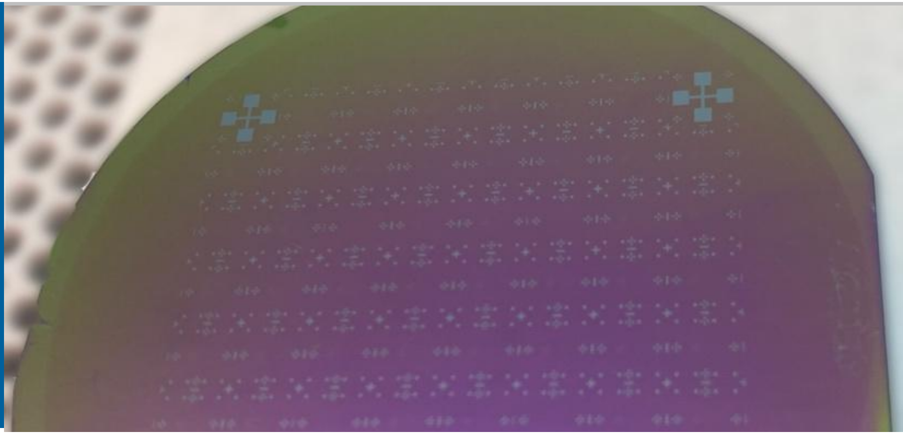
Applications of Superconducting Nanowire Detectors at the EIC (and JLab)

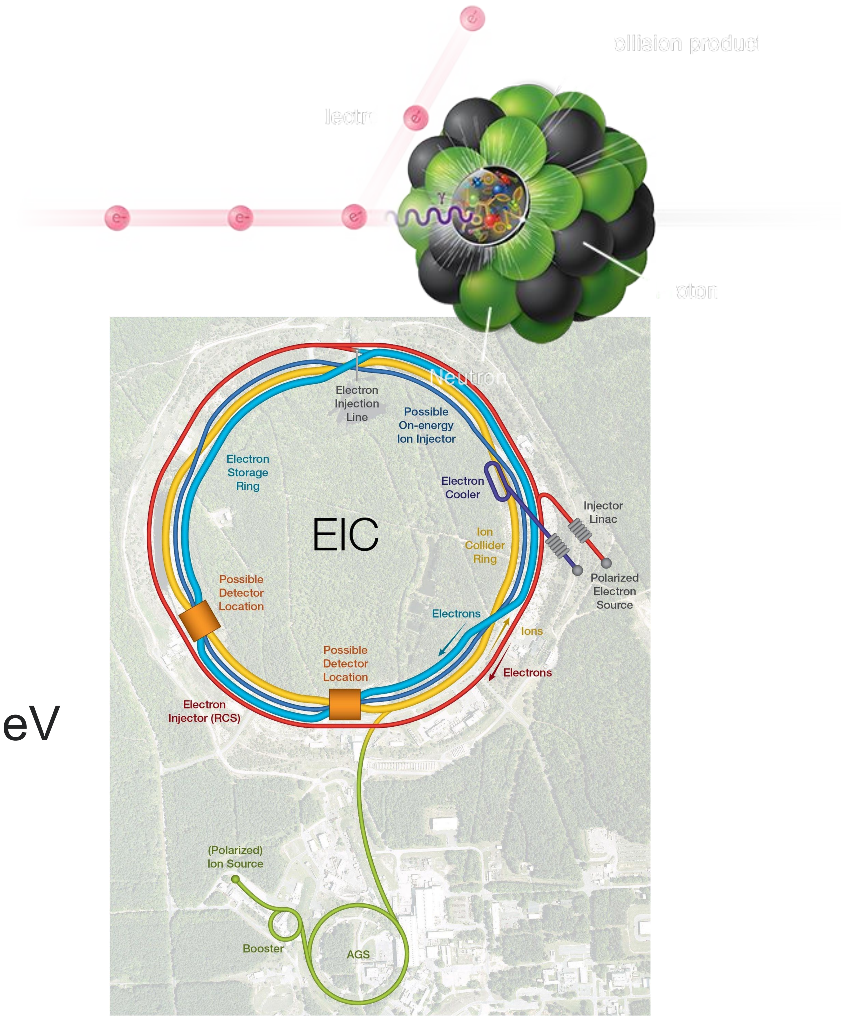


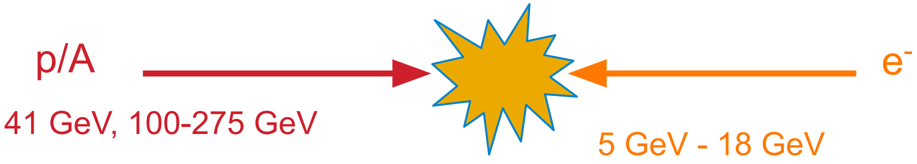
Whitney Armstrong, Kevin Bailey, Kawtar Hafidi, Sangbaek Lee, Zein-Eddine Meziani, Val Novosad, Tom O'Connor, Tomas Polakovic

Electron-Ion Collider

Key Machine Parameters:

- High Luminosity: L= 10^{33} - 10^{34} cm^{-2} s^{-1}
  - 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range:
  - E_{cm} = 29 – 140 GeV
- Many ions from protons to Uranium with polarized light nuclei
- Hermetic Detector Acceptance
- Proton beam energies: 41 GeV, 100-275 GeV
- Electron beam energies: 5 GeV to 18 GeV





EIC Science

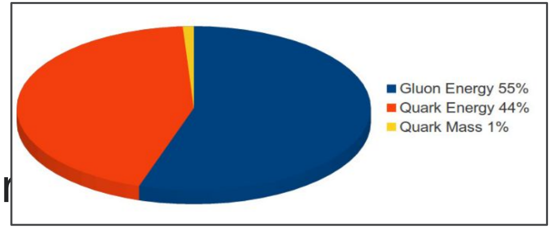
A machine to study QCD and Nuclear matter

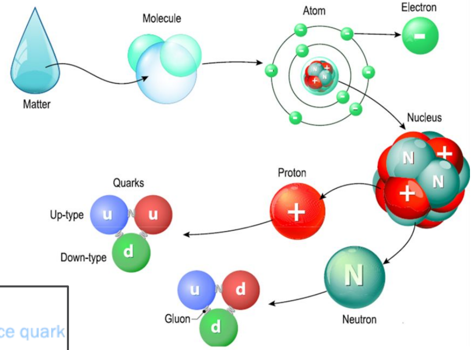
3D Imaging of quarks and gluons

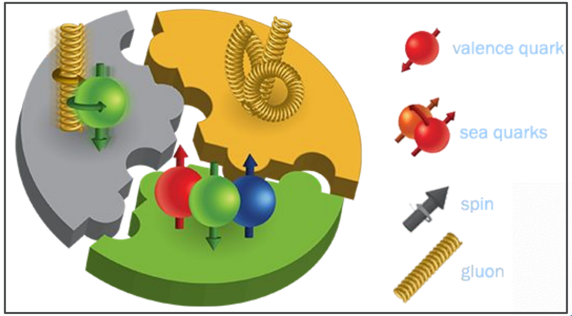
What is the origin of the proton mass?

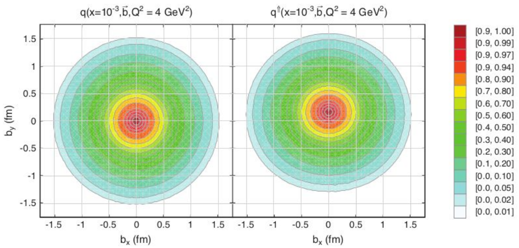
What is the origin of the proton spin?

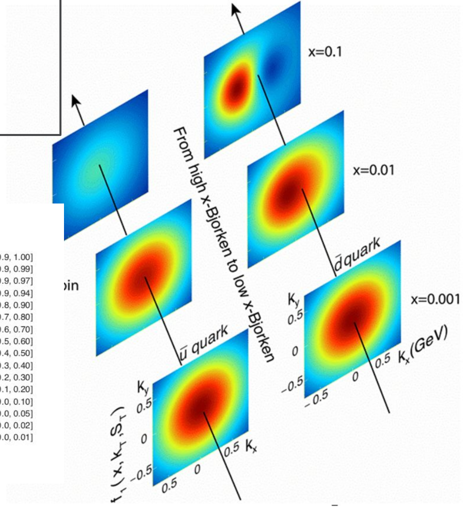
See the official website for more information and key documents

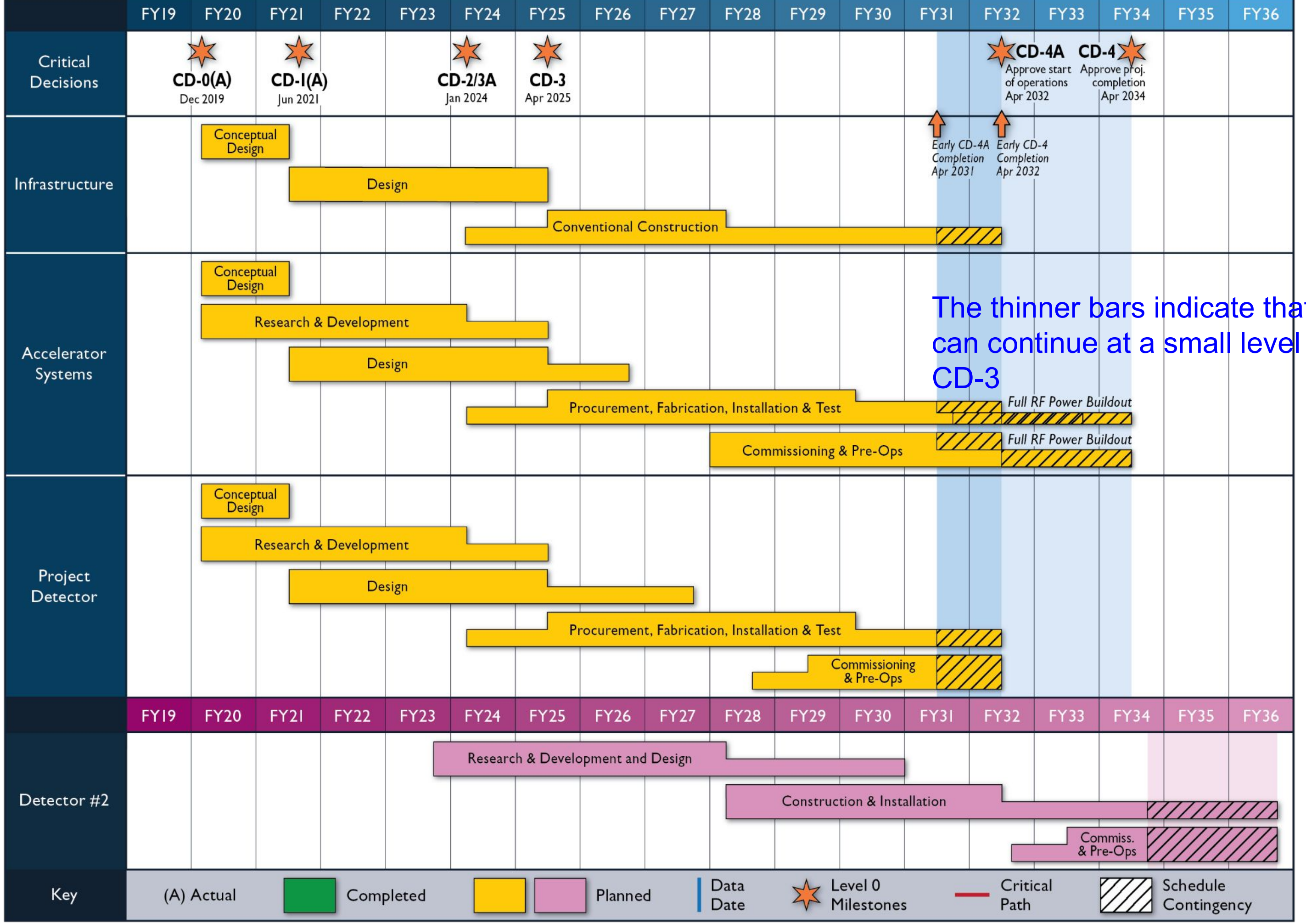












The thinner bars indicate that R&D and design can continue at a small level beyond CD-2 and CD-3

