eRD21 Progress Report and FY2021 Proposal

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We report studies of background effects in the EIC interaction region and detectors using GEANT4, FLUKA and two dedicated Synchrotron radiation codes. In particular, we have initiated studies using the pre-CDR Interaction Region magnetic optics for both synchrotron radiation and proton beam-gas interactions. We report synchrotron radiation doses in the central beam pipe and Si Vertex Tracker. These are based on the updated (May 2020) electron lattice design. We also suggest additional studies to mitigate the radiation dose. We used FLUKA simulations to compute hadronic backgrounds in the Experimental Hall, with the energy spectrum simulated all the way down to sub eV neutrons

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Project Name: **EIC Background Studies and the Impact on the IR and Detector**
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Project Leader : Latifa Elouadrhiri
Contact Person: Latifa Elouadrhiri

Project Personnel

1. Latifa Elouadrhiri:	JLab physics
2. Charles Hyde:	ODU physics
3. Vasiliy Morozov:	JLab accelerator
4. Christine Ploen:	ODU physics (Graduate Student)*
5. Marcy Stutzman:	JLab accelerator
6. Mike Sullivan:	SLAC physics
7. Yulia Furletova:	JLab physics
8. Mark Wiseman:	JLab engineering
9. Andrey Kim:	UConn physics (Research Scientist)*
10. Vitaly Baturin:	ODU physics (Post Doc)*
11. Youri Sharabian:	JLab physics
12. Nick Markov:	JLab physics
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CONTENTS

I. EXECUTIVE SUMMARY

Our original proposal aimed at the study of background effects on the EIC interaction region and nearby detectors with an initial focus on the JLEIC (EIC at Jefferson Lab) configuration. At the mid-term report we presented the tools we developed, their validation and the initial synchrotron radiation rates on the Silicon vertex tracker in the case of JLEIC design. In January 2020 DOE announced the approval of the EIC CD0 and the site selection to be BNL with Jefferson Lab as a major partner. Immediately after the DOE announcement we shifted our focus to work on the background studies for the official EIC IR in close collaboration with the BNL team. At the same time, we continued our effort in developing and refining our simulation tools.

We initiated studies using the EIC Interaction Region (IR) magnetic optics for both synchrotron radiation and proton beam gas interactions. We implemented the optimized May 2020 IR design in GEANT4, then we focused our effort on quantitative studies of the two major sources of background, synchrotron radiation and the evaluation of the neutron flux in the experimental Hall. In the case of the synchrotron radiation we used two simulation tools, SYNRAD (CERN) and Synchrotron radiation code developed at SLAC and adopted at Jefferson Lab. For the evaluation of the neuron flux we used Fluka and GEANT 4 simulations. All the results we are presenting in this report are based on EIC-IR May2020 design.

This is a critical task to finalize the IR and detector design and provide detector experts with the necessary information, in terms of rates, radiation doses, in order to make informed decision on the technology choices for the detectors and the associated readout electronics.

We have assembled a very strong team, including nuclear, accelerator and radiation scientists, mechanical and vacuum engineers, with expertise in simulations using complementary tools. Members of our team are taking leadership on this chapter of the Conceptual Design Report (CDR) in preparation of the CD1 Review, scheduled for January 2021 with the first step of the review schedule for September 2020.

As a team, we developed our path forward for this project as outlined in Section IV of this document. These studies are even more critical than before as it will guide the detector R&D, different beam tests, and IR- and detector-design as we move from conceptual design at CD1 to the technical design in preparation of CD2.

II. SYNCHROTRON RADIATION AND VACUUM STUDIES

We are using two distinct codes to simulate the synchrotron radiation in the interaction region: The CERN SYNRAD code and the SLAC code of Michael Sullivan, which we ported to JLab and adapted for this purpose. All references to “design values” or “pre-CDR” refer to [1].

