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OFFICE MEMORANDUM

TO : DISTRIBUTION

DATE: March 30, 1977

712975

FROM : Pete Berardo, MP-3, MS 809 SAB

SUBJECT : Pion 1 Calculation

SYMBOL : MP-3

MAIL STOP: 809

How is simple comparison of beam doing?

Please review the two attached outlines for proposed calculations to be done with PION 1 and return with your comments by 8 April 77.

PB/om

Attachments:

(1) Dose Perturbations at Interfaces Due to Pion Stars (PB).

(2) Calculations for Silicon Detector Response to the Pion Beam (CR).

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Dose Perturbations at Interfaces Due to Pion Stars

With conventional radiation using x-rays, gamma rays, or electrons, it is usual to find relative enhancements or decreases in dose across the interface between dissimilar media. This is primarily a electronic phenomenon explained by delta-rays and their subsequent scatterings. Pion stars, however initially distribute secondary particles isotropically with relatively little delta-ray production. We wish to determine the possible dose perturbations across bone/muscle interfaces in a regions of uniform and non-uniform spatial distribution of pion stars.

Background:

Aside from multiple scattering, the location of pion stars is determined by the initial energy spectrum and the mass-stopping-powers of the media through which it passes. This is primarily an electronic phenomenon and to frist order in biological tissues the number of stars per gram at a given range is a constant. The energy distribution from charged star secondaries is also determined by the mass stopping power of the various media. Since dose is the energy deposited in a volume divided by the mass of the volume, dose per unit path length along an ionization track is equivalent to stopping-power. Thus, to first order, dose does not change across an interface.

To second order, the mass-stopping-power does vary from one type of tissue to the next. For example, the ratio of bone to muscle is about 0.94 for pions. Such differences can cause more secondaries to pass from bone into tissue than the reverse, yielding an enhanced tissue dose and a depressed bone dose near the interface. Considering that bone and tissue doses would already differ by about 6%, the total effect across the interface could be around 10% in physical dose.

Next, it is noted that the excess of energy crossing from bone into tissue will be in the form of particles near the end of their range and the deficit of energy crossing from tissue into bone is the absence of such particles. Thus the energy enhancement in muscle is expected to be from particles with higher than average LET and the depression in bone is due the absence of such particles. Therefore, if there is a 10% difference in physical dose at the interface, there may be a significantly larger difference in effective dose.

Finally it is noted that the physical composition differs slightly between bone and muscle. For pion stars at rest it may be assumed that star formation for different nuclei scales as Z. Excluding hydrogen the average Z's are 7.6 for muscle and 8.3 for bone. This difference in effective Z is slightly less than the differences between carbon and nitrogen or nitrogen and oxygen. So it would appear that knowing the actual star products from calcium and phosphorous is less important than the differences between the much more common elements in both muscle and bone.

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For pion stars in flight, the cross sections may be scaled as $A^{2/3}$. Again excluding hydrogen, the average A's are 16.6 for bone and 15.3 for muscle, so that the bone/muscle ratio of inflight stars is about 1.06, which essentially offsets the lower stopping power in bone. Thus in the plateau region dose differences should be limited differences in primary flux caused by multiple scattering.

Calculations

Five calculations are to be considered and are defined in more detail below. Each has regions of high resolution. Three are concerned with a bone/muscle interface parallel to a standard beam. The first is a base case in a uniform phantom for comparision with experiment and PIPLAN calculations and to aid interpetation of the interface calculation. For the parallel interface there are three regions of interest: (1) bone stopping region next to muscle plateau region, (2) muscle stopping region past bone stopping region and (3) adjacent plateau regions. Calculations with multiple scattering turned on and off will allow separation of secondary and primary particle interface effects.

The remaining two calculations deal with interfaces in a uniform, extended stopping region (large momentum spread). Again there is a base case for comparison with experiment PIPLAN calculation, and PION 1 interface calculation. The bone in this case has interfaces both normal and parallel to the beam, edged onto the central axis, and centered in the muscle stopping region.

The geometries defined below should be compatible with present PION 1 capabilities. The main problem is one of statistics in small volume elements when the looked for effects are on the order of 10% perturbations. But these calculations would appear to be the best available and should serve as reliable guides in generally predicting interface effects. As such, the computer expense is warrented.

1. Base Case - Unspread Momentum

Dose distribution in muscle (TE fluid to be used in experiment), using beam type for Run 428, PØ = 168 MeV/c, TØ = 78.8 MeV. Pion range at 78.8 MeV is 18.8 cm in water, 19.0 cm in muscle.

