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NEW OPERATIONAL QUANTITIES FOR RADIATION PROTECTION BY ICRU AND ICRP: IMPACT ON WORKPLACES AT ACCELERATORS

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Abstract

In radiation protection, Effective Dose, E quantifies stochastic radiation detriment. E is defined as a weighted sum of absorbed dose to organs and tissues and cannot be measured directly. ICRU has defined operational quantities to measure effective dose approximately, such as Ambient dose equivalent $H^*(10)$. At high energies, the estimates provided by $H^*(10)$ deviate strongly from effective dose. In 2020, ICRU and ICRP have recommended new operational quantities for external radiation with a definition close to the one of effective dose, and published an extensive collection of conversion coefficients from particle fluence to the new quantities [1]. Ambient dose H^* serves for operational monitoring purposes. The new definition alleviates the observed discrepancies of $H^*(10)$ with effective dose. In this paper, we present a numerical study of effective dose E, ambient dose equivalent $H^*(10)$ and ambient dose H^* in radiation fields at workplaces at proton- and electron accelerators. These places include locations behind primary shielding, in access mazes and in the vicinity of activated accelerator components.

INTRODUCTION

In radiation protection, so-called *protection quantities* are introduced by ICRP, the International Commission for Radiological Protection, to estimate radiation risk and to define dose limits. The protection quantity for stochastic effects from low doses is *Effective Dose, E* [2]. E is defined as a whole-body average of dose to different organs of the body, weighted with coefficients for the effectiveness of the radiation type and the susceptibility of the organ to develop cancer. Defined over the whole human body, E cannot be measured, and ICRU, the International Commission for Radiation Units and Measurements and sister organisation to ICRP, defines *operational quantities* which are used for prospective assessments and measurement of radiation dose to persons. The operational quantities should represent a reasonable approximation of the protection quantities.

The previous operational quantities for external radiation, *personal dose equivalent* $H_p(10)$ and *ambient dose equivalent* $H^*(10)$ were introduced in [3, 4] and conversion coefficients from particle fluence, the physical quantity characterising the radiation field, were published in [5]. At the time of their introduction, most occupationally exposed persons worked in the nuclear industries. $H_p(10)$ and $H^*(10)$ deliver good estimates for effective dose from photons, electrons and neutrons in the dominant energy ranges common to the nuclear fuel cycle. Today, more persons are occupationally exposed in non-nuclear applications of radiation, introducing radiation at very low energy (medical applications like fluoroscopy, interventional radiology) and at very high energy (particle accelerators, in industry and research). In these energy ranges, the previous operational quantities deliver poor approximations to effective dose.

This brought ICRU to review its previous definitions of operational quantities for external radiation [1]. The new quantities are defined in close analogy to the protection quantities by using the same numerical phantoms for the calculation of conversion coefficients. *Personal Dose* H_p is used to assess the exposure of a person with help of dosimeters, and *ambient dose* H^* is used for the prospective assessment of workplaces with help of radiation monitors. By their definition, values of H_p and H^* in an arbitrary radiation field are numerically closer to the effective dose E than the previous quantities, whatever the particle type or energy.

More details on ICRU's reasoning for reviewing the operational quantity can be found in the original report [1] and in [6].

In this paper, we investigate the expected impact that the new operational quantities will have at radiation workplaces in accelerator environments. While the legal quantity for the assessment of radiation risk is effective dose, operational quantities are used in most situations as an approximation, because they can be readily determined with dosimeters and monitoring instruments. A significant difference between the values of the previous and new operational quantities could therefore question present radiation protection programs.

METHODS

Personnel at particle accelerators may be exposed to ionising radiation in two distinct scenarios:

- During accelerator operation, to *prompt radiation* from collisions of beam particles with elements of the accelerator and causing a cascade of high-energy secondary particles. Due to shielding and access restrictions to accelerator areas, this mode of exposure is rare under routine conditions.
- To radiation from activation products (*decay radiation*). Following the exposure to energetic particles, atomic nuclei in accelerator components may undergo nuclear reactions, leading to radionuclides with varying half lives, emitting photons, electrons and positrons. During maintenance of the accelerator, personnel are exposed to this radiation, which constitutes a large fraction of their total radiation dose.

To evaluate the impact of the new operational quantities on values of ambient dose equivalent and ambient dose, the Monte-Carlo program FLUKA 4-1.1 [7–9] with its graphical interface FLAIR [10] is employed to simulate fluence spec-

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tra of prompt and decay radiation in typical environments for accelerators, and to calculate from these spectra the values of $H^*(10)$ and H^* with the corresponding conversion coefficients.

Generic Study

Prompt Radiation In the generic study, an idealised accelerator geometry is assumed. A cylindrical target (100 cm long and 5 cm in radius, with an average composition of AISI 316LN-grade steel) is placed on the centre-axis of a cylindrical shielding wall with 2 m inner diameter and 2 m thickness. The target is hit in the centre of the circular face by a proton beam with a gaussian beam profile (FWHM = 0.5 cm). The beam energy is 100 MeV, 1 GeV or 10 GeV. Particle fluence spectra are scored in 90 cm vertical distance from the outside of the shielding wall. These spectra are multiplied with the corresponding conversion coefficients to yield values of $H^*(10)$ and H^*.

