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METALLIC-WEDGE DEGRADERS FOR RAPID ENERGY MEASUREMENT
OF BEVALAC HEAVY-ION BEAMS*

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Introduction

An ever-present need in an accelerator-based research program is knowing the energy of the beam delivered to the experimenter. Knowledge of accelerator parameters is generally good enough to predict the beam energy to within a few percent as it leaves the machine, but after passage through a complex switchyard, with air gaps, and "non-destructive" monitors, substantial changes in the energy can occur. Knowledge of the material in the beam path allows for calculations of expected energy loss, but this knowledge is not always complete, and the unforseen often plays tricks on the unwary experimenter, for example a section of beam-pipe inadvertently let up to air, or a monitor left in the beam-line from the previous run. Although such occurrences are rare, to say they do not happen would be grossly inaccurate. The only defense of the experimenter, then, is to have an accurate technique for determining the beam energy at his target location, a technique which requires little beam time and which is non-disruptive of his experimental setup.

The device to be described here meets all of these criteria, and is now used extensively in the Nuclear Science and Biomedical programs at the Bevalac.

Range-Measuring Technique

The basic idea is to determine the depth of penetration of the beam in a metallic wedge, extracting the beam energy using range-energy relationships. The penetration depth is measured by the wedge thickness which first allows beam to escape out the back of the wedge. By placing film behind the wedge one sees a clear demarkation line between exposed and unexposed film at the point where the beam is just stopped in the wedge. This technique was first developed at the Bevalac in the mid 70's by P. Lindstrom[1] who used a copper wedge to aid in characterizing the Bevalac heavy ion beams used in early fragmentation experiments[2,3]. This wedge was not widely used, however, because of its limited useful energy range (maximum wedge thickness was 2 cm) and because of difficulties in registering the demarkation line on the film with an actual location on the wedge.

The wedge pictured in Figure 1 has been developed by the authors to overcome these difficulties, and has been designed so that the resultant film contains all necessary information for the user to determine the beam-range in the wedge material and also to judge the quality of the measurement. This completeness arises entirely from the designed wedge-shape and the complex fiducial pattern machined onto the back face of the wedge. The usefulness of this fiducial pattern is seen by observing that particles passing through the grooves in the pattern will have traversed less material, so that key portions of the pattern will be imprinted on the film. (See Figure 2).

The wedge is cut at a compound angle, $45°$ along one axis, and $5.7°$ along the other. Thus the locus of equal-thickness points through the wedge will be a

Figure 1. Aluminum range-measuring wedge. The fiducial pattern machined on the back face of the wedge will be imprinted by the beam on photographic film placed against it.

line with a 1:10 slope along the back face of the wedge. The horizontal fiducial lines are machined at 5 mm intervals denoting 5 mm increments in the wedge thickness. For mechanical rigidity the minimum thickness of the wedge (upper right corner) was kept at 5 mm, so the first fiducial down represents 10 mm thickness, the 2nd 15, and so forth. Note that these values correspond to the thickness only along the right hand edge of the wedge. By locating where the line of demarkation crosses this edge one can read the thickness of the material penetrated. In addition, by using the 1:10 slope of the line as a Vernier scale, this penetration distance can be read to a high degree of accuracy. This is done by marking the intersection point of the demarkation line and a horizontal fiducial, and measuring the distance of this point to the calibrated edge of the wedge; every centimeter of distance corresponds to 1 mm of wedge thickness. Numerous measurements indicate that such intersection points can be determined reproducibly to about 2 mm on the film, leading to an accuracy of 0.2 mm in the measured range. A detailed accuracy discussion is given below.

The vertical fiducials, cut at slant angles, are designed to allow for location of a film image should the entire wedge not be illuminated by the beam. The varying spacing of these vertical lines, coupled with the holes along the center-line provide enough information to uniquely locate the film if as little as 10% of the wedge is illuminated.

The holes through the wedge serve not only as fiducials, but also as an alignment tool. Shining light through the holes allows one to visually align the wedge along the beam axis. Furthermore, should an exposure be performed with the wedge misaligned, the images of the holes on the film will not appear round. The ellipticity of the holes, growing more pronounced for the longer holes, is a direct measure of the degree of misalignment. If the wedge is

2.5° off, the bottom hole will disappear completely. Since the accuracy of the energy measurement depends critically on this alignment (see below) these fiducials are very valuable.