A. SYNRAD

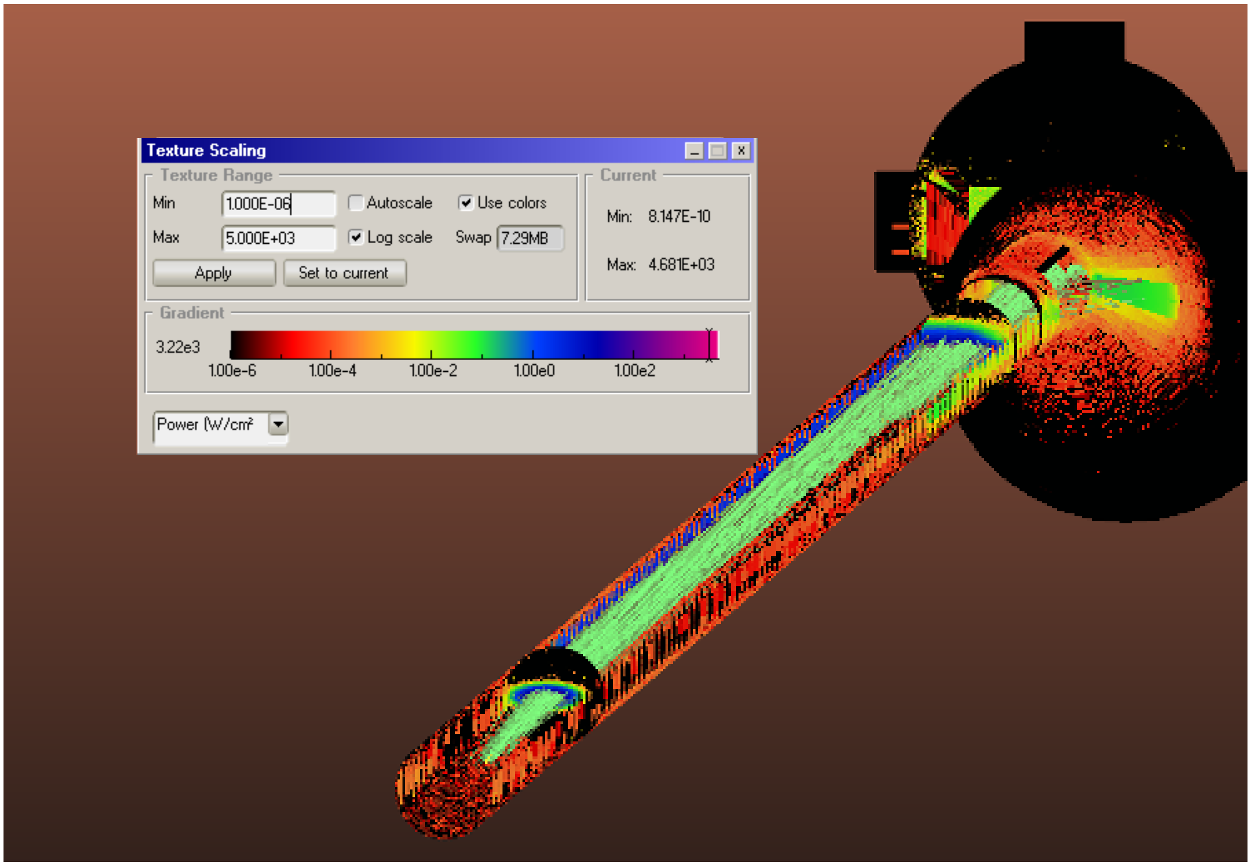

FIG. 1. SYNRAD generation of synchrotron radiation from 0.260 Amp of 18 GeV electrons. The color scale is logarithmic, with blue approximately 1 W/cm^2. Electrons enter from the lower left on the figure, the initial radiation fan is generated from the last dipole, at approximately 40 m upstream of the IP. Individual photons are traced by the green lines. The vertical striations on the beam pipe result from the sawtooth inner profile of the pipe, which ensures photons hit the wall locally head-on.

In collaboration with Charles Hetzel (BNL), Marcy Stutzman used a model of the electron beamline in SYNRAD, and generated synchrotron radiation at the maximal design value of 0.260 Amp of 18 GeV electrons, including 26 mA in a broad tail distribution. Fig. 1 shows a view of the upstream electron beamline and IP, with synchrotron radiation generated by the last upstream dipole and FFQ quadrupoles. Electrons enter from the lower left on the figure, at the location of the last dipole, $\approx$ 40 m from the IP. In the background, the IP itself is obscured by the hourglass shape of the central region of the beam pipe. The data file of photons has been transmitted to Jin Huang (BNL) who is using the Fun4All framework to study synchrotron radiation occupancy in an EIC detector.

B. MOLFLOW Vacuum Studies

Although not directly funded by this project, studies of the dynamic vacuum in the IR are directly linked to the synchrotron radiation flux impacting the beam pipe. Fig. 2 illustrates the static vacuum (without synchrotron radiation) in IR1, based on nominal out-gassing rates, the molecular flow conductance of the beam pipe, and the pumping speed of the NEG pumps at ±4.5 m.

