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EIC Detector R&D Progress Report

Project ID: eRD21
Project Name: R&D Proposal for EIC Background Studies and the Impact on the IR and Detector design
Period Reported: from 10/01/2018 to 12/28/2018
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Note: The project members listed in blue are supported by the eRD21 funds for their work on this project. The project members listed in green are our new collaborator from BNL.

Abstract

In this document, we report on the progress we made to close FY18 P and during the first phase of FY19 of eRD21 project (October 1, 2018). The first phase of the project is complete. It involved creating and benchmarking realistic simulation tools, techniques, and a validation procedure using JLEIC configuration. During this phase, we developed also detailed studies of the vacuum system with detailed design of the pumping system. Now we are ready of extending the studies to the new optimized JLEIC and eRICH optimized IR configuration with special focus on the neutron evaluation studies. The focus of phase II will be to perform a quantitative evaluation of background radiation due to photons, charged hadrons, and neutron flux, reaching the detectors and front-end electronics, in both JLEIC and eRHIC configuration. The detectors must be sufficiently well protected to prevent both excessive component occupancies and deterioration from radiation damage. Knowledge gained will be critical to the machine and detector designs at both JLEIC and eRHIC. Collaboration between the accelerator and detector groups from both laboratories and the users' interaction region (IR) working group is already in place to optimize resources and support an iterative design process that maximizes the capabilities of the physics program at an EIC.

Current status

Achievements and deliverables

Below is the list of deliverables planned for the FY19:

- Model the current baseline design of the JLEIC IR beam pipe concept in a 3D CAD model.
- Model the current baseline design of the JLEIC IR beam pipe concept in GEMC/GEANT4 simulations.
- Benchmark synchrotron radiation rates produced within GEANT4 and compare with SR code simulations and develop an interface of the SR code to GEMC.
- Determine background rates as a function of vacuum levels for the JLEIC configuration.
- Determine the intensity and distribution of the SR in the beam pipe and in the various detectors using GEMC interfaced with SR code.
- Interface CAD drawings with Molflow+ and Synrad.
- Using validated software tools and result of the beam pipe design, evaluate background contributions from hadron beam/gas interactions under nominal vacuum levels. Deliver a quantitative analysis of the amount and distribution of this background source using EIC parameters.

Determine background rates as a function of vacuum levels for the JLEIC configuration: Simulations to establish the relationship between vacuum density and rates of background due to hadronic beam/gas interactions for the JLEIC configuration are underway. The goals of this initial study of ion beam-residual gas interactions are to determine the relationship between vacuum density and background in the IP and to deliver an upper bound for IR vacuum requirements to the vacuum system engineers based on detector requirements. Since background contributions from beam gas interactions will be coming from residual gas directly in the ion path, a simplified model preserving parameters along the beam's trajectory will achieve the relationship between background and vacuum levels. This simplification is appropriate for determining the pressure/background relationship without the effects of beam tail/pipe interactions. However, hadronic background will likely be higher than this first estimate, due to ion beam interactions with the beam pipe. The geometry-dependent beam halo contributions to background will further refine vacuum requirements in section 1.1.8. Using GEANT4 for geometry and physics simulation, a minimal version of the JLEIC IR beam pipe was simulated by recreating key z axis parameters but assuming symmetry in x and y. Specifically, a cylindrical beryllium beam pipe of length 198 cm and diameter 3.2 cm was modeled, corresponding to the length and diameter of the central vacuum chamber around the IP. The Silicon Vertex Tracker (SVT) closely encapsulates the beam pipe at the IP, and will be the closest detector element to the interaction point (IP), so detector occupancy will be determined by background events detected in its surface. Residual gas was modeled as a hydrogen cylinder enclosed by the beam pipe and its density was scaled to represent variations in vacuum levels. The ion beam, comprising 100 GeV protons, was fired into the cylindrical beam pipe from the ion upstream entrance at a 50-mrad angle. Resulting beam/gas interactions were recorded in the SVT and detector occupancy was calculated by taking into the account the readout properties of the SVT tracker (10 ms integrating window during which the signal is accumulated) and time profile of the incoming beam. Finally, the number of simulated events will be scaled to consider bunch size and current in the final calculation. The nominal vacuum level will be determined such that the SVT occupancy from hadronic background is less than 1%. **Modeling is complete and simulation and analysis of the results are in progress.**

