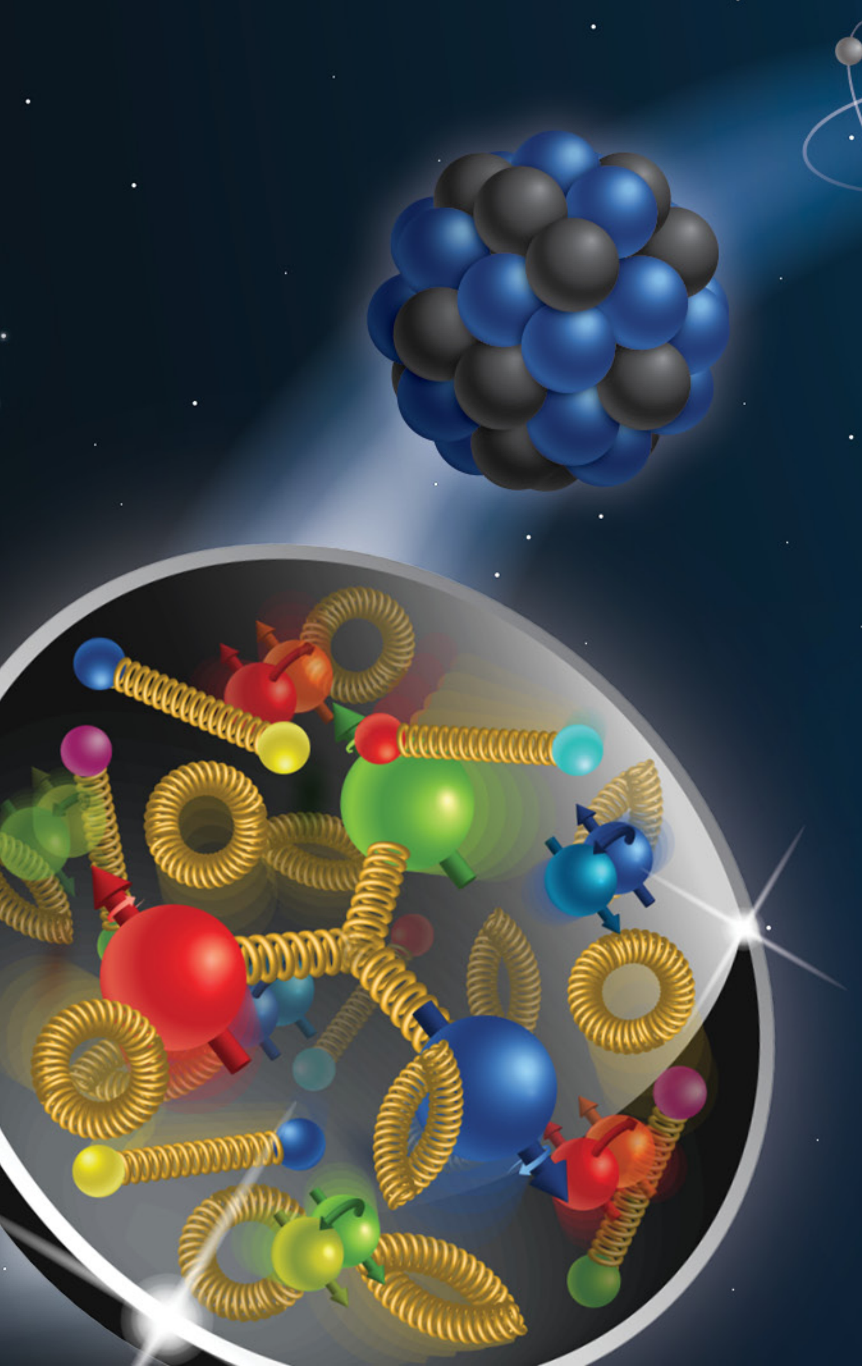


Progress of eRHIC Design

RHIC-AGS User's Meeting 2017

June 20-23, 2017

Ferdinand Willeke

BNL

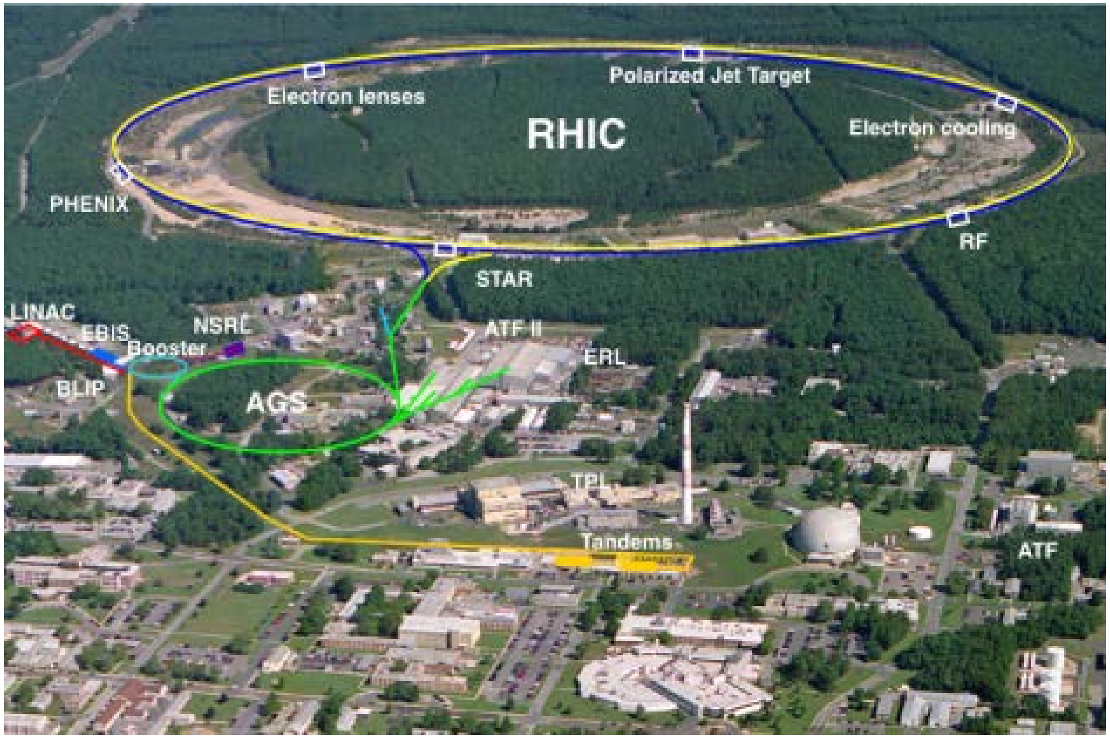
Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- eRHIC Requirements
- eRHIC Concept
- Accelerator Layout
- Accelerator Design and R&D
  - IR Design
  - Storage Ring Lattice
  - Beam-Dynamics Issues
  - Cooling
- Polarization
  - Injectors
- Timeline



Questions to be answered by an EIC

- **How is the proton and neutron spin of ½ composed by its constituents?**

We don't know how the proton spin is composed. We know that the most simple assumption of quark spin configuration was proven wrong in1987. Since then, despite many efforts, this remains an unresolved question. The EIC with its two colliding polarized beams be shed light on this mystery.

- **How are the gluons spatially distributed in the nucleons?**

There are hints that the high stability of the proton is due to the fact that the gluons are concentrated near the surface of the nucleon. An EIC will enable us to measure this.

