H^-

   a. Calculate the B field at injection and maximum energy.
   b. Make a plot of how the field varies radially.
   c. Synchrocyclotrons are pulsed machines. Why?
   d. How does TRIUMF manage to be CW (continuous beam) machine?
   e. Why does it accelerate H^-, and not protons?
   f. How is the beam extracted from the cyclotron?
   g. I can imagine that there are simpler ways of making the field vary radially than the complicated spiral ridges. What other purpose do the ridges have?
   h. Can you make an estimate of the horizontal and vertical betatron frequencies?
   i. What is the RF frequency of the accelerating voltage?

2. a) A quadrupole doublet consists of two lenses of focal length f_1 and f_2, and they are separated by a drift length l (in metres). Assume that these can be treated as thin lenses and show using the three transfer matrices, that

$$M = \begin{pmatrix} 1-l/f_1 & l \\ -l/f^* & 1-l/f_2 \end{pmatrix}$$

where

$$\frac{1}{f^*} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{1}{f_1 f_2}$$

b) A FODO cell my be considered to be one such matrix with $f_1 = +2f$ and $f_2 = -2f$ followed by another cell with $f_1 = -2f$ and $f_2 = +2f$. Write down the two transfer matrices and show that the product matrix for a half-cell from mid-F to mid-D quadrupole is

$$M = \begin{pmatrix} 1 - l^2/2f^2 & 2l(1 + l/2f) \\ -(l/2f^2)(1 - l/2f) & 1 - l^2/2f^2 \end{pmatrix}$$

c) I called α, β, γ the Courrant-Snyder parameters (actually most people call them the Twiss parameters….). The transfer matrix for a FODO period must have the form

$$\begin{pmatrix} \cos\mu + \alpha\sin\mu & \beta\sin\mu \\ -\gamma\sin\mu & \cos\mu - \alpha\sin\mu \end{pmatrix}$$

where μ is the phase advance per period.

A FODO structure has $B\rho =$ 26.68 Tesla-metre, Quadrupole lengths = 0.509 m, Quadrupole gradient = 12 Tesla/M, and a distance between the quadrupole centers of 6.545 m.

Take the trace of the transfer matrix, and use the result from part (a) to get an expression for μ. Calculate the numerical value of μ. Now use the relevant element of the transfer matrix to get β at the mid plane F of the quadrupole. What does this mean physically?

3. a) The skin depth δ of an AC current of angular frequency ω traveling on a conductor of bulk resistivity ρ is

$$\delta = \left(\frac{2\rho}{\mu_0\omega} \right)^{\frac{1}{2}}.$$

Show that the surface resistivity is given by

$$\rho_s = \left(\frac{\mu_0\omega\rho}{2} \right)^{\frac{1}{2}}.$$

Physically, the skin effect is explained by the fact that RF electric and magnetic fields applied at the surface of a conductor induce a current which shields the interior of the conductor from those fields. For frequencies in the 100 MHz

range, and for a good conductor such as copper , the skin depth δ is of the order 10^{-6} m and ρ_s is in the milliohm range.

The unit of surface resistivity is the ohm, but it is frequently stated in "ohms per square" (?square what?!). Calculate the RF surface resistivity of copper at 400 MHz, 1.3 GHz and 3 GHz. Use a DC resistivity of $\sigma^{-1}=1.7\times10^{-8}\Omega.m$.

Check your answer against the formula given the Review of Particle Physics. Comment. If you don't have a copy of the RPP, ask me for one.

b) The use of superconducting materials reduces the surface resistance dramatically. For the RF surface resistance of superconducting niobium, one can use

$$\rho_s = 9\times10^{-5}\frac{f^2(GHz)}{T(K)}\exp\left(-\alpha\frac{T_c}{T}\right)+R_{RES}$$

Where $\alpha=1.92$, and $T_c=9.2K$ is the critical temperature. R_{RES} is the residual resistance. It is determined by imperfections in the surface and is typically $10^{-9}-10^{-8}\Omega$.

Calculate the RF surface resistance of superconducting niobium at $400MHz$ and $1.3GHz$, assuming a residual resistance of $10^{-9}\Omega$. What is the ratio of the RF surface resistance of superconducting niobium to that of room-temperature copper? Assume (1) $T=4.2K$, (2) $T=2K$.

c) Calculate the Q value of a 400 MHz copper cavity, and hence the temperature stability needed to keep the cavity within resonance, for a constant driving frequency

4. Calculate the synchrotron oscillation frequency for the Fermilab 8 GeV booster. The maximum momentum is $cp_{max}=8.9\,GeV$, the harmonic number is $h=84$, the RF voltage is $V_{rf}=200kV$, the transition energy corresponds to $\gamma_{tr}=5.4$ and the RF frequency at maximum momentum is $f_{fr}=52.8MHz$. Calculate and plot the RF and synchrotron oscillation frequency as a function of momentum from the injection momentum of 400 MeV to the maximum momentum of 8.9 GeV. Take the synchronous phase as $\psi_s=45^o$. What is the momentum acceptance at injection and at maximum energy? How long does the acceleration last?

5. *I give a version of this out every year. If you go borrow the program from someone from previous years…. At least understand it, run it yourself, and discuss the results.*

Write a simple computer program that uses the difference equations

$$\phi_{n+1} = \phi_n + \frac{\omega_{rf}\tau\eta c^2}{v^2 E_s}\Delta E_{n+1}$$

$$\Delta E_{n+1} = \Delta E_n + eV\left(\sin\phi_n - \sin\phi_S\right)$$

a) Use the program to generate plots of $\dfrac{\Delta E}{E_s}$ against ϕ for the LHC, and for the CERN PS close to the maximum energy of the machine (these are both proton machines).

