Electron-Ion Collider Proposals Worldwide

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North American Particle Accelerator Conference (NA-PAC'13)
29 September – 4 October 2013, Pasadena, California

Outline

- Introduction
- Accelerator Designs
- Technology Innovation
- Outlook and Summary

Electron-ion collider → electron-proton collisions
+ electron-(light to heavy) ion collisions

1. Introduction

Electron-Ion Collider: The Next Generation

- HERA, the only electron-proton collider ever built and operated, ended its highly successful physics program in 2007.
- ***Five*** next generation electron-ion colliders have been envisioned worldwide for reaching new frontiers of high energy and nuclear physics.
- Four proposals are built upon existing or under construction facilities which provide one of two colliding beams. Only one proposal calls for a complete new facility in a green field design.
- Driven by the science programs, each of the new proposals focuses on a distinct CM energy range from a few GeV to above TeV, accommodates one to three interaction points, and aims for much higher collider performances than HERA.
- Presently, both the science cases and accelerator designs of these proposals are under active development. Collaborations among the physicists and accelerator designers are picking up momentum and have already yielded some interesting results.

Electron-Ion Collider on World Map

Science Goals

R. Ent
JLab

The High-Energy/Nuclear Science of LHeC

Overarching Goal: lepton-proton at the TeV Scale

Hunt for quark substructure & high-density matter (saturation)

High precision QCD and EW studies and ***precision Higgs measurements***

The Nuclear Science of eRHIC/MEIC

Overarching Goal: Explore and Understand QCD:

Map the spin and spatial structures of quarks and gluons in nucleons

Discover the collective effects of gluons in atomic nuclei

(role of gluons in nuclei & onset of saturation)

Emerging Themes:

Understand the emergence of hadronic matter from quarks and gluons & EW

The Nuclear Science of ENC and HIAF(?)

Overarching Goal: Explore Hadron Structure

Map the spin and spatial structure of valence & sea quarks in nucleons

Science Goals

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The High-Energy/Nuclear Science of LHeC

Overarching Goal: lepton-proton at the TeV Scale

Hunt for quark substructure & high-density matter (saturation)
High precision QCD and EW studies and ***precision H***

e-p **@ LHeC is a very serious & affordable Higgs facility**

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Overarching Goal: Explore and Understand QCD:

Map the spin and spatial structures of quarks and gluons in nucleons
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A Snapshot of Machine Design

Sources

HERA

- F. Willeke, talk at DIS 2004, April 17, 2004, Strbske Pleso

LHeC

- M. Klein, talk at IPAC11, San Sebastian, Sept. 4-9, 1011
- O. Bruning, talk at IPAC13, Shanghai, May 12-17, 2013
- LHeC Design Report

ENC

- K. Aulenbacher, talk at Spin 2010, Sept. 27, 2010, and *private communication*

HIAF

- J. Yang, *private communication*

eRHIC

- V. Litvinenko, talk at POETIC Workshop, Chile, March 4-8, 2013
- V. Ptitsyn, talk at PSTP 2013, UVA, Sept. 9-13. 2013

MEIC

- Y. Zhang, talk at talk at DIS 2013, Marseille, April 22-26, 2013
- MEIC Design Report

Acknowledgement I would like to thank authors for permitting me to use their slides

A Snapshot of Machine Design

Alessandra Valloni
"Beam Physics in Future Electron Hadron Colliders"

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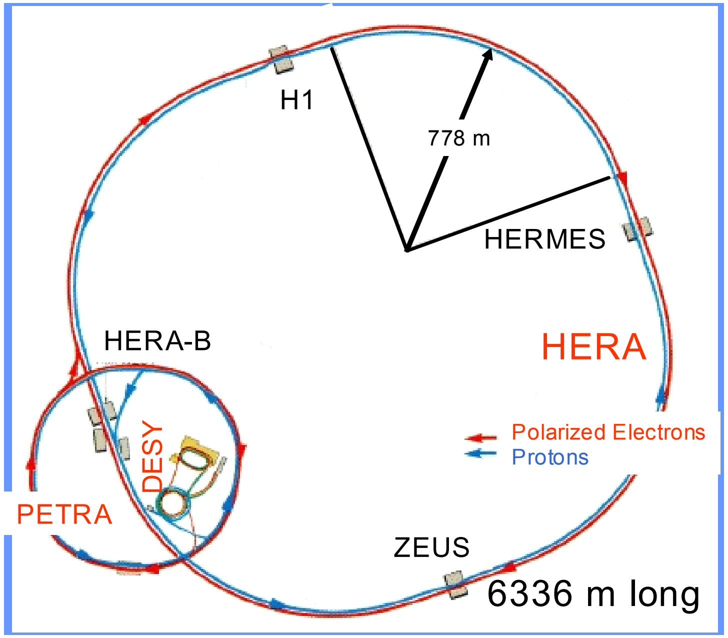
2. Accelerator Designs

(from high to low CM energy)

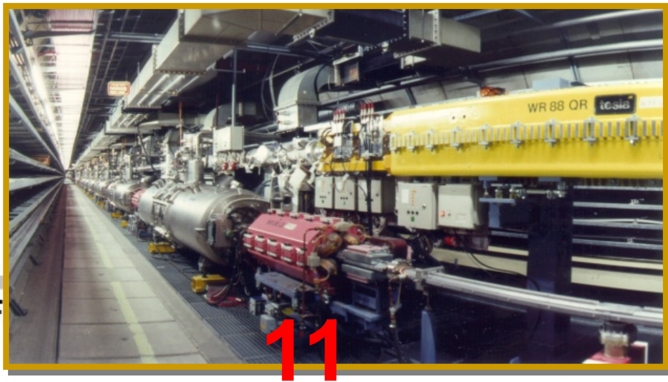
HERA: The 1st EIC Ever Built



		Lepton	Proton
Energy	GeV	27.5	920
Intensities	mA	60	180x10^{11}
Magnetic field	T	0.15	1.5
Acc. voltage	MV	130	2
e-polarization	%	30 to 50	--
Final luminosity	$cm^{-2}s^{-1}$	(1.5 to 5)x10^{31}	

A Ring-Ring (polarized) Lepton-Proton collider with 320 GeV CM energy

1981 Proposal
1984 Start construction
1991 Commissioning, first Collisions
1992 Start Operations for H1 and ZEUS,
➔ 1^{st} exciting results with low luminosity
1994 Install East Spin Rotators
➔ Longitudinal polarized leptons for HERMES
1996 Install 4^{th} Interaction region for HERA-B
1999 High Luminosity Run with electrons
2000 High efficient luminosity production:100 /pb/y
2001 Install luminosity upgrade,
Spin Rotators for H1 and ZEUS
2003 Longitudinal polarization in high energy collisions
2007 End of a highly successful program



