Generic R&D proposal: Simulations of the physics impact of a solenoid-based compensation scheme for the field of the main detector solenoid in IR8

Mark D. Baker[1], Paul Brindza[2,3], Alexander Bylinkin[4], Ross Corliss[5,6], Jaydeep Datta[5,6], Abhay Deshpande[5,6,7], Prakhar Garg[5,6], Ruthie Gu[6,8], Charles E. Hyde[3], Wenliang Li † [5,6], Brynna Moran[5,6], Vasiliy Morozov† [9], Pawel Nadel-Turonski† [5,6], and Barak Schmookler[10]

Generic EIC detector R&D meeting, November 15-16, 2022

Participating institutions

[1] MDBPADS LLC, Miller Place, NY 11764

[2] Jefferson Lab, Newport News, VA 23606

[3] Old Dominion University, Norfolk, VA 23529

[4] University of Bergen, 5060 Bergen, Norway

[5] Department of Physics, Stony Brook University, Stony Brook, NY 11794

[6] Center for Frontiers in Nuclear Science at SBU, Stony Brook, NY 11794

[7] Brookhaven National Laboratory, Upton, NY 11973

[8] Yale University, New Haven, CT 06520

[9] Oak Ridge National Laboratory, Oak Ridge, TN 37830

[10] UC Riverside, Riverside, CA 92521

Proposed work - overview

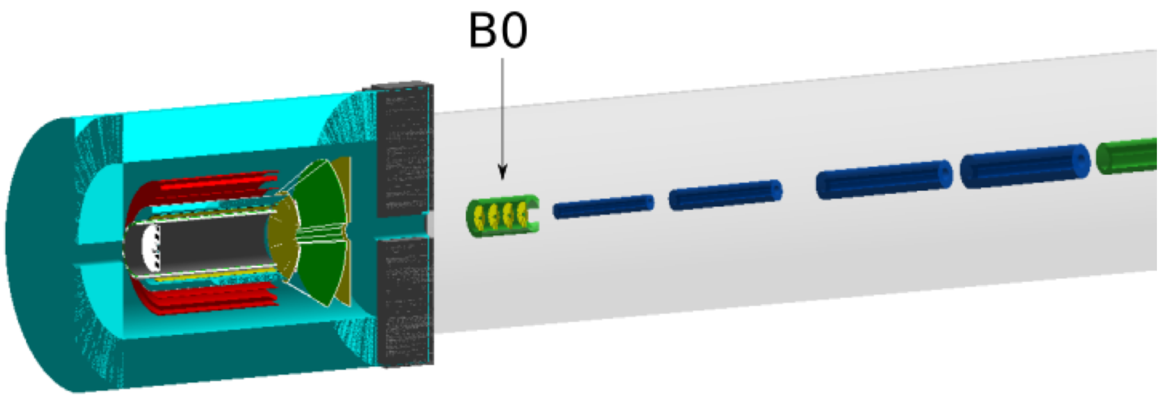
- Set up a Geant simulation for the forward instrumentation in the B0 / anti-solenoid region of IR8
  - In addition, SBU will work on developing the IR8 simulation framework as an in-kind contribution
- Carry out simulations of key processes to benchmark performance
  - DVCS on the proton and nuclei, coherent diffraction, rare isotopes

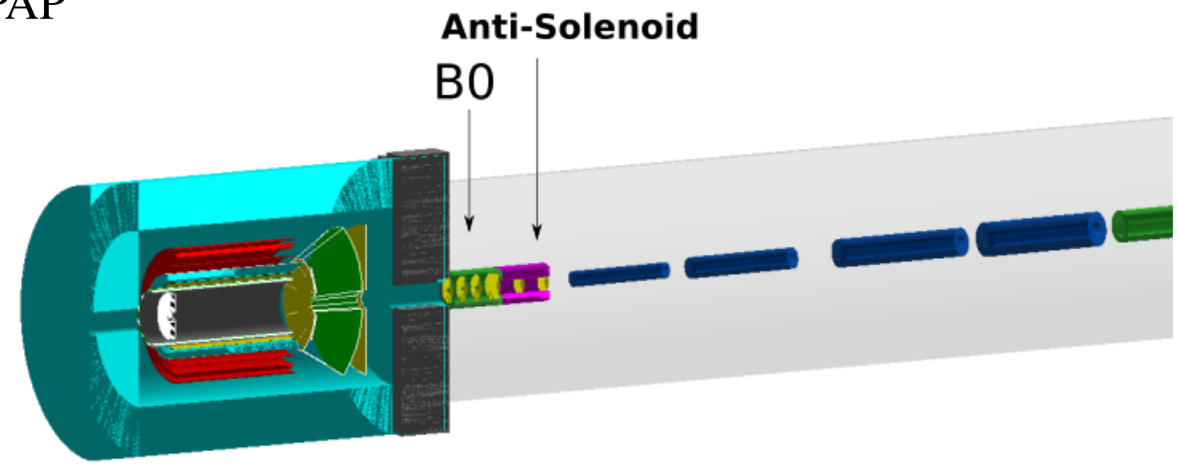
In-kind contributions

- Conceptual design of shifted B0 and anti-solenoid (as well as electron quad)
  - Work will be done by P. Brindza
- Exploration of focusing optics and forward acceptance optimizations. These are independent of the anti-solenoid, but would be useful to explore using the same simulation framework
  - Work will be done by V. Morozov

