BeAGLE: A Tool to Refine Detector Requirements for eA Collisions
EIC R&D Project eRD17: Progress Report (January-June 2020) and Proposal

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Abstract

The BeAGLE[1] program for simulating e+A collisions [1], 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 the EIC project, under the auspices of the "Yellow Report" process as well as the "machine baselining" process. During the next year or two, the EIC machine design will be finalized. Once that design is frozen, many aspects of the forward detector will be completely constrained, especially the possible acceptance. Therefore, FY2021, leading up to this "baselining", will be a critical year when the continued support of BeAGLE is essential. When asked, some of the Yellow Report physics and detector working group sub-convenors identified the continued support of BeAGLE as "indispensible", "essential and invaluable", "very important and essential" during the Yellow Report and subsequent TDR process. The Diffraction and Tagging Working Group conveners provided a joint statement to this effect, which is included as a supplementary document. Elke Aschenauer, Co-Associate Director for the Experimental Program of EIC, sent a letter directly to the committee emphasizing that BeAGLE support is essential for FY2021. In short, after five crucial years of support for this project, the EIC R&D committee has placed us in a position where we are not flying

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

blind during this critical year (FY2021) of the machine design process. Continued support for one more year will ensure that decisions regarding the IR/Forward Detector integration will be the best ones possible given realistic constraints and tradeoffs.

As requested by the committee, benchmark processes (key physics topics which are also very demanding on forward detection and IR integration) have been identified, in collaboration with YR convenors. These include: veto tagging of incoherent diffractive e+A collisions to access the gluon structure of the nucleus, tagging of the spectator protons in e+^{3}He to allow the extraction of neutron spin structure functions, the study of short range correlation (SRC) tagging and vetoing in both light and heavy nuclei in the EMC effect region ($0.2 < x < 0.8$), and the exclusive breakup of a deutron using J/ψ diffraction ($e + D \to e' + J/\psi + n + p$) to study the high relative momentum (k) tail of the deutron wavefunction.

In addition to supporting these ongoing analyses, we have made progress on and propose to continue the effort we proposed previously: tuning BeAGLE to the relevant E665 event-by-event e+A streamer chamber data [2, 3] in order to validate BeAGLE's physics model, particularly in the forward (ion-going) direction. 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. Because these simulations have such a strong implication for forward detector / IR design, it is imperative to validate the model with more — and more relevant — data. This work has progressed, but it was slowed down by the travel restrictions surrounding China before and during the COVID-19 crisis.

We therefore propose, during the remainder of FY2020 along with FY2021, a two pronged effort. First, to fully implement the benchmark processes described above and detailed below, along with supporting the physicists studying these processes as part of the Yellow Report process and the machine baselining process. Second, we propose to finish tuning to the most relevant data to ensure that the conclusions are as valid as possible. In particular, our goa for the tuningl is to answer two questions: First: 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. Second: is the description of the products of the INC in BeAGLE (DPMJet) accurate? I.e. do we have the correct distribution of momenta and most importantly angle for the protons, neutrons, deuterons, alphas et cetera that come from the collision? This will allow us to best understand the detector requirements for the critical and demanding benchmark physics measurements.

1 Introduction

As mentioned in the abstract and detailed below, a better simulation of key channels in e+A collisions is *essential* to EIC physics and to determining the detector requirements.

The organization of the remainder of the document is as follows. Section 2 summarizes the progress of the project from January-June 2020. Section 3 contains the proposal for the FY2020-2021 effort: upgrading BeAGLE to include a better description of benchmark channels 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 make key physics measurements on the other. Section 4 details personnel and funding issues. Section 5 discusses external funding as well as other projects and proposals involving BeAGLE and their synergy with eRD17. Section 6 lists the publications from eRD17. Finally, Section 7 contains a summary of the progress report and proposal.

1.1 EIC Physics Motivation for the Project

The committee summarized this very nicely in their last report: "BeAGLE is a generator to describe eA collisions for the EIC. . . . The code is being used for physics-driven refinements of detector requirements, particularly in the forward region and is essential in establishing EIC detector requirements" [4].

