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Estimation of the Radiation Environment Near the Interaction Vertex from Beam-Beam Collisions in RHIC

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I. Introduction

This note presents estimates of the radiation field very near the collision point from beam-beam interactions in RHIC. The concern in this region is possible radiation damage to silicon vertex detectors and circuits. Two types of radiation are important; (1) the hadron flux which causes "displacement damage" in silicon and (2) ionizing radiation which degrades the insulating properties of oxides in detectors and integrated circuits. The presence of material (calorimeters, magnet yokes) near detectors acts as a source of fast (≥1MeV) neutrons, dominantly from evaporation. There are several reasons for focusing on such neutrons when considering displacemnt damage effects: (a) the flux of such neutrons may (depending on the detector) dominate the hadron flux, (b) these neutrons are more damaging (higher non-ionizing energy loss than high energy pions by perhaps a factor of 2), and (c) displacement damage effects are most conveniently measured by using fast neutron sources. It should be kept in mind, however, that the total hadron flux, which includes directly produced hadrons as well as fast neutron "albedo" from the surrounding material, is the quantity of interest when displacement damage effects are considered. The *spirit* of the estimates presented below is an attempt to obtain factor of 2-ish accuracy for the radiation field in a proto-typical detector geometry Before proceeding with the radiation estimate, a very brief description of the damage phenomena is presented.[1]

At fast neutron fluences as low as 10^{10} n/cm^2, leakage (or "dark") current, caused by the introduction of "generation centers" at defects in the detector volume, becomes observable. Such currents do not degrade performance initially, but can cause serious noise problems and excessive voltage drops across bias resistors above 10^{12} n/cm^2. Operation at lowered temperatures (~0°C) can permit operation into the 10^{14}/cm^2 range.

At fluences approaching 10^{11} n/cm^2, a frequency dependent capacitance change occurs. While this effect does not, in general, degrade performance, its presence is a useful diagnostic to the detector's exposure.

The vacancies caused by displacement in the silicon lattice combine with themselves or with dopants to form several species of stable "compounds" which are electrically active. The net result of this activity is to deplete donors and increase acceptors which causes the silicon to become increasingly p-type, and an "inversion" of an original n-type material to a p-type material occurs at about 8×10^{12} n/cm^2. Although the detector continues to function (collect charge), it requires an increasing bias voltage as the resistivity decreases. Finally, a practical limit of 500V, for example, is reached at the ~10^{14} n/cm^2 range. Another effect at higher fluence levels is that of carrier trapping which removes charge from each event. However, the magnitude of this loss is typically 10% at 10^{14} n/cm^2 so that trapping is not a limiting effect.

Ionizing radiation creates charge in both the silicon and the passivating oxide. Some of the positive charge created in the oxide will accumulate at (or close to) the Si-SiO_2 interface. This induces an electron "accumulated" region near junction edges which can result in significant junction leakage current. Integrated circuits are generally more sensitive than detectors to this effect and others, and may suffer degradation at a level of tens of kilorads.

II. Fast Neutron Flux

The fast neutron flux is estimated by scaling calculations which have been made for albedo neutrons at the SSC to the RHIC environment. The "Groom Report"[2] estimates the neutron flux $\geq$ 160 kev in the interior of a uranium/scintillator calorimetric volume taken as a spherical shell with $|\eta| \leq 3$. For a 1m radius cavity the result (Ref.[2], pg. 50, scaled from 2m radius to 1m) is:

$$10^{13} \text{ n/cm}^2 \text{ SSC yr.}$$

An SSC year is 10^7 seconds or ~2780 hrs. at $L = 10^{33}/\text{cm}^2\text{sec}$.

I assume that the best scaling factor to another collider is the total number of hadrons (~ charged tracks) per unit time from the primary interaction with $|\eta| \leq 3$. This is the product of:

$$L \times \sigma \times \langle n \rangle_{ch}$$

where L (as above) is the luminosity, σ is the non-elastic cross section, and $\langle n \rangle_{ch}$ is the mean multiplicity for particles having $|\eta| \leq 3$.

