The Electron-Ion Collider – Accelerator Design Overview

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Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY   Jefferson Lab   U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

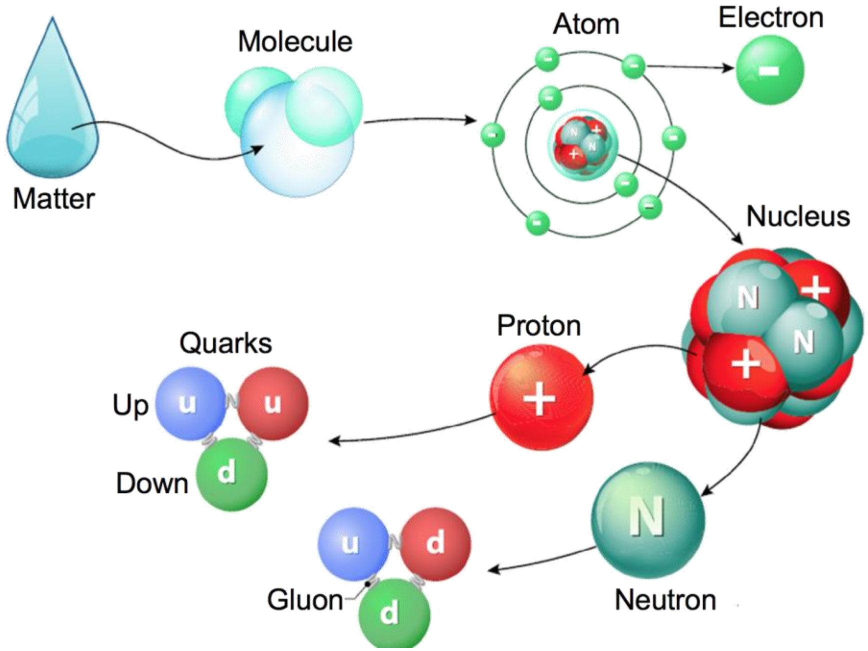
- Science case & path to project approval
- Project – very brief overview
- Accelerator design overview
- Summary

Back-of-the-envelope estimation example

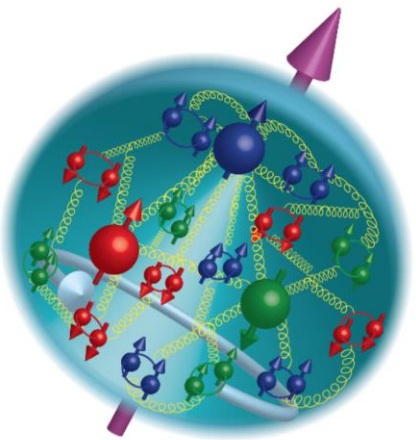
Inventive principle #21 and beam polarization

Acknowledgement: this talk includes materials from presentations of Tim Hallman (Associate Director of the DOE Office of Science for Nuclear Physics), Jim Yeck (EIC Project Director), Ferdinand Willeke (EIC Deputy Project Director and Technical Director), Elke Aschenauer and Rolf Ent (Co-Associate Directors for the Experimental Program) and many other members of EIC project team

Nucleons and Nuclei – fundamental questions



Nucleons



Mass
Spin
…

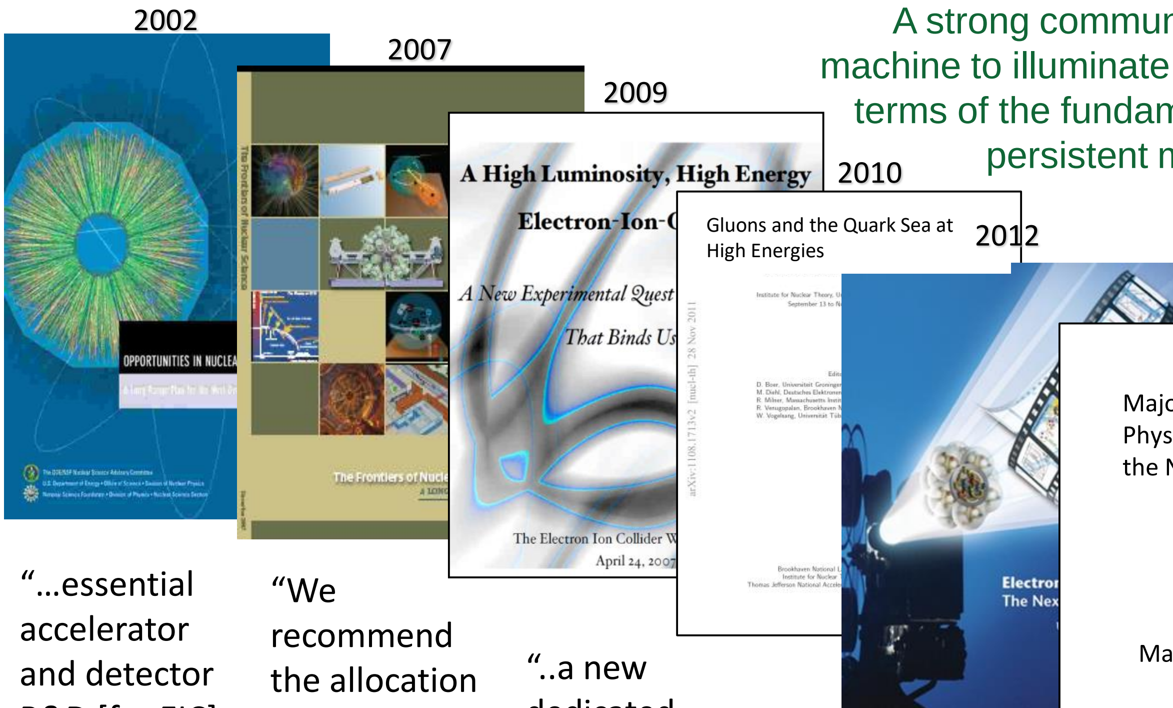
Arise out of quarks and gluons interacting through Quantum Chromodynamics (QCD)

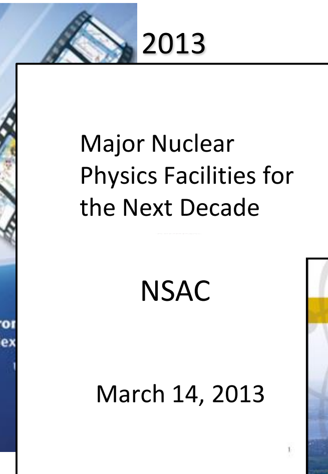
We have limited quantitative idea of how this happens because QCD is strongly coupled in the energy regime of the mass of Nucleons.

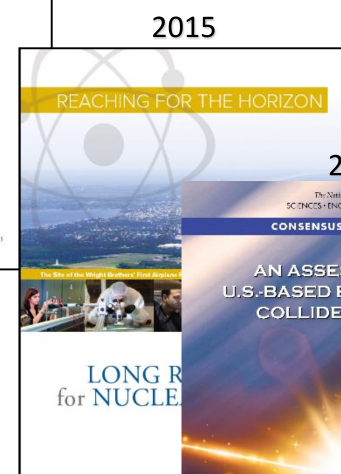
Nucleons and Nuclei and their properties can be thought of as *emergent phenomena* of QCD
We know this happens—the Quest is to understand exactly *How*.

Developing the EIC Science Case

A strong community emphasis on the urgent need for a machine to illuminate the dynamical basis of hadron structure in terms of the fundamental quark and gluon fields has been a persistent message for almost two decades







"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

"..a new dedicated facility will be essential for answering some of the most central questions."

"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider."

Electron-Ion Collider *absolutely central* to the nuclear science program of the next decade.

EIC User Community

EIC Users Group Formed in 2016
EICUG.ORG

Status July 2021:

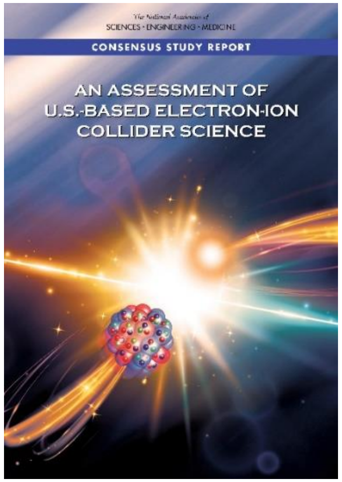
- Collaborators 1294
- Institutions 261
- Countries 35

Annual EICUG Meetings

2016	UC Berkeley
2016	Argonne
2017	Trieste, Italy
2018	Washington, DC
2019	Paris, France
2020	Miami
2021	TBD
2022	Warsaw, Poland

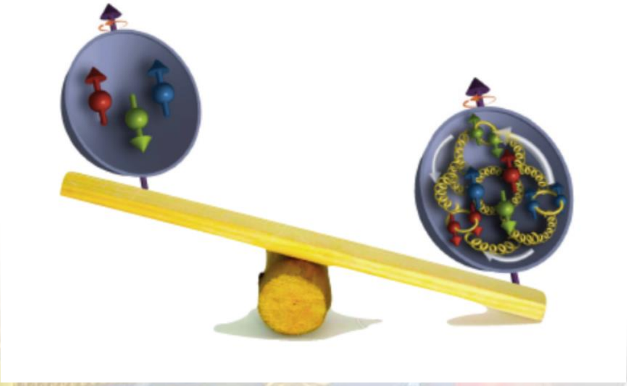
Independent Assessment of the EIC Science Goals

National Academy of Science Report: AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE



"An EIC can uniquely address three profound questions About nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

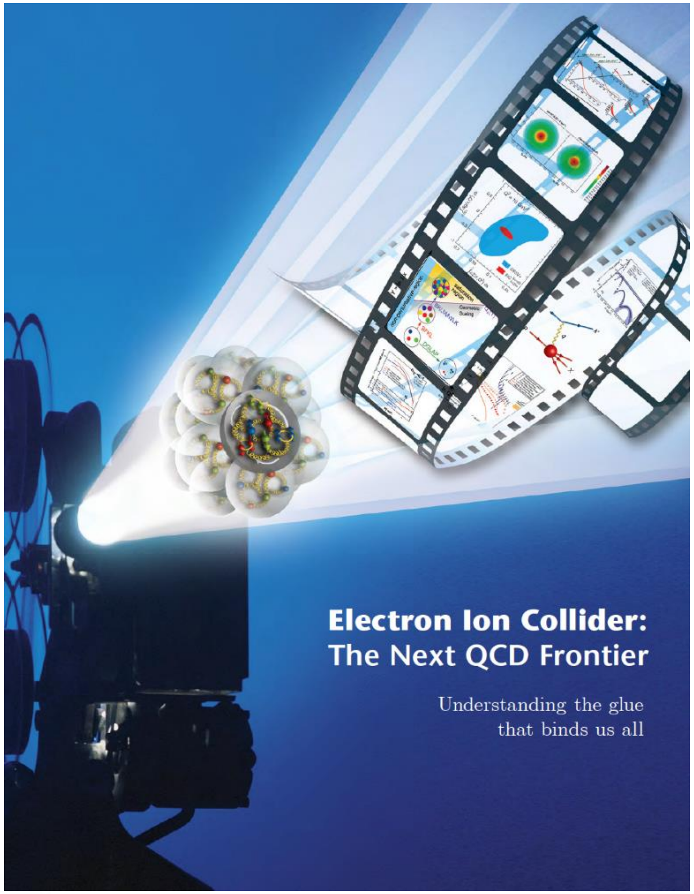
- **How does the mass of the nucleon arise?**
- **How does the spin of the nucleon arise?**
- **What are the emergent properties of dense systems of gluons?"**



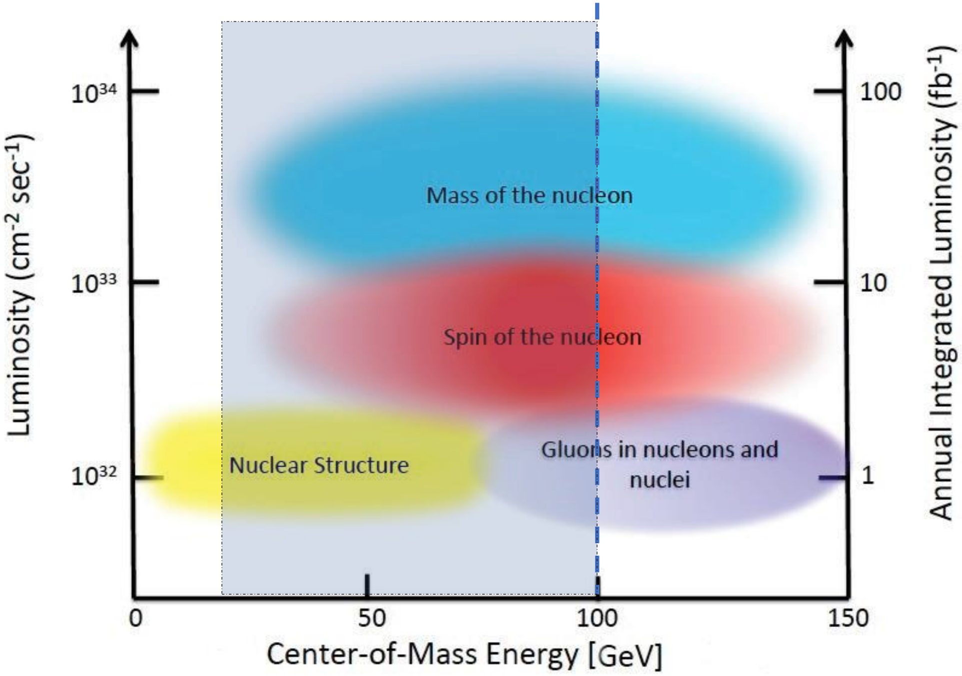
The EIC would be a unique facility & maintain leadership in nuclear science

The EIC would maintain leadership in the accelerator science and technology of colliders

NSAC 2015 LRP Performance Parameters

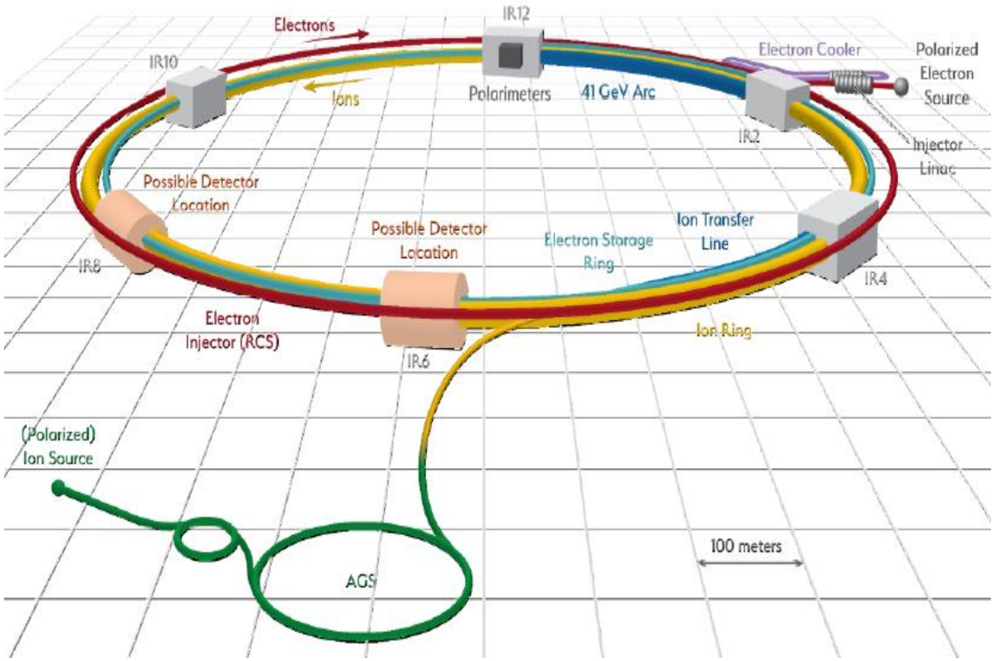


Community and NSAC defined the parameters of machine needed to address the science.