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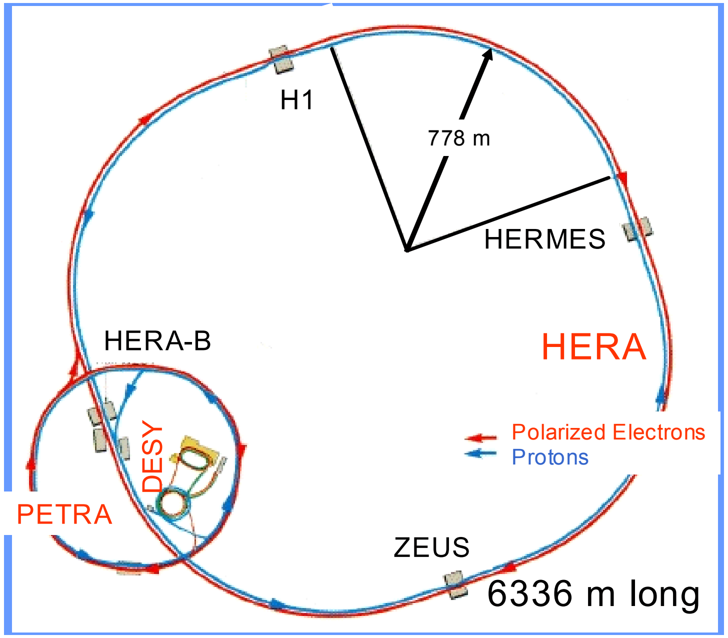

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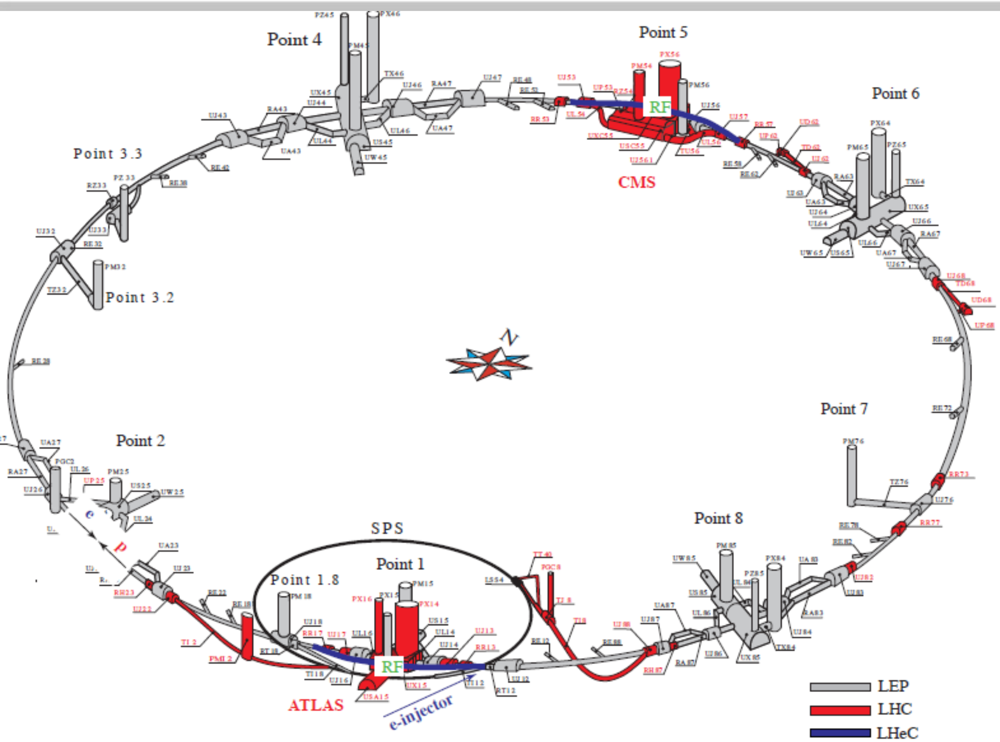
2007 En... ...gram

Successful end of HERA with 500 pb^{-1} delivered

LHeC: Ring-Ring



LEP*LHC (1984, 1990) - Lausanne, Aachen
E.Keil LHC project report 93 (1997)
Thera (2001)
QCD explorer (2003)
J.Dainton et al, 2006 JINST 1 10001

Early History

- Electron/positron is up to 60 GeV
- e+/e- stored in the main ring
- Needs a 10 GeV e+/e- injector, the current design is a recirculating linac
- Total filling time is less than 10 min

	Electrons	Protons
Energy	60 GeV	7 TeV
Current	100 mA	860 mA
Part. per bunch	2×10^{10}	1.7×10^{11}
Numb. of bunches	2808	2808
$\varepsilon_x / \varepsilon_y$	5.0 / 2.5 nm	0.5 / 0.5 nm
P_γ	< 50 MW	

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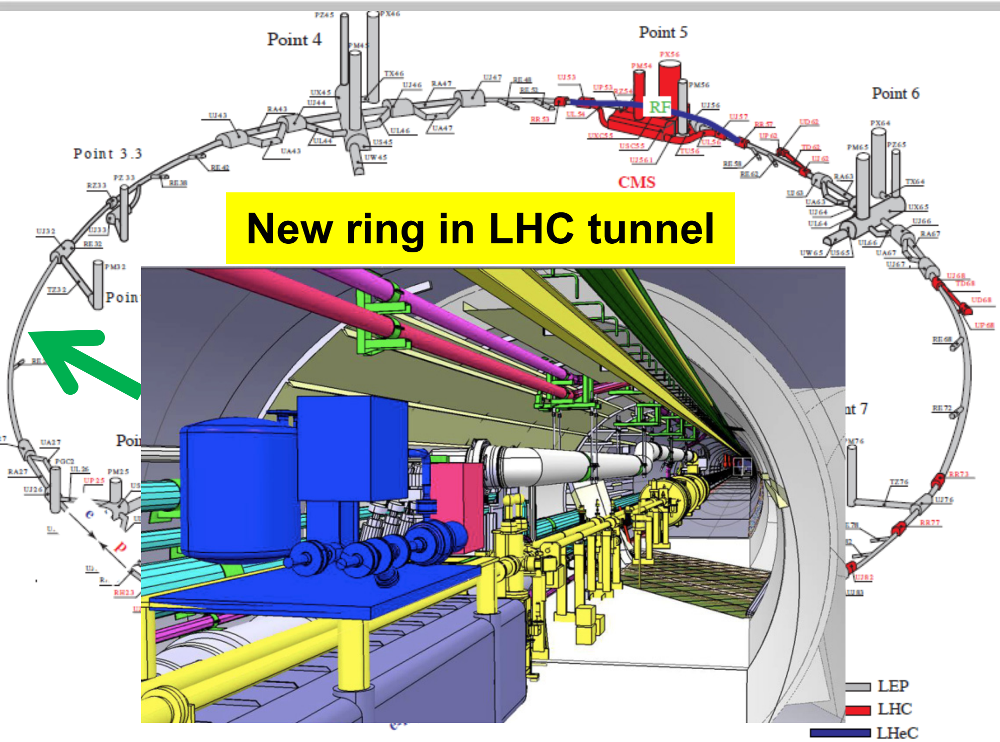