EIC Project Detector R&D Program

Project Detector R&D

- Builds on the success of the generic detector R&D
- Focus: R&D for systems in scope
  - ensure feasibility
  - reduce risk
  - optimization
- EIC Project DAC joined last generic EIC Detector R&D meeting (March 2021)
- DAC concurred with all Project and Generic tasks; advised to add few topics
  → This was folded into the Project Detector R&D plan
- We have initiated FY22 follow-up with user groups pursuing project-specific detector R&D common to all proto-collaboration EIC detector proposals
- ECal & HCal R&D on hold to adjust to outcome of consolidation outcome

R&D Topic	Project R&D	Generic R&D
Si tracker based on 160nm ALPIDE	X X	
Si tracker based on 65 nm MAPS/DMAPS		X X
Central TPC: hybrid GEM/Micromegas	X X	
Central TPC: RWELL		X X
Forward/Backward GEM Tracker	X X	
Cylindrical Micromegas/Silicon hybrid tracker		X X
Modular RICH (mRICH)	X X	
Dual Radiator RICH (dRICH)	X X	
High performance DIRC (hpDIRC)	X X	
TOF/tracker based on LGAD		X X
TOF/tracker based on LAPPD		X X
GEM-TRD/tracker		X X
EMCal W/SciFi	X X	
EMCal Shashlik	X X	
Scintillating Glass	X X	
Hadron Calorimeter (hCal)	X X	
Cerenkov/Scintillating Glass		X X
Far-Forward Detectors (Roman Pots)	X X	
Zero-Degree Calorimeter (ZDC)	X X	
Low-Q^2 Tagger	X X	
Compton Polarimeter	X (accel?)	
MCP-PMT/LAPPD		X X
Radiation Hard SiPMs	X	
MPGD-based Photon Detectors		X X
Superconducting Nanowires		X X
Front-end Electronics	X X	
Streaming DAQ/Filtering	X X	
Background Simulation	X	

X = DAC
X = Project - Current R&D Plan (v3.6)
X = Generic - Current R&D Plan (v3.6)

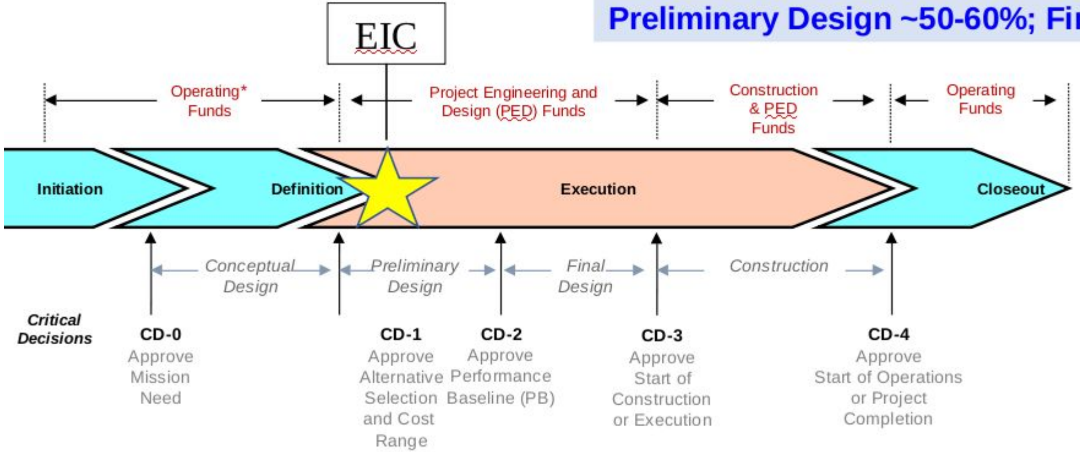
Want to be in the Project R&D column

Special Meetings:

- LAPPD 21st March 2022 https://indico.bnl.gov/event/15059/
- SiPM Use and Needs at EIC https://indico.bnl.gov/event/14715/
- follow ups and new topics are in the planning

DOE Project Decision Process

Preliminary Design ~50-60%; Final Design 85%



EIC Critical Decision Plan
CD-2/3a

January 2024
CD-3

April 2025
CD-4a early finish

April 2031
CD-4a

April 2032
CD-4 early finish

April 2032
CD-4

April 2034

CD-2 – Approve Performance Baseline: CD-2 is an approval of the preliminary design of the project and the baseline scope, cost, and schedule. What is most relevant is that CD-2 means there is now a definitive plan that the project will be measured against in cost, schedule and technical performance.
→ pre-TDR is required for CD-2
(pre-TDR = preliminary version of TDR)

CD-3 – Approve Start of Construction: CD-3 is an approval of the project's final design and authorizes release of funds for construction. What is most relevant is that projects can now proceed with construction related procurements and activities. CD-3 is sometimes split in CD-3A in a tailored approach to approve start construction for long-lead procurements.
→ TDR is required for CD-3

The EIC Project Is Moving Forward

How do we get a promising technology adopted?

- There are a number of applications for SNSPDs and superconducting electronics at the EIC
  - Forward and Far-Forward detectors, Compton polarimeters, beam loss monitors, …
- Generally, NP is quite conservative in adopting new technologies
- SNSPDs are a **fundamentally new particle detector technology** and present new opportunities for novel applications at accelerator facilities
  - EIC Project's Perspective: SNSPDs are unfamiliar, "risky", and have unknown cost
- The EIC Project's current position is that SNSPDs should be considered as an "upgrade" option (to a currently incomplete design)
- So it will certainly take some convincing to get offical project backing

Strategy for enhancing the EIC Physics Program

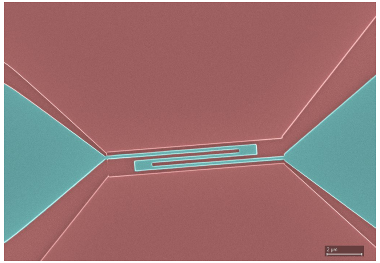
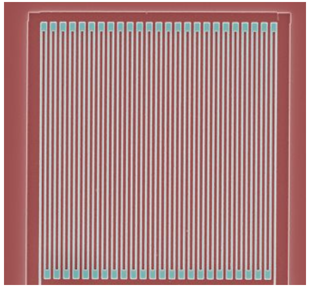
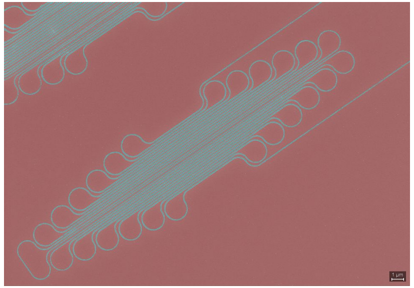
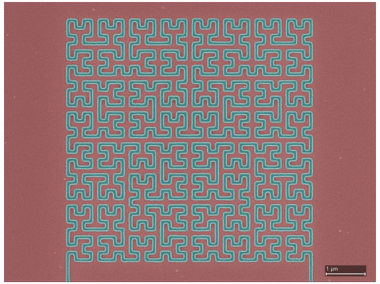
How to move the needle on SNSPDs at the EIC?

- Case for enhanced science program:
  - SNSPDs are a superior technology for small area tracking detectors (relative to the size of central detector)
  - A more hermetic detector: SNSPDs can operate at locations thought to be forbidden (radhard, cryogenic, B-fields)
  -
- What should be the first targeted EIC application?
- And what would be the (EIC Project) cost?
- How to quantify and mitigate associated risk?

SNSPD Properties and Characteristics

Quick Summary

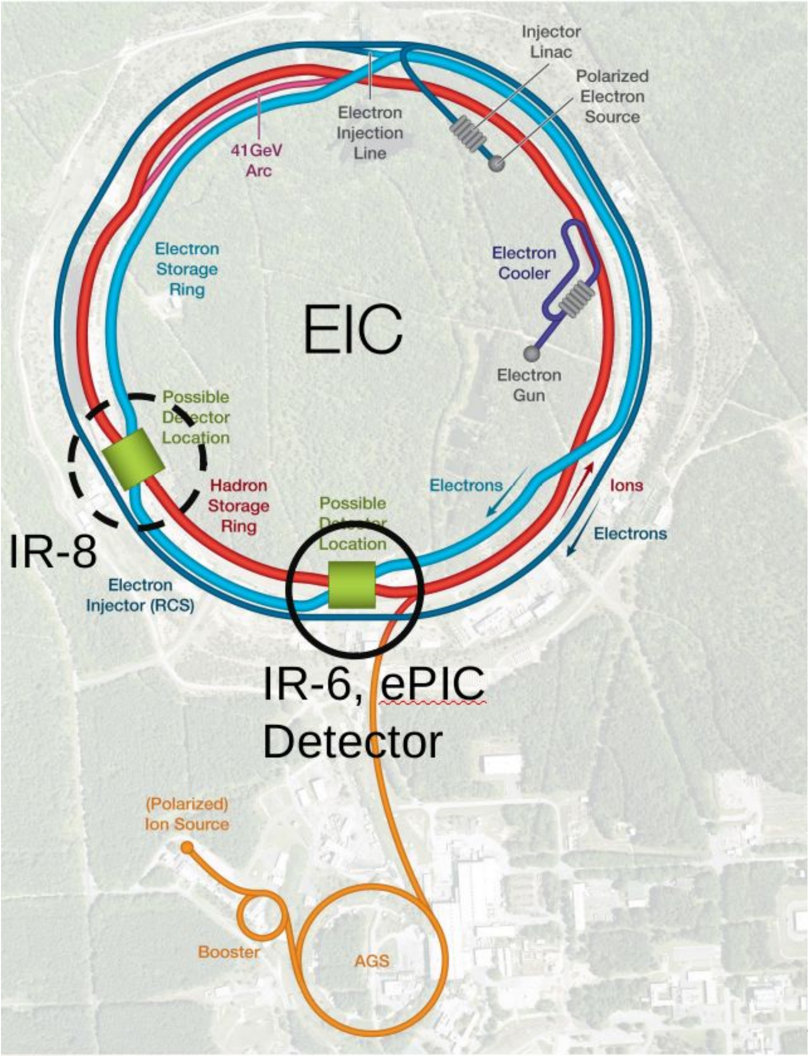
- Photon energy thresholds as low as ~100 meV
- Timing jitter 20–40 ps easily achieved (current record of 3 ps)
- Reset times can be as low as 5-10 ns (potentially <1 ns in the future)
- Pixels on the order of 10x10 μm^2 to 30x30 μm^2
- Fast, granular, high-rate pixel detector → low occupancies
- Conveniently operates at LHe temperatures (T < 5K)
- Photon detection efficiencies >90%
- Expected to very radiation hard (more on this later)
- Can be fabricated with different geometry or pixel dimensions

Applications at the EIC

EIC Machine Layout at BNL

Two Interaction Regions for detectors but only one official project supported detector at the moment (EPIC).



