BeAGLE: A Tool to Refine Detector Requirements for eA Collisions
EIC R&D Project eRD17: Progress Report (January-June 2019) and Proposal

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Abstract

The BeAGLE[1] program for simulating e+A collisions, largely developed as an EIC R&D project (eRD17), is being used to investigate the detector and IR integration requirements, particularly in the forward region (ion-going direction) for both eRHIC and JLEIC. Key topics which are very demanding on forward detection include: centrality tagging of e+A DIS collisions for enhancement of Q_s^2, tagging of incoherent diffractive e+A collisions to access the gluon structure of the nucleus, tagging of the spectator nucleon in e+D to allow the extraction of neutron DIS physics as well as to study short range correlations (and tensor NN forces) in the deuteron; and the study of short range correlations in both light and heavy nuclei.

In addition to supporting these ongoing analyses, we have made progress on and propose to continue the effort we proposed previously: extending BeAGLE to better describe the complete suite of physics (including incoherent diffractive physics) in e+A collisions. This will allow us to tune to the relevant E665 event-by-event e+A streamer chamber data and validate BeAGLE's physics model (DIS+diffraction+nuclear effects). Such validation is essential in order to understand how well the detector/IR designs support e+A physics already and to understand detector requirements and physics tradeoffs in detector/IR design decisions.

The forward detector physics and IR integration issues are particularly urgent at this time because the proposed accelerator designs are becoming increasingly mature

[1]**B**enchmark **eA** **G**enerator for **LE**ptoproduction

and are also facing a lot of cost pressure. These designs and the constraints that they place on the forward detectors are becoming increasingly difficult to change. In contrast, the central detector design is much more open and flexible at this time. If there are open spaces in the forward region where a detector is needed, we should claim the space and justify it as soon as possible. In order to do that we need a well understood, and as complete as possible, simulation of the physics. Because these simulations have such a strong implication for forward detector / IR design, it is also imperative to validate the model with more — and more relevant — data.

We therefore propose, during the remainder of FY2019 along with FY2020, to finish implementing BeAGLE w/ RAPGAP, to finish up long-planned minor improvements and to focus on tuning to the most relevant data to ensure that the conclusions are valid. In particular, our goal is to answer the question: Is it true that the intranuclear cascade (INC) effects are so modest in inelastic eA events (DIS & incoherent diffraction)? Practically this means confirming using event-by-event full acceptance μ+Xe data at a relevant s (E665 Streamer Chamber) that the INC formation time parameter τ_0 is in the range 5–7 fm/c as opposed to the naive expectation of 1–2 fm/c. This will allow us to best understand the detector requirements for the critical and demanding physics measurement: coherent diffraction in e+A collisions.

1 Introduction

As mentioned in the abstract and detailed below, a better simulation of diffraction in e+A collisions is *essential* to EIC physics and to determining the detector requirements. In particular, vetoing diffractive e+A events where the nucleus does not stay intact is challenging and we need a more accurate simulation than that provided by Pythia [1], combining the improved description of $\gamma^* N$ diffraction from RAPGAP [2] with the DPMJET-based [3] description of the formation-time intranuclear cascade, nuclear evaporation and breakup built into BeAGLE [4]. This will allow us to validate the model, fitting HERA e+p forward proton [5] and neutron data [6] along with E665 average evaporation neutron data [7] and event-by-event streamer chamber data [8, 9].

The organization of the remainder of the document is as follows. Section 2 summarizes the progress of the project from January-June 2019. Section 3 outlines the plans for the summer. Section 4 contains the proposal for the FY2019-2020 effort: upgrading BeAGLE to include a better description of diffraction by adding RAPGAP and confronting BeAGLE with a more complete set of E665 data. This would lead to a version of BeAGLE which will be optimal for understanding the tradeoffs between the completeness and quality of forward detection on the one hand and our ability to measure transverse spatial nuclear gluon distributions and saturation on the other. Section 5 discusses external funding as well as other projects and proposals involving BeAGLE and their synergy with eRD17. Finally, Section 6 contains a summary of the progress report and proposal.

1.1 EIC Physics Motivation for the Project

BeAGLE is currently the main general purpose e+A simulation model in use for understanding physics and detector design tradeoffs for e+A collisions at eRHIC and JLEIC. As pointed out by the committee, it is important to support and enable the growing widespread use of BeAGLE in the EIC community. This has therefore become one of the priorities of the effort.

In addition, we continue to put effort into improving and tuning the physics in BeAGLE, with some emphasis on the description of incoherent e+A diffraction, where the nucleus is excited and/or broken up while the struck nucleon may or may not be. The EIC White Paper [10] states the importance of diffraction as well as the experimental challenges quite clearly: "What makes the diffractive processes so interesting is that they are most sensitive to the underlying gluon distribution, and that they are the *only* known class of events that allows us to gain insight into the spatial distribution of gluons in nuclei. However, while the physics goals are golden, the technical challenges are formidable but not insurmountable, and require careful planning of the detector and interaction region." [Emphasis in the original].

Exclusive coherent vector meson production $e + A \to e' + V + A$ where the nucleus remains intact is expected to be one of the most important measurements at the EIC [10]. The measured quantity $d\sigma/dt$ can be directly related, through a Fourier-like transform, to the transverse spatial distribution of gluons in the nucleus $F(b)$. For Bjorken-x values $x < 0.01$ and at modest values of Q^2 (say $Q^2 > 1$ GeV^2), the effective renormalization scale, μ^2, at which we are sampling the gluon distribution $G(x, \mu^2)$ is $\mu^2 \sim \max(Q^2, M_V^2)$. The J/ψ particle, with $M^2 = 9.6$ GeV^2 should effectively sample the baseline, unsaturated, gluon distribution, while the ϕ particle with $M^2 = 1.0$ GeV^2 should be directly sensitive to gluon saturation as a function of Q^2.

Exclusive *incoherent* vector meson production in nuclei $e+A \to e'+V+X$ occurs when the nucleus breaks up due to its interaction with the vector meson. This physics is quite interesting in its own right and so it will be important to identify these events. The really challenging issue, though, is that for high values of $|t|$, the incoherent production swamps the coherent production and we need to be able to veto the incoherent case in order to measure the coherent production.

Studies using Sar*t*re [11, 12] indicate that in order to measure the gluon spatial distribution precisely with coherent production, you need to include the third dip in the spectrum, going out to $|t| \sim 0.15$ GeV^2, although you get a reasonable measurement with just the first two dips. If you omit the second dip, you make errors comparable to the expected size of the saturation effect. This allows us to set the scale for the required background rejection. Figure 1 shows the expected results for the J/ψ in the presence of saturation and in a model without saturation. Saturation actually makes our job easier by suppressing the background, but only slightly in the case of the J/ψ. The minimum requirement for any reasonable measurement would be that we need to be able to achieve a 1:1 S/N ratio for the second dip of the J/ψ which requires a one-hundred fold reduction in background or a 99% veto-tagging efficiency. A much better goal would be to achieve a 3:1 S/N ratio for the

