eRHIC Project

- Performance requirements
- eRHIC design
- R&D for eRHIC
- Cost and schedule

BROOKHAVEN NATIONAL LABORATORY

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NSAC Subcommittee on Scientific Facilities

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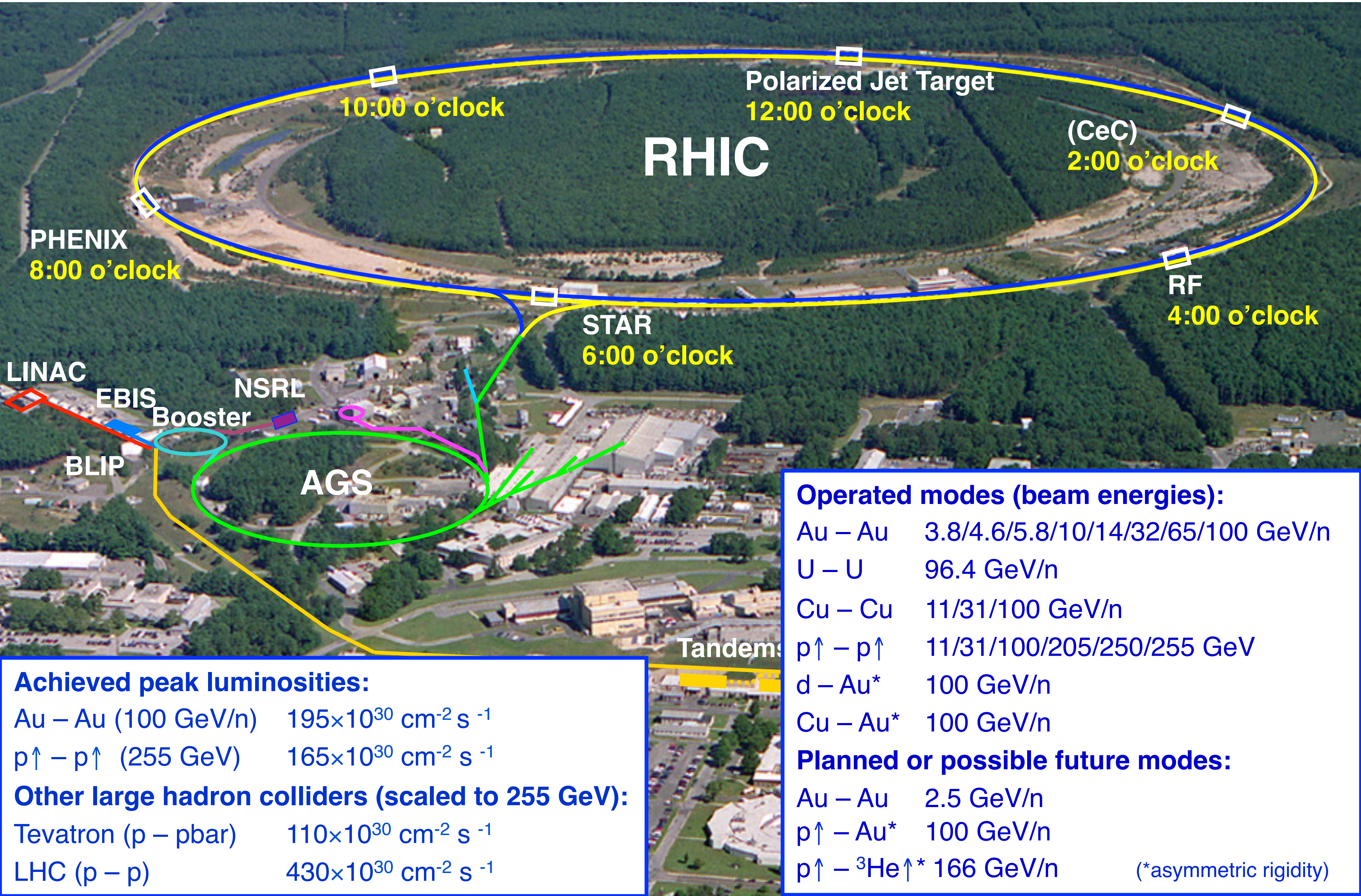
Performance requirements

- Highly polarized (> 70%) electron, proton and neutron (He-3) beams
- Ion beams from deuteron to the heaviest nuclei (uranium)
- Center of mass energy range: ~ 20 GeV to ~ 150 GeV
- Non-zero crossing angle to minimize synchrotron radiation background
- Possibility to have multiple interaction regions
- High luminosity: $10^{33} – 10^{34}$ $cm^{-2} s^{-1}$
- First stage to reach CM energy of $\gtrsim$ 70 GeV and luminosity of $10^{32} – 10^{34}$ $cm^{-2} s^{-1}$

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities:

Au – Au (100 GeV/n)	195×10^{30} cm^{-2} s^{-1}
p↑ – p↑ (255 GeV)	165×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 255 GeV):

Tevatron (p – pbar)	110×10^{30} cm^{-2} s^{-1}
LHC (p – p)	430×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

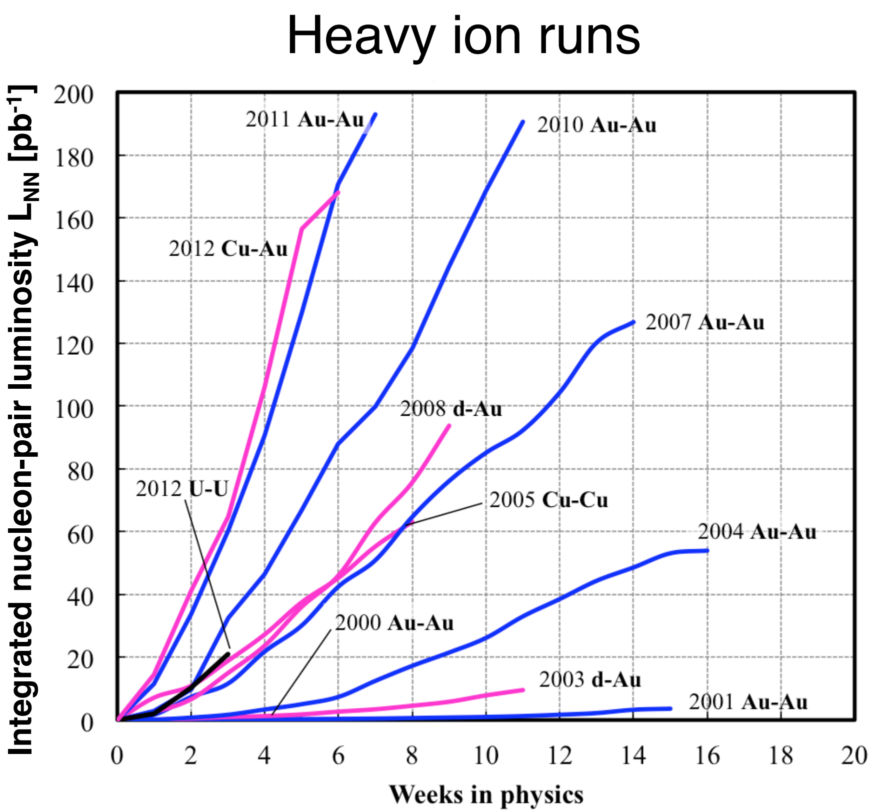
Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n

