AZIMUTHAL DISTRIBUTION OF BEAM LOSSES IN A CYCLOTRON
WITH AN INTERNAL TARGET, TAKING MULTI-TRAVERSALS INTO ACCOUNT

by

M. Barbier and C. Perret
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I. INTRODUCTION

It is important to figure out where the beam is lost in a cyclotron. The basic case is that of an internal target, because the cyclotron is at present operated in this way a large fraction of the time, and because this case is clear cut and its geometry is relatively simple to examine theoretically. Beam loss distribution in the machine tank, when using the regenerator and magnetic channel to extract a part of the proton beam, is far more complicated and will not be examined here.

The quantity we are after is the flux density distribution (in protons per sec and cm²) of the lost beam particles inside the tank. In an idealized manner we will be contented with the knowledge of this distribution on two planes at equal distances above and under the median plane of the machine. These planes may represent the dee, for instance, or the pole pieces.

The knowledge of the distribution of the losses in the machine is valuable from three points of view. Firstly, it gives the distribution of induced activity, which is, as one knows, proportional to the impinging flux for a given material. Secondly, for shielding purposes, it is important to know the location of the sources of secondary radiation, apart from the target, which usually absorbs a small fraction of the beam only. From the places where the beam hits the magnet or dees, one usually finds out the direction of emission of the secondary neutrons as well, which determine the arrangement of the shielding around the accelerator. Thirdly, if the number of traversals and the current at each of them is known, it is possible to compute the total number of particles which have undergone nuclear interaction in the target and the total number of particles which have traversed the front surface of the target.
The way in which these calculations have to be made is outlined in a previous report of one of the authors (CERN 64-9, Appendix II). It is stressed there that the dependence of the distribution upon radius can be neglected in a first approximation. The azimuthal distribution functions are thus the major part of the problem. The results were presented for one traversal of the beam through typical targets, and computing methods, in the case of many target traversals, were also indicated.

We will now present the results that were obtained when using the methods for computing the azimuthal distribution of the lost particles in the case where there is multitraversal of the target (which generally happens).

II. SOME PHYSICAL CHARACTERISTICS OF TARGETS

It is adequate to list some of the parameters relevant to the calculations made; in particular, the density \( \rho \) and the target material mean square spatial scattering angle per \( g/cm^2 \Theta_5^2 \). For a target of a given thickness \( \Delta \) we have then as mean square spatial scattering angle the quantity \( \rho \Delta \Theta_5^2 \), which is also indicated for the computed cases. This quantity is the characteristic value for the target from our point of view and permits a comparison of the effects due to targets of different thicknesses and materials. Table 1 gives a set of typical target data. We have also indicated the inelastic cross-section \( \sigma \) in barns. At each target traversal the protons that experience a nuclear interaction are being subtracted from the remaining beam current. The parameter \( \alpha \), called target transparency, gives the fraction of the beam which passes through the particular target without experiencing nuclear interactions. All these data are computed for a proton energy of 600 MeV, an orbit radius of 225 cm, and a distance of 6 cm between the intercepting plane and the median plane of the machine, which corresponds to our dee opening.
Table 1

Typical target data

<table>
<thead>
<tr>
<th>Element symbol</th>
<th>Atomic weight</th>
<th>Density $\rho$ (g cm$^{-3}$)</th>
<th>Mean square spatial angle $\Theta^2_s$</th>
<th>Thickness $\Delta$ (cm)</th>
<th>Target mean square spatial angle $\rho \Delta \Theta^2_s$</th>
<th>Inelastic cross-section $\sigma$ (barn)</th>
<th>Target transparency $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>9.013</td>
<td>1.8</td>
<td>0.16 $\times 10^{-4}$</td>
<td>0.2</td>
<td>0.058 $\times 10^{-4}$</td>
<td>0.19</td>
<td>0.9954</td>
</tr>
<tr>
<td>C</td>
<td>12</td>
<td>1.75</td>
<td>0.21 $\times 10^{-4}$</td>
<td>0.2</td>
<td>0.074 $\times 10^{-4}$</td>
<td>0.22</td>
<td>0.9961</td>
</tr>
<tr>
<td>Al</td>
<td>26.98</td>
<td>2.69</td>
<td>0.46 $\times 10^{-4}$</td>
<td>0.2</td>
<td>0.247 $\times 10^{-4}$</td>
<td>0.42</td>
<td>0.995</td>
</tr>
<tr>
<td>Cu</td>
<td>63.54</td>
<td>8.93</td>
<td>1 $\times 10^{-4}$</td>
<td>0.2</td>
<td>1.79 $\times 10^{-4}$</td>
<td>0.85</td>
<td>0.9852</td>
</tr>
<tr>
<td>W</td>
<td>183.96</td>
<td>19.3</td>
<td>2.4 $\times 10^{-4}$</td>
<td>0.2</td>
<td>9.3 $\times 10^{-4}$</td>
<td>1.7</td>
<td>0.9787</td>
</tr>
</tbody>
</table>

