# MEIC Detector and Interaction Region Design (and Current R&D)

- EIC Critical Capabilities and MEIC design
  (as relevant for this talk: science/interaction region)
- Where do particles go
  - Detection of Spectators
- Update on MEIC detector and interaction region
  "We are proud to announce that we have achieved a fully integrated detector and interaction region"
- JLab user proposals for generic detector R&D call
  - Some slides on one of these: DIRC
- Summary

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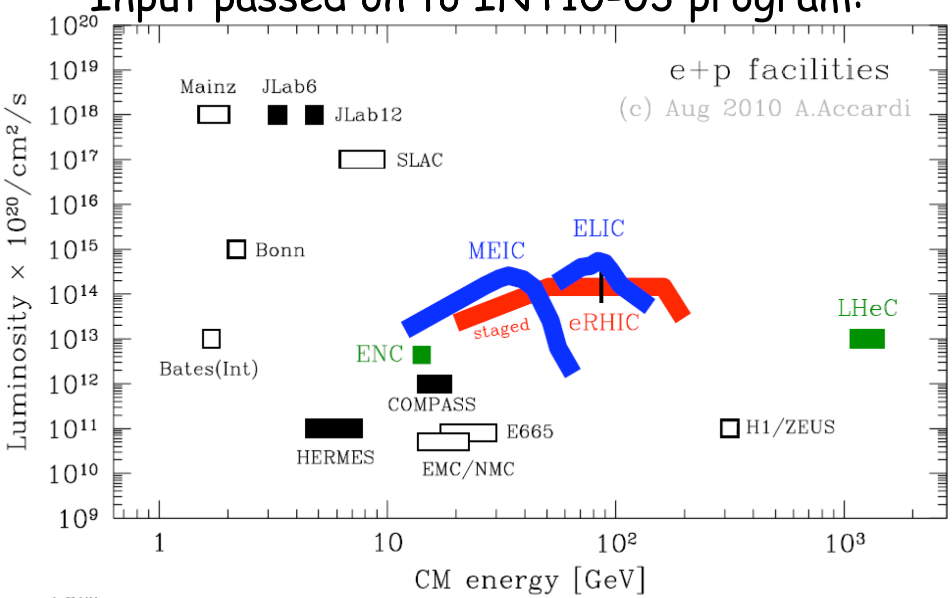
# EIC: Critical Capabilities

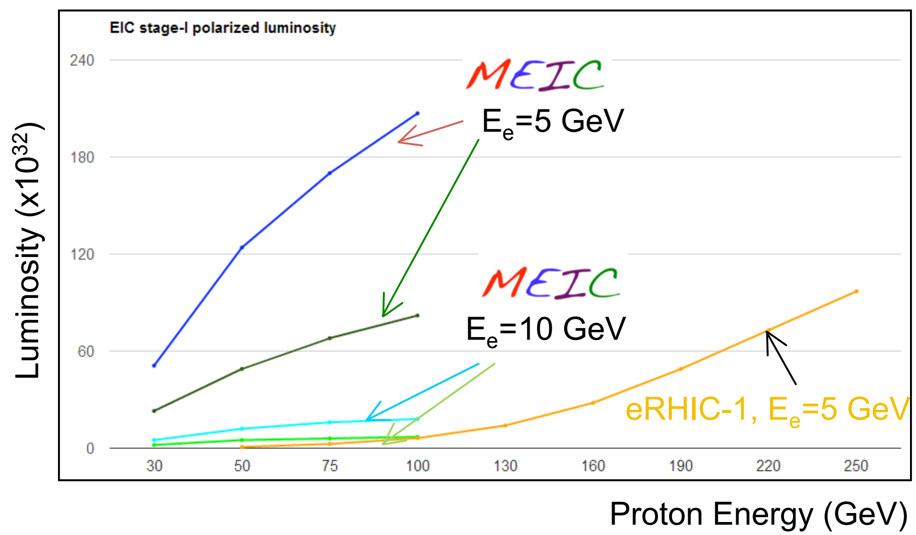
Base EIC Requirements *per Executive Summary INT Report*:

- range in energies from $\sqrt{s}$ ~ **20 to $\sqrt{s}$ ~ 70 & variable**
- fully-polarized (>70%), longitudinal and transverse
- ion species up to A = 200 or so
- high luminosity: **about $10^{34}$** e-nucleons $cm^{-2}\ s^{-1}$
- multiple interaction regions
- upgradable to higher energies ($\sqrt{s}$ ~ 150 GeV)

Input passed on to INT10-03 program:

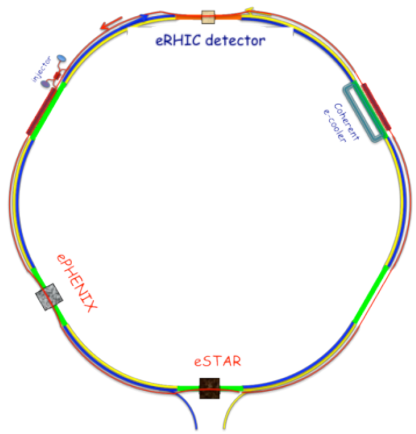


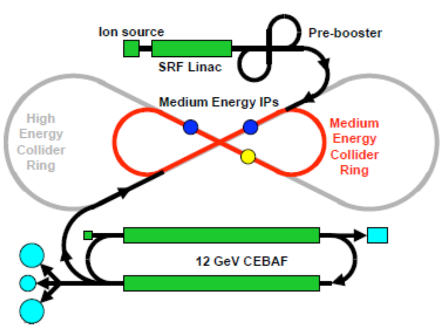

But MEIC/eRHIC get there in different ways:



# EIC – similar energies at both BNL and JLab

| | Stage I | Stage II |
|---|---|---|
| eRHIC @ BNL | $\sqrt{s}$ = 25 – 71 GeV<br>$E_e$ = 3 – 5 GeV<br>$E_p$ = 50 – 250 GeV<br>$E_{Pb}$ = up to 100 GeV/A | $\sqrt{s}$ = up to ~170 GeV<br>$E_e$ = up to ~30 GeV<br>$E_p$ = up to 250 – 300 GeV<br>$E_{Pb}$ = up to 100 – 120 GeV/A |
| MEIC / ELIC @ JLab | $\sqrt{s}$ = 15 – 66 GeV<br>$E_e$ = 3 – 11 GeV<br>$E_p$ = 20 – 100 GeV<br>$E_{Pb}$ = up to 40 GeV/A<br>(MEIC) | $\sqrt{s}$ = up to ~140 GeV<br>$E_e$ = up to ~20 GeV<br>$E_p$ = up to 250 – 300 GeV<br>$E_{Pb}$ = up to 100 – 120 GeV/A<br>(ELIC) |

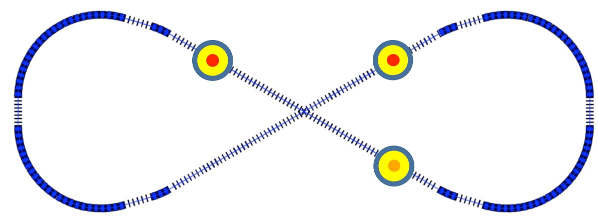



**MEIC: take advantage of lower proton/ion energies** (driven by JLab community science interest for deep exclusive/semi-inclusive reactions) **for detector/IR design**

# MEIC (= stage-I EIC @ JLab) Design

- Collider is based on a figure eight concept
  - Avoids crossing polarization resonances
    - Improves polarization for all species
    - Makes polarized deuterons possible
  - Advantage of having a new ion ring

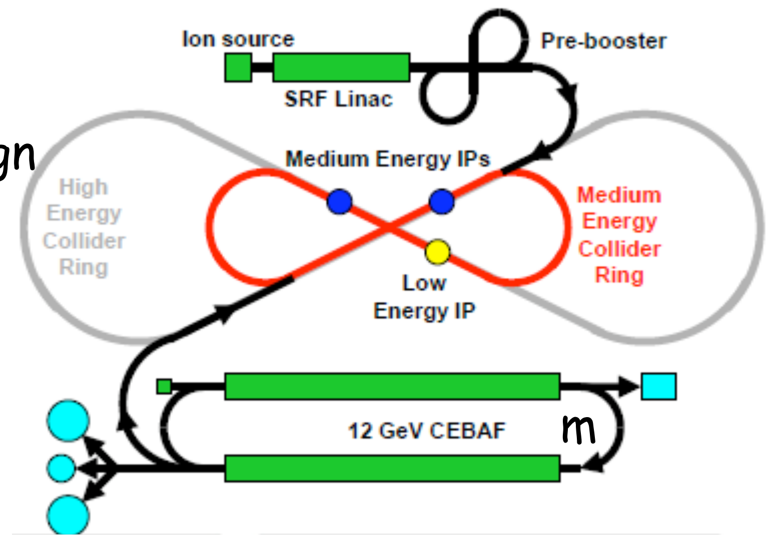


- Highest luminosity comes with final focus quadrupoles close together
  - Interferes with detection of particles at small angles
  - MEIC is designed around a high-acceptance detector with ±7 meters free space around the interaction point and a high-luminosity detector with ±4.5 meters free space

Emphasis on *integrated* detector/interaction region

- The present MEIC design takes a conservative technical approach by limiting several key design parameters within state-of-the-art. It relies on **regular electron cooling** to obtain the ion beam properties.