Figure 2 shows the image of a neon beam whose energy was 670 MeV/amu as it left the accelerator. The measured stopping distance in copper is 43.9 mm, which translates to 549 MeV/amu. Thus 121 MeV/amu has been lost in traversing air gaps, instrumentation, and the (very massy) beam preparation devices in the Bevalac Radiotherapy beam line.[4,5]
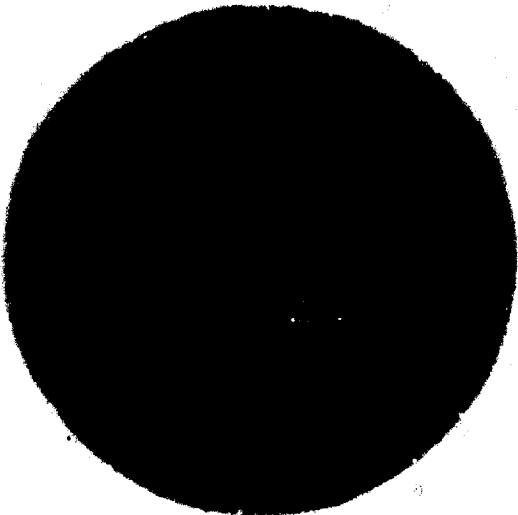

Figure 2. Photographic image from an exposure of Kodak XV x-ray film placed directly behind the copper wedge in the 20 cm diameter radiotherapy beam. Measurements with a ruler show the beam range to be 43.9 mm in copper. The circular images of the holes drilled through the block indicate good alignment with the beam.

Accuracy Estimates

Sources of error in the range determination can come from several factors, listed below.
1. Wedge alignment. Misalignment changes the path length traversed by the beam before reaching the fiducial pattern on the back of the wedge. The alignment criticality is greater in the vertical direction since the wedge slope is greater, about 1.7% path length error per degree of offset. The sensitivity in the horizontal direction is one tenth this. Vertical alignment is done with a bubble level, so is accurate to better than .01°. Horizontal alignment is done with the fiducial hole pattern in the wedge, and is accurate to about 0.5°. These uncertainties translate to a path length error of about .06 mm in traversed thickness.
2. Film thickness. One must correct for the thickness of the protective layers around the film pack, and guard that the emulsion is oriented towards the wedge. If one places two films behind the wedge one can clearly see the range shift in the second film due to the first one. However, keeping this in mind and correcting for it can remove this as a source of systematic error.
3. Non-sharpness of the Line-of-Demarkation. This arises from a number of causes; range straggling,

non-parallel beam effects, and multiple scattering. If the fall-off of particles at the end of the range is not sharp, then the exposure level of the film becomes critical. If the film is totally saturated where beam strikes it then the line of demarkation will appear to move towards an area of lower real particle density, giving a higher energy reading for the beam. It is desirable then to know the distance over which the particle density drops.
a. Range straggling. Best estimates place the effect of this for heavy ions at about 0.25%, or about 0.2 mm spread in the stopping point of the ions.
b. Non-parallel beam effects. Typical Bevalac beam emittance indicates that beam divergences will be less than 2 to 5 milliradians. This will spread the path lengths through the wedge by about 0.5%, or 0.4 mm worst-case length difference.
c. Multiple scattering. The path of the particle slowing down in a medium will spread into a cone by multiple scattering. In our wedges calculations show that the cone diameter of the stopped particles is about 0.5 mm. The angular divergence is most pronounced at the end of the particle range. To keep lateral displacement of the stopping particles to a very minimum, and thus preserve the sharpest possible image on the film, the film must be placed as close to the back of the wedge as possible. Even a few mm separation will produce a noticeable fuzzing of the image.