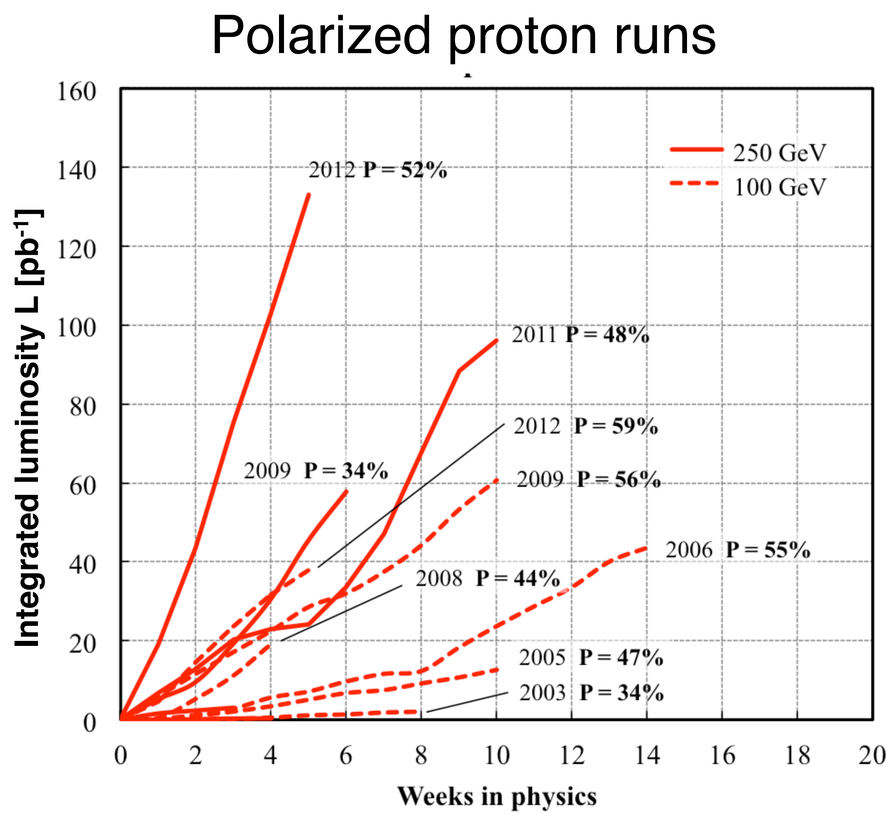
Planned or possible future modes:

Au – Au	2.5 GeV/n
p↑ – Au*	100 GeV/n
p↑ – ^{3}He↑*	166 GeV/n

(*asymmetric rigidity)

RHIC performance supports eRHIC requirements





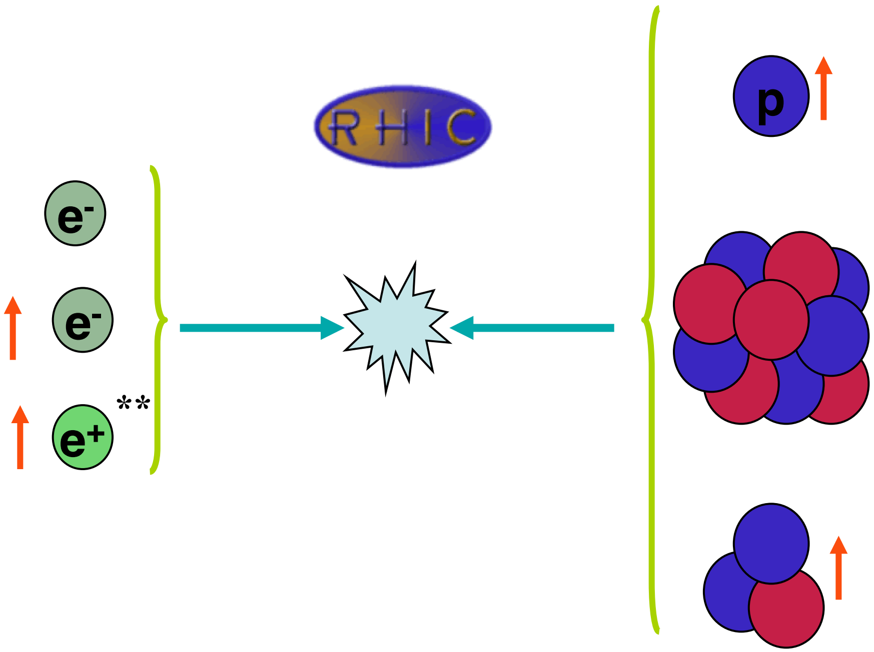
- Further upgrades:
  - 56 MHz superconducting storage rf system to reduce vertex length
  - Electron lenses to ~ double pp luminosity

Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

eRHIC: QCD Facility at BNL

Add an electron accelerator to the existing $2B RHIC and also using existing RHIC tunnel and cryo facility

Unpolarized and
80% polarized leptons
5 - 30 GeV

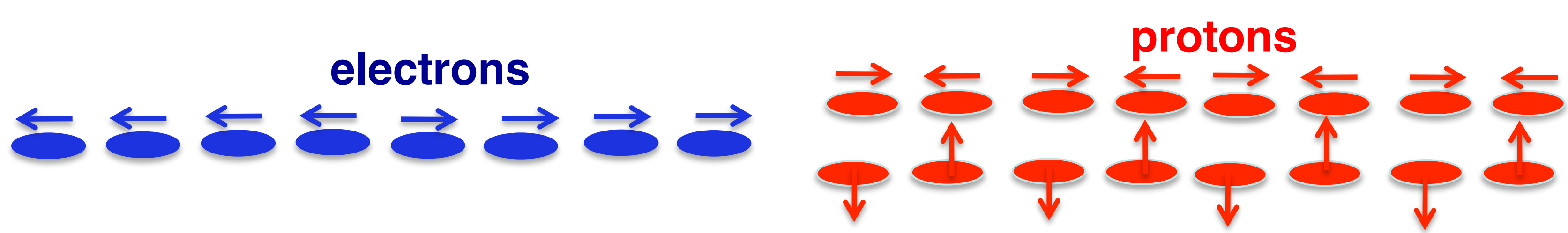


70% polarized protons
50 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
50 - 100 (110*) GeV/u

Pol. light ions (He-3)
50 - 167 (184*) GeV/u

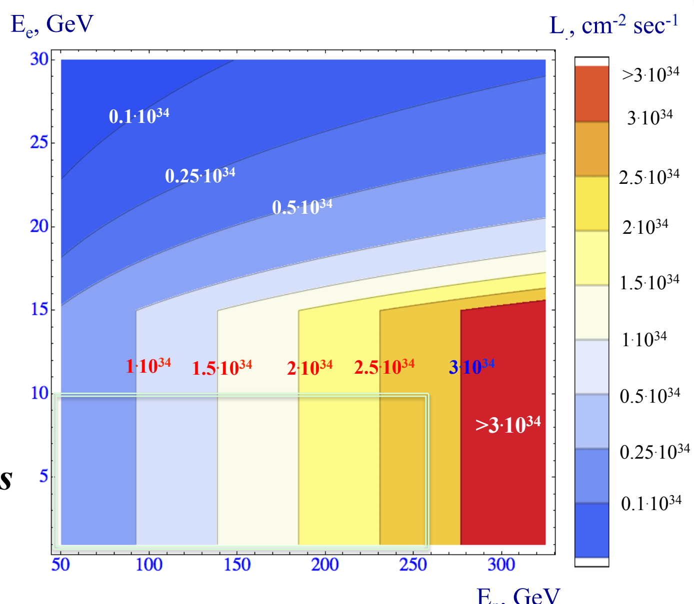
Center-of-mass energy range: 30 - 175 GeV
Any polarization direction in lepton-hadron collisions