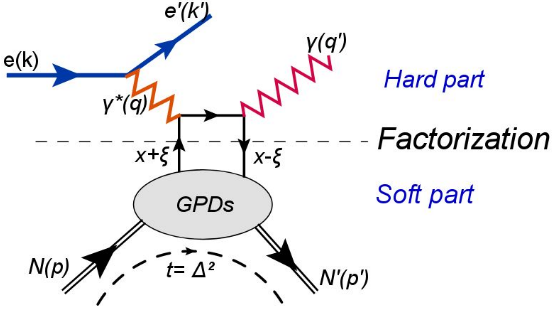
A Motivation for Nanowire Particle Detectors at the EIC

- GPD physics requires the momentum transfer $|t|/Q^2$ to be small.
- Lower limit determined by
  (1) $|t| > |t_{min}|$: physical threshold
  (2) the detector acceptances

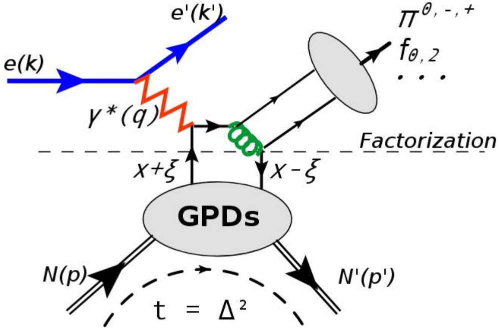
- Scattered protons
  – p_T > 0.2 GeV/c is "equivalent" to $|t| > 0.04$ GeV^2

- Scattered nuclei (coherent DVCS and DVMP)
  – Larger room between $|t_{min}|$ and the detector acceptance limit

- Aligned with Roman Pot requirements reported in YR
  – Fast timing
  – Radiation hardness
  – Fine position resolution



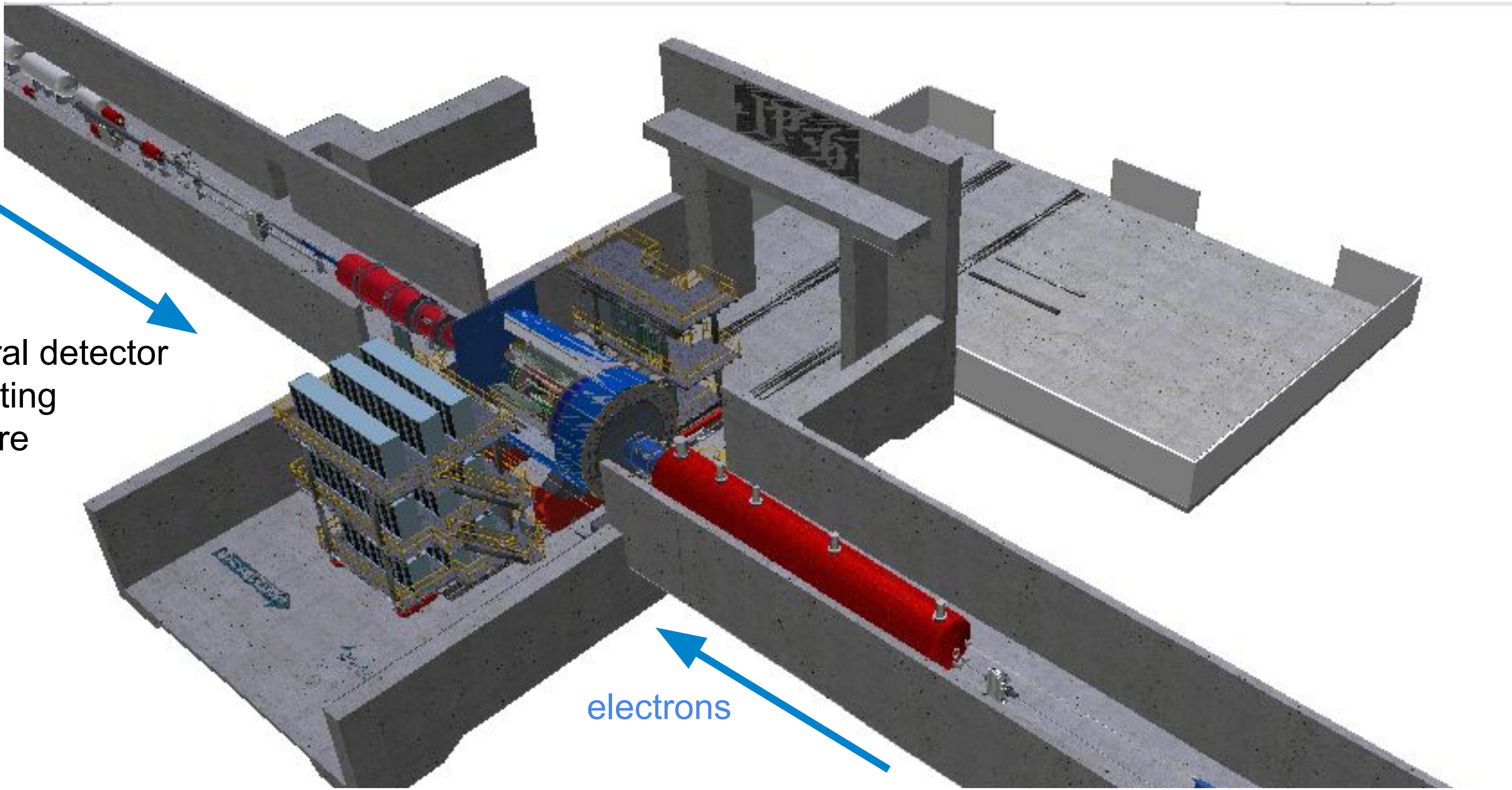
Deeply Virtual Compton Scattering



Deeply Virtual Meson Production

Interaction Point 6 (IP6)

