eRHIC Accelerator Design

- Ultimate eRHIC design
- Technology of major design components
- Low risk ERL-Ring and Ring-Ring eRHIC designs
- eRHIC R&D program
- Summary

Vadim Ptitsyn

EIC User Group Meeting
July 7, 2016

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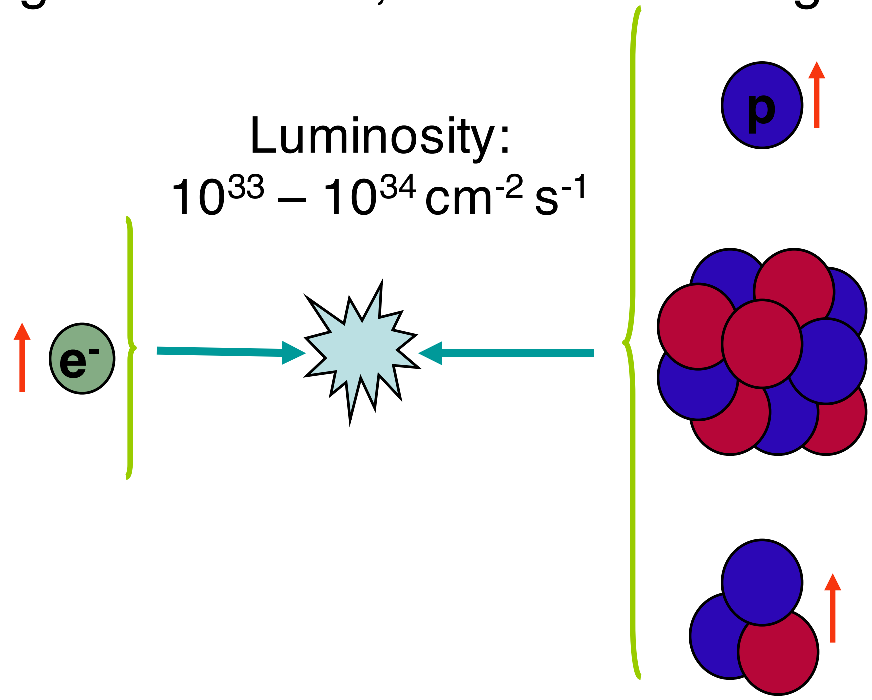
Office of Science
U.S. DEPARTMENT OF ENERGY

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC
including existing RHIC tunnel, detector buildings and cryo facility

80% polarized electrons:
1.7 – 20 GeV

Luminosity:
$10^{33} – 10^{34}$ cm^{-2} s^{-1}

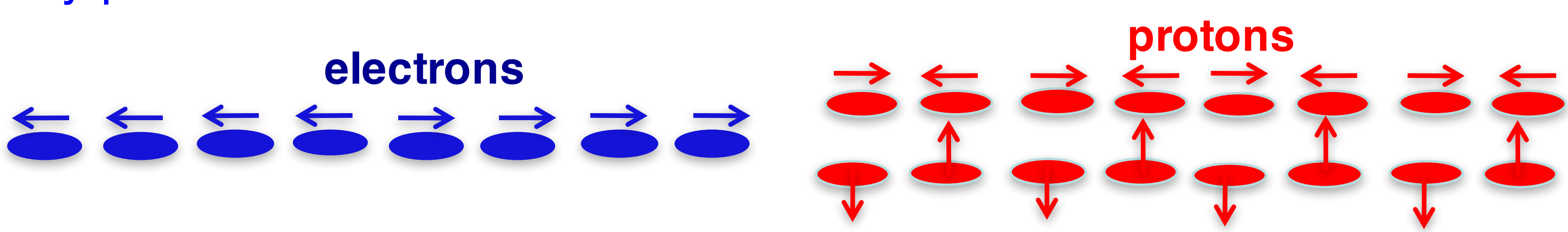


70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

Pol. light ions (He-3)
17 - 167 (184*) GeV/u

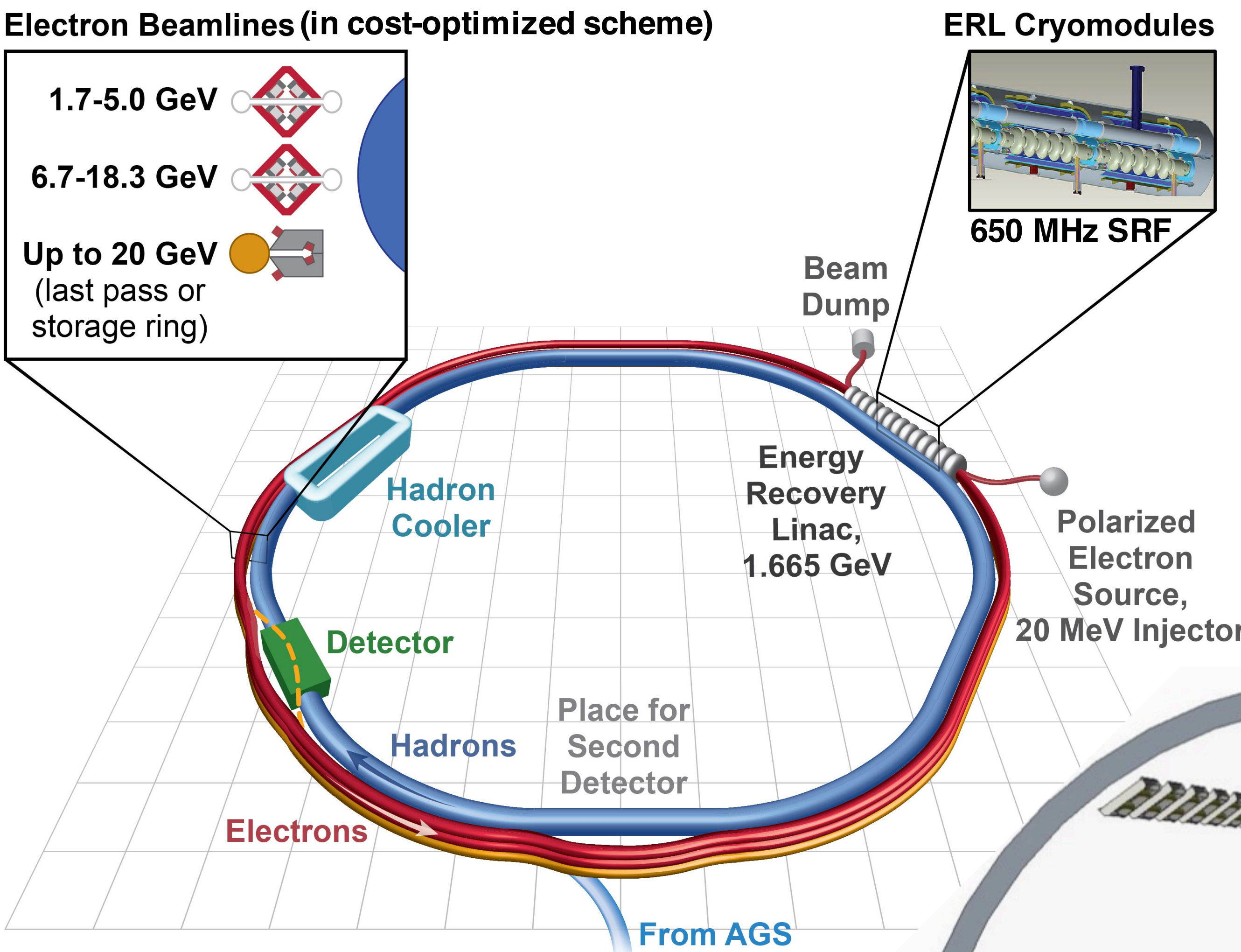
- Center-of-mass energy range: 20 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:

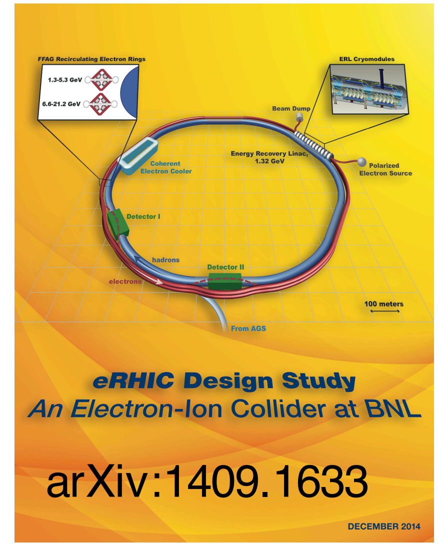


* It is possible to increase RHIC ring energy by 10%

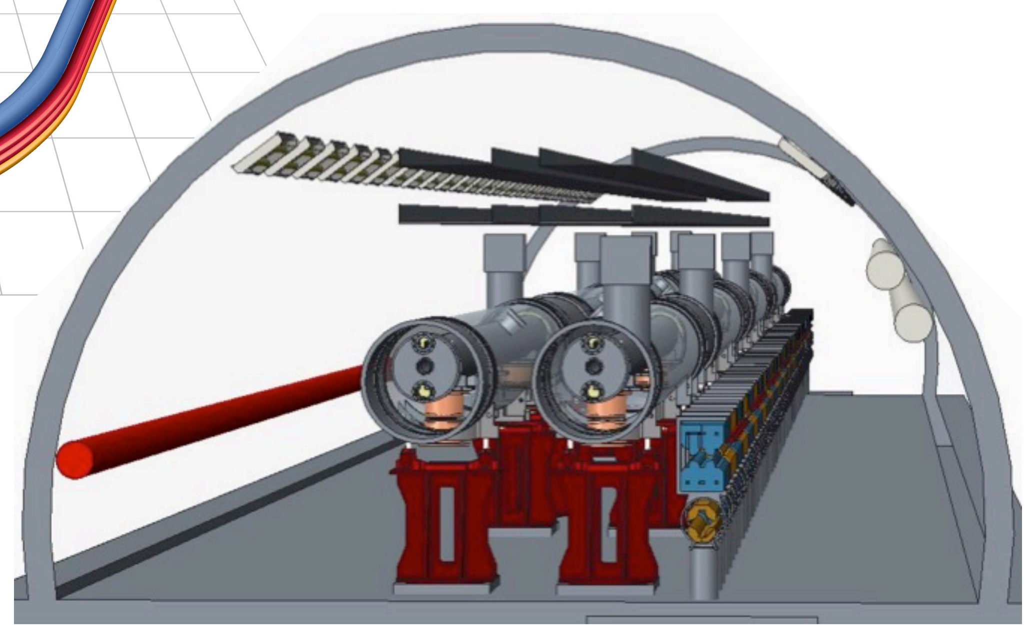
Ultimate eRHIC design

Highly advanced and energy efficient accelerator

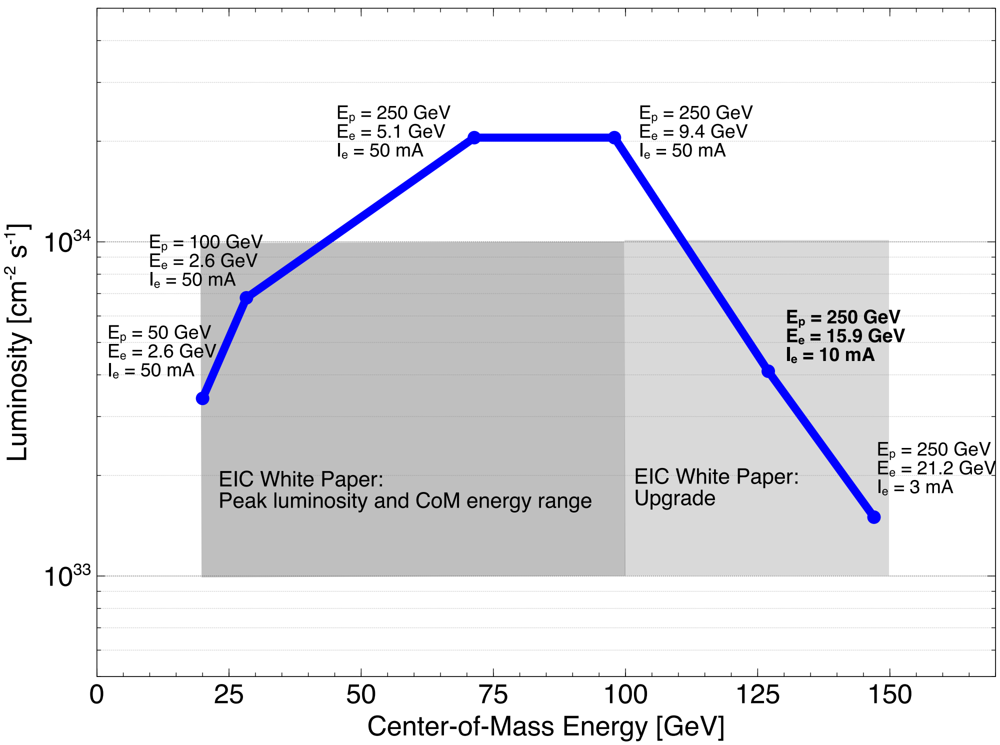


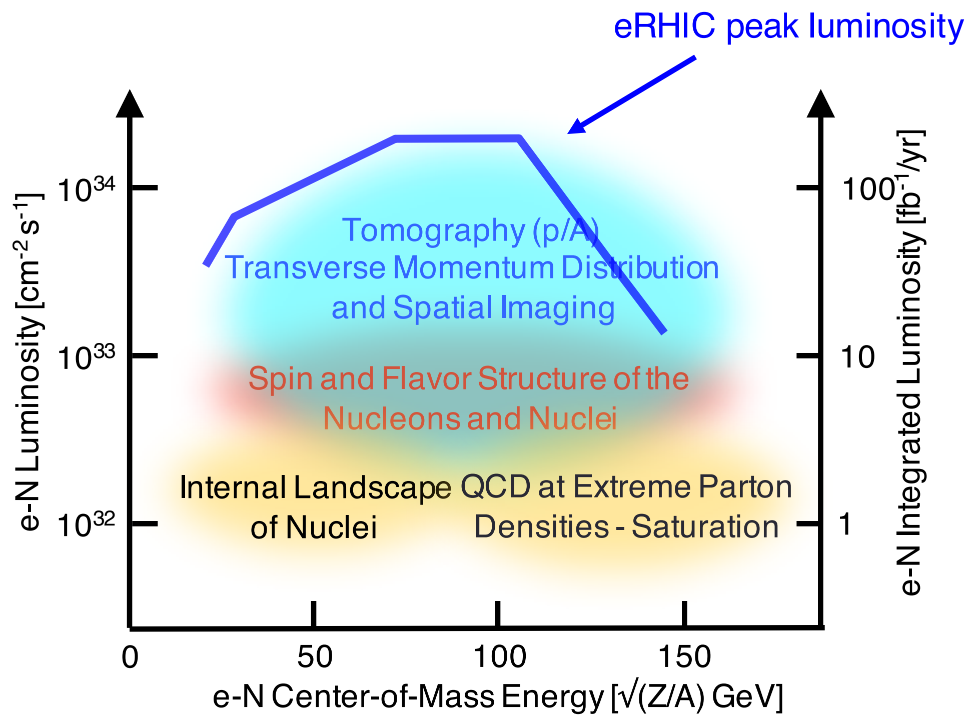


- Peak luminosity: 2×10^{34} cm^{-2} s^{-1}
- ERL, permanent magnet arcs and strong cooling of proton beam greatly reduce electric power consumption to about 15 MW!



Ultimate eRHIC Luminosities

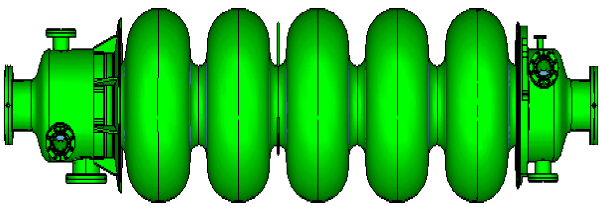


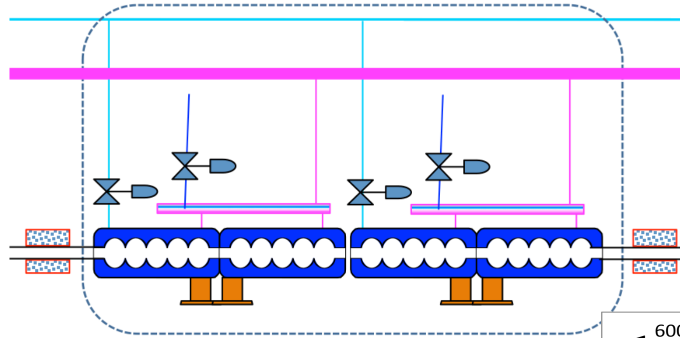


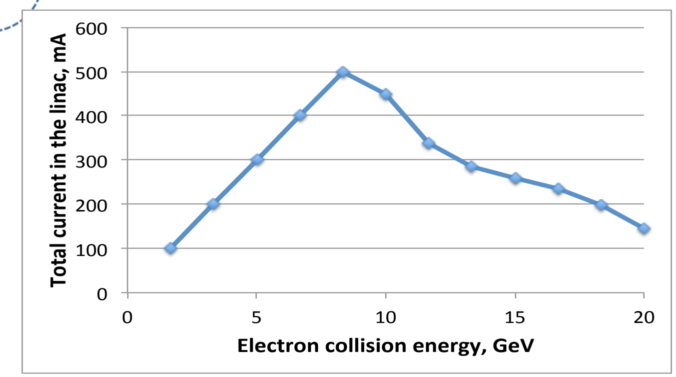
- Ultimate eRHIC design covers whole Center-of-Mass energy range, including “EIC White Paper Upgrade” region
- Small beam emittances and IR design allows for full acceptance detector at full luminosity

