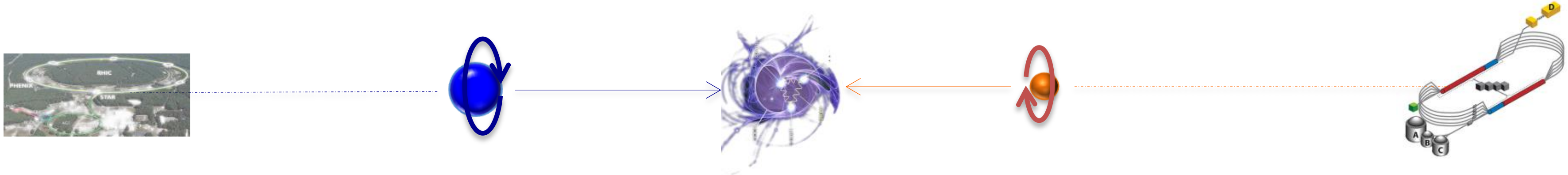


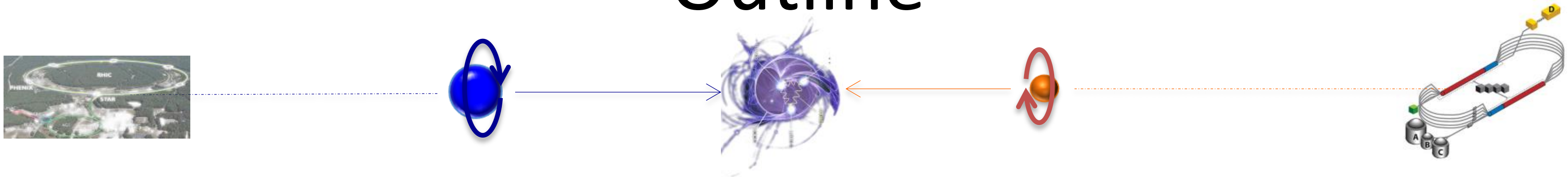
Electron-Ion Collider @ U.S.A.

M. Bai

Collider Accelerator Dept.

Brookhaven National Laboratory, Upton, NY, USA

Outline



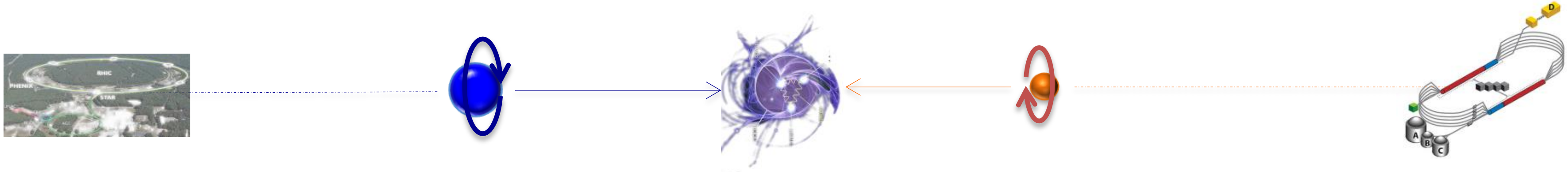
- Physics Motivation

- History of Development

- Current EIC development in the US
  - MEIC/EIC
  - eRHIC

- Summary

Physics Motivation



- **EIC, the QCD frontier**
  - **Unveil the deep secret of the glue that binds us all**
  - The polarized light ions enables the measurement of neutron's structure function $g_1(x,Q^2)$ in addition to the measurement of proton's structure function

$$g_1(x,Q^2) = \frac{1}{2}\sum e_q^2\left[\Delta q\left(x,Q^2\right) + \Delta\bar{q}\left(x,Q^2\right)\right] + \Delta g\left(x,Q^2\right)$$

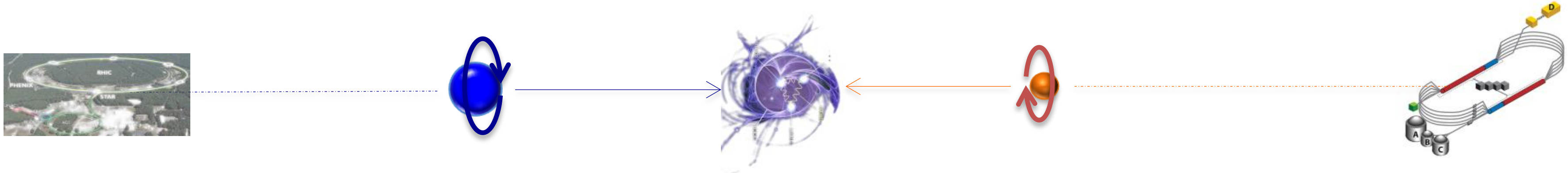
Quark electric charge [e_q^2]

Quark distribution [Δq, $\Delta\bar{q}$]

gluon distribution, only comes in at high order [Δg]

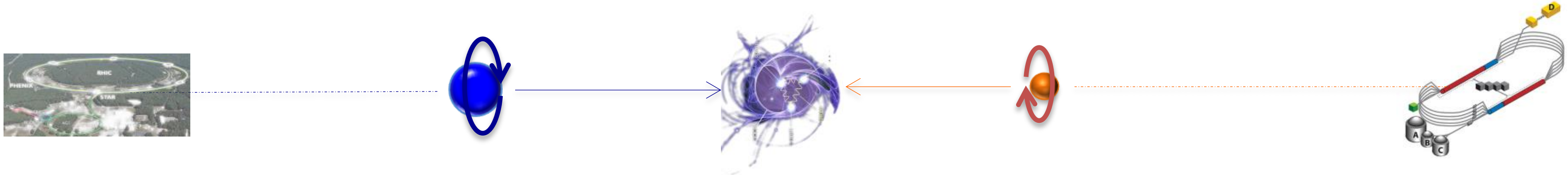
  - "The difference of the moments of proton and neutron $g_1(x,Q^2)$ allows a test of the fundamental sum rule by Bjorken", EIC white paper, BNL-98815-2012-JA, JLAB-PHY-12-1652, arXiv:1212.1701