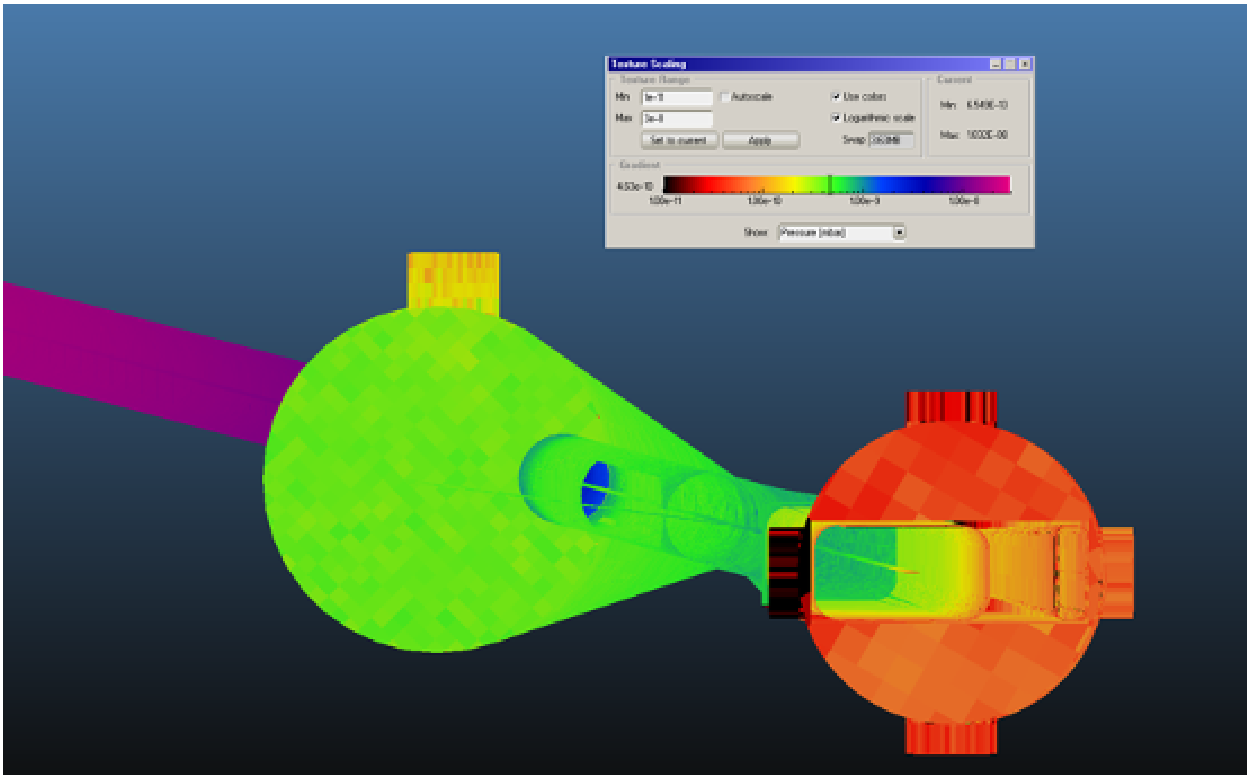

FIG. 2. MOLFLOW calculation (M. Stutzman) of the static vacuum in the IR. The beam pipe layout is the same as Fig. 1. In this view, the electron beam enters from the upper left and exits through the large horizontal aperture on the right. The incident ions enter from the right at $z = -4.5$ m via the smaller upright rectangular aperture. The light green color in the central region indicates a vacuum of $\approx 5 \cdot 10^{-9}$ mbar. The downstream ion beam pipe is not shown beyond the flange at z = 4.5 m.

C. SLAC Synchrotron Radiation Code

Following the January R& D meeting, we have imported the EIC Interation Region (IR) optics into the SLAC code. Andrey Kim and Christine Ploen built a GEANT4 model of the pre-CDR IR beam pipe design. Figures 3 and 4 illustrate the GEANT4 model of the beam pipe and Si Vertex Tracker (SiVT). The beam pipe design is essentially identical to the SYNRAD design in Fig. 1, these views simply highlight different features. A large statistics sample of synchrotron photons was generated by Vitaly Baturin and Mike Sullivan. These photons were then passed through the GEANT4 model with the results described in the next section.

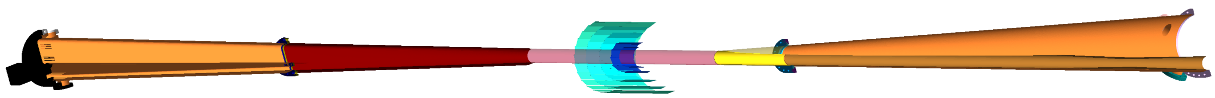

FIG. 3. GEANT4 model of IR1 Beam Pipe, with Si Vertex Tracker. The electron beam enters horizontally from the right, and exits in the rectangular beam channel to the left. The ion beam enters in the small tube on the lower left, and exits via the large cone on the upper right.

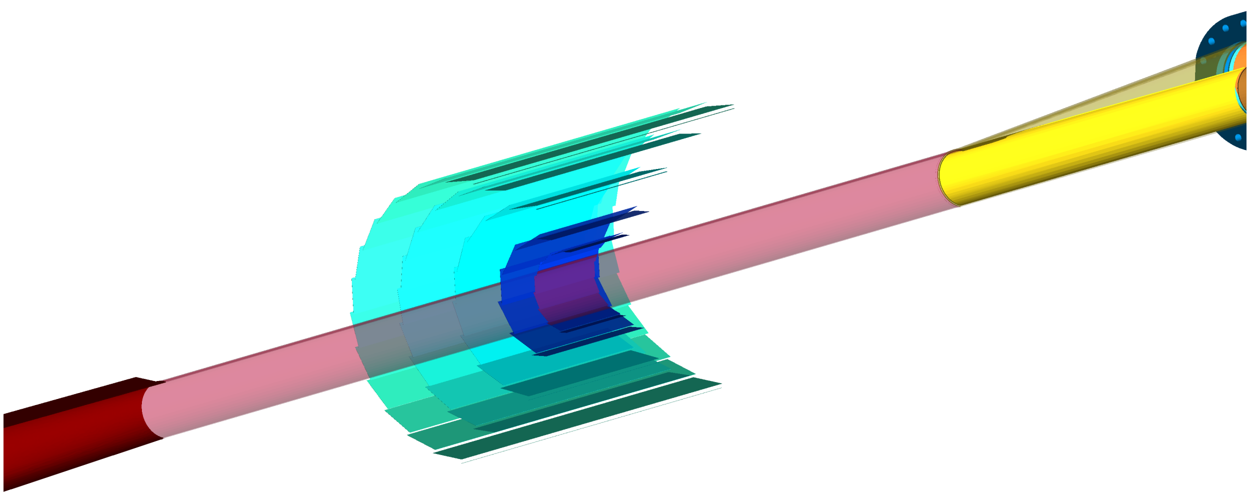

FIG. 4. Zoom of the GEANT4 model of IR1 Beam Pipe, at the IP. The electron beam is travelling from right to left. The central cylindrical region of the beam pipe is made of Be, and has an inner coating of several microns of Au. The five Si layers range in length from ±10 cm to ±30 cm.

D. Synchrotron Flux in IP Beam Pipe and Si Vertex Tracker

The energy deposition in the Be beam pipe and Si Vertex Tracker layers is illustrated in Fig. 5. The dose (energy per mass) in the Si layers is plotted in Fig. 6. The photon flux in these figures is integrated over 0.465μsec of an 18 GeV electron beam at the design current of 0.26 Amp, including a beam tail. The dose rate and total dose in a year of operations are summarized in Table I. Ref. [2] suggests Si sensors can survive X-ray doses of up to 10 MGy, so the maximum dose in Table I of 50 KGy/year is well below this limit.

