EIC capabilities for eA experiments

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Next generation nuclear physics with JLab 12 GeV and EIC,
Florida International University, Miami, February 10-13, 2016

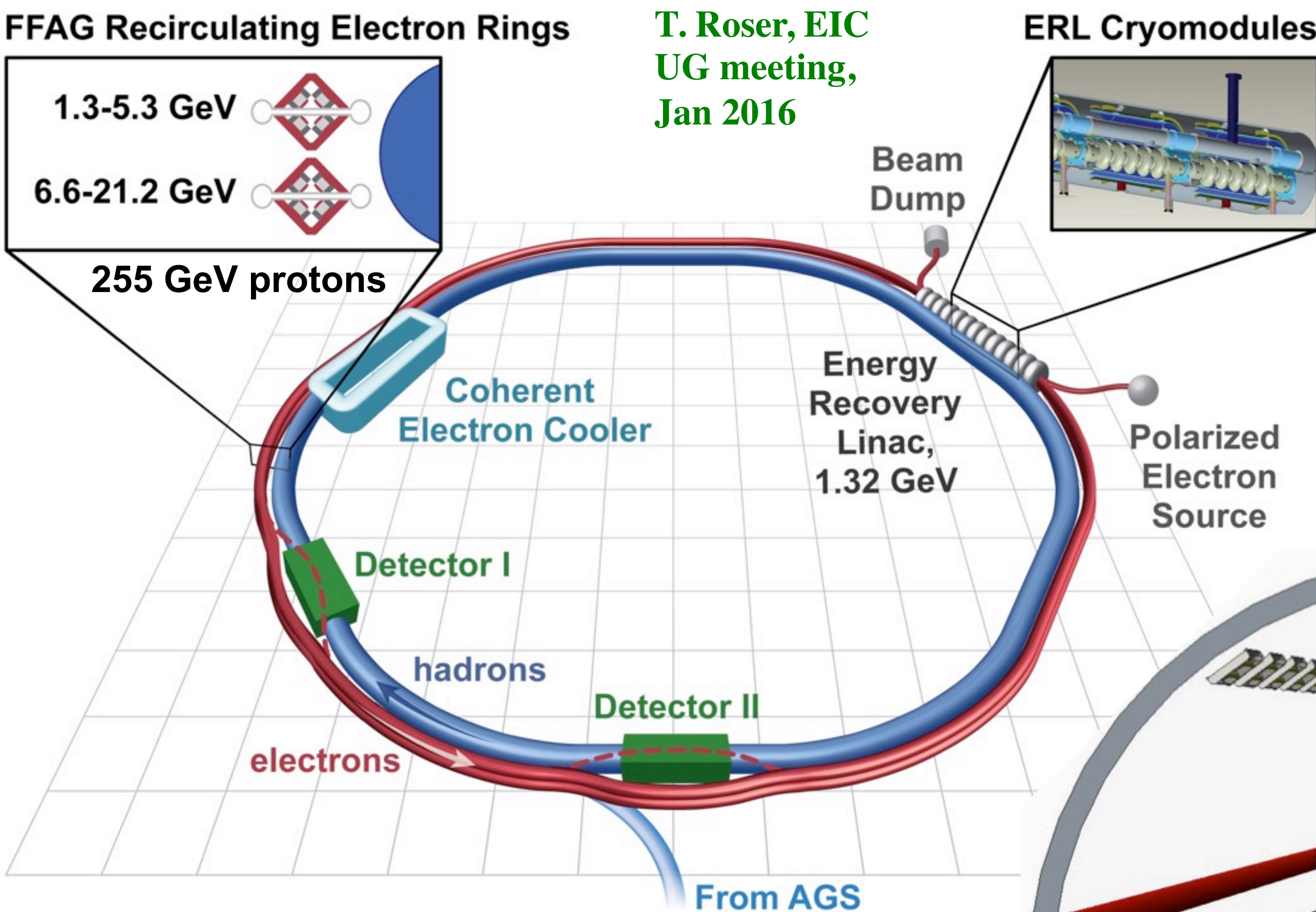
Jefferson Lab
Thomas Jefferson National Accelerator Facility

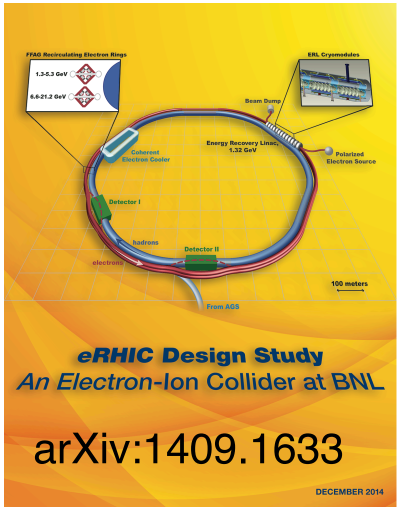
Outline

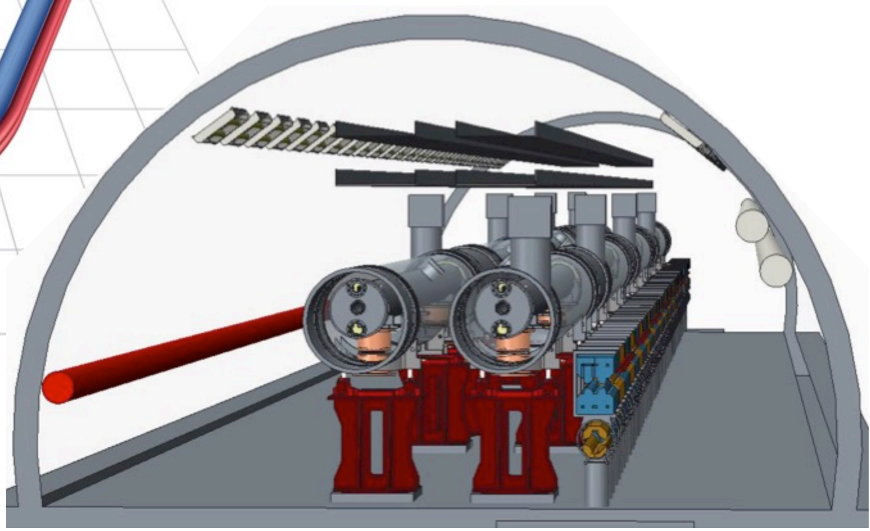
- Accelerator plans at BNL and JLab
- Ions, polarization, and polarimetry (ions and electrons)
- Interaction regions and small-angle hadron detection
- Central detectors

eRHIC linac-ring, “ultimate” version

T. Roser, EIC UG meeting, Jan 2016







- Peak luminosity: 2×10^{34} cm^{-2} s^{-1}
- ERL, permanent magnet arcs and strong cooling of proton beam

eRHIC low-risk ring-ring design

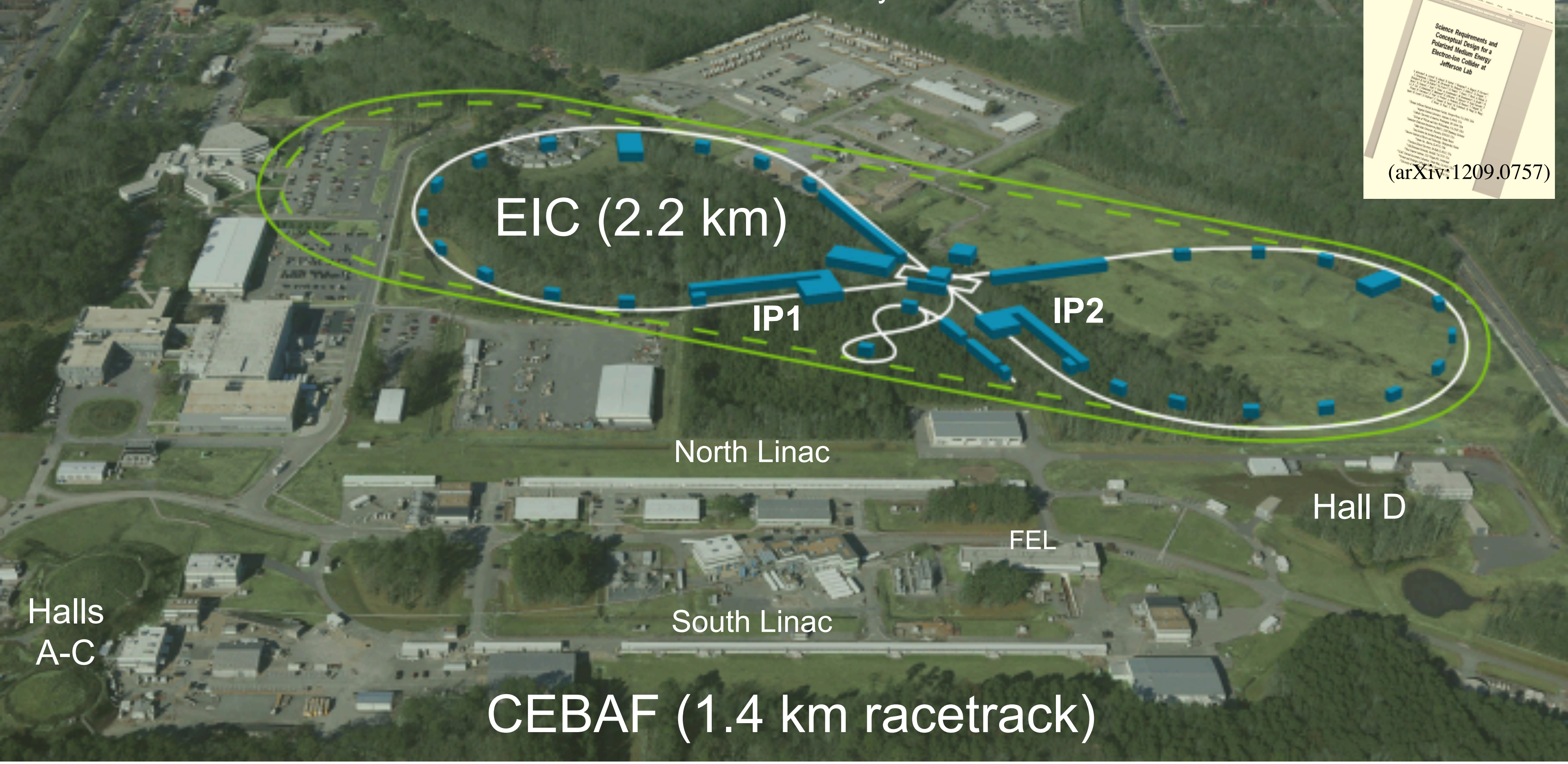
T. Roser, EIC UG meeting, Jan 2016

- ~ 5 x 10^{32} s^{-1} cm^{-2} luminosity ring-ring option covering whole energy range of EIC science case is possible using mainly existing technologies
- Spin experiments need bunch-to-bunch spin sign control. For Ring-Ring this requires full energy injector and frequent electron bunch replacement: use CEBAF-like accelerator (same as ERL but no energy recovery) in RHIC tunnel.
- Electron storage ring needs to operate over wide energy range, maintain electron polarization, and include spin rotators. The storage ring is very similar to the final pass in the ERL-Ring option.
- Little or no hadron cooling needed.
- Limit synchrotron radiation power to 10 MW: lower risk and cost, but still a major cost driver
- Upgrade to the higher luminosity ultimate ERL-Ring design is possible by recovering the electron beam energy in the CEBAF-like injector, converting it into the ERL.

JLab EIC (JLEIC) and CEBAF 12 GeV

- CEBAF as 12 GeV injector
- e-ring from PEP-II
- Possible to run fixed-target program concurrently

- Figure-8 ion ring for polarized deuterium
- 100 GeV protons with inexpensive 3 T super-ferric magnets
  - Upgradable (*e.g.*, 280 GeV with LHC-style 8.4 T magnets)
- Baseline is lowest-risk version (*e.g.*, single-pass e-cooling)
  - Peak luminosity ~ 10^{34} cm^{-2} s^{-1}

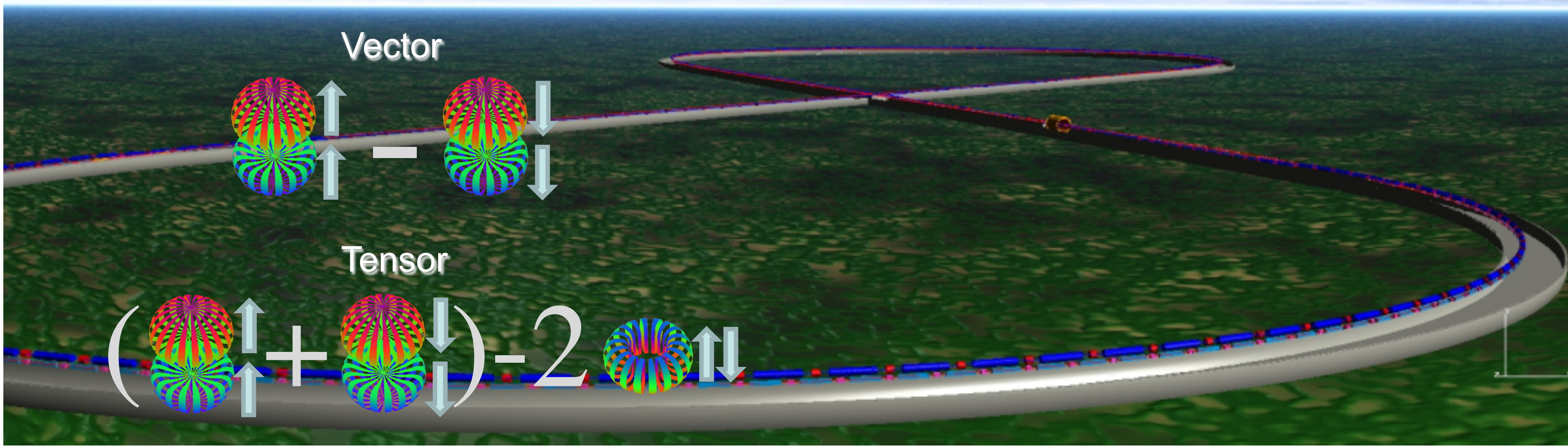


Ions, polarization, and polarimetry

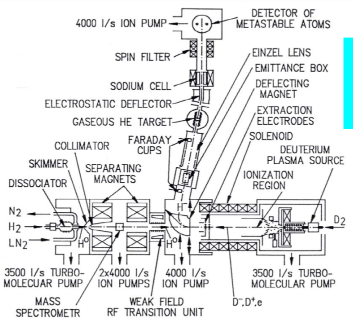
- Both JLab and BNL machines can accelerate and store most *unpolarized* ions (from ^{1}H to ^{238}U)
  - Limitations due to availability of (essentially site-independent) sources
  - BNL has a lot of experience with heavy-ion sources
- Operation with *polarized* beams is much more difficult
  - Polarization is lost during acceleration as resonances are crossed
  - The spin of ions with low g-2 is very difficult to control
- Hadron (proton) polarimetry at RHIC is well developed (few %)
  - Some R&D (*e.g.*, on H-jet) could be useful for EIC applications
  - Current methods are essentially site-independent
- JLab has great expertise in electron polarimetry (sub %)
  - JLab has a quite detailed EIC polarimeter implementation
  - BNL has started to investigate electron polarimetry for eRHIC

Polarized ions

- To improve proton polarization at high energy (250 GeV) from ~55% today to 70% for an EIC, BNL plans to dismantle one of the RHIC rings and add its spin manipulators (siberian snakes) to the remaining eRHIC ring.
- A simpler solution to avoid polarization losses during acceleration is to use a figure-8 ring, which removed many of the depolarizing resonances
- A figure-8 shape is also required to manipulate the spin of ions with low g-2, such as the deuteron. Using such polarized ions is thus unique to JLab

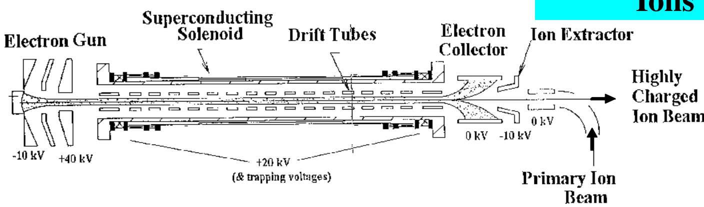


Ion sources



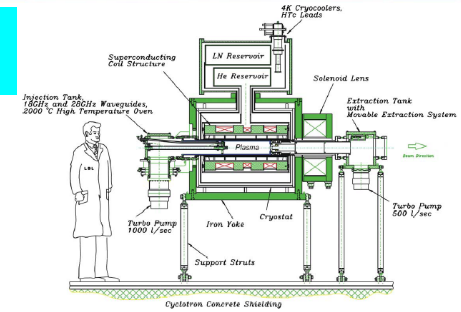
Polarized light Ions

Universal Atomic Beam Polarized Ion Sources (ABPIS)



Electron-Cyclotron Resonance Ion Source (ECR)

Non-Polarized Ions



Electron-Cyclotron Resonance Ion Source (ECR)

Ions	Source Type	Pulse Width (μs)	Rep. Rate (Hz)	Pulsed current (mA)	Ions/pulse (10^{10})	Polarization (P_z)	Emittance (90%) (π·mm·mrad)	Note
H^-/D^-	ABPIS	500	5	4 (10)	1000	>90% (95)	1.0 / 1.8 (1.2)	
H^-/D^-	ABPIS	500	5	150 / 60	40000/15000	0	1.8	
$^3He^{++}$	ABPIS-RX	500	5	1	200	70%	1	
$^3He^{++}$	EBIS	10 to 40	5	1	5 (1)	70%	1	BNL
$^6Li^{+++}$	ABPIS	500	5	0.1	20	70%	1	
Pb^{30+}	EBIS	10	5	1.3 (1.6)	0.3 (0.5)	0	1	BNL
Au^{32+}	EBIS	10 to 40	5	1.4 (1.7)	0.27 (0.34)	0	1	BNL
Pb^{30+}	ECR	500	5	0.5	0.5 (1)	0	1	
Au^{32+}	ECR	500	5	10.5	0.4 (0.6)	0	1	

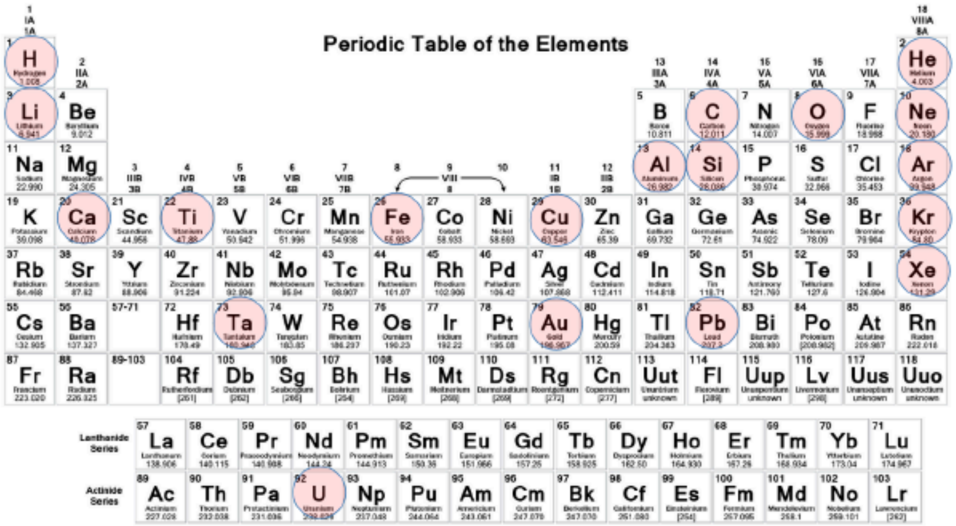
- Numbers in **red** are “realistic extrapolation for future”; numbers in **blue** are performance requirements of BNL EBIS

V. Dudnikov

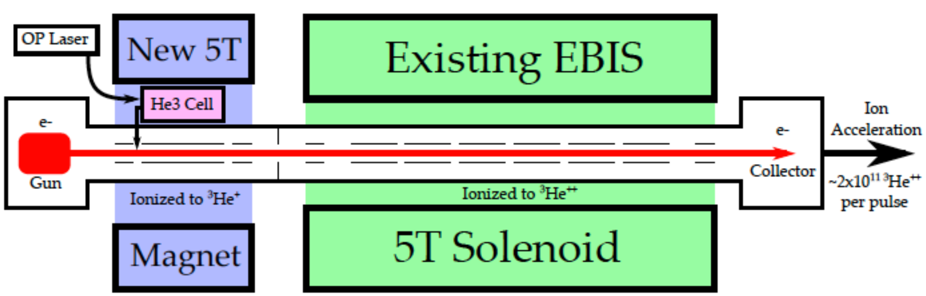
EBIS for polarized heavy ions?