Combining all of these errors yields a maximum spreading of the stopping beam of about 0.7 mm. This does not represent the magnitude of the error in the range determination, it only indicates the expected shift in the demarkation line for widely different film exposure levels. If care is taken not to saturate the film, the error in visually determining the line of demarkation (half-intensity point on the fall-off curve) can be reduced to about 0.2 mm. This is in fact borne out experimentally, repeated measurements of the same film by several observers give readings all within about 0.2 mm.
4. Wedge machining errors. Machining tolerances allowed only a few mils variation in all wedge dimensions; quick checking convinces one that path-length errors from this source will be of the order of .03 mm or less.
5. Range-energy relationships. Barkas and Berger proton range tables[6], scaled by Z^2/M remains the most widely used source of heavy ion ranges. Recent extensive theoretical work of Ahlen[7] has dealt directly with heavy ion effects, but a general lack of careful experiments clouds the accuracy of all heavy ion range-energy relationships. Best estimates are that potential deviations as large as 3% may exist between the best tabulated values and the real world. In the absence of experimental verification, this then must remain as the largest source of uncertainty in our measurements.

Accuracy - Summary

From the above discussions, we see that random errors in using the wedge for energy measurements are around 0.5%, while systematic errors from range-energy uncertainties could be as high as 3% for the heavier ions. This situation should be improved in the near future when a presently-planned program of time-of-flight measurements to determine dE/dx values for these ions gets underway.

Region of Applicability

The energy region over which this technique can be used is quite broad. At the lower end the beam must be able to penetrate the thinnest layer of the absorber and be able to reach the film emulsion,

implying a total range around 5 mm in a low Z material. At the upper end there is a practical maximum thickness of material which can be traversed above which the technique becomes difficult to apply. The growth in beam size due to range straggling and multiple scattering degrades resolution, and nuclear interactions substantially attenuate the primary beam. The nuclear mean free path for a typical heavy ion is around 10 gm/cm^2 of a medium-weight target, so a 1 GeV/amu neon ion will have gone through about 5 interaction lengths before stopping in copper. If less than a few percent of the primary beam survives to the stopping point the demarkation line on the film will become indistinguishable from the background of nuclear fragments. So, a maximum penetration thickness of about 50 gm/cm^2 represents about the upper limit of usefulness of this energy-measuring technique.

The energy ranges of these upper and lower thickness limits is summarized in Figure 3 for various ions. One sees that the range covered extends from about 100 MeV/amu for the lighter ions to several GeV/amu for the heavier ions.
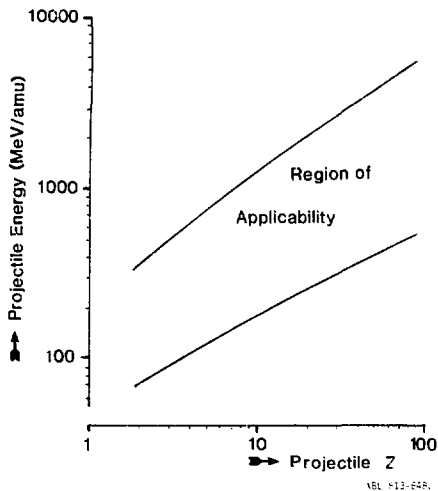

Figure 3. Region where the range-measurements discussed here provide good information about beam energy. At the low end a sufficient amount of material must be penetrated to expose the film, while multiple scattering, straggling and nuclear attenuation limit the upper end.

Summary

The measurement of range using a metallic wedge and photographic film as a detecting medium provides a rapid, efficient and quite accurate method of determining ion beam energies over a wide region of energies.

To most effectively cover different energy regions we have fabricated two wedges, one of aluminum the other of copper, and a set of rectangular blocks to provide total thicknesses of around 15 cm. This set very adequately covers most of the experimental beam/energy configurations encountered at the Bevalac.

References

1. P.J. Lindstrom, private communication.

2. P.J. Lindstrom, D.E. Greiner, H.H. Heckman, B. Cork, F.S. Bieser, LBL-3650, 1975.

3. D.E. Greiner, P.J. Lindstrom, H.H. Heckman, B. Cork, F.S. Bieser, Phys. Rev. Lett. 35, 152 (1975).

4. J.R. Alonso, J. Howard, T.L. Criswell, IEEE Trans. Nucl. Sci. NS-26, 3074 (1979).

5. J.R. Alonso, T.L. Criswell, J. Howard, W.T. Chu, R.P. Singh, D. Geller, M. Nyman, Proceedings of this conference.

6. W.H. Barkas and M.J. Berger, in Penetration of Charged Particles in Matter, U. Fano, ed. NAS-NRC Publ. 1133, Paper 7 (1967).

7. S.P. Ahlen, Rev. Mod. Phys. 52, 121 (1980).