ASSESSMENT OF NEUTRON SKYSHINE NEAR UNMODIFIED ACCUMULATOR/DEBUNCHER STORAGE RINGS UNDER MU2E OPERATIONAL CONDITIONS

J. Donald Cossairt

January 2011

Introduction

Preliminary plans for providing the proton beam needed by the proposed Mu2e experiment at Fermilab will require the transport of 8 GeV protons to the Accumulator/Debuncher where they be processed into an intensity and time structure useful for the experiment. The intensities involved are far greater that those encountered with antiprotons of the same kinetic energy in the same beam enclosures under Tevatron Collider operational conditions, the operating parameters for which the physical facilities of the Antiproton Source were designed. This note explores some important ramifications of the proposed operation for radiation safety and demonstrates the need for extensive modifications of significant portions of the shielding of the Accumulator Debuncher storage rings; notably that underneath the AP Service Buildings AP10, AP30, and AP50.

Extension of Existing Measurements to Present Calculations

In developing an understanding of the radiation situation in the vicinity of the Antiproton Source, it is fortunate that extensive measurements of prompt radiation fields made over the long operational history of the Accumulator/Debuncher with 8 GeV protons and antiprotons exist. These measurements are generally self-consistent and thus facilitate simple extrapolation to higher beam powers. A useful measurement of normalized dose equivalent rates dH_{equiv}/dt in the AP30 service building was conducted on April 3, 2000 (Le00) as illustrated in Fig. 1.

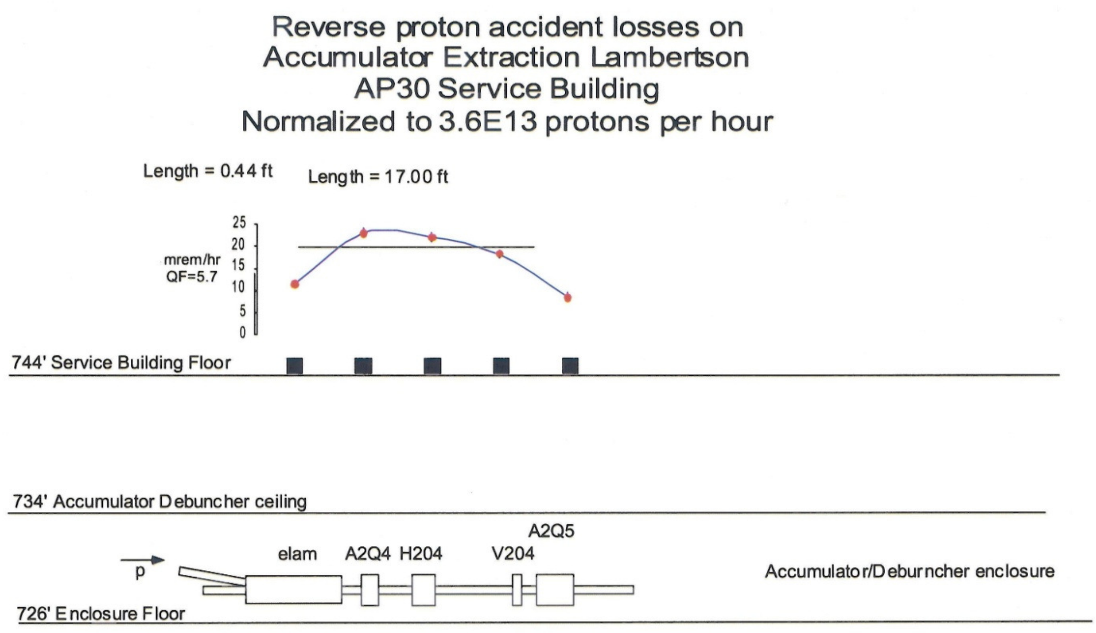

Fig. 1 Longitudinal elevation view of prompt radiation measurements made in April 2000 on the floor of the AP30 Service Building above a loss of the full 8 GeV proton beam on Lambertson magnet "elam".

In this measurement, the Lambertson magnet "elam" was turned off providing a localized, well-understood loss of the entire 8 GeV beam. Fermilab Chipmunk ionization detectors were used to measure the absorbed dose rate at the five locations. These measurements were made along a line directly above the beam centerline separated by 1.52 m (5 ft) in longitudinal coordinate z and immediately above the 3.05 m (10 ft) of intervening shielding (Le00). The beamline was a distance of 1.70 m (5.6 ft) beneath the ceiling and thus a total of 4.75 m (15.6 ft) below the horizontal plane where the measurements were conducted.

A separate radiation quality factor QF, measured to be 5.7 (Va00), was applied along with the beam intensity to provided normalized dose equivalent rates at the five measurement locations. For these measurements to be useful for assessing the situation with respect to Mu2e, they must be renormalized from this beam power of 12.8 W to the Mu2e design power of 25 kW. In addition, the Department of Energy revised its system of radiation protection in 2007 to require the use of effective dose H_{eff} for radiation protection purposes in place of dose equivalent H_{equiv}. H_{eff} is connected with absorbed dose by multiplying by a energy-dependent radiation weighting factor w_R instead of the quality factor QF. The energy dependences of QF and w_R for neutrons are somewhat different and have been discussed in detail elsewhere and reviewed by Cossairt and Vaziri (Co09a). For most neutron energy spectra H_{eff} is generally larger than H_{equiv}.