Motivation – overview

- Compensation of the field of the detector solenoid is necessary, and can be done either using a large number of skew quads or an anti-solenoid on either side of the detector, each compensating half the field.
  - Anti-solenoid: solenoid with opposite polarity to the main detector solenoid
  - Skew quad: quadrupole magnet / winding rotated by 45 degrees in azimuth
- The use of an anti-solenoid offers significant benefits for the accelerator and provides additional space behind the small B0 dipole for improved detection in the 5-20 mrad range.
  - An anti-solenoid was part of the original (JLab) IR concept that IR8 is based on
  - The use of an anti-solenoid was encouraged by the DPAP

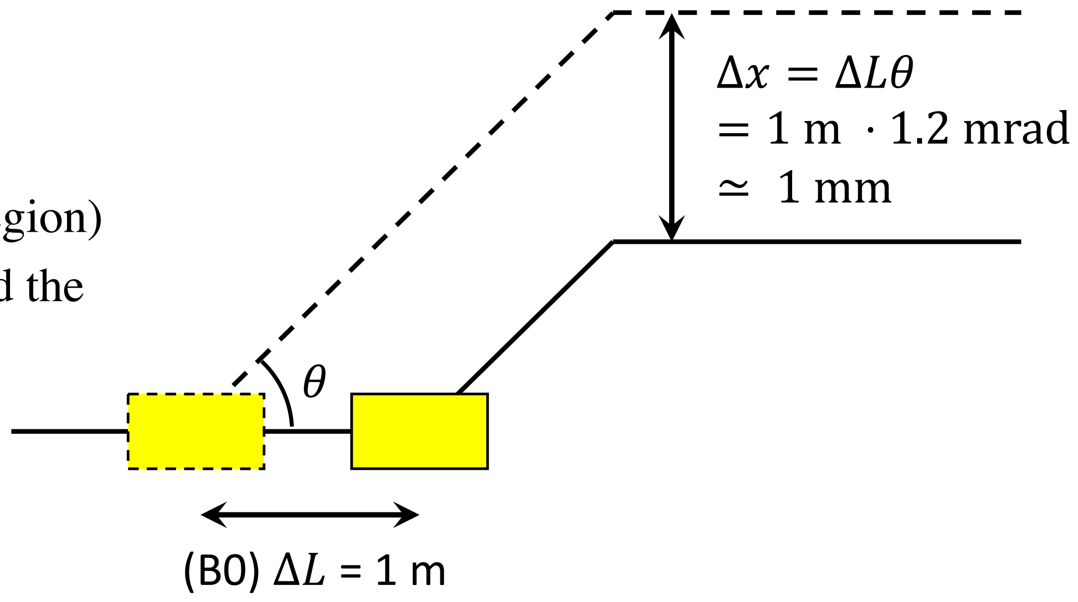




- An anti-solenoid can fit in the space in front of the ion FFQs (blue), located 7.5 m from the IP.

Impact on accelerator – beam geometry and orbit

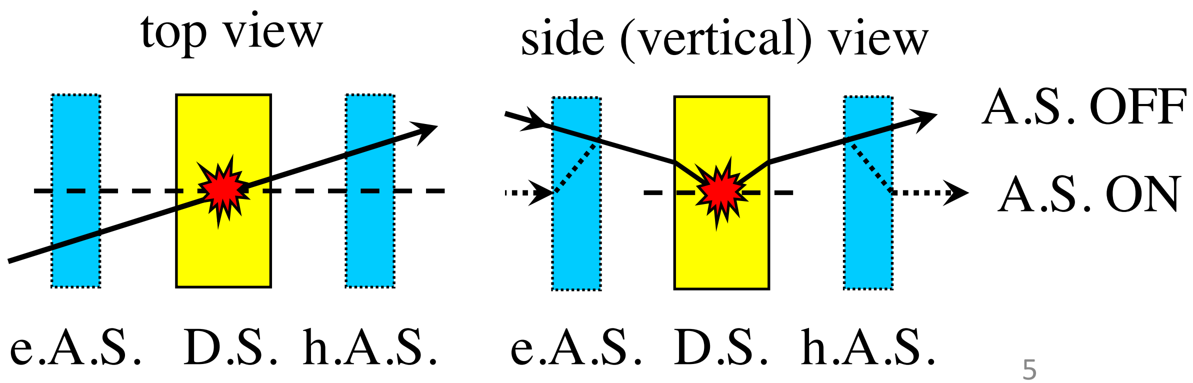
- Potential modifications compared to IR8 baseline
  - Relocation of the B0 1 m closer to the IP
  - Insertion of an anti-solenoid
  - Optimization of focusing (local to outgoing ion final-focus region)
    - *Note*: this is not required in order to move the B0 and add the anti-solenoid, but could offer additional benefits



- General constraints
  - All modifications are local to IR8 and compatible with IR6
  - Same engineering and dynamical limits as IR8 baseline

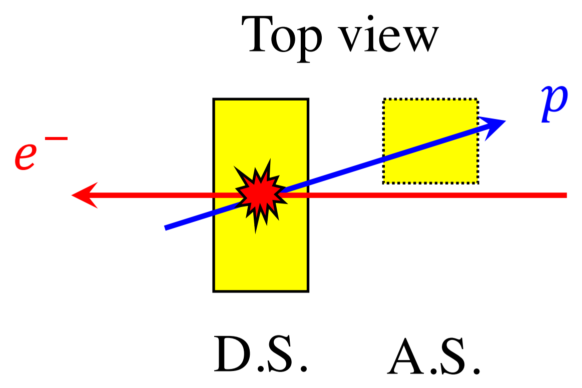
A.S. – anti-solenoid
D.S. – detector solenoid

- Geometry and orbit
  - Electrons: None
  - Hadrons:
    a. Shift of $B0$ result in only ~1 mm transverse shift
    b. Pathlength change is negligible
    c. Anti-solenoids help correct the ion closed orbit, preventing orbital offset in FFQs and eliminating need for dipole correctors on both sides of the IR