The LHC is a 7 TeV machine with an RF of 400 MHz. The slip factor is 3.47×10^{-4}. It has a circumference of 27km. **What is its transition energy?**

The PS is an injector for the LHC. It accelerates to 26 GeV, has a radius of 70 m, and an RF frequency of 40 MHz. It has $\gamma_{tr} = 6.1$. **Again what is the transition energy?**

Assume the synchronous phase for both machines is 45° *(does this make sense?)*. Also assume that there is only one RF cavity in each machine.

b) Generate plots for the PS above and below the transition energy.

c) Generate plots for an unaccelerated, but bunched beam at the maximum energy of the LHC.

d) Make the same plots for the SLAC LINAC. It is 3km long and an RF frequency of 2856 MHz. Assume that there is an RF cavity every 2 meters along the machine.

e) Comment on the differences between these plots

PRODUCTION OF SIMULTANEOUS, VARIABLE ENERGY BEAMS FROM THE TRIUMF CYCLOTRON

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Summary

An extracted beam at the design energy of 500 MeV was obtained at TRIUMF in December, 1974. Later, beams of varying energies between 180 and 520 MeV were extracted down beam line 4 and further work resulted in the simultaneous extraction of a 506 MeV beam down beam line 1 while variable energy beams were brought down line 4. In order to reduce initial activation of cyclotron components, time average beams have been restricted to 100 nA but 12 μA in a pulsed beam was very easily obtained at 500 MeV. Without much optimization of the injection conditions and without use of the harmonic trim coils an energy spread (full width) of 2.5 ~ 3.0 MeV has been observed. Ordinarily, the macro-duty factor has been 100% and the micro-duty factor corresponds to a 5 ns pulse every 44 ns. The transmission to 500 MeV is consistent with the expected loss due to gas stripping.

Introduction

TRIUMF is a meson factory[1] based on the acceleration of H^- ions in a sector focusing cyclotron. Actual construction of the facility began in 1971. The year 1973 and three months of 1974 were spent in measuring and tailoring the magnetic field to the precision required as a consequence of the 1200 turns in the acceleration, the large final radius (309 in.) and the fact that the RF is on the fifth harmonic of the ion frequency. The problem was exacerbated by the difference between the fields produced by the 1:10 model and the full scale magnet, as explained previously,[2] but a satisfactory solution was obtained by April 1974. This solution also required the use of most of the 54 circular trim coils either to correct B_z or B_r or both.

In the six months from April through October, 1974 the 80 resonators were installed, the cryolines and cryopanels were installed and tested and the radio-frequency system was gradually worked up in power as the vacuum was improved. The first beam was accelerated to 6 MeV on November 16 and over the next month it was gradually worked out in radius to 277 in. (360 MeV) by careful adjustment of the currents in the circular trim coils on the top and bottom of the vacuum chamber. On December 15 the beam was rapidly accelerated the rest of the way to the design energy of 500 MeV at 309 in., and within the hour it had been extracted and focused on an external beam dump.

Since that time we have verified the variable energy feature of TRIUMF by extracting beams at 50 MeV intervals over the range from 180 to 520 MeV and have transported the beam down several external beam lines of the facility.

The simultaneous extraction of beams of differing energy has been achieved by extracting a beam of over 500 MeV down beam line 1 while at the same time extracting beams of various energies between 500 and 300 MeV down beam line 4.

Beam currents so far have been restricted to tens of nanoamps in order to minimize induced activity. However, a test run has been made at 12 μA peak

current in a pulsed mode. The normal macroscopic duty factor is of course 100%; the microscopic duty factor is 11% -- 5 ns pulses every 44 ns.

Diagnostic Probes

Figure 1 is a plan view of the cyclotron showing the relative location of the diagnostic and extraction probes. The large scale of the machine together with the high magnetic fringe fields, the large resonator array and its associated RF fields and the high vacuum of the order of 10^{-7} Torr necessary for an H^- cyclotron presented a number of mechanical problems in the design of the diagnostic probes, but the use of H^- ions simplifies the beam detection at higher energies.
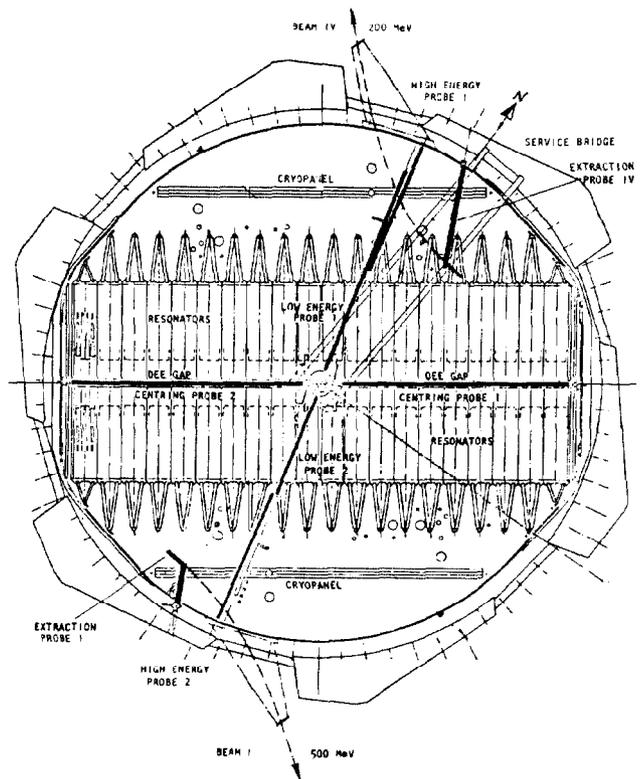

Figure 1. Plan view of the cyclotron vacuum tank showing the various diagnostic and extraction probes.

The full radial range of 315 in. is covered by sets of two current probes, the low energy probe which extends from the first turn to 145 in. (70 MeV) and the high energy probe which extends from 142 in. to 315 in. The probe arms are supported and driven from the lid of the vacuum tank and are lowered into the median plane for beam detection and retracted when not in use. Intercepting phase heads are being developed. The low energy head completely stops the beam and provides both vertical and radial information. The beam is stripped in the thin horizontal foils of the high energy head and the stripped electron current detected. The protons are dumped in a localized region at the tank periphery.

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The five current signals from each head are displayed as histograms on a storage scope, as analogue signals on electrometers or on a six-channel chart recorder driven synchronously with the probe. The vertical centroid and width of the beam are computed from the currents in the horizontal finger probe, and analogue signals are generated for display on the chart recorder. Typical radial beam plots are shown in Figures 4 and 5.

