DESIGN OF TARGET SHIELDS AND BEAM CATCHERS AT CYCLOTRON ENERGIES

M. Barbier, CERN, Geneva
C.B. Fulmer, Oak Ridge National Laboratory

(Presented by M. Barbier)

The interaction of high-energy nuclear particles with matter results in the production of neutrons, mesons, other charged particles and residual radioactivity. To achieve the maximum research capabilities of accelerators that produce high intensity beams of several hundred MeV particles (meson factories), careful consideration must be given to the important sources of radiation, and steps must be taken to minimize and contain the residual radioactivity. Two important sources of radiation are targets and beam catchers. Some ideas on the design of target shields and beam catchers are discussed in this paper. The present discussion is for 600 MeV protons. The general principles, however, should be applicable for other energies.

Target Shields

A thick target, such as one would use for meson production, will become very radioactive. During bombardment it is an intense source of high-energy neutrons. The target shield should protect the surrounding equipment, floors and walls from appreciable neutron fluxes from the target. On the other hand experience has shown the need for access to the target position. The shield should therefore consist of materials that produce predominately short lived radioactivities, and it should provide high absorption of the residual radiations. The volume and cost of the shield are also important factors in most installations.

Recent experiments at the CERN Synchro-Cyclotron[1,2] with 600 MeV protons yielded information that is pertinent to the selection of target shield materials. From Ref. 1, one may extract relaxation lengths for spallation neutrons in several materials. These results may be compared with published calculated mean free paths for inelastic collisions of high-energy neutrons[3] The factor of 10 relaxation lengths in centimeters are as follows:

	Carbon	Light Concrete	Iron	Lead	
Ref. 1	125	80	38	30	cm
Ref. 3	102.5	116	37.4	43	cm

From these one may estimate a value of about 200 cm for water. Also by assuming that high energy neutrons are removed by a geometric cross-section (and assuming $r_o = 1.25 \cdot 10^{-13}$ cm) one may calculate a factor of 10 relaxation lengths of 90 cm, 38 cm, and 41 cm for carbon, iron and lead respectively.
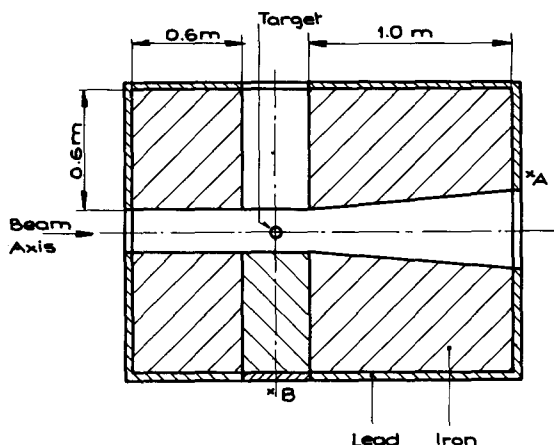
Fig. 1 Target shield.

An illustrative design of a target shield is shown in Fig. 1. It is desirable to keep the dimension in the forward direction as small as possible in order that the quadrupole lens may be effective in converging the charged mesons and for effective collection of the multiply scattered proton beam. Thus iron appears to be the best choice for target shielding material in the forward direction since it offers the smallest spallation neutron relaxation length of the readily available materials. For lateral shielding another material could be used, but the advantages of saving space are also important here. An outer layer of a few cm of lead surrounding the target shield should be included to shield against residual radiation; it was shown[2] that the residual radiation from lead is less intense and shorter lived than from iron.

Most target materials that are bombarded with intense beams of protons, become very radioactive. For thick targets in a meson factory beam it is important to have remotely controlled facilities for removing the target from the beam position to a shielded cooling area. A removable plug below the target position should be included to facilitate removal of anything that is accidently dropped inside the shield cavity.

The target shield shown in Fig..1 is proposed to provide minimum shielding for a 100 μA beam of 600 MeV protons bombarding a target of such thickness that 1/4 of the incident particles produce spallation reactions in the target. In this situation, 1/4 of the incident protons would produce about 3 neutrons each, of which about 1.3 are spallation neutrons. Thus the total fast neutron production would be about 2×10^{14} n/sec. If the angular distribution is assumed to be similar to that for 6.3 GeV spallation reactions in Cu[4], the fast neutron fluxes at points A and B will be about 2×10^7 and 10^7 n/cm^2 sec respectively. Without the target shield these fluxes would be 8×10^9 and 0.4×10^9 n/cm^2 sec respectively. These fluxes would, during an extended period of operation, induce radioactivities in neighboring equipment, floors and walls, that would result in residual radiation levels which would severely limit the access of personnel to the area. In principle the target should be placed far enough from the walls for geometric attenuation to reduce residual radiation to a tolerable level. In practice, however, this is often difficult to achieve, especially for the floors.

