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Characterization of Gas Bremsstrahlung sources at the Electron-Ion Collider

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Characterization of Gas Bremsstrahlung sources at the Electron-Ion Collider

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This report estimates the potential impact of Gas Bremsstrahlung, generated as the electron beam traverses the straight sections of the storage ring and impinges onto selected locations of the Electron-Ion Collider. The source terms were calculated for routine operation scenarios at three different energies: 5, 10 and 18 GeV, using the FLUKA Monte Carlo particle transport and interaction code. The source term's power distributions were validated and compared with the Gas Bremsstrahlung produced in the long straight sections of the National Synchrotron Light Source II storage ring

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ACRONYMS

BNL Brookhaven National Laboratory

EIC Electron-Ion Collider

ESR Electron Storage Ring

FLUKA FLUktuierende KAskade Monte Carlo particle transport and interaction code

GB Gas Bremsstrahlung

IP Interactio Point

MC Monte Carlo (method)

NSLS-II National Synchrotron Light Source II

RHIC Relativistic Heavy Ion Collider

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INTRODUCTION

The Electron-Ion Collider (EIC), currently under construction at Brookhaven National Laboratory (BNL), will provide the scientific community with data from collisions between polarized beams of electrons and ions at center-of-mass energies ranging from 20 to 140 GeV/n [1]. These data will be of great importance to help solve fundamental physics questions, particularly those involving nucleon formation and the study of mass and spin origins [2].

While the EIC will feature a modified version of one of the Relativistic Heavy Ion Collider (RHIC) rings for the hadron circulation, a new electron Storage Ring will be constructed to provide polarized electron beams up to 18 GeV. The electron ring layout is depicted in figure 1.

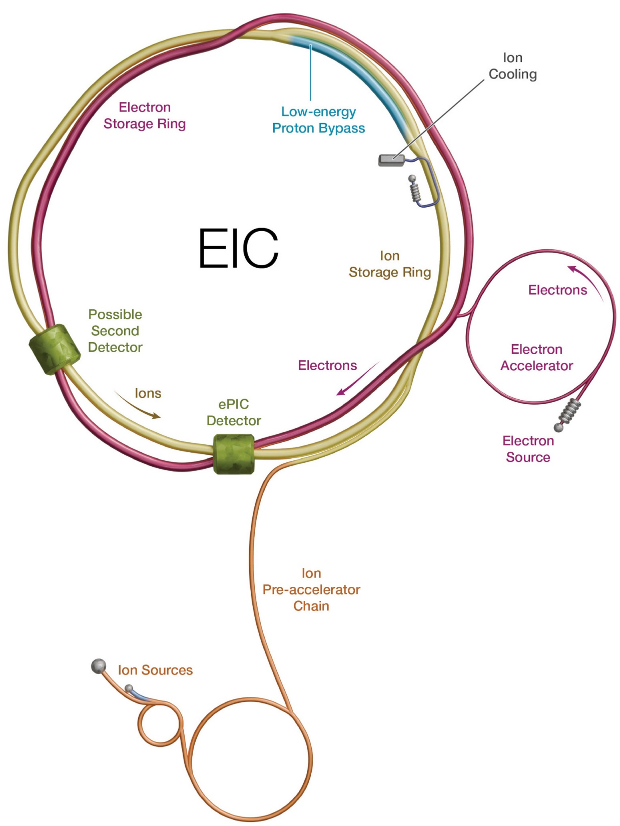

FIG. 1. *The EIC accelerator chain and major components as of March 2025* (https://www.bnl.gov/eic/machine.php)

Among the many relevant physics processes that occur in electron storage rings, *Gas Bremsstrahlung* (GB) can be a significant source of radiation. In most light sources, such as the National Synchrotron Light Source II (NSLS-II), GB is actually one of the main drivers of shielding requirements in beam lines, because of the latter's direct exposure to radiation generated along straight sections.

In the context of EIC, these radiation safety concerns related to GB are not applicable. However, given the large scale of its electron ring, high electron power, and multitude of other radiation sources, GB could be a non-negligible source of radiation from a beam-machine protection standpoint. Even if overall this power is expected to be relatively low, it could still be a meaningful source of dose to specific components over the course of several years of operation.

For the present work, the Monte Carlo (MC) particle transport and interaction code FLUKA 2025.1[3, 4] was used to generate credible GB source terms. The FLUKA 4-5.1 [5, 6] MC code was then employed for assessing the impact of GB downstream of Interaction Point 2 (IP2), after the beam traversed a straight section of 178.4 m.

