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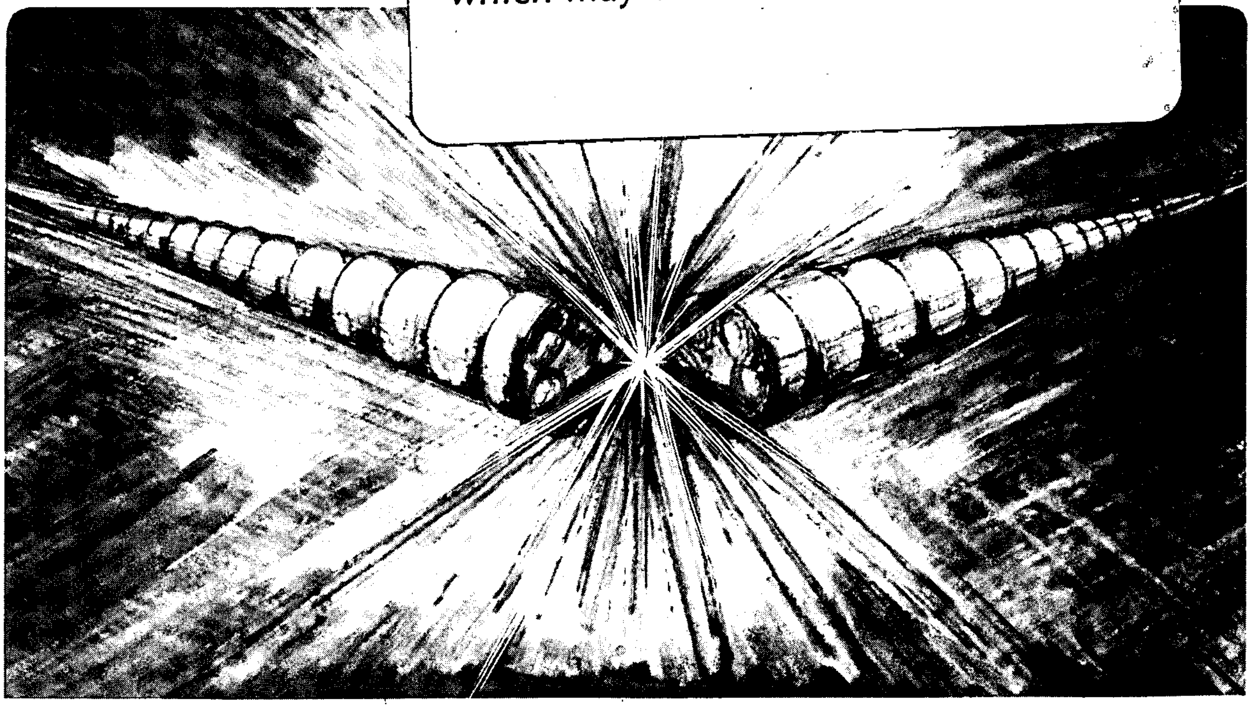

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MONITORING RELATIVISTIC HEAVY ION BEAMS AT THE BEVALAC*

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Summary

Beam fluence in high intensity proton and electron accelerators is usually measured with Secondary Emission Monitors(SEM) calibrated by an activation method. There were no such activation measurements available for relativistic heavy ion beams. Secondary electron production and energy loss of a charged particle in passing through material are a result of Coulomb interaction between the projectile field and electrons in the material. Therefore range measurements and secondary emission yield should follow the same functional relationship of velocity and charge as given by the Bethe-Bloch equation. A substantial amount of data on range in water for various ions has been collected at the Bevalac Biomedical facility. Using the same calculations that convert measured proton ranges to ion ranges and comparing the calculated values to measured values, provides an indirect way to verify the validity of the SEM calibration. The results of these measurements are discussed in this paper.

Introduction

At the Bevalac, we originally used the proton calibration corrected for the velocity and charge state of the heavy ion, when setting the electrometer to read the heavy ion fluence.[1] The original proton calibration of the SEM was done using both the carbon 11 and terbium from gold activation measurements. These results were good to ± 5%. It is possible to do an absolute calibration of the SEM against a scaler. Time structure on the beam can cause problems if there are multiple particles in the scaler within the time resolution of the discriminator gate. A calibration was done using an integrated photomultiplier signal compared to a photomultiplier scaler at a beam fluence low enough to minimise the multiple count problem. The beam fluence was increased two orders of magnitude, by means of calibrated attenuators, into the region where the SEM had a reasonable signal to noise ratio. The integrated photomultiplier signal, calibrated against a scaler, and the SEM, calibrated from proton data and corrected for charge and velocity of the heavy ion, were compared and gave results consistent to ± 5%.

