BNL's Plan for Completing the Mission of RHIC and the Transition to eRHIC
October 14, 2013

Sec. 1: Introduction and Overview…… 2
Sec. 2: Completing the RHIC Mission……..... 4
Sec. 3: The Role of sPHENIX……. 7
Sec. 4: eRHIC Accelerator Design…… 10
Sec. 5: Realizing eRHIC…… 12
Sec. 6: Letters of Intent and eRHIC Detector Plans…….. 14
Sec. 7: Engaging the EIC community—Outlook…….. 18

Attachments: sPHENIX proposal, ePHENIX and eSTAR Letters of Intent

Summary

BNL is well along in a conceptual design for a cost effective electron ion collider, eRHIC, that builds on the existing RHIC facility to address the vision for a long-term future of QCD-related research, as laid out in the community-wide 2012 white paper, "Electron-Ion Collider: the Next QCD Frontier". We provide here a status report on Brookhaven's plan to complete the scientific program of RHIC and make a smooth transition to the first eRHIC experiments by 2025, with minimal interruption of physics operation between the end of RHIC and start of eRHIC. The proposed sPHENIX upgrade of the PHENIX detector is an integral part of this plan. We emphasize that this plan is in a developing stage, and this preliminary document is not for general distribution.

The proposed eRHIC facility will provide 10 GeV electron beams colliding with the full array of RHIC hadron beams, with e-nucleon luminosity of ~10^{33} $cm^{-2}sec^{-1}$ for 10 GeV polarized electrons on both 250 GeV polarized protons and 100 GeV/u heavy ion beams. The machine can be upgraded to meet future requirements for increased luminosity and electron energy. We plan to utilize the existing experimental infrastructure in the PHENIX and STAR detector halls for the initial eRHIC experiments. The estimated base cost of the eRHIC accelerator is $550M (FY 2012$), including coherent electron cooling for the hadron beams and a single "standard" inter-section region (IR). This estimate does not include the cost of detectors, nor the cost of specialized IR configurations. Depending on the detector designs, the implementation of two IRs for initial experiments will incur estimated additional costs of 50-150M$, bringing the cost of the machine, including IRs, to $600-$700M (FY2012 $).

The plan presented here includes an operations schedule for RHIC through the transition period that allows significant re-direction of effort and funding resources, off-setting the cost of new construction for the eRHIC machine and detectors by approximately $200M (FY 2012 $). The schedule exploits the fact that RHIC cannot run in certain years (2017 and 2020) for technical reasons, when machine or major detector upgrades are being installed.

A key goal of the completion of RHIC's scientific mission is the exploitation of its upgraded luminosity to make definitive measurements of the color response the quark-gluon plasma to high-energy partons (jets) and to bound pairs of b-quarks (Upsilon mesons). The measurements will utilize the proposed sPHENIX upgrade that converts PHENIX to an open geometry detector with a 1.5 T superconducting solenoid (re-using the former BaBar magnet) and large acceptance electromagnetic and hadronic calorimetry. The sPHENIX upgrade, with an estimated cost (TPC) of $34M (FY 2012 $), is planned to be operational for the last RHIC physics runs in 2021-22. In addition to its central role in the final RHIC campaign, the sPHENIX configuration presents an excellent basis for an eRHIC detector capable of executing the compelling science program laid out in the EIC White Paper at the proposed facility.

Based on Letters of Intent received this month, the preliminary estimate of the cost to upgrade sPHENIX to a full capability eRHIC detector is ~$110M including contingency and overhead, some of which is expected to come from non-DOE sources. The estimate given for STAR upgrades to serve as eRHIC detector is ~$40M. The precise implementation and subsequent evolution of an experimental program for eRHIC will depend on funding and will be carried out through a proposal driven process.

Section 1: Introduction and Overview

Since it began physics operations in 2001 the Relativistic Heavy Ion Collider has been extra-ordinarily successful, and stands as one of the most versatile and scientifically productive accelerator facilities world wide. It has opened a new field of research in Nuclear Physics with a series of discoveries revealing the quark-gluon phase of matter. In addition, as the world's only polarized proton collider, RHIC is advancing our knowledge of the spin structure of the nucleon through measurements of gluon and antiquark polarization. Through continuous improvements, including the successful implementation of bunched beam stochastic cooling, RHIC's luminosity has reached 15 times the design luminosity and achieved the RHIC-II machine performance goals at a small fraction of the originally anticipated cost and half a decade earlier.

With major detector upgrades either completed or under way to exploit this enhanced capability, an energized and committed RHIC user community is poised to address many of the compelling science questions in hot and dense QCD matter physics that follow from the discoveries to date. In addition to these upgrades, the PHENIX collaboration has proposed a major upgrade of its detector "sPHENIX", which would enable high resolution, high acceptance jet and quarkonium measurements which uniquely probe the color response properties of the quark-gluon plasma and promise to identify the scale at which the matter turns from a quasiparticle plasma into a strongly coupled "perfect" liquid.

Concurrently, the Nuclear Physics community's vision for the long-term future of QCD-related research have led to a broad consensus on the requirements for an Electron Ion Collider as an essential new facility to pursue this physics as outlined in the 2012 EIC White Paper: http://www.bnl.gov/npp/docs/EIC_White_Paper_Final.pdf . An extensive accelerator R&D program has led to a cost-effective plan to realize such a facility at BNL, called eRHIC, utilizing the fully developed RHIC complex to provide intense, high-energy beams of ions and polarized protons in concert with high-energy, high- brightness polarized electron beam produced with an Energy Recovery Linac.

An important component of this planning is the consideration of how best to utilize the existing RHIC detector infrastructure for experiments at eRHIC. To this end, BNL's Associate Laboratory Director for Nuclear and Particle Physics issued, in May 2013, a charge to the PHENIX and STAR collaborations requesting that they each provide specific plans (Letters of Intent) to upgrade/reconfigure the detectors from their present form to first-generation eRHIC detectors. These LOIs have been submitted, and accompany this document. The PHENIX collaboration is proposing a major reconfiguration of the detector, called sPHENIX, to enable measurements of jet observables in heavy ion collisions as part of the RHIC program. The ePHENIX LOI describes the subsequent evolution of sPHENIX into an eRHIC detector. The proposal for sPHENIX is also provided with this document, and its role in the BNL plan to complete the RHIC program is discussed in Sec. 3 below.