Information about the neutron energy spectrum present is clearly highly useful. Fortunately, the neutron energy spectrum under similar beam loss conditions at both AP10 and AP30 were, among others, measured by Cossairt et al. using the Bonner sphere technique (Co88). There are some differences between the AP10 and AP30 geometric conditions for these measurements that were not completely documented. From the AP10 spectrum measurement a value of the QF=5.8 was inferred, quite close to that of 5.7 determined by the recombination chamber technique of Vaziri et al. (Va00). This is larger than the value of QF=4.2 reported for AP30 in (Co88). In reference (Co09a) the AP10 spectrum was re-analyzed to determine a value of w_R=7.54. For conservatism, the values of QF=5.8 and w_R=7.54 will be used henceforth in this analysis. The energy spectra reported for the AP10 and AP30 spectra in (Co88) differed significantly. The AP10 neutron spectrum "peaked" at a neutron energy of 10 MeV while the AP30 spectrum peaked at about 75 MeV. Given the uncertainties of these "historic" measurements and the general uncertainty of the Bonner sphere technique, the weighting factors of the 1988 AP10 measurement will be used in conjunction with the energy spectrum of the 1988 AP30 measurement as a conservative approach.

Table 1 quantifies the source strength adjustments and normalizations of the AP30 measurement illustrated in Fig. 1 for each measurement point as a function of longitudinal coordinate z. In Table 1 Column 3 makes the subtle, rather insignificant adjustment of the measured values of the QF to the chosen value of 5.8. Column 4 scales the Column 3 values up to the beam power of 25 kW and applies the radiation weighting factor w_R to get dH_{eff}/dt. Since the instantaneous dose rates are quite high, values of dH_{eff}/dt in units of mrem s^{-1} may be more useful and are given in Column 5. An average was taken of the five measurement points and provided in the bottom row of Table 1.

Table 1 Calculation of Dose Rates Above AP30.

z(m)	Measured dH_{equiv}/dt @ 12.8W (mrem h^{-1}, QF=5.7)	Measured dH_{equiv}/dt @ 12.8W (mrem h^{-1}, QF=5.8)	Scaled dH_{eff}/dt @ 25 kW (mrem h^{-1}, w_R=7.54)	Scaled dH_{eff}/dt @ 25 kW (mrem s^{-1}, w_R=7.54)
0.00	12.07	12.28	3.12x10^{4}	8.66
1.52	24.18	24.60	6.25x10^{4}	17.35
3.05	23.20	23.61	5.99x10^{4}	16.65
4.57	19.17	19.51	4.95x10^{4}	13.76
6.10	8.900	9.06	2.30x10^{4}	6.39
Average:	**17.50**	**17.81**	**4.52x10^{4}**	**12.56**

One needs to take into account the fact that over the rectangular surface of this thin shield, there is a falloff of the radiation levels with the value of x, the lateral distance from the beam centerline. This is due to both increased distance from the loss point and the penetration of a thicker shield. To take this into account, a calculation was performed that determined the "slant angle" from the loss point through the shield as a function of x with the slant angle defined to be equal to zero directly above the beamline. Using simple trigonometry the distance d between the surface of the service building floor and the loss point and also the additional shielding penetrated is readily found. The shielding between the enclosure ceiling and the measurement location is of uncertain composition but likely earth- or concrete-like. It is probable that the density is significantly lower than that of Fermilab clay soil (≈2.25 g cm^{-3}) or concrete (≈2.4 g cm^{-3}). Choosing a value of density of 2.0 g cm^{-3} along with the high energy limit of the neutron mean free path in earth or concrete of 117 g cm^{-2} (Co09c) results in mean free path of 0.585 m. The assumption about the density may not be "conservative", its value could be less than the 2.0 g cm^{-3} in view of the lack of complete knowledge of this material at this time (January 2011). At each value of x the reduction in radiation levels was estimated by applying two multiplicative factors: a line source "$1/d$" factor for the geometric reduction in dose rate (a conservative choice), and an exponential attenuation based on the additional shielding penetrated due to the slant angle based on the stated assumptions. It was found that at a value of $x=\pm 3.2$ m, the radiation levels were estimated to be at 10 % of those measured. Within the domain $-3.2<x<3.2$ m, by numerical integration it was inferred that the average dose rate is 65% of the measured value.

Skyshine Calculation

Since an estimate of neutron skyshine rates at distance away from this location were desired, one needs to find quantity proportional to the total rate of neutrons emerging from such a location of thin shielding per unit time. A simple method for accomplishing that is to multiply the average value of dH_{eff}/dt by the surface area of this source. From the above analysis of the lateral dependence, the source is well-described as a rectangle 6.1 m (20.0 ft) longitudinal by 6.4 m (21.0 ft) lateral. The source is this rectangle and has effective area A_s=39.0 m^2.