The extraction foils are suspended from a trolley which has three independent motions, a radial and azimuthal motion for positioning the foil for the desired extraction energy (180 to 520 MeV) and for centring the stripped trajectory at the combination magnet, and a vertical motion for partial extraction. Up to six foils are contained in a cartridge on the probe arm, and foil exchange either to replace a spent foil or to insert a special shape of foil is possible under vacuum.
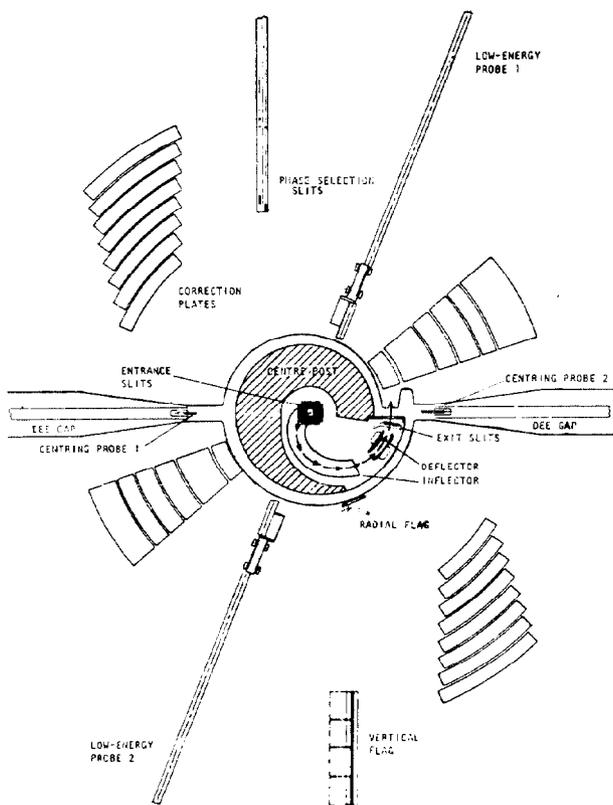

Figure 2. Central region probes, slits and steering elements.

Other diagnostic tools are slits at the inflector entrance and exit, centring probes located along the dee gap, a vertical flag for restricting the beam height at 4 MeV and moveable radial slits between 4 and 30 MeV for phase selection.

Beam Behaviour in the Cyclotron

Phase Acceptance and Microscopic Duty Factor

The 300 keV dc beam from the H⁻ ion source and injection system[3] enters the cyclotron vacuum tank axially from above and is then bent into the horizontal median plane by means of a spiral electrostatic inflector (Figure 2). After passing through an electrostatic deflector for radial steering, the ions cross the first RF accelerating gap and gain or lose

energy depending on their arrival time. Those arriving when the RF voltage is close to its peak accelerating value (phase ϕ = 0 deg) gain sufficient energy to clear the "centre post" (a structural member supporting a combined magnetic and vacuum load of 2700 tons) and receive further acceleration.

In order to examine the phase acceptance, the chopper[3] in the injection line was used to reduce the phase spread of the injected beam to about 15 deg. The total current on low energy probe LE1 was then measured as the chopper phase was varied (Figure 3).
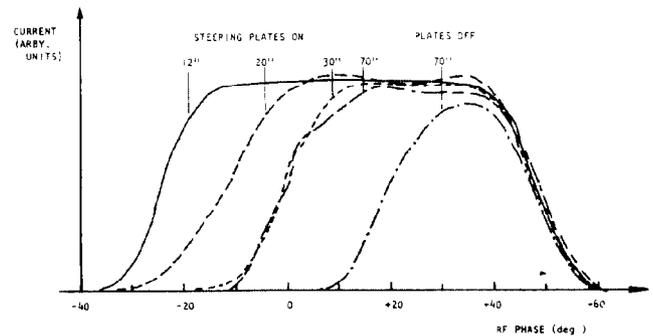

Figure 3. Total current recorded on probe LE1 at various radii as a function of the RF phase of the chopped beam.

At 12 in. radius (1.2 turns) the phase acceptance in the case shown is over 70 deg. As the beam is accelerated to a radius of 30 in. the acceptance falls to 45 deg, but from 30 in. to 70 in. there is no further loss. The ions lost on the first few turns are those with negative (leading) phases, which experience vertically defocusing impulses as they cross the dee gaps. For positive phases the impulses are focusing, though only weakly so for phases close to zero. Any coherent vertical motion induced by radial magnetic field components or dee misalignments will therefore have the largest amplitude for small positive phases. The electrostatic correction plates[4] shown in Figure 2 are used to steer the beam vertically over the first few turns. From Figure 3 we see that when these plates are turned off the phases with the weakest focusing from 0 deg to 20 deg are lost, while the transmission of more positive phases is unaffected, in agreement with expectations. The phases close to zero are potentially the most valuable, since, for a restricted phase acceptance, they are capable of yielding a finer energy resolution.

Three independent observations confirm a phase acceptance of 40-45 deg for the cyclotron:

(i) The total current measured on probe LE1 at a radius of 40 in. (5 MeV) amounts to about 11% of the dc beam from the ion source. Figure 4(a) shows an example where, out of a 1600 nA dc beam, 290 nA are measured on the first turn, corresponding to 65/360 deg, and 180 nA at 40 in. radius, corresponding to 40/360 deg. (The dips in total current at 16 in. and 19 in. radius are due to the width of the probe head being smaller than the radius gain per turn.)

(ii) The magnetic field was scanned through the cyclotron resonance at various radii, producing the characteristic trapezoidal variation in total beam current. The sides of the trapezoid had a width corresponding to $\Delta \sin \phi$ = 0.65, i.e. a phase spread of 40 deg.

(iii) Time of flight measurements[5] on the external beam indicated a phase spread of about 40 deg.
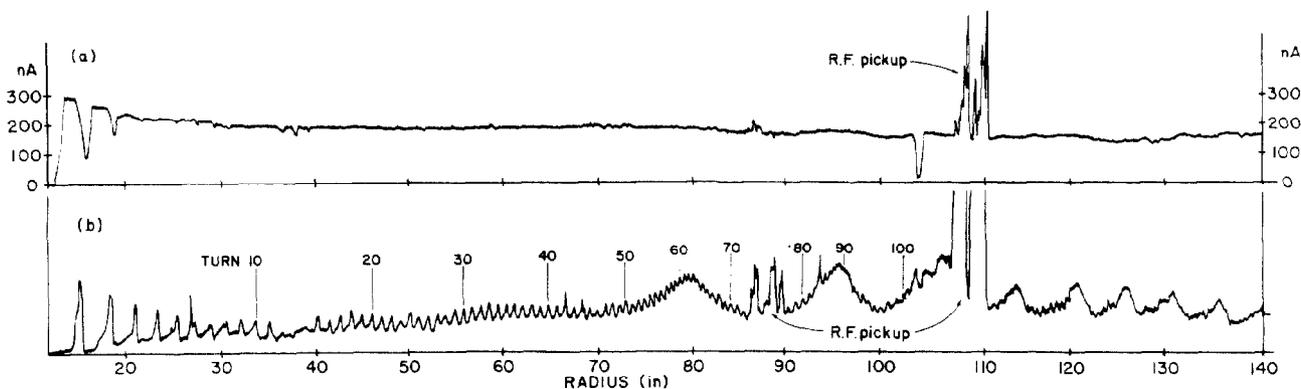
Figure 4. (a) Total current on the 2.0 in. wide x 2.2 in. high probe LE1 as a function of radius;
(b) current on the 0.2 in. wide differential section of probe LE1, with the beam steered off-centre to display radial precession patterns and turn structure at large radii. Both traces were taken with unrestricted phase acceptance.