I. SOURCE TERM SIMULATION

The GB source term consists of an approximately E^{-1} photon spectrum, up to the electron beam energy. As a by-product of the electron beam interacting with the residual gas inside of the ring, the GB photon flux distribution in a given location depends on several factors such as the energy and intensity of the primary beam, as well as the length of the section and media parameters. Some relevant GB parameters for NSLS-II and EIC are listed in table I as a comparison term.

TABLE I. *Parameters used for GB generation in the FLUKA 2025.1 simulations.*

Parameter	NSLS-II	EIC	EIC	EIC
Electron beam energy [GeV]	*3*	*5*	*10*	*18*
Section length [m]	*15.5*	*178.4*	*178.4*	*178.4*
Gas pressure [nTorr]	*1*	*5*	*5*	*5*
Beam intensity [A]	*.5*	*2.5*	*2.5*	*.227*

Simulations were carried out at atmospheric pressures, with scattering effects suppressed, so as to reproduce "near vacuum physics" [7], and then renormalized according to the residual gas pressure. It should be noted that GB spectra derived from air at atmospheric pressure are always an approximation, since the composition of residual gas inside the ring in the nTorr range is dominated by hydrogen (contrary to nitrogen in air [8]). Furthermore, the residual gas content might also change during operation, making accurate estimates relatively difficult without reliable data.

The GB spectra were simulated with a residual gas composition extrapolated from several references [8–10]. The composition assumed in the simulations is listed in Table II.

For the sake of consistency, each of the generated GB source terms' spectrum was scored in a squared area of 1 cm^2 at the end of the respective straight section.

Based on the parameters detailed in table I, the GB fluxes calculated with FLUKA 2025.1 can be found in figure 2.

TABLE II. *Residual Gas composition as simulated in FLUKA 2025.1*

Molecule	Fraction [%]
H_2	75
CO	12.5
CO_2	6.25
CH_4	6.25

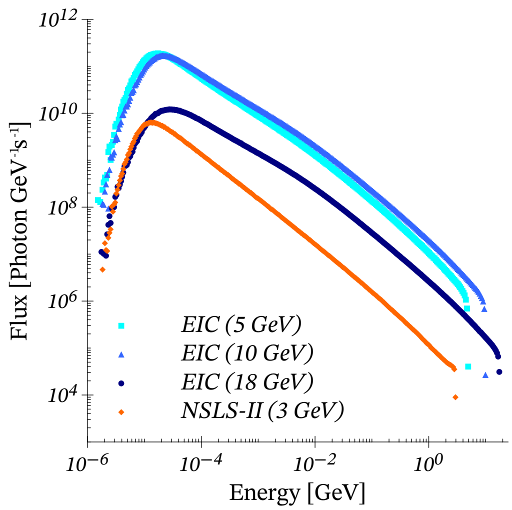

FIG. 2. *Calculated GB photon flux [photon* $\mathrm{GeV}^{-1}\,\mathrm{s}^{-1}$*] for the various source terms considered.*

II. GB POWER DISTRIBUTION

The power distributions corresponding to each of the source term fluxes detailed in figure 2 are denoted in figure 3.

The most relevant features of those distributions are detailed in table III. The critical energy E_c is hereby defined as the energy evenly dividing the power of a given source term.

TABLE III. *GB source terms' power characteristics calculated with FLUKA 2025.1.*

Source term	E_c [GeV]	Integrated power [mW]
NSLS-II (3 GeV)	*1.31 ±0.76%*	*.057*
EIC (5 GeV)	*1.895 ±0.26%*	*6.925*
EIC (10 GeV)	*3.92 ±0.26%*	*23.382*
EIC (18 GeV)	*7.13 ±0.14%*	*5.290*

III. VALIDATION OF SIMULATION RESULTS

At NSLS-II, the integrated power corresponding to the GB source term – for a 3 GeV and 500 mA electron beam traversing a 15.5 m section with residual gas at 1 nTorr – is considered to be 17 µW [11, 12]. As a rough approximation, this aforementioned reference power value can be scaled for the EIC cases employing the parameters listed in table I, to provide a semi-empirical estimate of the integrated GB power ($\mathcal{P}_\mathrm{E}$).

