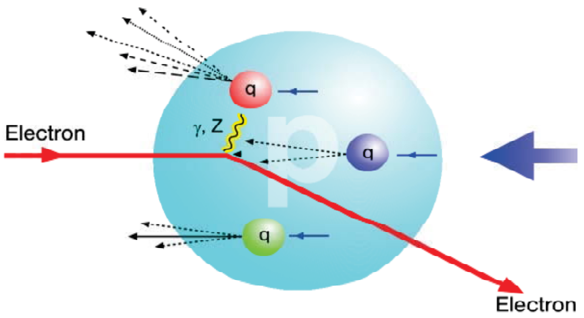
ERL-BASED ELECTRON-ION COLLIDERS

Vadim Ptitsyn
Collider-Accelerator Department
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)**

From HERA to future colliders

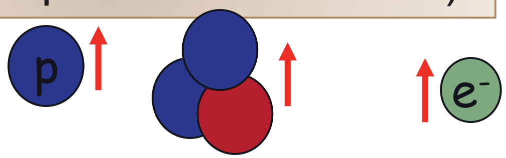
HERA

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

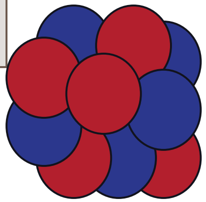
Future colliders

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

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



Heavy ion beams

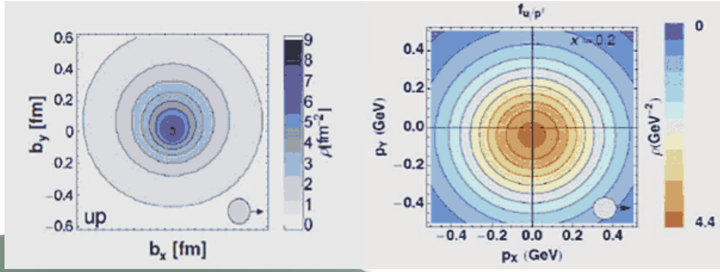


Different (and variable) Center-of-Mass Energy range

Major physics objectives of future electron-ion colliders

Electron-ion colliders

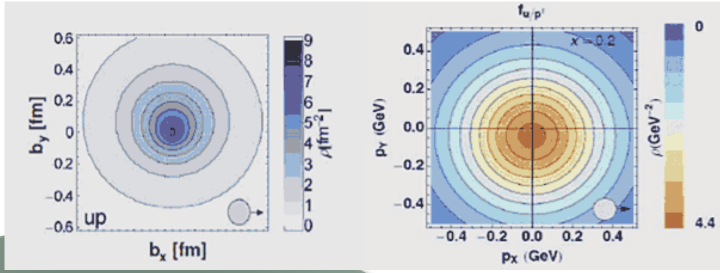
Major physics objectives of future electron-ion colliders



3-dimensional imaging of the nucleons

Electron-ion colliders

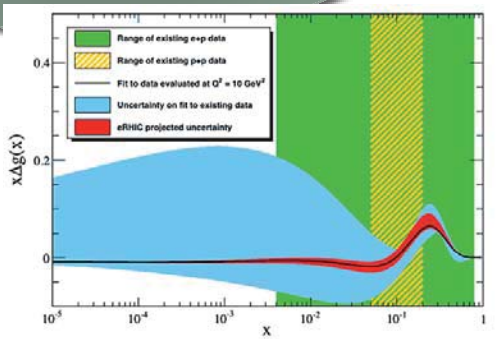
Major physics objectives of future electron-ion colliders



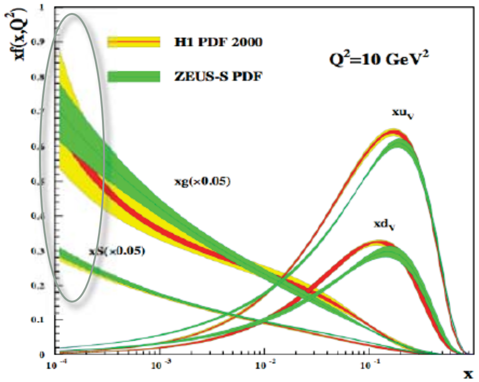
3-dimensional imaging of the nucleons

Electron-ion colliders

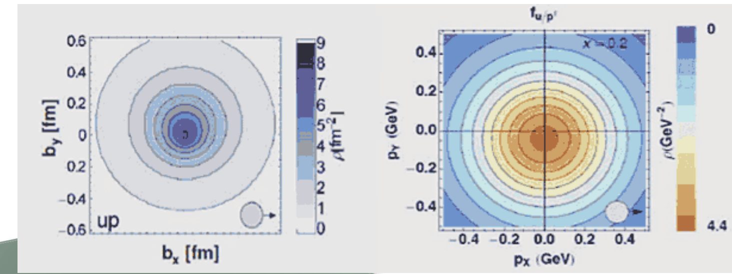
Probing the nucleon's spin structure



Major physics objectives of future electron-ion colliders



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



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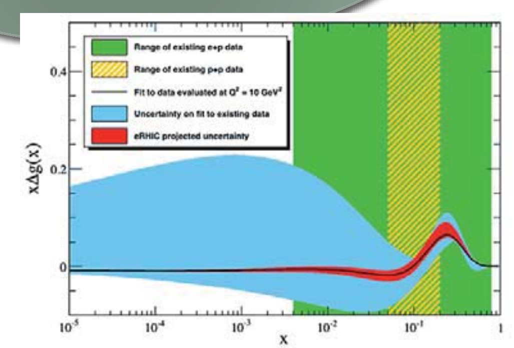

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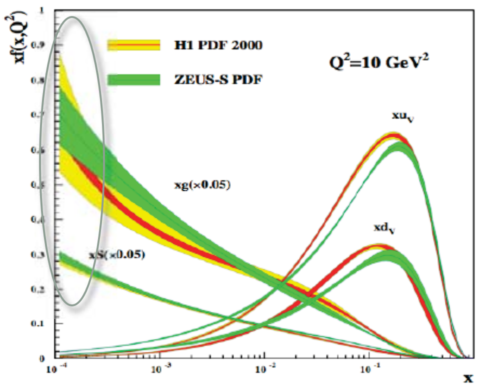
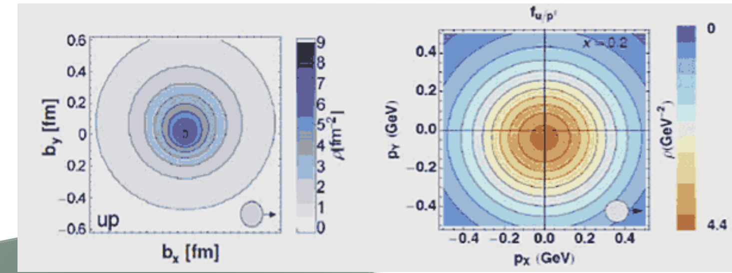




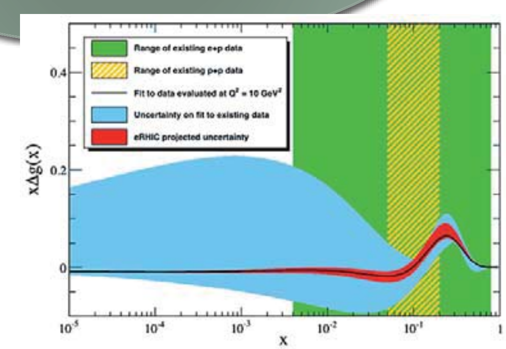
Mapping the gluon content of ions and protons; High-density gluon state