NSAC Performance Parameters:
A - Polarized e, p, light nuclei
B - Ion beam from deuterons to the heaviest table nuclei
C - Center of Mass energy 20-100 GeV
D - Capable of future Center of Mass upgrade to 140 GeV
E - High collision luminosity ~10^{33}-10^{34} cm^{-2} S^{-1}
F - More than one Interaction Region

EIC project



EIC scope includes the machine upgrade to RHIC asset and two interactions regions with one of the interaction regions outfitted with a major detector.

The EIC mission need statement (CD-0) approved by DOE in Dec 2019

The EIC will be located at BNL and will be realized with TJNAF as a major partner. The realization of the EIC will be accomplished over the next decade at an estimated cost between \$1.6 and \$2.6 billion.

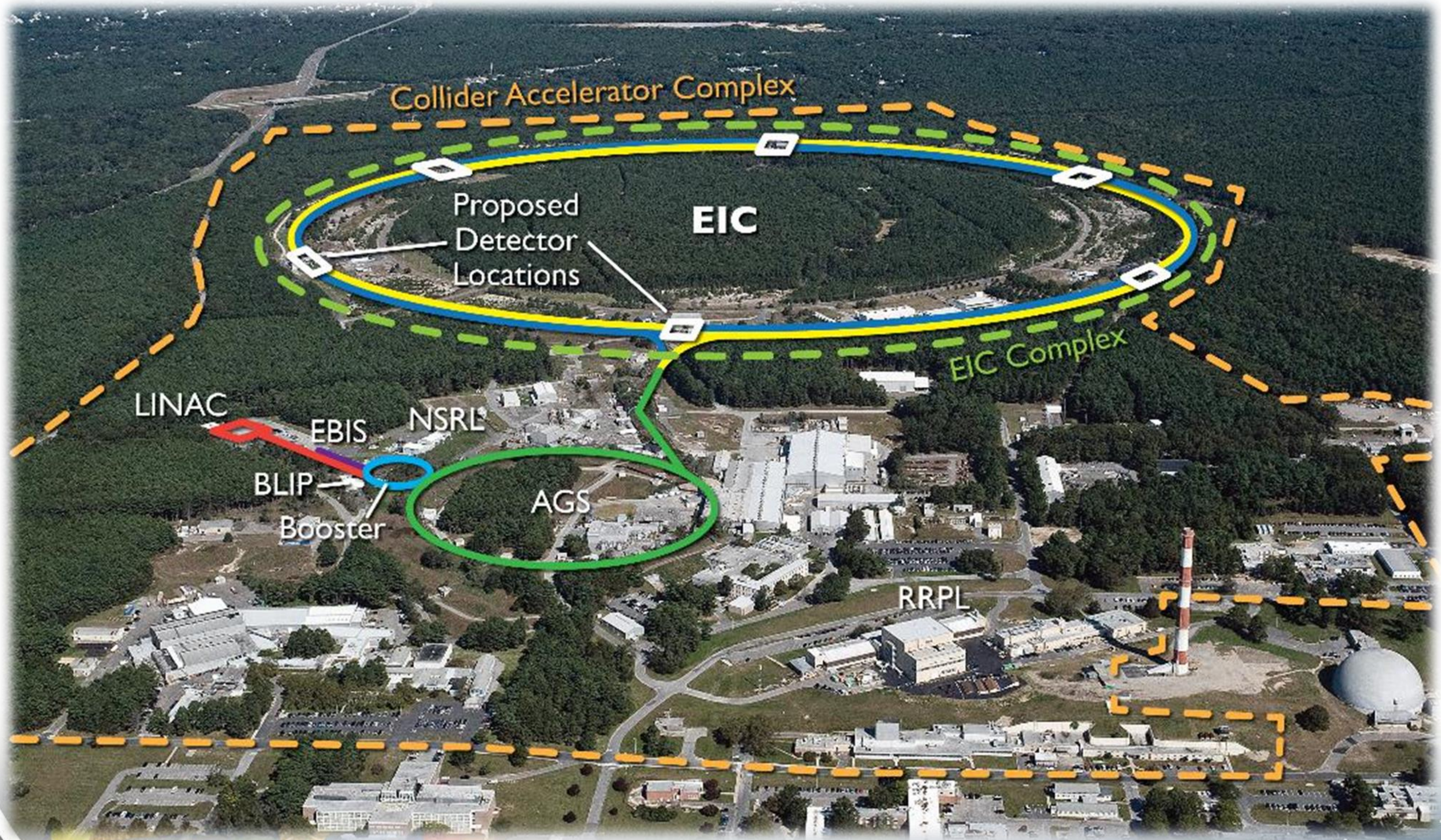
The CD1 approved in June 2021. The EIC team is working towards CD-2 in early 2023

The EIC's high luminosity and highly polarized beams will push the frontiers of accelerator science and technology and provide unprecedented insights into the building blocks and forces that hold atomic nuclei together.

Message from Tim Hallman - Associate Director of the DOE Office of Science for Nuclear Physics:

The EIC will be a game-changing resource for the international nuclear physics community. *DOE looks forward to engaging with the international community and the international funding agencies about potential collaborations and contributions to the EIC effort, in nuclear, accelerator and computer science.*

EIC Design Overview



EIC CDR: https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

EIC project requirements

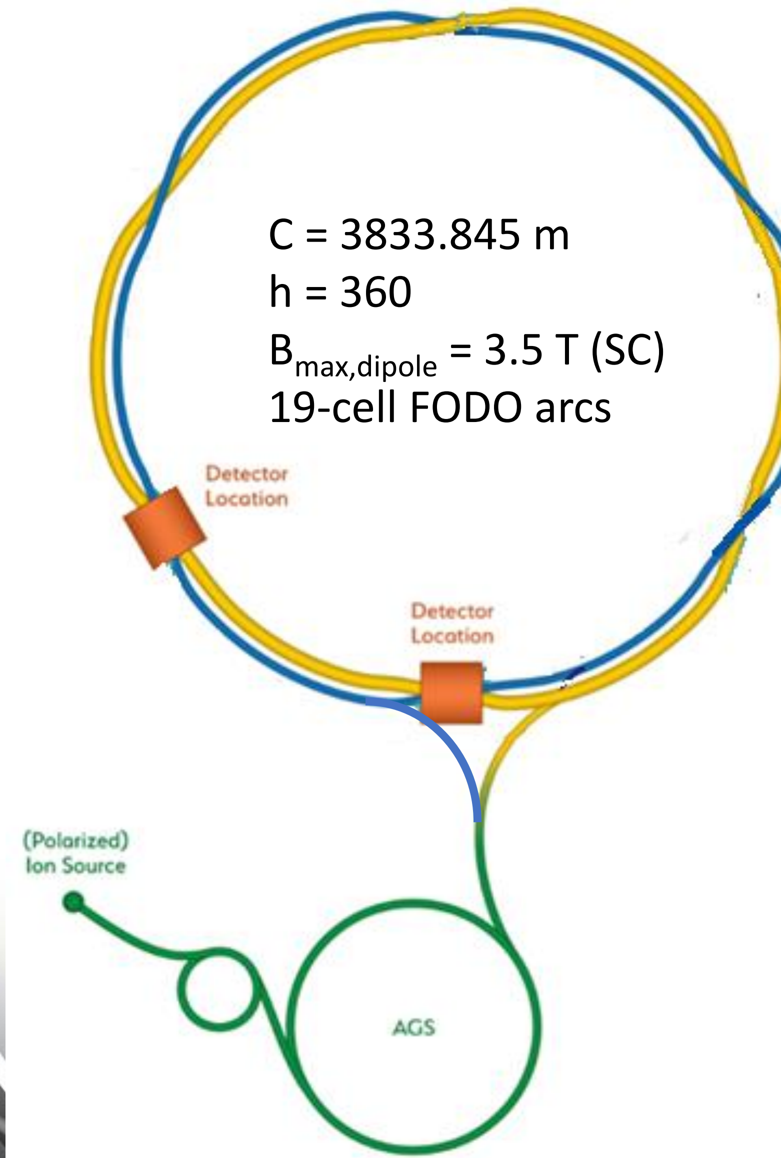
The EIC is a Nuclear Physics Collider Designed to meet NSAC and NAS requirements

- Collide polarized electrons and wide range of hadrons
  - Polarized protons and deuterons, otherwise unpolarized
  - In long term, possibly polarized positrons, ^3He

• Center of Mass Energies	20 GeV – 140 GeV
• Maximum Luminosity	10^{34} cm^{-2} s^{-1}
• Hadron Beam Polarization	>70%
• Electron Beam Polarization	>70%
• Ion Species Range	p to Uranium
• Number of interaction regions	up to two

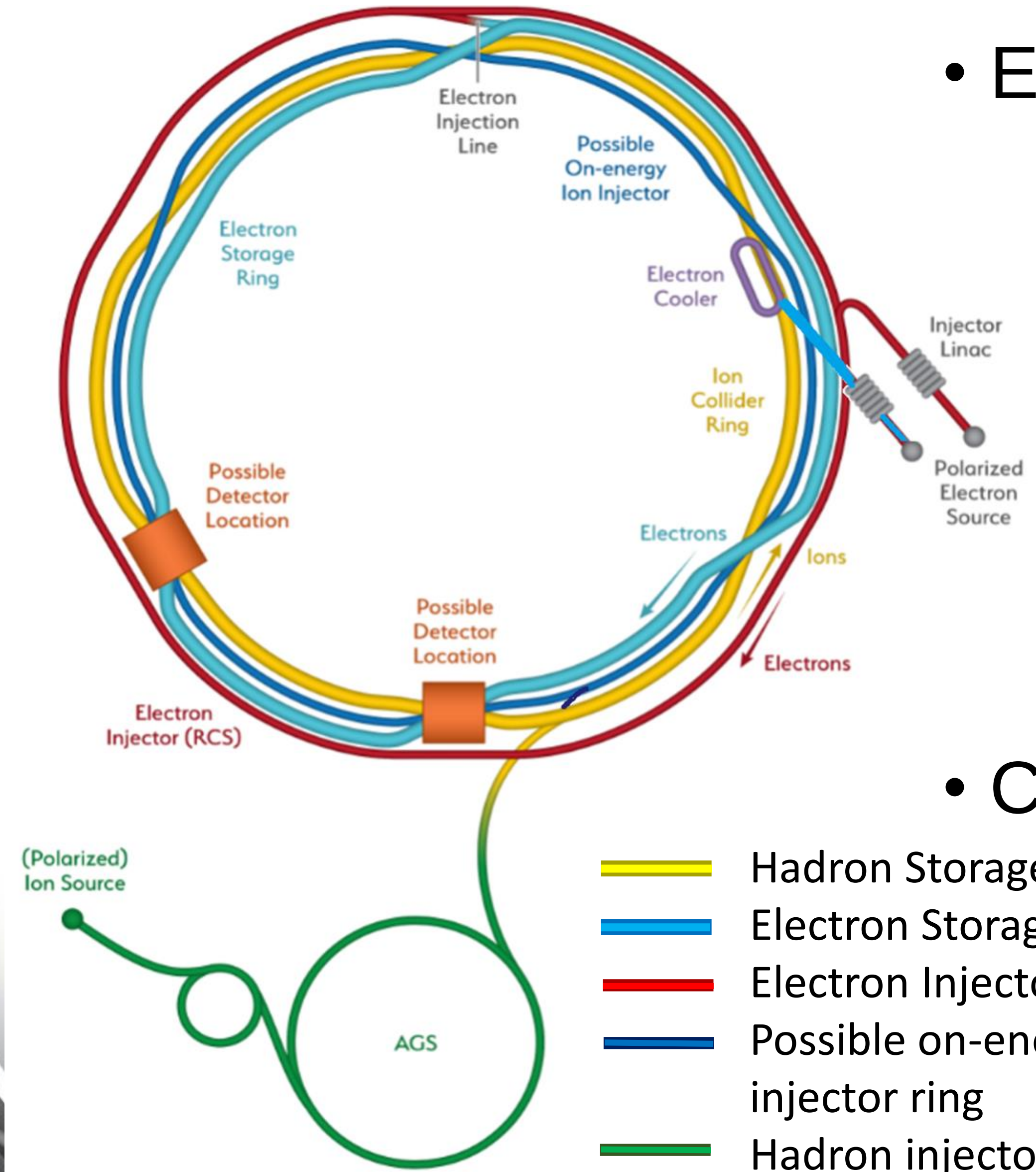
NSAC – U.S. Department of Energy Nuclear Science Advisory Committee
NAS – U.S. National Academies of Sciences, Engineering, and Medicine

From RHIC to the EIC: RHIC



- Existing RHIC facility
  - Hadron collider (h=360)
  - 6-100 GeV/u ions
  - 100-250 GeV polarized protons
  - Two independent rings
    - Asymmetric operations include e.g. d-Au collisions
- Constructed 1990-2000
- Will operate to ~2025

From RHIC to the EIC: EIC

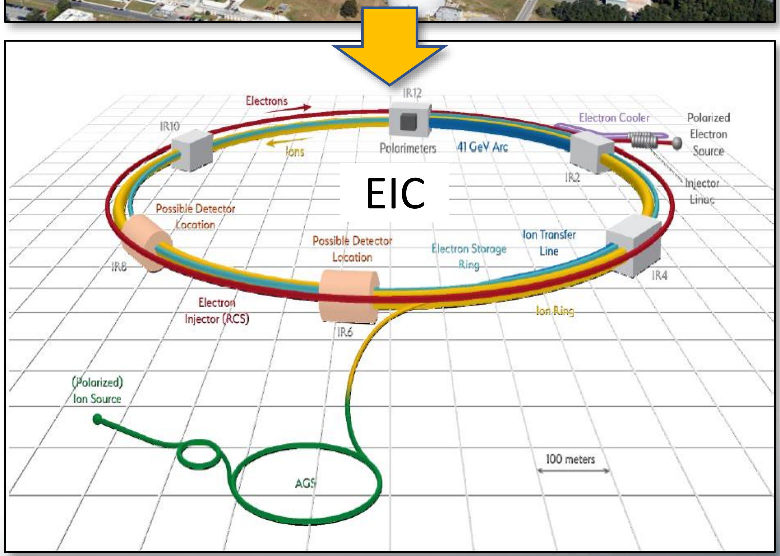


- Electron-Ion Collider
  - Lepton-hadron collider
  - Add electron storage ring
  - Add electron injectors
    - Full-size rapid-cycling synchrotron
  - Add “strong” electron cooling (ERL and insertion)
  - Add new detector
- Construction 2023-2030

