Overview of Asymmetric Hadron-Electron Colliders

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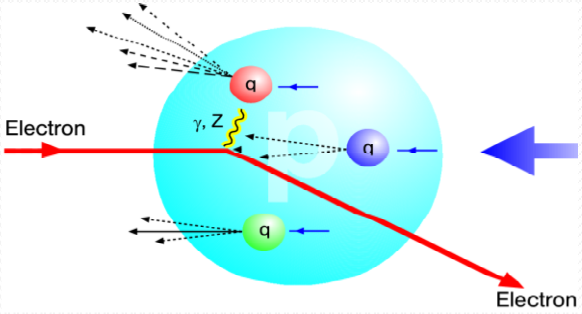
BNL

Lepton-nucleon scattering



- **Deep Inelastic Scattering (DIS)** of electron, muon and neutrino beams on nucleons (fixed targets) has been a vital scientific exploration tool for several decades.
- Experiments at SLAC (late 60s) led to the quark-parton model of nucleons, and ultimately to establishing QCD theory.
- Numerous DIS experiments in 70-80s uncovered the momentum and spin distribution of quark constituents of proton and neutron

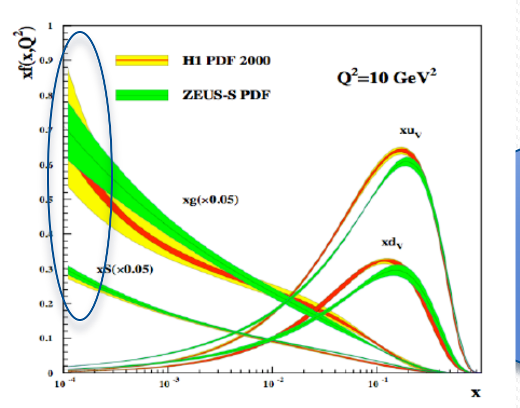
HERA (1991-2007): first electron-proton collider

Higher CME -> reach to the momentum distribution of quark and gluons at very low momentum fraction (x)

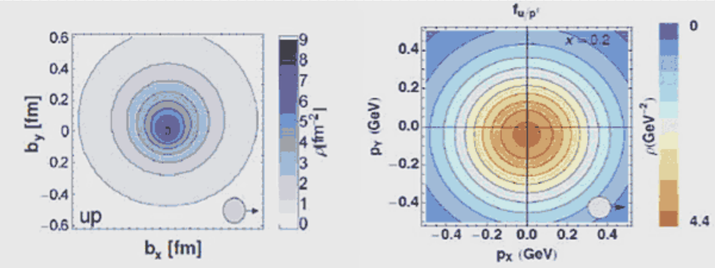
Selection of physics results:

- ➢ **precise data on details of the proton structure**
- ➢ **the discovery of very high density of sea quarks and gluons present in the proton at low-x**
- ➢ **detailed data on electro-weak electron-quark interactions**
- ➢ **precision tests of QCD (α_s measurements)**

Major physics objectives of future electron-ion colliders



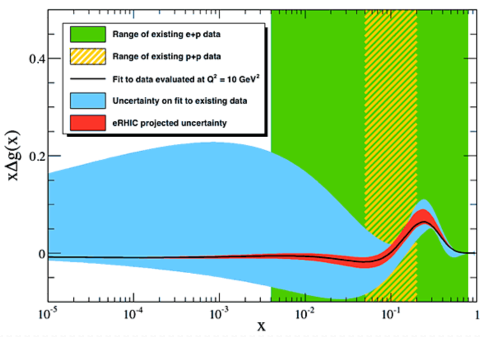
Mapping the gluon content of ions and protons;
High-density gluon state



3-dimensional imaging of the nucleons

Electron-ion colliders

Probing the nucleon's spin structure



Spatial and Momentum Structure of the Nucleus

Searches and the understanding of new physics
(GUT, LQs, Higgs, ….)

From HERA to future colliders

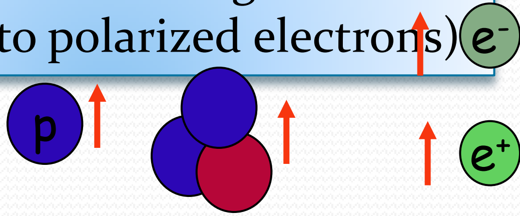
HERA

Polarized e^-,e^+ (27.5 GeV)
Unpolarized protons (920 GeV)
Peak luminosity: $5 \cdot 10^{31}$ cm^{-2} s^{-1}

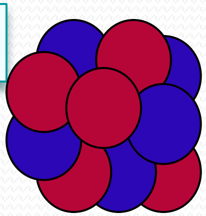
Future colliders

Much higher luminosity:
10^{33}-10^{34} cm^{-2} s^{-1}

Polarized protons and light ions
(in addition to polarized electrons)



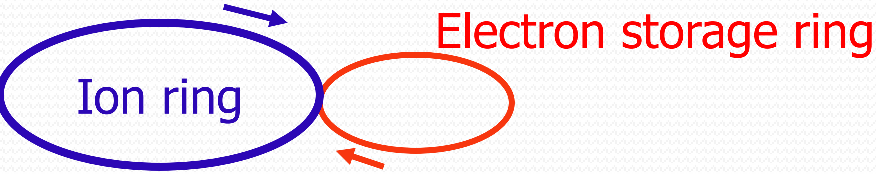
Heavy ion beams



Different (and variable) Center-of-Mass Energy range

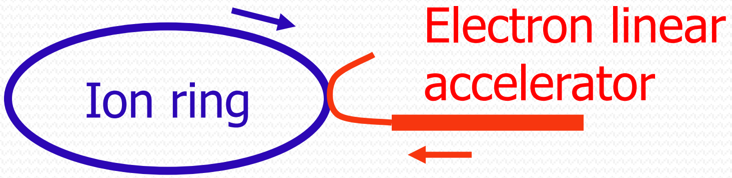
Future collider designs

Ring-ring



	Center of Mass Energy	On the base of
LHeC ring-ring	1.3 TeV	LHC (CERN)
MEIC	15-65 (140) GeV	CEBAF (JLab)
ENC	14 GeV	HESR at FAIR (GSI)

Linac-ring

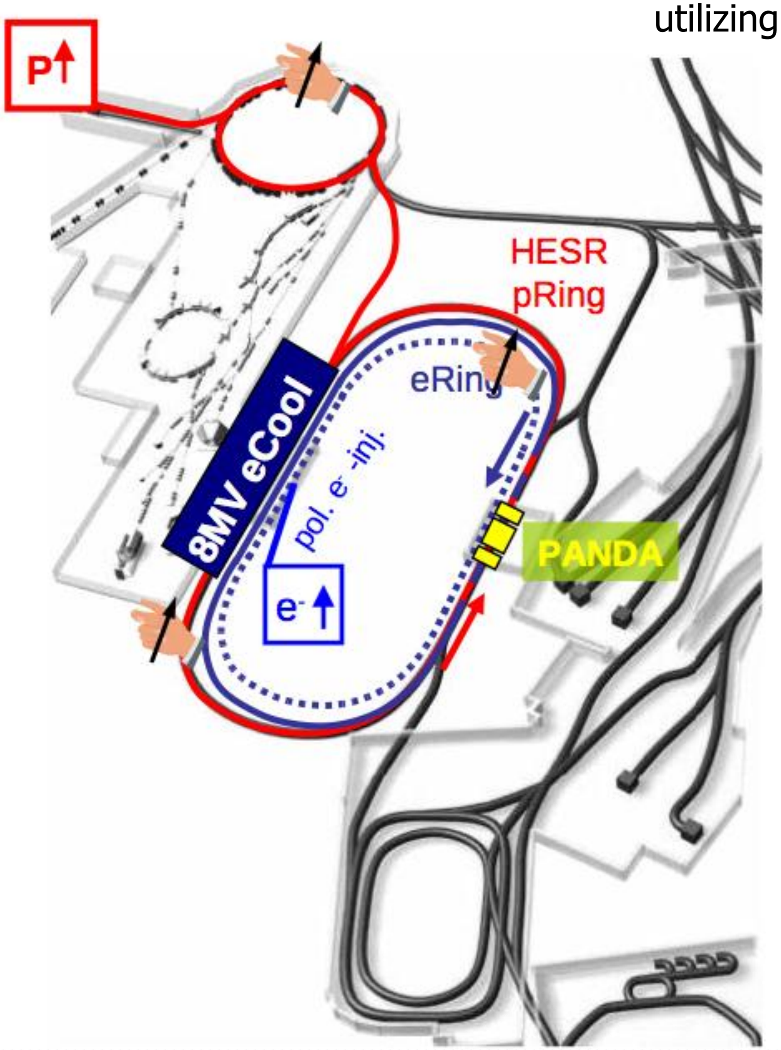


	Center of Mass Energy	On the base of
LHeC linac-ring	1.3 (2) TeV	LHC (CERN)
eRHIC	45-175 GeV	RHIC (BNL)

Energy Recovery Linacs have to be used for high luminosity in CW mode

ENC at HESR at FAIR

Jankowiak A et al. 2009 Concept of a polarized electron-nucleon collider utilizing the HESR storage ring at GSI/FAIR, Proc. of PAC 2009.



