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BEAM DIAGNOSTIC TECHNIQUES FOR CYCLOTRONS AND BEAM LINES

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Abstract

The paper will review methods of measuring and improving the beam properties and cyclotron performance for both the internal and external beams. Recent advances in computer assistance and instrumentation will be presented together with beam dynamics considerations used in planning and interpreting experiments. Features peculiar to the new high-energy, high-intensity machines and the coming generation of heavy ion machines will be discussed.

Introduction

The beam properties of interest have not changed since previous review papers.[1-3] However, the advent of multi-particle multi-energy machines with good beam quality has meant that diagnostic measurements are carried out more frequently than before. Also the investment in computer control of power supplies has been extended to computer-assisted diagnostics and to complete experiments, initiated by an operator, but carried out by a computer. High-energy, high-intensity machines require different techniques to be used in the design of probe heads, and more attention paid to beam losses. Conversely, some heavy ion machines may wish to operate with beams much less than 1 nA.

Signal Sources

Traditionally the beam is stopped in an electrically insulated probe head and the current brought through a vacuum feedthrough to a meter or amplifier. A probe head thickness of 1 to 2 cm of copper is sufficient to stop 100 MeV protons and any secondary particles produced are retained close to the probe head by the magnetic field of the cyclotron. In the field-free regions of the beam lines a bias potential of a few hundred volts is usually sufficient for this purpose. A 500 MeV proton has a range of 20 cm copper, and a conventional probe head would be unwieldy. The secondary particles have themselves a moderate range and magnetic rigidity and the problems of beam scattering and probe and equipment activation become more severe. Consequently indirect methods are employed that use probe heads with a minimum amount of material. The LAMPF Faraday cup is described in Ref. 4. The TRIUMF cup design is simpler, since the maximum proton energy is 520 MeV, but still consists of a re-entrant lead cavity 42 in. long weighing 600 lb. It is expected to measure beam currents up to 1 μA accurate to within 1%. The former limit is set partly by power dissipation and partly because several metres of shielding are required at high energies.

The secondary emission effect (SEM) is used at all meson-producing machines. Passage of a beam causes ionization within a material and electrons of a few eV can escape from the outer few 100 Å of the surface.[5] These may be removed by a clearing field of the order of 100 V/cm and the current from the material or on a collector recorded. The electron current is proportional to the incident beam current although the ratio for a beam incident normally on a foil is only a few per cent/surface. Where devices are installed in a strong magnetic field, the emitting foil is inclined at an angle to the field lines to allow electrons to escape. Such devices may be unbiased[6]; however, the weak clearing field, 10 V/cm, used at TRIUMF increased the SEM current by 30%. A bias voltage is essential for parallel plate emitter-collector devices. Leakage currents are reduced if the insulation separating emitter and collector has a ground point. Pulsing a bias voltage can induce a transient current which can serve to check the operation of the system.

The secondary emission coefficient is expected to vary with incident particle energy as the stopping power (dE/dx) for that particular medium. It is surface dependent and multiple electrode devices should be made from the same sample of material. If possible, devices should be enclosed in their own clean, high-vacuum system. Those exposed to working vacuums with periodic venting and pumping down show a secondary emission coefficient that varies with time and beam exposure. This aging effect is illustrated in Fig. 1 for a TRIUMF profile monitor made with 0.0013 in. carbon wire placed in front of the meson production target and exposed to 17,000 μA h of beam, including periods of operation with 100 μA.

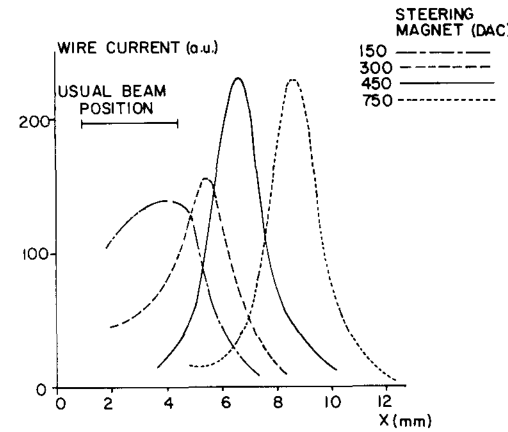

Fig. 1. Response of a TRIUMF carbon wire secondary emission profile monitor, exposed to 17,000 μA h, to beam steered across the surface.

After a preliminary aging the subsequent change is slow, perhaps a few per cent per month. At SIN secondary emission fingers several millimetres wide are placed parallel to the beams; the protons travel a greater distance in the surface, and SEM coefficients of 40-200% are reported.[7] The electrodes in multi-finger devices must be carefully aligned when this technique is used. For these reasons it is desirable to calibrate secondary emission devices against a reference device, or to cross-check the efficiency of multi-electrode devices by steering the beam.