In summary then, it appears that the microscopic duty factor of the beam is at least 11%, consisting of a 5 ns pulse each RF period of 44 ns. The macroscopic duty factor of the beam is of course normally 100%.

Transmission

After selection of the phase acceptance on the first few turns the beam continues to the full energy of 500 MeV with no significant localized losses. There is however a gradual loss with radius which is not inconsistent with stripping of the H⁻ ions by the residual gas molecules in the vacuum tank. From 40 in. to 140 in. radius (5 - 60 MeV) this gradual loss amounts to about 10%. Thus in Figure 4(a) the current falls from 180 to 160 nA over this region. (The small dips in the total current plot at low radii and the shallow dips at radii of 100 in. and 125 in. are caused by the uppermost segment of the differential probe head being inoperative during this run; the dip at 103 in. radius was caused by a momentary beam trip.)
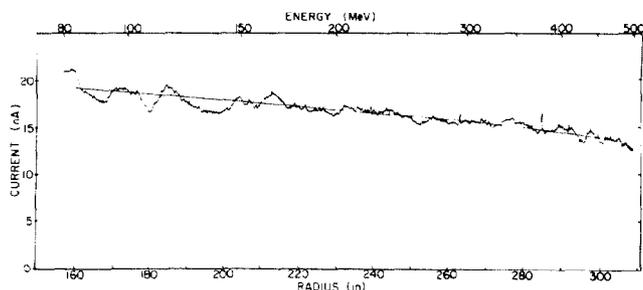

Figure 5. Total current on probe HE1 as a function of radius. The smooth curve illustrates the theoretical fall-off due to gas stripping. No electric stripping is discernable.

An example of the transmission observed in the outer region of the cyclotron, from 160 in. to 309 in. radius (80 to 500 MeV) is shown in Figure 5. The general trend is in good agreement with the smooth curve which represents the theoretical fall-off due to gas stripping[6] for a pressure of 2.8 x 10⁻⁷ Torr air equivalent, a dee voltage of 85 kV and a phase of 30 deg. The tank pressure was recorded as 1.7 x 10⁻⁷ Torr during this measurement; however, the average pressure seen by the beam will be considerably higher than this, since the orbits pass through the restricted space between the upper and lower RF resonators. The

smooth curve represents an overall transmission of 70% over this region.

A possible source of uncertainty in current measurements with the high energy probe is the electron capture efficiency. The 0.005 in. tantalum fingers are thick enough to stop the stripped electrons from the H⁻ ions; however, these electrons could be back-scattered before stopping and re-emerge. Furthermore, the fingers are not thick enough to stop the delta-rays produced by the primary beam. Monte Carlo calculations have therefore been made to determine the histories of the electrons released in the probe, including multiple scattering effects; indications are that the electron capture efficiency is about 80%, the exact value depending on the radius (because of the variation of magnetic field) and which of the five fingers is considered. The larger dips in the plot of total beam current are correlated with vertical excursions of the beam and could be evidence of different capture efficiencies for the different fingers.

There is no clear evidence for electric stripping of the H⁻ ions by their passage through the magnetic field of the cyclotron at relativistic speeds. From the magnetic field measurements this loss was expected to be virtually zero to 450 MeV, building up to 6% at 500 MeV. In Figure 5 an effect of this size is not distinguishable from the deviations from a smooth curve present at all radii.

Beam Intensity

In order to avoid activation of cyclotron components during the commissioning stage, beam currents so far have been restricted to the 10-100 nA range. To test operation at higher currents without exceeding this current level on average, the beam from the ion source was run in a pulsed mode with beam on for 120 µs every 10 ms. Also the RF buncher[3] in the injection line was used, yielding a gain of a factor 4 in beam intensity at 500 MeV for the normal unrestricted phase acceptance. During the pulses a current of 12 µA was accelerated to 500 MeV and extracted from the cyclotron without any problem.

Indeed a current of 100 µA, the design specifications, has previously been accelerated to 3 MeV in our "central region cyclotron",[7] a full scale model of the parts of TRIUMF which would be most sensitive to space charge problems. We therefore anticipate no serious problems in raising the current in the TRIUMF cyclotron to 100 µA, once the vacuum has been improved and sufficient shielding built around the external beam lines.

Radial Beam Quality

Figure 4(b) illustrates the current density observed with the 0.2 in. wide "differential" section of probe LE1 for a beam of unrestricted phase acceptance. Individual turns are identifiable up to turn 100 or so, and by deliberately steering the beam off centre, as in this example, individual turn structure can also be seen out to 60 MeV (140 in. radius) in the minima of the radial precession patterns.

By restricting the phase acceptance with the chopper to a narrow band near the peak of the RF voltage, completely separated turns have been observed out to turn 60.

Shadowing measurements to investigate the centring and emittance of the accelerated beam have been made using probes HE1 and HE2 at radii of 160 in. (70 MeV) and 309 in. (500 MeV). By 70 MeV the chief effects responsible for worsening the radial beam quality (unoptimized initial centring, radial longitudinal coupling, first harmonic magnetic field components) are expected to have completed their work, so that the radial beam properties measured there should be representative of those over the remainder of the cyclotron. At higher energies ν_r increases from 1.07 to 1.5 and the precession makes it more and more difficult to extract information on the radial emittance using probes 180 deg apart in azimuth.