The current design for the eRHIC machine is described in Sec. 4 of this document. The goal is to make the most effective use of the existing facility, with achievable technology advances and realistic budget assumptions, to provide a science program that can begin addressing the key measurements outlined in the EIC White Paper by the mid-2020's. eRHIC will provide a polarized electron beam with an energy of 10 GeV colliding with the full array of RHIC hadron beams, at a luminosity of 10^{33} $cm^{-2}sec^{-1}$ for 10 GeV polarized electrons on 250 GeV polarized protons. The machine is designed to be upgradable to meet future requirements for increased luminosity and electron beam energy.

The estimated base cost for the eRHIC machine is $550M (FY 2012$). This estimate includes the cost of coherent electron cooling for proton beams and a single "standard" intersection region (IR) capable of housing a collider detector. The implementation of a second IR would add an estimated $50M to the machine cost. As discussed in Sec. 4, a special "crab crossing" IR configuration has been designed to provide a collision region free of synchrotron radiation without requiring specialized dipole fields built into the detector. A crab crossing upgrade of a standard IR would add an additional $50M to the IR cost. Thus, based on these preliminary estimates, the implementation of two IRs will incur additional costs of $50M to $150M, depending on detector design, bringing the cost of the machine to $600M - $700M (FY 2012$).

The most cost-effective approach to an experimental program at eRHIC is to utilize the existing infrastructure of one or both of the current PHENIX (eight o'clock) or STAR (six o'clock) detector areas at RHIC. By calling for Letters of Intent, BNL has explored the possibility of realizing detectors for eRHIC through upgrades of PHENIX and STAR. It is, however, a key element of the Laboratory's plan that the eRHIC experiments will be formed and managed as new collaborations, open to participation by the entire worldwide nuclear physics QCD community.

In Sec. 5 we provide a notional plan for RHIC operations through the transition period, and corresponding construction schedules for sPHENIX, eRHIC, and an initial eRHIC detector complement. The operations plan for RHIC during this period includes gap years with no running. These gaps are necessary to accommodate installation of new equipment (low-energy electron cooling; sPHENIX, STAR forward upgrades). Our plan uses these years to provide periods when substantial amounts of labor and operations funds can be re-directed to offset, in part, the cost of sPHENIX and eRHIC construction.

In Sec. 6 we discuss the recently received Letters of Intent, and BNL's plans to engage the nuclear physics community in moving forward with an experimental program for eRHIC.

Section 2: Completing the RHIC Mission

The final RHIC campaign is envisioned to be carried out over roughly the next decade. Its purpose will be to complete critical measurements that take full advantage of the versatility of RHIC covering nearly the entire QCD phase diagram, ranging from nearly net baryon number free hot QCD matter to hot and extremely baryon dense QCD matter. It will also exploit the unique capabilities of RHIC as a polarized hadron collider. This final campaign must be one of definitive measurements with broad capability for new discovery, which, in combination with those at LHC and future facilities such as FAIR and an Electron Ion Collider, give as complete a picture as possible of the evolution and properties of QCD matter, and which permit to identify the physical mechanisms that are responsible for the unique properties of the strongly coupled, liquid quark-gluon plasma.

The RHIC campaign will focus on measurements that will provide critical information on the most characteristic properties of the quark-gluon plasma: its inability to easily transport energy and momentum, expressed in transport coefficients such as shear viscosity and momentum diffusion constant; its static and dynamical color response functions. In order to perform these measurements, the RHIC program will exploit machine improvements and detector upgrades to address three broad areas:

1. Utilize the new silicon vertex trackers to quantify the transport properties of the QGP employing heavy quarks as probes. Measurements to date showing surprisingly strong suppression of high p_T leptons in heavy ion collisions indicate that heavy quarks lose energy nearly as rapidly as light quarks in traversing the QGP, contrary to previous expectations from theory for parton energy loss in hot QCD matter. The PHENIX VTX and FVTX are operational with demonstrated performance capability. The STAR Heavy Flavor Tracker is in the final stages of construction, and expected to be commissioned and operational in Run 14. Both collaborations can now take advantage of micro-vertex detection to directly observe heavy quark decays and distinguish effects from c and b quarks in heavy ion collisions with large data samples made possible by the increased RHIC luminosity. This will enable detailed studies of parton energy loss and the degree to which c and b quarks participate in the thermalization and collective flow observed so far in lighter quarks. In light of the importance of such measurements, BNL's Program Advisory Committee (PAC) for RHIC has given highest priority to full-energy Au-Au collisions and corresponding comparison measurements in Runs 14-15.

2. Complete the QCD Critical Point search, with electron-cooled low-energy beams. The beam energy scan carried out at RHIC in 2010-2011 (BES-I) has produced a wealth of new data on the evolution of QCD matter as the baryon chemical potential changes. It has provided first indications that the transition from hadronic to quark-gluon degrees of freedom occurs within the energy range spanned at RHIC, offering a unique opportunity to study QCD properties from below to above the transition. This same scan has also shown fluctuation phenomena that suggest an approach toward the anticipated critical end point in the QCD phase diagram. With the BES-I scan RHIC has explored nucleon-pair c.m. energies ranging from 7.7 GeV to 200 GeV in Au-Au collisions, with strong indications of changing behavior at or below 20 GeV. At these energies, extending well below the original design range for RHIC, the collision rates are very low and results have large statistical uncertainties. A second beam energy scan (BES-II) is planned, utilizing electron cooling of the low-energy Au beams to provide enhanced luminosity and extending to c.m. energy as low as 5 GeV, to make precision measurements of the changing phenomena over a domain of the QCD phase diagram where the baryon chemical potential varies from near zero at the highest Au-Au energies to ~500 MeV at the lowest. Electron cooling for low-energy RHIC beams is currently under development as an AIP project, with installation planned in time to enable BES-II runs in 2018-2019.