An H^- beam current can be measured by stripping the electrons from the ions and recording the electron current. The electrons are quite energetic, 270 keV from 500 MeV H^- ions; they are bent into orbits with radius m_e/m_{H^-} of the ion radius and can pass through a thin foil several times before coming to rest. Electron-collecting caps should be provided above and below the foil, if possible, because the electrons can be scattered through quite large angles, and can even be backscattered out of a thick foil. It is difficult to provide caps for a probe[8] with several horizontal fingers, or foils that dip into the beam, and a Monte Carlo program PECS was written to estimate their electron capture efficiency by calculating electron trajectories. For a 450 MeV H^- beam normally incident on simple foil strips, without caps, installed parallel to magnetic field lines, it was found that the electron retention efficiency was 88% for aluminum and 69% for tantalum; it fell by about 50% if the foil was inclined at 5° to the vertical. The retention efficiency depends on beam energy and magnetic field. Such devices should also be calibrated. However, calculations and experiments show that a probe head equipped with adequate electron-collecting caps can be used to measure H^- beam current to within a few per cent.

Residual gas ionization and ionization chambers are also used to measure beam current and profiles. Passage of a 500 MeV proton beam through 1 cm-atm of argon produces an electron current of about 100 times the incident proton current. This gain is calculable, making ion chambers absolute devices. This is clearly useful for beams of low current that have sufficient energy to pass through the device; currents of ~1 pA have been measured. The response varies with energy and is proportional to stopping power of the medium; gain decreases due to space charge build-up have been reported[4] for beams of 10 pA/mm^2 in approximately 1 atm argon.

Timing information and signals proportional to current can also be obtained from non-intercepting capacitive or inductive pick-up monitors. It is claimed that capacitive devices usually have somewhat lower noise; inductive devices are more easily calibrated by means of an auxiliary winding carrying a pulse of known charge with a shape similar to the beam pulse. A resonant cavity at SIN measures currents to within 1% and is stable to 1% for periods of weeks when a simple recalibration is performed remotely. A recent theoretical study was made of capacitive devices by Cuperus.[9]

Scattered beam or secondary radiation can also provide timing information, monitor beam intensity or profiles (especially useful at high energies or low intensity), and identify primary beams of heavy ions. Calorimetric methods also yield intensity; neutron and γ ray loss at high energies may require corrections of about 20% depending on shielding. These methods do not interfere with beam delivery if existing targets, beam dumps or vacuum windows are used. At very low currents detectors may be placed in the primary beam. Machines may be set up using a more abundant particle with a similar charge/mass ratio.

Although sources yielding electrical signals are preferred because of their versatility in signal processing, visual methods are still important since scintillators are cheap, easily manufactured, yield x-y correlations and can often be attached to existing equipment. $A\ell_2O_3$, BeO, ZnS and various phosphors have been used; LBL report[10] a green phosphor P22 GR120 (U.S. Radium Corp.) which, when used in conjunction with a standard TV camera, was observed to respond to 1 electrical picoampere of 360 MeV $^{16}N^{6+}$.

Activation foils and auto-radiographs are useful off-line measures of the integrated beam behaviour. At medium energies cross sections are known to vary slowly with energy.[11] Aluminum and carbon are convenient materials to use and their products ^{11}C, ^{24}Na and ^{22}Na give a useful range of half-lives. The ^{22}Na product is regularly used at TRIUMF to monitor the integrated beam current for periods of months, and the results agree well with other logging methods. A second foil sandwich adjacent to the first but shielded from the proton beam is sometimes used near a beam dump to monitor neutron induced reactions. Auto-radiographs can be made conveniently with 3000 ASA Polaroid film; however, exposure times should be increased one-hundred fold over X-ray film: 20 h exposure for an activity of 1 mrem/h on contact. An aluminum activation foil placed at the vacuum tank wall 4.5 m downstream from a TRIUMF carbon stripping foil showed a pronounced peak in activation, 7 mm wide, due to H° ions from the foil. The ratio of H°/H^+ was 0.05%, larger than expected. An auto-radiograph of the stripper showed a beam spot ~4 mm wide and the two together gave a rough estimate of the emittance of 0.5π mm-mrad.

A multi-plate SEM current monitor was constructed[12] from $A\ell$ foils flashed with gold and the experiment illustrated in Fig. 2 used to calibrate it. The monitor has its own ion pump IP and the dark current is less than 0.3 nA, equivalent to 1 nA beam. The first bending magnet was used to switch the beam from the Faraday cup FC to the SEM monitor near the dump. The cyclotron current probe HE2, which recorded stripped electron current and was equipped with adequate caps, was used to shadow the stripper foil X4 and cross-calibrate the Faraday cup and SEM monitor. PM was a profile monitor. The experiment was performed at 210, 350 and 482 MeV. The currents

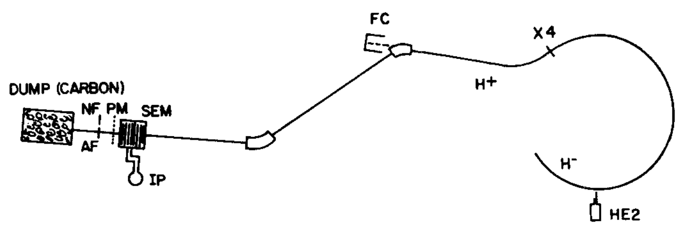

Fig. 2. Experiment to cross-calibrate various TRIUMF probes and monitors.

read by the Faraday cup and HE2 agreed to within ±4% with no obvious energy dependence. The SEM coefficient varied with energy as the stopping power of gold, as shown in Table I.

