eRHIC Design and Development

- eRHIC design goals
- Conceptual design study with reduced technical risk
- - Ring LINAC option
- - Ring-Ring option
- R&D for future upgrades

Ferdinand Willeke, BNL

EIC Workshop
Glasgow University
Ross Priory, 13-14 October, 2016

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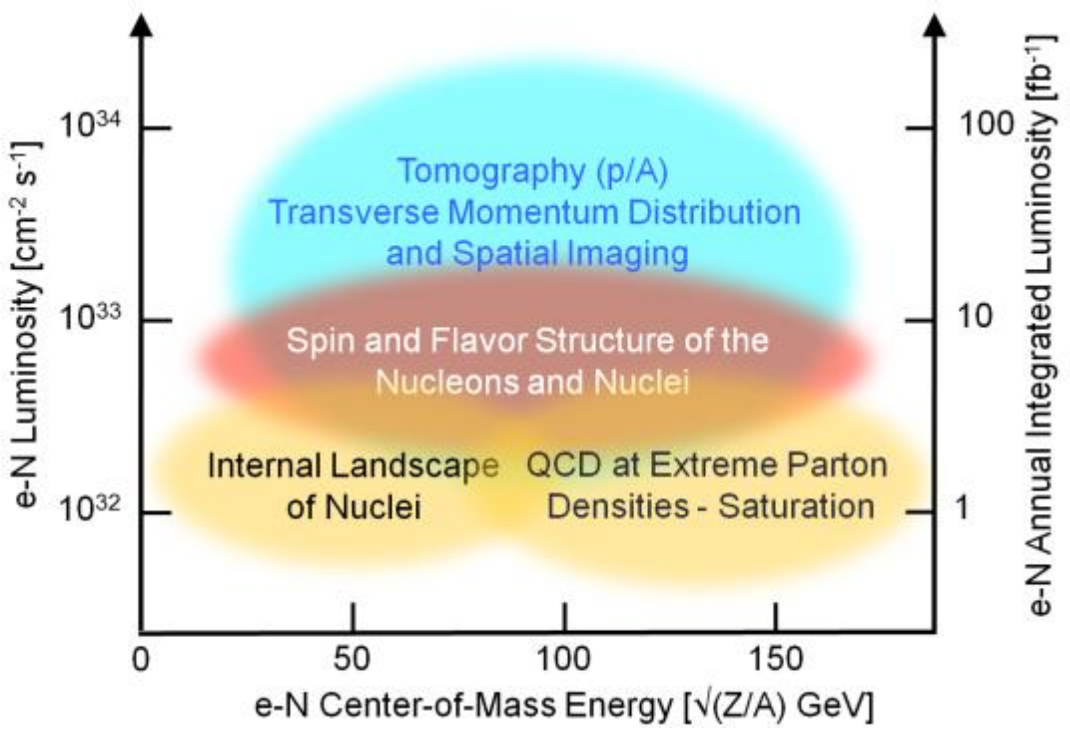
Office of Science
U.S. DEPARTMENT OF ENERGY

eRHIC Requirements (EIC White Paper)

- Large peak luminosity of preferably **$L = 10^{34} s^{-1} cm^{-2}$**, at least **$L = 10^{33} s^{-1} cm^{-2}$**
- Center of mass energy between (20-150) GeV
- Both Hadron and Electron beams are longitudinally spin polarized
- Large acceptance: - forward scattered protons (200 MeV $\leq p_T \leq$ 1.6 GeV/c)
  - forward neutron acceptance 4mrad
- Access to small Bjorken-X$<10^{-4}$ ➔ need Electron-Ion collisions; large Q^2



The Relativistic Heavy Ion Collider at BNL

Since 1999 operating with heavy ions and polarized proton collisions serving multiple experimental detectors

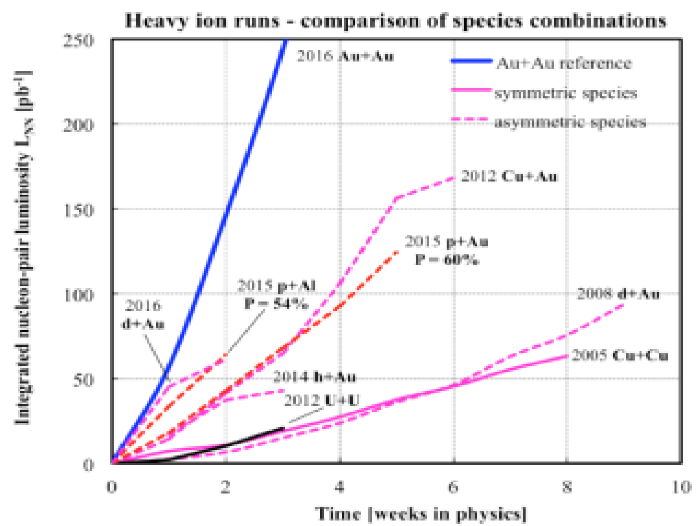
Circumference : 3.8 km
Max dipole field : 3.5 T
Energy : 255 GeV p …100 GeV Au
Species : p↑ to U (incl. asymmetric)
Experiments : STAR, PHENIX

Continuous Performance Increase

- Improving machine luminosity in every run
- Only facility with high energy polarized proton beams; *employing numerous techniques to achieve high proton polarization (up to 60%) in collisions*
- Present plan: to continue A-A and polarized p-p experiments till 2024

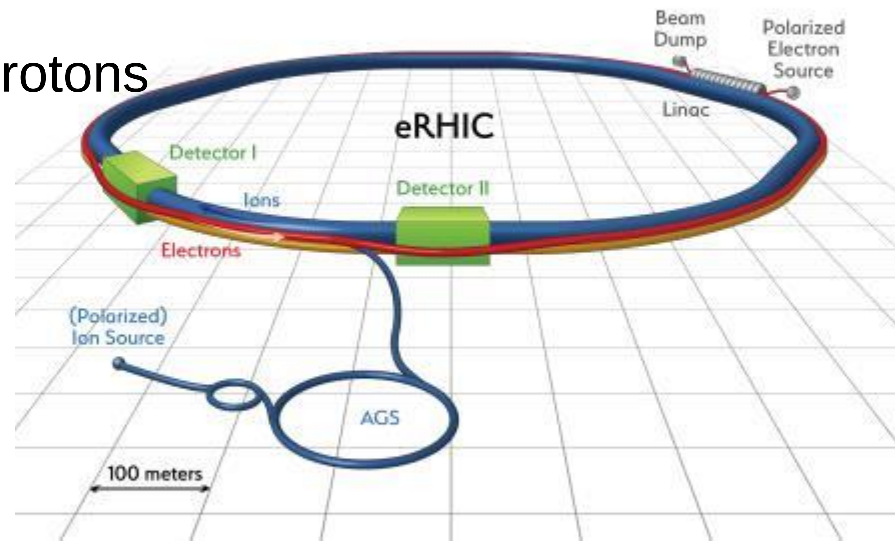
Rich Physics Program

- Discovery and detailed study of properties of quark-gluon perfect fluid matter,
- Study of proton spin composition, especially its gluon component



eRHIC Design

Exploiting the RHIC with its
- superconducting magnets, 275 GeV protons
- its large accelerator tunnel and
- its long straight sections
- its existing Hadron injector complex

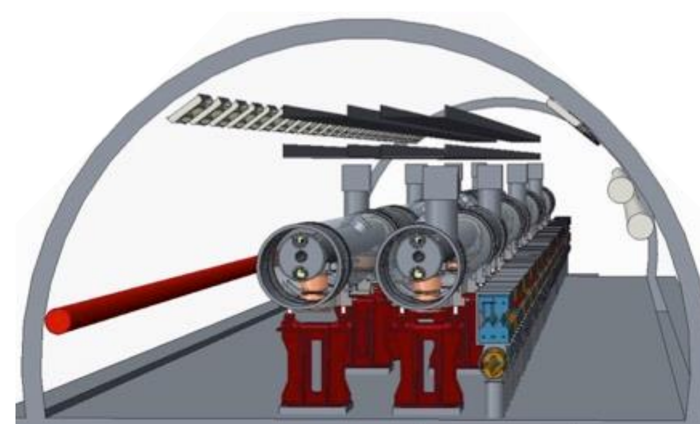


by
adding an electron accelerator
of 18 GeV in the same tunnel
- high energy reach in e-Ion collisions
- with modest synchrotron radiation, (low operating cost)
- making use of - superconducting LINAC technology
- and multi-turn recirculation
- using either the

energy recovery **(ERL)** concept
or
a high intensity electron storage ring

- achieve high luminosity

electron-Hadron collisions
over a large range of CM Energies

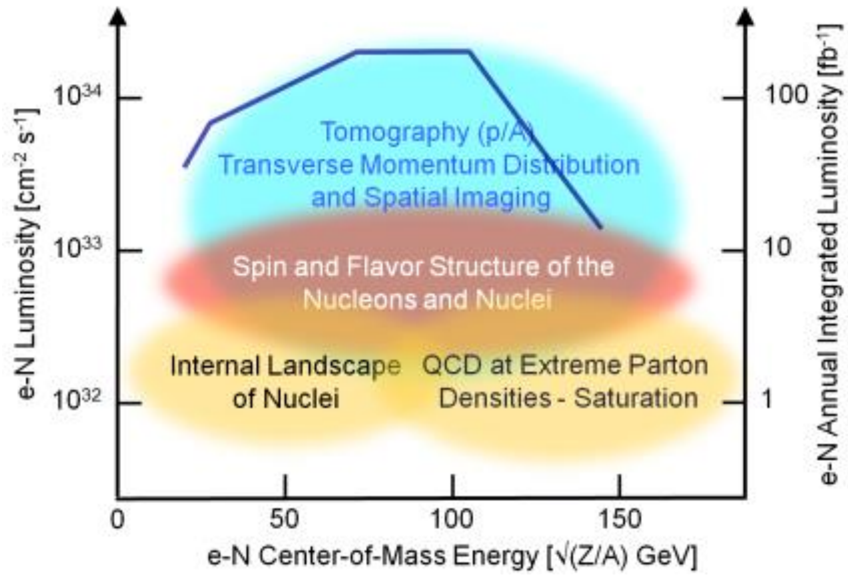


Ultimate eRHIC Design

An eRHIC design has been worked out (published 2014) meeting **all** the demanding requirements of the EIC physics program (EIC White Paper),

in particular

Luminosities **>10^{33}s^{-1}cm^{-2}** over the entire range of CM energies **25-140 GeV** with a maximum Luminosity in excess of **10^{34}s^{-1}cm^{-2}**