EBIS Beams Run to Date

Figures from J. Maxwell, seminar, Oct 2015

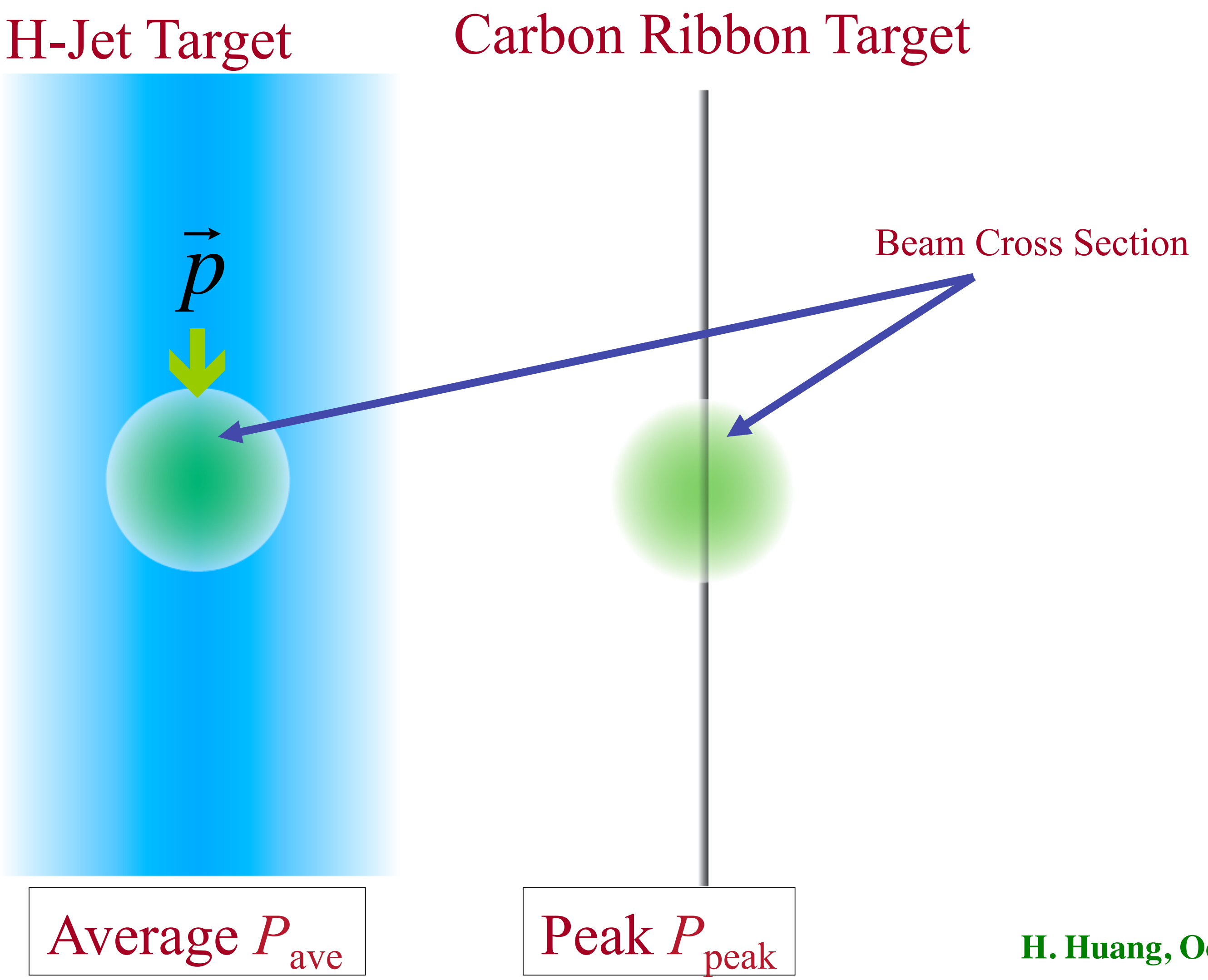


D, $^3He^{2+}$, $^4He^{1+,2+}$, Li^{3+}, C^{5+}, O^{7+}, Ne^{5+}, Al^{5+}, Si^{11+}, Ar^{11+}, Ca^{14+}, Ti^{18+}, Fe^{20+}, Cu^{1+}, Kr^{18+}, Xe^{27+}, Ta^{38+}, Au^{32+}, Pb^{34+}, U^{39+}. Capable of $^3He \Rightarrow {}^3He^{++}$ at nearly 100%



- An EBIS source, like the one at BNL, can provide a wide range of *unpolarized* ions
- The EBIS source at BNL is being modified to support polarized ^{3}He (blue part)
- Future R&D may allow *polarized* heavy ions from an EBIS source

Proton (ion) polarimetry at RHIC



H. Huang, Oct 2015

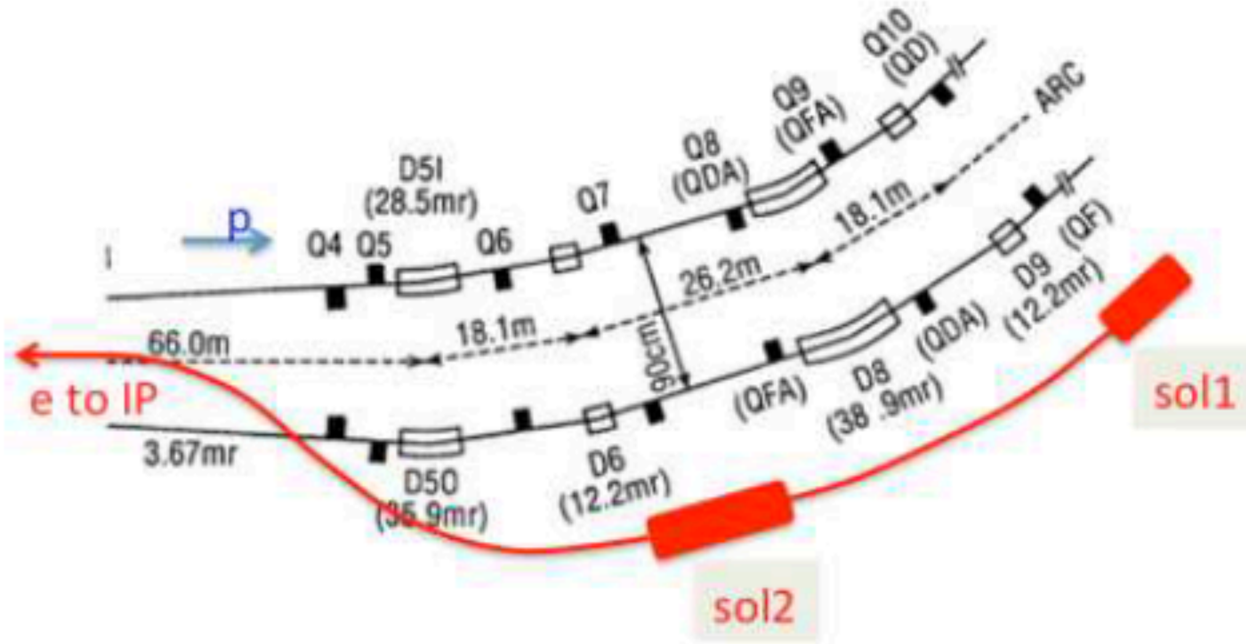
Proton (ion) polarimetry at RHIC

- Due to the target orientation and thickness variation, the calibration of p–Carbon polarimeter with polarized H-jet can not be once and done.
- The polarized hydrogen jet needs to be running in parallel.
- With upgraded Si detectors, the H-jet can give polarization error of ±3% for 8 hour store. (PNT: main source of uncertainty)
- In sweep mode, a polarization of ±2% measurement can be done by p-Carbon polarimeter in about 30 sec
- Normally, four sets of polarization measurements are done at store: 0, 3, 6, and 8 hours into a store. Each set consists of two polarization measurements done with horizontal and vertical targets, respectively. Besides polarization information, polarization profile information is also obtained.

H. Huang, Oct 2015

eRHIC ring-ring spin rotators

C. Montag, seminar, Nov 2015

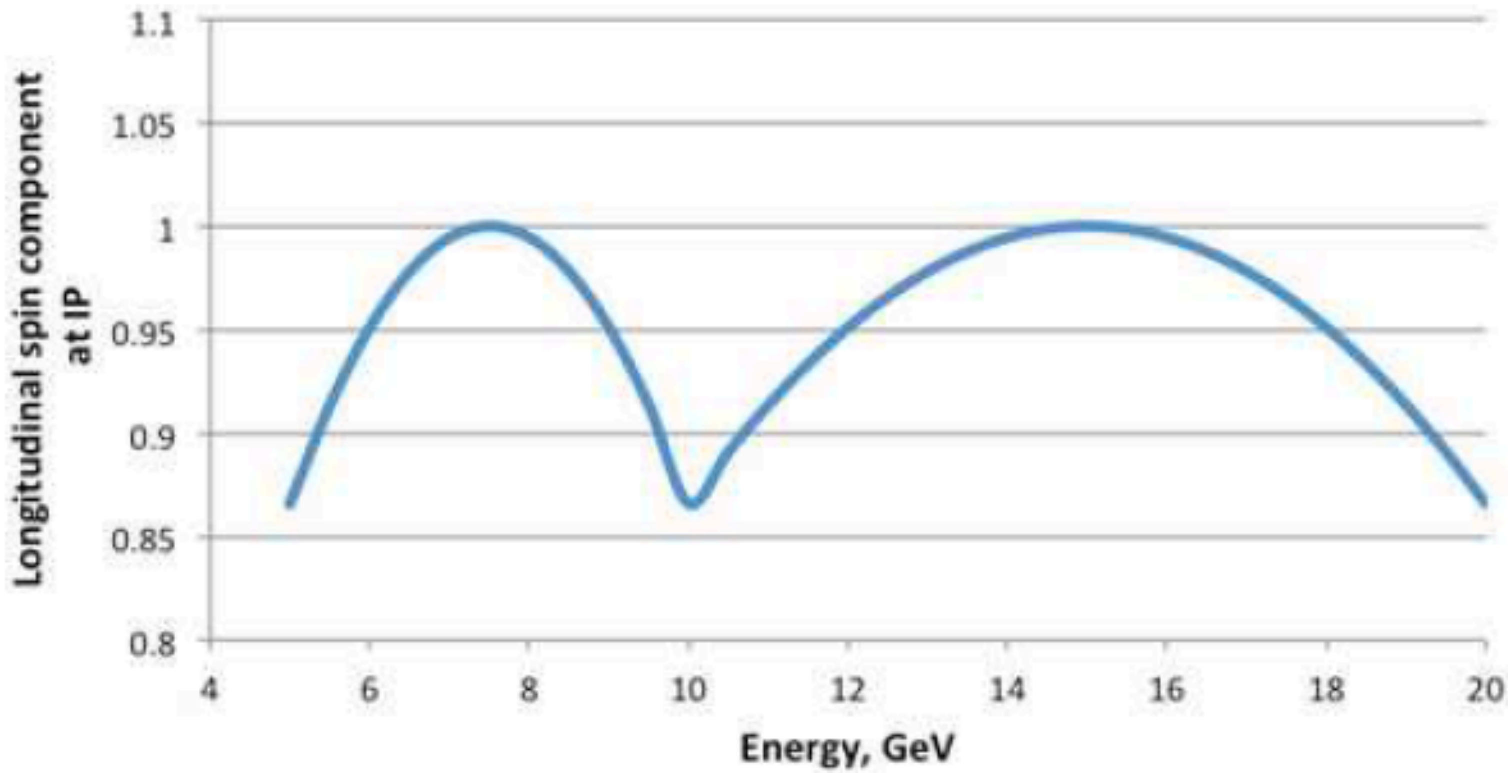


- Two solenoid type spin rotators provide longitudinal polarization in two different energy regimes
- Integrated fields: $B \cdot l[\mathrm{Tm}] = 5.24E[\mathrm{GeV}]$; 26-53 and 52-105 Tm, resp.

eRHIC electron polarization

C. Montag, seminar, Nov 2015

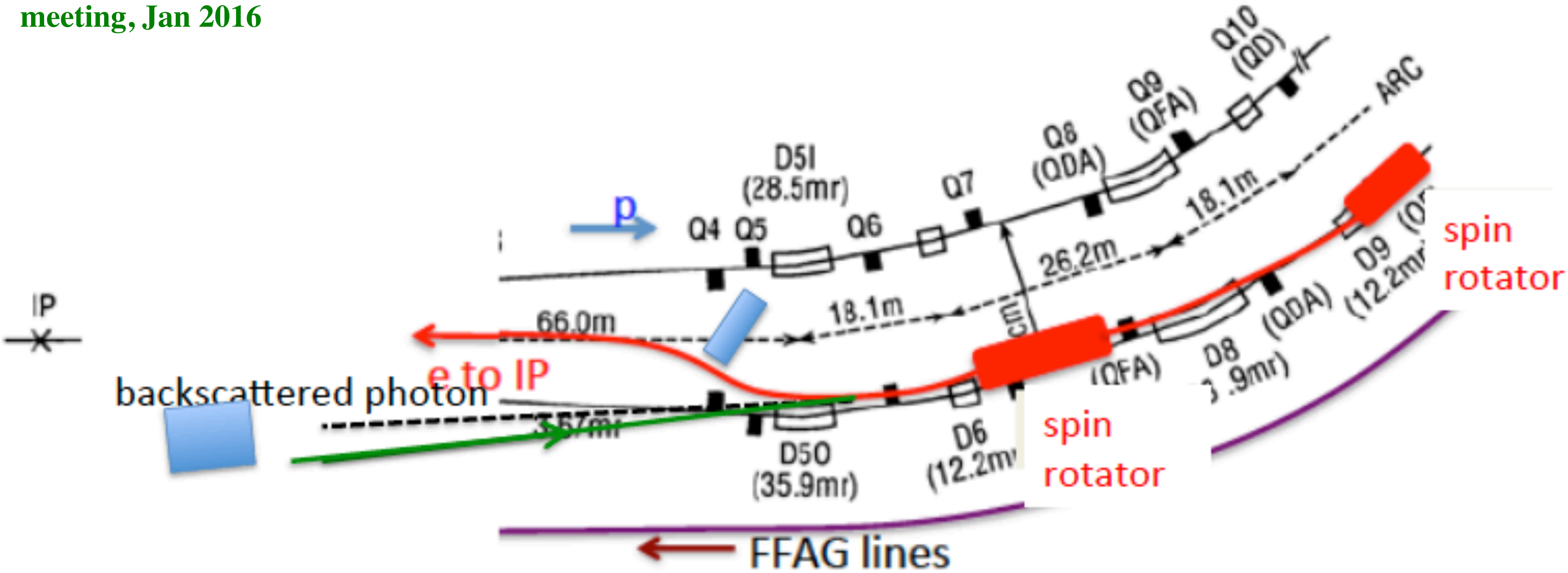
Longitudinal spin vs. energy (relative to source, *i.e.*, not always longitudinal)



Perfect longitudinal polarization at 7.5 and 15 GeV, some transverse component at other energies

eRHIC linac-ring spin rotators with Compton polarimeter

R. Petti, EIC R&D meeting, Jan 2016

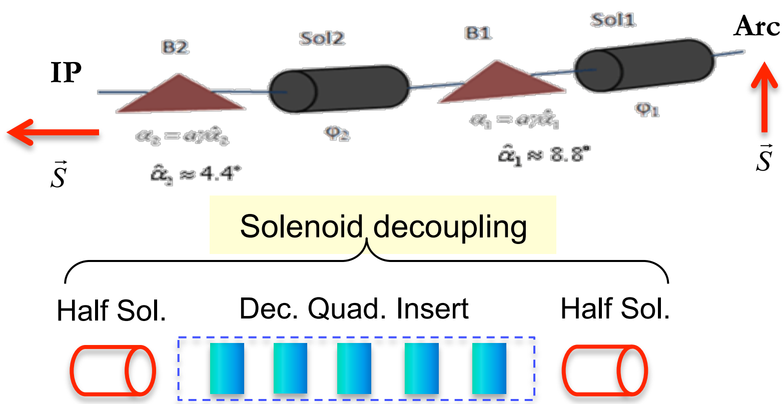


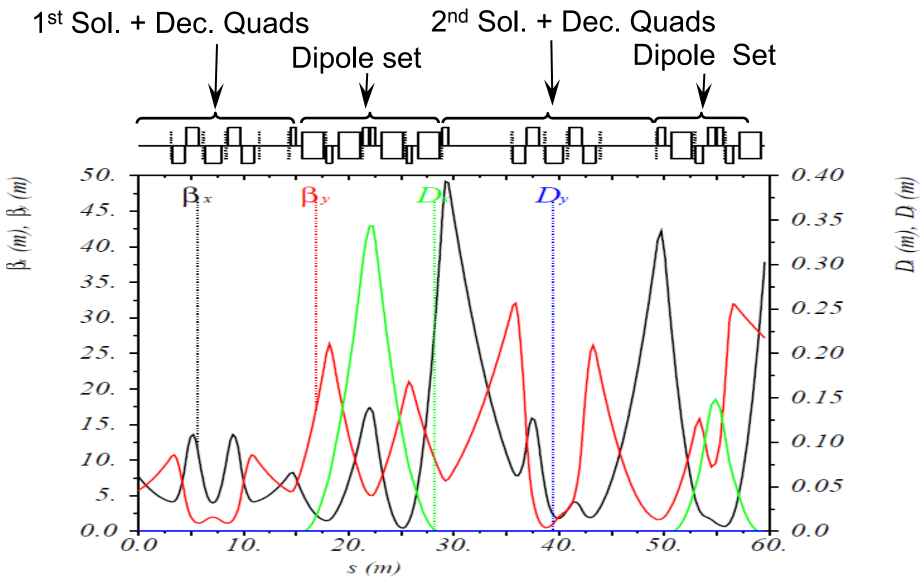
- general schematic shown
- detailed lattice design in this region does not yet exist

