# ERL-Ring and Ring-Ring Designs for the eRHIC Electron-Ion Collider

- From RHIC to eRHIC
- Two eRHIC design options
- Linac-Ring Design Features
- Ring-Ring Design Features
- eRHIC R&D Program
- Summary

Vadim Ptitsyn
on behalf of eRHIC design team

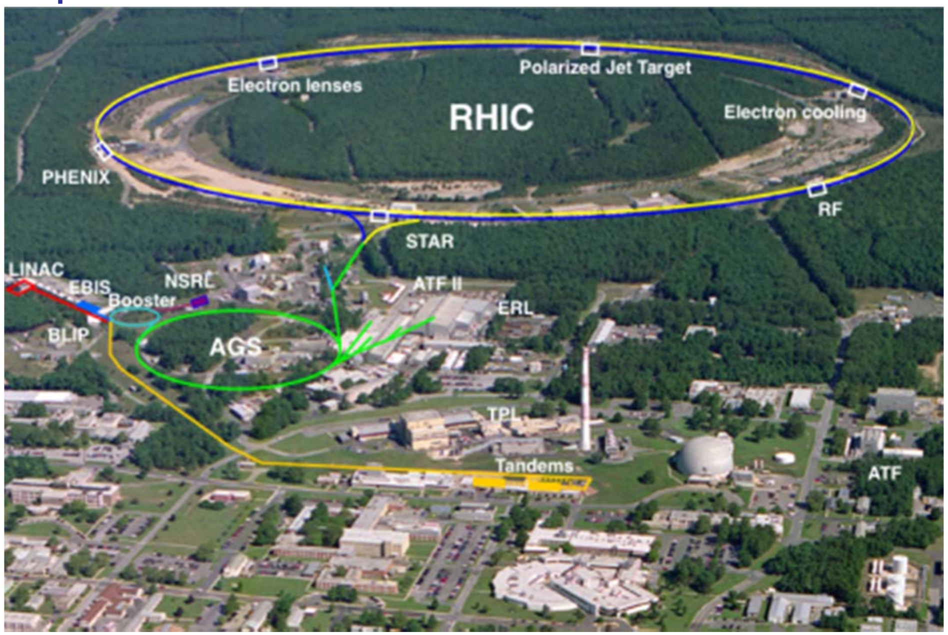
NA-PAC, Chicago,
October 10, 2016

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

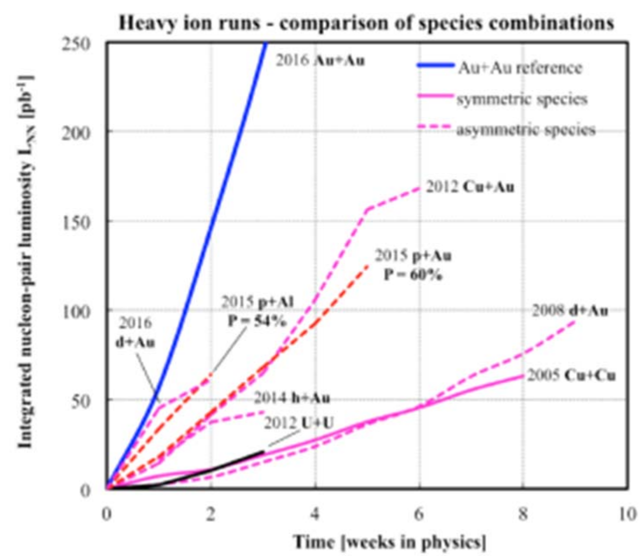
# Relativistic Heavy Ion Collider at BNL

From 1999 operating with heavy ions and polarized proton collisions in several experiments




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

- Discovery and detailed study of properties of quark-gluon perfect fluid matter, existing at very origin of the Big Bang
- Study of proton spin composition, especially its gluon component
- Improving machine luminosity in every run
- Only place in the world with high energy polarized proton beams; *employing numerous techniques and devices to achieve high proton polarization (up to 60%) of colliding beams*
- Present plan: to continue A-A and polarized p-p experiments till 2024



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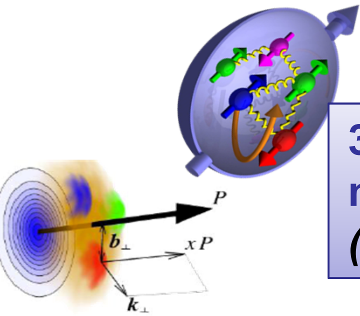
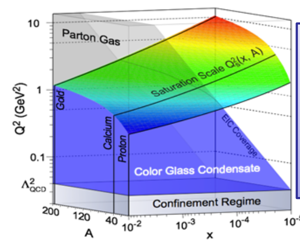



**3D nucleon imaging, nucleon spin origin *(high L, polarized e-p)***




**Study of gluon dominated matter, Discovery of color-glass condensate *(high CME , e-A)***

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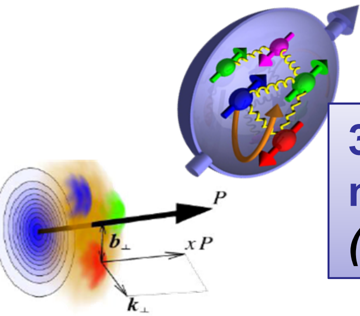


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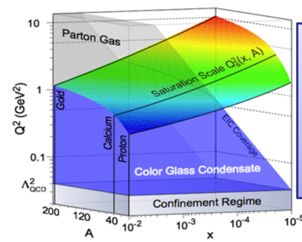


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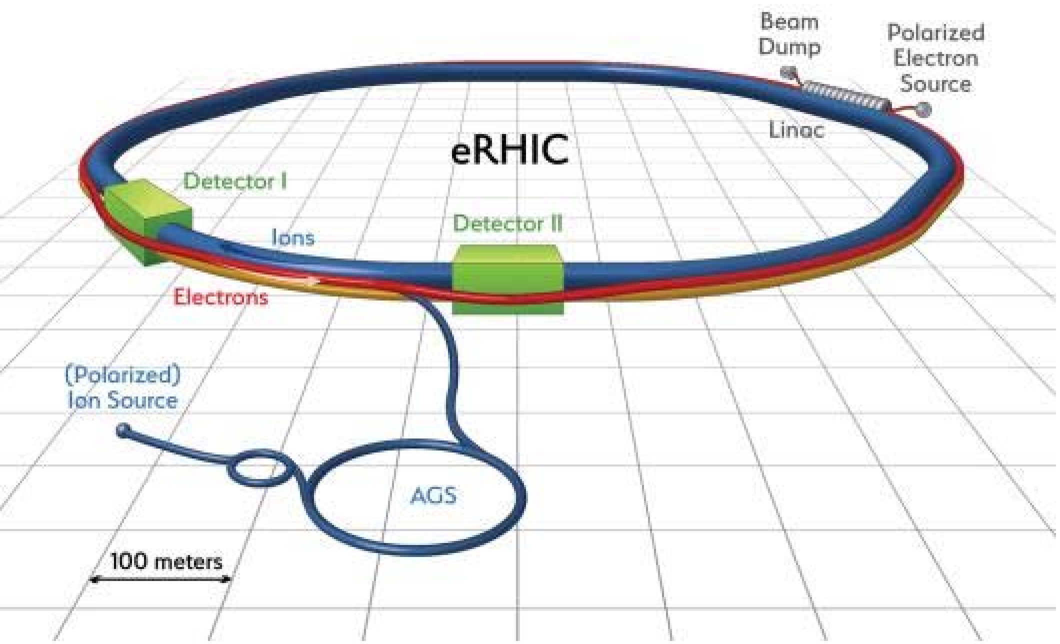

