Phase-space volume measurements on the Nuffield 60 in cyclotron

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1. FORMULATION OF THE PROBLEM

The Nuffield 60 in cyclotron is a classical machine originally designed before World War II. Being capable of reliable operation with large beam currents the cyclotron is often used for work in neutron physics. Time-of-flight techniques which utilise the intrinsically discontinuous nature of the particle beam presuppose very short pulses with well defined and known characteristics. The aim of this work was to investigate the waveform of the beam current and the relation between the energy of the particles and their time of arrival on the target. This relation expressed in the form of the phase-space volume had to indicate the most practical method of shortening the length of the beam bunch, if it could be done without undue loss in its intensity.

This work is a further development of the work done in Birmingham by M. Konrad,[1] who first used modern electronic techniques to resolve the fine structure of the beam.

2. METHOD OF MEASUREMENT

First a reliable method for the observation of the beam waveform had to be established. Initially we attempted to observe the beam on a fast oscilloscope, collecting it on a target that had a low capacitance to ground. This target in its enclosure formed a resonant cavity and it was not possible to remove the consequent ringing electronically. Application of a reverse Laplace transformation removed the oscillation from the record but showed that the method is very sensitive to noise present in the signal being unfolded. Fig. 1 shows the beam waveform before and after unfolding.[2,3]

Some experiments were also done with a fast scintillator (1·3 ns characteristic time) and a fast photomultiplier. Results of these measurements (Fig. 2) were in apparent disagreement with direct observation because of the relatively poor overall resolution of the system.

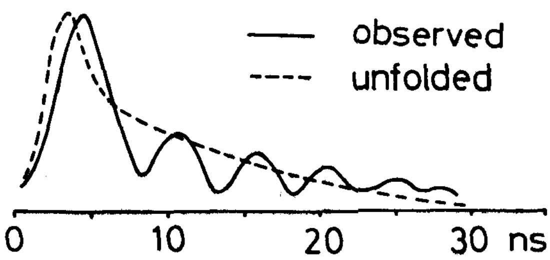

Fig. 1. Beam waveform recorded with a 'ringing' target and later, processed by a reverse Laplace transformation to remove ringing

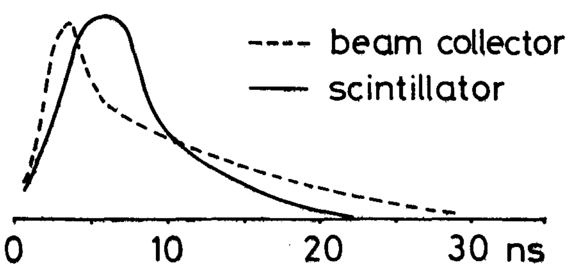

Fig. 2. Comparison between the beam waveform as recorded from a scintillator-photomultiplier system and from the current-collecting target