3. Exploit new probes of QGP with jet observables. RHIC has clearly established the existence of a strongly interacting partonic phase, the sQGP. As emphasized by the PAC in its 2012 review of the decadal plans, "The important question over the next decade is to understand the reason for this set of characteristics… to both identify the constituents

(effective degrees of freedom) of the sQGP, and clarify the nature and strength of their interactions". Key among these measurements is the use of reconstructed jet as probes of the QCD medium. Explicitly, the observable to be investigated is the opacity/transport parameter q-hat, and its dependence on color charge, parton mass, parton energy, path length, and energy density/temperature. With RHIC-II luminosity now in place, full jet measurements as well as jet-jet and γ-jet correlations will become available in the latter part of this decade through the reconfiguration of PHENIX to an open geometry detector with the proposed sPHENIX upgrade, and modest upgrades to the existing STAR detector. The role of sPHENIX is further described in the following section, and the sPHENIX proposal is attached to this document. This upgrade, with an estimated cost of $34M (FY 2012 $) is planned to be fully in place for RHIC operation beginning in 2021. Its further evolution to an eRHIC detector is the basis for the ePHENIX LOI.

The Table below shows the current plan for the RHIC operating schedule prior to the final shutdown for the installation of eRHIC. The plan includes early commissioning of a partially installed sPHENIX in the 2019 Run.

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p+p at 200 GeV p+Au, d+Au, ^{3}He+Au at 200 GeV High statistics Au+Au	Extract η/s(T) + constrain initial quantum fluctuations More heavy flavor studies Sphaleron tests Transverse spin physics	PHENIX MPC-EX Coherent e-cooling test
2017	No Run		Low energy e-cooling upgrade
2018-19	5-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR ITPC upgrade Partial commissioning of sPHENIX (in 2019)
2020	No Run		Complete sPHENIX installation STAR forward upgrades
2021-22	Long 200 GeV Au+Au with upgraded detectors p+p, p/d+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	sPHENIX
2023-24	No Runs		Transition to eRHIC

Table 2-1: A long-term view of the RHIC operations schedule leading to a transition to eRHIC.

The schedule in Table 2-1 includes continued exploration of cold nuclear matter and the proton spin structure, with polarized proton collisions at 200 GeV to tighten constraints on gluon helicity at medium to large x and continuing the study of transverse spin asymmetry, and collisions of polarized protons and light ions with Au beams to continue the study of possible gluon saturation effects at very forward angles as predicted, e.g. by the Color Glass Condensate model. Both STAR and PHENIX have discussed possible forward detector upgrades for such studies. These measurements will be precursors to the eRHIC program. The schedule shown in Table 2-1 does not include another long polarized proton run at 510 GeV beyond that carried out in 2013. Such a run would be needed to satisfy the NSAC performance milestone HP-13 at RHIC. In order to better assess the physics opportunities that will be lost with the schedule of Table 2-1, BNL has asked the RHIC collaborations to submit white papers describing future opportunities with polarized proton beams at RHIC in time for consideration at the next PAC meeting in June 2014.

Section 3: Role of sPHENIX

The PHENIX collaboration, in its decadal planning for measurements at RHIC and with an eye on future measurements with eRHIC, has developed a proposal for a major upgrade (sPHENIX) that will rebuild the central rapidity region of the present PHENIX detector. The aim is to provide high quality jet physics measurements in heavy ion collisions for the final, high-luminosity years of RHIC operation. These measurements probe the dynamical color response of the quark-gluon plasma. Foreign funded enhancements of the tracking capabilities of sPHENIX could also allow for high resolution, high statistics measurements of Upsilon states production, which probe the static color response (color screening) of the matter, the other defining property of the quark-gluon plasma. The sPHENIX upgrade would also position the detector well for subsequent instrumentation additions to address the physics of e-p and e-A collisions at eRHIC.

The phenomenon of jet quenching, among the earliest of RHIC discoveries, is a manifestation of the fact that energetic quarks and gluons moving through the strongly coupled QGP rapidly lose energy. The precise set of mechanisms of this energy loss is still not well understood, although there has been significant progress in recent years, both experimentally and theoretically, in quantifying the medium properties implied by the data. The capability to completely reconstruct high-energy jets provides full information on the fragmentation pattern of the leading parton and gives access to the soft particles that reflect the response of the medium to the nascent jet. Detailed, quantitative information on the scattered parton and the properties of the scattering medium is then accessible through jet-jet, jet-hadron, and γ-jet correlations. Analyses of this kind are being carried out at the LHC heavy ion experiments, where jet reconstruction techniques have been well developed making use of detectors with excellent, large acceptance calorimetry.

Since the response of the quark-gluon plasma is expected to be very sensitive to energy density, and hence to the collision energy, it is important to carry out high quality jet measurements over the RHIC energy range as well. Experiments at RHIC have the additional advantages that the virtuality of the produced jets is more closely matched to the characteristic scales of the matter, and that the soft background is lower by almost a factor 3. The updated sPHENIX proposal to carry out such measurements is included with this document.

The proposed sPHENIX detector covers 2 units of pseudorapidity and full azimuth (the present PHENIX central arms cover $\Delta\eta = 0.7$, $\Delta\varphi = 2 \times \pi/2$). It employs a 1.4 m inner diameter, 1.5 T superconducting solenoid magnet (the former BaBar magnet). The detection elements consist of the existing PHENIX Silicon Vertex Tracker (VTX) for tracking, a compact tungsten-scintillator sampling electromagnetic calorimeter with SiPM readout, and an iron-scintillator sampling hadronic calorimeter that doubles as the flux return for the solenoid. Fig. 3-1a shows a cutaway view of the detector. Fig. 3-1b shows the detector *in situ* in the PHENIX hall.

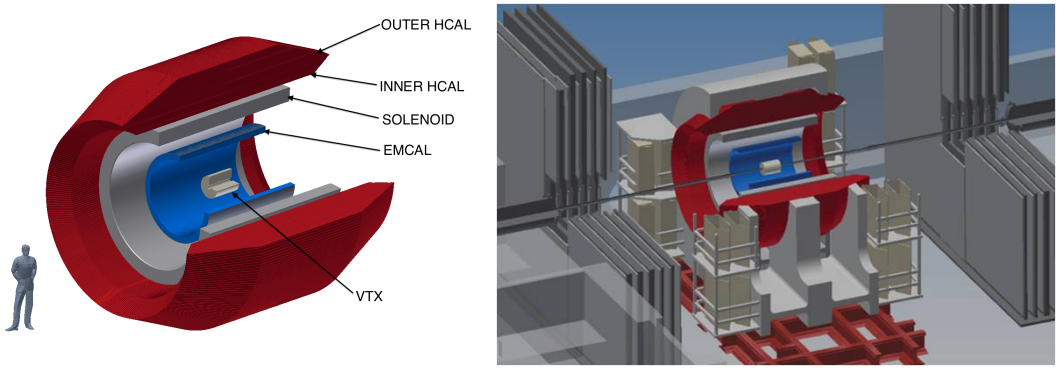

Figure 3-1: a (left) Cutaway view of the sPHENIX detector. b (right) sPHENIX in the PHENIX Hall.