The propagation of neutron skyshine will be calculated following standard methods described in more detail elsewhere (Co85, Co09c). The propagation with distance r (meters) away from the center of a given source is well-described by

$$\Phi(r)=\frac{aQ}{4\pi r^2}\left(1-e^{-r/\mu}\right)e^{-r/\lambda} \tag{1}$$

In Eq. (1) a=2.8 is an empirical result found at many high energy accelerators. The middle parenthetical factor is a buildup factor that approximates the observed phenomenon of the emitted neutrons scattering back to the ground subsequent to scattering from the air. A value for μ=56 m is found to universally describe the phenomenon. The value of λ in the final exponential factor is dependent upon the energy spectrum of the emitted neutrons. Q is representative of the source strength and must otherwise be dimensionally consistent with $\Phi(r)$. For example, if Q is the total number of neutrons emitted during some time interval, $\Phi(r)$ would be the fluence as a function of radial distance. No azimuthal dependence for such neutrons emerging from shielding is anticipated[1]. For present purposes, Eq. (1) can be productively rewritten as:

$$\frac{dH_{eff}(r)}{dt}=\frac{aA_s\left\langle\frac{dH_{eff}}{dt}\right\rangle_s}{4\pi r^2}\left(1-e^{-r/\mu}\right)e^{-r/\lambda} \tag{2}$$

where the product of effective area of the source A_s(m^2) and the average of the effective dose rate above the loss point, the term in brackets in the numerator, is explicit. Dimensional analysis leads directly to the value of the effective dose rate as a function of distance from the center of this source r at ground level.

A final ingredient needed in such a calculation is the value of λ. This parameter, a sort of "mean free path", is related to the energy spectrum of the emitted neutrons. Accelerator neutron spectra such as these are typically dominated by a "1/E" energy dependence, where E is the neutron energy. Stevenson and Thomas (St84) used more detailed calculations largely based on the work of Alsmiller et al. (Al81) to calculate values of λ for each of a set of "pure" 1/E postulated spectra of the neutrons emitted where each spectrum has a different "upper energy", i.e., high energy cutoff. These results have been summarized by Cossairt (Co09c) and are given here in Fig. 2.

A final technical point needs to be considered. The results shown in Fig. 2 are for the neutrons being emitted into a cone having a specific semi-vertical angle of 37°. The source in the present situation is clearly a rectangle. However if one takes the source to be a circle having the same area A_s, with a radius r_s=3.52 m, a cone having a base of this area and a height of 4.75 m has a semivertical angle of 36.6°. The dependence of the results of Alsmiller et al. (Al81) on semivertical angle is rather weak; thus applying them here is sensible.

[1] Most skyshine neutron distributions at high energy accelerators indeed possess no azimuthal dependence. However, at least one exception has been found where much higher energy (400 GeV) protons were incident on a target with extremely thin shielding in the forward direction (Co85). There a strong forward-peaking was found. Such forward angles are not encountered found here, supporting the assumption of no azimuthal dependence.

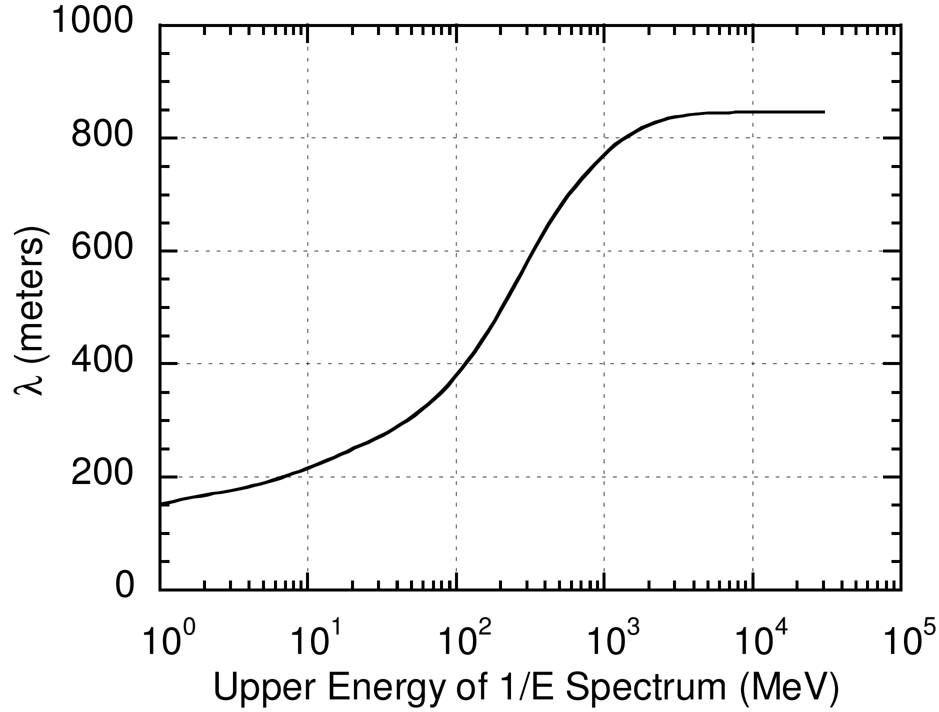

Fig. 2 Effective value of λ as a function of upper energy for pure 1/*E* spectra [Adapted from (St84) as in (Co09c).]