Major design components: main linac

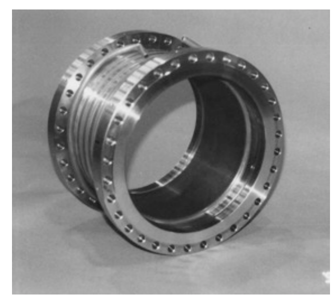
@W. Xu



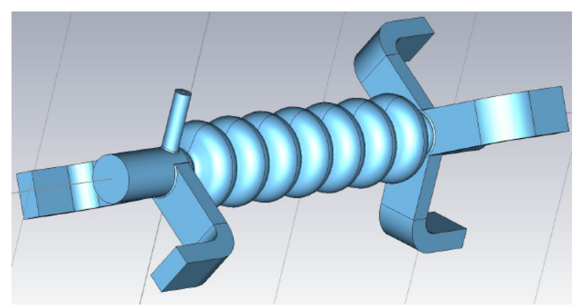




- The linac is placed into 200m long straight section of RHIC tunnel.
- 650 MHz frequency of main linac accelerating cavities is benefitting from the SRF development program for the Fermilab PIP II project.
- Several hundreds mA of total beam current in the Linac -> HOM power of several kW per cavity.
  - *This is similar to circulating beam in storage rings at KEKB and Cornell where ~10 kW of HOM power is absorbed with Ferrite or SiC beam- pipe dampers*



- Other possibility: HOM damping by combination of pipe absorbers and waveguides giving more compact construction.
  - *HOM waveguide damper technology has been developed for many years in Jlab, but is not considered yet as fully proven.*

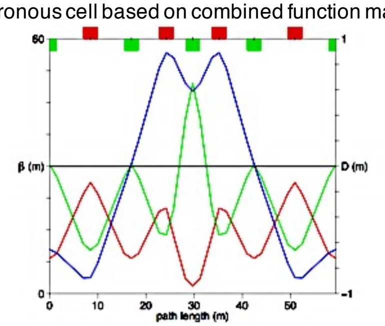


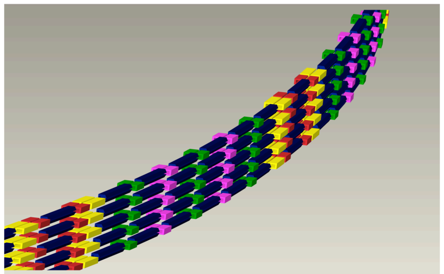
Major design components: recirculation passes

In the course of eRHIC design work two options for recirculation passes have been developed (one-more conventional, another-cost saving).

- Individual beamlines for each recirculation
  - Based on the experience of existing recirculating linacs. Notable examples:
    - *CEBAF with 6 recirculations*
    - *BINP ERL with 4 recirculations*
  - Isochronous cell
  - Minimized synchrotron radiation
  - Conventional orbit/lattice correction techniques

Isochronous cell based on combined function magnets

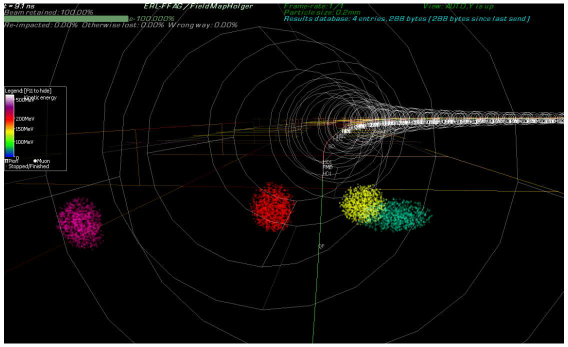


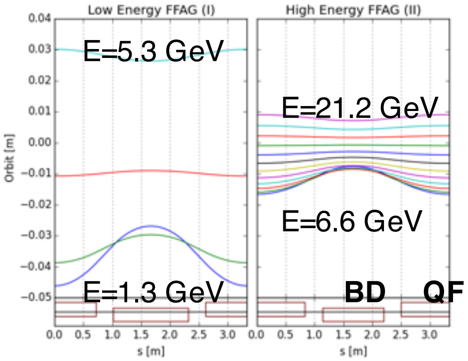


@D.Trbojevic

- FFAG beamline
  - Capable to transport beams in wide energy range
  - Used mostly for sub-GeV proton accelerators; only one test electron accelerator (EMMA)

@S. Brooks, D.Trbojevic



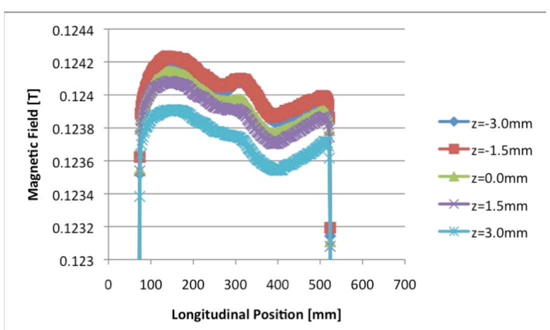


- Not isochronous; thus spreader/merger is more complex incorporating pathlength and R_{56} correction
- Considerable cost saving (for 20 GeV machine)

Recirculation Pass Magnets

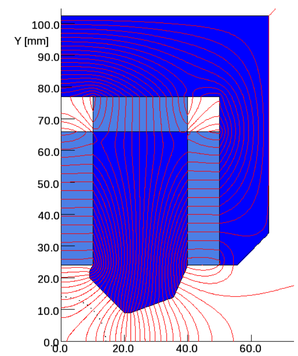
Two alternative magnet designs have been developed (one-more conventional, another-cost saving).

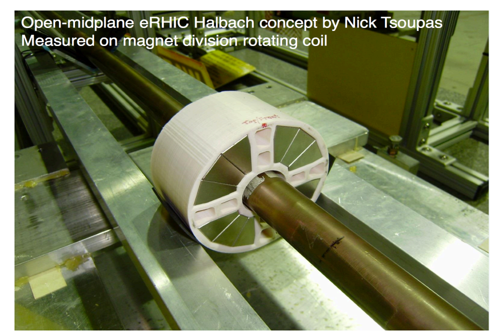
- Electromagnets
  - Conventional technology
  - Higher construction and operation costs.
    Considerable amount of cabling and power supplies.
  - Compact magnet prototypes have been built and measured



@V. Litvinenko, Y. Hao

- Permanent magnets
  - Cost saving: no need for power supplies, cables and cooling.
  - Fermilab has built a permanent magnet based recycler ring.
  - Technological challenges are related with satisfying eRHIC magnet field tolerance requirements and thermal stabilization
  - Permanent magnet prototypes (Hybrid-type and Halbach-type) has been bulit and measured.





@W.Meng, N. Tsoupas, S. Brooks

  - Planned Cbeta facility in Cornell University will use permanent magnets with eRHIC-like field tolerance requirements.

Initial eRHIC design: low risk ERL-R and R-R design options

- Presently our studies are concentrated on a lowest technical risk design, which can be considered as an Initial stage of eRHIC.
- Initial eRHIC design requirements:
  - The initial configuration of eRHIC should have enough center-of-mass reach 100 GeV (10 GeV e x 250 GeV p) and detector acceptance to cover the whole EIC science case. Upgrade to ~ 145 GeV should be possible with modest upgrade
  - The initial luminosity could be lower initially (10^{32}-10^{33} cm^{-2} s^{-1}) and would later be increased through incremental upgrades, as was done for RHIC and other colliders.
- Two designs are being developed:
  - **Low risk ERL-Ring**: Expected to have lower cost, especially if cost reduction R&D is successful
  - **Low risk Ring-Ring**: Based on mainly existing technology. Cost is expected to be higher than the ERL-Ring design.
- Both designs can be upgraded to the ultimate eRHIC ERL-Ring design for modest cost.
  - A CEBAF-like recirculating linac used as full energy injector for the Ring-Ring design can easily be converted to an ERL.