Determine the intensity and distribution of the SR in the beam pipe and in the various detectors using GEMC interfaced with SR code: Progress in the last year has included interfacing two different sources of synchrotron radiation code with GEMC; namely, utilizing the output of SYNC_BKG and MASKING as input for GEMC simulations, and expanding the GEMC source code (development version) to include the GEANT4 physics lists for synchrotron radiation production and tracking. Both have been experimentally validated and confer their own advantages. GEANT4 tracks every single photon through arbitrarily complex geometries, but requires longer runtime. The programs SYNC_BKG and MASKING are very fast, in part because MASKING is able to track only the photons scattering through the mask tip, and uses simplified geometries.

To determine the SR background rates in the beam pipe and detectors, the full chain JLEIC IR configuration was implemented in GEMC using the most current iteration of beam pipe imported from the engineering CAD model. An electron beam matched bunch distribution with beam halo was generated upstream from the first final focus quadrupole (FFQ) and tracked into the IP. The synchrotron radiation generated through the FFQs was tracked to the beam pipe and detectors. Modeling is complete and simulation and analysis of the results are in progress. Initial dose and distribution will be evaluated with only the SVT in place, but subsequent simulations will add additional elements. **This work was completed and it is going to be repeated based on the new optimized JLEIC and eRICH IR design.**

Interface CAD drawings with Molflow+ and Synrad: The static vacuum modeling with the Molflow+ software package has been completed for both the room temperature and with the cryostats for the magnets cold. The tools are working well and engineering designs can be imported successfully into the Molflow+ simulation software. Ongoing work includes determining saturation time for the cryogenic surfaces within the magnets and working with the engineering groups to determine physical geometries of the pumping configuration rather than the idealized pumping surfaces in the initial simulations. When the changes necessitated by the ion energy change are propogated through to a beamline design near the IR, the vacuum simulations will be modified to accurately reflect the design changes.

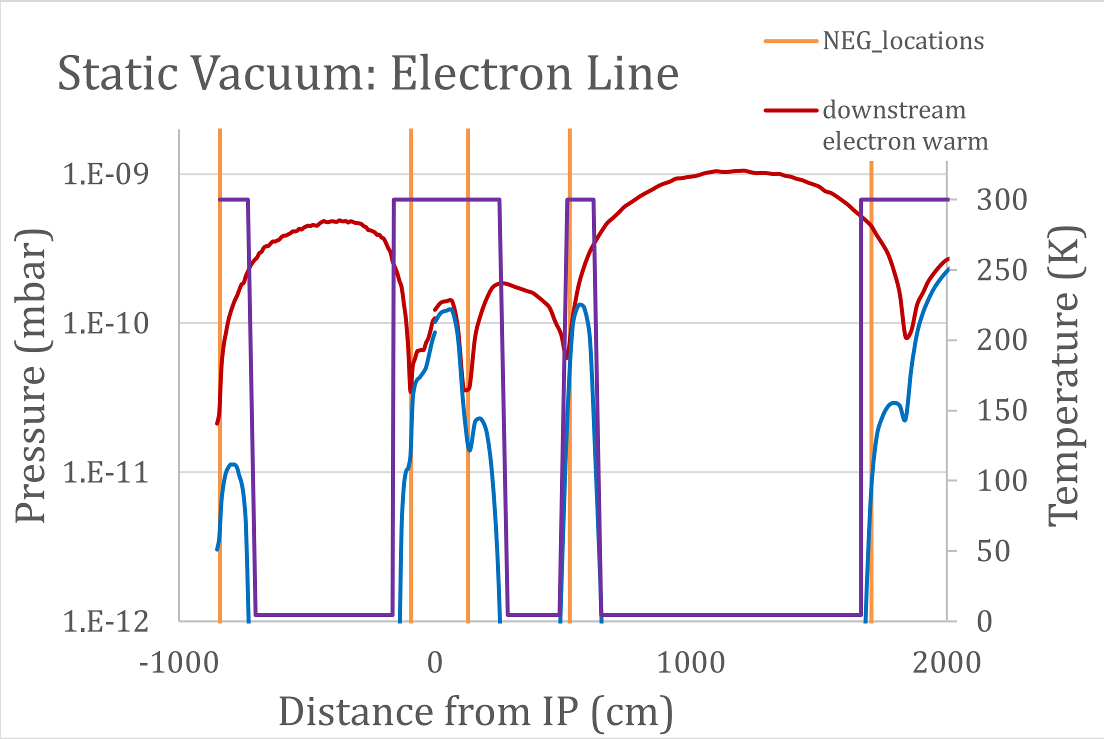

Figure 1: Moflow+ simulation of the pumping configuration and vacuum distribution along the electron beamline. Plots for the ion beamline are similar.