However, this design is based on novel technology
Coherent Electron Cooling, FFAG return loops, Multi-cathode Gun
➔ Requires strategic R&D program & demonstration of feasibility before a commitment can be made to build a large and costly facility based on this approach

Key Elements of the ongoing long term R&D program is **Coherent Electron Cooling**
➔ for small Hadron beam emittance for ultra-high luminosity

To move forward➔ Design towards lower Luminosity (10^{32}-10^{33}) s^{-1}cm^{-2} but provide access to all components of EIC physics program

eRHIC Design Study

with acceptable technical risk

Achievable Luminosity with proven technology is in the range of **L = $10^{33}s^{-1}cm^{-2}$**
will provide access to compelling initial physics program

The reduced luminosity goal makes a storage ring based collider (RR) an interesting alternative to and multi-turn ERL based concept.

➔ **Strategy towards eRHIC Design:**

- Study simultaneously **two** solutions, both based on existing technology:
  - multi-turn ERL (LINAC-Ring collider , LR)
  - storage ring based collider (Ring-Ring collider RR)
- carry common R&D elements (e.g. Crab cavity) in parallel
- Work on experimental verification of critical, yet to be demonstrated design elements (electron source, superconducting Linac)
- Carry out Value Engineering and R&D which might lead to saving cost (FFAG lattice with CBETA, Gatling Gun, Waveguide HOM damper)
- Compare the two options in terms of performance, cost and residual risk, and feasibility of high luminosity upgrade

➔ **Select a final eRHIC conceptual design as soon as possible**

- Pursue strategic R&D program addressing CeC, to pave the way for a high luminosity upgrade.

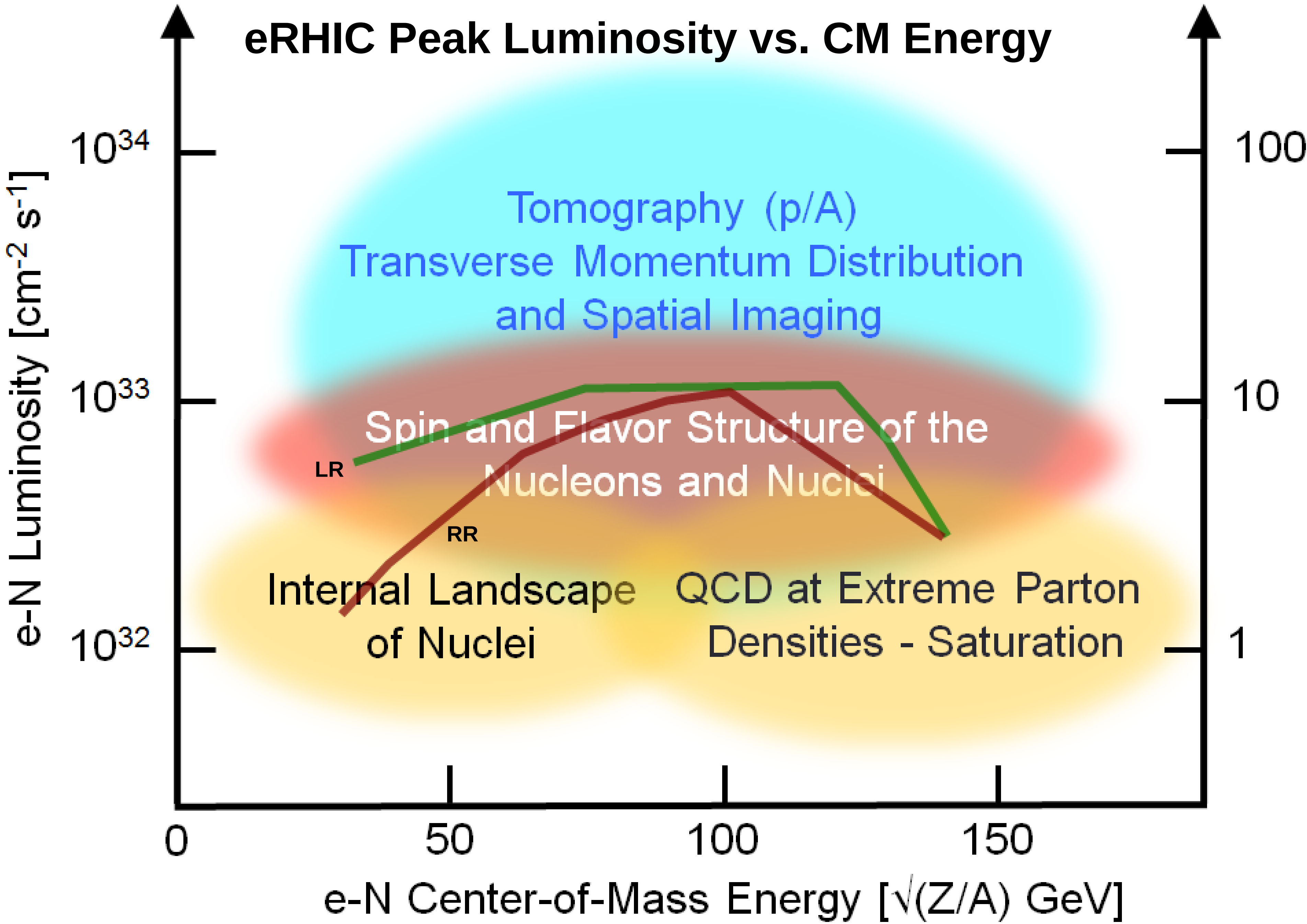
Primary eRHIC Design Requirements

Maximum Peak Luminosity	$\geq 10^{33} s^{-1} cm^{-2}$
Center of Mass Energies	20 GeV-140 GeV
Proton Polarization	70%
Electron Polarization	80%
p_T acceptance	200 MeV/c – 1.3 GeV/c
Forward Neutron acceptance	4 mrad
Upgradable to high luminosity	$L = 10^{34} s^{-1} cm^{-2}$

eRHIC Design Study: Important Parameters

RR Low risk design v4p5, 12Aug16

Parameters for Highest Luminosity design point				
	Ring-Ring		Linac Ring	
Parameter	e	p	e	p
Energy [GeV]	10	250	13	250
CM energy [GeV]	100		105	
Bunch frequency [MHz]	28.2		9.4	
Bunch intensity [10^{10}]	31	12	3.3	30
Beam current [mA]	1300	500	50	415
Beam Emittance h/v [nm]	24.2 / 3.86	17.7 / 6.7	1.9 / 1.9	1.9 / 1.9
Vertical β^* [cm]	7.4	4.2	17.5	13
Horizontal β^* [cm]	417	567	36	26
IP rms beam size h/v [μm]	318 / 17		30 / 21	
Beam Divergence @ IP [μrad]	110/230	80/400	120/120	120/120
max beam-beam parameter	0.1	0.015	1	0.004
e-beam disruption parameter	Neglig.		6	
rms bunch length [cm]	0.8	8	0.3	16
Polarization [%]	80	70	80	70
Peak Luminosity [10^{33}cm^{-2}s^{-1}]	**1.1**		**1.2**	



eRHIC Peak Luminosity vs. CM Energy
e-N Luminosity [cm-2 s-1]
10^34
10^33
10^32
100
10
1
Tomography (p/A)
Transverse Momentum Distribution
and Spatial Imaging
Spin and Flavor Structure of the
Nucleons and Nuclei
LR
RR
Internal Landscape
of Nuclei
QCD at Extreme Parton
Densities - Saturation
0
50
100
150
e-N Center-of-Mass Energy [√(Z/A) GeV]

Main Features of the Recirculating ERL-Based Concept

- Superconducting Multi-turn Energy Recovering LINAC
  two 1.5 GeV s.c. LINAC 6 return loops➔ 18 GeV (recirculation, energy recovery demonstrated)