The cost of this configuration is $34M (FY 2012$). A significant redirection of funds to cover the cost of sPHENIX is being studied as part of the RHIC operations plan described in Sec. 5. A breakdown of the costs and proposed funding profile for the project is shown in Table 3-1.

Budget Year	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	Total
Equipment	4.0	8.0	8.0	6.5	1.4	27.9
Labor	0.3	1.1	1.1	1.8	2.0	6.3
TPC	4.3	9.1	9.1	8.3	3.4	34.2

Table 3-1: sPHENIX funding (in FY2012 M$)

The sPHENIX proposal describes a plan to upgrade the detector with additional tracking between the VTX and the calorimeters, and a pre-shower detector in front of the EM calorimeter. The added tracking would be required for accurate charged particle measurements above $p_T = 5$ GeV/c and for tagging heavy flavor jets. The pre-shower detector would allow π^0/γ separation above 10 GeV/c (to 40 GeV/c) and e/π rejection for separation of Upsilon states. The goal is to have these upgrades installed and available for physics on Day-1, and toward that goal the PHENIX collaboration is actively pursuing funding through proposals to US-Japan, RIKEN, and JSPS.

In October 2012 BNL convened an independent panel to review the sPHENIX proposal for its scientific importance and technical feasibility. The panel members were M. Gyulassy (Columbia), J. Harris (Yale), M. Harrison (BNL), J. Proudfoot (ANL), R. Venugopalan (BNL), and B. Wyslouch (MIT). Xin Nian Wang (LBNL) also commented on the proposal, but was not able to be present for the review meeting. The committee report, which was provided to DOE in November 2012, strongly endorsed the science case for the program of measurements laid out in the sPHENIX proposal, noting that "*jet measurements offer a unique access to properties of the strongly coupled quark gluon plasma (sQGP), providing information that may be qualitatively different from the long wavelength properties of the medium, such as η/s and the speed of sound.*" The committee stressed the importance of implementing the tracking and pre-shower upgrades in order to achieve the full science potential. The proposed technical components were found by the committee to work well together to realize a compact detector with technologies that are either in hand or are being widely developed (e.g. SiPMs). The primary concern was the plan, at the time, to design and build a new superconducting magnet. The level of challenge is greatly reduced by the acquisition of the BaBar magnet, whose ownership has been transferred from SLAC to BNL for use as a suitable magnet at RHIC.

BNL management believes that this upgrade of the PHENIX detector is essential for carrying out the final, crucial element of the remaining RHIC mission, as described in Sec. 2. The STAR detector, with tracking, particle ID, and EM calorimetry over a large solid angle is also capable of carrying out jet measurements, but with its smaller magnetic field and lack of a hadronic calorimeter it is not optimized for such measurements over the entire RHIC jet energy range. While STAR would participate usefully in a run dedicated to jet observables, PHENIX in its present configuration would not. While the justification for a series of runs dedicated primarily to jet measurements lies in the compelling physics case, the ability to achieve the physics goals at RHIC rests largely on the sPHENIX upgrade and the intense work of both collaborations together with the theory community to master the tools of jet analysis in A-A collisions and ensure timely, impactful physics output.

As discussed in Sec. 6 and described in detail in the enclosed ePHENIX Letter of Intent, sPHENIX also provides the basis for a future upgrade to an all purpose detector for eRHIC.

Together with its critical role in completing the scientific mission of RHIC, the successful implementation of sPHENIX thus becomes a high priority component of the planned transition from RHIC to eRHIC.

Section 4: eRHIC Accelerator Design

The eRHIC accelerator is designed to provide timely and cost-effective access to the Electron Ion Collider physics program outlined in the White Paper produced in 2012 by the EIC community. The eRHIC design adds a high current, multi-pass Energy Recovery Linac (ERL) and electron recirculation rings to the existing RHIC hadron facility to provide a polarized electron beam with energy of 10 GeV colliding with ion species ranging from polarized protons with a top energy of 250 GeV to fully stripped uranium ions with energies up to 100 GeV/u, and e-nucleon luminosity of ~10^{33} $cm^{-2}sec^{-1}$. The eRHIC design is upgradeable to ultimately reach electron energy up to 30 GeV, with luminosity ~10^{34} $cm^{-2}sec^{-1}$ for electron energy up to 20 GeV. The bunch-crossing frequency at eRHIC will be the same as that at RHIC, so that detector electronics from RHIC can be carried over to eRHIC.

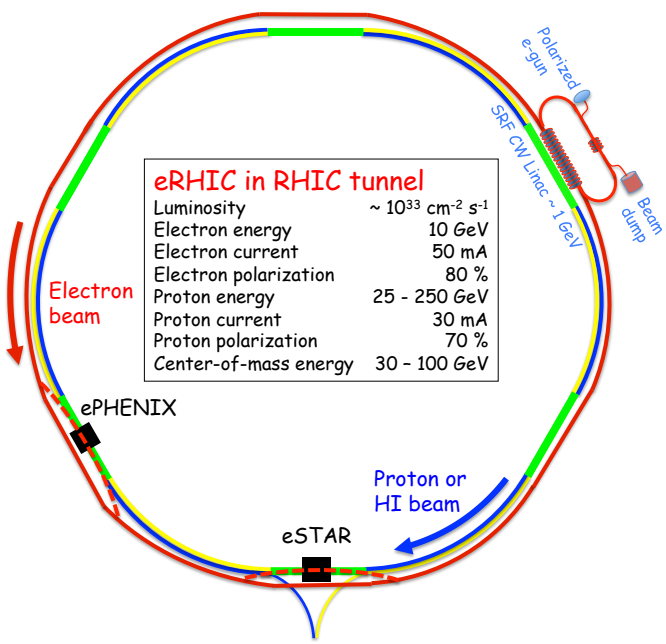

Figure 4-1: Layout and design performance parameters of the proposed eRHIC facility.