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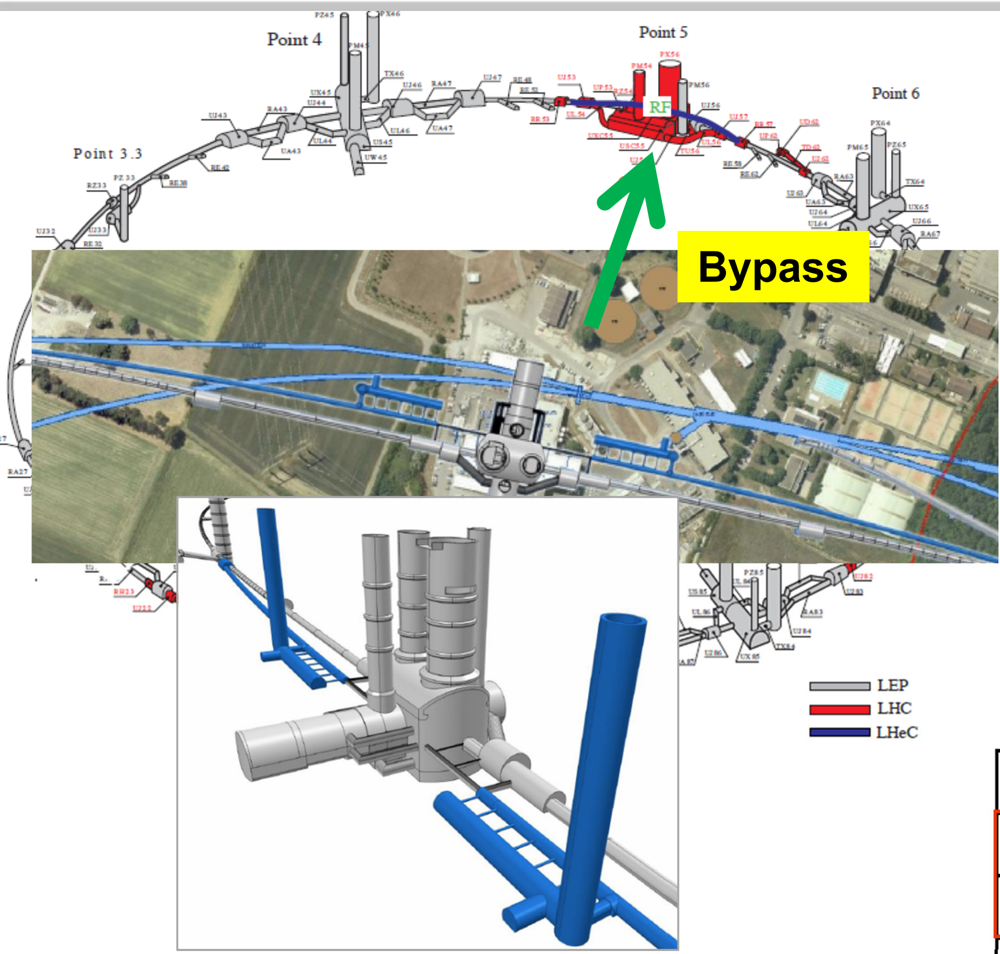

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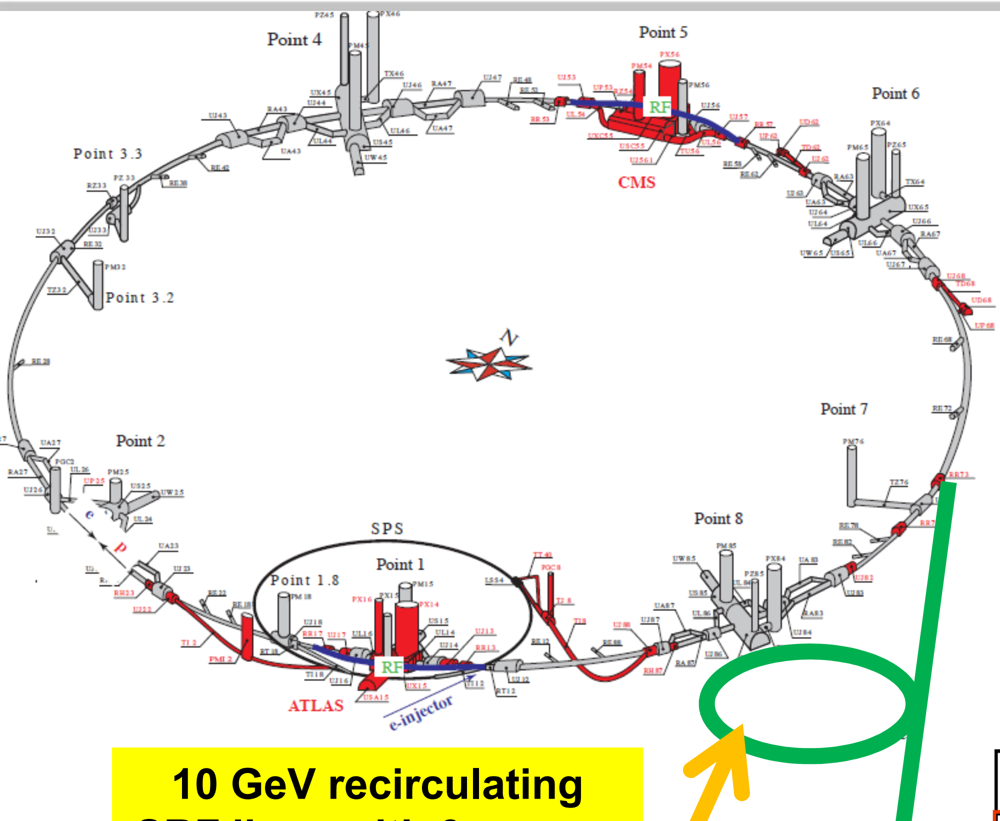
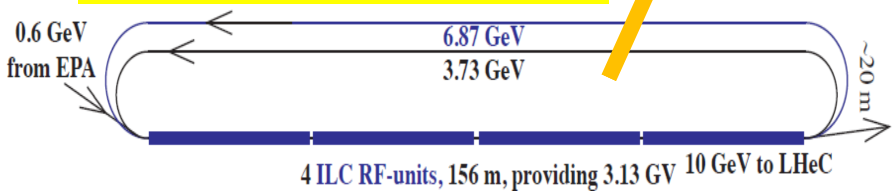