Ring – ring vs. ERL – ring

- To exceed the luminosity of HERA the limit due to the beam-beam effect of the high energy proton beam on the lower energy electron beam needs to be overcome:

- Ring – Ring
  - Many low intensity bunches
  - Increase luminosity by increasing number of bunches (and electron current and synchrotron radiation power)
  - Decrease electron current (and synchrotron power) by **cooling proton beam**
  - Larger electron beam emittance complicates detector design
  - Main challenge: High synchrotron radiation in detector and arcs
  - $L \sim E_e * E_p = 0.5 * E_{CM}^2$

- ERL – Ring
  - Single collision of each electron bunch. No limit of beam-beam effect or luminosity.
  - Increase luminosity and/or decrease electron current by **cooling proton beam**
  - Small electron beam emittance
  - Main challenge: Source with high polarized electron current
  - $L \sim E_p$

Low Risk ERL-Ring design features

- Maximum electron energy: 10 GeV
- All accelerator technologies are close to the present state-of-the-art level

- Main ERL SRF linac: 647 MHz cavities, two linacs 180 m long 200 m, 2.5 GeV/turn
  No higher harmonic cavities (for synchrotron radiation energy loss/spread compensation are required)

- Four individual re-circulation beamlines based on electromagnets
  Energy upgrade path: adding additional re-circulation beamlines. One FFAG beamline can increase the beam energy 20 GeV.

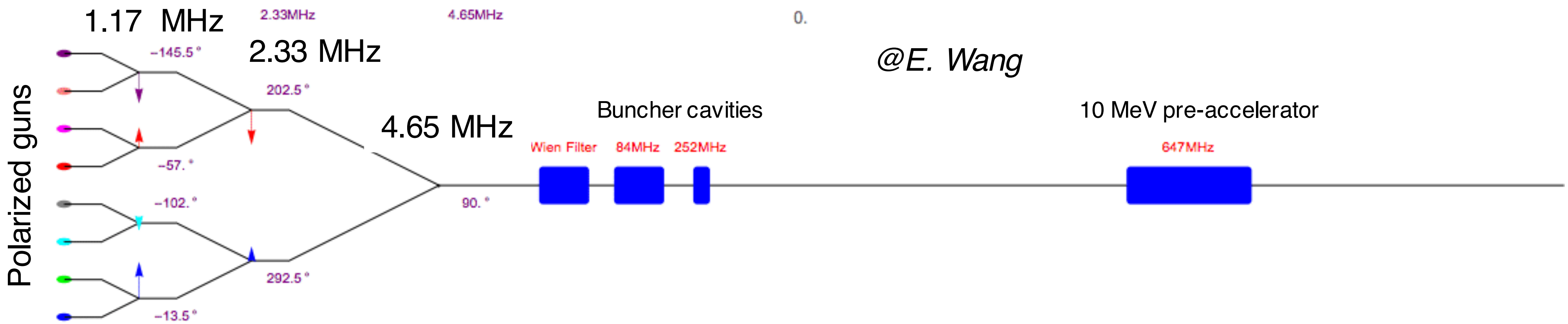
- No hadron cooling required for e-p
  Existing stochastic cooling system can be used for e-Au
  Luminosity upgrade path: adding a cooling system (CeC)

- Interaction region design with crab-crossing

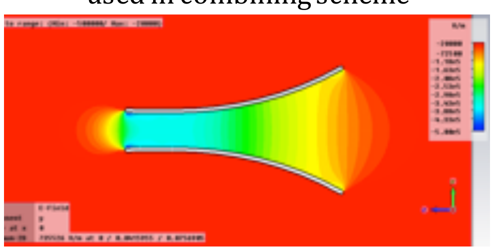
- Polarized electron source employing merging electron current produced by multiple electron guns

Low risk polarized source approach

- 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
- Low 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 cooper plate deflector, used in combining scheme

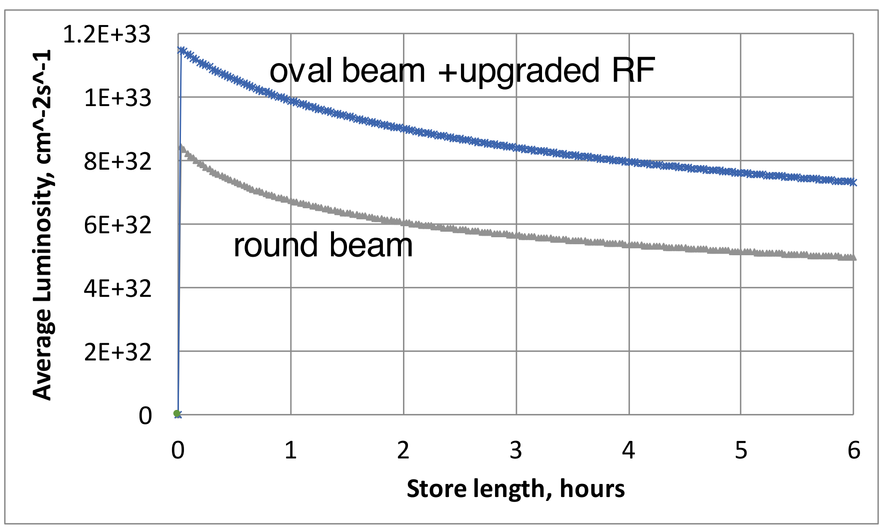


- On-going studies (2016-2017):
  - Finalizing the technicalities of the combining scheme
  - Detailed 3D simulations of high-charge bunch transport through all injector components
  - Experimental studies of single cathode lifetime dependencies (using a Gatling gun prototype)
  - Measurements of surface charge limit for SL cathodes using cathode preparation system.

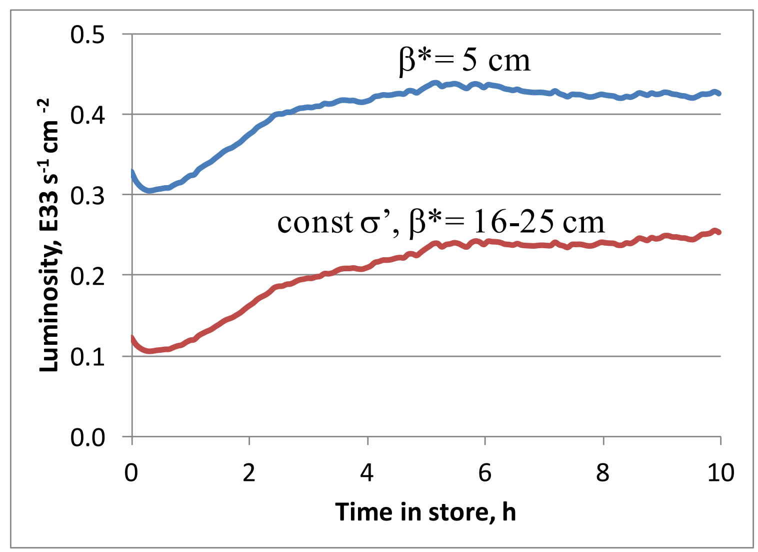
Low risk design: no proton cooling needed

- Strong cooling is essential to reach the Ultimate design luminosity ($>10^{34}cm^{-2}s^{-1}$)
- R&D on Coherent electron Cooling is underway
- Low risk design luminosities (in both ERL-Ring and Ring-Ring) are reached without cooling of RHIC proton beam. Required beam emittances are formed by injectors.
- Existing stochastic cooling system can be used for heavy ions

e-p average store luminosity vs the length of the store



e-Au store luminosity evolution with stochastic cooling



@M. Blaskiewicz, V. Ptitsyn

Low Risk Design and Cost Reduction R&D

Design component	Low risk design	R&D study	Cost reduction if R&D successful
Polarized source	Merging scheme using 8 Jlab-kind guns	"Gatling gun" or an other large cathode electron gun	~$40M
Main linac: HOM damping	Beam-line dampers (KEK, Cornell)	Waveguide dampers	~$30M
Recirculation loops	4 regular loops	1 FFAG + top energy loop	~$100M
Total:			~$170M