(a) p-p Running

The design L for 100 GeV/c proton beams is $4 \times 10^{30}/\text{cm}^2\text{sec}$. From pages 3 and 64 of Ref. [2], the inelastic cross section at $\sqrt{s} = 200$ GeV is ~ 40 mb, rising to ~90 mb at $\sqrt{s} = 40$ TeV. For the $\langle n \rangle$ ratios, Ref. [2] gives[2] 2.9/7.8. The scaling factor becomes

$$\frac{4 \times 10^{30}}{10^{33}} \times \frac{40}{90} \times \frac{2.9}{7.8} \cong 0.65 \times 10^{-3}$$

So the expected neutron flux is **6.5×10^9 n/cm^2 per 2800 hours**. For 250 GeV/c protons, the result is about 3 times this or ~ 2×10^{10} n/cm^2 per 2800 hrs.

(b) Au-Au Running

For heavy ions, the uncertainty in the scaling parameter, especially $\langle n \rangle$, is much larger.[4] I have chosen the values of both σ and $\langle n \rangle_{ch}$ to be consistent with those in the PHENIX CDR.[5] From Table 11.1 of that report and the acceptances given in Table 2.1 ($\Delta\eta = .70$, $\Delta\phi/2\pi = .5$), one obtains 6.2 barns which is in good agreement with the 6.7 barns used to derive the interaction rates in the RHIC CDR. Also from Table 11.1, the value of dn/dy of 211. for minimum bias events[6] gives $\langle n \rangle_{ch} = 211 \times 6 = 1266$. Since the time-averaged design L for Au on Au is 2×10^{26} the scaling factor becomes:

$$\frac{2 \times 10^{26}}{10^{33}} \times \frac{6.2}{.09} \times \frac{1266}{46.8} = 3.7 \times 10^{-4}$$

which gives ~ **4×10^9 n/cm² per 2800 hrs**.

Within the errors[7], the flux for both p-p and Au-Au are the same. Clearly the geometry of a specific RHIC detector in comparison to the "model" geometry must be considered. In particular, it should be noted that the PHENIX detector extends (in one direction) to higher η (~ 4.3) and hopes to run at an order of magnitude higher luminosity when that becomes possible.

III. Direct Hadron Flux

The direct hadron flux for Au-Au at the canonical luminosity of 2×10^{26} has been calculated by Bill Christie for the STAR SVT.[8] At the inner layer of the detector, which is 5 cm. from the beam line and 50 cm. in length, Ref. [8] gives a total hadron flux of ~ 875 /cm²sec. For the 10^7 sec year considered here, this gives a fluence of ~ 9×10^9 hadrons/cm².

An estimate of the fast neutron fluence accompanying the direct hadrons can be made from the results of the preceding section coupled with the (crude) approximation that the STAR magnet corresponds to a spherical cavity with a 3m radius. The $1/R^2$ scaling gives 5×10^8 n/cm², an order of magnitude reduced from the high energy hadron flux.

IV. Ionizing Radiation Field

In this section two calculations are presented, the first of which is expected to **underestimate** the ionization energy deposition and the second of which should **overestimate** this quantity. The estimates will be restricted to Au-Au collisions. The (gedanken) silicon "detector" is taken as a thin cylinder at a radial distance of 5 cm. from the beam center line. The detector is again conceptually within a spherical shell representing surrounding material.

(a) *Underestimate*

The underestimate is made by considering only the dE/dx loss from charged particles emanating from the collision point. In the Appendix it is shown that the energy density per interaction in a thin cylinder a transverse distance R from the beam is given by:

$$E_d = \frac{\frac{dn}{dy} \times \frac{dE}{dx}}{2\pi R^2}$$

To the extent that dn/dy is flat and variations in dE/dx with momentum can be neglected, therefore, there is no variation along the length of the cylinder. Taking dn/dy = 211 (again, from the PHENIX CDR),a cross section of 6.2 bn, the canonical $2 \times 10^{26}/cm^2sec$ average luminosity, the 5 cm. distance mentioned above, and 1.73 $MeV/g/cm^2$ for dE/dx[9] gives, for a 10^7 year:

462 rads per year

This result should be taken as an underestimate because it neglects (1) any contributions from energy loss mechanisms other than collisions with atomic electrons, and (2) any "albedo" ionizing radiation from the surrounding material.