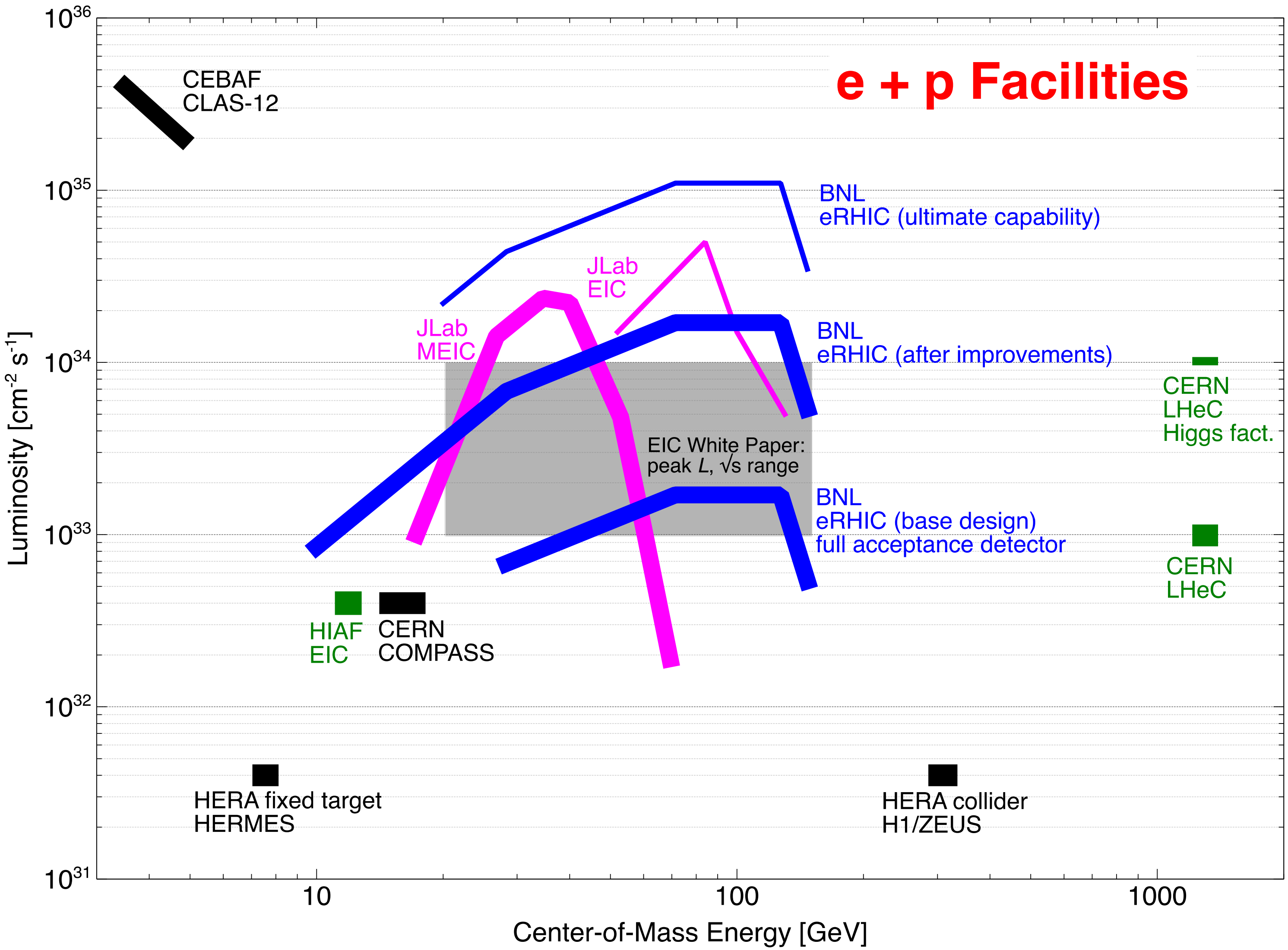
Electron-Ion Colliders



	location	status	type	species	luminosity $[cm^{-2} s^{-1}]$
HERA	DESY, Germany	1991-2007	Ring-ring, 6.3km	920GeV proton-27.6 GeV polarized electron	1.5 ~ 7×10^{31}
ENC	FAIR, Germany	proposed	Ring-ring	15GeV p^, 3.3GeV e^	10^{32}
eRHIC	BNL, USA	proposed 2025(2030) --	LINAC-Ring	255GeV pp, 100 GeV/c He3^, 100GeV/n Au 21.2GeV e^	10^{33}
MEIC/ EIC	JLAB, USA	proposed 2025(2030) --	Ring-Ring	3-12GeV e^, 25-100 GeV p^, 12-40GeV/n ions	10^{34}
HIAF	IMP, China	proposed	Ring-Ring	3 GeV e^, 12 GeV p^	$3\text{-}5 \times 10^{32}$
LHeC	CERN, Geneva	proposed	LINAC-Ring	7 TeV p, 60GeV e^	10^{32}

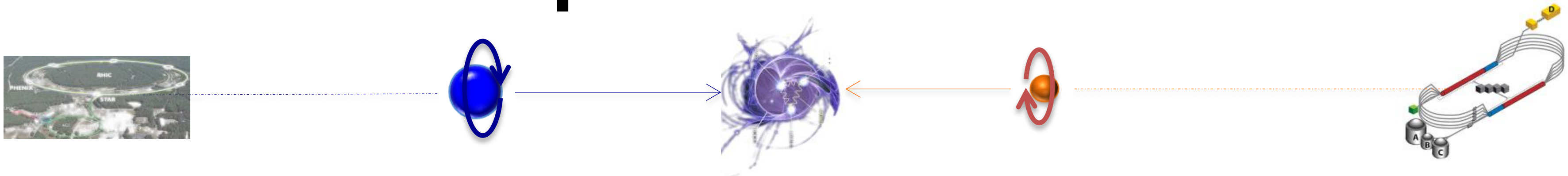
Electron-Ion Colliders





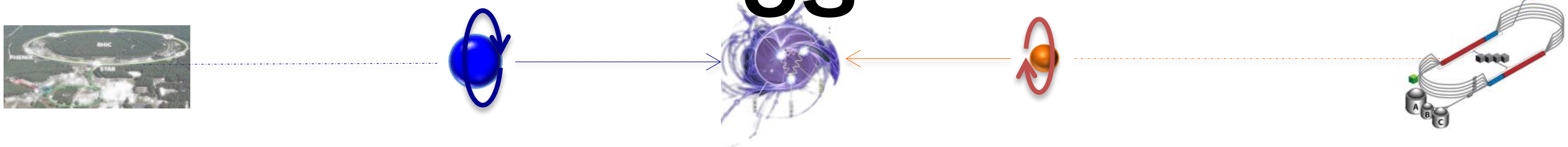
Courtesy of T. Roser

General Requirement for Future EIC



- High Luminosity
- Polarized electron beams as well as light ion beams including proton beams
- Provide heavy ion beams
- Flexibility in not only available species, but also center-of-mass energies

EIC Design and R&D Efforts in the US



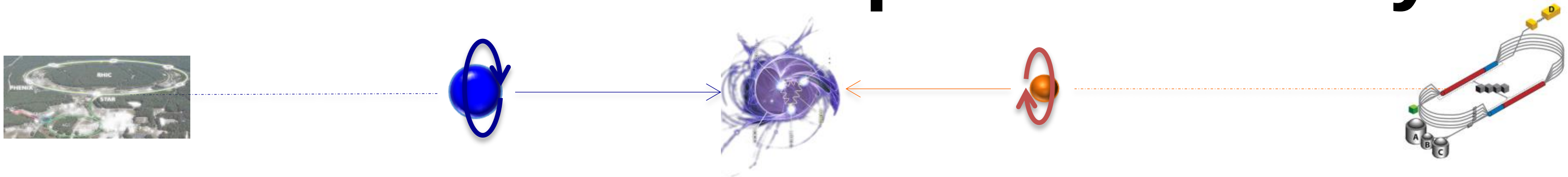
eRHIC

- Add a high efficiency multi-path Energy Recovery LINAC (ERL) for polarized electrons to the existing $2.5B RHIC including existing RHIC tunnel and cryo facility
- Hadron species:
  - Polarized protons, He-3
  - Heavy ions up to Uranium
- center-of-mass energy: 30-145 GeV
- Collision mode
  - 5 – 21.2 GeV polarized electron vs. 100-255GeV polarized protons, 100 GeV/n polarized He-3
  - 5 -21.2 GeV polarized electrons vs. 100 GeV/n heavy ions