Low risk Ring-Ring design

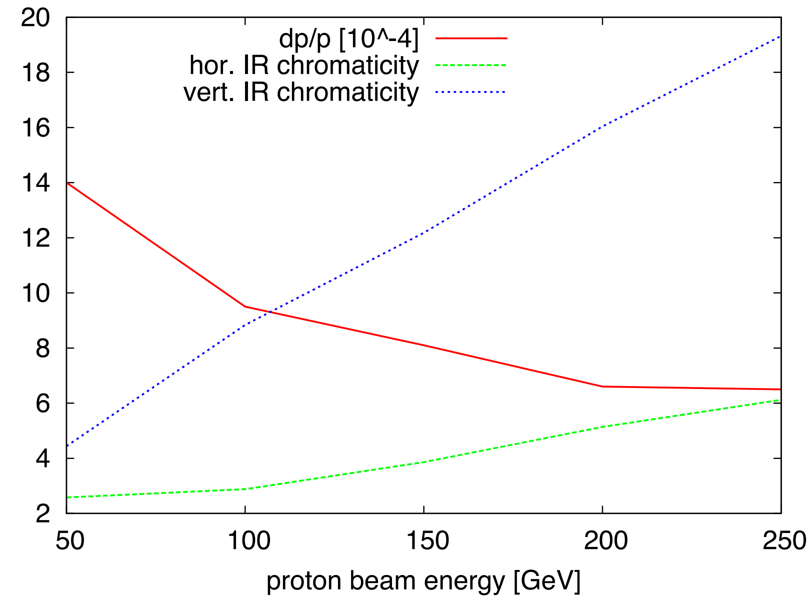
- A Ring-Ring design would use the more established technology of a synchrotron for the electron beam
- To reach high luminosity: increased number of bunches, high electron beam current, high synchrotron radiation damping for high beam-beam parameter and IR geometry and detector that can accept the larger electron beam emittance.
- Electron storage ring needs to operate over wide energy range, maintain electron polarization, and include spin rotators. The storage ring is similar to the final pass in the ERL-Ring option.
- Little or no cooling of hadron beam needed for initial Ring-Ring design
- Limit synchrotron radiation power to 10 MW: lower risk and cost, but still a major cost driver.
- Upgrade to the higher luminosity ultimate ERL-Ring design is possible by recovering the electron beam energy in the CEBAF-like injector, converting it into the ERL.

  The possibility of achieving the Ultimate design level luminosity in the Ring-Ring scheme by using strong cooling, very large number of bunches and low β^* interaction region is also being explored.

Proton beam parameters

- Only most extreme parameters are listed
- Proton emittances can be achieved by slight shaving (vertical, 25 percent reduction) and noise injection (horizontal) - long IBS growth time requires no cooling
- Necessary decoupling required for flat beams demonstrated at RHIC during 31.2 GeV d-Au run
- Very low IR chromaticity at low energy where dp/p is large

N_b		360
N_p	$[10^{11}]$	1.5
$\epsilon_{p,N}$ hor./vert.	$[\mu\mathrm{m}]$	4.7/1.8
σ_s	[cm]	8
$\Delta p/p$	10^{-4}	14
β^*	[cm]	4.4
$\widehat{\beta}$	[km]	0.9
τ_{IBS}	[h]	8.5
$\mathcal{L}$	$[10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}]$	2.1



Electron injector

- Spin experiments need bunch-to-bunch spin sign control. For Ring-Ring this requires full energy injector and frequent electron bunch replacement.

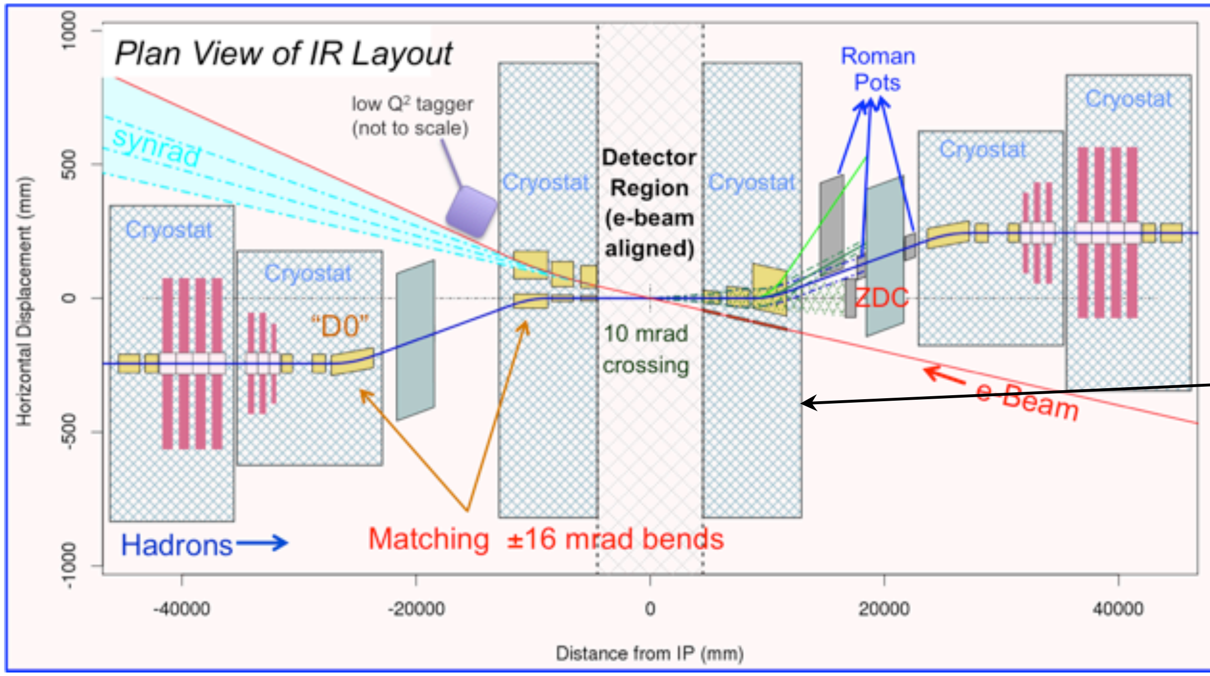
- By using CEBAF-like accelerator (same as ERL but no energy recovery) in RHIC tunnel the low risk RR can be easily upgraded to the Ultimate ERL-Ring design.

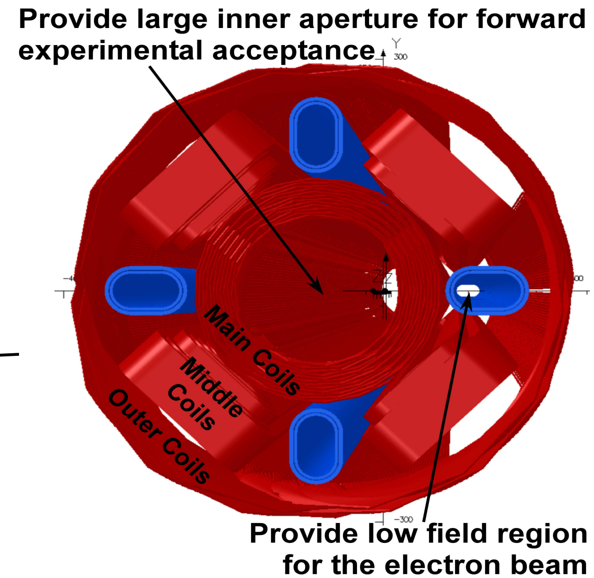
- Another considered injector option: recirculating linac based on XFEL/LCLS-2 cryomodules (two 2.5 GeV linacs).

- High charge (several tens of nC) bunch production and acceleration is being studied.

eRHIC high-luminosity, full acceptance IR

The same IR design works well for Ultimate and Initial ERL-R designs. *@B. Parker*

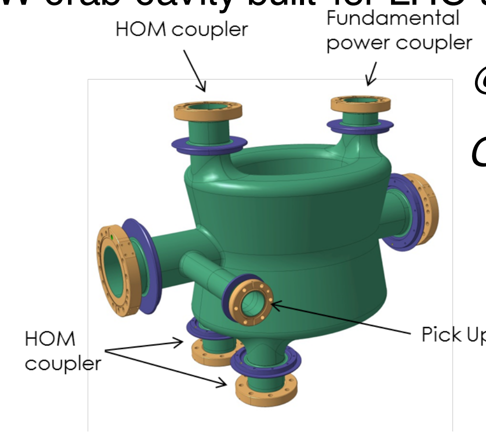




"Sweet spot" IR magnet design concept for the ERL-Ring option arranges a field-free electron pass between SC coils