The preliminary Synrad model of synchrotron induced radiation heating in the system uses a nominal beam emittance provided by the lattice calculations through the final three quadrupoles for the electron beamline. Synchrotron radiation is produced only by the halo electrons traveling through the quads, so accurate beam optics models of beam size and emittance can be determined and inserted into the Synrad software. The beam energy, species, current, magnetic fields and beam emittance are all able to be inserted into the Synrad program, which then is able to calculate the power distribution of the synchrotron radiation from these parameters. The mesh elements receiving synchrotron can then be assigned a dynamic beam induced outgassing rate based on the power and flux distribution, which is then imported into Molflow+ to determine the dynamic vacuum in the system. Synchrotron radiation from beam/residual gas scattering is not considered in this simulation, but GEANT simulations of these effects can be combined with the output of the Synrad software to generate a power distribution due to synchrotron radiation from the system.

Using validated software tools and result of beam pipe design, evaluate background contributions from hadron beam/gas interactions under nominal vacuum levels. Deliver quantitative analysis of amount and distribution of this background source using EIC parameters: Evaluating the hadron beam/gas interactions for the full chain JLEIC simulation has been completed as part of the 2018 project. In order to accomplish this, a detailed balloon of the interior of the central beam pipe must be constructed out of residual beam gas species with density scaled for simulation based on the nominal vacuum levels. An ion beam matched distribution including tails will be input just upstream of the ion entrance pipe at a 50 mrad angle. Resulting hadronic background will be tracked through the detectors and measurements of the ion downstream halo will be analyzed using a virtual disc detector outside of the interaction region. Several elements of the simulation are complete. Simulation of synchrotron radiation is fully implemented in GEMC. Models of the detectors and central beam pipe are complete in GEMC, and a script has been written to generate a matched distribution of the electron or ion beam. Options for modeling the ion beam halo with consideration to beam lifetime and particle density as well as the most effective approach to modeling the interior of the central beam pipe with scaled density vacuum are being researched through consultations with experts at JLAB, BNL and SLAC. This simulation accomplishes more than an extension of the geometry used in the previous study, as the background measurements will include halo particle generated by the ion beam tails interacting with the beam pipe. The quantity and energy spectrum of halo particles will depend on the detailed beam pipe geometry, which will likely reduce the upper acceptable vacuum limit. Results of this study will further refine IR vacuum requirements and provide important input to the next iterations of vacuum system and beam pipe designs as well as central and auxiliary detector placement and design. **This work has been completed as part of FY18 Proposal.**

Proposal for FY2019

The EIC machine design directly impacts the quantity and type of radiation reaching detectors in the interaction region, which, in turn, influences both the physics program and the detectors design. Background radiation also greatly affects the systematic uncertainties of the physics measurements. It is important to fully understand and minimize the systematic uncertainty, as it will dominate the high-precision physics measurements at high luminosity. Background radiation is influenced by the arrangement of the magnets which guide the beam, bunch spacing, beam current, and beam optics. Therefore, it is critical to perform a thorough study of the type and dose of machine-induced background now, before decisions regarding the interaction region layout are made final. This insight will inform decisions that minimize and mitigate sources of background at the early design phase and will inform detector placement and technology choices as well. Close collaboration between the accelerator and detector efforts is necessary to inform the design process in view of background conditions and maximize the potential of the physics program at the EIC. Experience at earlier facilities, especially the previous electron-proton collider at HERA at DESY, further motivates a detailed study of the background in the interaction region (IR). HERA-II upgrade planned to increase luminosity by a factor of seven by stronger beam focusing at the interaction points (IP). However, the upgraded machine generated severe levels of background in the interaction region. The primary sources of background were direct synchrotron radiation and beam gas scattering due to vacuum degradation. Ultimately the problems were addressed and the upgrade was a success, increasing luminosity by a factor of five; however, this experience underscores the need to begin studies in an early phase. Detailed simulations must be performed for relevant background sources.