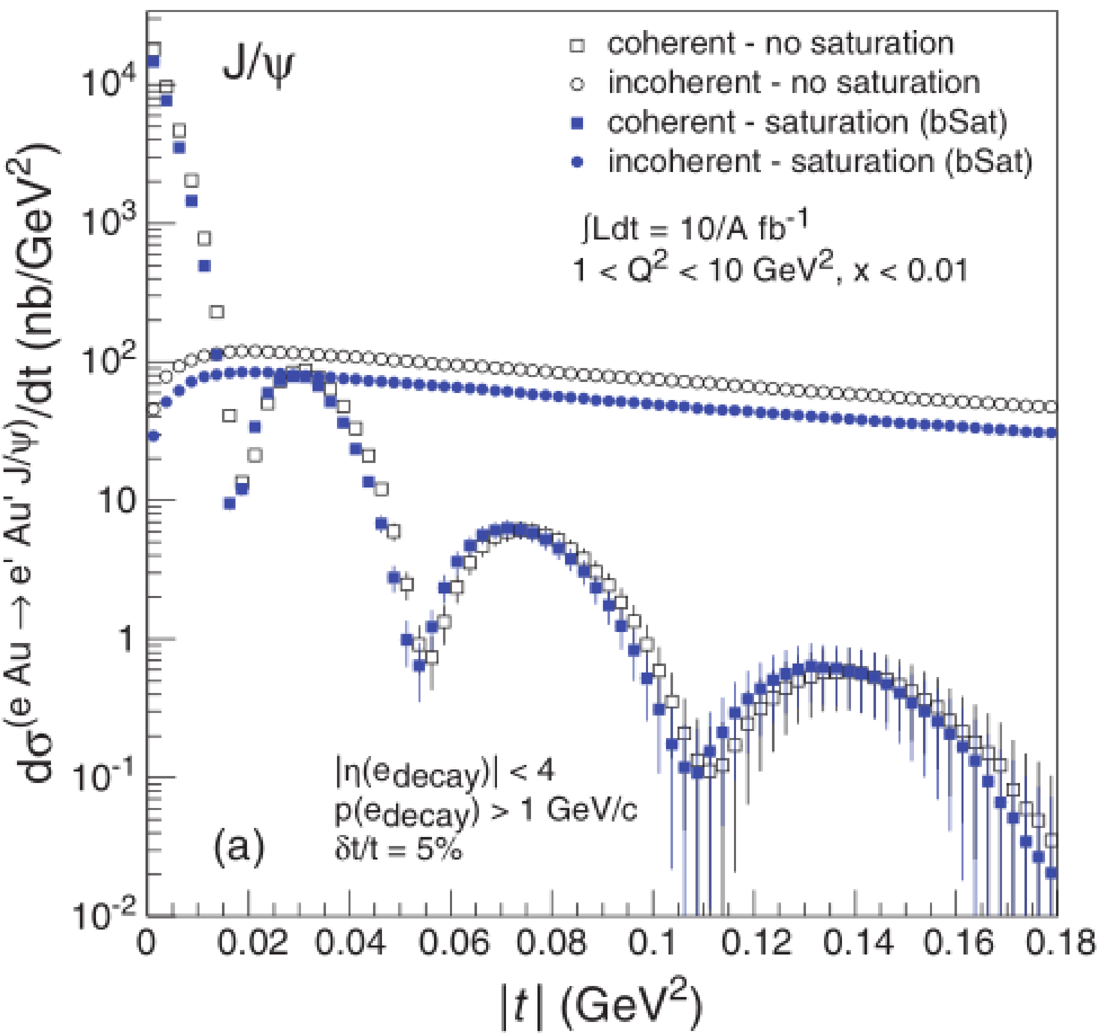


Figure 1: Cross-section for exclusive, coherent and incoherent, J/ψ production with and without saturation from Sar*t*re [10, 12].

third dip which requires a 1300-fold reduction in background or a 99.92% veto efficiency. So our target veto efficiency should be 99–99.92%.

The white paper was written before BeAGLE was available and its predecessor, DPMJetHybrid [13], was itself rather new. Therefore the quick studies of the detector capabilities used some crude estimates of how the nucleus would respond to an exclusive incoherent diffractive event. In particular, the nuclear excitation energy was assumed to be, on average, more than 10x larger than BeAGLE indicates it should be. Based on those crude assumptions, the white paper concluded that: "the nuclear breakup in incoherent diffraction can be detected with close to 100% efficiency by measuring the emitted neutrons in a zero degree calorimeter placed after the first dipole magnet that bends the hadron beam."

The current incarnation of BeAGLE has two features in the description of diffraction which need improvement. It uses Pythia rather than RAPGAP to estimate the behavior of diffractive events, and it also assumes that diffractive and DIS events have effectively the same dipole cross-section. Nevertheless, because it includes a good simulation of the multinucleon interaction, intranuclear cascade and nuclear evaporation and breakup, it is currently our best tool to estimate our vetoing efficiency. As discussed in last year's proposal [14], BeAGLE indicates the surprising result that even at high values of $|t|$, there are *zero* evaporation neutrons in more than 12% of the events! Basically, there is a chance that the struck nucleon is knocked cleanly out of the nucleus and the remnant nucleus manages to de-excite without neutron evaporation. The current BeAGLE estimate veto-tagging efficiency based on evaporation neutrons alone is about 88%, far short of the target 99–99.92%. The S/N at the second dip would be about 1:12 and at the third dip 1:36.

Of course, there are likely other particles in the event which will increase our ability to tag these events, but the main point is that the challenge is even greater than assumed in the white paper, and this study needs to be done. In summary:

1. The incoherent diffractive events described by BeAGLE are one of the most sensitive probes of saturation [10], and we need to make sure that we can identify them and measure their properties, ideally including geometry tagging (impact parameter).

2. In order to demonstrate our ability to achieve background rejection factors of 100–1300, we need an accurate description of the physics, and presumably a very good detector. This may be one of the key design drivers for forward detection and the IRs.

3. Until EIC comes online, the old E665 data provides our best chance to tune our models and understand what we can expect.

For eRD17, due to the importance of diffractive physics, including both incoherent and coherent, we proposed a project to improve BeAGLE's description of diffraction in several ways. First, we will implement a process-dependent effective "dipole" cross-section in BeAGLE. This will modify the relative A-dependence between diffraction and DIS (and possibly higher order hard processes). It will also allow the nucleus to respond differently to diffractive and DIS events. Second, we will implement RAPGAP as an alternative model to PYTHIA, controllable by a switch within BeAGLE. RAPGAP uses PYTHIA for fragmentation, but has a more sophisticated and up-to-date description of e+p diffraction physics. Finally, we will engage in a more comprehensive effort to confront BeAGLE with all relevant data. The E665 forward neutron data for e+Pb and e+Ca [7] and especially the E665 Streamer Chamber data [9] contain a complicated event mix including coherent diffractive, incoherent diffractive and DIS data. An optimal simulation of this data should mix our best understanding of each of these event types and then attempt to apply the event selection criteria used by E665. This is somewhat complicated, and many comparisons to E665 μ+Pb neutron data have assumed that the Pythia mix approximates the data which does not include coherent diffraction. Since we know that the coherent diffractive events (which contribute zero neutrons per event) make up at least 13% of the E665 μ+Xe data [9], this is certainly not correct.

The phenomena of diffraction, nuclear shadowing and parton saturation are increasingly topical and important in the study and interpretation of AA, pA and potential eA data at RHIC and LHC energies. In fact they provide a lot of connections between these data sets [15]. While we now have a significantly improved Monte Carlo Model in BeAGLE, especially for describing DIS in e+A, it is clear that the diffractive physics is still not optimally modeled and further improvements are needed. Since diffractive physics is likely to be one of the physics-based design drivers for the ongoing optimization of forward detectors and their integration with the IR and the EIC machine elements for both eRHIC and JLEIC, it is important to have a complete suite of accurate eA event generators as soon as possible.