As illustrated in Fig. 4-1, electrons are accelerated in multiple passes through an approximately 1 GeV ERL, located at the 2 o'clock straight section at RHIC. The electron transport rings are located inside the RHIC tunnel, with collisions possible at multiple intersection regions (IR). We are developing beam transport optics with very large beam energy acceptance using the Fixed Field Alternating Gradient (FFAG) technique, where a single ring can accommodate the required nine passes in a highly cost effective way. For practical and cost considerations the maximum

beam power loss due to synchrotron radiation is limited to about 9 MW, which corresponds to a 50 mA electron beam current. Since the ERL provides fresh electron bunches for every collision, the electron beam can be strongly distorted during the collision with the much stiffer hadron beam. This makes it possible to greatly exceed the beam-beam interaction limit that would otherwise apply in a storage ring. The ERL concept also allows for full electron beam polarization with an arbitrary direction at the interaction point over the whole energy range.

To achieve the very high luminosity without requiring a larger electron beam current and therefore unacceptably large beam power loss due to synchrotron radiation, the emittance of the hadron beam has to be very small – about 10 times smaller than presently available in hadron beams. This is also a requirement for certain small-angle physics measurements required of an EIC. This requires a level of beam cooling that can only be achieved using Coherent electron Cooling (CeC), a novel form of beam cooling that promises to cool ion and proton beams by a factor of 10, both transversely and longitudinally, in less than 30 minutes. CeC will be tested in 2015 in a proof-of-principle experiment at RHIC by a collaboration of scientists from BNL, JLab, and TechX. R&D is also under way at BNL on a high beam intensity ERL, and, at BNL, JLab, and MIT, on source techniques for producing a 50 mA polarized electron beam.

More so than in a hadron collider, the IR design in an electron ion collider is closely coupled with the detector design, as any bending of the electron beam near the collision point produces harmful synchrotron radiation. A high-luminosity IR design for eRHIC has been designed, and is described in the EIC White Paper. The layout is shown in Fig. 4-2. In it, the beams cross at a 10 mrad angle, with zero magnetic field along the electron beam trajectory, and hence no synchrotron radiation in the ±4.5m space reserved for the detector. For such a scheme to work, the finite-length bunches must be rotated so that they pass through each other at an effective angle of 0^0 as they cross. This "crab crossing" requires highly specialized RF cavities that are very much in the development stage.

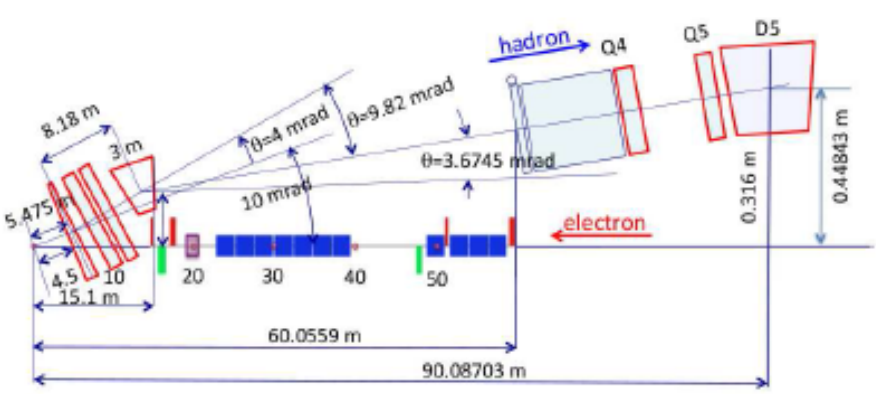

Figure 4-2: Layout of the right side of an eRHIC IR with crab crossing

It is estimated that outfitting a single IR with crab cavities will cost ~$50M. A more standard IR design is to have the beams cross at 0^0, similar to the case in RHIC, steered by dipole fields on either side of the collision point. To maintain the desired luminosity at eRHIC without a crab crossing would require a dipole field of ~0.3 T-m built into the central region of the detector and some compromise in acceptance to deal with the resulting "fan" of synchrotron radiation. The detector configurations described in the ePHENIX and eSTAR LOIs, both would require crab crossing IRs.

The estimated base cost of the eRHIC accelerator is $550M (FY 2012$). This would provide electron beam energy of 10 GeV, CeC for the RHIC hadron beams, and e-nucleon luminosity of 10^{33} $cm^{-2}sec^{-1}$. At present this cost estimate is a target that we believe can be achieved. The BNL group is in the process of finalizing a detailed, reviewable cost estimate.

If the experimental program includes more than one IR, and/or the implementation of crab crossing, additional costs will be incurred to outfit the IRs. For two detectors, a second "standard" IR would add an estimated $50M to the base machine cost. As discussed above, implementing the crab crossing configuration into a standard IR design would add an additional $50M to the cost of the IR. Thus, an experimental program with a single detector would incur an additional cost of $50M if a crab crossing were required. A program with two detectors would incur additional cost of $50M to $150M for the IRs, depending on the detector design.

Section 5: Realizing eRHIC

The conceptual design for eRHIC is well advanced. As noted above, in order to meet science-driven performance goals within realistic cost constraints the design incorporates several challenging technology developments. Foremost among these are the high energy multi-pass ERL, a high brightness, high current polarized electron source, and coherent electron cooling of the hadron beams. Each of these is being addressed by intensive R&D efforts at BNL and elsewhere. In addition a community-wide generic R&D program for EIC detector technologies has been funded at BNL. Over the past three years this peer-reviewed program has made good progress in clarifying detector design issues and beginning to address the needs for instrumentation development that arise from the scientific requirements and machine environment of an EIC. Based on the expected timelines for technical readiness and for the community and agency approval process for such a project, BNL is planning for a start of eRHIC construction in FY 2019, consistent with a CD-0 decision by 2016.

The graphic below shows a notional timeline for final RHIC operation and the transition to eRHIC, with corresponding construction schedules for eRHIC, sPHENIX, and an initial eRHIC

detector complement. For context, we show the current schedules for completion and operation of the JLab 12 GeV Upgrade and MSU FRIB projects.