3-dimensional imaging of the nucleons

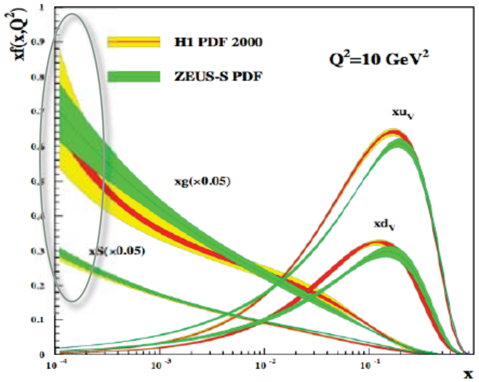
Electron-ion colliders

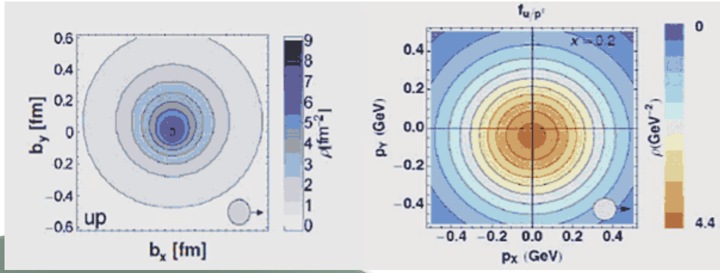
Spatial and Momentum Structure of the Nucleus

Probing the nucleon's spin structure



Major physics objectives of future electron-ion colliders





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

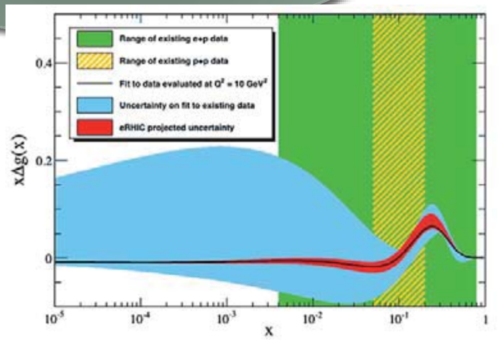
3-dimensional imaging of the nucleons

Electron-ion colliders

Spatial and Momentum Structure of the Nucleus

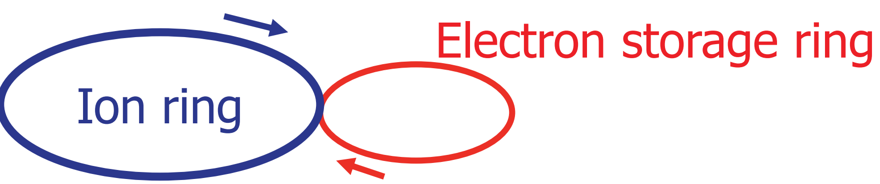
Probing the nucleon's spin structure

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



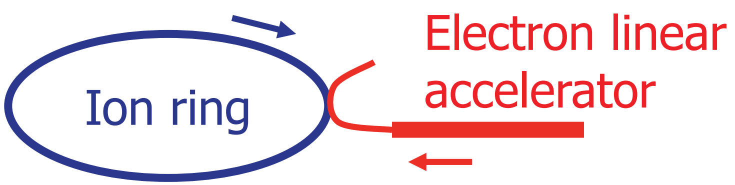
Electron-Hadron Collider Designs

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)
e-HIAF	12 GeV	HIAF (IMP)

Linac-ring ERL-based

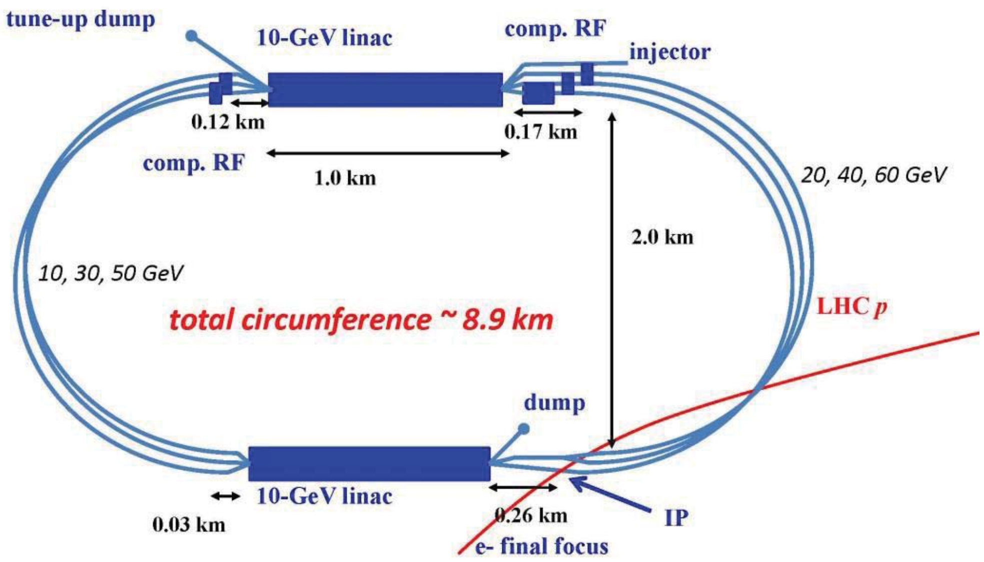


	Center of Mass Energy	On the base of
LHeC linac-ring	1.3 (2) TeV	LHC (CERN)
eRHIC	20-145 GeV	RHIC (BNL)

-Overcoming the electron beam-beam limit
-Spin transparency
Energy Recovery Linacs have to be used for high luminosity in CW mode

Large Hadron electron Collider at CERN

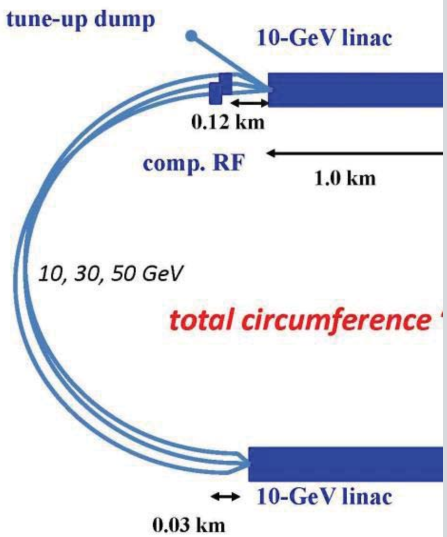
60 GeV (e) x 7 TeV (p)

