Assessment of R&D Needs for an EIC Detector

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Purpose of the Document

This document details an estimate of the R&D needs for a general-purpose EIC detector. This entails cost and timelines for R&D of all subsystems and technologies that are included in the reference detector, a as well as those that were identified as alternatives. While the reference detector is optimized for the EIC physics with subdetectors based on the most likely technologies, the final concept can be only defined once collaborations are formed.

Introduction

The need for R&D was realized early by the community and laboratories and in January 2011 Brookhaven National Laboratory, in association with Jefferson Lab and the DOE Office of Nuclear Physics, created a generic detector R&D program to address the scientific requirements for measurements at an EIC. The primary goals of this program were to develop detector concepts and technologies that have particular importance to experiments in an EIC environment, and to help ensure that the techniques and resources for implementing these technologies are well established within the EIC user community. It was also meant to stimulate the formation of user groups and collaborations that will be essential for the ultimate design effort and construction of the EIC experiments.

Many of the supported projects, ongoing or completed, developed technologies that are now integral parts of the reference detector or are regarded as potential alternatives. R&D on many of the technologies to implement a successful comprehensive are close to completion but will require further funding to achieve the maturity required to carry out preliminary and final design and eventually construction of the project scope elements. I many cases small prototypes exist that are not sufficient to demonstrate the required homogeneity and stability. In these cases, larger prototypes consisting of full chains (detector, electronics, supplies, and DAQ) are needed. These prototypes are typically segments or sectors of larger components, e.g. a TPC sector, a single ladder of an inner Si-vertex tracker, or a block of 4 calorimeter towers. Test beams at various facilities (FNAL, JLAB, CERN) or bench tests with X-rays or radioactive probes are then used to establish their functionality, performance, and reliability.

In what follows we discuss the R&D needs for the reference detector grouped by their purpose: Tracking, particle identification (PID), electromagnetic and hadronic calorimetry, auxiliary detectors, and electronic. At the end we discuss a set of R&D projects that are generic in nature and are not part of the reference detector. This entails more future-looking detector concepts and technologies that have the potential to enhance the scope of EIC science in the outyears or even could serve as potential alternatives.

The information for this document is based on information and planning documents provided by the scientists and engineers that are involved in R&D on the various detector subsystem. Cost and schedule were adjusted to match the latest timeline and project needs. It should be noted that this document represents only an estimate of the R&D needs as the final detector design and the number and type of subsystem will emerge in 2021/22.

1 R&D for Reference Detector

1.1 Tracking

1.1.1 Vertex Tracking

The EIC requires precision tracking with very low mass. The combination of very high single point spatial resolution and very low mass detector layers makes MAPS/DMAPS technology the most suitable candidate. While the current state-of-the-art ALPIDE chip does not meet all EIC requirements, it could do so after moderate modification.

The vertex tracker will consist of barrel (layers) and forward/backward (disks). The total Si-Vertex related R&D includes parts of the sensor development, the sensor modulization, the development of staves for the barrel tracker, disks development for the forward and backward tracker, cooling, service reduction, and integration.

The inner vertexing layers will be quite similar to the ALICE inner tracker ITS/ITS3. Much of the mechanics, cooling, and infrastructure can be simply modified for the EIC use case. This also includes the RDO. The scope of the R&D is to produce and test preliminary prototypes that meet the requirements of a working detector system and to demonstrate that the detector concepts are possible.

Strategy on the sensor side is to (i) development of a EIC specific DMAPS sensor, leveraging on the ITS3 effort at CERN (see 2.1) but have (ii) the existing ALPIDE chip as viable backup solution.

The timeline below outlines for the complete vertex tracker including service reduction (see section 0) and sensor development (see generic R&D section 2.1).

1.1.2 Service Reduction

It is critical for the EIC to minimize the number of services to and from the various subdetectors to minimize their respective material and thus reduce multiple-scattering and increase the resolution. In the context of service reduction, R&D will be needed in radiation tolerant multiplexing (probably using radiation tolerant FPGAs) and in high speed (5 GHz and above) fiber or multi-fiber optical transmission components. Both of these technologies are complimentary and urgent. Furthermore, investigating the possibilities of serial powering, possibly with on chip regulation and the use of on detector radiation tolerant DC-DC converters could reduce the material from power cables substantially. In general, the application of this type of R&D benefits most when it is co-developed with the detector technology (MAPS sensors, GEMS, etc.). This R&D should be considered as part of the system level approach to developing detector solutions. This is envisioned for a day one detector implementation.

Timeline:

Year	Task
2021	• Testing and characterization of MLR1 (Multi-Layer Reticle) • Sensor design for MLR2 • MLR2 submission • R&D into powering, stave/disc construction, cooling, overall infrastructure
2022	• Testing and characterization of MLR2 • Sensor design for ITS3 ER1 • ITS3 ER1 submission • R&D + prototyping into powering, stave/disc construction, cooling, overall infrastructure
2023	• Testing and characterization of ITS3 ER1 and assessment of yield • Assessment and planning for EIC sensor fork of ITS3 design • Fork off sensor design and work on EIC variant for staves and discs (may move to next year depending on results) • ER submission for EIC variant sensor (EIC ER1) for staves and discs • Detailed prototyping into powering, stave/disc construction, cooling, overall infrastructure • Investigation of adaptation of ITS3 design for use in EIC vertex layers (different radii, # layers, services from both ends to meet length requirements, etc.) with ITS ER1
2024	• Testing and characterization of EIC ER1 and assessment of yield • Si design for EIC ER2 • EIC ER2 submission for EIC variant sensor for staves and discs • Detailed prototyping into powering, stave/disc construction, cooling, overall infrastructure using EIC ER1 prototypes • Adaptation of ITS3 design for use in EIC inner layers with ITS2 ER2 (or integration of design into EIC ER2 if necessary).
2025	• Testing and characterization of EIC ER2 and assessment of yield • Complete stave and disks prototypes with EIC ER2 • Vertex layers prototypes with ITS2 ER3

1.1.3 Central Tracker TPC

The R&D of a TPC focuses solely on the read-out chambers. Gating grids that have been used in TPCs based on MWPC cannot be used in an EIC environment. The readout rate would not allow to cope with the luminosity requirement of the physics program. The obvious choice are readout chambers using micro-pattern gas detector (MPGD) technologies. This requires the investigation of MPGD-properties and different gas choices which find the optimum of relatively good ion back flow (IBF) suppression and optimum dE/dx resolution for charged particle identification (PID).

The Micromegas technology has the best intrinsic IBF suppression and is a good candidate for good dE/dx resolution. However, stability issues have to be investigated and is an indicator for R&D in the next time for pursuing the Micromegas option. A very promising candidate for combining very good IBF suppression and good energy resolution is the hybrid option of combining Micromegas and GEMs into a single amplification stage. The Micromegas acts as the main amplification stage and reduces the IBF to a minimum. The GEMs act as pre-amplifiers and provide the necessary field ratios to further suppress IBF. The combination of both technologies provides the robustness needed to operate in a high-rate environment. This amplification structure needs continued detailed investigation.

Even if the sPHENIX TPC is reused, new readout chambers will have to be installed since the sPHENIX TPC has been optimized to minimize the ion back flow (IBF) suppression sacrificing good dE/dx resolution. For the EIC program this feature has to be restored.

Timeline:

Year	Task
2021	Continue testing readout options (4 GEM vs 2 GEM + MMG, zigzag: charge sharing) using small scale prototype. Provide input on TPC design for hybrid detector design with TPC and Si inner tracker. In parallel, continue to investigate applicability of interleaved readout planes for a planar tracker option.
2022	Design and build prototype hybrid tracker and test in beam. Continue with engineering design and simulations for full scale detector.
2023	Revise engineering design based on results of prototype tests and design full scale prototype.
2024	Build full scale prototype and test in test beam. Revise final design based on prototype tests.
2025	Complete final design and prepare for construction.