- The present JLab EIC design focuses on a CM energy range up to 65 GeV



# How MEIC meets the Design Specs

## Base EIC Requirements per Executive Summary INT Report:

- center of mass energies from $\sqrt{s} \sim 20$ to $\sqrt{s} \sim 70$ GeV & variable

MEIC
  - *- electron energies above 3 GeV to allow efficient electron trigger*
  - *- proton energy adjustable to optimize particle identification*
- highly polarized (>70%) electron and nucleon beams
  - *- longitudinally polarized electron and nucleon beams*
  - *- transversely polarized nucleon beams*
- ion species from deuterium to A = 200 or so
- high luminosity ~$10^{34}$ e-nucleons $cm^{-2}$ $s^{-1}$
  - *- optimal luminosity in $\sqrt{s} \sim 30$-50 region*
  - *- luminosity ≥$10^{33}$ e-nucleons $cm^{-2}$ $s^{-1}$ in $\sqrt{s} \sim 20$-70 region*
- multiple interaction regions
- integrated detector/interaction region ← This talk

MEIC
  - *- non-zero crossing angle of colliding beams*
  - *- crossing in ion beam to prevent synchrotron background*
  - *- ion beam final focus quads at ~7 m to allow for full acceptance detector*
  - *- bore of ion beam final focus quads sufficient to let particles pass through up to $t \sim 2$ GeV$^2$ ($t \sim E_p^2 Q^2$)*
- upgradeable to center of mass energy of about $\sqrt{150}$ GeV

# The Physics Program of an EIC

I) Map the spin and spatial structure of quarks and gluons in nucleons

- Sea quark and gluon polarization
- Transverse spatial distributions
- Orbital motion of quarks/gluons
- Parton correlations: beyond one-body densities

Needs high luminosity and range of energies

II) Discover the collective effects of gluons in atomic nuclei

- Color transparency: Small-size configurations
- Nuclear gluons: EMC effect, shadowing
- Strong color fields: Unitarity limit, saturation
- Fluctuations: Diffraction

III) Understand the emergence of hadronic matter from color charge

- Materialization of color: Fragmentation, hadron breakup, color correlations
- Parton propagation in matter: Radiation, energy loss

# Where do particles go - general


Several processes in e-p:

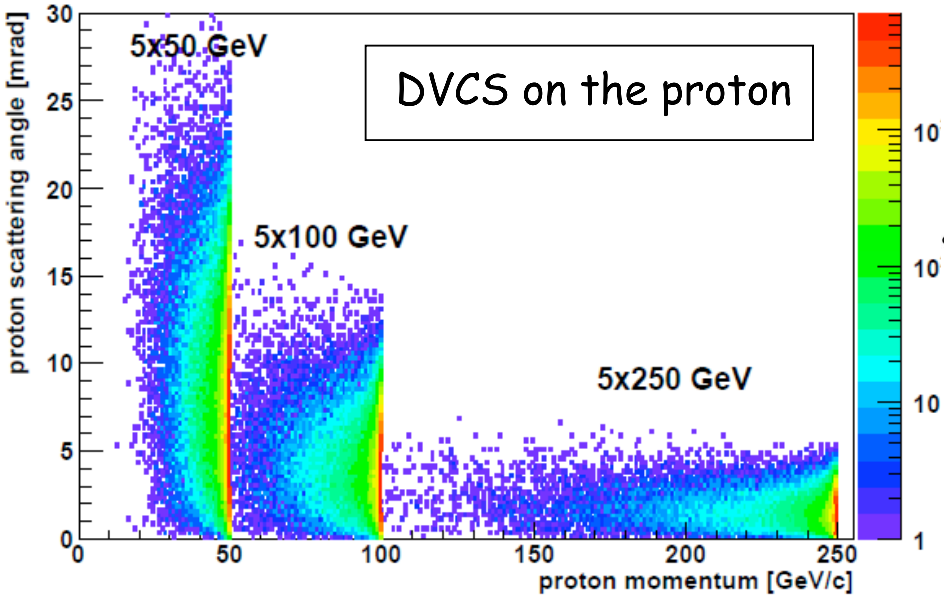
| | |
|---|---|
| 1)"DIS" (electron-quark scattering) | e + p → e' + X |
| 2)"Semi-Inclusive DIS (SIDIS)" | e + p → e' + meson + X |
| 3)"Deep Exclusive Scattering (DES)" | e + p → e' + photon/meson + baryon |
| 4)Diffractive Scattering | e + p → e' + p + X |
| 5)Target fragmentation | e + p → e' + many mesons + baryons |

Even more processes in e-A:

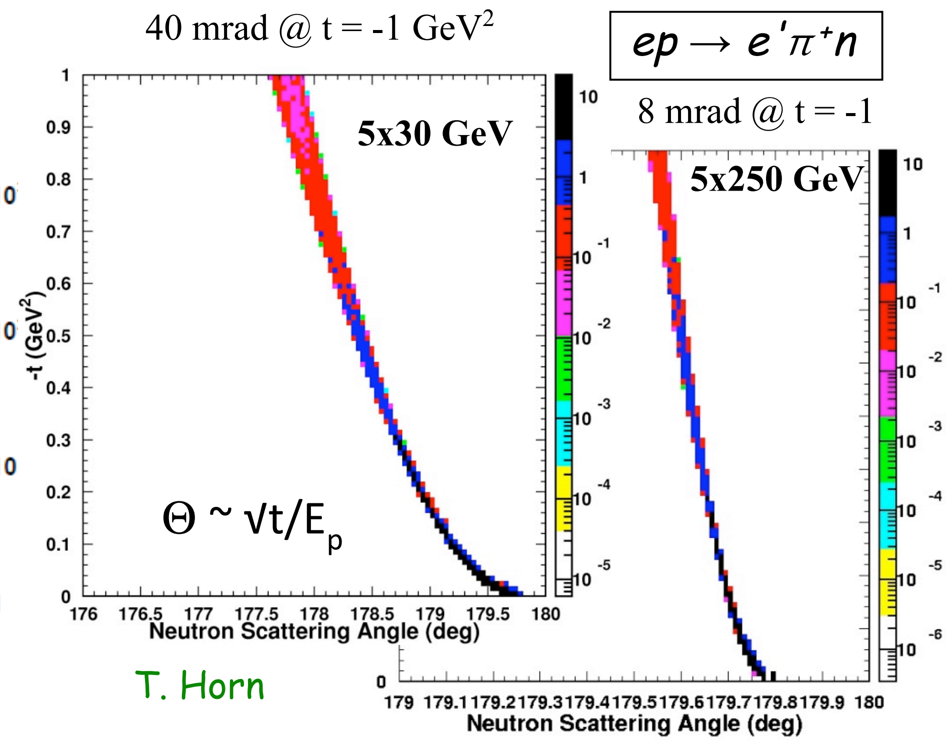
| | |
|---|---|
| 1)"DIS" | e + A → e' + X |
| 2)"SIDIS" | e + A → e' + meson + X |
| 3)"Coherent DES" | e + A → e' + photon/meson + nucleus |
| 4)Diffractive Scattering | e + A → e' + A + X |
| 5)Target fragmentation | e + A → e' + many mesons + baryons |
| 6)Evaporation processes | e + A → e' + A' + neutrons |

In general, e-p and even more e-A colliders have a large fraction of their science related to the detection of what happens to the ion beams. The struck quark remnants can be guided to go to the central detector region with $Q^2$ cuts, but the **spectator quark or struck nucleus remnants will go in the forward (ion) direction**.