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III. PRESENTATION OF THE DATA RESULTS

The azimuthal distribution of beam loss will be plotted as a function of the argument $Q\phi$ of the vertical betatron oscillation function. Here, $Q$ is the number of vertical betatron oscillations per turn and $\phi$ the azimuth taken around the machine in the beam direction with the target as origin. The plot ends, of course, at a quarter wavelength, where the beam loss is over. As in our machine the number of vertical oscillations per turn $Q = 0.22$ is roughly a quarter, this corresponds to about one revolution ($360^\circ$ in azimuth). It is interesting to note the arguments corresponding to the entry into and exit from the dee structure in both beam directions for the two target locations which are most used ($10^\circ$ and $39^\circ$ from the south to the west).

Table 2

<table>
<thead>
<tr>
<th>Target</th>
<th>Direction of beam</th>
<th>Magnetic field</th>
<th>Dee entry</th>
<th>Dee exit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Azimuth degrees</td>
<td>$Q\phi$ rad</td>
</tr>
<tr>
<td>10$^\circ$</td>
<td>as for extraction</td>
<td>down</td>
<td>120</td>
<td>0.45</td>
</tr>
<tr>
<td>10$^\circ$</td>
<td>opposite</td>
<td>up</td>
<td>90</td>
<td>0.35</td>
</tr>
<tr>
<td>39$^\circ$</td>
<td>as for extraction</td>
<td>down</td>
<td>149</td>
<td>0.575</td>
</tr>
<tr>
<td>39$^\circ$</td>
<td>opposite</td>
<td>up</td>
<td>61</td>
<td>0.23</td>
</tr>
</tbody>
</table>

The quantity which is plotted as an ordinate in the first series of curves is

$$y = \frac{dI}{I d\phi}$$
where \( \frac{dI}{I} \) is the fraction of the beam current that falls after a given traversal of the target on one plane at a height \( h \) (here 6 cm) over or below the median plane, per unit of \( Qd\phi \), i.e. per unit argument of the betatron oscillation. Thus, if one integrates \( \frac{dI}{I} \) over \( Qd\phi \) from 0 to \( \pi/2 \) and sums over all traversals, one should get the value 0.5. When adding the contribution from the other plane, the total value obtained is then 1. However, as the fraction of the beam experiencing nuclear interaction at the target has been subtracted each time, the values will be slightly lower than these figures. The first of the curves presented below show the beam loss density distributions as a function of the argument \( Q\phi \) of the vertical betatron oscillation for each target traversal. The induced radioactivity has the same distribution, as it is proportional to the impinging flux density.

Another quantity which is of interest when considering multi-traversals is the total fraction of the beam lost at each traversal. It is in fact

\[
\frac{\pi/2}{\int_0^\pi/2 \frac{dI}{Id\phi} d\phi}
\]

which is integrated over the angle. This quantity is referred to as FERSUM, and is a function of the order \( n \) of the traversal, and of the target parameters. It will be plotted as a function of \( n \) and also of the mean square scattering angle \( \rho h \langle \Theta^2 \rangle_s \).

Finally, the total number of particles having undergone nuclear interaction in the target and the total number of particles having traversed the front surface of the target will be presented as a function of the mean square scattering angle for the various materials considered.
IV. DATA VALID FOR THE 600 MeV CERN SYNCHRO-CYCLOTRON

a) Azimuthal distribution of beam loss

Beam loss distribution curves with the traversal order n as parameter for various target thicknesses and materials are shown in Figs. 1-10.

Figure 1 shows these curves for a thin beryllium target (0.2 cm). After the first traversal, very little beam is lost, because the target is not thick enough to scatter the protons appreciably. The loss increases with successive traversals up to the sixth and decreases again thereafter, as the beam intensity itself is becoming lower. This behaviour is typical for not too thick or heavy targets. One finds it again in Figs. 2 and 3, for Be targets 0.4 and 1 cm thick and in Fig. 6, for a carbon target of 0.4 cm. However, if the scattering power of the target is larger, as in Figs. 4 (Be 4 cm), 7 (C 4 cm), and in all subsequent cases, the beam loss decreases gradually with increasing traversal order.