Secondary electron production is a surface phenomenon with the collection of electrons of about 5 to 10 eV. The dE/dX described by the Bethe-Bloch equation is for a volume effect and the production of higher energy electrons. These higher energy electrons can in turn produce secondary electrons at the surface as they pass through. The secondary electron yield for protons with beta approaching 1 is typically about 2% per surface for aluminum foils. As the theory available in the literature indicates that the SEM yield follows the same relationship as the energy loss in passing through matter [2,3], then it seems reasonable to use the proton calibration corrected by Z^2/β^2 for monitoring heavy ions. There are a number of questions about the validity of a simple Z^2/β^2 correction for energy loss of heavy ions. Charge exchange or average charge state when passing through matter plus the correction terms in the full energy loss equation must be considered. Direct secondary emission measurements are difficult measurements to make. Range measurements are routine measurements at the Biomed facility. As the theory for SEM yield follows the relationship for energy loss in the material, it seems reasonable to carry this same relationship over into heavy ion yields. Then the range measurements provide an easy check on what mass and energy particles can be handled by the simple Z^2/β^2 correction. A substantial amount of data on range in water for various ions has been collected at the Bevalac Biomedical facility. This, plus a better determination of kinetic energy of ions in the Bevalac[4], allow a comparison between calculated and measured ranges.

Range Measurements

At the Biomedical facility, a range measurement is done with two ion chambers and a water column that allows the path length through the water to be varied. One ion chamber is upstream of the water column and the second is just downstream of the water column. The amount of water can be varied from 0 to about 40 centimeters ± 0.01 cm. The charge collected in the ion chambers is converted to equivalent dose in rads that would be deposited in water at that position. The ratio of the downstream ion chamber to the upstream ion chamber is recorded as a function of the amount of water path in the beam. This ratio is normalized to one with zero water in the beam. A plot of this, called a Bragg curve, is shown in Fig 1.

The range must be distinguished from the path length in the medium which is greater than the range because of scattering of the projectile in passing through matter. Straggling occurs in the range of the particles. This data is tabulated in range tables for protons. There are several sets of tables by different authors. I have used the Janni Tables [5] for proton ranges so that calculations by the accelerator operations group would be consistent with the data used by the Biomedical group. I have fitted the Janni data with a ten point curve fit using a ninth order polynomial in a PC computer program. It is fitted in two parts, from 10 to 100 MeV/amu (atomic mass units); and from 100 to 1000 MeV/amu. The program takes the kinetic energy, atomic mass, and charge state of the projectile and the thickness in centimeters of water equivalent material in the beam and outputs the energy after passing through the material, the dE/dx in water at that energy, and the residual range in centimeters of water. It should be noted that the entering argument in range tables is proton energy while in fact it should be beta. Therefore, as heavy ion energies are normally refered to in energy/amu, the proton energy number in the table must be divided by the mass of the proton (1.007276) to convert it to MeV/amu.

The problem now is to decide what the range is from the Bragg curve measurement. If we plot the dE/dx of a stopping particle as β goes to zero, the dE/dx increases very rapidly as shown in Fig. 2. We