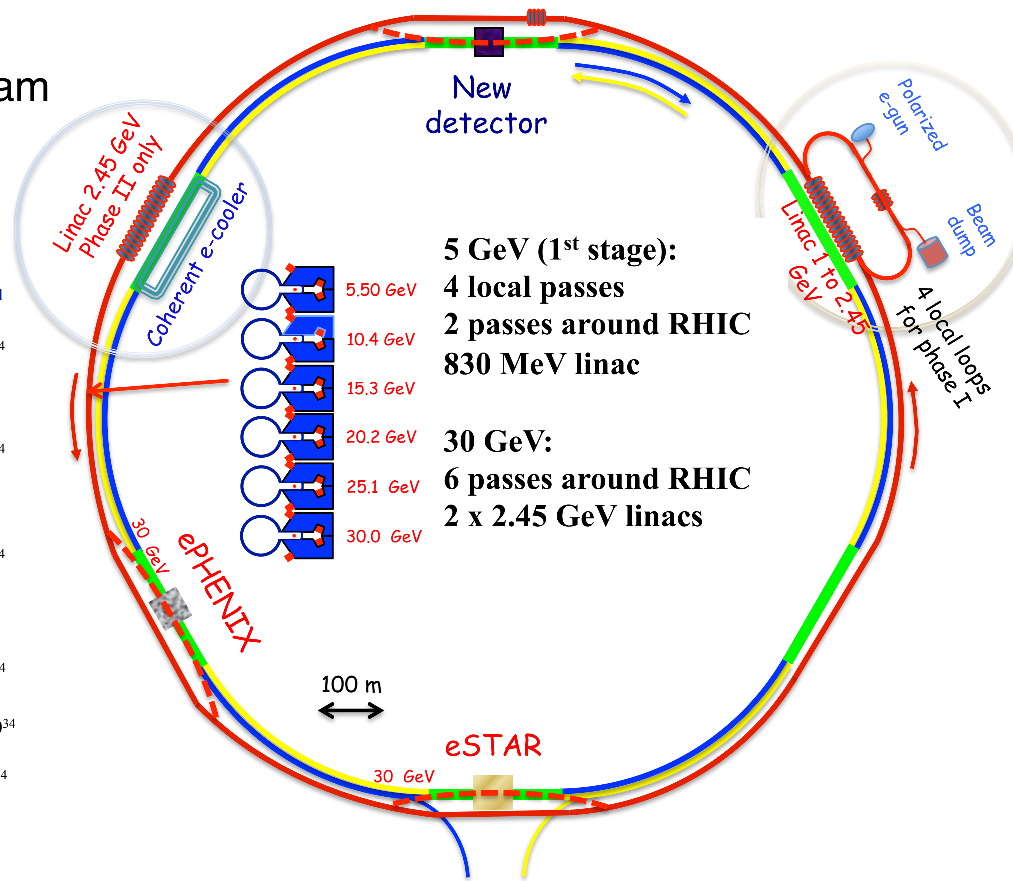
*** It is possible to increase RHIC ring energy by 10%**
**** positrons-ion collider possible at lower luminosity with extra ring**

eRHIC design

- 5 – 30 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV polarized protons and 100 GeV/n HI RHIC beams
- Single pass allows for large collision disruption of electron bunch, giving high luminosity (~ 10^{34} cm^{-2} s^{-1}), and full electron polarization transparency
- Accelerator R&D for highest luminosity:
  - High current (50 mA) pol. electron gun
  - Multi-pass high average current ERL
  - Coherent electron cooling of hadron beam
- 1^{st} stage: 5-10 GeV electron beam
  - Similar to CEBAF 12 GeV upgrade (1 GeV SRF linac + recirculating arcs)



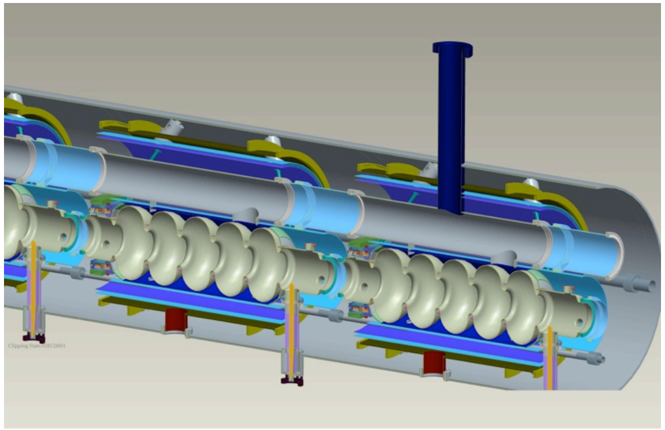
Box area corresponds to the first stage

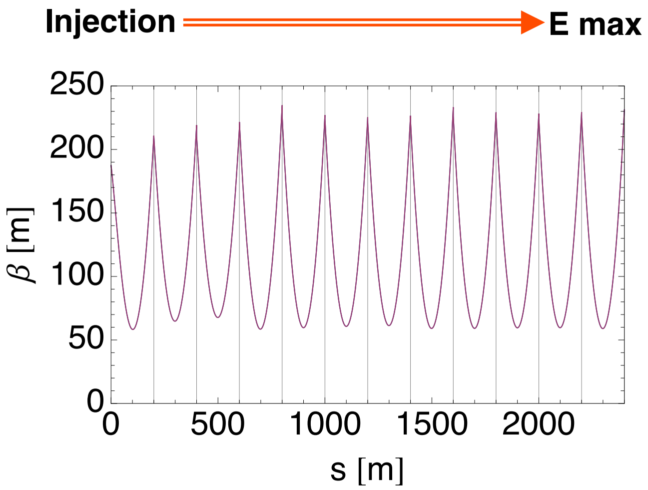


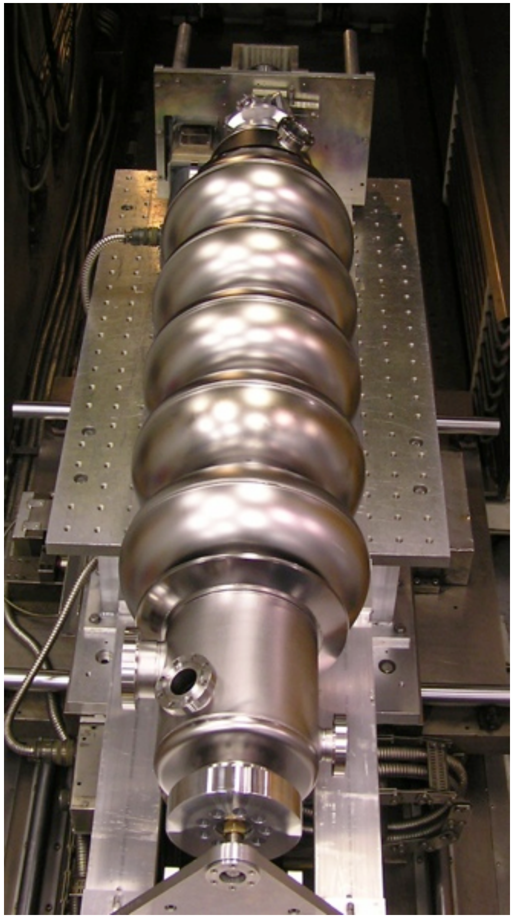
Main elements of the concept

- Single pass ERL for electrons allows for large collision disruption of electron bunches, giving high luminosity (~ 10^{34} cm^{-2} s^{-1}), and full electron polarization transparency
- Small electron beam size allows for small magnets with gaps of 8 mm (and 13 mm at the two lowest energy orbits)
- Linac-ring collider uniquely allows energy change of colliding hadrons from 50 GeV to 250 GeV
- Using recent advances in super-conducting quadrupole technology allows design IR with $\beta^* = 5$ cm
- Crab-crossing with large crossing angle following success at KEK-B
- Need 50 mA of polarized electron beam current for high luminosity
- Strong cooling of hadron beam (÷10 emittance) in both longitudinal and transverse directions using coherent electron cooling
- Together results in eRHIC luminosity of 10^{34} cm^{-2} s^{-1}

