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EXPANDING SCIENTIFIC CAPABILITIES OF THE ELECTRON-ION COLLIDER (EIC) INTO THE DARK SECTOR: A SEARCH FOR LIGHT DARK MATTER (LDM) PARTICLES VIA SYNCHROTRON BEAM DUMPS

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EXPANDING SCIENTIFIC CAPABILITIES OF THE ELECTRON-ION COLLIDER (EIC) INTO THE DARK SECTOR: A SEARCH FOR LIGHT DARK MATTER (LDM) PARTICLES VIA SYNCHROTRON BEAM DUMPS

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Abstract

The possibility of the experimental discovery of Light Dark Matter (LDM) candidates at Brookhaven National Laboratory's Electron-Ion Collider (EIC) complex is discussed. The production and detection of LDM particles are possible with the beam dumps of the storage rings (Hadron Storage Ring and Electron Storage Ring), and the Alternating Gradient Synchrotron (AGS) via the Z-Line target or the historic muon g-2 beamline. The theory and the feasibility of each experiment (110 GeV gold ions, 28 GeV protons, and 10 GeV electrons): figure of merit, experimental facility, comparison to other existing experiments (Jefferson Lab, CERN, Fermilab, and SLAC), and technical requirements are discussed.

THE DARK SECTOR

Every known atoms, elements, and materials to date are made of the elementary particles found in the Standard Model. However, there are a set of hypothetical particles that are yet to be discovered but found to intervene the physical interactions of the Standard Model particles [1]. These particles are called Dark Matter. The force carrier of dark matters is called Dark Photon [2]. The mass range of dark matter ranges from 10^{-20} eV to several TeV as shown in Figure 1 [3]. The mass of Light Dark Matter (LDM) candidates ranges from keV to GeV, which is the energy range found in most particle accelerators. LDM candidates are of interest for the detection experiments at Brookhaven National Laboratory's Electron-Ion Collider complex.

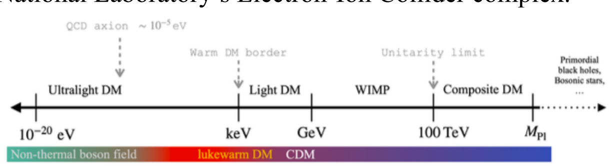

Figure 1. Dark Matter Mass Ranges

BEAM DUMP EXPERIMENT (BDX)

The Beam Dump Experiment (BDX) is an investigated method in dark matter search efforts, where a high-energy charged particle beams are bombarded onto a beam dump of particle accelerators. Existing accelerator facilities including Fermi National Accelerator Laboratory, Thomas Jefferson National Accelerator Facility, Stanford National Accelerator Laboratory, and CERN (NA64) currently, or plan to host BDX programs with different beam species.

Such an experiment consists of an incident beam (GeV) bombarding onto a high-Z beam target, and a downstream detector. The beam interacts with the beam target nuclei either electromagnetically via bremsstrahlung on spectator Z (1), or through hadronic processes that produce mesons. The hadronic process is subject to proton or ion induced production (2). Dark sector particles such as dark photons (A') or dark matter (χ) are produced in these interactions. The beam target absorbs all Standard Model particles but is effectively *transparent* to hidden sector particles. The downstream will be detecting the hidden sector particles via scattering.

$$e^- + Z \rightarrow e^- + Z + A' \tag{1}$$

$$p + N \rightarrow \pi^0, \eta, \rho^0, \omega, \cdots + X \qquad \pi^0, \eta, \cdots \rightarrow \gamma A' \tag{2}$$

Note that dark photons (A') are common byproduct for both reactions. Upon the kinetic allowance, dark photon(s) convert into a dark matter particle and dark matter antiparticle(s) (3). This is similar to $\gamma \rightarrow e^- + e^+$.

$$A' \rightarrow \chi \bar{\chi} \tag{3}$$

A standardized BDX configuration is shown in Figure 2 [4] and a Feynman diagram of the interaction is shown in Figure 3 [5]. The incident beam, electron in this case, bombards into the (a) beam target (beam dump structure). Electrons will undergo bremsstrahlung interaction with the target nucleus (hadronic process for protons and ions) and dark photons are produced in this stage. The dark photons will then convert into dark matter particle and propagate further. Since dark matter candidates are weakly interacting with ordinary matter, especially with low atomic number elements, they will penetrate through additional shielding stage(s) like the earth (b), in which its composition is mostly low-Z elements. This further filter ordinary matter byproducts from the beam bombardment, or byproducts from cosmic rays, if the detector is installed underground.