Sources of background observed at other facilities are listed below. Neutrons with energies around a few hundred keV can be detrimental to detector components. For instance, silicon photo-multiplier tubes are especially vulnerable. A quantitative estimate of the neutron flux is needed for detector development and placement. To achieve this, modeling the full neutron thermalization from beam-gas events in the experimental hall is a possible future extension to this study. The focus of the first two years of this proposal is on the synchrotron radiation and beam-gas interactions.

Background Sources.
Detailed simulations must be performed for relevant background sources. Sources of background observed at other facilities are listed below, followed by relevant information and its potential impact on detectors.

- Synchrotron radiation
- Beam-gas interactions
- Beam halo
- Beam loss
- Neutron flux
- Elastic eA scattering and eA bremsstrahlung.

The focus of the first two years of this proposal is on the synchrotron radiation and beam-gas interactions and neutron flux.

Synchrotron radiation.
Synchrotron radiation can significantly impact physics measurements in both main and auxiliary detectors. It is primarily generated as the electron beam bends through the machine lattice magnets. In addition to impacting the detector systems, synchrotron radiation can have a deleterious effect on the vacuum quality by heating residual beam gas or causing enhanced desorption of gas from vacuum chamber walls. This, in turn, causes beam loss due to interactions with the ion beam. Furthermore, excessive heating due to synchrotron radiation could damage flanges, gaskets, and certain types of detector technology.

Current JLEIC design attempts to reduce the amount of synchrotron radiation generated and lessen its effects on the ion beam and surrounding detectors. The long, straight section of electron beam line pipe prevents much contribution from the magnet lattice, and the large beam crossing angle mitigates the effect of synchrotron radiation on vacuum quality in the IR.

Beam gas interactions.
Beam-gas interactions occur when proton or ion beam particles collide with residual beam gas. That is, these interactions are fixed-target p+A or A+A collisions. The problematic background experienced after the HERA II upgrade was predominantly due to such events. Design choices in the upgraded IR, such as the zero angle crossing and long section of shared beam pipe, exacerbated the beam-gas problem. Synchrotron radiation heated the beam pipe, which released residual gas particles from the beam pipe walls and degraded the vacuum. This increased the number of beam-gas interactions at the IR and near the detectors. The large background rate was mitigated by baking out the beam pipe gas by running high proton beam currents for an extended time and by regularly warming up the final focus quadrupoles to remove frozen gas.

While the JLEIC design incorporates a large crossing angle and limited shared beam pipe region to reduce the effect of beam-gas interactions, the baseline beam currents are significantly higher than those of HERA II. Thus, detailed simulations to compare to the HERA II experience and determine a working range of vacuum quality are proposed.

Neutron flux.

Neutrons with energies around a few hundred keV can be detrimental to detector components. For instance, silicon photo-multiplier tubes are especially vulnerable. A quantitative estimate of the neutron flux is needed for detector development and placement. To achieve this, modeling the full neutron thermalization from beam-gas events in the experimental hall is a possible future extension to this study.

FY19 Project Status

The focus of FY19 work plan is on the use if the validated tools and procedures developed in FY18 to perform a quantitative evaluation of the background radiation, type, and distribution of machine-induced background generated in the Interaction Region (IR) reaching the detectors and front-end electronics. The rate and the type of background signal impacts the technology choices for the central and auxiliary detectors and their readout electronics. This work is being performed in an iterative process working in close collaboration with the different teams from detector, machine, IR design teams and vacuum engineers in order to optimize the overall design and minimize the background reaching the detector and front-end electronics for both JLEIC and eRICH teams. The goal is also to refine and document the tools techniques and procedures keeping in mind the general applicability to any EIC IR design. We started working closely with the IR users' working group and both teams from both Jefferson Lab and Brookhaven National Laboratory. In addition to our working group weekly meetings we organized monthly meeting with the complete team from Jefferson Lab and BNL.

Optimization of the machine lattice in simulations is under complete redesign:
Figure 4 shows layout of JLEIC's full acceptance detector region. The electron and ion beams cross at a relatively large angle of 50 mrad to:

1. Allow forward ion detection,
2. Improve the momentum resolution for hadrons detected within a few degrees of the ion beam direction,
3. Eliminate parasitic collisions of closely-spaced bunches,
4. Provide sufficient transverse beam separation near the IP to place electron and ion interaction region magnets,
5. Reduce the detector background by shortening the section of the detector beam pipe common for both beams.

