TARGET EFFICIENCY CALCULATIONS

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INTRODUCTION

The basic phenomena determining the efficiency of multitraversal targets in alternating gradient accelerators, namely the particle dynamics in such a machine and the interactions of high energy protons with matter, are sufficiently well understood to make possible a theory describing the fundamental aspects [1]. On the other hand the parameters in practical cases are sufficiently complicated to make an analytic treatment very difficult, if not impossible, but make the problem a good candidate for Monte Carlo procedures.

We define the efficiency of a target in a proton synchrotron as the fraction of accelerated protons which make nuclear interactions (including diffraction scattering) in the target. For calculating the production of secondary particles this efficiency must, of course, be multiplied by the ratio of the total cross-section to the absorption cross-section: This factor is $2/3$ for light nuclei [2].

Computer programmes have been written to calculate the efficiency and the burst shape for targets used in the CPS. They take into account the material, shape and size of the target and its support, as well as the machine energy, the size of the accelerated beam and the effective aperture of the vacuum chamber. For some 40 to 100 protons the actual or the probable path inside the machine is calculated by using random numbers for the effective Coulomb scattering at any given target traversal. Since measurements for the absolute target efficiency are not yet available, the results of the calculation for different target positions and for sweeping the beam at different speeds across very small targets have been compared with measurements. There was good agreement in change of efficiency, burst shape and remaining fraction of the beam.

* The report was not read.
have been written. The first one checks for each revolution of the proton whether it hits the target and whether it hits the chamber wall. The second programme does not follow the path of the proton for each revolution. It compares the amplitudes of the oscillations in the two planes with the size of the target, and so calculates the probable number of revolutions to hit the target. At this instant, the actual position of the proton is fixed with random numbers. Several comparisons have shown that the two programmes give practically the same results, so that both programmes have been used for calculations.

Both programmes are arranged for any kind of targets which are composed of two rectangular bars one being the target head and the other one the support; these two bars may be put at any position within the chamber. The effective aperture of the chamber is defined as an ellipse, which is determined by its two half axes. In a revised version a difference is made between the focusing and defocusing sections of the machine, and in this case the aperture is the common area of two ellipses. This makes it possible to distinguish between loss on the radial and vertical apertures.

As initial conditions we take protons randomly distributed within a beam of given horizontal and vertical size, and they are taken to be mono-energetic. We calculate in the absence of radio-frequency acceleration, but the whole beam can be displaced horizontally, and in one of the programmes also vertically, during the burst. Furthermore, there is the possibility of stopping the calculation at any given moment and continuing with another mode of beam displacement. In this way the beam can be used first on one target and then the remainder on another. Results of the calculation are the percentages of the primary beam which makes interactions in the target head, the support, and the wall, as well as the percentage of beam which is left in the chamber. All these results are given in time distribution, so that the efficiency within a given time can be seen as well. This is of special interest for bubble chamber bursts.
COMPARISON WITH MEASUREMENTS

Looking with a telescope counter [3] at a short burst target, the dependence of target efficiency on the target radial position has been investigated. For the same case, the calculation shows a very similar curve (Fig. 2). The small difference between calculation and measurement is probably due to the target support, which had in this case a rather massive piece right at the top which was still inside the chamber. Unsatisfactory in this case is the fact that no absolute values can be allocated to the measured curve, so that only the shape can be compared. Furthermore, there is some doubt about the fraction of interactions in the support that are seen by the counter.

Another comparison with measurements is shown in Fig. 3. In this case a very thin target of beryllium was used. The beam was steered at two different speeds across the target and finally steered against the wall of the chamber. The beam displacement speed for these two cases has been determined experimentally by moving the radial position of the target a few millimetres. The effective radial aperture of the chamber was measured by finding the target radial position at which the target burst just disappears. These two values have been put into the calculation, besides the known dimensions of the target. There is a good agreement between calculation and measurement for the amount of beam consumed while crossing the target, and the burst shape. The two curves for the measurements represent two targets which should be equal in their behaviour.

One of the two calculations was stopped just after the target burst, and the density distribution of the protons which remain in the chamber at this instant has been plotted. The curves encircle the given percentages of the remaining beam. The instant for this distribution is marked with an arrow in the left hand graph. The only appreciable discrepancy between measurement and calculation in Fig. 3 is the time distribution of final beam loss against the wall in the right hand graph. In this case, the beam was steered across the target with radio frequency in operation.

This may have changed the energy distribution in the beam after the target burst, so that the remaining beam was more compact when it hit the chamber wall.
Fig. 3. Burst shape and beam intensity versus time compared with measurements (points correspond to calculation) for two different speeds of beam steering to the outside (thin point source target in a focusing section). The two measured curves correspond to two with support to the bottom. The two plotted beam in the left hand graph (total intensity for beam after burst 53%). Target Be $\phi 1 \text{ mm} \times 20 \text{ mm}$, support Be $\phi 1 \text{ mm}$:

- $a$ — beam speed 5 mm/ms;
- $b$ — beam speed 11 mm/ms;
- $1$ — measurement;
- $2$ — support;
- $3$ — proton beam before burst;
- $4$ — to ring centre;
- $5$ — target;
- $6$ — vacuum chamber aperture.