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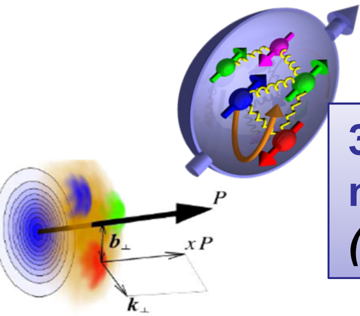


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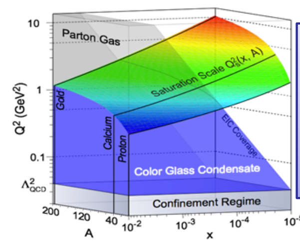


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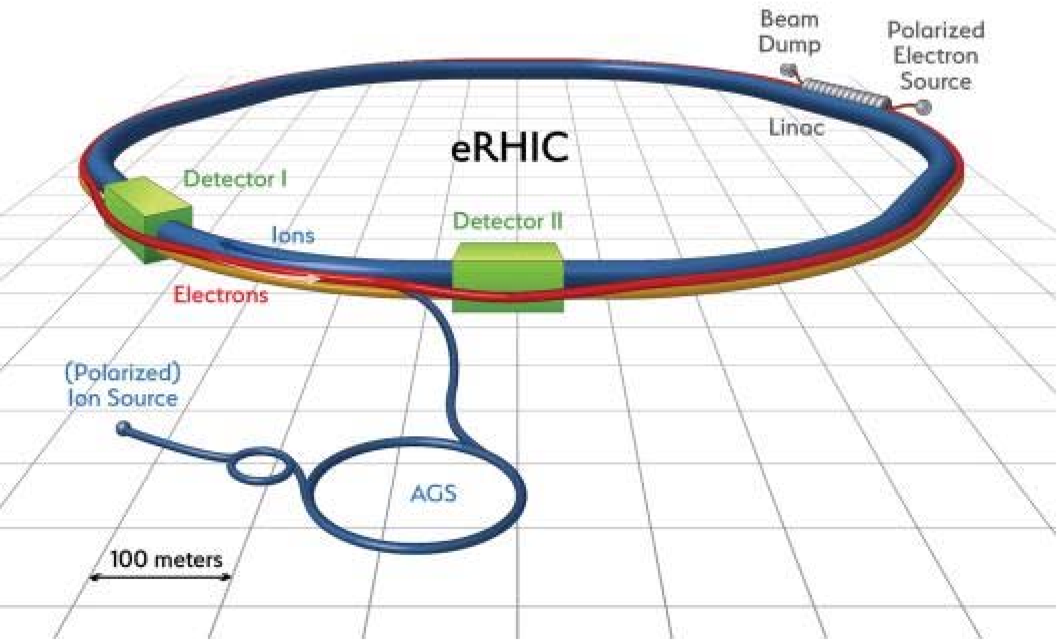


- Add an 18 GeV electron accelerator to the existing **$2.5B** RHIC complex
- In addition to the hadron machine eRHIC will re-use the existing infrastructure: RHIC tunnel and buildings, detector halls and cryo facility
- Take full advantage of existing polarized proton capability
- Take full advantage of existing heavy ion capability and large energy reach for gluon saturation studies

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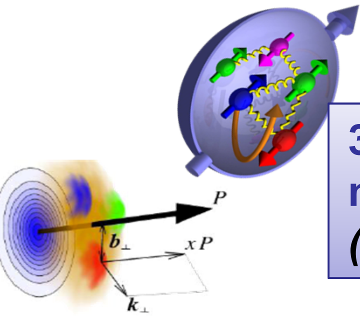

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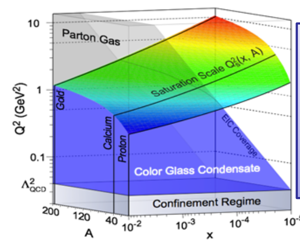


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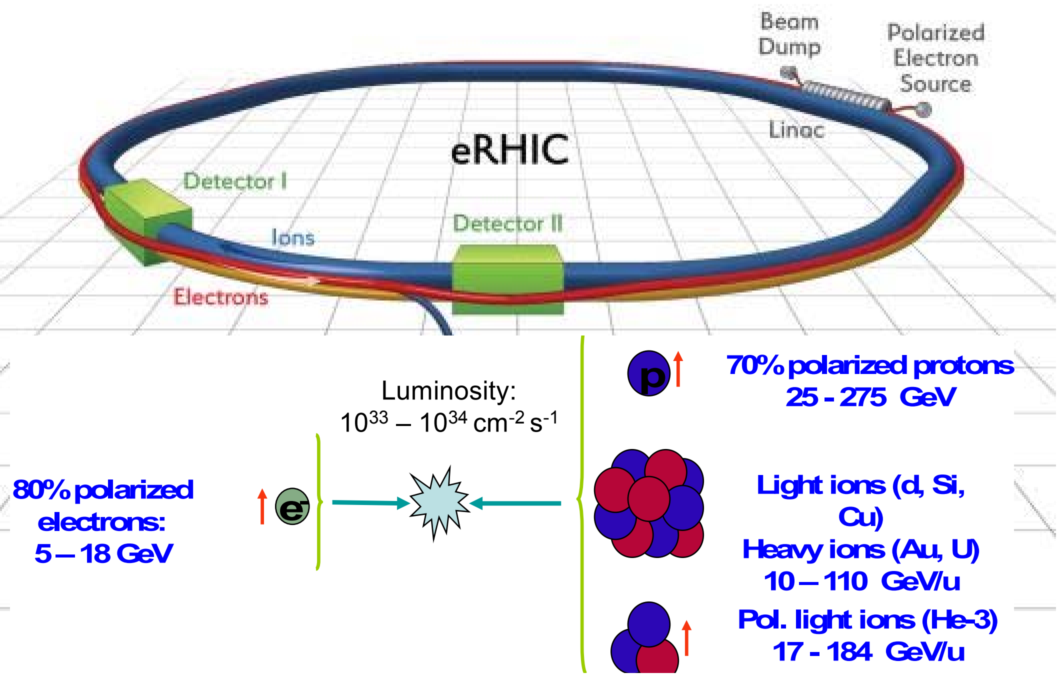


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# Two eRHIC Design Options

- **Main goals (and challenges) of eRHIC accelerator design:**
  - L ~$10^{33}$-$10^{34}$ $cm^{-2}s^{-1}$ (exceeding HERA luminosity by 2 orders of magnitude)
  - High electron and proton polarization (>70%); Realizing complex spin pattern
  - Satisfying large acceptance detector, with detector elements integrated in the accelerator IR for forward particle detection
  - Minimizing the construction and operational cost of accelerator