eRHIC Linac

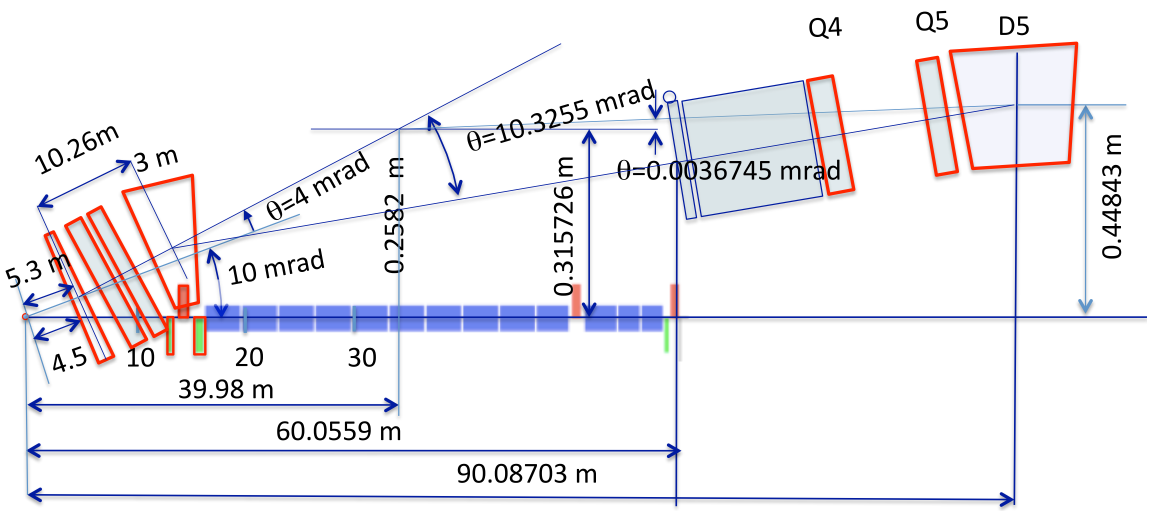


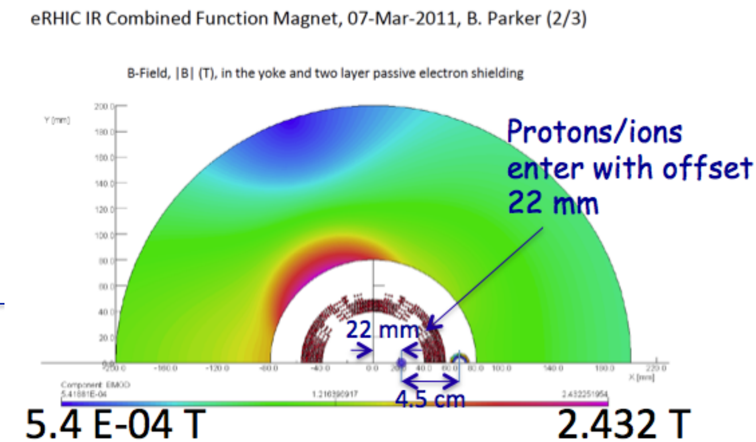




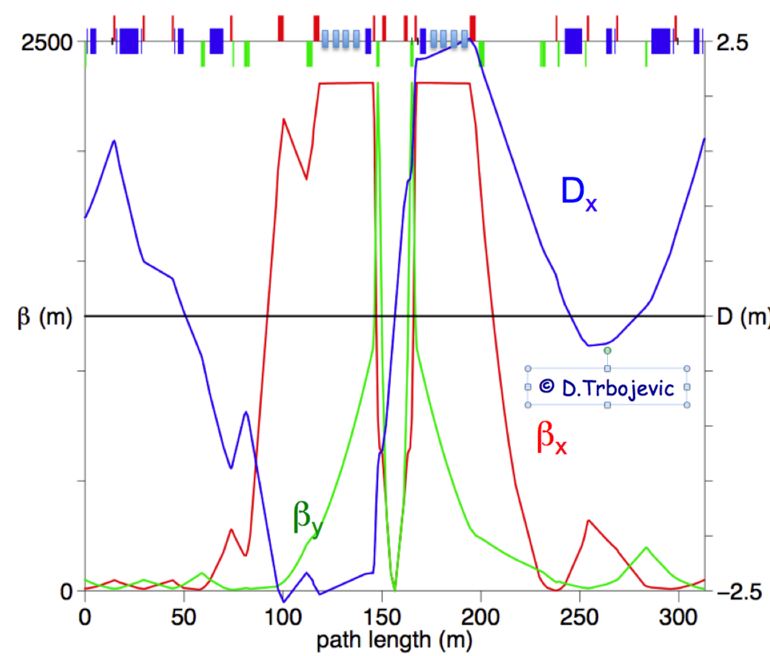
- Total Linac length: ~ 200 m (70m for 1st stage)
- Warm-to-cold transitions only at the ends
- No quadrupoles in Linac
- Maximum energy gain per pass: 2.45 GeV (0.8 GeV for 1st stage)
- Accelerating gradient: 19.2 MV/m
- Based on BNL SRF cavity with fully suppressed HOMs, critical for high current multi-pass ERL
- eRHIC cavity & cryostat prototypes are under development

eRHIC high-luminosity IR with $\beta^* = 5$ cm

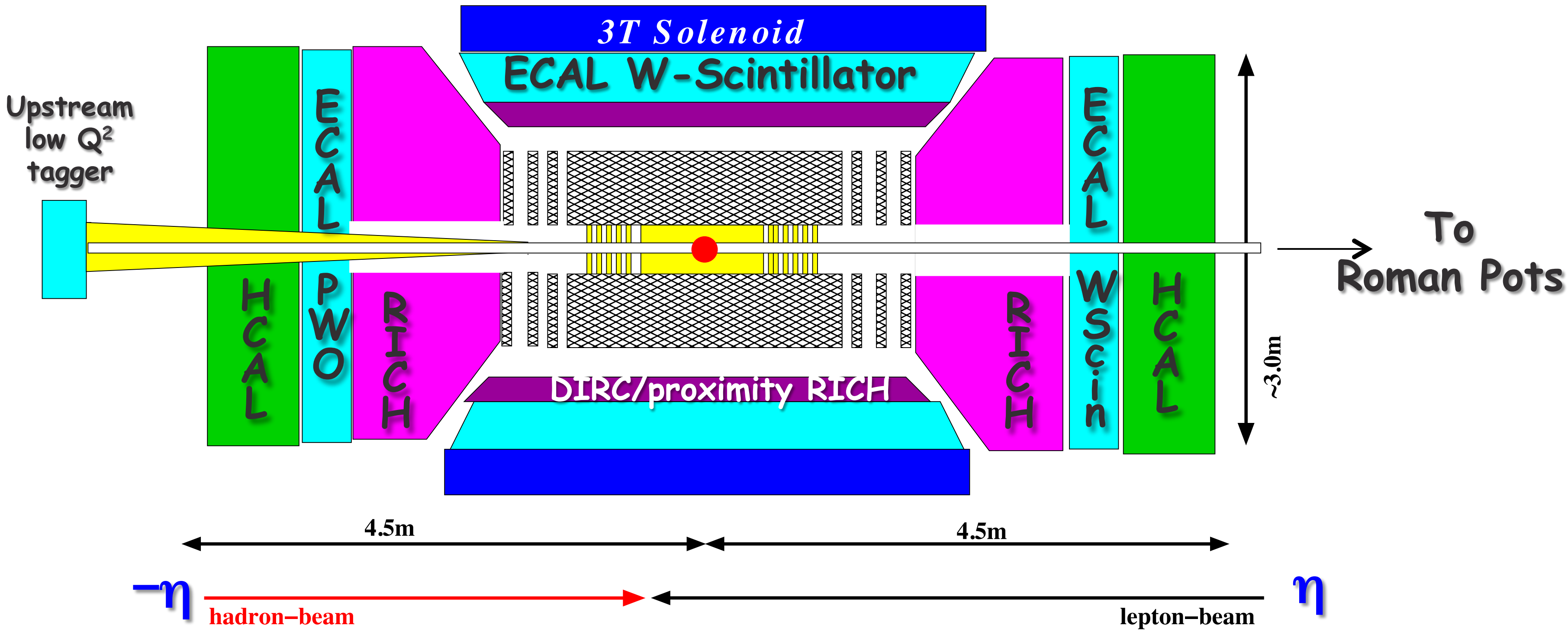




- 10 mrad crossing angle and crab-crossing
- High gradient (200 T/m) large aperture Nb3Sn focusing magnets
- Free-field electron pass through the hadron triplet magnets
- Integration with the detector: efficient beam separation and detection of low angle collision products
- Gentle bending of the electrons to avoid SR
- Simpler solution possible for 1st stage



1st eRHIC Detector Design Concept



- High acceptance (η: ± 5) central detector with good PID and vertex resolution
- Tracking and calorimeter with same coverage → good momentum resolution
- Low material density for minimal multiple scattering and bremsstrahlung
- Magnetic field critical for good tracking resolution in forward direction
- Integration of detector into IR design
  - *Roman Pots, ZDC, low e-tagger for very forward electron and proton/neutron detection*
- Very active EIC detector R&D (back-up slide)