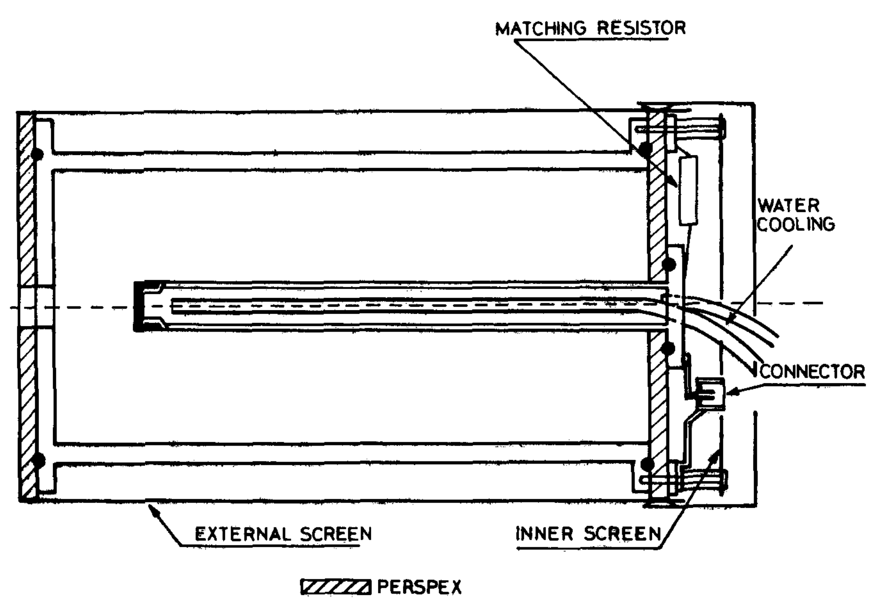

Fig. 3. Cross-section of the coaxial target

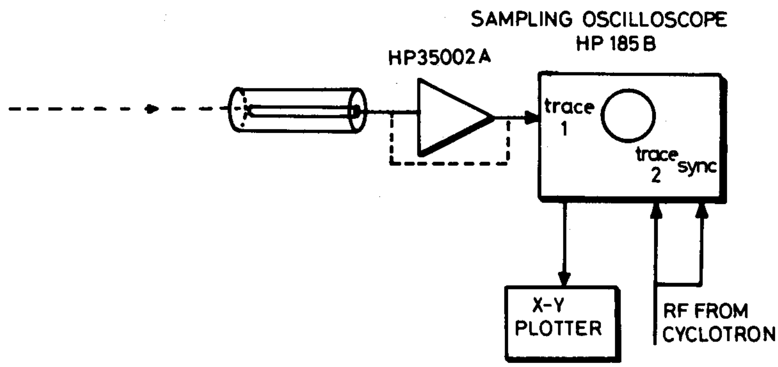

Fig. 4. Sampling arrangement for observation of the beam waveform

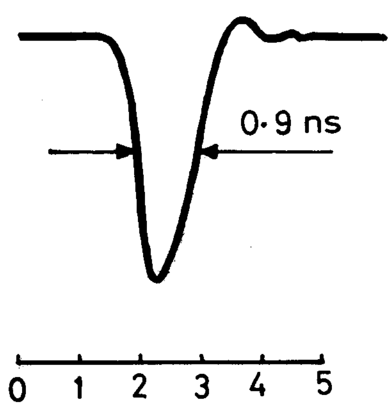

Fig. 5. Pulse shape from the step recovery diode sharpener, as used for system testing

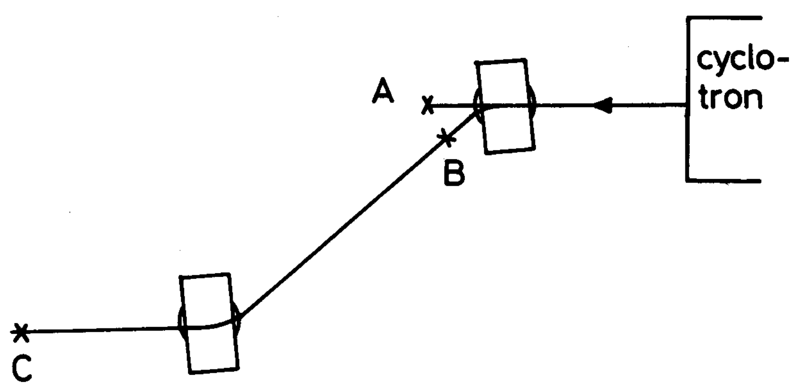

Fig. 6. Three positions where the beam waveforms were recorded

In order to eliminate ringing and improve the resolution time we turned to a coaxial target coupled to a sampling oscilloscope with 350 ps resolution either directly or through an amplifier. In the latter case the resolution was about 1·2 ns though this could have been reduced by using an amplifier with a shorter risetime. Some investigators[4] use low capacitance targets, but we have found that it is easier to avoid 'ringing' by using coaxial structures which have a well-defined characteristic impedance. The signal is equal to:

$$U = I_{\mathrm{beam}} \times Z$$

where Z is the impedance of the target. For a coaxial structure in vacuum the characteristic impedance is given by:

$$Z = 138 \log_{10} R/r$$

where R and r are the radii of the outer and inner current-carrying surfaces respectively.