- **Idea emerged Aug 2008**
- $\sqrt{s} > 10$ **GeV**
  3.3 GeV/c e^- on 15 GeV/c p
- **polarised** e^- ($> 80\%$)
- **polarised** p, d ($> 80\%$)
  (transversal & longitudinal)
- use as much of PANDA detector as possible
- Common effort of German universities (Bonn, Mainz, Dortmund) in collaboration with Research Centres Jülich, DESY, GSI, . . .

Medium Energy Electron-Ion collider (MEIC) and its upgrade on JLab Site Map

12 GeV CEBAF used as the electron injector

New electron storage ring

New hadron accelerator complex

Figure-8 shaped geometry

Electron 3 to 11 GeV, proton 20 to 100 GeV, ion 12 to 40 GeV/u

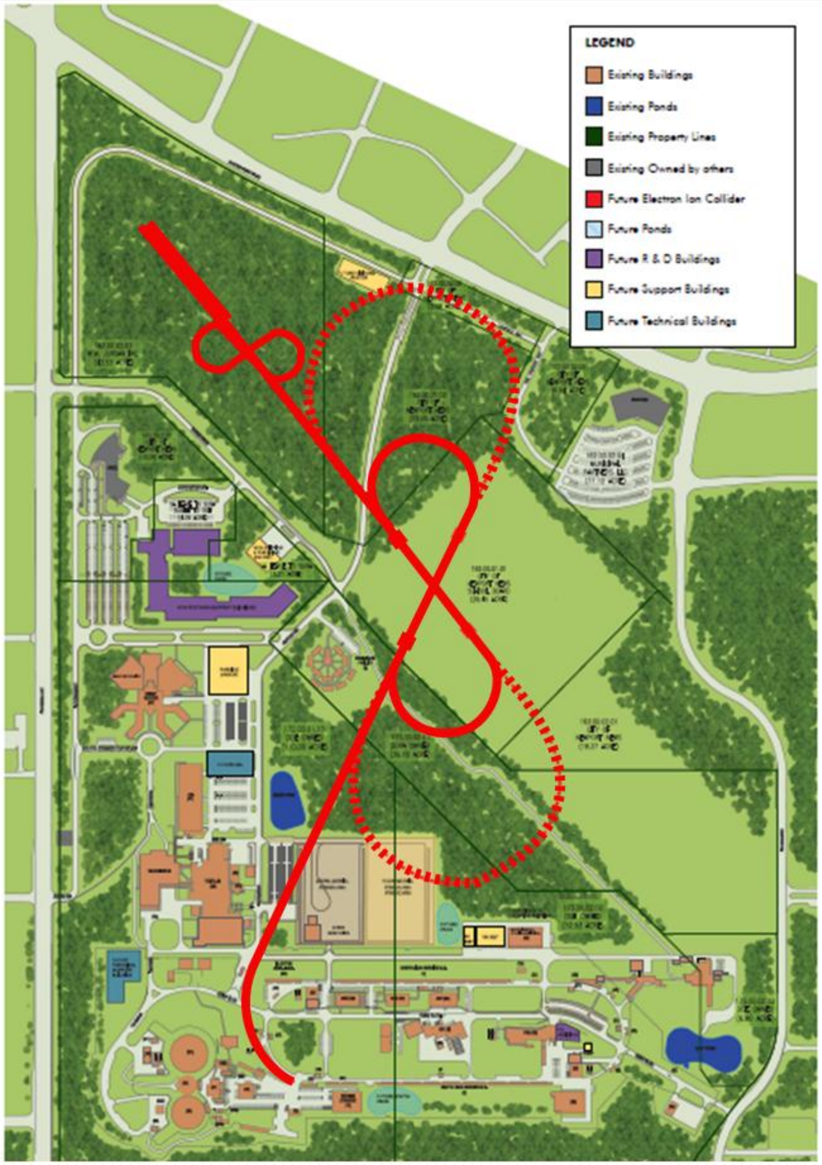
Design point: 60 GeV p on 5 GeV e

Ion species:

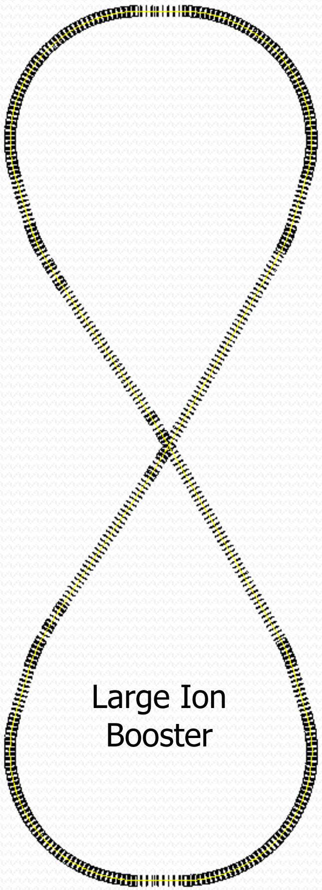
Polarized light ion: p, d, ^{3}He and possibly Li

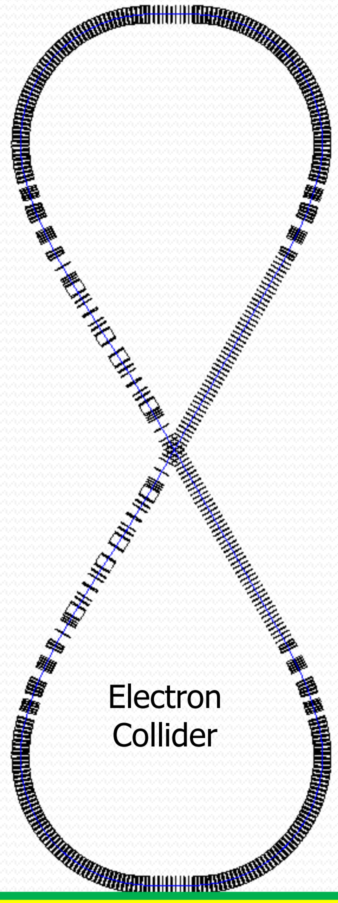
Un-polarized ions up to A=200 or so (Au, Pb)

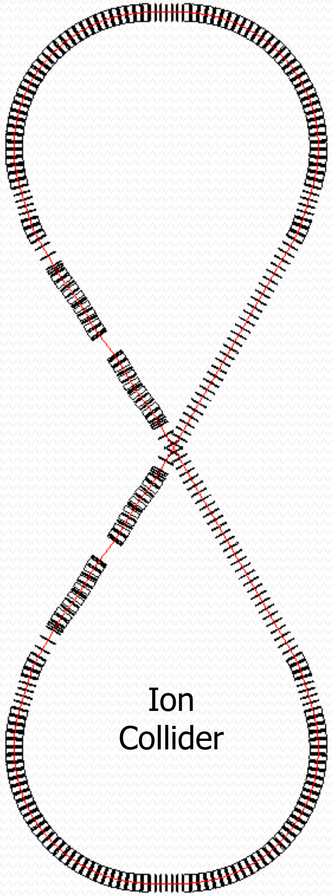
Possible upgrade by addition of the larger Figure 8-shape hadron and electron rings (dashed line). Up to 250 GeV protons and 20 GeV electrons.