When asked, some of the Yellow Report physics and detector working group conveners mirrored the committee, identifying the continued support of BeAGLE as "indispensible", "essential and invaluable", or "very important and essential" during the Yellow Report and subsequent TDR process. The Diffraction and Tagging Working Group conveners provided a formal joint statement to this effect, which is included as a supplementary document. Elke Aschenauer, Co-Associate Director for the Experimental Program of EIC, sent an email to the committee emphasizing that BeAGLE support is essential for FY2021.

Continued support of this project for one more year will ensure that the final decisions regarding the IR/Forward Detector integration will be the best ones possible given realistic constraints and tradeoffs.

2 Progress Report: Achievements through June 2020

2.1 What was achieved?

Our main achievements during this time period include:

- Supporting and enabling physics-driven studies of EIC forward detector performance and requirements
- Implementation of the correct light-front wavefunction and kinematics for the deuteron in BeAGLE.
- Submission to a journal of a paper using BeAGLE [5].
- Successful comparison of BeAGLE and E665 kinematic data and a first look at the hadronic distribution.

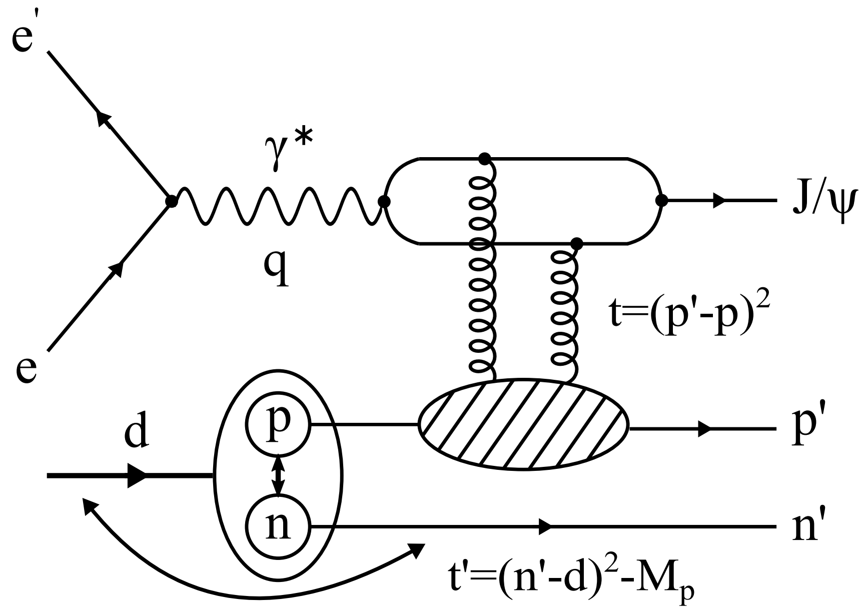

Figure 1: Diagram of incoherent diffractive J/ψ production in electron-deuteron scattering. Figure taken from Ref. [5]

A small subset of the results from the submitted paper [5] can serve to illustrate the level of detail and the type of plots available for relating the benchmark physics results to the detector/IR configuration. Figure 1 is a schematic diagram of incoherent diffractive J/ψ production in electron-deuteron scattering. This is one the identified benchmark channels discussed in Section 3.1 below. The basic idea is that the virtual photon fluctuates into a J/ψ particle which can then scatter off of one nucleon in the deuteron, dissociating the deuteron, a leaving a spectator nucleon. In general the spectator can be either the proton or the neutron, but Figure 1 shows the case of a struck proton and spectator neutron. In Fig. 2, the geometric layout of the far-forward region of the IR of the hadron-going direction is shown, together with a tentative conceptual design of far-forward particle detectors. The green rectangular boxes denote the dipole magnets; the green cylindrical boxes denote the quadrupole focusing magnets; the gray cylindrical tube is a simple representation of the beam pipe in the drift region where many of the far-forward protons and neutrons are detected. A detailed engineering design of the beam pipe is currently in progress.