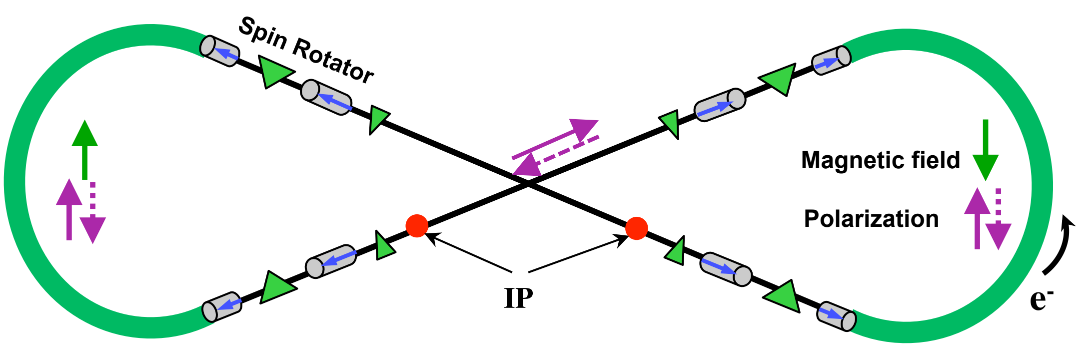
JLab: electron spin rotator

- Schematic drawing and lattice of USR

P. Chevtsov et al., Jlab-TN-10-026



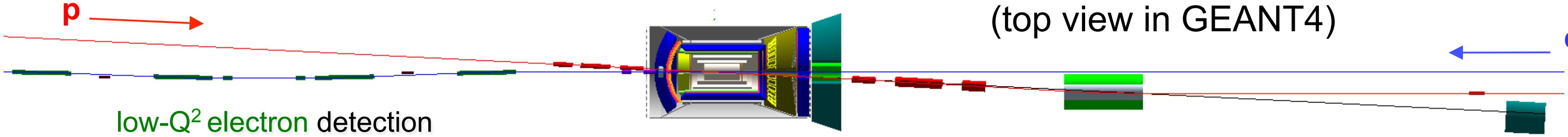


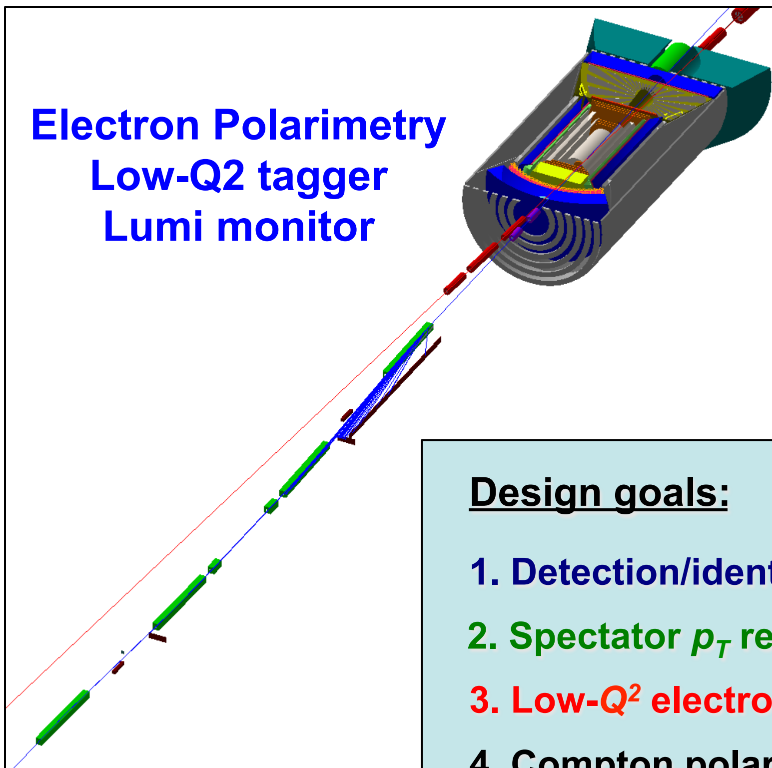


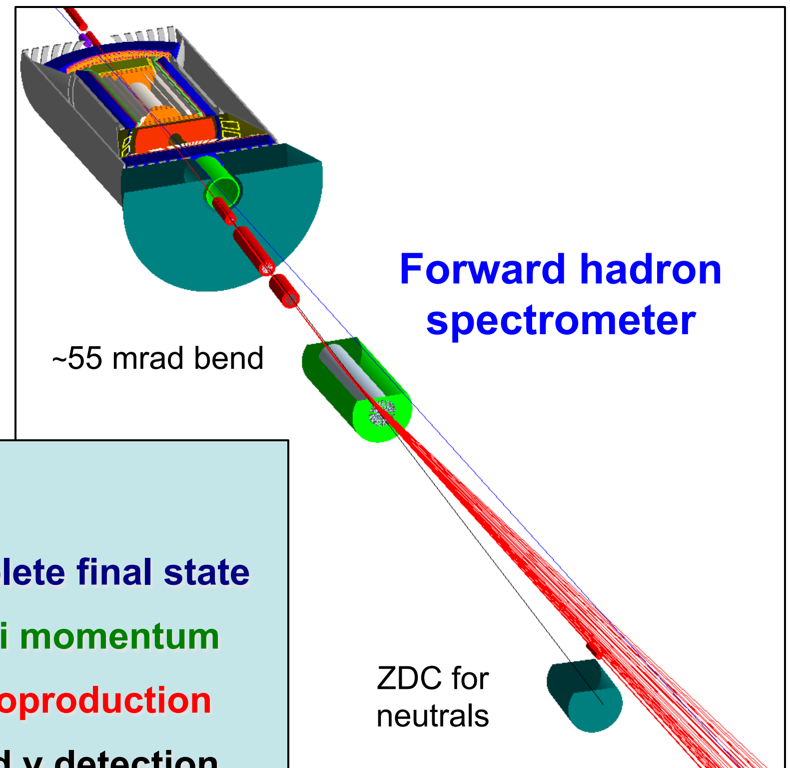
- Universal spin rotators allow full longitudinal polarization for all electron energies

- USRs also allow a "spin dance" scanning procedure to experimentally determine the longitudinal beam spin alignment

JLab: integrated detection and polarimtery







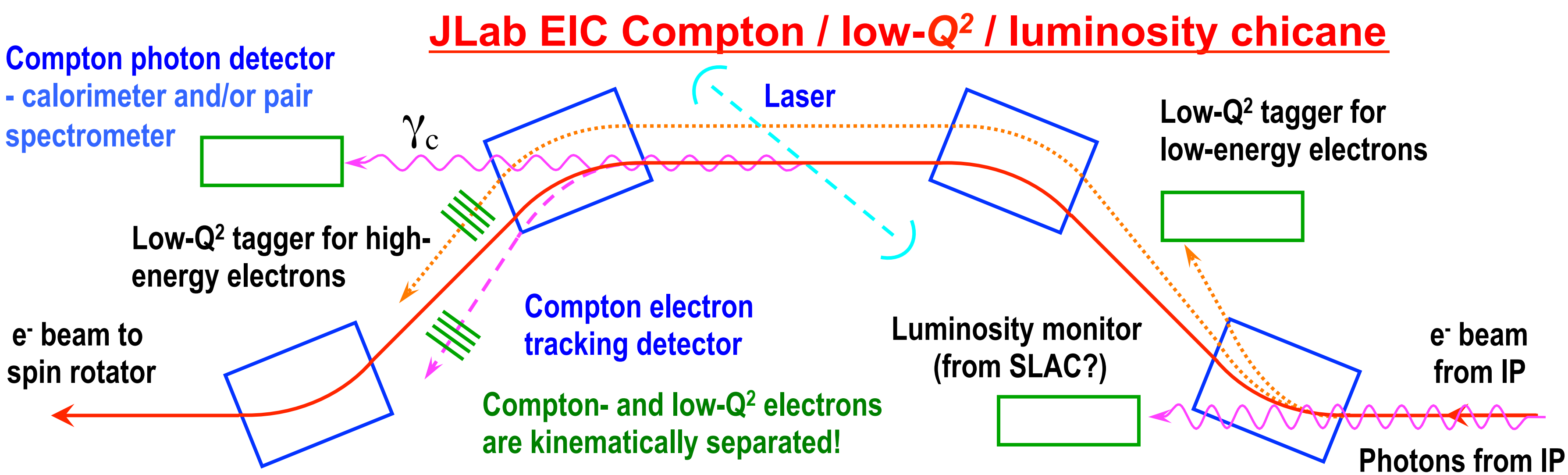
Design goals:

1. **Detection/identification of complete final state**
2. **Spectator p_T resolution << Fermi momentum**
3. **Low-Q^2 electron tagger for photoproduction**
4. **Compton polarimeter with e^- and γ detection**

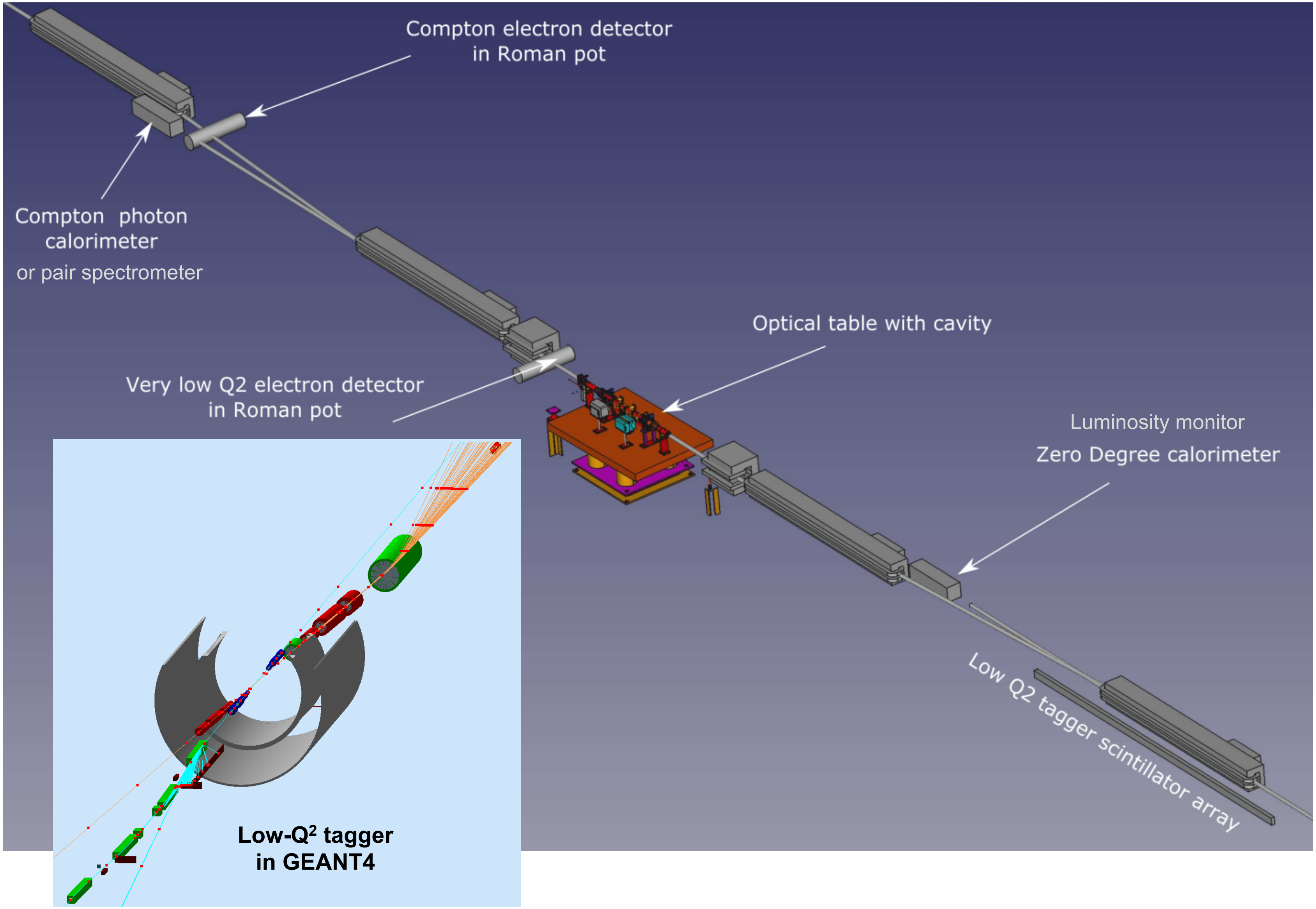
JLab: Compton polarimeter and low-Q^2 tagger

- Experience from HERA: uncertainty ~ 1.4%
  - Limited to detection of Compton photon only
  - Accelerator limitations (non-colliding bunches)
- Experience from JLab and SLAC
  - SLD at SLAC reached 0.5% detecting the Compton electron
  - Compton polarimeters in Halls A/C at JLab reach << 1% detecting both γ *and* e
  - Polarization at center of chicane exactly that same as at IP!

    Laser at chicane center and symmetric dipoles can cancelling net spin precession



JLab: Compton/low-Q^2 chicane layout



Interaction regions and forward detection

- The JLab detector was built “outside-in,” starting with the IR, forward hadron detection, and accelerator integration
  - This has resulted in an stable IR concept

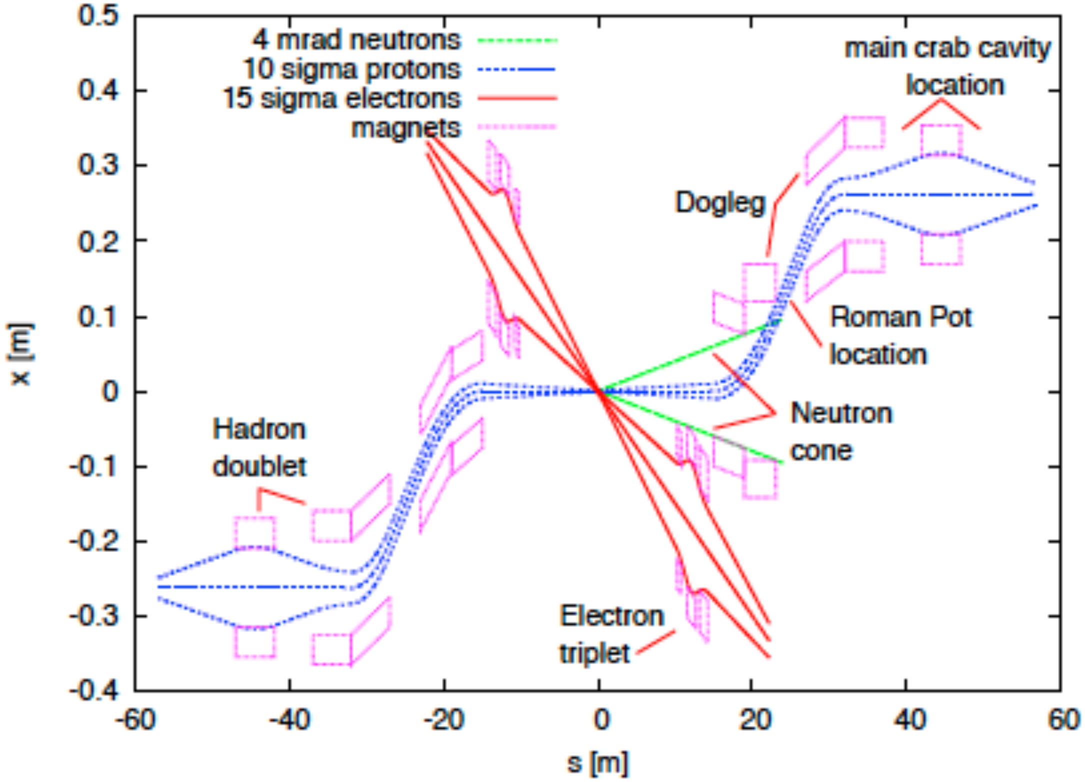
- The BNL detectors were built “inside-out,” starting with the central detector, while the IR was defined by accelerator boundaries
  - Several IR concepts were developed for the linac-ring eRHIC
  - Lately more were added for the ring-ring eRHIC
  - Can be a little confusing to an outsider...

- But most importantly, today both BNL and JLab agree on the importance of full acceptance and excellent forward detection
  - This is a good starting point!

eRHIC ring-ring IR

C. Montag, seminar, Nov 2015

PNT: Details of suitable detectors are not yet worked out, but note the huge space reserved for the central detector!