Decay Radiation In the generic simulation set-up for the decay radiation study, a steel target with 30 cm length and 4 cm radius is is placed free in air. The target is irradiated for 180 days by a proton beam with $E = 3.5$ GeV, a gaussian beam profile (FWHM = 0.5 cm) and a beam intensity of 10^{10} protons/s. Fluence spectra of decay radiation (photons, electrons and positrons) are scored after waiting times of 1 h, 1 d and 1 y in 100 cm vertical distance from the target's symmetry axis. These spectra are multiplied with the conversion coefficients to yield values of $H^*(10)$ and H^*.

Radiation from the LBE Beam Dump of Linac4

Linac4 is a 160 MeV H^- linear accelerator, the first member of CERN's accelerator chain leading to the LHC. Recently commissioned, it started in 2020 to inject H^-- ions into the Proton Synchrotron Booster. For beam setup, an intermediate beam dump is used at the end of the LBE beam line, as shown in Fig. 1. The ambient dose (equivalent) rate of prompt and decay radiation from the beam dump in the surrounding area is estimated from fluence spectra simulated with FLUKA 4-1.1.

RESULTS

Generic Study

Prompt Radiation Dose rates of prompt radiation from the irradiated steel target were evaluated by folding the fluence spectra of particles in the cascade $(n, p, \gamma, e^{+/-}, \pi^{+/-}, \mu^{+/-})$ with the respective conversion coefficients for either H^* or $H^*(10)$. Table 1 shows ratios between new and previous operational quantities for the most important components of the radiation field.

Decay Radiation Dose rates of decay radiation $(\gamma, e^{+/-})$ from the irradiated steel target were evaluated for either H^* or $H^*(10)$. Figure 2 shows the photon and electron spectra scored after one hour of decay time, with the two conversion functions as overlay, and Table 2 the resulting

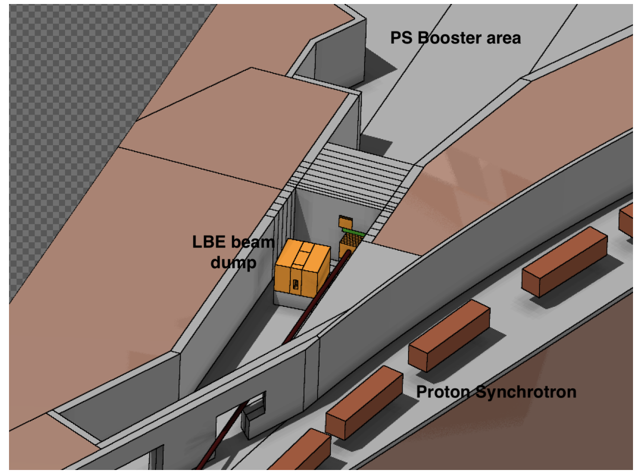

Figure 1: The LBE beam dump and PS Booster shielding and area.

Table 1: Ratio of Prompt Ambient Dose H^* to Ambient Dose Equivalent $H^*(10)$ and its Principal Components for a Proton Beam Impinging on a Steel Target with Different Proton Energy Outside of a Concrete Shielding

Beam Energy	100 MeV	1 GeV	10 GeV
Neutron	1.00	1.17	1.19
Proton		1.07	1.15
Photon	1.10	1.10	1.18
$e^{+/-}$	0.18	0.22	0.33
Total	**0.99**	**1.16**	**1.18**

Table 2: Ratio of Ambient Dose H^* to Ambient Dose Equivalent $H^*(10)$ and its Components of the Decay Radiation from an Activated Steel Target at One Hour, One week and one Year After the End of Irradiation

Decay Time	1 hour	1 week	1 year
Photon	0.87	0.86	0.86
Electron	2.9	2.0	2.2
Positron	0.9	1.0	1.0
Total	**0.87**	**0.87**	**0.86**

values of H^* and $H^*(10)$. In the energy range of radionuclides, H^* is lower than $H^*(10)$ for photons, for electrons, $H^*(10) = 0$ for energies below 2 MeV, but growing above more rapidly than H^*. The net effect for radionuclides is $H^* < H^*$ (10).