MEIC three Figure-8 shape ring structure



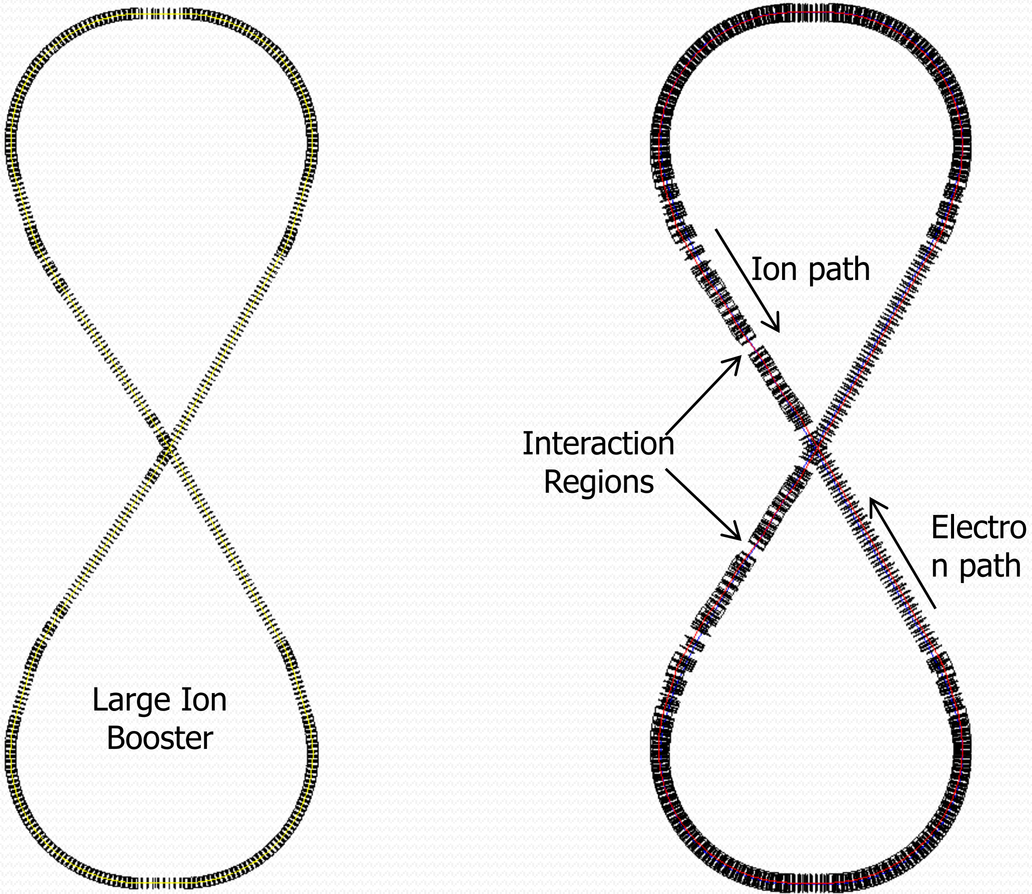




- Vertical stacking for identical ring circumferences
- Horizontal crab crossing at IPs due to flat colliding beams
- Ion beams execute vertical excursion to the plane of the electron orbit for enabling a horizontal crossing

- **Ring circumference: 1340 m**
- **Maximum ring separation: 4 m**
- **Figure-8 crossing angle: 60 deg.**

MEIC three Figure-8 shape ring structure



Interaction point locations:

- **Downstream ends of the electron straight sections to reduce synchrotron radiation background**
- **Upstream ends of the ion straight sections to reduce residual gas scattering background**

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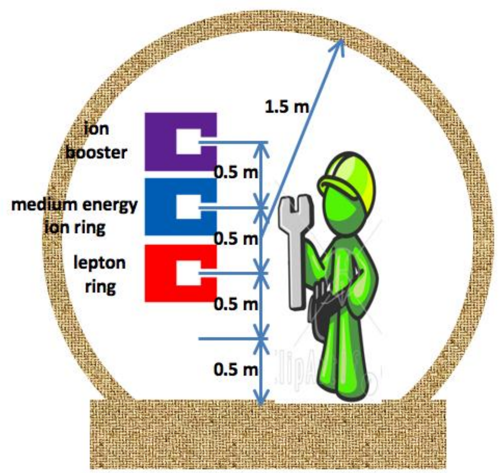

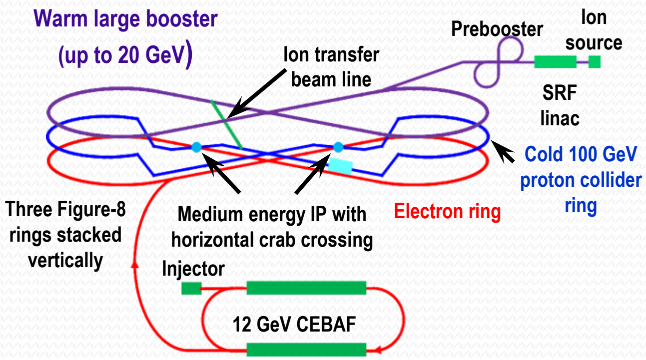

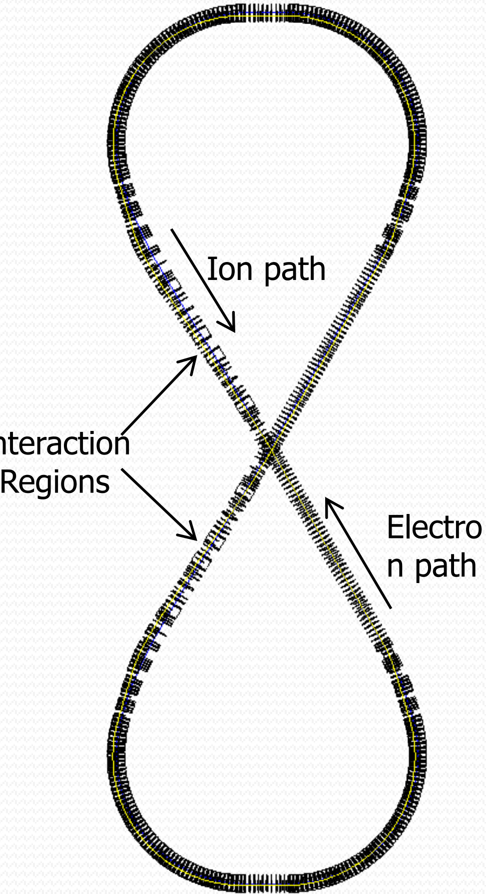

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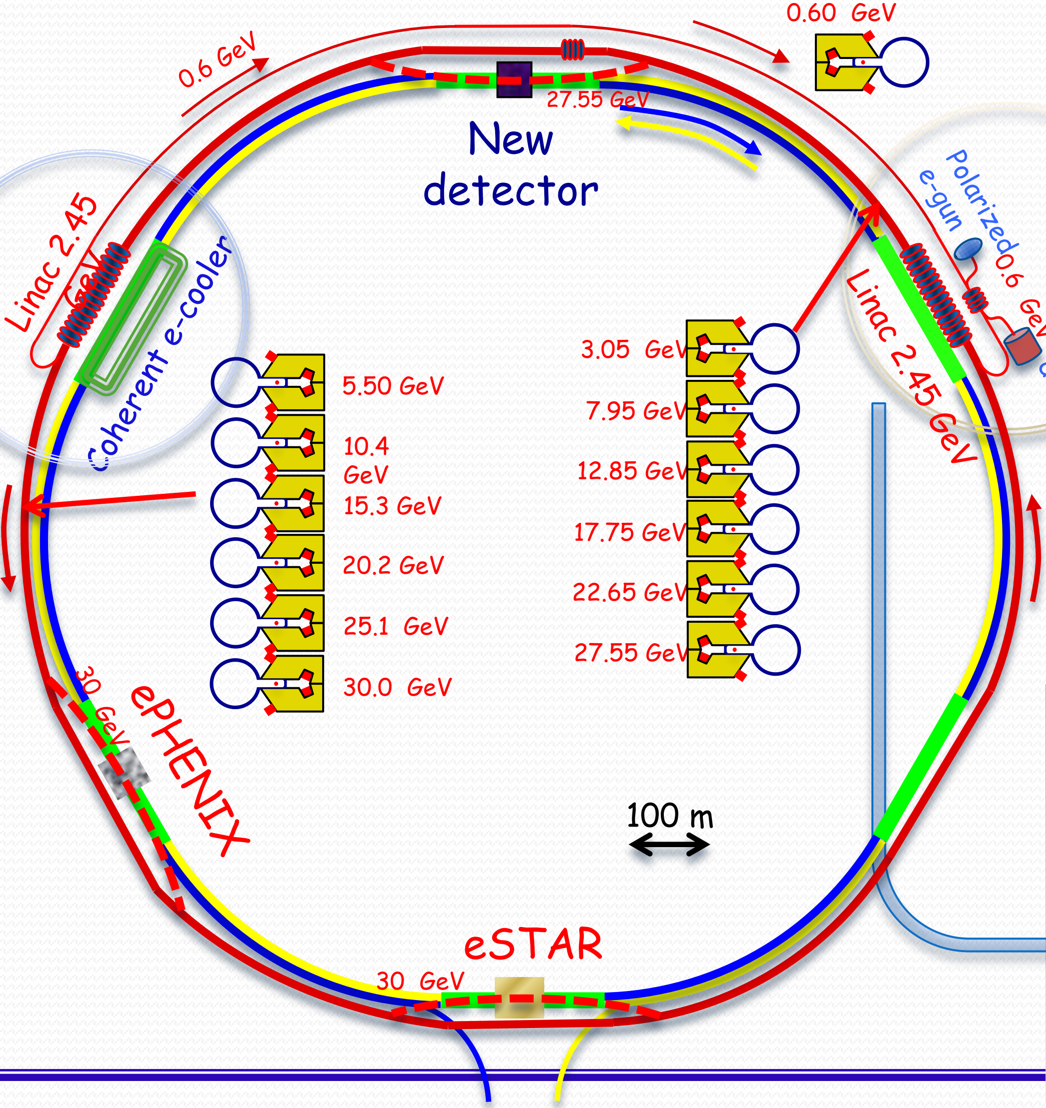
ERL-based eRHIC at BNL