# Example: Transverse spatial imaging – recoil baryons



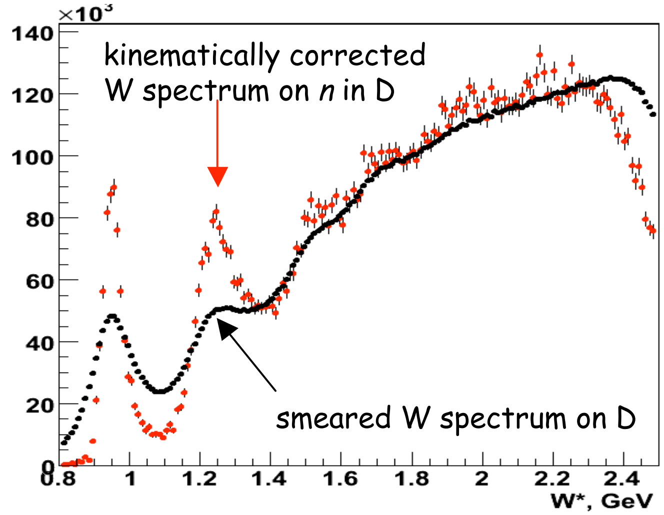

J.H. Lee



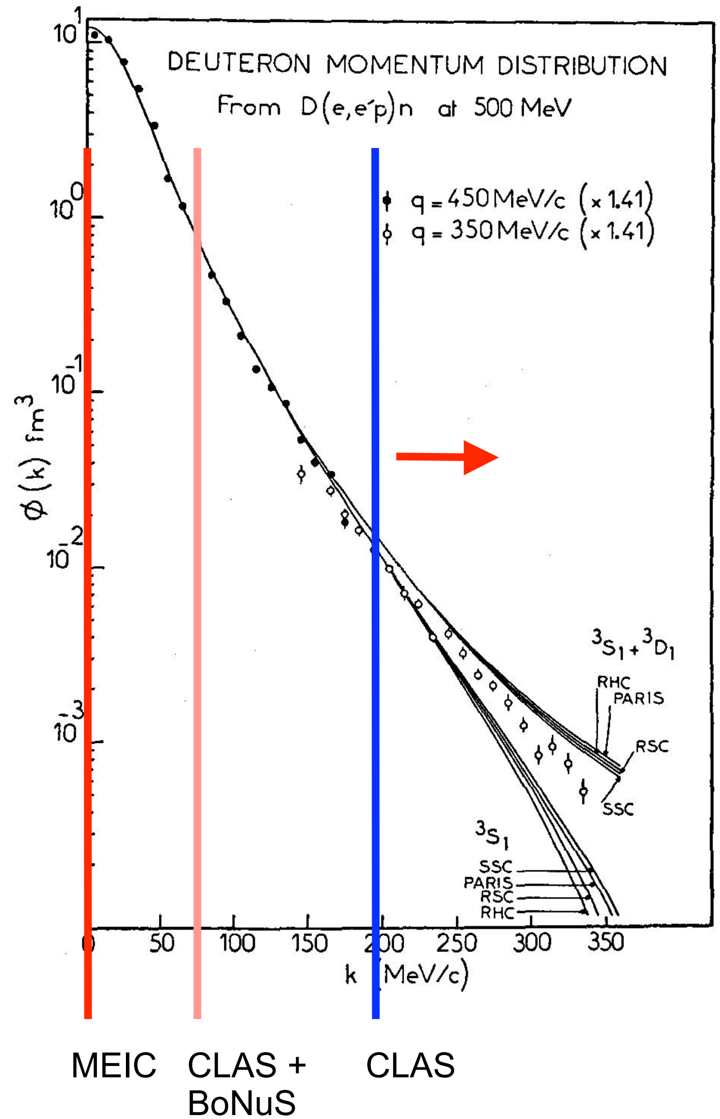

T. Horn

- Colliders allow straightforward detection of recoil baryons, making it possible to map the t-distribution down to very low values of *-t*
- At very high proton energies, recoil baryons are all scattered at small angles
  - Moderate proton energies give the best resolution
- High luminosity at intermediate proton energies and excellent small-angle detection make the MEIC a perfect tool for imaging of the proton

# Example: Spectator tagging

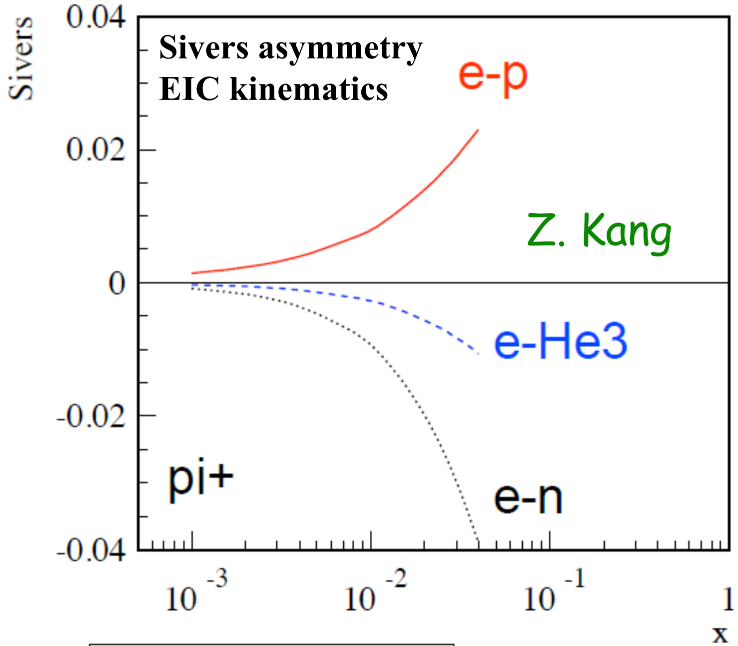


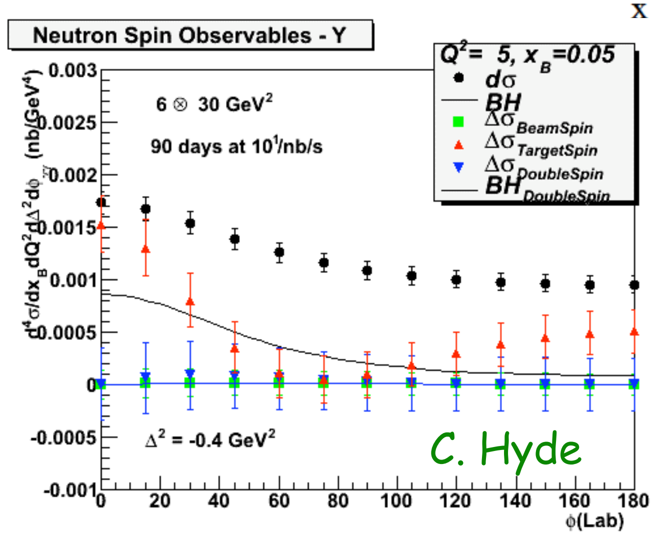

BoNuS data with tagged spectators




- In fixed target experiments, scattering on bound neutrons is complicated
  - Fermi motion, non-nucleonic degrees of freedom, and binding effects like the EMC effect and shadowing
  - Low-momentum spectators
- A collider allows straightforward tagging of spectators, and in general, nuclear fragments