Rectangular dose accumulation gird, 1 cm resolution for $-6 \leq X \leq +6$ cm, $-6 \leq y \leq +6$ cm, $0 \leq Z \leq 24$ cm; embedded in this gird are 3 high resolution bands as follows:

(1) $\Delta X = 1$ mm for $-1.0 \leq X \leq +1.0$ cm
(2) $\Delta Z = 1$ mm for $17.0 \leq Z \leq 21.0$ cm
(3) $\Delta Z = 1$ mm for $9.0 \leq Z \leq 13.0$ cm.

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2. Parallel Interface

Same geometry and dose accumulation grid as in Bone Case 1 above, except replace muscle with bone for $X<0$. Range of 78.8 MeV π^- in Bone is 20.25 gm/cm^2. Assume physical density of 1.85 gm/cm3 or range of $\sim$11 cm.

A. Run with multiple scattering turned off.

B. Run with all interactions enabled.

3. Base Case - Spread Momentum

Dose distribution in muscle using beam tape for run 428. Change momentum to give uniform stopping distribution from 9.0 to 15.0 cm, but with range-straggling included. In muscle 67.8 MeV pions have a range of 15 cm and 49.4 MeV pions have a range of 9 cm.

Rectangular dose distribution, 1 cm resolution for $-6 \leq X \leq +6$ cm, $-6 \leq y \leq +6$, $0 \leq Z \leq 20$ cm; embedded in this grid is a high resolution volume with $\Delta X = \Delta Z = 1$ mm, $\Delta y = 1$ cm for $-1.0 \leq X \leq +1.0$ cm, $-6.0 \leq y \leq +6.0$ cm, $11.0 \leq Z \leq 13.0$ cm.

4. Interface Normal to Beam

Same beam and dose grid as in Case 3 above, except replace muscle with bone for volume with $X<0$ and $Z>12$ cm.

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Muscle and Bone Composition

(From Berger, Seltzer - NASA VSP - 3036)

				MUSCLE		BONE	
	A	Z	A/Z	% WT.	% LBS	% WT	% LBS
H	1.008	1	1.008	10.2	63.3	6.4	52.8
C	12.011	6	2.001	12.3	6.38	27.8	19.2
N	14.008	7	2.001	3.5	1.56	2.7	1.6
O	16.000	8	2.000	72.9	28.5	41.0	21.3
Na	22.991	11	2.083	0.08	0.02	—	—
Mg	24.320	12	2.027	0.02	0.005	0.2	0.067
P	30.975	15	2.065	0.02	0.041	7.0	1.88
S	32.066	16	2.004	0.05	0.10	0.2	0.5
K	39.1000	19	2.058	0.3	0.048	—	—
Ca	40.08	20	2.004	—	—	14.7	3.05

Muscle

Average Z = 3.49, Average Z (Z>1) = 7.66
Average A = 6.25, Average A (Z>1) = 15.3

Bone

Average Z = 4.48, Average Z (Z>1) = 8.29
Average A = 8.45, Average A (Z>1) = 16.64

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π⁻ Stopping Power MeV-cm²/gm
Berger, Seltzer NASA SP-3036