EIC Design Concept

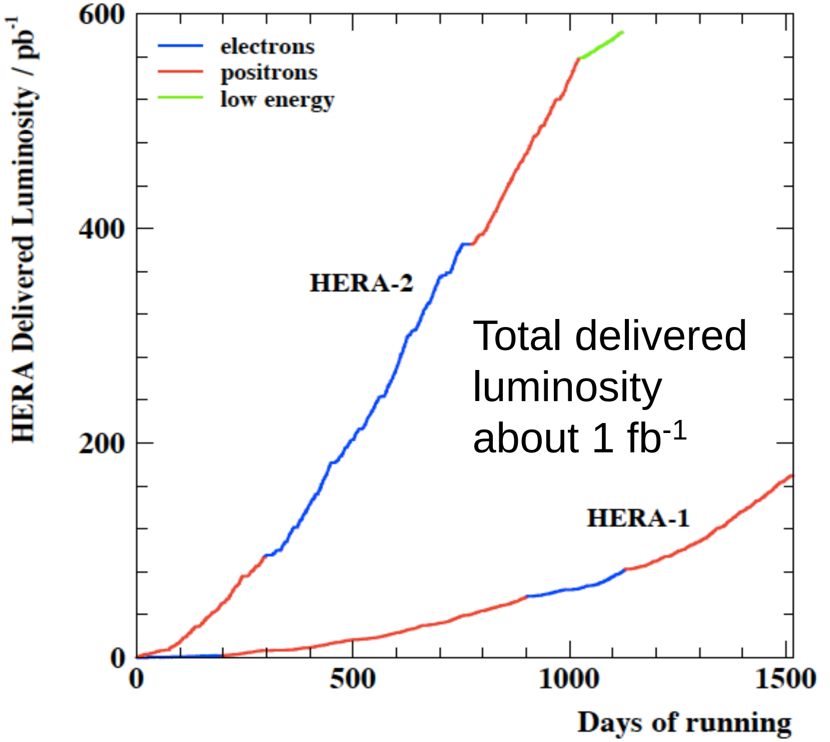
Design based on **existing** RHIC facility
RHIC is well-maintained, operating at its peak

- **Hadron storage ring 40-275 GeV** (existing)
  - Many bunches (max 1160)
  - Bright beam emittances (for hadrons)
  - Need **strong cooling**
- **Electron storage ring 2.5–18 GeV** (new)
  - Many bunches (max 1160)
  - Large beam current (2.5 A) ➔10 MW SR power
- **Electron rapid cycling synchrotron** (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (new)
  - Luminosities up to 10^{34} cm^{-2} s^{-1}
  - Superconducting magnets
  - 25 mrad crossing angle with crab cavities
  - Spin rotators (longitudinal spin)
  - Forward hadron instrumentation



HERA lessons

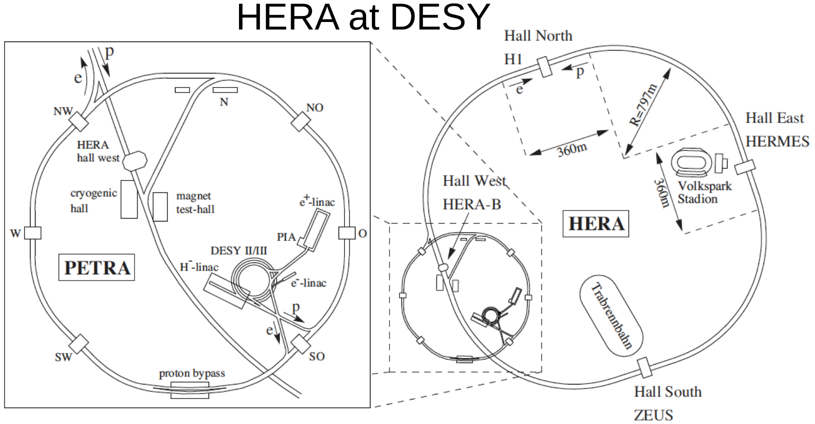
- The first and only lepton-hadron collider, operated for physics 1992-2007
- Collided 27.5 GeV spin polarized leptons (e+; e-) with 920 GeV protons
- Reached luminosity of 5×10^{31} cm^{-2} s^{-1}
- HERA lessons relevant for EIC
  - Vertical beam-beam tune shift for lepton beam reached values planned for EIC
  - The necessity to minimize synchrotron radiation in the IR, IR vacuum pressure, and to avoid halo of the proton beam



B-Factories lessons

- When B factories design started ~1990, e+e- colliders barely reached 10^{32} cm^{-2}s^{-1}
- PEP-II and KEKB aimed in their design to luminosity of 0.3 – 1 x 10^{34} cm^{-2} s^{-1}
  - Achieved and even exceeded the goals
- Approach: build-in necessary features to achieve high Lumi into the design
  - Crossing angle and crab cavity; Local chromaticity correction; RF cavities and vacuum chamber compatible with ampere-scale beams; Bunch-by-bunch feedback; Continuous top-up injection

HERA at DESY



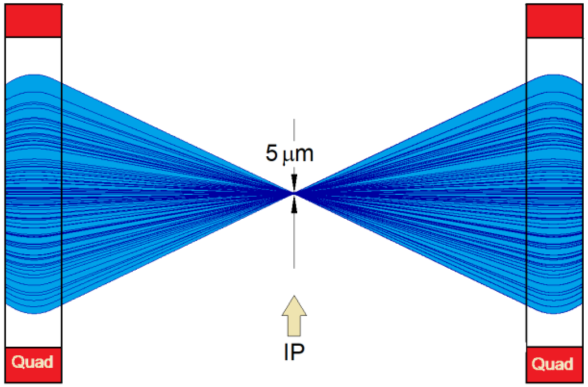
F. Willeke, HERA and the Next Generation of Lepton-Ion Colliders", in Proc. of EPAC'06 , Edinburgh, paper FRXBPA01

EIC achieves high luminosity $L = 10^{34}\,cm^{-2}s^{-1}$

- **Large bunch charges** $N_e \leq 1.7\cdot10^{11}$, $N_p \leq 0.69\cdot10^{11}$

- **Many bunches,** n_b=1160
  - crossing angle collision geometry
  - large total beam currents
  - limited by installed RF power of 10 MW

Strong focusing β_y =5 cm



- **Small beam size** at collision point achieved by
  - small emittance, requiring either:
    - strong hadron cooling to prevent emittance growth **or**
    - frequent hadron injection
  - and strong focusing at interaction point (small β_y)
  - flat beams $\sigma_x/\sigma_y \approx 10$

- **Strong, but previously demonstrated beam-beam interactions**

$\Delta\nu_p$ = 0.01 demonstrated in RHIC

$\Delta\nu_e$ = 0.1 demonstrated in HERA, B-factories

Electron-Ion Collider

EIC covers full center of mass energy range of 20 GeV – 140 GeV

Protons up to 275 GeV:

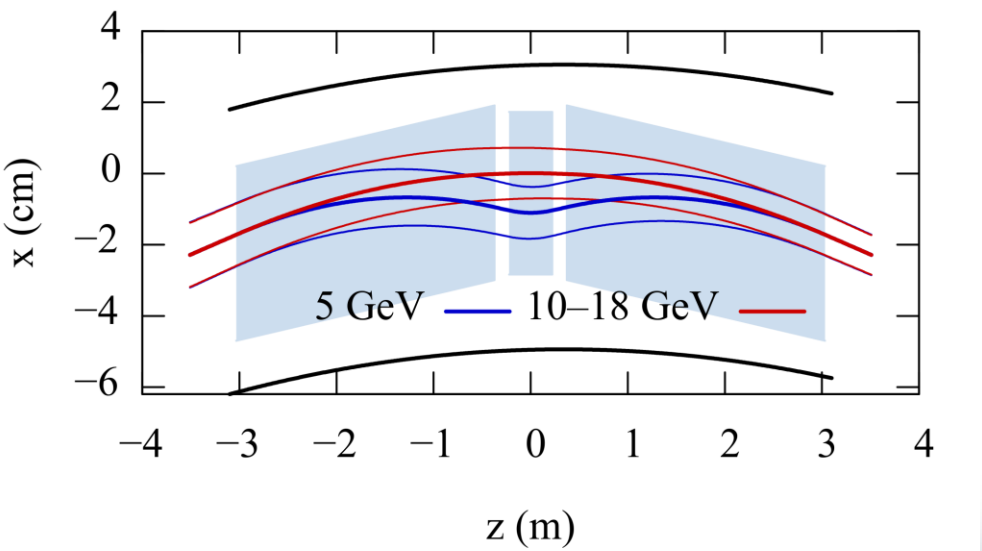
- Existing RHIC with superconducting magnets allow up to **E_p = 275 GeV** and down to **E_p = 41 GeV**
- RHIC beam parameters are close to what is required for EIC

Electrons up to 18 GeV:

Electron storage ring with up to **18 GeV** installed RHIC tunnel,

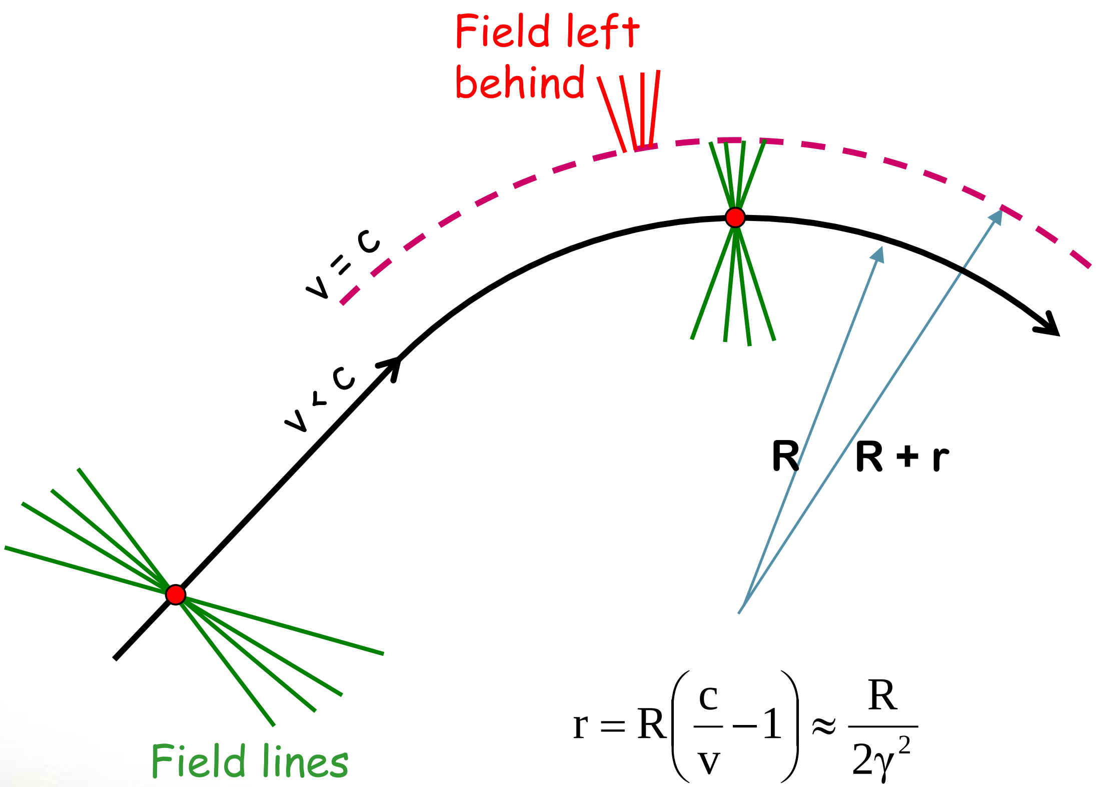
readily achievable with

- large circumference of 3870 m and
- available superconducting RF technology ➔ U_{rf} = 62 MV



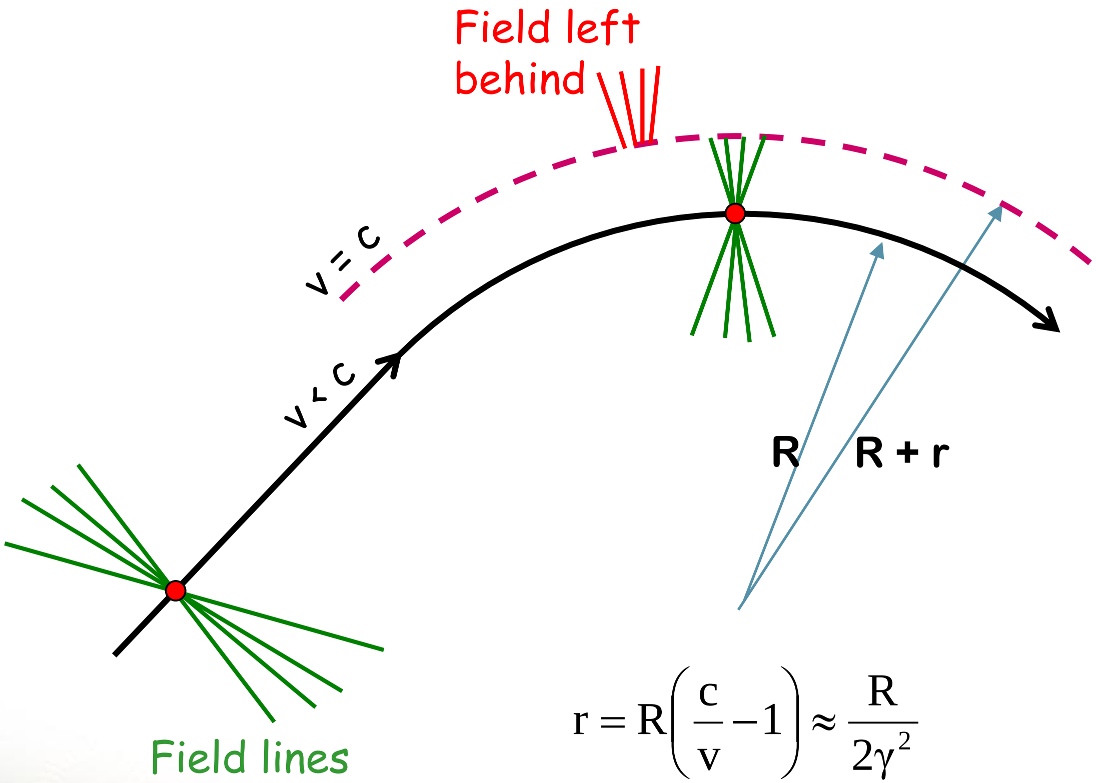
Super bends: Electron Storage Ring arc dipoles split into 3 segments
Above 10 GeV all segments powered uniformly to reduce SR power
At 5 GeV and below, short center dipole provides a reverse bend to increase damping decrement

Synchrotron radiation
on-the-back-of-the envelope – power loss



$$r = R\left(\frac{c}{v} - 1\right) \approx \frac{R}{2\gamma^2}$$

Synchrotron radiation
on-the-back-of-the envelope – power loss

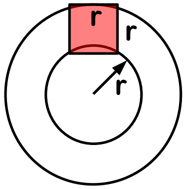


$$r = R\left(\frac{c}{v} - 1\right) \approx \frac{R}{2\gamma^2}$$

Energy in the field left behind (radiated !):

$$W \approx \int E^2\, dV$$

The field $E \approx \frac{e}{r^2}$ **the volume** $V \approx r^2\, dS$



Energy loss per unit length:

$$\frac{dW}{dS} \approx E^2 r^2 \approx \left(\frac{e}{r^2}\right)^2 r^2$$

Substitute $r \approx \frac{R}{2\gamma^2}$ **and get an estimate:**

$$\boxed{\frac{dW}{dS} \approx \frac{e^2\gamma^4}{R^2}}$$

Gaussian units on this page!