# Spectator tagging – polarized deuterium

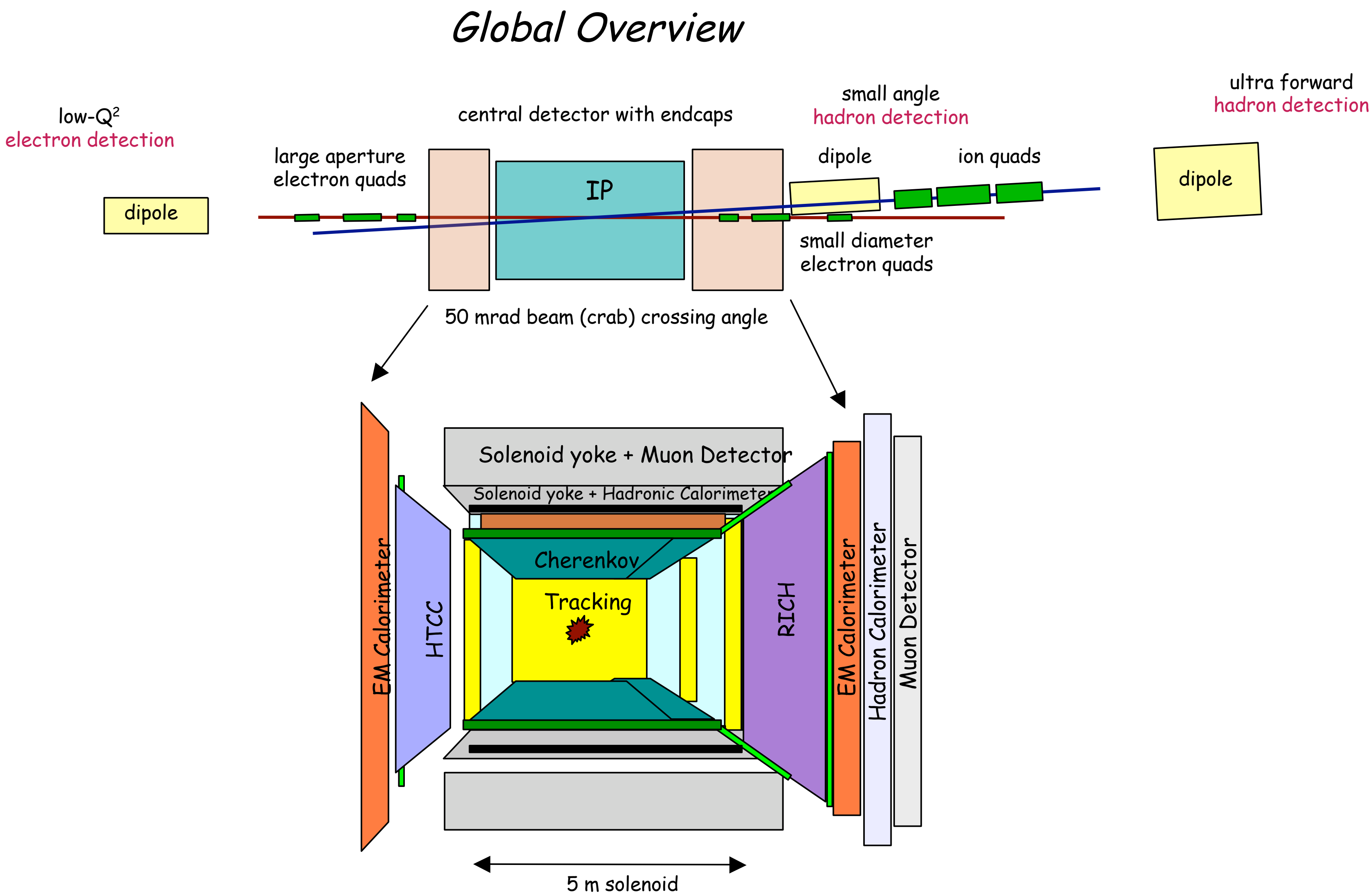



„If one could tag neutron, it typically leads to larger asymmetries" Z. Kang

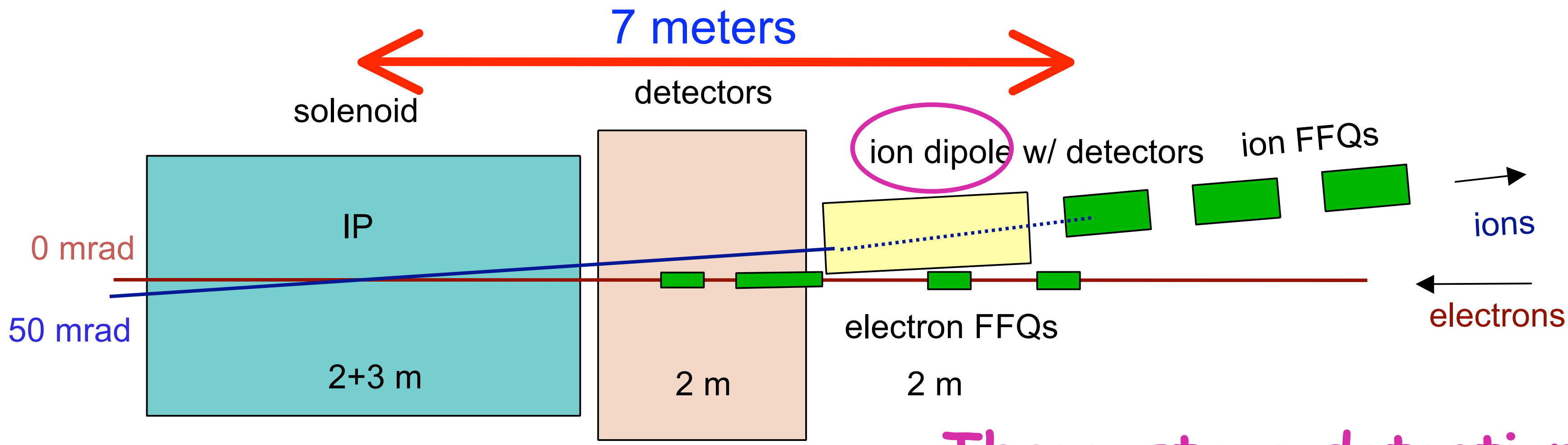
- MEIC will provide longitudinal and transverse polarization for d, $^3$He, and other light ions
- Polarized neutrons are important for probing d-quarks through SIDIS
- Measurements of exclusive reactions like DVCS also greatly benefit from polarized neutron "targets"
  - *c.f.* Hall A and B programs @JLab

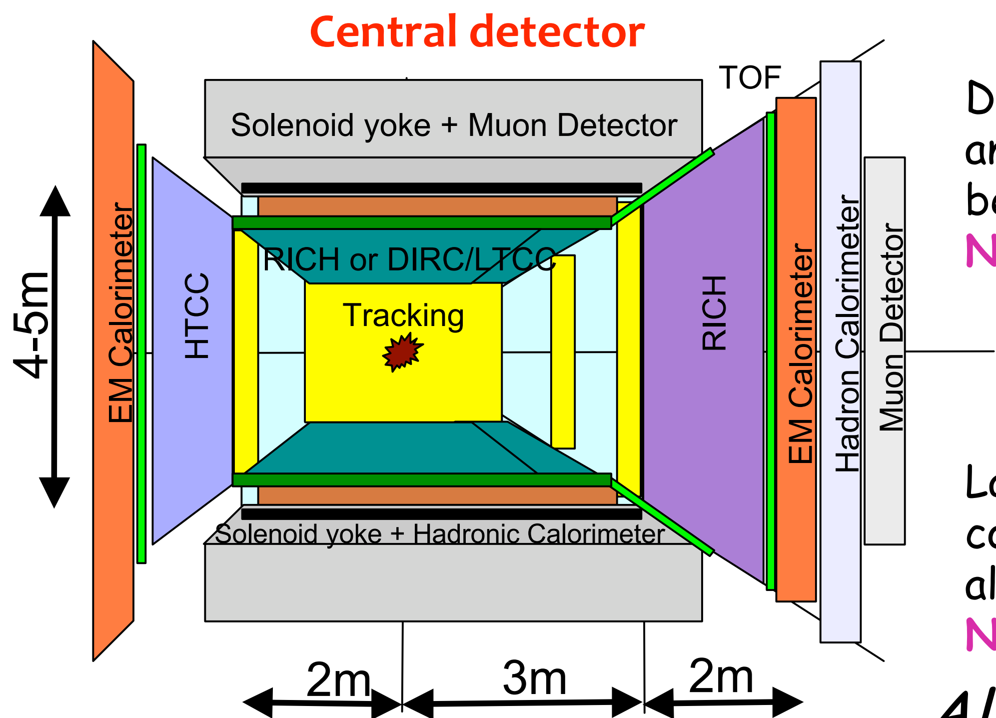
# MEIC – integrated full-acceptance detector




- A second high-luminosity detector can have a more compact interaction region

# MEIC: Full Acceptance Detector




## Three-stage detection

Detect particles with angles down to 0.5° before ion FFQs.
**Need 1-2 Tm dipole.**

Detect particles with angles below 0.5° beyond ion FFQs and in arcs.
**Need 4 m machine element free region**

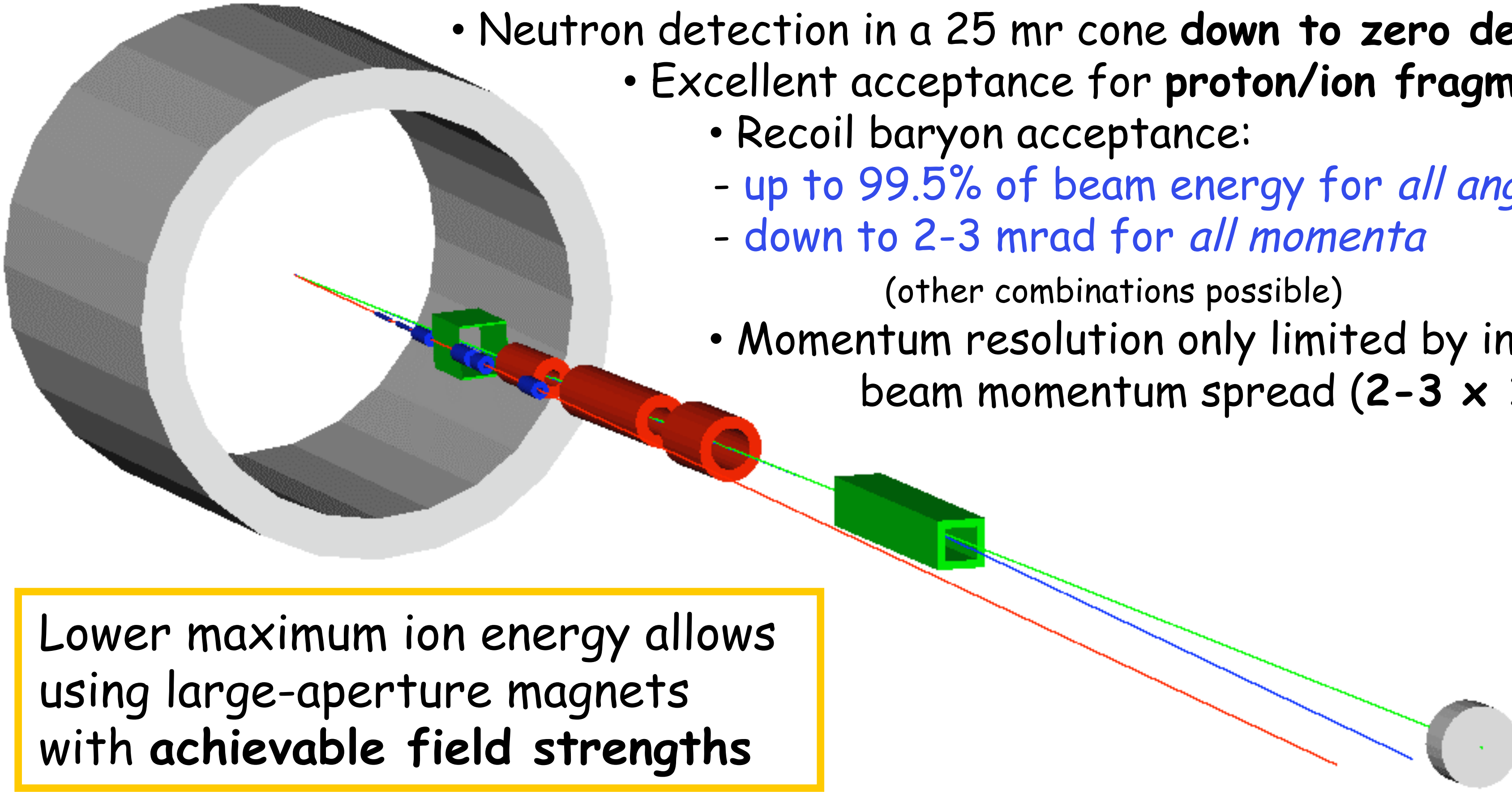
Very-forward detector

Large dipole bend @ 20 meter from IP (to correct 50 mr ion horizontal crossing angle) allows for very-small angle detection (<0.3°).
**Need 20 m machine element free region**