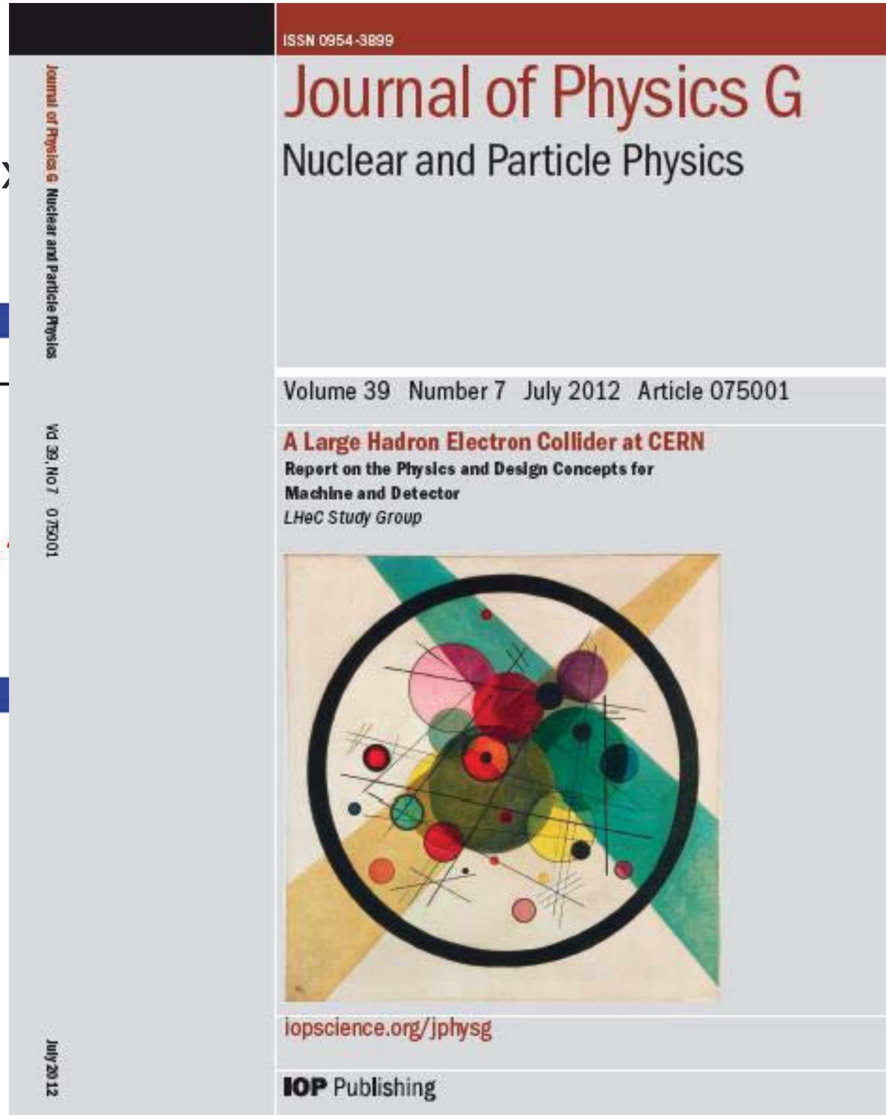


- Protons/ions from LHC
- 0.5 Gev injector
- A pair of SCRF linacs with energy gain 10 GeV per pass
- Six 180° arcs, each arc 1 km radius
- Re-accelerating stations to compensate energy lost by SR
- Switching stations at the beginning and end of each linac
- Matching optics
- Extraction dump at 0.5 GeV

Large Hadron electron Collider at

60 GeV (e) x





ns from LHC

jector

CRF linacs with energy
eV per pass

rcs, each arc 1 km radius

rating stations to
te energy lost by SR

stations at the beginning
each linac

optics

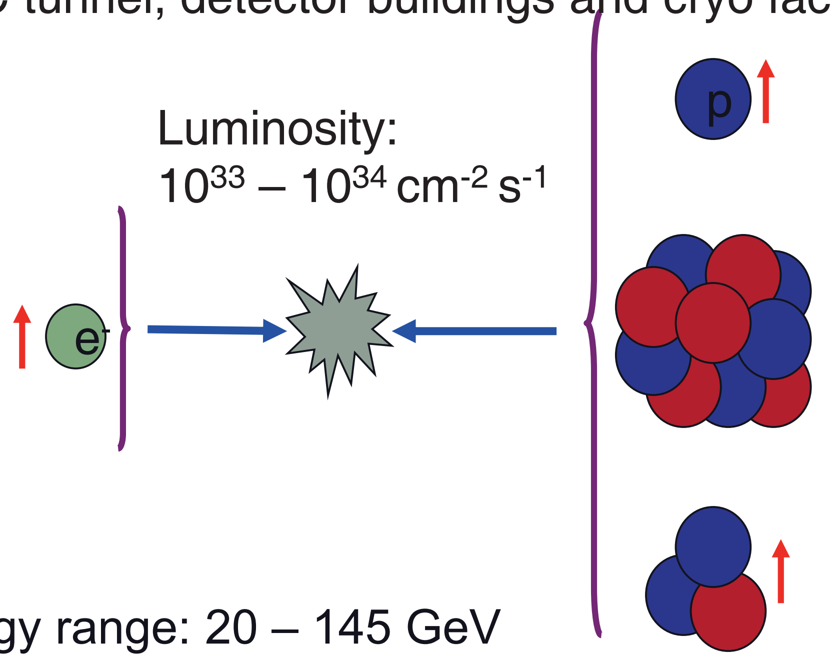
dump at 0.5 GeV

eRHIC at BNL

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

80% polarized electrons: 1.3 – 21.2 GeV

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

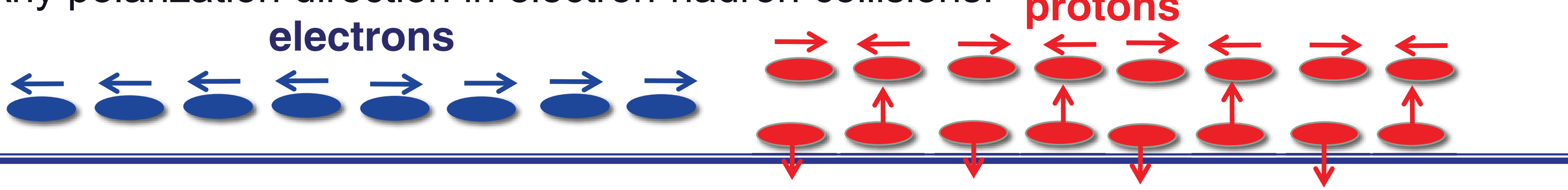


70% polarized protons
25 - 250 (275*) GeV

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

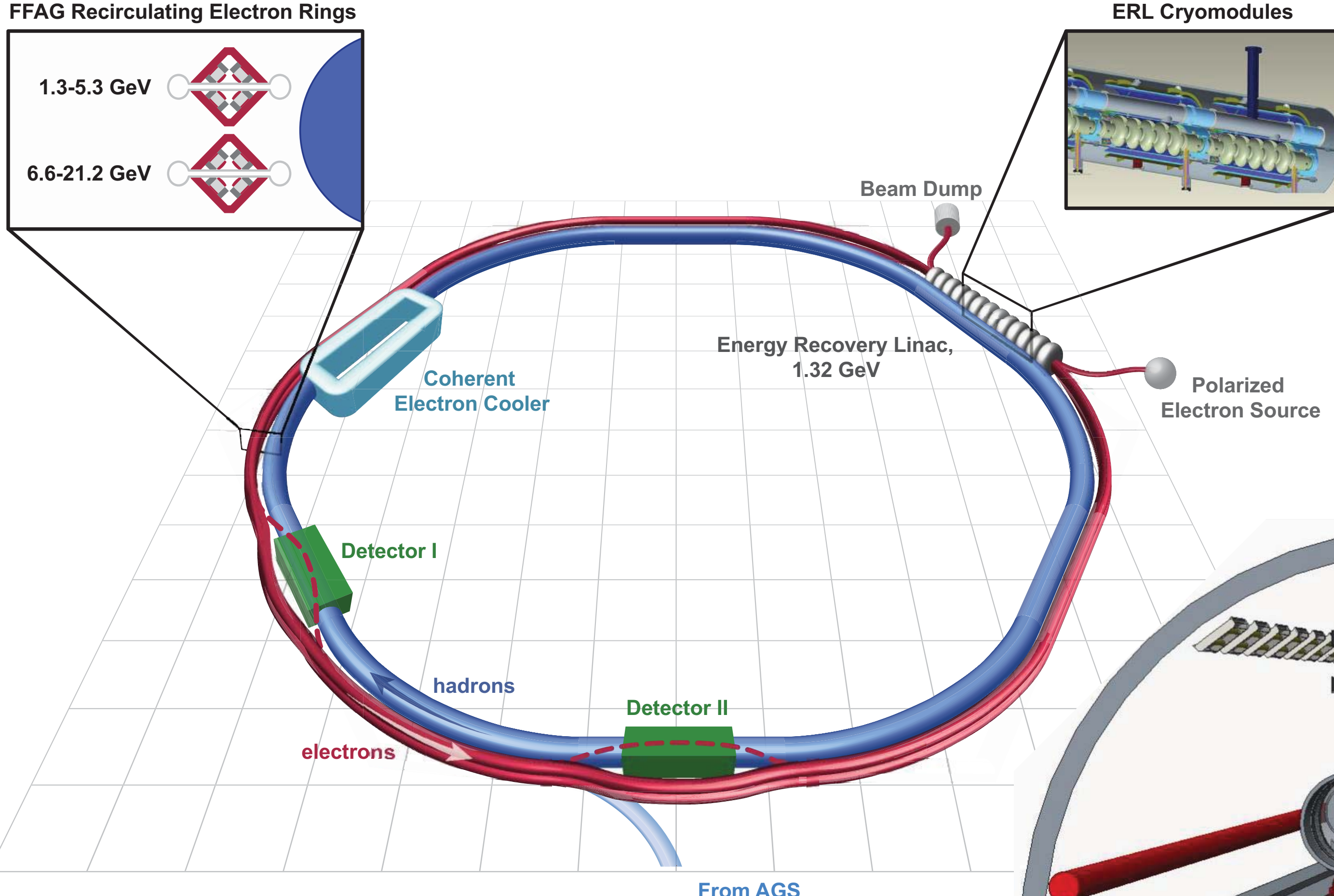
Pol. light ions (He-3)
17 - 167 (184*) GeV/u

