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EXTRACTION OF A BEAM MADE UP OF TWO SPATIALLY SEPARATE COMPONENTS

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Abstract.- Using a stripping foil structure made up of two segments we have experimentally stripped, transported and focused a beam into two spatially separated spots. The inner part of the foil structure, a narrow "finger", was separated by 6 mm from the main part of the foil. The use of a 2 segment foil increases the overall horizontal emittance; nevertheless, the beam was transported to a focus with no significant increase in the beam line spill. The fraction of the total beam in the "tooth" part was varied from 0 to 40% by adjusting the height of the stripping foil. Monte Carlo calculations were in good agreement with the observed double beam spot profiles and the low beam spill. Additional calculations indicated that we could obtain two beam spots at a desired location and with sufficient separation to allow the clean insertion of a septum to deflect the beam produced by the "finger" into a line feeding a new high flux biomedical pion channel.

1. Introduction.- Electrostatic and magnetic beam splitters have long been proposed and used to divide a particle beam between two independent experiments [1]. Most recently [2] an electrostatic splitter has been developed at the SIN laboratory to divide a high intensity (100-200 μA) 580 MeV proton beam, one part feeding the Piotron, a large acceptance superconducting pion applicator. The extraction system of a charge exchange cyclotron is already admirably suited to serve several experiments with beams of different energy. We will show that it is also suited for easing the design and operation of beam splitters.

The TRIUMF cyclotron accelerates negative hydrogen ions to about 520 MeV. Extraction is accomplished by passing the hydrogen ions through a thin foil which strips off the associated electrons. The foil area illuminated by the beam serves as the object for the ion optical system transporting the beam to the experimental area. If the stripping foil were made up of 2 or more separate parts, each illuminated by the beam, and if the ion optical system were adjusted to form an image of the foil, then there would be 2 or more spatially separated beams at this focus. Such a separated beam at the entrance to a splitter would much reduce beam loss, improve operational reliability and could permit the employment of a magnetic splitter if the separation were large enough. The beam width need no longer be large to reduce loss on the splitter septum, although the spot size and separation are related.

The principle has been demonstrated at TRIUMF with 500 MeV beams sufficiently intense that any changes in beam spill along the transport system would be observed. The multi-component beam will occupy a larger emittance than one extracted by a single foil alone.

2. Extraction foils.- The stripping foils in regular use at TRIUMF are made from 0.025 mm thick pyrolitic graphite (Pfizer Inc.). This material radiates the 50 W per 100 μA beam deposited by the stripped electrons. It is sufficiently thin that the degradation of the extracted beam quality due to scattering is acceptable yet sufficiently strong that foils as narrow as 0.5 mm may be cut with a razor blade, mounted and used.

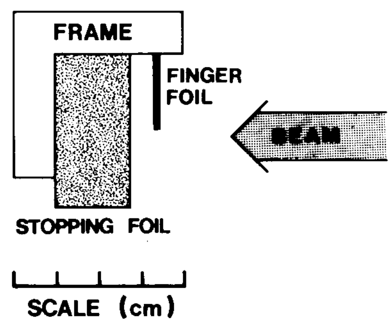

Fig. 1 : Composite stripping foil. The amount of beam extracted by the finger is altered by raising or lowering the frame.

The composite foil shown in figure 1 was assembled for this experiment. The outer component was a C-type or stopping foil. A narrow 7.5×10^{-2} cm finger, or A-type foil, was placed at the smaller radius, the distance between the two being about 0.6 cm. The vertical extent of the beam at this energy is about 1 cm, and the length of the finger was chosen to be 1.5 cm shorter than the height of the C foil so that the assembly could be raised to allow all the beam to pass under the finger and be extracted by the second component. An increasing fraction of beam would be intercepted by the finger as the assembly was lowered. A narrow foil extending through the beam extracts approximately 1% of circulating beam per 25 μm width.

3. Numerical simulation.- Several Monte Carlo codes are used to estimate beam selection by stripping foils, scattering in the foil and losses during beam transport.

The quality of the extracted beam can be materially affected by the shape and nature of the stripping foil. The divergence of the proton beam will be increased by multiple scattering in the foil. A C-type foil, extending from above to below the beam and wider than three or four times the radial betatron amplitude, will extract all beam accelerated up to it. Charge exchange extraction violates Liouville's theorem and, at large values of ν_R, a beam whose incoherent radial amplitude is several times larger than the radius gain per turn