Table I

Proton energy (MeV)	SEM coefficient/ surface (%)	SEM coefficient/ $(dE/dx)_{Au}$
210	5.5	2.4
350	4.1	2.5
482	3.5	2.4

An aluminum activation foil (AF) was compared with the integrated output of the calibrated SEM monitor for a beam of about 1 μA of 482 MeV protons over two days. The two measurements agreed to within 1%; the ^{22}Na activity in the adjacent neutron foil NF was 1% of that in AF.

Comparison of gold-flashed aluminum and aluminum foils did not give SEM coefficients in the expected ratio of the stopping powers for the two materials. CERN report[13] that the same device used for protons and ^3He ions did not give a response in the ratio of (dE/dx) for the two ions. The deviations from expected values were about 20%.

Equipment and Techniques

Cyclotron

The beam can be worked out of a cyclotron using just a basic current-measuring probe that moves with radius. By powering trim coils to produce a B_z or B_r component, any loss can be identified as a phase or height excursion. Once a beam is established at extraction radius, the effect of any variable on the machine acceptance can be measured and that variable optimized. As mentioned below, quantitative information can be obtained from these detuning techniques; however, they are often slow and sometimes difficult to interpret due to competing phenomena; also the parameter being measured

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can be distorted when detuned. Additional equipment to provide direct measurements is to be preferred.

Radial Properties. One of the simplest and most valuable modifications is to create a differential probe by dividing the head into two regions, one being a radially narrow finger to give density information. The interpretation of these density patterns has been reviewed elsewhere.[1,14,15] Suffice to say that if individual turns and their spacing ΔR can be distinguished over a precession cycle in the adiabatic region, then the coherent amplitude A_c may be determined from $(\Delta R_{max}-\Delta R_{min})/4\pi(\nu_r-1)$, ν_r from the number of turns per cycle and a value of the energy gain/gap crossing by comparing ΔR with precalculated values. If the phase spread is known, then the incoherent amplitude A_i may be estimated from the turn width. If the width of the turn oscillates at twice the precession frequency, it implies a mismatch between radial emittance and acceptance. If the width oscillates with the same frequency, then the energy spread is not matched to the cyclotron.

If the cyclotron does not have separated turns, density measurements can still assist when empirically optimizing the radial quality, but shadow measurements can be used to determine A_c and A_i. The beam is intercepted on a fixed probe and a second probe, separated by a large angular distance, is driven in from the point of no interception to complete interception of the beam. This distance is called the shadow width. Measurements should be made at several fixed probe positions spanning a precession cycle and the results interpreted with care[16] since the particle distribution in phase space is in general neither uniform nor regular. Nevertheless, a measurement of A_c at TRIUMF gave 0.075 in. with the shadow technique and 0.068 in. with a differential probe. It is often difficult to determine the radii where a shadow starts and finishes; Monte Carlo calculations for a variety of beams at TRIUMF have shown that the shadow width defined from 5% to 95% interception averaged over a precession cycle is about $3A_i$. This is good enough to provide a figure of merit when comparing beam quality with different injection conditions.

At large values of ν_r (high energies) it is not possible to obtain A_i or A_c by either the shadow or differential probe techniques unless the turns are separated. At $\nu_r = 1.5$ a differential head sees the same beam density for all values of A_i or A_c, provided $A_i > \Delta R$/turn. However, at TRIUMF the energy spread, and to a lesser extent the divergence, of the extracted beam is correlated with radial amplitude.

Beam-intercepting fingers or slits can be used to give density information, the current modulation being observed on a stationary probe at larger radius. The technique is less desirable than a direct density reading, especially when setting slits, but is useful in regions where the RF pick-up is comparable to the beam current signal. Such fingers are used in the TRIUMF dee gap to minimize radial-longitudinal coupling effects arising at injection.[24]

Vertical Properties. The vertical position can be measured with a probe head divided horizontally into several segments; this is often combined with the differential feature. Studies at TRIUMF showed that a simple algorithm, based on the first moment of the current on the five fingers of the probe of Ref. 8, gave the position to about 1 mm—almost as precisely as several more sophisticated algorithms. It is difficult to get an accurate estimate of the vertical width unless many narrow fingers are used. A better method is to scan a wire or pin through the beam or to excite a trim coil pair asymmetrically to produce a $\bar{B}_r$ component and scan the beam across a finger of known width. If the coil form factor is known, this type of measurement can give a good value of ν_z^2 from $\nu_z^2 = (\bar{R}\cdot\bar{B}_r/\bar{B}_z\cdot\Delta_z)$.[18] A correction, less than 15% in TRIUMF, must be made for the modulation in beam height produced by sector focusing. If turns are separated, ν_z can be measured by inducing a coherent oscillation.