The 70 MeV measurement indicated that the orbits were centred to 0.15 ± 0.1 in. and that the maximum radial betatron oscillation amplitude $A_r \approx 0.7$ in. At 500 MeV the centring was 0.1 ± 0.1 in. Assuming no deterioration in A_r as the beam is accelerated beyond 70 MeV, we would expect the energy resolution ΔE of a 500 MeV extracted beam to be about 3.5 MeV; in fact it was observed to be slightly smaller than this (see below).

The observed values of A_r and ΔE are considerably larger than the design specifications of 0.14 in. and 1.2 MeV, but no worse than might have been expected from the residual harmonic components measured at the end of the magnetic field survey. However, the tune-up of the cyclotron has so far been directed entirely at maximizing the transmission; no attempt has yet been made at improving the beam quality. To do this will require careful tuning of the central region (for which the probe LE2 must be installed) and of the harmonic coils.

The precision of the centring allows us to place rather tight error bars on the energy of a beam stripped at a given radius. Thus a nominally 400 MeV beam is expected to have a mean energy 400 ± 3 MeV. The BASQUE experimental group[5] have made an independent measurement of the energy of a nominally 400 MeV external beam by a time of flight technique, with the result 403 ± 10 MeV.

Vertical Motion of the Beam

In the presence of an average radial field component $\overline{B_r}$, the equilibrium orbit at the mean radius R will be displaced from the geometric median plane by

$$\bar{z} = \frac{R}{\nu_z^2} \frac{\overline{B_r}}{\overline{B_z}} \tag{1}$$

where $\overline{B_z}$ is the average axial component of magnetic field and ν_z is the axial tune. Thus the TRIUMF cyclotron, which is designed with relatively low $\overline{B_z}$ (to avoid electric stripping of the H⁻ ions), low ν_z^2 and

large R, is particularly susceptible to vertical excursions caused by B_r components. Because of the scalloping of the orbits, harmonic components of B_r and B_θ can also contribute to the vertical displacement $\bar{z}$, effectively increasing $\overline{B_r}$. At the most sensitive radius, where ν_z^2 is at a minimum of 0.02, a 1 in. excursion can be caused by an effective $\overline{B_r}$ of only 0.3 G. To steer the beam between the 3 in. high gap between the resonators therefore required very careful adjustment of those of the circular trim coils which were powered asymmetrically (i.e. currents flow in opposite directions in upper and lower coils). Nevertheless, it has been possible after careful tuning to keep the mean height of the beam (as computed on-line from the currents on the five fingers of probe HE1) within ±0.3 in. of the median plane from 70 to 500 MeV. To steer the beam to this accuracy in the presence of rapid radial variations in the mean height, manual tuning was supplemented by computer calculations of the current changes required in several neighbouring trim coils together. Under these optimum conditions virtually all the beam was found to be on the three central fingers (total height 1.5 in.) of probe HE1. Where ν_z^2 was large for radii < 170 in. the beam was contained on one finger (height 0.5 in.) only.

The relation (1) above suggests a direct method of measuring the axial tune ν_z by observing the change in mean height of the beam for a given change in $\overline{B_r}$, obtained by adjusting the trim coil currents. In practice, the currents were adjusted in a group of neighbouring coils so as to give a uniform change in $\overline{B_r}$ over a range of radii. The observed change in mean height at the probe azimuth was corrected for the sector modulation of the envelope to give the true change in the azimuthally averaged height. Figure 6 illustrates the results of the measurement, compared to a curve derived from orbit calculations based on the magnetic field survey. The agreement appears to be reasonably good. The accuracy of the measurements was chiefly limited by the requirement that no beam should be driven off the probe head; as a result the permissible displacements were only of the order of the finger width, and sometimes smaller.
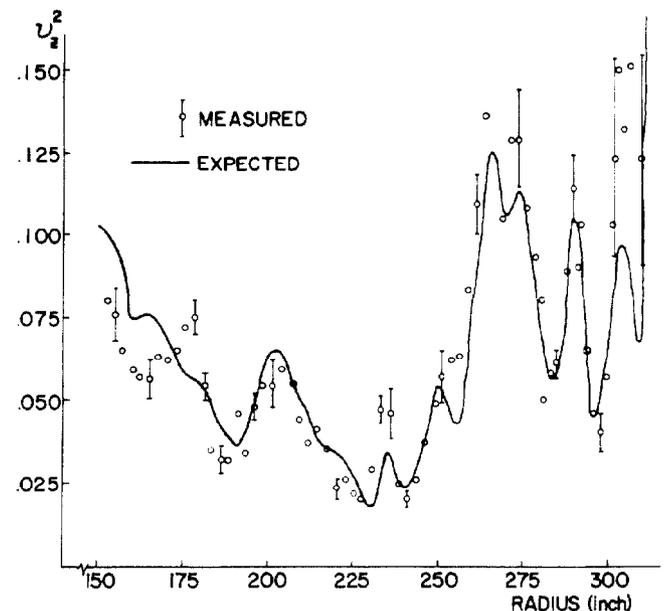

Figure 6. ν_z^2 as a function of radius. The points were obtained from measurements with the beam, the curve from calculations based on a magnetic field survey.

Extracted Beams

As mentioned above, following the first acceleration of a beam to 500 MeV on December 15, 1974, a beam was extracted within the hour from a fixed stripping foil down beam line 4 (Figure 7) to a temporary beam stopper in the corner of the cyclotron vault.
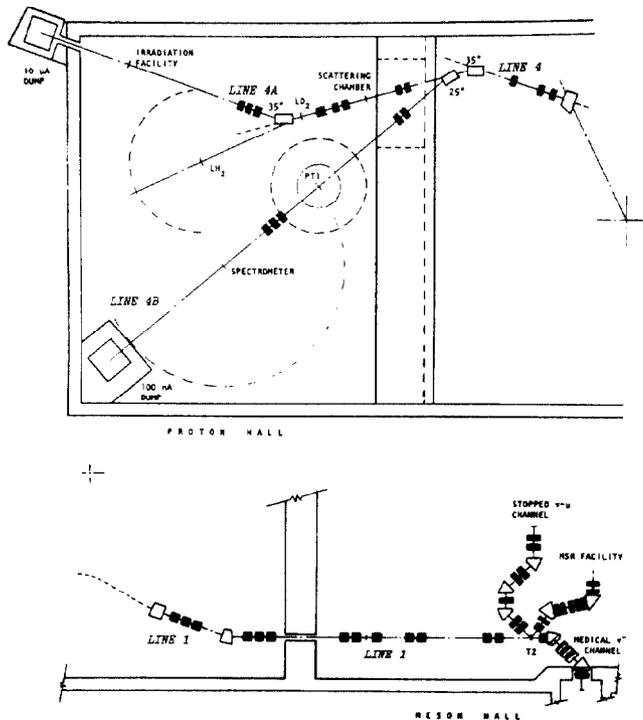

Figure 7. The experimental halls and beam lines.