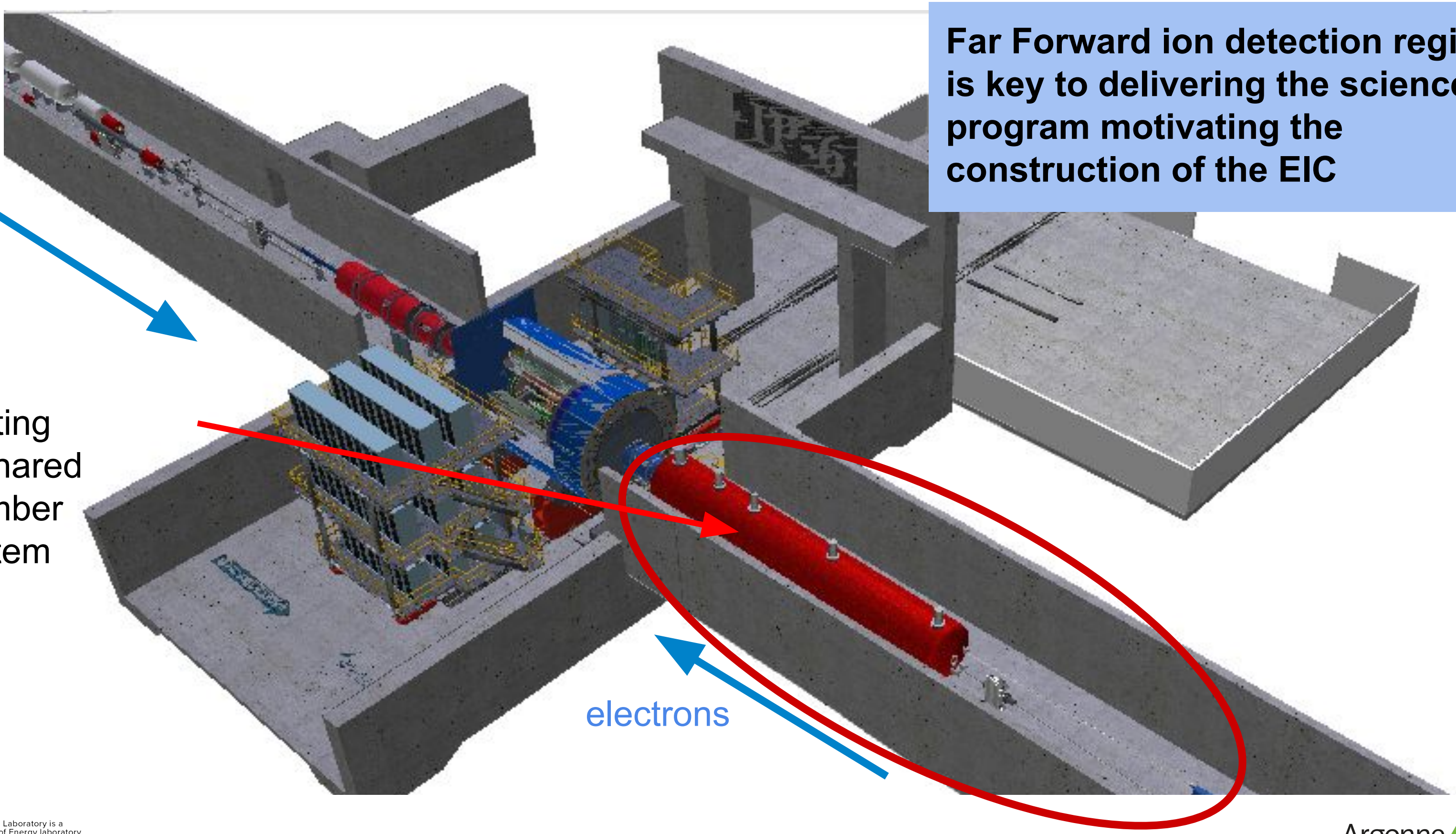
ions



Large central detector and supporting infrastructure

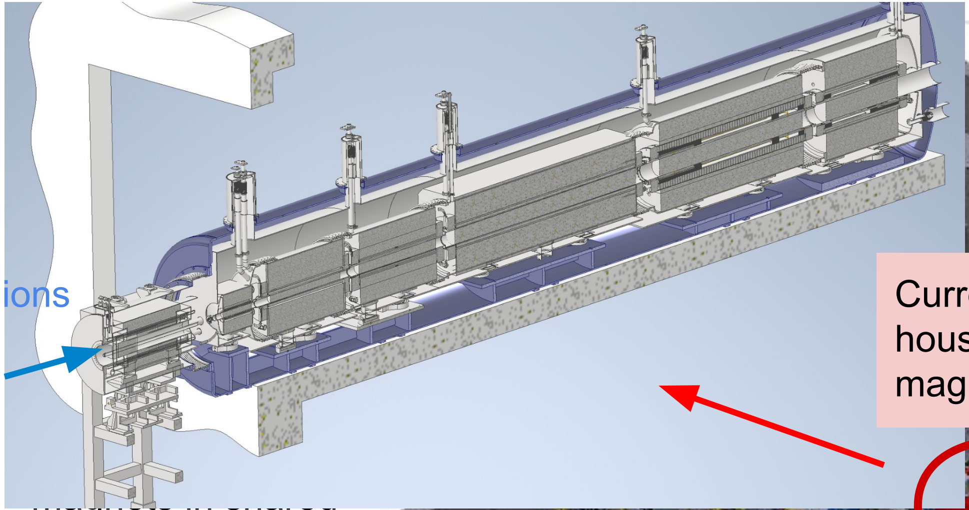
electrons

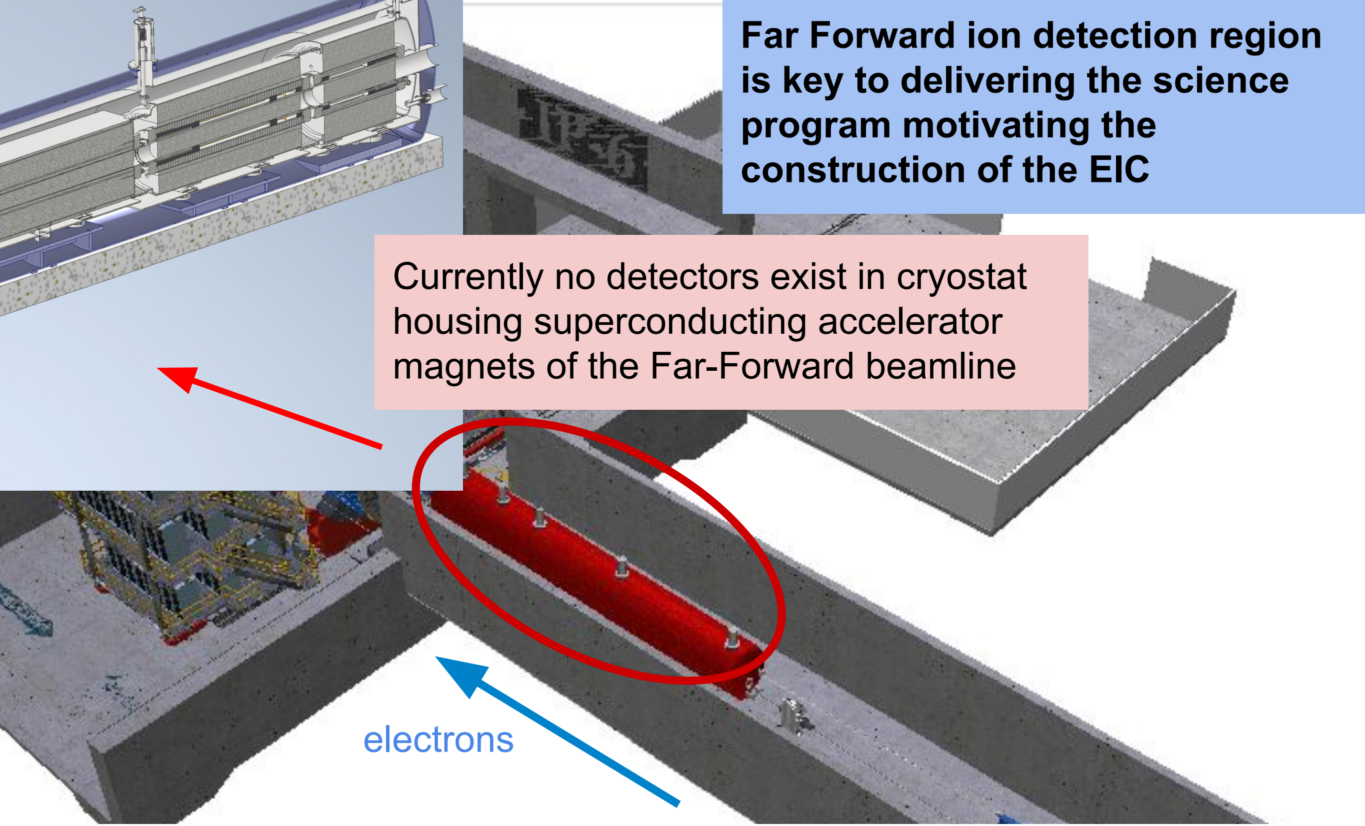
Interaction Point 6 (IP6)



Far Forward ion detection region is key to delivering the science program motivating the construction of the EIC

Interaction Point 6 (IP6)





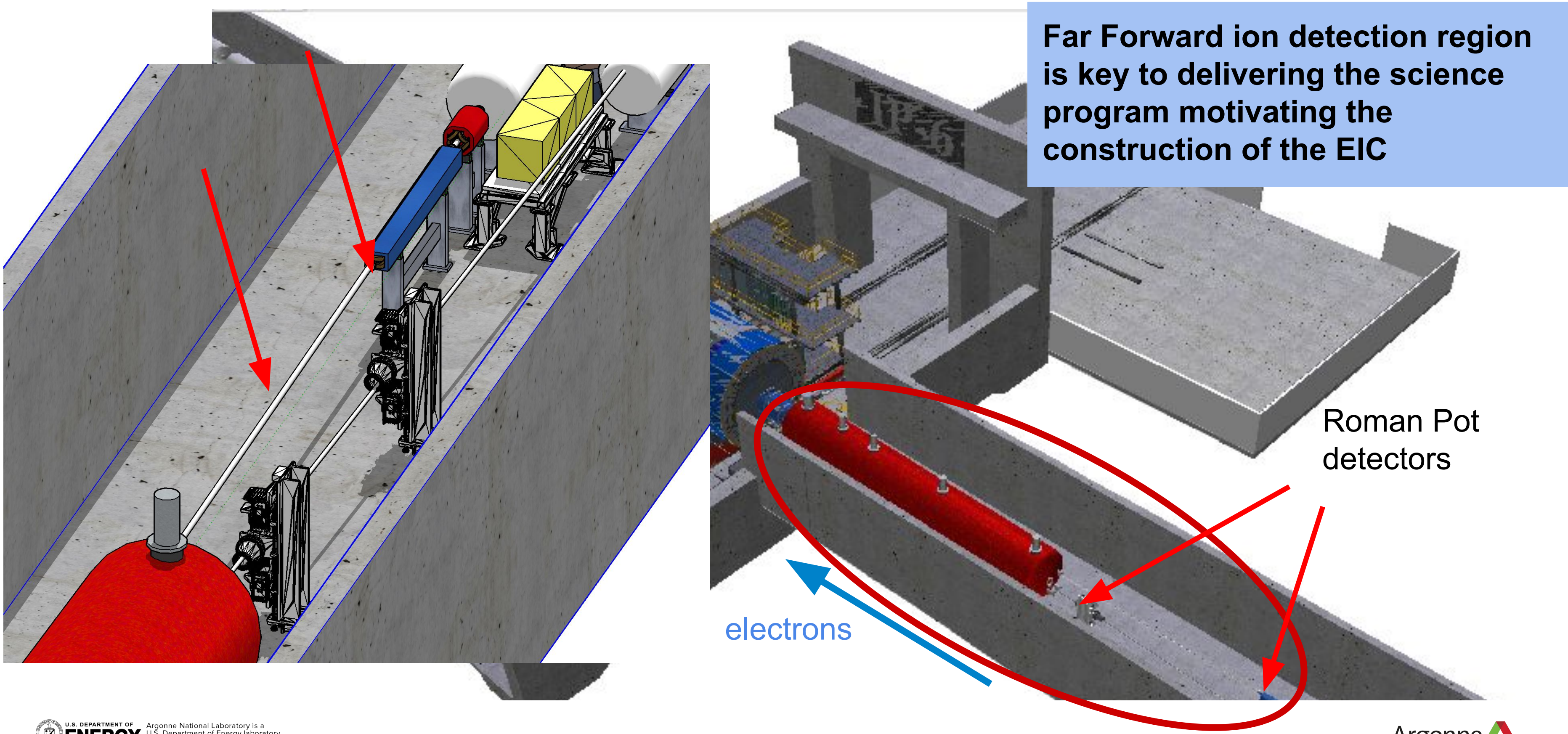
Far Forward ion detection region is key to delivering the science program motivating the construction of the EIC

Currently no detectors exist in cryostat housing superconducting accelerator magnets of the Far-Forward beamline

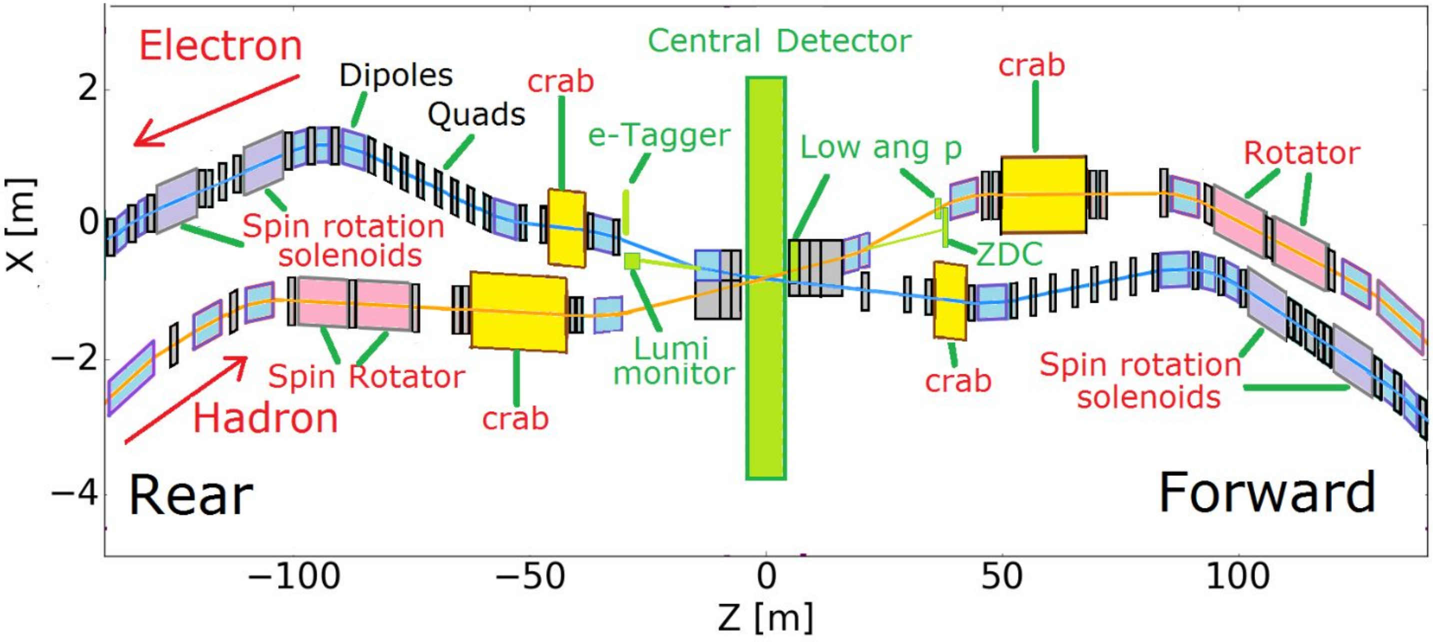
vacuum chamber and cryo-system

Interaction Point 6 (IP6)