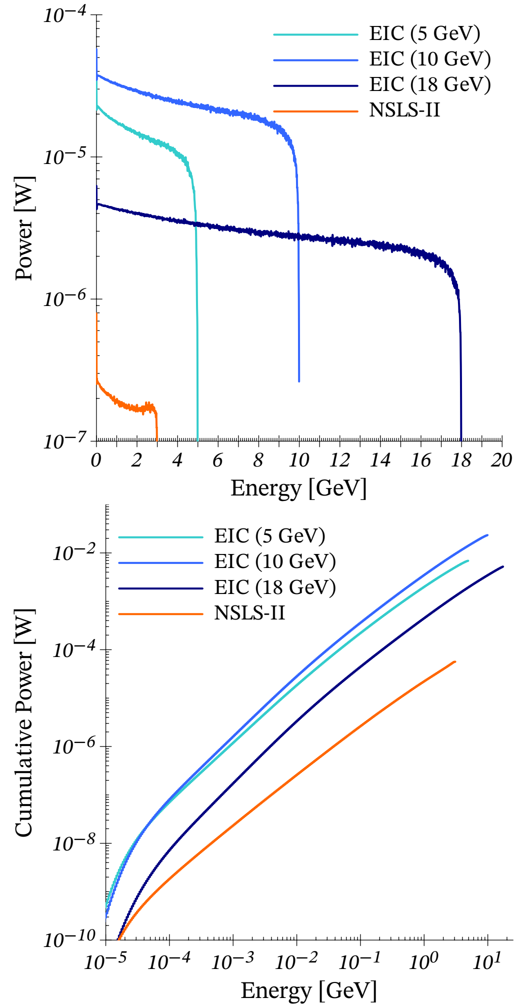

FIG. 3. *Top panel: GB power distribution [W] as a function of energy for the various source terms calculated with FLUKA 2025.1. Bottom panel: cumulative power [W].*

The GB power can also be calculated analytically. One example, is via the expression 1, adapted from Dooling and Emery [13] to estimate GB power ($\mathcal{P}_\mathrm{A}$) in mW.

$$\mathcal{P}_\mathrm{A} = 2.7237 \times 10^6 \left(\frac{p\, I\, \rho}{X_0\, T}\right) L_{ss}\, E_k\,, \qquad (1)$$

where p is the pressure [nTorr], I the current [A], ρ the medium density [$\mathrm{g\,cm^{-3}}$], T the temperature [K] and X_0 the radiation length [$\mathrm{g\,cm^{-2}}$]. As for L_{ss} it corresponds to the straight section length [m] and E_k the electron kinetic energy in [GeV]. The radiation length depends of the medium and, for air, it was found to be 37.06 [$\mathrm{g\,cm^{-2}}$] in reference [13].

As in the referenced study, the temperature used was 298 [K]. A value of 1.5844×10^{-15} [$\mathrm{g\,cm^{-3}}$] for the residual gas density was also extrapolated from reference [13].

Table IV lists the integrated GB power calculated with both the semi-empirical and analytical methodologies proposed, as well as the FLUKA 2025.1 simulation results previously denoted in table III.

TABLE IV. *GB integrated power estimates, $\mathcal{P}$, all results are given in* mW

Source term	$\mathcal{P}_{\mathrm{E}}$	$\mathcal{P}_{\mathrm{A}}$	$\mathcal{P}_{\mathrm{FLUKA\ 2025.1}}$
NSLS-II (3 GeV)	*.017*	*.091*	*.057*
EIC (5 GeV)	*8.153*	*43.564*	*6.925*
EIC (10 GeV)	*16.305*	*87.128*	*23.382*
EIC (18 GeV)	*2.665*	*14.240*	*5.290*

IV. THE EFFECT OF RESIDUAL GAS COMPOSITION

For the worst case scenario determined in this work, from an integrated power standpoint – i.e., the 10 GeV EIC GB source term – additional calculations were performed assuming either a fully hydrogenated or a carbon monoxide residual gas composition.

The GB fluxes and power distributions were recalculated with the alternative media, and the respective results are shown in figure 4.

The integrated power for the H_2 gas amounted to only 2.3 mW. Conversely, for the CO gas counterpart the integrated power was found to be approximately 27.6 mW.