The detection of the light dark matter candidates can be accomplished via a detector installed downstream of the beam target. The dark matter entering the detector may interact with electrons or nuclei, via ionization or elastic nuclear scattering. Such a detector shall be positioned along the forward direction, where the $\chi \bar{\chi}$ flux is the largest. In the detector, two primary interactions are most relevant, namely, Dark Matter – Electron Scattering (4) and Dark Matter Nucleon Scattering (5)

$$\chi + e^- \rightarrow \chi + e^- \tag{4}$$

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(4) Dark Matter – Electron Scattering induces an energetic electron recoil. This interaction is typically clear and provides electromagnetic signal similar to neutrino-electron scattering at different kinematic distributions.

$$\chi + N \rightarrow \chi + N \quad (5)$$

(5) Dark Matter Nucleon Scattering induces a nuclear recoil or hadronic activity depending on the type of the detector. This interaction exhibits coherence at low momentum transfer.

The noise signal of the detector can be mitigated by installing the beam dump underground or with an additional, substantial shielding. While all standard model particles (electrons, protons, pions, muons, photons) are fully absorbed by the beam dump and shielding (earth), the dominant background (noise source) are originated from cosmogenic sources or neutrino interactions. These noise sources are not completely preventable. However, the measured noise can be subtracted or filtrated with *cosmic runs*.

The event rate of the detection is proportional to the number of interaction byproduct particles from (4) or (5) entering the detector, thus the incident $\chi\bar{\chi}$ flux and contributed by other factors: detection efficiency, scattering cross section, differential dark matter flux at the detector. These can be incorporated with a generic formula (6),

$$N_d = N_i \int dE_\chi \frac{d\Phi_\chi}{dE_\chi} \sigma_{\chi T}\,(E_\chi)\, \epsilon(E_\chi) \quad (6)$$

where N_d is the number of detection events, N_i is the number of interaction byproduct particles (electrons of nuclei) in the detector, $d\Phi_\chi/dE_\chi$ is the differential dark matter flux at the detector (particles/cm^2/s/GeV), $\sigma_{\chi T}\,(E_\chi)$ is the scattering cross section of the detector medium (cm^2), and $\epsilon(E_\chi)$ is the detection efficiency.

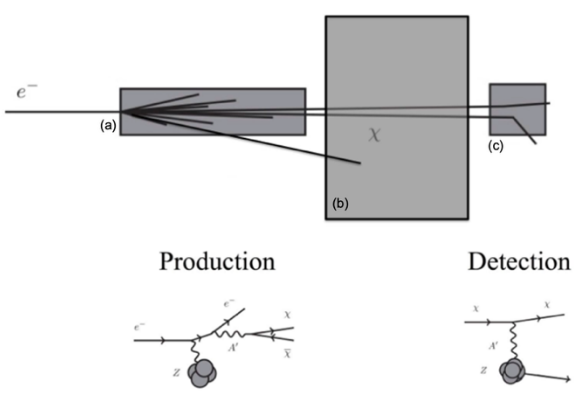

Figure 2. Standardized Beam Dump Experiment

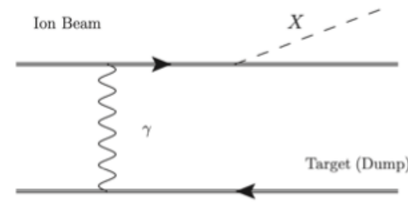

Figure 3. Feynman Diagram of a BDX Interaction

THE ELECTRON-ION COLLIDER (EIC)

The Electron-Ion Collider (EIC) is the next generation, and the only collider in the United States as the successor of the Relativistic Heavy Ion Collider (RHIC). The primary science goal of EIC is to *produce snapshots of the internal nuclear structure*. EIC has the maximum proton energy of 275 GeV, 110 GeV/nucleon for ions, and 18 GeV for electron. It is designed to collide relativistic hadrons (protons or ions) and electrons, via the Hadron Storage Ring (HSR) and the Electron Storage Ring (ESR). The design luminosity of electron-proton collision is 1.0e+34 cm^{-2} s^{-1}. This is achieved by the increased number of bunches of 1160, which is a significant improvement compared to its RHIC, with the maximum bunch number of 111. The aerial view of the EIC complex is shown in Figure 4.