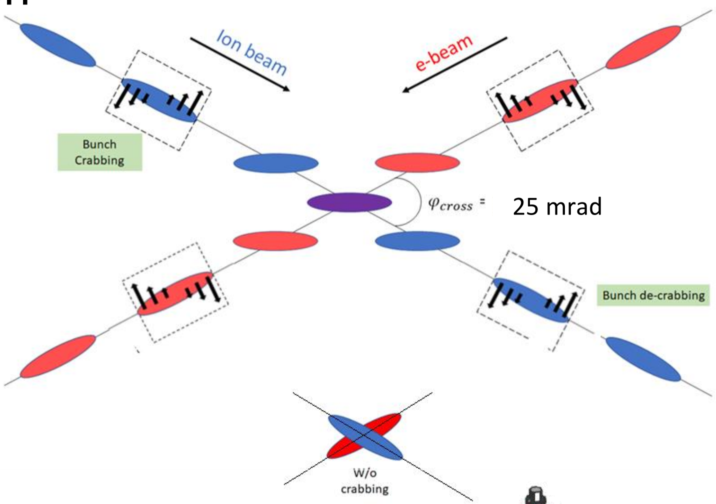
Compare with exact formula: $\frac{dW}{dS} = \frac{2}{3}\frac{e^2\gamma^4}{R^2}$ **or** $\frac{dW}{dS} = \frac{2}{3}\frac{r_e\gamma^4}{R^2}mc^2$

EIC High Luminosity with a Crossing Angle

- **Modest crossing angle of 25 mrad**
  - Avoid parasitic collisions due to short bunch spacing
  - For machine elements, to improve detection
  - Reduce detector background

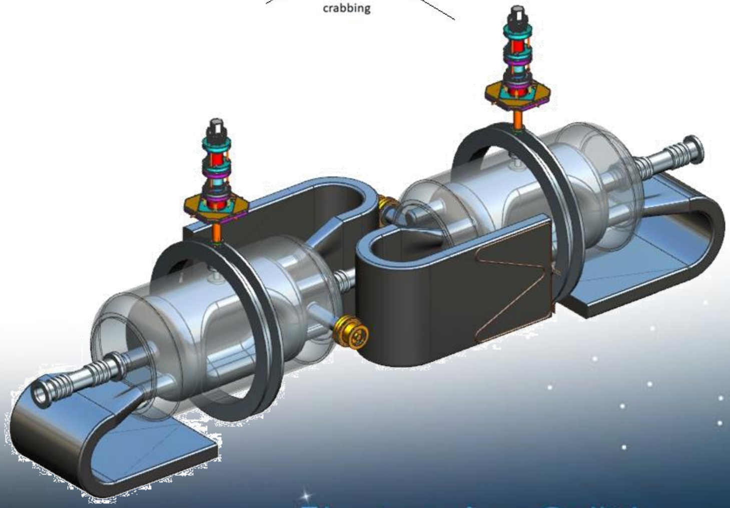
- **However**, crossing angle causes
  - Low luminosity
  - Beam dynamics issues

- **avoided by Crab Crossing**



Then :
  - Effective head-on collision restored
  - Beam dynamic issues resolved

- RF resonator (crab-cavity) prototypes built and tested with proton beam in the CERN-SPS
  - The EIC crab-cavity need large waveguide ports to allow the trapped modes to escape



EIC Design Parameters

Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

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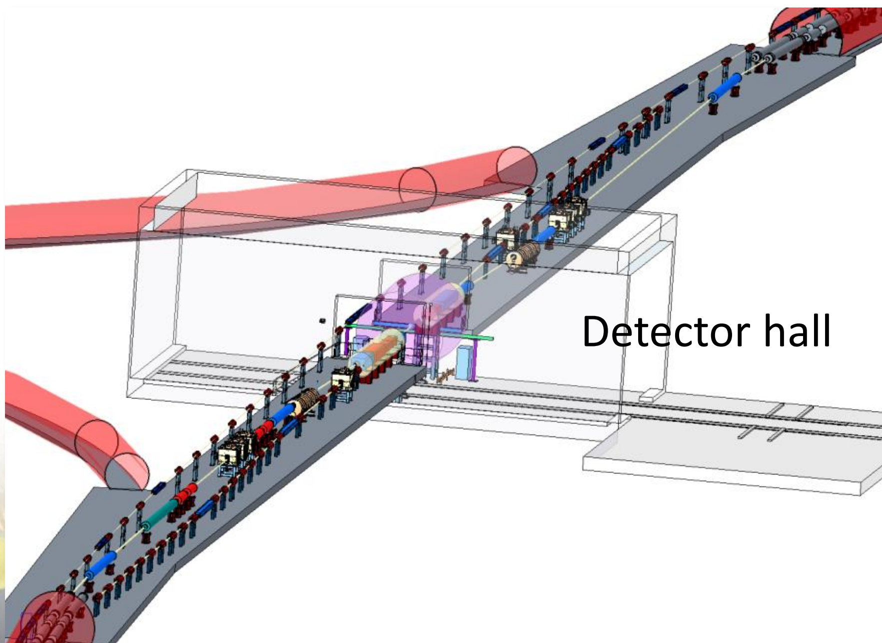
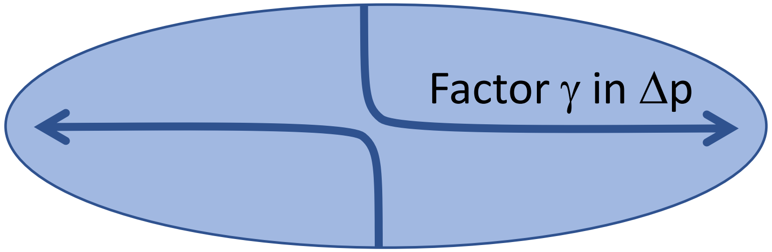
EIC Interaction Region

- Beam focused to $\beta_y \leq 5$ cm @ $\sigma_y = 5\ \mu$m, gives $L = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- Manageable IR chromaticity and sufficient dynamic aperture
- Full acceptance for the colliding beam detector
- Accommodates crab cavities and spin rotators
- Synchrotron radiation and impedance manageable
- EIC final focus magnets based on conventional NbTi superconducting magnets using collaring and direct wind technology



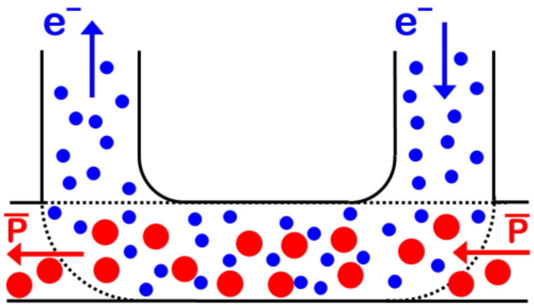
The need for beam cooling – IBS

- Intrabeam Scattering (IBS): Lorentz boosted Coulomb scattering inside bunches

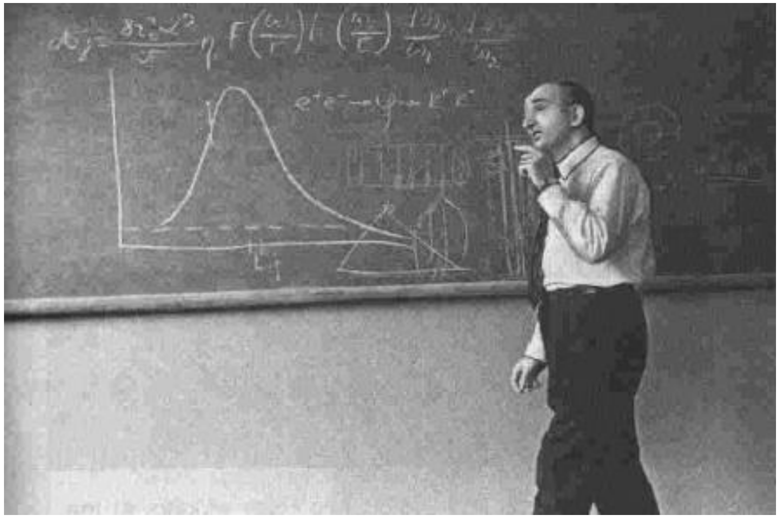


- Higher charge and smaller emittances increase IBS growth rate
- IBS can be partially mitigated by reducing dispersion and increasing energy spread
- IBS rates for EIC parameters ~2 hour
- Beam cooling methods needed to counteract IBS

Electron Cooling



Electron cooling concept

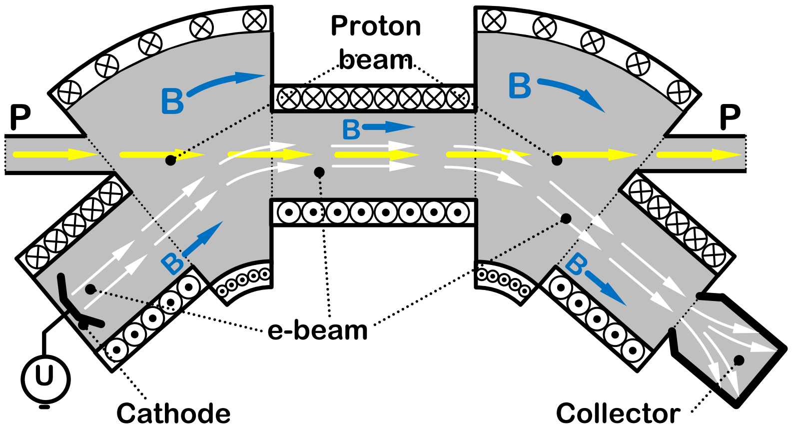


Budker G.I., Effective method of damping particle oscillations at proton antiproton storage rings, Atomic Energy 1967, v.22, №5, p.346

When electron cooling idea was first presented (1966), the common opinion of the community was – "brilliant idea, but unfortunately non-realistic"

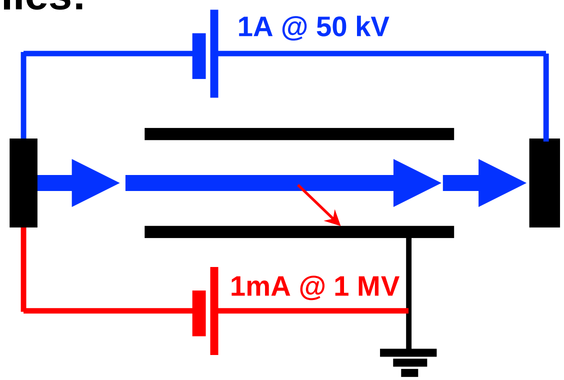
First e-cooler at INP, Novosibirsk, ~1974

Electron Cooling & Energy Recovery



Typical scheme of a standard electron cooler for low energy range (~several tens MeV of p energy)

- **Standard electron cooling use energy recovery**
  - **For example, if we need 1A @ 1MeV electron beam*, it does not mean we need 1 MW power supply**
- **Typical arrangements of e-cooler power supplies:**



- **Losses of 1A e-beam due to interaction with p-beam or scattering are low**
- **Thus, power of 1MV power supply is defined by e-beam losses and can be much lower than 1MW, just 1kW in example above**

* Numbers are for illustration only

Electron Cooling & Electron Beam Magnetization

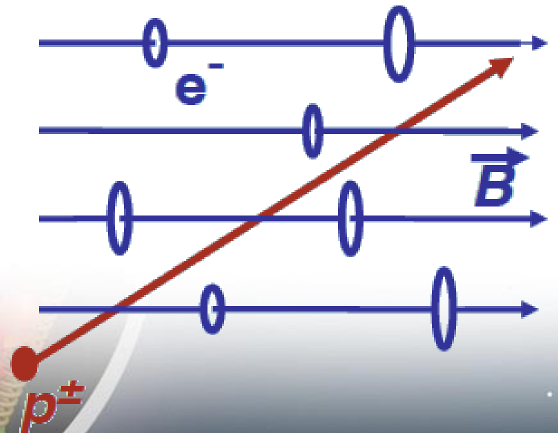
Initial measurements at INP show cooling time of 17 s (protons, 65 MeV)
There was expectation that protons will cool to equilibrium temperature of 1000K (cathode temperature)

$$\frac{MV_i^2}{2} = \frac{mV_e^2}{2} = T_{equilibrium}$$

However, after alignment improvement of the magnetic system, the cooling time became 0.05 s, consistent with electron beam temperature 1K
Reasons:
1) Longitudinal T of electrons flattens due to acceleration:

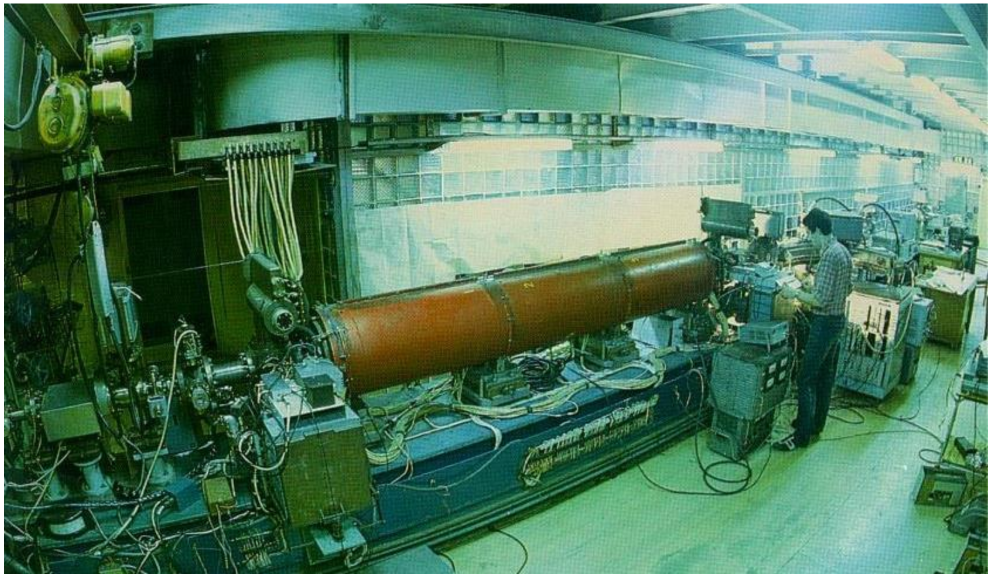
$$T_{//} = \frac{T^2_{Cathode}}{\beta^2 \gamma^2 mc^2}$$

2) Transverse T of electrons does not play any role if Larmor radius << $n^{-1/3}$

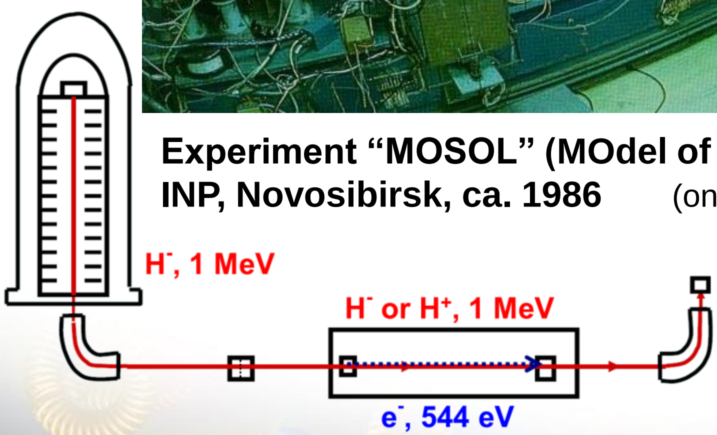


The magnetization effects in electron cooling, Ya. Derbenev, A. Skrinsky, Rus. Plasma Physics, v.4 (1978) 492