During TRIUMF commissioning the multifinger probe showed apparent excursions in height that oscillated more slowly with radius than expected from ν_z, yet faster than the expected vertical equilibrium orbit. The oscillations were high on one side of the machine and low on the other. An explanation is illustrated in Fig. 3 which shows the height of a particle with a radial amplitude greater than the radius gain per turn oscillating about the equilibrium orbit near $\nu_r-\nu_z = 1$. The oscillation is such that the probe would only intercept the particles approximately every $1/(\nu_r-1)$ turn. When observed, the particle always has the same phase of vertical oscillation and the apparent height deviates from the true mean height, oscillating with typical "beats" as the probe moves away from the resonance region. This was observed for a beam of 40° phase width at the resonance energies up to 400 MeV. It was surprising to find evidence of coherent motion for a beam of such wide phase width after 1000 turns; however, Monte Carlo studies showed that in fact the radial phase space can have a local dense region which does not coincide with the "centre of gravity" of the entire bunch.

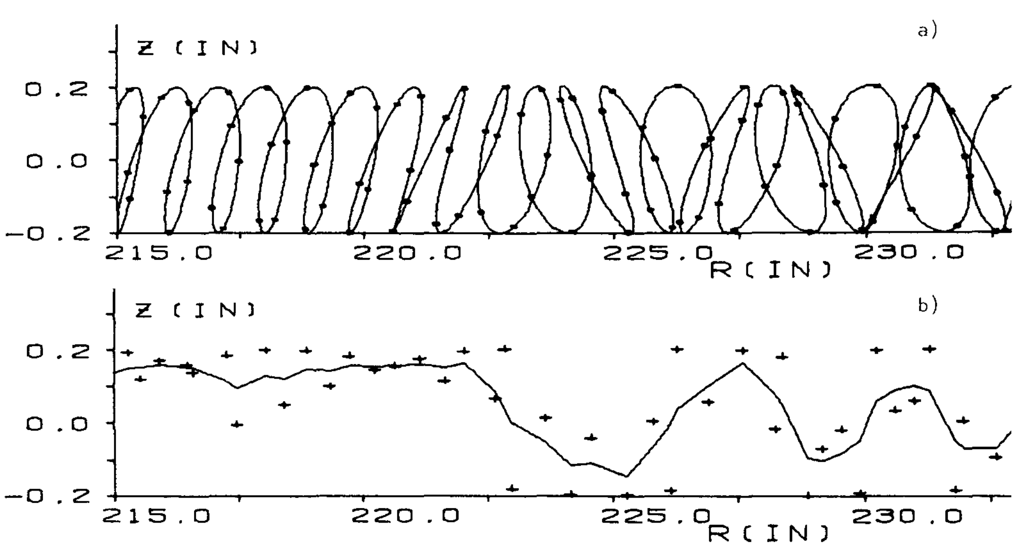

Fig. 3

(a) The dots show the calculated turn by turn position of a particle with radial amplitude larger than the radius gain per turn near the $\nu_r-\nu_z=1$ resonance at 221.9 in.
(b) The turns that would be intercepted by a probe show an apparent vertical deviation from the equilibrium orbit.

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The effect could be accentuated or diminished by altering harmonic coil settings.[8]

High Power Operation. SEM devices are made thin to reduce operating temperature as well as activation. The beam power input depends on the mass of material, while the heat dissipated by radiation depends on the surface area. A molybdenum finger 2 mm long in the beam direction and 0.2 mm wide was used at SIN to measure the beam density distribution at extraction. Thermionic emission was observed with beams of 30 μA. A replacement finger, made out of 15 μm Mo sheet bent double for rigidity, has operated at 70 μA and theoretically should work at 200 μA.[7] The spill at 70 μA from even this thin finger is close to tripping radiation monitors. Both SIN and TRIUMF have found that it is possible to perform diagnostic operations at low current and then increase the intensity. However, both use a water cooled probe at low energies when commissioning the injection system. SIN has a 3 kW differential probe operating between 70 and 90 MeV; TRIUMF has a 2 kW probe at 20 MeV.

Most machines have liners to protect their dee tips from vertical beam excursions. The meson factories are concerned about losses of 1% or less. SIN has simple air ionization chambers around the cyclotron to observe local spills on internal beam stops. TRIUMF has two collimating bars equipped with thermocouples mounted on the upper and lower resonator between injection and 70 MeV. Between 70 and 500 MeV thin scraper foils are mounted above and below the beam plane to define the vertical aperture.[17] H^- ions hitting the foils are stripped and the protons travel through secondary emission monitors at the tank wall that measure the lost beam directly.

Timing. The phase of the beam bunch with respect to the accelerating voltage and the phase width can be determined as a function of radius by detuning the RF or the magnet trim coils.[1,19] However, the method is slow and there is coupling between phase and radial motion. A phase shift, especially near a radial resonance, can alter the centring and affect the phase history in regions where no field change has been made.[14] An improvement was to place a γ-ray detector close to the vacuum tank, intercept the beam with a current probe and time the arrival of the radiation pulse with respect to the RF. This method gives the sign of the phase deviation from isochronism, has a resolution of about 1 ns and can give a measure of the phase width. The γ-ray yield is reduced at low energies, so at MSU[20] the central region has been explored by placing a MgO scintillator on the probe head and piping the light down a copper tube to a photomultiplier. The resolution is similar to that of the γ-ray technique.