✓Existing RHIC hadron accelerator

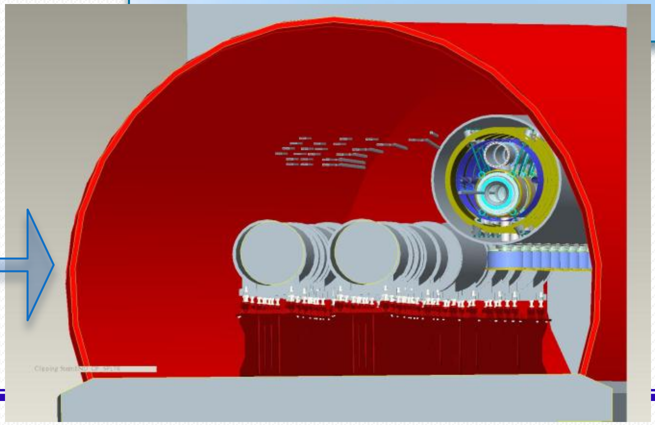
✓New electron accelerator inside the RHIC tunnel:

-injector and 0.6 GeV ERL pre-accelerator

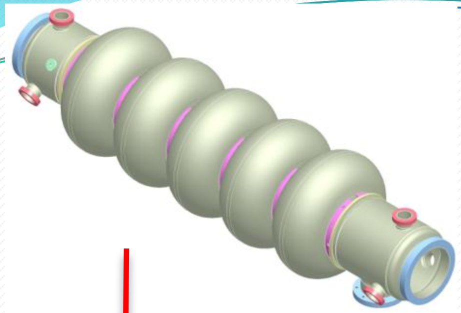
-two 2.45 GeV energy recovery linacs - 6 vertically stacked recirculation passes in the arcs

✓Staging: the electron energy will be increased in stages, from 10 to 30 GeV, by increasing the linac lengths .

✓Up to 3 experimental locations

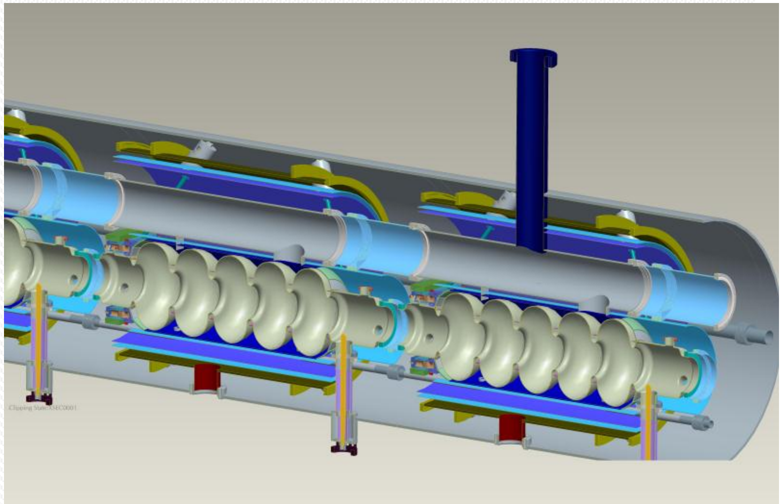


eRHIC SRF Linac

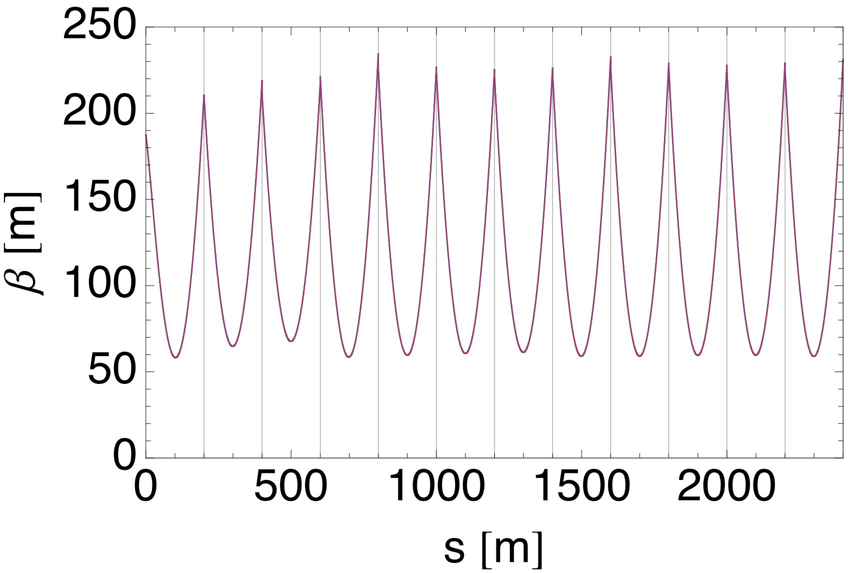


- ✓ **Based on BNL 704 MHz SRF cavity with fully suppressed HOMs**
- ✓ **This is critical for high current multi-pass ERL**
- ✓ **eRHIC cavity & cryostat designs are still evolving**

Total linac length -> 200 m
Two warm-to-cold transition only at the ends
Maximum energy gain per pass -> 2.45 GeV
Accelerating gradient – 19.2 MV/m