MEIC

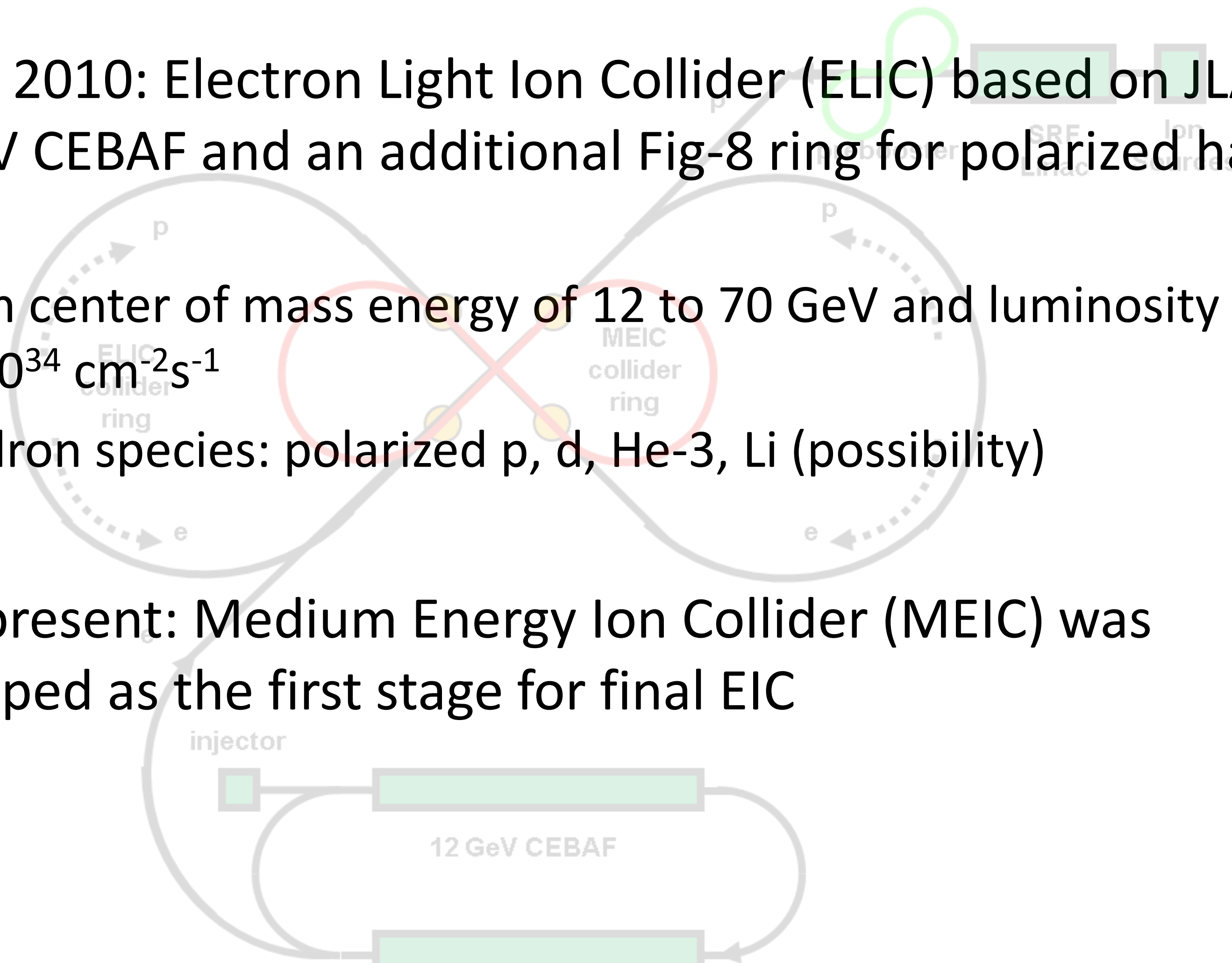
- Add Fig-8 synchrotrons that are spin transparent for acceleration as well as collider ring. Polarized electrons are from newly upgraded CEBAF@12 GeV
- Hadron species:
  - Polarized protons, deuterons, He-3 and Li
  - Heavy ions
- Center-of-mass energy: 12~70 GeV
- Collision mode:
  - 3 -12 GeV/c polarized electron beams vs. 100 GeV/c polarized proton beams
  - 3 -12 GeV/c polarized electron beams vs. up to 50 GeV polarized deuterons, up to 66.6 GeV/n for polarized He-3, and up to 40 GeV/n heavy ion beams

MEIC/EIC Development History

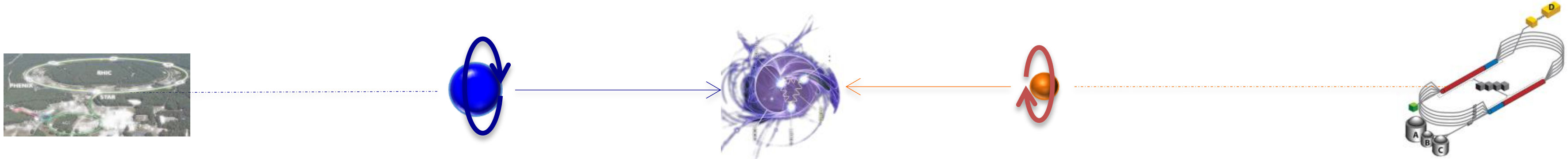


- Before 2010: Electron Light Ion Collider (ELIC) based on JLAB 12-GeV CEBAF and an additional Fig-8 ring for polarized hadron beams
  - with center of mass energy of 12 to 70 GeV and luminosity up to 8×10^{34} $cm^{-2}s^{-1}$
  - Hadron species: polarized p, d, He-3, Li (possibility)

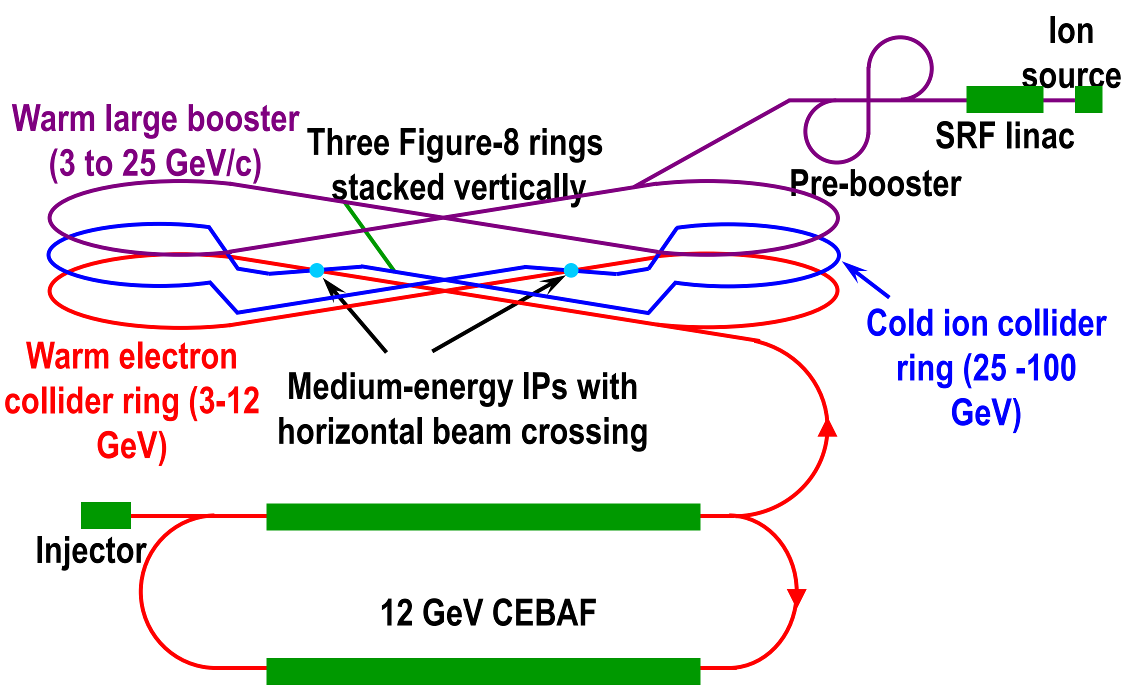
- 2010-present: Medium Energy Ion Collider (MEIC) was developed as the first stage for final EIC

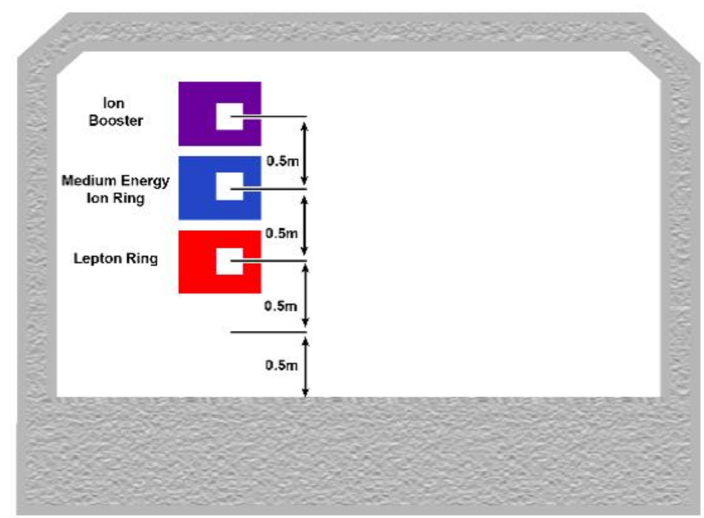


MEIC: EIC@JLAB

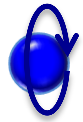


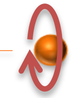
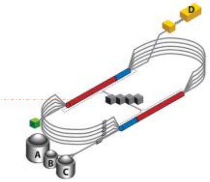
- Full coverage of √s from 12 to 70 GeV: e 3-12 GeV, p 20-100 GeV, ions 12-40 GeV/u
- Above 10^{33} $cm^{-2}s^{-1}$ per IP in a broad CM energy range. Maximum luminosity > 10^{34} per IP optimized to be around √s=45 GeV
- Fig-8 ring option provides spin transparent lattice to achieve > 70% polarizations
  - Polarized electrons, protons, deuterons, He-3, and possibly Li
  - Unpolarized heavy ions upto Au
- Upgradable to higher energies and luminosity: 20 GeV e, 250 GeV p, and 100 GeV/u ion