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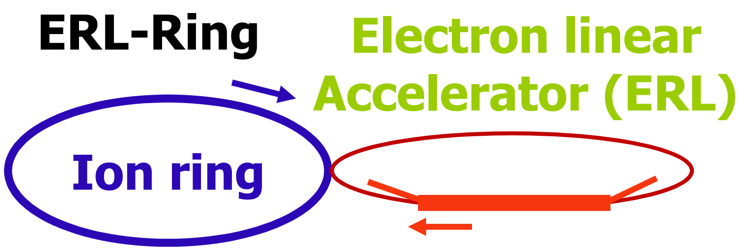

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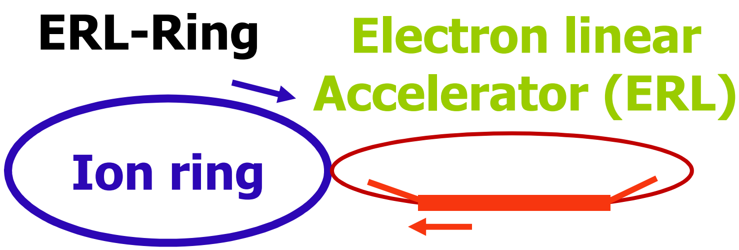


- High luminosity is based on small beam size in IP
- L ~ $E_p$
- Straightforward luminosity increase by hadron cooling
- Cost efficient
- Requires some accelerator technology beyond present state-of-the-art
- Main challenge: polarized electron source

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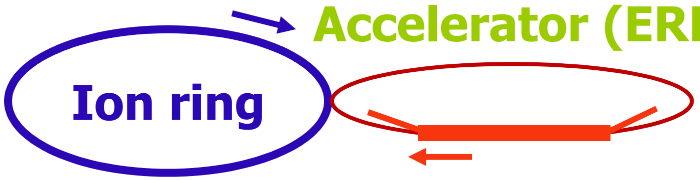
**ERL-Ring** **Electron linear Accelerator (ERL)**




- High luminosity is based on small beam size in IP
- $L \sim E_p$
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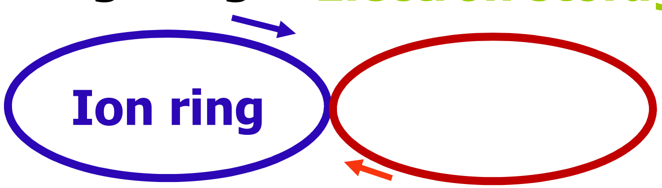
**Ring-Ring** **Electron storage ring**



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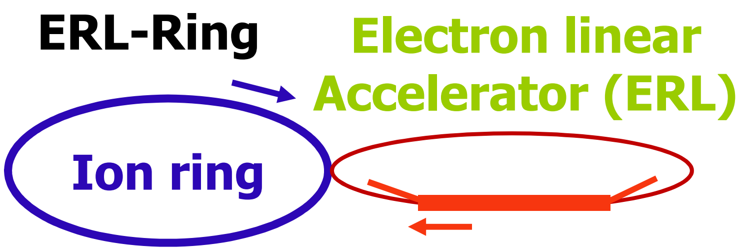


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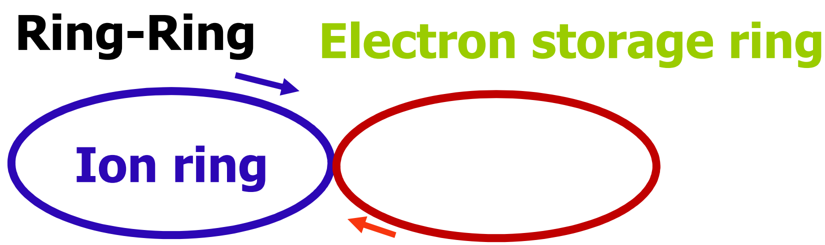
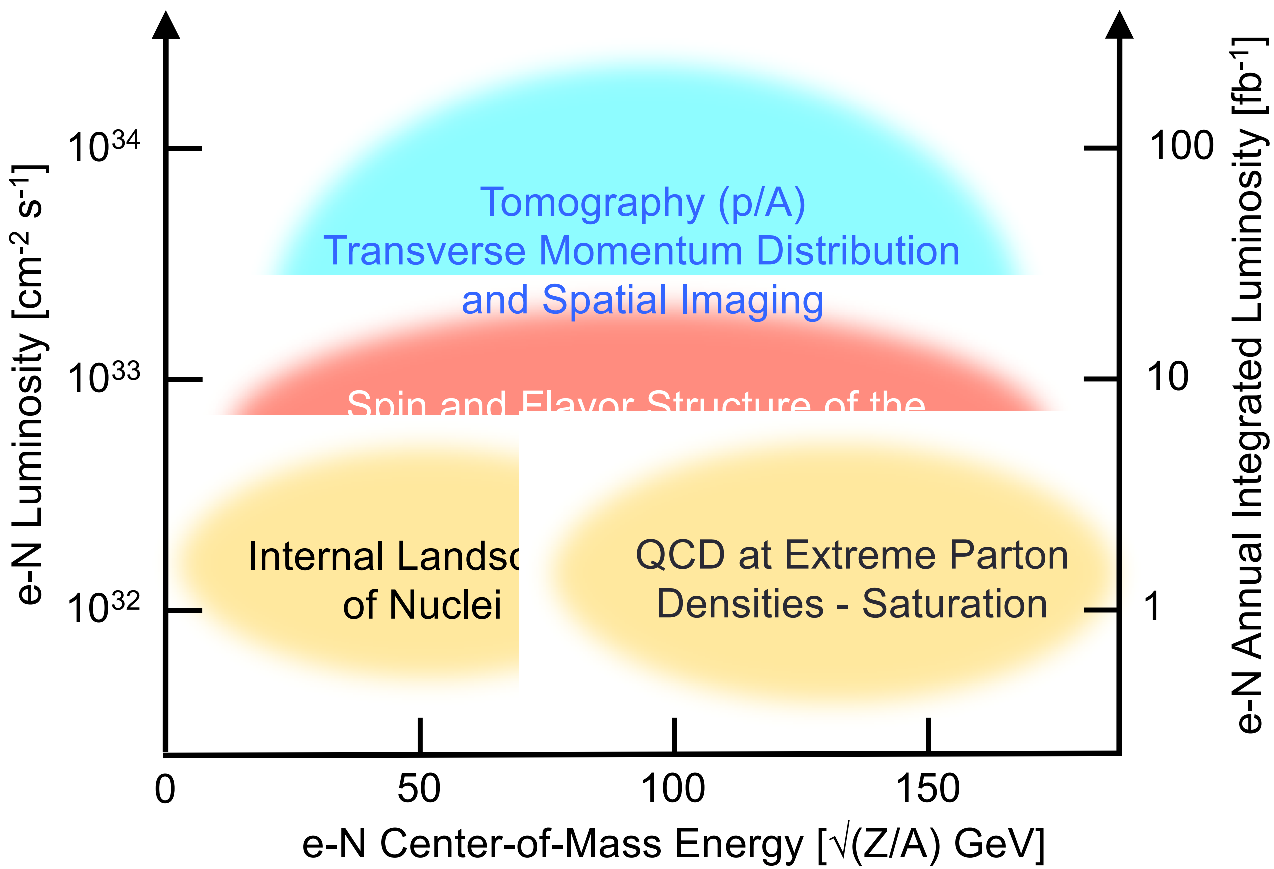