- **How does the gluon density saturate?**

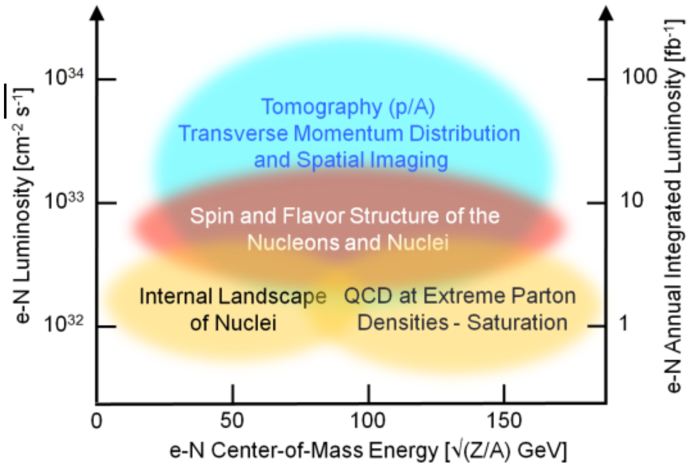
Earlier lepton hadron scattering experiments showed that the density of the gluons increases dramatically if they carry smaller fraction of the nucleon's momentum. First principles tell us this density increase must saturate, but we do not know when and how. Is saturation related to other unexplained phenomena? Electron-Ion collisions at high collision energies will make a significant step forward to understanding.

- **The EIC will enable novel measurement of nuclear structure** and dynamics which will enhance our understanding of the "nucleon's inner landscape".

Requirements on an EIC

EIC White Paper 2014

- Large Luminosity, scattering cross sections are small
  ➔ L = $(10^{33} - 10^{34})\ s^{-1}\ cm^{-2}$,
  large average luminosity



- Large range of center of mass energy

$$E_{cm} = 2\sqrt{E_{hadron} \cdot E_{electron}} = (30 - 140)\ \text{GeV}$$

  - Electrons: (5-18) GeV
  - protons: (50-275 GeV), and corresponding
  - Ion Energies up to 100 GeV/nucleon

		Hadrons (GeV/u)		
		50	100	275
Electrons, GeV	5	p, Au	p, Au	
	7.5	Au		
	10		p	p
	15		Au	
	18	Au	Au	p

- Large span of ions (from light to heavy)
- Large detector forward, backward acceptance, in particular in particular for forward scattered Hadrons at small angle
- Fast, bunch-by bunch luminosity and polarization measurement to be accommodated
- The two beams must be longitudinally spin polarized in collisions 70% hadrons, 80% electrons
- All combinations of spin orientations present in one fill

eRHIC Design Concept

- Based on existing RHIC with up to 275 GeV polarized protons
- Additional electron storage ring with (5 – 18) GeV in the RHIC tunnel
  - Up to 2.7A electron current – 1320 bunches per ring similar to B-Factories
  - 10 MW maximum RF power (administrative limit)
- Flat proton beam: 2.4mm horizontal, 0.1mm vertical

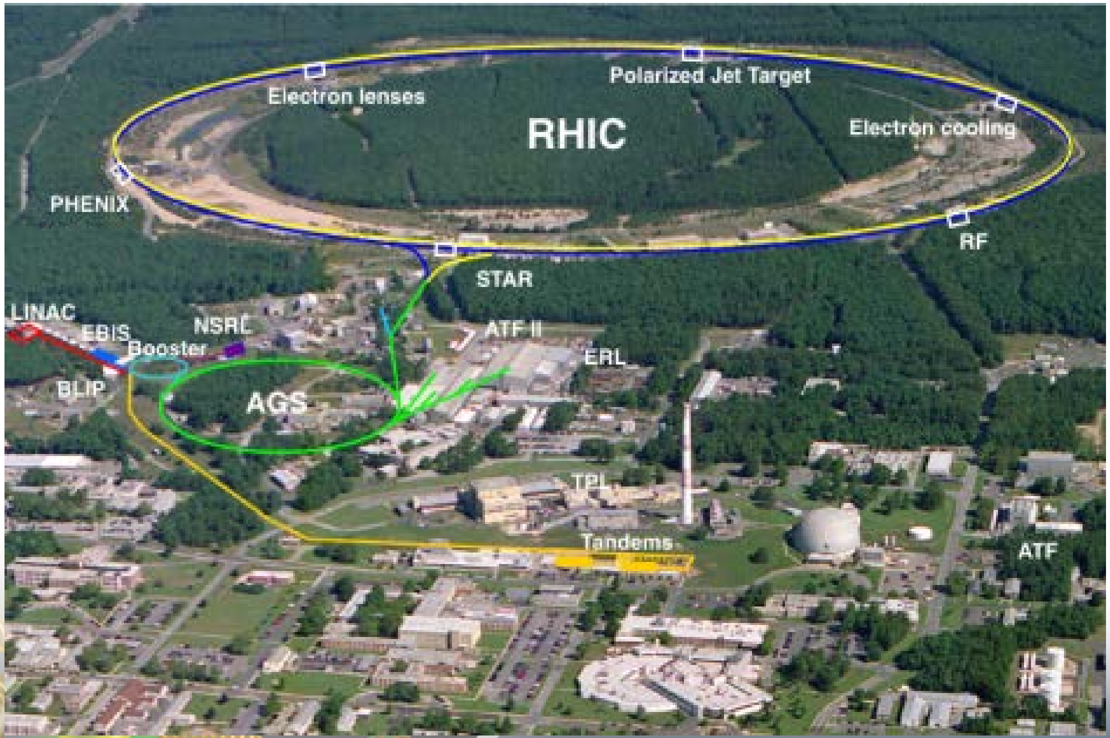
➔need strong cooling of the hadron beam emittances

- Proton bunch intensities moderate: $0.75 \cdot 10^{11}$,achieved in RHIC
- On-energy polarized electron injector (up to 18GeV)
- Full energy polarized electron injector (recirculating LINAC default, rapid cycling synchrotron cost saving option)

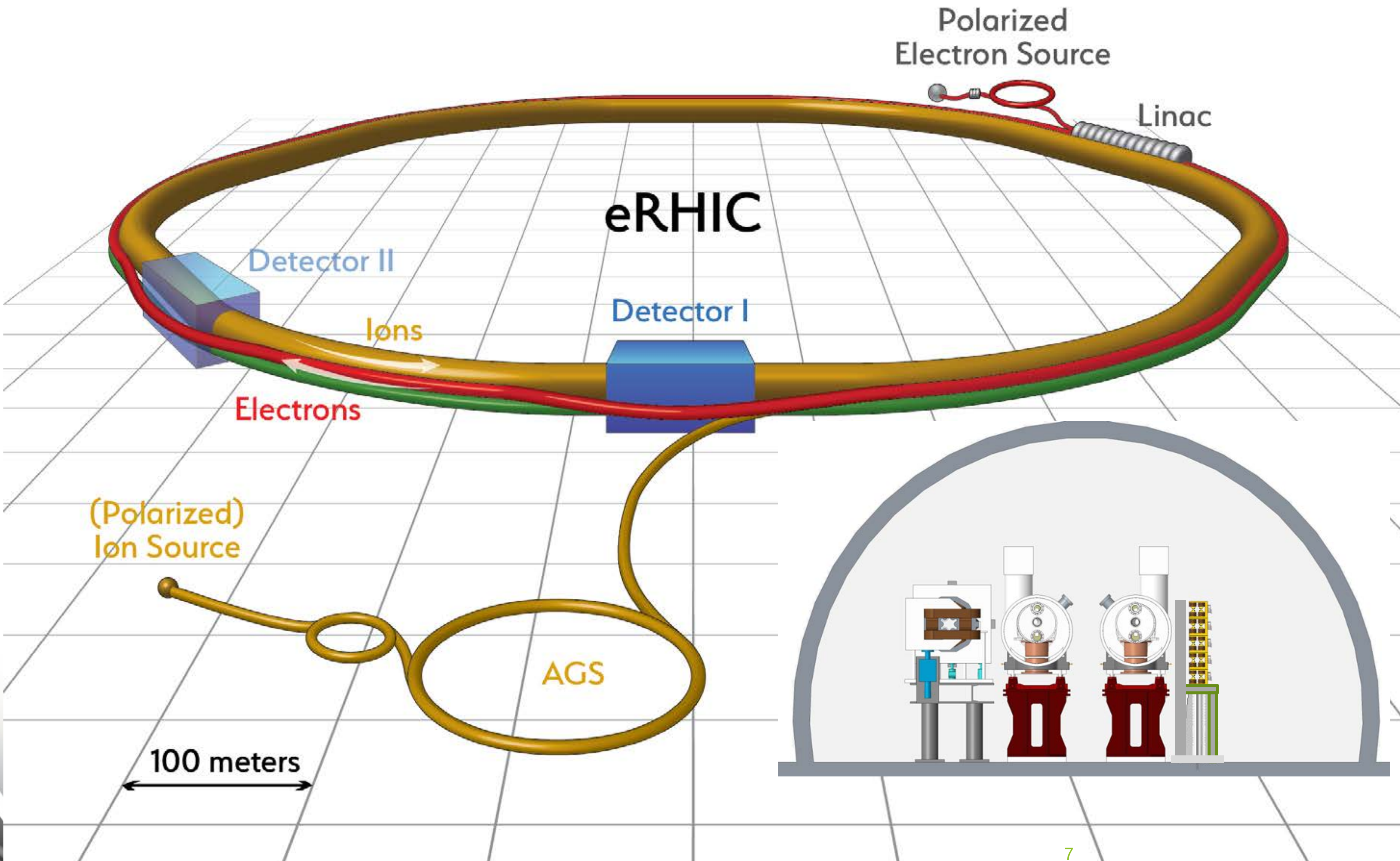
Designed for Peak Luminosity: $1.1 \times 10^{34} cm^{-2} sec^{-1}$