Readiness of eRHIC

- 1st stage eRHIC using existing, demonstrated technology has an initial luminosity of about 10^{32} cm^{-2} s^{-1} (2 x max. HERA luminosity) and 80% e-beam polarization (~ 2 x HERA e-beam polarization)
  → ready to initiate construction

  - 4 mA polarized e beam source demonstrated at Jlab
  - High energy ERL demonstrated (CEBAF), multi-pass ERL demonstrated (BINP)
  - Performance of existing BNL 704 MHz srf cavity supports eRHIC linac
  - Use present RHIC polarized proton beam emittance of ~ 2 μm

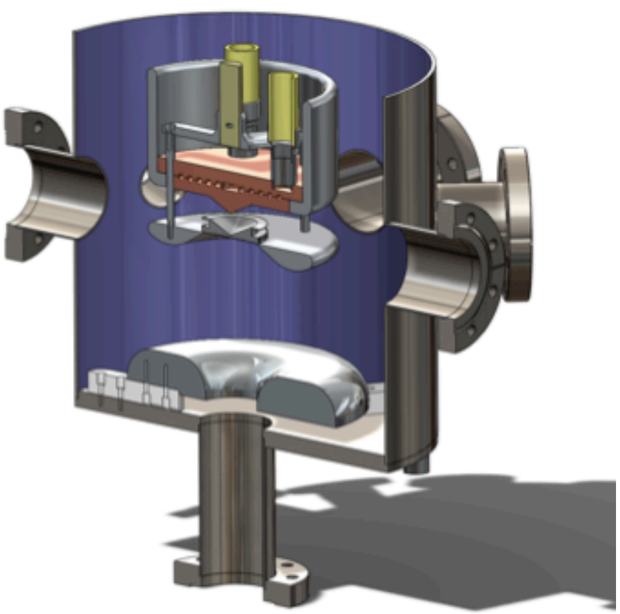
- Ongoing eRHIC R&D is aimed at increasing eRHIC luminosity to 10^{34} cm^{-2} s^{-1}:

  - Increase of e-beam current to 50 mA using multiple cathodes (10^{33} cm^{-2} s^{-1})
    - *Low risk development; likely available for eRHIC construction; incl. in cost estimate*
  - High average current ERL to support operation with high current e beam
    - *Results from test-ERL in 2014*
  - Strong cooling of hadron beams to ~ 0.2 μm (10^{34} cm^{-2} s^{-1})
    - *Coherent electron Cooling is best concept and needs R&D; CeC PoP in 2015*

High CW current polarized electron gun

- Matt Poelker (JLab) achieved 4 mA polarized e-beam with good lifetime
- More current with (effectively) larger cathode area
- Gatling gun R&D: twice the current from two cathodes with same lifetime

Single large area cathode



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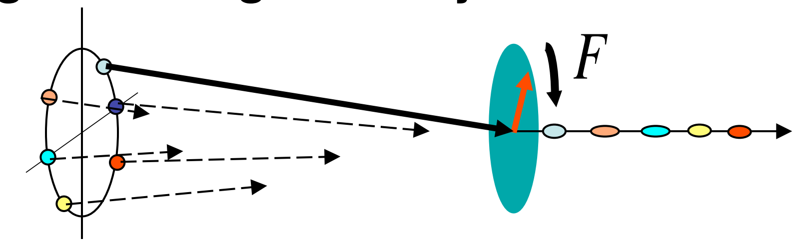
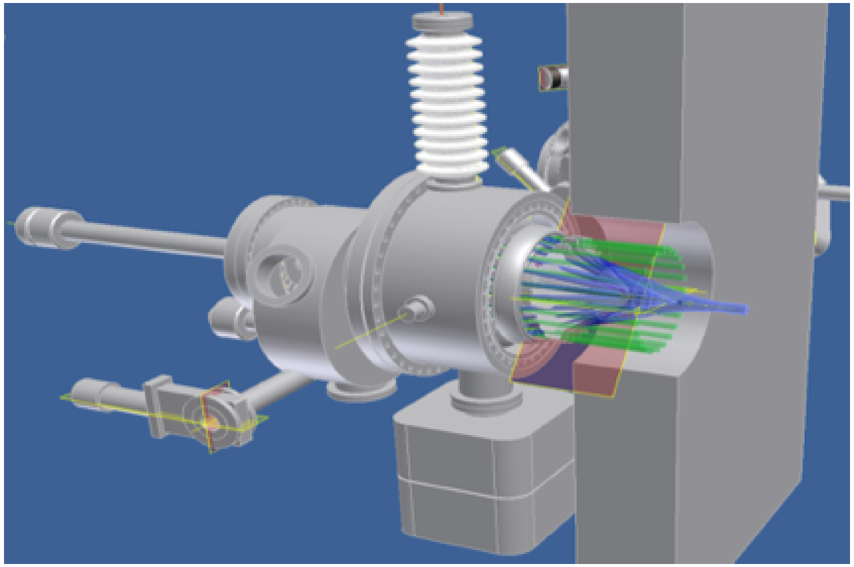
Gatling electron gun: many smaller cathodes

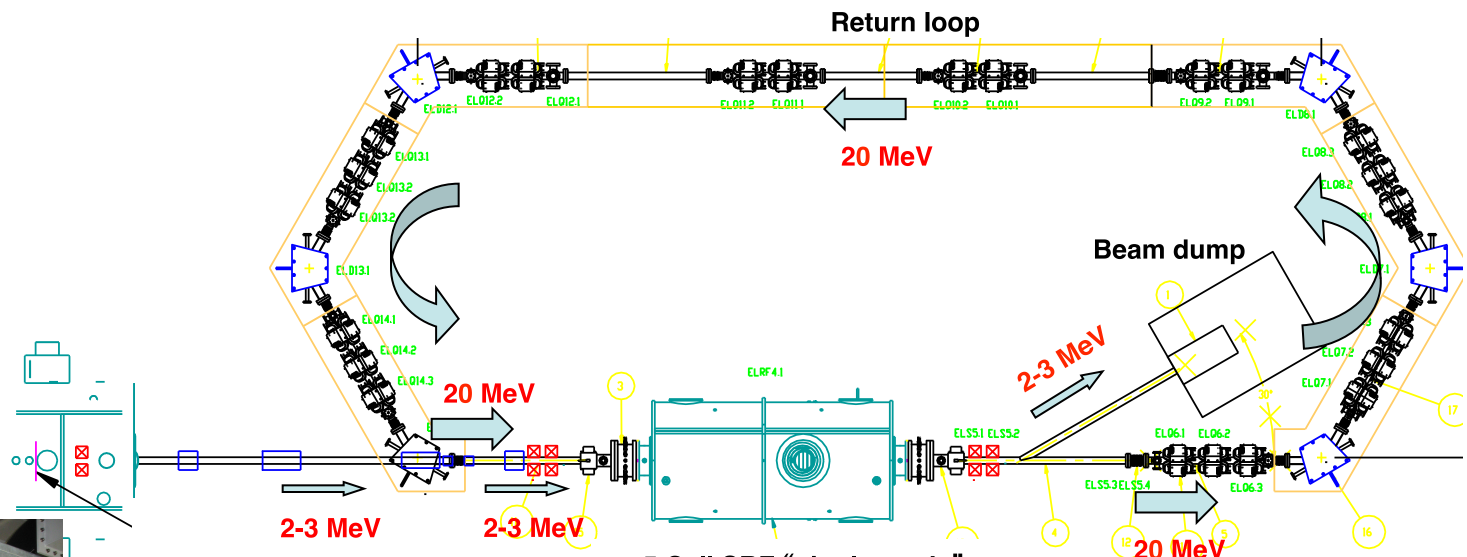




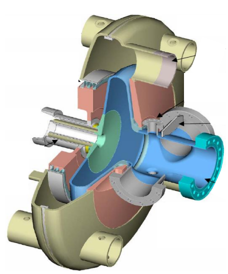
LDRD, BNL

Energy Recovery Linac (ERL) Test Facility

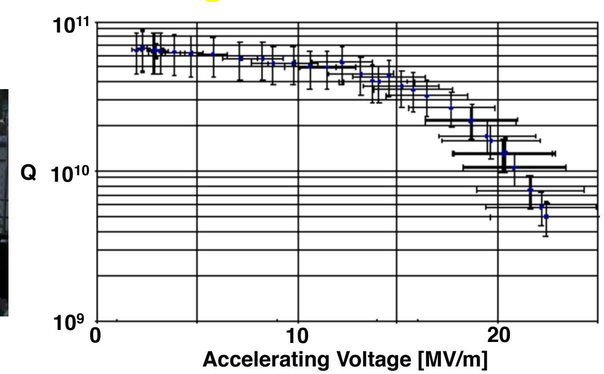
- Test of high current (0.3 A, 6-passes eRHIC), high brightness ERL operation
- Highly flexible return loop lattice to test high current beam stability issues
- Allows for addition of a 2nd recirculation loop
- Gun rf tested at 2 MV; beam from gun: ~ 4/2013; recirculating beam: 2014