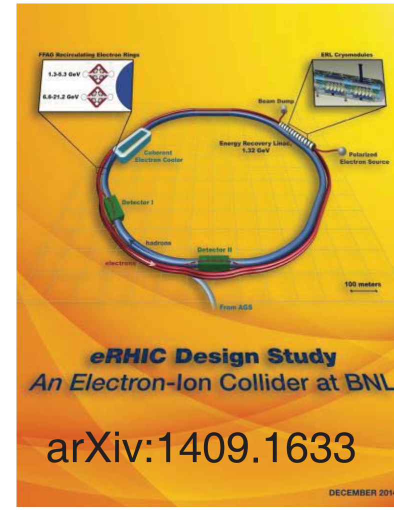
- Center-of-mass energy range: 20 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:

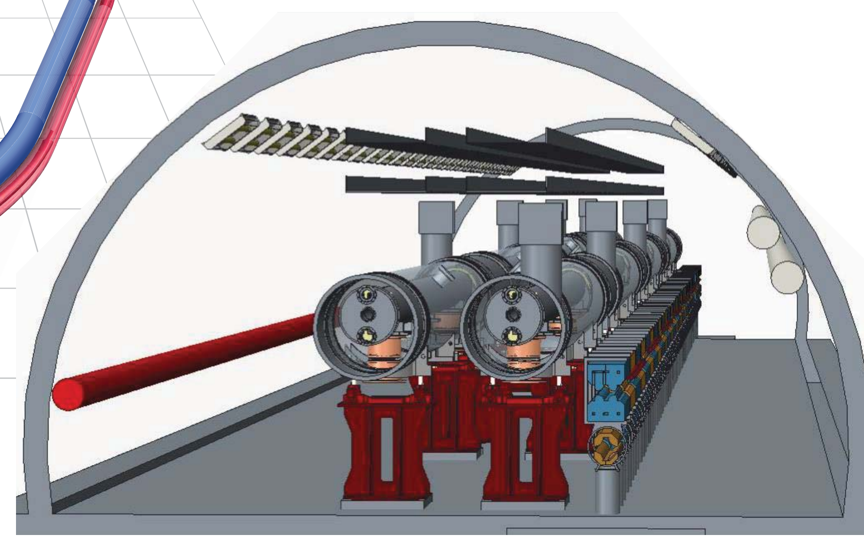


* It is possible to increase RHIC ring energy by 10%

ERL-based eRHIC





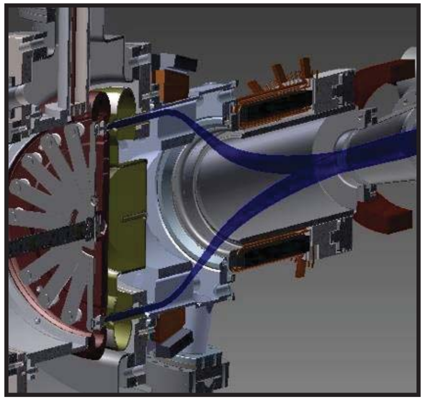


Novel FFAG lattice allows 16 beam re-circulations using only two beam transport loops

Parameter Table

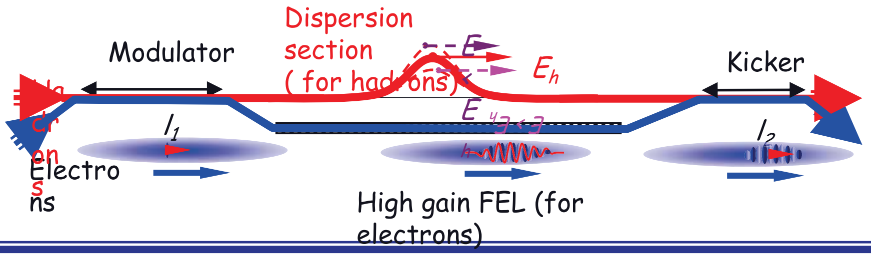
Parameters	eRHIC		LHeC	
	e	p	e	p
Energy (GeV)	15.9	250	60	7000
Bunch spacing (ns)	106		25	
Intensity, 10^{11}	0.07	3.0	0.01	1.7
Current (mA)	10	415	6.4	860
rms norm. emit. (mm-mrad)	23	0.2	50	3.75
$\beta_{x/y}^{*}$ (cm)	5	5	12	10
rms bunch length (cm)	0.4	5	0.06	7.6
IP rms spot size (μ m)	6.1		7.2	
Beam-beam parameter		0.004		0.0001
Disruption parameter	36		6	
Polarization, %	80	70	90	None
Luminosity, $10^{33} cm^{-2} s^{-1}$	3.3		1.3	

Technological challenges

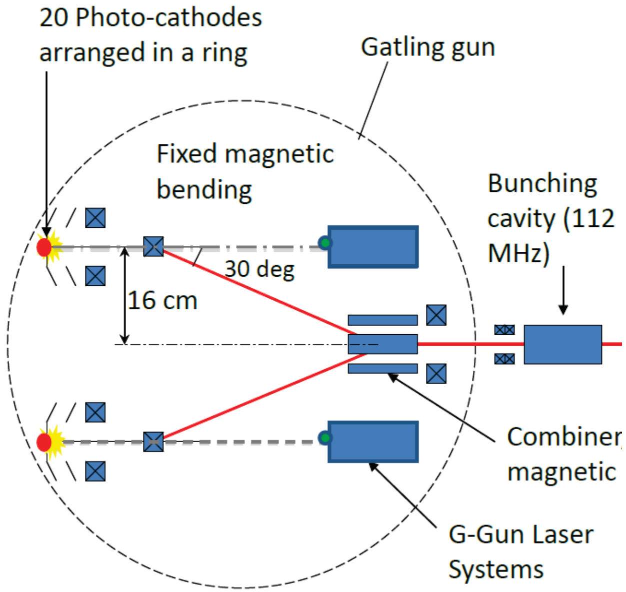


- High intensity (6 – 50 mA) polarized electron source
- High power ERL with multiple re-circulations (high current SRF cavities, machine protection, MBBU, …)

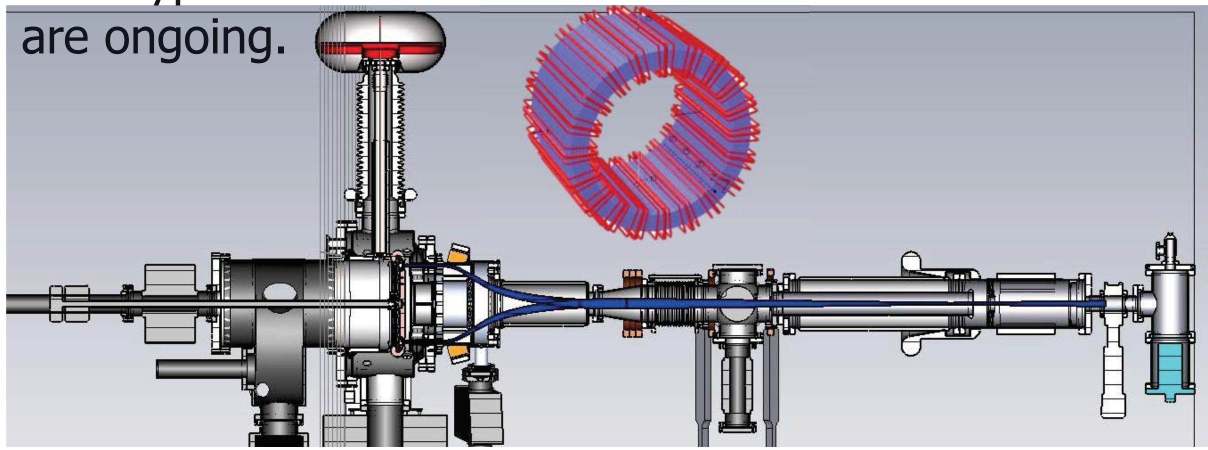
- Strong cooling of hadron beams *(eRHIC)*
- Low hadron β^* interaction region
- Crab-crossing *(eRHIC)*
- Beam-beam effects
- Techniques for intense e^+ beam *(LHeC)*