ENERGY MEV	LIQUID H2 I= 18.7	LIF I= 88.9	SI I=172.0	GE I=343.0	PROPANE I= 50.3	FREON I=204.7	MUSCLE I= 66.2	BONE I= 85.1	BONE/MUSCLE
2.0	7.956E 01	2.904E 01	2.752E 01	2.074E 01	4.079E 01	2.423E 01	3.638E 01	3.353E 01	.92
4.0	4.440E 01	1.663E 01	1.602E 01	1.236E 01	2.310E 01	1.418E 01	2.070E 01	1.918E 01	.93
6.0	3.168E 01	1.201E 01	1.166E 01	9.099E 00	1.660E 01	1.035E 01	1.491E 01	1.385E 01	.93
8.0	2.503E 01	9.561E 00	9.329E 00	7.328E 00	1.317E 01	8.297E 00	1.185E 01	1.102E 01	.93
10.0	2.092E 01	8.033E 00	7.863E 00	6.206E 00	1.104E 01	7.002E 00	9.939E 00	9.258E 00	.93
14.0	1.607E 01	6.217E 00	6.113E 00	4.855E 00	8.520E 00	5.453E 00	7.680E 00	7.164E 00	.93
18.0	1.330E 01	5.171E 00	5.099E 00	4.067E 00	7.071E 00	4.553E 00	6.380E 00	5.957E 00	.93
22.0	1.150E 01	4.488E 00	4.435E 00	3.548E 00	6.127E 00	3.964E 00	5.533E 00	5.170E 00	.93
26.0	1.024E 01	4.007E 00	3.966E 00	3.180E 00	5.464E 00	3.547E 00	4.936E 00	4.615E 00	.93
30.0	9.301E 00	3.650E 00	3.617E 00	2.906E 00	4.972E 00	3.237E 00	4.494E 00	4.204E 00	.94
34.0	8.582E 00	3.374E 00	3.348E 00	2.694E 00	4.593E 00	2.997E 00	4.153E 00	3.886E 00	.94
38.0	8.011E 00	3.155E 00	3.134E 00	2.525E 00	4.292E 00	2.806E 00	3.882E 00	3.634E 00	.94
42.0	7.547E 00	2.977E 00	2.960E 00	2.388E 00	4.047E 00	2.651E 00	3.662E 00	3.429E 00	.94
46.0	7.164E 00	2.830E 00	2.816E 00	2.274E 00	3.845E 00	2.523E 00	3.480E 00	3.259E 00	.94
50.0	6.843E 00	2.706E 00	2.695E 00	2.178E 00	3.675E 00	2.415E 00	3.326E 00	3.114E 00	.94
60.0	6.228E 00	2.468E 00	2.463E 00	1.995E 00	3.351E 00	2.209E 00	3.034E 00	2.842E 00	.94
70.0	5.794E 00	2.299E 00	2.300E 00	1.865E 00	3.121E 00	2.063E 00	2.827E 00	2.649E 00	.94
80.0	5.472E 00	2.173E 00	2.179E 00	1.769E 00	2.952E 00	1.955E 00	2.672E 00	2.504E 00	.94
90.0	5.227E 00	2.077E 00	2.080E 00	1.691E 00	2.822E 00	1.873E 00	2.556E 00	2.390E 00	.94
100.0	5.035E 00	2.001E 00	2.009E 00	1.636E 00	2.721E 00	1.809E 00	2.465E 00	2.306E 00	.94
110.0	4.882E 00	1.941E 00	1.953E 00	1.592E 00	2.641E 00	1.758E 00	2.391E 00	2.238E 00	.94
120.0	4.757E 00	1.892E 00	1.907E 00	1.556E 00	2.575E 00	1.717E 00	2.331E 00	2.183E 00	.94
130.0	4.655E 00	1.851E 00	1.869E 00	1.527E 00	2.522E 00	1.684E 00	2.282E 00	2.137E 00	.94
140.0	4.571E 00	1.817E 00	1.838E 00	1.503E 00	2.478E 00	1.656E 00	2.241E 00	2.099E 00	
150.0	4.500E 00	1.789E 00	1.812E 00	1.484E 00	2.439E 00	1.634E 00	2.207E 00	2.067E 00	
160.0	4.441E 00	1.765E 00	1.790E 00	1.467E 00	2.406E 00	1.615E 00	2.178E 00	2.040E 00	
170.0	4.390E 00	1.745E 00	1.772E 00	1.453E 00	2.377E 00	1.599E 00	2.154E 00	2.017E 00	
180.0	4.347E 00	1.727E 00	1.756E 00	1.441E 00	2.353E 00	1.586E 00	2.133E 00	1.998E 00	
190.0	4.311E 00	1.712E 00	1.743E 00	1.431E 00	2.332E 00	1.575E 00	2.115E 00	1.981E 00	
200.0	4.280E 00	1.699E 00	1.731E 00	1.423E 00	2.313E 00	1.566E 00	2.099E 00	1.966E 00	
220.0	4.230E 00	1.678E 00	1.713E 00	1.410E 00	2.284E 00	1.551E 00	2.074E 00	1.942E 00	
240.0	4.193E 00	1.663E 00	1.700E 00	1.401E 00	2.262E 00	1.542E 00	2.055E 00	1.924E 00	
260.0	4.165E 00	1.651E 00	1.691E 00	1.395E 00	2.245E 00	1.535E 00	2.041E 00	1.910E 00	
280.0	4.141E 00	1.642E 00	1.684E 00	1.391E 00	2.232E 00	1.529E 00	2.031E 00	1.900E 00	
300.0	4.123E 00	1.636E 00	1.680E 00	1.389E 00	2.223E 00	1.526E 00	2.023E 00	1.893E 00	
320.0	4.109E 00	1.631E 00	1.677E 00	1.388E 00	2.216E 00	1.524E 00	2.017E 00	1.888E 00	
340.0	4.098E 00	1.628E 00	1.675E 00	1.388E 00	2.210E 00	1.524E 00	2.013E 00	1.885E 00	
360.0	4.089E 00	1.625E 00	1.674E 00	1.388E 00	2.207E 00	1.524E 00	2.010E 00	1.883E 00	
380.0	4.083E 00	1.624E 00	1.675E 00	1.390E 00	2.205E 00	1.525E 00	2.009E 00	1.882E 00	
400.0	4.078E 00	1.624E 00	1.676E 00	1.391E 00	2.203E 00	1.526E 00	2.008E 00	1.881E 00	