1.1.4 Low-Mass Forward/Backward GEM Tracker

Gas Electron Multipliers (GEMs) are a well-established MPGD detector technology that will soon be operational on a large scale in current NP and HEP experiments, e.g., SBS tracker, ALICE TPC upgrade, and CMS muon upgrade. In a day-one EIC detector, they do provide cost-efficient fast tracking with good spatial resolution in the forward and backward regions because they can cover a large area.

The plan is to complete characterization of the two large GEM prototypes (UVa & FIT) by December 2021. To bring low-mass GEM tracker technology to a state where it can be implemented in an EIC detector some modest R&D is still required. This includes improvements in the simulations and a second test beam.

The simulations need to be repeated and refined. The actually measured spatial resolutions and realistic support materials need to be incorporated properly into the simulation, in particular the materials in the TPC endplates, MAPS support structures, and the GEM support frames. Their impacts on forward/backward tracking performance and RICH seeding need to be fully quantified. This should take six months to a year to complete.

For the glued prototype at UVa different types of zebra strip connectorizations need to be tested. The mechanically stretched FIT prototype with carbon fiber frames has been undergoing major refurbishments of it mechanics and its operation needs to be confirmed. If successful, both prototypes will be evaluated in a second beam test at Fermilab planned for Summer 2021 to finalize the spatial resolution studies and the overall performance characterization of the prototypes.

Timeline:

Year	Task
2021	June: Test performance in beam test at FNAL December: Finalize FNAL test beam data analysis
2022	July: Completion of R&D program

1.2 Particle Identification

1.2.1 Modular RICH (mRICH)

mRICH stands for compact and modular Ring Imaging CHerenkov detector, which is designed for K/π separation in a momentum range of 3 to 10 GeV/c and e/π separation below 2 GeV/c for the future EIC experiments.

The key components of a mRICH module include an aerogel radiator, a Fresnel lens, a mirror set, and a photosensor. A realistic GEANT4-based simulation for mRICH has also been developed and verified with beam test data. Two rounds of detector prototyping and beam tests were completed with a focus on verifying the detector working principle and performance. The second beam test was done in 2018 and the data analysis is still ongoing. Two more beam tests with particle tracking capability, crucial to evaluate the Cherenkov single photon resolution, are under preparation in order to quantify the mRICH PID performance and new photosensors. One was originally planned for March ’21 but is now postponed due to the COVID pandemic. Attempts are under way to have test beams beginning of June ’21 (May 25 to June 15) for testing the mRICH also with a LAPPD. The other test is planned at JLab in summer of 2021 using secondary electrons in momentum range from 1 to 6 GeV/$c.

To meet the needs of EIC experiments, a proper photosensor choice is critical. The planned beam test at Fermilab in May/June ‘21 (pending DOE travel approval to FNAL) will help to evaluate the integration and performance with LAPPD. During the second mRICH beam test in 2018, three SiPM matrices were tested with varying cooling temperature range from -30 C degree to room temperature. The radiation damage effects to SiPM performance is currently under study at INFN.

In regarding to the possible kinematic coverage in EIC experiments with mRICH modules, one can envision deployment in the electron endcap and the hadron endcap ($1 < \eta < 2.5$). The mRICH is considered as a day-1 detector.

Besides the two planned mRICH beam tests in the coming year, there are R&D efforts towards engineering design which includes: (i) high quality mirror and mirror assembly, (ii) mRICH holder box engineering for reducing total weight, easy assembling, and projective installation, and (iii) continued test with available photosensor options.

Timeline:

Mar 2021	mRICH Timeline Estimate	2021				2022				2023				2024			
					FY22				FY23				FY24				
Beam tests / data analysis	Complete 2nd beam test data taken with SiPM matrices	▓	▓	▓	▓												
	mRICH beam test at JLab with tracking	░	░	░	▓	▒	▒										
	mRICH/LAPPD beam test at Fermilab with tracking	░	░	░	▓	▓	▒										
	JLab and Fermilab beam tests data analysis				░	░	░	░	░								
	More beam tests with new photosensors and readout						▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	
mRICH simulation studies	Fine tune GEANT4 simulation of mRICH (2nd prototype)	░	░	░	░	░	░										
	mRICH array simulation study using Fun4All framework	▓	▓	▓	▓	▓	▓	▓	▓								
	Simulation studies of physics impact using mRICH			▓	▓	▓	▓	▓	▓	▓	▓	▓	▓				
	mRICH-based PID algorithm development	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒				
mRICH engineering design	Optimizing the mechanical design of mRICH	░	░	░	░	▓	▓	▓	▓	▒	▒	▒	▒				
	Optimizing the design and assembly of optical components	░	░	░	░	▓	▓	▓	▓	▒	▒	▒	▒				
	Optical characterization of aerogel, fresnel lens and mirror	░	░	░	░	▓	▓	▓	▓	▒	▒	▒	▒				
	Optimizing readout integration with mRICH optical section					▒	▒	▒	▒	▒	▒	▒	▒				
mRICH optical components	Aerogel acquisition (with INFN team) and characterization					▒	▒	▒	▒	▒	▒	▒	▒				
	Fresnel lens acquisition and characterization					▒	▒	▒	▒	▒	▒	▒	▒				
	High quality mirror acquisition and characterization					▒	▒	▒	▒	▒	▒	▒	▒				
Sensors and Electronics	Collaboration effort within eRD14	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒				
TDR									▓	▓	░	░	░	▓	▓		

Note: In the timeline above the light gray color in the progress bars indicate optional activities while the dark gray stands for planned/required activities.

1.2.2 Dual-Radiator Ring Imaging Cherenkov Detector (dRICH)

The dual-radiator Ring Imaging Cherenkov (dRICH) detector is designed to provide continuous full hadron identification (π/K/p) separation better than 3σ from 3 GeV/c to 50 GeV/c in the forward range. It also offers a electron and positron identification (e/π separation) from few hundred MeV up to about 15 GeV/c. Achieving such a momentum coverage in the forward ion-side region is a key requirement for the EIC physics program.

A small-scale prototype is being developed to investigate critical aspects of the proposed dRICH detector, in particular related to the interplay and long-term performance of the two radiators and the simultaneous imaging. The prototype vessel is composed by standard vacuum parts to contain the cost and support pressures different from the atmospheric one. This would allow efficient gas exchange and, in principle, adjustment of the refractive index and consequent flexibility in the gas choice (in the search for alternatives to greenhouse gases). The prototype supports the usage of various type of photosensors, in particular SiPM matrices and MCP-PMTs.

A program has been planned to study the potential of SiPM sensors for Cherenkov applications, aiming to an assessment of the use of irradiated SiPM in conjunction with the dRICH prototype. The SiPM response before and after irradiation will be characterized and their imaging potential will be studied with customized electronics. High-frequency sampling and Time-of-Threshold-based readouts will be compared. Of particular interest is the ALCOR front-end chip designed to work down to cryogenics temperatures. The irradiated sensors will be cooled down to the working temperature (down to -40 C) to instrument an area suitable for imaging tests with the dRICH prototype. After an initial survey of the most promising candidates available on the market, a dedicated R&D needs to be pursued to meet the EIC specifications. Despite the tight schedule, the group is on track for the tests scheduled in mid-May. They have acquired all the sensors and produced the relative SiPM carrier boards, and the test plan for the SiPM characterization as well as for the administrative controls, is being developed.

Besides the first SiPM irradiation campaign and the baseline prototype realization, there is a need for R&D efforts towards engineering design which includes: (i) light and stiff support structure in composite materials, (ii) a high-quality mirror assembly and (iii)), the cost-effective production of high-quality aerogel, (iv) the study of alternatives to the originally envisioned greenhouse gases, and (f) dedicated readout electronics and cooling.