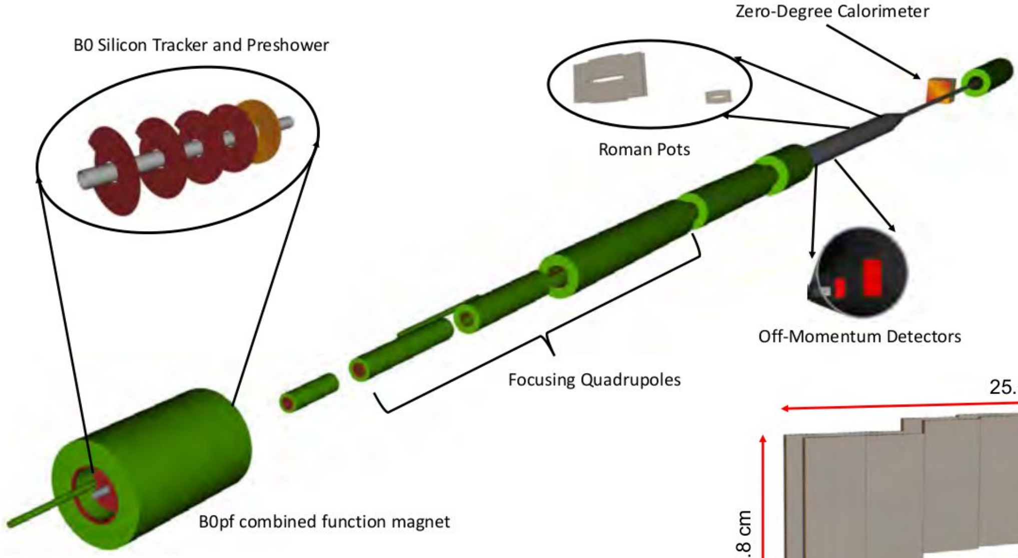
Far Forward ion detection region is key to delivering the science program motivating the construction of the EIC

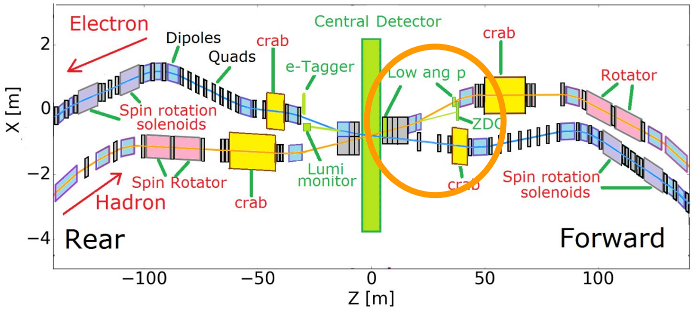


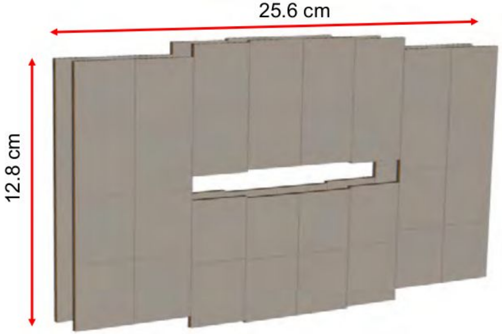
EIC Interaction Region



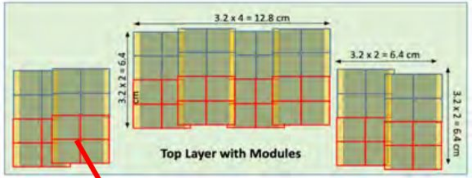
Current Far Forward EIC Design

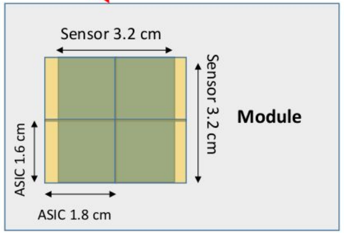






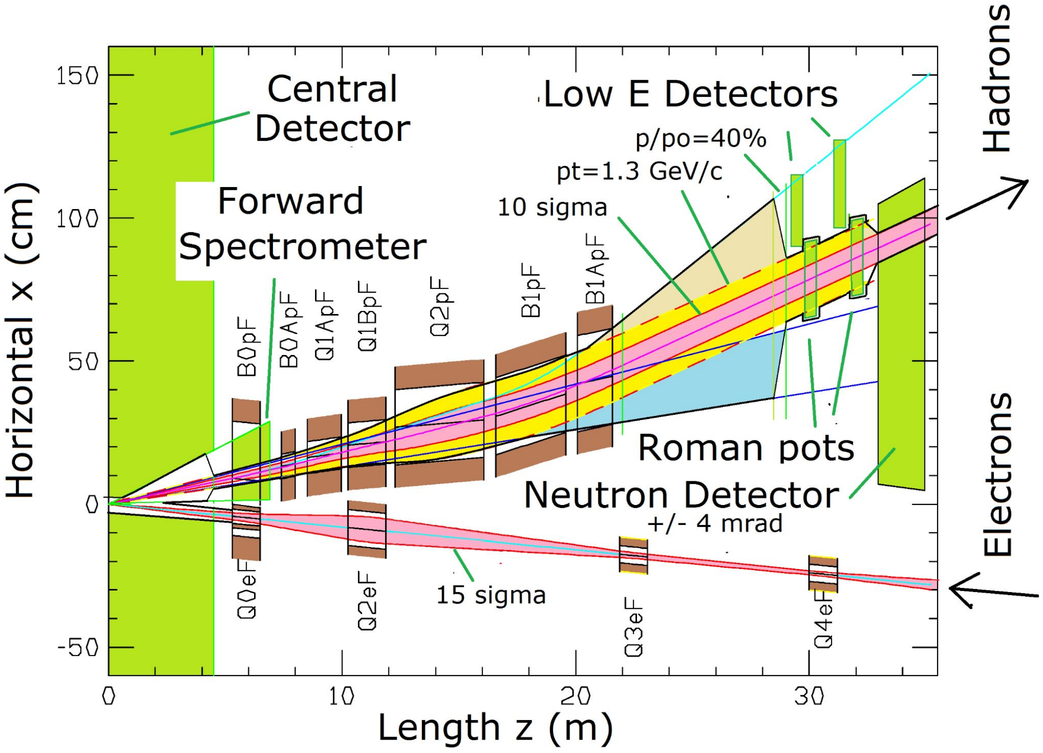
DD4HEP GEANT Simulation





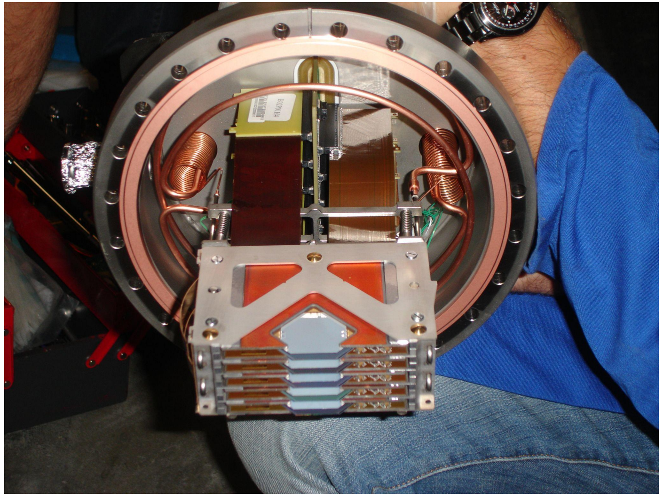
Far Forward Detector

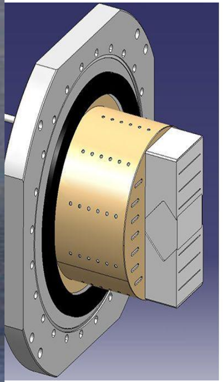
- We can use nanowire tracking detectors in a Roman pot configuration
- Ultrafast timing – demonstrated to be less than 20 ps
- Small basic pixel size, allowing for µm position precision if needed.
- **Edgeless sensor configuration** – sensitive element positioned to within a few 100 nm of the substrate edge,
- Eliminating detector dead zone.
- Wide choice of substrate material – the detectors can be fabricated on membranes as thin as few 10 µm, cutting down on material thickness.
- Radiation hardness – operate in close proximity of the beam and interaction regions with long lifetime.

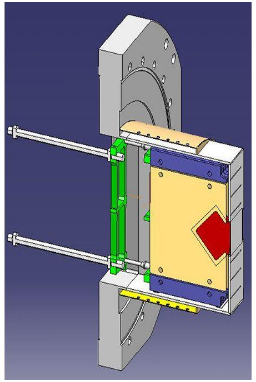


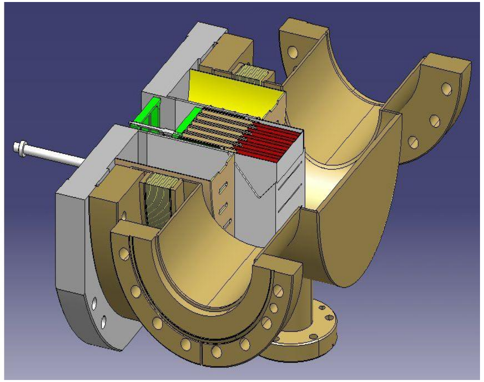
Roman Pot Detectors

TOTEM Roman Pots

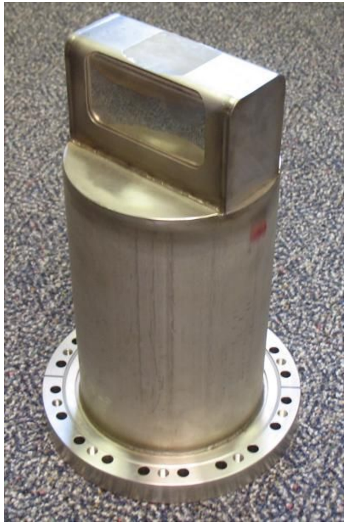






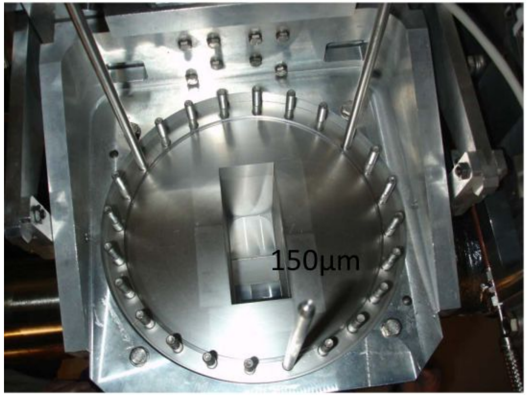


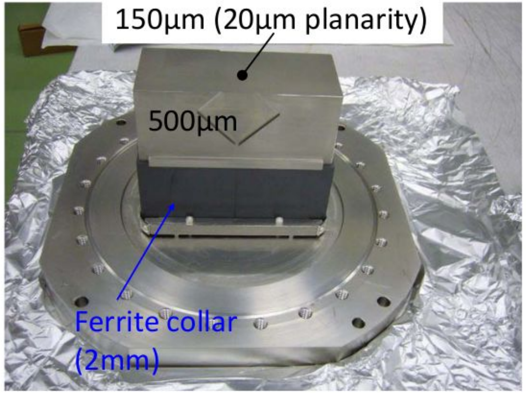
Roman pot



The Pot

Separates the high vacuum of the machine from the detector's vacuums.





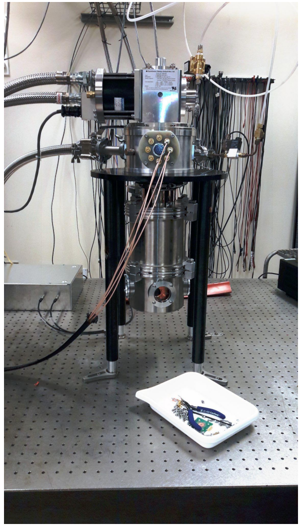
- Reduced material budget
- Tightness
- Stiffness (controlled deformations)

- Low beam coupling impedance (< .18mΩ)

The ferrite collar added to the pot removes all the resonances within the frequency domain relevant for the LHC, i.e. 0 – 1.5 GHz.