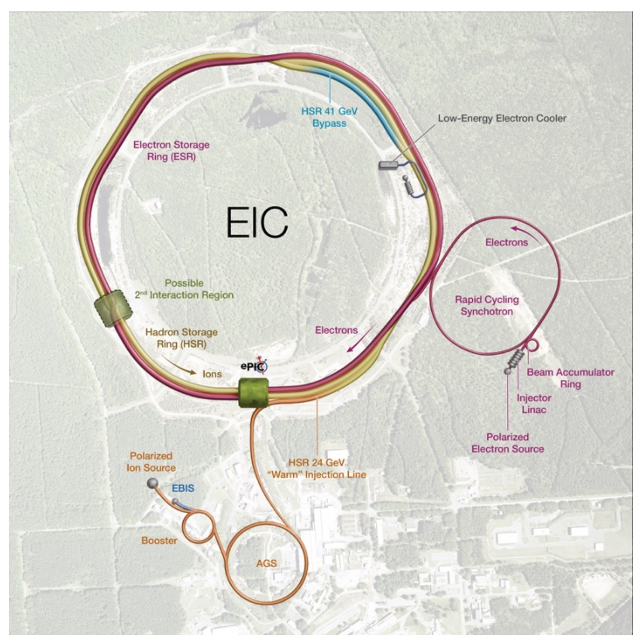

Figure 4. Electron-Ion Collider Complex

28 GeV RELATIVISTIC PROTON BEAM DUMP EXPERIMENT (pBDX)

The Alternating Gradient Synchrotron (AGS) is a circular accelerator that is part of the injectors for the Relativistic Heavy Ion Collider (RHIC) and the future Electron-Ion Collider (EIC). The aerial schematics of the collider complex is shown in Figure 5. It has been in operation for

65 years as of 2025, and has delivered protons/polarized protons with energies of 28 GeV per nucleon, and gold ions with an energy of 10 GeV per nucleon [6]. The beam intensity in AGS is competitive for BDX; the highest proton intensity at which AGS operated was in an order of 1.0e+13 protons/cycle. One AGS supercycle (from source to extraction) averages to 5 seconds. This will result in the figure of merit (POT, Proton on Target) of N = 6.31e+19 POT/year (7).

N_{AGS} = (1e+13 *p*/bunch) (1 bunch/cycle) (1 cycle/5 seconds) (3600 seconds/1 hour) (24 hours/day) (365 days/1 year) = 6.31e+19 protons on target (7)

The experiment may be commenced at the *Z*-Line beamline facility of AGS complex. Over the past runs, it has been used as the fixed target bombardment/irradiation facility for various purposes. The *Z*-Line is a part of the AGS to RHIC (AtR) transport beamline. Two beamlines (*Z*-Line and *V*-Line) split from the earlier part of the AtR beamline (*U*-Line). The *V*-Line was used for the muon g-2 experiment program. The *Z*-Line is indicated with a red arrow. See Figure 5.

The *Z*-Line may be the most compatible for BDX. A beam dump can be installed at the end of the beamline. The downstream of the beam dump is sealed by soil (berm), which can function as the low-*Z* filter for the ordinary matter byproducts. The muon g-2 facility also may be compatible for BDX. It has a beam target and beamline infrastructure, in which LDMs can be produced at the previous muon beam target, and a detector can be installed in the muon storage ring building. Both options will require a significant level of reconstruction and commissioning.