Practical considerations limit the characteristic impedance to about 100Ω, for which the ratio of radii is about 5·4. Hence, 100Ω was the characteristic impedance of the target used (Fig. 3). Proper termination was secured with the help of six resistors placed radially between the inner and outer conductors. The oscilloscope probe could be directly plugged into the target or through the amplifier (Hewlett-Packard HP 35002A, with 20 dB gain). The input impedance of this amplifier is 50Ω and therefore it was necessary to introduce a 50Ω series resistor thereby losing half of the available gain.

Adjustment of the input impedance to minimise oscillations was done while using a pulse generator capacity coupled to the centre conductor of the target. This generator provided pulses with 5 ns risetime and 10 MHz repetition rate, the signals being sharpened to 140 ps risetime with a step recovery diode HP 0300.[5, 6]

The whole system had a satisfactory signal-to-noise ratio for beam currents over 5 μA. When working without the amplifier most of the noise was contributed by the sampling head.

A desirable increase in the characteristic impedance can be achieved by introducing material with high μ to the interior of the target. No beam trials have been done as yet but bench experiments indicate that Z can be increased significantly with very little deterioration of the waveform, even using a ferrite material not intended for VHF work (Mullard B3).

The experiment covered measurement of the beam waveform for various conditions of the cyclotron, in three places along the beam transport line (Fig. 6). Energy selection, with rather low resolution, was done by means of the bending magnet used as a magnetic analyser. Characteristics of the magnetic analyser were known from other experiments.

Finally, another series of measurements was directed to the determination of cyclotron beam emittance in two transverse directions, in order to find the practical influence of beam-optical elements on the quality of the beam.

3. RESULTS

The waveforms were measured for 10 MeV protons. It was found that in the position A the beam reveals a rather complex structure (Fig. 7). The risetime is

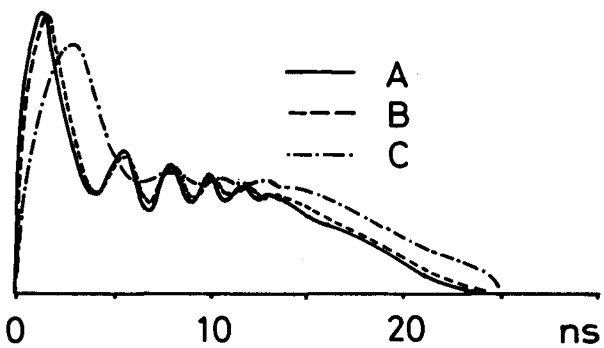

Fig. 7. Current waveform in three positions (typical)

about 1 ns (depending upon operating conditions; 1 ns is the best risetime that can be obtained in position 'A') and the total pulse length is about 20 ns, when measured at 10% level. Conditions of the accelerator have very little influence upon the length of the pulse, but affect the shape. Oscillations in the 'tail' were not an artefact but could be 'tuned out' by changing the resonant condition of the machine. The frequency of this oscillation was quite stable, about 400 MHz, and the stable position of the peaks indicates that they are 'locked' to the machine rf. We do not know the origin of these oscillations, which may have something to do with the presence of relatively strong higher harmonics of rf in the cyclotron tank.

The waveform at point 'B' was a little 'smoothed'. The difference was small and was due to the action of the bending magnet. At point 'C' the oscillations were hardly visible, the risetime of the front edge could not be made better than 2 ns. The total length of the pulse reached 25 ns.

Using a 'trigger count-down' unit which permits analysis of every *n*th pulse it was found that there are some second and third subharmonics present in the beam pulses.[7]

The energy spectrum was more complex. The total energy spread was determined in Birmingham by T. Solaija[8] and is usually about 70 keV *FWHM*. The energy resolution in our experiments was about 25 keV *FWHM*. It was found that this selected three arbitrary components of the beam current which have at 'A' the distribution in time shown in Fig. 8. The leading edge is mostly made of the slower component, the tail is made of all three components. Over the whole path difference between 'A' and 'C' (9·5 m) the difference in the time-of-flight is just enough to obscure the oscillatory structure, but the general shape of the pulse changes very little. The measured lengthening from 20 ns to 25 ns is probably due to experimental errors and it should not be more than 2 ns.