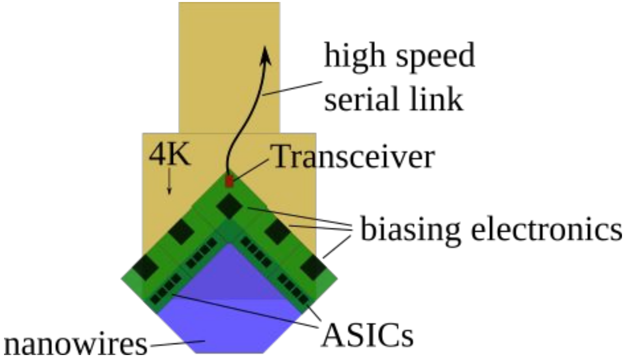
Cooling infrastructure

Please provide some idea of the infrastructure that would be needed to cool the detectors to superconducting temperatures without interfering with the primary beam.



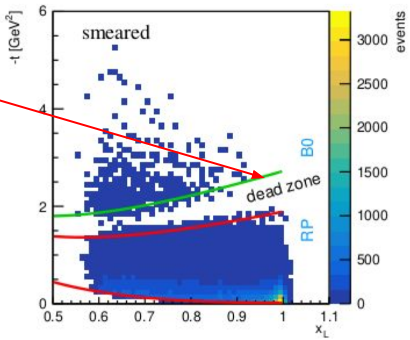
- Our nanowire detectors operate at LHe temperatures ~4K
- We can tap into the upgraded 4.5K and 2K cryosystems for the EIC at BNL
- A conservative estimate for a wire is roughly 20 nW when it is latched – normal conducting with most current going through shunt resistor
- The total power of the sensors does not necessarily scale with area – it is set by the number of wires
- With a detector area of 25cm x 10cm, if all sensors latched (a malfunctioning detector with 100% occupancy), the cryosystem would see a load of ~0.5 W.

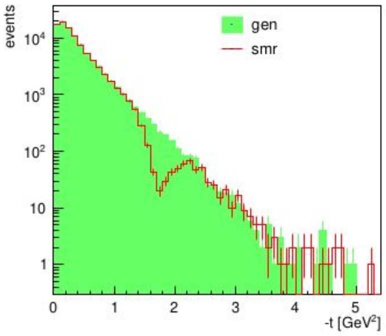
Conceptual layout of beamline detector



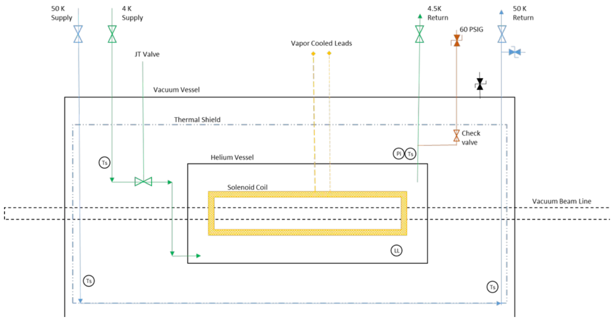
Superconducting Magnet integrated particle detector

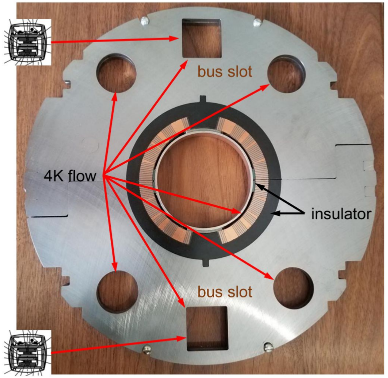
- Avoid the “dead zone” between roman pot detectors and B0 detectors
- Tie into superconducting magnets’ 4K supply
- Design a mechanical/thermal mounting location in the bore of the magnet





From Figure 8.125 of YR





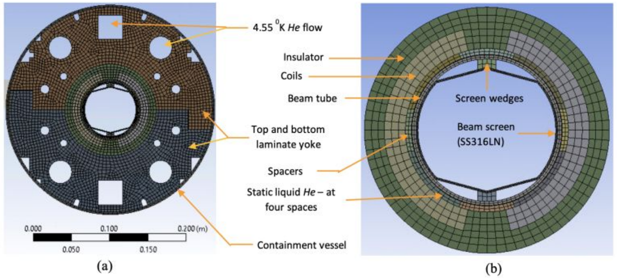
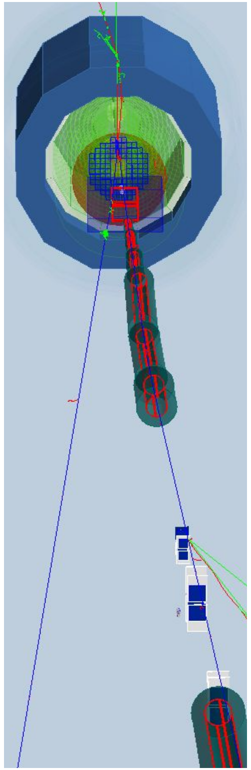


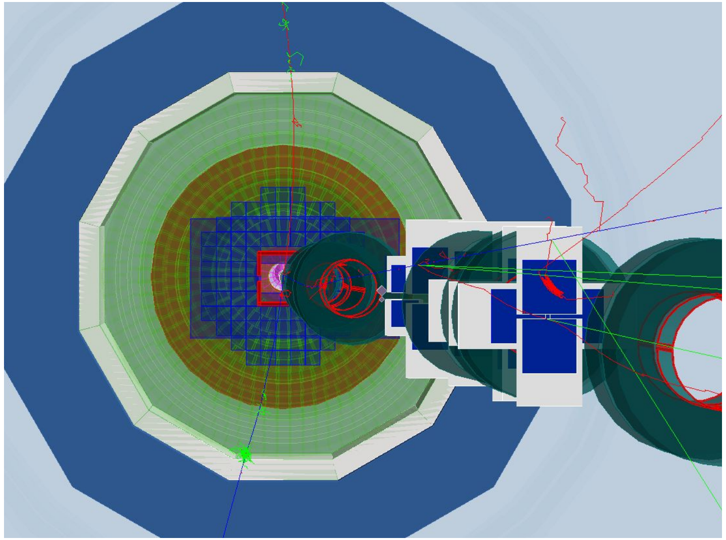
Figure 6.148: Finite-element model of (a) the RHIC arc dipole magnet cold mass cross-section and (b) close view around the beam tube.

SS Vacuum Pipe Beam Screen - Copper liner (coated with carbon to reduce secondary electron yield)

Neutral particle detector

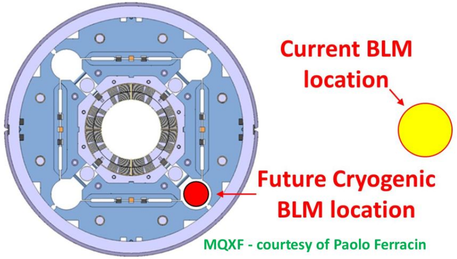
- A radiation hard pixel detector could provide useful tracking for the ZDC
- Also a photon (or electron) detector for compton polarimeter which can operate at high rate and last the lifetime of the EIC.





Beam Loss Monitors at Accelerators

Requirements of Cryogenic BLMs



MQXF - courtesy of Paolo Ferracin

Mechanical requirements:

- total radiation dose of 2MGy,
- low temperature of 1.9K,
- 20 years, maintenance free operation,
- resistance to magnetic field of 2T,
- resistance to a pressure of 1.1 bar, and capability of withstanding a fast pressure rise up to 20bar in case of a magnet quench.

Electronic requirements:

- direct current readout,
- response linear between 0.1 and 10 mGy/s, and
- response time faster than 1 ms.

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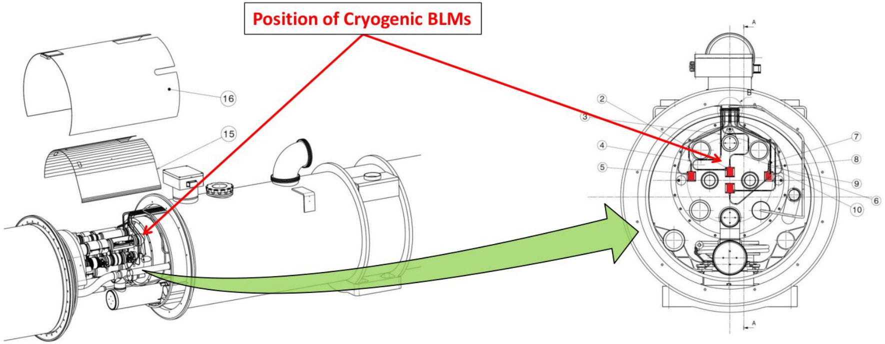
Cryogenic BLMs in LHC ring



Long term correlation between Ionization Chamber BLM and Cryogenic BLM to be done in 9R7 and 9L5

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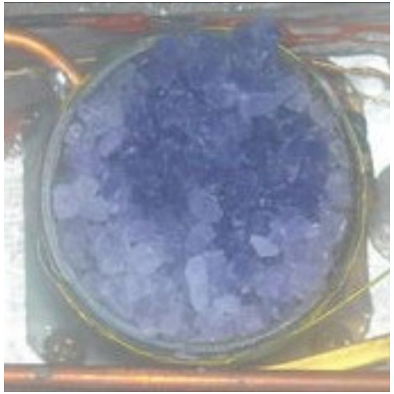
Anticipate similar applications at the EIC

Applications at JLab

An Active Polarized Target at JLab

Look at the figure of merit for a polarized target



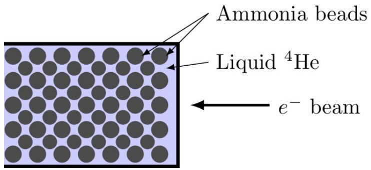
Time needed to measure an asymmetry with statistical uncertainty □A

$$t \propto \frac{1}{{P_T}^2} \frac{1}{f^2} \frac{1}{\delta A^2}$$

$$F.o.M. = f^2 P_T^2$$

$$df(W,Q^2) = \frac{N_p\sigma_p(W,Q^2)}{N_p\sigma_p(W,Q^2) + \sum_i N_i\sigma_i(W,Q^2)}$$

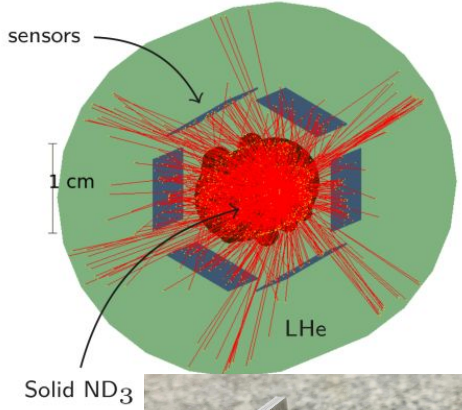
- F.o.M. depends on target polarization Polarized ND_3 and the target dilution factor
- Dilution factor is the ratio of cross sections from polarized target material to everything else.
- Typical dilution factor is on the order 15 - 30% depending on how you slice it
- Active target is designed to identify events scattering from polarized material → f = 100%
- F.o.M. improved by a factor of 25 to 80!