The methods above interrupt beam delivery, and non-intercepting pick-up probes are to be preferred. These were reviewed previously,[1] and since that time marked improvements in sensitivity have occurred. An advance came when the probe signal was filtered and the second harmonic compared with the doubled dee frequency, $2f_d$, since the odd RF harmonics tend to dominate the probe noise. Nevertheless, some laboratories report pick-up contributions to the second harmonic component equivalent to several microamperes of beam current, varying with operating conditions. Machines with variable frequency often require tunable filters, amplifiers, etc.; this is eliminated by employing the heterodyne technique.[21,22,31] A local oscillator is tuned to a frequency (f_1+2f_d), where f_1 is constant, and mixed separately with probe and dee signals. The two mixer outputs, now at the fixed frequency f_1, pass through narrow bandwidth crystal filters with good noise rejection to a phase detection circuit. The systems can operate with beams of about 10 nA. At VICKSI the signals from several probe heads are multiplexed to a common set of electronics[22] for better relative stability; the fourth harmonic is used since it is the stronger component of the beam pulse and gives better time resolution of 1° or 2° RF. At Groningen MOS-FET amplifiers have been placed within a few millimetres of the probe heads[23]; this presents a high input impedance, and the actual pulse shape can be observed from the amplifier output. The amplifiers have lasted 1.5 yr in moderate radiation fields. Groningen also modulate the beam intensity at low frequency, un-modulated RF pick-up is rejected by a synchronous detector and a resolution of 1° RF is obtained with nanoampere beams. Similar techniques can be used in beam lines but are less sensitive since a probe head in the cyclotron extends over several turns.

The beam current is modulated at other laboratories also. At MSU[20] a frequency of 25 kHz is superimposed on the beam and the modulation detected on the differential probe. It is hoped to provide a means of automatically counting turn number, especially in the case when centring is so poor that overlapping turns occur. At TRIUMF the beam is normally pulsed at approximately 1 ms on, 0.01 ms off. The beam-off signal is detected by non-intercepting monitors in the beam lines to give information on current and the flight time through the cyclotron. The latter is affected by magnet tune, dee voltage and frequency variations.[24]

With a variable energy H^- cyclotron one can extract the beam and time the arrival of scattered ions with respect to the RF. The sign of the phase deviation can be resolved by slipping the beam in phase and extracting both the accelerated and decelerated components.[19]

This deceleration technique is useful in that the decelerated beam passes through a region twice, and comparison with the accelerated beam can serve to identify small non-adiabatic changes in beam properties. Figure 4(b),(c) gives evidence for a non-adiabatic increase in vertical amplitude between 300 and 400 MeV, probably due to coupling at $\nu_r-\nu_z=1$, and shows that the mean polarization of the beam can alter with energy. Both effects depend on machine tune. This technique is not limited to negative ion machines since accelerated and decelerated components can be distinguished by non-intercepting monitors or the current read on a finger inserted vertically. The technique may be useful for very high-energy machines that pass through several resonances, with the caveat that the beam quality may deteriorate during the phase slipping and that the coherent behaviour will not have the same phase with respect to the magnetic field.

Beam Lines

Profiles and Position. Beam profiles and position can be determined by several devices. Rotating or oscillating scanning wires and blades are commonly used at frequencies of up to 25 Hz and are commercially available. They can stop the beam or emit secondary electrons, and different devices have operated down to 10 nA at both low and high energies.[25,26] A bare wire is often used, although clearing fields are sometimes necessary; LAMPF[27] report them necessary to describe the tails of an H^- distribution but not necessary with proton beams. Rotating loops are used at VICKSI; they are mechanically rigid and display two peaks which coincide when the beam is centred on the loop. The beam must be steered so that the peaks exactly coincide, or are completely separate, to get accurate profiles. Jaws can be moved across the beam and the output differentiated to give a profile, but this technique is more useful for investigating the halo surrounding the beam core.

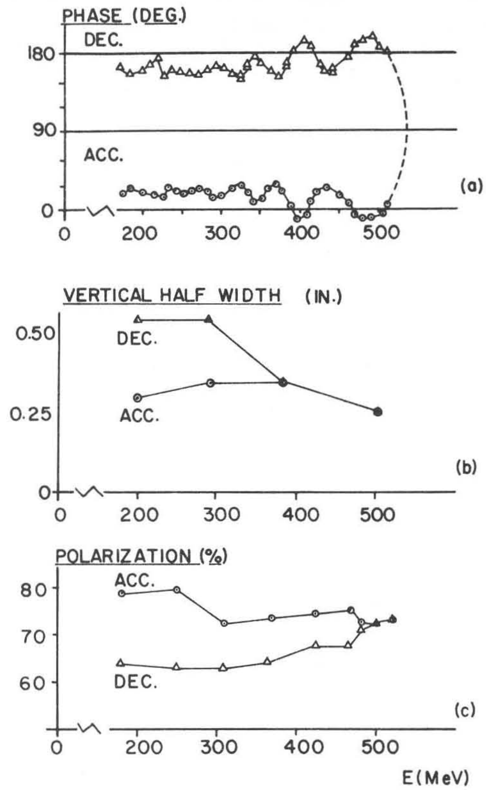

Fig. 4. Comparison of the properties of accelerated and decelerated beams: (a) Phase history obtained by timing the extracted beam with respect to RF; (b) Height measured by lowering a finger foil into the beam; (c) Polarization measured for beams extracted by a vertically long, radially narrow foil.