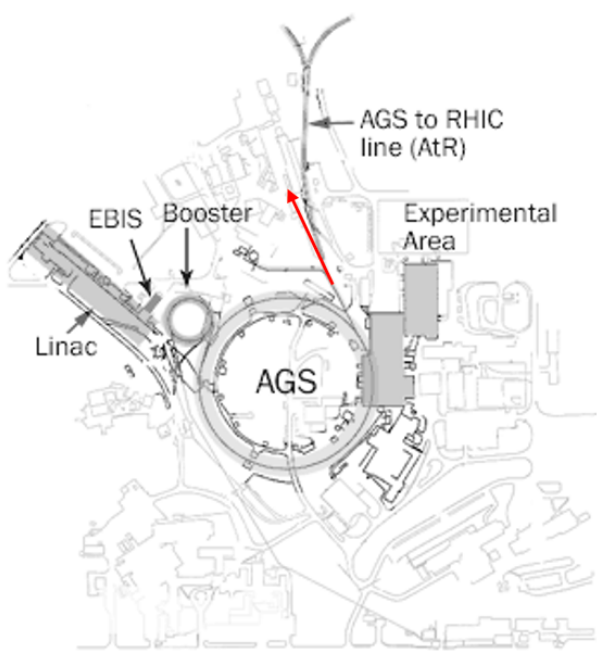

Figure 5. AGS Complex. Red arrow indicates the *Z*-Line.

The figure of merit comparison between the AGS pBDX and the CEBAF eBDX (JLab) is shown in Figure 6. Note that the number of DM events per year (y-axis) is an arbitrary normalization for comparison purposes. The mediator mass has a unit of MeV. Due to the higher beam current availability at CEBAF, the number of DM events is significantly larger than AGS pBDX. However, CEBAF can provide electron beams with energies of 3 GeV. This results in the larger number of events at the lower mediator mass channels. Conversely, AGS pBDX is available at 28 GeV protons with a lower beam current, hence AGS pBDX is more competitive for the higher mediator mass channels with comparably a smaller number of DM events.

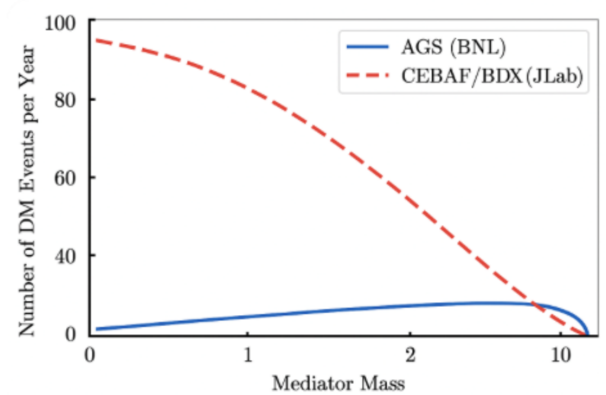

Figure 6. Comparison of LDM Detection Events

10 GeV ELECTRON BEAM DUMP EXPERIMENT (eBDX)

The beam dump of the Electron Storage Ring (ESR) is capable of an electron Beam Dump Experiment (eBDX) with the 10 GeV electrons. The maximum beam energy of ESR is 18 GeV. However, the 10 GeV configuration features the highest electron beam intensity of 1.80e+13. The schematics of the beam abort system is shown in Figure 7. The yellow rectangular block is the proposed beam dump [7]. An LDM detector may be installed several hundreds of meters downstream of the beam dump.

Unlike AGS, the figure of merit of BDX in storage rings of colliders is significantly less than non-colliding synchrotrons because of beam store time. EIC proposes a store time of 4 hours [8]. Assume 5 hours to include the ramp and refill process. The total intensity of 1.80e+13 is equal to 1160 bunches, and 17.2e+10 electrons per bunch. This results in the Electron on Target (EOT) of 3.49e+17/year (8). For spin preservation purposes, ESR will *swap-out* an electron bunch every few minutes at the RCS-ESR transfer dump. The EOT estimation (8) will not take this into account at this time.

N_{ESR} = (17.2e+10 *e*/bunch) (1160 bunches/store) (1 store/5 hours) (24 hours/day) (365 days/1 year) = 3.49e+17 electrons on target/year (8)