- Full dogleg and > 2 m space for Roman Pots
- 15 mrad crossing angle with crab cavities
- Proton quad aperture could be increased to accommodate low energy beams without cooling; peak field for apertures shown only 1.1 T

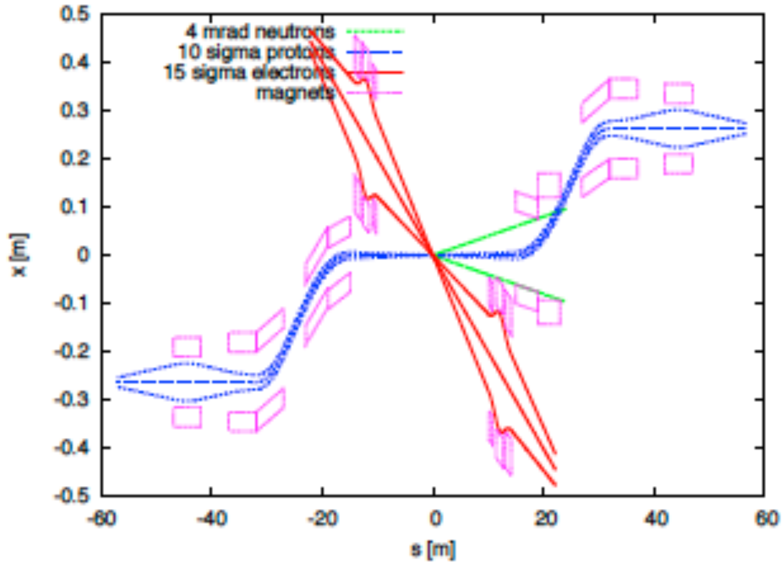
eRHIC ring-ring IR w/ better cooling

Required IR changes for moderate cooling

(Emittance reduction by factor 2 in all planes)

C. Montag, seminar, Nov 2015

PNT: good cooling is essential for *coherent reactions on nuclei* and low-t *recoil baryon detection* (*e.g.*, DVCS)



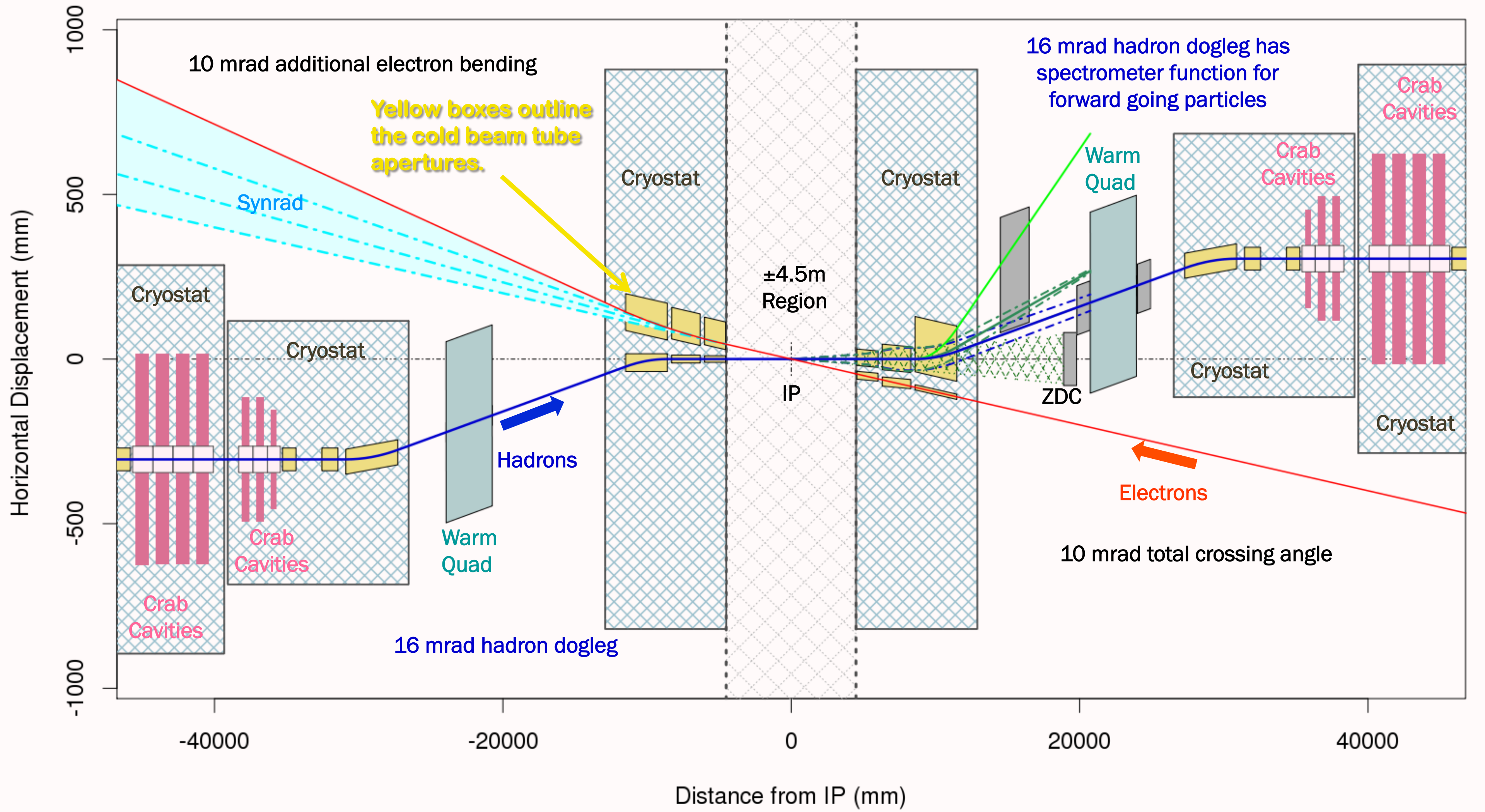
Modified layout:

- 20 mrad crossing angle instead of 15 mrad
- larger electron triplet aperture

Cooling to even smaller emittances requires larger crossing angles; feasible if bunch length shrinks accordingly

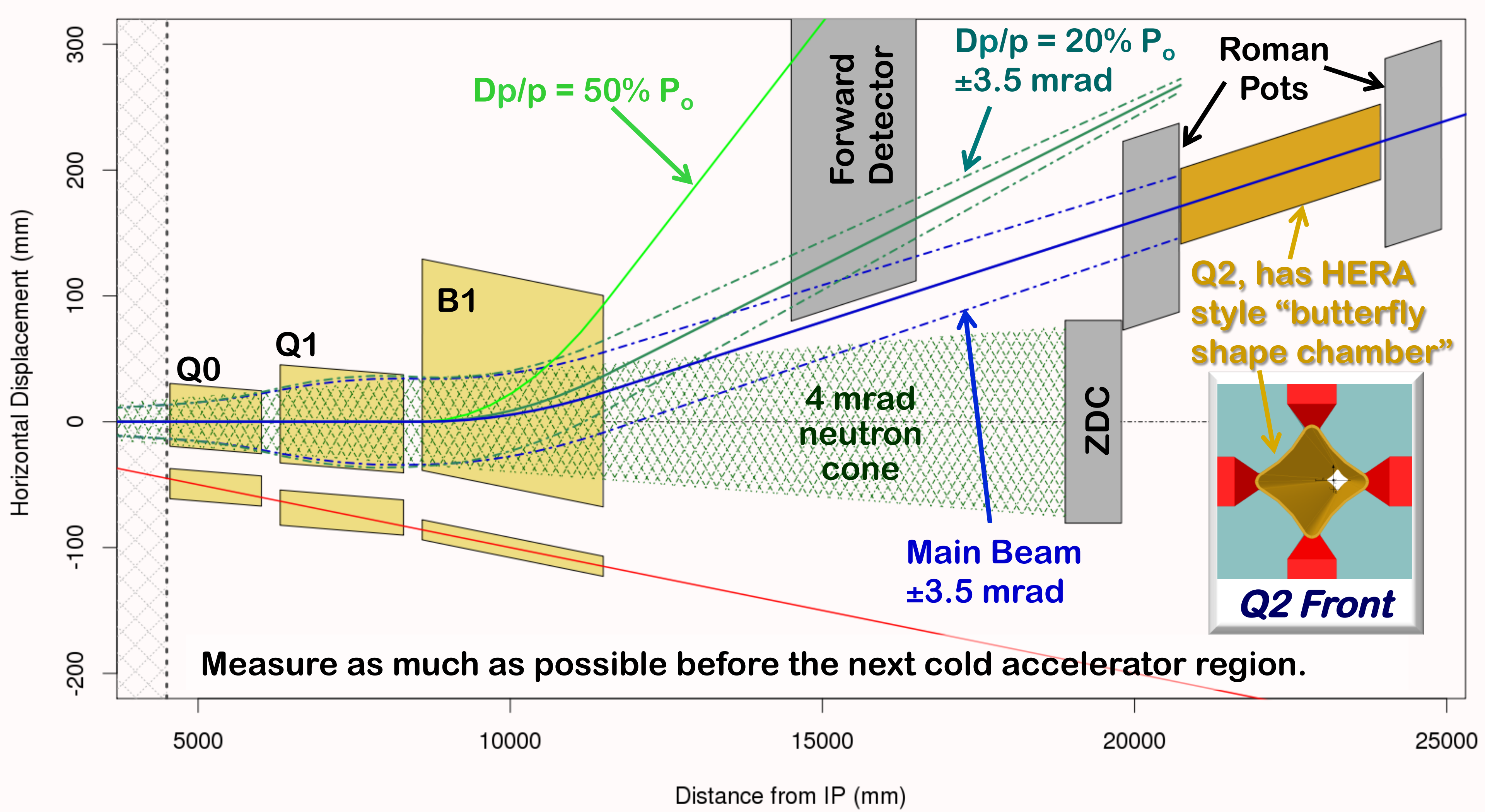
eRHIC linac-ring IR version 2.5

B. Parker, ODU, March 2015

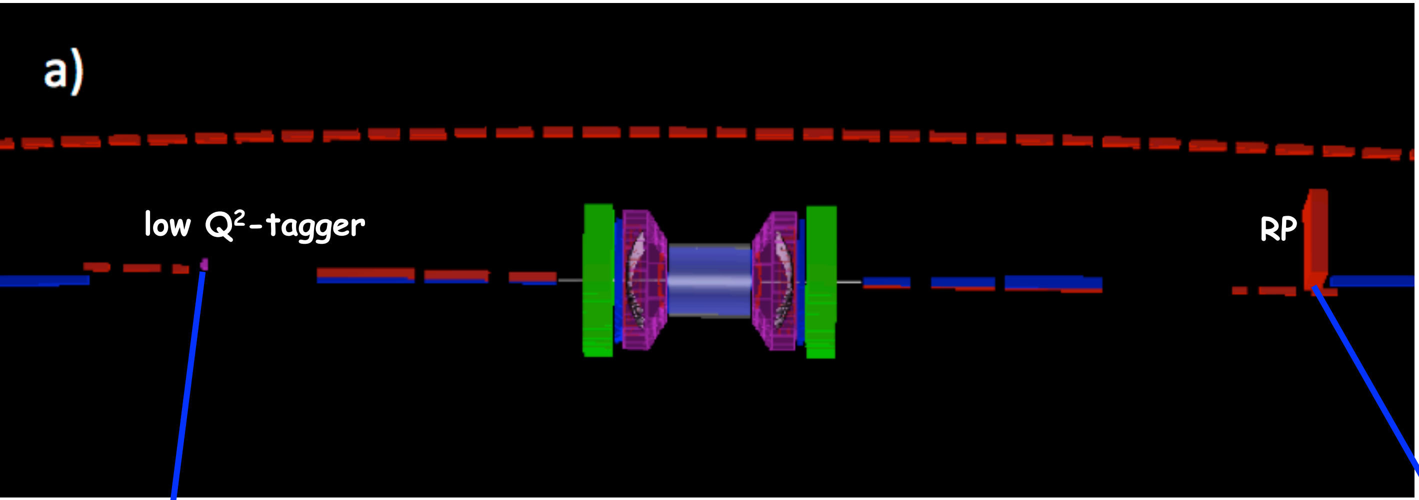


Outline

B. Parker, ODU, March 2015

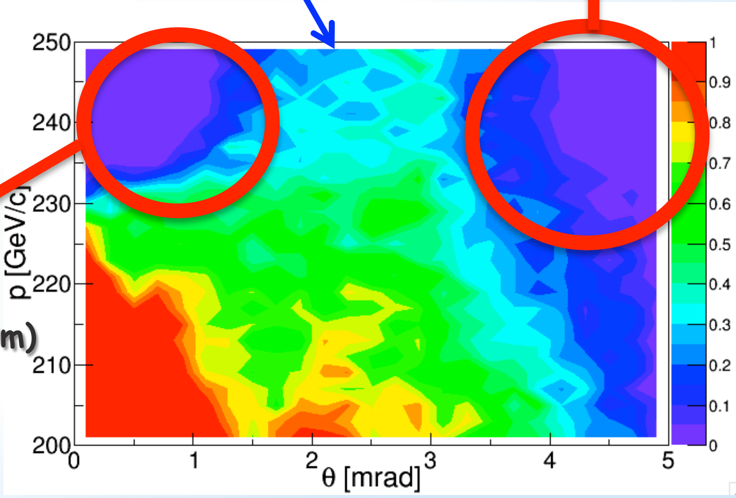


Extended IR region and by pass modeled in Geant

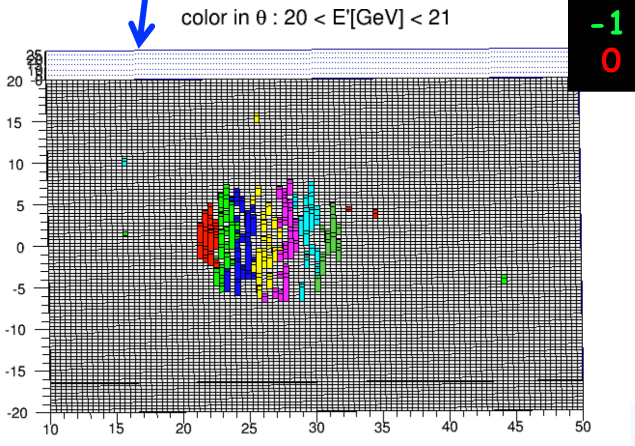


e-polarimeter and luminosity detector are next to be integrated in IR and modeled in Geant

- seems to be lost in magnet yoke
- can work with CAD to improve



- $-6 < \theta < -5$ mrad
- $-5 < \theta < -4$ mrad
- $-4 < \theta < -3$ mrad
- $-3 < \theta < -2$ mrad
- $-2 < \theta < -1$ mrad
- $-1 < \theta < 0$ mrad
- $0 < \theta < 1$ mrad

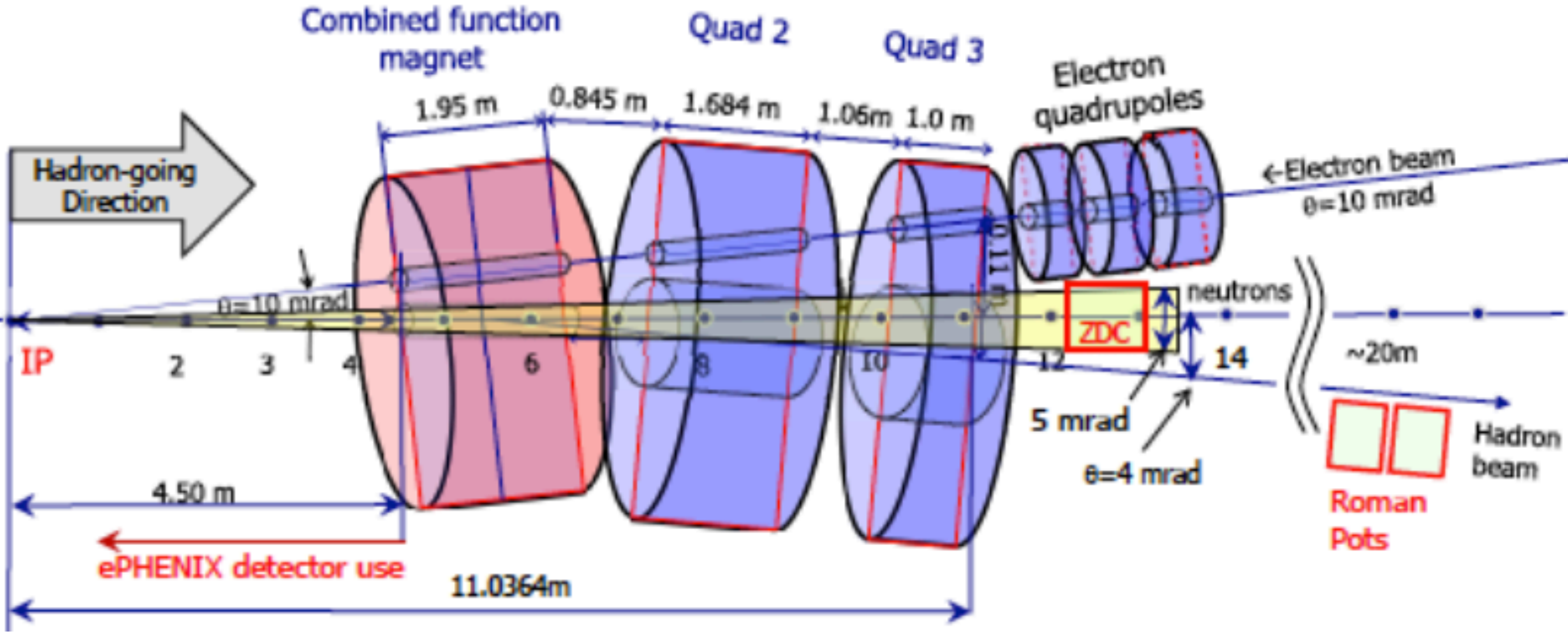


- gain acceptance with a station very far down (>40m)
- still need to model this

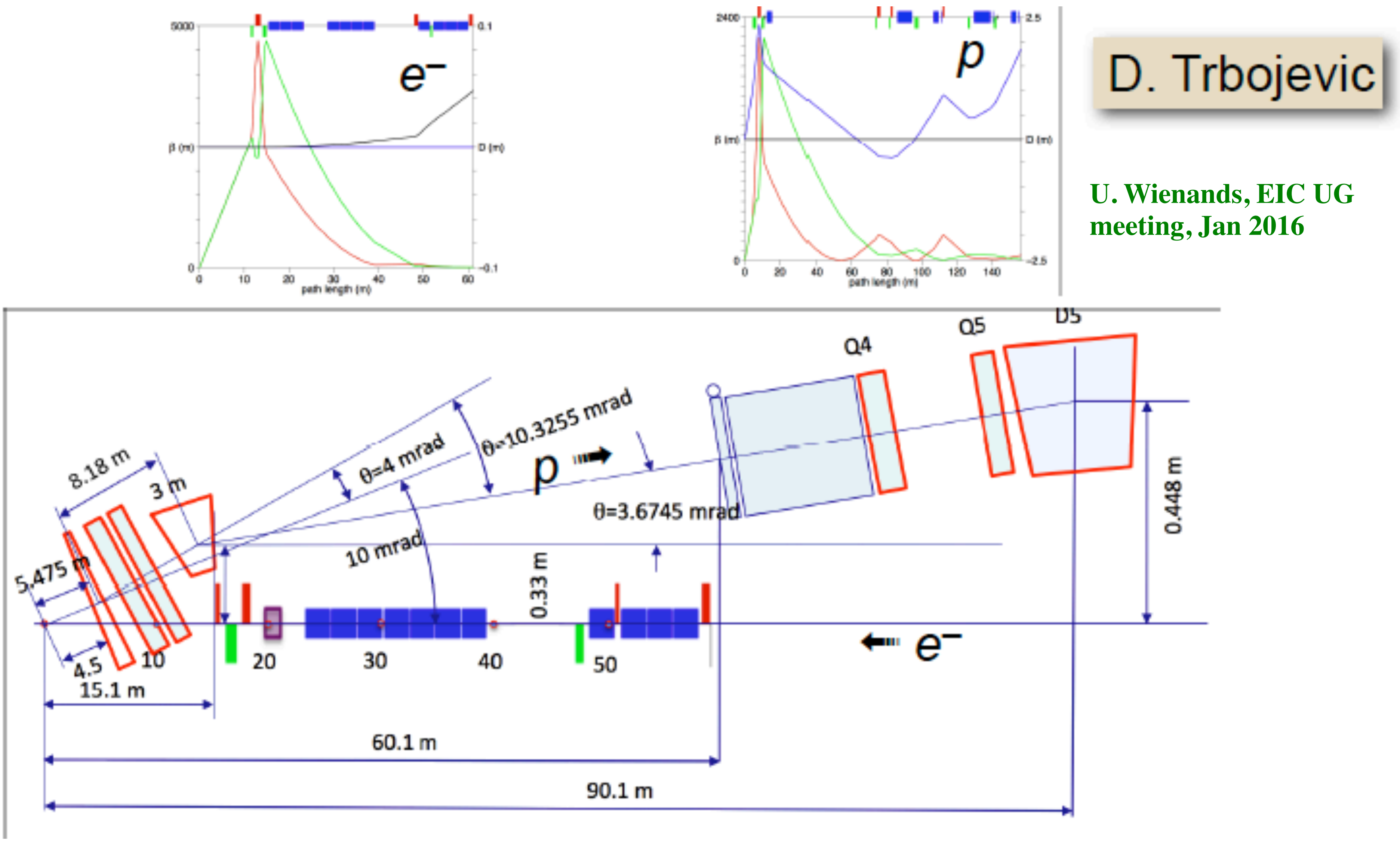
E.C. Aschenauer, EIC UG meeting, Jan 2016

eRHIC linac-ring IR (alternative)