2 BeAGLE Status: Achievements through June 2019

Our main achievements during this time period include:

- Supporting and enabling physics-driven studies of EIC forward detector performance and requirements
- Detecting three bugs in DPMJET-F which affect charge and 4-momentum conservation particularly in heavy e+A collisions.
- Fixing two of the three bugs and narrowing the third one down to the intranuclear cascade process.
- Fixing J/ψ and ϕ particles to decay outside the nucleus instead of promptly.
- Comparing BeAGLE and E665 kinematic data (Q^2, ν, x, W^2 distributions) and starting to develop a model for the E665 trigger.

The BeAGLE installation at JLAB, originally restricted to a particular collaboration, was made publically available to JLAB users and is now being used to study the physics reach and detector requirements for J/ψ diffractive e+D and e+Pb collisions as well as quasi-elastic e+C collisions with Short-Range Correlations (SRCs). The BeAGLE installation at BNL is also available and is also being used for several studies, including: diffractive J/ψ collisions in both e+D and e+Pb; kinematic reconstruction (Q^2, x, etc.) using hadrons as well as the scattered lepton in e+A collisions; the impact of detector location on forward proton acceptance for e+A collisions; and the impact of calorimeter resolution on centrality tagging capability in inelastic e+A. As various users run into problems running the code, we get them going and also take the opportunity to improve the documentation so that future users will not run into the same confusion.

As an example of the kind of work ongoing, we will briefly cover the forward proton acceptance studies that have begun for eRHIC. Then we will discuss the bugs and finally the E665 kinematic comparison.

2.1 Impact of Detector Location on Forward Proton Acceptance at eRHIC

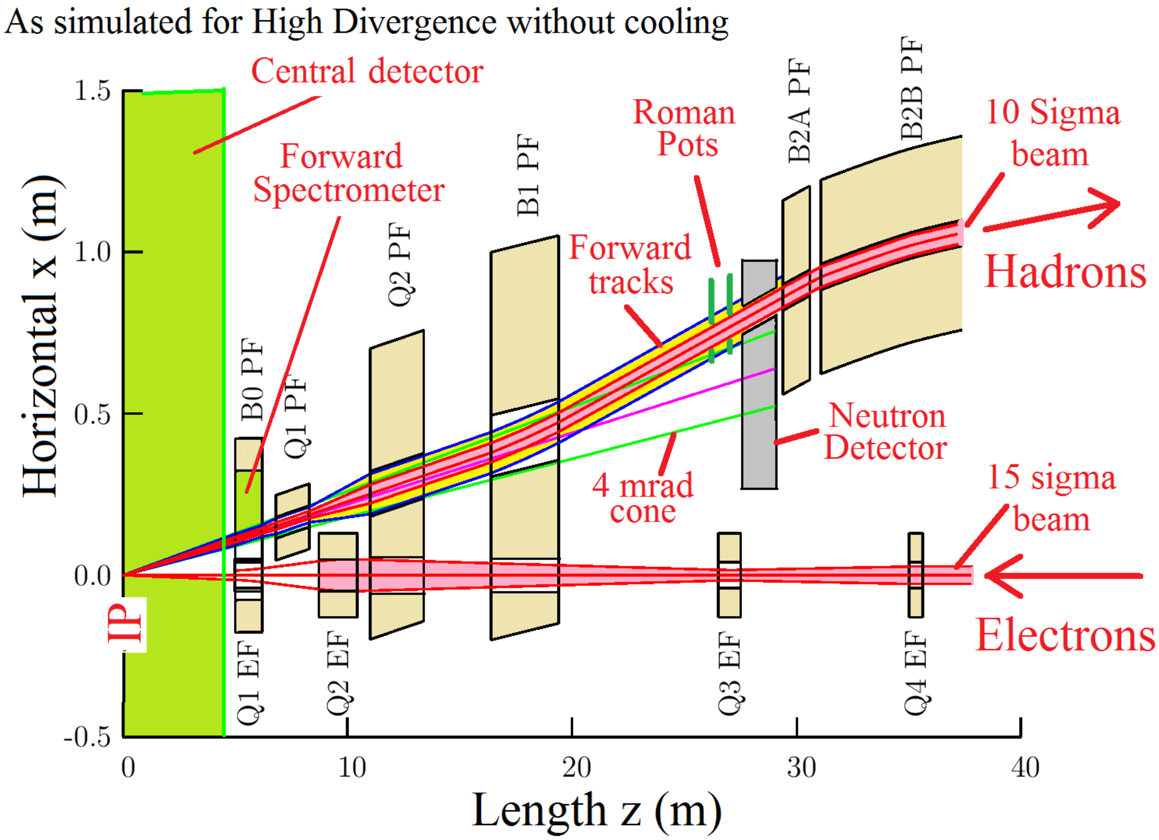
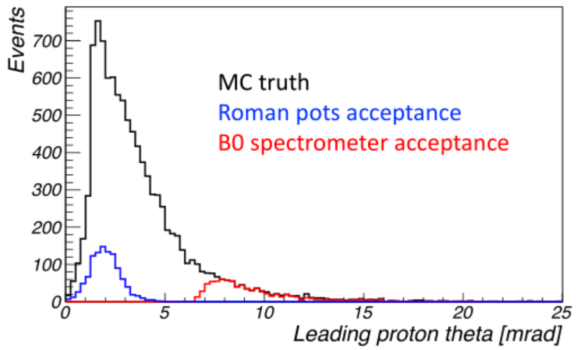


Figure 2: Forward detector and magnet suite for eRHIC in the ion-going direction. Drawing taken from Reference [16].

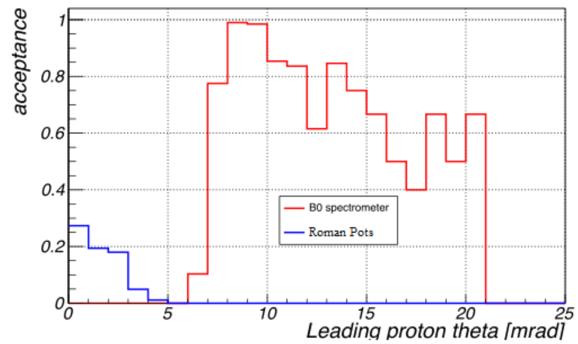
Figure 2 shows a recent iteration of the design of the forward detector/IR suite in the ion-going direction [16]. The key detectors for the forward protons are labeled "Forward Spectrometer" (also known as the B0 spectrometer) and "Roman Pots". The Roman Pots accept the most forward particles while the B0 spectrometer accepts particles at a midrange. The central detector covers $|\eta| < 4.5$ or $\theta > 22.2$ mr with near 100% acceptance. Figure 3 shows all simulated forward protons from BeAGLE for diffractive $J/\psi\ e + Pb$ collisions at 18x110A GeV as well as those which would be detected in either the B0 spectrometer or the Roman Pots. The ratio of these is the acceptance which is also shown.

It is clear from these figures that real estate is very tight, but that the detector still needs optimization. Furthermore, it is essential to optimize the detector before the real estate gets even tighter!