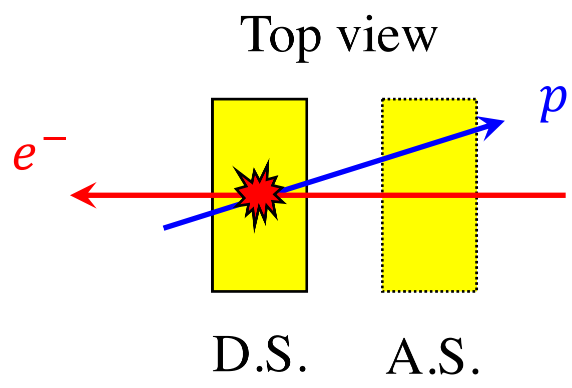


Impact on accelerator – polarization and optics

- Polarization
  - Electrons: same (with $\int B_{sol}dl$ not compensated) or improved spin-matching (with $\int B_{sol}dl$ compensated)

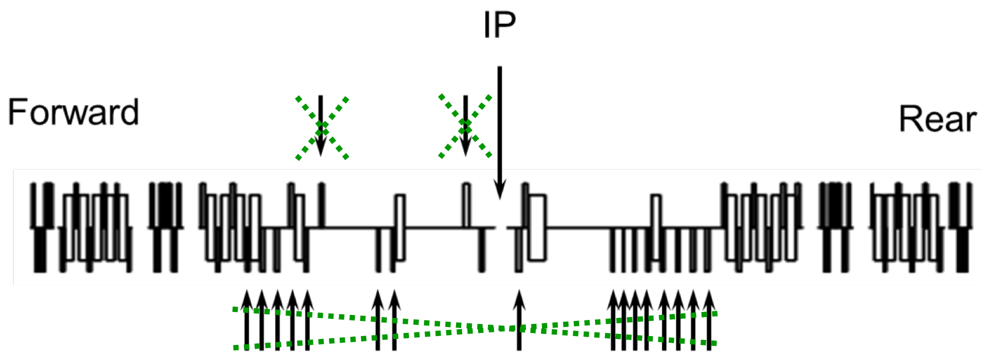


or



  - Hadrons: less correction necessary by spin rotators

- Optics
  - Electrons: same (with $\int B_{sol}dl$ not compensated) or compensation simplified (with $\int B_{sol}dl$ compensated)
  - Hadrons: great simplification of solenoid integration by simultaneous compensation of betatron and crab coupling



Eliminates the need for ~18 skew quads (shown by arrows)

Some of the benefits of using anti-solenoids instead of skew quads

- Reduced cost and complexity
  - A skew-quad based compensation system for ions is very challenging
  - A design for IR6 is underway, but is not yet ready
- Better forward acceptance
  - Skew windings in the FFQs will increase peak fields and thus reduce apertures
  - This is not yet considered in the IR6 simulations
- Reduced space requirements in the IR
  - The large number of skew quads take up significant space
- Simplified accelerator operations
  - Tuning all the skew quads is complicated
- Simplified forward detection
  - Since the solenoid field is independent of the beam energies, the impact of the quad windings in the FFQs on forward detection will vary between settings, making reconstruction more challenging.

Impact on accelerator – engineering

- Analog of B0 for IR8
  - Same field integral and therefore bending angle
  - Nearly same beam separation due to shift closer to the IP at a larger crossing angle (35 mrad vs 25 mrad)
  - Field-free region for electron beam without quadrupole
- Anti-solenoid
  - At the same distance as the first electron quad
  - Common solenoid for both beams with or without shielding of the electron beam
    or
    small solenoid for hadrons and quadrupole for electrons side by side
  - Does not appear challenging
  - Operational and equipment cost savings compared to a skew quad scheme

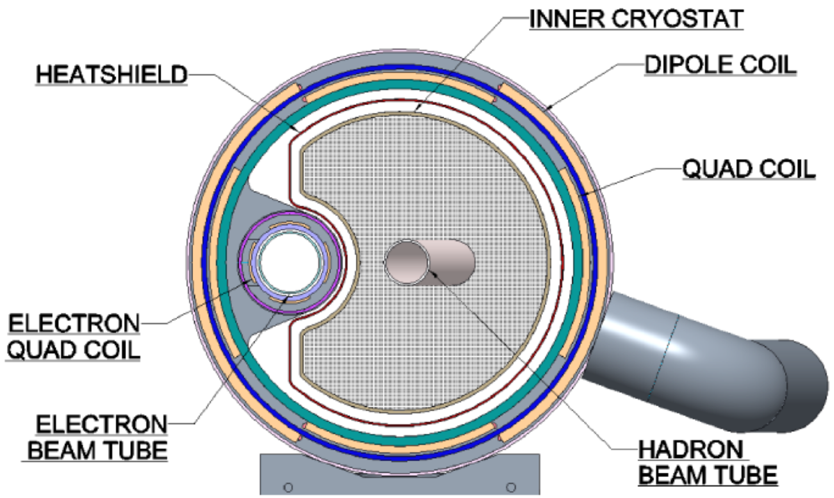
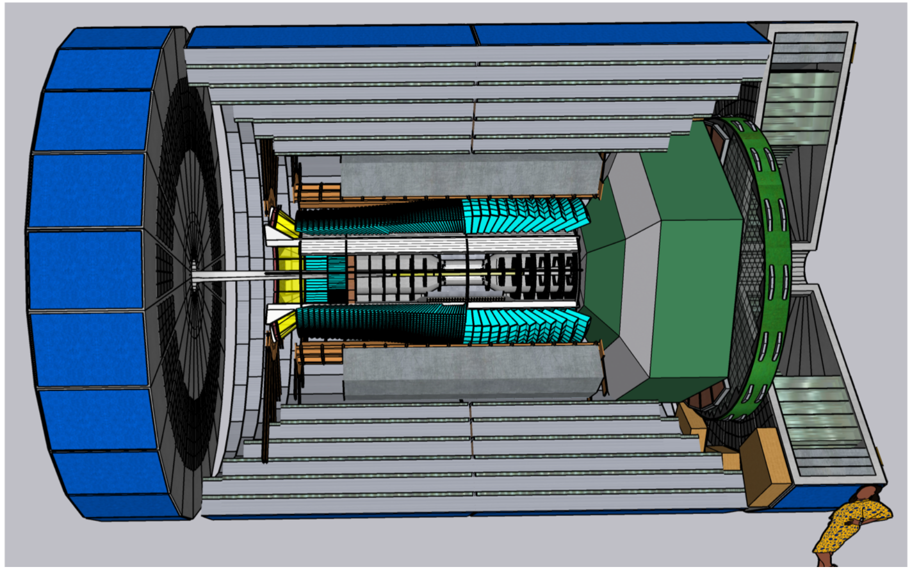