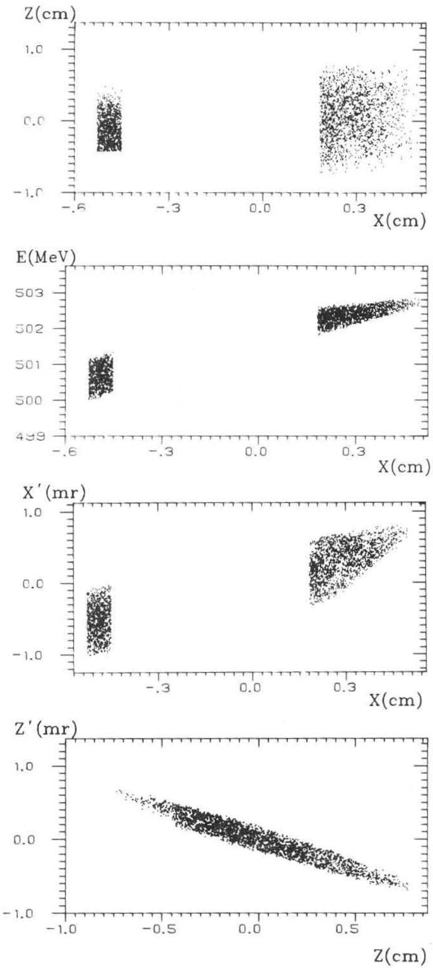

Fig. 2 : Monte Carlo calculation of the beam extracted by the foils of figure 1, not including the effects of scattering in the foil. The portion at positive x is that extracted by the stopping foil and is similar to the beam normally run. The composite foil increases the horizontal emittance and energy spread several fold. The vertical emittance is barely affected.

will be extracted over relatively few turns and give a smaller lateral spot and energy spread than would be expected from considerations of the betatron amplitude alone. Narrow foils or wires do not improve the energy spread but can provide a spot of small radial and vertical size. The vertical divergence is reduced for cases where the foil is dipped partially into the beam since there is strong correlation between height Z and momentum P_Z.

The estimation of particle properties selected by the stripping foils is now made using the linear motion code COMA [3]. Although a large number of particles may be tracked from injection to extraction, the end result is very sensitive to assumptions made concerning certain cyclotron parameters. In practice these parameters are tuned empirically for optimum transmission. For the present purposes we assumed that complete phase space mixing occurs during the preceding 1700 turns and that the shape of the particle distribution in transverse phase space matches the ellipses predicted by the equilibrium orbit code CYCLOP. The size of the phase space ellipse was adjusted to correspond to the measured radial and vertical amplitudes near the point of extraction. The RF phase width is also measurable and the energy distribution within a turn was inferred from the radial amplitude. We did not include

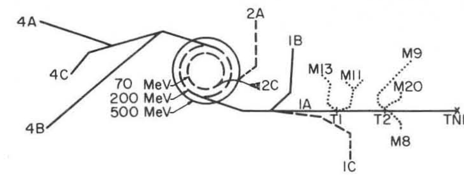

Fig. 3 : Schematic representation of the TRIUMF cyclotron and beam lines. Proton beam lines are shown solid (—), meson channels dotted (···), proposed lines dashed (---). Consideration is being given to the installation of a beam splitter in line 1A to direct a portion of the beam into the proposed line 1C feeding a superconducting medical Piotron.

correlations between different planes in phase space.

Such a distribution of 2500 particles was started 10 MeV before the composite foil of figure 1. The distribution of parameters selected by the foil is shown in figure 2. This distribution is used as input to the beam line Monte Carlo program REVMOC [4]. We calculated first the consequences of multiple and nuclear scattering in the foil. The parameters of the original 2500 particles from COMA were input several times to obtain improved statistics in subsequent calculations. Ellipses were matched to the REVMOC output and used with TRANSPORT to calculate a beam line tune within the appropriate constraints. REVMOC was again used to estimate beam loss by multiplying the particle parameters and beam line transfer matrices. Of the 50,000 particles in the enlarged emittance, only 1 was lost.

Figure 3 is a layout of the TRIUMF cyclotron and laboratory. The calculations and measurements were made for beam line 1A which feeds the most intense currents to the primary meson production targets 1AT1 and 1AT2. These are followed by a proton irradiation isotope facility and neutron facility incorporated into the beam dump (TNF).

4. Profile monitors.- A stationary multi-wire "harp" system is used. The current on individual wires is integrated and read sequentially to produce a histogram representing the particle distribution projected into the horizontal and vertical planes. For low currents, the wire planes are placed in an ion chamber, the protons ionise the gas and the charge drifts to the nearest wire. All protons contributed to the output. The secondary emission effect is utilised at high currents: the wire planes and the voltage planes providing a clearing field are placed in the beam line vacuum. The device responds only to those protons passing through a wire; the majority of protons have no effect on the signal. Their properties are discussed further in Ref. 5.

5. Tests with beam.- The beam line quadrupoles were altered to the values predicted to give a focus, rather than a waist, at a carbon wire secondary emission monitor 1AMT1 on the 1AT1 target ladder. Immediately two peaks were seen in the horizontal profile. A horizontal steering magnet was then altered in steps to sweep the beam across the monitor. This procedure gives a very detailed measurement of the profile with steps much smaller than the 1 mm spacing of the wires; the operation is similar to, but more tedious than, using a scanning wire. Minor adjustments in quadrupole settings sharpened the image and gave a spacing between peaks similar to that predicted by REVMOC calculations. The measured horizontal profile is compared with that predicted from the Monte Carlo calculations in figure 4. The excellent agreement gives support for other details of the calculations which will be discussed below.