A histogram of the beam profile can be obtained from wire grids, either used as SEM monitors (Fig. 5), or enclosed in ionization chambers (Fig. 6). The TRIUMF ionization chambers[28] can give profiles of beams of 0.1 nA; a complete readout of all the wires takes place every few milliseconds depending on beam current. Scattering-induced beam spills prevent operation at currents above 10 nA. They must be replaced every year or so as a coating appears on the wires over the region normally hit by the beam when in use and the profile becomes distorted. The multi-wire ionization chamber appears to overestimate the beam current in the tails. Figure 7 compares a profile with the halo observed by steering the beam to intercept first one side and then the other of a calibrated halo monitor. The LAMPF and TRIUMF multi-wire SEM monitors are built with 0.0013 in. carbon wires; they are calculated to operate at 800°K

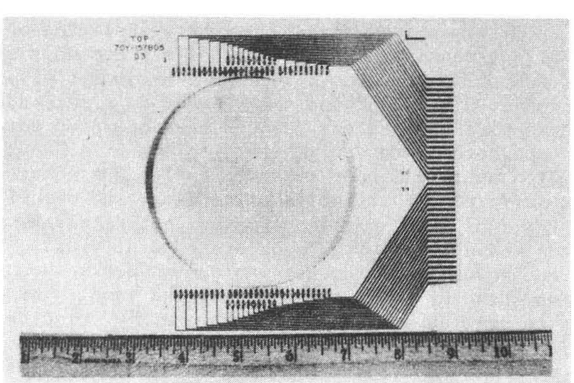

Fig. 5. LAMPF profile monitor. Carbon wires soldered to an alumina circuit board.

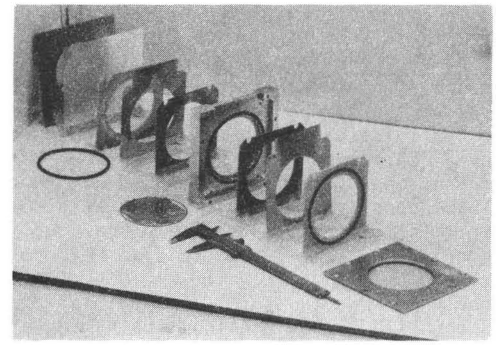

Fig. 6. Components for a TRIUMF multi-wire ionization chamber (MWIC) profile monitor.

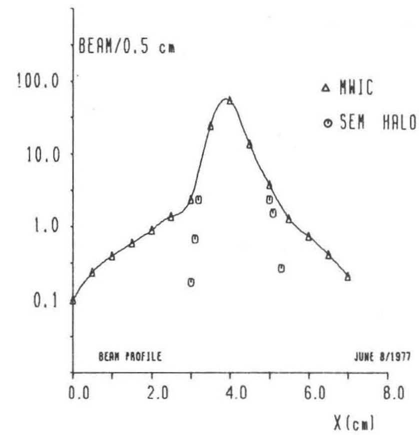

Fig. 7. Multi-wire ionization chamber profile compared with tails seen by a secondary emission halo monitor.

for a beam spot 1 cm high and 500 μA/cm^2 at TRIUMF. LAMPF have also used 0.002 in. SiC which is stronger and easier to handle than carbon but have observed a 1% elongation after exposure to 10^{20} protons/cm^2,[27] causing wires to sag on their largest monitors: 13 in. I.D. The carbon wires are plated and soldered to radiation-resistant circuit boards made from high-purity alumina. It can be observed from Fig. 5 that the solder pads present a charge-collecting area similar in size to the wires, and precautions must be taken to shield these pads from stray particles.

Multi-wire monitors have very simple, or no, moving parts; however, if aging effects occur, scanning wires or blades give a better representation of the beam profile since the single, aged blade treats halo and core uniformly, but each wire on a multi-wire device ages differently. Both SEM and ionization devices give a larger response to low-energy particles; this could affect their location downstream of a target.

Other beam profiles have been measured using protons scattered from a wire or blade; this should be done with care at very high energies since the cross sections vary steeply with scattering angle.[29] Extremely narrow profiles of the order 0.001 in. have been measured[30] by observing a scintillator with a high power optical system (Fig. 8). This is used for rapid dispersion matching of spectrometer and beam line and in an emittance measurement.

Meson production targets are often small, to reduce meson absorption, and some form of non-intercepting position monitor is necessary. Figure 9 shows an induction device used at SIN; the coils are formed by a

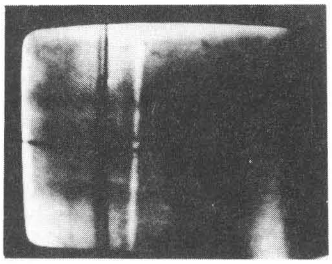

Fig. 8. Beam spot on a scintillator at the focal plane of the MSU spectrometer. The wires are 25 μ diam.