N. Feege, EIC UG meeting, Jan 2016

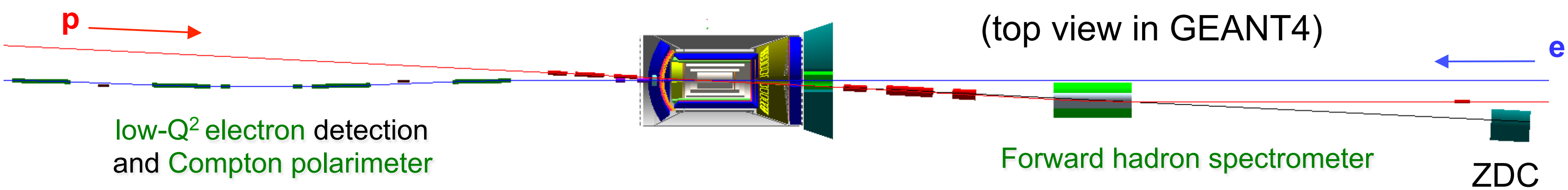


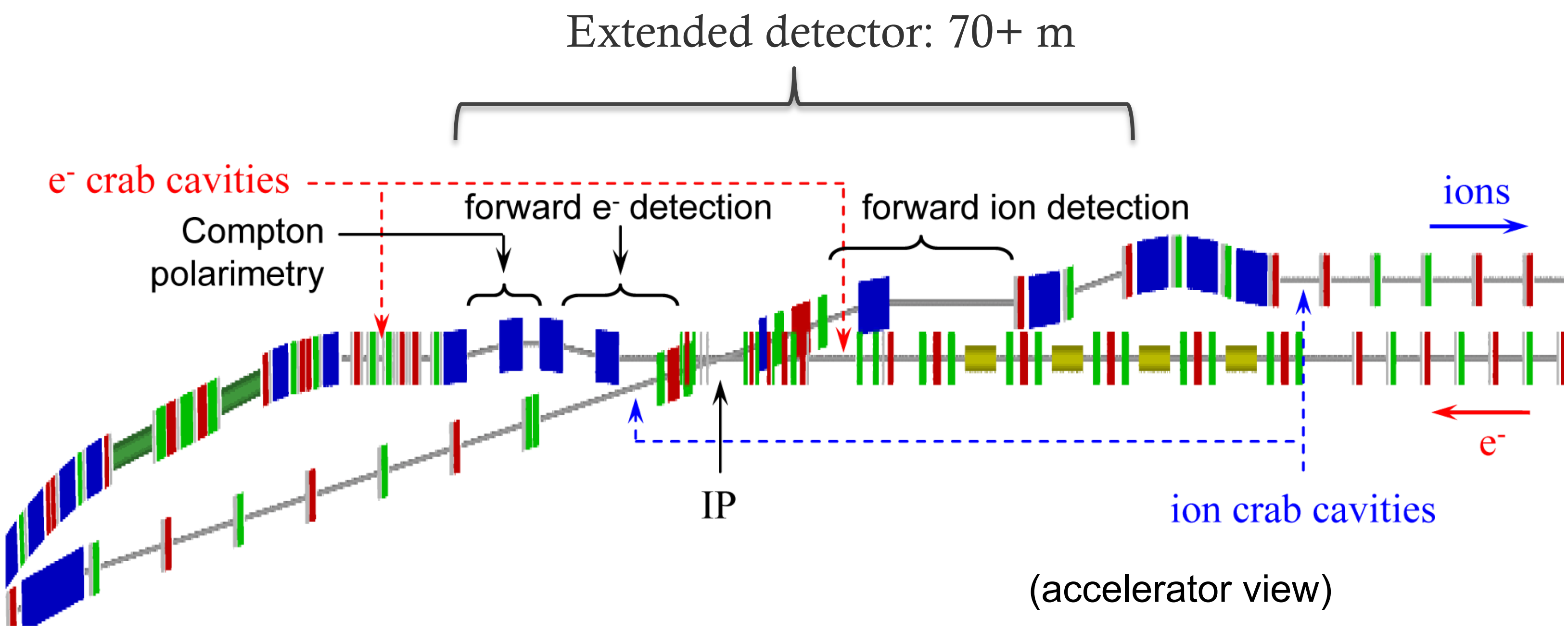
eRHIC linac-ring IR (alternative)



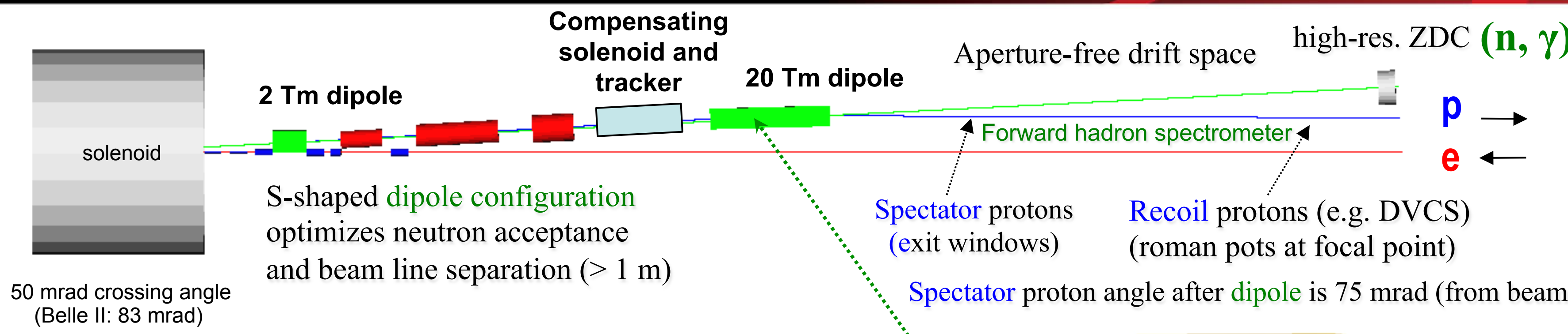
U. Wienands, EIC UG meeting, Jan 2016

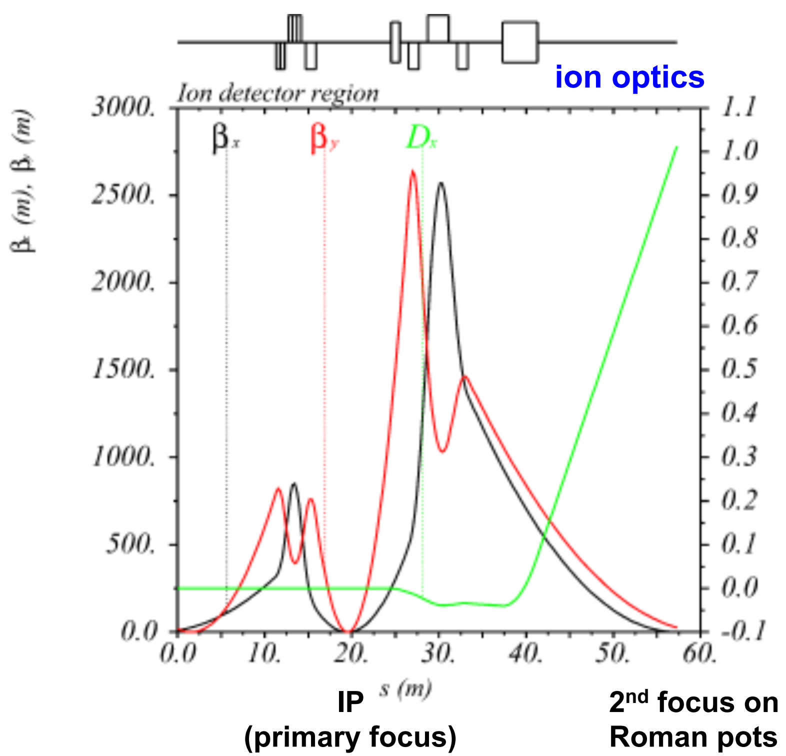
JLab: detector and interaction region

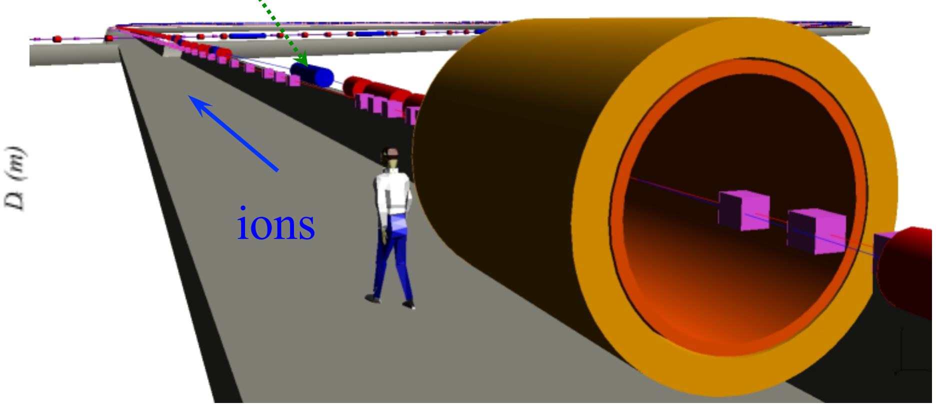




JLab: forward hadron spectrometer







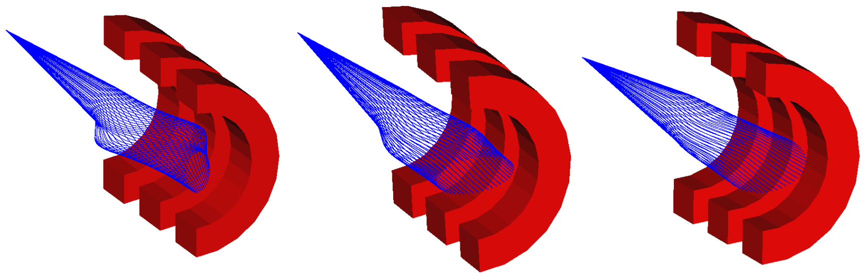
- Large 20 Tm dipole provides excellent resolution
- Large *dispersion* and small *beam size* at secondary focus ensure good acceptance for recoil baryons
- Large quadrupole apertures (1 / *max* beam energy) give good acceptance for hadronic and nuclear fragments, charged and neutral (high res. ZDC).

JLab: fragment acceptance and resolution

dp/p

proton-rich fragments
"spectator protons from ^{2}H"

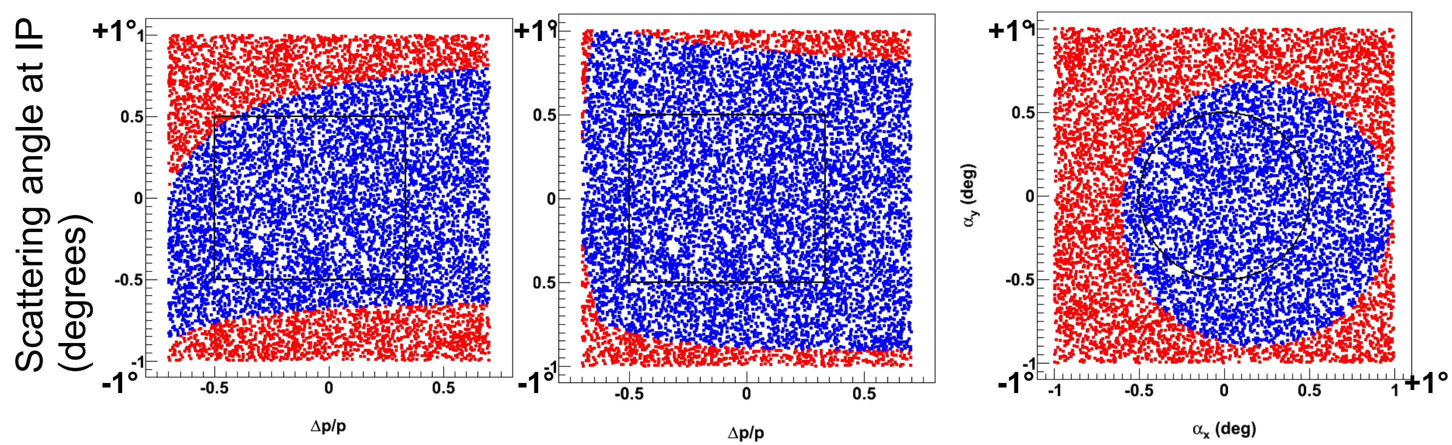
neutron-rich fragments
"tritons from N=Z nuclei"



Forward charged-particle acceptance

horizontal plane **vertical plane**

Neutron acceptance (x and y): *25 mrad cone*

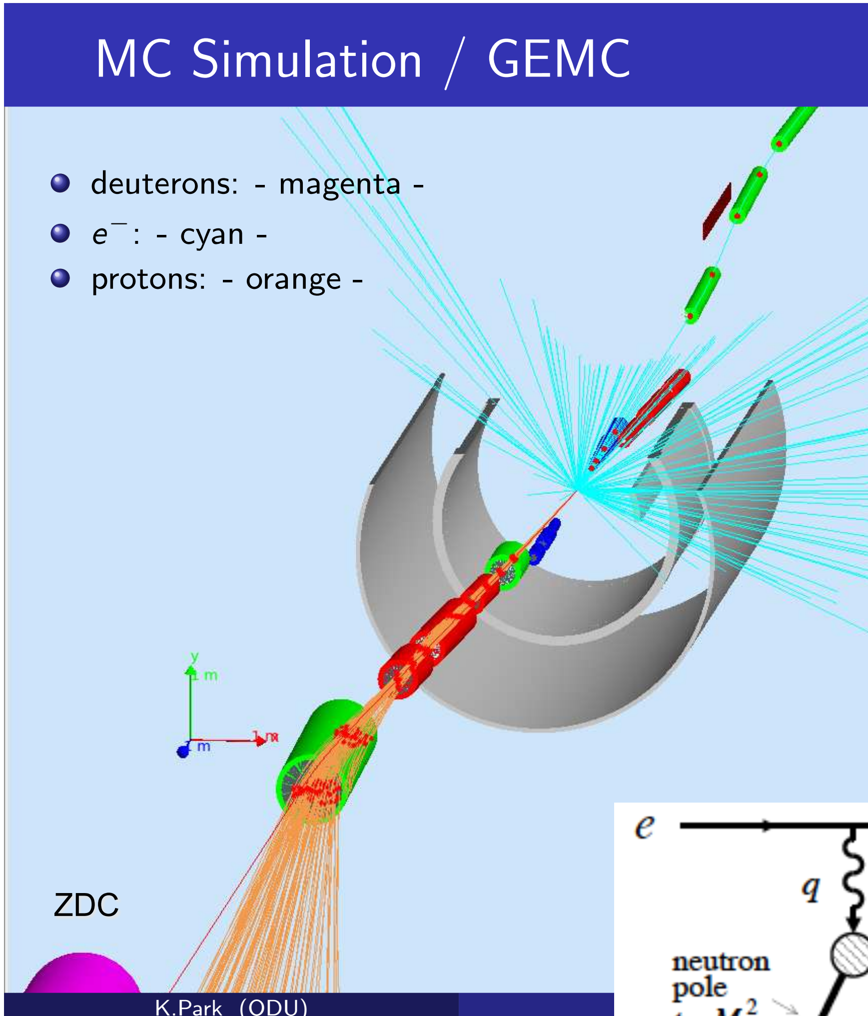


- Full acceptance for all partonic and nuclear fragments achieved!
  - Low gradient, large aperture magnets (quadrupoles)
- Detector resolution designed to be better than intrinsic momentum and angular spread of the beam
  - Longitudinal (dp/p): *few x10^{-4}*
  - Angular (θ, for all φ): *< 0.3 mrad*