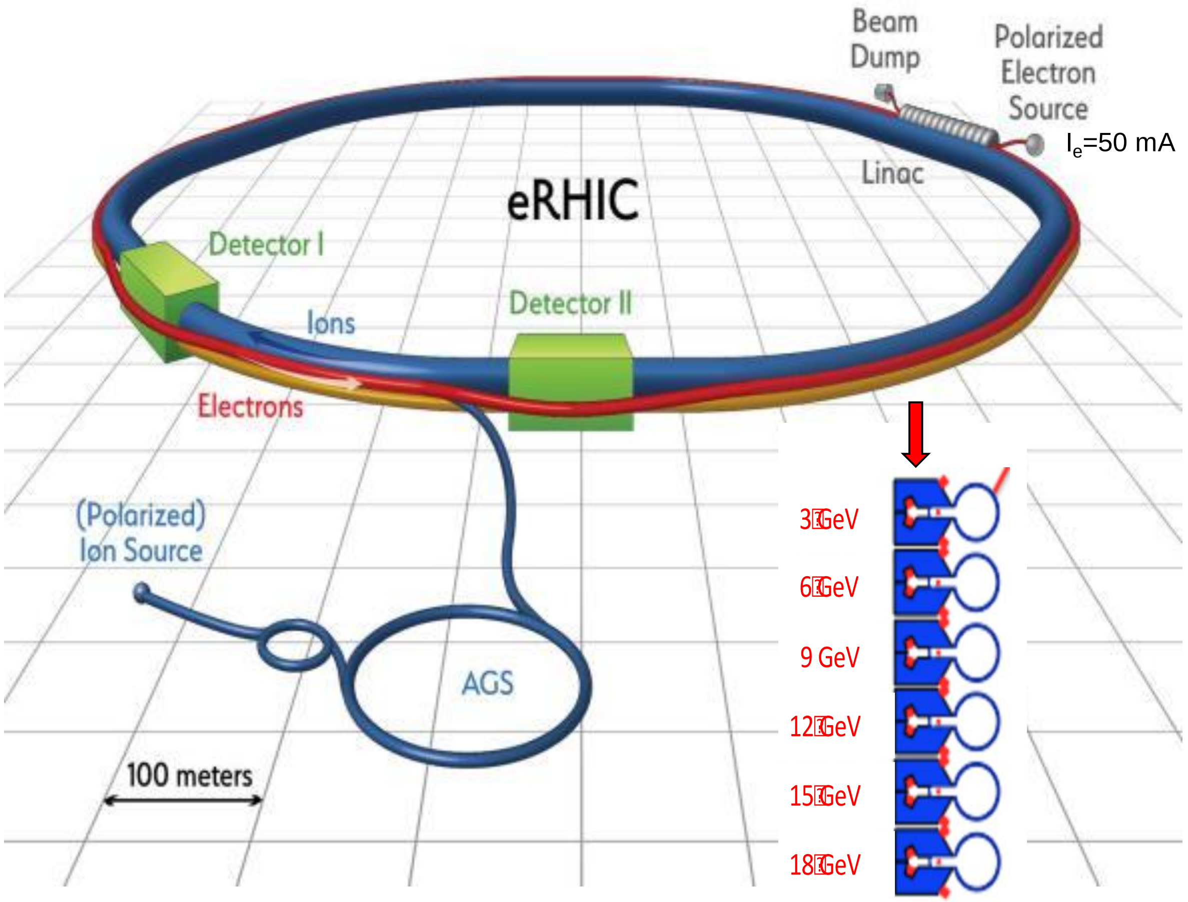
- High current polarized electron source:
  Eight parallel polarized guns each delivering 6.25 mA electrons 5nC/bunch, 10 MHz bunchfrequency, fast switching between them

- Low emittance RHIC protons and stochastically-cooled Heavy Ions, present operating parameters

- Crossing angle collision geometry (14 mrad) requiring crab cavities

- Spin rotator after injector and pair of spin rotators around IR

eRHIC LR Schematic View



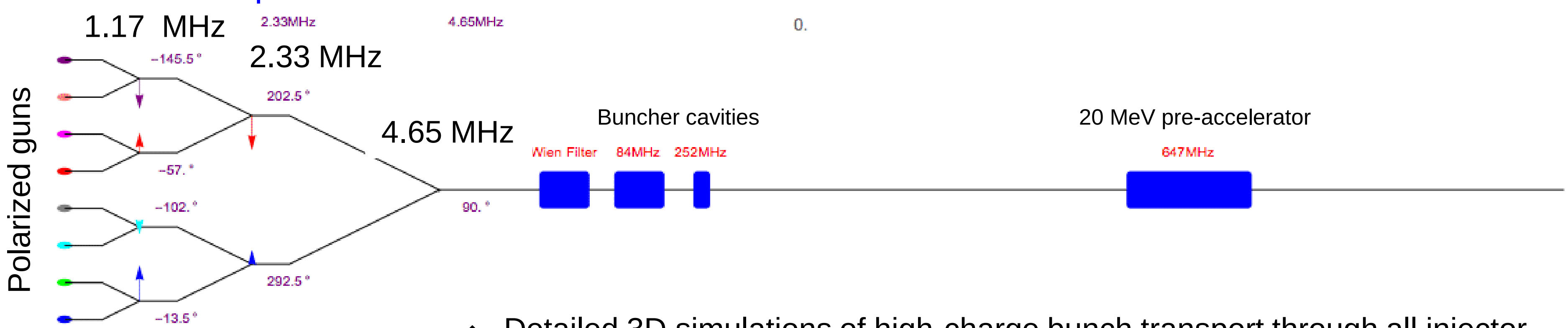
- **Maximum electron energy: 18 GeV**
- **50 mA polarized electron source employing merging electron current produced by multiple electron guns**
- **Main ERL SRF linac(s): 647 MHz cavities, 3 GeV/turn**
- **Six individual re-circulation beamlines based on electromagnets**
- **No hadron cooling required for e-p in initial design.** ***Existing stochastic cooling system can be used for e-Au Luminosity upgrade path to the Utlimate design: adding a cooling system (CeC)***
- **Interaction region design with crab-crossing satisfying detector acceptance requirements**

ERL-Ring Polarized Source Using Merging Scheme

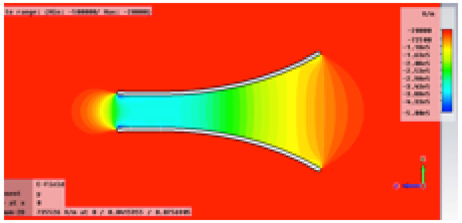
- 4 mA polarized electron beam current was demonstrated in dedicated experiments in JLab

  Although the Jlab gun design is not optimal for high bunch charge mA scale operation: small cathode size, no cathode cooling

- Lowered risk eRHIC polarized source employs eight JLab-like guns (possibly with improved gun geometry, cathode size and cathode cooling) and combining scheme to produce up to 50 mA current at the source exit



Field distribution of copper plate deflector, used in combining scheme



- Detailed 3D simulations of high-charge bunch transport through all injector components are underway
- Experimental studies of single cathode lifetime dependencies (using a Gatling gun prototype)
- Measurements of surface charge limit for SL cathodes using cathode preparation system.
- **A prototype gun is being designed, and will be built next year**

Polarized Electron Source

Need $3 \cdot 10^{10}$ electrons per bunch at 9.8MHz @ 50 mA; 70% polarized

Meet this requirement using 8 parallel photo gun, fast switching between them

➔ **5.3 nC at 9.8MHz @ 6.25 mA; 70% polarized, GaAs Cathode, 350KeV, peak current**

~beam current similar to JLAB polarized gun (4 mA),

but required peak current of ~5 A is 50 x larger (0.07 A) than JLAB Gun

~peak current of 5 A is similar to SLC gun (2.7 A),

but average current of 6.25 mA is much larger

however, SLC repetition frequencywas limited by other factors (LINAC, DR..) ➔ no attempt to obtain high average current

➔This requires an experimental verification by a prototype

- **Comprehensive development program underway to build prototype and demonstrate eRHIC Performance Parameters**

High Current Polarized Photo Electron Gun Design

Cathode Material: Ga-As (proven, but very sensitive material (short cathode lifetime due to ion bombardment) ➔ need extremely good vacuum (XHV) $P=10^{-12}$ torr; available now

Alternative materials:

Require long time R&D

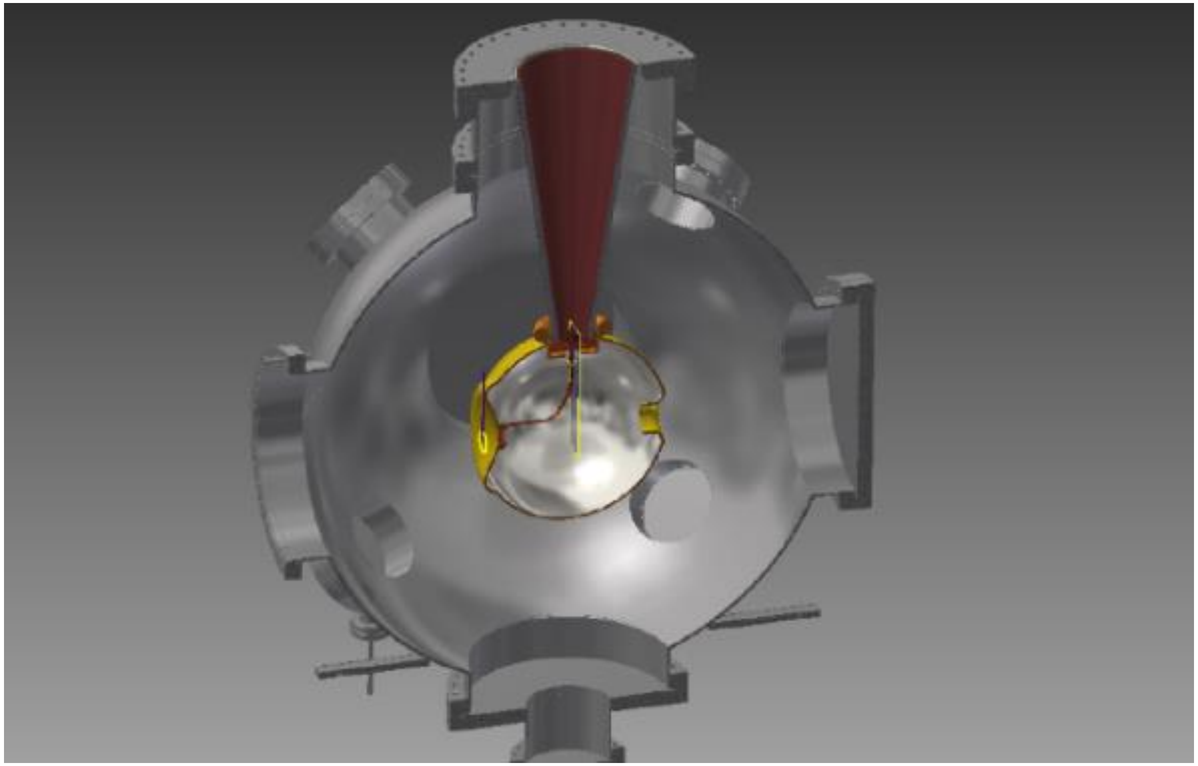
Cathode Parameters:

Extra large cathode (25 mmØ)

Large Laser spot 5 mm

Large laser pulse length:1.5 ns

High Voltage: 350 kV



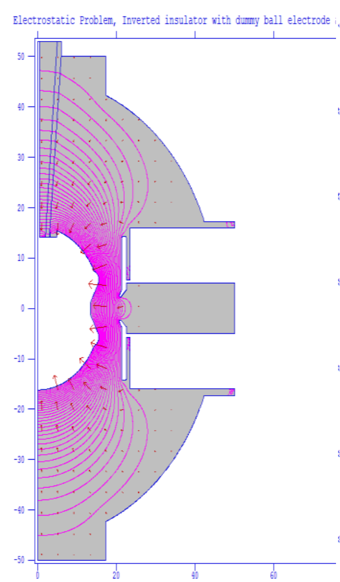
Status:

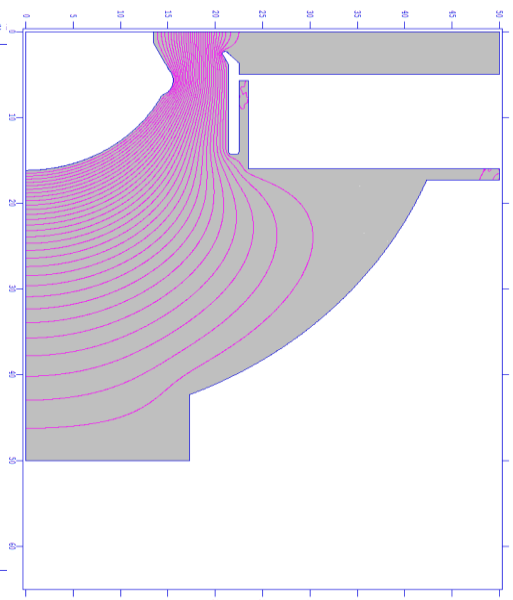
Gun parts in procurement

Schedule: Test end of 2017

Electron Gun Design

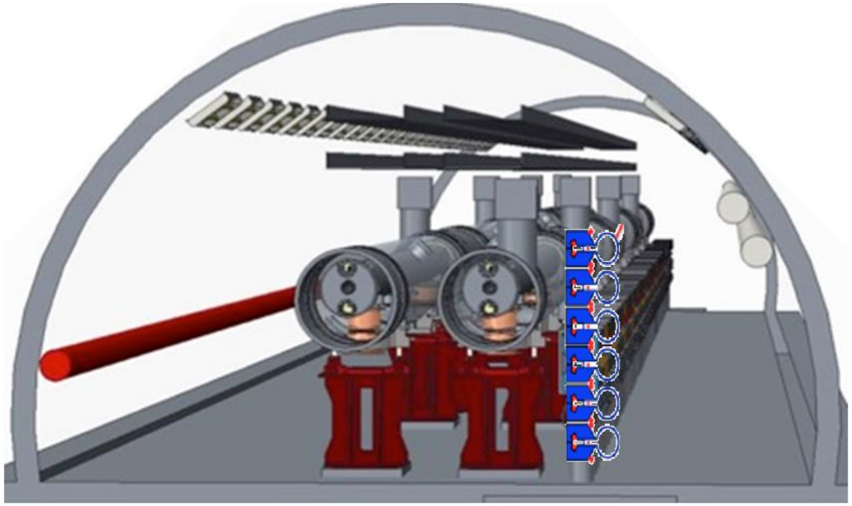
Gap distance	6.4 cm
Voltage	350kV
Cathode size	2.5 cm
Electrodes angle	27.5 degs
Surface gradients	2.5 MV/m
Maximum gradient	9.8 MV/m

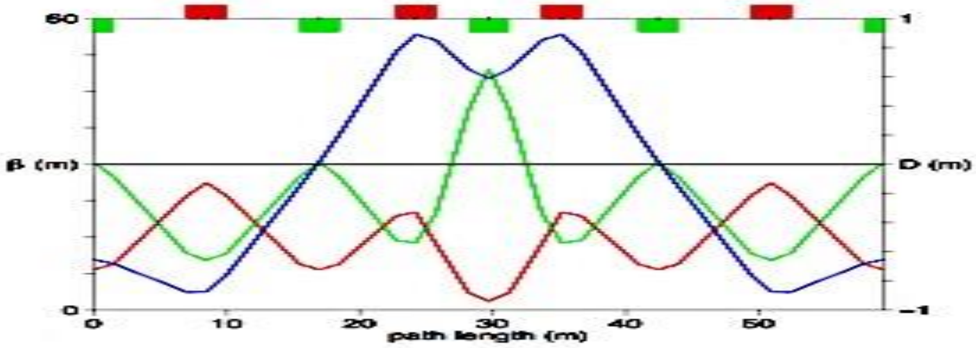




Superconducting Multi-turn Energy Recovering LINAC

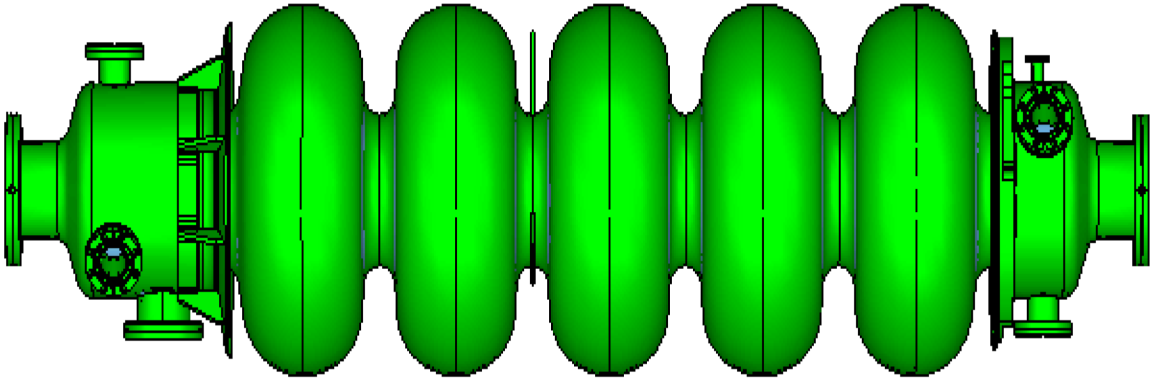
- 2 x {1.5 GeV SC Linac, 200m long, 18 MV/m 36 cryo-modules, 6 turns } ➔ 18 GeV
- 6 vertically stacked isochronous return loops in the RHIC Tunnel





- Beam current 600 mA (50mA/turn), 3mm bunches, Bunchpatterns optimized to minimize **BBU**
- > 463 kW HOM power with beam-pipe HOM dampers (demonstrated at KEK and Cornell)

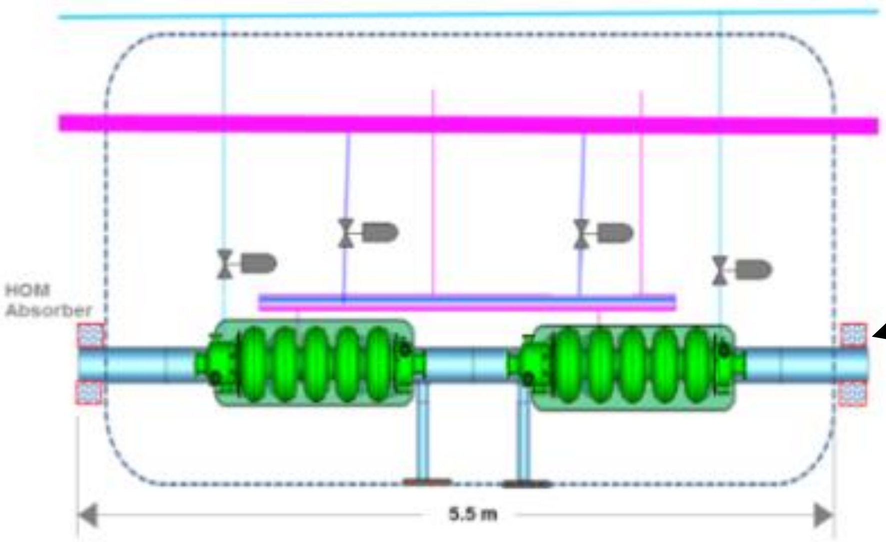
647 MHz Cavity

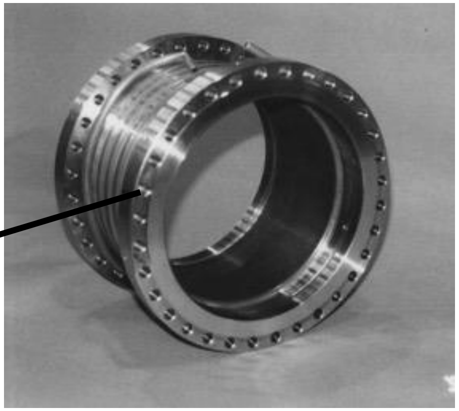


- 18 MV/m, CW, $Q = 3 \cdot 10^{10}$
- Cooling 1.9K Lhe
- $Q_{ext} = 10^7$
- RF power 26.7 kW
- HOM power/cavity 3-8 kW
- Total amount: 144 cavities in 72 cryostats