As shown in Fig. 4, the crossing angle is arranged by shaping the end section of the ion arc upstream of the IP. The ion beam line segment downstream of the IP is designed to produce a 1.5 m transverse separation between the ion and electron beams. The same section is used to suppress the dispersion. The electron detector region has no net bend or shift. It is aligned with the detector axis to avoid generation of synchrotron radiation by the detector solenoid field.

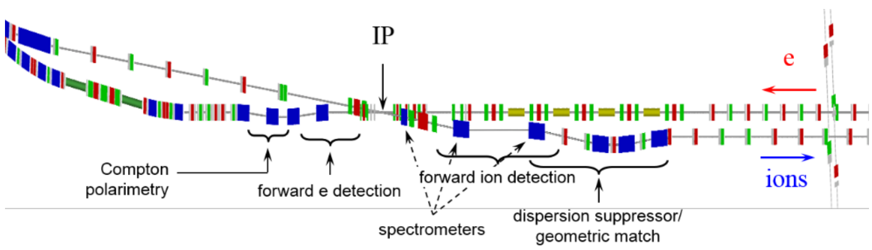

Figure 2: Layout of the detector region

The downstream ion and electron final focusing quads are designed with large apertures for forward detection and are followed by spectrometer dipoles. Additionally, as shown in Figs. 5 (left) and 5 (right), both the ion and electron beams are focused again towards the ends of the element-free spaces downstream of the respective spectrometer dipoles to allow closer placement of the detectors at those locations, which, in combination with the relatively large dispersion values in those regions, enhances the forward detectors' momentum resolution. The dispersion generated by the spectrometer dipoles is suppressed on the ion side by a specially designed section, which also controls the beam line geometry, while on the electron side the dispersion suppression is done by a simple dipole chicane whose parameters are chosen to avoid a significant impact on the electron equilibrium emittances. The chicane is designed to accommodate a Compton polarimeter and a luminosity monitor. Special attention is paid to sizes and positions of the detector region elements to avoid them interfering with each other and with the detector functionality.

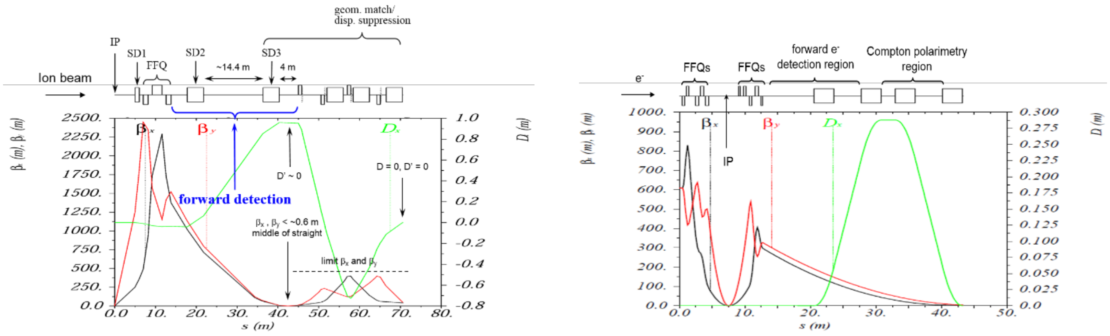

Figure 3: Magnetic optics of the ion (left) and electron (right) detector regions.

The full-acceptance detector region has been optically and geometrically integrated into the electron and ion collider ring lattices. It has been demonstrated to meet the detection and beam dynamics requirements. However, as one can see in Fig. 4, the area around the detector is densely packed with machine and detector elements and, to finalize the integrated design, the machine lattice still needs to be optimized from the points of view of the:

1. Magnet engineering design,
2. Vacuum system requirements and design,
3. Detector background.

A number of iterations of the lattice design have to be completed considering the above items to make it more realistic. Each iteration involves changes in the locations, sizes, apertures and strengths of the interaction region magnets. These changes are small but have to be accounted for in the optics, which, in turn, provides feedback for the next iteration. For example, Fig. 6 shows a CAD drawing of the forward ion section of the detector region. In the process of developing this design, the magnet parameters and locations were modified to provide adequate space for other magnets, coil ends, beam correction elements, warm-to-cold transition areas, etc. A vacuum system design satisfying the vacuum requirements still needs to be developed and integrated into the interaction region. This may lead to further changes in the lattice design. These changes may, in turn, affect collimation of the synchrotron radiation and therefore the detector background levels.