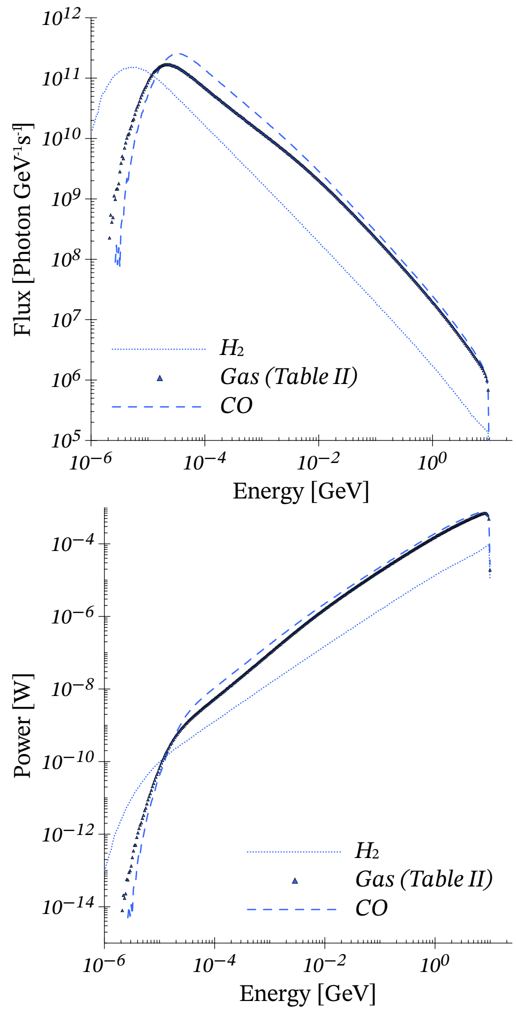

FIG. 4. *FLUKA 2025.1 calculated GB fluxes and power for the alternative gas composition.*

V. IMPACT STUDY

For the GB impact calculations, the 10 and 18 GeV ESR GB source term spectra in figure 2 were used as a source term at the first dipole bend downstream of the straight section of IP2, impinging onto the beam pipe at the second ESR dipole location. For modeling the detailed ESR magnet elements, the new capability of importing detailed unstructured meshes found in FLUKA 4-5.1 was utilized. A visualization of the geometry in *flair* (3.4-4) [14] is provided in figure 5, with the electromagnetic radiation fluence of the 10 GeV scenario superimposed over the geometry in the region of interest, comprising the ESR standard arc dipole and quadrupole models as well as the ESR beam pipe.

The 10 and 18 GeV operational modes were selected as the most impactful cases based on their power considerations and GB photon critical energies, while the 5 GeV case was deemed redundant compared to the 10 GeV case due to the latter fourfold higher power and lower GB photon critical energy. (see table IV).

The absorbed dose rates were scored in the vicinity of the region where the GB source term interacts with the beam pipe. The FLUKA 4-5.1 dose maps are depicted in figure 6 using the power values shown in Table III. Integrated absorbed dose values estimated for 40000 hours of operation (10 years of 4000 hours annually) in the magnet coils were estimated using a 3D cartesian dose map. An X-Y cross-section at the peak Z direction a few centimeters downstream of the impact point is shown in figure 6. The maximum levels observed at the coils were below 100 and below 10 kGy, for the 10 and 18 GeV cases respectively.

DISCUSSION

GB source term definition

The GB source terms were calculated for the reference NSLS-II scenario and three EIC-ESR cases at different electron energies – 5, 10 and 18 GeV. The highest fluxes were identified at the 5 and 10 GeV EIC GB source terms, by almost an order of magnitude at peak value with respect to their counterparts, as denoted in figure 2. These highest fluxes were found to be driven mainly by the in-