In January, the moveable extraction probe 4 (Figure 1) was installed and beams were extracted at 50 MeV intervals from 180 MeV to 520 MeV. On average 10 to 15 minutes were required to locate and extract each of the lower energy beams. Subsequently these beams were transported down beam line 4B and, in some cases, down line 4A for the use of the experimental groups.

On February 20 beam was first extracted down beam line 1 to the vault wall from a fixed stripping foil at 506 MeV radius. Extraction probe 4 was then introduced into the circulating beam to produce a simultaneous 506 MeV beam down beam line 4. Subsequently beams of various energies down to 305 MeV were extracted down line 4 simultaneously with the 506 MeV beam in line 1.

Figure 8 shows a CRT display[8] of a 400 MeV beam spot taken on a multiwire chamber stationed at the LD$_2$ target position on line 4A (Figure 7). The wire spacing is 3 mm, so that the full width of the beam is 6 mm horizontally by 15 mm vertically.

Energy Resolution

The momentum spread Δp in the extracted beam has been measured by running beam line 4B in a dispersive mode and observing the beam width at the PTI target position. The observation was made using a gas filled multiwire chamber with 2 mm wire spacing. The beam line was set up in its normal achromatic mode for a 500 MeV beam and then switched to the theoretical dispersive settings. Calculations lead us to expect that more than 75% of the spot width is attributable to
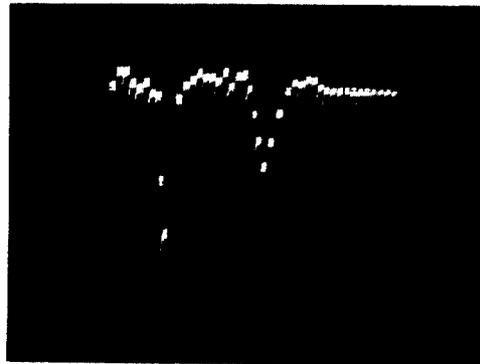

Figure 8. Multiwire chamber display of the beam spot at the line 4A target position. The horizontal and vertical displays are on the left and right respectively; the wire spacing is 3 mm.

dispersion, while the magnification of the achromatic spot is small. The dispersion at the detector was 12 cm/percent ($\Delta p/p$). The momentum spread measured for the 500 MeV beam corresponded to an energy resolution of between 2.5 and 3 MeV (full width), depending on exactly how the cyclotron was tuned.

Observations of the energy spectrum of scattered protons are consistent with these values. The University of Alberta group[9] scattered 400 MeV protons from a polyethylene target and stopped the 150 MeV protons scattered at 49 deg in a 3 in. x 5 in. sodium iodide crystal in coincidence with the recoil proton. The resulting energy spectrum is shown in Figure 9. The full width at half-maximum is 3 MeV; of this 2 - 3 MeV represents instrumental resolution, leaving 0 - 2 MeV for the energy spread of the 150 MeV protons. This corresponds to an energy spread of 3 ± 3 MeV in the primary proton beam.
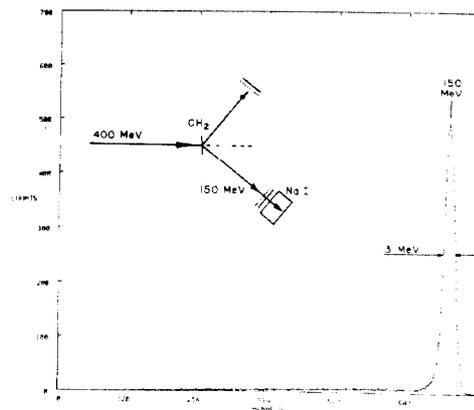

Figure 9. Pulse height spectrum of 150 MeV scattered protons stopped in a sodium iodide crystal.

Operation and Stability

Since mid-November, TRIUMF operation has been on a two-shift per day, 14-shift per week basis. Beam has been accelerated on about 50% of the days with the remaining time primarily for installation of new equipment such as the extraction probes and external beam lines. Since January the available beam time has been divided roughly equally between beam dynamic studies in the cyclotron, commissioning the external beam lines and delivering beam to expimenters' targets. The beam stability on target has been very satisfactory with periods of several hours running with no operator intervention.

Conclusion and Future Developments

The achievements of the first three months of operation of TRIUMF can be listed as follows:

1) Acceleration of an H^- beam to an energy of 500 MeV and above.
2) Variable energy extraction down a 30-meter beam line to a dump has been demonstrated over the energy range 180 - 520 MeV.
3) Simultaneous extraction of beams of differing energies has been demonstrated.
4) Some progress has been made in understanding and improving the performance of the accelerated beam.
5) Some short periods of beam time have been provided to experimental groups for lining up and timing in their counters.

Further work in the development of TRIUMF can be summarized in the following objectives.

1) To improve the vacuum by about a factor of 5 from the present operating pressure of 2×10^{-7} Torr.
2) To improve the reliability and stability of the facility -- although the latter appears to be very good indeed.
3) To improve the energy spread of the raw beam by optimizing the injection conditions and by working with the sets of harmonic coils, the defining slits and eventually with the third harmonic of the RF. It should be possible to achieve an energy spread of much less than 0.1% with these techniques.
4) To further progress in understanding and improving other properties of the accelerated beam.
5) To accelerate H^- ions from a Lamb shift type polarized ion source, which has already been commissioned at 300 nA, 80% polarization.
6) Finally, to start as soon as possible, delivering stable, long-term and simultaneous beam allocations to the various experimental groups.

References

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John Reginald Richardson

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The recent death of Reg Richardson has robbed the cyclotron community of its most senior figure. His many achievements over a long career include the first demonstration of phase stability, the first synchrocyclotron, the first sector-focused cyclotron, and one of the two cyclotron meson factories.

1 Introduction

John Reginald Richardson, who was one of the dominant figures in the development of cyclotrons over his long career, and a founder of these conferences, died in California on November 25, 1997, after a lengthy illness.