The timeline for “sensors and electronics” in the table below refers to the "Collaboration effort within eRD14" that comprises synergy developments and alternative technology comparison. The activity foreseen for 2024 (not included in the table) is meant to finalize dRICH dedicated solutions, in particular regarding engineering and integration into EIC. In any case, the table presents an aggressive plan assuming an adequate funds availability, with manpower support being the most critical.

Timeline:

Mar 2021	dRICH Timeline Estimate	2021				2022				2023				2024			
					FY22				FY23				FY24				
Simulation/Reconstruction	Simulation: Prototype and beam line	■	■	■	■	■	■	■	■								
	Simulation: Integration into EIC simulation and analysis platforms	■	■	■	■												
	Simulation: dRICH model refinement with the beam-test results				■	■	■	■	■	■	■	■	■	░			
	Simulation: dRICH model optimization in EIC spectrometer									■	■	■	■	░			
	Reconstruction: reconstruction optimization / ML												■	■	■		
dRICH Prototype	Basic prototype design	■	■														
	Basic prototype mechanics	■	■	■													
	Basic tracking and components, reference readout			■	■												
	Upgrade of sensors and readout electronics					■	■	■									
	Precise tracking/alignment						■	■	░								
	Custom components, optimized readout								■	■	■	■	░	░			
	Beam test data analysis					■	■	■	■	■	■	■	■	░	░		
Optical Components	First selection and tests	■	■	■	■												
	Refinement and cost reduction study					■	■	■	■	■							
	Alternatives and optimization								■	■	■	■	░	░	░	░	░
Beam-Tests	Proof of principle (reference sensors and readout, ideal beam)				■												
	Performance assessment (hadron tagged beams)							■	░								
	Performance assessment with optimized components											■	░	░	░		
EIC Integration	Cooling R&D						■	■	■	■	■	■	■				
	EIC configuration engineering and integrated PID								■	■	■	■	■	■			
	Engineering of cooling and ancillary services											■	■	■	■		
Sensors and Electronics	Collaboration effort within eRD14	■	■	■	■	■	■	■	■	■	■	■	■				
TDR									■	■	░	░	░	■	■		

1.2.3 High-Performance DIRC (hpDIRC)

The high-performance DIRC (hpDIRC) is a proposed hadronic PID system for the barrel region of the central detector, capable of π/K separation with 3σ or more up to at least 6 GeV/c momentum over a wide angular range. It can also contribute to e/π identification at lower momenta.

The R&D of the hpDIRC is at an advanced stage. It has low demands on the detector infrastructure (no cryogenic cooling, no flammable gases) and is easy to operate. The PID performance estimate is based on test beam results, with excellent agreement between simulation and prototype data.

Several areas still require significant R&D. Optimizing the cost-efficient design, matched to the final EIC detector layout, in simulation and validating it with the full system hpDIRC prototype is the most critical item. R&D will be needed to develope a procedure to disassemble the BaBar DIRC bar boxes and extract high-quality radiator bars for hpDIRC. These tests will happen at SLAC with local support. If possible, these test could be even earlier. The hpDIRC performance does not depend much on the type of bar, if they are reused from BaBar or brand new (plan B) - as long as the optical and mechanical quality of the disassembled bars is good. The main impact of a negative outcome of the reuse R&D would, therefore, be financial. There used to be a significant schedule risk associated with the mass production of new bars but the recent success of the bar production for PANDA has shown that this risk can be assumed to be only minor for the EIC detector as well.

Support is needed soon to upgrade the PANDA DIRC prototype, which is being transferred from GSI to CUA/SBU, to fully equip it with new sensors and electronics, in order to validate the resolution and PID performance with cosmic muons and/or particle beams. A new Cosmic Ray Telescope (CRT) facility is being developed for the hpDIRC in collaboration between SBU, ODU, and CUA to study the prototype prior to possible tests in particle beams. This CRT will be available for use by other EIC systems.

Note that the MCP-PMTs for the prototype test require substantial funding (~$200k) in FY22. These sensors can be later used in the actual hpDIRC detector. They will be also used for mRICH (see Sec. 1.2.1) and dRICH (see Sec. 1.2.2) prototype tests.

Timeline:

Mar 2021	hpDIRC Timeline Estimate	2021				2022				2023				2024			
					FY22				FY23				FY24				
Simulation/Reconstruction	Simulation: Prototype, beam line, cosmic ray setup (CRT)	■	■	■	■	■	■	■	■	■	■						
	Simulation: Lens characterization	■															
	Simulation: Explore hpDIRC design options (e/π,π/K)	■	■	■	■	■	■	■	■	■	■	■	■				
	Simulation: Cost/performance optimization	■	■	■	■	■	■	■									
	Reconstruction: reconstruction optimization / ML	■	■	■	■	■	■	■	■	■	■	■	■				
hpDIRC system prototype	Transfer of PANDA prototype from GSI to CUA/SBU	■	■	■													
	Design and construction of CRT	■	■	■	■	■											
	Initial protoype commissioning in cosmic ray setup (CRT)				■	■	■										
	Upgrade of sensors and readout electronics					■	■	■									
	Commissioning of upgraded prototype, CRT data analysis						■	■	■	■	■	■	■	■	■	■	■
	Optional beam test at Fermilab										▨						
	Beam test data analysis										▨	▨	▨	▨	▨	▨	▨
Lens evaluation	Upgrade of ODU laser setup	■															
	Characterization of prototype lenses	■	■	■	■												
	Neutron irradiation and analysis		■	■	■	■											
BaBar DIRC bar reuse	Plan, preparation					■											
	Bar box disassembly, bar decoupling						■	▨	▨								
	Validate mechanical and optical properties							■	▨	▨							
Sensors and Electronics	collaboration effort within eRD14	■	■	■	■	■	■	■	■	■	■	■	■				
TDR						▨	▨	▨	■	■	▨	▨	■	■			

1.2.4 Fast Timing Silicon Sensor: LGADs

The Low Gain Avalanche Detector (LGAD) is an ultra-fast silicon sensor technology, which has recently been chosen for constructing a fast-timing layer in the forward rapidity region of CMS and ATLAS for high-luminosity LHC starting in 2027. LGAD sensors can achieve a typical time resolution of about 30 ps. With excellent timing and position resolutions, the LGADs provide an attractive option for constructing a ToF system and are the technology of choice for far-forward hadron spectrometer (Roman Pots). In addition, the LGADs have several other key advantages such as being highly tolerant to strong magnetic fields, radiation-hardness, and compactness.

While LGAD silicon sensors used by CMS and ATLAS can provide a time resolution of 30-50 ps, particle flight distance at an EIC detector is much shorter due to tight space constraints. Therefore, a total time resolution (including readout electronics) of 20 ps or better per layer is needed. Improvements can be achieved by reducing the thickness of the sensor and optimizing internal and external gains. Resolutions of 20-25 ps are expected to be feasible. To serve as (part of) a tracking system as is the case for the far forward spectrometer and ToF/tracker, a position resolution better than the 1 mm pixel size has to be accomplished. To achieve this two solutions exist: Trench-isolated LGADs and AC-coupled LGADs where the latter is seen as preferrable for the EIC. R&D is needed to fully characterize the AC-LGAD performance, test their robustness and optimize their design for the specific implementation in Roman Pots and possibly ToF detectors. The intrinsic sensor gain and thickness needs to be optimized to improve the time resolution, finer spatial resolution can be achieved by exploiting the signal sharing properties of neighboring pixels, and larger area prototypes with advanced designs need to be fabricated and tested.

The needs for better timing performance and finer granularity also pose significant challenges to the readout electronics and specifically to the ASIC readout chips. Most critical at this point in time is the development of an architecture of the readout electronics, and more urgently the ASIC R&D.

Timeline:

In a timeframe of 2 years, thanks to prototyping and laboratory testing, the AC-LGAD can be confirmed as the baseline technology for Roman Pots, while an optimization of the sensor readout can be achieved in a 5-year time scale. In a 2-year timeframe the readout architecture can be developed, and its viability demonstrated via simulations as well as laboratory tests based on existing prototypes for the LHC, while in a 5-year time scale a more detailed design of the ASICs and the readout chain, including initial prototyping, can be achieved.