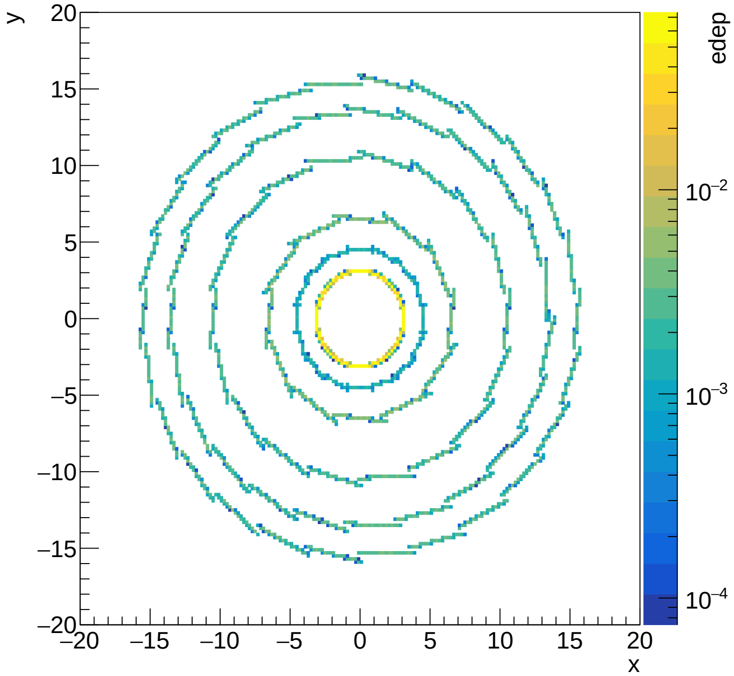

FIG. 5. Synchrotron energy deposition in central Be pipe and 5 layers of SiVT, radiation generated with SLAC code. Energy is integrated over the length of each element.

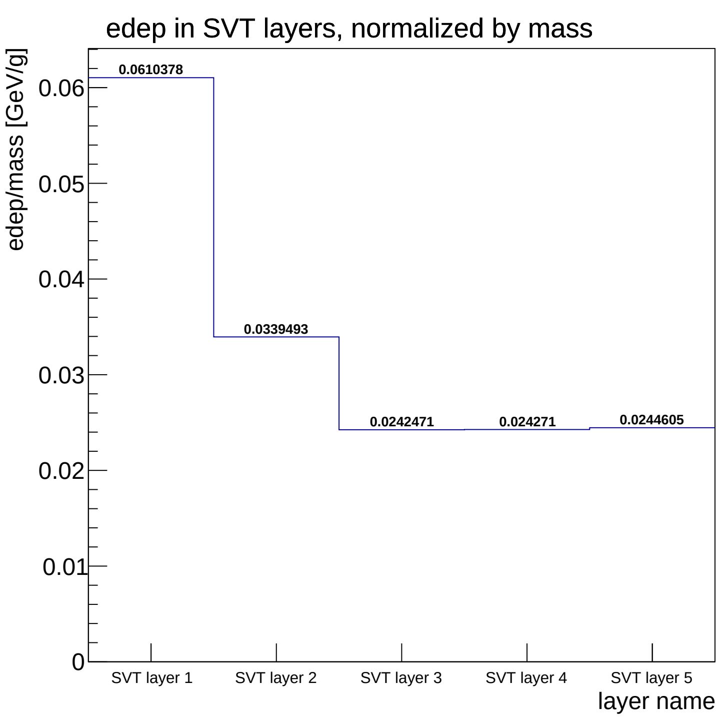

FIG. 6. Synchrotron radiation dose (GeV/gram) in each of 5 layers of SiVT. Layer 1 is the innermost layer. The radiation flux was generated with the SLAC code, and then passed through the GEANT4 model. Dose is averaged over the length of each element.

TABLE I. Synchrotron radiation deposition from $7.5 \cdot 10^{10}$ incident 18 GeV electrons. Dose rates are computed for electron beam current of 0.26 Amp, and dose per year values assume 10^7 sec/year.

SiVT layer	1	2	3	4	5
Energy Deposition (GeV)	0.061	0.034	0.024	0.024	0.024
Mass (gram)	4.1	30.2	60.4	116	174
Dose Rate $\left(\frac{\text{GeV}}{\text{g sec}}\right)$	$32.0 \cdot 10^3$	$2.42 \cdot 10^3$	855	450	303
Dose per Year (Gray/year)	$51.2 \cdot 10^3$	$3.88 \cdot 10^3$	$2.37 \cdot 10^3$	720	484

III. FLUKA SIMULATIONS OF BEAM-GAS INTERACTIONS

A. FLUKA Model of Interaction Region

Vitaly Baturin created a model in FLUKA of the interaction region-1 (IR1), ± 30 m, including all magnets, the tunnel walls, the detector cavern, and a simplified representation of the detector. This is illustrated in Fig. 7. We are currently working to expand the model to include the full tunnel and additional magnets of the IR, arc to arc. A more detailed view of the detector model is presented in Fig. 8.