eRHIC uses the Relativistic Heavy Ion Collider RHIC

- The major part of a future eRHIC facility already exists
- eRHIC uses the **Yellow Ring** and parts of the Blue Ring
- Most of RHIC will remain untouched
- RHIC beam parameters will satisfy eRHIC requirements
- Some changes in the straight sections are required to maintain a constant revolution time independent of energy



eRHIC Schematics

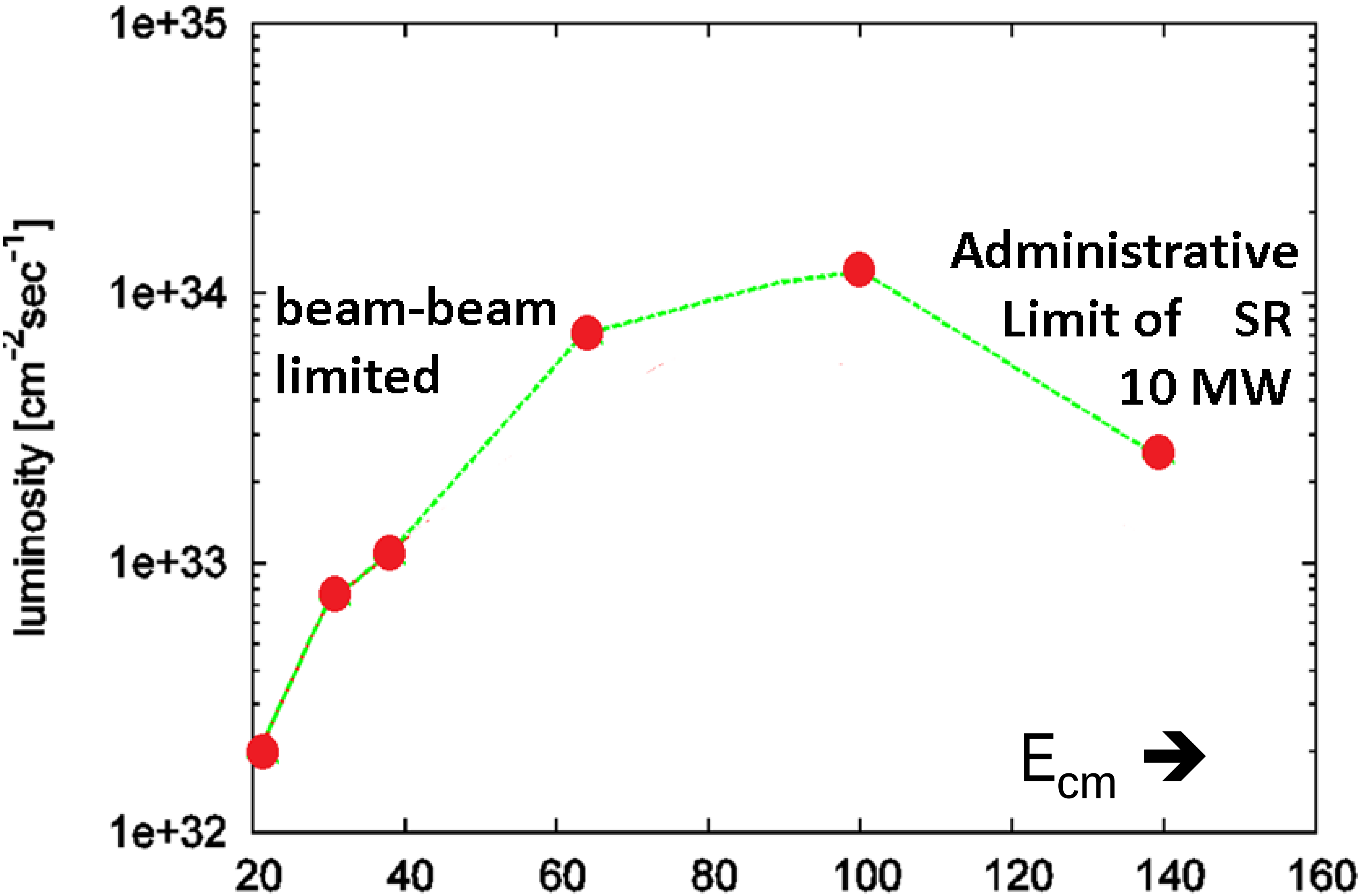


Main Parameters for Maximum Luminosity

E_p = 275 GeV, E_e= 10 GeV

		No Hadron Cooling		Strong Hadron Cooling	
Parameter	**Units**	**Protons**	**Electrons**	**Protons**	**Electrons**
Center of Mass Energy	GeV	100		100	
Beam Energy	GeV	275	10	275	10
Particles/bunch	10^{10}	11.6	31	5.6	15.1
Beam Current	mA	456	1253	920	2480
Number of Bunches		330		1320	
Hor. Emittance	nm	17.6	24.4	8.3	24.4
Vertical Emittance	nm	6.76	3.5	3.1	1.7
β_{x*}	cm	94	62	47	16
β_y*	cm	4.2	7.3	2.1	3.7
σ_x'*	mrad	0.137	0.2	0.13	0.39
σ_y'*	mrad	0.401	0.22	0.38	0.21
Beam-Beam ξ_x		0.014	0.084	0.012	0.047
Beam-Beam ξ_y		0.0048	0.075	0.0043	0.084
τ_{IBS} long/hor	hours	10/8	-	4.4/2.0	-
Synchr. Rad Power	MW	-	6.5	-	10
Bunch Length	cm	7	0.3	3.5	0.3
Luminosity	$10^{34}cm^{-2}s^{-1}$	0.29		1.21	

Luminosity vs. Center of Mass Energy



High Beam Current

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High Bunch Frequency:
➔ fast kickers with <10 ns rise times for injection of electrons and hadrons

Electrons

Total Beam Current: up to 2.7 A

- Not unprecedented (KEK-B, Super-B), but N_b=330, beam heating more challenging
- Synchrotron radiation limited to 10 MW
- RF cost: 30 single cell s.c. 560MHz cavities
- Peak linear power density<6 kW/m
  ➔ok with Cu beam pipe
- Coupled Bunch instability: need active damper
- Resistive Wall Instability ok
- Fast Ion instability growth time manageable