1.3 Electromagnetic Calorimetry

1.3.1 Scintillating Glass & Crystals

The requirement of high-precision detection of electrons at forward rapidities is driven mainly by inclusive DIS where the scattered electron is critical for all processes to determine the event kinematics. Excellent electromagnetic calorimeter resolution of better than $2\%/\sqrt{E}$ is required at small scattering angles. For hadron physics measurements with electromagnetic reactions, the most common precision calorimeter material of choice has been lead tungstate, $PbWO_4$. However, the production of crystals is slow and expensive.

The technology goal of SciGlass R&D is to develop a scintillating glass for homogeneous electromagnetic calorimetry. SciGlass fabrication is expected to be cheaper, faster, and more flexible than $PbWO_4$ crystals. SciGlass is being developed by Scintilex, LLC in collaboration with the Vitreous State Laboratory at CUA. Tremendous progress has been made in the formulation and production of SciGlass that improves properties and solves the issue of macro defects. Scintilex has demonstrated a successful scaleup method and can now reliably produce glass samples of sizes up to 10 radiation lengths. Simulations combined with initial beam tests at photon energies of 4-5 GeV suggest that high resolution competitive with $PbWO_4$ can be reached.

The areas of needed R&D for SciGlass include the final formulation optimization, scale up to block sizes $\gtrsim 15\ X_0$ (most critical item) and beam tests to establish characteristics like energy resolution. The evaluation of SciGlass as particle detector has been shared in part with activities on $PbWO_4$ crystals for the electron endcap calorimeter, including simulations, radiator characterization and prototype construction, commissioning, and beam tests. The approximate timeline for completing the SciGlass R&D is about 1.5 years. The goal is to be ready for a day-1 detector. SciGlass could also be available for future detector upgrades.

Timeline:

Year	Task	
	$PbWO_4$	SciGlass
2021	Complete prototype tests with different readout options	Final formulation optimization, scale up to block sizes $\geqslant 15\ X_0$, and establish SciGlass characteristics.
2022		Prototype and beam tests. Process design verification to scale up.

1.3.2 W powder SciFi, Pb(W)/Sci Shashlik, and Lead Glass

An EIC detector does require a hermetic coverage ($\eta < |3.5|$) of electromagnetic calorimetry with varying requirements depending on its η range. Various technologies are available, all requiring R&D to optimize the light collection and resolution. The construction of a full chain prototype to verify and test the performance parameters are highly desired.

Tungsten scintillator calorimetry can play a major role in many of the regions of an EIC detector. It offers a very compact design in terms of its short radiation length as well as providing a small Moliere radius which limits the lateral extent of the shower, therefore allowing good separation between neighboring electromagnetic showers. There are primarily two candidates that are being considering for a W/Scint calorimeter for EIC. One is a tungsten scintillating fiber (W/SciFi) SPACAL, which consists of a matrix of tungsten powder and epoxy with embedded scintillating fibers. The blocks are read out using SiPMs that are coupled to the blocks using short light guides.

No R&D is required for producing the blocks. However, the method used for reading out the blocks with SiPMs needs to be improved. This would include the use of large area SiPMs to provide more photocathode coverage and eliminate the boundaries between the light guides which leads to non-uniformities in the energy response.

The second W/Scint technology that is being considered is a tungsten shashlik (W/Shashlik) design. A W/Shashlik design offers some distinct advantages but also poses some significant challenges. In addition to being compact and being able to tune the energy resolution as in the W/SciFi, a W/Shashlik offers the possibility of improving the light collection and providing better uniformity by reading out each individual WLS fiber with its own SiPM. Also here, R&D is need to optimize the light collection and resolution as well as full-chain prototype.

Other technologies are considered such as lead glass, which has the advantage that many lead glass blocks exist and could be reused. Same R&D needs as for W/SciFi and W/Shashlik applies.

Timeline:

Year	Task	
	W/SciFi	**W/Shashlik**
2021	Continue testing readout options to increase photocathode coverage. Design small prototype (4x4 blocks) to test actual performance. Begin engineering design(s) for actual detector. Barrel and Endcap would require completely different designs.	Design medium size (~ 25 cm^2) prototype. Carry out simulations for expected performance. Develop method for making modules projective. Begin engineering design(s) for actual detector. Barrel and Endcap would require completely different designs.
2022	Build small prototype and test in test beam. Continue with engineering design(s) for full scale detector.	Build prototype(s) and test in test beam. Will likely require at least 2 iterations. Barrel and Endcap would require separate prototypes. Continue with simulations and engineering designs. Design of readout electronics would need to go on in parallel.
2023	Revise engineering design(s) based on results of prototype tests and design full scale prototype(s).	
2024	Build full scale prototype(s). Test in test beam if possible.	Revise engineering design(s) based on results of prototype tests. Design full scale prototype(s).
2025	Complete final design and prepare for construction.	Build full scale prototype(s). Test in test beam if possible.
2026		Complete final design and prepare for construction.

1.4 Hadron Calorimetry

The requirements for the resolution of the hadronic calorimeter are different for the endcaps and the barrel region. The most challenging is the forward region of hadronic endcap where pure calorimetric measurements starts to outperform particle-flow like approaches due to the degradation of tracker performance. For the electron endcap and the barrel region, only modest hadronic energy resolution is required.

It is believed that the barrel HCAL can be built using standard construction methods and no additional R&D efforts other than the construction and testing of a full chain prototype is needed.

For the hadronic endcap, where better energy resolution is required, modest R&D efforts will be needed to improve the performance of these systems.

At more forward rapidities in the hadron endcap the requirements on energy resolution become more stringent. Here it is important to have the best possible performance of the calorimeter system. The main constrain is the lack of space for a high sampling fraction and high sampling frequency calorimetry system, both of which are required to achieve good resolution. Developing a high-resolution calorimetry system for this region will require significant R&D efforts. At present we believe that there is only one technology option that may be suitable for this region, which is a very high density, approximately compensated fiber calorimeter, which could serve as both the EMCAL and HCAL with a common readout.

The readout with SiPM sensors may be challenging at the forward rapidities of the hadron endcap due to the relatively low light yield of hadron calorimeters (compared to EM calorimeters), and the high neutron fluences in this region, which will lead to significant degradations in SiPM performance. Future R&D is therefore needed in this direction.

Timeline:

Year	Task
2021	Finish optimization of light collection for HCal (WLS/SiPMs). Work out tile catcher integration and frontend electronics for Fe/Sc HCAl Preparation for the construction (need authorization to order long lead time materials. Start construction of 0.6 x 0.6 WScFi + Fe/Sc hadron endcap
2022	Completion of construction of a full-scale hadron endcap prototype Beam testing at FNAL in the fall if beam available
2023	More beam testing if needed, Update TDR

1.5 Auxiliary Detectors

1.5.1 Low Q2 Tagger

The low-Q^2 taggers consist of a set of small-scale trackers and an electromagnetic calorimeter to capture angle and energy/p of the scattered electron ~15m away from the IP. They will be finely segmented to disentangle the multiple electron hits per bunch crossing from the high-rate bremsstrahlung process. The taggers need to have position sensitive detectors to measure the vertical and horizontal coordinates of electrons. The combined energy and position measurements allow reconstruction of the key kinematic variables. If the position detectors have multiple layers and are able to reconstruct the electron direction this will over constrain the variable reconstruction and improve their measurement; this may also provide some measure of background rejection. There will provide resolution for Q^2 as low as 10^{-3} GeV^2 in the range accepting $-6.9 < \eta < -5.8$.

No R&D is needed for a low-Q^2 tagger, except the construction of a prototype and verification of its performance in test beams.

Timeline: not critical

1.5.2 Roman Pots

A far-forward proton/ion spectrometer, based on the well-known technique of Roman Pots, is an integral part of an EIC detector system, essential for the success of its physics program and thus is envisioned as a subsystem for a day-one EIC detector.