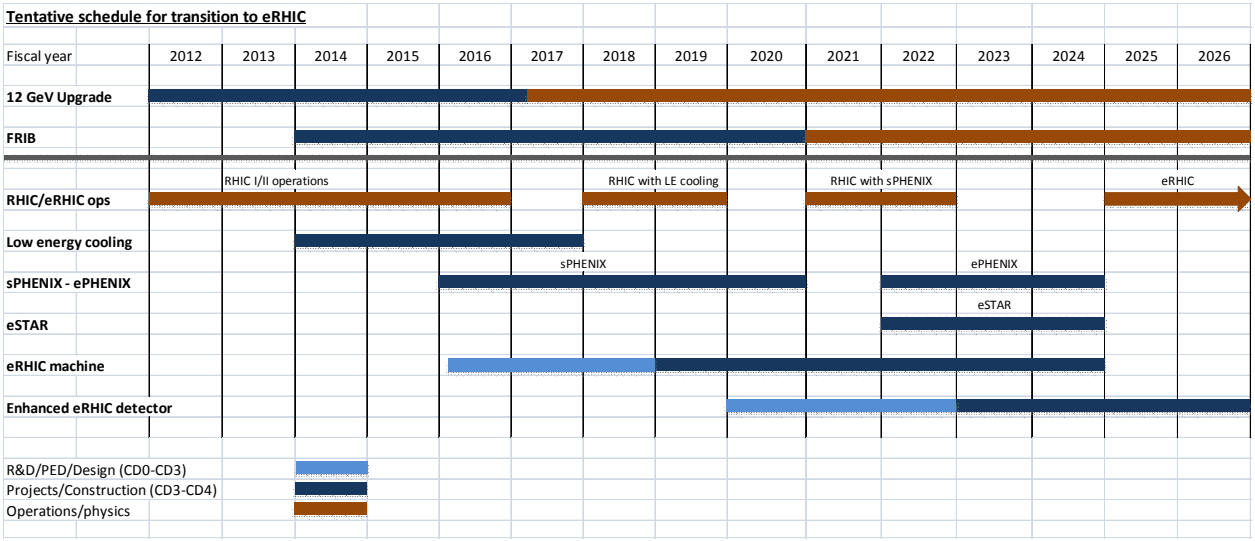

Figure 5-1: Notional timeline for the transition from RHIC to eRHIC

The schedule shown for RHIC operations corresponds to that shown in Table 2-1, outlining the plan for completing the RHIC science program. There are gap years during which the RHIC beams and experiments are not operating. The first of these is in 2017 when the electron cooling system for low-energy beams will be installed, prior to the scheduled Beam Energy Scan-II runs in 2018-19. Another gap year is 2020, corresponding to the completion of the installation of sPHENIX and possible forward upgrades of STAR. RHIC operations cease after FY 2022, with two gap years prior to start-up of eRHIC operations in 2025.

The years when RHIC is not operating provide extended shut-down periods needed for major equipment installation. They also provide opportunities for re-directing significant amounts of workforce and other resources from RHIC operations toward offsetting the cost of eRHIC construction, including new detector equipment. Optimizing the amount of this cost offsetting is a key element of the strategy for a cost-effective transition to eRHIC.

The C-AD and Physics departments at BNL have begun a detailed study of the amount of labor and M&S funds that could be re-directed, year-by-year, from RHIC operations during the course of this plan, and the extent to which the skill sets of available labor can be matched to the construction needs. It is difficult to do this with precision, especially recognizing that not all of the eRHIC construction effort is likely to take place at Brookhaven. Nonetheless, we believe that a substantial portion of the cost of eRHIC machine and detectors – approximately $200M (FY 2012$) – can be offset by this means.

The timeline in Fig. 5-1 shows construction lines for two eRHIC detectors to be available on Day-1. This is entirely notional at this stage. Given the breadth of the EIC physics program and the size and diversity of the expected user community, it may be desirable to have more than one general purpose detector at eRHIC. As discussed in the following section, the Letters of Intent from PHENIX and STAR indicate that existing RHIC detectors can be upgraded for eRHIC physics at relatively modest cost, and, in particular, sPHENIX, if implemented, provides an excellent and cost effective starting point for an eRHIC detector. In practice, the initial detector configuration will be determined through a proposal-driven process, with the outcome very dependent on funding realities and the amount of non-DOE investment. Based on the estimates given in the Letters of Intent, a minimal cost for a single detector would be ~$100M (FY 2012$).

The line called "enhanced eRHIC detector" is intended to provide possibly required funds to upgrade (or perhaps make whole) the initial detector configuration within a few years of eRHIC start-up. As was the case with the Additional Experimental Equipment funds for RHIC, this could have a big impact on the early physics output of the facility, and offers an additional opportunity for new user groups to participate in detector design and construction. We estimate the funds associated with this line to be $50-100M (FY 2012$).

It is worth noting that since the current design of eRHIC involves operating and maintaining only one hadron ring, along with the new electron beam, it is expected that the operating cost for eRHIC will be about the same as that for RHIC.

Section 6: The Letters of Intent and eRHIC Detector Plans

As part of the community-wide effort that led to the 2012 EIC White Paper, a broad international activity has developed computer models and simulation tools to allow quantitative understanding of the detector requirements to address the "golden measurements" outlined in the EIC White Paper. BNL's EIC Science Task Force played a central role in this activity, which has been strongly encouraged and partially funded by the EIC Generic Detector R&D program and its Advisory Committee. A detailed summary of the requirements for kinematic coverage, tracking, and particle ID to meet the basic requirements for the essential EIC measurements has been prepared by the BNL Task Force.[1] The EIC White Paper shows an example of a conceptual detector layout that illustrates these requirements. This layout is reproduced in Fig. 6-1.