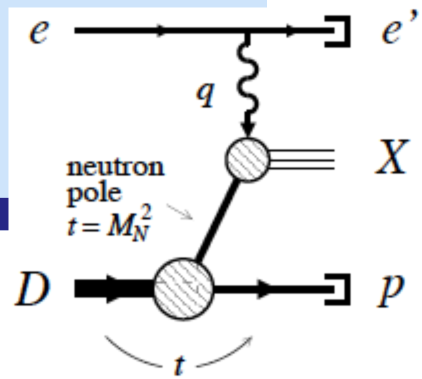
Red: Detection *before* ion quadrupoles

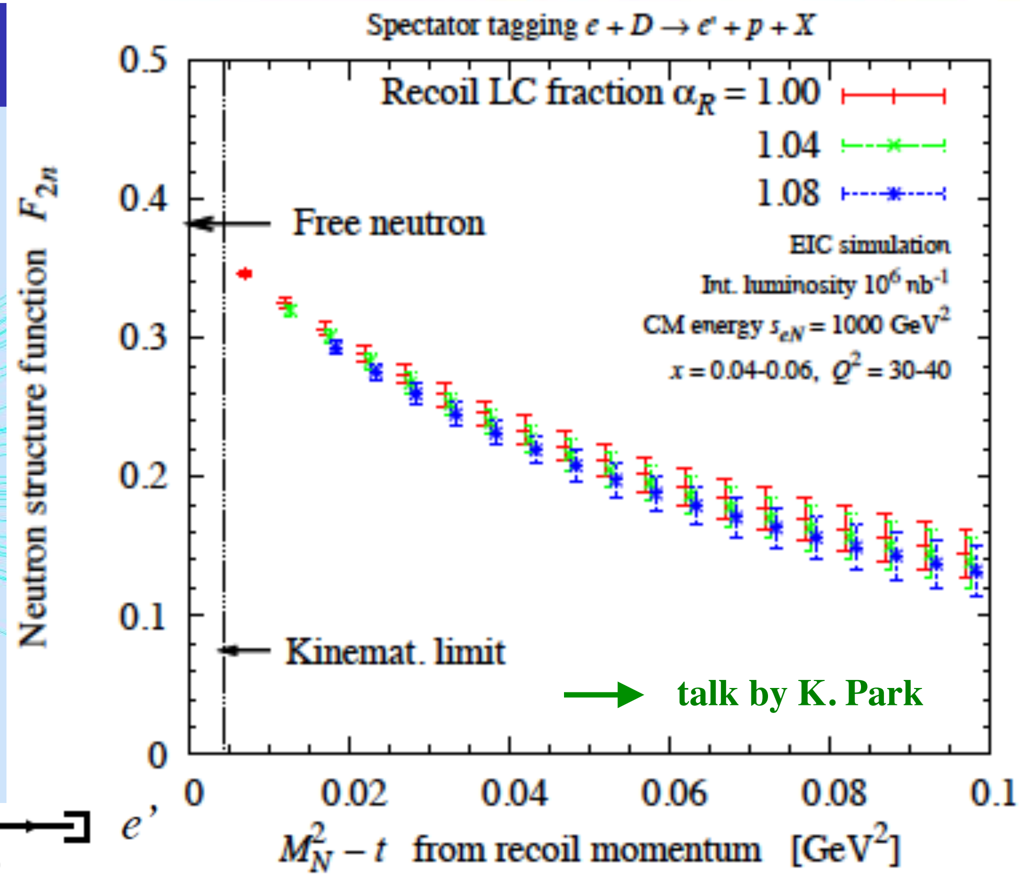
Blue: Detection *after* ion quadrupoles

JLab: spectator tagging & neutron structure



Tagged spectator protons
(no lower limit since rigidity
is different than the beam)



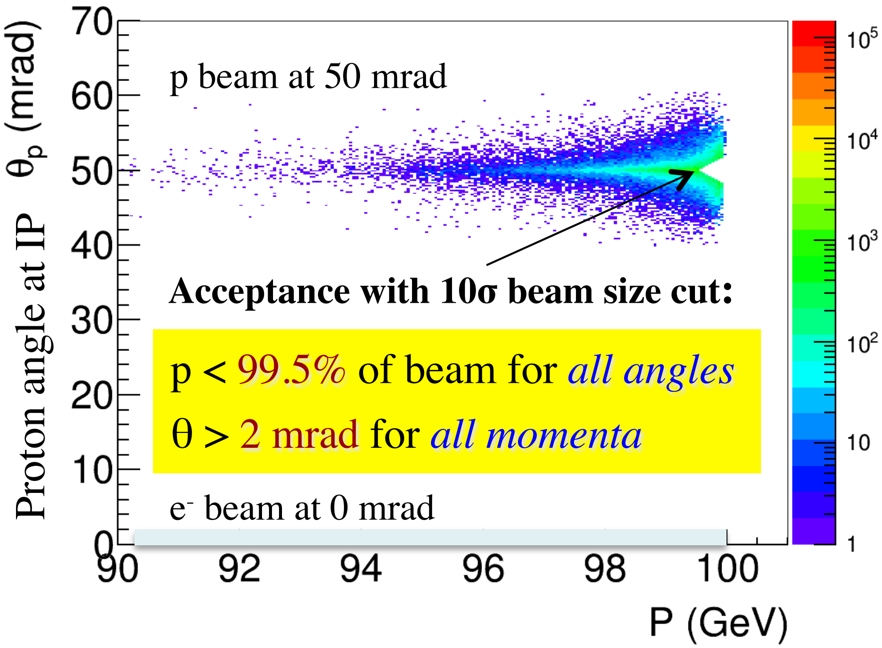


- On-shell extrapolation of F_{2n}
  - *Requires resolution better than Fermi momentum (< 20 MeV/c)*
  - Resolution scales with p
  - JLab design can reach 20 MeV/c even with 50 GeV/A deuterium!

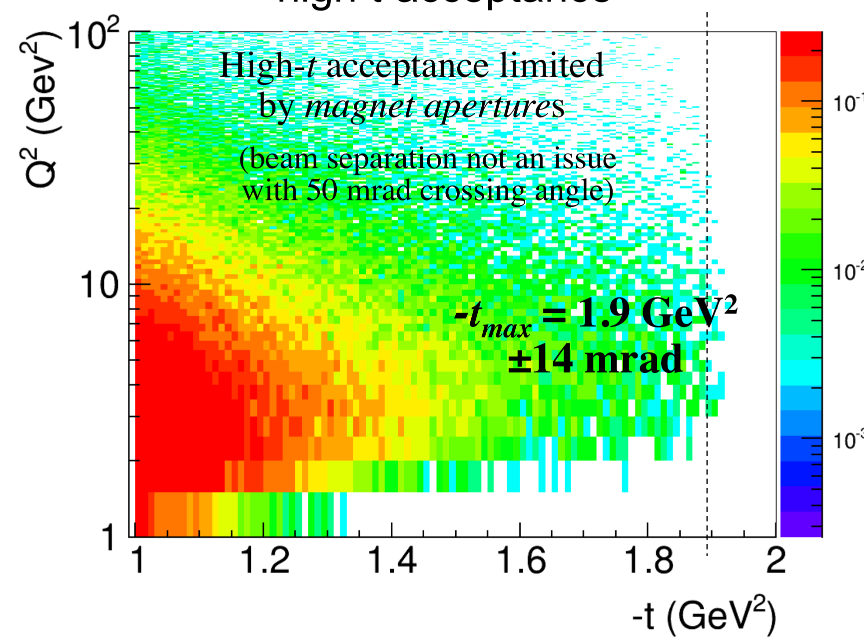
JLab: DVCS recoil proton acceptance

- **Kinematics:** 5 GeV e^- on 100 GeV p at a crossing angle of 50 mrad.
  - Cuts: $Q^2 > 1$ GeV^2, $x < 0.1$, $E'_e > 1$ GeV, recoil proton 10σ outside of beam
- **GEANT4 simulation:** tracking through magnets done using GEMC

low-*t* acceptance



high-*t* acceptance



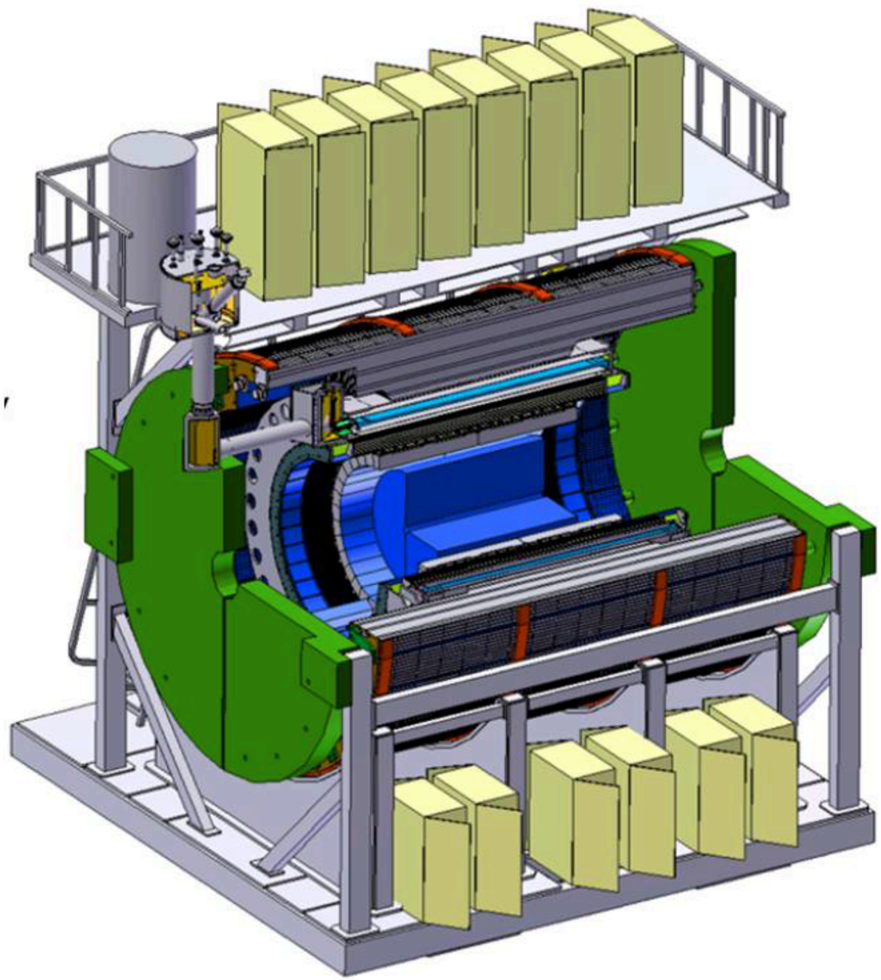
- Recoil proton angle is independent of electron beam energy: $\theta_p \approx p_T/E_p \approx \sqrt{(-t)}/E_p$
- The ion beam size (focusing, emittance, *cooling*) introduces a low-p_T (-t) cutoff
- Larger cone at lower E_p pushes the *low*-t cutoff lower, and make precise tracking easier

Central detectors

- Today there are three relatively mature EIC concept detectors
  - ePHENIX at BNL (based on the BaBar magnet)
  - BeAST at BNL
  - JLab IP1 (full-acceptance)

PHENIX upgrade (sPHENIX) at RHIC

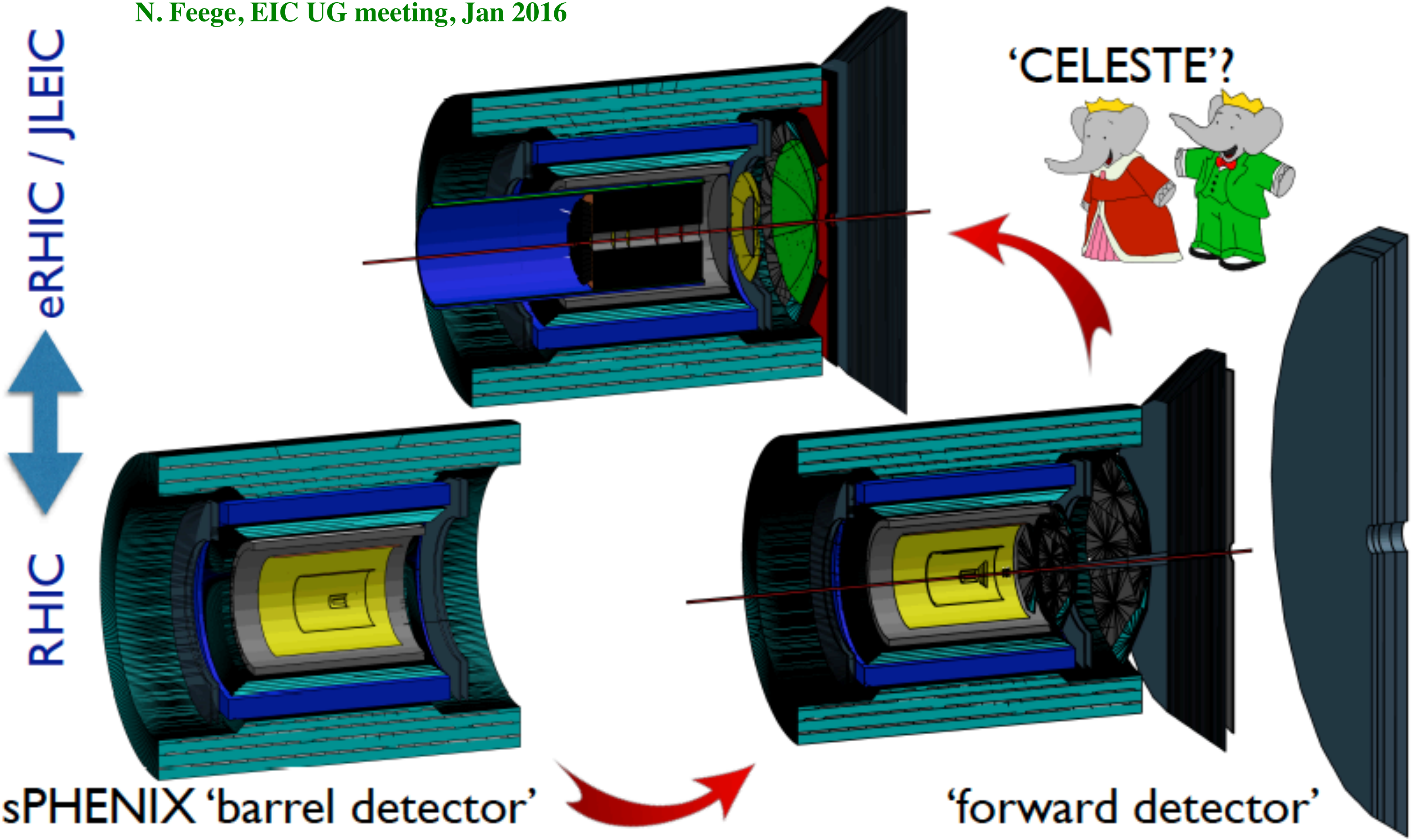
N. Feege, EIC UG meeting, Jan 2016



- Objective: Study Quark Gluon Plasma with jet and Upsilon probes
- 1.5 T BaBar solenoid magnet with tracking, ECAL, and HCAL coverage |η| < 1.1
- Passed DOE Scientific Review in April 2015
- Completed preCDR document
- Collaboration formed in December 2015