Fig. 9 shows three error ellipses for three arbitrary components of the beam; the ellipse encompassing the three components is an approximation of the longitudinal volume of the phase-space in ΔE, Δt co-ordinates.[9] The phase-space occupied by the beam in Δt, ΔE co-ordinates is usually $(0{\cdot}9 \pm 0{\cdot}1) \times 10^{-3}$ eV.s. Change of the rf frequency or magnetic field does not affect this value; it was, however, noticed that change in the dee voltage may increase the longitudinal emittance up to $(1{\cdot}3 \pm 0{\cdot}1) \times 10^{-3}$ eV.s.

The fact that the leading edge of the beam bunch is formed of slower particles may well be because extraction takes place from orbits which are not well separated or oscillating radially. The observed shift of the leading edge is 2·8 ns, in agreement with the calculated phase lag per orbit of 2·3 ns.

The longitudinal component of the beam emittance uses conjugate co-ordinates p_z, z (longitudinal momentum and the linear co-ordinate in the direction of motion) measured relatively to the average values. Conjugate co-ordinates ΔE, Δt are equivalent to p_z, z.[10] The drift space between any points 1 and 2 transforms the components according to:

$$\begin{bmatrix} \Delta t_2 \\ \Delta E_2 \end{bmatrix} = \begin{bmatrix} 1 & T/2E \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} t_1 \\ E_1 \end{bmatrix}$$

where E = average energy

T = time-of-flight between 1 and 2

or

$$\begin{bmatrix} \Delta t_2 \\ \Delta E_2 \end{bmatrix} = \begin{bmatrix} 1 & L\sqrt{m/8E^3} \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} t_1 \\ E_1 \end{bmatrix}$$

where L = drift length.

The scanning action of the deflector across the circulating beam depresses the lower energy component of the beam. On the other hand, the increase of B from the optimum value causes a decrease in the high energy component. The main factor which determined the shape of the beam pulse was the field-frequency relationship. There was also some, rather small, influence from the position of the ion source. The dee voltage and the potential of the deflector mainly affected the balance between the components of the bunch, but also had an influence on the total beam intensity.

We have tried to elucidate the origin of the long tail by observation of the waveform of the internal beam. Although the probe was not efficiently shielded

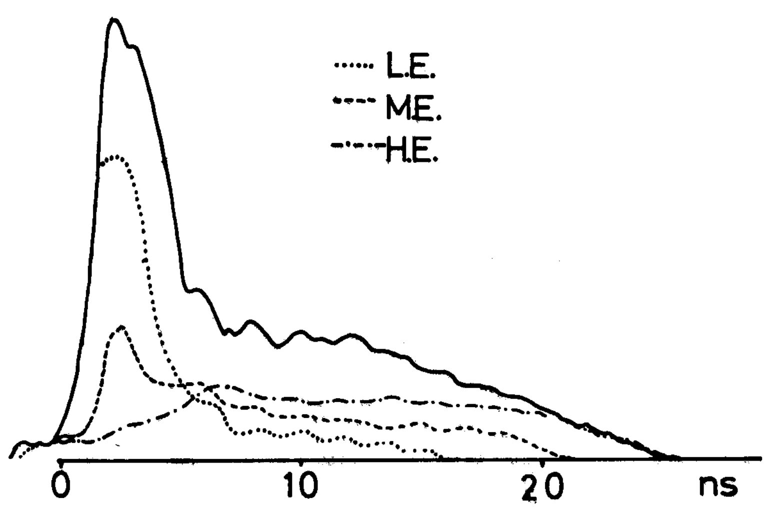

Fig. 8. Decomposition of the beam pulse into three components with energies chosen arbitrarily and ±25 keV vs the average energy

from rf pick-up, it was possible to find that the tail originates inside the machine, at least one-third of the way before extraction.

As all measurements were done by averaging methods and individual bunches were not recorded one cannot exclude that the emittance is to some extent 'blown up' by the effect of fluctuations of dee voltages.