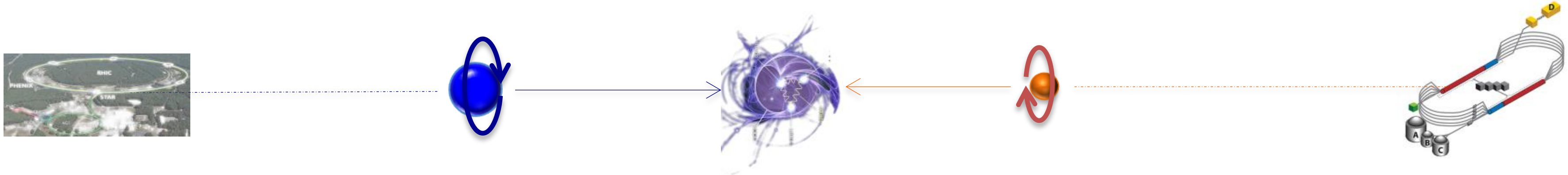
MEIC Parameters at One Exemplary Design Point

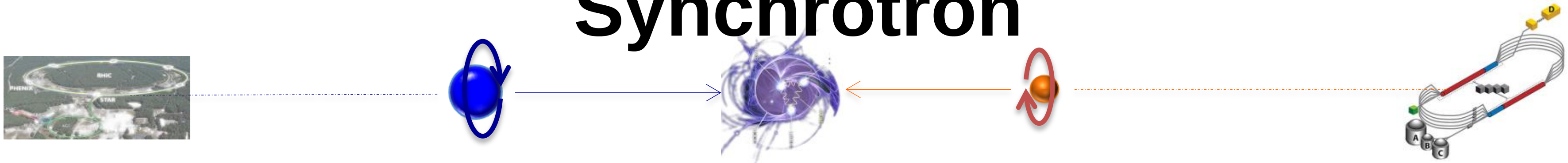
Courtesy of Y. Zhang

Detector		**Full Acceptance**		**Large Acceptance**	
		Proton	Electron	Proton	Electron
Beam energy	GeV	60	5	60	5
Collision frequency	MHz	750	750	750	750
Particles per bunch	10^{10}	0.416	2.5	0.416	2.5
Beam Current	A	0.5	3	0.5	3
RMS bunch length	cm	1	0.75	1	0.75
Normalized horizontal emittance	µm rad	0.35	54	0.35	54
Normalized Vertical emittance	µm rad	0.07	11	0.07	11
Horizontal and vertical β^*	cm	10 and 2	10 and 2	4 and 0.8	4 and 0.8
Vertical beam-beam tune shift		0.014	0.03	0.014	0.03
Laslett tune shift		0.06	Very small	0.06	Very small
Distance from IP to 1st FF quad	m	7 (down) 3.5 (up)	3	4.5 (down) 3.5 (up)	3
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	**5.6**		**14.2**	
Polarization		70%	80%	70%	80%

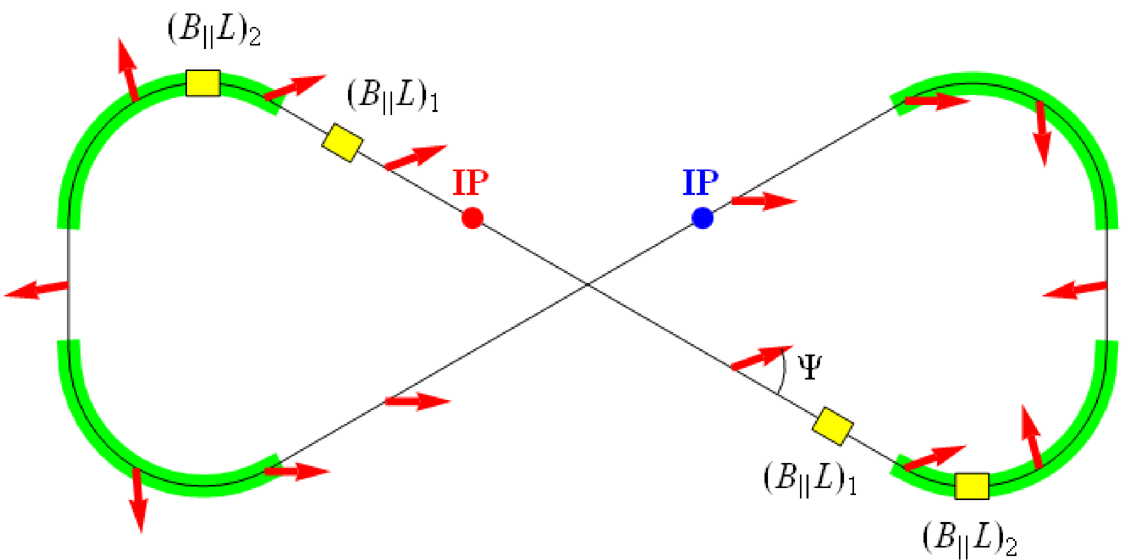


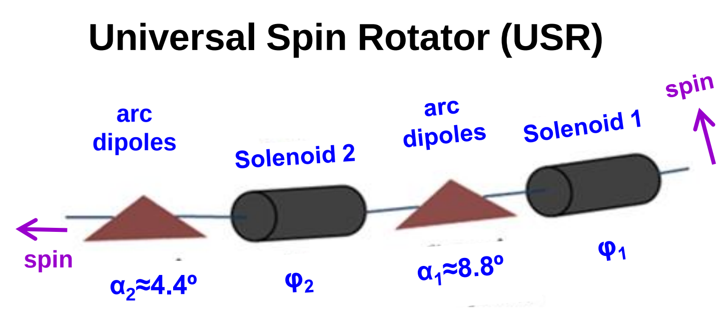
Key gradients to achieve the MEIC design performance

Fig-8 Ring: Spin Transparent Synchrotron

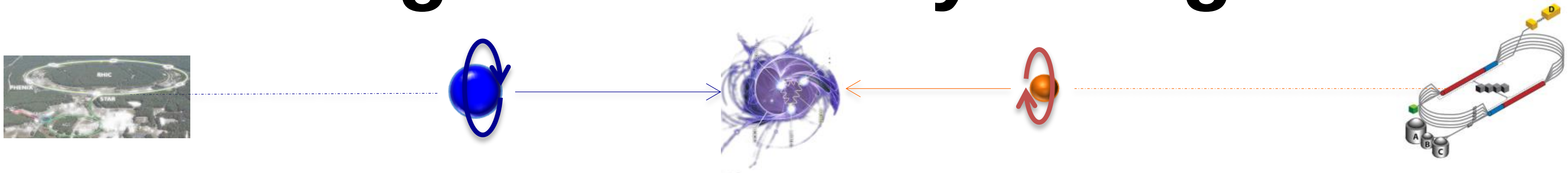


- Automatically cancels the spin precessions between the two parts of the ring
  - yields spin tune = 0, i.e. energy independent
  - applicable to all species including deuterons that have small g-2 factor and difficult to manipulate its spin at high energy
  - intrinsically spin instable. Can be mitigated with a modest spin rotation
  - still requires spin manipulation for all species if longitudinal polarization at IP is required. Can be mitigated by universal spin rotator