Figs. 3 and 4 show the results of these calculations for the value of $dH_{eff}(r)/dt$ as a function of distance from the source *r*. Fig. 5, alternatively, gives the product $r^2H_{eff}(r)/dt$. This plot format more clearly illustrates the buildup phenomenon by removing the inverse square law factor and may thus be somewhat easier to read. These graphs show results for a number of assumed neutron energy spectra upper energies. For conservatism and in view of the measured Bonner spheres and weighting spectra discussed above, it is prudent to use the 100 MeV results in further discussions. This value of the so-called "upper energy" is consistent with both the recombination chamber measurements of the radiation quality and a conservative assessment of the measured low-resolution spectra made using the Bonner sphere technique.

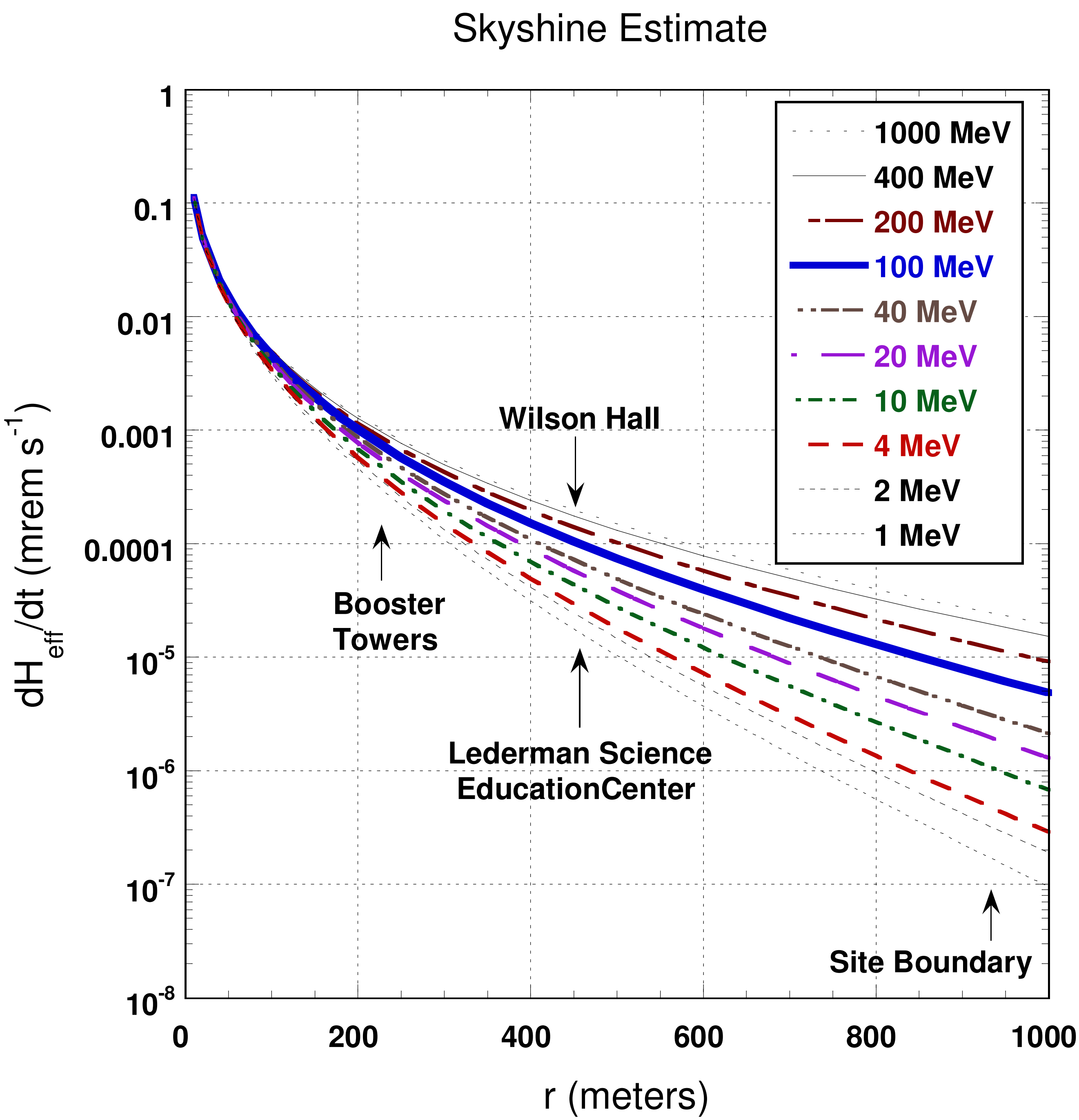

Fig. 3 *dH_{eff}/dt* as a function of horizontal distance *r* from the source. The locations of prominent Fermilab landmarks are indicated. The energies indicated are postulated "upper energies" of the emitted neutrons.