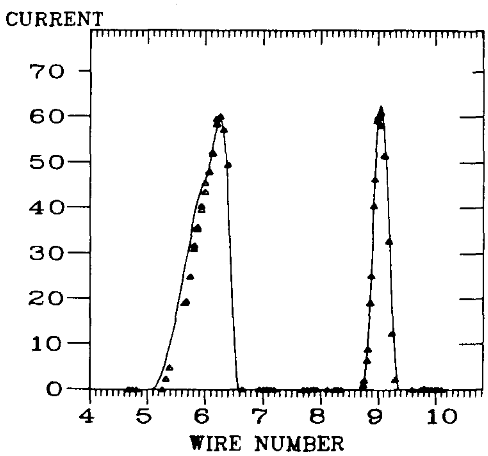

Fig. 4 : Profile obtained by scanning the beam from a composite foil across the wires of a profile monitor at the location of target 1AT1 in line 1A. The solid lines result from Monte Carlo calculations, the dots are measured points. The wire spacing is 1 mm.

Profiles made at different stripper foil heights showed that the population in the peak from the finger foil varied from zero to 40% of the extracted beam. The projected vertical profile was little changed.

The very slight change in beam line tune from a waist to a focus at 1AT1 meant that the beam could be transported to the dump without difficulty. The beam current was increased to 40 µA and inspection of the beam spill monitors along the line upstream of the focus showed no change from their readings during normal operation with a C-type foil. The position of the spot at the focus was stable to 0.1 mm over an hour or so; it would be worse away from the focus. There is no doubt that the emittance has been increased; however, beam loss occurs for those particles at the extreme of the distribution. These are most likely produced by scattering in the foil and should be little affected by the separation of the two foil components.

The beam line was retuned to form a focus at the multi-wire ion chamber closest to the proposed 1A/1C splitter location. Figure 5 shows a series of profiles at this location at different relative heights of beam and foil. It can be seen that the separation between the two components is close to 1 cm, which may be adequate for the introduction of a magnetic septum. Calculations show that it would be necessary to add additional quadrupoles to the main beam line to transport the beam to the dump. It was not possible to run more than a few nanoamperes in the absence of these quadrupoles.

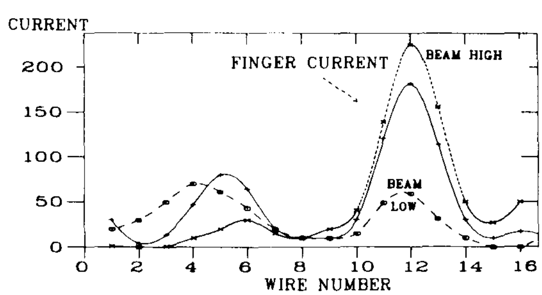

Fig. 5 : Beam profiles with no normalisation at the proposed splitter location 1A/1C for different relative heights of beam and composite foil. Wires are 3 mm apart.

6. Applications of a multi-component foil.- In common with other meson facilities TRIUMF incorporated a pion therapy facility sharing a meson production target with other experiments. The treatment takes place at the end of a fairly conventional meson channel, M8 in figure 3. Even with 100 µA on a 10 cm beryllium target the therapists desire a significant increase in pion flux to shorten their irradiation times to a few minutes. Very large acceptance pion applicators such as the Piotron[2] and a device considered at Los Alamos [6] yield an adequate flux with 20-30 µA protons. TRIUMF has several unused exit ports, and a dedicated stripper mechanism and beam lines could be built to provide this. However, it will probably be easier to use a splitter and the proposed line 1C to feed a device near the existing medical annex. A decoupling of the nuclear experimental and human irradiation programs is also desirable since the latter imposes considerable constraints on the beam time scheduling, nature of the production target and the beam intensity.

Calculations show that the separation between the inner edges of the beam envelopes is little changed from that in figure 5 for distances 0.5 m up- and downstream. This should ensure minimal loss on the splitter. The relative proton current in 1A and 1C would be adjusted by changes in foil height. This should not alter the spot on the experimental target. Should the line fed by the outer foil not require beam, the outer foil may be shadowed by the foil of another beam line, or the frame raised, the foil radius changed and the beam moved to the other side of the splitter.

A two-component foil of the form shown is also useful in setting up beam optics. Beam line 1A is tuned to form an image of the target 1AT1 spot on target 1AT2 and an image of the latter at the TNF. This means that the spot size at downstream locations is independent of upstream target thickness. In the past the optics have been adjusted and checked by inserting targets of various thickness and checking the profile at the downstream focus. It should be possible to do this more precisely and rapidly by imaging a multi-component object such as the foil shown in figure 1. This is similar to the use of L-shaped apertures in beam lines at low energy laboratories.

Picket fence foils with 7 fingers have been used to deliver beam to line 1A while improving the quality of the transmitted beam which was extracted by a narrow foil down beam line 4 [7].

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