- Cu model and Nb prototype underway

Major design components: main linac cryo modules





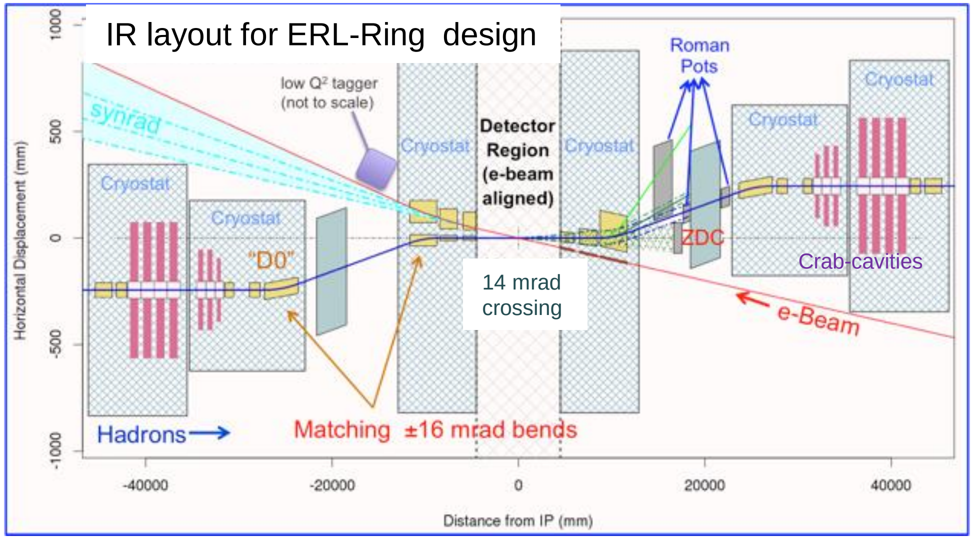
SiC beam pipe HOM Damper

- The 2 linacs are placed in two long straight sections of RHIC of 200 m length each
- There is a total of 2 x 36 5,5m long cryo-modules
- Each has two 647 MHz cavities which provide 42 MV
- Cryostat design is benefitting from the SRF development program for the Fermilab PIP II projectTwo cavities connected by 4K Stainless steel beam pipe
- 600 mA of total beam current in the Linac ➔ HOM power of 6-14 MW cryostat

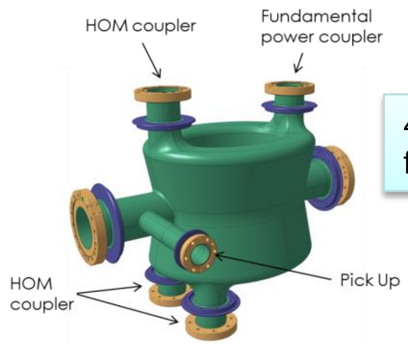
- similar to storage rings at KEKB and Cornell with Ampere of beam currents where ~10 kW of HOM power is absorbed with Ferrite or SiC beam- pipe HOM damper

- Space consuming, waveguide coupler would be more compact (Value Engineering R&D)

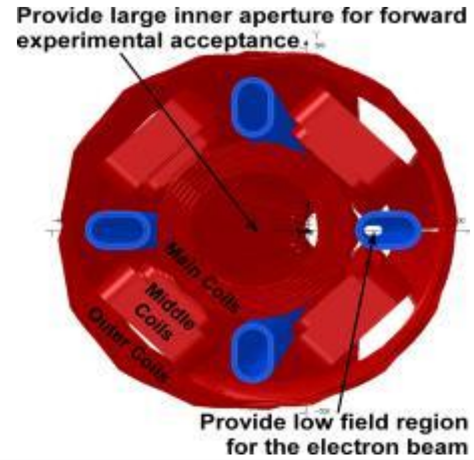
eRHIC High-luminosity, Full Acceptance IR



- Crab-crossing scheme (14 mrad crossing angle; 140-340 MHz SRF crab cavities)
- Special design of SC IR magnets to satisfy forward acceptance requirements and arrange passage of electron beam
- Detector elements (Roman Pots, ZDC, luminosity monitor) integrated into the IR design
- Soft bending of electron beam within 60 m upstream of the IP to simplify SR protection



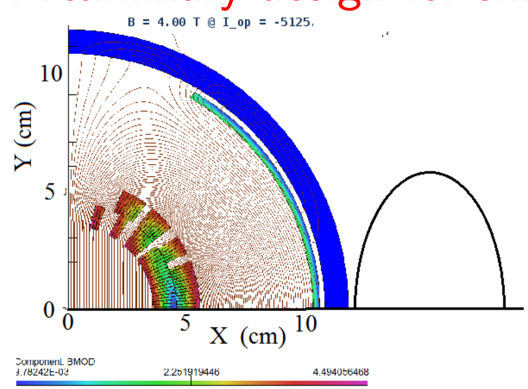
400 MHz DQW crab-cavity built for LHC upgrade



ERL-ring design: “Sweet spot” IR magnet design concept arranges a field-free electron pass between SC coils.

Ring-ring design: an outer coil is used to have magnetic flux contained. Utilizing active shielding technique developed for ILC.

Preliminary design for shielded dipole



Luminosity

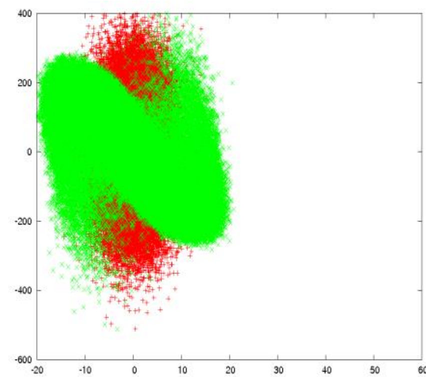
$$\mathbf{L}= f_c \gamma_h \xi_h \frac{Z N_h}{\beta^* r_h} H_{hg} H_p$$

<u>Limitations:</u>

- Polarized Electron Average current 50mA
- Minimum b* of 5cm (electrons, hadrons)
- Hadron Space charge tune-shift < 0.08
- Electron Beam Synchrotron Radiation power < 3 MW

<u>Note</u>: *Limits are not achieved simultaneously*

Note: e beam disruption is not considered a limitati



disruption parameter $D_{x,y} = \sigma_z / f_{x,y}$, where $f_{x,y}$ is the focal length

$$D_x = \frac{2 N r_e \sigma_z}{\gamma \sigma_x (\sigma_x + \sigma_y)} \qquad D_y = \frac{2 N r_e \sigma_z}{\gamma \sigma_y (\sigma_x + \sigma_y)}$$

Main Feature of the Ring-Ring Design Option

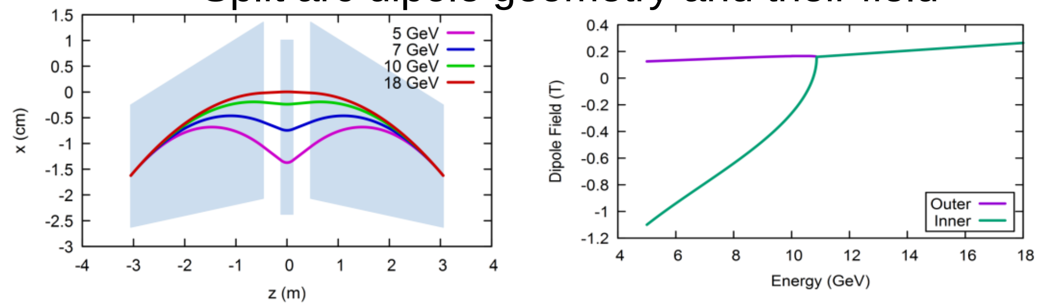
- Full Energy, Polarized Electrons injected and stored in a Storage ring
- To reach high luminosity operate with many bunches and high electron beam current, flat beams
- IR geometry and detector that can accept the larger electron beam emittance.
- Crossing angle collision geometry (22 mrad) requiring crab cavities
- Bunch-to-bunch spin sign control by full energy injector and frequent electron bunch replacement
- Injector based on low current polarized gun, small accumulator ring recirculating s.c. linac for low beam current (4mA), runs at 1Hz , doesn’t need energy recovery
- RHIC hadron beams
- Electron beam current limited by synchrotron radiation at high electron energies power need 10 MW RF power (high cost)

Ring-Ring Design: Reaching High Luminosity

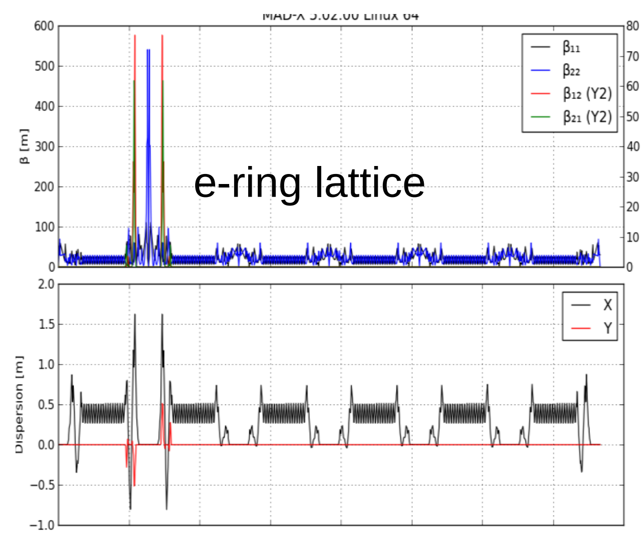
- High electron beam current
  (up to 1.3 A)
  Demonstrated at B-factories;
  Linear SR power load < 4 kW/m