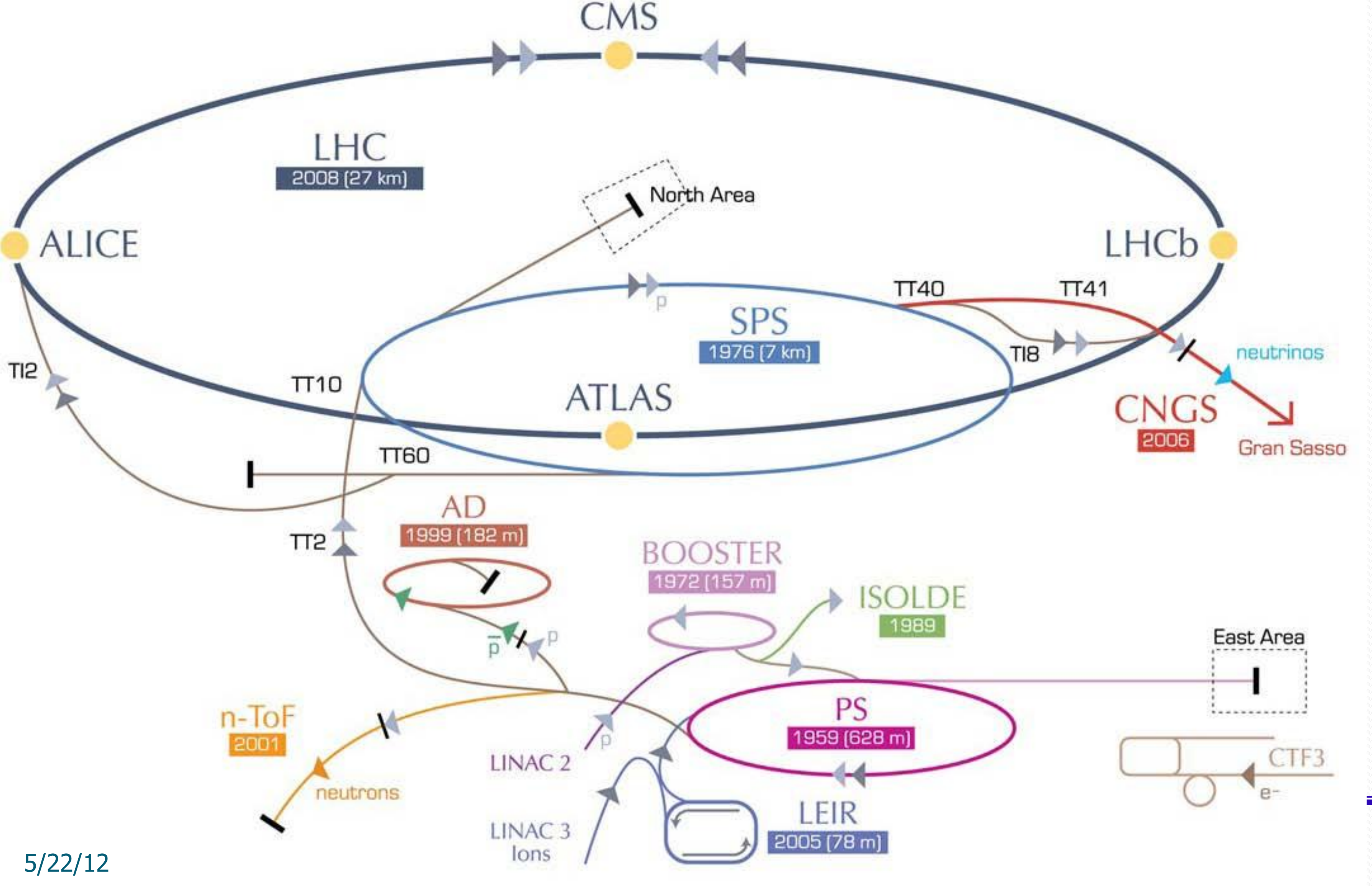


Injection → **E max**



Large Hadron electron Collider

Two design options of the 60 GeV electron accelerator have been developed in parallel: ring-ring (RR) and linac-ring(LR).



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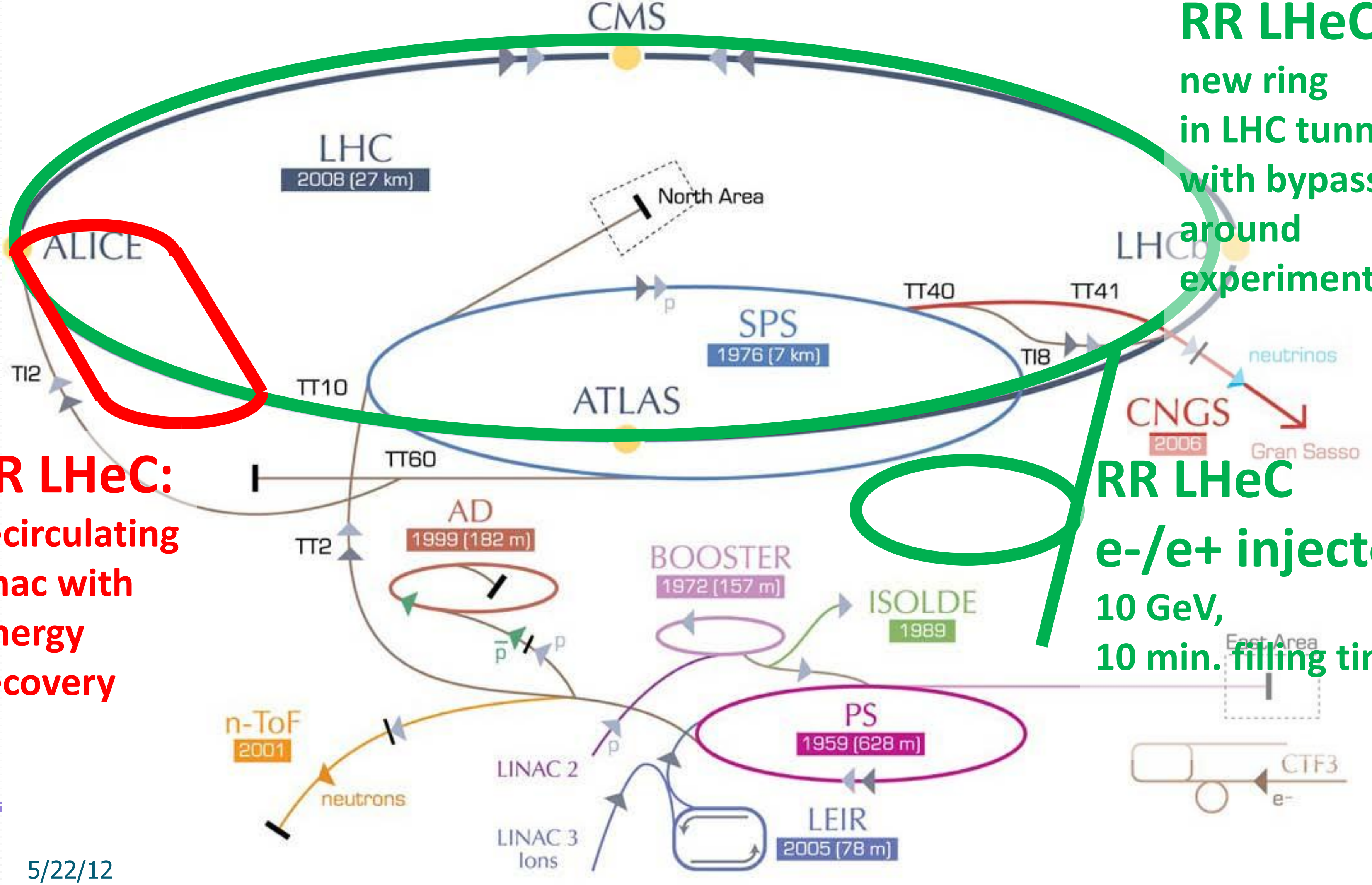


RR LHeC:

new ring in LHC tunnel, with bypasses around experiments

LR LHeC:

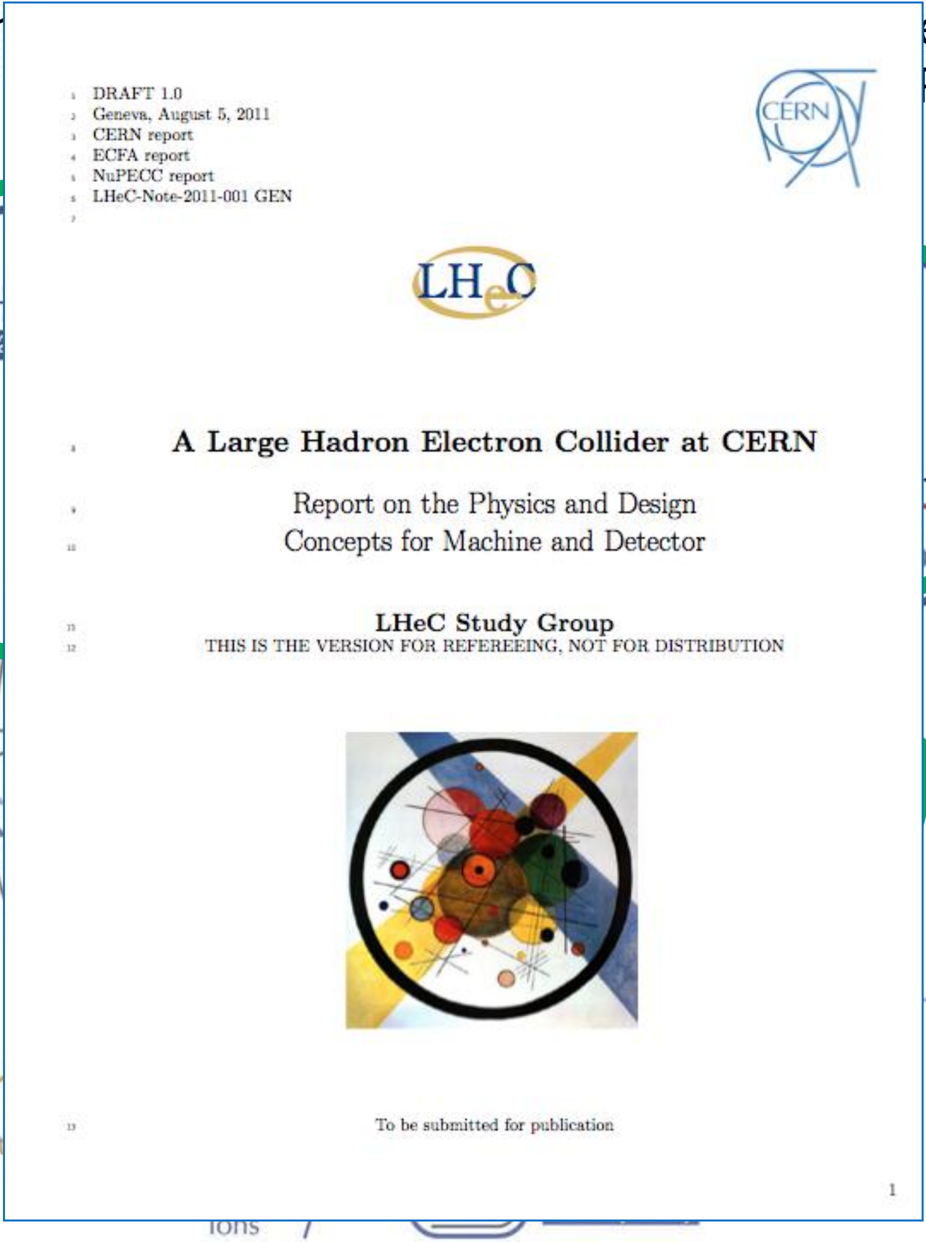
recirculating linac with energy recovery

RR LHeC e-/e+ injector

10 GeV, 10 min. filling time

Large Hadron electron Collider

Two design options of th eveloped in parallel:
R).



DRAFT 1.0
Geneva, August 5, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-001 GEN

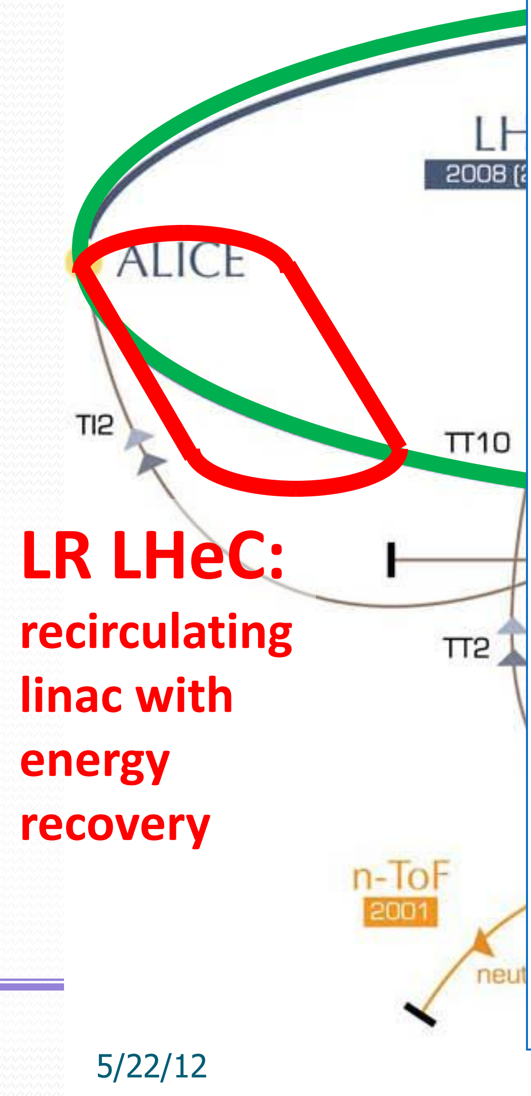
A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group
THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

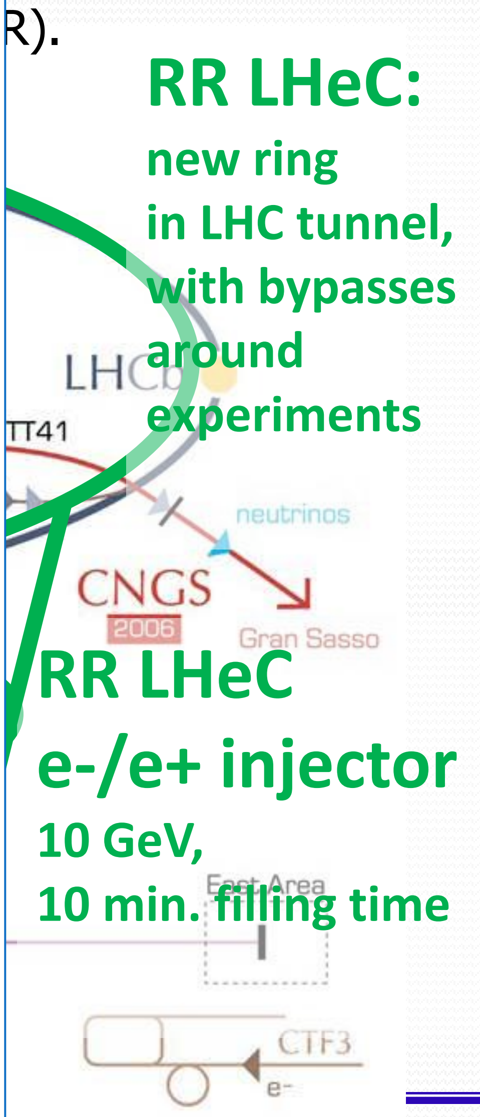
To be submitted for publication

1



LR LHeC:

recirculating linac with energy recovery



RR LHeC:

new ring in LHC tunnel, with bypasses around experiments

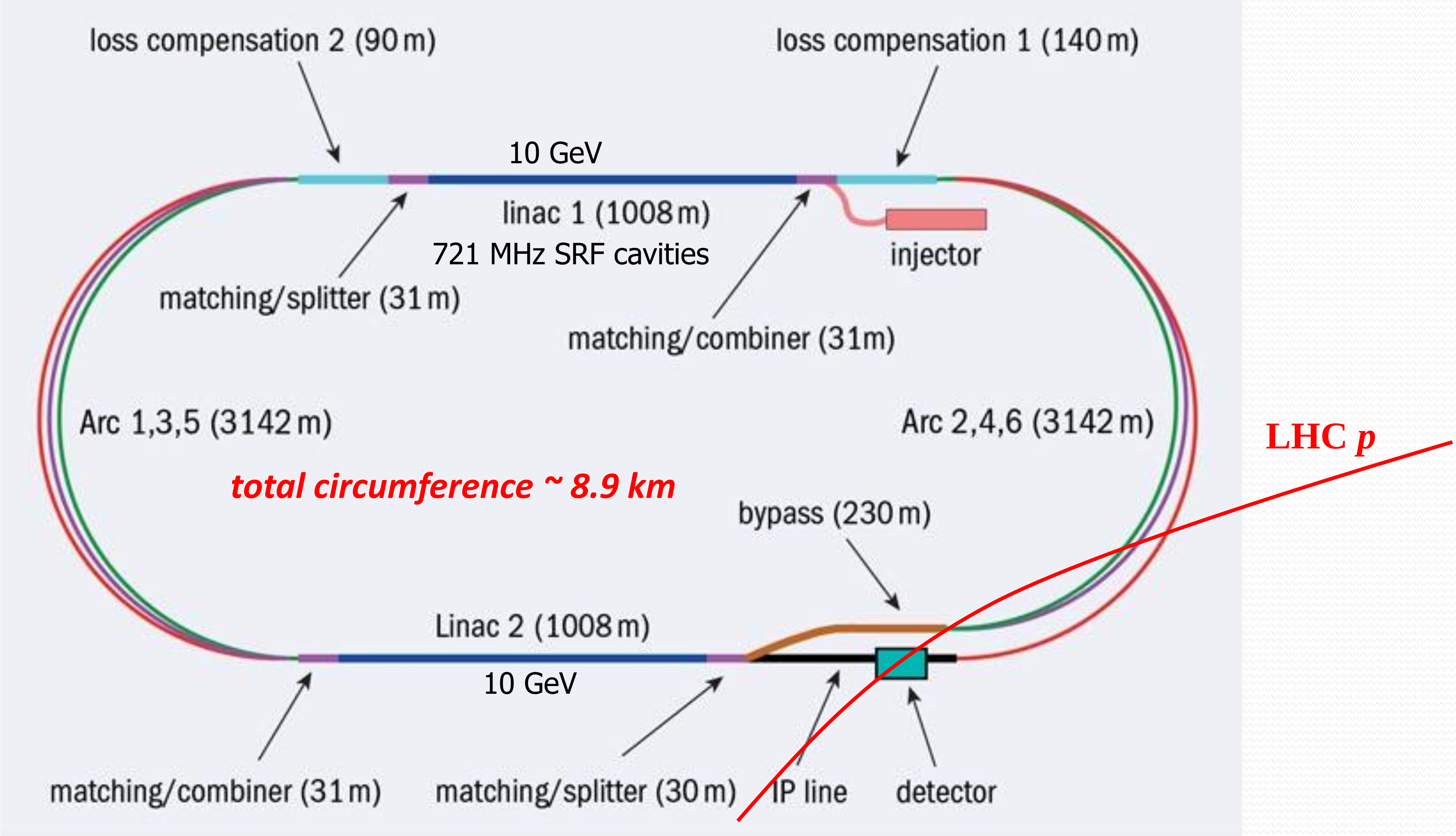
RR LHeC

e-/e+ injector

10 GeV,

10 min. filling time

LHeC ERL configuration



total circumference ~ 8.9 km

Beam parameters for highest luminosity e-p design

	HERA		ENC		MEIC		eRHIC		LHeC linac-ring		LHeC ring-ring	
	p	*e*	*p*	*e*	*p*	*e*	*p*	*e*	*p*	*e*	*p*	*e*
Energy, GeV	920	27.5	15	3	60	5	250	20	7000	60	7000	60
Bunch frequency, MHz	10.4		52 (104)		750		14.1		20		40	
Bunch intensity, 10^{11}	0.72	0.29	0.54(0.36)	2.3	0.042	0.25	2	0.22	1.7	0.02	1.7	0.2
Beam current, mA	100	40	450 (600)	1900	500	3000	420	50	430	6.4	860	100
Normalised rms emittance,x/y,µm	5	1100/ 180	2.3/ 0.8	930/ 320	0.35/ 0.07	54/11	0.18	26.4	3.75	50	3.75	580/ 290
β*, x/y, cm	245/18	63/26	30 (10)	30	4/0.8	4/0.8	5	5	10	12	180/50	18/10
Beam size at IP, x/y, µm	112/30		200/120		15/3		6/6		7/7		30/16	
Bunch length, cm	19	1	30 (20)	10	1	0.75	8	0.2	8	0.03	8	1
Polarization, %	0	45	80	80	>70	80	70	80	0	90	0	40
Peak Luminosity, 10^{33} cm^{-2}s^{-1}	0.04		0.2 (0.6)		14.2		9.7		1.0		1.7	

Beam parameters for highest luminosity e-p design

	HERA		**ENC**		**MEIC**		**eRHIC**		**LHeC linac-ring**		**LHeC ring-ring**	
	p	*e*	*p*	*e*	*p*	*e*	*p*	*e*	*p*	*e*	*p*	*e*
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	HERA	**ENC**	**MEIC**	**eRHIC**	**LHeC LR**	**LHeC RR**
$(\sigma_x\sigma_y)_{HERA}/(\sigma_x\sigma_y)$	1	0.13	77	100	67	7

Beam size at IP, x/y, μm	112/30		200/120		15/3		6/6		7/7		30/16	
Bunch length, cm	19	1	30 (20)	10	1	0.75	8	0.2	**8**	0.03	**8**	1
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Accelerator technology for EICs

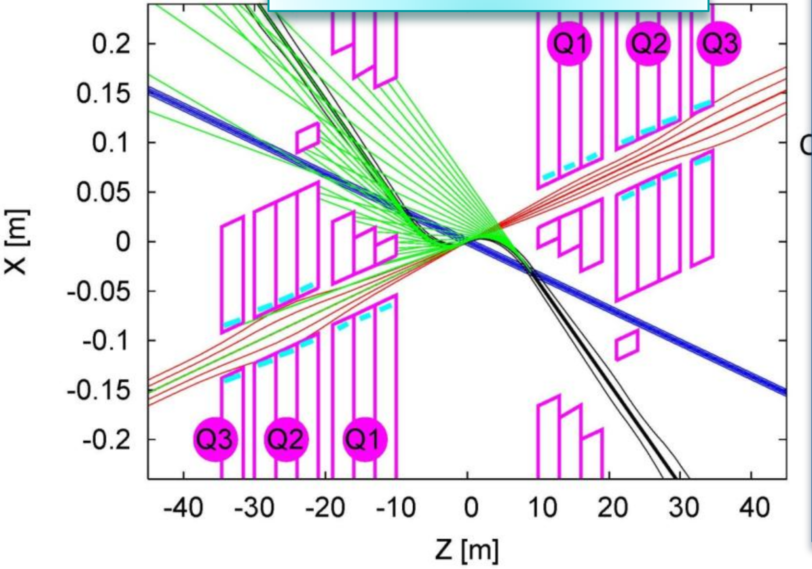
- Cooling of hadron beams; Electron cooling, Coherent electron cooling; (eRHIC; MEIC; ENC)
- Low hadron β^* interaction region (all designs)
- High beam power ERL; high beam current SRF cavities (linac-ring designs)
- Crab-crossing; (eRHIC; MEIC)
- Beam polarization:
  - Preserving e-beam polarization (LHeC RR; MEIC)
  - High current polarized e-source (eRHIC; LHeC LR)
  - Figure-8 design (MEIC)
- Techniques for intense e^+ beam (LHeC LR)

IR design

Using HERA and B-factories experience to resolve IR design issues:

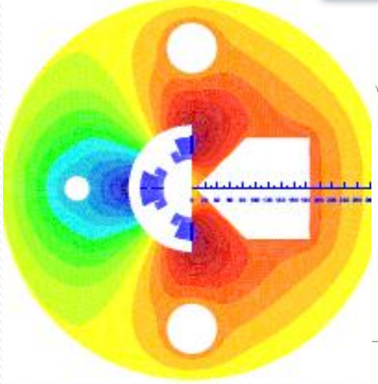
- ➢Strong beam focusing
- ➢Fast separation *(avoiding parasitic beam-beam)*
- ➢Managing synchrotron radiation fan *(absorbers, masks; precise orbit control; protection of SC magnets)*
- ➢Detector integration (*Large acceptance; Large magnet apertures for propagation of the collision products*)
- ➢Correction of chromatic effects