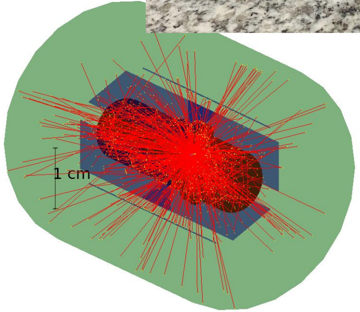


An Active Polarized Neutron Target Concept for CLAS12

SNSPDs are the enabling technology for concept

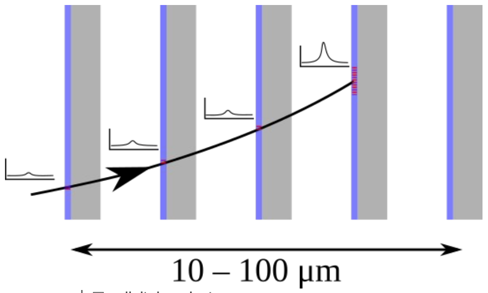
- Detect the recoil spectator proton in polarized deuteron: eliminate large dilution
- Only photon detectors needed
- Challenge: Optical properties of polarized target material
- Previous attempts at Mainz struggled to detect a few photons guided out of the cryostat
  - Was both a detector and target material challenge
  - SNSPDs solve the cryogenic detector problem
- Can we use the standard material for JLab: ND3
- Replace walls of target cup with SNSPD devices
  - Can a 5 MeV proton recoiling in the standard ND_3 target produce enough photons to escape to the cup permeter?
  - Range in LHe is about 0.5cm
  - Would introduce little new material to the RGC target.

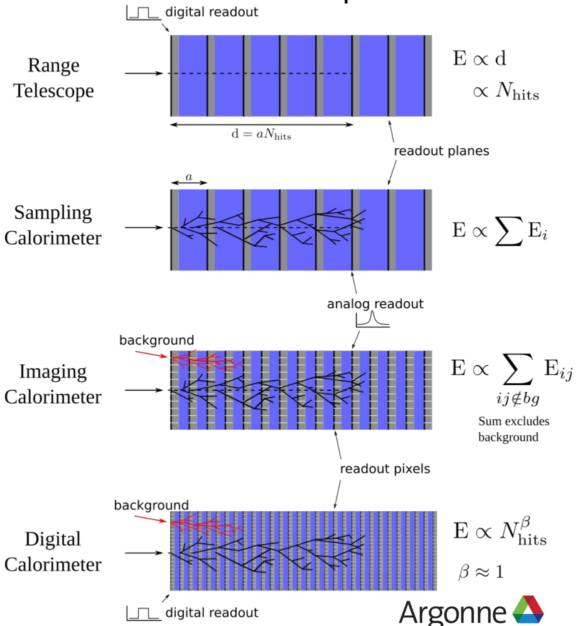


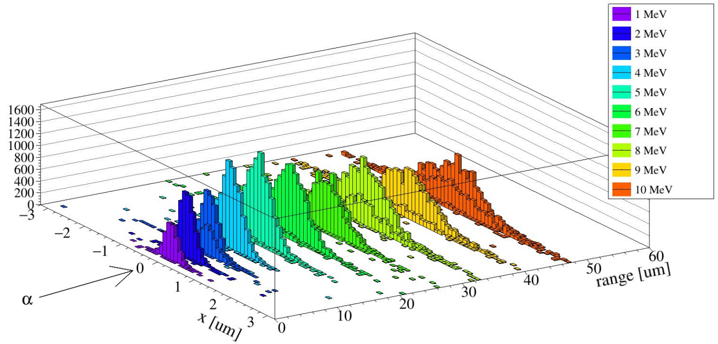


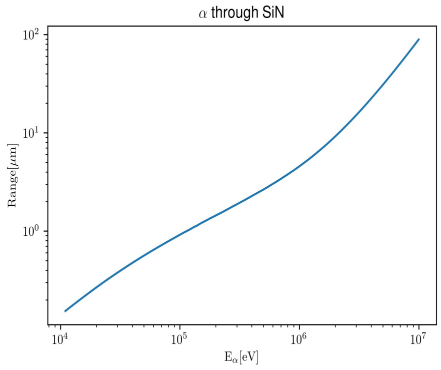
Micro Range Telescope for Active LHe Target

- Measure kinetic energy of recoils
- # layers, material thickness and size depend on application
- Alpha recoil: low density, few um spacing
- Low energy proton recoil: few 10s um spacing
- Vertexing/tracking for higher energy particles
- Alternatively, leverage scintillation properties of LHe and excellent SNSPD time resolution to create ultrafast photon TPC









Measuring the Neutron Spin Structure Function

The polarized EMC effect for the neutron g_1^n

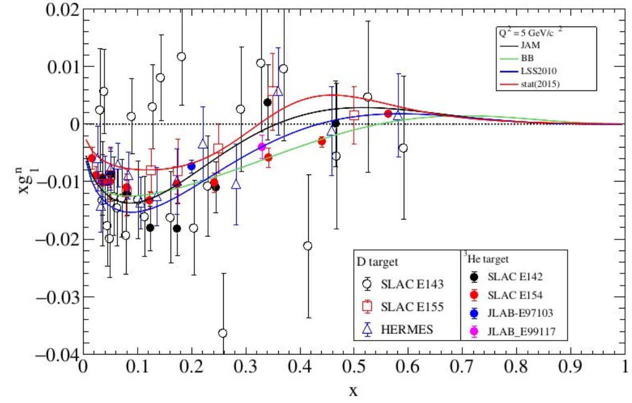
The polarized EMC effect in the neutron is challenging:

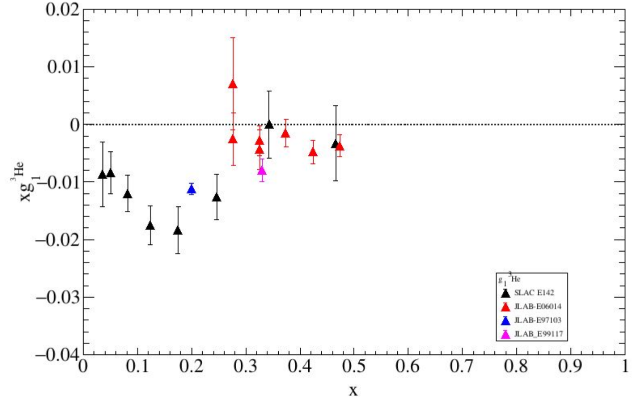
- Sign change in g_1^n (x), location of zero crossing not well constrained.
- Extraction of g1n from ^{3}He and D is very different.
- D has a large subtraction of g1p, ie:

$$g_1^n \simeq \frac{2}{1-1.5\omega_D} g_1^d - g_1^p$$

- ^{3}He spin is dominated by polarized neutron but is more deeply bound nuclear system:

$$g_1^n = (g_1^{^3He} - 2P_p g_1^p)/P_n$$
$$P_n = 0.879 \text{ and } P_p = -0.021$$



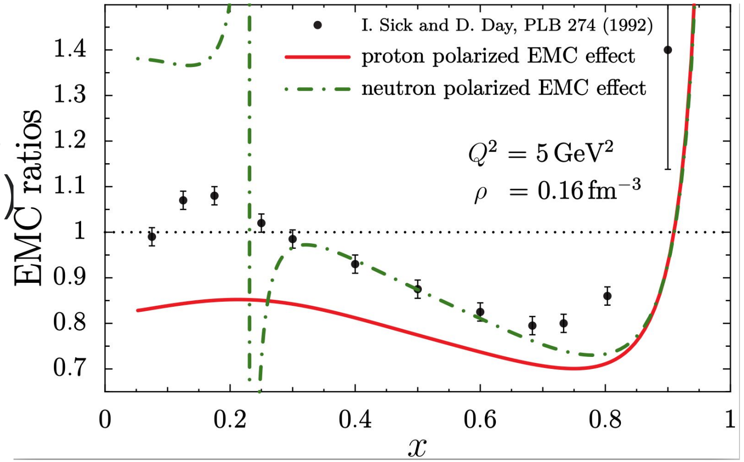


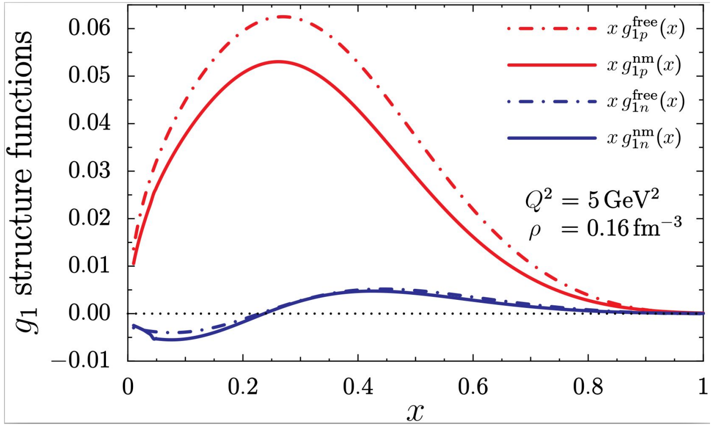
Polarized EMC effect

Looking at the neutron

- Active polarized neutron target complements polarized ^{3}He target in CLAS12 (C12-20-002)
- Measure the best “free” neutron spin structure function with the deuteron
- Form the pEMC ratio with the ^{3}He in numerator
- Is the zero crossing of g_1^n useful to measure?
- Sensitive to non-nucleonic degrees of freedom

$$R_{As}^{^3\mathrm{He}} = \frac{g_1^{^3\mathrm{He}}}{P_n g_1^n + P_p g_1^p}$$

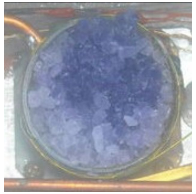
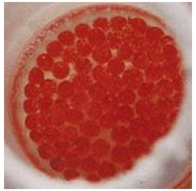




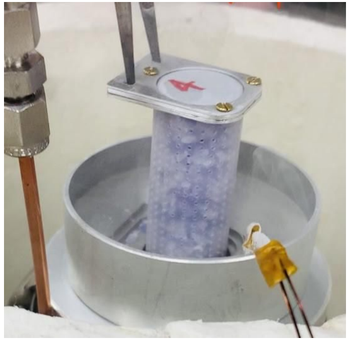
I. C. Cloet, Wolfgang Bentz, and Anthony William Thomas. EMC and polarized EMC effects in nuclei. *Phys. Lett. B*, 642:210–217, 2006.