SRF Gun
2MV, 0.5A

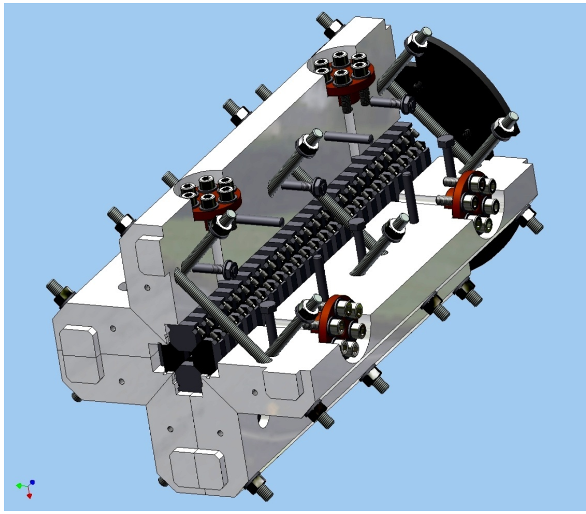


5 Cell SRF "single mode" cavity
Q > 10^{10} @20 MV/m CW



Coherent electron cooling

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high brightness electron beams and FEL technology
- ~ 20 minutes cooling time for 250 GeV protons → 10x reduced proton emittance gives high eRHIC luminosity
- Proof-of-principle demonstration planned with 40 GeV/n Au beam in RHIC (~ 2015)

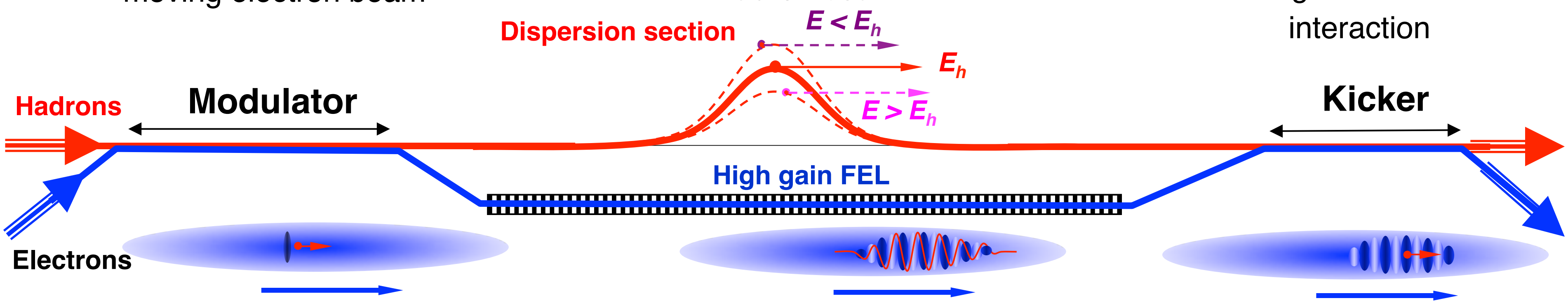


Helical wiggler prototype

Pick-up: electrostatic imprint of hadron charge distribution onto co-moving electron beam

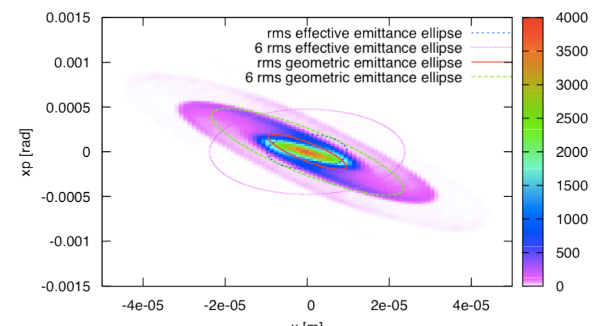
Amplifier: Free Electron Laser (FEL) with gain of 100 -1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

Kicker: electron beam corrects energy error of co-moving hadron beam through electrostatic interaction

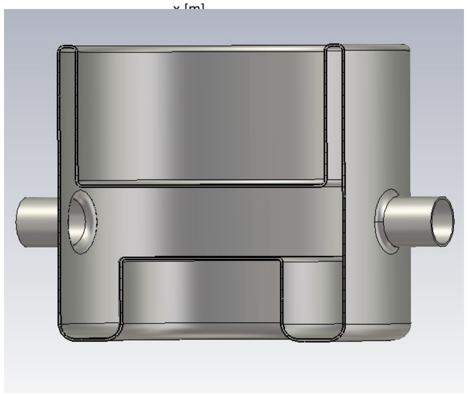


Recent developments of eRHIC design

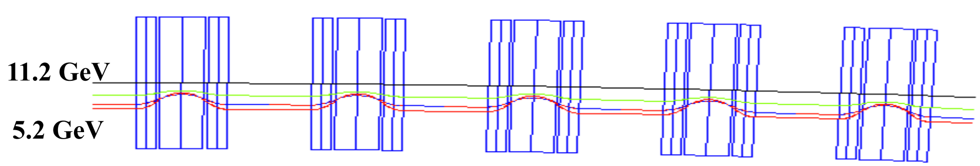
- External eRHIC design review (8/1-3/2011):
  - "The committee is highly satisfied with the material presented, covering most of the relevant subjects. The committee did not see any significant holes in the concept."
- Numerous external reviews of eRHIC R&D effort (EICAC; C-AD MACs; individual reviews of test-ERL, Gatling Gun, CeC; DOE ONP Accel. R&D review)
- Comprehensive simulations of e-beam disruption by proton beam. Acceptance of deceleration path is larger than disrupted e-beam for 8 mm magnet gap (13 mm at low energy).



- Studied effect of small gap magnets and surface roughness on impedance and energy loss and spread.



- Developed crab cavity design for eRHIC with 6 MV/m deflection gradient and no acceleration gradient.
- Large momentum acceptance arcs (FFAG) to replace multiple recirculation arcs.