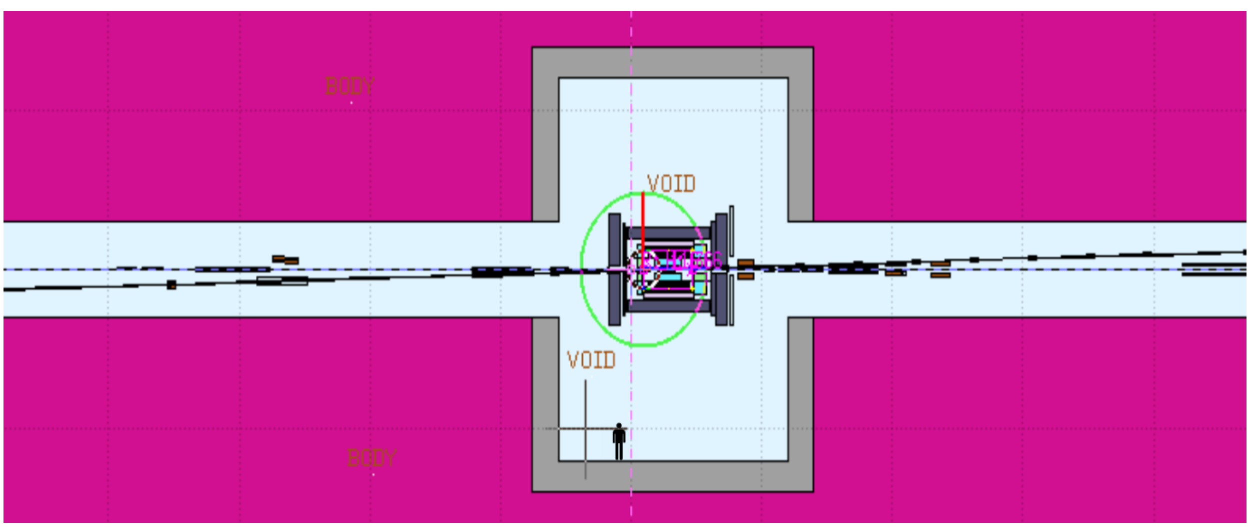

FIG. 7. Top view of FLUKA model of EIC Interaction Region 1 (person for scale is lying down). Ions enter from lower left, electrons enter on the solenoid axis from the right.

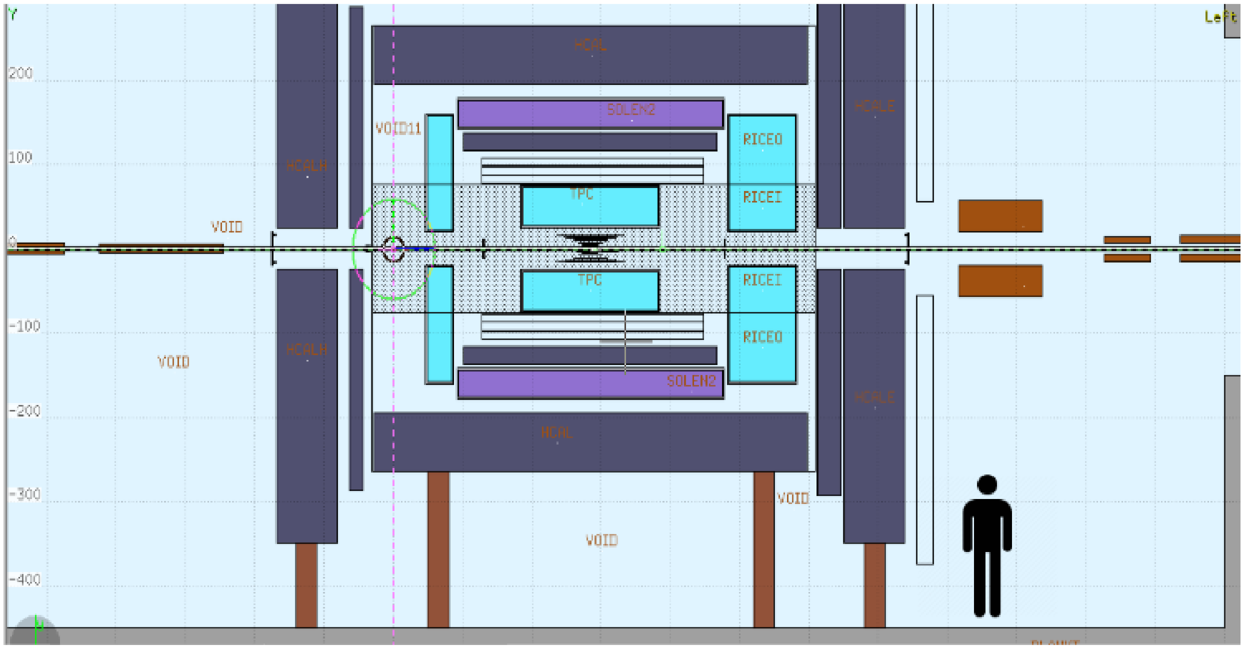

FIG. 8. Elevation view of FLUKA model of EIC Detector. The Si Vertex Tracker (SiVT) in this rendition includes six layers.

B. Beam-Gas Interaction Results

In order to efficiently simulate the interactions of the ion beam with the residual gas in the beam-line vacuum, we artificially create a thin "pencil" (diameter 3mm) of air at pressure $P_F = 100$ mbar along the beam-line. A global view of the neutron fluence is presented in Fig. 9. The simulation includes the full cascading and thermalization of secondaries from the primary beam-gas interactions. The figure illustrates the fact that the detector itself, especially the iron flux return, serves as both a neutron sink and neutron source.

The energy spectrum of beam-gas particles at the central Si Vertex Tracker (SiVT) is illustrated in Fig. 10. The energy distribution shows a clear peak of fully thermalized neutrons below 1 eV, as well as a knee around 10 MeV from evaporation neutrons. Neutron damage to Si sensors occurs primarily via displacement of nuclei from their ideal lattice positions. This can happen both by direct nSi scattering, and also by recoil from Si(n,γ) reactions. The latter can dislodge nuclei, even for neutron energies well below 1 eV.

The damage induced by neutrons is frequently quantified by an equivalent flux of 1 MeV neutrons. This is computed in Fig. 11.