- Luminosity is defined by beam-beam limits:
  $\xi_p < 0.015$, $\xi_e < 0.1$.
  Split arc dipoles are used to enhance radiation damping at lower electron energies

Split arc dipole geometry and their field

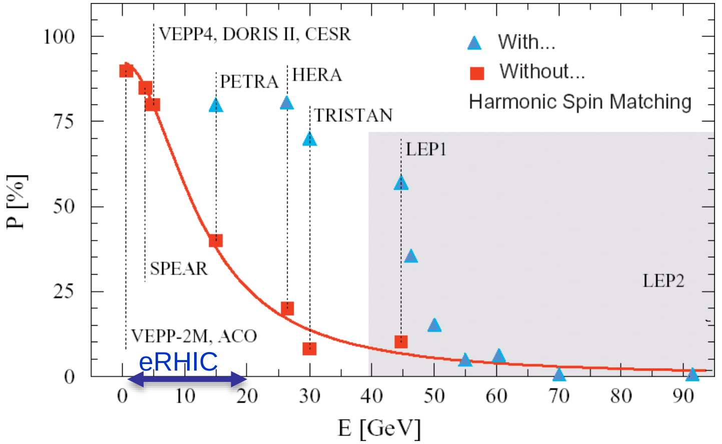


- Increased number of RHIC hadron bunches (by factor 3 from present)
  - Injector system upgrade; (~10 nsec kicker risetime)
  - Copper coating of RHIC beam pipe. In-situ coating methods are being developed
  - Electron cloud and associated heating load is being evaluated



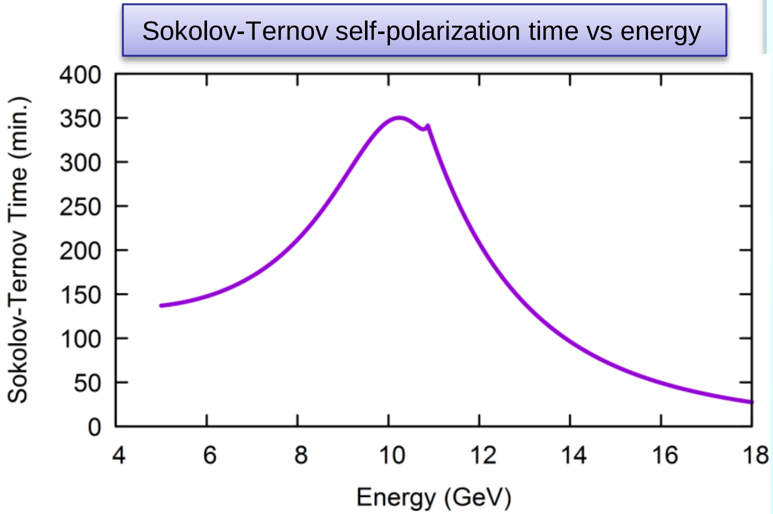
- Robinson wigglers in straight sections:
  to provide proper electron emittance control for matching hadron beam size at IP at different hadron energies

Ring-Ring: Achieving High Electron Polarization



The accelerator technology to achieve high polarization at high energies includes:

- highly efficient orbit correction,
- beam-based alignment of Beam Position Monitors relative to quadrupole field centers
- harmonic spin matching
- well controlled betatron coupling
- spin matching of spin rotator insertion



❖ Beam polarization requirement determines the injector features:

- Full energy injector
  To provide the complex spin pattern
- Frequent electron bunch replacement (up to 1Hz replacement rate)
  To have average beam polarization above 70%.
- Low average current, high bunch charge polarized e-source (similar to a SLAC polarized source)
- Considered injector options:
  - *650 MHz SRF linac, consistent with following upgrade to the Ultimate ERL-Ring*
  - *Recirculating linac based on XFEL/LCLS-2 cryo-modules.*

Ring-Ring Interaction Region

More challenging since electron maximum beta should not become too large

➔

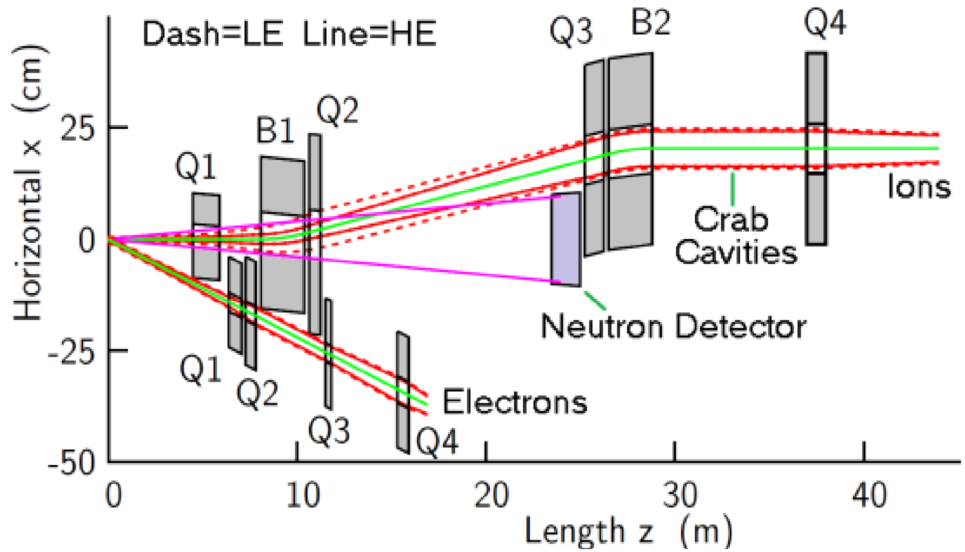
Interleaved electron and hadron low beta quadrupoles

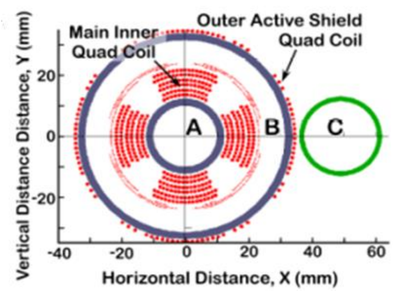
Need actively shield coil to cancel unwanted stray fields

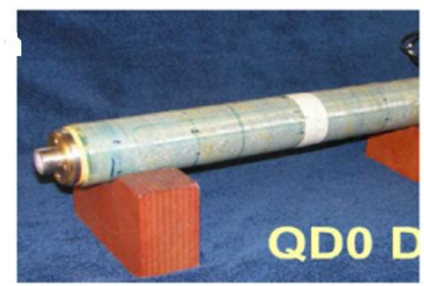
Magnet design study performed with direct wound coil like for

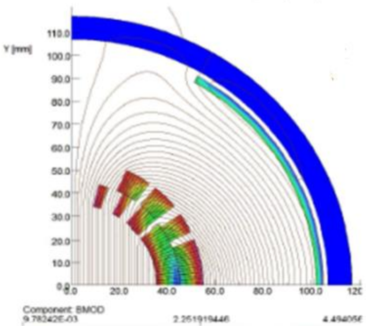
Full acceptance for Neutrons and p_T

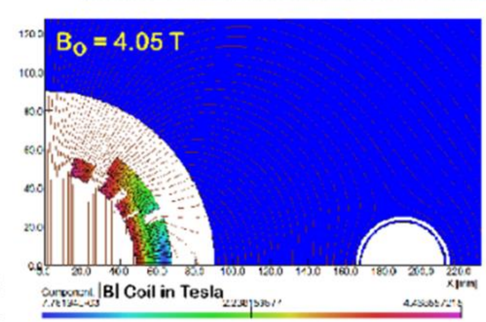
Large Luminosity gain (2.6) for limited p_T acceptance