Figure 4 shows a set of idealized detector planes embedded in the simulation in order to determine where the protons are being lost. Figure 5 shows the fraction of forward protons



(a) Simulated and detected protons.



(b) Fractional acceptance.

Figure 3: Simulated and detected protons in the forward (ion-going) direction and their ratio (acceptance) vs. angle for diffractive J/ψ $e + Pb$ collisions at 18x110A GeV.

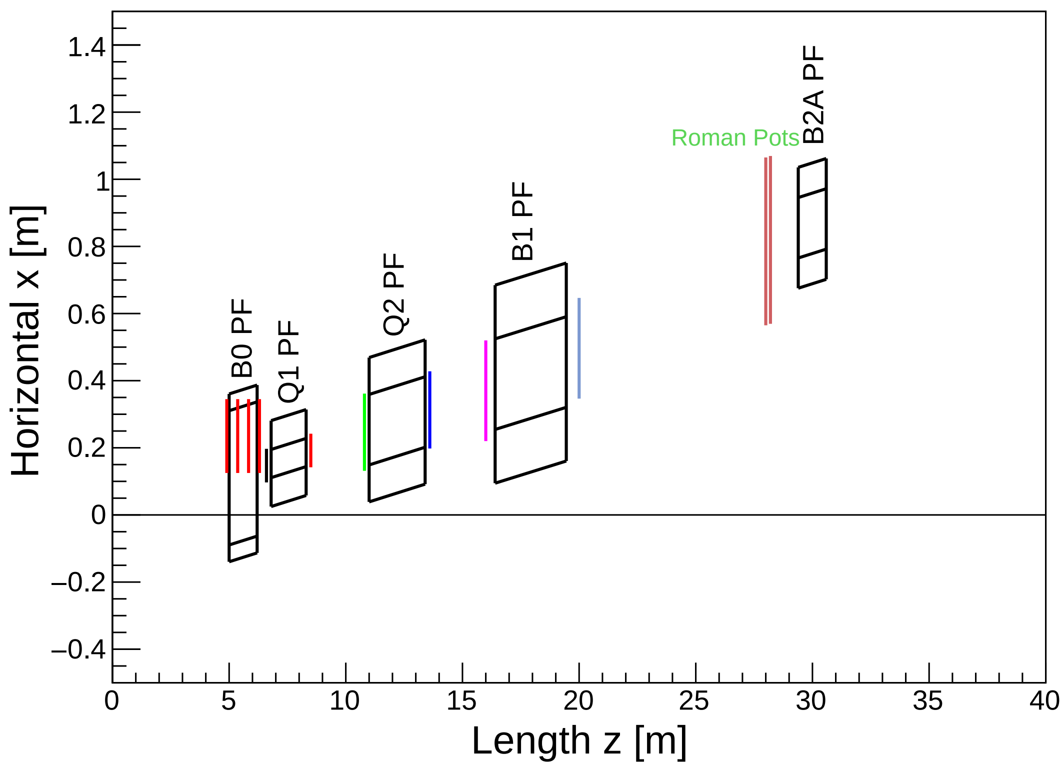


Figure 4: Idealized detector planes embedded in the magnet suite for eRHIC in the ion-going direction.

that are accepted at a given ideal plane location. Note: the "Roman Pot" ideal plane result is very similar to the result of the more realistic simulation (see Figure 3b). These studies

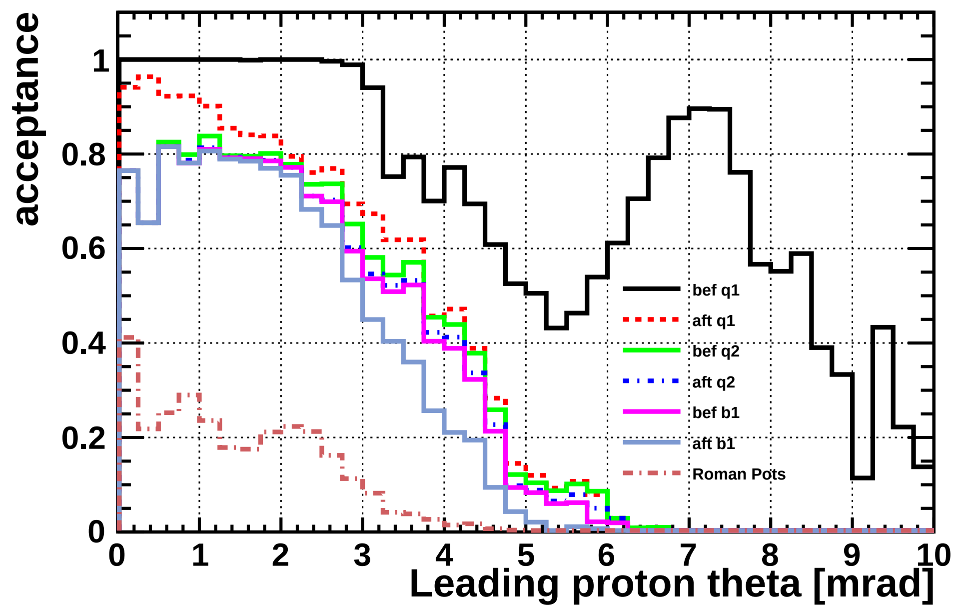


Figure 5: Acceptance of idealized detector planes.

are just beginning, but will be essential to our understanding of the forward detector / IR integration issues.

2.2 Nonconservation bugs

In the process of studying how to correctly handle 4-momentum conservation in e+D collisions, as discussed in the January 2019 update, we noticed that most (∼97%) $e + Pb$ collisions fail to conserve 4-momentum. In addition, we noticed that a small fraction of events (0.1–0.2%) failed to conserve charge. These problems occur in the DPMJET-F part of the code which handles the intranuclear cascade and the decay of the excited nucleus. This means that the bugs affect both the standard BeAGLE mode using Pythia and also the new BeAGLE/RAPGAP mode which we are still testing. For this reason, we put these bugfixes at the highest priority (after responding to various user requests for help in running the code).

2.2.1 Charge conservation

The total charge for any $e^- +^{208} Pb_{82}$ event is $Z = 81$ since the electron has a negative charge. If we sum up all stable final state particles, that is what we should get. Figure 6 shows what happens before the bugfix. A small fraction of the events have $Z = 82$ or an extra positive charge. The origin of this error is interesting. It turns out that about 1% of all nuclear remnants in BeAGLE $e + Pb$ inelastic collisions are actually hypernuclei.

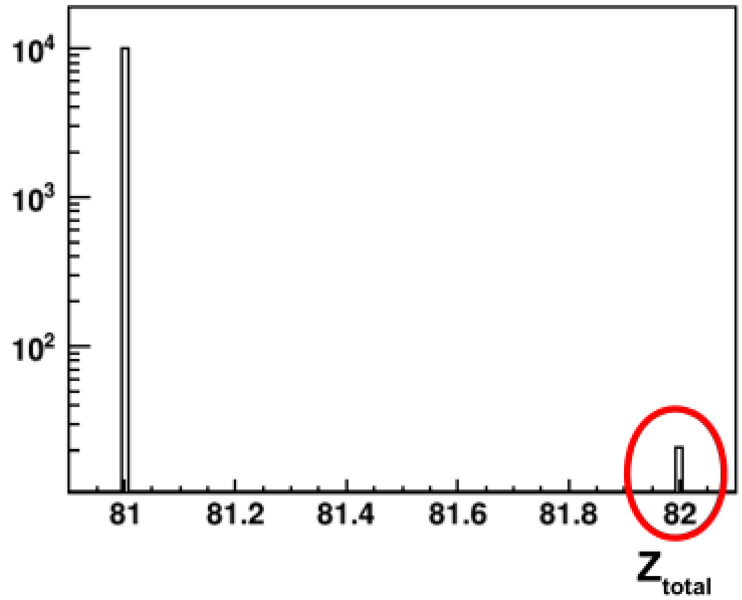


Figure 6: Total final state charge for $e + Pb$ events in BeAGLE before the bugfix.