[1] Available at the URL https://wiki.bnl.gov/eic/index.php/Detector_Design_Requirements

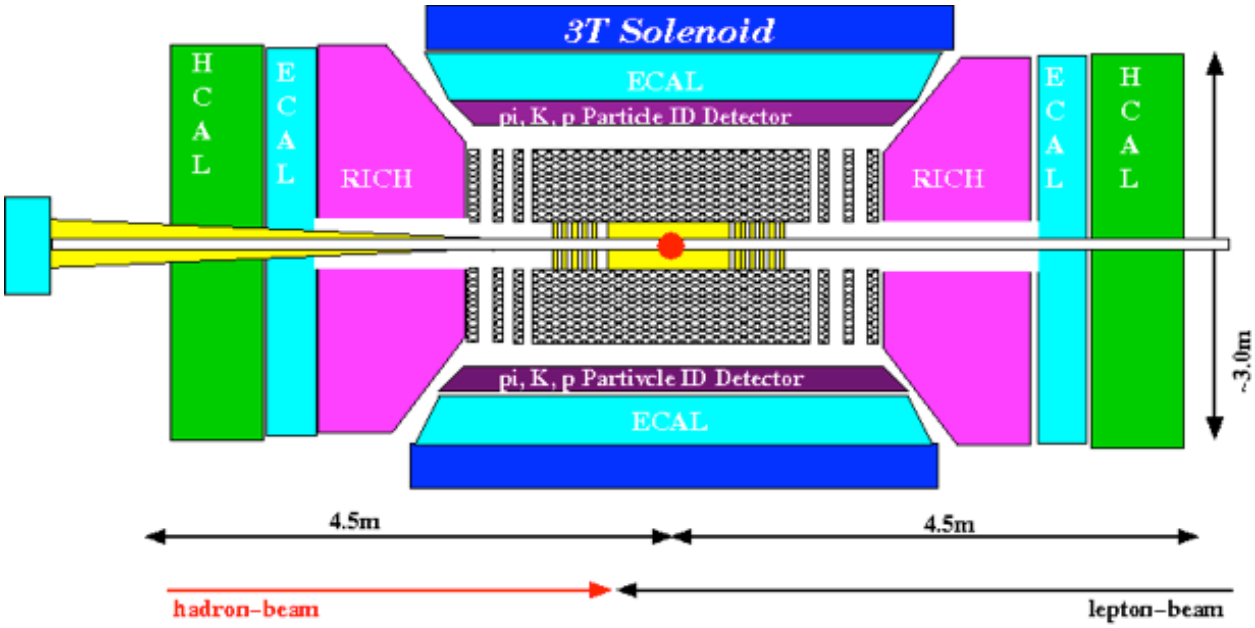

Figure 6-1: Conceptual layout of a detector for an electron ion collider, as shown in the EIC White Paper.

While both the PHENIX and STAR collaborations expressed interest in electron ion collisions in their respective decadal plans submitted in 2012, the Letters of Intent prepared over the past several months give a first look at concerted efforts by the existing RHIC collaborations to address the scientific opportunities and the technical and demographic implications of a transition from RHIC to eRHIC. For both collaborations these LOIs reflect an intense effort over a relatively short period of time to assess the feasibility of meeting the EIC requirements, given the machine parameters specified for eRHIC, through upgrades of the existing RHIC detectors. In the case of PHENIX, the starting point is the sPHENIX configuration assumed to be in place at the conclusion of the RHIC program. The STAR design includes incremental upgrades to the Time Projection Chamber, a forward calorimeter and its associated tracking systems, as well as the DAQ and trigger electronics, that are planned for the final RHIC runs. The proposed layouts of ePHENIX and eSTAR are shown in Figures 6-2 and 6-3, respectively.

In both cases the existing magnet and much of the central-region instrumentation are retained. As noted in Sec. 4, the beam crossing rate for eRHIC is the same as that for RHIC, allowing the continued use of existing readout electronics. Upgrades to both detectors are required for high-purity identification of the scattered electron, for good particle ID extending to large rapidities in the hadron-going direction, and for particle detection at very small angles along the hadron beam line, including zero degree calorimeters and Roman pots. Not surprisingly, many of the elements seen in the conceptual detector shown in Fig. 6-1 can be seen in these layouts.

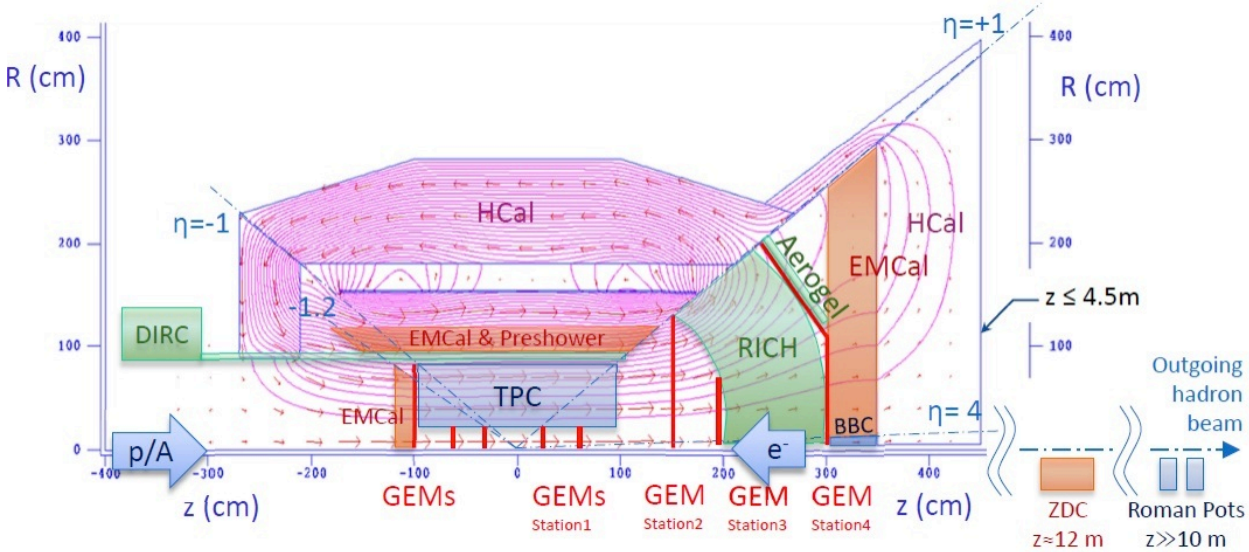

Figure 6-2: Cross section through the top half of the ePHENIX detector concept.