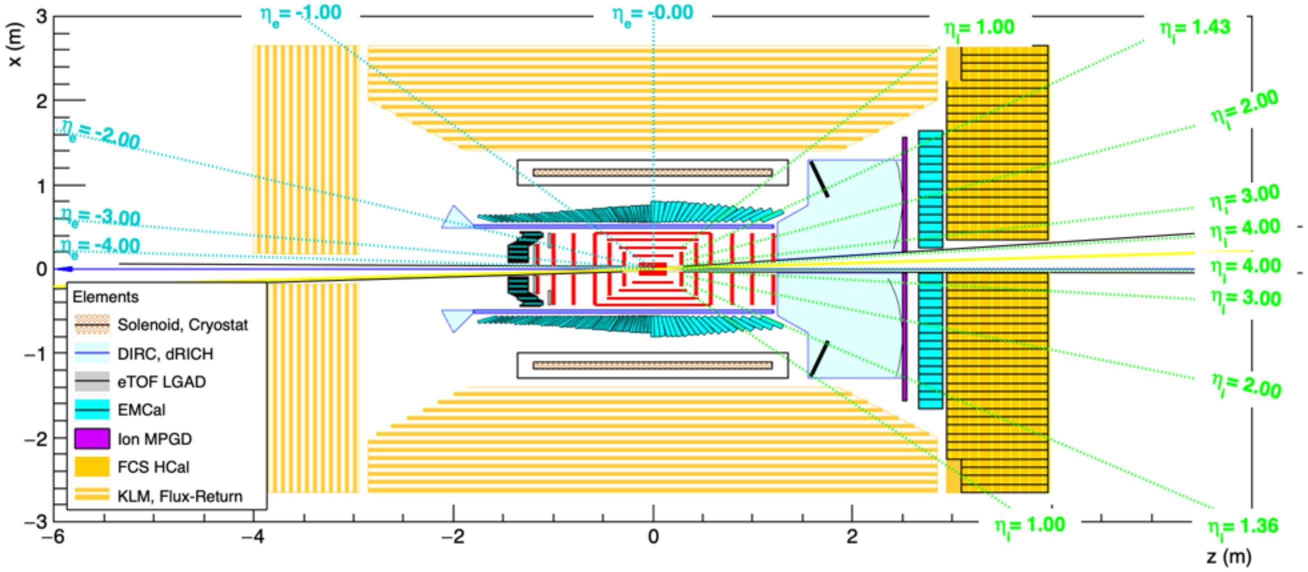
Figure 3.4: Cutaway view of the B0 spectrometer with warm space for detector elements highlighted in the cross hatch region. The view is from the IP end of the magnet with the electron beam pipe on the left and the hadron beam pipe on the right. As described in the text, B0 uses a combination of superconducting coils to provide pure focusing (with zero dipole field) at the electron beam and a 1.3 T average magnetic spectrometer field at the hadron beam.

Impact on central detector - length

- In both IR6 and IR8 the ion FFQs start at 7.5 m from the IP.
  - Holds hadron side of the detector, the B0, and gaps.
- Originally 4.5 m was allocated for the detector.
  - The EPIC detector uses a very long (4 m) solenoid, and the detector space was extended to 5 m.
- A compact (2.5 m) solenoid and an all-Si tracker allow a reduction of the detector space on the hadron side to 4 m.
  - This would leave 3.5 m for the B0, anti-solenoid, and gaps (although 3 m would likely suffice).