- High luminosity is based on high current of electron and proton beams
- $L \sim E_e * E_p = 0.5 * E_{CM}^2$
- Less technological challenges than in ERL-Ring
- Main challenge: High synchrotron radiation in detector and arcs

# 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.



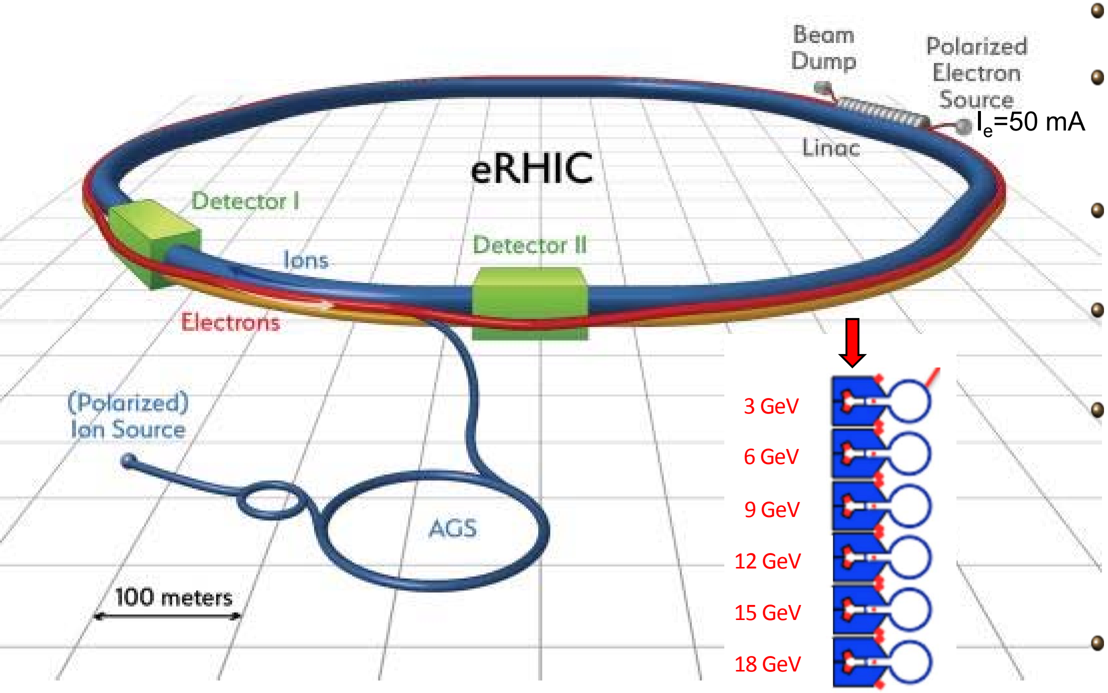

Ultimate ERL-Ring design (using hadron cooling)

Initial ERL-Ring design, $P_{synch}$ ~ 1 MW

Initial Ring-Ring design, $P_{synch}$ ~ 10 MW

# ERL-Ring Design Features

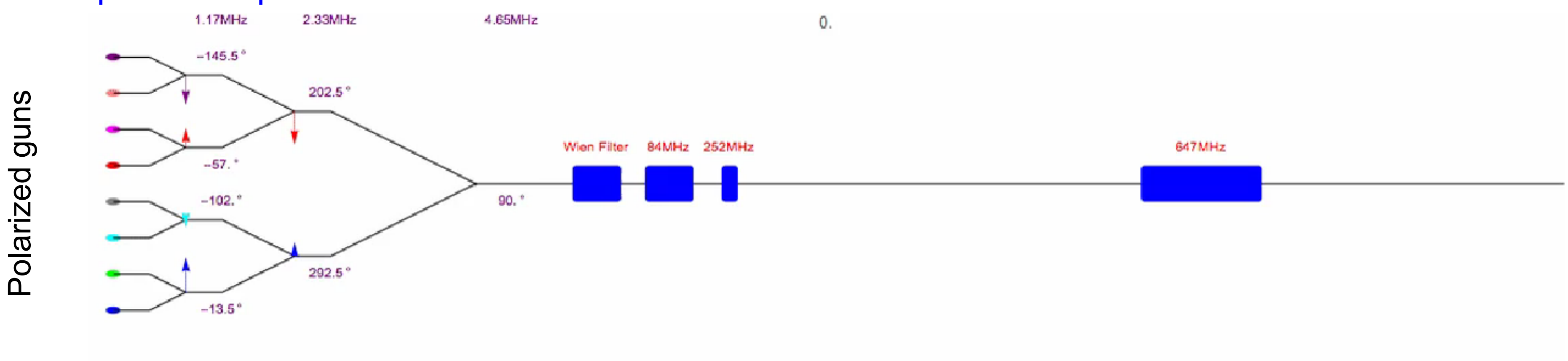
- Based on re-circulaitng electron linac (12 GeV CEBAF) and high current Energy-recovery linac (ERLs at Jlab and BINP) technologies.
- Beyond present state-of-the-art: 50 mA polarized electron source and high-energy high-power ERL.
- Single collision of each electron bunch. No limit of electron beam-beam effect on luminosity.
- Small electron beam emittance.



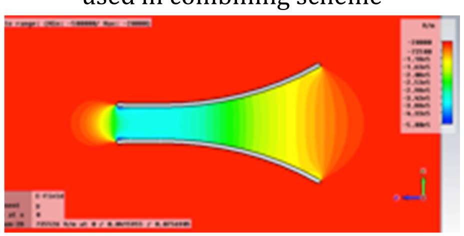

- Maximum electron energy: 18 GeV
- 50 mA polarized electron source employing merging electron current produced by multiple electron guns
- Main ERL SRF linac(s): 647 MHz cavities, 3 GeV/turn
- Six individual re-circulation beamlines based on electromagnets
- No hadron cooling required for e-p in initial 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