TARGET EFFICIENCY FOR LONG BURST OPERATION

In order to study the different influences on the target efficiency, cases with CPS standard long burst beryllium targets have been calculated. To get some idea about the influence of material, all these cases have also been calculated for equally shaped targets made out of copper. Fig. 4 shows the influence of the target position in the machine. For both materials the most efficient target position is in about 20 mm to the outside of the chamber centre. The amount of efficiency which is lost on the target support is in the order of 15% for beryllium and 25% for copper. The loss on the chamber wall is for beryllium mainly a radial loss, while in the case of copper the vertical loss is much more important than the radial one. The shaded region between these two parts of the loss is determined by the particles which have been scattered so far that they are lost out of both ellipses. The dotted curves in Fig. 4 represent the situation for targets in a horizontal defocusing section, where the effective height of the chamber is about 1.35 times as big and the radial width by the same factor smaller.

The influence of the size of the chamber aperture has been investigated separately for radial and vertical width (Figs. 5 and 6), always leaving the second dimension equal to the CPS standard value. For all these calculations the target was placed in the middle of the aperture. For the radial chamber size the results show that the efficiency has only a small increase when the chamber is made bigger. The increase of the vertical size of the chamber does also not much affect the efficiency of the beryllium target; however, the effect for the copper target is very big, due to the fact that there the main loss was a ver-
Fig. 4. Effect of target radial position on target efficiency for CPS standard long burst targets of beryllium and equivalent ones of copper in F- and D-sections. For targets in F-sections, the loss is split in radial and vertical loss. Radial loss occurs in F-sections around the machine. Target Ø1 mm, 20 mm long; support Ø1 mm, 20 GeV, burst 100—150 ms. A — target position Δr.

Fig. 5. Change of target efficiency with horizontal radius of the effective aperture for long burst operation (see also caption of Fig. 4). Target Ø1 mm, 20 mm long; support Ø1 mm, burst 100—150 ms.
Fig. 6. Change of target efficiency with vertical radius of the effective aperture for long burst operation (see also caption of Fig. 4). Target Ø 1 mm, 20 mm long, support Ø 1 mm, burst 100—150 ms, 20 GeV.

Fig. 7. Change of target efficiency with energy of proton beam for long burst targets of beryllium (left) and copper (centre), and for short burst targets of beryllium with aluminium support (right hand graph). For short bursts the efficiency (especially the fraction with 1 ms) changes with the speed of beam steering. a: target Ø 1 mm, 20 mm long, support Ø 1 mm, burst 100—150 ms; b: target 4×3×40 mm, support Al 2×2 mm², beam speed 20 mm/ms. Note: in both cases (a and b) target is in centre of vacuum chamber.
tical one. Rather surprising is the fact that for beryllium targets even with a very small vertical chamber size rather high target efficiencies are obtained.

The influence of the primary beam energy on the target efficiency is very important. The two graphs on the left hand side of Fig. 7 show this dependence again for the two long burst targets of beryllium and copper. There is for copper about a linear increase of the efficiency with the energy. For beryllium the increase of efficiency starts already to become smaller and smaller at higher energies.

TARGET EFFICIENCY FOR SHORT BURST OPERATION

The influence of the proton energy for short burst operation is shown in Fig. 7 also for a beryllium target with an aluminium support. Since the target mass is much bigger in this case, so is its ratio to the mass of the support and the consumption by the support is less than in the long burst case. The speed of beam displacement in this case is chosen very high, so that part of the beam is steered right across the target before it is scattered far enough to be lost onto the chamber wall. The percentage of the target burst produced within one millisecond is in this case very high, because of the high beam displacement speed which has been chosen.

The last Fig. 8 shows the effect of the total target mass for the production of short bursts. The small efficiencies for the small target masses are due to the fact that the beam is steered too rapidly across the target, so that a fraction remains unused in the chamber. For beryllium targets there is no difference whether a small long target is well aligned with the beam or, in order to give a proper point source for the outgoing beam, is inclined a few degrees to the primary beam. Very different is the behaviour of copper targets in this respect. The chosen length for this example of 80 mm makes these targets already twice as efficient as very short copper targets. This influence of the target length for a constant target mass is given in the right hand graph. In order to realize this gain of efficiency with length the target has to be perfectly aligned with the primary beam.

Fig. 8. Influence of target volume on the target efficiency for short burst targets at fixed beam speed, and influence of target length in beam direction at constant volume. Corresponding points in the three graphs are marked with A and B. All targets in centre of chamber with support $2 \times 2$ mm$^2$ Al, beam speed $= 4$ mm/ms, 20 GeV: $\sigma$ = targets 80 mm long at 0°, 3° and 6°; $\beta$ = targets 80 mm long at 0° only; $\gamma$ = volume 0.16 cm$^3$ for Be, 0.04 cm$^3$ for Cu.
FURTHER OUTLOOK

Since the results of the target efficiency calculation have shown very good agreement with measurements, and the time required on the computer to calculate a given case is only between 3 and 5 min, the choice of target size and target material for special beam designs can already be improved by checking with this calculation. We are also hoping to find, by the use of these programmes, the most effective modes of target sharing. Some rather curious practical results about target sharing have been already explained by computing. Furthermore, this computing of the target burst provides some check for counter signal, which have not always been completely reliable in representing the burst shape. The influence of the radio-frequency in cases where bursts are made with RF on, and of the initial energy spread for cases with RF off, will also be studied.

REFERENCE