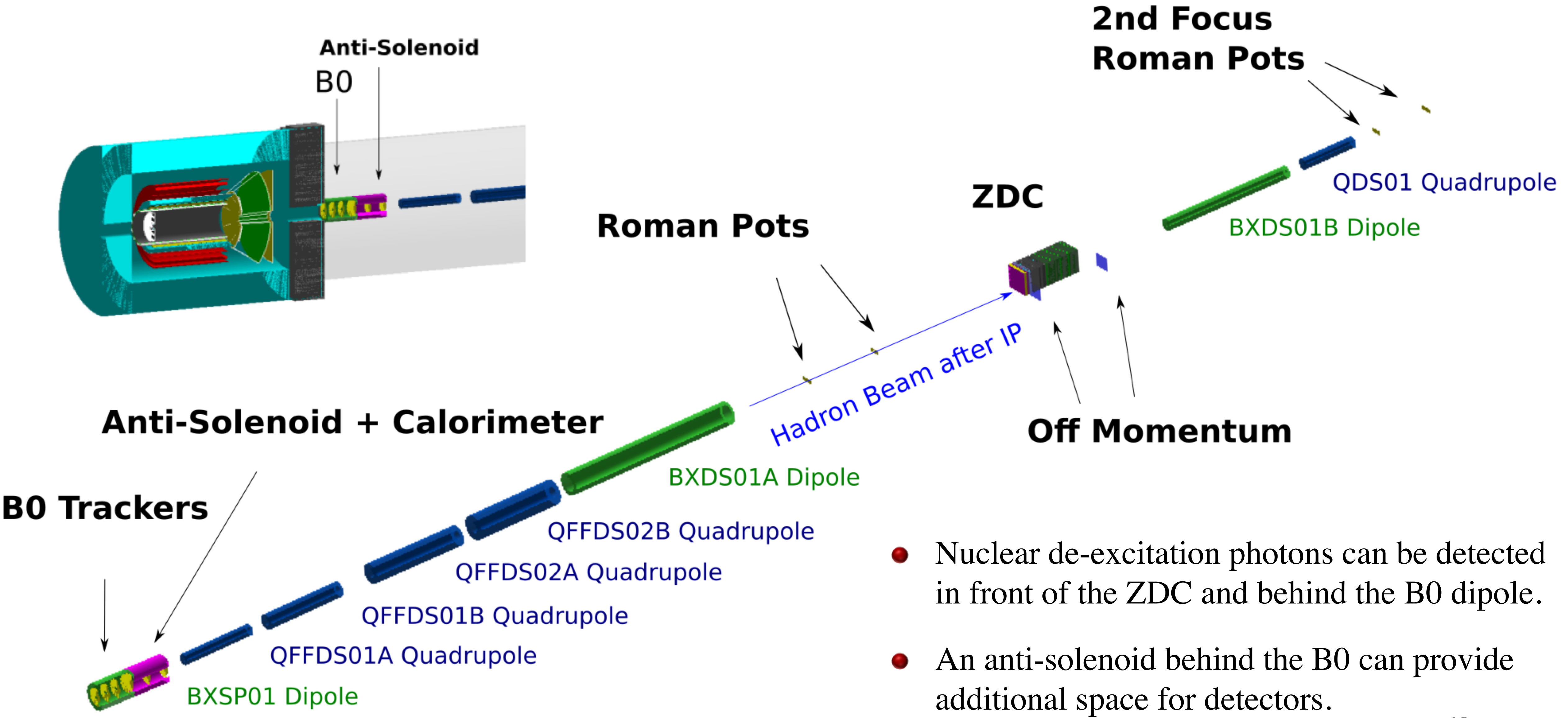


COmpact detectoR for Eic (CORE)



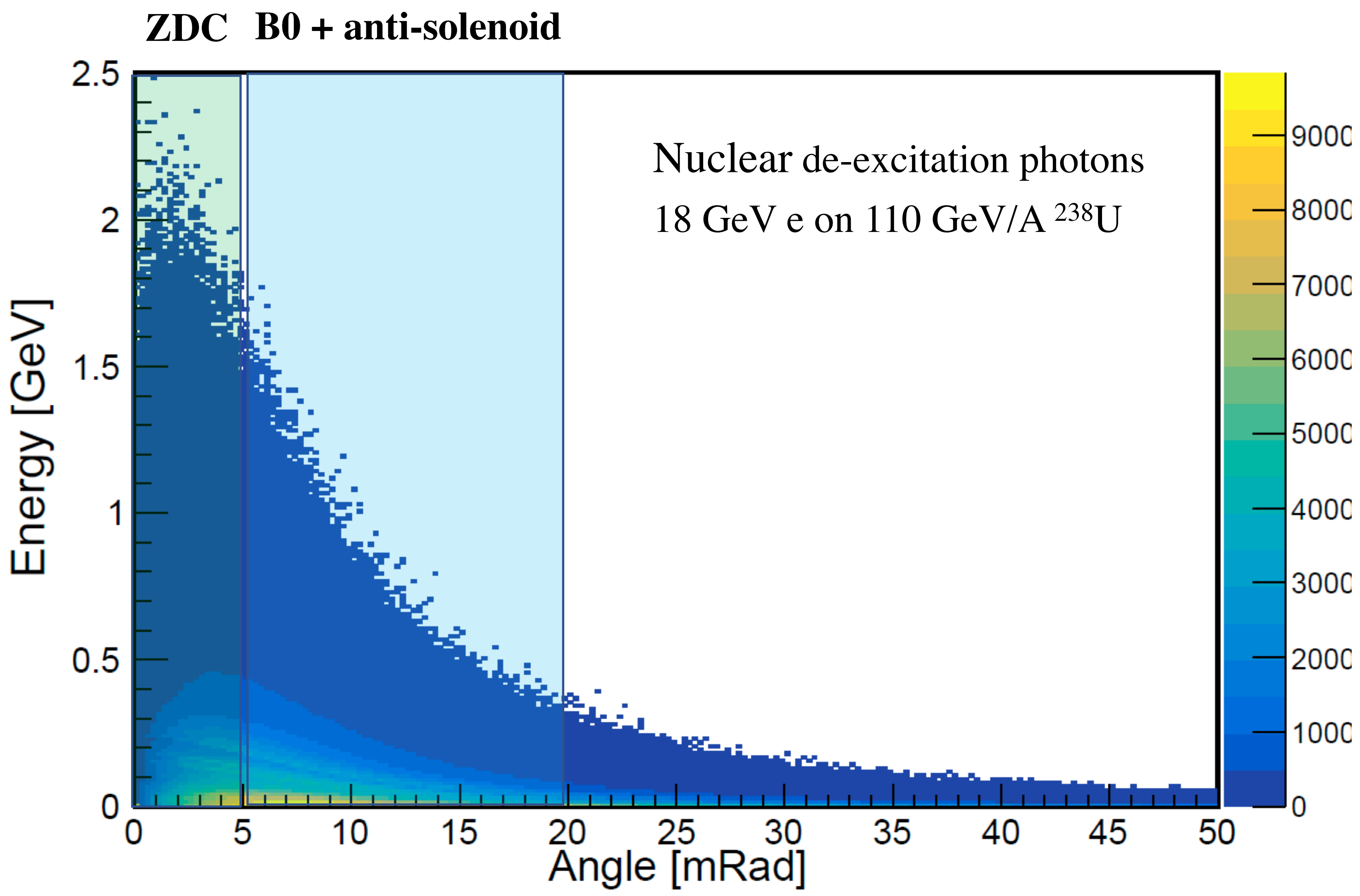
- A compact (2.5 m) solenoid was used in the CORE proposal for a 2nd detector, and could be used in any 2nd detector configuration. Not a major constraint.
- The DPAP review concluded that all three proposals, including CORE, "will be able to fully realize the baseline physics case and to make significant contributions in areas beyond."