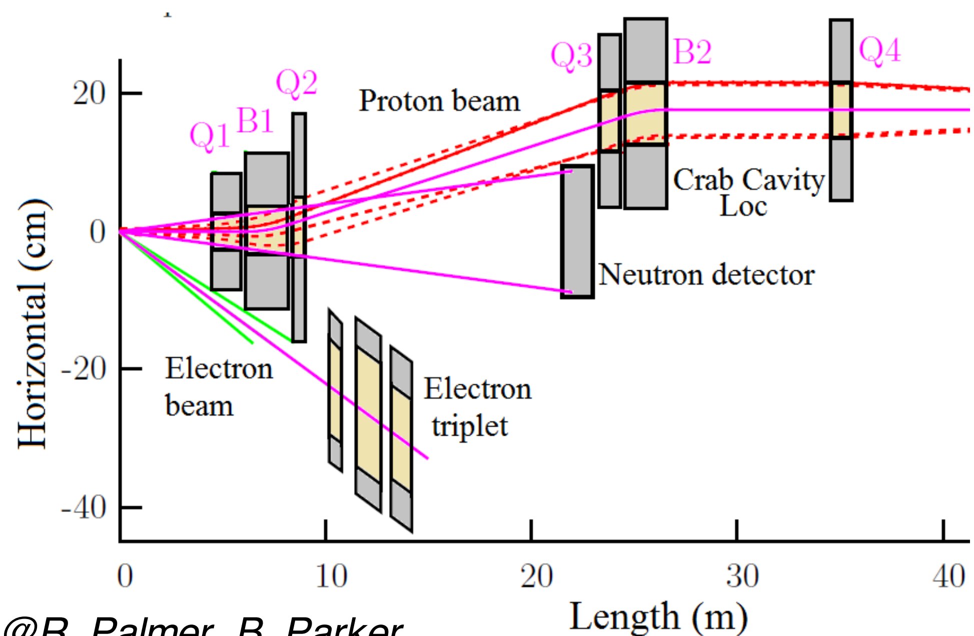
- 14 mrad crossing angle and use of crab cavities to achieve head-on collisions
- 90 degree lattice and beta-beat in adjacent arcs to reach beta* of 5 - 10 cm with good dynamic aperture.
- Final focus doublet plus dipole with large aperture for forward collision products and with field-free passage of electron beam
- Only soft bends of electron beam within 60 m upstream of IP

DQW crab-cavity built for LHC upgrade



@I. Ben-Zvi, Q. Wu

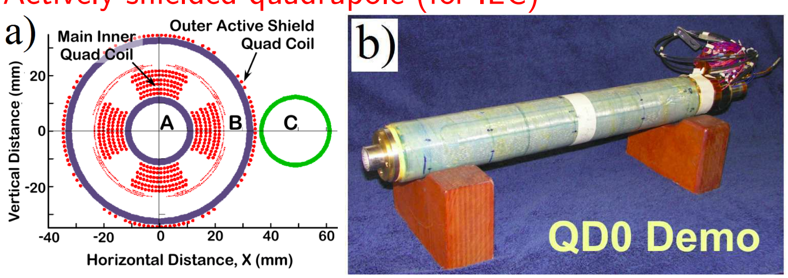
eRHIC Ring-Ring IR



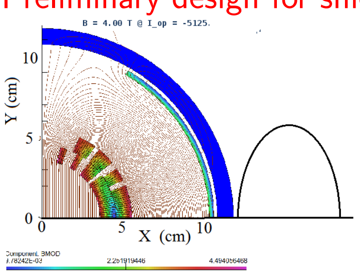
@R. Palmer, B. Parker

- 20 mrad crossing angle and use of crab cavities to achieve head-on collisions
- Oval beams at IP: σ_x/σ_y up to 13.
- Small β_y = 4 cm

Actively shielded quadrupole (for ILC)



Preliminary design for shielded dipole

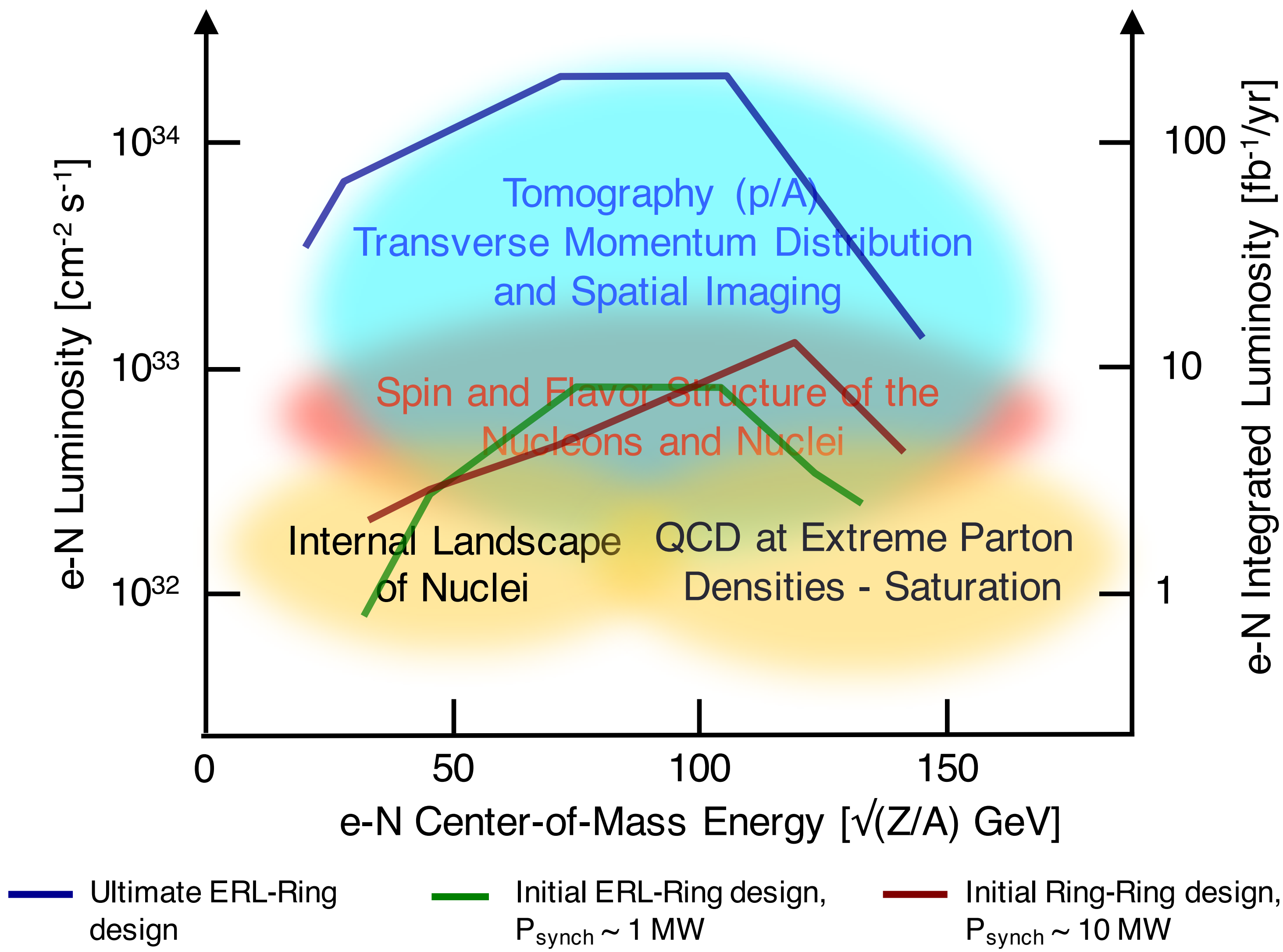


Stray field less than earth's

- Additional outer coil is used to have magnetic flux contained
  actively shielding the electron beam pass area
- Active shielding technology was developed for ILC IR quadrupoles

eRHIC Peak Luminosity vs. CoM Energy

- Science case areas indicate the range of peak luminosities with which a statistically significant result can be achieved in about one year (10^7 sec) of running.