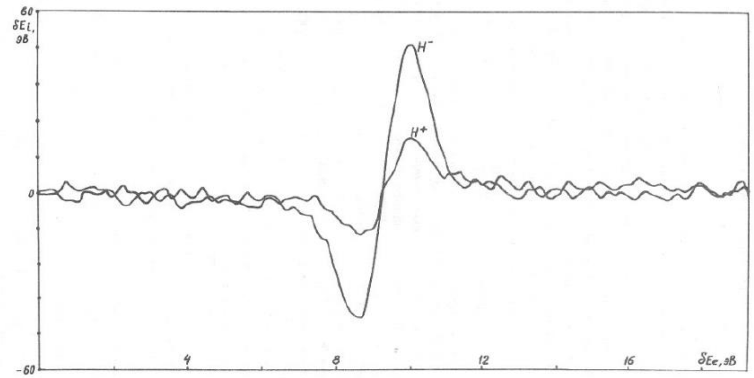
Single Pass Electron Cooling Experiment



Experiment "MOSOL" (MOdel of SOLenoid) – Budker INP, Novosibirsk, ca. 1986 (on the photo – today's speaker)



Magnetization effects allowed to observe the difference of the e-cooling friction force (which is normally $\sim e^2Z^2$) on the charge of the particle

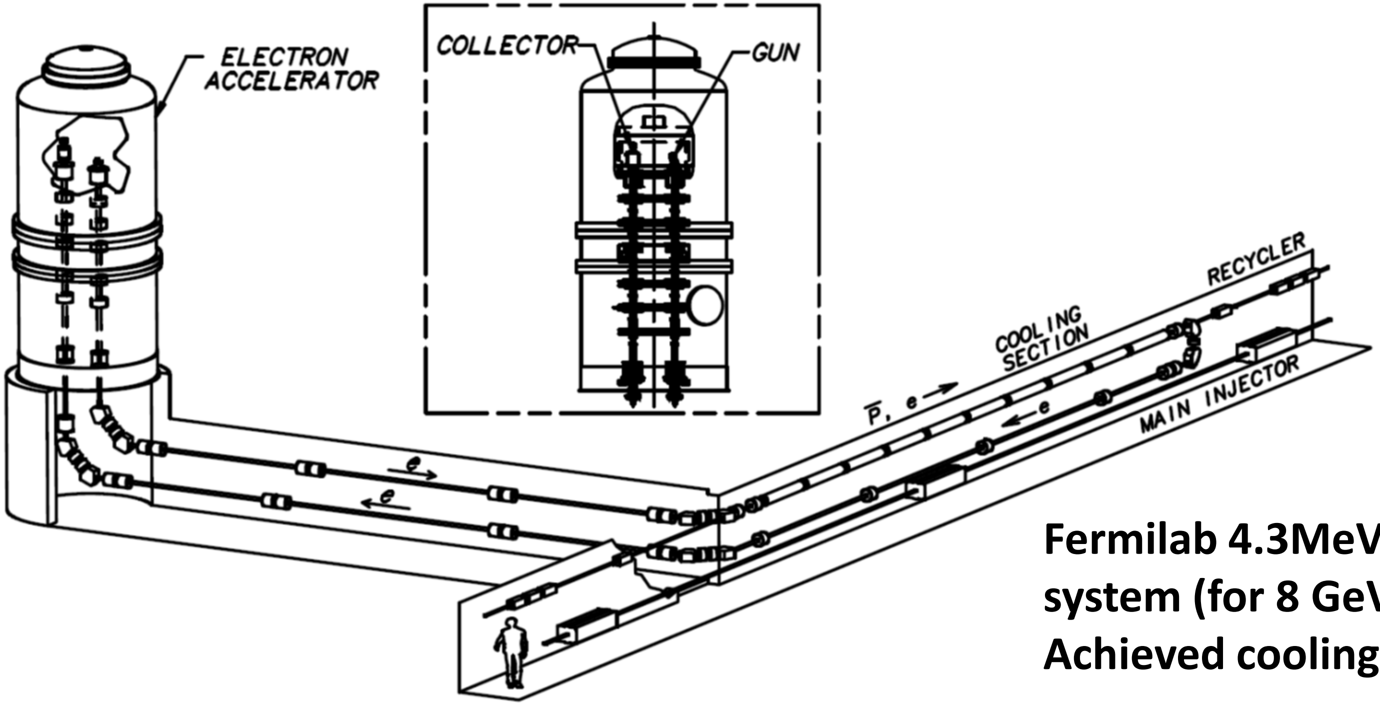


Experiment at MOSOL revealed large difference in cooling force for positive and negative particles

Reason: in magnetized case and low relative velocity, the negative ion reflects the electron, making a large momentum transfer, while for positive ion the electron is first attracted and then pulled back, minimizing momentum transfer

Taking Electron Colling to higher energy

- **Energy recovery is even more important for high energy electron cooling**



Fermilab 4.3MeV electron cooling system (for 8 GeV antiprotons) Achieved cooling times ~0.5 hours

- **The electron cooling time has a very unfavourable beam energy scaling ~$\gamma^{2.5}$**
- **Mitigating scaling dependence by a) increasing cooling section length; b) higher electron current – has practical limits**

- **For 41-257 GeV energy of EIC proton beam – standard electron cooling would be extremely challenging**

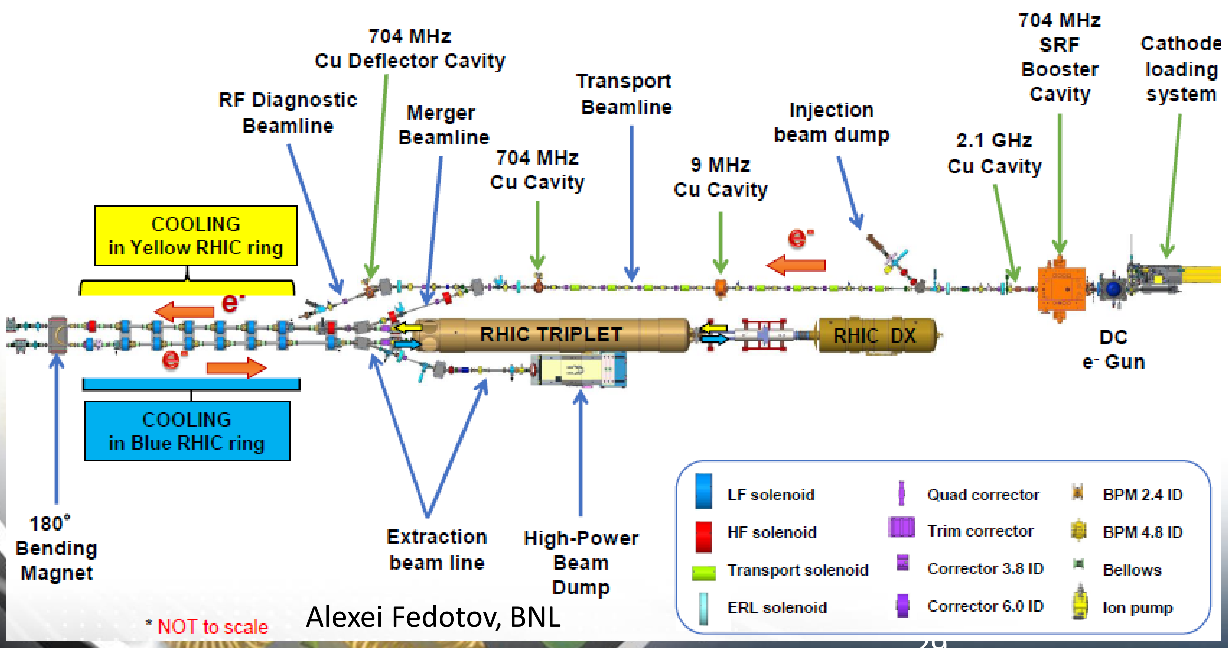
Getting electron cooling to higher energy

Low-Energy RHIC electron Cooler (LEReC) at BNL:

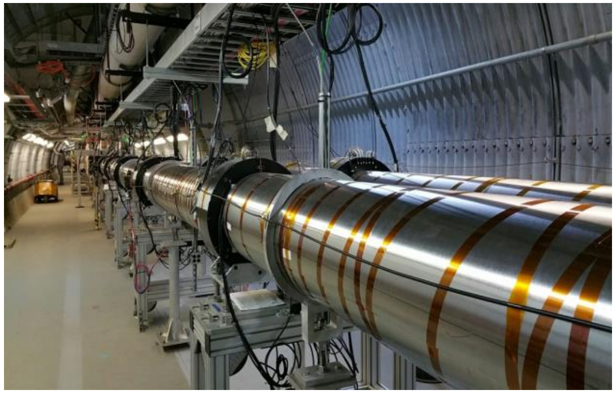
- First e-cooler based on the RF acceleration of e-beam (of up to 2.6 MeV energy)
- **Observation of first cooling using bunched electron beam on April 5, 2019**
- LEReC will be used in RHIC Beam Energy Scan II for Low energy ($\sqrt{s_{NN}}$ = 7.7, 9.1, 11.5, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity
- Cooling using bunched electron beam produced with RF acceleration is new, and opens the possibility of electron cooling at high beam energies

LEReC Accelerator

(100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF systems, including one SRF, many magnets and instrumentation)



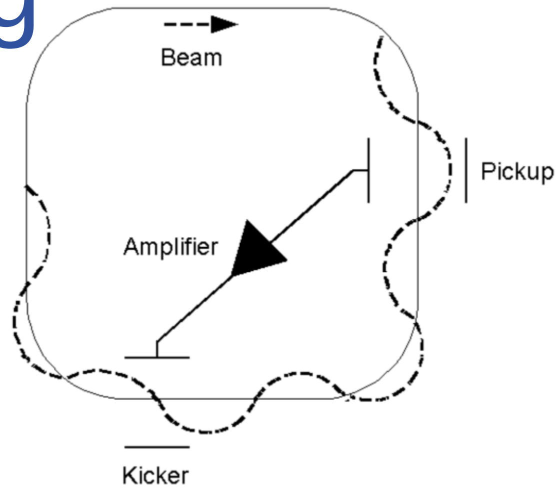
Alexei Fedotov, BNL



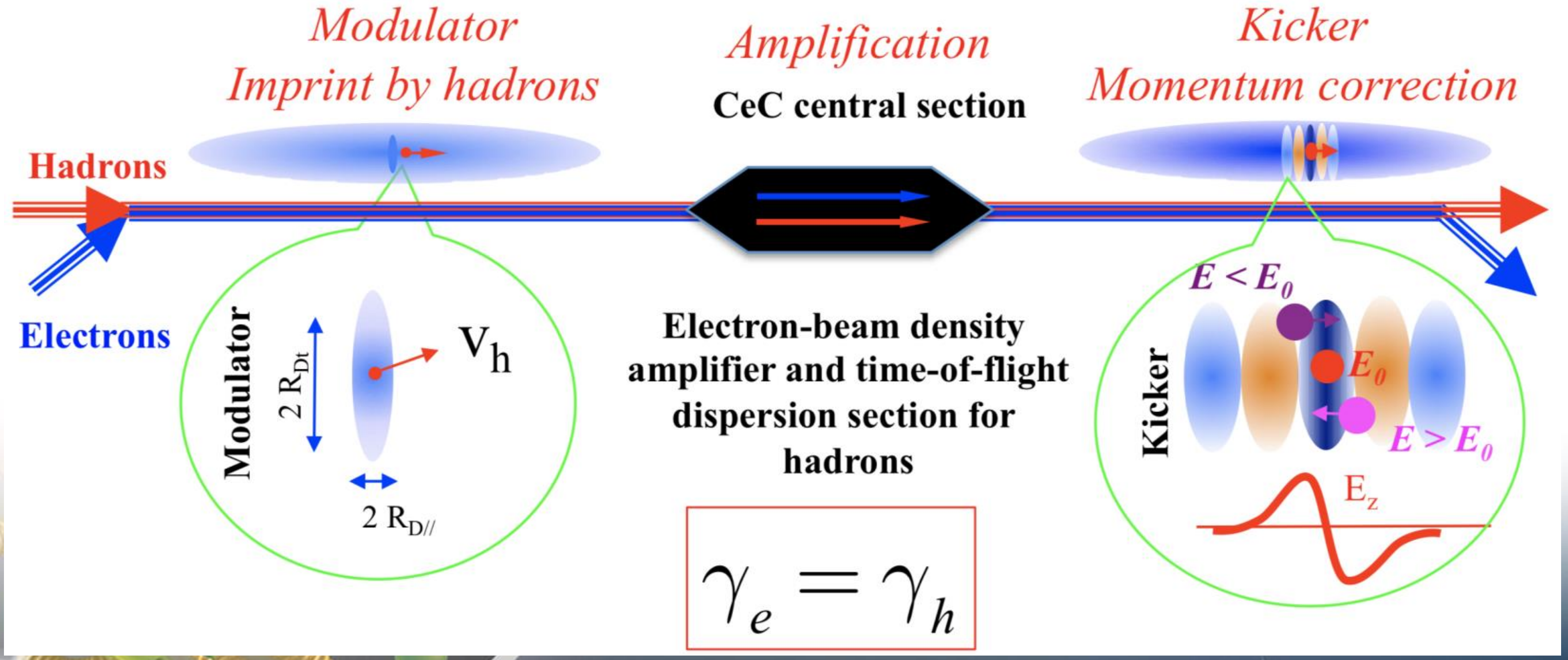
LEReC approach can be used for EIC as injection energy pre-cooler.
However, at collision energy enhanced/strong cooling mechanism is needed.

Coherent Electron Cooling

- **“Classical” electron cooling**: thermal exchange of equal-velocity ”cold” electron and “hot” hadron beams
- **”Stochastic” cooling**: Negative feedback of statistical fluctuations in beam distribution (wide-band pickups, amplifiers, and kickers)



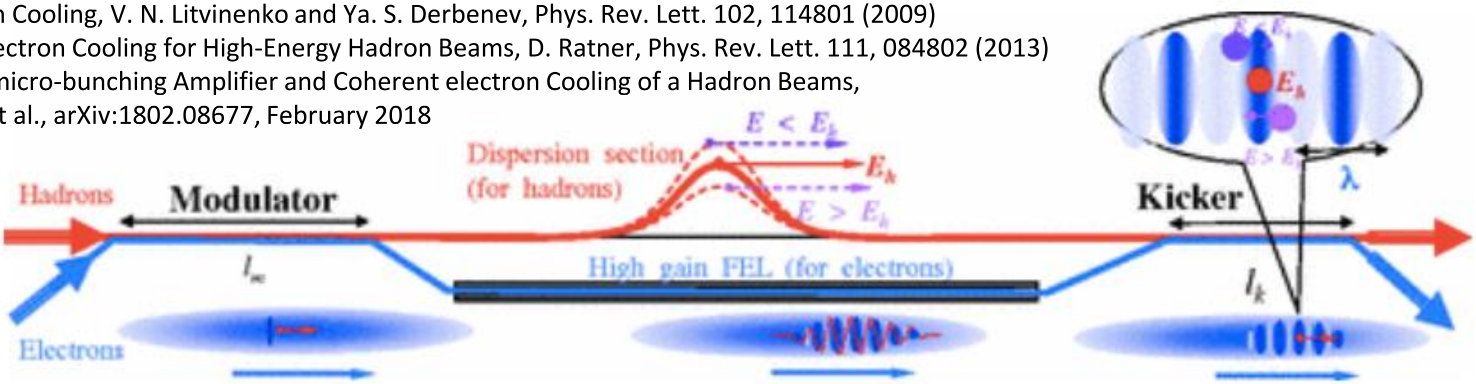
- **”Coherent” electron cooling**: stochastic cooling of hadron beams with very large bandwidths, using electron beam as pickup/amp/kicker.