10 GeV recirculating SRF linac with 3 passes



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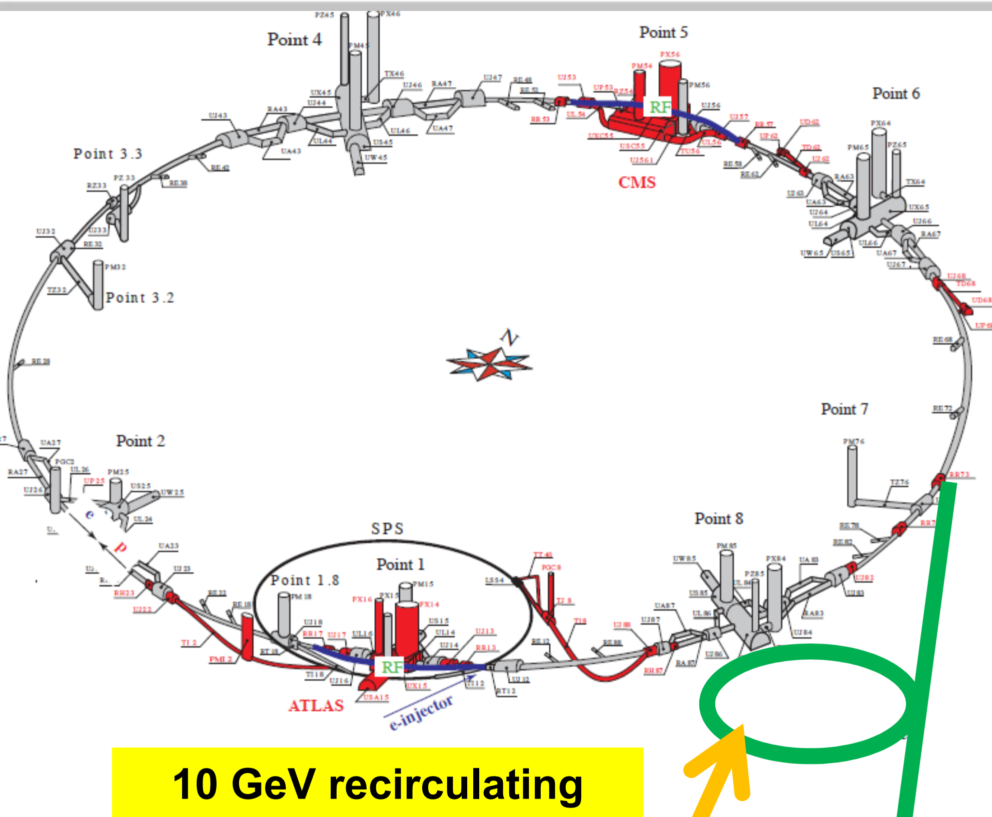

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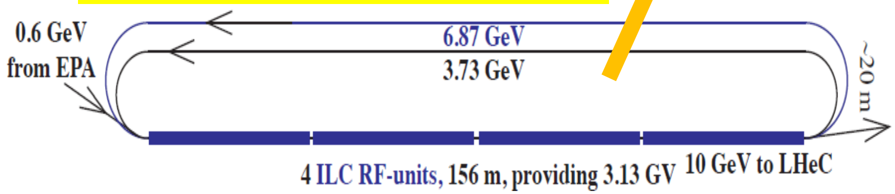

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P_γ	< 50 MW	

Power Limit: 100 MW wall plug!

LHeC: Ring-Ring

High Acceptance (1 deg.)	Electrons	Protons
β_x	0.4 m	4.05 m
β_y	0.2 m	0.97 m
l*	6 m	22.96 m
σ_x	45 μm	
σ_y	22 μm	
Crossing angle	1 mrad	
Luminosity	$8.54\ 10^{32}\ cm^{-2}\ s^{-1}$	
Luminosity loss factor	86%	
Luminosity	$7.33\ 10^{32}\ cm^{-2}\ s^{-1}$	
P_γ	51 kW	
E_c	163 keV	

High Luminosity (10 deg.)	Electrons	Protons
β_x	0.18 m	1.8 m
β_y	0.1 m	0.5 m
l*	1.2 m	22.96 m
σ_x	30 μm	
σ_y	15.8 μm	
Crossing angle	1 mrad	
Luminosity	$1.8\ 10^{33}\ cm^{-2}\ s^{-1}$	
Luminosity loss factor	75%	
Luminosity	$1.34\ 10^{33}\ cm^{-2}\ s^{-1}$	
P_γ	33 kW	
E_c	126 keV	

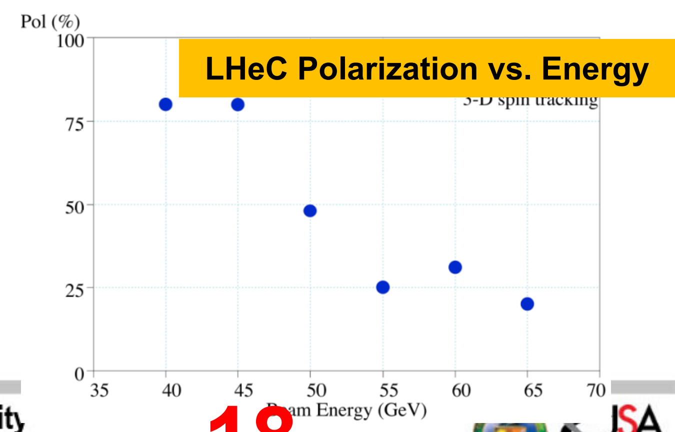
e-A Collisions

- Assuming present **normal Pb beam in LHC**
  - Same beam size as protons
  - Few bunches (592)
  - $7x10^7$ fully stripped $^{208}Pb^{82}$
- Assuming e-injector chain can provide the design bunch pattern (596 bunches of $6x10^{10}$)
- Electron SR loss 45 MW
- Lepton-nucleon Luminosity at 60 GeV lepton energy

$$L_{eA}=1x10^{32}\ cm^{-2}s^{-1}$$

Lepton polarization

- Polarization of 25% to 40% can be reasonably aimed for at 60 GeV with harmonic closed orbit spin matching
- Precision alignment of the magnets to better than 150 μm RMS needed to achieve a high polarization level
- Option of having Siberian snake



LHeC: Ring-Ring

No principal problem found yet!