IP8 with an EM calorimeter inside the anti-solenoid behind the B0 dipole



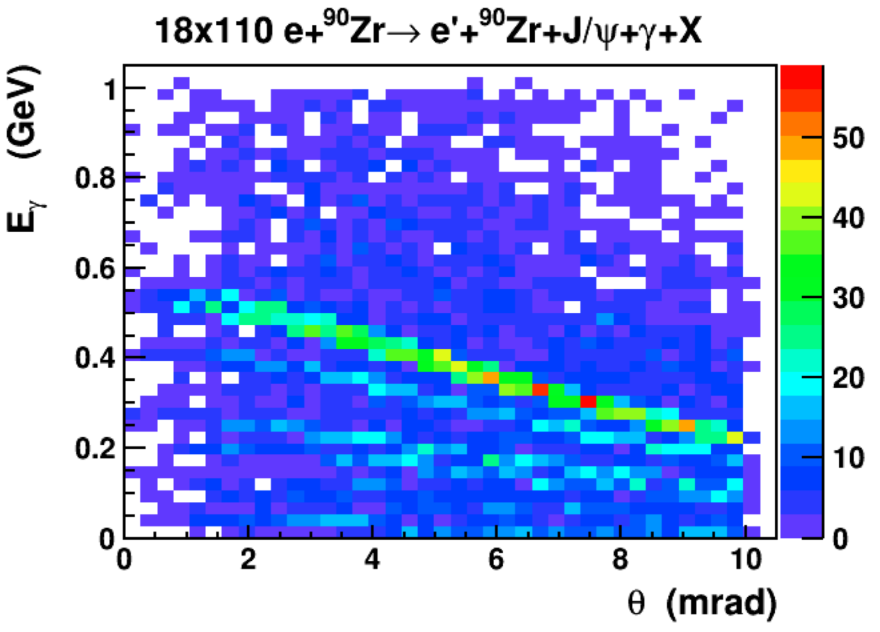
- Nuclear de-excitation photons can be detected in front of the ZDC and behind the B0 dipole.
- An anti-solenoid behind the B0 can provide additional space for detectors.

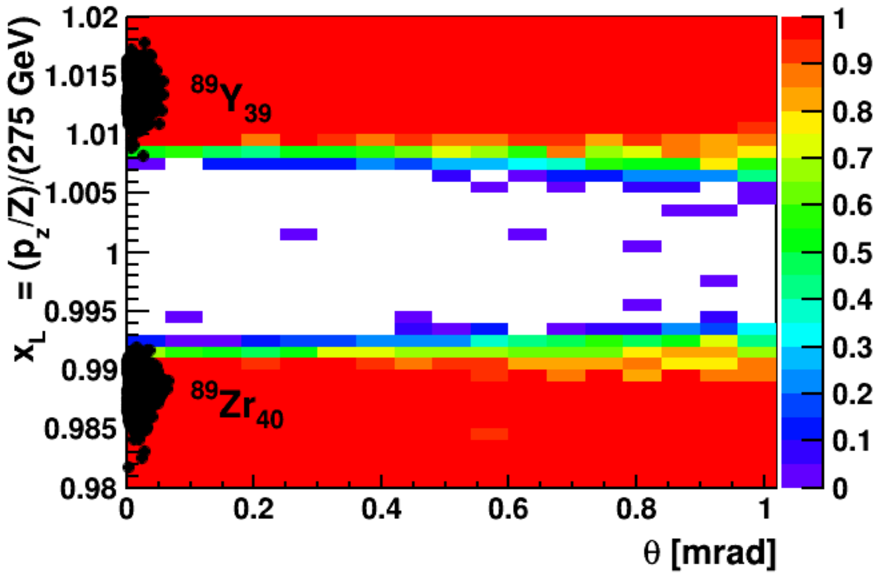
Example of improved physics capabilities – forward photon detection



- The B0 is instrumented with trackers, but the anti-solenoid could also house an EMcal.
- Extending the angular coverage for nuclear photons will
  - improve the veto efficiency for nuclear breakup
  - identify excited final nuclei
  - greatly simplify spectroscopy of rare isotopes
  - improve acceptance for forward-going photons from, DVCS and π^0 (*e.g.*, u-channel).
  - *Synergetic with the 2nd focus*