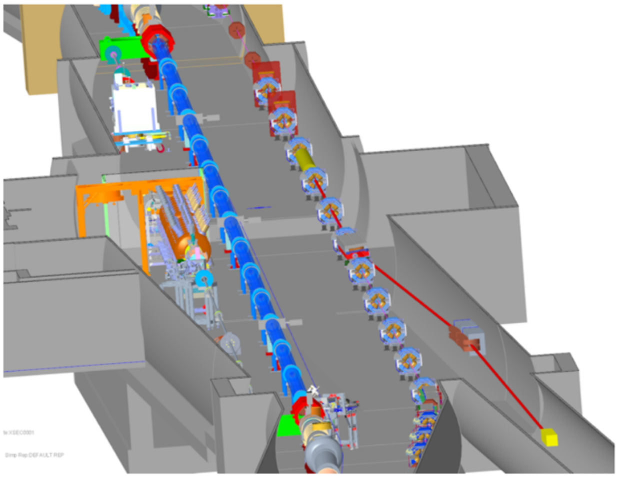

Figure 8. ESR Beam Extraction System Layout

The electron beam extraction will be executed upon an end-of-store beam dump or an emergency abort. Upon such triggering, all 1160 bunches will be extracted via kicker magnets that will cause an orbit excursion and guide the beam into the septum magnet. The septum magnet is the junction that separates the extracted beam from the circulating orbit. The extraction beamline further delivers the extracted beam into the beam dump located in the stub tunnel. The downstream of the beam dump is a berm, which is appropriate for an BDX infrastructure.

The extraction beamline trajectory is shown in Figure 9 [9]. The beamline prior to the septum magnet is a part of the circulating ring. The black elements are quadrupole and sextupole magnets for the storage ring. IP2 is the center of the Interaction Point at Sector 2. The beamline after the septum is the extraction beamline. The extracted beam is initially bent towards the outside of the ring. At about 20 meters downstream, the beam is bent back towards the inside of the ring to avoid interference with the tunnel wall.

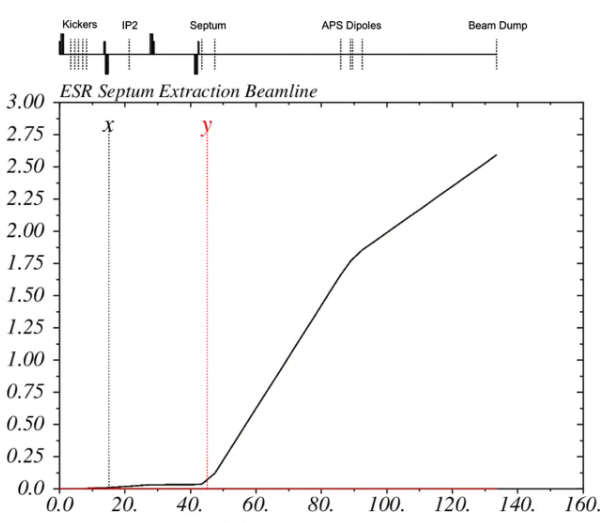

Figure 9. ESR Beam Extraction Trajectory

The extraction beamline is designed with no additional quadrupole magnets to maintain the optics of the beam, as there is no need. This is rather advantageous because the beam will expand in size naturally, along the beam trajectory. The expansion of the beam size dilutes the beam energy density. This is crucial for high power electron synchrotrons like EIC Electron Storage Ring. The total beam energy of the 10 GeV configuration is 320 kJ. Furthermore, the beam energy is being deposited into the beam dump within a few microseconds. This short impact results in several gigawatts of beam power.

The beam size of the electron bunches in the Electron Storage Ring is in the order of a few mm, depending on the betatron function in *s*-location of the storage ring. Given the gigawatts scale of beam power, such beam sizes impose destructive beam energy densities. A reduction in the beam energy density can be achieved by increasing the betatron function as shown in Figure 10 [10]. It is achieved by an absence of quadrupole magnets in the beamline.