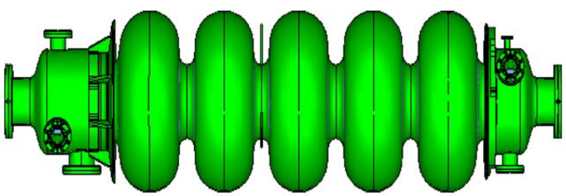


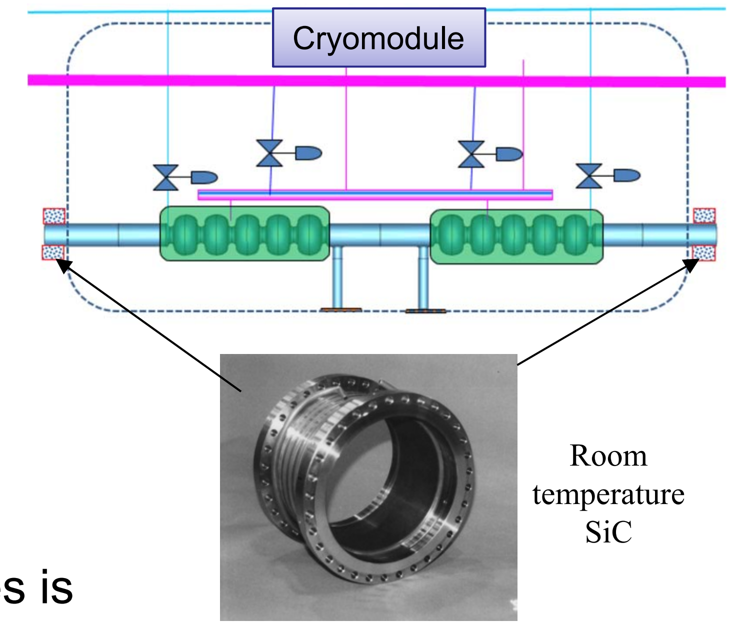

Field distribution of copper plate deflector, used in combining scheme



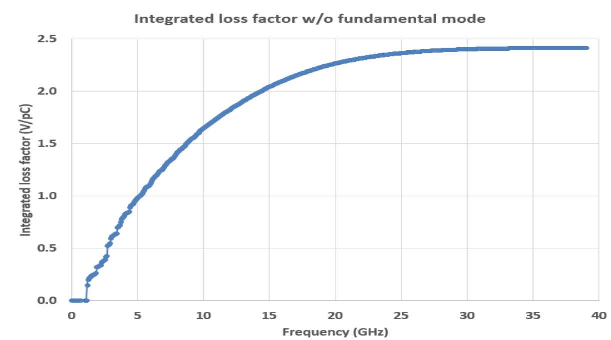
- Detailed 3D simulations of high-charge bunch transport through all injector components are underway
- Experimental studies of single cathode lifetime dependencies (using a Gatling gun prototype)
- Measurements of surface charge limit for SL cathodes using cathode preparation system.
- **A prototype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

# ERL-Ring Design: Main Linac SRF





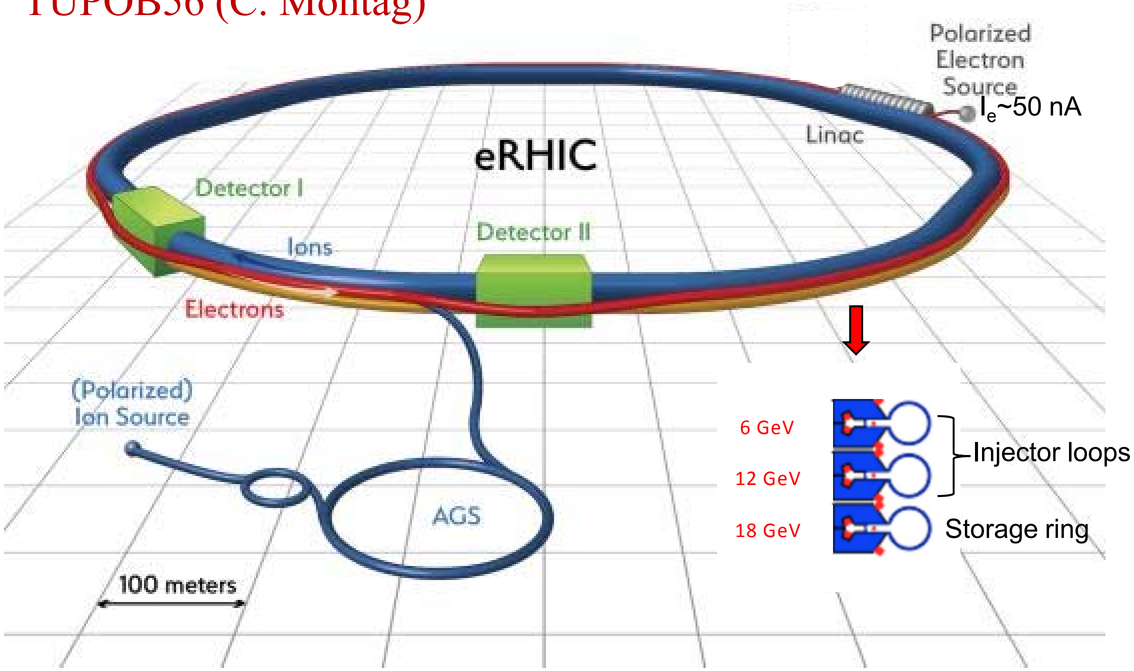

- 647 MHz 5-cell cavity
- Gradient: 18 MV/m@Q0=3e10.
- FPC power: 30 kW, Qext: 1.7e7
- Frequency of main linac accelerating cavities is benefitting from the 650 MHz SRF development program for the Fermilab PIP II project.
- Several hundreds mA of total beam current in the Linac -> HOM power up to 7 kW 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*
- Low risk baseline: room temperature SiC absorbers
- Multi-pass BBU studies confirmed viability of the 50 mA design beam current



# Ring-Ring Design Features

- Based on high current electron storage ring technology (B-factories) and the colliding beam performance in lepton and proton colliders (B-factories, RHIC, LHC)
- Storage ring (5-18 GeV) and a full energy injector with its two recirculation passes are placed in RHIC tunnel
  *Storage ring can employ some of PEP-II components (magnets, vacuum system)*
- Limit synchrotron radiation power to 10 MW (4 kW/m linear load)
- Full energy injector: 6 GeV/turn pulsed linac(s)
  *High charge (up to 50 nC) bunch production and acceleration is being studied.*

TUPOB56 (C. Montag)




- No cooling of hadron beam for initial Ring-Ring design
- The storage ring is similar to the final pass in the ERL-Ring option.
- With a proper design arrangement for the injector, it can be easily upgraded to the Ultimate ERL-Ring design

# Ring-Ring Design: Reaching High Luminosity

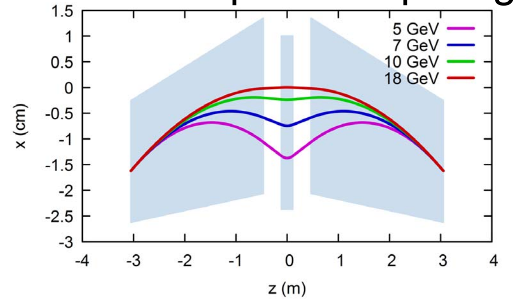
- High electron beam current
  ( up to 1.3 A)
  Demonstrated at B-factories;
  Linear SR power load < 4 kW/m

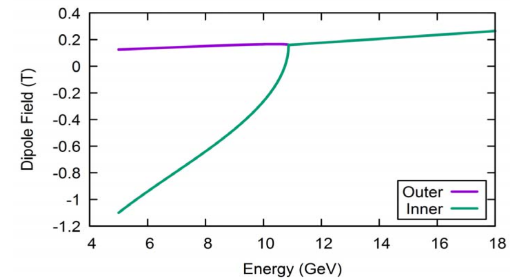
- Luminosity is defined by beam-beam limits:
  $\xi_p < 0.015$, $\xi_e < 0.1$.
  Split arc dipoles are used to enhance radiation damping at lower electron energies