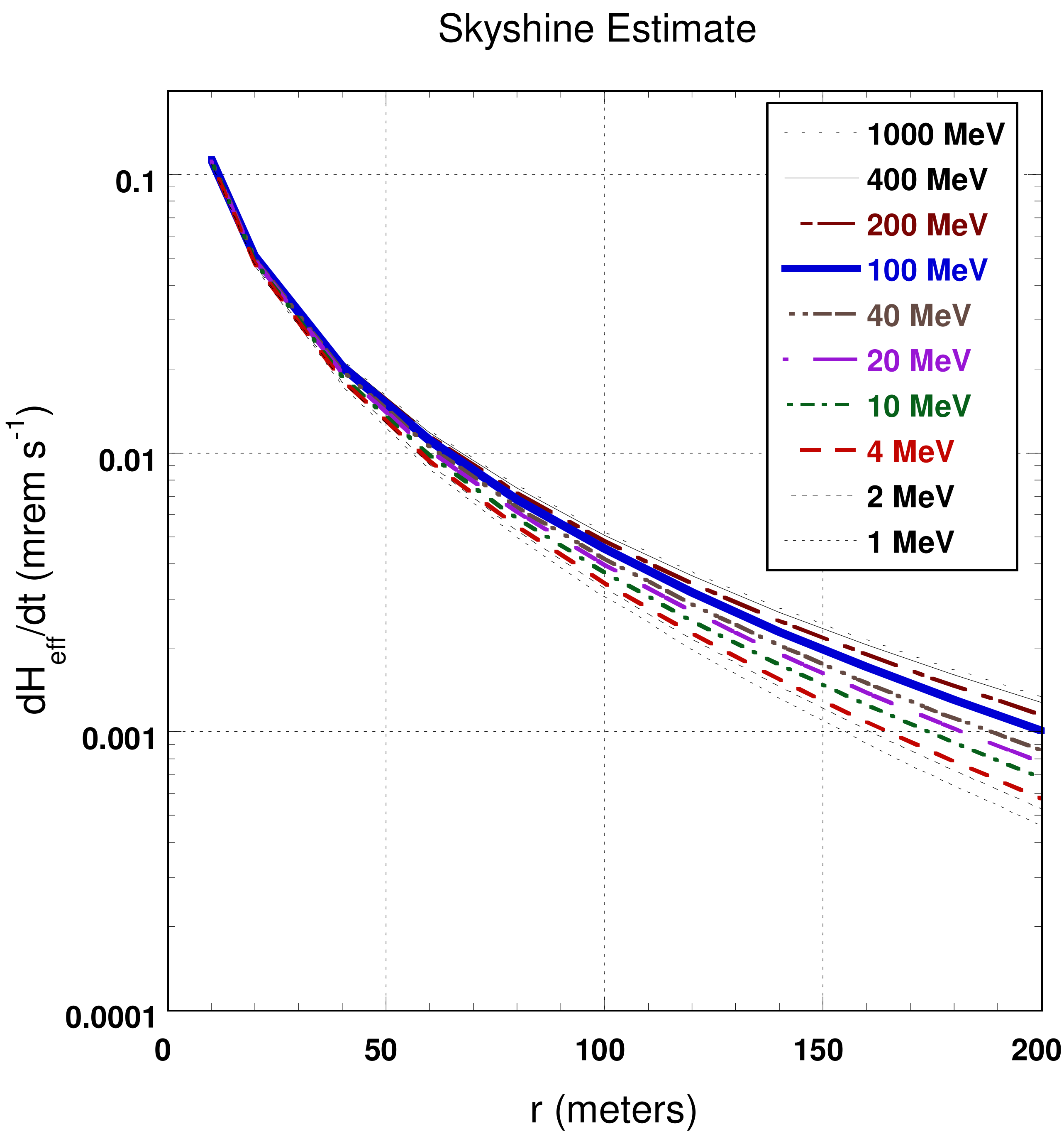

Fig. 4 *dH*$_{eff}$*/dt* as a function of horizontal distance *r* from the source. The results are the same as those shown in Fig. 3 over a more limited radial domain.