An innovative silicon technology, based on AC-LGAD, is proposed to instrument the Roman Pots, which has the potential to combine in a single sensor fine spatial resolution and precise timing. The development and optimization of the sensors is discussed in Sec. 1.2.4.

The adaption of the sensors and corresponding FEE (ASICS) and optimization for the Roman Pots will require R&D. In addition, a larger area prototypes with advanced designs need to be fabricated and tested.

Timeline (see 1.2.4)

1.5.3 Zero Degree Calorimeter (ZDC)

The ZDC will serve critical roles for a number of important physics topics at EIC, such as distinguishing between coherent diffractive scattering in which the nucleus remains intact, and incoherent scattering in which the nucleus breaks up, measuring geometry of e+A collisions, spectator tagging in e +D/ 3He, asymmetries of leading baryons, and spectroscopy.

These physics goals require that the ZDCs have high efficiency for neutrons and for low-energy photons, excellent energy, p_T and position resolutions, large acceptance and sufficient radiation hardness.

It is anticipated to be a sampling type calorimeter with a sufficient longitudinal size of$\sim$10 interaction length. It is also required to have a sufficient transverse size of$\sim$2 interaction length to avoid transverse leakage of the hadron shower and to achieve good hadron energy resolution. There are various technologies available, such as the one used for the FOCAL calorimeter in ALICE, Cherenkov calorimeters, as well as technologies envisioned already for the EIC like crystals, scintillating glasses, and W/SciFi calorimetry. Cerenkov calorimeters, which measure only the high energy component of the showers, give excellent position resolution and tight containment but are non-compensating and thus non-linear. Sampling all charged particles produced, gives better energy resolution at the cost of worse lateral containment. For the ZDC one will need to exploit both techniques to maximize both the energy and position resolution as was shown be possible using quartz fibers developed or the LHC ZDCs.

For the ZDC much use can be made of past R&D. ZDC specific R&D is therefore not needed, except the construction of a full chain small to moderate prototype and test beam.

Timeline: not critical

1.6 Electronics

Substantial R&D will be need for the development of Front-End Electronics (FEE). Here we define FEE as ASIC, Front-End Board (FEB), and Front-End Processor (FEP). FEPs are needed if the ASIC does not provide all features needed. The choice of using streaming read-out for the EIC excludes several existing ASIC chips. Although one can possibly run ASICs not intended to operate in streaming mode, in a way that emulates such with local trigger or in self-triggered mode, it brings with it a high risk, especially in the presence of background which increases the deadtime and inefficiency to unacceptable levels.

ASICs exist for the Si-Vertex (DMAPS) detector, since the current ALICE ITS ships meet EIC requirements. ASICs for the readout of LGADs/AC-LGADS need to be urgently developed but their development is already contained in the LGAD R&D needs as discussed in Sec. 1.2.4.

We estimate the need for 3 ASICs used for the readout of (i) SiPM (calorimetry), (ii) MCP-PMT/PMT (PID), and MMG/GEM2/μRWell (tracking). This will require 3 FEB and likely 1-2 FEP.

Timeline: ASIC development takes 4-5 years. Considering the project deadlines (CD-1 to CD-4), developments of the various parts will likely have to occur concurrently, so multiple groups will have to be involved. Final requirements can only be established once the detector technologies are finalized (Q1 2022) but should not prevent first R&D efforts.

2 Generic R&D for Alternative Technologies

Here we list various alternative technologies that are not part of the reference detector but are potential candidates. Some will require substantial generic R&D to reach maturity.

2.1 Development of DMAPS Sensor for the EIC

The goal of this R&D is to develop sensors that meet the stringent EIC requirements for vertexing and tracking. The combination of very high single point spatial resolution and very low mass detector layers makes MAPS/DMAPS technology the most suitable candidate. The needed R&D is in parts to support the development of a MAPS sensor based on the ITS3 effort currently underway at CERN. The goal of this consortium is to develop a MAPS sensor and associated powering, support structures, control and ancillary parts as necessary to produce a detector solution for silicon tracking and vertexing for the central tracking parts of an EIC detector. This will include 1 MLR run shared with ITS3 (FY22), 1 engineering run shared with ITS3 (FY23), and 2 engineering runs for EIC chips only. Each of the runs is followed by a phase of intensive testing and characterization of the produced chips

It is estimated that 80% FTEs for silicon development would likely come from members of the EIC silicon consortium with support from their funding agencies. This would include DOE for US institutions with the contribution presumably on their base grant as well as foreign contribution funded from their host agencies.

For complete timeline (see section 1.1.1)

Timeline (short version):

Year	Task
2021	Submission of the second MLR
2022	Submission of the first engineering run (ITS)
2023	Submission of the first engineering run (EIC variant), second engineering run (ITS3).
2024	Submission of the second engineering run (EIC variant).
2025	Integration of prototype sensors into disc and stave. Possible contingency submission of EIC variant.

2.2 Central Tracker Cylindrical μRWELL

One significant need for large cylindrical μRWELL layers in the central barrel region is to provide high angular resolution for barrel PID detectors. This additional tracking information can aid in the PID particle seed reconstruction leading to better particle separation. For the scenario where a TPC is chosen as the central tracker option for the EIC detector a cylindrical μRWELL layer serves as a high space point resolution tracking layer to aid in the TPC field distortion corrections and TPC calibrations.

The simple construction of a μRWELL detector relative to a triple-GEM detector makes it an ideal MPGD technology to use in a cylindrical geometry. There are several R&D items related to its construction and performance that still need to be investigated. The first is related to the μRWELL technology itself. Efforts are needed to reduce the overall material budget of the current "standard" μRWELL. This involves the development of low mass amplification and readout structures. Ideally the cylindrical μRWELL would consist of one large foil and thus have no dead region in the active area. However, like with GEMs, μRWELL raw material is limited to a width of about 50 cm. To provide proper coverage for a barrel PID detector, several μRWELL will be needed to form the full cylindrical layer. R&D is needed to determine best way to integrate the μRWELL into one large cylindrical detector while minimizing dead regions in the active area. Another area of R&D that is needed is related to the support structure of the cylindrical μRWELL layer. This involves developing large, high strength and lightweight cylindrical μRWELL supports to hold the detector's cylindrical shape. Additionally, end cap structures to hold the cylindrical detector in place need to be designed. Several performance studies such as rate capabilities, dE/dx, tracking, and timing resolutions need to be carried out. The detector's cylindrical uniformity, discharge rate and aging properties will also need to be assessed.

Timeline:

Year	Task
2021	Completion of mechanical mockup. Procure components and begin building small-radius functional cylindrical prototype.
2022	Complete construction of small cylindrical prototype. Commission prototype. Perform beam test of small cylindrical prototype. Analyze beam test results. Design and procure materials for full-size mechanical mock-up.
2023	Finish analyzing beam test results. Build full-size mechanical mock-up ad evaluate. Design and build large-radius cylindrical μRWell prototype.
2024	Complete large prototype. Perform beam tests with large prototype.
2025	Complete analysis from test beam of large cylindrical μRWell prototype. Ready for design of potential production detectors.

2.3 Central Tracker Cylindrical Micromegas

Large cylindrical Micromegas layers in the central barrel region serve the same purpose as described in Sec. 2.2. Micromegas detectors have been already successfully employed for building compact and light trackers in various experiment (e.g. CLAS12). R&D is therefore limited to reducing the material budget (minimizing X_0), readout adaption and optimization and the construction of a full chain prototype.

On most MPGDs, copper is the chosen readout material with a thickness of at least 9 μm. The use of lower mass material for the strip readout such as metalized aluminum of about 0.4 μm requires R&D. The aluminum strips will have to be protected by a resistive layer to prevent vaporization of the metalized layer due to sparks.