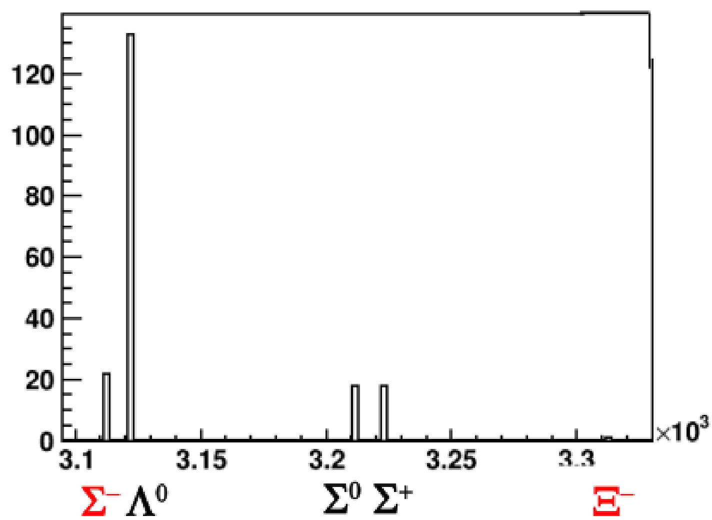


Figure 7: Particle ID for nonnucleonic baryons in the excited nuclear remnant from $e + Pb$ events in BeAGLE. The numbers on the x-axis correspond to the PDG MC particle ID convention while the symbols identify the non-nucleonic baryons (hyperons) which are present.

Figure 7 shows the identity of the nonnucleonic baryon in these events. For the 20,000 events simulated, there were no events with more than one hyperon in the nucleus. The bug in DPMJET-F was that when it assembles the remnant nuclei, the logic implicitly

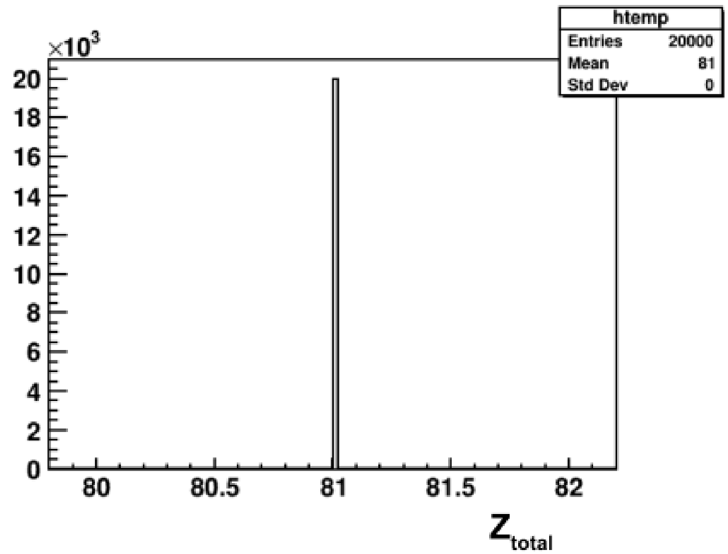


Figure 8: Total final state charge for 20,000 $e + Pb$ events in BeAGLE after the bugfix.

assumes that all nucleons which are not charge +1 are charge 0. So negatively charged baryons such as Σ^- and Ξ^- are treated as neutral, increasing the charge by +1 in a small fraction of events. This bug was fixed as can be seen in Figure 8.

Two things should be noted. First, the fact that 1% of all events contain hypernuclei is quite interesting. It is entirely possible that there is a physics program there if we can detect the final state from the nuclear breakup well enough. Second, even after the bugfix, BeAGLE's handling of the hypernuclear decay is still not ideal. Basically a hypernucleus is treated like a nucleus of the same A and Z, with the extra mass in the hyperon contributing to the nuclear excitation energy. The strangeness is ignored. If,at some point, we want to study hypernuclei, this treatment should be improved. In particular, FLUKA has a provision for handling hypernuclei which could be used. At this point in time, such improvements are beyond the scope of the project.

2.2.2 Energy conservation

Figure 9 shows the two types of energy nonconservation bugs. The error is easiest to see in the Ion Rest Frame (IRF)[2]. The x-axis shows the total energy of all stable particles (including the scattered electron) after the collision in the ion rest frame minus the energy of the incoming state (electron + ion) for a set of simulated high energy $e + Pb$ collisions. The majority of the events (about 95%) show a loss of energy in this frame ranging from a small error up to 2 GeV depending on y. A small fraction of the events(2–2.5%) have the correct energy. Finally, another small fraction (2–2.5%) of the events have an excess

[2]For fixed target this would be called the lab frame (lab) or target rest frame (TRF) but neither of these terminologies seem quite correct for a collider...

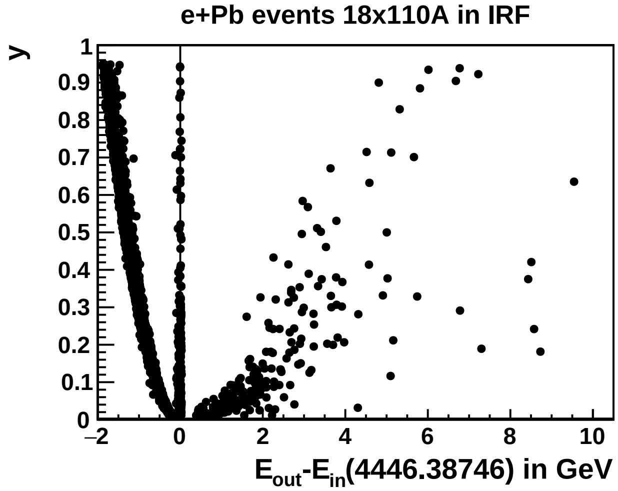


Figure 9: Fractional energy loss $y \equiv \nu/E_e^{(IRF)}$ versus energy nonconservation in the ion rest frame before the bugfix.

energy. It should be noted that there are errors in $\vec{p}$ in this frame as well for the bad events, but it sufficient to classify them by their energy effect.

The energy loss bug was confusing to find because it's main symptom was that FLUKA returned stable nuclei with an incorrect mass — and FLUKA is a black box: we are only using FLUKA libraries; the source code is unavailable without heroic effort. Fortunately, the problem is not inside FLUKA, but rather that DPMJET-F prepared the excited nucleus in an inconsistent way. There was a section of code that took a perfectly valid excited nuclear remnant in the $\gamma * N$ center of mass frame (nucleon-HCMS) and rescaled its 3-momentum while leaving the total energy and the excitation energy fixed. This was then inconsistent and apparently confused FLUKA. Once that code was removed, then the energy loss bug was fixed. It should be noted that the 3-momentum of the nucleus in the nucleon-HCMS grows with y, explaining the correlation. For low y the HCMS and the IRF nearly coincide and the incoming nucleus and the nuclear remnant have very little momentum, so rescaling its momentum has very little effect.