In this section we estimate the lifetime of the semiconductor in the area of the innermost SiVT layer. For this estimate we assume the following parameters:

- The critical integrated fluence for significant damage is

$$\Phi_{\rm 1MeVEq} = 10^{14}\ \text{neutrons/cm}^2 \tag{1}$$

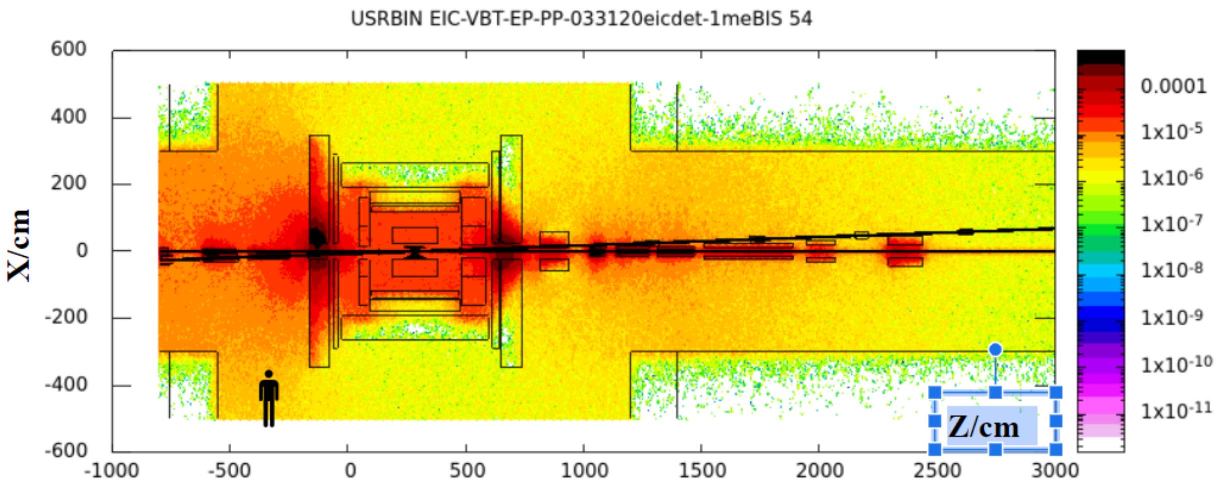

FIG. 9. Neutron fluence map from $p + Air$ interactions in the beam pipe at proton energy $E_p = 275$ GeV and an artificial pressure P_F ("P-FLUKA") in a thin cylinder along the beam line. The IP is located at $Z = 285$ cm. Neutron fluence is given by the color chart at the right side of the plot in units of neutrons/cm^2/proton at $P_F = 100$ mbar. Normalized rates for current $I = 1$ Amp and a realistic average beam-line vacuum $P = 10^{-9}$ mbar are obtained by multiplying the color values by $(I/e)(P/P_F) = 6.25 \cdot 10^7$ protons/sec. Thus dark red regions (almost yielding to black) correspond to a realistic fluence of $\approx 6 \cdot 10^4$ neutrons/sec/cm^2.

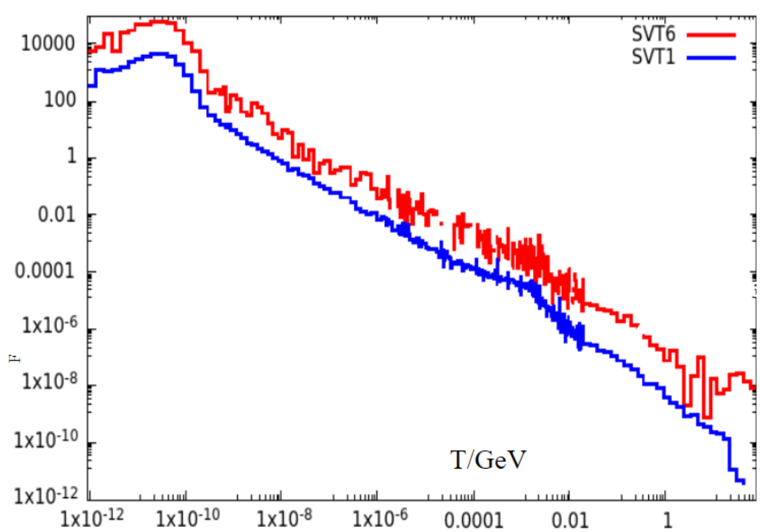

FIG. 10. Neutron energy spectra from FLUKA simulations in two layers of the SiVT : (1) Outer-most Si layer (SVT1) and (2) Inner-most Si layer (SVT6). The vertical scale is fluence in units of $neutrons/GeV/sr/cm^2/proton$ at pressure $P_F = 100$ mbar. The horizontal scale is neutron energy in GeV. Absolute realistic flux in neutrons/sec/sr/cm^2/GeV is obtained by mulitplying the vertical axis by $\approx 6.25 \cdot 10^7$ protons/sec (see Fig. 9 caption).

- Each year of operations is equivalent to 10^7 seconds of operation at 1 Amp protons.

- Average beam line vacuum is $P = 10^{-9}$ mbar.

To obtain the yearly neutron dose, the fluence values of Figs. 11, 12 must be multiplied by

$$\text{Yearly Fluence Factor } = \frac{P}{P_F}\frac{Q_p}{e} = \left(10^{-11}\right)\left(\frac{10^7\text{Coul}}{1.6\cdot 10^{-19}\text{Coul}}\right) \approx 6\cdot 10^{14}. \qquad (2)$$

From Fig. 12, we obtain an annual dose of $6 \cdot 10^{10}$n/cm^2 (1 MeV equivalent) in the SiVT. This is more than three orders of magnitude less than the suggested tolerance of 10^{14}n/cm^2.