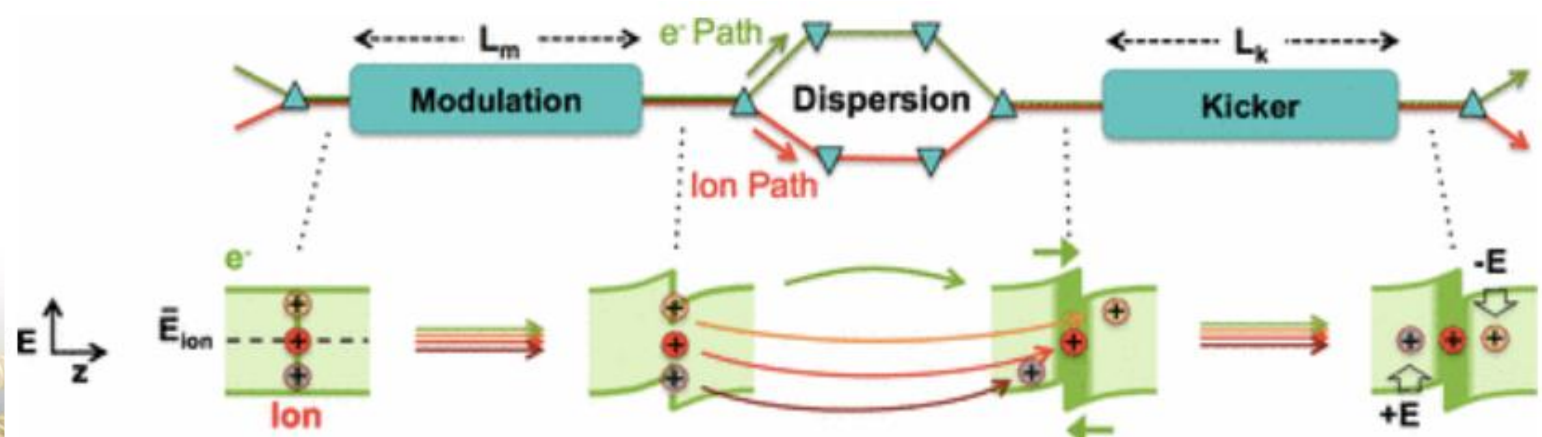


Enhanced / coherent electron cooling

Several amplification mechanisms has been considered: FEL-based, microbunching mechanisms (basis for EIC CDR design), plasma cascades amplification (being experimentally tested at RHIC)

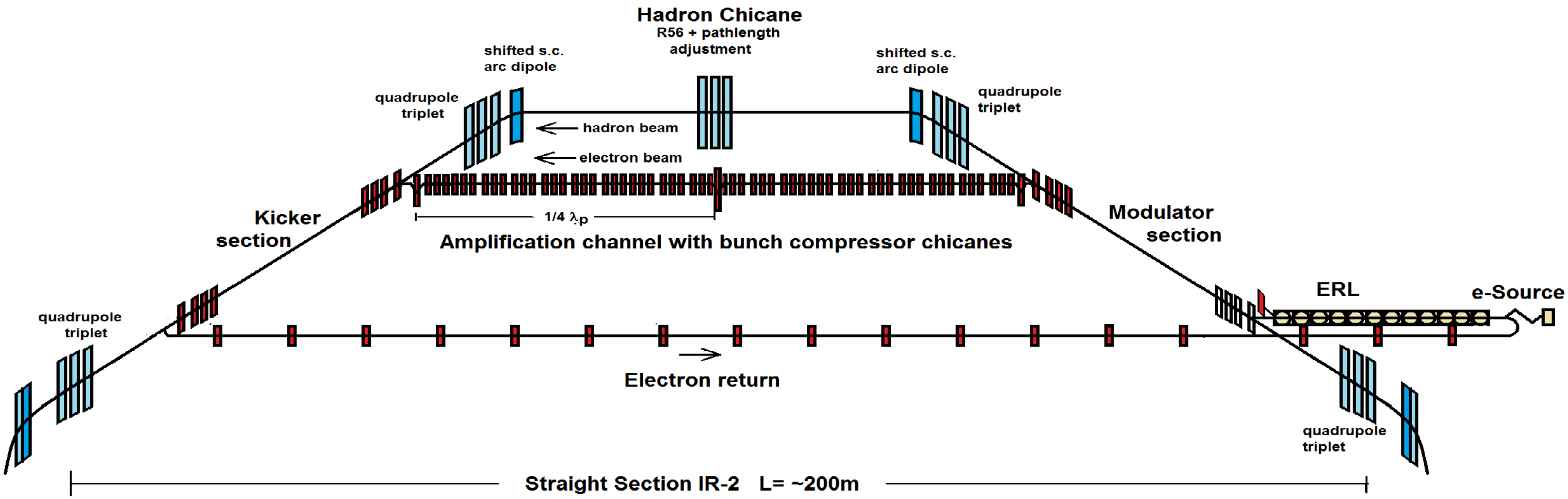
- Amplification the electron cooling by instability inside electron beam, Y.S. Derbenev, Proceedings of the 7th National Accelerator Conference, V. 1, p. 269, (Dubna, Oct. 1980)
- Coherent Electron Cooling, V. N. Litvinenko and Ya. S. Derbenev, Phys. Rev. Lett. 102, 114801 (2009)
- Microbunched Electron Cooling for High-Energy Hadron Beams, D. Ratner, Phys. Rev. Lett. 111, 084802 (2013)
- Plasma-Cascade micro-bunching Amplifier and Coherent electron Cooling of a Hadron Beams, V.N. Litvinenko, et al., arXiv:1802.08677, February 2018





EIC Strong Hadron Cooling

Coherent Electron Cooling with μ-bunching amplification

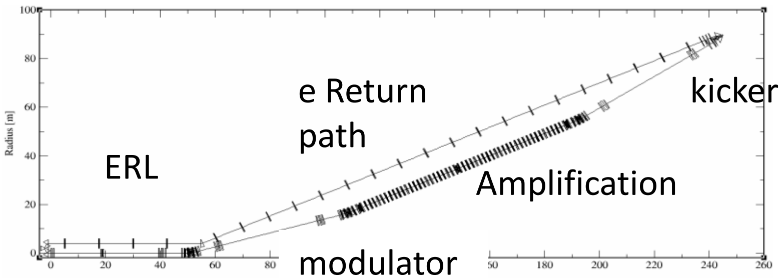


- The EIC cooler requires up to 150 MeV electron beams with average electron beam current of ~100 mA => 15 MW
- Requires use/design of a world-class SRF **energy-recovery linac** (ERL)
- Electron/hadron beams separate and rejoin each other
  - Adjustable R_{56} for electrons to tune amplification
- Electron source/accelerator must be **extremely "quiet"** (no substructure)
  - avoid amplification of "shot noise", electron beam structure not from hadrons

Electron-Ion Collider

Progress on Strong Hadron Cooling

Optics and Geometry



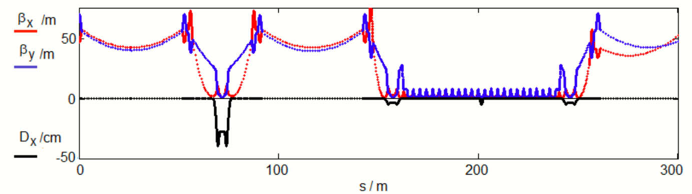
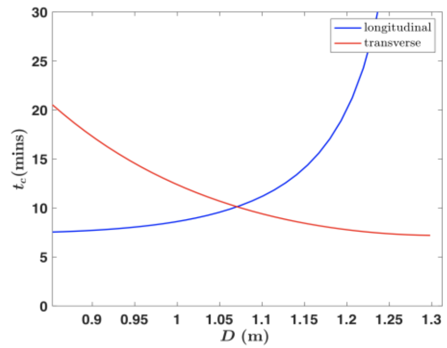
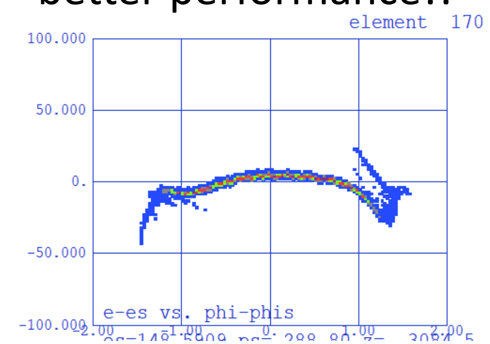


Figure 2: Electron beam optics in the cooling section

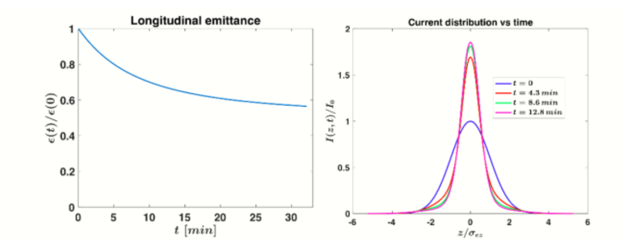
Optimization of transverse vs longitudinal cooling



ERL optimization:
Less components,
better performance!!



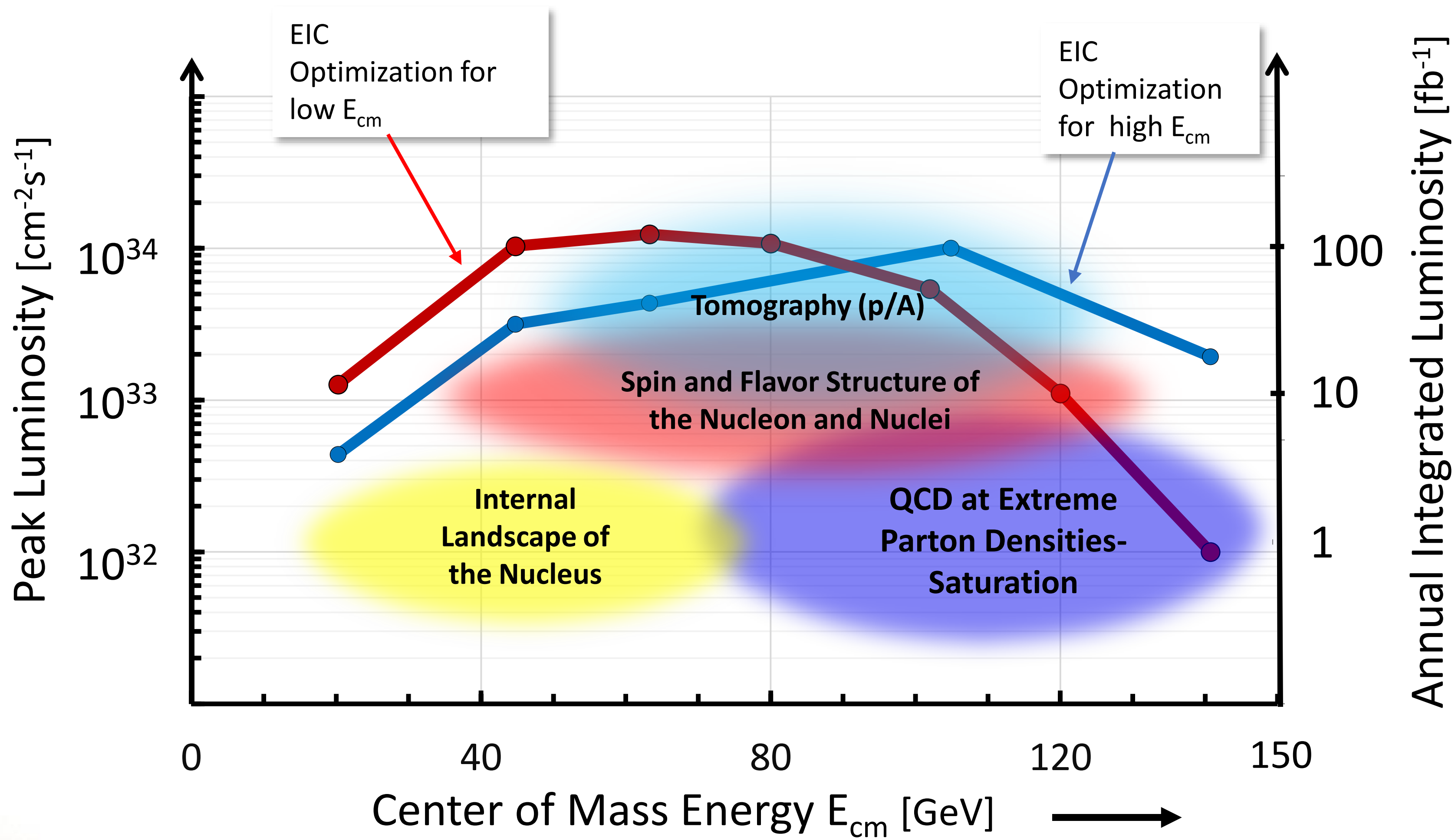
Cooling Simulation
1h cooling time !!



Evolution of the longitudinal emittance of the proton beam (left plot) and the longitudinal distribution function at several moments of time.

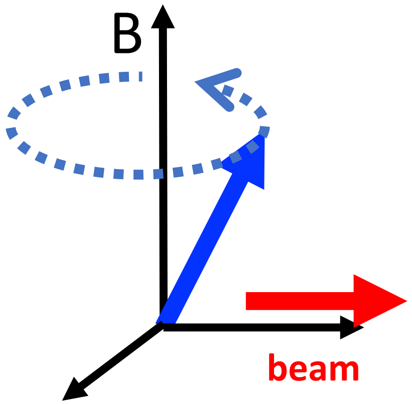
- CeC test set up in RHIC: Plasma cascade amplification section with strong solenoids

EIC e-p Luminosity vs CM Energy



Polarization preservation

- Spin motion in accelerator: spin vector precesses around its guiding field along the vertical direction



- Spin tune Qs: number of precessions in one orbital revolution: Qs = γG
  - Anomalous g- factor for proton G= 1.793

Depolarization due to resonances:

Imperfection resonances:

Qs = n

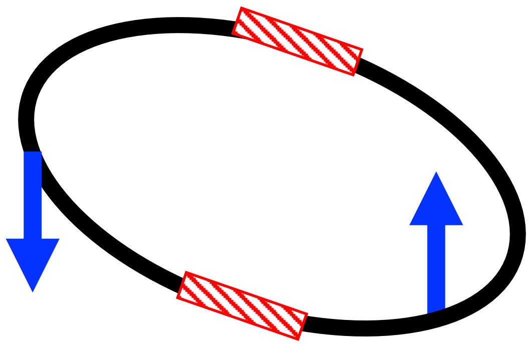
Intrinsic resonances:

Qs = nP +- Qy

Here n – integer, P – number of superperiods

Polarization preservation – Siberian snakes

- Siberian snakes – special (e.g. helical) magnets that rotate spin (preserving orbit outside)

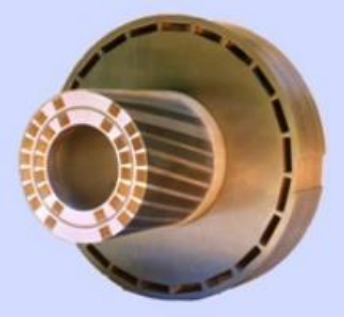


Polarization kinematics of particles in storage rings.
Ya.S. Derbenev, A.M. Kondratenko (Novosibirsk, INP) Jun 1973.
Zh.Eksp.Teor.Fiz.64:1918-1929,1973

- Full Siberian snakes flip spin 180 degrees. Two full snakes make Qs = 1/2
  - Two full snakes control:
    - Intrinsic resonances
    - Imperfection resonances
- Partial Siberian snake
  - Break coherent build up of perturbation of spin
    - Some control of imperfection resonances

Polarization preservation – Siberian snakes

- Siberian snakes in RHIC – two full snake than make Qs = ½



RHIC snake: 4T, 2.4m/snake, 360^{o} twist, 100mm aperture

First Polarized Proton Collisions at RHIC. T, Roser, et al,
AIP Conference Proceedings 667, 1 (2003)