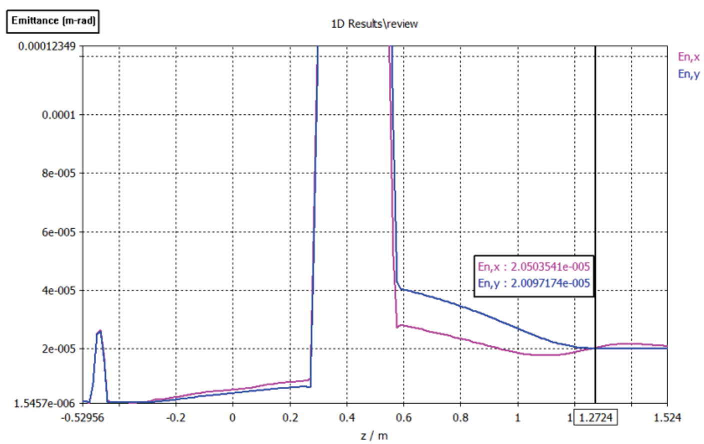
Polarized e-source: BNL Gatling Gun



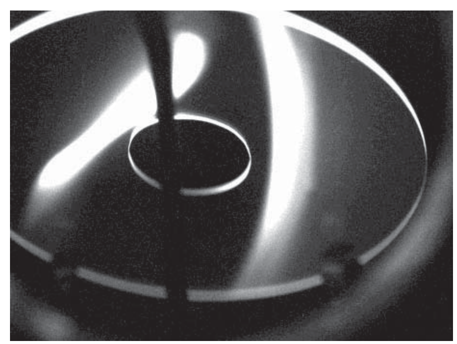
Prototype has been built. Initial tests with 2 cathodes are ongoing.

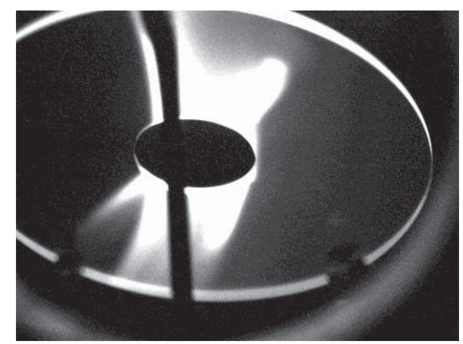


Ultimate goal: 2.5 mA/cathode, 50 mA total



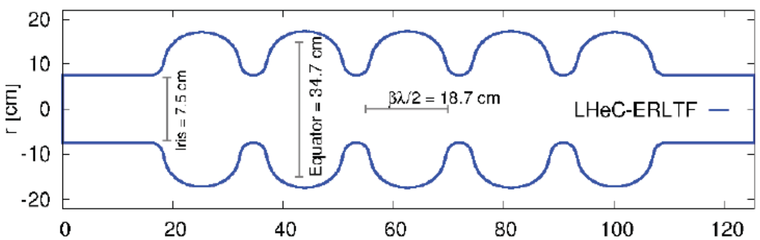
First beam detected by the YAG screen.





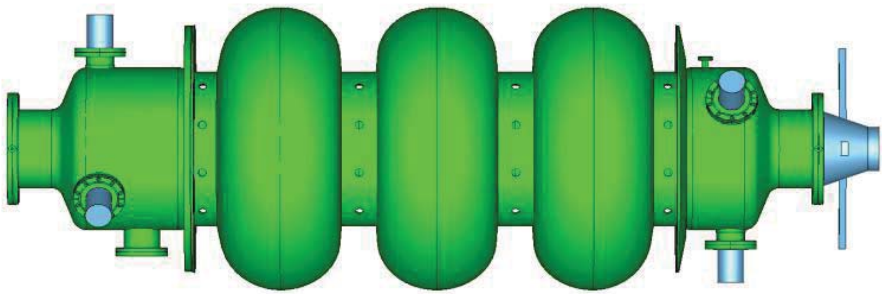
High current SRF cavities

LHeC: 802 MHz cavity and cryomodule development.
CERN-JLab-Mainz Collaboration



Parameter	Value
$_c\ n_{cc\,acc}$	5
$_c\ W_{acc}$	18 MV
f_0	801.58 MHz
W	131 J
aperture ∅	75 mm
equator ∅	347 mm
R/Q	462 Ω
G	276 Ω
$_a\ E_{pp\,acc\,pp}$	41 MV/m
$_a\ B_{pp\,acc\,pp}$	86 mT
P_{dd} ◀ 2K	< 28 W

eRHIC: 422 MHz cavity
Designed prototype:



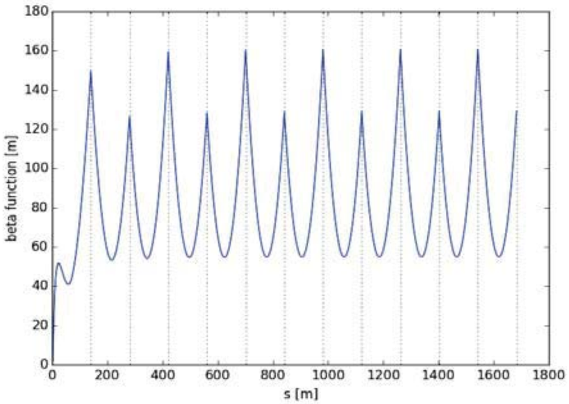
@W.Xu

Largest total beam current: 700 mA
(for 9.3 GeV top electron energy)

HOM power must be effectively damped:
LHeC: ~200 W
eRHIC: ~8 kW (in worst case)

Multipass Beam Break-Up

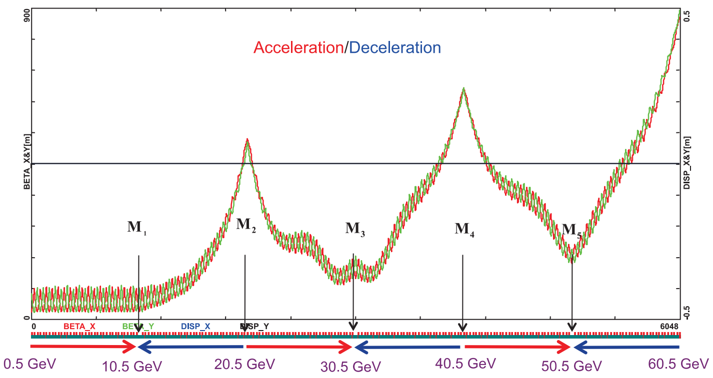
eRHIC

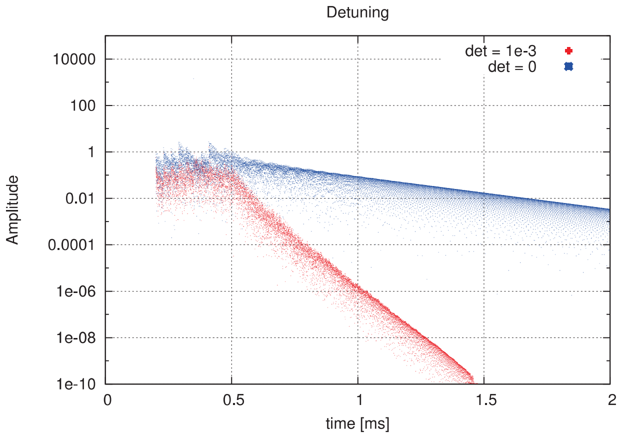


Multipass beam-breakup thresholds
for 16 pass operation (simulation results)