It is interesting to note that the observations of the waveform are in good agreement with hypothetical models of acceleration discussed by Tinta, *et al.*[11] They calculated the shape of the pulse from the ion source dependence upon the dee voltage. Our observations indicate that the best agreement can be found assuming that the ion current is drifted out from the ion source following the laws of space charge flow ($i \sim U^{3/2}$).

The technique of emittance measurement adopted utilises a radiation-sensitive PVC film (Craytherm, Greenwich Plastics Ltd.). The film develops a brown coloration when heat treated, the density of the coloration increasing monotonically with radiation dose over a wide range. Direct comparisons can be made between films which have been heat treated (80°C for 30 min) together.

For emittance measurements the material is placed inside the beam tube at a

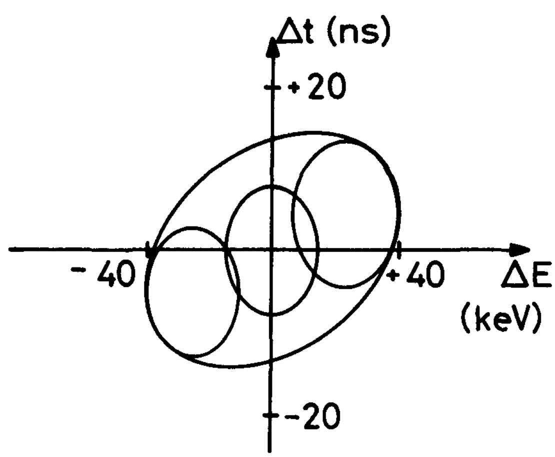

Fig. 9. Phase volume in ΔE, Δt *co-ordinates*

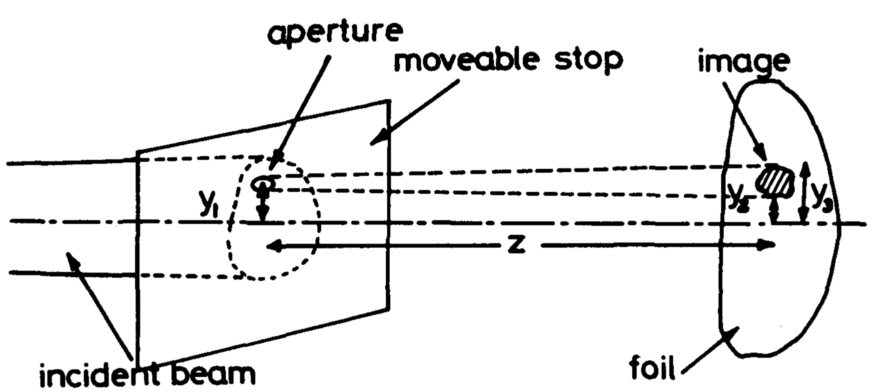

Fig. 10. Measurement of beam emittance with PVC foil

convenient distance from a small movable stop. A series of exposures is made with identical machine conditions, the stops being moved between exposures. The PVC foils are then developed and scanned with a microdensitometer. The divergence from the central ray of the beam passing through the stop can be readily calculated (Fig. 10).

If it is assumed that the divergence of the beam is the same at all points on the stop, then the effect of the stop is to increase the penumbra around the recorded beam spot by an amount equal to the radius of the stop.

By plotting the divergencies corresponding to different optical densities emittance diagrams can be drawn containing different fractions of the beam.

In the case of the measurements reported here, the emittance diagram was obtained by plotting the distance of the aperture in the stop from the central ray (Y_1) against the angle subtended by the spot image on the film $(Y_3 - Y_1)/Z$ and $(Y_2 - Y_1)/Z$; 90% of the beam was included in the diagram. The emittance was assessed by taking the area enclosed on the diagram and dividing by π.

Table 1

Drift space	*Vertical emittance* (mm mrad)	*Horizontal emittance* (mm mrad)
Undeflected beam	38	29
60° deflected beam	39	28
2 × 60° deflected beam	29	26

The results given in Table 1 indicate that the bending magnet does not increase the beam emittance significantly. The apparent improvement after the second bending magnet is due to the magnet aperture which acts as a collimator.

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