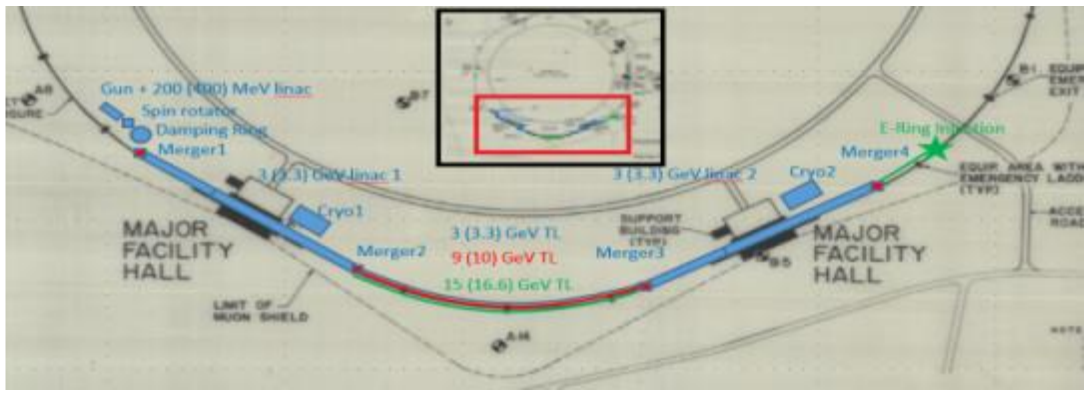


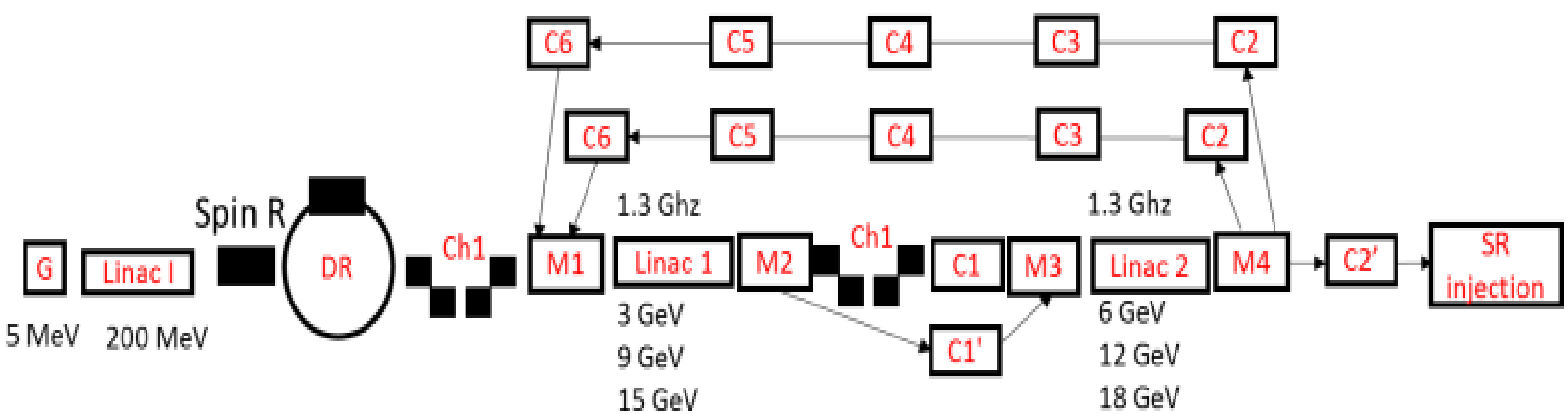
Electron injector

- Recirculating linac pulsed RF

  - XFEL/LCLS-2 modules, With two 2.25 GeV linacs in two adjacent RHIC straights, 3 re-circulations 4 passages to 18 GeV or

- Alternatively 18 x 650MHz cryo-modules operated at 25 MV/m (makes the designs more compatible and easier interchangeable)





Studies + R&D for eRHIC Design in Progress

A) R&D on critical designs where demonstration is deemed necessary (highest priority)
B) Designs which take a long time for optimization and prototyping (medium priority)
C) R&D for cost saving designs (value engineering), (medium priority)
D) R&D for luminosity Upgrade (low priority)

A) **R&D for required demonstration**
- 50 mA polarized electron source (LR)
- 18 MV/m, 500 mA beam current superconducting accelerator structures (LR)
- Simulation study of beam beam iteraction with aggressive parameters (RR)
- Simulation of beam polarization preservation in the storage ring (RR)
- Fesibility of synchrotron radiation generated bckgounds by high intensity electron beams in the IR (RR)

B) **Long Term design and prototyping effort**
- Crab cavity prototyping (collaboration with CERN) (LR+RR)
- Study of in situ copper coating (LR+RR)
- Design of new hadron injection kickers (RR)

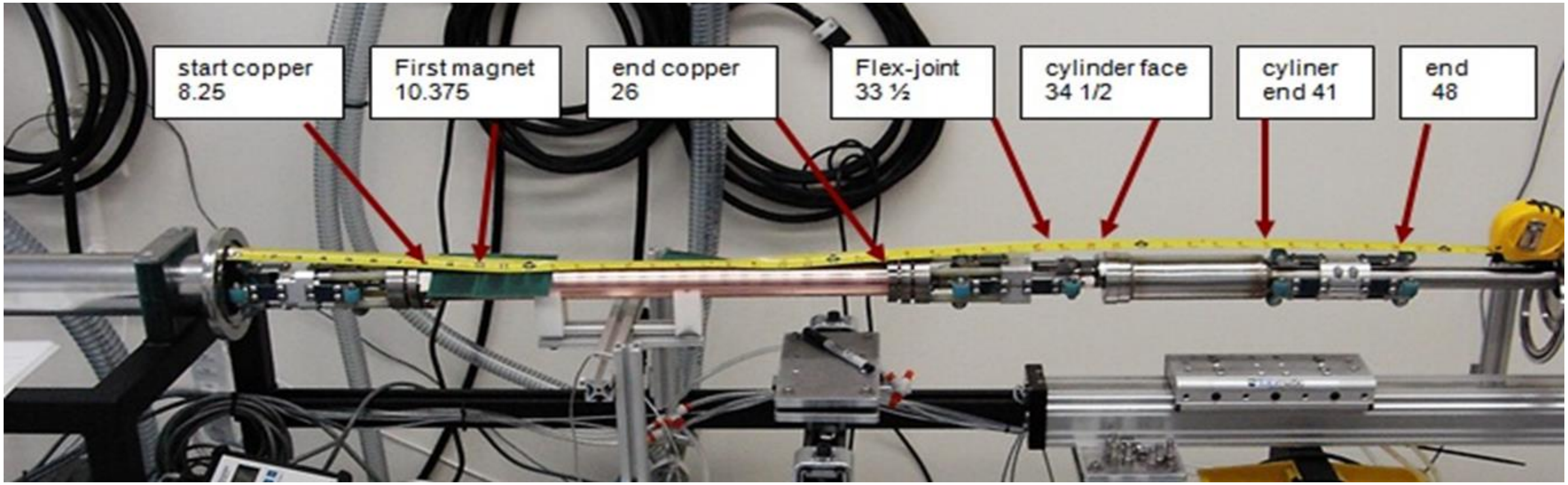
(C) **Value Engineering**
- Gatling gun concept (LR)
- HOM Wave guide coupler (LR)
- FFAG return loops for acceleration and energy recovery FFAG; prototype ERL ➔ Cbeta @ Cornell

(D) **Luminosity Upgrade**
- Demonstration of coherent electron Cooling

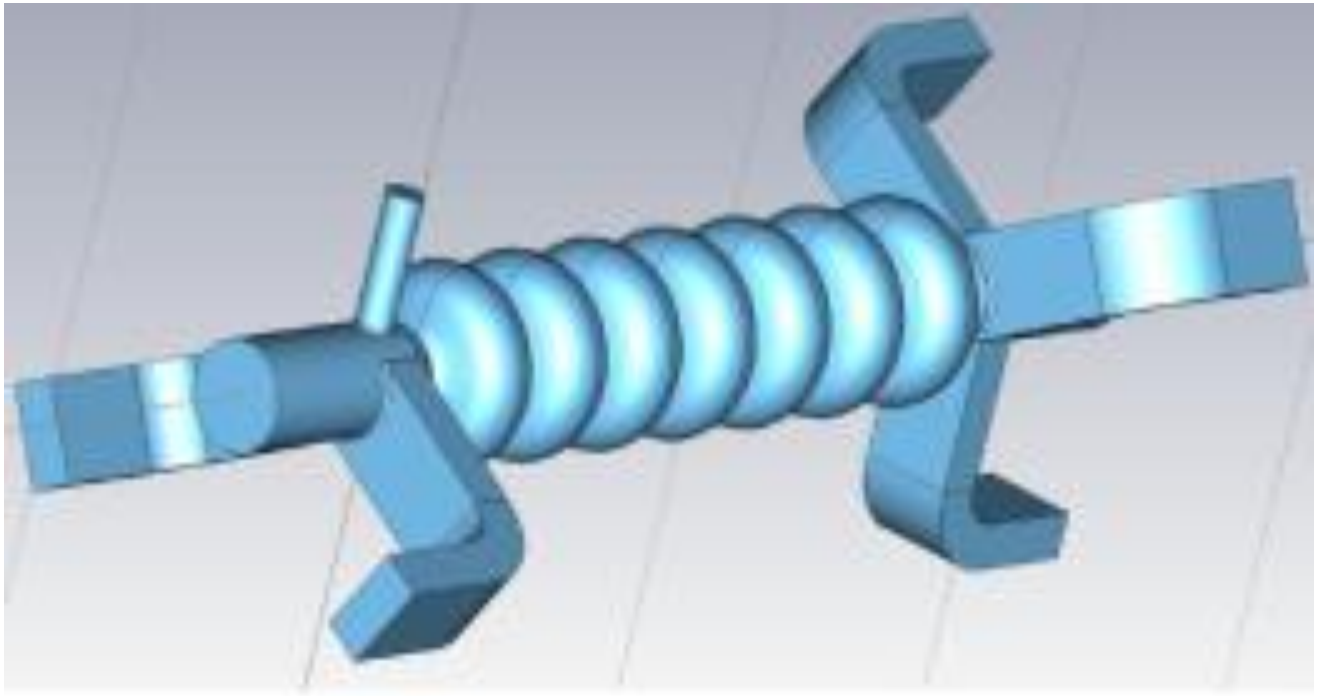
Critical Design Component for Ring-Ring and Linac Ring

Large Hadron currents in eRHIC >500 mA (especially for luminosity upgrade) require Cu coating of of the RHIC beStainless steel beam pipe

➔ Design of a mole for in situ Cu coating with Ion bombardment to achieve good conductivity at cryogenic tempereatures