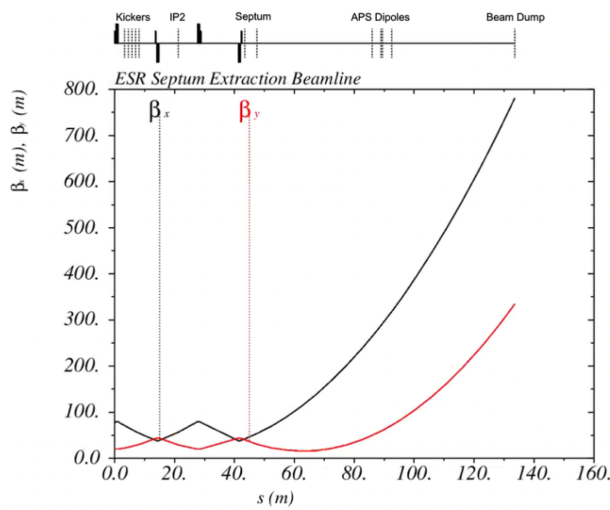

Figure 10. Betatron Function of ESR Beam Extraction

It is often considered that beam dumps made of high-*Z* elements are effective for BDX. However, the high beam energy density characteristics of ESR, and the penetrating depth of 10 GeV electrons will not allow the ESR beam dump to be made of high-*Z* elements. Instead, ESR will employ a beam dump made of graphite. Graphite offers a larger penetration depth due to its low density, which attenuates the beam energy over the longer penetration distance. This prevents excessive heat being developed inside the beam dump which may result in a deformation or an explosion. The beam dump design is shown in Figure 11 [11]. The beam dump consists of 1.2 meters long graphite, followed by a concrete block. The concrete block attenuates the secondary radiation, but will allow dark sector particles to penetrate through. The dark sector particles will travel further into the accelerator tunnel and its berm (soil), and then reach the detector. An additional attenuation may be required with the soil because of the low attenuation properties of ESR's low-*Z* beam dump.

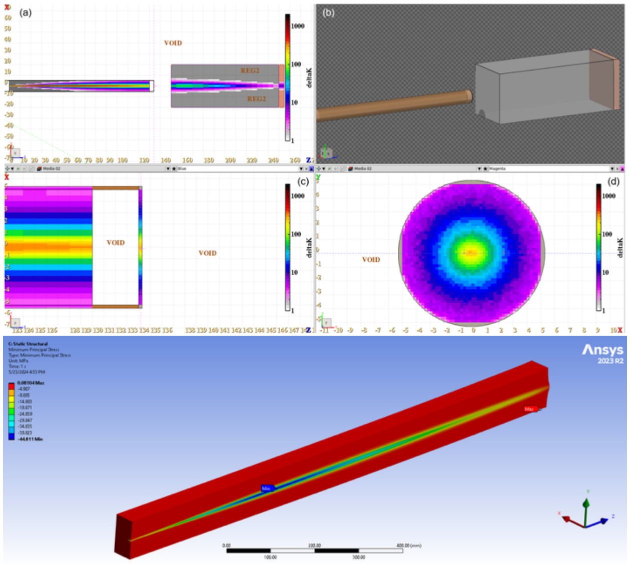

Figure 11. ESR Beam Dump Design and Simulations

The simulations performed in Figure 11 are FLUKA and ANSYS. FLUKA was performed to assess the viability of the beam dump by the beam impact. For the given beam dump design, FLUKA can analyze the temperature increase within the beam dump, as well as the penetration depth, depending on the beam species, beam energy, beam energy density, and the total beam power. The result shows the maximum temperature increase of 500 Kelvin, which is acceptable for a graphite beam dump with no concern of deformation or long term degradation. ANSYS further verified that the pressure and stress on the beam dump introduced by the beam impact is within tolerable levels. The concrete shield located on the downstream of the beam dump will further absorb the secondary radiation.

110 GeV/NUCLEON ION AND 275 GeV PROTON BEAM DUMP EXPERIMENT

The beam dump of the Hadron Storage Ring (HSR) will be capable of hosting both an ion Beam Dump Experiment (iBDX) and a proton Beam Dump Experiment (pBDX). As a part of the EIC collider complex, the HSR can store 110 GeV/nucleon gold ions and 275 GeV protons in 1160 bunches, to be collided with electrons from the Electron Storage Ring. At the end of store, or upon an emergency abort, the full hadron beam will be extracted into the HSR beam dump. This abort dump can serve as the production target for dark sector particles in a BDX configuration.

The beam dump system of the Hadron Storage Ring is shown in Figure 12 [12]. The beam dump is being reused from its predecessor – the Yellow Ring beam dump of the Relativistic Heavy Ion Collider. In HSR, the location will not change, but will employ additional number of kicker magnets, because the bunch spacing is shorter in EIC. The beam dump is installed around the circulating beam pipe. This implies the secondary radiation will point towards the outer wall of the collider tunnel. A BDX detector for HSR may be installed on the outer side of the collider tunnel. A BDX detector for HSR may be installed on the outer side of the collider tunnel. The beam dump composition is shown in Figure 13 [13]. The circulating beam will escape its closed orbit by the kicker magnets and then enter the vacuum window. The beam will then be disposed inside the graphite composite known as carbon-carbon (C-C). This material is designed for use in fusion reactor walls and missile tips due to its capability of withstanding a large thermal shock [14].