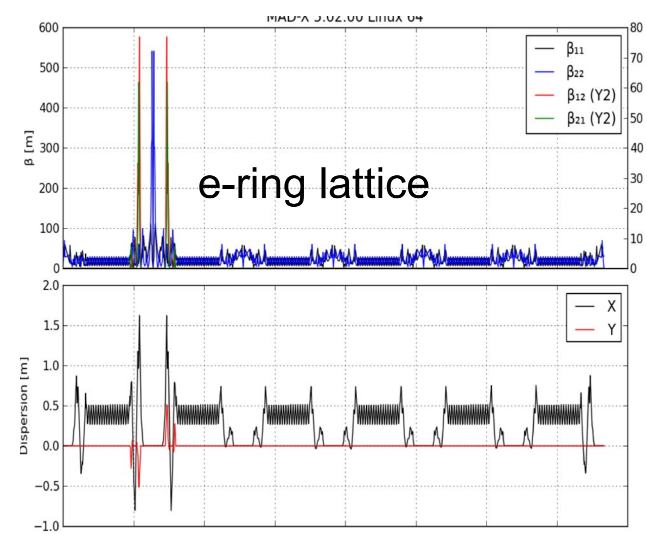
- Increased number of RHIC hadron bunches (by factor 3 from present)
  - Injector system upgrade; (~10 nsec kicker risetime)
  - Copper coating of RHIC beam pipe. In-situ coating methods are being developed
  - Electron cloud and associated heating load is being evaluated

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

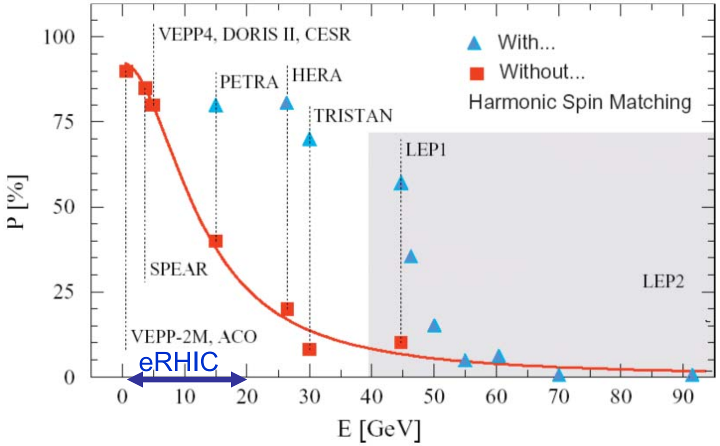
Split arc dipole geometry and their field



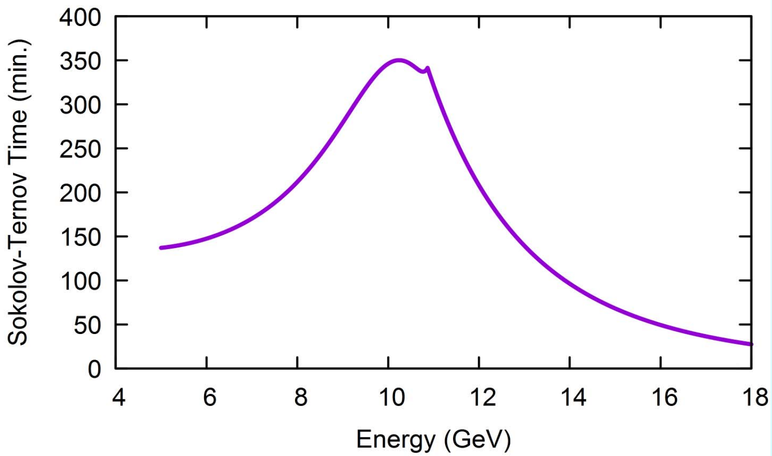
# Ring-Ring: Achieving High Electron Polarization




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

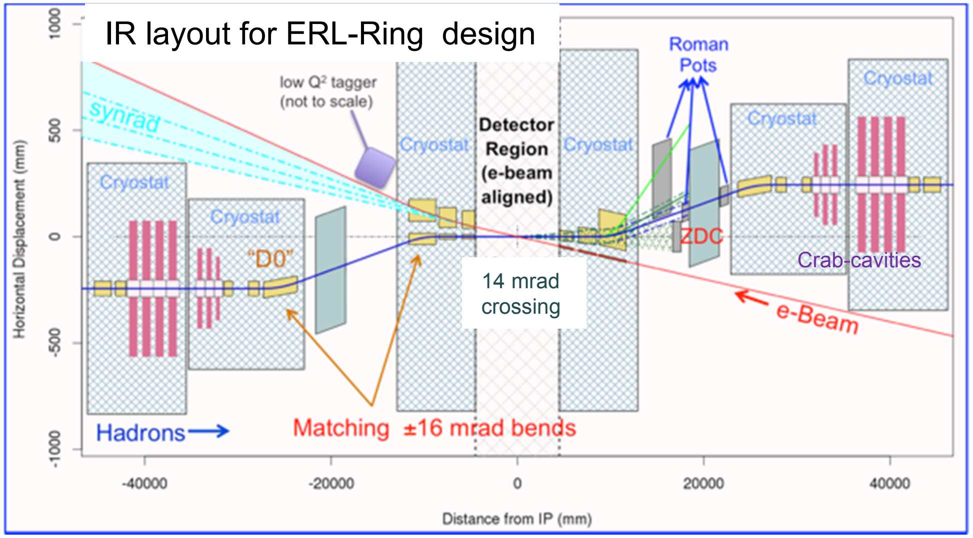
- highly efficient orbit correction,
- beam-based alignment of Beam Position Monitors relative to quadrupole field centers
- harmonic spin matching
- well controlled betatron coupling
- spin matching of spin rotator insertion

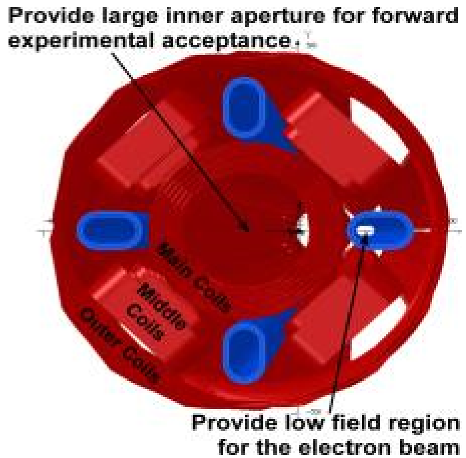
Sokolov-Ternov self-polarization time vs energy