High Acceptance (1 deg.)

	Electrons	Protons
β_x	0.4 m	4.05 m
β_y	0.2 m	0.97 m
l*	6 m	22.96 m
σ_x	45 μm	
σ_y	22 μm	
Crossing angle	1 mrad	
Luminosity	[illegible]	
Luminosity loss [illegible]	[illegible]	
Luminosity	[illegible].33 10^{32} cm^{-2} s^{-1}	
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E_c	163 keV	

High Luminosity (10 deg.)

	Electrons	Protons
β_x	0.18 m	1.8 m
β_y	0.1 m	[illegible]
l*	[illegible]	[illegible]
σ_x	[illegible] μm	
[illegible]	15.8 μm	
[illegible]gle	1 mrad	
[illegible]uminosity	1.8 10^{33} cm^{-2} s^{-1}	
Luminosity loss factor	75%	
Luminosity	1.34 10^{33} cm^{-2} s^{-1}	
P_γ	33 kW	
E_c	126 keV	

e-A Collisions

- A[illegible] present **normal Pb** [illegible] **LHC**
  - Same beam size as protons
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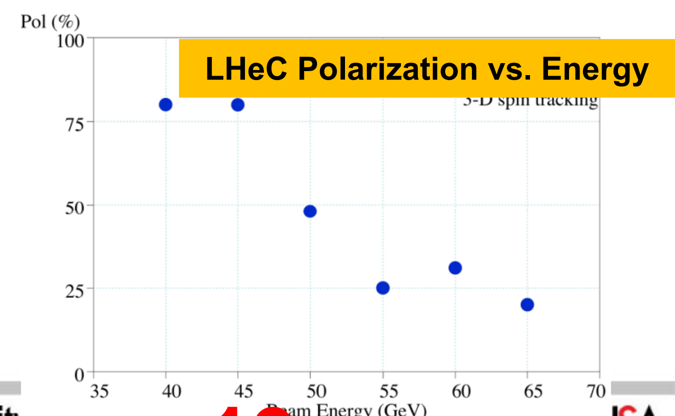

LHeC: Ring-Ring

No principal problem found yet!

Installation is very challenging!

High Acceptance (1 deg.)

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Crossing angle	1 mrad	
Luminosity	8.5[illegible]	
Luminosity loss f[illegible]	[illegible]	
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	Electrons	Protons
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l*	[illegible]	[illegible]
σ_x	[illegible] µm	
σ_y	15.8 µm	
[illegible]gle	1 mrad	
Luminosity	1.8 10^{33} cm^{-2} s^{-1}	
Luminosity loss factor	75[illegible]	
Luminosity	[illegible]	
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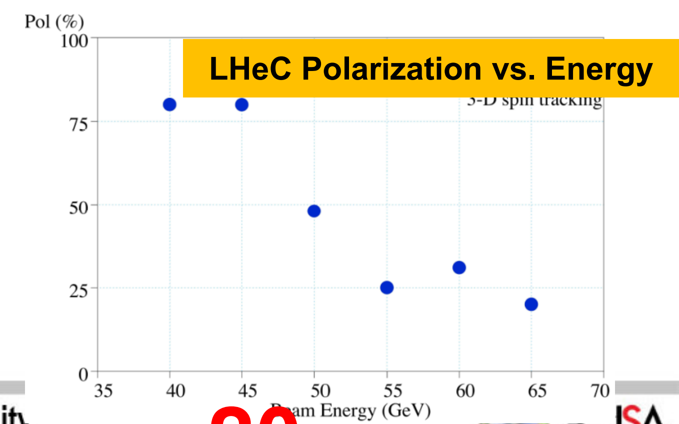
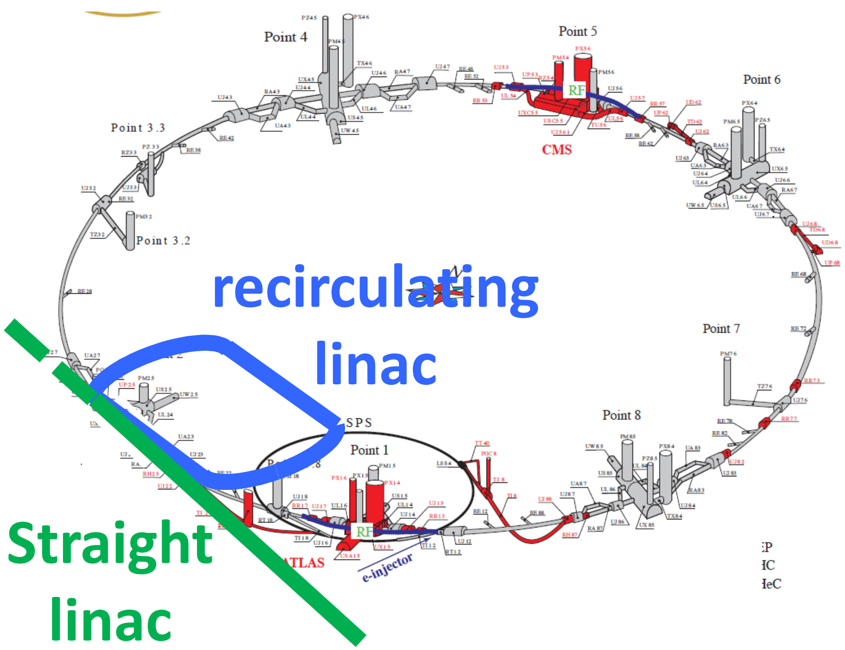
LHeC Polarization vs. Energy



LHeC: Linac(ERL)-Ring

Lots of linac options



Why ERL?

- High energy, high current beams require GW-class RF systems in conventional linacs
- ERL alleviates extreme RF power demand ➔ nearly independent of beam current
- ERL maintains superior beam quality: emittance, energy spread, short bunches