In Fig. 3, the three-momentum distribution of the proton spectator, p_{m}, associated with incoherent diffractive J/ψ production in *ed* collisions is shown. The truth level simulation from BeAGLE is shown by solid star markers, while the open circles represent the results after the realistic simulation of the detector acceptance and forward instrumentation. The results of the full simulations (open square markers) include acceptances, smearing effects coming from intrinsic detector resolution, and beam-related effects. The p_{m} distribution reflects the internal nucleon momentum at the initial state of the deuteron wave function.

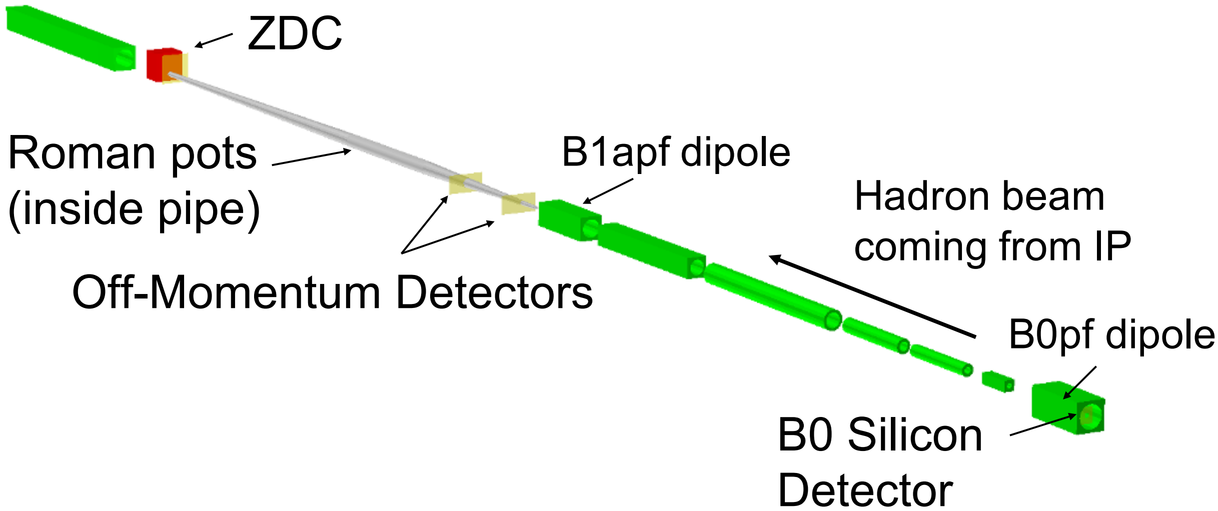

Figure 2: The layout of the EIC far-forward region depicting the detectors for proton and neutron detection. Figure taken from Ref. [5].

For momentum ranges from 0–300 MeV/c, this region is usually regarded as the mean-field region, while after $p_{\mathrm{m}} > 300$ MeV/c, the high momentum tail is regarded as the SRC region. We can see from the figure that the dominant detector effect for this variable is acceptance, while the resolution and beam smearing effects only show up at the very highest values of p_{m}. As the forward proton detection is refined this plot will need to be revisited, and this is an example of a plot which can be used to quanitify the importance of retaining or even improving, if possible, the acceptance of the forward proton detector.

In Fig. 4, the light-cone momentum fraction α of spectator neutrons is shown, for the same set of events as used in Fig. 3. It should be noted that the α variable of the spectator nucleon, along with p_{T} (discussed in the paper, but not here), parametrize the light-cone spectral function of the deuteron, which will be an important observable for measuring the SRC in the deuteron. For this variable, the acceptance has little effect as the ZDC is large enough to catch all spectators at this energy (110 GeV/nucleon deuteron beam). The momentum resolution and/or beam smearing effects, however, are much more significant here. This is an example of a plot which might change if we vary the ZDC energy resolution and could lead to a quantification of tradeoffs between ZDC quality and physics.