(b) *Overestimate*

For an overestimate, we take the results of a previous calculation[10] of energy deposition in a solid block of silicon. This result was obtained by combining a file from HIJET (circa 1990) minimum bias events with the hadron cascade program CASIM.[11] The geometry of this calculation is shown in Fig. 1. As seen from the geometry in this figure, the entrance deposition is taken in a shell of silicon whose smallest dimension is in the 1-2 cm. range. Combining this with the fact that the entrance shell is in intimate contact with the surrounding "medium" makes this geometry significantly worse than the thin layer of (relatively isolated) silicon considered above; hence the term "overestimate."

If one scales the entrance doses[12] shown in Fig. 2 to a 5 cm. radius, the result turns out to be[13] 1440 rads per year which is a factor of 3.1 higher than obtained above. In the interest of comparing apples to apples, I have attempted to remove the HIJET, FRITIOF difference by scaling this result by the charged multiplicities of the two models shown in Fig. 1 of Ref. [4].[14] A 1.18 factor reduces the "discrepancy" to a factor of 2.6.

Some of the differences in a 2-cm thick slab of silicon and an infinitely thin one can be quantitatively estimated. One of these differences is that CASIM, as well as other hadron cascade programs, deposits more than dE/dx from ionization for charged hadrons as they transverse material. The reason for this is that a part of the de-excitation energy from struck silicon nuclei is appears in the form of heavy fragments which are not tracked. Since a sizable amount of this energy may be deposited in even very thin detectors, it seems prudent to increase the "underestimate" by the ratio of the "effective" dE/dx used in CASIM (2.0 $MeV/g/cm^2$) to the dE/dx value used in the preceding section. This raises the "underestimate" value from 462 rads to 534 rads per year and reduces the "discrepancy" to a factor of 2.3.

There are at least three additional mechanisms of energy deposition in the thick entrance layer of silicon shown in Fig. 1 which do **not** apply (or apply only greatly reduced in magnitude) to the model thin cylinder. The first is direct π^{o}'s, which is a ~10% effect.[15] The second is the remainder (excluding the heavy fragments) of the nuclear de-excitation energy (photons and evaporation nucleons) which is isotropic. Finally, in the geometry of Fig. 1, even high energy products from secondary interactions in the bulk silicon can contribute to the energy deposition in the entrance bins. This is illustrated schematically in Fig. 2, which is simply a reproduction of Fig. 1 showing a interaction vertex "feeding" energy into one of the entrance bins. A dashed line in this figure is drawn to the bin at ~90° to illustrate that, for this bin, such a mechanism is expected to be very much reduced because the bin is a backward angle with respect to the assumed interacting hadron direction. Indeed, if only the value of radiation at this angle[12] had been considered, together with the rapidity (θ) invariance as derived in the preceding section, the remaining factor of 2 difference rather neatly disappears.[16] This observation does not prove that the remaining difference in the calculations is completely accounted for[16], but it does indicate (in this author's opinion) that a factor of 2 difference between the thick silicon shell considered here and the thin cylinder of the previous section is plausible.

(c) *Recommendation*

A reasonable estimate for rads per year (10^7 sec) from Au-Au at $2 \times 10^{26}/cm^2sec$ in a thin silicon cylinder at 5 cm transverse distance would be 534 **plus some allowance** for albedo ionizing radiation from the surrounding material. Since a calculation for a very thick detector is a factor of ~ 2 higher, the allowance can be substantially smaller than this. However, for design purposes, it would seem prudent to also allow for some variation in heavy ion production models, which will even plague the most detailed Monte Carlo calculations. Allowance for a factor of 1.5 above the "underestimate", or **800 rads per year**, is therefore recommended.