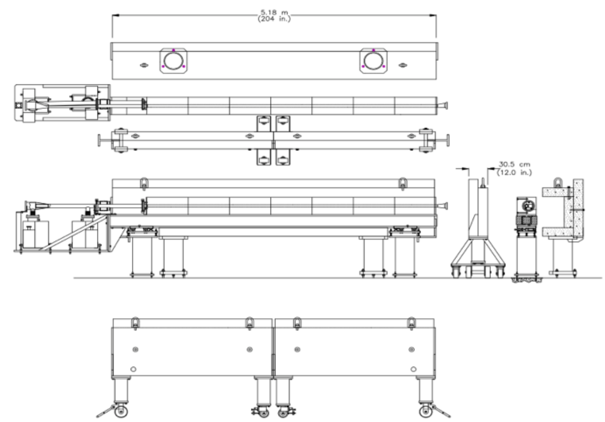

Figure 12. HSR Beam Dump Geometry

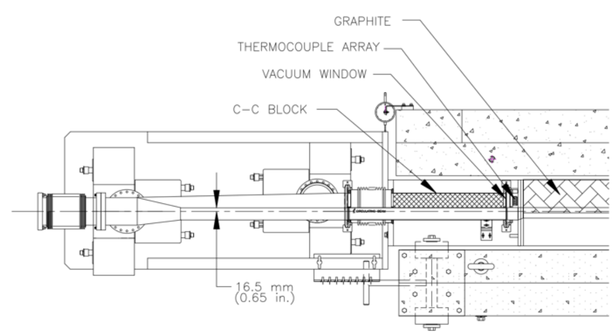

Figure 13. HSR Beam Dump Composition

In contrast to AGS, the figure of merit of BDX in the HSR is limited by the store time. The nominal hadron store time is 4 hours. Assuming continuous operation with one store every 4 hours and 1 hour of refill and acceleration, the number of ions on target (IOT) and protons on target (POT) per year can be estimated in the same manner as the AGS (7) and ESR (8) calculations. The HSR IOT will be 1.02e+15 IOT/year (9).

$N_{\text{HSR IOT}}$ = (0.05e+10 ions/bunch) (1160 bunches/store) (1 store/5 hours) (24 hours/day) (365 days/1 year) = 1.02e+15 ions on target/year (9)

Similarly, for the 275 GeV proton configuration the bunch intensity if 6.9e+10 protons/bunch. Under the same assumption of one 4-hour store and 1 hour of refill and acceleration, the POT per year is 1.40e+17 POT/year (10).

$N_{\text{HSR POT}}$ = (6.9e+10 ions/bunch) (1160 bunches/store) (1 store/5 hours) (24 hours/day) (365 days/1 year) = 1.40e+17 protons on target/year (10)

These figures of merit are smaller than the AGS pBDX POT (6.31e+19 POT/year), primarily because the AGS can cycle multiple per minute while the HSR stores the beam for several hours at a time. However, the significantly higher beam energies (110 GeV/nucleon ions and 275 GeV protons) compensate for the lower POT/IOT by improving the sensitivity to higher mediator masses and by accessing different production channels.

For the proton BDX at 275 GeV, dark photons can be produced efficiently via hadronic processes (meson production and decay) as well as proton bremsstrahlung on the spectator nucleus. The higher proton energy extends the kinematic reach to heavier mediators compared to the 28 GeV AGS pBDX. For the ion BDX, the 110 GeV/nucleon gold beam introduces additional coherent and incoherent production mechanisms, including photon-nucleus interactions and secondary meson production from ion-target collisions. These channels may provide complimentary sensitivity to dark photons that couple to quark and gluons, and they offer a unique opportunity because very few existing facilities operate at comparable ion energies.