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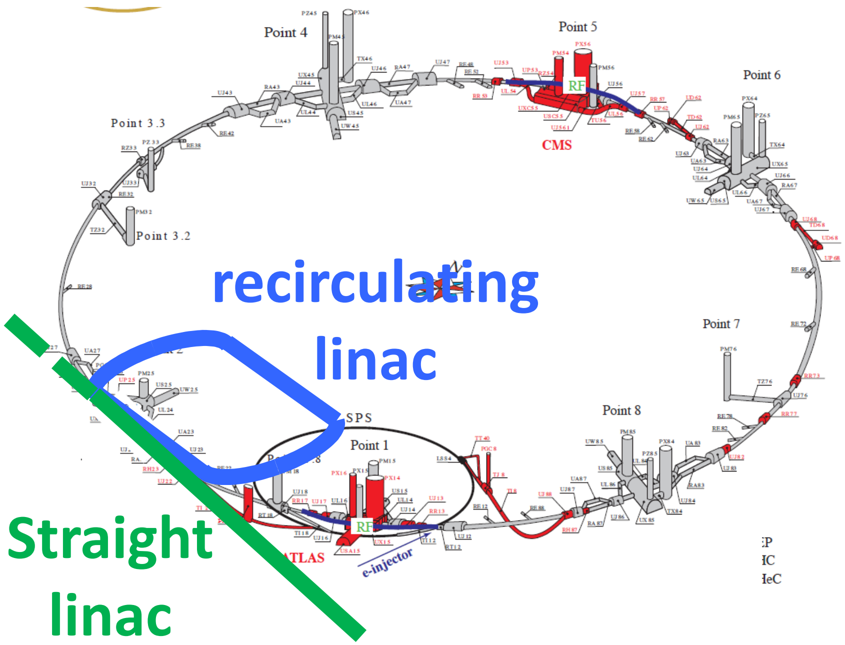

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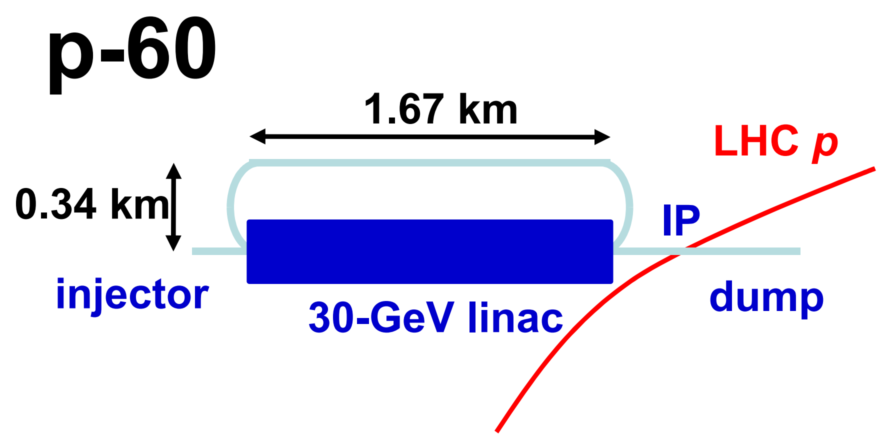

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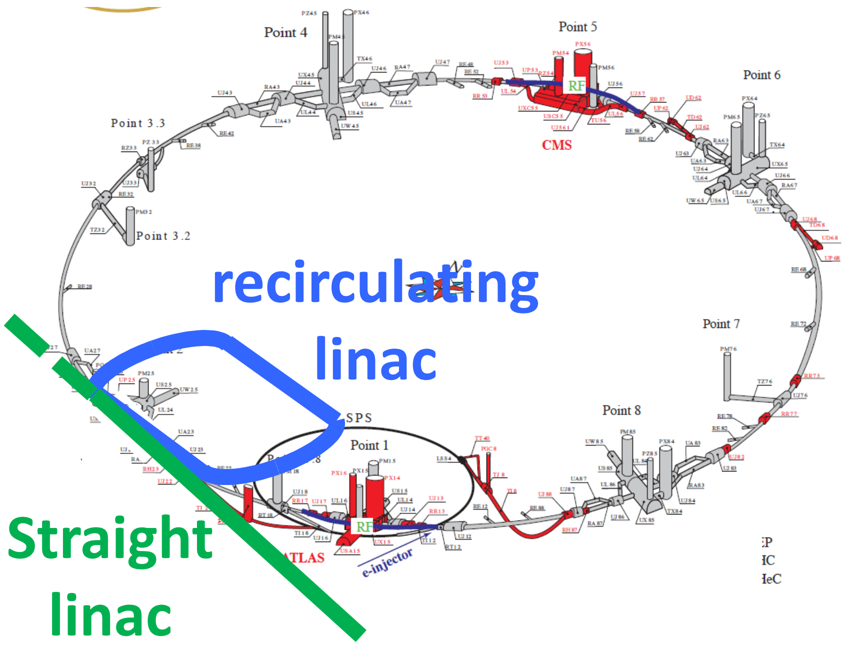

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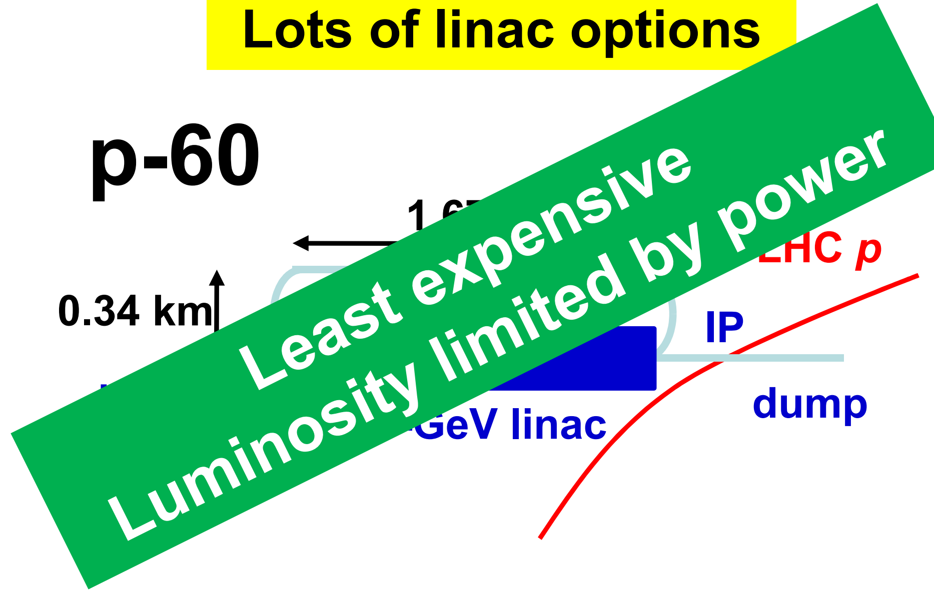