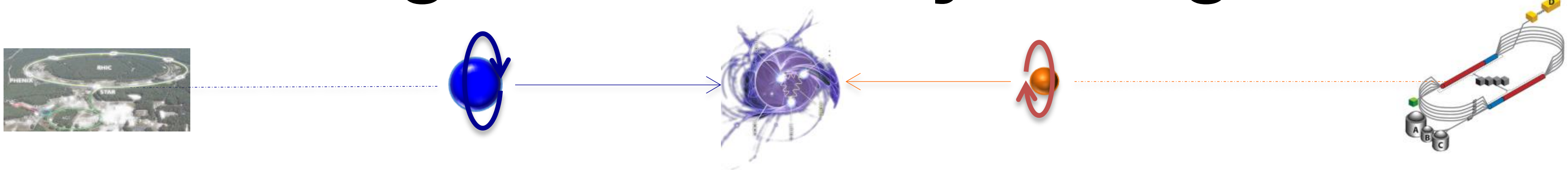


High Luminosity Design

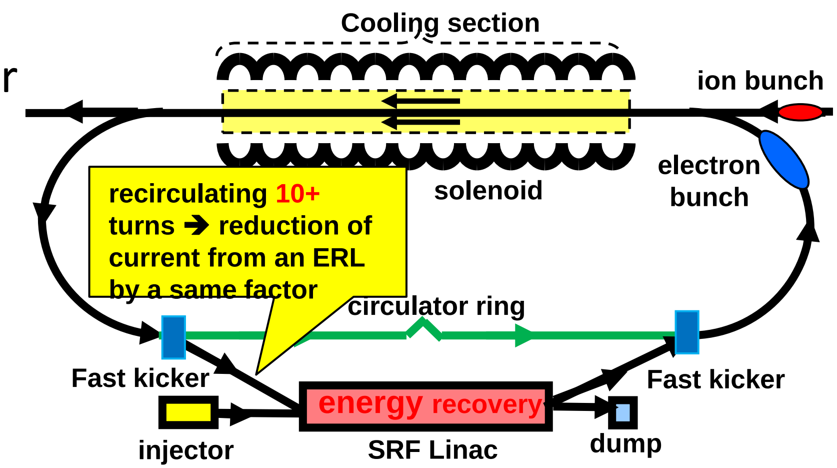


- High bunch repetition rate CW colliding beams
  - Requires the sophisticated RF manipulation to achieve 750 MHz bunch repetition rate with 1.3ns bunch spacing
    - Injecting and accelerating with low harmonic RF cavity (~1MHz). At store energy, adiabatically switch off the low harmonic RF cavity and turn on high harmonic (3372) SRF cavity (0.75GHz)
    - Advantage: achieve high repetition rate with relatively low bunch intensity to avoid beam instability
    - Needs to validate the beam dynamics to make sure the beam stability as well as no longitudinal emittance blowup
    - This technique may also exclude the possibility of having alternating spin pattern for hadron bunches, if such an option is needed for the physics program

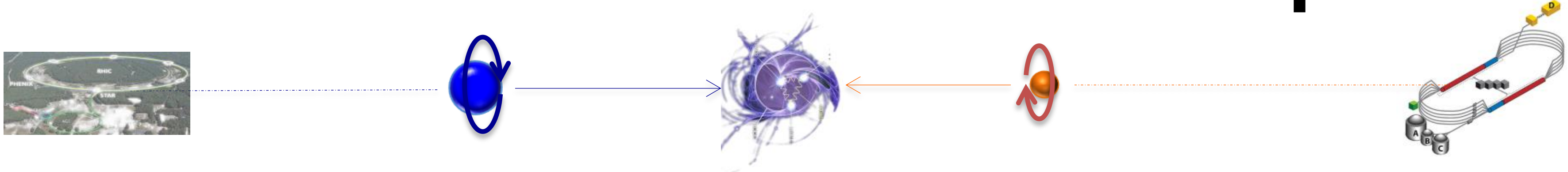
High Luminosity Design



- Multi-phased hadron beams cooling
  - Traditional DC electron cooling in pre-booster
  - ERL based electron cooling in the collider
- Strong beta squeeze to achieve very small beta* at IP
  - 10 cm – 0.8 cm beta* for both hadron and lepton beams
  - Requires dedicated chromaticity compensation section
  - Requires sophisticated non-linear correction to maximize dynamic aperture for reasonable beam lifetime
- Crab crossing
  - Two crab cavities on either side of the IP to mitigate the short bunch spacing in the mode of high bunch repetition rate

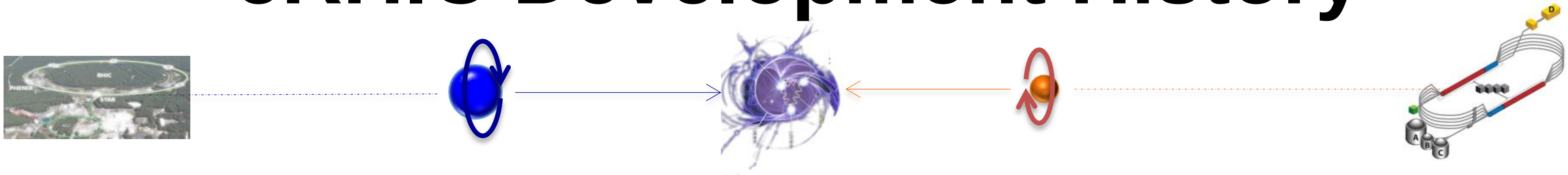


Current Status of MEIC Development



- Reached a matured design of overall complex: ion source, injector chain, as well as the collider
- Main design parameters are stabilized
- Integrated IR design is also developed
- Key R&D items are identified and are in working progress
  - Continue machine design optimization
  - Crab cavity development
  - ERL circulator cooler development
    - Electron source with high bunch intensity at high repetition rate
    - Fast kicker for injection and extraction
    - Design of ERL as well as Circulator Cooler Ring
  - Beam dynamics for both collider as well as circulator cooler ring
- Comprehensive cost estimate

eRHIC Development History



- 2001: I. Ben-Zvi, J. Kewisch, J. Murphy, S.Peggs, "Accelerator Physics Issues in eRHIC", Nuclear Instrumentations and Methods in Physics Research A 463 (2001), p.94., both ring-ring and LINAC-ring were explored

- 2004: eRHIC ZDR (the ring-ring design with $L \sim 10^{32}\ cm^{-2}\ s^{-1}$; ERL linac-ring as backup)

- 2006: ERL-based eRHIC with separated re-circulating passes
  - $L \sim 10^{34}\ cm^{-2}\ s^{-}$, high hadron beam intensity, upgrades in hadron ring, Space Charge Compensation
  - Energy staging. First stage eRHIC: 4-5 GeV electron machine.

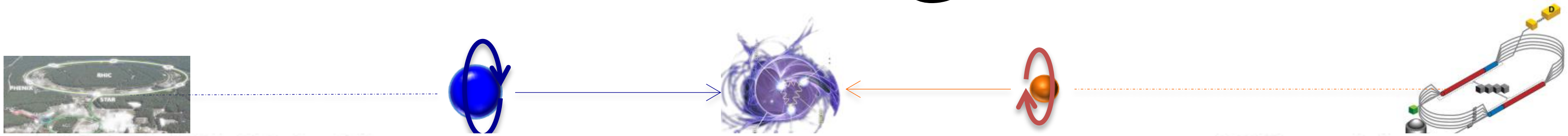
- 2012-2013: <u>Work on cost optimized machine design.</u>
  - Bottom-up cost estimate and optimization: minimal cost first stage (5 GeV) eRHIC with separated re-circulating passes: $530 millon. (detector(s) not included).

- 2013-2014: FFAG re-circulating passes + permanent magnets
  - construction and operational cost savings
  - No energy staging. Using FFAG passes widens the energy reach at moderate cost.
  - 10 GeV FFAG design has been evaluated by Machine Advisory Committee (Nov. 2013) : "The MAC congratulates the eRHIC design team for its ingenious and novel use of the FFAG concept."