Figure 1: Reg Richardson - 1940 and 1975

Reg was born in Edmonton in western Canada in 1912. His parents were professional musicians who had emigrated from Scarborough in England in 1905. The family soon moved to Vancouver and he spent his early boyhood just a few blocks from Stanley Park. Then at the age of 10 his parents moved on again to California. After high school in Los Angeles he attended UCLA, where Glenn Seaborg was a contemporary and remembers him as the top physics student in their class of '33.

Already showing a talent for recognizing the best scientific opportunities available, Reg then enrolled at Berkeley and acquired Ernest Lawrence as his supervisor, receiving his Ph.D. in 1937 for a study of the photo-disintegration of the deuteron. Following a year as National Research Fellow at the University of Michigan, he was appointed Assistant Professor of Physics at the University of Illinois - in both places continuing his studies of nuclear structure and bringing Berkeley expertise to bear on newly-constructed cyclotrons. In 1942, however, following U.S. entry into the war, he returned to Berkeley to work on developing calutrons for electromagnetic separation of uranium for the Manhattan Project.

2 Phase Stability and Synchrocyclotrons

When the principle of phase stability was discovered by Veksler and McMillan, it was at first thought that moderately high-energy injection was required, so that it could not be readily applied to cyclotrons. Reg, however, from his calutron experience, was able to show that 1-5% of the ions emerging from an ion source could be captured in the stable bucket. In 1946 he led an *ad hoc* group of Ed Lofgren, Ken MacKenzie, Bernard Peters, Fred Schmidt and Byron Wright in converting the fixed-frequency 37-inch cyclotron at Berkeley to fm operation as the first synchrocyclotron [1]. This not only provided the first demonstration of the phase-stability principle (Goward and Barnes' first operation of a synchrotron followed a few months later), but also confirmed the feasibility of converting the 184-inch cyclotron from classical to synchro-cyclotron. Lawrence's decisive reaction to this result is described by Reg in his recollections [2].

That year he also took up a faculty appointment at UCLA, and was soon joined by MacKenzie and Wright, and also by David Saxon, forming a strong nuclear physics group. Moreover, the 37-inch cyclotron was obtained from Berkeley and converted to a 20 MeV synchrocyclotron, providing a leading research facility and an essential tool for the many graduate students attracted there. In this small group lively political and social dis-
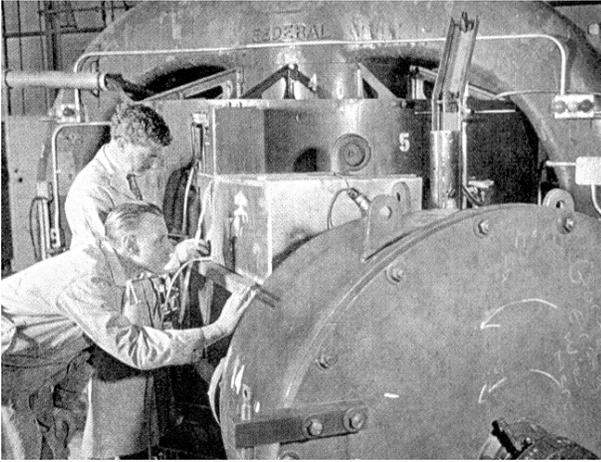
Figure 2: Reg and Ernest Lawrence with the modified 37-inch cyclotron (rotating capacitor in foreground).

cussions took place, with Reg being conservative and the others liberal. David Saxon particularly remembers the time of the loyalty oaths at the university, when Reg readily agreed to testify on his behalf at a hearing, although their political beliefs were very different.

3   Sector-Focusing Cyclotrons

In the next few years many higher-energy synchrocyclotrons were built, providing usable secondary beams of pions and muons, and inaugurating the era of accelerator-based particle physics. But the pulsed operation of these machines limited beam intensities to < 1 μA, so when a need for intense 200-300 MeV deuteron beams led to the construction of the 60-foot diameter Mark I linac at Livermore, Reg championed a more modest alternative, a cw cyclotron based on L.H. Thomas's pre-war suggestion of using a magnetic field increasing radially to maintain fixed orbit frequency into the relativistic regime, while varying azimuthally to provide axial focusing. He had retained his connexions with Berkeley, and there in 1950 he led David Judd, John Jungerman, Elmer Kelly, Robert Pyle, Robert Thornton and Byron Wright in building the first sector-focused cyclotrons – two electron models (Figure 3) which reached $\beta = 0.5$ [3]. Such cyclotrons are not as forgiving to tune as synchrocyclotrons, and require very accurately tailored magnetic fields (to about 0.1% in this case). This could not be achieved by shaping the iron alone but required the adjustment of over 50 trimming coils, using the beam as probe. Reg's skill and perseverance in bringing the beam to full energy led one of the engineers, who normally classified physicists as "2-knob men" or "4-knob men", according to their tuning ability, to concede that here was a "10-knob man".

This work remained classified until 1955, but once the secret was out sector-focused cyclotrons rapidly proliferated. With the incorporation of further ideas, such as strong focusing via spiral sectors, superconducting magnets, separated sectors and external injection , there are now more than 250 operating around the world, providing beams ranging from 1.5 mA of 590 MeV protons to a few pA of 25 MeV/u $^{238}U^{39+}$.

Back at UCLA Reg led the design and construction of a 50 MeV cyclotron (Figure 4), taking full advantage of Kerst's spiral sector focusing and Wright and Rickey's H^- ion acceleration concept to provide clean beam extraction at variable energy. This was completed in 1962 [4], greatly increasing the range of experiments available. Reg was determined to show that a small lab could be the first to produce relativistic protons at high intensity, and indeed UCLA won the race with the much better funded national labs at Berkeley and Oak Ridge by a year.

One example of Reg's skill at cyclotron design is illustrated by the time that the UCLA magnetic field data was sent to Berkeley to run on an IBM computer to verify his hand calculations. When there was a big disagreement between the two, Reg declared that the computer was wrong! It turned out that a sector number of 3 instead of 4 had been used at Berkeley by mistake, and when the correction was made the agreement was fine. This reinforced Reg's lifelong suspicion of computers.

Tom Cahill remembers the tuning method used by Reg to make sure the beam was at full energy. Before the cyclotron was moved to its shielded vault, he put a radiation meter on the control console and set it to 100 mR/h. He then tuned up the beam until the meter reached full scale, when he sent everyone else out of the building and continued tuning.