Standard connectors made of plastic and brass contacts are quite heavy in term of material budget. If the active area is segmented, the multiplication of connectors can be a problem. Further R&D is need for testing Kapton connections with metal pixels clamped with light materials (carbon or 3D printed plastic).

Timeline:

Year	Task
2021	Ultra-light: R&D Goal: from 0.5% X_0 (Clas12) to 0.05% X_0 through R&D Full simulation of ultra-light MM design Design and construction of stretch bulked Kapton demonstrator (no FR4) 2D readout design studies: Procurement of large pads readout PCBs Finalize 2D zigzag readout pattern studies
2022	Ultra-light: Aluminium based strips Thin aluminium mesh manufacturing with laser ablation Readout studies: Bulking and test of large pads readout Cylindrical MM: Design of MM tracker support structure within EIC detector
2023	Ultra-light: Prototype construction Cylindrical MM: Final prototype with 2D zigzag readout

2.4 GEM-TRD/Tracker

A high granularity tracker combined with a transition radiation option for particle identification would provide additional information necessary for electron identification or hadron suppression. The scope of the project is to develop a transition radiation detector/tracker capable of providing additional pion rejection (> 10-100).

A low mass radiator available for mass production is critical and various materials still need to be tested and optimized. This includes the optimization of a pseudo-regular radiator using thin Kapton foils and thin net spacers and a detailed test of available fleece/foam materials for TR-yield. The transition radiation detector readout is based on well-established GEM technology but features a thick drift volume. In order to keep a uniform electric field, a special field cage needs to be developed. This includes the mechanical design and construction of the field-/gas-cage to minimize a Xe-filled gas gap between radiator and the drift cathode. The anode readout PCB layer of the current GEM-TRD prototype is based on a readout developed for the COMPASS experiment. While this is optimal for a high occupancy environment, the large number of channels does increase the price of the readout electronics. R&D is needed way to develop a new concept of pad readout better suited for GEM-TRD applications.

The use of existing readout chips (SAMPA) that meet the requirements will need to be evaluated in detail. Development of a new readout chip will be needed to enable the streaming of zero-suppressed data over fiber links.

Over the past few years, the price of Xe has gone up significantly. Design and Development of a recirculation system to purify, distribute, circulate, and recover the gas, possibly based on a design of ATLAS TRD gas system at CERN will be necessary but will require only moderate R&D.

Timeline:

Year	Task
2021	• Test of different readout architecture (strips, pad,zig-zag) to minimize the noise level, number of readout channels, and spatial resolution. This requires building several small (10x10 cm2) prototypes with different readouts options and test them at JLAB and Fermilab. • Tests of a new streaming readout architecture hardware (SRO125) and ML-FPGA -based data reduction concepts. • Test of different TR-radiators.
2022	• Build and test large-size modules in order be able to workout possible issues: like noise, gain-uniformity, drift-time issues, HV stability, etc. A field/gas-cage needs to be developed and optimized for TRD applications. • Test beams at Fermilab with electron and pion beams
2023	• Design and development of a recirculation gas system to purify, distribute, circulate, and recover the gas (in collaboration with other labs/universities). • Test beams at Fermilab with electron and pion beams
2024	• Development of final design specifications for the streaming readout architecture as input to a coordinated ASIC design program.

2.5 Time-Of-Flight Detector (ToF)

Two time-of-flight detector techniques are under consideration. One is using AC-LGAD precision timing silicon detectors; the other option is making use of the excellent timing performance of LAPPDs. Due to the compactness of the EIC detector, flight paths are short and resolutions in the order of ~10-20 ps will be needed. It is expected that AC-LGAD will be able to reach resolution if 20-35 ps and LAPPDs of ~10 ps.

Another option that has not received much attention yet but might have quite some potential is the technology used in the Barrel Timing Later (BLT) of the CMS-MTD design, i.e. using crystals with SiPM readout. Test beams confirm resolutions of 30ps that would fill in the PID gap with 3σ separation for particles with p < 2-3 GeV/c

ToF are considered in the forward direction to enhance PID, and in the barrel in the case of an all-Si tracker (instead of a TPC) to compensate the loss of PID provided through the TPC's dE/dx measurements at low-p_T.

R&D efforts focus mostly on the development of LGAD sensors only and are discussed in Sec. 1.2.4 for AC-LGAD and Sec. **Error! Reference source not found.** for LAPPDs. Note that even if no AC-LGAD based TOF will be chosen for the final detector that sensor R&D part is still needed since it is the technology of choice for the Roman Pots.

Current plans are to follow the CMS-MTD concept. The LGAD technology is being applied to the upgrade of CMS and ATLAS timing layers for the high-luminosity LHC program. Many technical and engineering challenges for constructing and operating a full detector are being addressed there. Therefore, the LGADs is a mature technology that is ready for EIC detectors. At EIC, the detector radiation hardness is not a concern but requirements on the precision of PID and tracking are more demanding, requiring targeted R&D efforts to take advantage of most recent LGADs technologies and develop readout electronics with finer granularity and better power efficiency.

Besides R&D work on the sensors, the priority and potentially challenge is to develop a strategy toward developing the readout electronics needed. ASIC chips developed at CMS and ATLAS can serve as a starting point but more work is needed to optimize the jitter, power consumption and demonstrate the feasibility of reducing the granularity to as small as 500 μm (forward region). Efforts on initial designs of modules, mechanical structure, cooling service, data flow, clock distribution etc. are required for the TDR, by leveraging and optimizing designs at LHC experiments.

Note that this effort is tightly connected to 1.2.4.

Timeline: much in flux. Depends strongly on choice of chosen technologies (LAPPD, LGAD, LYSOL+SiPM).

2.6 Photosensors

The choice of photosensors is essential for reaching the cost and performance goals of all EIC PID subsystems. Solutions for each detector is driven by the detector's specific operational parameters. Ultimately, it would be preferable to use a common photosensor thus reducing development and procurement costs.

Microchannel-plate photomultipliers (MCP-PMTs) from commercial vendors have shown superior good timing and position resolution as well as moderate magnetic field tolerance but are generally far too expensive for large area coverage. The recently commercialized new type of MCP-PMT using the atomic layer deposition technique as a large area picosecond photodetector (LAPPD) provides a promising cost-effective MCP-PMT for the EIC RICH detectors.

R&D efforts using a small format of LAPPD build at Argonne, has demonstrated all the required parameters, especially a magnetic field tolerance over 1.5. To expedite the application of MCP-PMT for EIC Cherenkov detectors, a 10x10 cm^2 MCP-PMT fabrication facility is under construction to produce larger size, high-performance MCP-PMTs. The commercial available LAPPD module has also achieved almost all the requirements except fine pixel size and magnetic field tolerance. R&D efforts and close collaboration with INCOM are needed to overcome its shortcoming and produce a viable solution.

To validate the LAPPD performance and apply this new technology to the EIC-PID subsystems, critical R&D is needed in the next two years. A bench test and multiple beam tests of Cherenkov prototype detectors using the MCP-PMT/LAPPD will need to be performed.

The required R&D is aimed at both near-term and future detector designs.