If we assume the specific activation of lead to be similar to that of tantalum then the dose rate near the surface of the shield can be estimated from Ref. 2. This estimate, based on long term exposure of lead to fast neutron fluxes of 2×10^7 n/cm^2

sec, yields dose rates of ~ 70 mr/hr one day after shutdown, ~ 20 mr/hr one week after shutdown, and ~ 6 mr/hr one month after shutdown. These values do not include contributions to the radiation level from other sources in the area.

Beam Catchers

For beam catchers one must consider two effects that are not included in the above discussion of target shields. These are neutron production and heat removal. From Ref. 4 it is seen that the n/p ratio for 600 MeV protons is 1.3, 3.5 and 25 respectively for carbon, copper and uranium. Thus one might expect that for lead it would be much higher than for a material in the region of iron or copper. If space is an important factor, as it is in most installations, high density materials should be used for the beam stop. The best compromise between high density and low neutron production appears to be iron or copper.

The proposed beam catcher for up to 100 μA of 600 MeV protons is shown in Fig. 2. To facilitate heat removal the iron that stops the proton beam is laminated with circulating water filling the space between iron sheets and around the iron region. Iron is also suggested for the outer part of the beam stop because of its favorable neutron relaxation length. An outer layer of a few cm of lead should be included because of its lower residual activity and favorable shielding properties for residual radiation from the iron.
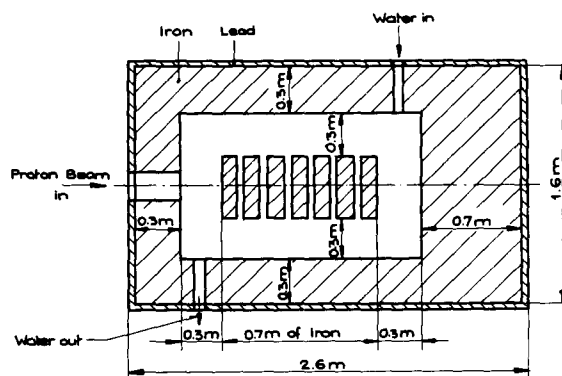

Fig. 2 Beam catcher.

If 100 μA of 600 MeV protons are stopped in iron, the cascade neutron production rate is estimated from Ref. 3 to be about 2 x 10^{15} neutrons/sec. The beam stop and surrounding shield should reduce the neutron flux at the surface of the shield to the same level as that of the thick target shield that was discussed above. This criterion and the choice of materials determine the size of the beam stop shield.

Our estimate of an adequate beam stop are 70 cm of iron (that is the proton range plus one ten folding length for neutrons) surrounded by 30 cm of water, and an iron container for the assembly that is 70 cm thick in the forward direction. For the lateral and backward walls of the container 30 cm of iron is adequate. The fast neutron flux at the outer surface of the beam stop will be ~ 10^7 neutrons/cm^2 sec if 100 μA of 600 MeV protons are stopped. Thus the residual radiation levels near the beam stop will be about the same as around the thick target shield that was discussed above.

The evaporation neutrons produced in the beam stop will be thermalized in the water volume. The thermal neutron flux will be attenuated by neutron capture in the

outer region of iron. For 30 cm the attenuation is about a factor of 700. Further reductions of thermal neutron fluxes can be easily achieved by a small thickness of cadmium or boron carbide.

Conclusion

Although the suggested designs for target shields and beam stops discussed here include some extrapolations, they demonstrate the feasibility of such devices for reducing the residual radiation levels by a few orders of magnitude. Tolerable levels for necessary personnel access to the area can be maintained.

References

1. M. Barbier and C. Perret, Internal Report MSC-22/86(M11), unpublished.
2. J.P. Blaser, et. al., Shielding and Activation of High Intensity Cyclotrons, see paper IV-6.
3. S.J. Lindenbaum, Shielding of High Energy Accelerators, Annual Review of Nuclear Science, 11 (1961), 213.
4. R. Wallace, Nuclear Instr., 18-19 (1962), 405.

DISCUSSION

LIVINGSTON : You showed on your sketch an outside layer of lead. How much effect does this give, and would you recommend putting lead perhaps in other places around the cyclotron?

BARBIER : The initial activity of lead per gram is not much bigger than that of iron under the same conditions of irradiation. However, it decreases much quicker. Furthermore, it absorbs gamma radiation better than iron. The figure of merit is really the activity per gram divided by the mass absorption coefficient for gamma rays.

LANGMANN : Did you investigate the shift in the mean neutron energy when using lead instead of iron as a primary absorber? Because, if there was a great shift in the mean energy, this could mean that the amount of shielding needed behind your target could be smaller.

BARBIER : I have not done this investigation.