- 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.*

# eRHIC High-luminosity, Full Acceptance IR



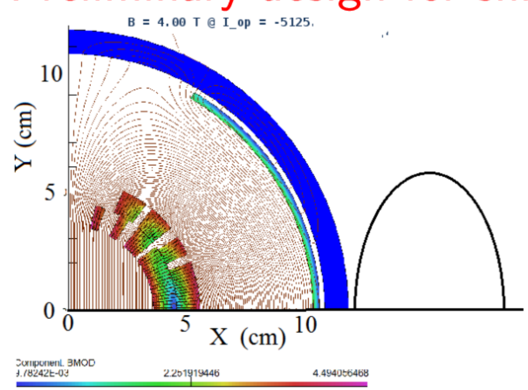



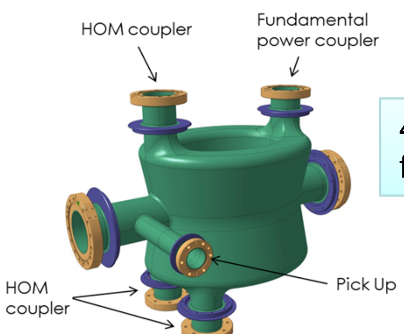

- Crab-crossing scheme (14/22 mrad crossing angle; 140-340 MHz SRF crab cavities)
- Special design of SC IR magnets to satisfy forward acceptance requirements and arrange passage of electron beam
- Detector elements (Roman Pots, ZDC, luminosity monitor) integrated into the IR design
- Soft bending of electron beam within 60 m upstream of the IP to simplify SR protection

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




400 MHz DQW crab-cavity built for LHC upgrade

# eRHIC R&D Program

- R&D for elements of initial design ($L \sim 10^{33}\ cm^{-2}s^{-1}$):
  - *Polarized electron source based on merging scheme (for ERL-Ring)*
  - *Methods for In-situ copper-coating of RHIC beam pipe*
  - *Crab-cavities: prototypes and study of related beam dynamics*
  - *e-p beam-beam effects*
  - *Polarized He3 production and acceleration*

- The cost reduction R&D *(for ERL-Ring):*
  - *Polarized electron source with up to ~ 50 mA current using Gatling gun or a Large cathode gun*
  - *HOM damping of 650 MHz cavities using combination of pipe absorbers and waveguide dampers*
  - *Re-circulation loops based on FFAG lattice, capable to transport beams in wide energy range:* ***Cbeta FFAG-ERL test facility at Cornell University***

  *Potential saving for ERL-Ring design due to the successful cost reduction R&D ~$200-300M.*

- R&D for higher luminosity ($L > 10^{34}\ cm^{-2}s^{-1}$):
  - *Coherent electron Cooling; Proof-of-Principle test of this novel technique at RHIC*

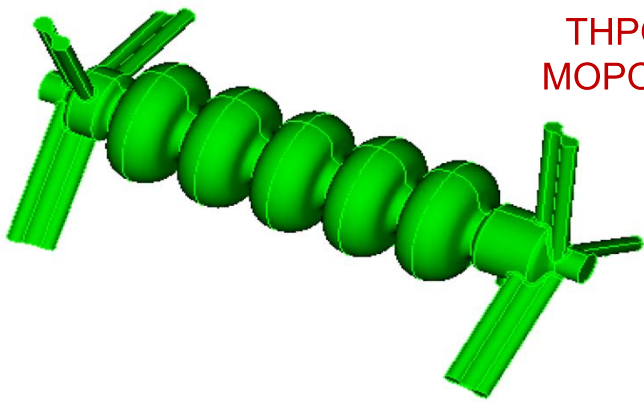
# R&D for 650 MHz Cavity and HOM Damping

- 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.

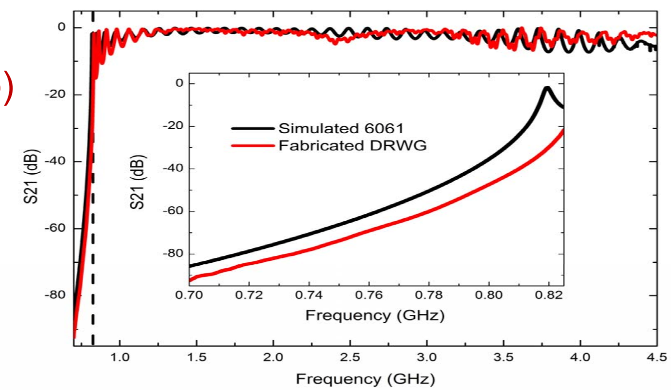
- HOM waveguide damper technology has been developed for many years in Jlab, but is not considered yet as fully proven.

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

THPOA54 (Y. Gao)
MOPOB48 (T.H. Luo)



650 MHz cavity with ridge waveguide dampers

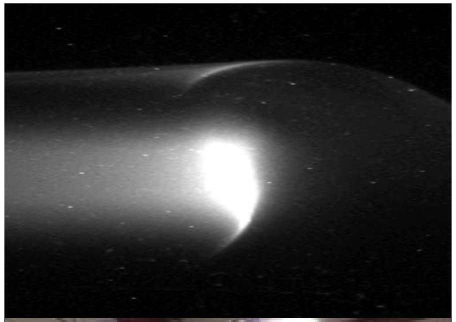



Ridge WG is a natural high pass filter with higher bandwidth, smaller size than regular WG.

- 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

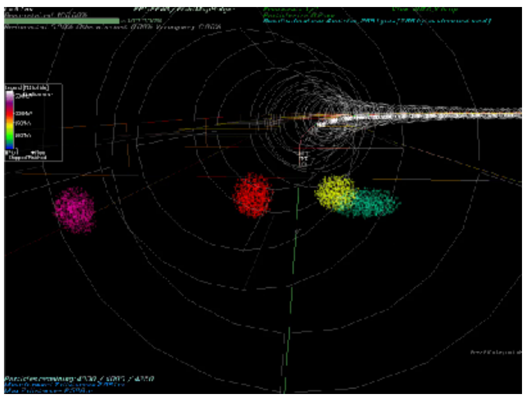
- DOE NP R&D project aiming for demonstration of CeC technique is in progress since 2012
- Phase I of the equipment and most of infrastructure installed into RHIC's IP2
- First beam from SRF gun (3 nC/bunch, 1.7 MeV) on 6/24/2015; exceeds performance of all operating CW electron guns
- 20 MeV SRF linac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

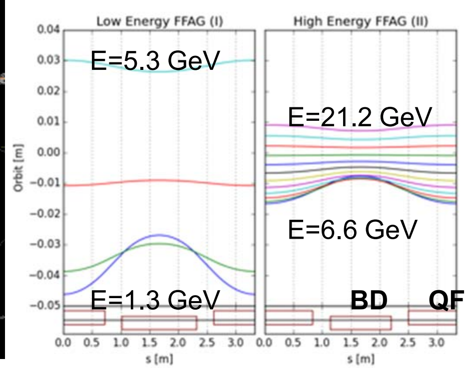


WEPOA59 (V.N.Litvinenko)
WEPOB60 (I. Pinayev)

# R&D for FFAG Recirculation Passes Based on Permanent Magnets

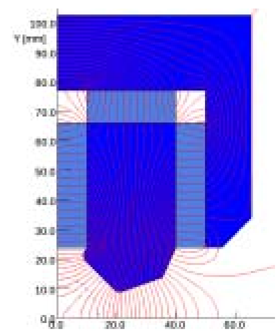
- FFAG beamline
  - Capable to transport beams in wide energy range ($E_f/E_{in}$ ~3-4)
  - Used mostly for sub-GeV proton accelerators; only one test electron accelerator (EMMA)

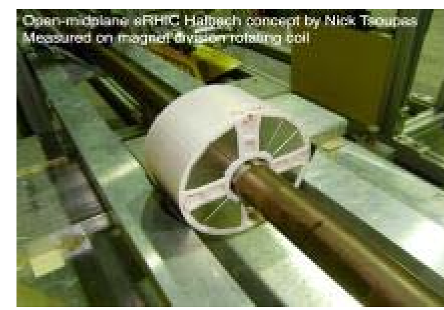





  - Not isochronous; thus spreader/merger is more complex incorporating pathlength and $R_{56}$ correction
  - Considerable cost saving

- 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 built and measured.