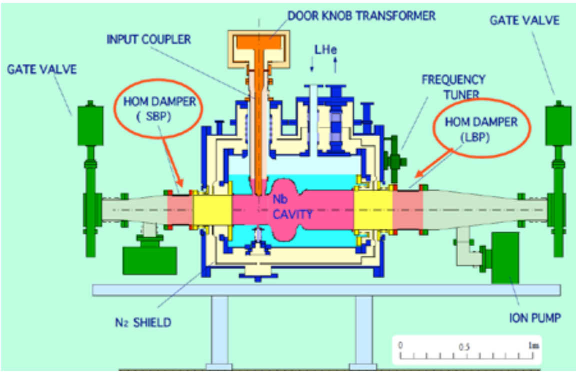
Protons

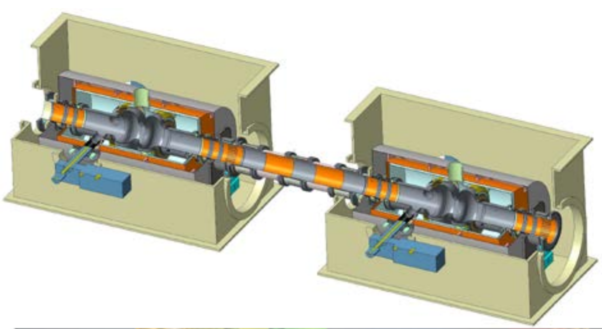
Total Beam Current up to 920mA
(factor 2 above present RHIC)

- Coupled Bunch Instability, ok
- e-Cloud: Need Cu coating of RHIC beam pipe + carbon layer for SEY suppression: prototype coater tested

RF Cavity Options

- Staged RF installation: 1st 10GeV Operations with optimized coupling for High Intensity Operations, then RF installation for 18GeV but only 200 mA of current

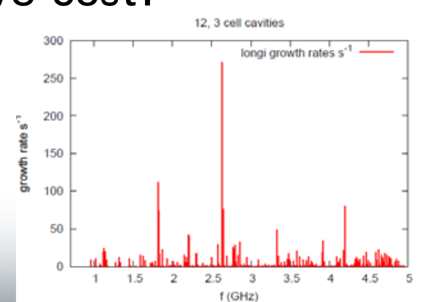




- Option 1: KEK-B cavity has been operated successfully under comparable conditions, semi-commercial need 15-34 units for 10-18 GeV, Assuming U = 2MV and P= 400kW➔ $$

- Option 2: CESR-B Cavity is successfully operated in several light sources, for example NSLS2, commercially available. Would need 15-34 units for 10-18 GeV, Assuming U = 2MV and P= 400kW➔ $$
  Would have to use coaxial coupler (design completed) and fix the Indium-seal, the weak point of the design

- Option 3: In-house development of a 3-cell cavity in progress to save cost.



Impedance 12 2-cell units, Work in progress

All solutions: Broad and narrow band impedance manageable; TMCI ok, Coupled bunch Growth rates < 1kHz

Considerable electron single bunch currents

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I_b = up to 3.8 mA

- I_e x I_{eb} = 0.0046 amp^2 factor ~10 larger than confirmed by B-Factory experience
- Avoid heating of vacuum components (bellows) ➔ needs careful low impedance design (in progress)
- Single bunch instabilities:
  - TMCI ok for typical impedance < 1MΩ,
  - microwave instability ok

Small emittance @ required bunch current and length

$L = 1.2 \cdot 10^{34} cm^{-2}s^{-1}$ requires vertical normalized proton emittance of ε_{yN} = 2.2 mm rad @ I_{bp}= 0.7 mA, σ_s = 7 cm. These Hadron beam parameters are subject to **strong IBS** and can be achieved and maintained only be **strong active cooling of the Hadron beams** with cooling times in the order of 30 minutes.

Major technical challenge for any EIC design

➔ Cooling time < IBS growth time only 0.5 h

- This exceeds the cooling rates possible with stochastic cooling by several orders of magnitude
- **Coherent Electron Cooling** promises to provide required cooling rates
- Novel scheme, never implemented
- Proof of principle tests in progress

➔ **Need novel cooling schemes to meet this challenge**

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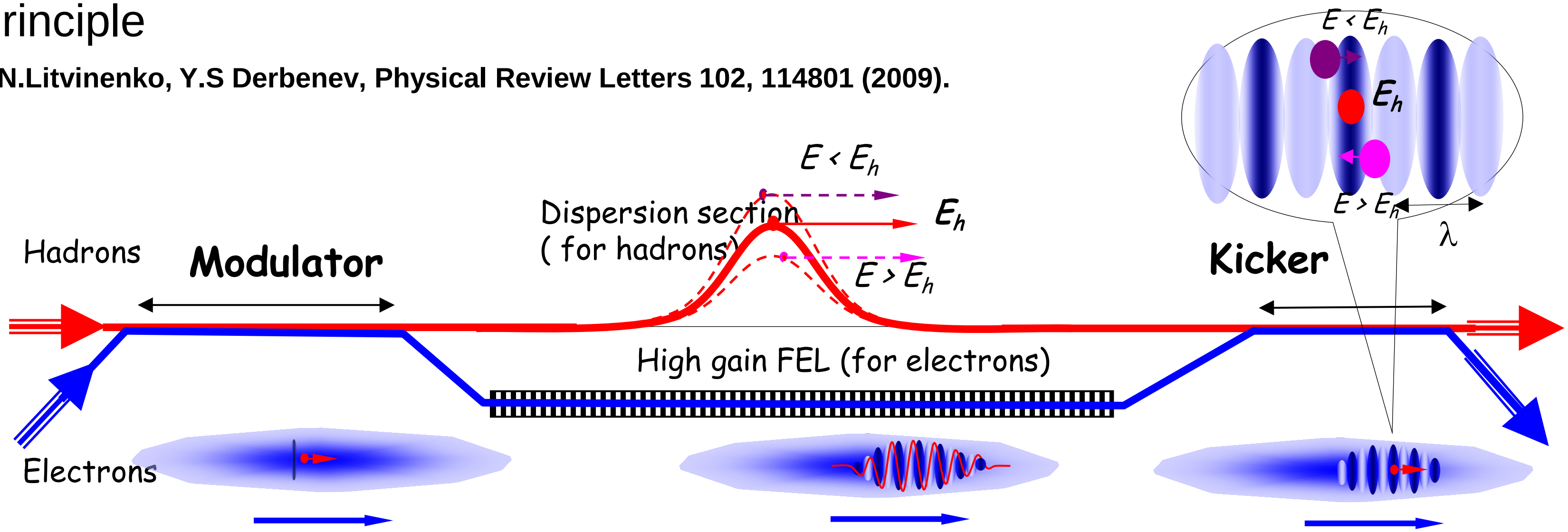
Fastest IBS growth for High Acceptance Optics with L~ 10^{34} t_{ibs} > 0.3h (might be able to avoid)

eRHIC Choice is to go with CeC but will consider alternative schemes as well

Coherent Electron Cooling

Principle

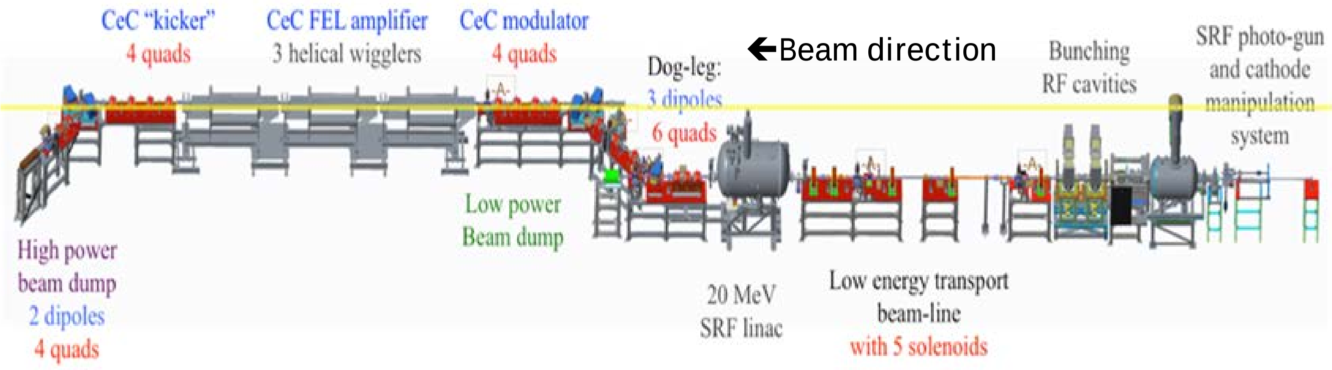
V.N.Litvinenko, Y.S Derbenev, Physical Review Letters 102, 114801 (2009).