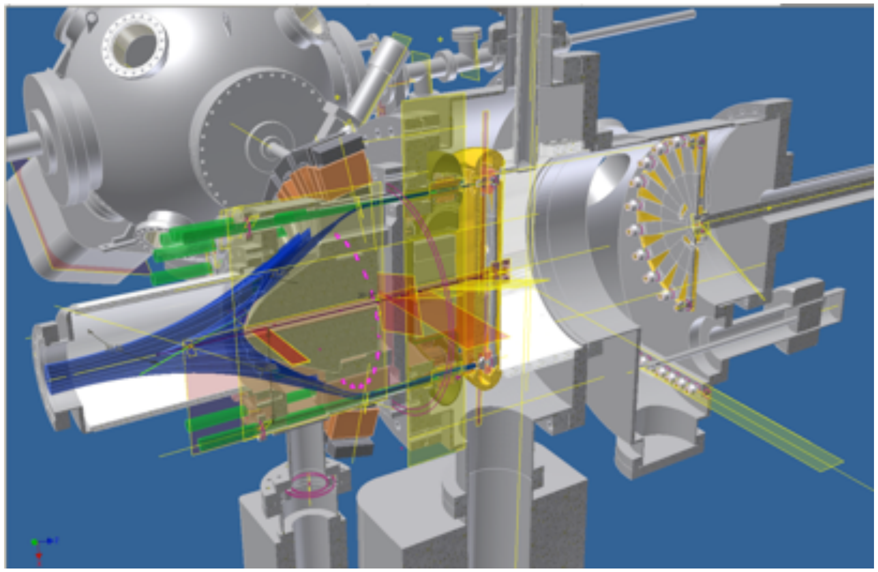


Pre-project eRHIC R&D Items

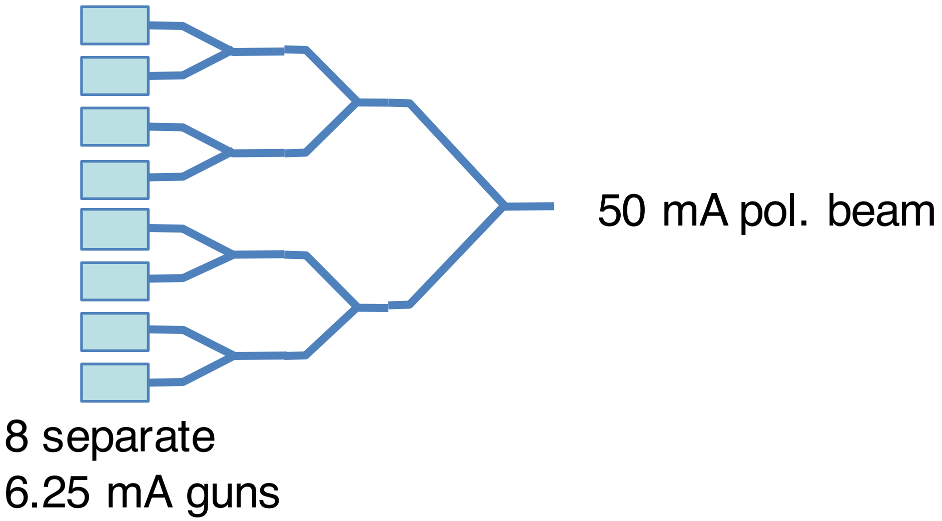
- There are four high priority eRHIC R&D items to be completed in 2 – 3 years:
  - Test of high intensity polarized electron source with up to ~ 50 mA current
  - Test of ERL acceleration cavity with full Higher Order Modes (HOM) damping using beam line and waveguide dampers
  - Complete Coherent electron Cooling Proof-of-Principle (PoP) test at RHIC
  - High intensity, multi-pass test-ERL with single recirculation loop (FFAG) to be built using the Cornell high intensity electron injector and CW SRF Linac
- Additional eRHIC experimental R&D elements, at a lower priority, are:
  - Development of SRF crab cavities (part of LARP and HL-LHC)
  - Experiment of a multi-turn high energy ERL using CEBAF

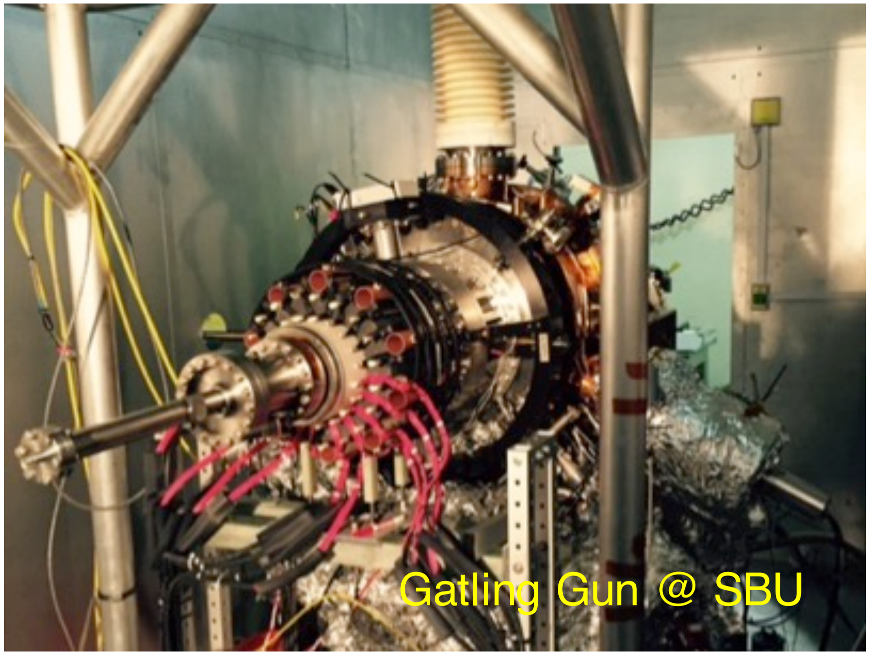
High CW current polarized electron gun

- Gatling gun principle: multiple guns/cathodes with same charge lifetime
  - Requires fast switching between guns/cathodes
  - Gatling Gun test-stand at SBU
- Low risk approach to single high current gun: Fast switching between eight 6.25 mA guns



@J. Skaritka, E. Wang



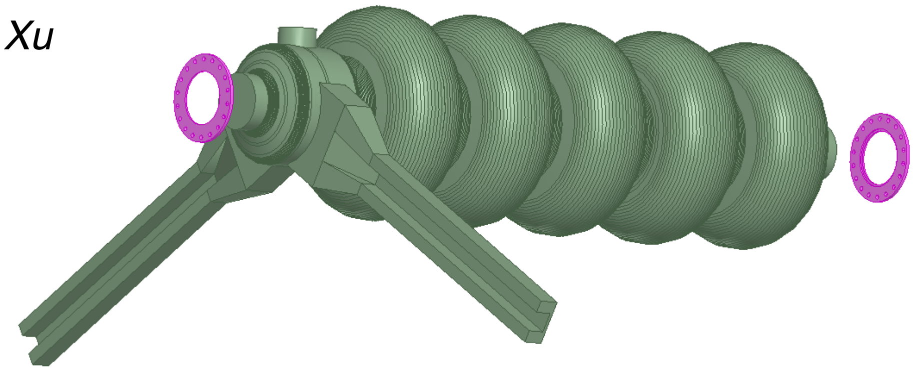


R&D for 650 MHz cavity and HOM damping

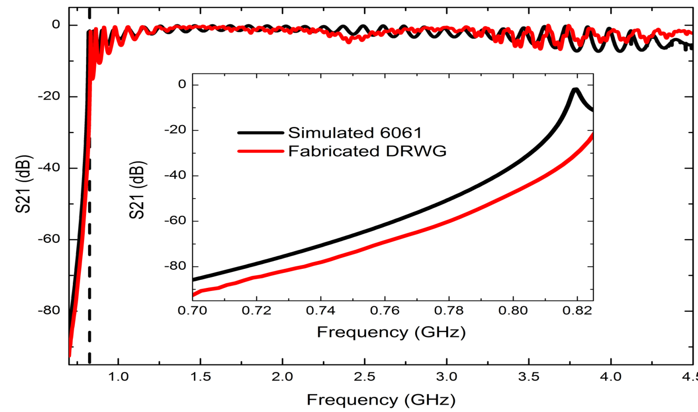
- The 650 MHz 5-cell cavity was designed. Warm (Cu) and SC prototypes are being fabricated by RI. A performance study for SRF cavity will be carried out early 2017. Funded by BNL LDRD.

650 MHz cavity with ridge waveguide dampers

@W. Xu



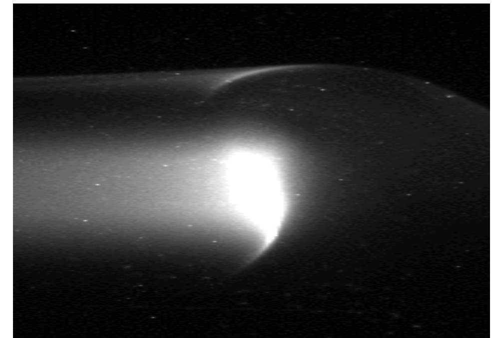
Ridge WG is a natural high pass filter with higher bandwidth, smaller size than regular WG.



- HOM damping technology using ridge waveguide dampers and beam pipe absorbers will be tested with cavity prototypes (2016-2018). Funded by BNL LDRD.