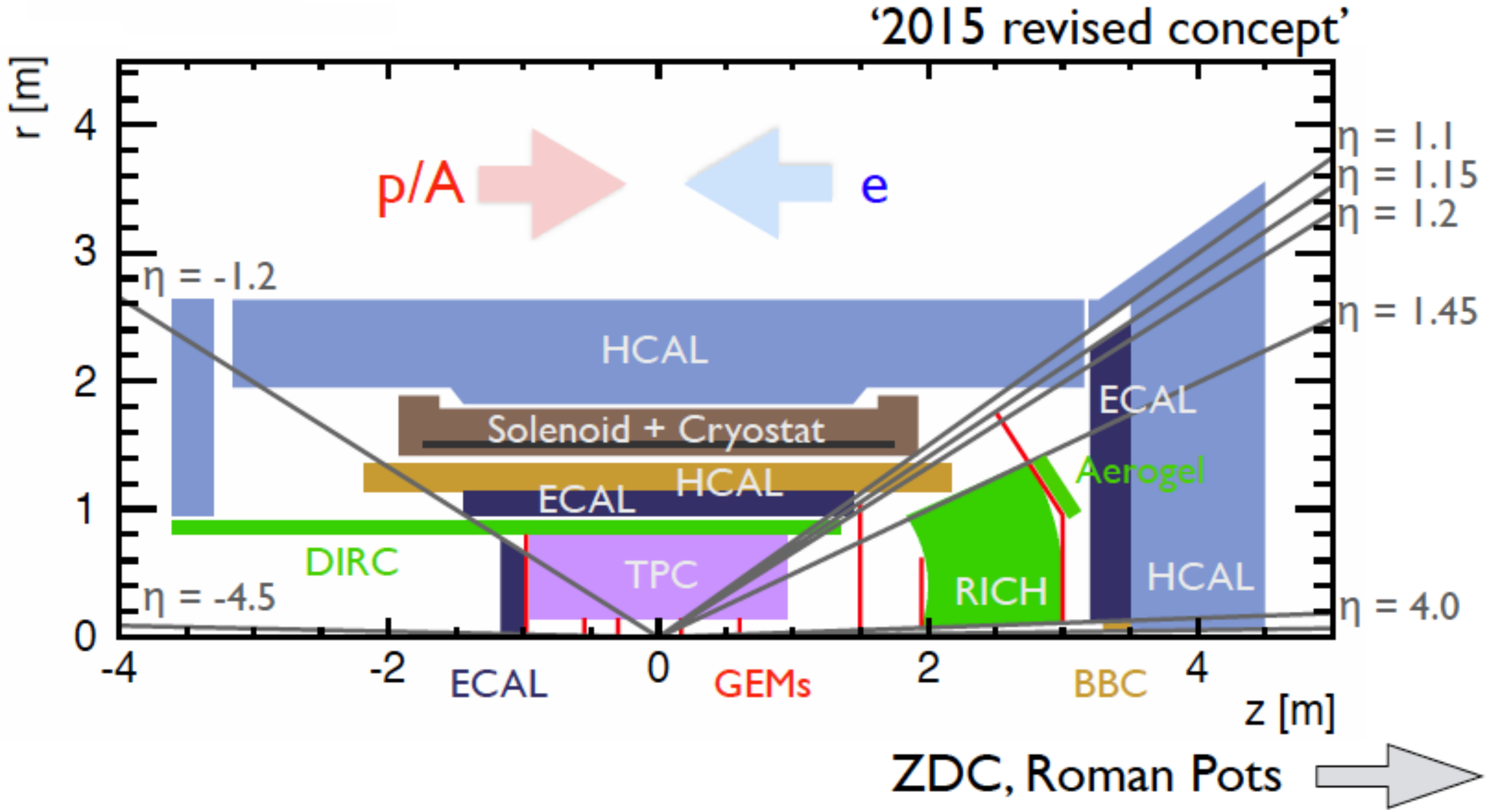
Further sPHENIX upgrade ideas

N. Feege, EIC UG meeting, Jan 2016



Revised ePHENIX/CELESTE concept

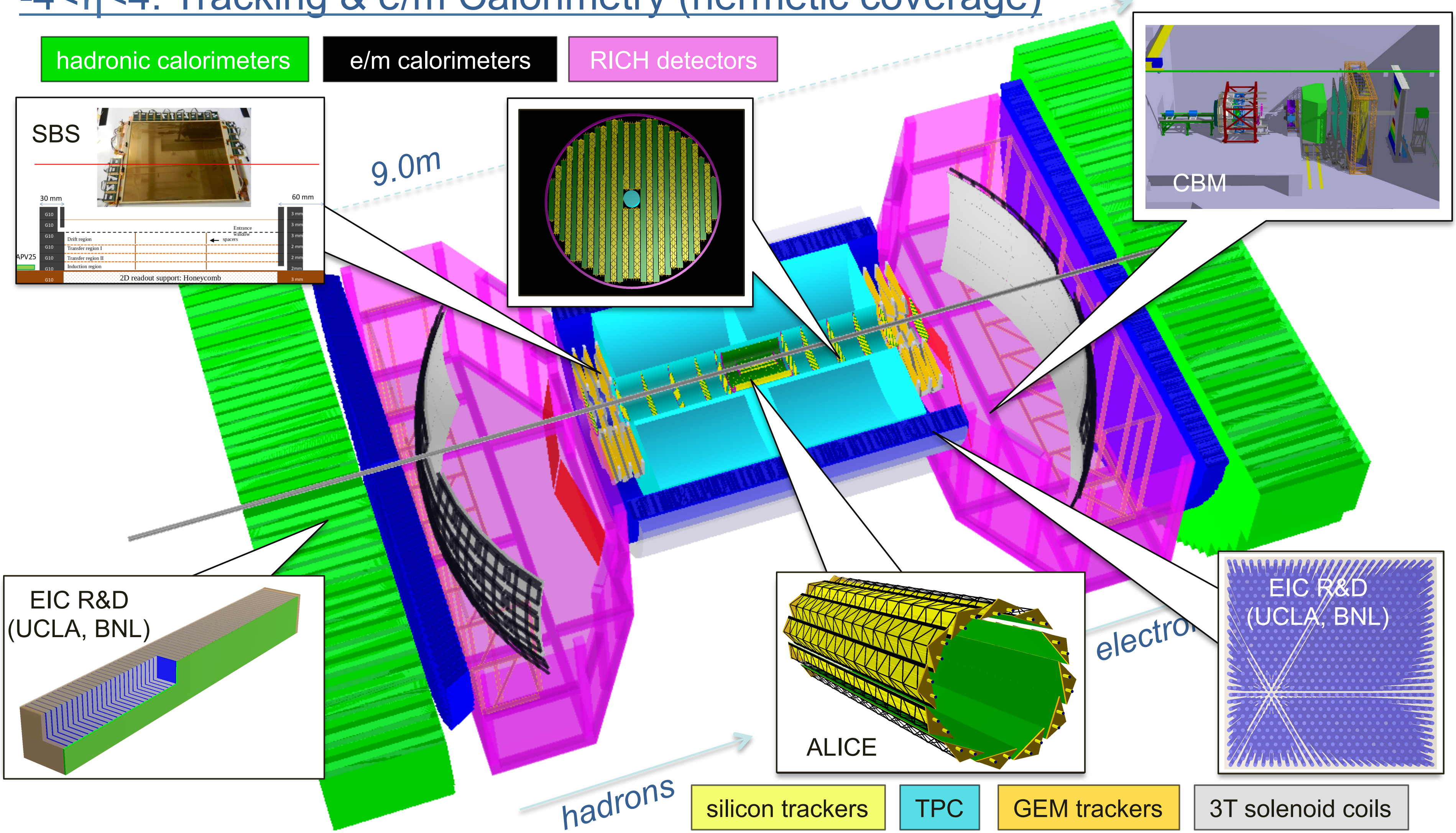
N. Feege, EIC UG meeting, Jan 2016



BeAST detector (BNL)

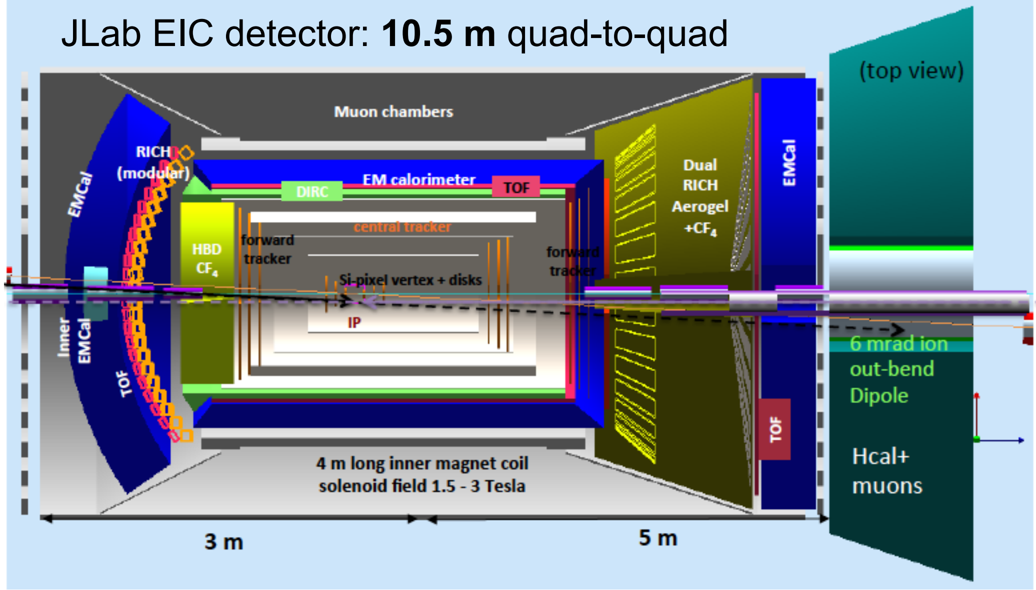
A. Kiselev, EIC UG meeting, Jan 2016

-4<η<4: Tracking & e/m Calorimetry (hermetic coverage)



JLab: central detector design considerations

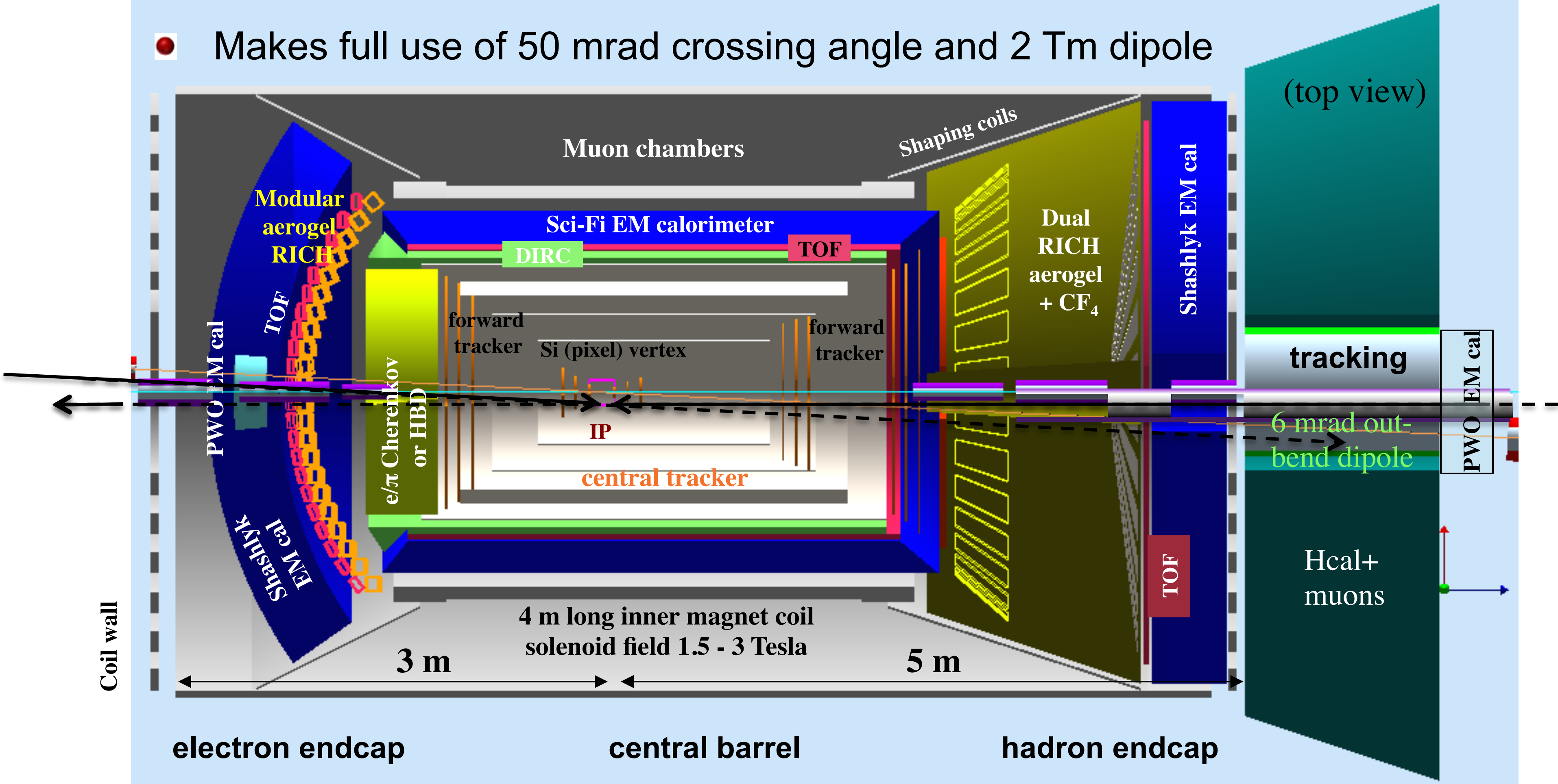
- Modular design, compatible with CLEO and BaBar 1.5 T solenoids, or a new 3 T solenoid
  - 4 m long coil, 3 m diameter
  - FOM ~ BR^2 for tracking in barrel
  - Central tracker resolution is not an issue if R is utilized well
- Luminosity ~ *1 / (total distance)* between ion quadrupoles
  - Stat. error ~ √(distance)
  - Important, but not at the 10% level
  - Endcap space allocation should be driven by physics, not accelerator
  - *Same conclusion for ring-ring eRHIC*
- EIC physics requires very good PID
  - At least one detector must provide it!
  - Most challenging requirement - drives layout and size of the central detector



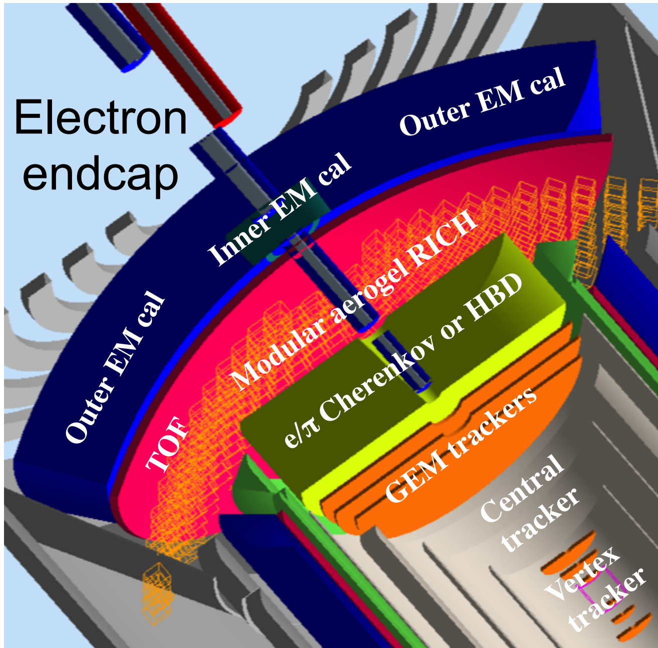
- Excellent reconstruction and identification of individual particles
  - Important for 3D structure (exclusive, SIDIS), heavy flavor (+ spectroscopy) low-multiplicity jets, etc
- 4π Hcal for high-multiplicity jets at IP1 possible but…
  - adding a smaller, calorimetric IP2 detector could be more cost-effective

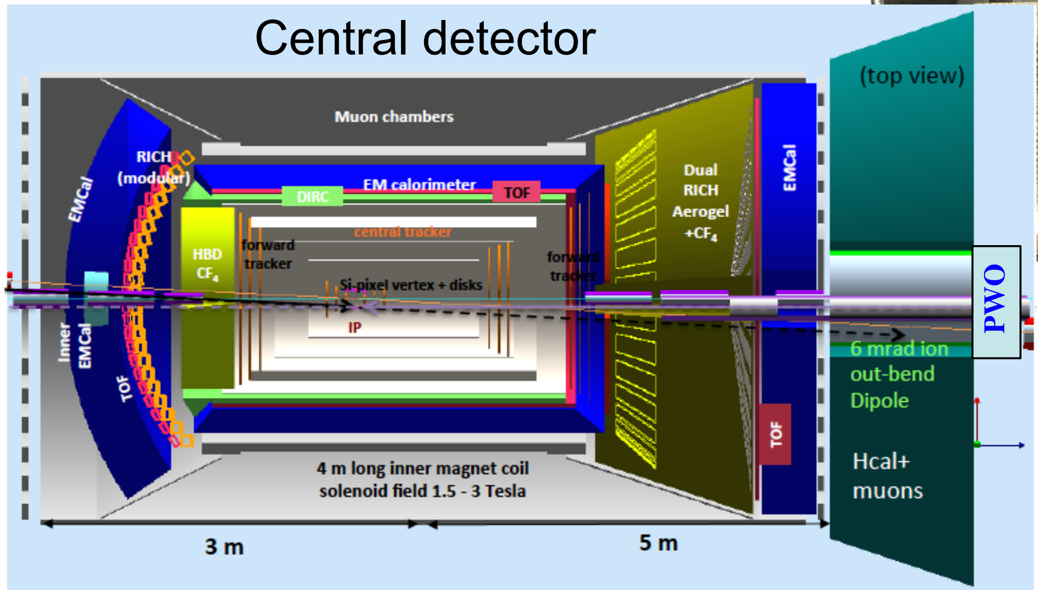
JLab: central detector overview

- Doubly asymmetric: IP location within solenoid and different endcaps
  - Maximizes solid angle for electron endcap
  - More space for tracking and ID of high-momentum forward-going particles
- Makes full use of 50 mrad crossing angle and 2 Tm dipole

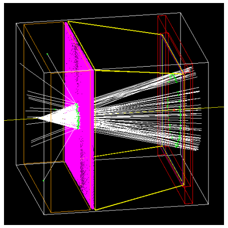


Generic EIC detector R&D program

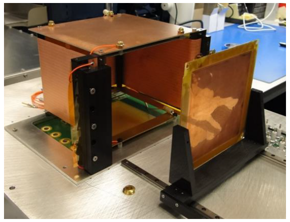




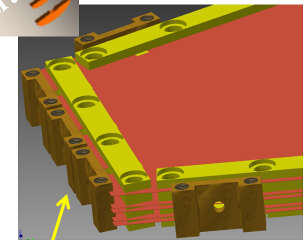
eRD1 – PWO_4 small-angle EMcal



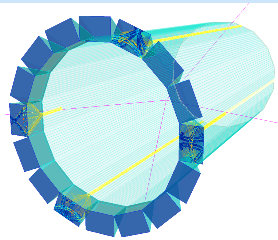
eRD14 – modular aerogel RICH



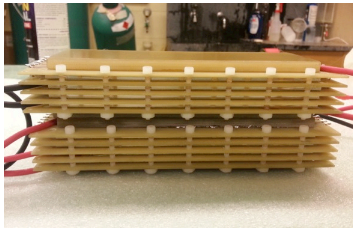
eRD6 – HBD/TPC



eRD3 & eRD6 – GEM trackers



eRD14 – DIRC

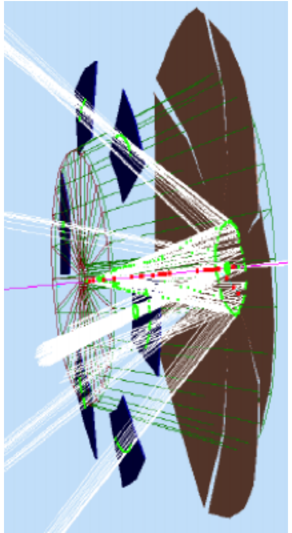


eRD14 – MRPC TOF

BNL & JLab staff and users actively participate in the program
JLab detector implements many of the projects in its baseline
Program is managed by T. Ullrich (BNL) and open to everyone

eRD14 – photosensors

eRD14 – dual-radiator RICH



Summary and Outlook

- The EIC is and electron – ***ion*** collider, and will regardless of implementation offer exciting opportunities for eA physics!
  - Many ion species
  - Polarized light ions
  - Excellent detection opportunities

- At the same time, now that the eA capabilities of the EIC are better understood, it is important to revisit the detailed requirements for various measurements and complementarity with JLab 12 GeV.

- This workshop could be a step in that direction!