Figure 5, where the y curves for various n are compared relatively to their maximum in the case of the Be 0.2 cm target, shows how the maximum of the loss distribution moves upstream backward to the target as the traversal number grows.

Figures 8, 9, and 10 show the distribution curves for aluminium, copper and tungsten targets, all 4 cm thick. The number of traversals for a substantial beam decreases considerably and in the last two cases one can say that the beam is lost almost entirely at the first traversal. Also the maximum of the distribution is shifted very near to the target as a result of the larger mean square scattering angle $r \Delta \theta^2$. As a complement, Fig. 11 shows the distribution after the first traversal for Be targets of increasing thickness, all plotted together with a logarithmic scale of ordinates. The same is done in Fig. 12 for targets with various elements but the same thickness, whereby the scattering increase is due to the increase in the atomic mass A. The same shift upstream is observed.
An interesting result of these computations is the position of the maximum of the distribution curve for \( n = 1 \) which we will conveniently plot as a function of \( \rho \Delta \Theta_s^2 \) for all the cases considered. Figure 13 illustrates the situation and can be used to predict the position of the maximum loss for any given target. It shows well how this position moves upstream as the scattering power is increased.

b) Fraction of beam lost in the machine after each target traversal

Now that we have dealt with the distribution curves, we can consider the losses at each traversal as a whole and examine how they depend on the traversal number and \( \rho \Delta \Theta_s^2 \).

The fraction of beam lost at each traversal, as a function of traversal number \( n \), is shown in Fig. 14 for targets of various materials having all the same thickness, i.e. 0.2 cm. For W and Cu targets, beam loss is strongest at the start; for Al, C, and Be targets, it increases first and decreases later; in this case \( \Delta = 0.2 \) cm.

The fraction of beam lost at a given traversal depends, in fact, only on the quantity \( \rho \Delta \Theta_s^2 \). In order to be able to use all the accumulated data for predictions in case of any new target, we have plotted the beam fraction lost (PERSUM) as a function of \( \rho \Delta \Theta_s^2 \) for the 1st, 2nd, 3rd, 4th, and 5th traversals on Figs. 15, 16, 17, 18, and 19. It is apparent that for higher scattering angles the major part of the beam is lost at the first traversal; the curve in Fig. 15 is being asymptotic to the value 0.5. The last points are, however, lower because of the subtraction of the beam fraction undergoing nuclear interactions.

c) The beam fraction undergoing nuclear interactions in the target and the current traversing the front face of the target

From the multitraversal calculations that have been made, one can still extract useful data about the target irradiation. Let the circulating machine beam current be \( i_0 \). After the first traversal, the current coming out of the target will be \( ai_0 \). Of this we lose 2 Persum (1) on the upper and lower dee, so that the current hitting the front face of the target for the second time is \( ai_0 - 2 \) Persum (1), and so on, \( 1 - a \) being each time the fraction undergoing nuclear interaction in the target.
Figure 20 shows the total fraction of the machine current, having made nuclear interactions in the target, plotted as a function of $pA \theta^{2}_{s}$. It appears that it does not vary very much as a function of target thickness for a given material; however, lighter materials are more advantageous. Also it is not possible to get more than 10% of the beam as a whole to react in a target (materials lighter than Be omitted).

Figure 2 shows the total current experienced in terms of the original machine current, that traverses the front face of the target. This is what would count, for instance, if one wanted to activate a very thin foil placed on the target. With a thin Be target (0.4.), one arrives at about 10 times the machine current, and could do even better with thinner targets.

The data on the fraction of beam reacting in the target presented in Fig. 20 cannot really be related to the meson production in a given target, or at least to the meson beam extracted from an internal target into a given direction or channel. One has to take into account the meson absorption in the target, which depends on the meson energy, the angle at which the particular beam leaves the target its momentum, and so on. The data considered would almost be proportional to the total number of neutrons emitted. However, one has to consider that the neutron emission, for a given incident flux, varies with the material, being larger in the case of higher atomic weights.

V. CONCLUSIONS

The results presented above lead to interesting conclusions on three different aspects of cyclotron operation: activation, shielding, and target efficiency.