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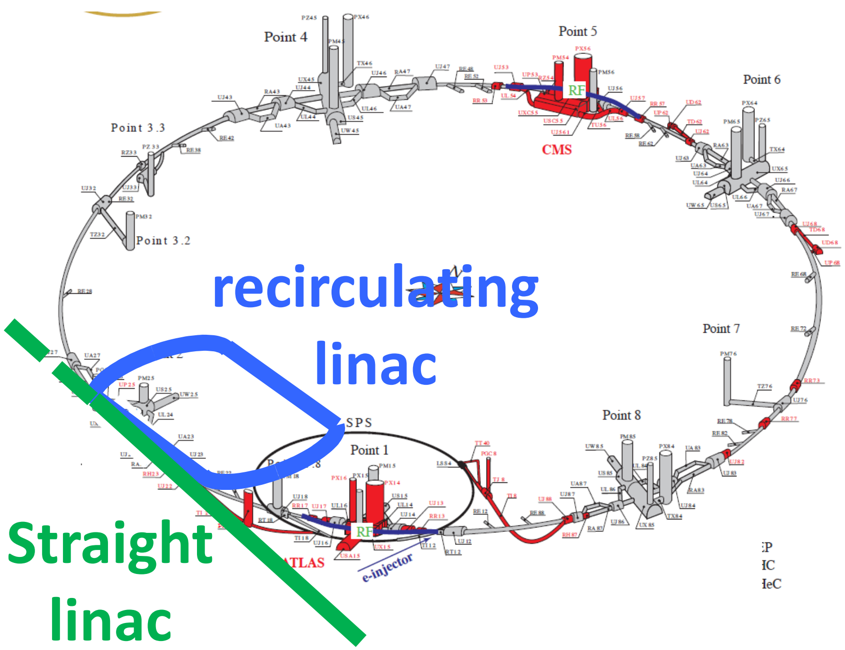

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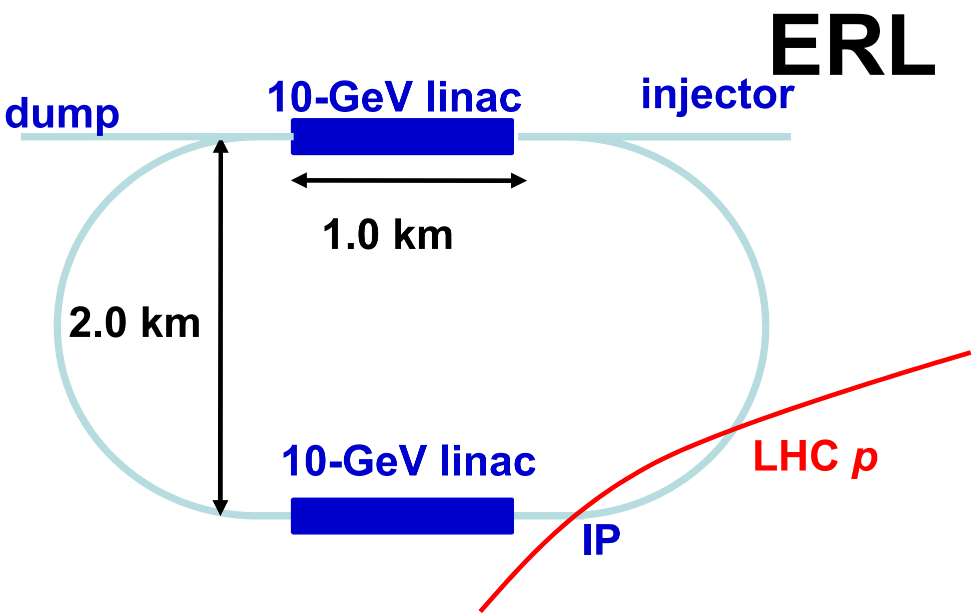

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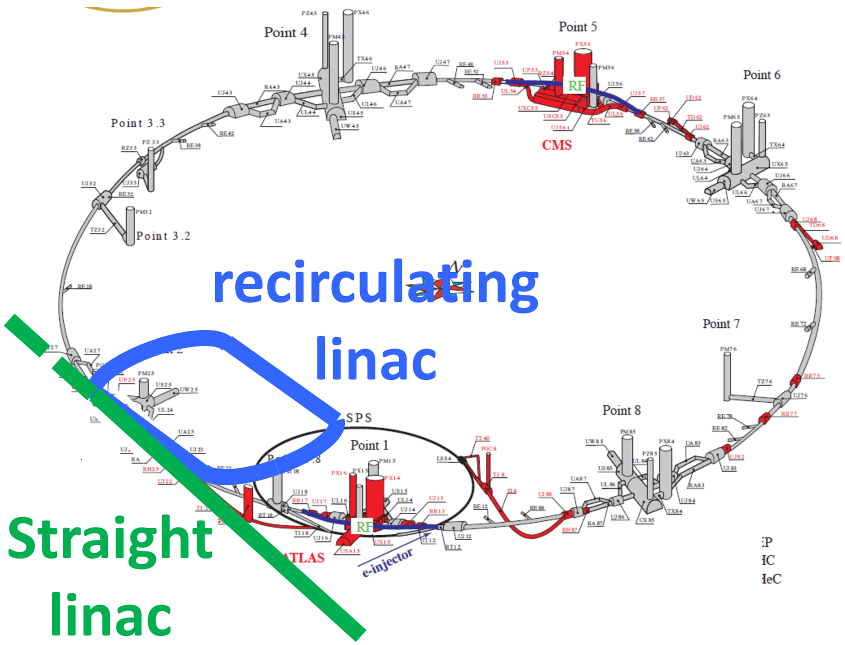

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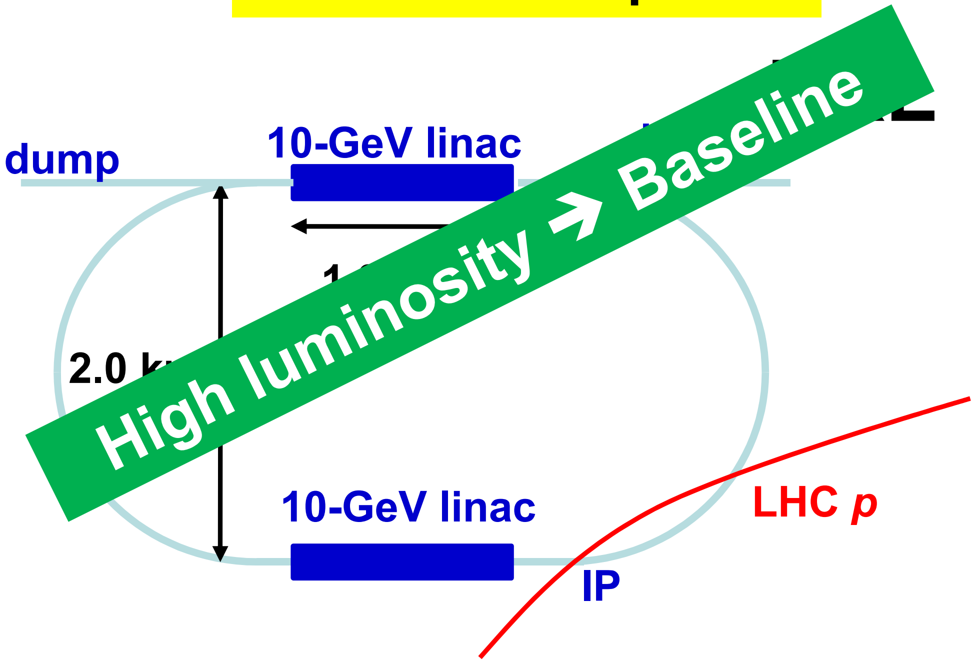