➔ cooling of high energy Hadron beams with high band-width; BW: **1THz**
cooling times of sec-min to balance strong **IBS**

Proof of Principle Experiment

Installed in RHIC IR-2



Status:

- all hardware components in place,
- improvements after first commissioning in 2016 implemented,
- recommissioning in progress
- Cooling studies planned for FY18

Critical Beam-Beam Parameters Electrons

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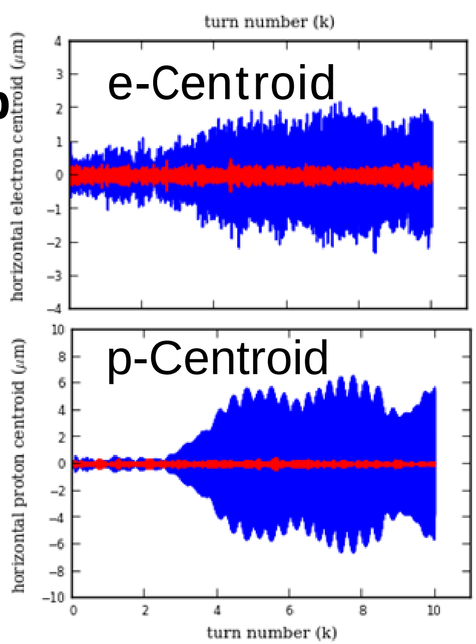
Simulation: Coherent bb Instability Threshold

Red: $N_p=10^{11}$ stable

Blue: $N_p=3\cdot10^{11}$ unstable



The beam-beam parameters for eRHIC are ambitiously high

- e b-b parameters have been achieved in e+e- colliders (B-Factories)
- Choice of eRHIC e Tunes take into account Polarization
- Hadron B-B parameters routinely achieved in RHIC
- However, HERA operated with lower values, especially in the horizontal plane x_x=0.03, x_y=0.05
- Occasionally Coherent BB instabilities were observed in HERA
- Additional concern Hadron emittance growth (none observed in HERA)
- Hadron beam tails and large detector backgrounds

➔ Concern addressed in comprehensive b-b simulation study (strong-strong; weak strong)

Results so far: Threshold for coherent instabilities factor 2 above operating point, for optimized tunes no or little proton emittance growth

Beam-Beam Parameters Electrons

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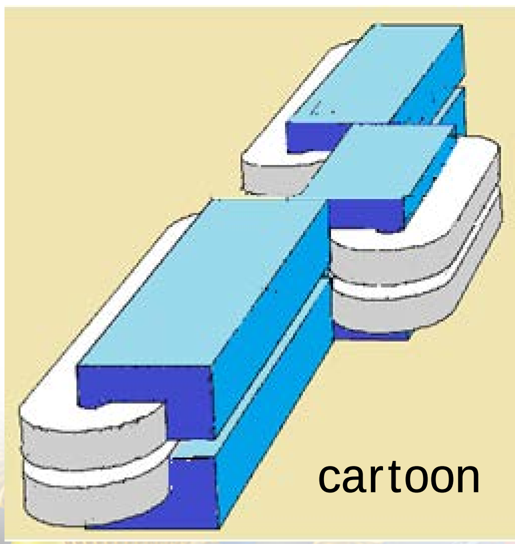
Additional Concern:

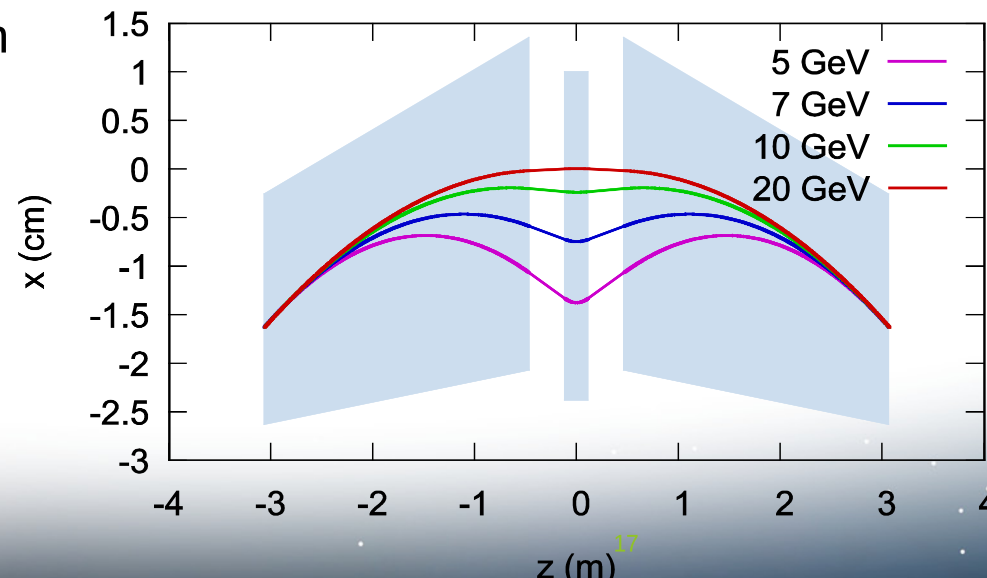
Strong electron Beam-Beam effects require strong radiation damping. Between 5-18 GeV, τ_x changes by a factor **50 (**without further measures).

<u>With" super-bend" lattice:</u>

- achieve 11 GeV damping times at 5 GeV to match KEKB damping decrement
- overcomes as well the E^2 scaling of beam emittance,
- helps with polarization



Radiation Power: $\sim E^2 B^2$



Small beta, IR design

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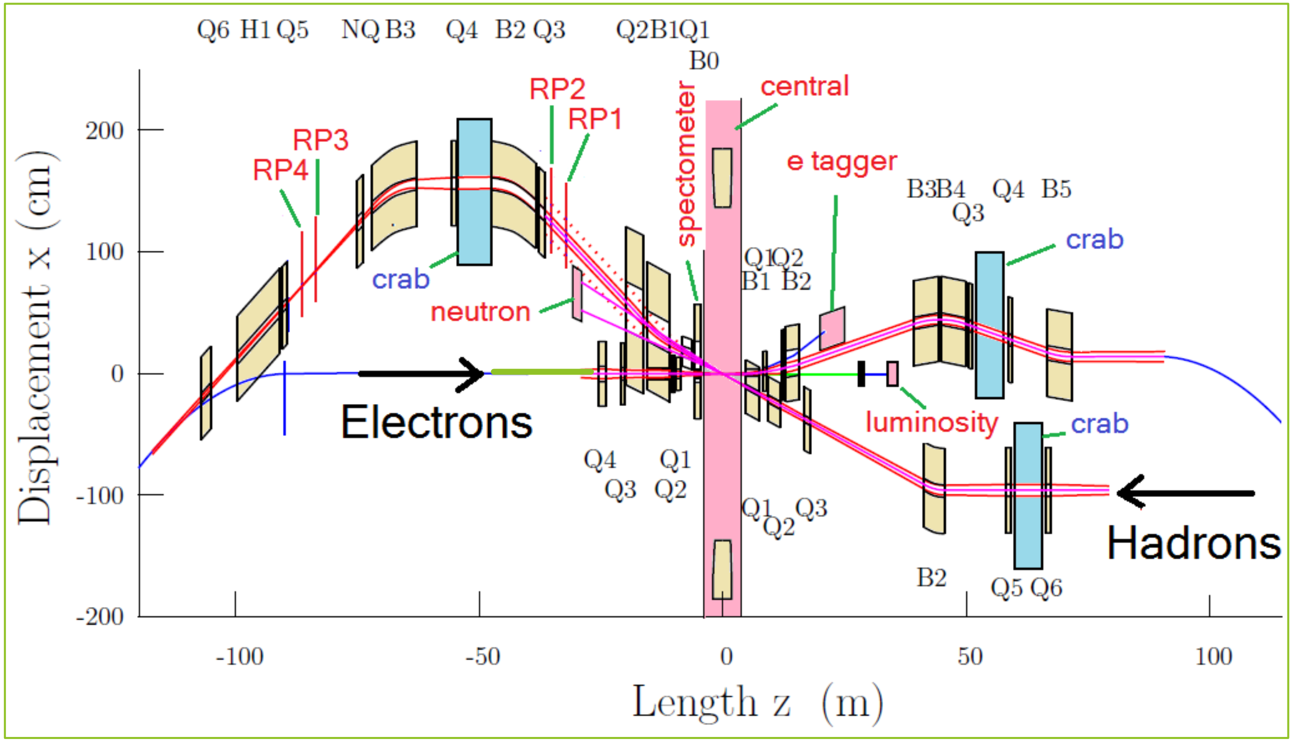
Layout of the Interaction Region