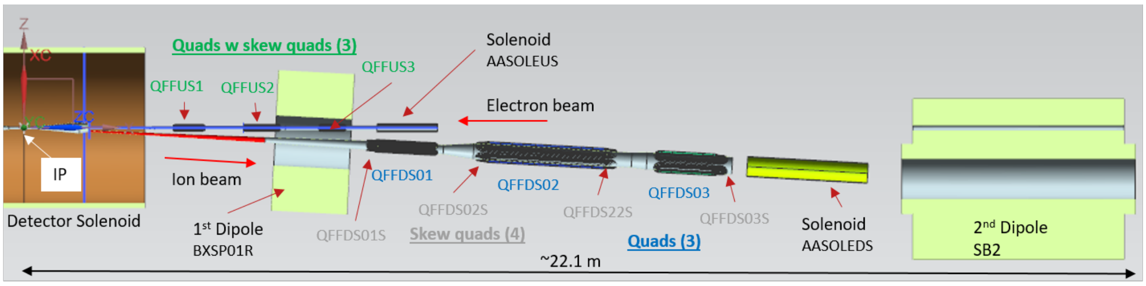

Figure 4. CAD drawing of the forward ion section of the IR

In general, as the detector region design matures and becomes more and more detailed, it is important to reflect these developments in the lattice design. Since the updated lattice design then feeds back into the overall detector region design, it is necessary to synchronize the lattice and GEANT4 detector region models at each iteration step. To make optimization most efficient, it is important to streamline the transfer of updates between them. This is now automatically done by extracting the necessary magnet parameter and position information from a MAD-X file of the lattice and converting it to a GEANT4 model of the beam lines. To demonstrate this approach, we developed a prototype Python script that uses a table produced by MAD-X to generate all of the geometry and magnet field files necessary for a GEANT4 simulation. Figure 7 shows an example of an automatically generated GEANT4 model of the electron beam line. The electron track in Fig. 7 verifies the proper geometry and field setup.

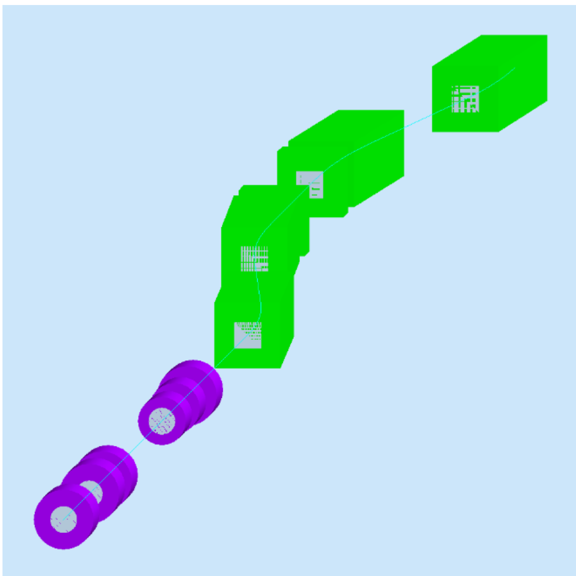

Figure 5: Automatically generated GEANT4 model of the e beam line

Using this approach, we can easily generate and track matched beam distributions through the beam lines. A matched beam distribution is generated based on the optics parameters at the start point and reproduces the beam size and angular divergence everywhere along the beam line. This is particularly important for accurate simulations of the synchrotron radiation background, which is largely determined by the sizes of the beam and its halo inside the electron final focusing quadrupoles.
Having a lattice file, we can generate a GEANT4 model of any section of the beam line or even of the whole ring. This is important for simulating background sources located

far from the interaction point, for example, synchrotron radiation background due to electron scattering on the residual gas in a long straight section upstream of the IP and neutron ration background.

The lattice development and optimization is supported by JLAB's base funding. We need % fraction of the postdoc to further develop the tool for conversion from MAD-X to GEANT4 and, more generally, ensure agreement between the MAD-X and GEANT4 models of the detector region throughout the project.