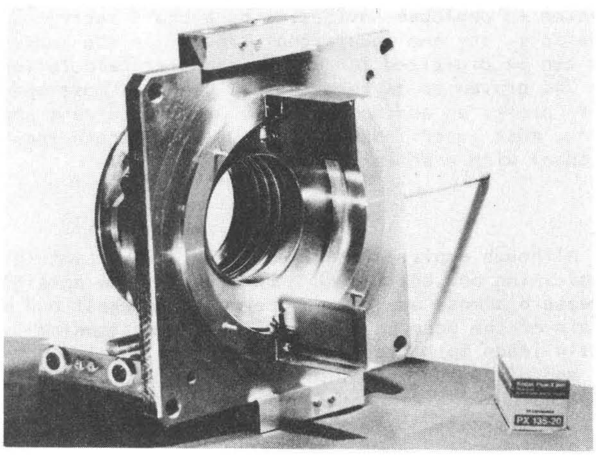

Fig. 9. Coils of SIN non-intercepting position monitor.

printed circuit technique and the device locates the beam centre to 0.5 mm at a current of 3 μA. A halo monitor is usually a set of four jaws defining an aperture through which the core of the beam passes; they can detect as little as 10^{-5} of the beam. LAMPF observes spill from movable jaws, TRIUMF the SEM current, and Osaka[31] identifies the bremsstrahlung X rays associated with the halo material. SEM halo protection devices are acceptable if calibrated occasionally since aging is worse at the edge, giving an accelerated response to a mis-steered beam.

Emittance. Many institutions have on-line systems that measure and display the emittance in seconds. At moderate energies a common system uses a slit, followed by a drift space and a plate composed of electrically separate strips parallel to the slit. Slit and plate move together across the beam so that the strips are at a constant angle with respect to the slit. A computer can process the strip signals to produce a contour plot of the emittance. A compact version is used in the Grenoble 10 keV injection line[32] where the emittance is large, several hundred mm-mrad. The slit and target strips lie on the circumference of a common circle, 12 cm diam, and rotate in opposite directions (Fig. 10).

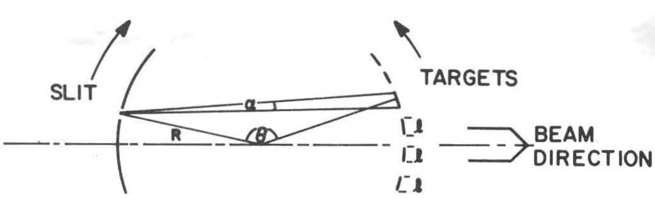

Fig. 10. Principle of Grenoble emittance-meter.

Each target maintains the same angular position with respect to the slit, and the geometry is such that all subtend the same angle. The emittance can quickly be measured to a precision of 0.25 mm and 4 mrad; the computer makes a correction for the effective reduction in slit width with angle.

A different principle is illustrated in Fig. 11. The beam is steered through two fixed slits into a current monitor and the magnets scanned to sample the beam.[33,34] It yields emittance and also correlations in the x-y plane. A similar technique using electrostatic plates and slits has been used to measure the vertical emittance in a cyclotron.[35] There are no precise motions required. Delft[36] has used a system with two plates separated by a drift space; the plates have holes drilled in a spiral fashion. One plate rotates 100 times faster than the other, a mask uncovers each hole in turn and the transmitted current is recorded; again x-y correlations can be measured. Nuclear techniques could be applied with these methods to measure energy and time structure of the transmitted beam and further correlations obtained.

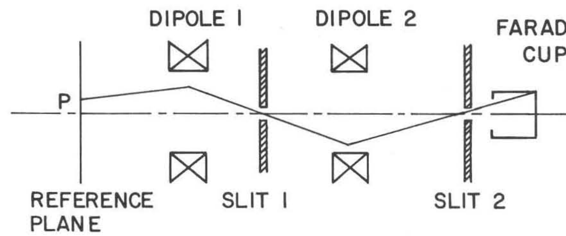

Fig. 11. Principle of the 2 bend-2 slit emittance-measuring system (which gives correlations in x and y phase space).

The low energy measurements give detailed information about the emittance which may be neither elliptical nor symmetrical. They may be extended up to perhaps 200 MeV before multiple scattering in the slit ruins the profile resolution. At higher energies the situation is not so attractive; several methods have been reported in which the emittance is assumed to be elliptical. SIN have had some success by measuring the profiles at twelve locations, some where the beam is wide and some at a waist. If the beam profiles are clean and bell-shaped, presumably corresponding to an elliptical emittance, then values of the ellipse parameters can be calculated that enable predictions to be made and the beam line tune improved.[37] Several tomographic techniques are under development[37,38,19]; they interpret the details of the beam profile and calculate the population in phase space not assumed to be elliptical. Different "views" are taken by rotating the emittance at a monitor using quadrupoles or by using monitors at several positions; a waist must be included. These methods require very precise profile measurements to yield good results.