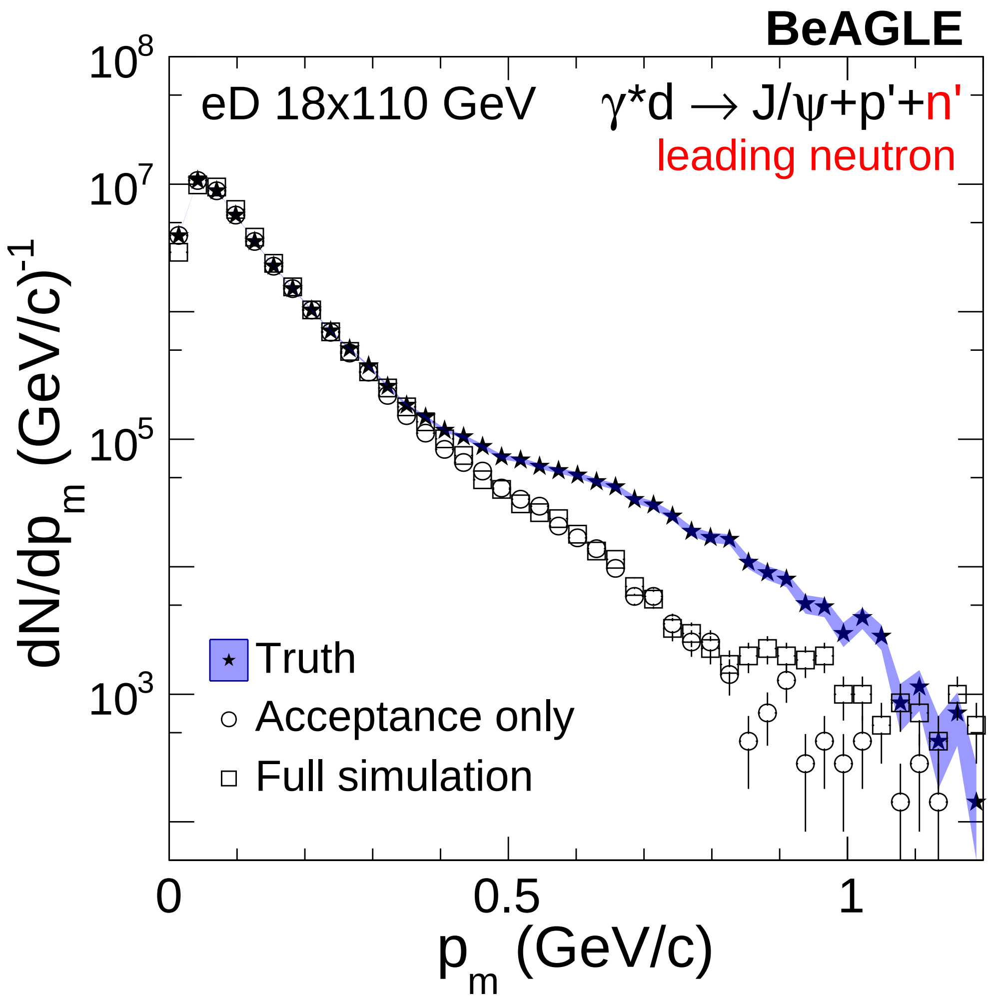

Figure 3: The three-momentum distribution of the spectator proton in events associated with incoherent diffractive J/ψ vector meson production in ed collisions is shown for the BeAGLE event generator. The simulations at the generator level, with acceptance effects only, and for the full simulations, are shown with solid, open circles, and open square markers, respectively. Figure taken from Ref. [5].

