Nuclear Instruments and Methods in Physics Research A 835 (2016) 13–33

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Shielding NSLS-II light source: Importance of geometry for calculating radiation levels from beam losses ☆

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ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form
6 August 2016
Accepted 6 August 2016
Available online 10 August 2016

Keywords:
Radiation Shielding
Beam losses
Radiation Dose Estimation

ABSTRACT

Third generation high brightness light sources are designed to have low emittance and high current beams, which contribute to higher beam loss rates that will be compensated by Top-Off injection. Shielding for these higher loss rates will be critical to protect the projected higher occupancy factors for the users. Top-Off injection requires a full energy injector, which will demand greater consideration of the potential abnormal beam miss-steering and localized losses that could occur. The high energy electron injection beam produces significantly higher neutron component dose to the experimental floor than a lower energy beam injection and ramped operations. Minimizing this dose will require adequate knowledge of where the miss-steered beam can occur and sufficient EM shielding close to the loss point, in order to attenuate the energy of the particles in the EM shower below the neutron production threshold (<10 MeV), which will spread the incident energy on the bulk shield walls and thereby the dose penetrating the shield walls. Designing supplemental shielding near the loss point using the analytic shielding model is shown to be inadequate because of its lack of geometry specification for the EM shower process. To predict the dose rates outside the tunnel requires detailed description of the geometry and materials that the beam losses will encounter inside the tunnel. Modern radiation shielding Monte-Carlo codes, like FLUKA, can handle this geometric description of the radiation transport process in sufficient detail, allowing accurate predictions of the dose rates expected and the ability to show weaknesses in the design before a high radiation incident occurs. The effort required to adequately define the accelerator geometry for these codes has been greatly reduced with the implementation of the graphical interface of FLAIR to FLUKA. This made the effective shielding process for NSLS-II quite accurate and reliable. The principles used to provide supplemental shielding to the NSLS-II accelerators and the lessons learned from this process are presented.

1. Introduction

The NSLS-II synchrotron light source (SLS) was designed as an Ultra-high brightness X-ray SLS with 3 GeV energy, sub-nm beam emittance, high beam current and short bunch electron beam in a 792 m circumference ring. The novel ring design will naturally lower the beam emittance as damping wigglers and other strong undulators are added to the ring [1]. With these parameters the beam lifetime is expected to be small ($\sim$3 h at 500 mA) requiring Top-Off injection into the ring to stabilize the beam power heating to the beamline optics and accelerator components. The required injected charge rate is $\sim$7.5 nC/min under these circumstances. Although oversight committees are quite concerned about miss-steering the injection beam down an open beam line shutter during Top-Off, this is highly unlikely. With Top-Off requiring full energy injection, the more likely abnormal event is miss-steering the injection beam with the beam hitting components inside the storage ring tunnel. Because of the intense forward cone of the EM shower, this requires the installation of supplemental shields (SS) at the most likely loss locations to attenuate this shower before hitting the outer shield walls.

The failure to identify a possible miss-steered beam location and the intense forward radiation exposure the EM shower can create, was observed early in the commissioning of the NSLS-II linac, which had a major impact on the commissioning. The bulk shielding around the linac tunnel was designed only to address transverse radiation from a relatively low fractional beam loss and not the intense forward radiation shower from the entire beam current. Even if commissioning took place at lower beam currents, future operation would require full beam intensity from the injector and miss-steering can and are likely to occur due to equipment failure

☆This work is supported in part by the U.S. Department of Energy (DOE) under Contract no. DE-AC02-98CH1-886.
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http://dx.doi.org/10.1016/j.nima.2016.08.017
0168-9002/

and operational errors. Those are the times when occupancy restrictions won't easily be implemented due to increased user activity to implement and improve their beam lines. The requirement to keep the dose to staff and users "As Low As Reasonably Achievable" (ALARA) means effort needs to be spent understanding where these possible loss locations are and a reliable estimate of the dose each fault condition could create to occupied areas.

1.1. Bulk shield wall specifications (analytic shielding model estimates)

The bulk shield walls for NSLS-II were designed assuming a specified fraction of the beam current, I_{av}, was lost at any location along the accelerator (Linac, booster or storage ring) vacuum chamber at the operational electron beam energy, E, [2]. The concrete wall thickness was increased until the calculated dose equivalent rates outside the shield walls were less than 0.5 mrem/h (5 μSv/h). The dose rate was calculated using an Analytic Shielding Model [ASM] that assumes the radiation of concern originates from a beam having a beam power, J, hitting a thick target [2]. The thick target needs to have greater than 10 radiation lengths and greater than 5 Moliere radii in transverse size, in order to generate a significant EM shower and transfer sufficient energy to the shower particles. All radiation components are assumed generated in this target with source terms for each components of radiation emitted (i. e. gamma rays, low energy and high energy neutrons of concern here) expressed as dose equivalent factors F_i (source term) for each component *i*. These F_i are the unshielded ambient dose equivalent (or dose rate) for that component per unit of incident beam energy J (or power), at a distance $R=1$ m from the target. Each radiation component is then shielded by the material of thickness t, with an average attenuation length λ_i for the component, *i*. The shielded total dose equivalent rate H [μrem/s, 0.01 μSv/s] is estimated by the sum of each attenuated radiation component for the incident total beam power loss, $J=E/e^{*}I_{av}$ (J/s), at a total distance R from the target, by the equation

$$H = \left(J/R^2\right) \bullet \Sigma_i F_i \bullet \exp\left[-t/\lambda_i\right] \quad (1)$$