(d) *Electrons*

The estimates of ionizing radiation presented above do **not** include the contribution from electrons which arise from pair production in the Coulomb field of the heavy ions. Such a contribution may be sizable[18] but, since the spectrum is extremely soft, **the effect is extremely detector dependent** and is not considered here.

V. Summary

The presence of material acts as a source of fast "albedo" neutrons which adds to the hadron flux for silicon detectors and circuits near the interaction vertex. A model detector is considered wherein a thin silicon cylindrical is surrounded by a one meter radius spherical shell composed of heavy material extending to $|y| = 3$. Scaling SSC calculations for this geometry to the RHIC environment gives an albedo fast neutron flux of **~5×10^9 n/cm² per 10^7 seconds (1-yr)** for either Au-Au or p-p collisions at 100 GeV per nucleon at their design luminosities. An estimate of the **direct** ionizing radiation for such a detector placed at a distance of 5 cm. from the beam line for Au-Au is ~530 rads/yr. Based on a calculation of a thick silicon "detector", a recommendation is made that designing for a **total** ionization radiation burden of **800 rads a year** is likely to be conservative enough to allow for both albedo ionization and at least some production model uncertainty.

It should be noted that the ionization radiation from electrons is not included in the ionizing radiation considered. Also, no effects due to beam-gas or bunched beam - "DC beam" interactions[19] have been considered.

References/Footnotes

[1]H. Kraner, private communication. The topics of annealing and radiation hardening are complex and are entirely omitted from the brief discussion in the text.

2. D.E. Groom, Ed., "Radiation Levels in the SSC Interaction Regions," SSC-SR-1033, 1988. Pure Fe should not differ dramatically from the U-scint. model. Although many more neutrons originate in the uranium, the free hydrogen in the scintillator degrades their energy very effectively.

3. The values in the text are the dn/dy values averaged over the $|y| \leq 3$ interval from DTUJET. These values are taken from Fig. 2.2 of Ref. [2]. For the SSC, a dn/dy of 7.8 over ± 3 units of y (rapidity vs. pseudo-rapidity are not carefully distinguished here) gives $\langle n \rangle_{ch} = 7.8 \times 6 = 46.8$.

4. See M. Ye et. al., "Compilation of Histograms Generated by FRITIOF, HIJET and VENUS," RHIC/DET Note 2 , 1992. The VENUS generator predicts $\langle n \rangle_{ch}$ well over a factor of 2 higher than FRITIOF averaged over the $|\eta| \leq 3$ interval.

5. PHENIX Conceptual Design Report, January, 1993.

6. The dn/dy value of 878 for central collisions in Table 11.1 of the PHENIX CDR is in good agreement with the FRITIOF generator of Ref. [4].

7. Besides the uncertainty in the scaling parameters, the "Groom estimate" itself is considered to be accurate to no better than a factor of 2.

8. W. B. Christie, "Charged amnd Neutral Particles Fluxes in Silicon Vertex Tracking (SVT) Detector," RHIC/STAR Collaboration Note #15 (1991).

9. The dE/dx value is from the Barkas and Berger tables assuming 1 GeV/c and a species mixture which is .95 pion and .05 proton. The conversion to rad is 6.24×10^4 GeV/g = 1 rad.

10. "Fourth Workshop on Experiments and Detectors for a Relativistic Heavy Ion Collider," M. Fatyga and B. Moskowitz, Eds., BNL 52262, p.256, 1990. This reference also considers a solid block of Fe. Within 30% or so, the estimates made in the text for silicon would also hold for the absorbed "entrance" dose in Fe.

11. A. Van Ginneken, "CASIM; Program to Simulate Hadron Cascades in Bulk Matter," Fermilab FN-272 (1975).

12. Ref. [9] shows only selected angles. The angles selected and corresponding entrance absorbed doses at 1 meter for 1000 hrs at 2×10^{26} in the block of silicon are the following: (1.27° —1150 rad, 3.24°—340 rad, 7.65°—85 rad, 19.3°—13.8 rad, 41.4°—3.4 rad, 86.7°—.5 rad). The value of the statistical error is not clear, but is likely in the 5-10% range.