Radiation Resistance. Mineral-insulated cable is tricky to use for diagnostic leads since it is not flexible and the seals must be well made to keep the leakage resistance high. A cable with inorganic insulation rated at 10^{13} rad and 10^{22} nvt is available (Boston Insulated Wire Co.).

Computer Assistance

In many laboratories power supplies are computer controlled and the results of beam property measurements are avilable to the computer; these provide a powerful diagnostic aid. About 40% of respondents to the survey were performing some diagnostics on line. One useful feature is the provision of "super-knobs" that control several power supplies at once to produce a change in one beam parameter while maintaining other conditions. At TRIUMF several trim coil power supplies can be programmed to provide a certain phase or height variation with radius; the amplitude of the variation can be altered smoothly. Alternatively, a "super-meter" can interpret many signals and display a single calculated parameter in analogue form for tuning.

Much tedious manual work can be eliminated where diagnostic data are digitized for on-line or later off-line analysis. The TRIUMF off-line interactive program OPDATA[39] has proved useful. It performs algebraic operations on data and fits to arbitrary functions using a non-linear least squares method. Plotting and smoothing capabilities are available. It was used to generate Figs. 3 and 7. A computer can also carry out a search procedure efficiently.[40,41]

A complete experiment may be reduced to a set of instructions and initiated by an operator when desired. Figure 12 shows some of the experiments available at Karlsruhe.[42] Such programs require an investment in time and in capital, and it is wise to consider the future savings to be made in time and convenience before going ahead. Automatic beam-centring programs are

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CICERO TABLE               PAGE 1
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0     - PHASE WIDTH INTERNAL
1     - PHASE WIDTH EXTERNAL
2     - PHASE POSITION PHI=F(R)
3     - EMITTANCE EXTERNAL BEAM
4     - STATUS EXTERNAL BEAM
5     - STATUS CYCLOTRON
6     - DIFF. TARGET R=100-1040
7     - AXIAL TARGET R=100-1040
8     - ABS. ENERGY MEASUREMENT
9     - CONTR. OF PULSING SYSTEM
----------------------------------
'RET' - NEXT PAGE
-     - PREVIOUS PAGE
Z     - BACK TO CICERO
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Fig. 12. Computer-controlled diagnostics programs at Karlsruhe.

under development at laboratories with high energy injection, e.g. SIN, VICKSI, but have been removed from the libraries of machines with central sources (MSU, Karlsruhe) where the space is better used for something else. At the latter laboratories it is faster to observe turns as they are being displayed on a chart recorder, make an empirical change and repeat the measurements. On-line applications are most useful when a result is to be obtained from several pieces of information or in operations involving simple but tedious arithmetic, e.g. the beam height from a multi-finger probe, shadow measurements, emittance measurements.

Some rules for successful programs are:

1) Allow operator intervention at critical points, display the data and computed interpretation and permit operator rejection or modification of the latter before proceeding.

2) Ensure that the beam is on when taking data, don't store noise!

3) Take data at more frequent intervals than would be required for manual interpretation. Programs to analyse a differential probe trace require typically 10 points per peak.

4) Use experimentally measured transfer functions, not computed ones. Measure at the point of interest.

5) Solve small systems. A large problem, e.g. a complete beam line optimization, tends to be ill conditioned; it is better to optimize a series of small sections sequentially. Converge slowly.

Hardware

Many laboratories are transferring the programs controlling diagnostic experiments and the display of data from the main control computer to small computers or microprocessors in order to reduce conflicts in space and time with the main logging and control functions and in order to provide faster updating of displays.

At TRIUMF any signal already digitized by the control system (over 2000 analogue parameters) can be directed to analogue devices, e.g. a chart recorder. Conversely, any analogue signal present in the control room can be digitized for use in computer calculations. This has proven to be very useful. Whereas most operators prefer an analogue display of beam current when tuning, most experimenters prefer a pulse train they can count with a scalar.

Conclusion

Although empirical tuning is still important in establishing and optimizing a beam, it is now possible to measure almost any beam property of interest and be certain of the beam behaviour. This understanding usually leads to better understanding of machine operation and often suggests improvements to equipment, mode of operation or a completely new facility; it assists manual optimization and is a requirement for computer control.

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** DISCUSSION **

J. REICH: Could you give some numbers on the precision of the different emittance measuring methods?

G. MACKENZIE: The Grenoble method, which uses a very small device, can measure to about 0.25 mm and 4 mrad. The tomographic methods are about 25% accurate. The slit methods should be much more accurate but I don't have a figure.

D. CLARK: Beam phase can also be measured by a direct interception probe and coaxial line to about 1 ns accuracy at a level of a few μA. It was done very early by the University of Birmingham, the University of Michigan, LBL and others.

G. MACKENZIE: Thank you, this is a method that interrupts beam delivery and I just went straight into non-intercepting methods. I should mention that Indiana has one of these probes that works at 1 μA at 200 MeV. Of course, these measurements get somewhat more difficult at high energies because the beam is a little more dilute.

W. JOHO: I would like to comment that, for very high currents, the tomographic method for emittance measurements might be useful even at low energies, because if you intercept with slits you destroy the space charge influence.

G. MACKENZIE: Yes. That is probably true.