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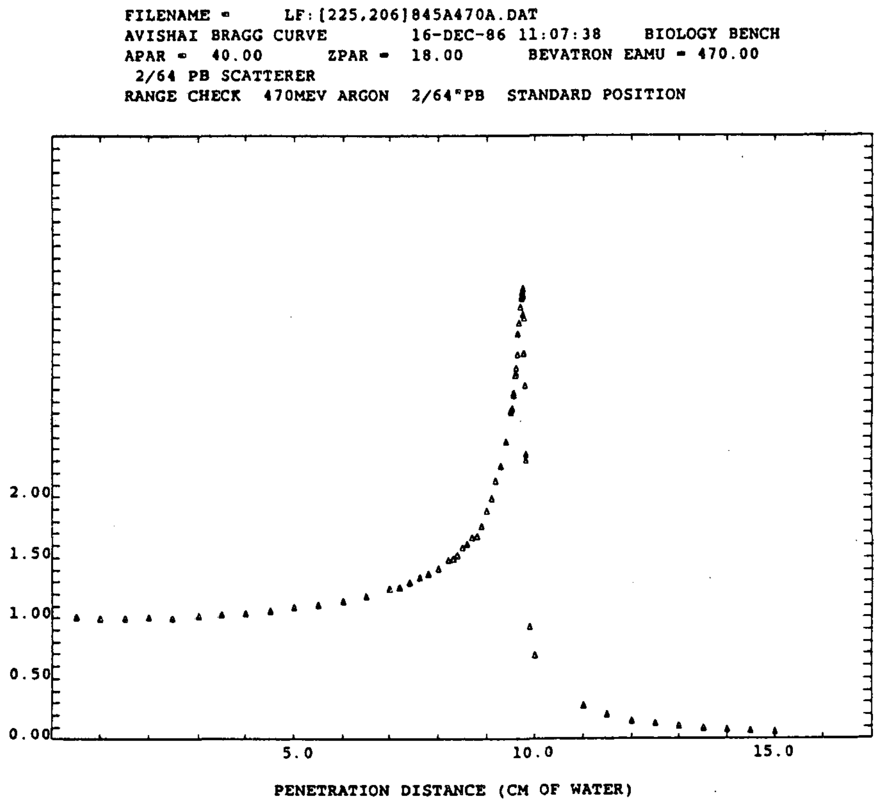

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Fig. 1. Ratio of dose in downstream ion chamber to dose in upstream ion chamber as a function of distance in water.

must, however, put a shift around the stopping point to represent the energy spread of the incoming particles as well as the straggling of the range as the ion travels through the material. This smearing out of the sharply rising stopping point would produce a shape as observed in the Bragg curve (Fig. 1). Let's choose the Bragg peak as the measurement of the range and examine the possible errors of this choice later.

The long tail in the Bragg curve beyond the high peak is caused by fragments of the primary particles after a nuclear interaction. As the fragments may have the same energy as the primary ion but are of a lower charge state than the primary beam, they will have a longer range.

We wish to compare the observed range to the calculated range for a particle at machine energy. It is necessary to include all the material the beam passes through when calculating this range. All the beam windows in vacuum pipes, all diagnostic instuments (SEM, scintillators, air gaps in the beam line) must be included. For high mass particles at lower energies, changes in rigidity as a result of energy loss may require retune of the beam line downstream of the material each time the particle passes through matter.

Argon Range Measurements

The corrected energy for the argon ions in the Bevalac was 473.45 MeV/amu ± 1.25 percent. The Janni tables give a range of 13.311 cm ± 1/2% in water, when corrected for Z^2/β^2, for this particle. Staggling would produce about a one percent spread in the range which is 0.133 cm. The energy spread of the particles in the Bevalac is ± 0.55 MeV/amu which calculates to ± 0.022 cm range variation for this particle. The total spread then would be 0.155 cm. Table I contains the tabulated values that are plotted in the Bragg curve Fig. 1. The peak is at 9.720 cm with a value of the ratio of 3.681. The ratio drops rapidly to 0.923 at 9.900 cm.

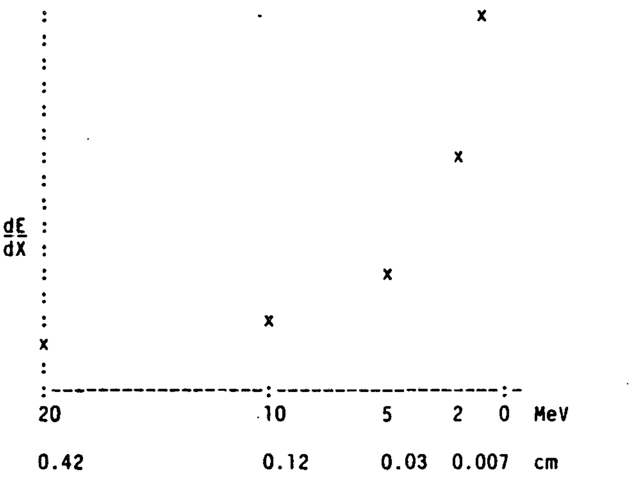

Fig. 2. Relative energy loss vs kinetic energy in MeV and range in centimeters for protons in water as β goes to zero.