Vacuum modelling.
Thus, far we have successfully determined how to manipulate parameters such as the 3D CAD designs of the system, the magnets and the beam optics so that we can use the Molflow+/Synrad software to investigate the JLEIC interaction region vacuum. The remaining goals for modelling the JLEIC IR with Molflow+/Synrad include improvements in accuracy from all aspects of the system: the physical pump placement, the beam size and behaviour through the quads, and the gas load generated by the synchrotron radiation induced desorption and heating.

We will need close work with the mechanical engineering team and the detector team to find locations for physical pumps in the system and with the accelerator beam optics group to have a better idea of the beam halo and other parameters defining the generation of synchrotron radiation. The final significant effort will be to determine relevant outgassing rates for the materials of the scattering chamber for the anticipated radiation loads. Many heat and synchrotron induced outgassing can be found in the literature, but extrapolating measured values at other systems to the expected conditions at the JLEIC IR will require an extensive effort.

The time estimate for this project is estimated from the 2 months with two researchers required for the KEK interaction region modeling effort. A full time effort of at least 3 months for one FTE will be required to model the system, explore the parameter space in physical parameters, pump placements, outgassing rates and optics settings. This will be an iterative process with the updates in beam lattice and engineering design requiring adjustments to the model.

The deliverables at the end of the year are a Molflow+ vacuum model that includes estimates for increased gas desorption from synchrotron radiation as modelled with varied beam parameters by Synrad. Materials properties such as the increased thermal outgassing due to synchrotron radiation absorption will be estimated for the JLEIC IR using data available in the literature for similar radiation loads and similar machine performance.

CAD Model Development.
Based on the input from the preliminary studies we will update the IR vacuum tube design for further studies. This will include adding the preliminary vacuum pump station designs to the model. We will also develop the three draft vacuum vessel designs needed in the IR area so that these can be included in the tracking studies for detector development. The three vessels are identified in Figure 8 as ion up beam, electron entrant, and ion down beam. The vacuum vessel will just be the vacuum shell and not include the details of the magnet, helium vessel, supports, etc. as these are beyond the

needs of this study. The vacuum vessel model will be translated into GEMC for the background and tracking studies.

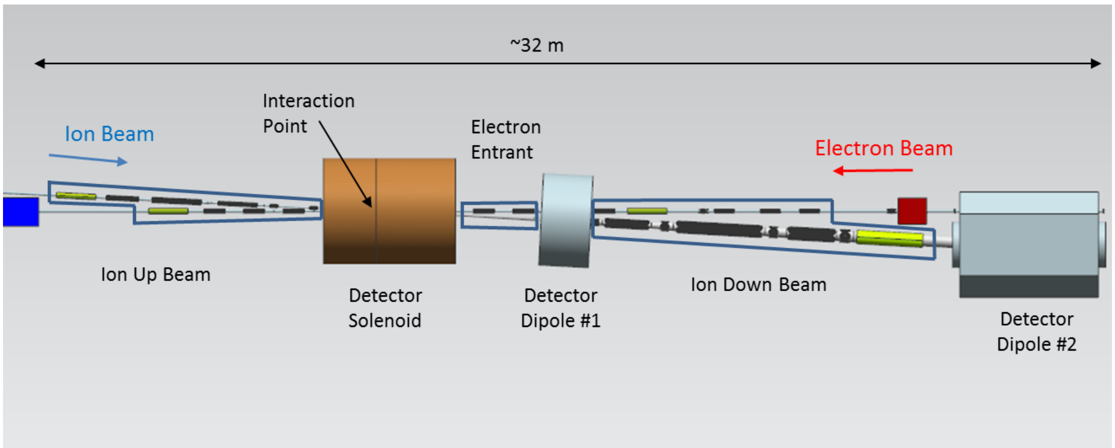

Figure 6: CAD geometry of the central interaction point region

Background simulation tasks:
The realistic model of the vacuum in the interaction region was incorporated in the GEMC. It is a significant upgrade over previously used cylinder enclosed by the beam pipe, and allows for more realistic estimation of the background.
With this model we can specify any pressure in the interaction region and calculate corresponding occupancy in the Silicon Vertex Tracker (SVT) taking into account real bean properties and SVT granularity and readout timing.
Several variations of the vacuum level, 10^{-10} tor, 10^{-9} tor, 10^{-8} tor, are currently implemented.
Simulation is in progress.