Δf/f (rms)	Current Threshold (mA)
0	53
5e-4	95
1e-3	137
3e-2	225
1e-2	329

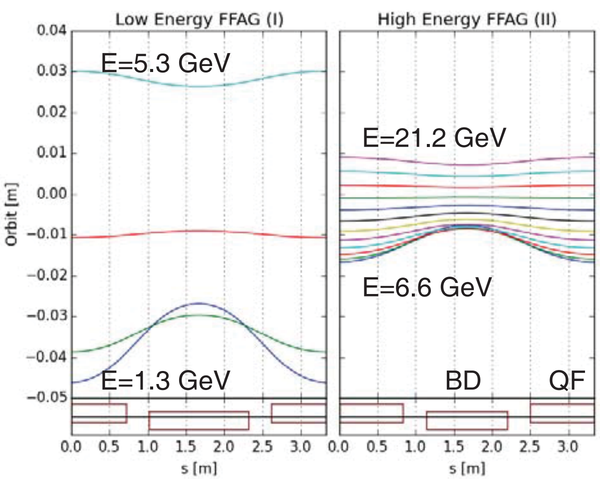
LHeC



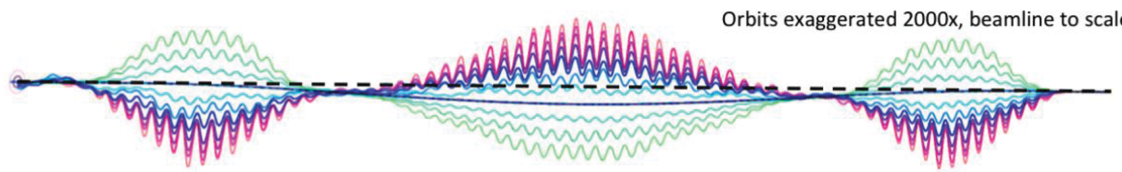


FFAG recirculation passes

- eRHIC uses two FFAG beamlines to do multiple recirculations.
  (FFAG-I: 1.3-5.4 GeV, FFAG-II: 6.6-21.2 GeV)
- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, with dipole field correctors).
- Permanent magnets can used for the FFAG beamline magnets (no need for power supplies/cables and cooling).



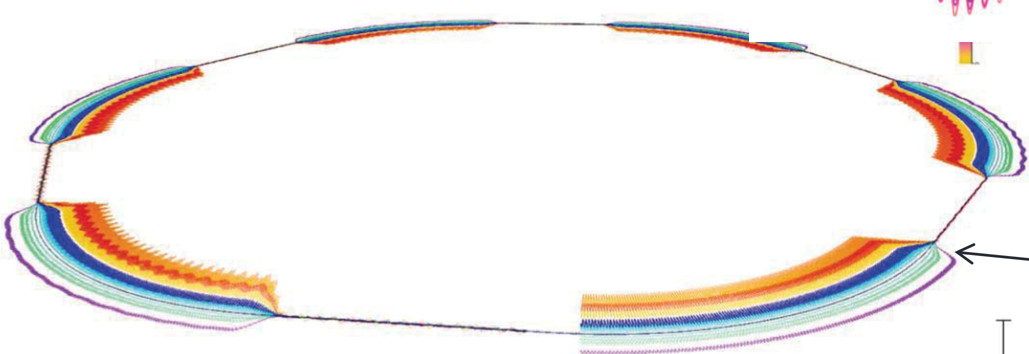
@S.Brooks, D.Trbojevic

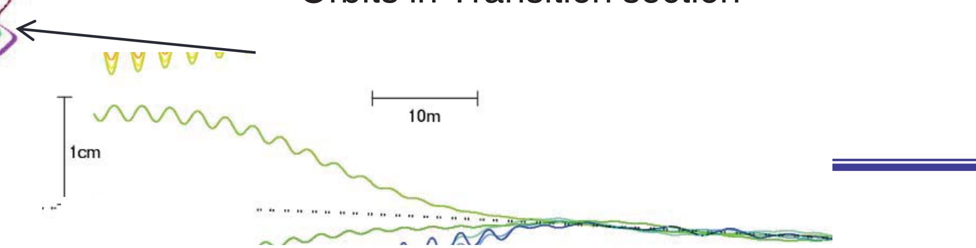


Orbits in Detector bypass section

Quad offsets evolve adiabatically

Orbits in Transition section



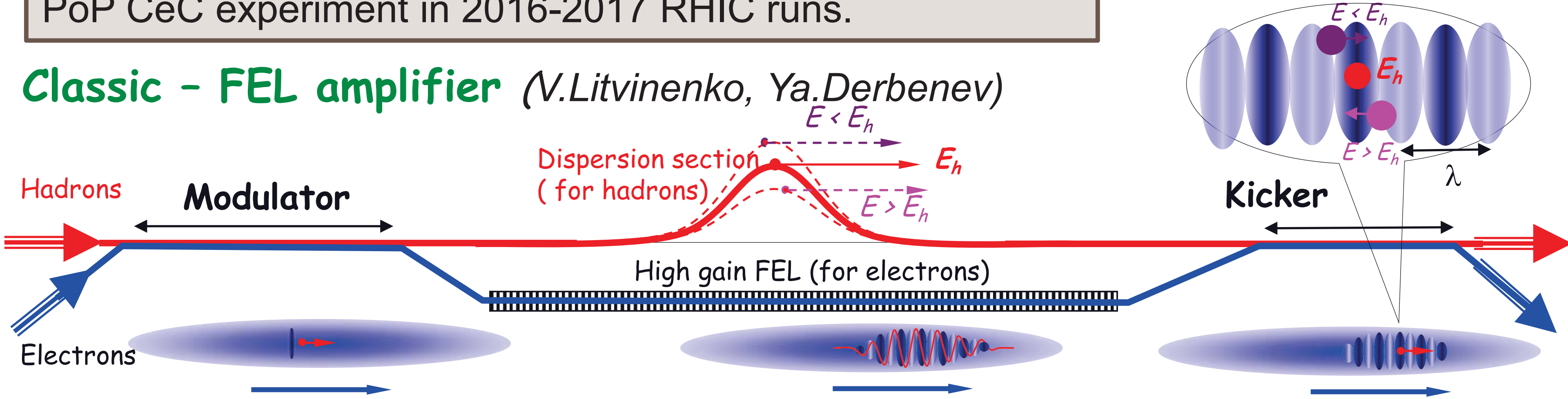


Each of two eRHIC FFAGs contain 1066 FFAG cells

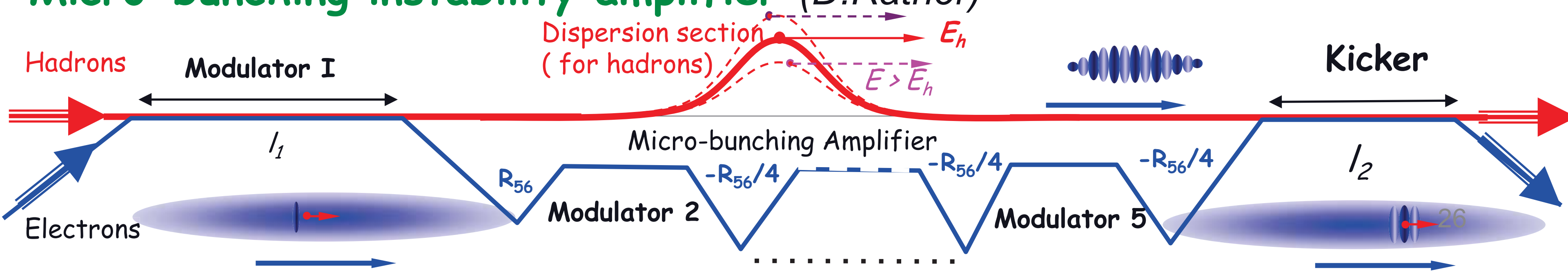
Advanced Cooling for eRHIC ion beam

High energy, high density ion beam need cooling with high band-width. **Coherent electron cooling: 10^{13}-10^{17} Hz**
PoP CeC experiment in 2016-2017 RHIC runs.