- The "eRHIC Design Study" report includes the Accelerator Design Chapter presenting main features of eRHIC FFAG design.

Courtesy of V. Ptitsyn

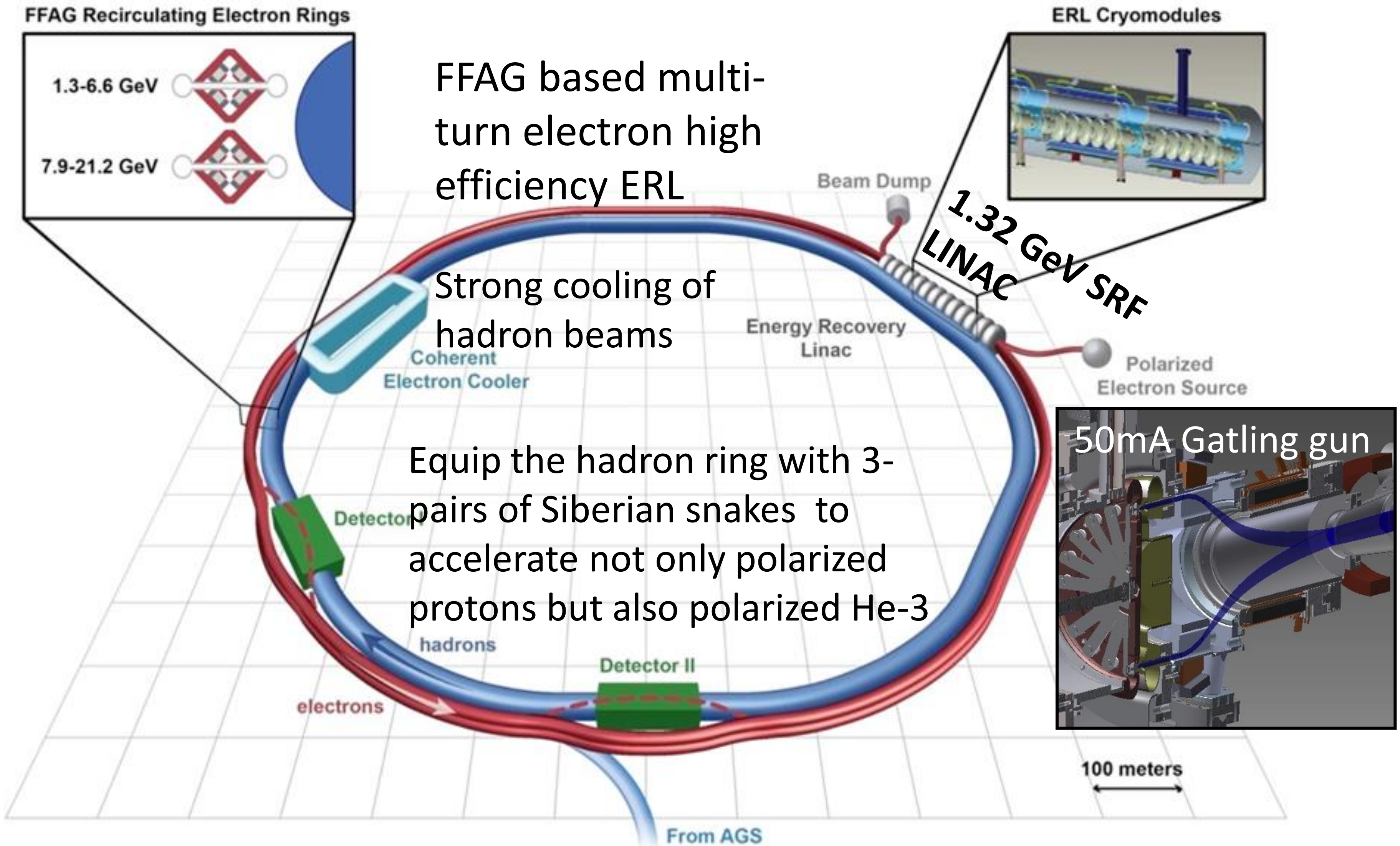
eRHIC: EIC@BNL



FFAG based multi-turn electron high efficiency ERL

Strong cooling of hadron beams

Equip the hadron ring with 3-pairs of Siberian snakes to accelerate not only polarized protons but also polarized He-3



eRHIC Design Performance

	e	p	$^{3}He^{2+}$	$^{197}Au^{79+}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		122.5	81.7	63.2
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.33	0.3	0.6	0.6
Bunch charge, nC	5.3	4.8	6.4	3.9
Beam current, mA	50	42	55	33
Hadron rms norm. emittance, μm		0.27	0.20	0.20
Electron rms norm. emittance, μm		31.6	34.7	57.9
Beta*, cm (both planes)	5	5	5	5
Hadron beam-beam parameter		0.015	0.014	0.008
Electron beam disruption		2.8	5.2	1.9
Space charge parameter		0.006	0.016	0.016
rms bunch length, cm	0.4	5	5	5
Polarization, %	80	70	70	none
Peak luminosity, 10^{33} $cm^{-2}s^{-1}$		1.5	2.8	1.7

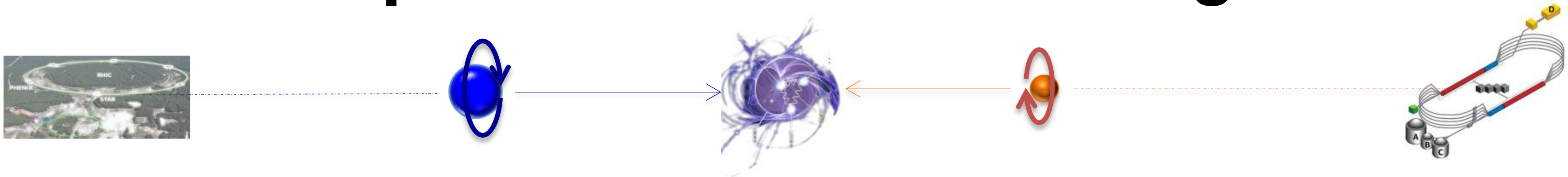
- **15% of the hadron beam intensity presently achieved in RHIC: allows to operate with present RHIC vacuum chamber (e.g. no coating is needed) and without space-charge compensation at lower hadron energies.**
- **With vacuum chamber coating a 10-fold higher luminosity can be reached.**

Courtesy of V. Ptitsyn, T. oser

RHIC Achieved Performance and Projection

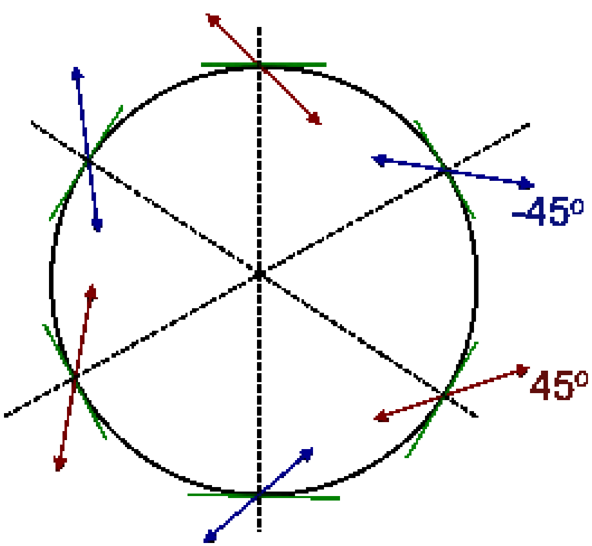
p- p operation		2009	2012	2013	2015
Energy	GeV	100/250	100/255	255	100/255
# of collisions	…	107	107	107	107
Bunch intensity	10^{11}	1.3/1.1	1.3/1.8	1.85	2.0
Beta*	m	0.7	0.85/0.65	0.65	0.65
Peak L	**$10^{30}cm^{-2}s^{-1}$**	**50/85**	**46/165**	**245**	**65/280**
Average L	**$10^{30}cm^{-2}s^{-1}$**	**28/55**	**33/105**	**160**	**38/170**
Polarization P	**%**	**56/35**	**59/52**	**56**	**65/57**