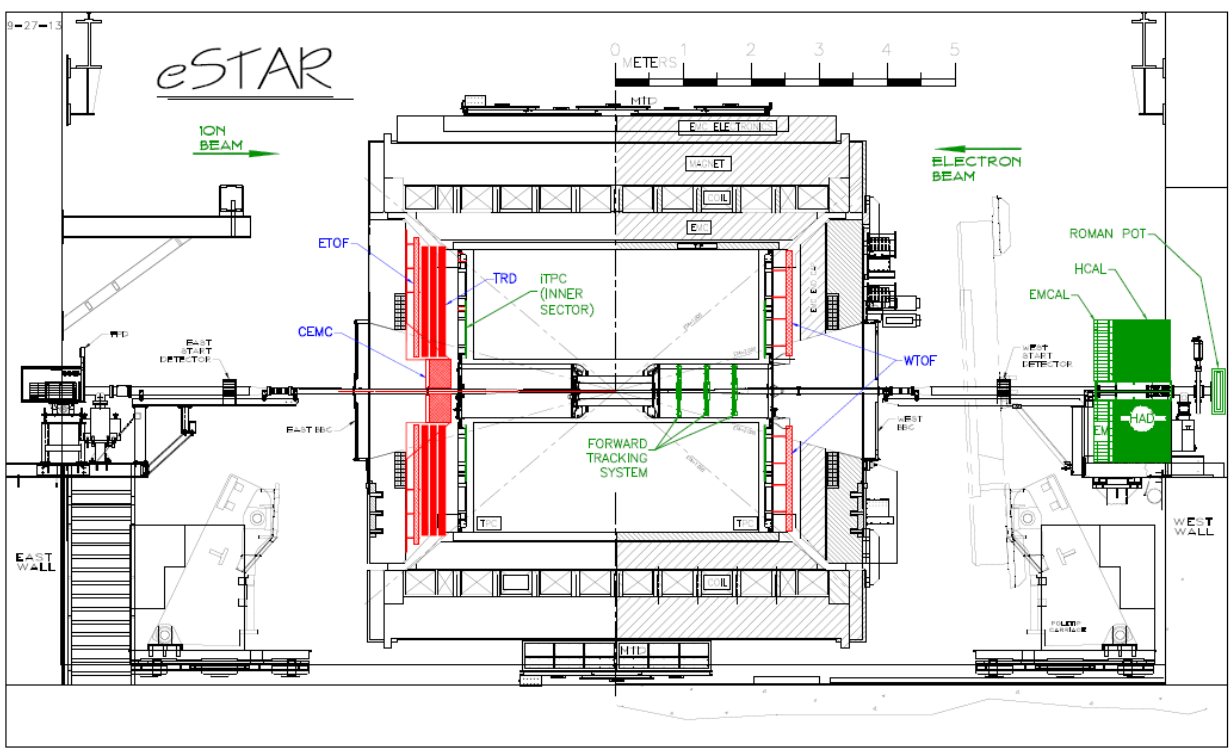

Figure 6-3: eSTAR detector layout.

Although more detailed physics simulations will ultimately be required, both collaborations have presented extensive simulations indicating that a significant portion of the important EIC physics measurements can be addressed with the upgraded detectors, both in polarized e-p and in e-A collisions. These measurements will enable the execution of a compelling physics program exploring the still mysterious spin structure of the nucleon, the nature of the possibly universal dense gluon ocean in nuclei, and the poorly understood transition from quarks to hadrons using the target nucleus as a "femtoprobe".

Both collaborations have provided estimates of the cost and schedule for upgrading to an eRHIC detector. BNL has not yet undertaken a detailed analysis or review of these estimates. Nonetheless, in view of considerable experience of these collaborations, the estimates given may serve as a credible indicator of the scale of effort and cost for the upgrades. The schedules presented are consistent with the timelines given in Fig. 5-1.

In the case of ePHENIX, the estimated equipment cost is ~$80M, and the labor cost ~$30M, in FY 2012$, including contingency and overhead. This assumes that the BaBar magnet and the electromagnetic and hadronic calorimetry for sPHENIX are already in place for the final RHIC run. The PHENIX collaboration states that there are "significant opportunities" to offset some of these costs through international and other non-DOE funding sources.

In the case of eSTAR, the total cost of needed upgrades is estimated at $42M, in FY 2012$. Of this, approximately $28M is for upgrades intended to be in place prior to the final RHIC runs, although formal proposals have not yet been presented. It is expected that a significant fraction of the total upgrade cost from STAR to eSTAR will come as in-kind contributions from foreign collaborators.

Both the ePHENIX and eSTAR detectors described in the Letters of Intent would require the implementation of crab-crossing cavities in the IR. As discussed in Sec. 4, this would incur additional cost.

In preparing these LOIs, each group was asked to address the question of how the collaboration is expected to evolve into the eRHIC era, and the related question of the size and breadth of the scientific staffing required to carry out these plans. Both envision a new collaboration arising to bring about an eRHIC detector. While precise numbers are not presented, both collaborations see a solid core of the present institutional participants showing an interest in proceeding with the development of an eRHIC program, with a number of institutions moving on to other pursuits at the end of the RHIC program. Both groups agree that a collaboration of a size comparable to the present PHENIX or STAR (~400-500 active members) will be required to develop, build, and carry out the physics at an eRHIC detector, and each emphasizes the importance of attracting new members with experience in DIS experiments.

Section 7: Engaging the EIC Community -- Outlook

At this early stage BNL regards these LOIs as a healthy indicator of the level of engagement of the RHIC community in the development of a scientific program for eRHIC, and a credible demonstration that the large RHIC detectors can form a cost-effective base for detectors that can carry out the experimental program of an electron-ion collider with the envisioned parameters of eRHIC. The proposed sPHENIX project, especially in light of the recent availability of the BaBar superconducting magnet, provides a viable starting point for such an eRHIC detector.

Of course, a successful transition from RHIC to eRHIC needs the engagement and participation of the larger nuclear physics QCD community. As noted, the PHENIX and STAR collaborations are already thinking along these lines. The intention is that new collaborations will form for the construction and the scientific exploitation of the experiments. We expect that there will be movement of collaborators and significant injection of new collaborators who are not participating in the RHIC. There is also interest in the community for developing a purpose-built detector that could be mounted in either of the two presently used experimental halls. We expect that, at an appropriate time in the near future, a proposal-driven process will be initiated to determine the scope and implementation of the experimental program for eRHIC.

The leadership at BNL is currently working with their counterparts at JLab to bring together the interested EIC user community, currently spread between users of BNL/RHIC, JLab/CEBAF, and CERN/COMPASS, and former users of DESY/HERA and SLAC, for a series of workshops and meetings during the coming year to continue the effort represented in the 2012 White Paper, furthering the development of the science case and refining the plans and techniques for experiments.