Graduate education at the UCLA cyclotron was very much in the Lawrence tradition, with students being given full responsibility for building their equipment, and
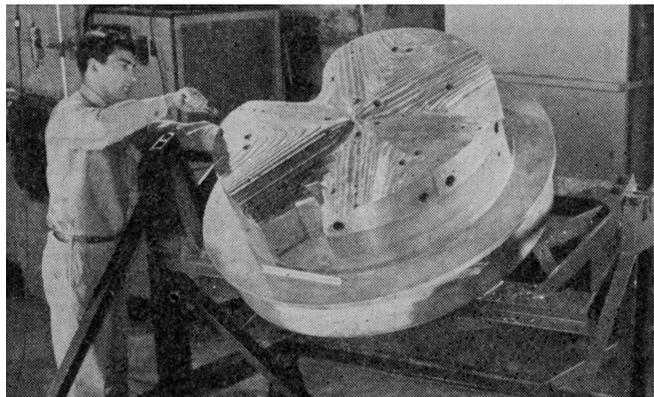

Figure 3: One of the magnet poles for the second electron model sector-focused cyclotron.

Figure 4: Reg and Byron Wright with the UCLA H⁻ cyclotron.

receiving hands-on training from the technicians in skills such using a lathe and hard soldering. Each student had to complete an experimental project before going on toward his Ph.D. There were no engineers so students had to make their own drawings of new equipment. Reg and the other faculty were excellent teachers and recruited many students from their courses. Graduate student Tom Cahill relished "the freedom Reg gave us as students, with real responsibilities for important components of the program. How often today do graduate students have the freedom to fail, without which success is a bit hollow? Reg trusted us, and we responded."

Each year Reg's birthday was celebrated by taking left-over alcohol from the deflector cleaning supply and adding it to orange juice. When everyone reached a good mood, Reg could be persuaded to sing his composition "The Cyclotron Song" to the tune of "Sweet Betsy from Pike" (or "The Ould Orange Flute"):

Oh the cyclotron protons swing round all the day;
They bump into copper and tungsten we say,
Into zinc, into fluorine, into tantalum too,
But my boy (or girl) just take care they don't bump into you!!

A range of six meters in air do they have.
If they hit you, my boy, no more hair will you have;
So it pays to take care when the beam's in the air,
Or you'll lose all your interest in the charms of the fair!

Those protons excite some compound nuclei,
Which emit some fast neutrons of energy high;
If those neutrons collide inside of your hide,
To you sex will be theory that's never applied.

By this time Reg had become a major figure in national and international physics. Within the U.S. he was a member of the Committee of Senior Reviewers for the USAEC, and served on review committees for various national laboratories. He also spent two sabbatical years in London as liaison scientist for the U.S. Office of Naval Research.

Internationally, he had become well-known as the author of two major review articles – one on cyclotrons in the 1948 *Encyclopaedia Britannica*, and one on sector-focused cyclotrons in *Progress in Nuclear Techniques* [5], which became a bible for many of us in the sixties. He was also one of the founders of this conference series, hosting the second conference at UCLA in 1962, and initiating its sponsorship by IUPAP.

4 Meson Factories

His 1963 proposal for a 750 MeV H⁻ cyclotron "meson factory" [6] – a term he coined – was unsuccessful in attracting funds to UCLA, but was adopted in Canada in a downsized version, making possible the successful construction of the 520 MeV, 200 μA TRIUMF cyclotron (Figure 5) – a project over whose construction and commissioning [7] Reg presided with great effectiveness as the second director (1971-6). He personally tuned the beam from injection to extraction – a much-enjoyed reward for all the years of planning and administration. His personal involvement with the project and its staff in those formative years inspired great devotion and provided an important lesson in management style.

Figure 5: Reg (centre) and the TRIUMF staff during assembly of the 520 MeV cyclotron.

It was not inappropriate that Reg's meson factory should be built near Vancouver: since 1946, he had maintained a summer home nearby on Galiano Island, and it was there that the design was conceived. After retiring as director, another relaxing summer on Galiano produced schemes of kaon factories – and the ink on the 30 GeV KAON proposal was hardly dry before he had

schemes afoot for the addition of a superconducting ring to reach 100 GeV [8].

5 Nuclear and Particle Physics

Throughout his career Reg continued to participate in nuclear and particle physics experiments, the most notable perhaps being those which introduced the Kurie plot for determining β-decay energies [9], the first measurement of the lifetime of the charged pion, some "tweaking of the dragon's tail", and comprehensive surveys of nucleon-nucleon scattering.

In 1948 Reg visited Berkeley to measure the lifetime of the π^- meson. He used the cyclotron principle that ions in a magnetic field take a constant time to make a revolution, independent of their speed, measuring the π^- intensity with photographic plates after 0.5 and 1.5 revolutions in the 184-inch cyclotron fringing field. This was surely one of the last papers [10] to report measurement of a fundamental particle property by a single author!

During this time Reg also worked with David Judd and others on a system in which the "dragon's tail was tweaked". This involved rotating disks of fissile material through a slot in a subcritical sphere to produce a burst of neutrons for testing shielding in a proposed airplane to be powered by a nuclear reactor [11].

The nucleon-nucleon scattering experiments started at UCLA at energies up to 14 MeV, continued up to 50 MeV with the new cyclotron, and concluded at TRIUMF over the range 180-520 MeV. He was one of the founders of the International Conference on Few-Body Problems in Physics.

6 Concluding Remarks

Reg's greatest legacy, however, must be the more than 250 sector-focused cyclotrons now in operation around the world, whose intense beams have opened up new opportunities in many fields. This was acknowledged when he was awarded the Wilson Prize of the American Physical Society in 1991, the citation reading:

> "For his original contributions to the development of cyclotrons. These include the first experimental demonstration of phase stability, the first synchrocyclotron, and the first sector-focused cyclotron. This work is the basis of numerous cyclotrons that have had and continue to have major impact on nuclear physics, solid state physics, chemistry and medicine."

Reg will be greatly missed by his colleagues, past students and family, to whom he was devoted. He greatly enjoyed water sports, including boating and snorkeling, and in well-organized retirement was able to split the year between his three homes in Malibu (California), Maui (Hawaii) and Galiano Island (British Columbia). He will be remembered not only for his monumental achievements and his impact on generations of nuclear and accelerator physics students, but also for his elegant style and for the warm hospitality which he and his family always offered.

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