Classic – FEL amplifier *(V.Litvinenko, Ya.Derbenev)*



Micro-bunching instability amplifier *(D.Ratner)*



Beam-Beam Effect in Linac-Ring Scheme

@Y.Hao

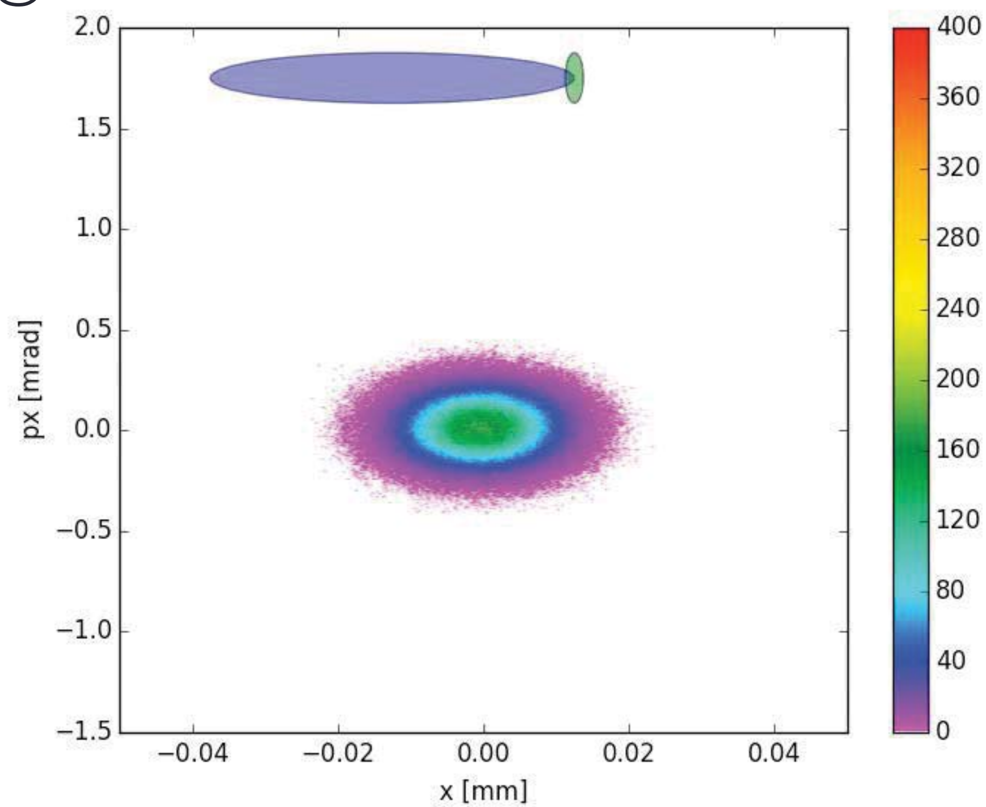
Since using ERL:
Beam quality must be acceptable for deceleration.
Halo formation by due to electron beam disruption by the beam-beam interaction should be moderate.

Other specific beam-beam effects of linac-ring scheme:
-Kink instability of hadron beam
-Heating of protons by electron parameter (orbit offset, intensity, emittance) fluctuations.

The effects are being studied by simulations and experimentally.

Beam-Beam Effect in Linac-Ring Scheme

@Y.Hao



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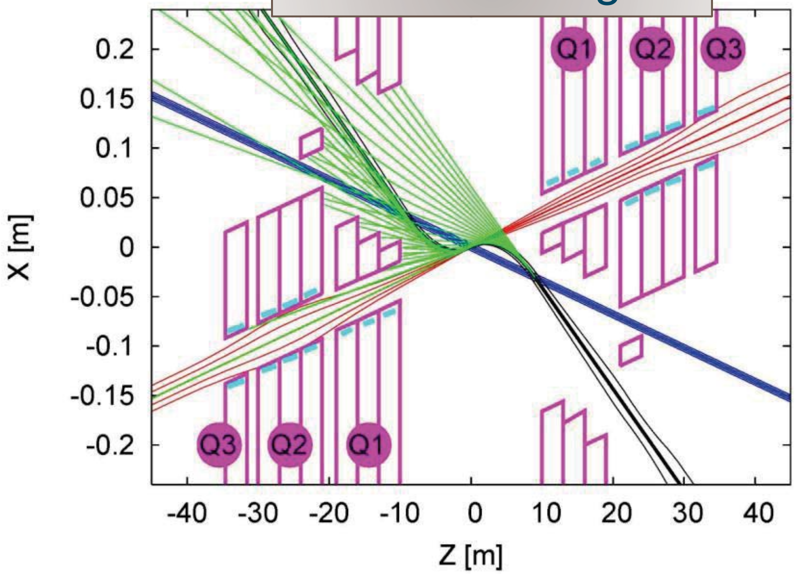
IR design

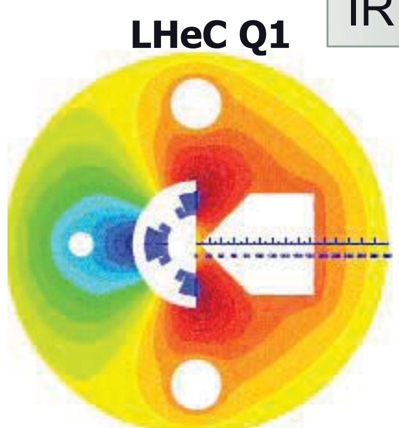
LHeC linac-ring IR

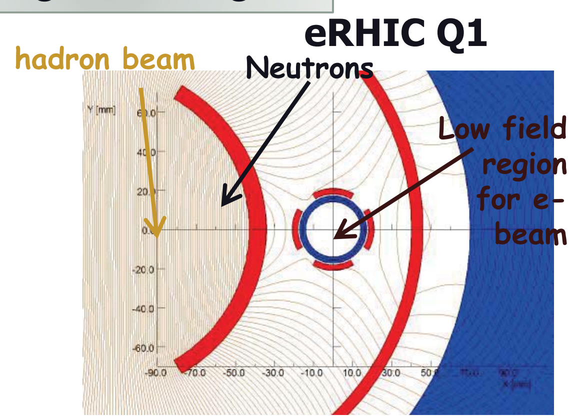


Using HERA and B-factories experience to resolve IR design issues:

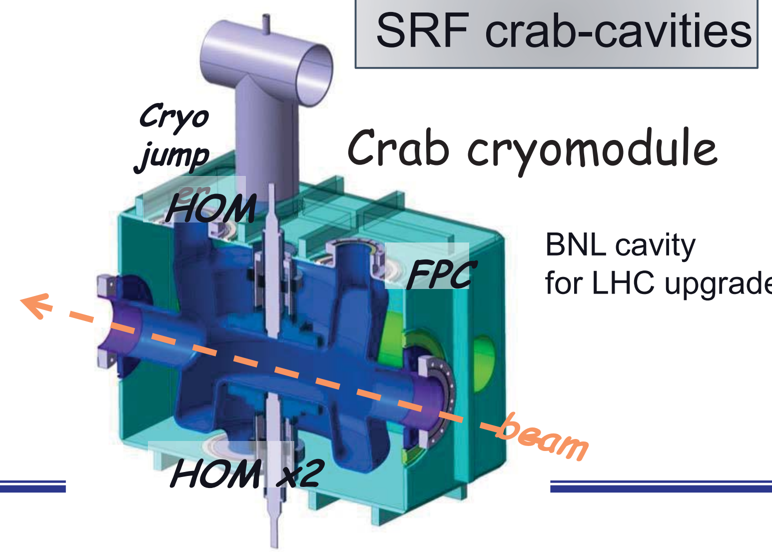
- ➢Strong beam focusing
- ➢Fast separation *(avoiding parasitic beam-beam)*
- ➢Managing synchrotron radiation fan *(absorbers, masks; precise orbit control; protection of SC magnets)*
- ➢Detector integration (*Large acceptance; Large magnet apertures for propagation of the collision products*)
- ➢Correction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