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PION RANGE gm/cm²
Berger, Seltzer NASA SP-3036

ENERGY MEV	LIQUID H2 I= 18.7	LIF I= 88.9	SI I=172.0	GE I=343.0	PROPANE I= 50.3	FREON I=204.7	MUSCLE I= 66.2	BONE I= 85.1	Bone/muscle
2.0	1.364E-02	3.845E-02	4.159E-02	5.692E-02	2.694E-02	4.753E-02	3.042E-02	3.324E-02	1.09
4.0	4.893E-02	1.336E-01	1.409E-01	1.868E-01	9.514E-02	1.600E-01	1.067E-01	1.157E-01	1.08
6.0	1.031E-01	2.773E-01	2.894E-01	3.781E-01	1.989E-01	3.275E-01	2.223E-01	2.403E-01	1.08
8.0	1.748E-01	4.654E-01	4.826E-01	6.248E-01	3.353E-01	5.449E-01	3.741E-01	4.035E-01	1.08
10.0	2.626E-01	6.947E-01	7.172E-01	9.227E-01	5.019E-01	8.085E-01	5.593E-01	6.024E-01	1.08
14.0	4.832E-01	1.267E 00	1.300E 00	1.659E 00	9.188E-01	1.462E 00	1.022E 00	1.099E 00	1.08
18.0	7.584E-01	1.976E 00	2.021E 00	2.564E 00	1.437E 00	2.270E 00	1.597E 00	1.715E 00	1.07
22.0	1.083E 00	2.810E 00	2.865E 00	3.621E 00	2.047E 00	3.215E 00	2.273E 00	2.438E 00	1.07
26.0	1.453E 00	3.755E 00	3.821E 00	4.814E 00	2.740E 00	4.284E 00	3.040E 00	3.259E 00	1.07
30.0	1.863E 00	4.803E 00	4.879E 00	6.132E 00	3.509E 00	5.467E 00	3.891E 00	4.169E 00	1.07
34.0	2.312E 00	5.945E 00	6.030E 00	7.564E 00	4.347E 00	6.753E 00	4.818E 00	5.160E 00	1.07
38.0	2.795E 00	7.172E 00	7.266E 00	9.099E 00	5.249E 00	8.134E 00	5.815E 00	6.225E 00	1.07
42.0	3.310E 00	8.478E 00	8.580E 00	1.073E 01	6.210E 00	9.601E 00	6.877E 00	7.359E 00	1.07
46.0	3.854E 00	9.857E 00	9.967E 00	1.245E 01	7.224E 00	1.115E 01	7.998E 00	8.557E 00	1.07
50.0	4.426E 00	1.130E 01	1.142E 01	1.425E 01	8.289E 00	1.277E 01	9.175E 00	9.813E 00	1.07
60.0	5.961E 00	1.518E 01	1.531E 01	1.906E 01	1.115E 01	1.711E 01	1.233E 01	1.318E 01	1.07
70.0	7.629E 00	1.939E 01	1.952E 01	2.425E 01	1.424E 01	2.180E 01	1.575E 01	1.683E 01	1.07
80.0	9.407E 00	2.387E 01	2.399E 01	2.976E 01	1.754E 01	2.679E 01	1.939E 01	2.072E 01	1.07
90.0	1.128E 01	2.858E 01	2.869E 01	3.554E 01	2.101E 01	3.202E 01	2.322E 01	2.481E 01	1.07
100.0	1.323E 01	3.348E 01	3.359E 01	4.156E 01	2.462E 01	3.746E 01	2.721E 01	2.907E 01	1.07
110.0	1.525E 01	3.856E 01	3.864E 01	4.776E 01	2.835E 01	4.307E 01	3.133E 01	3.348E 01	1.07
120.0	1.732E 01	4.378E 01	4.382E 01	5.412E 01	3.219E 01	4.883E 01	3.557E 01	3.800E 01	1.07
130.0	1.945E 01	4.913E 01	4.912E 01	6.060E 01	3.611E 01	5.471E 01	3.991E 01	4.264E 01	1.07
140.0	2.162E 01	5.458E 01	5.452E 01	6.720E 01	4.012E 01	6.070E 01	4.433E 01	4.736E 01	
150.0	2.382E 01	6.013E 01	6.000E 01	7.390E 01	4.418E 01	6.678E 01	4.883E 01	5.216E 01	
160.0	2.606E 01	6.576E 01	6.555E 01	8.068E 01	4.831E 01	7.294E 01	5.339E 01	5.703E 01	
170.0	2.832E 01	7.146E 01	7.117E 01	8.753E 01	5.250E 01	7.916E 01	5.801E 01	6.196E 01	
180.0	3.061E 01	7.722E 01	7.684E 01	9.444E 01	5.672E 01	8.544E 01	6.268E 01	6.694E 01	
190.0	3.292E 01	8.304E 01	8.256E 01	1.014E 02	6.100E 01	9.177E 01	6.738E 01	7.197E 01	
200.0	3.525E 01	8.890E 01	8.831E 01	1.084E 02	6.530E 01	9.814E 01	7.213E 01	7.704E 01	
220.0	3.995E 01	1.007E 02	9.993E 01	1.225E 02	7.400E 01	1.110E 02	8.172E 01	8.728E 01	
240.0	4.470E 01	1.127E 02	1.117E 02	1.368E 02	8.281E 01	1.239E 02	9.141E 01	9.763E 01	
260.0	4.949E 01	1.248E 02	1.234E 02	1.511E 02	9.168E 01	1.369E 02	1.012E 02	1.081E 02	
280.0	5.431E 01	1.369E 02	1.353E 02	1.654E 02	1.006E 02	1.500E 02	1.110E 02	1.186E 02	
300.0	5.915E 01	1.491E 02	1.472E 02	1.798E 02	1.096E 02	1.631E 02	1.209E 02	1.291E 02	
320.0	6.401E 01	1.614E 02	1.591E 02	1.942E 02	1.186E 02	1.762E 02	1.308E 02	1.397E 02	
340.0	6.898E 01	1.737E 02	1.711E 02	2.086E 02	1.277E 02	1.893E 02	1.407E 02	1.503E 02	
360.0	7.377E 01	1.860E 02	1.830E 02	2.230E 02	1.367E 02	2.024E 02	1.506E 02	1.609E 02	
380.0	7.866E 01	1.983E 02	1.949E 02	2.374E 02	1.458E 02	2.155E 02	1.606E 02	1.715E 02	
400.0	8.356E 01	2.106E 02	2.069E 02	2.518E 02	1.548E 02	2.287E 02	1.705E 02	1.822E 02	