*All incorporated in MEIC design*

# MEIC Detector & Interaction Region

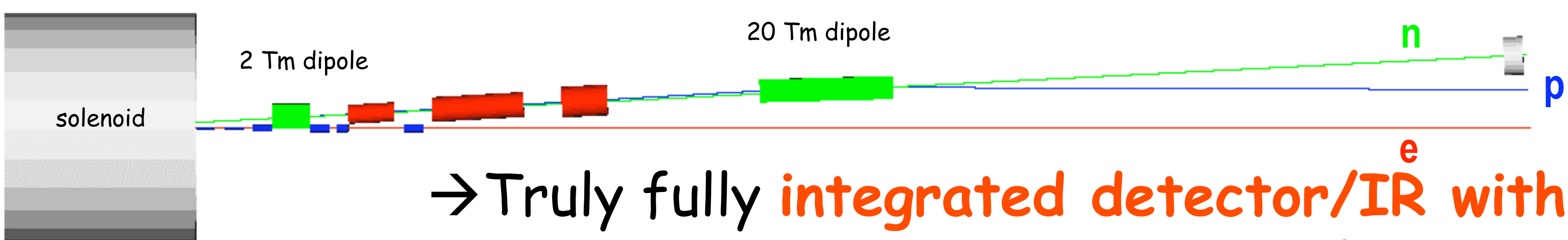
GEANT4 model of extended IR exists



- Neutron detection in a 25 mr cone **down to zero degrees**
- Excellent acceptance for **proton/ion fragments**
- Recoil baryon acceptance:
  - up to 99.5% of beam energy for *all angles*
  - down to 2-3 mrad for *all momenta*

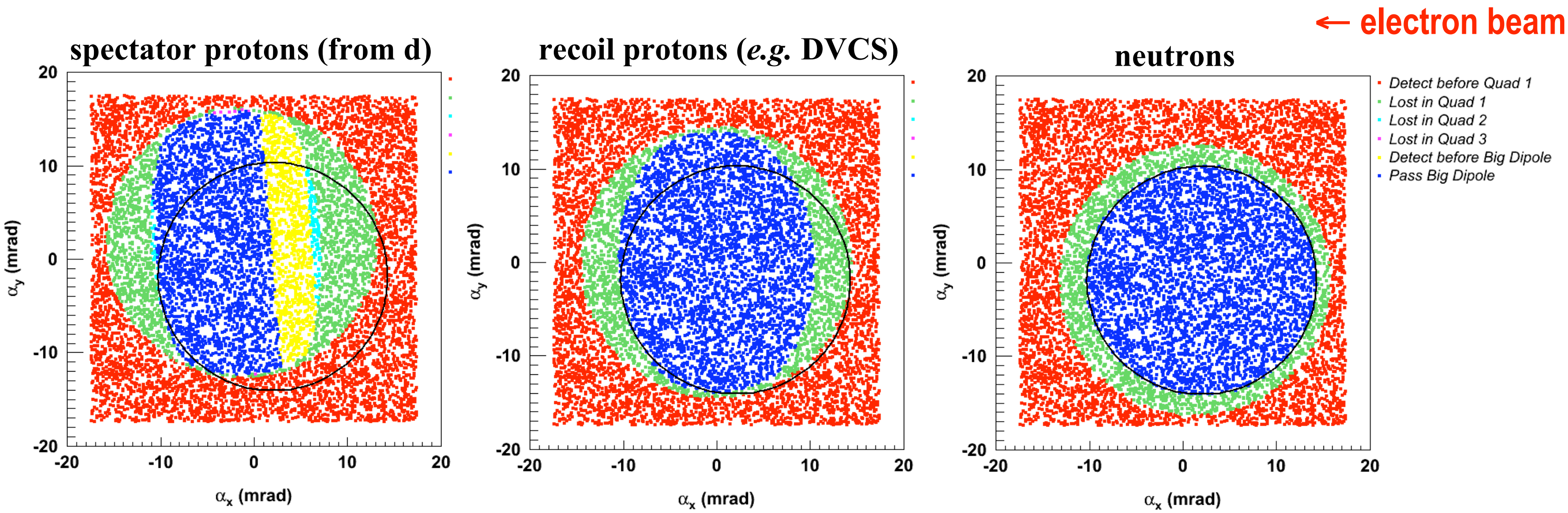
  (other combinations possible)
- Momentum resolution only limited by intrinsic beam momentum spread (**2-3 x $10^{-4}$**)

Lower maximum ion energy allows using large-aperture magnets with **achievable field strengths**




→Truly fully **integrated detector/IR with FULL acceptance detector**

# Small-angle detection – ion acceptance




Red and Green: Detection between upstream 2 Tm dipole and ion quadrupoles

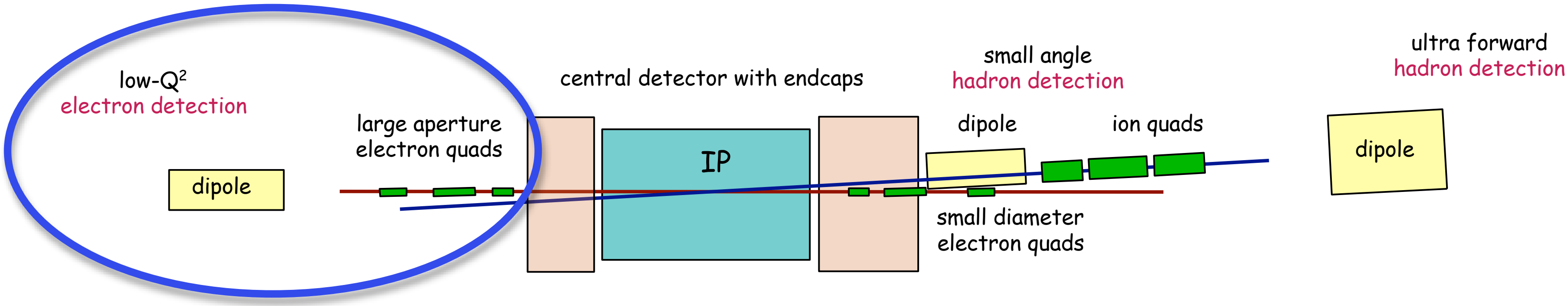
Yellow: Detection between ion quadrupoles and downstream 20 Tm dipole

Blue: Detection after the 20 Tm downstream dipole

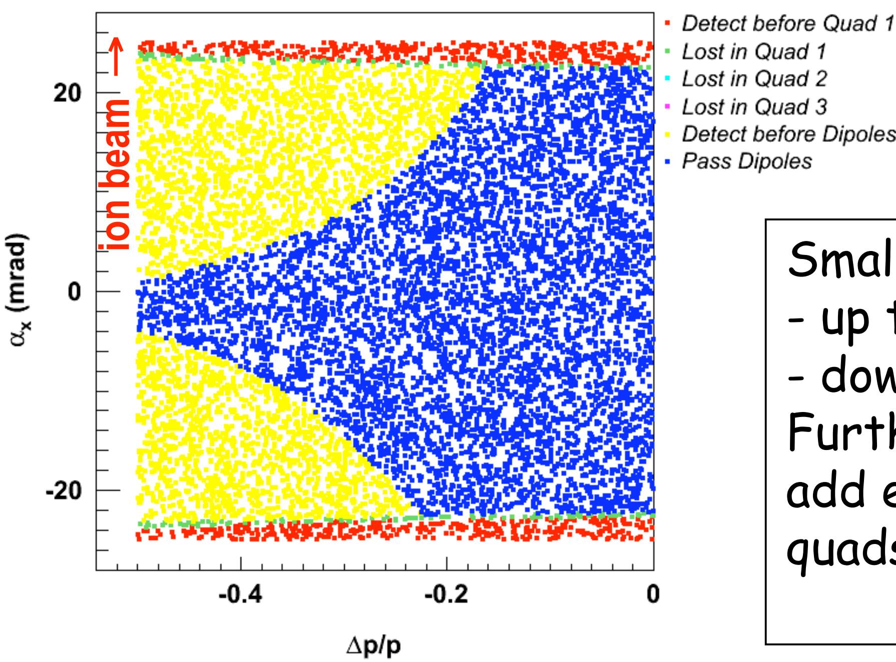
- Reasonable ion quad peak fields at maximum ion energy: 9 T, 9 T, and 7 T
  (limiting to 6 T peak fields is still o.k. for up to 60 GeV proton beams, but small loss for higher energies)
- Aperture of downstream dipole (blue) can be adjusted – shown shifted for illustration
- Angles shown are scattering angles at the IP with respect to the ion beam direction

# MEIC Detector & Interaction Region

## Acceptance of Downstream Electron Final Focus – Low-$Q^2$ electron tagger




- 5 GeV/c e⁻, uniform spreads: -0.5/0 in $\Delta p/p$ and ±25 mrad in horizontal/vertical angle
- Apertures: Quads = 6, 6, 3 T / ($\partial B_y/\partial x$ @ 11 GeV/c), Dipoles = ±20 × ±20 cm




Yellow: Detection between quadrupoles and downstream dipole

Blue: Detection after the downstream dipole

(Long drift space between quads and dipole allows for easy analysis of "yellow" electrons)

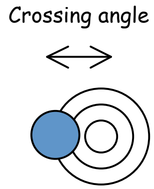
Small-angle electron acceptance:
- up to 99% of beam energy for *all angles*
- down to 0.4-4 mrad for *all momenta*

Further optimization ongoing, and can also add electron detectors before final-focus quads and dipoles.