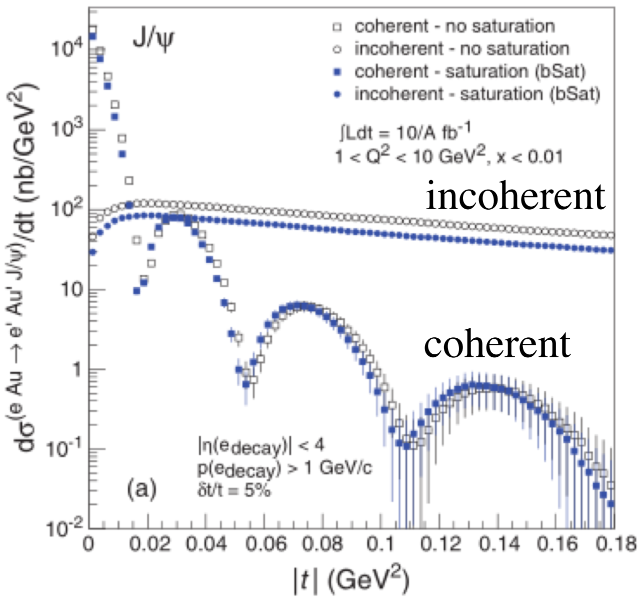
Simulations of coherent diffraction with ^{90}Zr

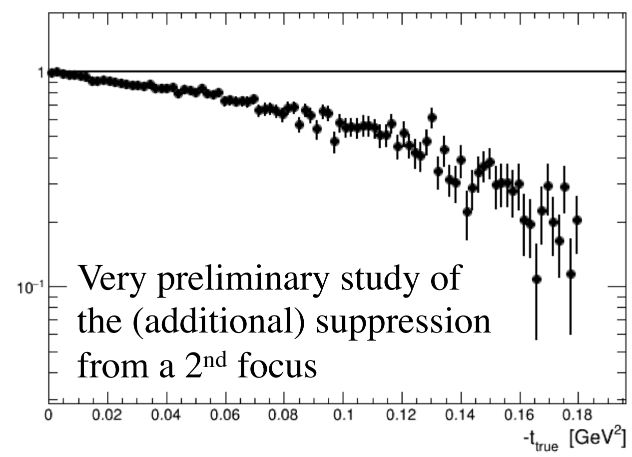




- Extended forward photon detection is synergetic with the 2nd focus in IR8.
- ^{90}Zr is ideal for benchmarking:
  - The ability to tag A-1 nuclei in the 2nd focus and detect a large fraction of nuclear photons has the potential to significantly improve the suppression of incoherent backgrounds in coherent diffraction.
  - The photon detection will also help to distinguish reactions where the final nucleus was in the ground state or an excited state.
  - The figures on the left show the photons and A-1 fragments from e+^{90}Zr
  - The figures on the right show coherent and incoherent components in e+Au and a very preliminary study of the suppression at high t from fragments detected at the 2nd focus.

e+Au (not Zr)





Nuclear Simulations for Proposed IR8 Optimization

- Baker's effort (0.15 FTE-year): Primarily expert guidance on nuclear simulation.
- BeAGLE generator development is just a 1-2 day project and does not take 1/3 of requested funds.
  - Port an existing I/O afterburner into BeAGLE code.
  - May actually lead to a small net savings in effort as it simplifies the workflow.
- The simulation of e+Zr coherent diffractive scattering is essential for discussion with the stakeholders.
  - Veto tagging of nuclear remnants in coherent e+Zr diffraction is a unique, complementary capability which can be built into the 2nd IR/detector.
  - ^{90}Zr is a perfect benchmark nucleus for IR8 since it offers the possibility of A-1 tagging (with a knocked-out neutron), and greatly benefits from an extended acceptance for nuclear photons – a synergy made possible by this proposal.
  - Initializing Sartre by generating new cross-section tables to handle a new species (^{90}Zr) is time-consuming in both CPU-years and calendar time.
  - Expert advice is essential in order for this to converge.
  - Baker was a key player in the release of the Pb tables that were used during the recent EIC Detector Proposal process.
- Much less expert advice should be needed in the out-years.
  - Rerunning the simulations due to detector/IR design iterations involves GEANT and not the generators.
  - Rerunning the generators (Sartre or BeAGLE), at different energies for instance, is quick and should involve minimal or no expert guidance once the Zr tables are generated and the initial analysis has been performed in year one.

Simulation framework and related software

- Implementation strategy
  - Initially, work within Fun4All (where an IR8 implementation already exists)
  - Translate the developments into Single Stack Software (used for EpIC)
- Synergies with other R&D projects
  - Strategy similar to the KLM proposal (SBU will provide software support for both)
- Service to the community
  - Configure both **baseline design** and **proposed improvement** into Single Stack Software
  - Development will be shared with the community who are interested in a 2nd detector and IR8
- The efforts aims to bring more personnel into EIC related research
  - Work closely with the EpIC software team
  - Minimal distraction to the IR6 software development
- Benefits to IR6 simulations
  - There is currently no solenoid compensation scheme implemented for IR6/Detector 1 (EpIC)
  - IR8 simulations including solenoid compensation will thus also benefit forward detection studies done for IR6, making it possible to quantify uncertainties from neglecting the solenoid compensation.

Budget for Year 1

	100%	80%	60%
MDBPADS LLC (M. Baker)	42.3k	42.2k	35.2k
SBU postdoc (50% FTE)	52.5k	52.5k	52.5k
SBU graduate student (50% FTE)	28k		
SBU undergraduate student (8 weeks)		6k	
Travel	5.3k	1k	
Total	128k	101.7k	87.7k

All costs include overhead at the respective institution

Thank you!