Highly constraint problem:

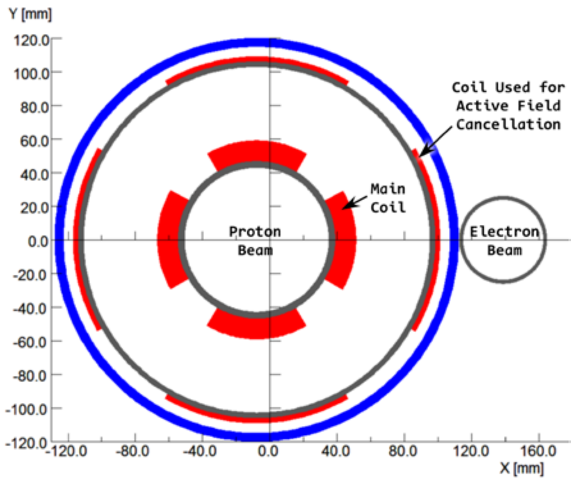
- Focus both beams to small size ➔ large luminosity
- Separate the beams quickly to allow for magnets close to the focal point,
- Crossing Angle Geometry **22 mrad**
- Crab cavities to be accommodated in the IR for both beams
- Avoid excessive Chromaticity generated in the IR
- Shield Electrons from strong focusing and deflection magnets for hadrons
- Provide large acceptance for small angle scattered hadrons (close to beam detectors or Roman Pots) is in conflict with small beam size which implies large beam divergence
- Large acceptance for entire detector
- No accelerator components near the interaction point (+/-4.5 m)
- Avoid generation of synchrotron radiation which destroys sensitive detectors and can produce significant backgrounds
- Provide acceptance for luminosity measurement and forward neutron detection
- Accommodate spin rotators
- Accommodate near-beam detector components (Spectrometer magnets, roman pots)

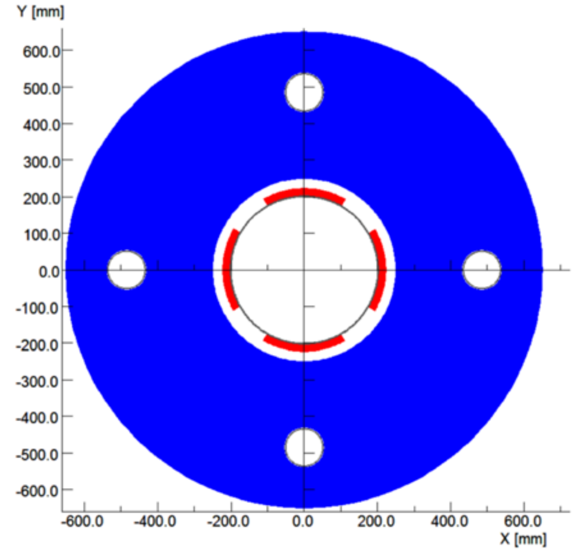
Interaction Region Layout (note distorted scale)



- Interleaved arrangement of electron and hadron quadrupoles
- 22mrad total crossing angle, using crab cavities
- Beam size in crab cavity region independent of energy – crab cavity apertures can be rather small, thus allowing for higher frequency
- Forward spectrometer (B0) and Roman Pots (R1-R4) for full acceptance

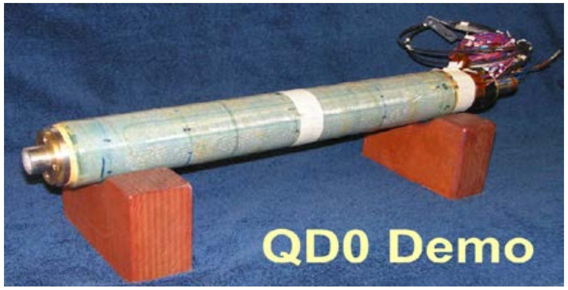
Conceptual Layout of IR Magnets with active shielding





magnets with direct-wound coil including cancelling dipole to shield electron

Prototype for actively shielded quadrupole Q1 already exists as part of ILC work



Hadron superconducting quadrupole with hoses in the return yoke for electrons

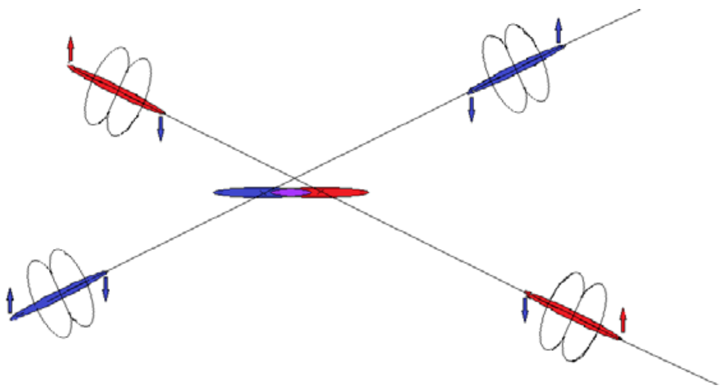
Spectrometer magnet in the Hadron line close to detector: detection of forward scattered Hadron

Generation of dispersion downstream for increased p_t acceptance

Conceptual design for super-ferric dipole

With actively shielded pipe for electrons

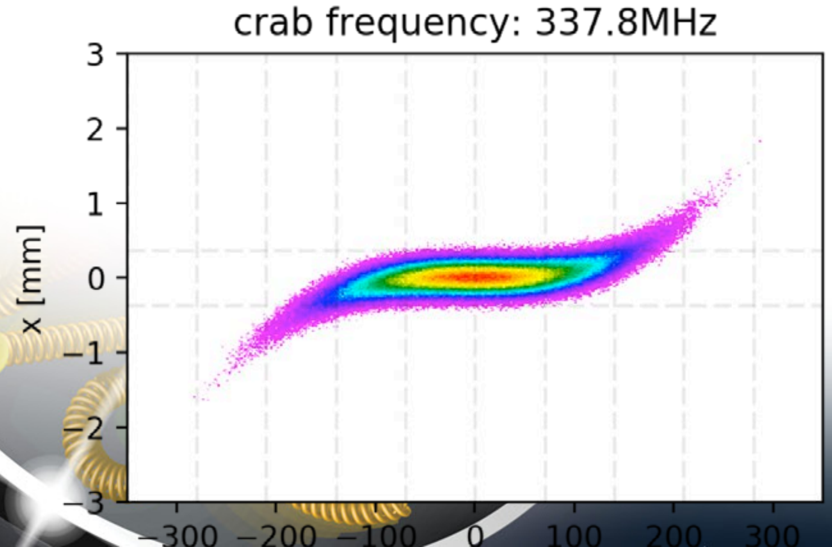
Crossing Angle Geometry and Crab Cavities



Prototype of a double quarter wave length s.c. crab cavity (father of the prototype to be installed in SPS for the LHC crab cavity test)

Simulation of crabbing and crab cavity effects just started ➔ needs more effort

Example: Results on the quest of Higher Harmonic Crab Cavities



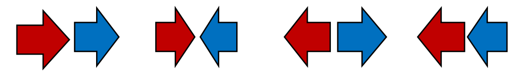
Simulation taking into account

- linear BB,
- Energy pick up in the cavity
- Path length and orbit effects due to dispersion in the crab
- Crab dispersion effect
- Nonlinear BB with crab: in progress