The protons scattered by the target get lost in the first quarter of a betatron oscillation wavelength. The maximum of beam deposit takes place at about one-eighth of a wavelength downwards from the target. In our cyclotron, the dee there acts as the main beam dump.
From the relatively thin dee plate, the beam goes into the pole pieces. One sees the necessity of plating the pole faces in the dee region with low activity absorbers. Also the dummy dee receives a large quantity of particles, practically all those which have not fallen on the dee. The region of the pole pieces outside the dee is also activated, but there the activating flux is the neutron flux from the target; this is not considered in this report.

The fact that the main beam loss occurs in the dee region has also an importance for the shielding. We have found that the fraction of the beam reacting in the target is always less than 10%. The protons incident on the dee and pole pieces give rise to neutrons which are emitted with a broad angular distribution around the direction of incidence of the proton. It is seen that the origin of the radiation lies in the dee region, which acts as a source region for all secondary particles.

Finally, the targets that seem to utilize the beam with maximum efficiency with respect to nuclear interactions seem to be targets of the lightest elements. The target thickness does not seem to have an important rôle in target efficiency. Only in the case where one wants to activate thin foils will it be advisable to use as thin a target as practicable.

The results obtained should be partly applicable to other machines as well, at least for the first quarter betatron wavelength downstream from target.

ACKNOWLEDGEMENTS

We would like to thank Mr. F. Hoffmann who has plotted all the charts and made some numerical calculations.
LITERATURE


W.J. Knox, Multiple traversal of high-energy particles in a cyclotron beam through thin targets, Phys.Rev. 81, 693 (1951).

M. Barbier, Radioactivity induced in materials by high-energy particles, CERN 64-9.
Fig. 1  Beam loss distributions for beryllium target 0.2 cm thick with traversal order $n$ as parameter.
Fig. 2 Beam loss distributions for beryllium target 0.4 cm thick with traversal order n as parameter.
Fig. 3  Beam loss distributions for beryllium target 1 cm thick with traversal order $n$ as parameter.
Fig. 4  Beam loss distributions for beryllium target 4 cm thick with traversal order $n$ as parameter.
Fig. 5  Beam loss distributions for a 0.2 cm beryllium target plotted relatively to the maximum value for each traversal.
Fig. 6  Beam loss distributions for carbon target 0.4 cm thick.
Fig. 7 Beam loss distributions for carbon target 4 cm thick.
Fig. 8  Beam loss distributions for a 4 cm aluminium target.
Fig. 9  Beam loss distributions for a 4 cm copper target.
Fig. 10  Beam loss distributions for a 4 cm tungsten target.
Fig. 11  Beam loss distribution after first target traversal for beryllium targets of different thicknesses.
Fig. 12 Beam loss distribution after first target traversal for 0.2 cm thick targets of various materials.
Fig. 13 Azimuthal position of the maximum of the beam loss distribution after the first traversal, as a function of mean square scattering angle of target $\rho \Delta \theta_s^2$. 
Fig. 14 Fraction of beam lost at each traversal as function of traversal order $n$ for 0.2 cm targets of various materials.
Fig. 15 Fraction of beam lost after first traversal as a function of $\rho \Delta \theta^2$. 

$\rho \Delta \theta^2$
Fig. 16. Fraction of beam lost after second traversal as a function of $\rho \Delta \theta^2$. 

- Be
- C
- Al
- Cu
- W

10^{-1} - 10^{-2} - 10^{-3} - 10^{-4} - 10^{-5} - 10^{-6}

- Be
- C
- Al
- Cu
- W

10^{-1} - 10^{-2} - 10^{-3} - 10^{-4} - 10^{-5} - 10^{-6}
Fig. 17 Fraction of beam lost after third traversal as a function of $\rho \Delta \overline{\Theta_s^2}$. 
Fig. 18  Fraction of beam lost after fourth traversal as a function of $\rho \Delta \bar{\theta}^2_s$. 
Fig. 19 Fraction of beam lost after fifth traversal as a function of $\rho \Delta \theta_s^2$. 

- Be
- C
- Al
Fig. 20  Fraction of the machine current has made nuclear interactions in the target as a function of $\rho \Delta <\Theta_s^2>$. 
Fig. 21  Total current expressed in terms of beam current traversing
the front face of the target as a function of $\rho \Delta \theta_s^2$. 

\[ z = 2 \sum_{n} i_n \]