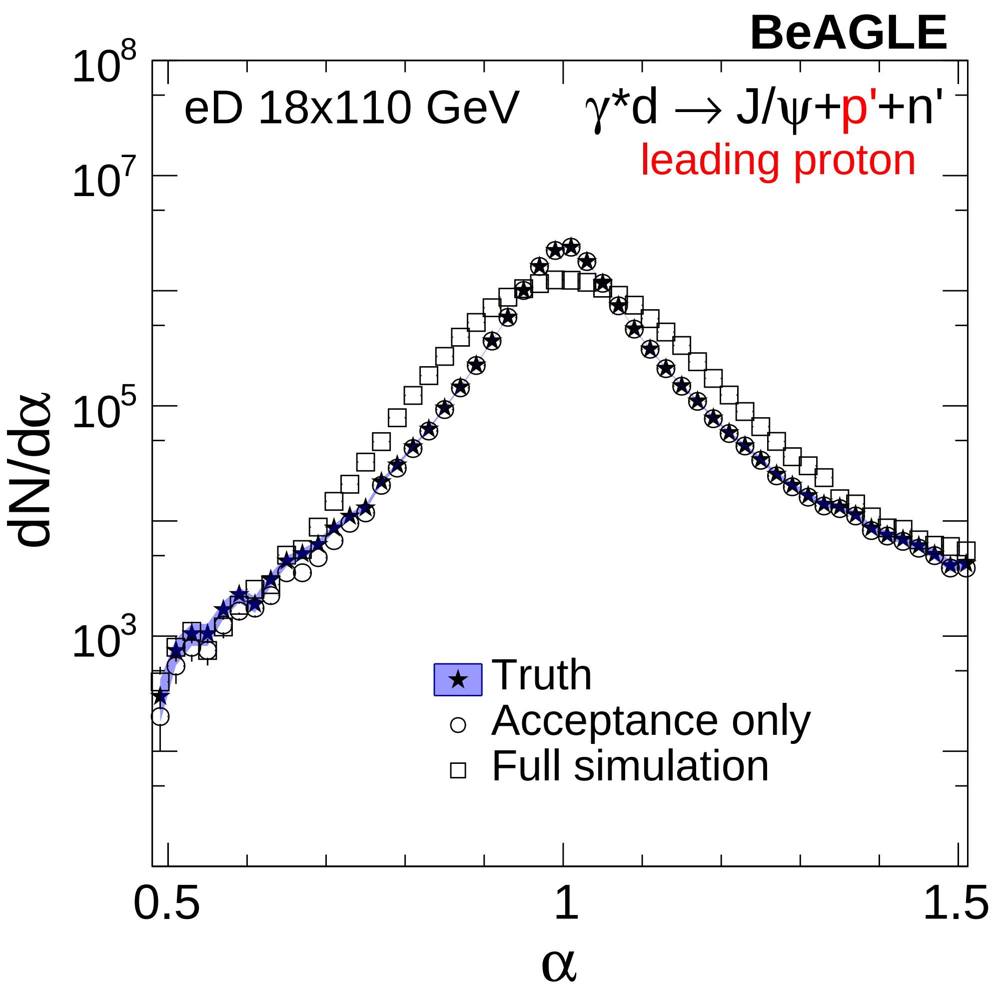

Figure 4: The light-cone momentum fraction α of the spectator neutrons are shown in events associated with incoherent diffractive J/ψ vector meson production in ed collisions. Simulations at the generator level, with acceptance effects only, and for full simulation, are shown with solid, open circles, and open square markers, respectively. Figure taken from Ref. [5].

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

The full RAPGAP installation was postponed, as we realized that it was lower priority than other tasks. No real correction is needed.

Matching of BeAGLE and E665 data was hampered, especially in early 2020, by the need to collaborate remotely. We adjusted by having more frequent remote meetings and including an additional collaborator, Alex Jentsch, who is focusing on the detector and IR modeling for EIC.

2.3 How did the COVID-19 pandemic and related closing of lab and facilities affect progress of your project?

Two of our collaborators, Liang Zheng and Wan Chang, work for universities in Wuhan, China(!). Fortunately, they are fine. However, they were both unable to spend any time at BNL in CY2020, which decreased the efficiency of their contribution. In particular, Liang was unable to spend a month at BNL as originally planned. Wan had been stationed at BNL, but happened to be in China for the New Year when the restrictions hit, so she had to continue her work from China. The poor internet connectivity for Wan and the need for remote supervision have slowed down our efforts on comparing and tuning to E665 data, although some progress has been made. We have frequent email contact and biweekly remote meetings on BlueJeans which do work well.