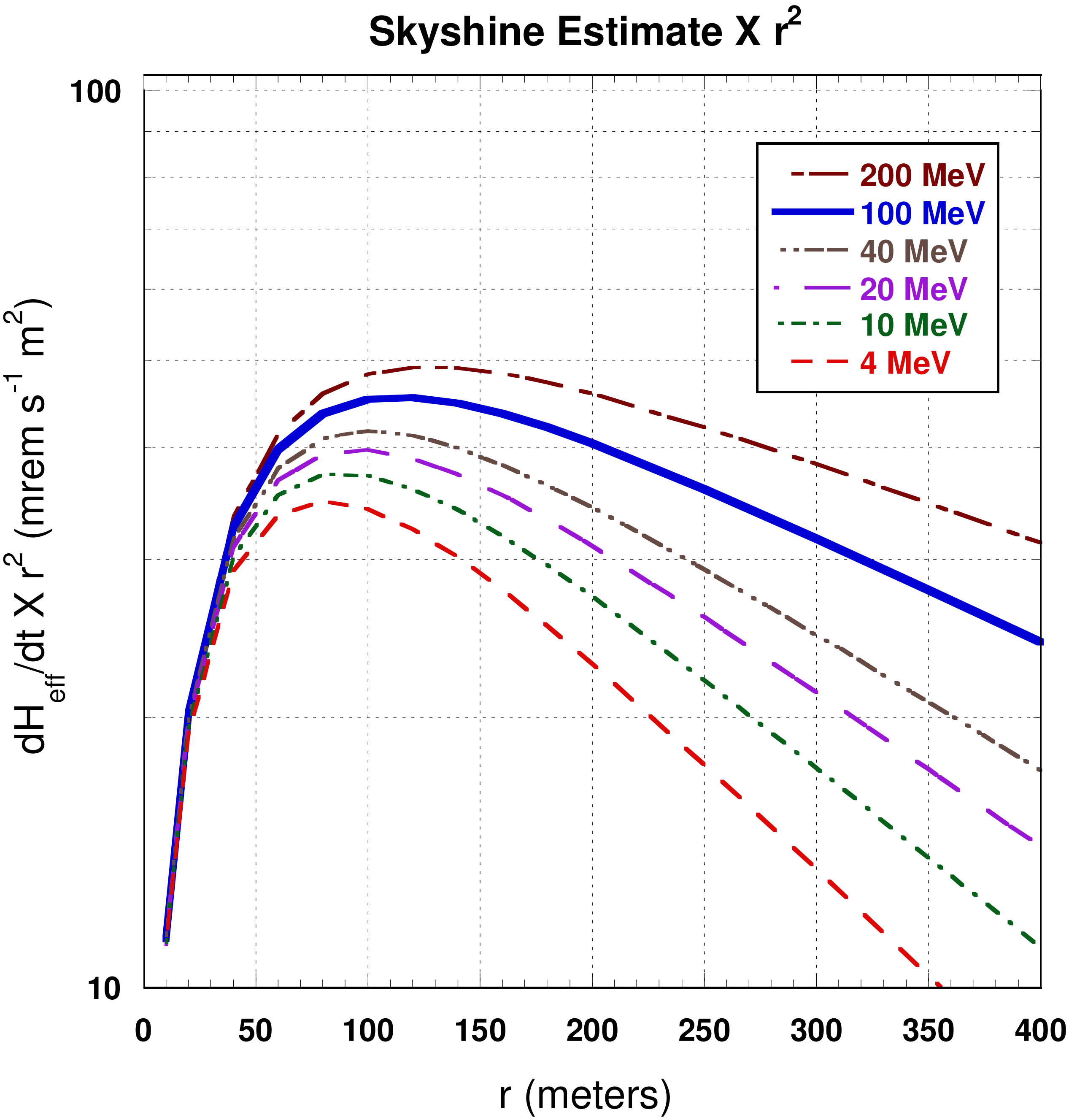

Fig. 5 $r^2 dH_{eff}/dt$ as a function of horizontal distance r from the source. The results are the same as those shown in Fig. 3 over more limited radial domain with the $1/r^2$ factor removed.

Direct Radiation at Elevated Locations

One needs to be concerned about prompt radiation at tall structures that might "look" directly into the source and thus be exposed to direct radiation in addition to the scattered skyshine neutrons. Wilson hall, at r=460 m away, is 73 m tall. Relative to the nearest Antiproton Source Service Building, the top of this structure is at a vertical angle of α=0.16 radians (9.0^o) and at r=466 m from the source. For a 1/E neutron spectrum with an upper energy of 100 MeV, the mean free path in air λ=372 m (see Fig. 2). It is a reasonable assumption that the neutrons emerging from this flat, horizontal planar source are uniformly omnidirectional. Viewed directly from above, at distance r this source would subtend a solid angle $\Omega = A_s/r^2$. At a vertical angle α, the source subtends a smaller solid angle $\Omega' = A_s\cos(\pi/2-\alpha)/r^2$. Applying the reduced solid angle, the inverse square law, and the attenuation of the neutrons by the intervening air, the direct prompt effective dose rate at the top of Wilson Hall is estimated for the loss of the full beam to be

$$\frac{dH_{eff}(r)}{dt} = (12.56)\frac{\Omega'}{\Omega}\left(\frac{r_s}{r}\right)^2 \exp(-r_s/\lambda) \text{ mrem s}^{-1} =$$

$$(12.56)0.16\left(\frac{3.52}{466}\right)^2 \exp(-466/372) = 3.3\times10^{-5} \text{ mrem s}^{-1}. \tag{3}$$

This value is about 30% of that due to skyshine at that distance and additive to the skyshine. Values at lower floors of Wilson Hall would be exposed to reduced radiation from the direct beam due to reduction of the solid angle subtended by the source at lower elevations. At the lowest levels of Wilson Hall the prompt radiation at Wilson Hall would be essentially all due to neutron skyshine.