LHeC linac-ring IR

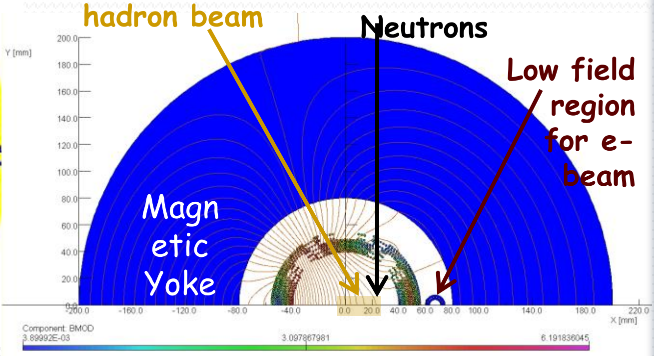


IR magnet designs

LHeC Q1

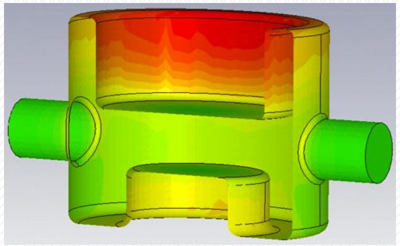


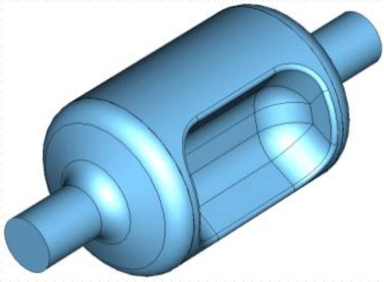
eRHIC Q1



SRF crab-cavities

QWR design (BNL)
181 MHz; 6 MV



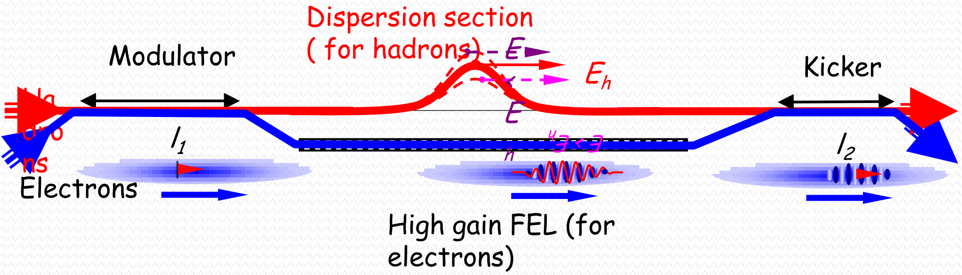


Trapezoidal cavity (ODU/JLab)
750 MHz; 0.2 MV

High Energy Cooling

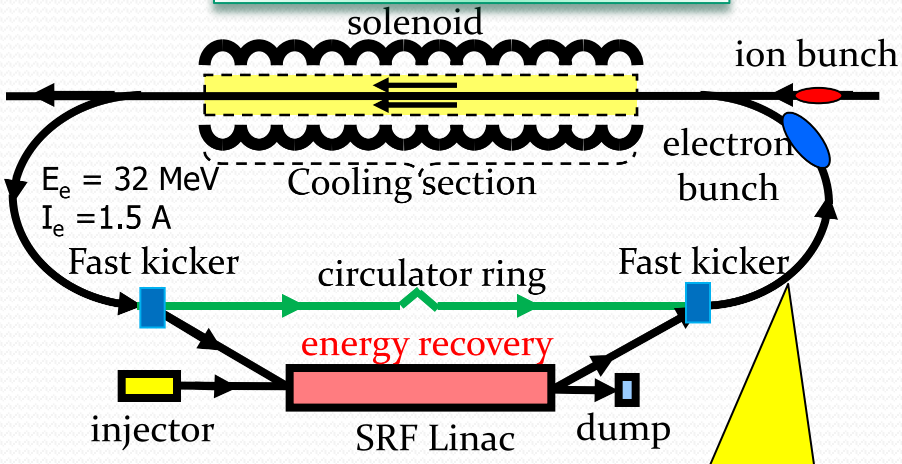
R&D is pursued by BNL and Jefferson Lab

BNL: Coherent Electron Cooling



- PoP experiment in RHIC by the collaboration: BNL, JLab, Tech-X
- Funded by DOE NP Office of Science
- Projected dates: 2014-2016
- Aim : demonstration of longitudinal cooling of 40 GeV/u Au ion beam

JLab: Electron Cooling



Electron bunches circulate 10 to 100 times

Test facility is considered at JLab FEL ERL :

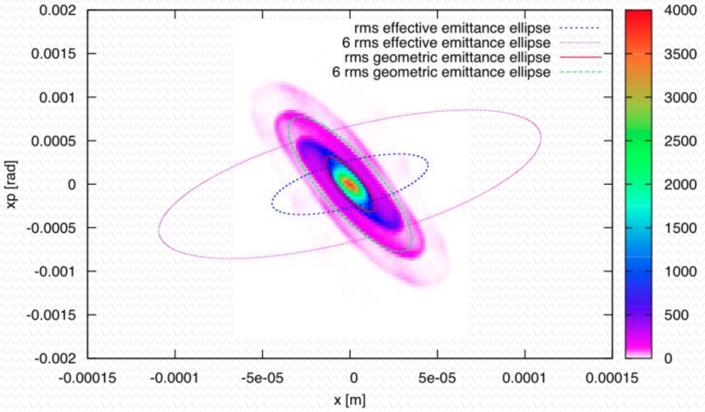
- Beam quality lifetime of a bunch in the circulator ring.
- Feasibility of magnetized electron gun.
- Fast kickers.
- Beam dynamics of an ERL with recirculation
- Proposed completion date: 2015

Asymmetric design issues

➢Matching beam cross sections at the IP for different collision energies.
variable electron β^* and/or emittance; the lattice and the electron gun

➢Matching electron and hadron bunch frequencies at various hadron energies.
Hadron revolution frequency varies with the energy.
Electron or hadron circumference lengthening; RF harmonic switching; appropriate tuning range of SRF cavities

➢Beam-beam effects in the linac-ring scheme.
LR scheme allows for more intense beam-beam interaction -> the luminosity gain


eRHIC e-beam disruption simulations; D=140

Specific effects of LR scheme:
- •Electron beam disruption
- •Kink instability of the hadron beam
- •Effect of electron beam parameter fluctuations on hadrons

IPAC posters:

LHeC:

TUPPR076: The LHeC Project Development Beyond 2012, O. Bruning et al.
TUPPC036 Integration with the LHC of Electron Interaction Region Optics for a RR LHeC, H. Burkhardt, et al.
TUPPC037 Update on LHeC Ring-Ring Optics, H. Burkhardt, et al.
TUPPC038 Interaction Region Optics for the Non-Interacting LHC Proton Beam at the LHeC, O. Bruning et al.
TUPPC039 Synchrotron Radiation Studies for a Ring-Ring LHeC IR and Long Straight Section, O. Bruning et al.
TUPPR075: Challenges for the Magnet System of LHeC, S. Russenschuck et al.
TUPPR023: Final-Focus Optics for the LHeC Electron Beam Line, J.L. Abelleira et al.
WEPPR076: Positron Options for the Linac-Ring LHeC, F. Zimmermann et al.

MEIC:

TUPPR082 MEIC Design Progress, Y. Zhang, et al.
MOEPPB006 Formation of Beams in the Ion Accelerator Complex of the MEIC, B. Erdelyi, et al.
TUPPR081 A Test Facility for MEIC ERL-Circulator-Ring Based Electron Cooler, Y. Zhang, et al.
THPPP027 The Design of a Large Booster Ring for the Medium Energy Electron-Ion Collider, E. Nissen, et al.
TUPPC098 Electron Polarization in the Medium-Energy Electron-Ion Collider at JLAB, F. Lin, et al.
TUPPR079 Ion Polarization in the MEIC Figure-8 Ion Collider Ring, V. Morozov, et al.
TUPPR080 Integration of Detector into Interaction Region at MEIC, V. Morozov, et al.
TUPPC099 Optimization of Chromaticity Compensation and Dynamic Aperture in MEIC, F. Lin, et al.
WEPPC100 Design of Electron and Ion Crabbing Cavities for an Electron-Ion Collider, A. Castilla, et al.

eRHIC:

MOEPPB007 Studies of eRHIC Coherent Instabilities, G.Wang
MOPPC052 Calculation of Synchrotron Radiation from High Intensity Electron Beam at eRHIC, Y. Jing, et al.
TUEPPB005 Novel Technique of Suppressing TBBU in High-energy ERLs, V. Litvinenko
TUPPP088 Bunch Compressor Design for Potential FEL Operation at eRHIC. Y. Jing, et al.
TUPPR084 HOM Damping and Multipacting Analysis of the Quarter-wave Crab Cavity, Q.Wu
TUPPR083 Kink Instability Suppression with Stochastic Cooling Pickup and Kicker, Y. Hao, et al.
WEPPC109 SRF system for eRHIC, S. Belomestnykh et al.
WEPPC113 Progress on High-Current 704 MHz SRF cavities at BNL, W. Xu, et al.
WEPPR017 Wake Fields Effects for the eRHIC Project, A. Fedotov, et al.

Summary

- Several designs of the electron-hadron colliders are under development, eRHIC at BNL, MEIC at Jlab, LHeC at CERN and ENC at GSI.

- Novel accelerator technologies are applied in the accelerator designs to achieve considerably higher luminosities than in HERA.

- At the end the cost and the importance of the physics that can be explored at a particular collider will be important factors for a success of one or another design.

Acknowledgements to I. Ben-Zvi, S. Belomestnykh, O. Bruning, Y. Hao, A. Lehrach, V.N. Litvinenko, T. Roser, B. Parker, I. Pinayev, D. Trbojevic, F. Zimmermann, Y. Zhang.