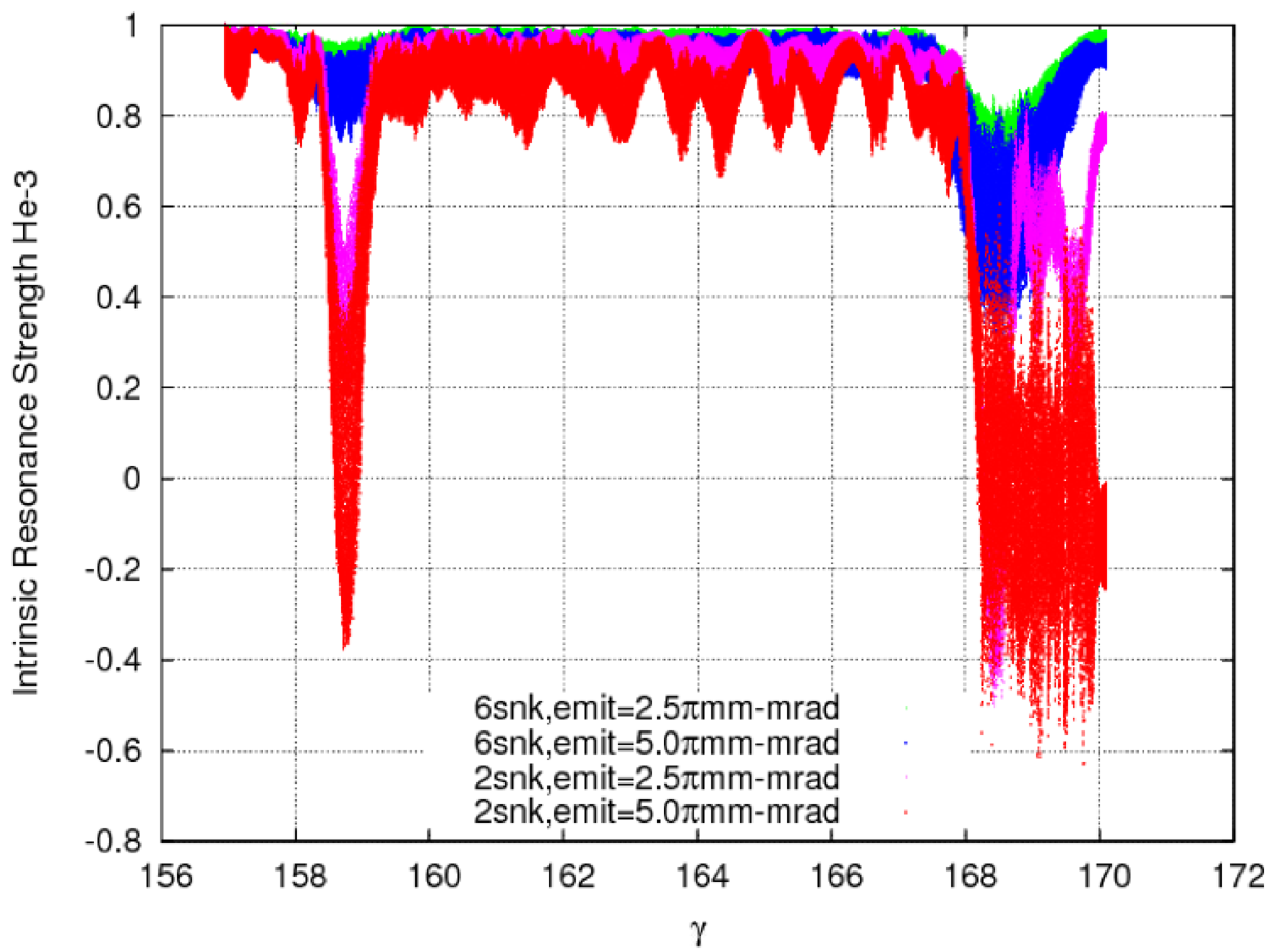
eRHIC polarized hadron configuration



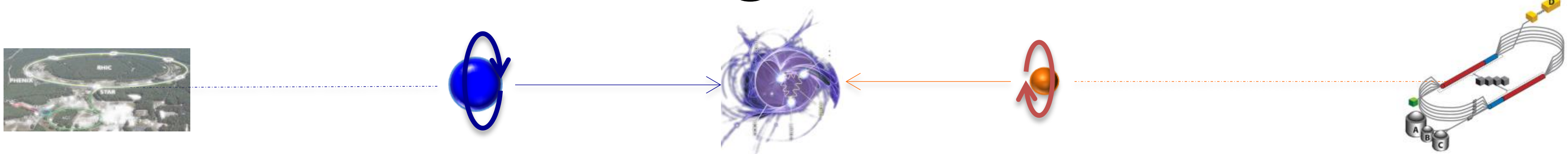
- Six-snake scenario:

  The spin rotation axis of each snake alternates between 45 degrees and −45 degrees w.r.t beam direction for all six snakes.