Timeline:

Mar 2021	Photosensors Timeline Estimate	2021				2022				2023				2024			
					FY22				FY23				FY24				
High-B Sensor Program	Scan of 10-µm XP85122-S, HiCE Planacon			■				■									
	Scan of 6-µm Photek MCP PMT, MAPMT253			■				■				■					
	Full-area uniformity scan with UHawaii electronics							■				■					
	Incom GEN-III (HRPPD) scan						■				■						
MCP-PMT/LAPPD	Beamline test of MCP-PMT/LAPPD with pixel readout			■	■												
	mRICH-LAPPD-ToF experiment with Gen-II LAPPD			■	■												
	Magnetic field test of LAPPD prototypes			■	■												
	Fabrication of 10x10 cm MCP-PMT for prototype validation					■	■	■									
	Bench evaluation of MCP-PMT, LAPPD and HRPPD					■	■	■									
	Integration of UHawaii electronics with available sensors						■	■	■	■							
	Beamline evaluation of RICH subsystems with available MCP-PMT/ LAPPD								■	■	■	■	■				
SiPM program	Status-of-the-art sensor selection	■															
	Irradiation and temperature treatment (standard sensors)		■	■	■												
	Post-irradiation response with dedicated readout				■	■	■	■									
	Custom sensor solutions (with manufacturers)					■	■	■	■	■	■	■	░	░	░	░	░
	Irradiation and temperature treatment (custom sensors)						■	■	■	■	■	■	░	░	░	░	░
	Engineering of cooling and services									■	■	■	■	■	■		
Sensors and Electronics	Collaboration effort within eRD14	■	■	■	■	■	■	■	■	■	■	■	■				
TDR									■	■	░	░	░	■	■		

3 Generic R&D for Outyears

The R&D needs listed in the previous section are for a day-1 detector. However, further opportunities do remain. These are driven both by pursuing alternative detector technologies for a complementary second fully integrated EIC detector and Interaction Region, and to prepare for future cost-effective detector upgrades to enhance capabilities addressing new nuclear physics opportunities. Furthermore, the EIC will be a two-decade Nuclear Physics facility after its construction is completed and will in this period likely require further detector upgrades driven by its science findings. It is expected that further physics opportunities enabled by new detector capabilities will already arise during the EIC design and construction phase.

In the remainder of this section, we list possible generic topics of high relevance for an EIC detector.

3.1 MPGD for RICH/Nano-Diamond Materials

Single Photon Detectors (PD) for Cherenkov imaging devices represent a key challenge at EIC where minimum material budget and operation in high magnetic field is required. Gaseous PDs, which have played a major role in establishing and operating Ring Imaging CHerenkov (RICH) counters, satisfy these requirements and they represent the most cost-effective solution when equipping large detector areas. So far, the only photon converter successfully coupled to gaseous detector is CsI with Quantum Efficiency (QE) limited to the far UV domain. Optimized detector architecture and operative conditions have to be established to ensure effective photoelectron extraction. MPGD technologies are considered to be useful in this context.

An R&D program for further developments of an hybrid approach (THGEMS and resistive MICROMEGAS) which is in operation in the COMPASS experiment is desirable. R&D includes: (i) Establishing the hybrid PD for a windowless RICH approach to increase the number of detected Cherenkov photons and (ii) coupling of the THGEMs with a novel and more robust photoconverter made out of Hydrogenated Nano Diamond powder (HND). The latter will overcome the limitation imposed by the use of CsI due to its chemical fragility in contaminated atmosphere or under ion bombardment, that imposes gain limitations and complex handing. Very promising initial studies are already ongoing.

Timeline:

Year	Development of MPGDs for high momentum hadron PID: Development of MPGD sensors for single photons
2021	Complete construction of prototype version 2 Initial labe test of prototype version 2 Read-out chain based on VMM2 FE fully operational
2022	Complete lab test of prototype version 2 Validate the read-ou of single photoelectron signals with VMM3
2023	If selected for the EIC detector, detailed engineering

Timeline:

Year	Development of MPGDs for high momentum hadron PID: New photocathode materials for gaseous detectors
2021	H-ND effective QE in different gas mixtures H-ND effective QE after thermal cycle in inert gas Construction of complete detector with H-ND photocathodes Coating substrate sample with CSI for comparative studies
2022	Perform comparative studies of H-ND and CsI Lab test of the complete detector with H-ND photocathodes Quantify the radiation hardness of H-ND photocathodes
2023	Systematic measurements of H-ND with different grain size Systematic measurements of H-ND with different graphite content Systematic measurements of H-ND with different providers Systematic measurements of H-ND with different B doping
2024	Completion of 2023 exercises

3.2 CSGlass for Hadronic Calorimetry

There is a need to improve the energy resolution of hadron calorimetry. The technology goal of CSGlass R&D is to develop a scintillating glass for improving hadronic calorimeter resolution, which is desired or measurements of hadronic jets. CSGlass is optimized for the dual readout approach, where one compares the signals produced by Cherenkov and Scintillation light in the same detector. This approach has been a promising method to achieve better performance for hadron calorimeters.

The areas of needed R&D for CSGlass include the demonstration of CSGlass with sufficient UV transparency for Cherenkov light collection, clear separation of Cherenkov and Scintillation light of sufficient intensity, low cost, and characterization of CSGlass in the lab and with test beam R&D prototypes. The most critical items are the formulation optimization and production of CSGlass test samples. Some of the CSGlass R&D is shared with SciGlass and PbWO4 crystals for EM calorimeters. The approximate timeline for completing the CSGlass R&D is ~3 years assuming R&D funds are available. CSGlass could be ready for future detector upgrades.

Timeline:

Year	Task
2021	Production of test samples to demonstrate sufficient UV transparency for Cherenkov light collection
2022	Composition optimization and initial scale up, establish CSGlass characteristics, e.g. measurements of separation of Cherenkov and Scintillation light of sufficient intensity.
2023	Final formulation optimization and scale up to full module size; establish CSGlass characteristics
2024	Prototype and beam tests. Process design verification to scale up.

3.3 Particle ID in Barrel for High-p_T

Recent studies showed that by extending the particle ID capabilities of an EIC detector at mid-rapidities out to momenta of 10 GeV/c or higher would allow to expand the EIC's physics potential substantially. To-date few solutions exist that fit in the given space. New ideas have to be explored on how to reach high-p_T PID. Possible solutions could include novel methods such a Long Shadow Detector (LSD) which is in an early conceptual stage.

Timeline: unknown

3.4 Nanowires

Superconducting Nanowire Single-Photon Detectors (SNSPDs) have become the dominant technology in quantum optics due to their unparalleled timing resolution and quantum efficiency. Attempts to transform these sensors into a novel particle detector for the EIC are underway.

These sensors can operate in magnetic fields greater than 5 T at a high rate with very high efficiencies. They provide a timing resolution of better than 20 ps. First R&D effort aims to produce a small superconducting nanowire pixel array for detecting high energy particles.

This first of its kind detector will have the flexibility to be used in multiple far forward detector systems. It can extend the EIC's scientific reach beyond what is possible with contemporary technology for far-forward detection in large parts due to their radiation hardness that allows for a longer service cycle of detectors operating near the beam and interaction regions. One possible implementation at an EIC would include placing the detector inside the magnet and integrating it with the magnet's cooling system, eliminating the need for a separate cryogenic system.

The required R&D will require several years of generic R&D.

Timeline:

Design of a first generation of individual pixel of few-pixel array detectors can be completed within 2021, depending on when the institutions lift their current work restrictions. After another 6 months to a year, results gathered during that period can be integrated and a process will be developed to fabricate optimized detectors at relevant scales. Thus, after 2 years, the sensor modules of Roman Pot-like superconducting nanowire particle detectors or Compton polarimeter components can be available for full scale prototype testing assuming the availability of appropriate readout electronics.

3.5 Radiation Hard SiPM

Most likely, all EIC calorimeter technologies will use SiPMs as photosensors, but it is well known that these devices are subject to radiation damage, particularly neutrons. The development of more radiation hard SiPMs would be of great benefit for calorimetry and (if high stability is reached) also for all PID detectors. Developing radiation hard SiPMs would take several years of R&D and require a substantial investment and collaboration with the manufacturers.

Timeline: May 2021 test beam (protons) …

4 Cost and Schedule

The following table shows the anticipated costs in US$ per fiscal year from FY22 to FY26. It is subdivided into the section discussed above. This list is all-inclusive. The project will fund the necessary R&D projects choosing a selection that is generic and of priority for all detector concepts under consideration.