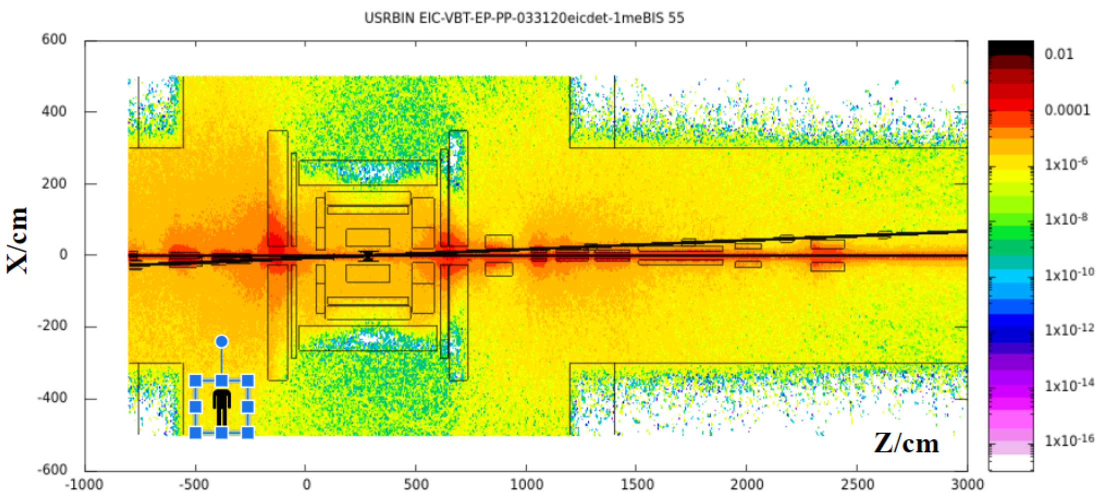

FIG. 11. Map of neutron fluence, the damage of which is equivalent to that of 1 MeV neutrons; $p + Air$ interactions in the beam pipe at proton energy $E_p = 275\ GeV$. Fluence is given by the color chart at the right side of the plot in units of $neutrons/cm^2/proton$ at beam-line pressure $P_F = 0.1$ bar.

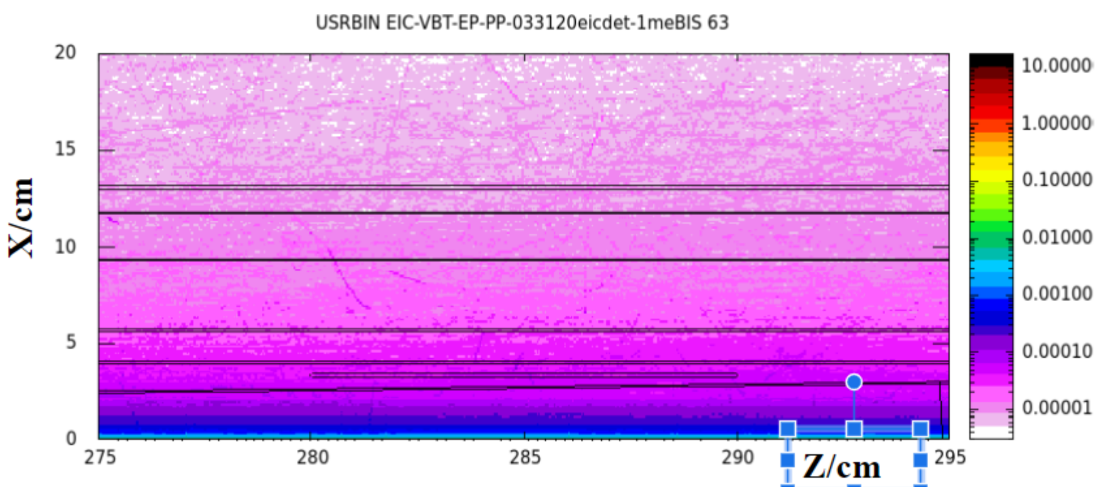

FIG. 12. One MeV equivalent neutron fluence map in the area of SiVT; $p+Air$ interactions in the beam pipe at proton energy $E_p = 275\ GeV$. IP is located at $Z = 285\ cm$. Fluence is given by the color chart at the right side of the plot in units of $neutrons/cm^2/proton/P_F$, where $P_F = 0.1\ bar$ is the pressure used in the FLUKA model.

IV. PROPOSED FY2021 ACTIVITIES

A. Synchrotron Radiation

The layout of the electron optics for IR1 are rapidly evolving, primarily to minimize the impact on the detector of synchrotron radiation.

We will update our models and simulations as new designs become available. We will also implement the design of a potential IR2, when it becomes available.

A particular focus of study for either interaction region will be the potential placement of one or more small aperture absorbers in the upstream electron beam line, between the last FFQ and the IP. This would narrow the downstream synchrotron radiation fan – potentially allowing for more compact downstream electron quadrupoles, that would be considerably simpler to build. The potential impact of these modifications on either the IR1 design or a potential IR2 is illustrated in Fig. 13. The apertures of the downstream electron quads are dictated by the size of the fan of synchrotron radiation generated by the upstream quadrupoles.