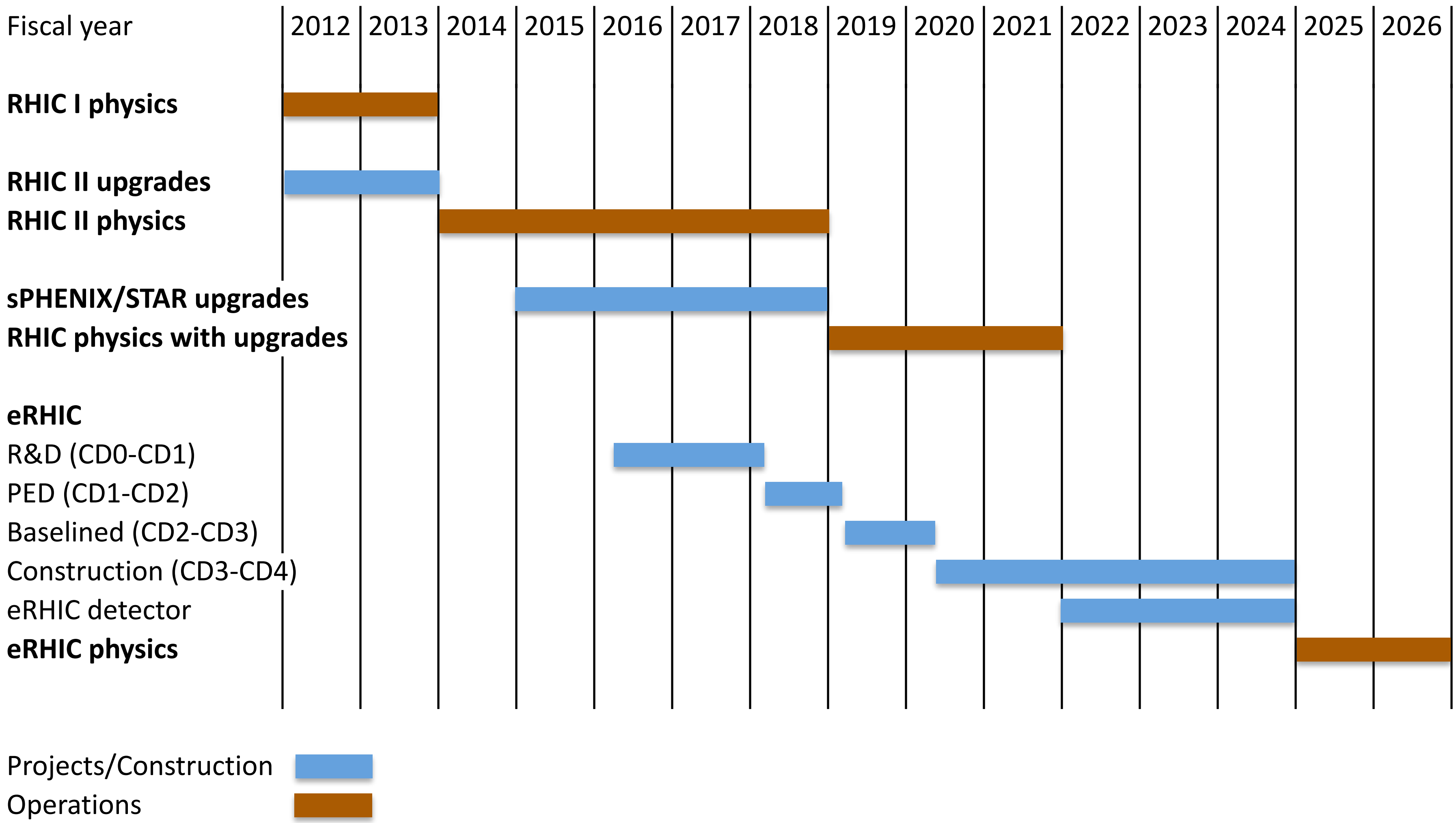


eRHIC Cost Optimization

- Bottom-up cost estimation for eRHIC first stage (5 GeV e-beam) has been done during 2012 (full TPC in FY12$ including ~ 33% average contingency, not including detector):
  - Complete cost estimate for the design with two main linacs and 6 recirculating passes in RHIC tunnel: ~ $765M TPC
  - Cost optimization for layout with 4 local recirculation passes for low energy and 2 re-circulating passes in RHIC tunnel: ~ $550M TPC
  - Note: 1st stage eRHIC scope is similar to CEBAF 6 to 12 GeV upgrade (1 GeV CW SRF linac plus 6 upgraded recirculation passes)

- Further value engineering is in progress, which could reduce the cost and/or increase performance:
  - FFAG design of recirculation passes (large momentum acceptance arcs), possibly with permanent magnets, could replace multiple passes with single pass.
  - Could reach 10 GeV electron energy for similar cost.

eRHIC schedule



Summary

- Linac-ring design of eRHIC reaches high luminosity (10^{34} cm^{-2} s^{-1}) over wide CM energy range

- Uses existing RHIC facility for HI and polarized proton beam ($2B replacement value) and existing RHIC tunnel and cryo-facility for e-beam.

- 1st stage eRHIC (5 GeV e-beam with 10^{32} - 10^{33} cm^{-2} s^{-1} initial luminosity using existing technology) has preliminary cost estimate of ~ $550M and is ready to initiate construction

- R&D under way to support highest luminosity (10^{34} cm^{-2} s^{-1}) and to achieve cost effective path to 10 GeV e-beam (FFAG arcs)