Table I. Ratio of ion chamber doses (y) as a function of distance in water (x). Note some duplication of distances give a variation in value of the ratio.

x	y	x	y
0.500	1.004	1.000	0.990
1.500	0.996	2.000	1.007
2.500	0.990	3.000	1.017
3.500	1.029	4.000	1.034
4.500	1.059	5.000	1.083
5.500	1.104	6.000	1.139
6.500	1.181	7.000	1.242
7.200	1.255	7.400	1.288
7.600	1.335	7.800	1.362
8.000	1.410	8.200	1.475
8.300	1.489	8.400	1.514
8.500	1.585	8.600	1.612
8.700	1.663	8.800	1.677
8.900	1.759	9.000	1.876
9.100	1.980	9.200	2.122
9.300	2.245	9.400	2.459
9.500	2.699	9.600	3.026
9.700	3.674	9.800	2.302
9.900	0.923	10.000	0.683
9.500	2.724	9.520	2.729
9.540	2.850	9.560	2.869
9.580	3.015	9.600	3.076
9.620	3.185	9.640	3.358
9.660	3.452	9.680	3.590
9.700	3,662	9.720	3.681
9.740	3.524	9.760	3.193
9.780	2.930	9.800	2.352
9.700	3.680	9.720	3.744
9.740	3.679	9.710	3.716
9.730	3.703	9.750	3.492
11.000	0.274	11.500	0.199
12.000	0.154	12.500	0.125
13.000	0.104	13.500	0.090
14.000	0.076	14.500	0.069
15.000	0.069		

This is a distance of 0.180 cm beyond the peak. The calculated spread from straggling and energy spread was 0.155 cm. Therefore choosing the peak as the measure of range is an easy point to select on the Bragg curve data and the error can not be very great.

There are 3.343 cm of water equivalent material in the beam line exclusive of the water in the water column. The calculated range on the Biomedical bench is 9.951 cm. The measured Bragg peak is at 9.720 cm (Table I). This is a difference of 0.231 cm or 1.2 percent variation in kinetic energy of the particle or 2.4 percent variation in range.

Data from runs with carbon, neon, silicon, and argon ions are shown in Table II. The first two entries were done with logging of Bevatron parameters (magnetic field and frequency) at the same time the Bragg curves were being measured. The other data, which goes back to 1979, includes some of the Bevatron data for nominal operating conditions rather than data taken at the time of the range measurement. In addition, curve fitting for both the Janni tables and the calculations for Bevatron energy corrections have been improved over the years and are used in the first two tabulated measurements.

The results show good agreement between calculated and measured ranges using just a simple Z^2/β^2 correction for heavy ions from proton data. The argon results show a larger deviation than the lighter ions. Iron has been run at the Biomed facility with no substantial changes from calculations observed but data is unavailable. The deviations in range shown are well within the original ± 5% calibration from activation measurements. As the same corrections apply to secondary electron production, we can have confidence that the same correction applied to the original proton activation calibration for the SEM gives us a valid intensity measurement for heavy ions at least up to iron.

Table II. Calculated and measured ranges for some ions measured at the Bevalac.

ION	Machine KE MeV/amu	Calculated RANGE cm	Measured RANGE cm	R_m-R_c R_m Percent
argon	473	9.951	9.720	2.4
neon	427	12.830	12.760	-0.5
neon	667	33.290	33.180	-0.3
silicon	667	20.84	20.60	-1.1
silicon	320	3.92	3.92	0.0
carbon	406	24.78	25.01	0.9
carbon	476	32.93	32.90	0.1

Conclusions

Examination of the Bethe-Bloch equation show considerably more terms than the Z^2/β^2. The higher mass particles will show deviations from the simple correction used in this paper. Some early data on the complete Bethe-Bloch equation for heavy ions can be found in Reference 6. It should also be noted that as the ions slow down, the equilibrium charge state changes while going through matter[7]. This will also cause deviations from the simple proton curves used here. However up to at least iron ions the simple Z^2/β^2 correction to proton range and energy loss tables give results for heavy ions that are accurate to a few percent.

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