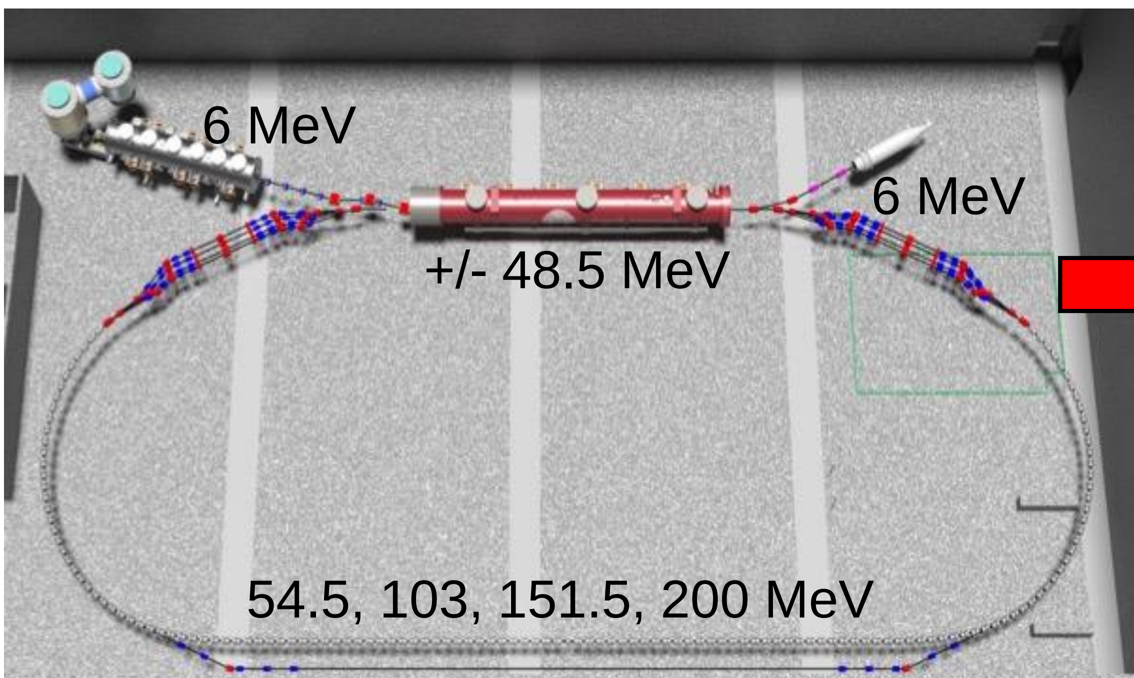
R&D Wave Guide HOM Couplers

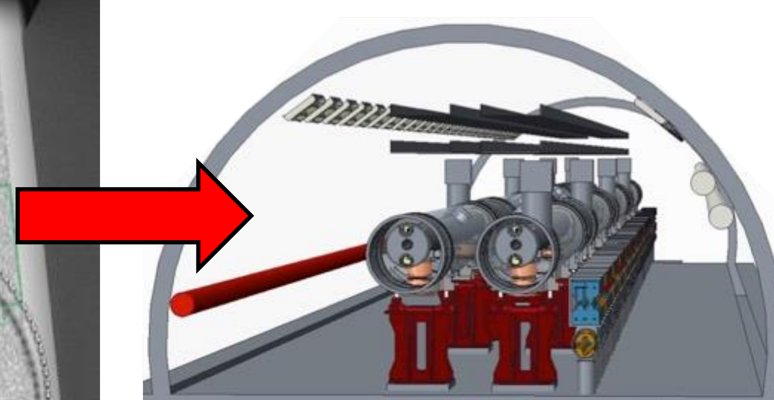


- Is part of Value Engineering effort
- Reduced need of longitudinal space
- Saves Cost
- Design not yet started

Multi-pass FFAG test-ERL at Cornell – an eRHIC prototype

- Uses existing 6 MeV low-emittance and high-current injector & 48.5 MeV CW SRF Linac
- ERL with single four-pass recirculation arc with x4 momentum range
- Permanent magnets used for recirculation arc
- Adiabatic transitions from curved to straight sections
- Test of spreader/combiner beam lines
- High current can be used to test HOM damping by replacing Linac with eRHIC Linac cryostat
- NY State funding
- Cost/schedule review ("CD2/3") in October





Crab Cavity Development

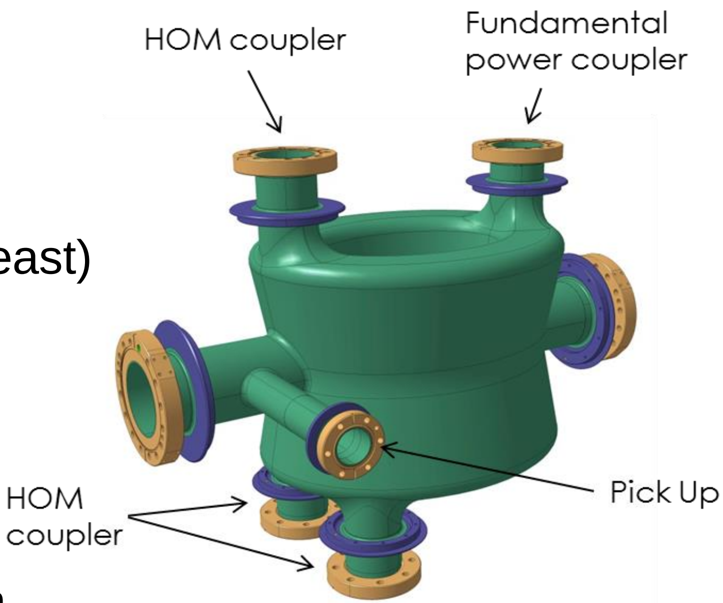
Crossing Angles 14 mrad (LR)

22 mrad (RR)

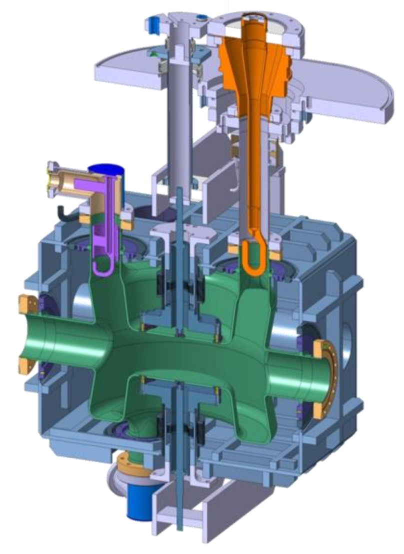
➔ Need Crab Cavities for Hadrons (at least) to eliminate impact on luminosity

Frequencies: 122 MHz, 422 MHz,

Voltage = 53 MV, 3 MV



- Crab Cavities needed to achieve high luminosity in eRHIC design option
- Critical R&D Effort
- BNL in-house design
- Prototypes being developed in collaboration with CERN (needed for LHC luminosity upgrade)
- Two prototypes under construction at CERN and BNL



Performance Upgrade

- Ultimate luminosity in excess of $10^{34}s^{-1}cm^{-2}$ requires the implementation of the novel Coherent electron cooling scheme (LL and LR)
- Both design concepts can be upgraded to higher luminosity by implementation of **Coherent Electron Cooling** of the Hadron beams
- For LR with CeC is the major required additional system
- RR can be upgraded with CeC and by further increasing bunch frequency and beam current

alternatively

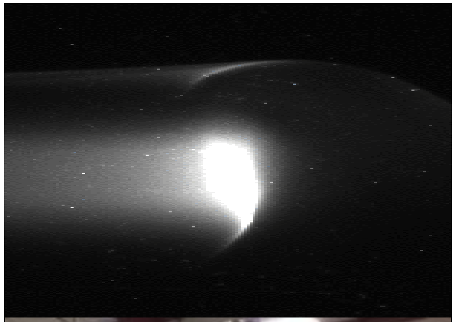
- RR could be upgraded to ultimate luminosity by turning into an ultimate LR
  - needs more study
  - Efforts to make LL and LR designs more similar with more common components started

➔CeC proof of principle test in RHIC is in progress (see V. Litvinienko's presentation)

	Ultimate ERL-Ring Design	
	e	p
Energy [GeV]	8.3	250
CM energy [GeV]	91	
Bunch frequency [MHz]	9.4	
Bunch intensity [10^{10}]	3.3	30
Beam current [mA]	50	415
rms norm.emittance h/v[um]	16.5/16.5	0.27/0.27
rms emittance h/v [nm]	1.0/1.0	1.0/1.0
beta*, h/v [cm]	7/7	7/7
IP rms beam size h/v [um]	8.4/8.4	
IP rms ang. .spread h/v [urad]	120/120	120/120
max beam-beam parameter	4.1	0.015
e-beam disruption parameter	36	
max space charge parameter	8.6e-4	0.058
rms bunch length [cm]	0.3	5
Polarization [%]	80	70
Peak luminosity [$10^{33}cm^{-2}s^{-1}$]	14.4	

Coherent electron Cooling (CeC) Demonstration Experiment

- DOE NP R&D project aiming for demonstration of CeC technique is in progress since 2012
- Phase I of the equipment and most of infrastructure installed into RHIC's IP2
- First beam from SRF gun (3 nC/bunch, 1.7 MeV) on 6/24/2015; exceeds performance of all operating CW electron guns
- 20 MeV SRF linac and helical wigglers for FEL amplifier are installed, 8 MeV beam transported to beam dump (June 2016)
- Proof-of-principle demonstration with 40 GeV/n Au beam scheduled during RHIC Run 17
- Micro-bunching test also planned with same set-up



WEPOA59 (V.N.Litvinenko)
WEPOB60 (I. Pinayev)

Summary

- eRHIC design covers the complete EIC White Paper science case, provides $L = 10^{32} - 10^{33}\ s^{-1}\ cm^{-2}$ luminosity and is highly cost effective.

- Two design options studied at present:

  - ERL-Ring eRHIC design worked out which combines high performance and relatively low technical risk with high energy efficiency.

  - Ring-Ring eRHIC design, meets high performance requirements using existing technology.

➔ While developing cost estimates for final comparison and design choice carry out critical R&D on Crab cavities, 50 mA electron source as well as value engineering which could enable substantial cost savings

- Cost effective upgrade to ~ $10^{34}\ s^{-1}\ cm^{-2}$ luminosity ERL-Ring design possible for both options.
- Crucial R&D programs underway to mitigate technical risks of ultrahigh luminosity (CeC)
- Efforts to improve organization of Design and R&D process and keep well aligned with development of EIC physics case