Polarized Target Material

Finding the best material

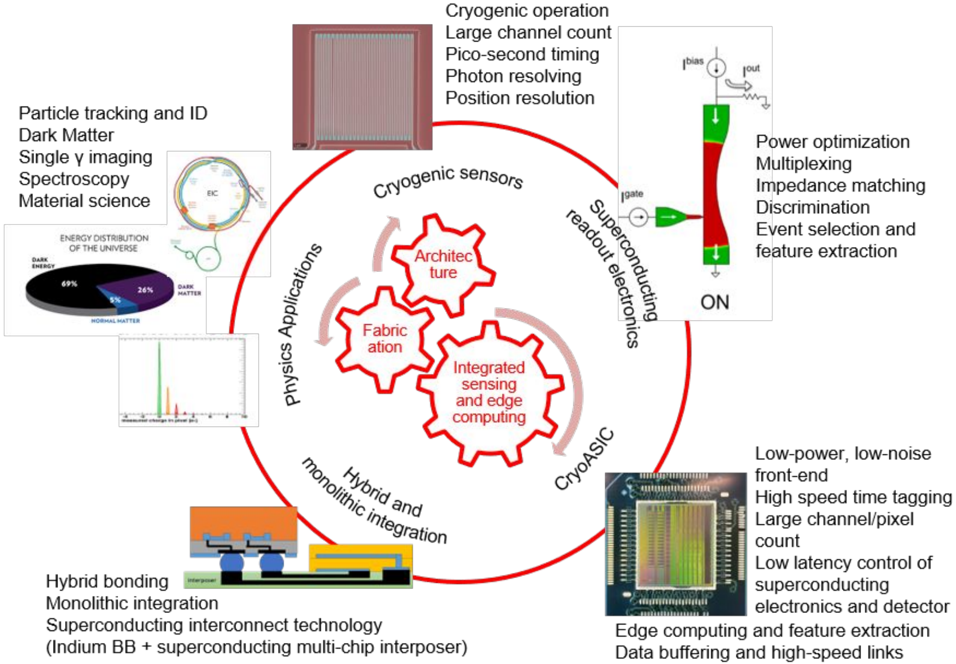
Material	Pros	Cons
ND_3	Used for RGC	beads and optical properties not well understood
d-Butanol	easy to polarize	radiation damage
d-Polyethelene	mechanically sound, easy to polarizem,optical properties favorable	radiation damage unknown
LiD	Easily formable, radiation hard	relatively opaque



Applications at JLab

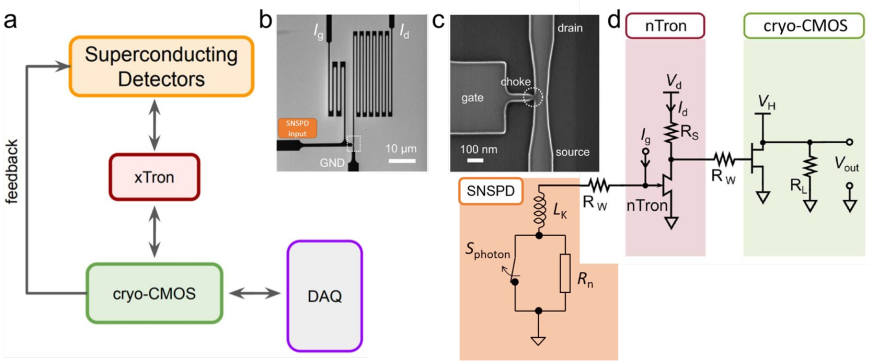
DOE already invested in SNSPDs at the EIC

A microelectronics co-design project



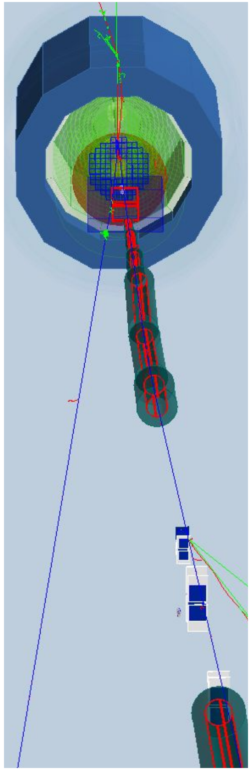
Hybrid Cryogenic Detector Architectures for Sensing and Edge Computing enabled by new Fabrication Processes

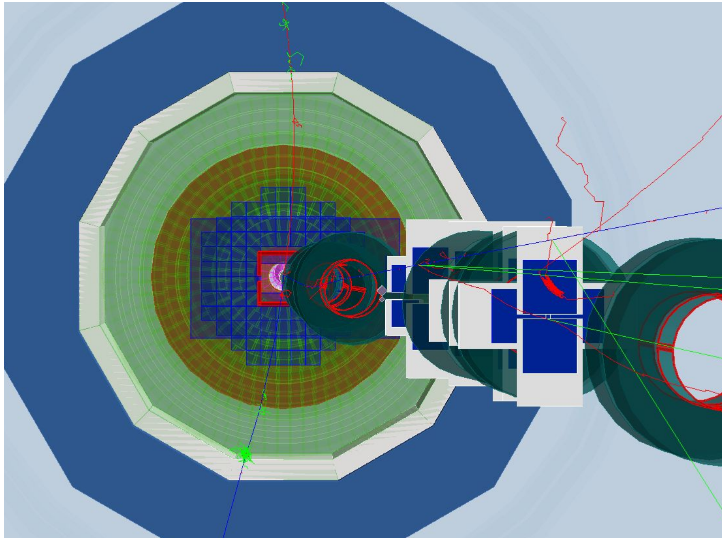
And many other projects



SUPERCONDUCTING NANOWIRE DETECTORS FOR THE ELECTRON ION COLLIDER

Successful proposal (2020) for EIC Detector R&D at BNL: eRD28

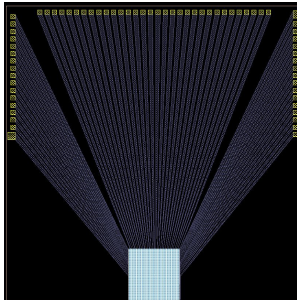


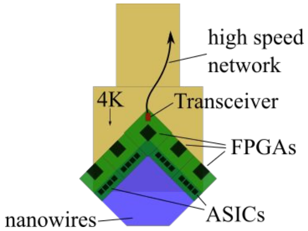


BNL EIC Detector R&D Committee:

Superconducting nanowires have never been deployed in a particle or nuclear physics experiment to our knowledge. As such, this proposal represents a true spirit of detector R&D. This project will have to solve many issues before it would have a working detector as indicated above. There are interesting synergistic activities with other projects under this program such as the polarimetry measurement. The idea to test a device in the Fermilab test beam and study the response to protons, electrons and pions is a very worthwhile exercise and would provide new information. We strongly recommend that at the least this aspect of the project is supported, funding permitting

- Will demonstrate the detection of low energy particles from radioactive sources at high rate and in high magnetic field.
- Fabricate a small pixel array for high energy particle detection



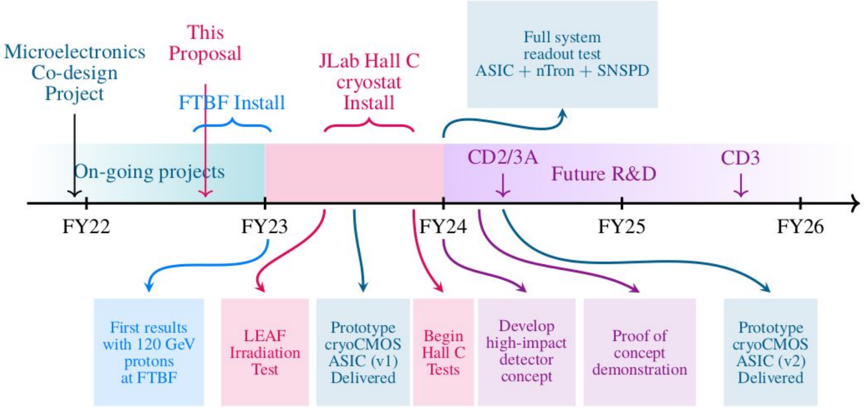


EIC-related Generic Detector R&D

- Proposed R&D radiation hardness tests of SNSPDs, superconducting electronics and cryo-CMOS

Submitted in July 2022

1. **Irradiation at LEAF (total of 1 week)**
   a. Radiation hardness of SNSPDs
   b. Measure onset of change in performance
   c. Identify upper limit for the onset of defects and device failure.
2. **JLab test-bed**
   a. Baseline background error rate for superconducting shift registers
   b. SNSPD efficiency in high radiation environment
   c. Single Event upset cross-section for prototype cryo-CMOS ASIC



Summary and Discussion

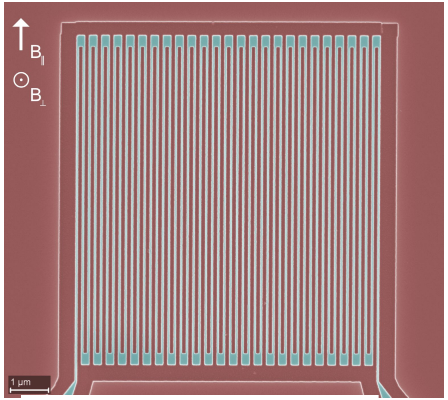
- Nanowires can enhance the EIC science program
- A lot of R&D needs to be done to realize detectors at the EIC
- DOE is already invested the success of SNSPDs at the EIC
- There are approved EIC-Related Generic R&D

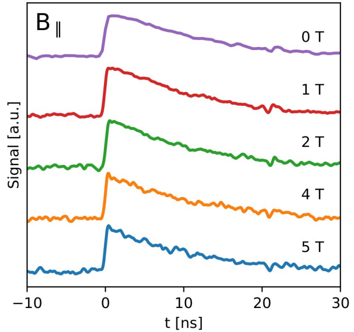
What are the next steps in realizing nanowires at the EIC?

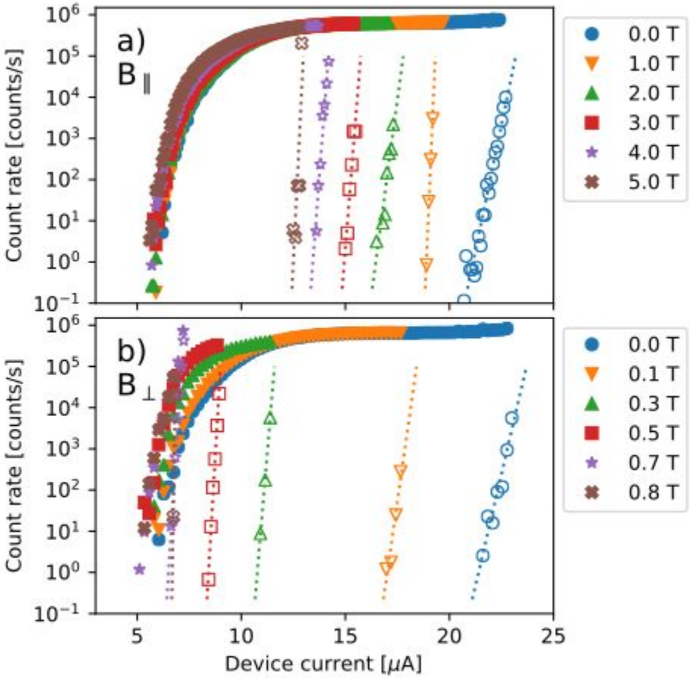
Thank you!

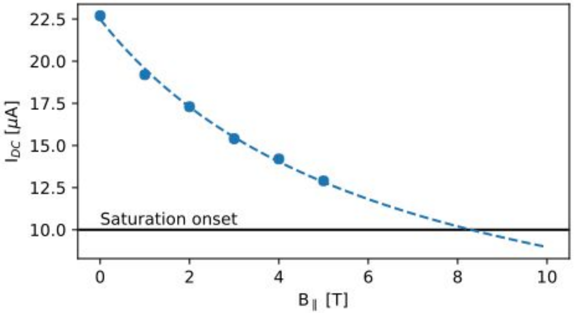
Backup

Strong Magnetic fields and high rates









Can operate on strong magnetic fields with nearly zero dark count

Particle Detection Status

At Argonne we have detected photons, alphas, betas

Particle	Energy	Approximate Energy loss in 100 µm silicon	Approximate Energy loss in 15 nm NbN	Detected
photon	0.1 eV - 2 eV	all	all	✔
alpha	5 MeV	5 MeV	9.1 keV	✔
beta	1 MeV	15 keV	15.8 eV	✔
electron	100 MeV	100 keV	~100 eV	?
proton	120 GeV	40 keV	24 eV	?
pion /muon	10 GeV	30-45 keV	~20 eV	

Demonstrating high energy proton detection is the key test needed for the EIC

No show stoppers expected…

See Adam McCaughan's talk.