*This side looks easy*

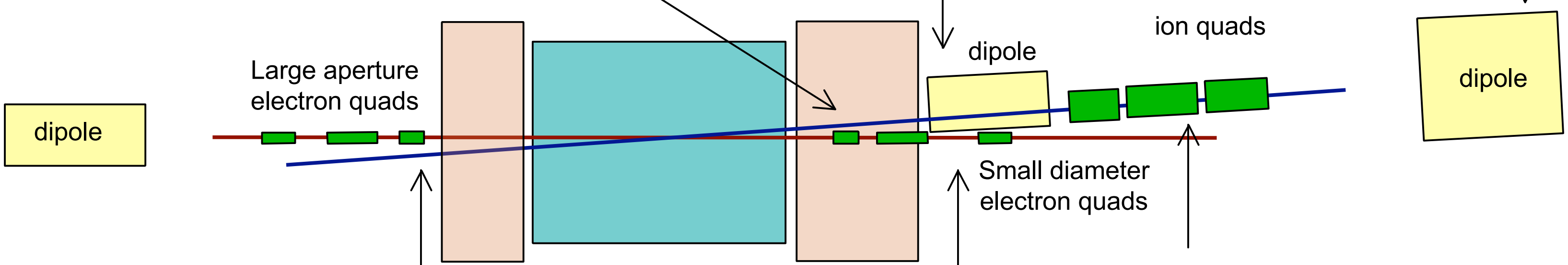
# MEIC Interaction Region Physics Magnets

Electron quads
- 3.5 m from IP
- 0.3 m
- 3 cm bore
- 100 T/m
- outer edge < 8.5 cm
  (i.e. block up to 1.5 deg)




Dipole
- 5 m from IP
- 0.8-1.0 m
- 2 Tm
- 1-5 deg
- B @ $e^-$ beam < 20 G

Dipole
- 18 m from IP
- 3.5 m
- 20 Tm
- gap +/- 20 cm




Solenoid
- 5 m long
- 2 - 4 T
- Return Yoke can be here
  (at +/- 5 meters)

Ion quads
- 7, 9, 13 m from IP
- 1.2, 2.4, 1.2 m
- 14, 24, 34 cm bore
- 89, 51, 36 T/m
- Outer edge < 20, 30, 50 cm
- B @ $e^-$ beam < 10 G

All achievable magnets in terms of peak fields and gradients

# MEIC Detector & Interaction Region

- Oct. 31 – Nov. 4: visit Mike Sullivan (SLAC/BABAR IR expert)

  Goals:
  - Validation of Extended Interaction region design
  - Estimation of Synchrotron/neutron backgrounds
    (including revised look at IR beam pipe design)
  - Conceptual look at all IR magnets
    (solenoid + return yoke, dipole, $e^-$ and Ion FF quads)

October 31 1:00 – 5:00 MEIC Detector and IR Design Mini-Workshop
November 1 2:30 – 4:30 IR Magnet Discussion (w. SC magnet experts)

Closeout info on:
http://casa.jlab.org/meic/workshops/detector_2011/detector_ir_workshop_2011.shtml

Mike Sullivan conclusions:
- IR design is converging to a good, robust interaction region
- The design has been stable for some time
- The design looks to be flexible enough to bend under new demands
  - Initial impression on IR magnets is encouraging

# Developing a Cost Estimate

- Internal cost estimate is conducted by two external consultants and JLab engineers, supported by the MEIC accelerator design teams

- Two-step process
  - Step 1: the consultants provide an itemized cost estimate, and also identify top three cost drivers
    - Ion linac (SRF modules)
    - Refrigeration system
    - SC magnets and SRF cooling in the ring
  - Step 2: JLab engineers perform a detailed cost studies on the top three cost drivers

- This will allow us to develop a cost estimate where the cost drivers are accurately known and the error bar on the rest can be reasonably estimated

- Expected completion date for internal evaluation: March/April

# Generic Detector R&D for an EIC

Approved Detector R&D items after 1st call/meeting

(see also https://wiki.bnl.gov/conferences/index.php/EIC_R%25D)

1) DIRC-based PID for the EIC Central Detector
   Catholic U A, Old Dominion U, GSI/Darmstadt, Jlab
2) Proposal to test improved radiation tolerant Silicon PMTs
   JLab Radiation Detector & Imaging (RDI) Group
3) Letter-of-Intent for detector R&D towards an EIC detector
   BNL-based collaboration, includes UVa (+Temple for 2nd call)

Submitted in response to 2nd call for proposals

1) DIRC-based PID for the EIC Central Detector
   Includes SiPMT, augmented with USC & JLab RDI Group
2) Micro-Pattern Gaseous Detectors for a Vertex Tracker in EIC
   Saclay, MIT, Temple
3) Development of a Spin-Light Polarimeter for the EIC
   Mississippi State U, ANL, Mainz, Stony Brook U, UVa, W&M

First two approved, third was well received but got homework assignment to "further develop this very interesting proposal"

# Generic Detector R&D for an EIC

(see https://wiki.bnl.gov/conferences/index.php/EIC_R%25D)

Approved and to be submitted in response to 3rd call for proposals

1) DIRC-based PID for the EIC Central Detector
   Includes SiPMT, CUA, ODU, GSI/Darmstadt, USC & JLab
2) Micro-Pattern Gaseous Detectors for a Vertex Tracker in EIC
   Saclay, MIT, Temple

(requested to return with proposal(s))

3) Letter-of-Intent for detector R&D towards an EIC detector
   Mainly BNL-based collaboration, includes UVa +Temple

(resubmitted)

4) Development of a Spin-Light Polarimeter for the EIC
   Mississippi State U, ANL, Mainz, Stony Brook U, UVa, W&M

(to be submitted)

5) RICH-based PID for EIC
   INFN, JLab, …

(maybe?)

6) Incorporate tracking info in pipelined trigger electronics/DAQ
   JLab Fast Electronics Group

# R&D Example: DIRC R&D for an EIC

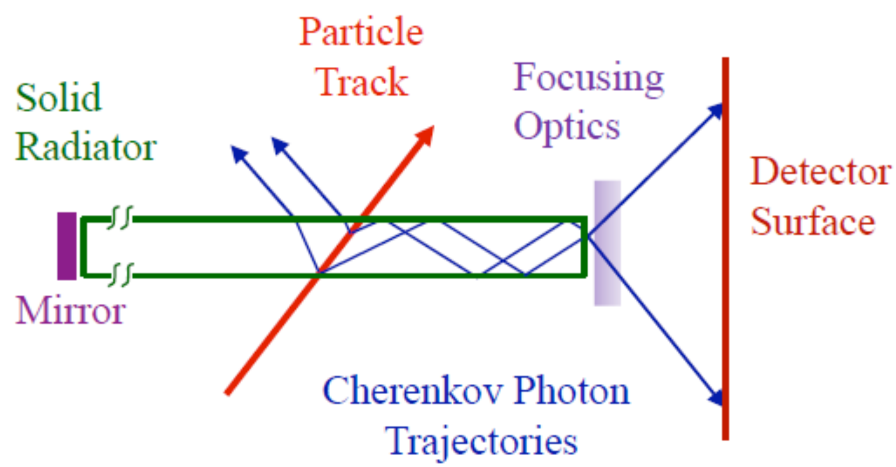
Detection of Internally Reflected Cherenkov light

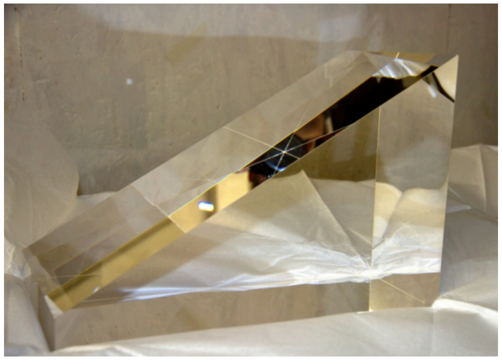
Catholic U A, Old Dominion U, GSI/Darmstadt, U South Carolina, JLab

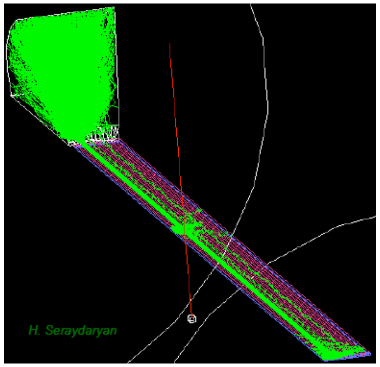
- DIRCs are a very compact form of imaging Cherenkov detectors providing e/π, π/K, and K/p separation.

- CUA, ODU, USC, GSI, and JLab have received $400k over 3 years as part of the program for Generic Detector R&D for an Electron-Ion Collider (EIC) to develop a DIRC-based PID for the central detector.

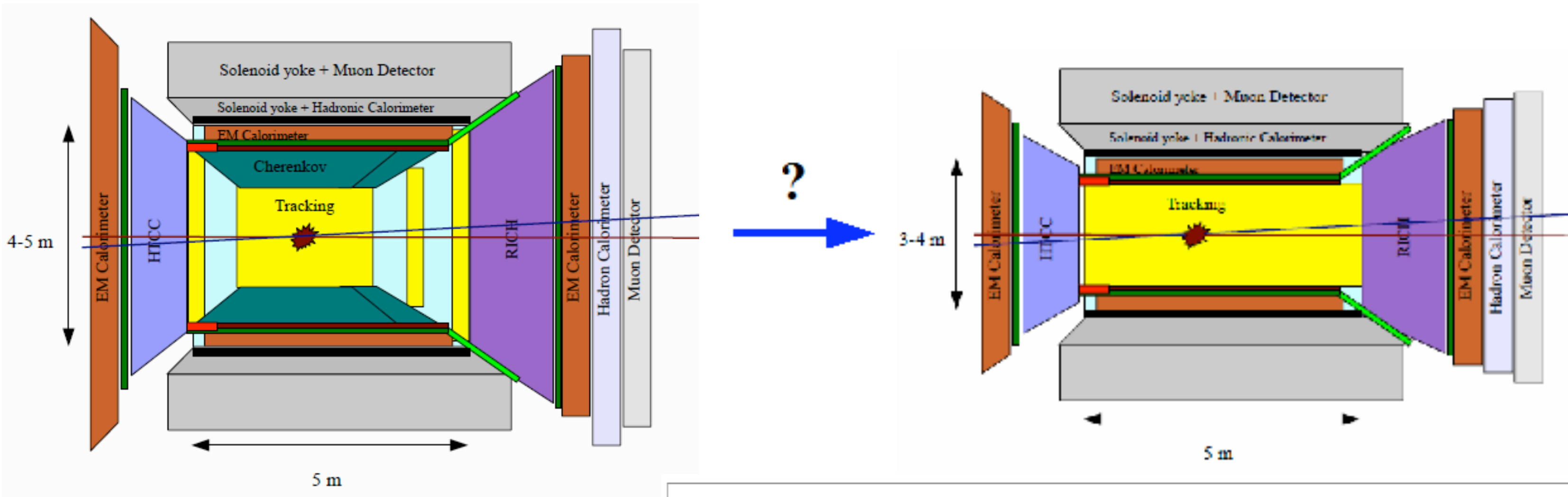
- Simulation and design work is ongoing!