IR magnet designs





SRF crab-cavities



ERL SCRF facility at CERN

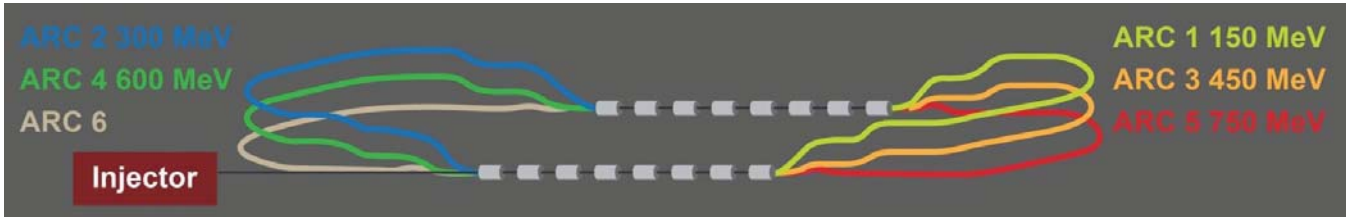
D.Pellegrini's Plenary talk

- Test facility for SCRF cavities and modules
- Test facility for multi-pass multiple cavity ERL
- Injector studies: DC gun or SRF gun
- Study reliability issues, operational issues
- Vacuum studies related to FCC
- Possible use for detector development, experiments and injector suggests ~1 GeV as final stage energy
- Test facility for controlled SC magnet quench tests
- Could it be foreseen as the injector to LHeC ERL and to FCC?

TARGET PARAMETER*	VALUE
Injection Energy [MeV]	5
Final Beam Energy [MeV]	900
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	50
Beam Current [mA]	10
Bunch Spacing [ns]	25 (50)
Passes	3

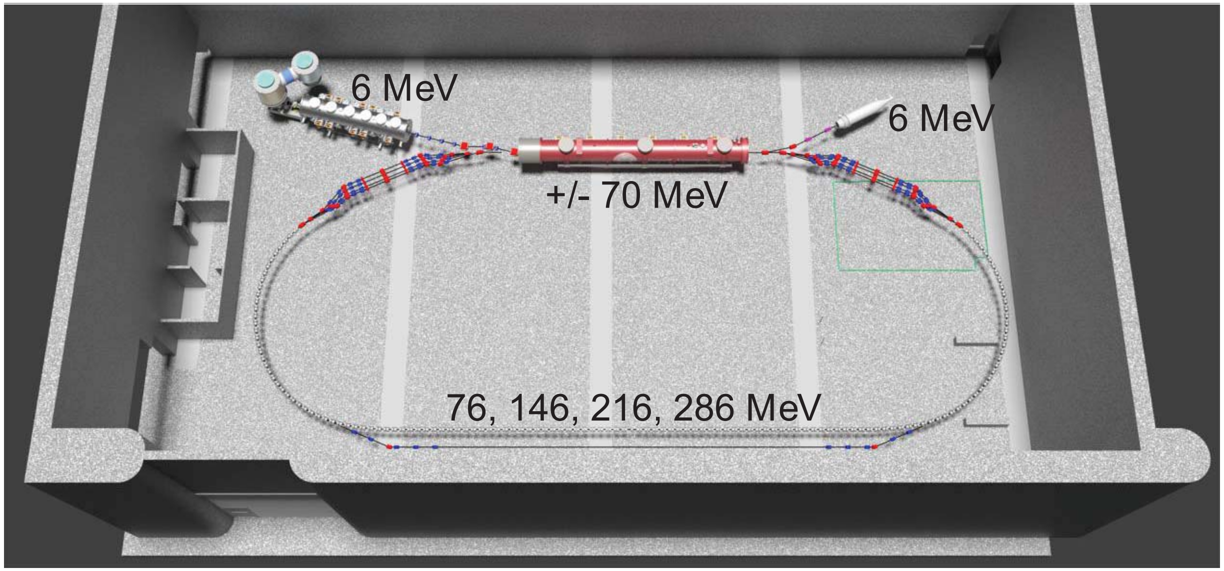
*in few stages

Conceptual Design Study is underway



Cornell-BNL FFAG-ERL Test Facility (Cβ)

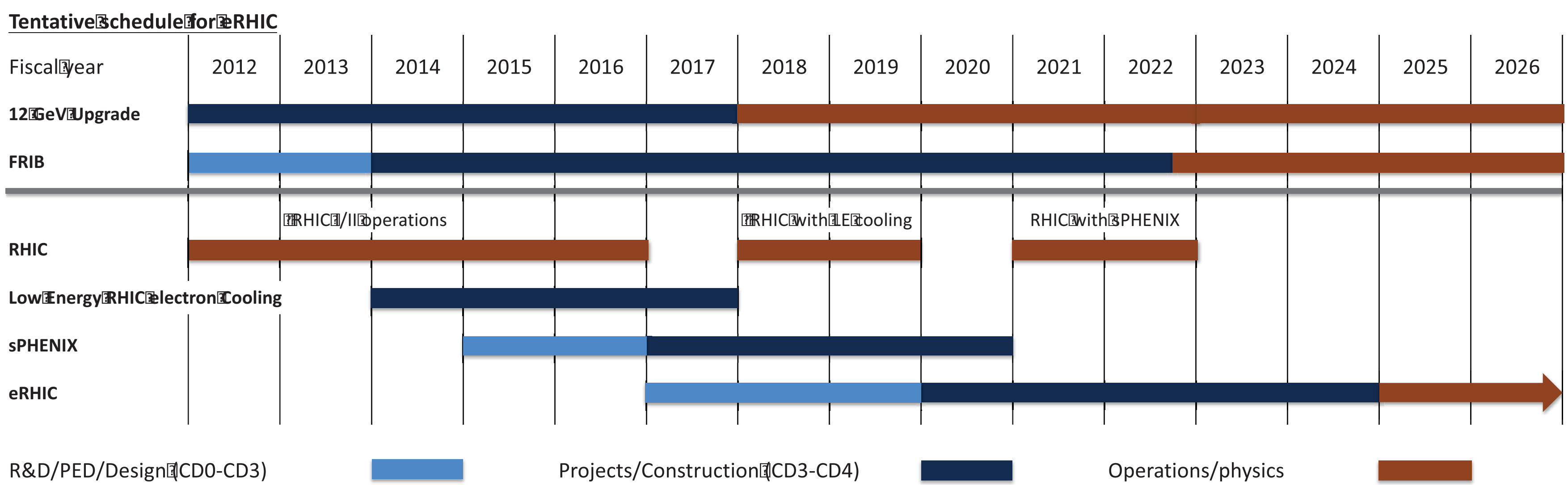
- NS-FFAG arcs, four passes (similar to first eRHIC loop)
- Momentum aperture of x4, as for eRHIC
- Uses Cornell DC gun, injector (ICM), dump, 70MeV SRF CW Linac
- Prototyping of essential components of eRHIC design



G.Hoffstaetter's Plenary talk

Also, possible ERL-related experiments for eRHIC are under consideration in JLab. (Sattelite meeting, Thursday morning, Lecture Hall 1)

DOE NP Facilities and possible eRHIC schedule



Summary

- ERL technology provides a pathway for a high-luminosity electron-ion collider
- ERL-based EIC designs have been developed in CERN (LHeC) and BNL (eRHIC)
- Several R&D projects are underway to address the technological challenges for an ERL-based collider
- ERL test facilities are planned in order to verify related technologies

eRHIC, Luminosity