2.4 How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

All of our travel funding from FY20 will carryover to FY21. In addition, there were unrelated visa difficulties in 2019, which caused us to not spend travel funding in that year either. All told, we have $28,500 of unspent travel money. We propose to spend that money in FY2021 on supporting Baker insted of travel and we are not asking for any new travel money.

2.5 Do you have running costs that are needed even if R&D efforts have paused?

No. In any case, the R&D efforts have not paused.

3 Future / FY2021 Proposal

3.1 Benchmark Processes

In the January 2020 report [4], the committee requested "an implementation of a selected set of benchmark channels which would be handed over to the community for designing the EIC detectors". In practice the channels are not just "handed over" but rather it is an ongoing collaborative effort between BeAGLE developers and the physics/detector experts. The committee has already pointed out that BeAGLE has been developed unusually rapidly. A side effect of this is that it is not a polished product that can be just handed over, but rather requires significant back and forth as well as a bit of a fuzzy boundary between "developers" and "users". Nevertheless, we agree that a more focused set of channels would be useful, so we discussed this with the community and the following processes were identified as "benchmark channels":

- The channel $e + D \rightarrow e' + J/\psi + n + p$ represents diffractive J/ψ-induced breakup of the deuteron. This would allow us to tag and measure the high k tail of the deuteron wavefunction at a wide variety of values of x and Q^2, where k is the relative momentum of the proton and neutron. In particular, unlike in quasi-elastic events, we do not need to demand e.g. $x > 1.2$ which significantly distorts the acceptance in k_z (along the $\gamma*$ direction). This measurement also allows us to measure the size of nucleons in the deuteron and compare the high and low k cases (with or without short-range correlations) . A paper has been submitted [5] (led by Z. Tu). Note: This result does not involve nuclear breakup using DPMJET and FLUKA and therefore does not rely on BeAGLE tuning.

- The channel $e + Pb \rightarrow e' + V + X$ (with $V = J/\psi, \phi$) represents veto tagging of incoherent diffraction in order to allow the measurement of the t distribution of coherent diffraction. This in turn would provide unique information on the spatial distribution of gluons in the nucleus and the effects of gluon saturation, as we have discussed in previous reports. A paper is under preperation (led by T. Ullrich). As discussed before, this topic is difficult and may well drive the design of one or both IRs. The main issue remaining from a BeAGLE point fo view is validation and better understanding of the angular distributions of the nuclear reaction products by tuning BeAGLE to E665 data.

- The channel $e + A \rightarrow e' + (NN)_{SRC} + X$ in the EMC region $0.2 < x < 0.8$ represents our ability to tag (or veto) the existence of short-range correlations on an event-by-event basis in order to test more directly the model that the EMC effect is due to SRCs alone. This channel will require us to use GCF-DIS for the hard interaction and BeAGLE to model the hadronization as well as the nuclear response, including FSI between the pair nucleons and the nuclear remnant. This capability needs to be included in BeAGLE.

- The channel $e +^3 He \rightarrow e' + p + p + X$ represents quasi-free neutron scattering with tagged double-proton spectators. This channel is valuable to our capability to precisely measure the neutron spin using ^3He, but may be challenging to detect efficiently. We do not propose to model the spin structure function, but just the double-spectator proton tagging capability. DPMJet-F, a key component of BeAGLE, currently handles this process incorrectly, apparently confused into thinking that when the neutron is struck, that the remnant di-proton is a nucleus when of course it is unbound. This needs to be debugged. Apart from this bug, this channel is not sensitive to details of the nuclear remnant breakup in BeAGLE, just the correct handling of the "Fermi motion" which has been correctly implemented already.

3.2 Immediate Plans

The main and highest priority activity planned for the remainder of FY2020 is to implement and take at least a first look at all of the benchmark processes as well as tuning BeAGLE to the E665 data as far as it is possible. The main issues for the benchmark processes are to fix the DPMJET-F bug for the $e +^3 He \rightarrow e' + p + p + X$ channel and to implement the ability for BeAGLE to read in GCF-DIS events and simulate the nuclear response. The main issue for tuning BeAGLE is making sure that we understand the E665 data well enough to know that we are comparing apples to apples.