This equation is only strictly valid for transverse radiation dose rate at ~90° (transverse tunnel walls) to the incident beam direction and for thick targets as described above. Typically the bulk shield walls will be transverse to the beam direction, however in light sources a forward ratchet wall is provided for the photon beam transport out of the tunnel. In the forward direction the ASM can still be used but with larger values for the F_i, that increase proportionally to the incident particle beam energy, *E*. The values for F_i used to design NSLS-II accelerator shield walls [2,3] are listed in Table 1. The neutron component is actually broken into two components; a low energy neutron ($E_n < 25$ MeV) and a high energy neutron ($E_n > 25$ MeV) terms, but only their total is listed in the table. The shield wall thickness was adjusted until the ASM estimated dose rate given by Eq. (1). (for a specified operational beam power loss J and distance *R* from the accelerator vacuum chamber) was below the targeted value, typically less than 0.5 mrem/h (5 μ Sv/h) for the experimental floor of the NSLS-II Storage Ring (SR) and other occupied areas.

The Monte Carlo radiation transport code FLUKA [5] was used to estimate the dose equivalent factors for electron beams hitting a 30 cm long × 10 cm diameter iron target. The dose distribution around the target for two beam energies is shown in Fig. 1. This shows the increased forward dose rate as the beam energy increases, but the transverse dose shows less energy dependence. The dose equivalent, at $R=1$ m from the unshielded target was calculated for electron energies (0.2, 1, and 3 GeV). Table 1 lists the 3 GeV normalized dose equivalent values calculated with FLUKA at 1 m from the target and scaled by the beam energy in Joules. These values can be compared with the F_i values used in the ASM [2]. The calculated FLUKA Amb74 dose equivalent values use the fluence-to-ambient dose equivalent conversion factors proposed by the ICRP Publication 74 [6]. The Amb74 dose is the ambient dose equivalent (Quality Factor weighted) for the radiation field penetrating a 1 cm depth in the direction of an oriented and expanded radiation field for an ICRU sphere [6]. All references to calculated dose in this paper will refer to ambient dose equivalent. The dose values listed in Table 1 were scored for all particles (Total Dose), the gamma ray and the total neutron dose components of the radiation field. The difference between the total dose and the sum of the other two dose components yields the charged particle component, which is not included in the ASM, but is always present where gamma and neutrons are part of the radiation field. Also listed is the exponential factor from a power law fit to the dose as a function electron beam energy *E*, for the three energies simulated. For the transverse dose calculated with FLUKA, the scaling with J of the ASM the F_i appears quite reasonable, since the power of *E* dependence parameters being compatible with zero. However the FLUKA data does show a small dependence on *E* for the neutron component. This arises from a greater number of photons being produced in the target with energies above the neutron production threshold of $E > 2$ MeV as *E* increases. Clearly the ASM over estimates the total and gamma dose values for these source terms (~2.5 times the gamma dose compared to Amb74 dose), however the neutron dose is under estimated and fails to include this increasing source term with *E*. This dependence is shown in Fig. 2 where the FLUKA simulated transverse Amb74 doses at a distance of 1 m from the target are plotted versus longitudinal coordinate for $E=0.2$, 1 and 3 GeV. The total (and gamma) dose data shows an increase of greater than 20% at angles relative to beam direction $\theta < 70°$ ($z > 40$ cm), as compared to the $\theta=90°$ dose ($z=0$). The neutron dose, Fig. 2(b), shows the largest energy increase from 0.2 to 1 GeV and a smaller from 1 to 3 GeV, as well as an isotropic production distribution around the center of

Table 1
The values used for the Dose Equivalent Factors, F_i used for NSLS-II shield wall thickness specifications and the FLUKA calculated unshielded scaled dose rates from a 30 cm long, 10 cm diameter iron target. The units for Dose Equivalent Factors are μrem m^2/J or 0.01 μSv m^2/J. The parameters for a power of E are from a fit to calculated doses versus beam energy.

Radiation Component	Unshielded dose at $R=1$ m from target					
	Transverse 90° [μrem m^2/J]			Forward 0° [μrem m^2/J]		
	Anal. Dose factors, F_i [2,3]	FLUKA Amb74 F_i(3 GeV)	Power *E*	Anal. Dose Factors, F_i[4]	FLUKA Amb74 F_i [×10^3]	Power *E*
Total Dose	1693	1149 ± 15	0.02 ± 0.015	8.33 × 10^6 *E*	5.922 *E*	0.81 ± 0.02
Gamma Dose	1380	535.5 ± 2.6	−0.026 ± 0.02	8.33 × 10^6 *E*	3.469 *E*	0.79 ± 0.02
Neutron Dose	313	436.5 ± 9.7	0.29 ± 0.03	405.5	0.102	0.43 ± 0.04
Charge part.		176.6 ± 18	−0.22+0.04		2.419 *E*	0.84 ± 0.03
				E in GeV		