Beam Polarization

Requirements

- The two beams must be longitudinally spin polarized in collisions
- 70% hadron polarization, 80% electron polarization
- All combinations of spin orientations present in one fill



Hadron Polarization

- Polarized protons with P > 60% are already provided by RHIC and its injector chain ➔ no design concern at this point

- H^3 Polarization: source available soon, requires additional Siberian Snakes taken from the Blue Ring

Electron Polarization

Sokolov-Ternov either too slow (at 5-18 GeV) or detrimental for spin || B-dipole ➔

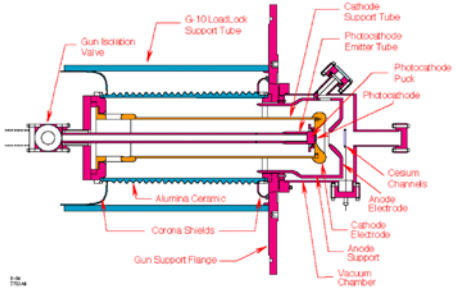
- Storage ring requires full energy injection of polarized bunches, no top off
- Drives the requirements of the injector chain from source to high energy accelerator
- 50nC polarized source: SLAC gun: 16 nC 120 Hz, eRHIC 50nC 1 Hz, may need accumulator
- superconducting recirculating linac $$ or rapid cycling synchrotron

Storage Ring Polarization

- Spin || B-dipole: depolarization by Sokolov-Ternov effect, need exchange bunches every 6 minutes (kick-in / kick out)
- Spin Polarization preservation will be based on HERA experience: Spin matching, harmonic orbit control, choice of tunes near integer resonance, ….

Polarized Electron Source

- R&D activity for a polarized source (80%) underway:
- Goal 5 nC bunches spaced by 100 ns ➔ 50 mA
- For present eRHIC design approach need a 50 nC polarized (80%) electron gun with 1 Hz repletion frequency
- SLAC Gun might be a good starting point. It delivered 16nC @120 Hz
- In conjunction with a small accumulator ring, it will satisfy the demand



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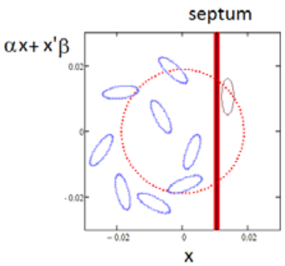
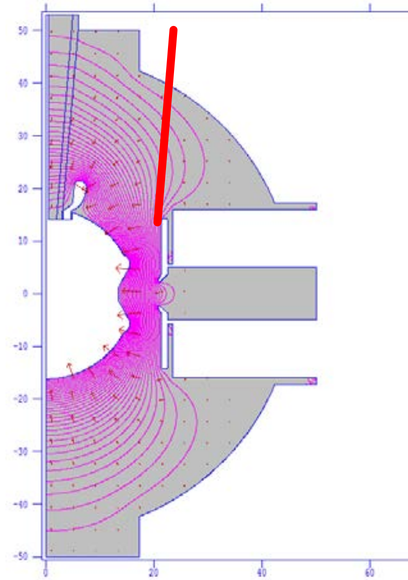
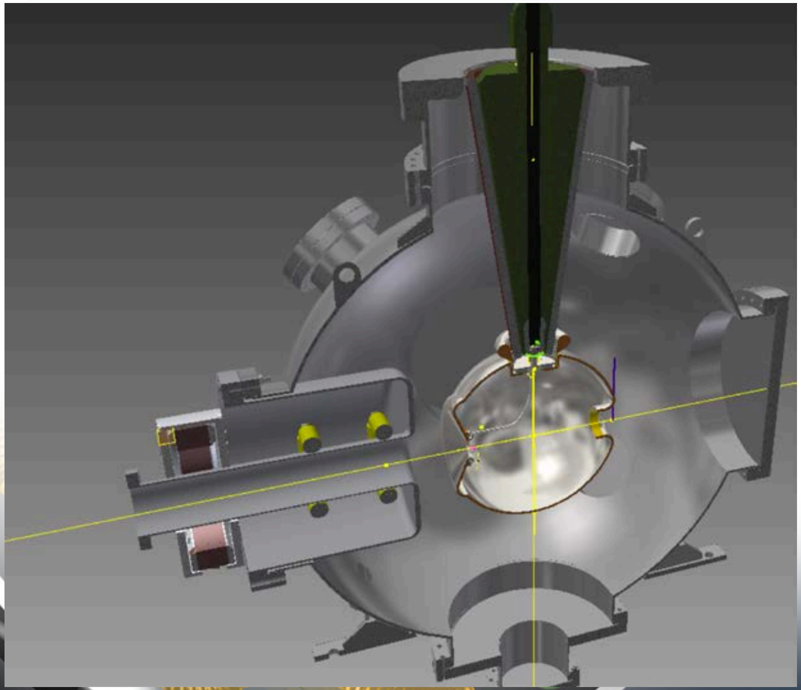


- However polarized gun designs have been improved since the SLAC gun was developed and operated and these improvement promise
- eRHIC inverted gun with large cathode size promises performance of 50 nC within surface charge limit. 50nC beam transport looks ok

Polarized eGun R&D: Beyond State of the Art Design

	Variant 1	Variant 2	Variant 3
Ball size	32 cm	32 cm	20 cm
Gap distance	7.3 cm	4.7	5.7
Voltage	350kV		
Cathode size	2.5 cm		
Electrodes angle	26 degs	26 degs	26 degs
Cathode gradients	2.7 MV/m	4.3 MV/m	3.5 MV/m
Maximum gradient	9.8 MV/m	9.9MV/m	9.9MV/m





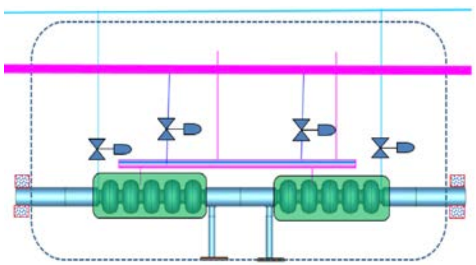
Gun Vessel

10^{-12} torr

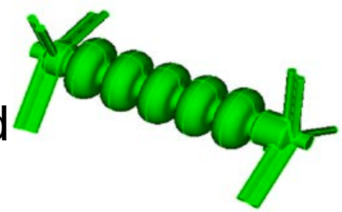
Spin Transparent Electron Acceleration

Straight forward Choice:

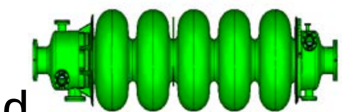
- Recirculating s.c. LINAC, 647 MHz, 3 GeV, Accelerating gradient: 25MV/m
- Rep Rate 1 Hz, single bunch **50 nC**