Figure 10 shows the result after the bug was fixed. It should be noted that the main effect of this bug was to change the mass of the final stable nuclear remnant, typically by less than a percent. Fortunately, this means that most of our previous results, involving hadrons, were not affected and are still valid. Some JLEIC studies on the rigidity of the final remnant were slightly affected, but again by only a small amount.

The remaining events ($\sim$2.5%) with increased energy are still not fully understood, although it has been isolated to a mistake that occurs during the intranuclear cascade. We expect this bug to be fixed relatively soon, probably before the July meeting.

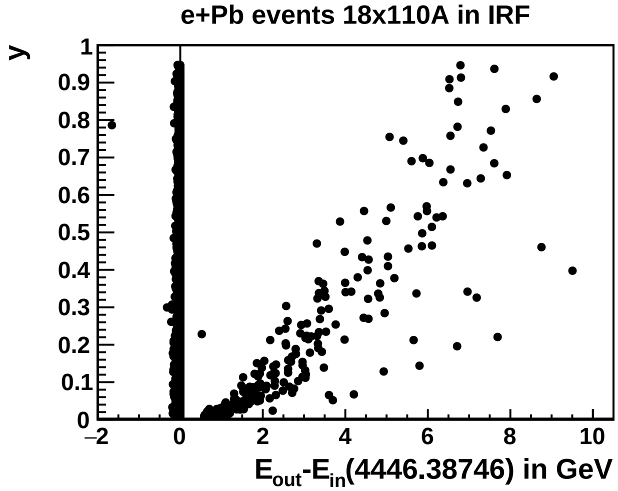


Figure 10: Fractional energy loss $y \equiv \nu/E_e^{(IRF)}$ versus energy nonconservation in the ion rest frame after the bugfix.

2.2.3 Decays inside vs. outside the nucleus

One subtle point that we dealt with already in BeAGLE is the fact that certain particles need to propagate through the nucleus and decay outside of it. Particles such as a π^0, J/ψ or ϕ are usually decayed promptly in Monte Carlos because the decay length is too short for the decay products to ever be detected as coming from a distinct vertex. However these particles have a $c\tau$ of 25 nm, 2 pm=2000 fm, and 47 fm respectively, so their mean decay length $\gamma\beta c\tau$ will typically be well outside the nucleus.

The π^0 was already set to decay outside the nucleus, meaning that it propagates and undergoes intranuclear cascading as a π^0, but then decays promptly, usually to 2 photons, before being output as part of the standard BeAGLE output.

The J/ψ and ϕ particles had been set to decay, however, inside the nucleus. This lead to some subtle problems where the decay products (e.g. $\mu^+\mu^-$ for the J/ψ) interact with the Coulomb field of the nucleus distorting the invariant mass distribution. They have been set to decay outside the nucleus now.

2.3 E665 data kinematic comparisons

Figure 11 shows our first look at simulating the E665 Streamer Chamber $\mu^+ + Xe$ data [8]. We used 490 GeV positive muons and $^{131}Xe_{54}$ nuclei at rest in the simulation. E665 used a natural mix of xenon which has an atomic weight near 131. We matched the kinematic cuts: $\theta > 3.5$ mr, $Q^2 > 1$ GeV^2, $8 < W < 30$ GeV,$x_{Bj} > 0.002$, and $0.1 < y < 0.85$. There is a substantial discrepancy at low Q^2 or low x and also at high y or W. Unfortunately the E665 trigger efficiency is not 100% in this region and they did not provide corrected data or a detailed trigger efficiency so we will need to simulate the trigger ourselves based on the description provided by E665 [17]. Other possible sources of the discrepancy include

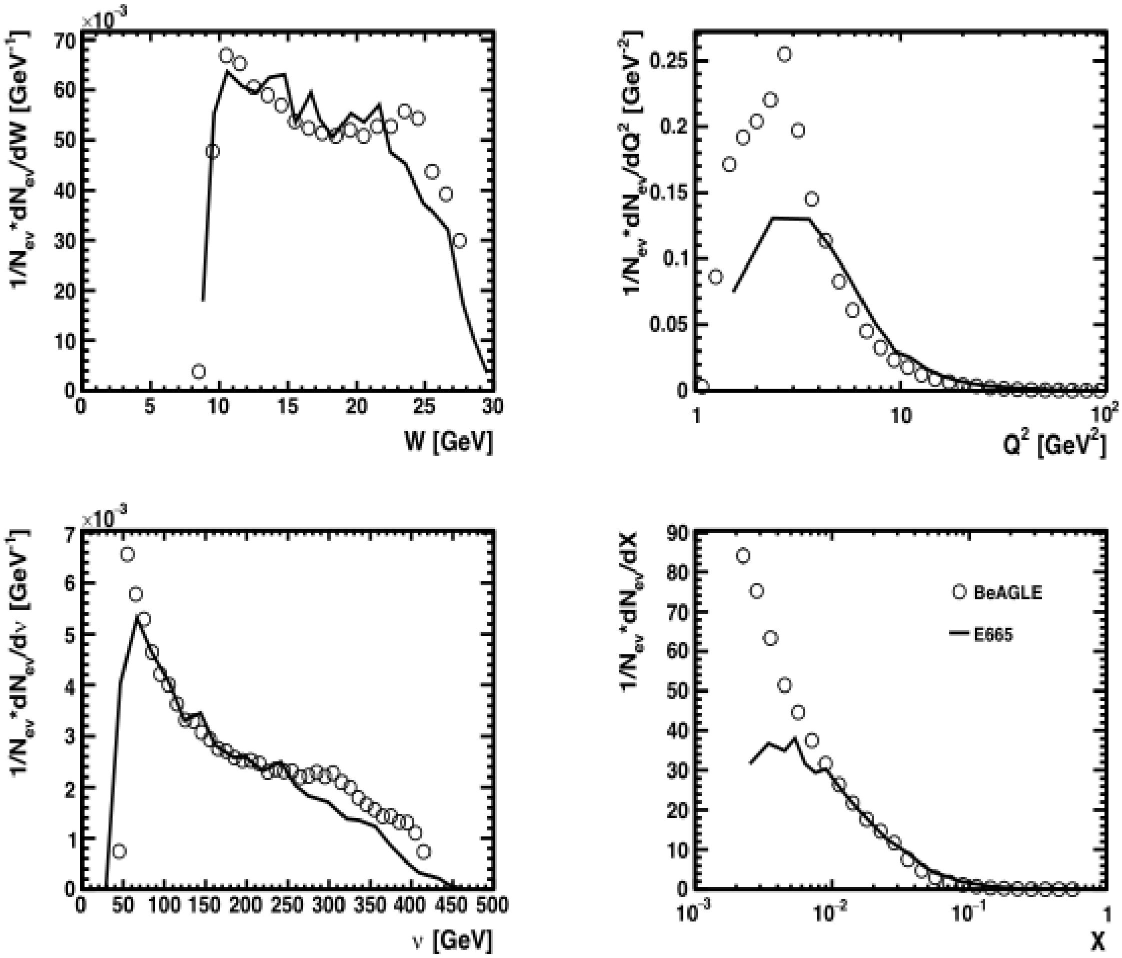


Figure 11: A comparison of BeAGLE simulations with kinematic cuts but no trigger simulation (circles) and E665 data (lines).

reconstruction inefficiency in E665 and the structure function used for the simulation.