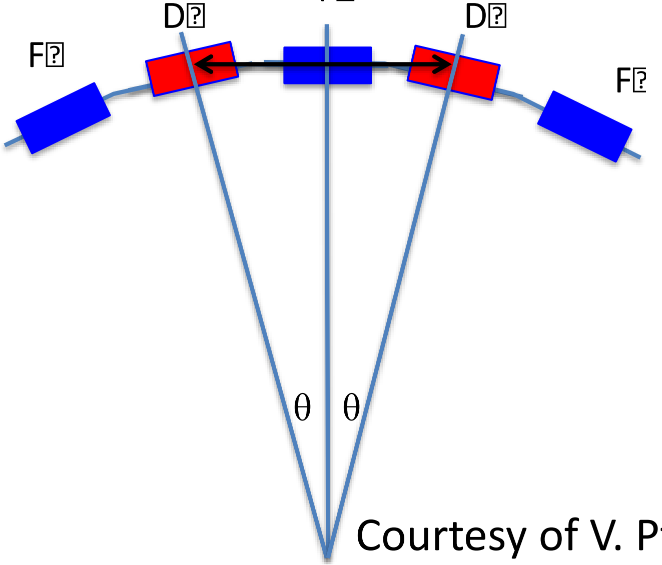




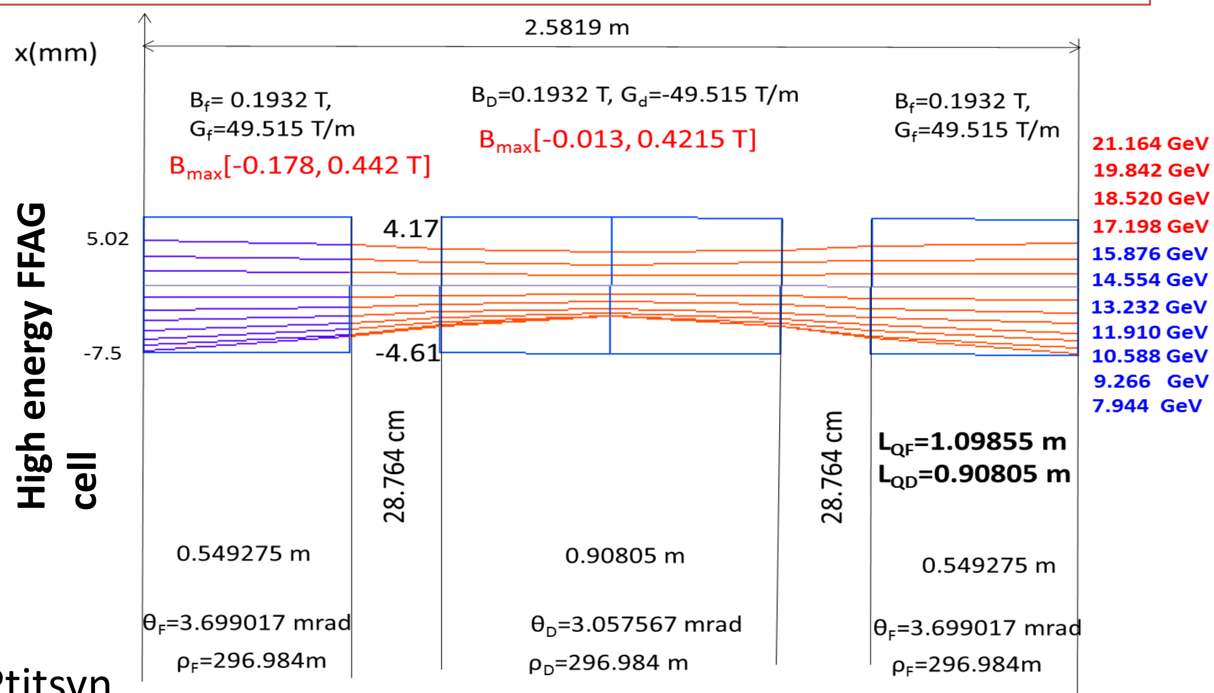
eRHIC Non-scaling FFAG Recirculation



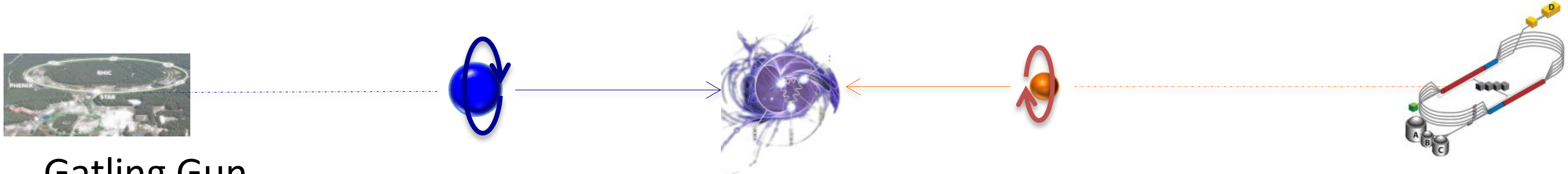
- Consists of strong focusing FODO cells with all quadrupoles shifted horizontally w.r.t. each other
- This provides small dispersion function and trajectory for all energies
  - Huge cost saving: permanent magnet to avoid power supplies, cables and cooling
  - Avoid staging: reaching 21 GeV electron beam



Courtesy of V. Ptitsyn

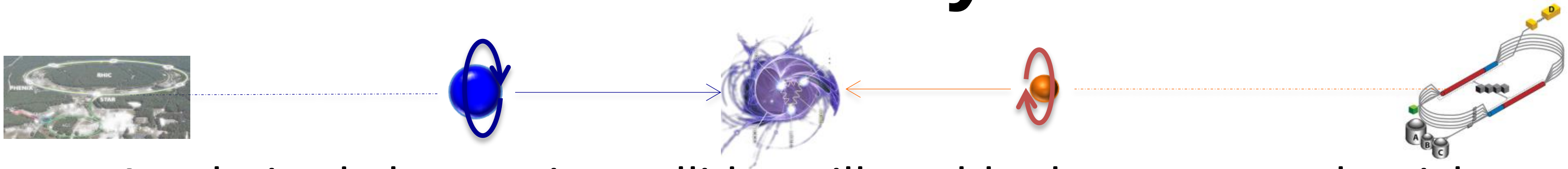


Current eRHIC Status



- Gatling Gun
  - Prototype of up to 20-cathodes Gatling Gun is developed. Photo current from 2 cathodes was tested at Stangenes Industries of CA. The gun will be tested at the end of 2014 in StonyBrook of NY
- Coherent electron cooling proof-of-principle will be demonstrated with RHIC 40 GeV/c/n heavy ion beam in 2016
- Non-scaling FFAG recirculation lattice was thoroughly optimized based on its energy acceptance, spreads of orbit and time-of-flight, and SR power
  - Preliminary permanent magnet design was achieved
  - Lattice of beam combiner and spreader between recirculation and SRF LINAC was also optimized
  - Beam dynamics of 16-turn recirculation SRF ERL was studied and beam parameters like bunch pattern were optimized to mitigate the potential beam breakup
- Electron polarization was also examined, and confirmed that this design expects to reach 80% electron polarization up to 21.2 GeV/c. The direction of polarization at collision point is controlled via a wien-filter in the injection section of ERL
- IR design with 5cm beta*, as well as synchronization between the electron beam and hadron beam were achieved

Summary



- A polarized electron ion collider will enable the access to the rich QCD physics. It has been identified as an important project for US nuclear physics community
- Two independent efforts are devoted to the future EIC at US, BNL and JLAB. And both reached matured and stable designs to provide high luminosity and high polarization collisions

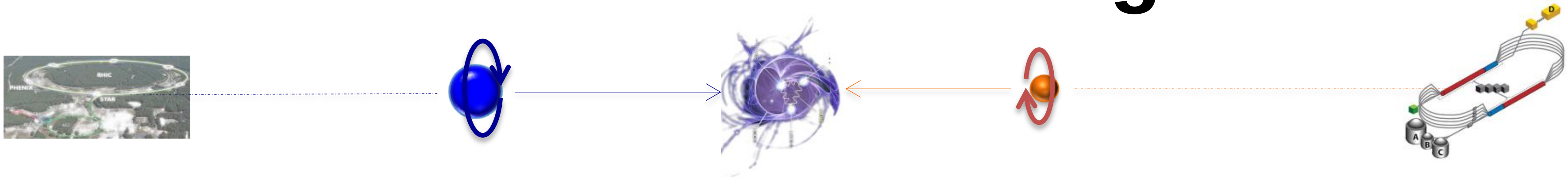
eRHIC@BNL

- LINAC-RING design by adding an ERL based electron accelerator to RHIC polarized hadron accelerator
- non-scaling FFAG
  - Collision of 21.2GeV electron with 255 GeV/c polarized protons or 100 GeV/n heavy ions available on DAY 1
  - Allows permanent magnet option for significant cost effective

MEIC@JLAB

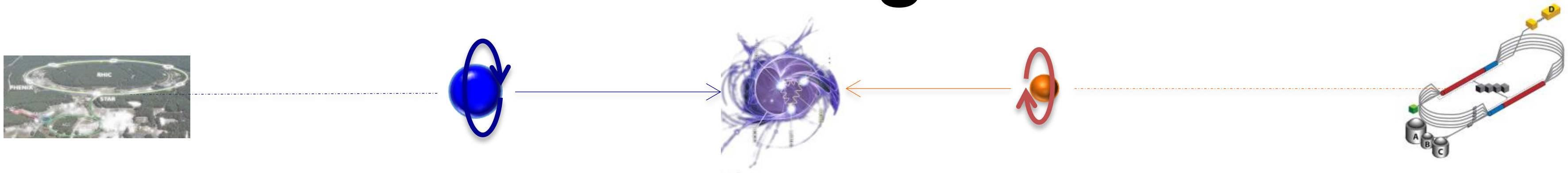
- RING-RING design by adding a set of Fig-8 synchrotrons for accelerating and colliding hadron beam with CEBAF 12GeV polarized electron beam
- High bunch repetition rate for collision
- Polarized electron beam Top-off injection to mitigate the polarization lifetime issue
- Can be upgraded to 20 GeV electron collision

EIC Novel Technologies



- High intensity polarized electron gun
- Strong beam cooling for high energy hadron beams
  - Coherent electron cooling (BNL)
  - ERL based electron cooling (JLAB)
- Spin transparent Fig-8 ring for polarized beam acceleration and collider
  - Allows high energy polarized deuteron beams
- Multi-pass high efficiency ERL
- Non-scaling FFAG beam recirculation
  - Demonstrate the non-scaling FFAG feasibility
  - Demonstrate the significant cost savings design

Acknowledgement



- This presentation is based on the inputs from Dr. T. Roser (BNL), Dr. V. Ptitsyn (BNL), Dr. Yuhong Zhang (JLAB), and Dr. E. Aschenauer (BNL)
- References used in this presentation
  - V. Ptityn, eRHIC, FFAG workshop, 2014
  - T. Roser, new facilities, PANIC, 2014
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