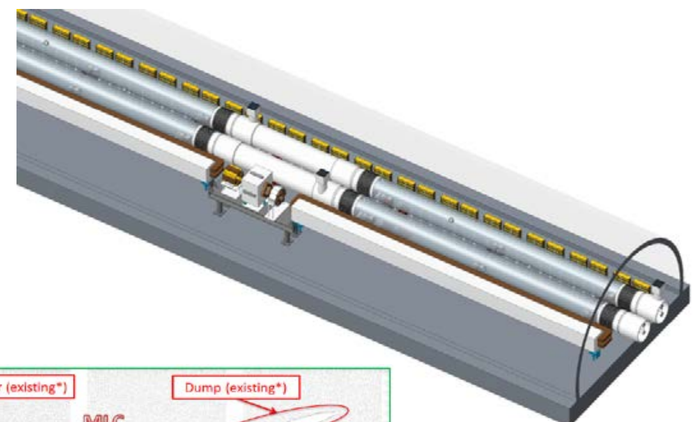


Need some waveguide HOM damping to avoid accumulation of beam induced fields

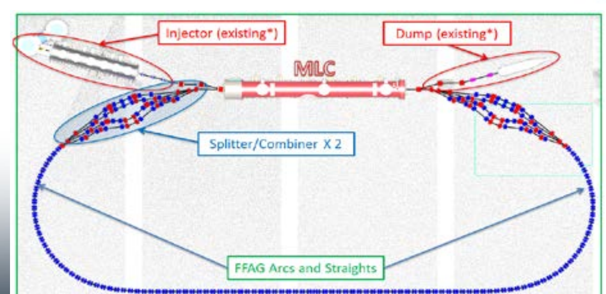


Prototyping of Cu model and Nb cavities and waveguide HOM underway





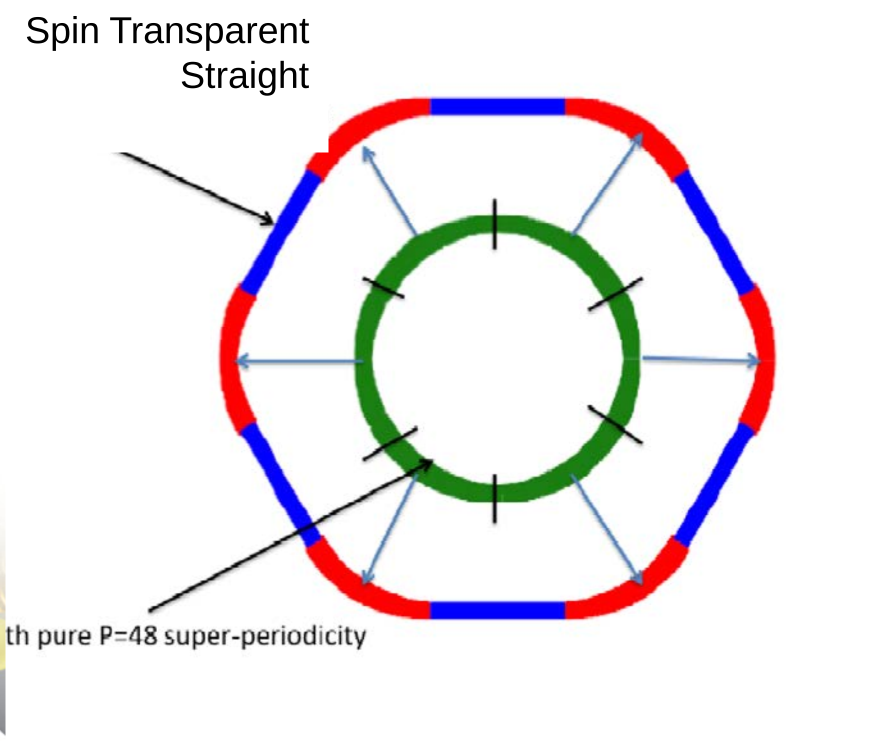
- Five re-circulation loops
- Challenge to fit in the RHIC tunnel together with
- 2 RHIC rings and Storage Ring
- LINAC beam dynamics has been checked ok Dp/p for SR injection
- Energy spread at SR injection manageable
- Main Disadvantage of this scheme:
- cost, need 120 m of active structure at ~>(1-1.5) M $/m
- Plus 250 M$ for five return loops.
- FFAG based return loops could save some of this cost.
- ➔ Cbeta test accelerator at Cornell Univiersity (under construction)

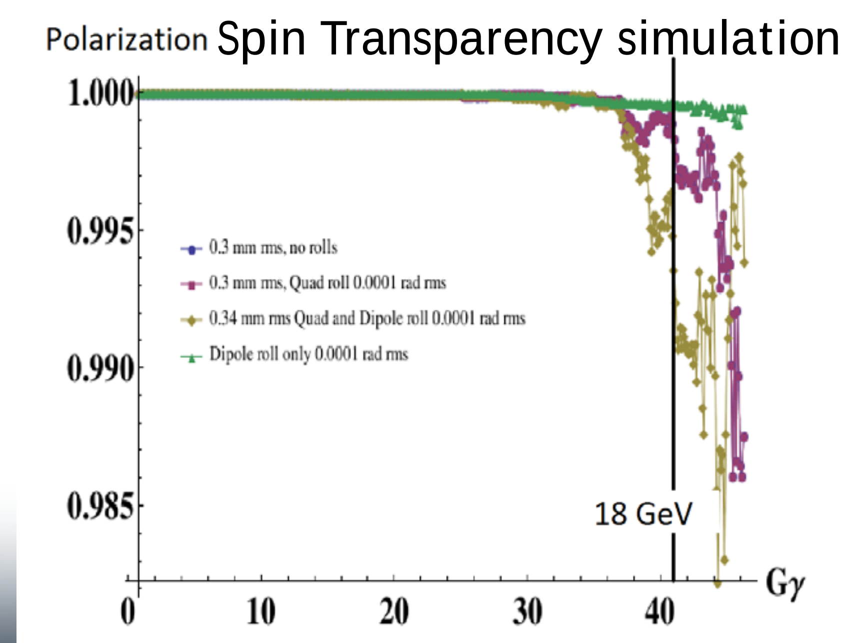


Alternative Spin Transparent Electron Accelerator

Rapid Cycling Synchrotron with Suppressed Intrinsic Spin Resonances due to high 48-fold quasi Symmetry

Costly Linac can be replaced by much cheaper fast cycling synchrotron
If electron polarization can be preserved.
Idea: synchrotron with highly symmetric arcs connected by lattice with unity beam transport
First simulation results without error compensation and 5 ms ramp time





Envisioned eRHIC Time Line

- April 2017 Design Choice Validation Review
- 2017/18: Work out a pre-conceptual design report
- 2018: eRHIC Design Review
- 2019: Mission need acknowledged by DOE, critical decision zero (CD-0)
- 2019-2021: Conceptual design
- 2021: CD1: site decision
- 2021-2022: preliminary design project baseline in scope cost, and schedule scope
- 2022: CD2
- 2022-2023- Engineering design (final design)
- 2023: CD-3 Start Construction
- 2028 CD-4 Completion

SUMMARY

- The planned construction of an Electron In Collider is supported by the Nuclear physics community and is prominent part of the NP long range plan.
- Accelerator based nuclear physics experiments and studies in the field have led to a strong and exciting physics case of the EIC which is acknowledged not only in the Nuclear Physics community but also stirred the interest in the High Energy Physics Community in particular in the Deep Inelastic Scattering Community, as fundamentally new physics could emerge from an EIC physics Program.
- The BNL version of the EIC makes use of the existing RHIC accelerator complex, which constitutes more than 2/3 of the cost of such a facility is called eRHIC.
- The eRHIC design has evolved recently
  - from an ERL based solution which is quite cost effective but has unresolved technical risks
  - to a concept based on an Electron Storage Ring with peak luminosity in excess of $10^{34}cm^{-2}s^{-1}$ and cm energy ranging between 30 GeV and 140 GeV
- The accelerator design uses only accelerator components and electron and Hadron beam parameters which have already been demonstrated,
- While luminosities of a few times $10^{33}cm^{-2}s^{-1}$ are considered reasonably likely, reaching luminosities of $10^{34}cm^{-2}s^{-1}$ and beyond need strong hadron cooling, still to be demonstrated
- There is a significant cost saving opportunity by using equipment from retired facilities.
- An R&D program is underway to explore cost saving technology

- eRHIC promises to be an exciting opportunity for the science in the next 2-3 decades

Cooling: Risk Mitigation

- Coherent electron cooling is a novel technique
- There are number of risks associated with the technical implementation, if not with the principle itself.
- Thus there is a risk that strong Hadron cooling will be not available or will be delayed

These risks are mitigated as follows:

- A moderate Luminosity solution with $3 \cdot 10^{33}$ $cm^{-2}s^{-1}$ luminosity would support a compelling physics program
- A moderate solution can be upgraded to $5 \cdot 10^{33}$ $cm^{-2}s^{-1}$ by increasing the number of bunches by factor ~1.7 and the beam current. **No cooling would be required** and the high beam currents are addressed in the design
- Magnetized cooling is an alternative option, however it equally challenging to implement, though there are less concerns about the cooling principle. Implementation is possibly quite expensive. **RHIC has an active electron cooling program to as part of FY19-20 operations plan.**