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

3.3 Proposal for FY2021

The proposed main goals through January 2021 are to test and debug BeAGLE, especially in the benchmark channels and to support the Yellow Report and machine baselining simulations.

The main goal for the remainder of FY 2021 is to support the ongoing machine baselining simulations and to respond to new requests which arise in that context. In addition, we need to quantify the systematic uncertainty in our understanding of the nuclear response based on our ability (or not) to tune to the E665 data. In particular, we should understand the impact that these uncertainties have on our conclusions concerning the feasibility of the benchmark channels.

4 Personnel and Funding

4.1 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.

Person	Institution	Effort (FTE-year)	Cost to Proposal	Remarks
M.D. Baker	MDBPADS[6]	0.45	$93,000	
W. Chang	CCNU/BNL	0.50	$0	salary covered by CCNU
A. Jentsch	BNL	0.20	$0	cost covered by BNL
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:		1.50	$93,000	

Table 1: Personnel Budget Breakdown for FY2021 (new money)

Item	Cost
Personnel:	$93,000
TOTAL:	$93,000

Table 2: Total Budget Breakdown for FY2021 (new money)

4.2 Personnel, Timetable and Budget

Estimated milestones for FY2021 include:

Nov. 21, 2020 Presentation of new BeAGLE results at the Yellow Report meeting.

January 2021 BeAGLE benchmark channels in good enough shape to be used by the community for the Yellow Report.

May 2021 BeAGLE improved according to feedback during the baselining project

Sept. 30, 2021 Quantification of the uncertainties in the simulation.

In order to help accelerate the work during this critical year (FY2021) when external support is likely to dry up, we propose to spend all of our carryover ($28,500) and add $93,000 of new money to support Baker at his maximum capacity (0.45 FTE). This represents a "bottom up" estimate of what is needed in order to support and enable the ambitious goals of the community of writing the Yellow Report by January 2021 and making adequate progress towards CD-2. It is fortunate that this bottom up request implies only a 6% nominal increase over last year's approved budget of $88,020 for FY2020.

Table 1 shows the personnel budget breakdown for FY2020. Table 2 shows the total budget (new money).

4.3 Impact of Reduced Funding

Table 3 shows the impact of reduced funding. With full funding we expect to complete the project — upgrading BeAGLE to cover all benchmark processes and using E665 SC

FY2021 Funding	Total Funding (incl. carryover)	%Funding	Baker FTE	Result
$93,000	$121,500	100%	0.45 FTE	Project goals completed
$74,400	$102,900	80%	0.38 FTE	Goals may slip
$55,800	$ 84,300	60%	0.31 FTE	Unlikely to finish in FY2021

Table 3: Impact of Reduced Funding in FY2021

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. We will also support the community in applying BeAGLE to these goals. At the 80% funding level, we will significantly reduce the chances of project completion in FY2021. It would only be possible if we are extremely lucky and everything goes unusually well. Most likely some important information will be unavailable to the detector/IR design process. At the 60% level, the project will almost certainly be incomplete.

Having a validated version of BeAGLE as soon as possible is very important. BNL is naturally "locking in" critical accelerator/IR decisions and even pushing back by asking questions about the physics impact and importance of forward particle detection. Furthermore a second IR is being considered. 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

The BeAGLE effort was strongly supported by JLAB LDRD from FY2017-FY2019. This support included 0.2 FTE support for Baker as well as 0.5 FTE postdoc support for running BeAGLE and simulating key physics/detector questions. Due to the change in the EIC project status, this support was reduced in FY2020 and support is not currently foreseen in FY2021. MITLNS (Or Hen) also supported GCF [7]/BeAGLE integration for 3 months at 0.2 FTE during FY2020.

No large scale external funding at the level seen in FY2017-2019 is foreseen for FY2021.