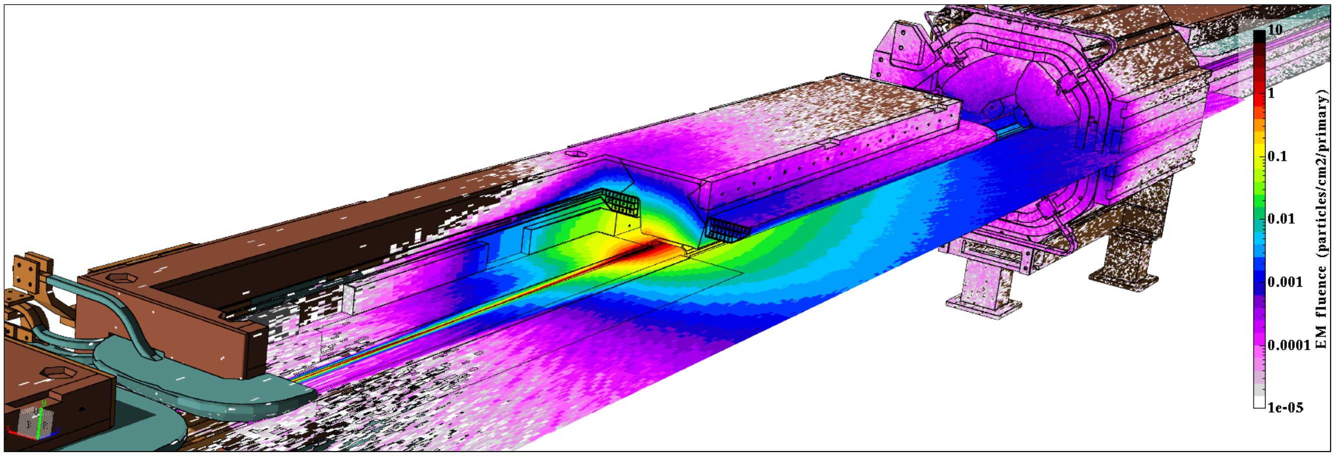

FIG. 5. *Qualitative view of the electromagnetic particle fluence ($\gamma + e^{+}\&e^{-}$) distribution, scored via FLUKA 4-5.1 for the 10* GeV *GB scenario. The result is superimposed to the ESR geometry within the* flair *(3.4-4) environment.*

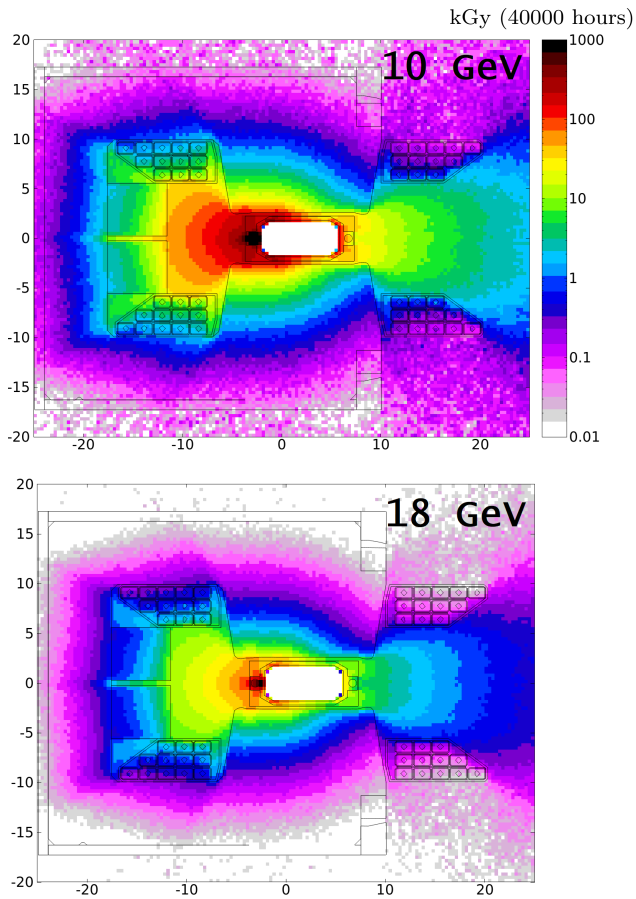

FIG. 6. *FLUKA 4-5.1 absorbed dose rate maps, in units of* kGy *integrated over 40000 hours, in the region of interest. The maps are projected over a depth of 10* cm.

tensity of the electron beam when compared directly to the 18 GeV EIC case, 2.5 A at 5 and 10 GeV compared to 227 mA at 18 GeV.

Correspondingly, the power distributions scored in figure 3 confirm that the 5 and 10 GeV EIC GB source terms indeed carry the most power load. However, despite their disparity in fluxes, the EIC cases 5 and 18 GeV have relatively similar integrated power values (within 25%). This is explained by the fact that the power distribution is concentrated at the high energy end of the GB spectra as denoted in figure 3 and is also made evident in the E_c values stated in table III. On the other hand the 10 GeV GB power is almost 4 times larger than either its 5 and 18 GeV counterparts as per table III. Thus, the worst-case scenario from a power load point of view is given by the 10 GeV GB source term. However, for the power deposition and absorbed dose beyond the beam pipe the 18 GeV had to be studied as well due to its higher GB photon critical energy which could have disproportionally impacted the magnet coils.