13. A small Fortran program was written to integrate the entrance energy deposition given above from "sources" corresponding to a Gaussian beam distribution with a σ of 20 cm. The result was flat in the beam (Z) direction over a region extending from $-32 < Z < 32$ cm.

14. Unfortunately, the changes in HIJET do not appear to be well documented. Averaging the multiplicities in Fig. 1 of Ref. [4] over the $-3 < y < 3$ interval gives the 1.18 factor higher multiplicity in the text. However, this figure applies to central events; applying the same factor for minimum bias events is simply an assumption..

15. The energy in the first 2 cm of a silicon slab from 1 GeV/c normally incident π^0's is 10% of that of charged pions. It should be noted that all energy deposition mechanisms are energy dependent; taking 1 GeV/c as "typical" may well underestimate the "corrections" between thin and thick geometries.

16. The 0.5 rads (Footnote 11 above) at 1 m for 1000 hours scales to 428 (±10%) rads per 10^7 seconds if the same model difference and direct π^0 reduction factors are used. A spectrum softer that 1 GeV/c would, however, lessen the magnitude of these factors.

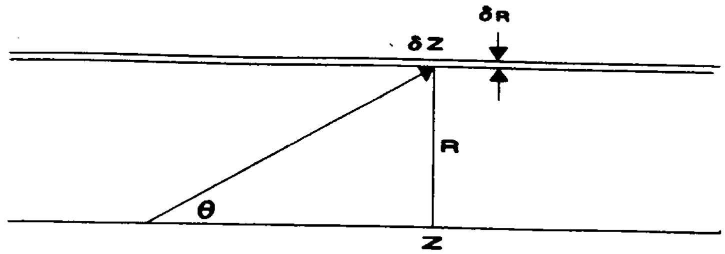
17. A simple estimate of "sidewise" (90°) feed through was made by comparing the results from 2 CASIM runs where pions are incident normal to a block of silicon. In the first run, a parallel beam is distributed uniformly over a radius of 0.5 cm. The energy within this radius over the first 2 cm in length defines the "effective" dE/dx. In a second run, the beam is taken to have a radius of 5 cm. The energy within the 0.5 cm radius per particle incident in this restricted area is higher than in the first run because of the feed through. For 1 GeV/c incident pions, this was found to be a 10% effect which rises to 22% at 5 GeV/c. Such "feed through" should be a strong function of angle.

18. STAR Conceptual Design Report, June, 1992. Fig. 4C-28 of this report shows an estimate of the number of electrons in a given time interval greater than a given p_t set by the field and radius.

19. The "DC beam" refers to a possible build-up in the RHIC collider of ions which are lost from the rf buckets due to intra-beam scattering. If nothing perturbs the orbits of such ions in the transverse direction, the ions would tend to form a "DC beam". The magnitude of the loss from intra-beam scattering is expected to be large only for Au ions.

Appendix

The geometry is as is shown in the sketch below. Charged particles at a nominal angle θ with respect to the beam axis and angular spread δθ deposit ionization energy in a thin cylindrical shell of volume 2πRδRδZ.



The energy per volume per interaction is then:

$$E_d = \frac{E}{V} = \frac{\frac{dn}{d\theta} \times \delta\theta \times \frac{dE}{dx} \times \frac{\delta R}{\sin\theta}}{2\pi R \delta R \delta Z}$$

Since tanθ = R/Z and R is fixed, one readily shows that δθ/δZ = - $\sin^2\theta$/R, and the energy density becomes:

$$(1) \qquad E_d = -\frac{\frac{dn}{d\theta} \times \sin\theta \times \frac{dE}{dx}}{2\pi R^2}$$

Now the rapidity variable *y* is defined by:

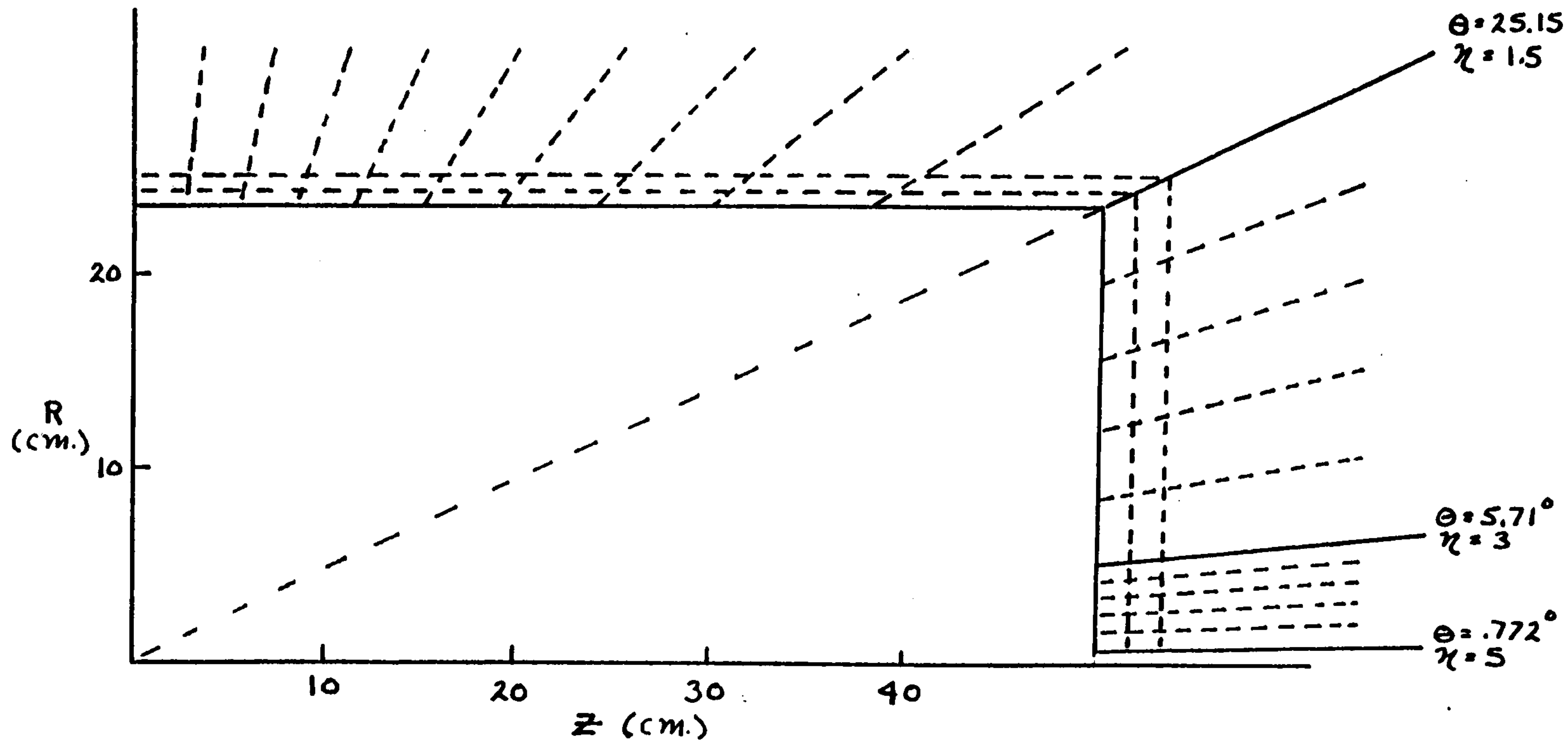
$$y = \frac{1}{2}\ln\frac{(E+p_L)}{(E-p_L)} = \ln\frac{(E+p_L)}{\sqrt{p_T^{\,2}+m^2}}$$

If the mass is ignored (pseudo-rapidity) one obtains

$$y \cong \ln\frac{p+p_L}{p_T} = \ln\frac{1+\cos\theta}{\sin\theta} = -\ln\tan\frac{\theta}{2}$$