CONCLUSION

In this work, the feasibility of searching for light dark matter candidates at the Brookhaven National Laboratory Electron-Ion Collider complex has been discussed, as well as an introduction to the experimental detection methods of light dark matter (LDM) particles. The primary focus has been placed on utilizing existing and planned multi-GeV synchrotrons, namely, the 28 GeV proton and 10 GeV/gold nucleon Alternating Gradient Synchrotron, the 10 – 18 GeV Electron Storage Ring, and the 110 GeV/gold nucleon and 275 GeV/proton Hadron Storage Ring, as sources of dark sector particles for beam dump experiments. By repurposing or augmenting the beam dump infrastructures of these machines, the EIC complex can host a diversified BDX program without interfering with the primary collider operations.

The AGS pBDX configuration at the *Z*-Line beamline offers the largest figure of merit in terms of POT per year, taking advantage of the high intensity 28 GeV proton cycles and the existing fixed target infrastructure. The ESR eBDX provides access to electron induced dark photon production at 10 GeV with its extraction and beam dump system capable of handling the gigawatt scale instantaneous beam power. Finally, the HSR iBDX and pBDX configurations extend the search to 110 GeV/nucleon ions and 275 GeV protons, probing heavier mediator masses and alternative production channels that are difficult to realize at other laboratories. These three machines establish a complementary program in dark sector physics at Brookhaven.

A qualitative comparison of the expected number of LDM detection events for the AGS pBDX, AGS iBDX, ESR eBDX, and HSR iBDX/pBDX configurations, together with an external reference from CEBAF/BDX at Jefferson Lab, is shown in Figure 14. The vertical axis indicates the number of dark matter events per year with an arbitrary normalization, and the horizontal axis is the mediator mass in MeV. At low mediator masses, the high current CEBAF/BDX electron beam provides the largest event yield, while the AGS proton configuration benefits from its very large POT figure of merit and remains competitive in the sub-GeV range. The HSR proton and ion curves, although suppressed in overall normalization by the longer store time, become relatively more important at larger mediator masses, where the higher hadron beam energies (275 GeV protons and 110 GeV/nucleon ions) enhance production of heavier dark photons. In this sense, the EIC complex can cover a broad range of mediator masses when the AGS, ESR, and HSR BDX programs are considered together, with CEBAF/BDX serving as a complementary low mass benchmark.

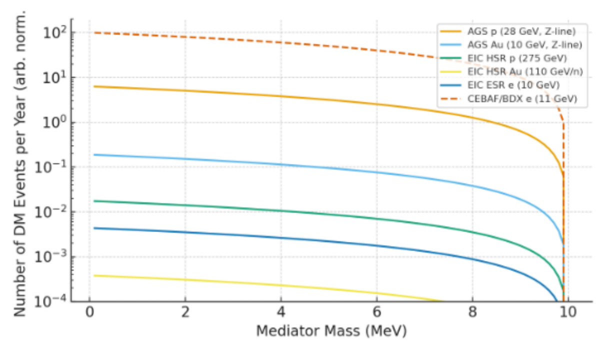

Figure 14. LDM Detection Comparison

The next steps toward a realistic implementation will involve detailed technical feasibility assessments. This includes Monte Carlo simulations of the beam dump geometries, secondary particle production, and dark sector yields; optimization of detector placement downstream of the dumps; and engineering studies of additional shielding, civil construction, and integration into the EIC accelerator complex. Radiation safety analyses and machine protection considerations must also be carried out in collaboration with the accelerator physics and engineering teams. These efforts can be coordinated through dedicated fixed-target and beam-dump working groups and workshops, such as the recent AGS fixed-target workshop and EIC ion beam-dump meetings, and expanded into a broader community effort.

From a physics perspective, dark sector searches at EIC would significantly broaden the scientific impact of the facility. The EIC is primarily motivated by precision studies of the internal structure of hadrons, yet its high energy, high intensity beams and sophisticated accelerator complex naturally lend themselves to hidden sector searches. Establishing a dedicated LDM program at the EIC complex would attract researchers from the high energy physics, astrophysics communities, and create new opportunities for students and early career scientists to work at the interface between nuclear physics and particle physics. In the long term, a successful dark sector program at Brookhaven could transform the EIC into a multipurpose discovery machine, capable of delivering both precision QCD measurements and potential breakthroughs in our understanding of the non-luminous matter that dominates the universe.

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