- AGS – partial Siberian snakes

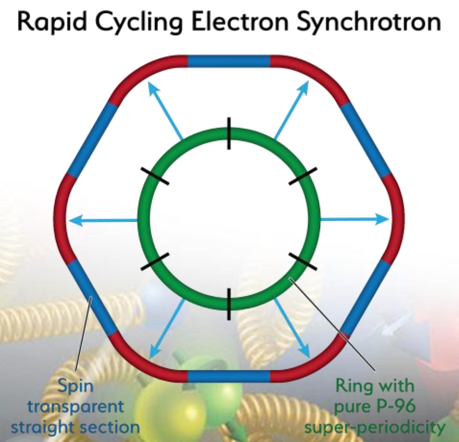
Warm partial AGS Snake

18 GeV Rapid Cycling Synchrotron enables high electron polarization in the electron storage ring

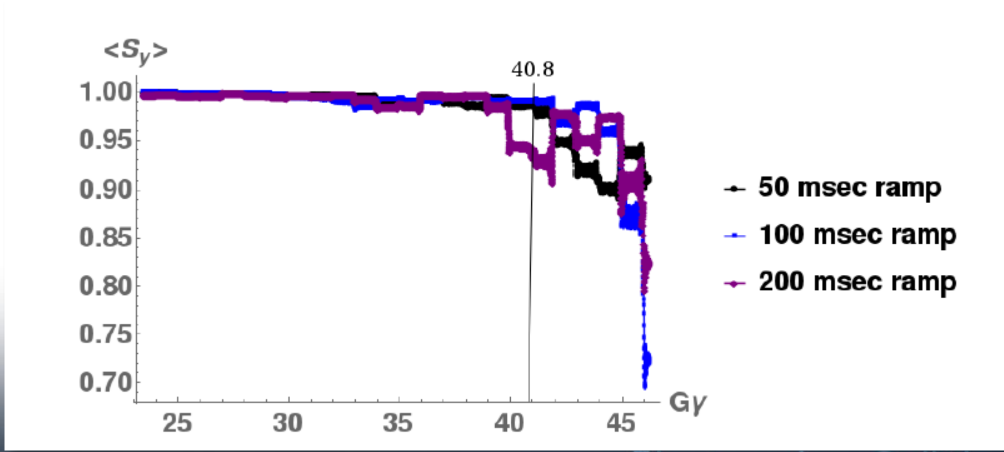
- 85% polarized electrons from a polarized source and a 400 MeV s-band linac get injected into the fast cycling synchrotron in the RHIC tunnel
- AGS experience confirms depolarization suppressed by lattice periodicity
- RCS with high (P=96) quasi-periodicity arcs and unity transformations in the straights suppresses all systematic depolarizing resonances up to E >18 GeV
- Good orbit control $y_{cl.o.} < 0.5$ mm; good reproducibility suppresses depolarization by imperfection resonances

➔ No depolarizing resonances during acceleration 0.4-18 GeV
no loss of polarization on the entire ramp up to 18 GeV (100 ms ramp time, 2 Hz)

RCS Design

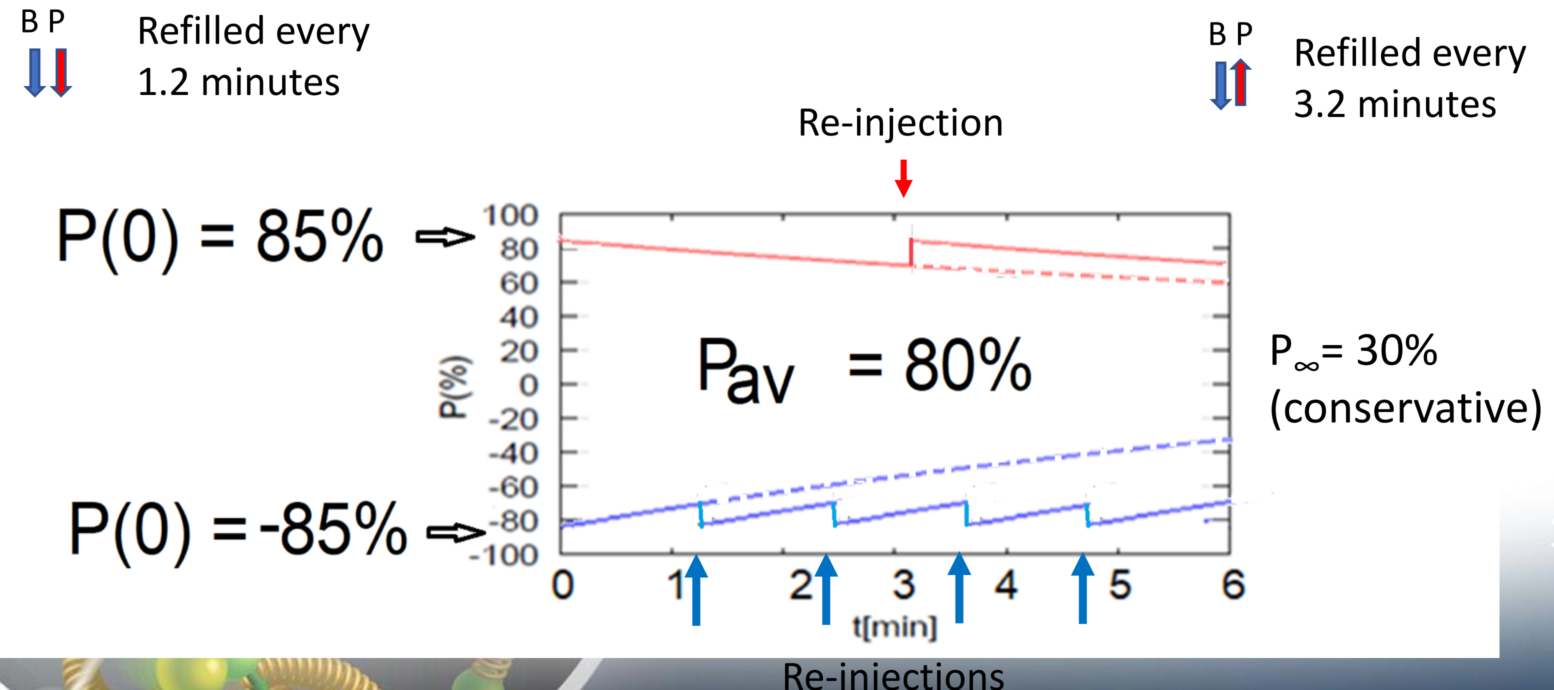


RCS Polarization Performance confirmed by extensive simulations



High average polarization at electron storage ring of 80% by

- Frequent injection of bunches on energy with high initial polarization of 85%
- Initial polarization decays towards P_∞ < ~50%
  (equilibrium of self-polarization and stochastic excitation)
- At 18 GeV, every bunch is refreshed within minutes with RCS cycling rate of 2Hz
- Need both polarization directions present at the same time



EIC Hadron Polarization

- Existing p Polarization in RHIC achieved with “Siberian snakes”
- Near term improvements will increase proton polarization in RHIC from 60% to 80%
- ^{3}He polarization of >80% measured in source
- 80% polarized ^{3}He in EIC will be achieved with six “snakes”,
- Acceleration of polarized Deuterons in EIC 100% spin transparent
- Need tune jumps in the hadron booster synchrotron

Electron beam ion source EBIS with polarized ^{3}He extension

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Electron beam ion source EBIS with polarized ^3He extension

TRIZ inventive principle #21

21. Skipping

- **Conduct a process , or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.**

TRIZ – Theory of inventive problem solving

TRIZ inventive principle #21

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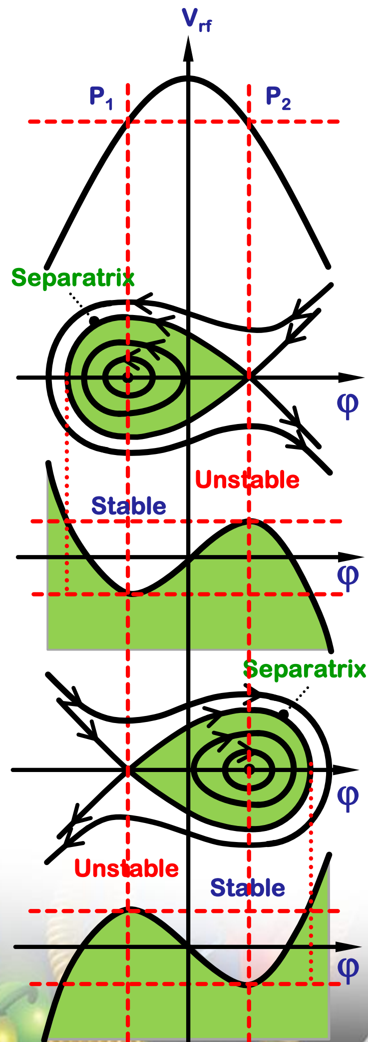
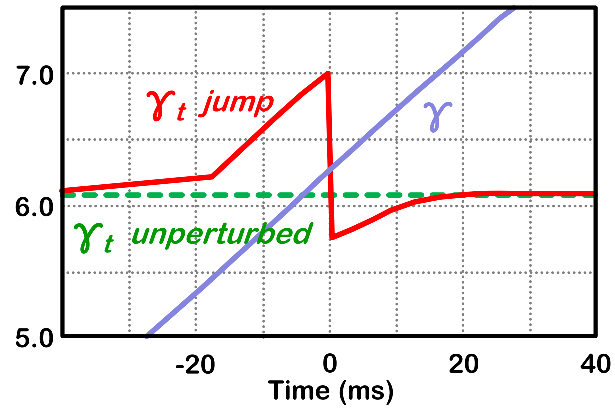
- **Conduct a process , or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.**



Crossing transition energy with γ_t jump technique



Tune jump for polarization preservation conceptually similar

See more examples in "Accelerating Science TRIZ inventive methodology in illustrations" [arXiv:1608.00536]

The existing RHIC ion sources & ion acceleration chain provide already **today** all ions needed for EIC

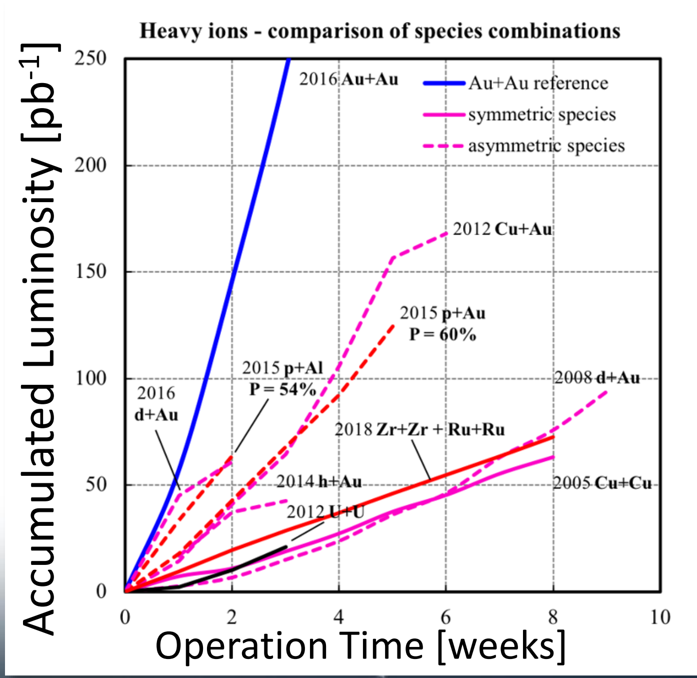
- Ions from He to U have been already generated in the Electron-Beam-Ion-Source ion source (EBIS), accelerated and collided in RHIC
- EBIS can generate any ion beam from ^{3}He to U for the BNL EIC
- Existing EBIS provides the entire range of ion species from He to U in sufficient **quality** and **quantity** for the EIC

Enormous versatility! is a unique capability!

<u>Ion Pairs in the RHIC Complex</u>

Zr-Zr, Ru-Ru	(2018)
Au-Au	(2016)
d-Au	(2016)
p-Al	(2015)
h-Au	(2015)
p-Au	(2015)
Cu-Au	(2012)
U-U	(2012)
Cu-Cu	(2012)
D-Au	(2008)
Cu-Cu	(2005)

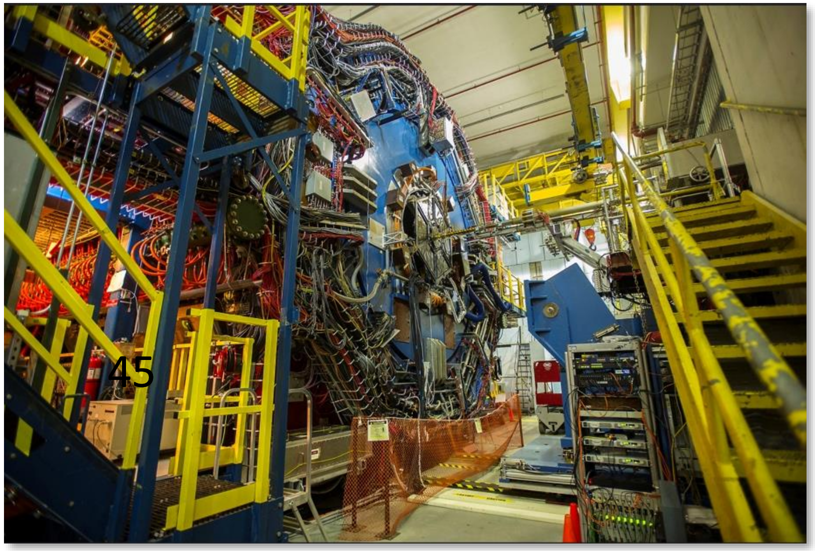
Ion-Ion Luminosity Runs in RHIC 2005-2018



The EIC will benefit from two large existing detector halls in IR 6 and IR 8

- Both halls are **large** and **fully equipped** with infrastructure such as power, water, overhead crane, ….