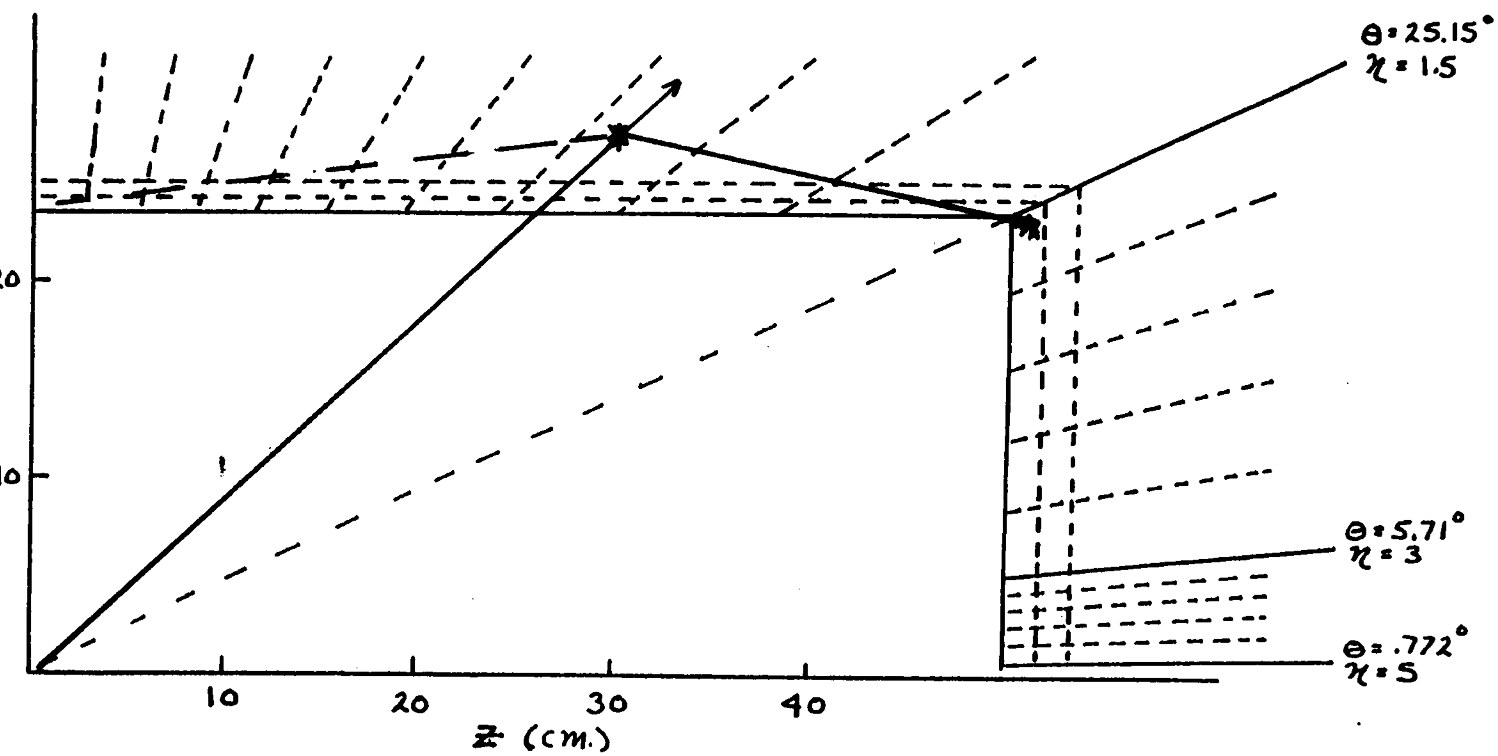
Differentiating yields, after a little algebra, d*y* = - dθ/sinθ. Writing dn/dθ in Eqn (1) above as dn/dy ×dy/dθ gives the final expression for the energy density:

$$E_d = \frac{\frac{dn}{dy} \times \frac{dE}{dx}}{2\pi R^2}$$



GEOMETRY OF RADIATION
DAMAGE CALCULATION

Fig. 1 From Ref. [9]



GEOMETRY OF RADIATION
DAMAGE CALCULATION

Fig. 2. As Fig. 1 showing "Feed Through"