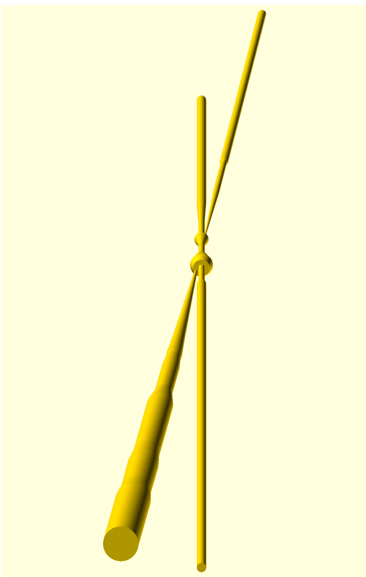

Figure 8 Vacuum implementation in the CAD.

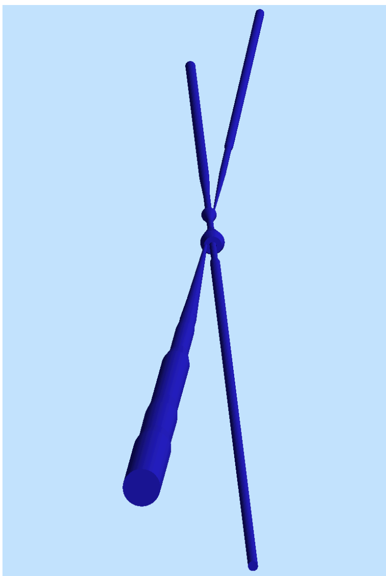

Figure 7 GEMC implementation of the interaction region in the GEMC.

Project deliverables for FY19

1. Optimize the machine lattice and track matched beam to evaluate changes in background carried to IR and detectors.
This work is completed on the first version of the IR and beam pipe design. However, it has to be repeated on the new IR design for both JLEIC and eRICH designs.

2. Develop an efficient method to streamline the transfer design between Lattice and GEANT4, ensuring agreement between the MAD-X and GEANT4 models of the detector region throughout the project.
This work has been completed and tools are now in place and are being used to transfer machine design into the simulations, this includes beam line components as well as magnetic fields maps with desired step sizes.

Design and optimize the collimation of the synchrotron radiation and therefore the detector background levels: **This work is completed on the first version of the IR and beam pipe design. However, it has to be repeated on the new IR design for both JLEIC and eRICH designs.**

3. Import detailed engineering model of machine lattice magnets and IR design from CAD to GEMC.
This project is completed, the procedures in place are now being used for detailed simulation of the current design of JLEIC configuration and will be extended the new JLEIC and eRICH beam line designs.

4. Evaluate quantitatively the background type and distribution due to the SR radiation, giving feed back to the machine and IR designer towards design optimization.

This project is completed, the procedures in place are now being used for detailed simulation of the current design of JLEIC configuration and will be extended the new JLEIC and eRICH beam line designs.

5. Use Molflow+ and Synrad to realistically simulate vacuum conditions.
This work has started, the procedures in place are now being used for detailed simulation of the current design of JLEIC configuration and will be extended the new JLEIC and eRICH beam line designs.

6. Design vacuum system based on requirements of the IR vacuum tube and vacuum vessels and its translation into the simulation.
This work has started, the procedures in place are now being used for detailed simulation of the current design of JLEIC configuration and will be extended the new JLEIC and eRICH beam line designs

The items below are on scheduled to start second and third quarter of FY19, the team are already assembled:

7. Use SR level to determine the level of dynamic vacuum.

8. Evaluate the background type and distribution due to the beam gas interaction giving feed back to the vacuum engineer and IR designer towards design optimization.

9. Estimate rates, due to both beam gas interaction and SR, in the detectors and beam pipe in the configuration including realistic lattice, vacuum levels and IR. This will serve as an input to the iterative procedure of the lattice and vacuum system optimization.

10. Develop an interface to Fluka and GRANT3 to evaluate neutron flux from our simulation framework.

11. Benchmark comparison of neutron flux from Fluka, GEANT3 and GEANT4 by checking the list of all the relevant physics processes.

12. Evaluate neutron flux from Fluka/GEANT3 by comparison with GEANT4 in the EIC configuration. This is critical task as it has severe impact on detector and electronics life time.