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Calculations for Silicon Detector Response to the Pion Beam

It would be helpful to have a theoretical guide to the response of a small detector of silicon, to the beam. The detector is small compared to the size of the field. It's a flat cylinder 2 mm in diameter and 50 μm thick.

In particular the dose produced by the pions, the protons and other singly charged particles, and the α's and other heavy particles would be calculated to see if a separation can be made. Experimentally this separation appears practical.

The calculation should be made for tune 23 and range shifter function 8K if possible.

It is convenient in this work to define the function F(E) which is the energy per unit logarithmic interval in energy deposited in the detector. Let N(E) be the number of pulses in the detector of energy between E_1 and E_2 then

$$F(E) = \frac{N(E)E}{\ln E_2 - \ln E_1} \qquad E = \frac{E_1+E_2}{2}$$

The function F(E) is obtained from the experimental data.

Different thickness of detectors are being used to separate the particles. The calculations could be a guide as to when the separation is double. We can go down to 7 μm thickness easily and 2 μm if necessary.

For obtaining the LET spectra the distribution of path lengths for the protons and the α's is necessary.

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Experimentally there are three distinguishable groups of particles; the first group consists of pions, muons and electrons, the second group consists of the singly charged particles, and the third group consists of the multiply charged particles.

For biology the proton component can probably be lumped with the pion component, but to elucidate the physics these components should be kept apart.

As a final goal we need to aim for an approximate analysis of the energy spectra of these particles. The final dose calculations as obtained from an ion chamber depends on these spectra thru the W valves.

For a therapeutic guide we also need the function

$$\sigma(E) = \int_E^{\infty} F(E)\, d\ln E$$

From such a function, one can read off the dose in various finite intervals of LET.

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