B. Beam-Gas Interactions

We will expand the scope of our beam-gas interaction studies as follows:

- Diversify the beam ion species to include *e.g.* d, He, O, Ca, Pb, U.
- Tune the residual beam gas. In CY2019 we simulated pure H, our current studies are with air. Future studies will be with approximately 95% H, 5% CO, and possible additional species including H_20.
- Extend the simulation from the current ± 30 m to arc-to-arc ($\approx \pm 100$ m). An initial study suggests this will have a minor effect on the dose rates at the IP.
- Include realistic non-uniform pressure profiles. We will incorporate dynamic vacuum studies (including synchrotron radiation induced out-gassing) into the residual gas model in FLUKA.
- Quantify the dose rates at key locations (e.g. Si Photosensors).
- Include ep and eA collisions in the FLUKA studies. Although PYTHIA and GEANT4 are excellent tools for simulating the high energy particles (above 10 MeV), we suspect there may be significant differences in the estimation of the lower energy part of the spectrum.

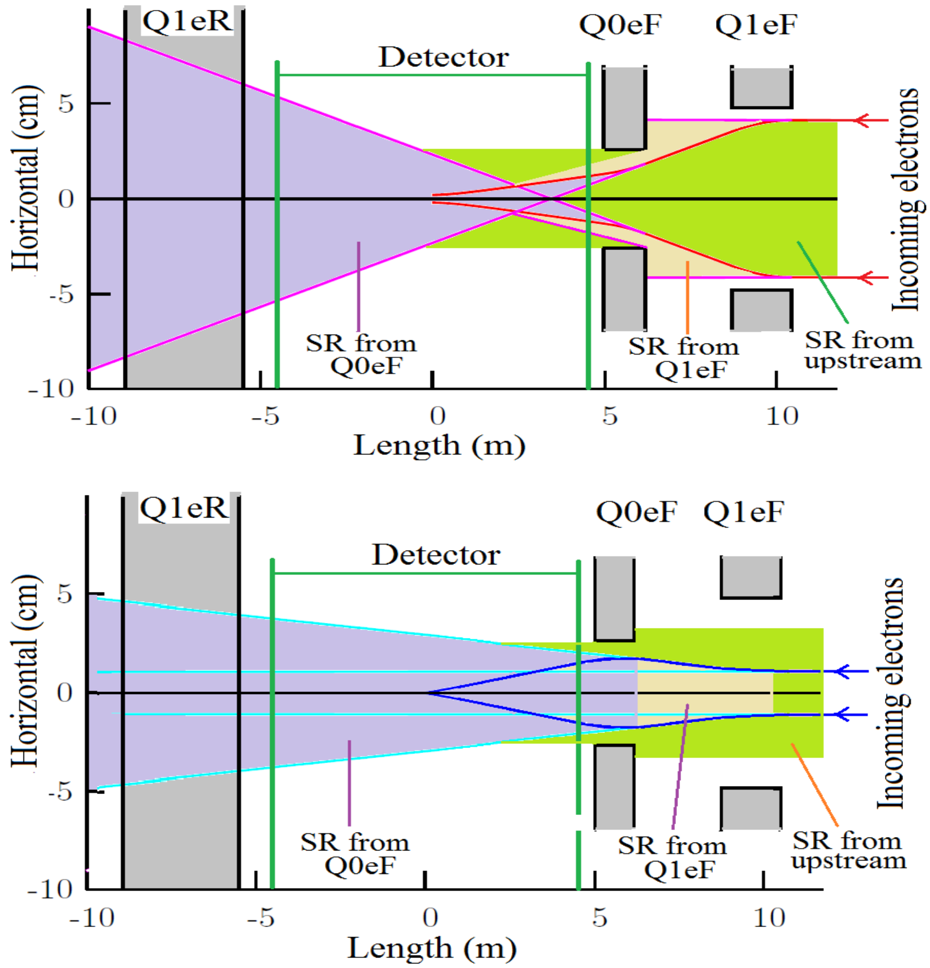

FIG. 13. Synchrotron radiation fan in electron beam line, Fig 3-30 from EIC pre-CDR [1]. The Interaction Point is at 0. The bottom plot is mislabeled, and is the vertical profile. Not shown on the figure is the last upstream ion quad, Q1ApR, which occupies the same longitudinal space. The aperture of Q1ApR in the horizontal plane spans −11.5 cm to −15.5 cm at $z = -5.4$ m, leaving only ≈ 6 cm of flux return iron between the two independent field configurations.

[1] Public version of BNL EIC pre-CDR: `https://wiki.bnl.gov/eic/upload/EIC.Design.Study.pdf`

[2] J. Zhang, E. Fretwurst, R. Klanner, H. Perrey, I. Pintilie, T. Poehlsen and J. Schwandt, JINST **6**, C11013 (2011) doi:10.1088/1748-0221/6/11/C11013 [arXiv:1111.1180 [physics.ins-det]].

Appendix A: Budget Proposal

We present our proposed budget for FY2021 in Table. II. The 4% fringe rate on C.Ploen's stipend is a mandatory Health Insurance subsidy. Travel is for Michael Sullivan to JLab, and for travel by C. Hyde and L. Elouadrhiri to BNL for R& D Committee meetings. No travel is expected before calendar year 2021.

TABLE II. Requested eRD21 Budget for FY2021. The personnel classifications are A. Kim: Staff Scientist; V. Baturin: Post-Doc; C. Ploen: GRA.

Personnel	Salary (12 month)	Fringe Rate	IDC Rate	FTE %	Budget	Institution
Andrey Kim	\$70,000	43%	26%	40%	\$50,450	UConn
Vitaly Baturin	\$50,000	39%	26%	50%	\$43,785	ODU
Christine Ploen	\$25,000	4%	26%	—	\$32,760	ODU
Other costs						
Tuition (15 credit hours)					\$8,265	ODU
Travel	\$9,740	—	0%	—	\$9,740	BNL
Total					\$145,000	