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

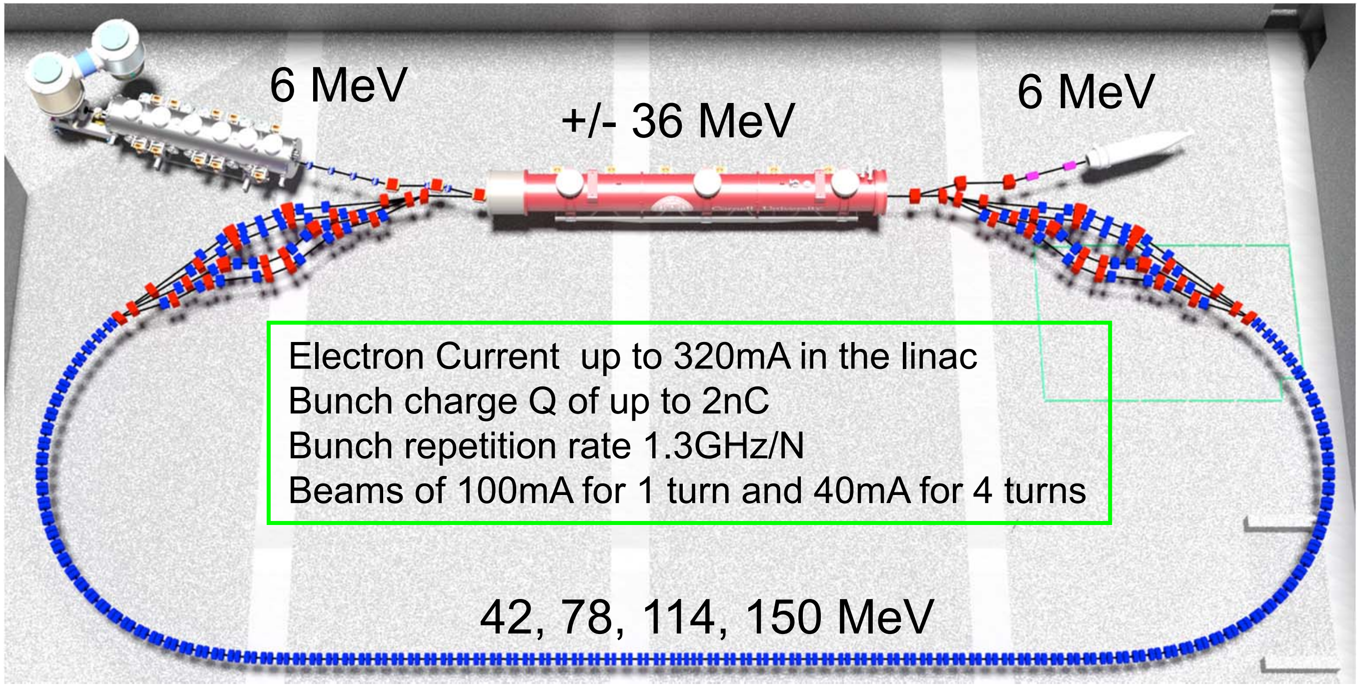
**TUPOB60 (N. Tsoupas)**
**MOPOB75 (H. Witte)**

# 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

- $25M funding from NY state has been approved
- Magnet prototypes are being built and tested
  - *Hybrid magnet design (laminated Iron+ NdFeB)*
  - *Thermal effect compensation using NiFe alloy*

WEPOA61
(C.E. Mayes)



# 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
  - JLab – polarized gun, CEBAF 8 GeV ERL experiment and SRF.
  - Cornell – FFAG multi-pass ERL experiment, high intensity electron source
  - LBNL – simulations of beam-beam interactions; HOM damping
  - ANL – low-energy injector cavities.
  - 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 option 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.
- Cost effective, reduced technological risk ERL-Ring and Ring-Ring eRHIC design options with required energy coverage and $10^{32}$ - $10^{33}$ $s^{-1}$ $cm^{-2}$ luminosity is a 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

## My acknowledgments to the eRHIC design team:

*E. Aschenauer, G. Bassi, J. Beebe-Wang, I. Ben-Zvi, J.S. Berg, M. Blaskiewicz, J.M. Brennan, S. Brooks, K.A. Drees, A. Fedotov, W. Fischer, Y. Hao, A. Hershkovitch, H. Huang, Y. Jing, P. Kolb, V.N. Litvinenko, C. Liu, Y. Luo, F. Meot, M. Minty, C. Montag, R.B. Palmer, B. Parker, S. Peggs, R. Petty, I. Pinayev, V. Ptitsyn, T. Rao, G. Robert-Demolaize, T. Roser, S. Seletskiy, T. Shaftan, J. Skaritka, V. Smaluk, K. Smith, S. Tepikian, R. Than ,D. Trbojevic, N. Tsoupas, J. Tuozzolo, E. Wang, G. Wang, F. Willeke, H. Witte, Q. Wu, C. Xu, W. Xu, A. Zaltsman, W. Zhang*

## List of poster and oral presentations on eRHIC design topics and related R&D:

- MOPOB48, Progress on the Design of Ridge Waveguide HOM Damper for High Current ERL SRF Cavity, *T.H. Luo, D. Li, S. Persichelli, Y. Yang (LBNL)*
- MOPOB75, Halbach Magnets for CBETA and eRHIC, *H. Witte, J.S. Berg (BNL)*
- MOPOB76, Field Emission Dark Current Simulation for eRHIC ERL, *C. Xu (BNL), et al.*
- TUPOB56, The eRHIC Ring-Ring Design, *C. Montag (BNL), et al.*
- TUPOB59 , Simulation of Beam-Beam Noise Effect in Linac-Ring Scheme eRHIC, *K. Shih, Y. Hao (BNL)*
- TUPOB60, Permanent Magnets for High Energy Nuclear Physics Accelerators, *N. Tsoupas* (BNL), et al.
- WEPOA61, New ERL with NS-FFAG Arcs at Cornell University, *C.E. Mayes (Cornell University), et al.*
- THPOA54, HOM Power and HOM spectrum of the RW HOM Damping Scheme, *Y. Gao(PKU), I. Ben-Zvi, H. Hahn, K.S. Smith, W. Xu (BNL)*
- WEPOA59, Progress with Coherent Electron Cooling at RHIC, *V. Litvinenko (BNL)*
- WEPOB60, Commissioning of CeC PoP Accelerator , *I. Pinayev (BNL), et al.*