Linac4 LBE Beam Dump

Prompt Radiation The 160 MeV H^- ions from Linac4 are sent to an intermediate beam dump at the end of the LBE beam line. The radiation dose rate generated during beam operation next to dump and in the adjacent area of the PS Booster is of interest as workers may be present in the latter during specific operation conditions at the initial commissioning. The radiation field is dominated by neu-

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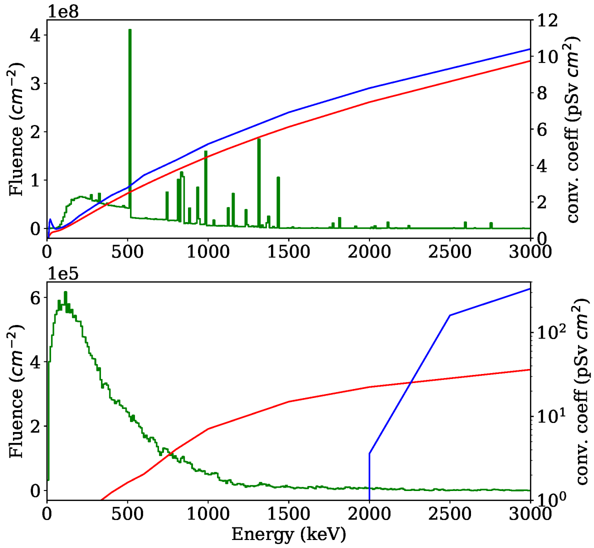

Figure 2: Photon (top) and electron (bottom) decay radiation fluence spectra of the irradiated steel target, scored 1 hour after the end of the irradiation (left abscissa). The conversion coefficients for H^* (red) and $H^*(10)$ (blue) are overlayed (right abscissa).

trons which penetrate the massive shielding between the two areas. Figure 3 shows the ratio of H^* to $H^*(10)$ for prompt radiation. The ratio varies significantly in areas where the dose is coming from down-scattered neutrons.

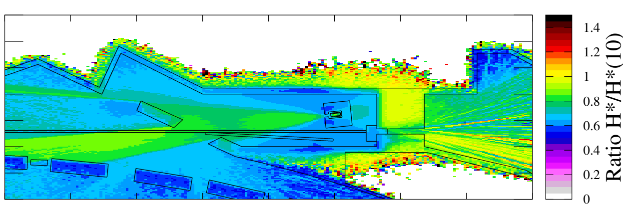

Figure 3: 160 MeV H^- on the LBE beam dump (tilted rectangular object), generating prompt radiation in the area and penetrating into the PS Booster area (left side). The heat map is showing the ratio H^* to $H^*(10)$.

Decay Radiation The dose rate from decay radiation from activation of the beam dump was determined for different decay times between 1 hour and 1 year, after an operation time of approximately 3 months. This reflects the commissioning conditions for the LBE beam line at the end of 2019. Figure 4 shows the time evolution of the dose rate ratio H^* to $H^*(10)$ for different positions in the LBE dump area and Fig. 5 the corresponding photon spectra. The observed differences can be explained by the change in the photon spectra in these locations with time due to the decay of short and medium lived radioisotopes and scattered photon radiation emitted mainly from the dump beam catcher.

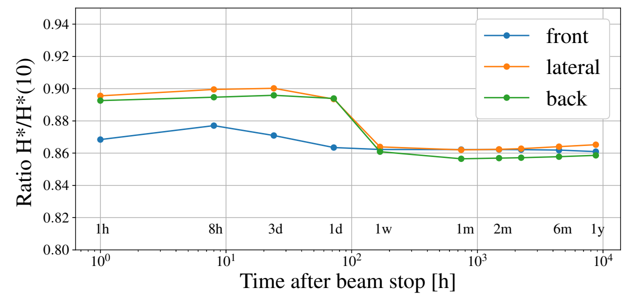

Figure 4: Dose rate ratios H^* to $H^*(10)$ from decay radiation at different locations in front, laterally and at the back of the LBE dump against decay times between 1 hour and 1 year.

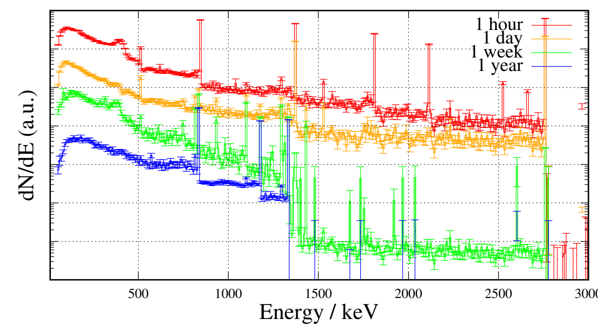

Figure 5: Photon spectra at a location close to the LBE dump at different decay times between 1hour and 1 year.

CONCLUSION

This paper is a first exploration of the consequences that the new operational quantities from ICRU and ICRP [1] will have on dosimetric estimations and measurements at workplaces at particle accelerators. From the generic study follows for accelerators with $E > 1$ GeV, that outside of shielding, ambient dose H^* exceeds ambient dose equivalent by 15 to 20%. For a 100-MeV accelerator, the two quantities yield similar results. Values of ambient dose H^* from decay radiation are about 15% lower than ambient dose equivalent.

These findings are confirmed in a more realistic example, at the LBE dump of CERN's Linac4 beam transfer line to the PS Booster.

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