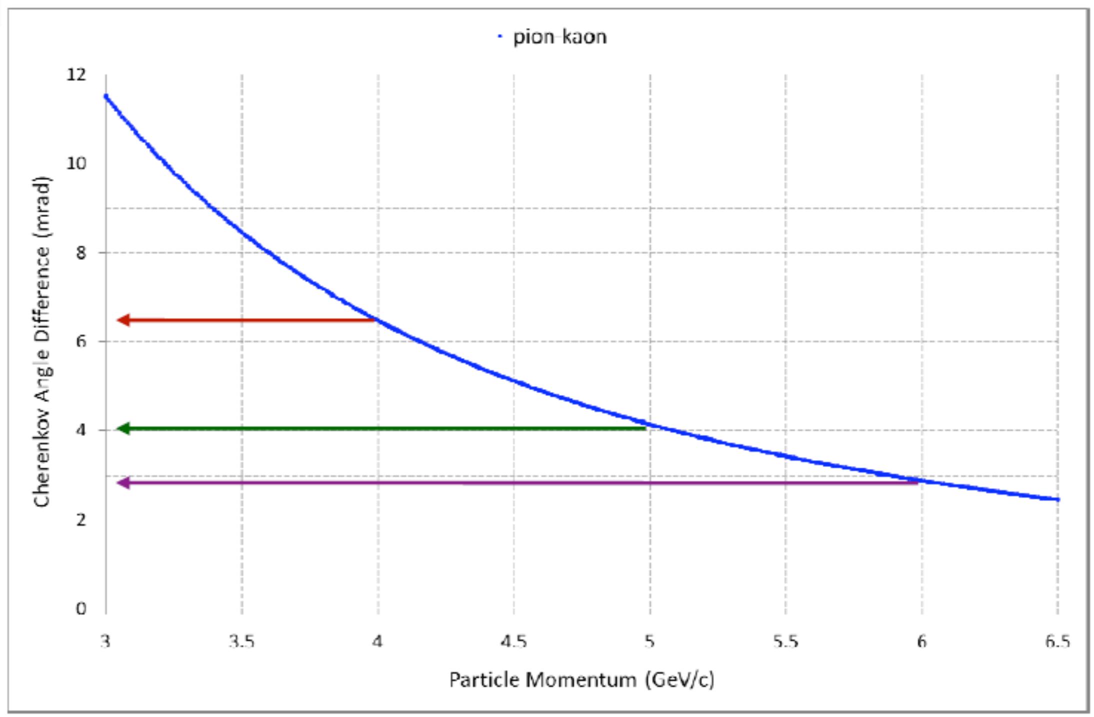


# Improving the DIRC momentum coverage




- Improving the Cherenkov angle resolution by a factor of two would push the 3 $\sigma$ $\pi/K$ separation from 4 to 6 GeV/c

- Eliminating the need for supplementary Cherenkov detectors would have great impact on the layout of the central detector



# MEIC Detector/Interaction Region Status

• Reiterated on integration of detector & interaction region to confirm full hermetic detector over $E_p$ = 20-100 GeV.
High praise from (BABAR) expert for integration.

• Design directly driven by science requirements

• Required magnets in extended IR do not push parameters

• MEIC Intermediate Design Report in final editing stage

• Independent report being worked on for electron cooling,
Many aspects of cooling can be tested at JLab/FEL

• Plan for Cost Estimate developed, estimates for 3 cost drivers ongoing (Ion Linac, Refrigeration System, SC Magnets & SRF Cooling)

• JLab user community involved in ongoing detector R&D
- DIRC (including Silicon PMT radiation hardness tests)
- Gaseous tracking detectors (MicroMegas and GEM-based)
- Spin-Light Polarimeter (<0.5% electron beam polarization uncertainty)
- Planning for RICH PID detector R&D proposal

**Established fully integrated detector/interaction region!**

# Backup Slides

# Why an Electron-Ion Collider?

- Easier to reach high Center of Mass energies ( $E_{CM}^2 = s$ )
  - $s = 4E_eE_p$ for colliders (e.g., 4 x 9 x 60=2160 GeV$^2$)
  - $s = 2E_eM_p$ for fixed target experiments (e.g., 2 x 11 x 0.938) = 20 GeV$^2$)

- Spin physics with high figure of merit
  - Unpolarized FOM = **Rate = Luminosity x Cross Section x Acceptance**
  - Polarized **FOM = Rate x (Target Polarization)$^2$ x (Target Dilution)$^2$**
  - No *dilution* and high ion polarization (also *transverse*)
  - No current (*luminosity*) limitations, no holding fields (*acceptance*)
  - No *backgrounds* from target (Moller electrons)

- Easier detection of reaction products
  - Can optimize kinematics by adjusting beam energies
  - More symmetric kinematics improve acceptance, resolution, particle ID, etc.
  - Access to neutron structure with deuteron beams ($p_p \neq 0$ )

| Target | $f_{dilution, fixed\_target}$ | $P_{fixed\_target}$ | $f^2P^2_{fixed\_target}$ | $f^2P^2_{EIC}$ |
|---|---|---|---|---|
| p | 0.2 | 0.8 | 0.03 | 0.5 |
| d | 0.4 | 0.5 | 0.04 | 0.5 |

# Backgrounds and detector placement

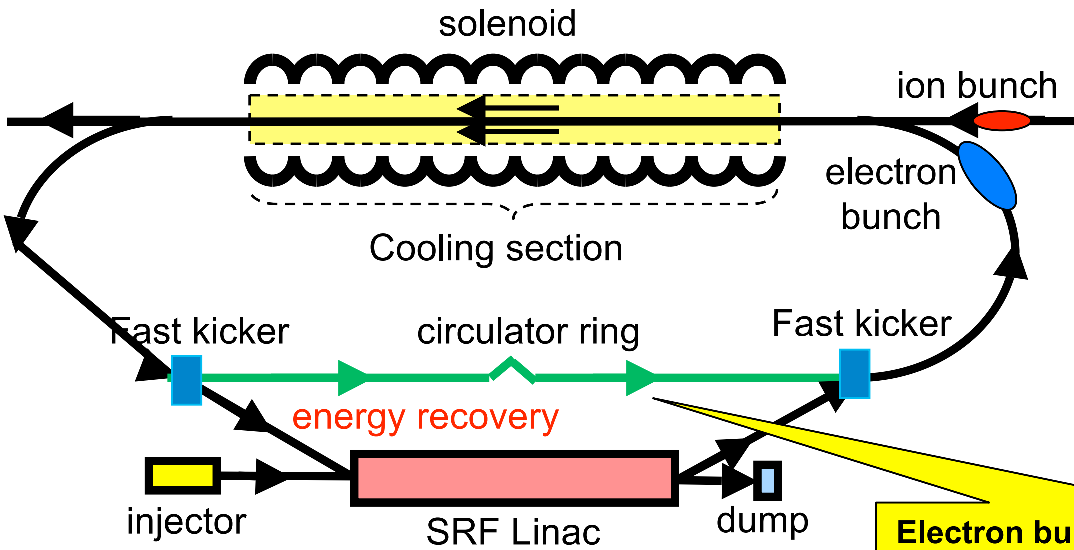
## Synchrotron radiation

- From arc where electrons exit and magnets on straight section

## Random hadronic background

- Dominated by interaction of beam ions with residual gas in beam pipe between arc and IP
- **Comparison of MEIC (at s = 4,000) and HERA (at s = 100,000)**
  - Distance from ion exit arc to detector: 50 m / 120 m = 0.4
  - Average hadron multiplicity: $(4000 / 100000)^{1/4} = 0.4$
  - p-p cross section (fixed target): $\sigma(90\text{ GeV}) / \sigma(920\text{ GeV}) = 0.7$
  - At the same ion current and vacuum, MEIC background should be about 10% of HERA
    - Can run higher ion currents (0.1 A at HERA)
    - Good vacuum is easier to maintain in a shorter section of the ring
- **Backgrounds do not seem to be a major problem for the MEIC**
  - Placing high-luminosity detectors closer to ion exit arc helps with both background types
  - Signal-to-background will be considerably better at the MEIC than HERA
    - MEIC luminosity is more than 100 times higher (depending on kinematics)

# ERL Based Circulator Electron Cooler




Electron bunches circulate 10-100 times, leads to a factor of 10-100 reduction of the current from a photo-injector/ERL