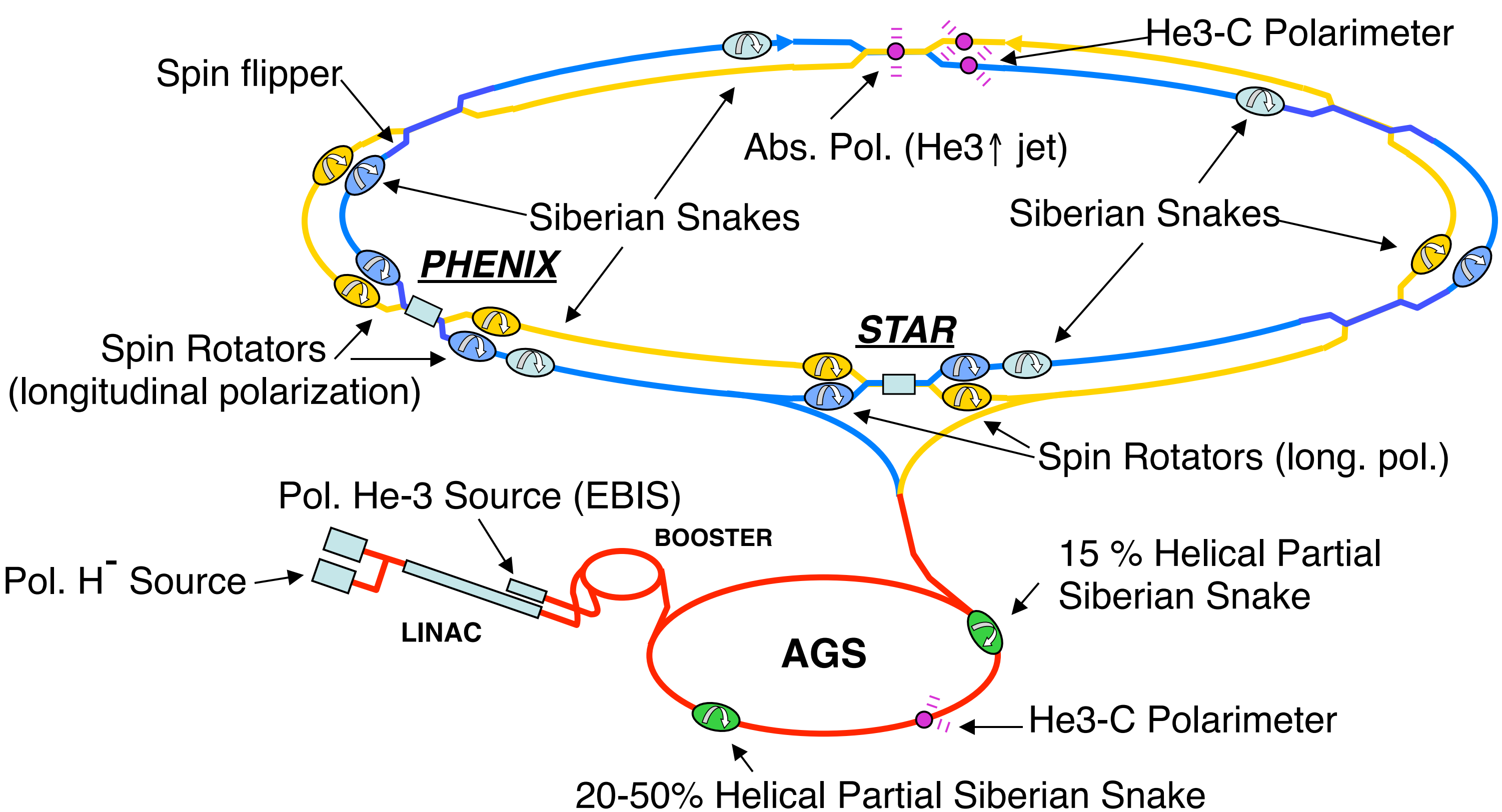
Back-up slides

Recent Reviews

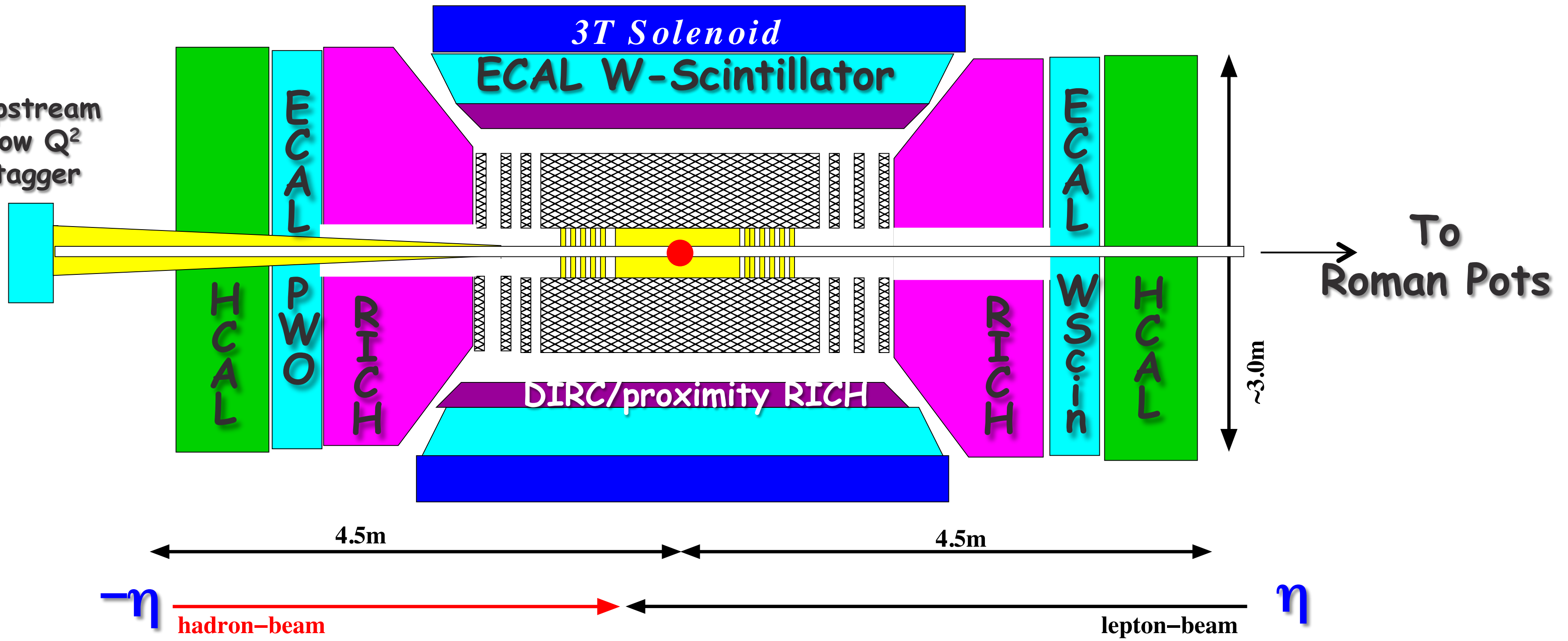
- eRHIC design review (8/2011)
  - J. Delayen (ODU), G. Ganetis (BNL), H.-C. Hseuh (BNL),V. Lebedev (FNAL), M. Poelker (TJNAF), E. Pozdeyev (MSU/NSCL), P. Wanderer (BNL), F. Zimmermann (CERN, chair)
- DOE ONP C-AD Accelerator R&D review (12/2011)
  - A. Chao (SLAC), P. Ostrumov (ANL), K. Robinson (LBNL), C. Sinclair (Cornell), J. Delayen (ODU), J. Galayda (SLAC)
- Gatling Gun Advisory Committee review (6/2012)
  - K. Aulenbacher (Mainz, Chair), A. Brachtmann (SLAC), H.-C. Hseuh (BNL), M. Poelker (TJNAF)
- Recent C-AD MAC review of test-ERL (10/2012)
  - J. Jowett (CERN), G. Krafft (TJNAF), SY Lee (Indiana) K. Ohmi (KEK), V. Shiltsev (FNAL), P. Spiller (GSI), R. Talman (Cornell), F. Zimmermann (CERN, Chair)
- CeC Proof-of-Principle review (12/2012)
  - O. Brüning (CERN), H. Padamsee (Cornell), R. Palmer (BNL), V. Lebedev (FNAL, Chair)

Polarized He-3 in RHIC

- Recent workshop to review status and R&D needs for polarized He-3 acceleration
- Polarized He-3 from new EBIS; test soon possibly starting with unpolarized He-3
- Polarimetry:
  - Relative: He3-C CNI polarimeter;
  - Absolute: He3-He3 CNI polarimeter using polarized He-3 jet
- Depolarizing res. are stronger; no depolarization expected with six snakes in RHIC



BNL: 1st Detector Design Concept



PID:

-1<η<1: DIRC or proximity focusing Aerogel-RICH

1<|η|<3: RICH

Lepton-ID:

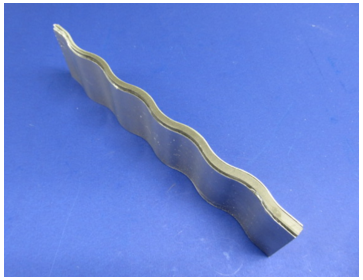
-3 <η< 3: e/p

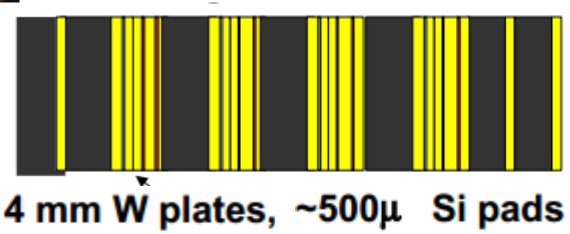
1<|η|<3: in addition Hcal response & γ suppression via tracking

|η|>3: ECal+Hcal response & γ suppression via tracking

-5<η<5: Tracking (TPC+GEM+MAPS)

Vibrant Detector R&D Program

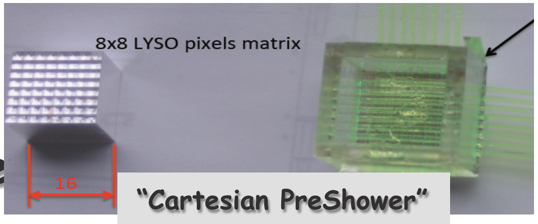




- ❑ Calorimetry
  - ➢ W-Scintillator & W-Si
    - ➢ compact and high resolution
  - ➢ Crystal calorimeters PbW & BGO

BNL, Indiana University, Penn State Univ., UCLA, USTC, TAM

- ❑ Pre-Shower
  - ➢ W-Si
  - ➢ LYSO pixel array with readout via X-Y WLS fibe

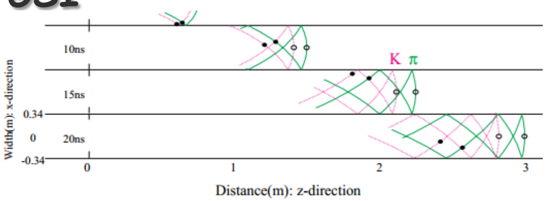


Univ. Tecnica Valparaiso

- ❑ PID via Cerenkov
  - ➢ DIRC and timing info

    Catholic Univ. of America, Old Dominion, South Carolina, JLab, GSI
  - ➢ RICH based on GEM readout
  - ➢ e-PID: GEM based TRD → eSTAR

    BNL, Indiana Univ., USTC, VECC, ANL



- ❑ Tracking

BNL, Florida Inst. Of Technology, Iowa State, LBNL, MIT, Stony Brook, Temple, Jlab, Virginia, Yale

- ➢ μ-Vertex: central and forward based on MAPS
- ➢ Central: TPC/HBD provides low mass, good momentum, dE/dx, eID
  Fast Layer: μ-Megas or PImMS

Forward: Planar GEM detectors