Implications

The applicable radiation protection requirements are expressed in the Federal Regulation 10 CFR Part 835, "Occupational Radiation Protection". Environmental radiation protection requirements are found in DOE Order 5400.5, "Radiation protection of the public and the environment", a DOE Directive that is currently (as of January 2011) under revision[2]. The DOE requirements only provide requirements applicable to a wide variety of radiological facilities and do not address many details found only at particle accelerators. Fermilab's implementation of these requirements takes these details into account in the Fermilab Radiological Control Manual (FRCM). Thus FRCM Article 236 categorizes the controls of access, postings, and interlock status of areas for "normal" and "accident" conditions in accordance with Tables 2 and 3 below.

[2] The most important requirements of DOE 5400.5, and of drafts seen to date (January 2011) of the proposed replacement, DOE O 458.1, are that the effective dose to members of the public must be kept less than 100 mrem in a given year and that at levels above 10 mrem to members of the public in a year, DOE must be notified.

The **accident condition** for this situation may be easier to address and will be discussed first. Directly above AP30, at full design beam power (25kW) Table 1 gives a dose rate of 12.56 mrem s^{-1} of direct radiation at the Service Building. If one assumes that one can utilize radiation safety interlocks to limit the duration of such a full power beam loss, one can obtain the above-ground precautions needed directly from Table 3 by just determining the duration of such losses and how many would be allowable during a given hour. For example, if the duration of the beam losses could be rigorously (i.e., subject to review and approval in accordance with Fermilab's shielding assessment (FRCM Chapter 8) and safety assessment document (SAD) processes (Fermilab ES&H Manual Chapter 2010) enforced to be less than 0.57 seconds and only once per hour, the area above the enclosure could be of minimal occupancy according to the second row of Table 3. With respect to the skyshine, even as near as 10 m, the skyshine effective dose rate under such a full-power loss is only about one per cent of the direct radiation value[3]. Under such a condition, the levels due to both direct and skyshine radiation would be negligible at Wilson Hall, even at the upper floors. Allowance for more lengthy full power losses or multiple losses during a one hour period will lead to the need for more stringent precautions specified in Table 3.

Table 2 Control of Accelerator/Beamline Areas for Prompt Radiation Under Normal Operating Conditions {See FRCM Article 236.2(b) for more details.} [This is Table 2-6 in the FRCM.]

Dose Rate (DR) Under Normal Operating Conditions	**Controls**
DR < 0.05 mrem/hr	No precautions needed.
0.05 ≤ DR < 0.25 mrem/hr	Signs (CAUTION -- Controlled Area). No occupancy limits imposed.
0.25 ≤ DR < 5 mrem/hr	Signs (CAUTION -- Controlled Area) and minimal occupancy (occupancy duration of less than 1 hr).
5 ≤ DR < 100 mrem/hr	Signs (CAUTION -- Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological Worker Training required.
100 ≤ DR < 500 mrem/hr	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted. Radiological Worker Training required.
DR≥ 500 mrem/hr	Prior approval of SRSO required with control measures specified on a case-by-case basis.

[3] More detailed calculations using, e.g., the code MARS are likely needed to better quantify the region of, say, 3<*r*<10 m.

Table 3 Control of Accelerator/Beamline Areas for Prompt Radiation Under Accident Conditions When It is Likely that the Maximum Dose Can Be Delivered {See FRCM Article 236.2b for more details.} [This is Table 2-7 in the FRCM.]

Maximum Dose (D) Expected in One hour	Controls
D < 1 mrem	No precautions needed.
1 < D ≤ 10 mrem	Minimal occupancy only (duration of credible occupancy < 1 hr) no posting
1 ≤ D < 5 mrem	Signs (CAUTION -- Controlled Area). No occupancy limits imposed. Radiological Worker Training required.
5 ≤ D < 100 mrem	Signs (CAUTION -- Radiation Area) and minimal occupancy (duration of occupancy of less than1 hr). The Division/Section/Center RSO has the option of imposing additional controls in accordance with Article 231 to ensure personnel entry control is maintained. Radiological Worker Training required.
100 ≤ D < 500 mrem	Signs (DANGER -- High Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological Worker Training required.
500 ≤ D < 1000 mrem	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted. Radiological Worker Training required.
D ≥ 1000 mrem	Prior approval of SRSO required with control measures specified on a case-by-case basis.