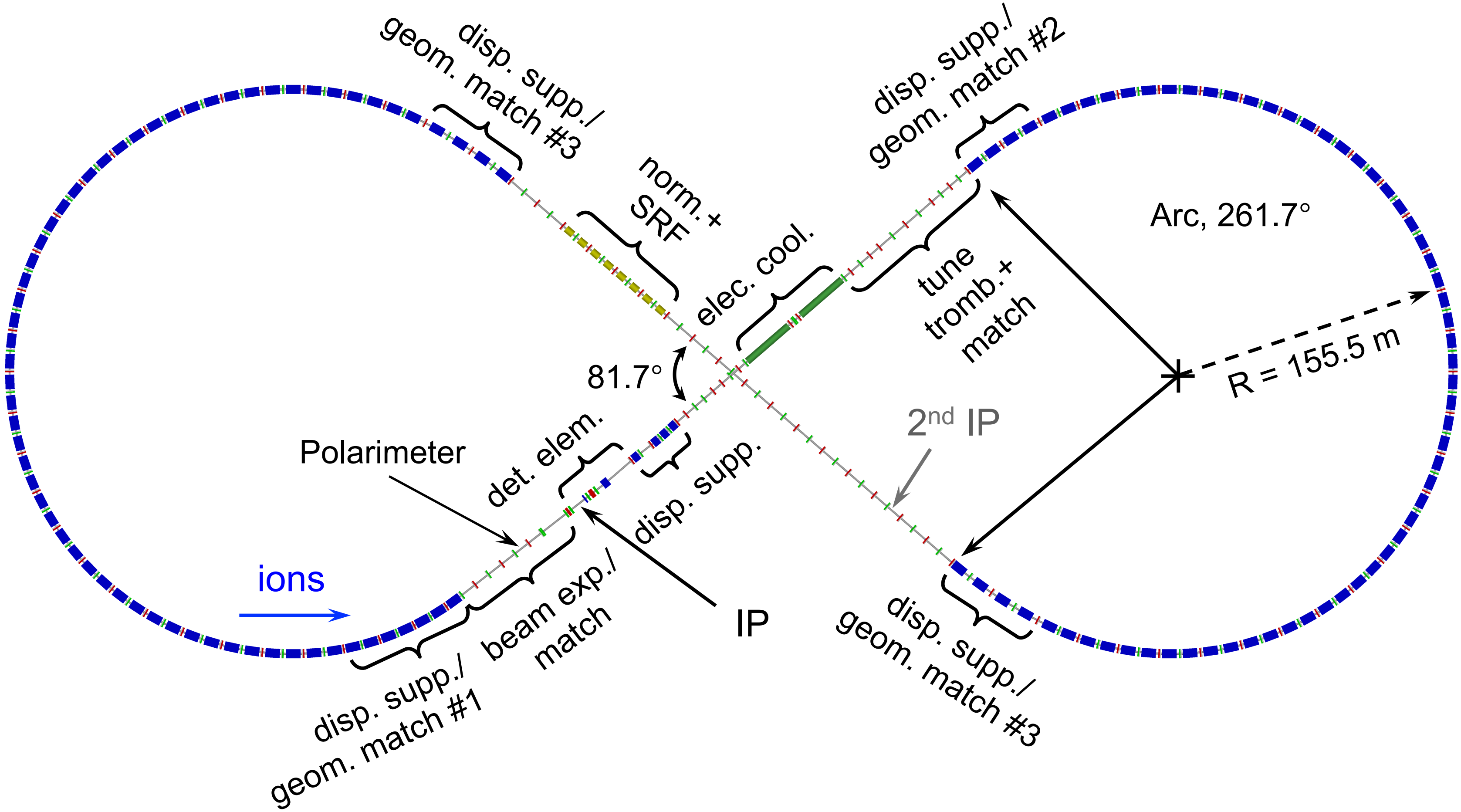
Backup

eRHIC linac-ring, reduced risk version

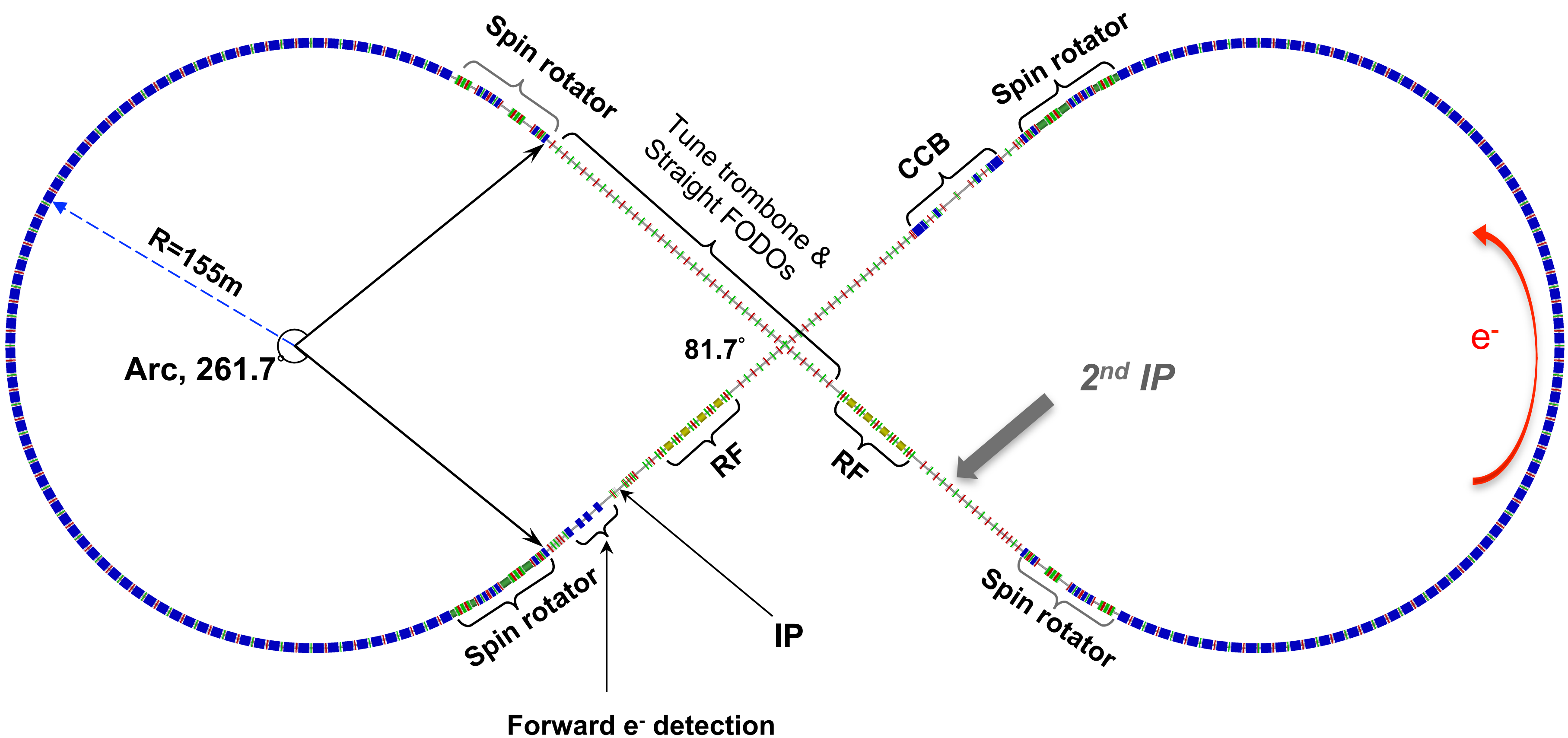
T. Roser, EIC UG meeting, Jan 2016

Technical risk:	Mitigation:
High energy fast hadron cooling	No cooling needed for protons for lower initial luminosity, existing stochastic cooling for heavy ions
Large pol. electron current: 50 mA	Backup: use two high current guns and switch frequently
High power multi-pass ERL: 20 GeV, 16 passes, up to 700 mA total current in the linac	Increased linac energy to reduce passes to 12, which gives lower total current in linac; BNL-Cornell eRHIC prototype
8kW/cavity of HOM power in SRF linac	Reduced total linac current; use RT ferrite dampers for high frequency HOM
10 different types of SRF cavities	Number of SRF cavity types reduced to 3 (no energy spread and loss compensation, single type of crab cavity)

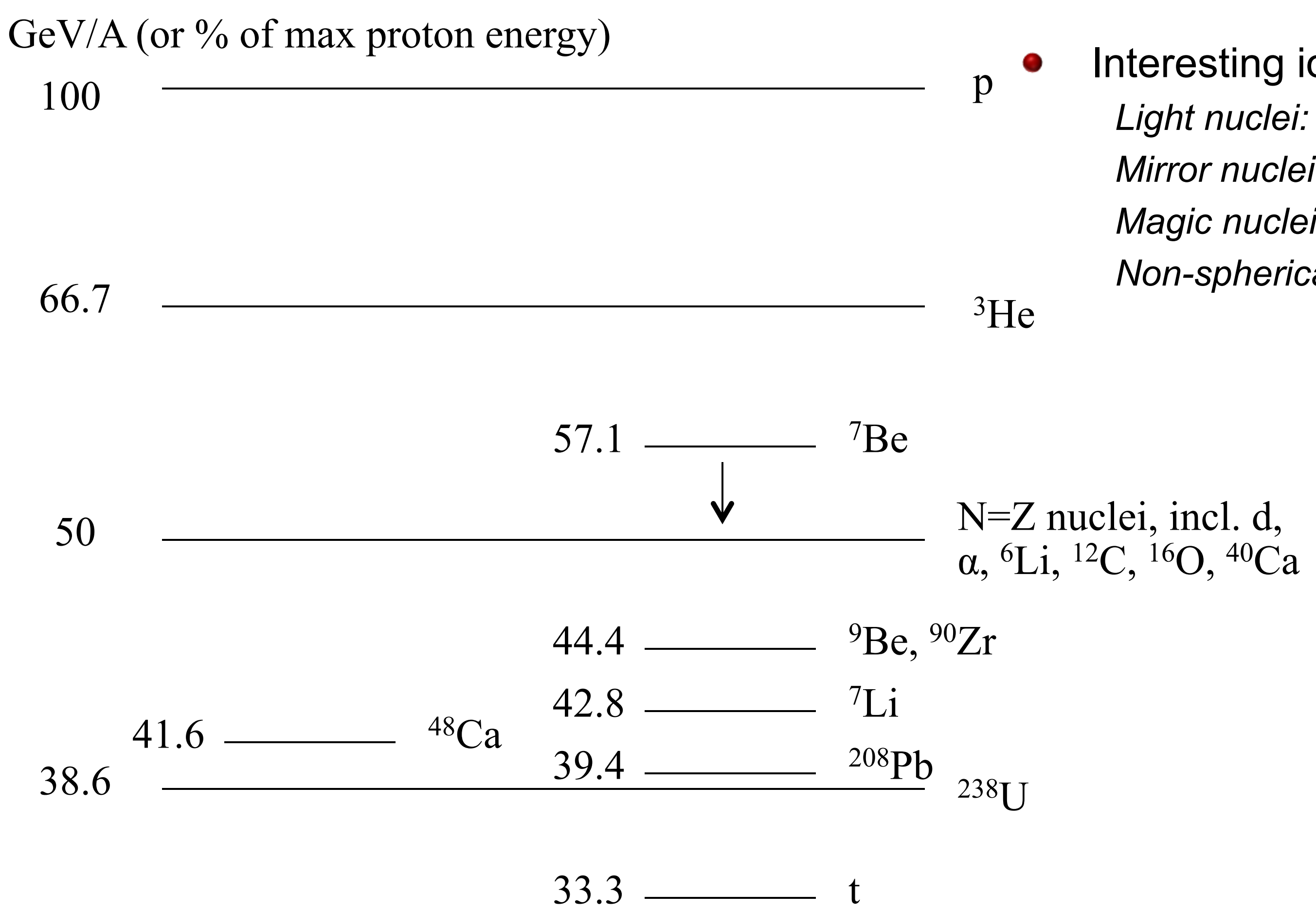
JLab EIC (JLEIC) ion ring



JLab EIC (JLEIC) electron ring



The four "universal" ion beam energies

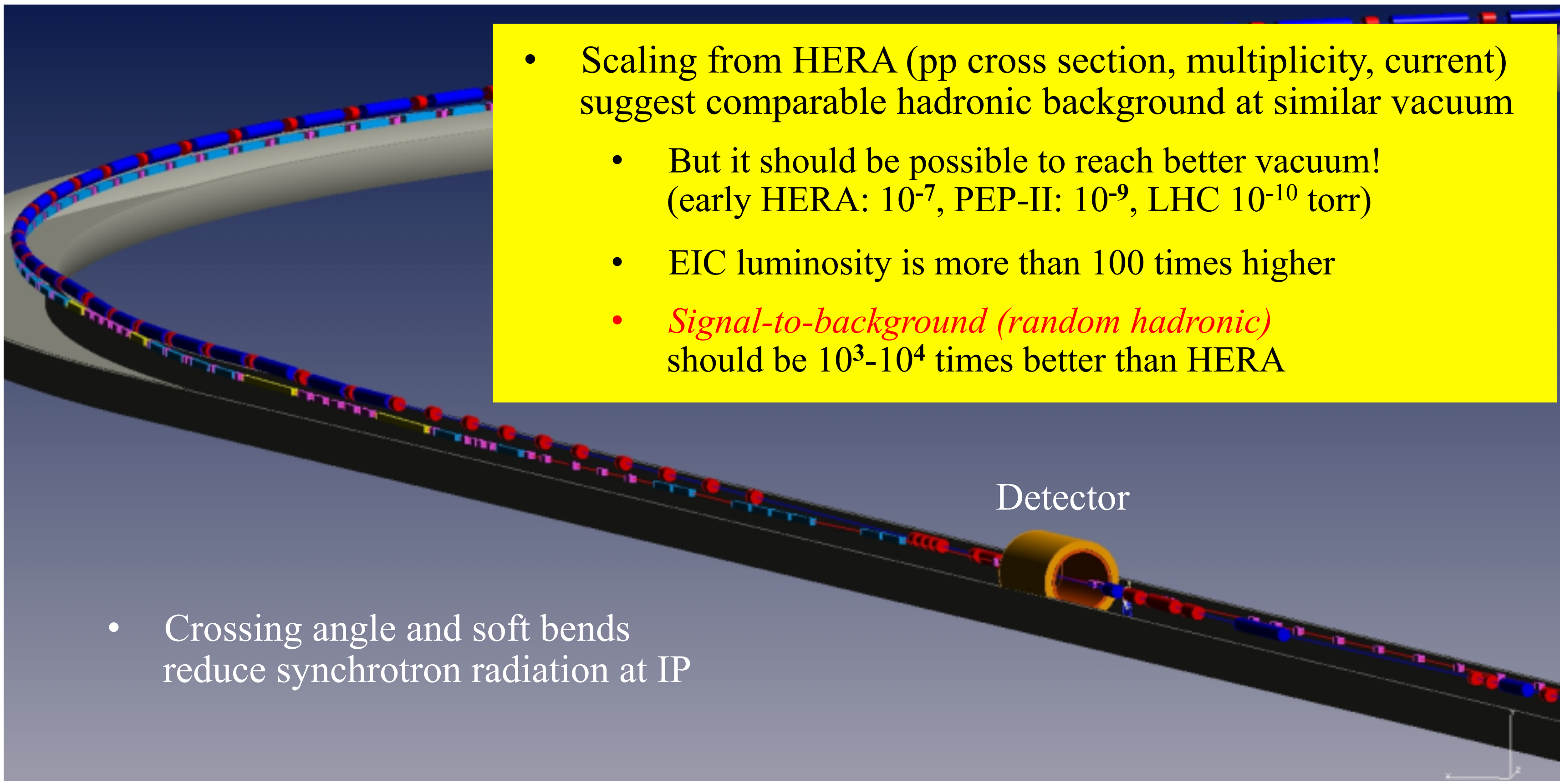


- Interesting ions
  - *Light nuclei:* d, ^{3}He, ^{9}Be
  - *Mirror nuclei* ^{7}Be, ^{7}Li
  - *Magic nuclei:* α, ^{16}O, ^{40}Ca, ^{208}Pb
  - *Non-spherical heavy nuclei:* ^{238}U

- The baseline EIC program can be completed using only four energies
  - Protons will be run at all four, ions at and/or below their max energy

JLab: Detector locations and backgrounds

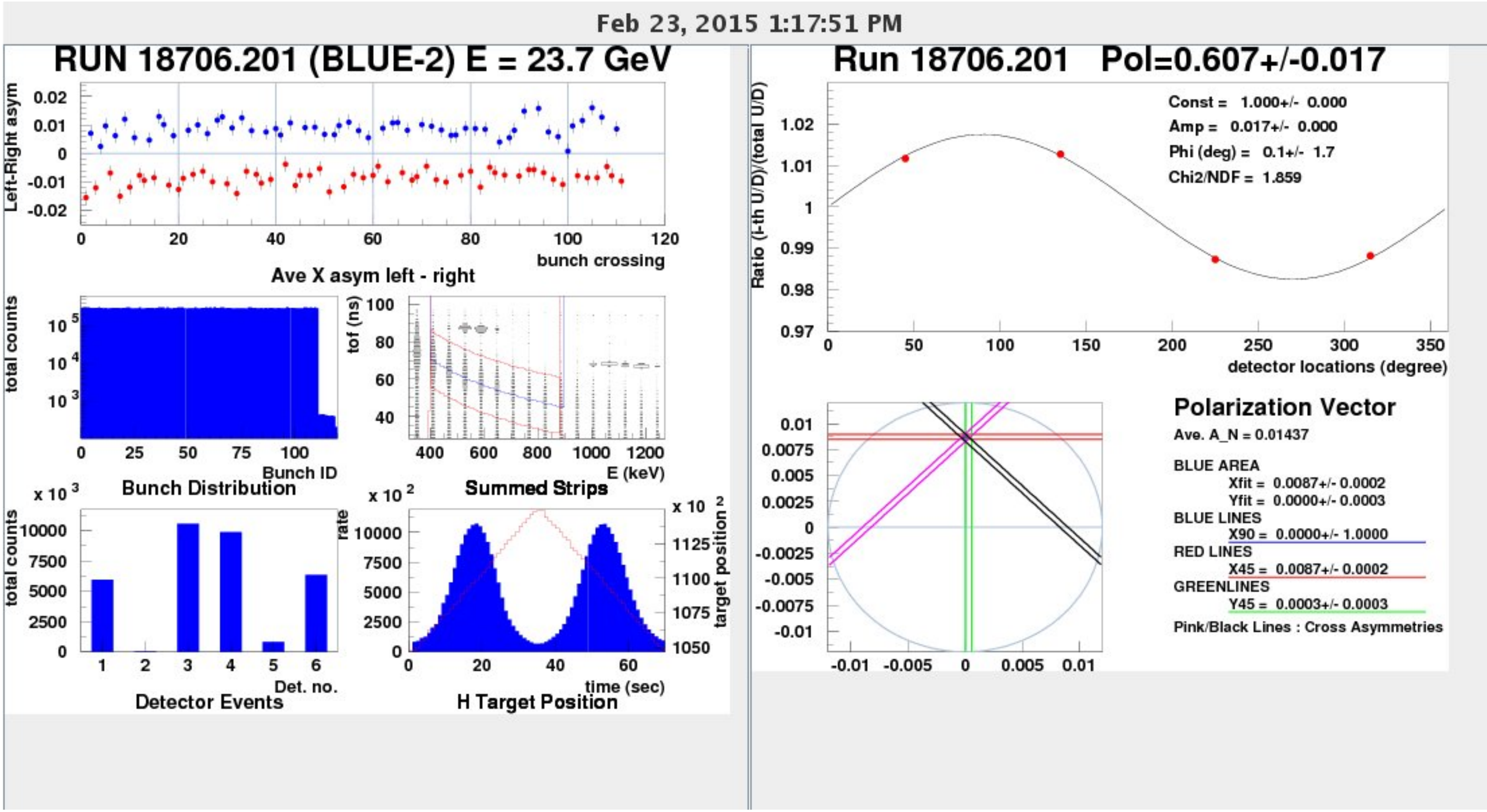
- IP locations reduce synchrotron- and hadronic backgrounds
  - *Far* from arc where electrons exit (synchrotron)
  - *Close* to arc where ions exit (hadronic) – shown below



- Scaling from HERA (pp cross section, multiplicity, current) suggest comparable hadronic background at similar vacuum
  - But it should be possible to reach better vacuum! (early HERA: 10^{-7}, PEP-II: 10^{-9}, LHC 10^{-10} torr)
  - EIC luminosity is more than 100 times higher
  - *Signal-to-background (random hadronic)* should be 10^{3}-10^{4} times better than HERA

- Crossing angle and soft bends reduce synchrotron radiation at IP

Bunch by Bunch Polarization is a Long Shot



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