R&D Subsystem	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**
Reference Detector – Project (Section 1)					
Si-Vertex (barrel & disks) w/o sensors	340,160	680,820	680,320	567,600	0
Service Reduction	42,840	85,680	85,680	71,400	0
TPC [1]	100,000	150,000	50,000	0	0
Low-Mass GEM Tracker	20,000	0	0	0	0
Modular RICH (mRICH)	140,000	140,000	140,000	0	0
Dual Radiator RICH (dRICH)	260,000	200,000	77,000	0	0
High-Performance DIRC[2]	450,000	250,000	80,000	0	0
LGAD[3]	235,000	240,000	240,000	240,000	200,000
ECAL: Sc. Glass & Crystals	90,000	50,000	50,000	0	0
ECAL: W powder SciFi, Pb(W)/Sci Shashlik, Lead Glass	90,000	50,000	50,000	0	0
HCAL (forward)	100,000	200,000	100,000	0	0
HCAL (barrel)	200,000	100,000	0	0	0
Low-Q^2 taggers	100,000	50,000	0	0	0
Roman Pots	40,000	40,000	20,000	0	0
ZDC	100,000	50,000	0	0	0
Electronics/ASIC	275,000	900,000	760,000	500,000	0
Total (Reference)	2,583,000	3,186,500	2,333,000	1,379,000	200,000
Generic - Alternatives and Improvements to Reference Detector (Section 2)					

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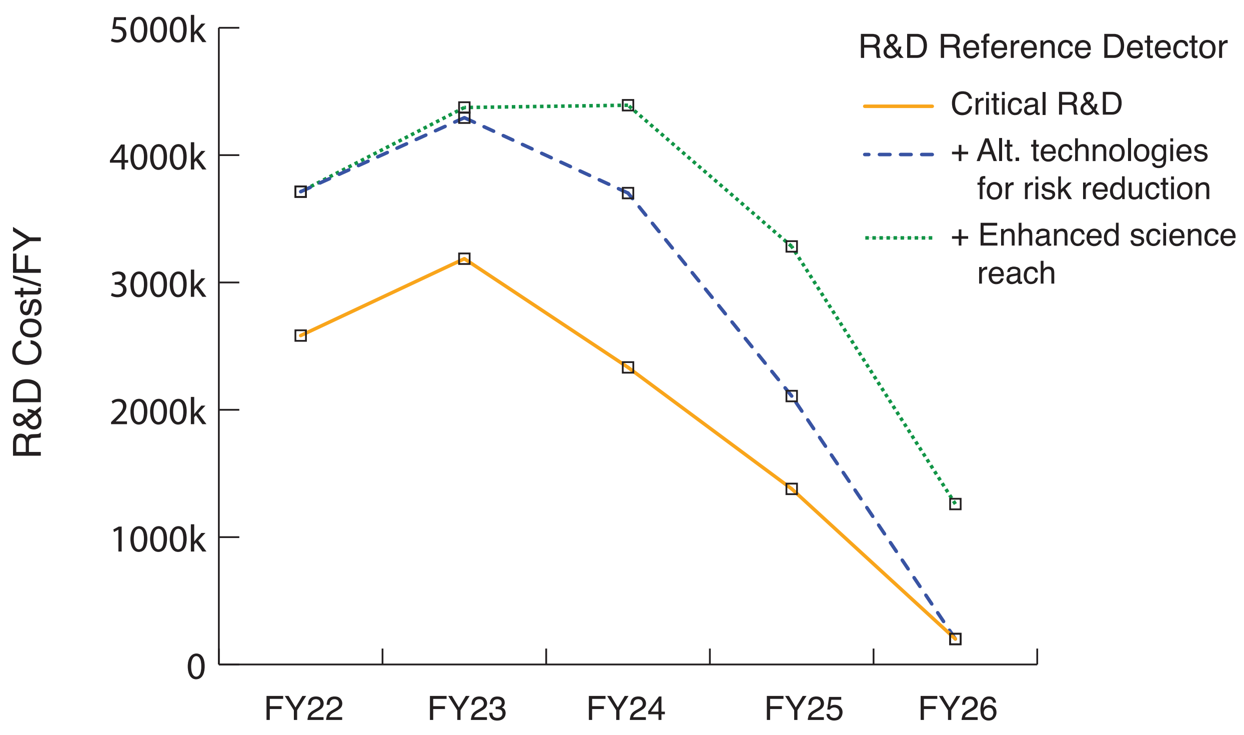
[1] Given the status of planning in the proto-collaborations a TPC is increasingly unlikely to be used which would eliminate it from the R&D program.

[2] 200k is for MCP-PMTs to be used in prototypes. They are likely to be used in final detector.

[3] Referring beam line detector (Roman Pots) will/can come in late.

Si Sensor Development	740,000	852,500	1,189,000	639,000	0
Central Tracker Cylindrical µRWELL[4]	130,000	50,000	0	0	0
Central Tracker Cylindrical Micromegas[4]	10,000	50,000	5,000	0	0
GEM TRD[4]	70,000	30,000	60,000	0	0
Time-of-Flight[4]	0	45,000	90,000	90,000	0
Photosensors[4]	180,000	80,000	25,000	0	0
Total (Generic)	1,130,000	1,107,500	1,369,000	729,000	0
Generic - Future Updates and Improvements (Section 3)					
MPGD for RICH/Nano-Diamond Materials	0	0	70,000	130,000	130,000
CSGlass for Hadronic Calorimetry	0	30,000	130,000	200,000	180,000
Particle ID in Barrel for High-pT (LSD)	0	50,000	200,000	350,000	250,000
SC Nanowires	0	0	90,000	95,000	100,000
Radiation-Hard SiPM	0	0	200,000	400,000	400,000
Total (Generic Future)	0	80,000	690,000	1,175,000	1,060,000



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[4] Given the status of the discussions within the proto-collaborations this project could become generic and project funded.

5 Appendix

The advisory committee of the Generic EIC Detector R&D Program[5] met over the days of March 24-26, 2021, to review the progress of the various R&D programs presently being funded by the EIC program. When possible, the meetings (both presentations and executive sessions) were attended by members of the EIC Detector Advisory Committee (DAC). The DAC was primarily charged with providing advice about the division of the R&D effort between project R&D, to address any risk in completion of the planned EIC (Reference) detector, and generic R&D, to address developing new technologies that could substantially increase the range and precision of the proposed program of EIC physics measurements if developed in time.

On June 29, 2021 the DAC submitted their report. The table below summarizes their recommendations:

R&D Topic	**Project R&D**	**Generic R&D**
Si tracker based on 160nm ALPIDE	X	
Si tracker based on 65 nm MAPS/DMAPS		X
Central TPC: hybrid GEM/Micromegas	X	
Central TPC: μRWELL		X
Forward/Backward GEM Tracker	X	
Cylindrical Micromegas/Silicon hybrid tracker		X
Modular RICH (mRICH)	X	
Dual Radiator RICH (dRICH)	X	
High performance DIRC (hpDIRC)	X	
TOF/tracker based on LGAD		X
TOF/tracker based on LAPPD		X
GEM-TRD/tracker		X
EMCal W/SciFi	X	
EMCal Shashlik	X	
Scintillating Glass	X	
Hadron Calorimeter (hCal)	X	
Cerenkov/Scintillating Glass		X
Far-Forward Detectors (Roman Pots)	X	
Zero-Degree Calorimeter (ZDC)	X	

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[5] https://wiki.bnl.gov/conferences/index.php/EIC_R%25D

Low-Q^2 Tagger	X	
Compton Polarimeter	X (accel?)	
MCP-PMT/LAPPD		X
Radiation Hard SiPMs	X	
MPGD-based Photon Detectors		X
Superconducting Nanowires		X
Front-end Electronics	X	
Streaming DAQ/Filtering	X	
Background Simulation	X	

The provided recommendations are fully aligned with the plan outlined in this document with two exceptions: (i) the current R&D plan does not include any R&D on background simulations since these efforts are now included in the IR design efforts funded by the project, and (ii) the current plan does not consider R&D on radiation hard SiPMs as an urgent item to be supported at this time since efforts in this direction are already under way in Europe that can be leveraged.