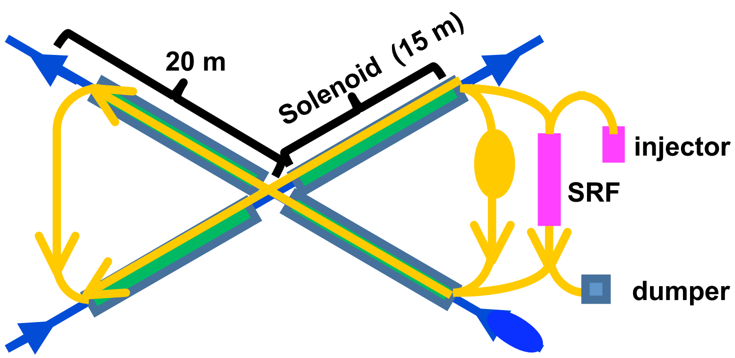
## Design Choice

to meet design challenges
- RF power (up to 50 MW)
- Cathode lifetime (130 kC/day)

## Required technology

- High bunch charge gun ERL (50 MeV, 15 mA) (Ultra) fast kicker/RF separator

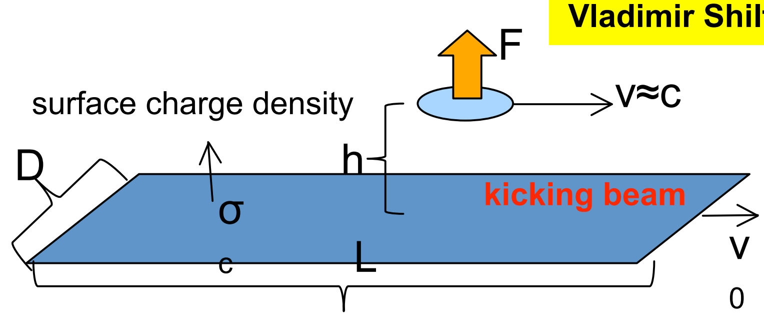
## Cooling at the center of Figure-8



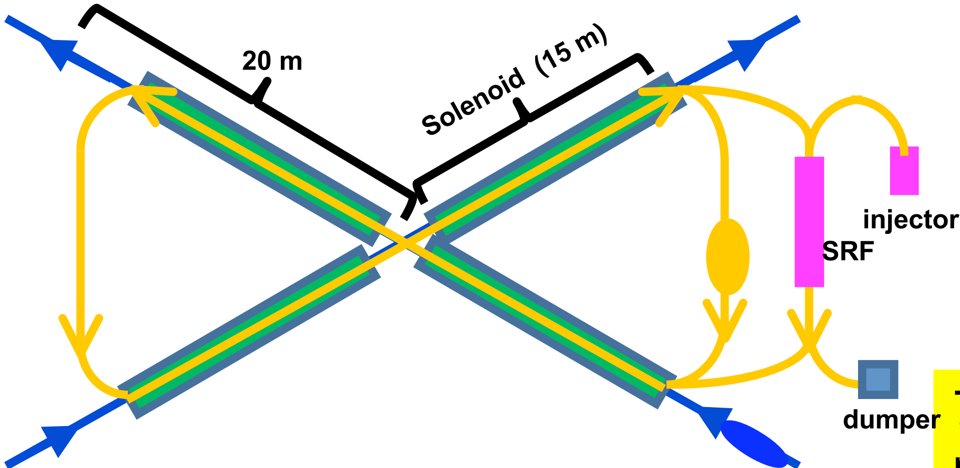

Eliminating a long return path could
- cut cooling time by half, or
- reduce the cooling electron current by half, or
- reduce the number of circulations by half

## Beam-beam fast kicker

Vladimir Shiltsev



# Proposal of MEIC e-Cooler Test Facility



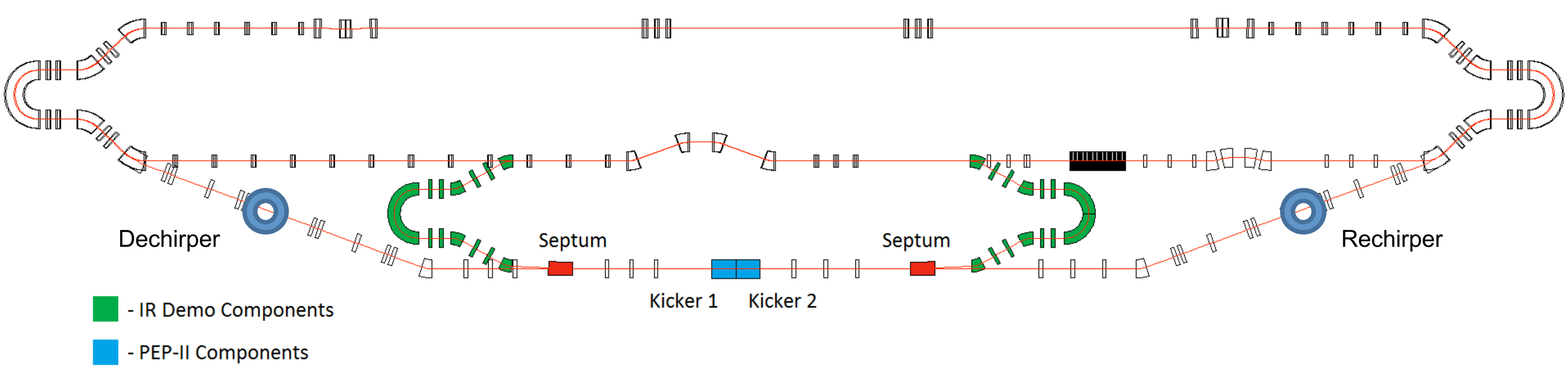

**Baseline Design Concept**

- Energy recovery linac (for solving high RF power problem)
- Circulator ring (for solving short e-source life-time problem)

75 MHz ERL, tossing 1/10 bunches to reduce beam-beam interaction seems moderate risk for source and beam transfer

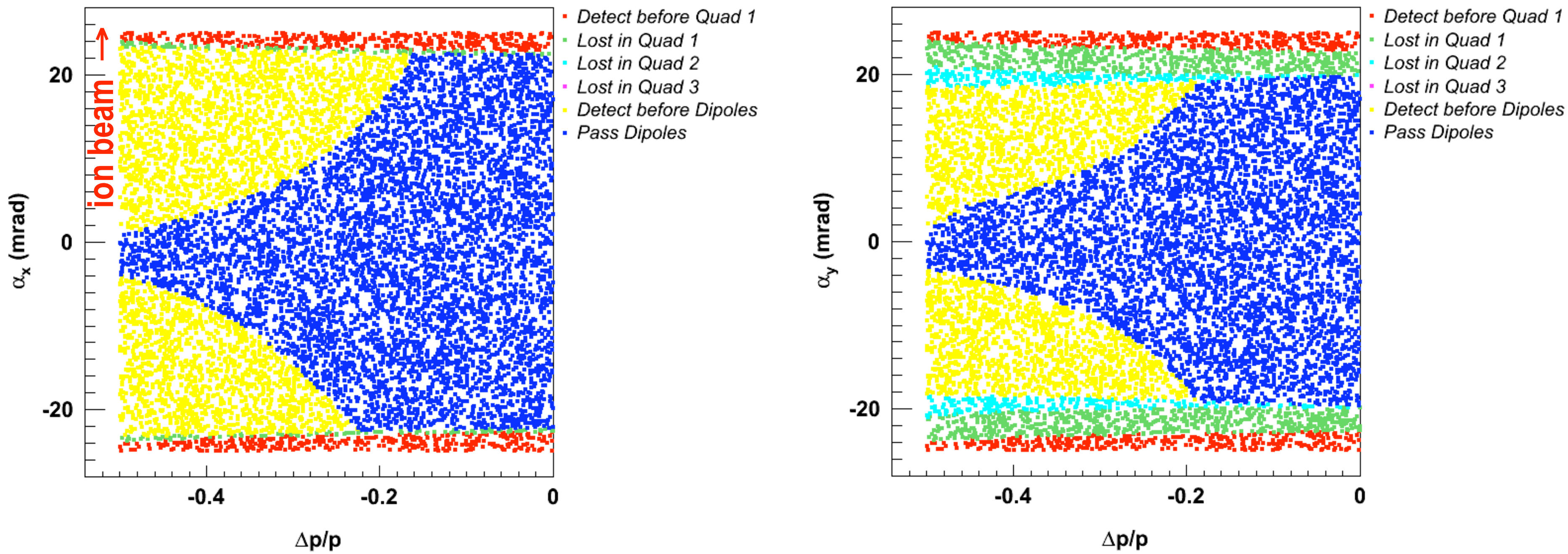
**Idea: use JLab FEL as test facility**

- Cover the right energy range, need to add a circulator ring
- Much major hardware (e-source, ERL, magnets) exists → cost-effective
- JLab FEL team helped to develop concept



# Acceptance of Downstream Electron Final Focus

- 5 GeV/c $e^-$, uniform spreads: -0.5/0 in $\Delta p/p$ and ±25 mrad in horizontal/vertical angle
- Apertures: Quads = 6, 6, 3 T / ($\partial B_y / \partial x$ @ 11 GeV/c), Dipoles = ±20 × ±20 cm




$$|\Delta p/p| > 0.01 \ @ \ \theta_{x,y} = 0$$

$$|\theta_x| > 0.4\text{-}4 \text{ mrad} \ @ \ \Delta p/p = 0$$