- The R&D plan includes also testing 650 MHz cavity cryomodule with HOM damping under condition of high electron beam current in Cbeta ERL-test facility.(2018)

Coherent electron Cooling (CeC) demonstration experiment



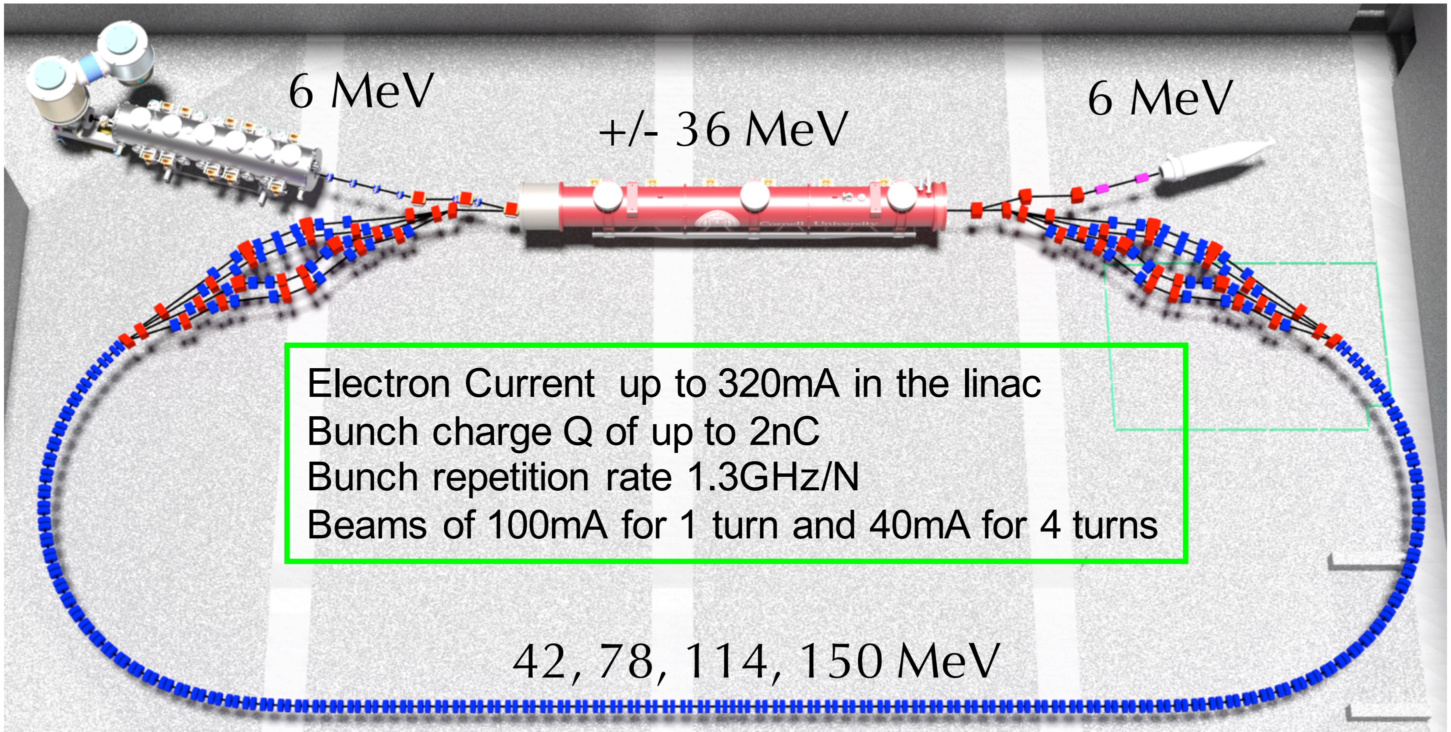
- DOE NP R&D project aiming for demonstration of CeC technique is in progress since 2012
- Phase I of the equipment and most of infrastructure installed into RHIC's IP2
- First beam from SRF gun (3 nC/bunch, 1.7 MeV) on 6/24/2015; exceeds performance of all operating CW electron guns
- 20 MeV SRF linac 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

@V. Litvinenko, I. Pinayev

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

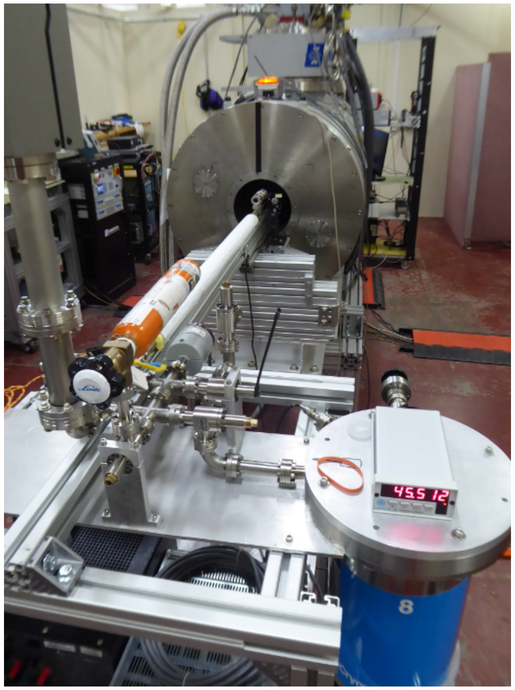
- Uses existing 6 MeV low-emittance and high-current injector and 36 MeV CW SRF Linac
- ERL with single four-pass recirculation arc with x4 momentum range
- Permanent magnets used for recirculation arc
- Adiabatic transitions from curved to straight sections
- Test of spreader/combiner beam lines
- High current can be used to test HOM damping by replacing Linac with eRHIC Linac cryostat
- Cost/schedule review ("CD2/3") in September

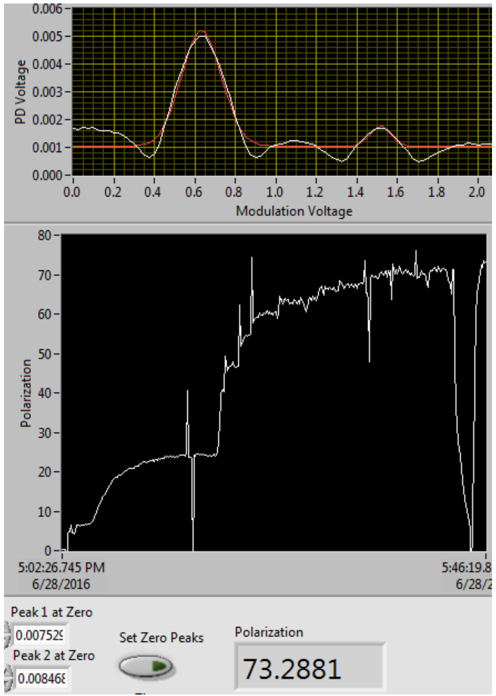
@G. Hoffstaetter



Polarized ^{3}He developments

- Polarized source has been designed and built by MIT-BNL collaboration.
- Polarization from the source up to 73% has been demonstrated in initial tests(June 2016)





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- Successful acceleration of unpolarized $^3He^{+2}$ beam in Booster and AGS has been demonstrated

Collaboration network

- We are collaborating with a number of institutions on various aspects of eRHIC R&D. And we intend to expand this network.
  - MIT – electron polarized gun R&D and polarized ^{3}He source
  - CERN – crab cavities for HL-LHC and eRHIC (ERL-Ring or Ring-Ring)
  - JLab – polarized gun, CEBAF ERL experiment and SRF.
  - Cornell – FFAG multi-pass ERL experiment, high intensity electron source
  - Berkeley – numerical simulations of beam-beam interactions.
  - ANL – low-energy injector cavities (on halt at this time).
  - FNAL – 650 MHz SRF ERL cavities (in preparation stage)
  - Various SBIR projects – high-efficiency RF amplifiers, polarized cathode material, SRF cavities, in-situ RHIC beam pipe coating, eRHIC permanent magnet development.

Summary

- eRHIC design covers the complete EIC White Paper science case and is highly cost effective.
- The ERL-Ring eRHIC design combines high performance with unprecedented energy efficiency, an imperative requirement today not only to minimize operations cost but also to conserve resources.
- The Ring-Ring eRHIC design, operating at the beam-beam limit, reaches high performance using mostly existing technology.
- Developing cost effective, low risk ERL-Ring and Ring-Ring eRHIC design options with required energy coverage and 10^{32} - 10^{33} s^{-1} cm^{-2} luminosity. Basis for eRHIC project proposal.
- Cost effective upgrade to ~ 10^{34} s^{-1} cm^{-2} luminosity ERL-Ring design possible for both options.
- Developed focused eRHIC R&D plan that addresses all critical technical risks of the eRHIC design over the next 2-3 years