The **normal condition** situation may be far more important. Making the perhaps extremely optimistic assumption that the beam loss can be limited by heroic efforts to a maximum of 1.0%, the direct radiation dose above the source becomes 452 mrem h^{-1}. This puts the area nearly at the highest level of the second-most stringent category of precautions in Table 2 where 8 ft high fences, interlocked gates, etc. are required. It is nearly certain also that to achieve such a low percentage beam loss, if feasible at all, extensive radiation safety interlocks and beam control systems with appropriate approvals would be needed. Furthermore, at a sustained loss even as low as 1.0%, the skyshine is a significant problem. At r=10 m the dose rate due to skyshine alone at this rate of beam loss would be 4.08 mrem h^{-1}, requiring the precautions of the 3rd line of Table 2. To get below the level of 0.05 mrem h^{-1} (1.39×10^{-5} mrem s^{-1}) where "no precautions" are required at this rate of beam loss, one has to be at r>176 m, a very large zone in which one would need to assure minimal occupancy, etc. Tables 2 and 3 were largely developed for occupational concerns and occupancy conditions. In such an outdoor area on the "open", accessible Fermilab site, one also needs to consider the environmental reporting level of 10 mrem in one year. Assuming 4000 hours y^{-1} of operation, to be below 10 mrem in a year the dose rate must be kept below 2.5×10^{-3} mrem h^{-1} (6.9×10^{-7} mrem s^{-1}), achieved at these postulated conditions at about r=510 m, a huge area to maintain clear of persons and inclusive of Wilson Hall and many other occupied structures such as much of the Accelerator Footprint Area, where even higher levels would be found. This implicitly also assumes that the 1.0% loss would be the total for all 3 locations (AP10, AP30, and AP50) since distant points will receive skyshine neutrons from all of them.

At the distance of Wilson Hall, a structure of high occupancy, *r*=460 m. The skyshine dose rate at 1.0% beam loss is 3.6×10^{-3} mrem h^{-1}. However, due to the skyshine alone, one reaches the level of 10 mrem appropriate for members of the public after only 2800 hours of operation, a severe constraint. Similar levels would be encountered at the Lederman Science Center, another "public" location. As discussed above, at the higher floors of Wilson Hall such a level would be reached in a shorter period of time given additional "direct component".

It should also be mentioned that at the Fermilab site boundary nearest point ($r \approx 943$ m), the skyshine dose rate due to this 1.0% beam loss is estimated to be 2.3×10^{-4} mrem h^{-1} (6.4×10^{-8} mrem s^{-1}), or 0.92 mrem in 4000 h year of operations.

Conclusions

While existing shielding is adequate for the current operating mode of the Accumulator/Debuncher as part of the Antiproton Source used in the Tevatron Collider program, without significant modifications of the shielding configuration in the Accumulator/Debuncher region and/or beam loss control systems far more effective than seen in most applications at Fermilab, the proposed operational mode for Mu2e is not viable for the following reasons:

1. Due to skyshine alone, under normal operational conditions large areas of the Fermilab site would be exposed to unacceptable levels of radiation where most of the Laboratory workforce and some members of the general public who regularly visit Fermilab would receive measurable doses annually, contrary to workforce, public, and DOE expectations concerning the As Low as Reasonably Achievable (ALARA) principle.

2. Under normal operational conditions, a sizeable region of the Fermilab site would also require fencing due to skyshine. The size of the areas involved would likely invite public inquiry about the significant and visible enlargement of Fermilab's posted radiological areas.

3. There would be aesthetics questions about the employment of so much new fencing on the Fermilab site.

4. The assumption of only 1.0% "normal condition" beam losses over the three locations is regarded as being extremely optimistic.

Thus, it is evident that it is necessary to pursue shielding improvements to support viable operation of the Mu2e experiment.

Acknowledgments

The author would like to thank Tony Leveling, Kamran Vaziri, and Robert Bernstein for helpful discussions.

References

Al81 R. G. Alsmiller, Jr., J. Barish, and R. L. Childs, "Skyshine at Neutron Energies $\leq$ 400 MeV", Part. Accel. 11 (1981) 131-141.

Co85 J. D. Cossairt and L. V. Coulson, "Neutron Skyshine Measurements at Fermilab", Health Phys. 45 (1983) 651-658.

Co88 J. D. Cossairt, A. J. Elwyn, W. S. Freeman, W. C. Salsbury, and P. M. Yurista, "Measurement of Neutrons in Enclosures and Outside of Shielding at the Tevatron", FERMILAB-Conf-88-106 (1988).

Co09a J. D. Cossairt and K. Vaziri, "Neutron Dose per Fluence and Weighting Factors for Use at High Energy Accelerators, Health Phys. 96 (2009) 617-628.

Co09b J. D. Cossairt, D. W. Grobe, and M. A. Gerardi, "Measurements of Radiation Quality Factor using a Recombination Chamber", Fermilab TM-1248-REV (1984, revised 2009).

Co09c J. D. Cossairt, "Radiation Physics for Personnel and Environmental Protection", Fermilab TM-1834, Revision 10, 2009.

Le00 T. Leveling, "AP30 Measurements", April 3, 2000 (unpublished).

St84 G. R. Stevenson and R. H. Thomas, "A Simple Procedure for the Estimation of Neutron Skyshine from Proton Accelerators", Health Phys. 46 (1984) 115-122.

Va00 K. Vaziri, T. Leveling, J. Larson, F. Krueger, "AP30 Measurements" (unpublished), April 21, 2000. This work reported measurements of quality factors using the recombination chamber technique discussed by Cossairt (Co09b) at two similar locations. The value of 5.7 is the average of the two results and thus applied to the measurements of absorbed dose rates to obtain the values provided in Fig. 1 and Table 1.