IR 8 detector hall with PHENIX detector (transitioning to sPHENIX)

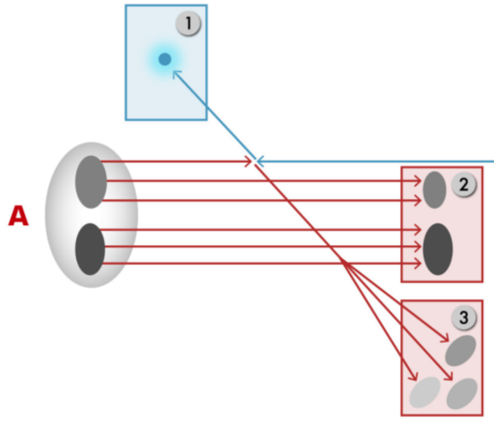


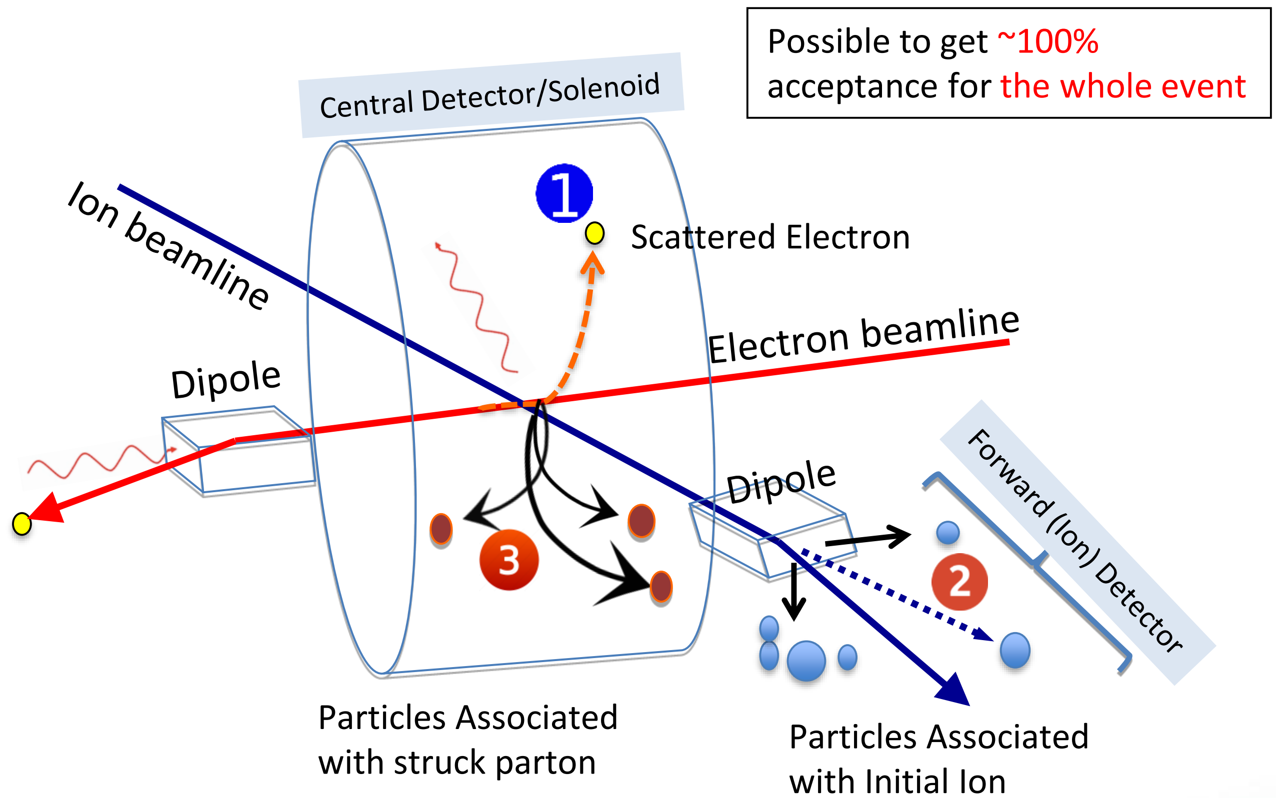
IR 6 detector hall with STAR detector

- Both IRs can be implemented simultaneously in the EIC lattice and be accommodated within beam dynamics envelope
- 2 IR's: laid out <u>identically</u> or <u>optimized for maximum luminosity at different</u> E_{CM}

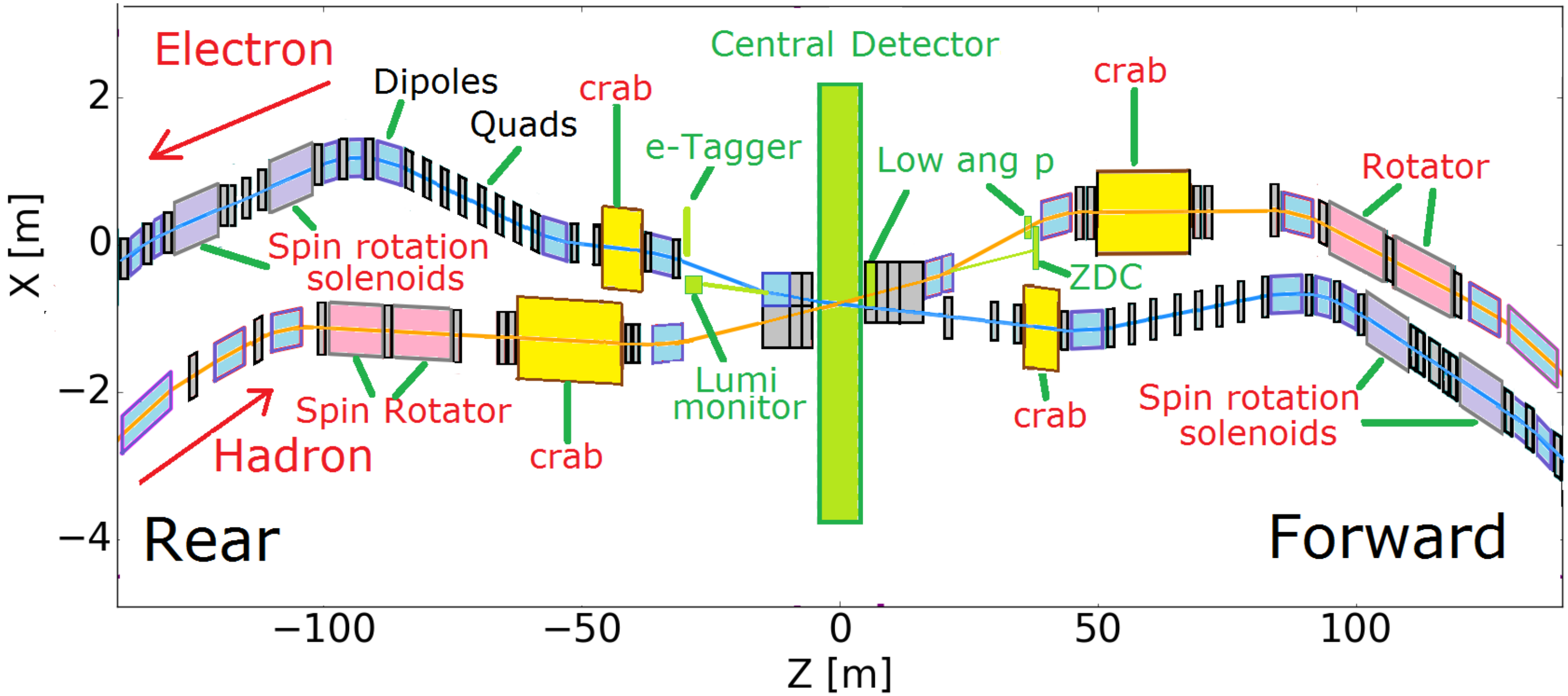
Interaction Region Concept

EIC detector must accept and measure *all* particles from the interaction. (Unlike existing collider detectors!)



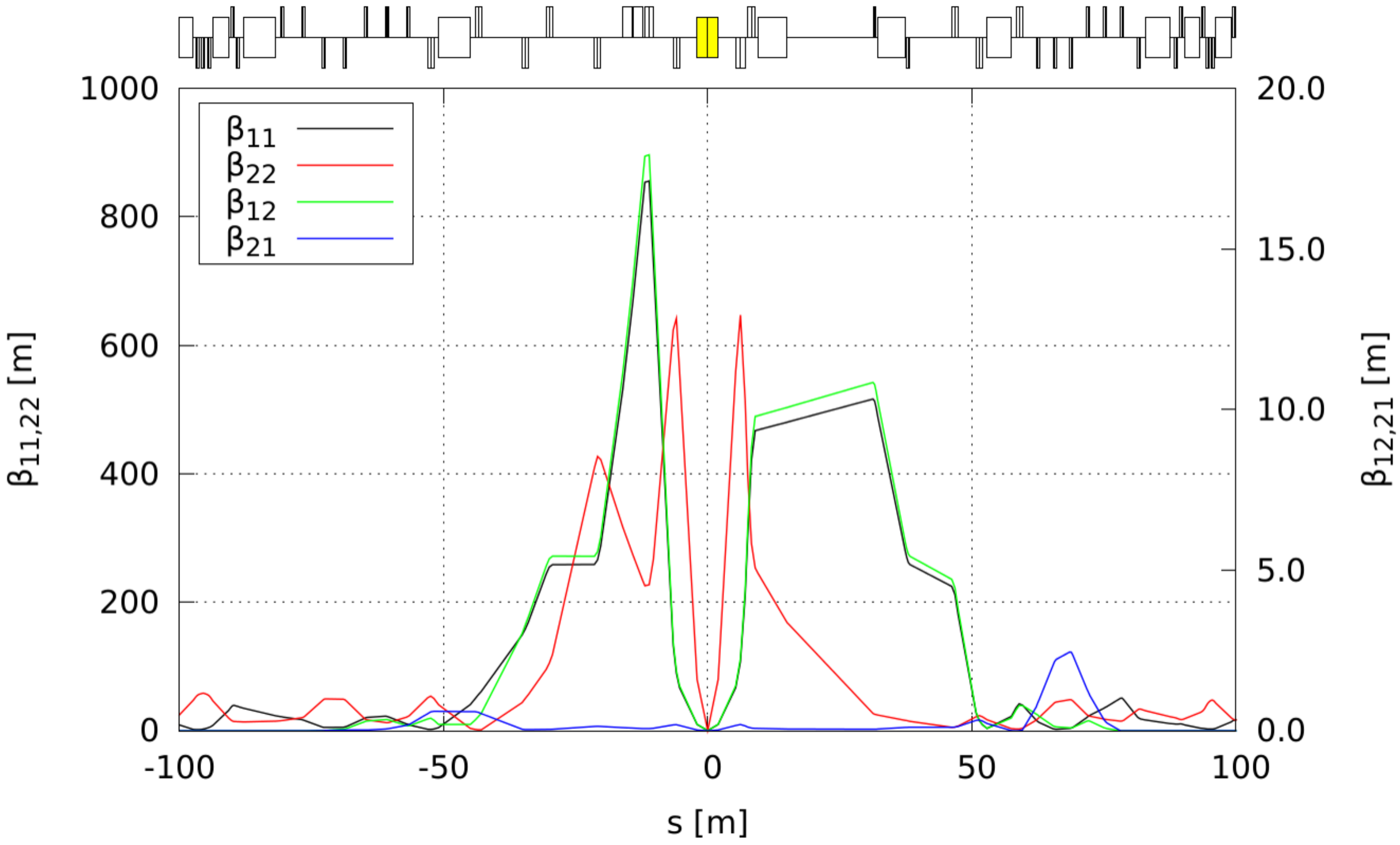


Interaction Region Design



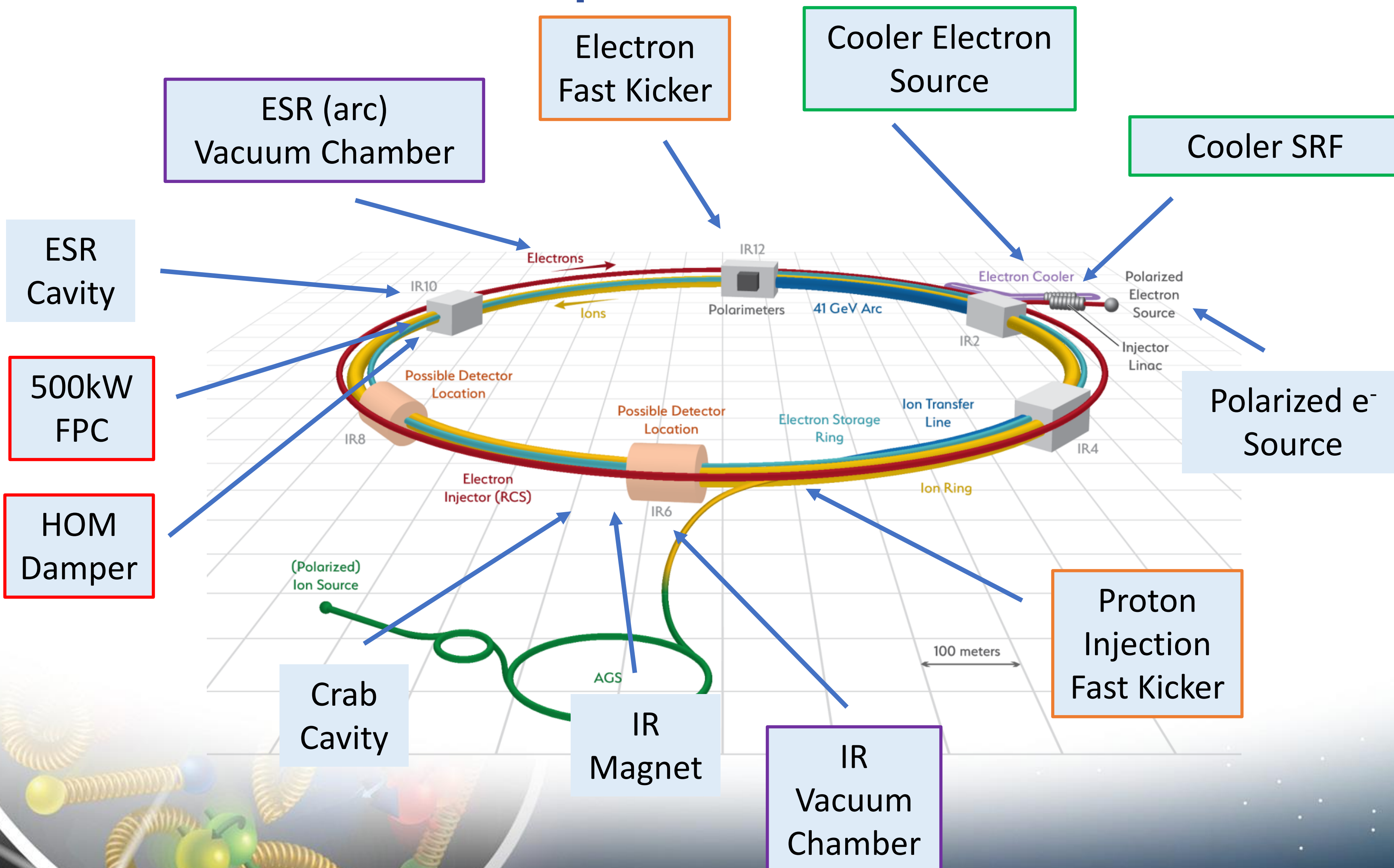
- Interaction Region, the accelerator around the colliding beam detector is the most complex and most constrained section of a collider
  - First IR: +/- 4.5 m machine-element free space for central detector; 25 mrad total crossing angle; Transverse momentum acceptance down to 200 MeV/c; Peak magnetic fields below 6T (NbTi sufficient); Most magnets direct-wind; few collared magnets
  - 2nd IR and 2nd detector is not in the project scope but we unanimously agree that the EIC should have 2 detectors (and 2 IR s)

Interaction Region Lattice



- Maximum beta-functions in FFQs around 900m
- Very asymmetric
- 300-500m beta in crab cavities

EIC R&D Scope



Electron Fast Kicker
Cooler Electron Source
ESR (arc) Vacuum Chamber
Cooler SRF
ESR Cavity
500kW FPC
HOM Damper
Polarized e$^-$ Source
Proton Injection Fast Kicker
Crab Cavity
IR Magnet
IR Vacuum Chamber
Electrons
IR12
IR10
Ions
Polarimeters
41 GeV Arc
Electron Cooler
Polarized Electron Source
IR2
Injector Linac
Possible Detector Location
IR8
Possible Detector Location
Electron Storage Ring
Ion Transfer Line
IR4
Electron Injector (RCS)
IR6
Ion Ring
(Polarized) Ion Source
AGS
100 meters

Summary

- The EIC will be a discovery machine, providing answers to long-elusive mysteries of matter related to our understanding the origin of mass, structure, and binding of atomic nuclei that make up the entire visible universe
- EIC project is underway aiming to start physics in about a decade
- EIC will be state of the art collider pushing the frontiers of accelerator science and technology
- The EIC project will work closely with domestic and international partners to deliver the EIC construction project and then begin EIC operations
- **Collaboration in EIC design, construction and scientific exploration is welcome!**