2.4 FY2019 Technical Progress and Timetable

Table 1 is an update of the standard eRD17 Status Report table. As mentioned above, our main achievements during this time period include:

- Supporting and enabling physics-driven studies of EIC forward detector performance and requirements
- Detecting three bugs in DPMJET-F which affect charge and 4-momentum conservation particularly in heavy e+A collisions. **Items 19c–e**.
- Fixing two of the three bugs and narrowing the third one down to the intranuclear cascade process. **Items 19c–d**.
- Fixing J/ψ and ϕ particles to decay outside the nucleus instead of promptly. **Item 24**
- Comparing BeAGLE and E665 kinematic data (Q^2, ν, x, W^2 distributions) and starting to develop a model for the E665 trigger. **Item 12a**.

What was not achieved, why not, and what will be done to correct?

What did *not* occur during this time period was item 19f, releasing the tested version of BeAGLE/RAPGAP. Supporting and integrating the efforts of various users/collaborators, including new ones, took some time. In addition, isolating and fixing the bugs item (19c–e) is also higher priority since these bugs affect BeAGLE/RAPGAP as well as the standard (Pythia-based) BeAGLE running.

Understanding the E665 trigger (item 12a) and releasing BeAGLE/RAPGAP (item 19e–f) is now the highest priority item for the remainder of the fiscal year.

In summary, substantial progress has been made in this reporting period. BeAGLE is being used at both BNL and JLAB and its use is expanding. Detector/IR optimization studies have begun. We have started looking at E665 data. The remaining tasks to be completed will be detailed below in Section 3.

2.5 Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project.

The only funded manpower consists of Baker, who spends 25% of his time on the project.

Zheng contributed a significant amount of effort, about 10%, in consulting on technical questions, running simulations, and making plots. He also did the bulk of the work in fixing item 24 from Table 1.

Student Wan Chang and Goldhaber Fellow Zhoudunming Tu joined the project spending roughly 50% and 20% effort respectively for the last six months. At this point they have gotten up to speed and are contributing significantly to the effort. This represents a substantial contribution from BNL, leveraging the eRD17 funding. Chang is doing most

Feature added or error corrected	01/2019	06/2019	07/2019(proj.)
1-8,10,13-17,20-22. Completed BeAGLE tasks.	YES	YES	YES
9. Shadowing coherence length	NO	NO	NO
11a. Effective σ_{dipole} for J/ψ averaged over x & Q^2	YES	YES	YES
11b. Effective σ_{dipole} for ϕ averaged over x & Q^2	YES	YES	YES
11c. Eff. $\sigma_{dipole}(x,Q^2)$ for $V=\psi,\phi,\rho,\omega$ from Sartre (ePb)	NO	NO	NO
11d. Use correct $R_{diff}^{(A=208)}(x,Q^2)$ for V from Sartre	NO	NO	NO
11e. Improved σ_{dipole} for V, if necessary	NO	NO	NO
12a. Understand E665 Event Trigger (& Q^2 dist.)	NO	Started	????
12b-?. Tune to E665 μA Streamer Chamber data	NO	NO	NO
18. Tune the t distribution for multiple scattering.	NO	NO	NO
19a. Release α version BeAGLE/RAPGAP	YES	YES	YES
19b. Release β version BeAGLE/RAPGAP	YES	YES	YES
19c. Fix charge non-conservation bug (DPMJET-F)	NO	YES	YES
19d. Fix lost energy bug (DPMJET-F)	NO	YES	YES
19e. Fix excess energy bug (DPMJET-F?)	NO	NO	YES
19f. Release tested version BeAGLE/RAPGAP	NO	NO	????
19g. Extend RAPGAP to include e+n (w/ H. Jung)	NO	NO	NO
22a. Update relative nucleon mom. dists. for e+D	YES	YES	YES
22b. Variety of well-motivated distributions for e+D	NO	NO	YES
23a. Put e+D on mass-shell (ad-hoc)	YES	YES	YES
23b. Put e+D on mass-shell, light-cone prescription	NO	NO	NO
24. Fix J/ψ & ϕ to decay outside the nucleus	NO	YES	YES

Table 1: Technical Progress / Plans for eRD17

of the work in running and analyzing the simulations for forward proton acceptance and comparison to E665 data. Tu has provided enthusiasm, leadership and organization and has taken over from Lee as co-PI of the project (along with Baker). He has also played a substantial role in improving the BeAGLE e+D simulation.

Aschenauer is actively supervising Chang and Aschenauer and Lee both participate in regular meetings and contribute advice.

3 Immediate Plans

The main and highest priority activity planned for the remainder of FY2019 is to finish fixing the known BeAGLE bug and finalizing the implementation of RAPGAP into BeAGLE in the e+p hard subevent incarnation (**item 19e–f**). In addtion we are working on understanding the kinematic distributions and trigger in the E665 data (**item 12a**) and providing a variety of well motivated distributions for the relative nucleon momentum ($n(k)$) in $e + D$ collisions (**item 22b**). Currently, we are using a distribution which fits the data up to k =2.5–3fm^{-1} and is an extrapolation for higher values. In principle, there is reason to believe that at high values of k, a power law distribution of some kind takes over and significantly increases the distribution that we would otherwise expect. Furthermore, the distribution at high values of k is important because they contain information about the nucleon-nucleon (NN) interaction at short distances.

These projects are well in hand for finishing this fiscal year. No showstoppers are foreseen.

In addition, we would like to submit at least one paper for publication by the end of the calendar year. Given all of the activity on BeAGLE, it is becoming important to document these results more formally.

4 Proposal for FY2020

The proposed main goals for FY2020 are to complete the upgrade of BeAGLE, using a better description of diffraction; to clean up and document the code; and to make a concerted effort to tune BeAGLE, as well as possible, to the relevant data from E665, in particular including the event-by-event hermetic streamer chamber μ+Xe data. This will provide the community with a unique, calibrated tool to best understand incoherent exclusive vector meson production through diffraction in e+A collisons, as well as DIS. This physics is a key EIC measurement in its own right and is also the main background to another key EIC measurement: *coherent* exclusive vector meson production through diffraction in e+A collisions. Coherent production itself would not be directly included in BeAGLE, but it would be straightforward to mix background events from BeAGLE with coherent events from Sar*t*re and then present those events to GEMC (JLAB) or eicroot/eic-smear (BNL) in order to understand the effect of the detector design on the measurement.

This project is essential and timely because BeAGLE remains one of our best tools to simulate e+A collisions at an EIC in order to estimate the physics reach and to understand the forward detector & IR requirements as well as the tradeoffs between physics reach and detector/IR considerations. Nevertheless, conclusions from studies using BeAGLE contain one key assumption which rests on a limited amount of not fully understood data. In particular, the event-averaged neutron multiplicity from E665 μ+Pb data [7] was lower than originally expected, which suggests a reduced amount of intranuclear cascading (INC), implemented in BeAGLE as a relatively long formation time (τ_0) for produced particles from the hard collision. This line of reasoning in indirect in two ways. First, we have to estimate, rather than measure, the relative amount of coherent diffraction, incoherent diffraction and DIS in the E665 data, leading to an uncertainty in the correct τ_0 parameter. Second, the observed neutrons primarily come from neutron evaporation after the collision is over and we do not directly measure the INC products. We are assuming that a reduction in INC products leads to a reduction in nuclear remnant excitation which, in turn, leads to a reduction in neutron evaporation.