With respect to the validation of the integrated power simulated results, it was observed that the semi-empirical reference value of 17 µW was indeed within a factor of $\sim$ 3.3 from the FLUKA calculated value (56 µW) for NSLS-II, as detailed in table IV. For the EIC cases, the agreement between the semi-empirical integrated power values and the FLUKA calculated results is within a factor of 2. This agreement is also an indication that the parameters listed in table II are indeed of key importance when it comes to extrapolating the GB integrated power vis-a-vis with a simulated value. Concerning the analytical solutions calculated in this work, listed in table IV, the integrated results were found to be consistently and substantially higher than the simulated results, by as much as a factor of over 6 in the EIC 5 GeV case. Conversely, the analytical result is within a factor of 2 and 3 from the simulated NSLS-II and 18 GeV EIC cases, respectively. Because the expression used to estimate the integrated power contains only linear terms, and the baseline value for NSLS-II is already relatively high, the EIC results are high as well. It should be noted that this analytical method was originally employed in a framework applicable to storage rings akin to that of NSLS-II and probably not intended to 'scale' up for an EIC setup, or at least not without further refinement.

Moreover, the analytical power calculation was performed with a residual air based on a typical air composition instead of the residual air composition employed in the FLUKA 2025.1 simulation, detailed in table II. This could definitely be a factor contributing to the differences between simulated and analytical integrated powers. A comparison of GB source terms simulated with FLUKA 2025.1 assuming residual gas compositions comprising CO, H_2, as well as the gas content stated in table II, was able to confirm that indeed the gas composition can substantially affect the GB power. For instance, in the top panel of figure 4 the GB flux generated in the hydrogenated gas is clearly shifted to a lower energy by approximately a factor of ten. Consequently, the GB power scored with the hydrogen based gas also lower by almost one order of magnitude with respect to CO and the residual gas composition detailed in table II. In fact, the differences between the two latter are relatively minor, with the GB power resulting from a CO gas being less than 20% higher than our original residual gas mixture.

Absorbed dose impact assessment

The electromagnetic radiation distribution, depicted in figure 5, confirm that the GB source term impact is relatively forward projected but localized along the beamline axis. Furthermore, the absorbed dose maps in figure 6 denote how the GB is heavily attenuated within the magnet on the radial direction. In the coils of the quadrupole, dose levels can attain up to 100 kGy over the course of 10 years assuming a yearly operation of 4000 h. Dose variations between the 10 and 18 GeV cases were found to be significant, with the magnitude of latter case being lower by a factor of almost 10 closer to the coils. This is mainly due to the 18 GeV case's lower power but also due to its harder gamma rays that spread the energy downstream of the peak dose location.

Overall, the dose impact of GB can be considered relatively minor, since the dose limits of the coils are about 20 MGy. In fact, the GB dose contribution in the coils were found to be quite comparable to that of the beam losses - also about 100 kGy over 10 years, assuming a 20 $\mathrm{MHz\,m^{-1}}$ loss rate [15] - hence their joint effect remains well within the coils' dose limit.

Note that both the GB and beam losses contributions are effectively overshadowed by SR derived dose [16], and lead shielding was found to be required due to the latter. Such shielding will definitely attenuate and contain the electromagnetic component of the radiation plumes from GB, further mitigating its dosimetry impact in the coils.

CONCLUSION

The GB source terms were generated for the three EIC operational scenarios, and the NSLS-II, using the Monte Carlo code FLUKA. It was observed that the power of the GB spectrum for the EIC could exceed that of NSLS-II by over two orders of magnitude.

Moreover, it was verified that in between the EIC GB power loads, the 18 GeV case was almost a factor 5 lower than the 10 GeV case, and quite comparable to the 5 GeV case.

Validation of the simulated power results was carried out using both an analytical and semi-empirical methodology, with all results agreeing within a factor of ~ 5.

The effect of the residual gas composition on the GB source term was also quantified, and found to be quite significant. For instance, it was observed that the GB power output for the 10 GeV case in a hydrogenated gas could be lower by almost an order of magnitude with respect to the gas mixture assumed in the current work.

Absorbed dose results from the calculated 10 and 18 GeV EIC GB source terms were resampled at the end of IP2 straight section, and the absorbed dose on the downstream magnet coils quantified. It was found that the 10 GeV case was indeed the most impactful (due to flux/power considerations), yielding up to 100 kGy in the magnet coils integrated over 40000 hours of operation. However, the GB impact on the lifetime of the magnets was found to be negligible since the coils' dose limit is 20 MGy.

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