A 2nd focus in IR8 greatly improves forward acceptance

- New physics opportunities
- Complementarity with Detector 1 (EPIC) @ IR6
- Potential synergies with Detector 2 and IR8 forward instrumentation

Key features include

- Excellent low-p_T acceptance for protons and light nuclei from exclusive reactions
- Detection of target fragments makes it possible to
  - veto breakup to study coherent processes
  - study the final state when breakup occurs

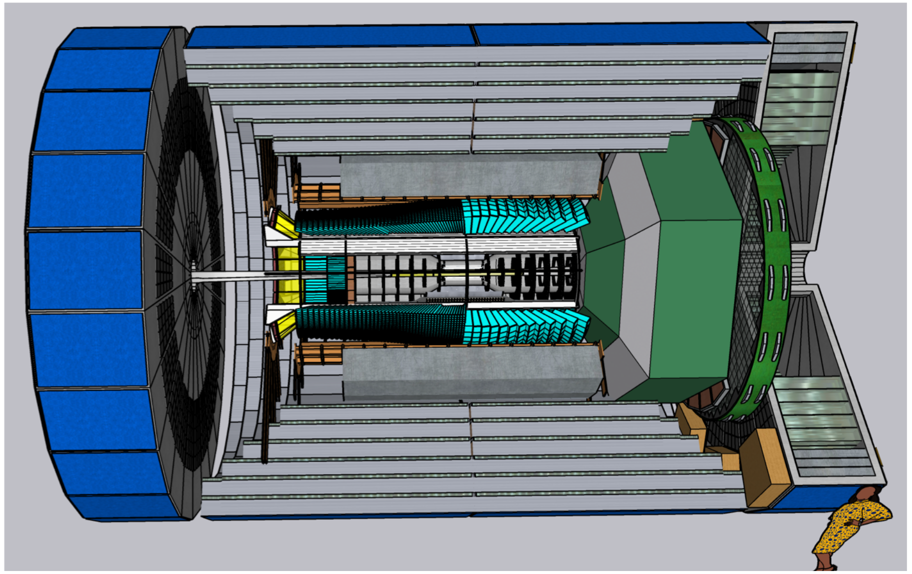
Also, note that the acceptance is much better than in fixed-target experiments like CLAS12 or SoLID, making Detector 2 particularly attractive for JLab users.

2^{nd} focus – assessment in the DPAP report

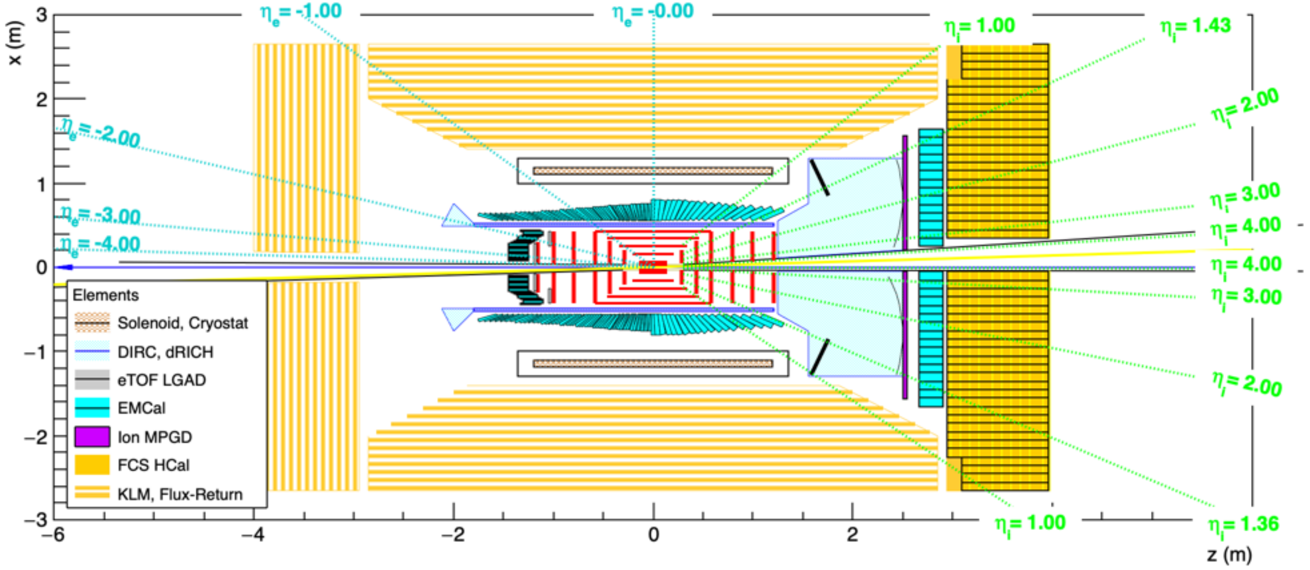
The CORE proposal makes a convincing case for the significant gain in physics reach achievable with a secondary focus:

- increased acceptance in the invariant momentum transfer t of the scattered proton in ep collisions, which directly translates into an increased resolution power for imaging partons in the transverse plane,
- significantly improved abilities to detect nuclear breakup in exclusive and diffractive scattering on light and heavy nuclei. The distinction between coherent and incoherent scattering is essential for the physics interpretation of these processes,
- prospects for a program of low-background γ gamma spectroscopy with rare isotopes in the beam fragments.

Example – CORE space allocation for subsystems the hadron side



COmpact detectoR for Eic (CORE)



- Solenoid: 2.5 m total length
  - 1.25 m length on the hadron side.
- All-MAPS silicon tracker: 2.4 m length.
  - 1.2 m on the hadron side.
- Dual-radiator RICH: 1.2 m.
  - 0.2 m in the narrower "neck" region.
- MPGD post-dRICH tracker: 0.1 m.
- Endcap Fe/Sci calorimetry: 1.5 m
- *Note: The proposed optimization was to allocate 0.5 m to the EMcal and 1 m to the Hcal, but CORE is compatible with an ATHENA-like configuration with 0.3 m EMcal and 1.2 m Hcal sections*