Adding RAPGAP as an option in BeAGLE as well as tuning to the fixed target E665 Streamer Chamber data [9] will improve this situation dramatically. The E665 Streamer Chamber data measures almost all[3] charged particles coming from the collision including most of the INC products directly. This will allow us to confirm that the modest amount of evaporation is due to a modest amount of INC. Also the data are reported event-by-event so distributions in multiplicity and rapidity gap will allow us to directly constrain or tune the relative amount of different event classes (DIS vs. diffractive etc.).

4.1 Personnel, Timetable and Budget

The goal for FY2020 remains to upgrade BeAGLE to include RAPGAP (extended to include en), to make any necessary improvements to BeAGLE's multiple scattering model (items 9,11,18 in Table 1) and to tune BeAGLE to the E665 Streamer Chamber data as well as the E665 neutrons, while preserving the agreement with HERA e+p data on forward protons, forward neutrons and J/ψ production. This will include a rough simulation of the E665 trigger and event selection for the two papers as well as an estimate using Sar*t*re and Pythia(BeAGLE) of the relative cross-sections of DIS, incoherenet diffractive and coherent diffractive events.

Estimated milestones for these tasks are:

Jan. 15, 2020 BeAGLE cleanup and full RAPGAP installation (includes e+n)

Jan. 15, 2020 Submission to a journal of at least one paper on BeAGLE.

Apr. 30, 2020 Compare BeAGLE to E665 data using our best current information.

Sept. 30, 2020 Tune BeAGLE to the data to our best ability.

[3]Very low momentum particles as well as the heavy nuclear remnant and most light ions will be absorbed in the target or other material.

Person	Institution	Effort (FTE-year)	Cost to Proposal	Remarks
E. Aschenauer	BNL	0.05	$0	cost covered by BNL
M.D. Baker	MDBPADS[18]	0.25	$65,520	
W. Chang	CCNU/BNL	0.50	$0	salary covered by CCNU
J.H. Lee	BNL	0.05	$0	cost covered by BNL
Z. Tu	BNL	0.20	$0	cost covered by BNL
L. Zheng	CUGW	0.10	$0	salary covered by CUGW
TOTAL:		1.15	$65,520	

Table 2: Personnel Budget Breakdown for FY2019

Item	Cost
Personnel:	$65,520
Chang per diem and housing	$15,000
Zheng Travel	$6,000
Other Travel	$1,500
TOTAL:	$88,020

Table 3: Total Budget Breakdown for FY2020

In order to help accelerate the work, as suggested by the committee in July 2018 and reiterated in January 2019, we are proposing to partially support Wan Chang's housing and per diem. The plan is for her to work 50% on eRD17 in FY2020 with eRD17 contributing 3 months of support (half of 50% of a year) and BNL providing the other 3 months (as well as 6 additional months for non-eRD17 activities). Her salary is covered by her home institution.

We are also proposing travel money for Liang Zheng to visit BNL for a month during the summer of 2020. When possible, these visits are very valuable as a lot more is accomplished face-to-face, especially since the internet connection to Wuhan suffers from substantial lag. Note that all other project members are on Long Island. This is estimated to cost about $6000. In addition we are asking for $1500 for a possible domestic trip for Baker to a meeting or for some other experts to visit BNL.

Table 2 shows the personnel budget breakdown for FY2020. Table 3 shows the total budget, including the new budget item: Chang per diem and housing.

4.2 Impact of Reduced Funding

Table 4 shows the impact of reduced funding. With full funding we expect to complete the project — using E665 SC data to tune and validate BeAGLE — providing the community with a version of BeAGLE which will be optimal for understanding the tradeoffs between the completeness and quality of forward detection on the one hand and important physics goals. At the 80% funding level, we will significantly reduce the chances of project completion in

Funding Level	%Funding	Baker FTE	Travel	Result
$88,020	100%	0.25 FTE	$22.5k travel	FY2020 goals completed
$70,420	80%	0.25 FTE	$5k travel	Goals may slip
$52,810	60%	0.20 FTE	$0 No travel	Unlikely to finish in FY2020

Table 4: Impact of Reduced Funding in FY2020

FY2020. It would only be possible if we are extremely lucky and everything goes unusually well. Most likely the project would have to be extended into FY2021. At the 60% level, the project will almost certainly take an additional year.

Having a validated version of BeAGLE as soon as possible is very important. Both laboratories are already "locking in" critical accelerator/IR decisions and even pushing back by asking questions about the physics impact and importance of forward particle detection. It is urgent to understand how well the current designs work for the critical physics goals of the e+A part of the program and to understand if the detectors in the forward region can be conventional, need to be state-of-the-art or need to be cutting edge detectors requiring substantial R&D.

5 External Funding

5.1 FY2019

During FY2019, Aschenauer, Chang, Lee, Tu and Zheng's salaries were provided by their home institutions. BNL provided per diem and housing for Chang.

Baker, Tu and Zheng participated in a JLAB LDRD "Tagged Short-Range Correlations for Medium to Heavy Ions at JLEIC" (D. Higinbotham et al.) in FY2019, which included support for Baker. One important new feature was added to BeAGLE: the capability of inputting hard events from an external generator known as the "Generalized Contact Formalism Event Generator" (GCF) [19] and using FLUKA [20] to decay the excited nucleus. Future plans include adding intranuclear cascading as well. The JLAB LDRD work is synergistic with eRD17, but is explicitly designed to not duplicate effort.

5.2 FY2020

During FY2020, Aschenauer, Chang, Lee, Tu and Zheng's salaries are expected to still be provided by their home institutions. We have proposed that BNL and the eRD17 project split the per diem and housing support for Chang (3 months each, based on 0.5 FTE participation in eRD17).

Baker, Tu and Zheng will continue to participate in the LAB LDRD if it is extended to FY2020 as expected. The main thrust of this project, which is orthogonal to the EIC R&D proposal, is to extend BeAGLE to include short range nucleon-nucleon correlations in the nucleus. This leads to long tails in the Fermi momentum of the struck nucleon as well as a correlated spectator partner. In addition, this effort would include an overhaul of the Fermi momentum in BeAGLE. The magnitude and shape of the distribution will be better matched to data and the Fermi momentum will be applied *before* the hard e+N collision, obviating the need to "post-fix" the momentum non-conservation.

6 Summary

The BeAGLE program for simulating e+A collisions is now being used at both prospective host laboratories for physics-driven refinement of detector requirements, particularly in the forward region. As discussed in the last few meetings, we have discovered that a key EIC physics measurement, incoherent diffractive exclusive vector meson production in e+A collisions, is likely to be an important driver of forward detector requirements, but is not yet well simulated. This measurement, especially in the case of ϕ production, is sensitive to gluon saturation. The process, especially in the case of the J/ψ, is also a background to coherent production, which would allow the measurement of the transverse spatial gluon distribution along with saturation effects.

We therefore proposed to extend BeAGLE to better describe diffractive physics in e+A collisions. We have made significant progress and are on track to complete the project in FY2020, providing the community with a significantly improved and validated e+A model code. Given the ongoing detector and machine design optimization, this project is urgent and should not be delayed.

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