6 Publications

We submitted a BeAGLE publication to Physics Letters B, in collaboration with the Yellow Report Diffraction/Tagging Working Group. It is entitled "Probing short-range correlations in the deuteron via incoherent diffractive J/ψ production with spectator tagging at the EIC" [5]. This paper addresses one of the benchmark processes discussed above in Section 3.1. A small subset of the results were shown and discussed above in Section 2.

More publications are expected over the next year, covering more of the benchmark processes as well as a paper describing BeAGLE and comparing it to E665 data.

7 Summary

The BeAGLE program for simulating e+A collisions is now being heavily used for physics-driven refinement of detector requirements, particularly in the forward (ion-going) region. The community has recognized that it is absolutely essential for the next year (FY2021) as we prepare the Yellow Report and the CDRs on the way to the CD-2 DOE milestone (see attached letter plus that provided by Elke Aschenauer). As requested by the committee we have identified "benchmark processes" to focus on which are important measurements for EIC physics that are particularly demanding for forward detection.

We propose to support the ongoing use of BeAGLE by the growing user base, to extend BeAGLE to fully describe the physics needed for the benchmark processes, and to finish comparing and tuning BeAGLE to E665 data so that the conclusions are more trustworthy. Due to the urgency of this project during the next year, we propose a very slight (6%) increase in funding which, in conjunction with the carryover, will allow almost a doubling of Baker's effort on eRD17.

References

[1] https://wiki.bnl.gov/eic/index.php/BeAGLE

[2] M.R. Adams et al., "Production of charged hadrons by positive muons on deuterium and xenon at 490 GeV", Z. Phys. **C61** (1994) 179.

[3] M.R. Adams et al., "Nuclear shadowing, diffractive scattering and low momentum protons in μXe interactions at 490 GeV", Z. Phys. **C65** (1995) 225.

[4] M. Demarteau, C. Haber, P. Krizan, I. Shipsey, R. VanBerg, J. Va'vra, G. Young, "Report of the 18th Electron Ion Collider Detector R&D Meeting, January 30–31, 2020", https://wiki.bnl.gov/conferences/images/a/a5/EIC_Review_2020-Jan.pdf

[5] Z. Tu et. al,"Probing short-range correlations in the deuteron via incoherent diffractive J/ψ production with spectator tagging at the EIC", submitted to Physics Letters B, https://arxiv.org/abs/2005.14706

[6] http://mdbpads.com

[7] A. Schmidt. 2nd Workshop on quantitative challenges at SRC and EMC research, MIT, Cambridge, MA. (2019), http://www.mit.edu/~src_emc/fri/schmidt_20190322.pdf

25 June 2020

Dear Dr. Mark Baker:

As the conveners of the EIC Yellow Report Working Group on "Diffraction and Tagging," we would like to support the EIC R&D proposal for continued development of BeAGLE.

BeAGLE is an essential tool for simulating reactions that are important for our working group. Examples include incoherent production of vector mesons in electron-light-ion and electron-heavy-ion collisions. Although other Monte Carlos can simulate vector meson production, BeAGLE is the only tool that can simulate the ion final state, providing kinematics for the nucleons and photons from nuclear dissociation. This is critically important in determining how well we can separate coherent and incoherent photoproduction, something that is needed to study the physics laid out in the 2012 EIC White Paper. Similarly, it is the only generator suitable for SRC studies that can account for FSI and other competing reaction effects that impact the detector requirements.

In short, BeAGLE is very useful in characterizing detectors in the far forward region. This is extremely important as we start to firm up the detector requirements and characteristics as part of the Yellow Report process and future Conceptual Design Report.

Sincerely,

Prof. Wim Cosyn
Florida International University

Prof. Or Hen
Massachusetts Institute of Technology

Dr. Douglas Higinbotham
Jefferson Lab

Dr. Spencer Klein
Lawrence Berkeley National Lab

Prof. Anna Stasto
Pennsylvania State University

Conveners of the EIC Yellow Report Working Group on "Diffraction and Tagging"