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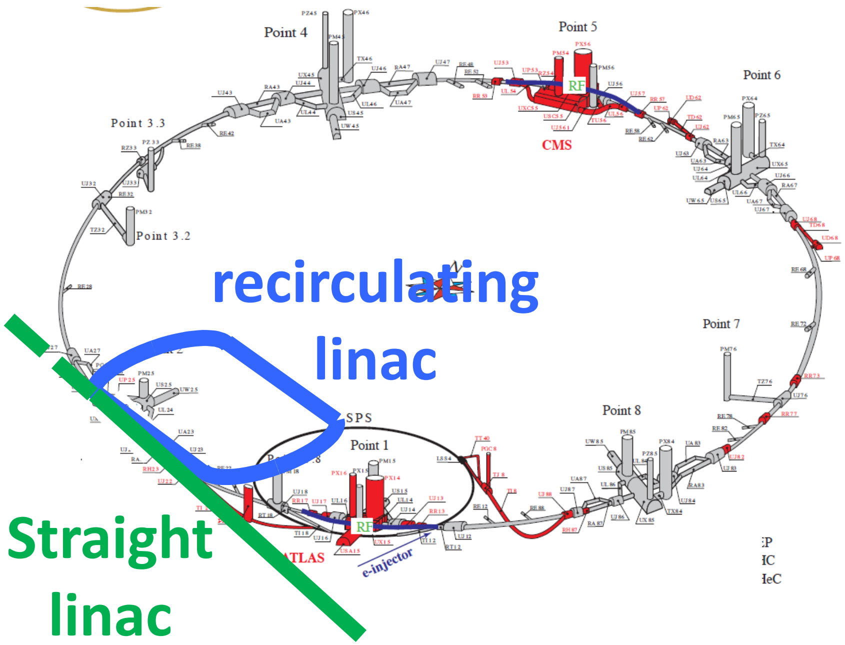

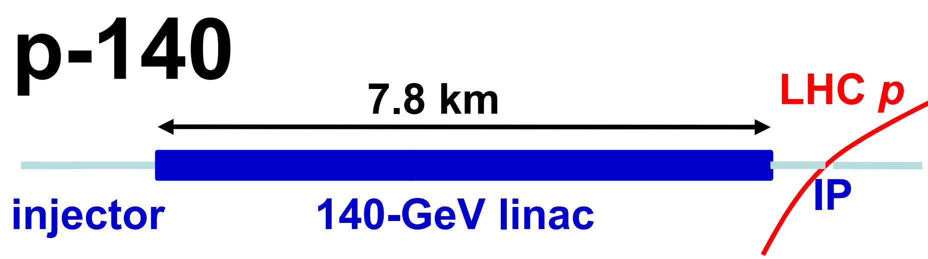

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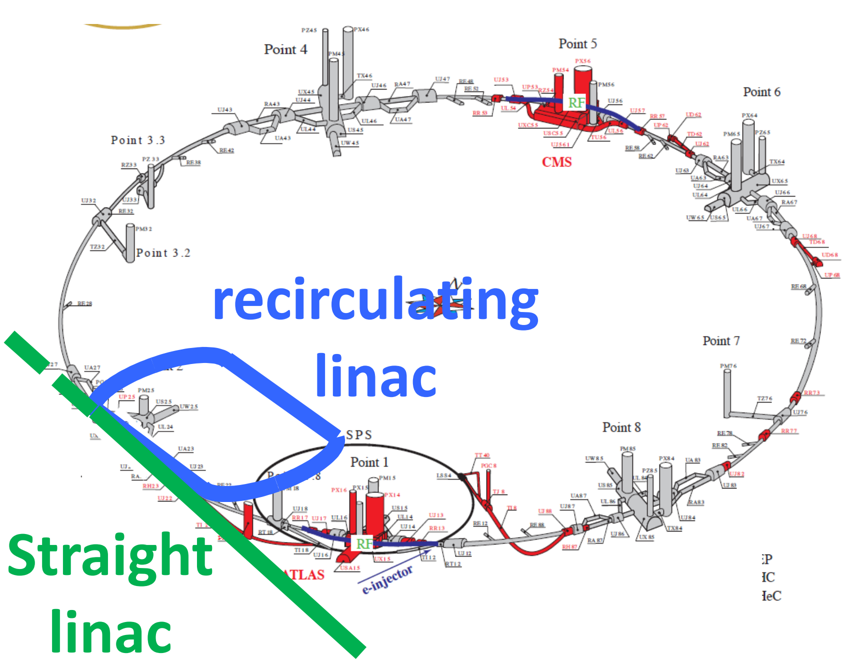

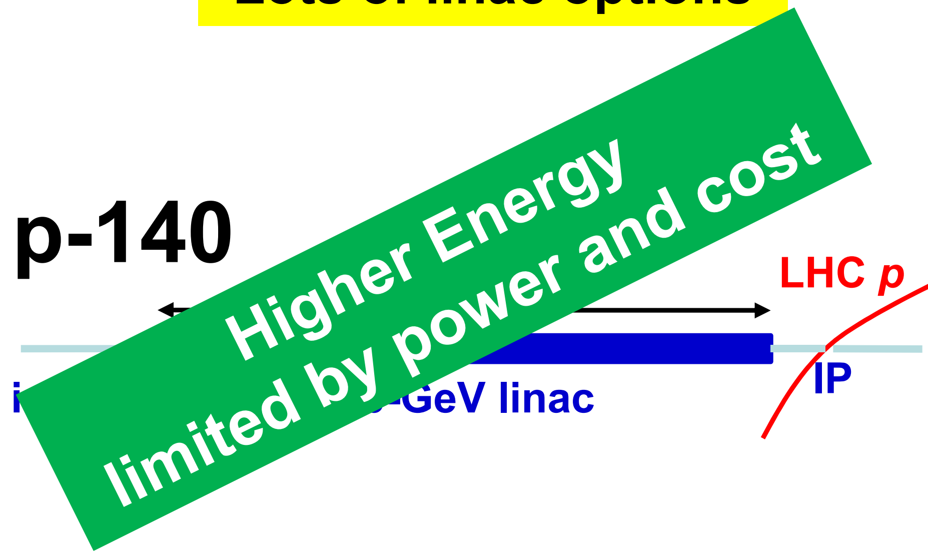

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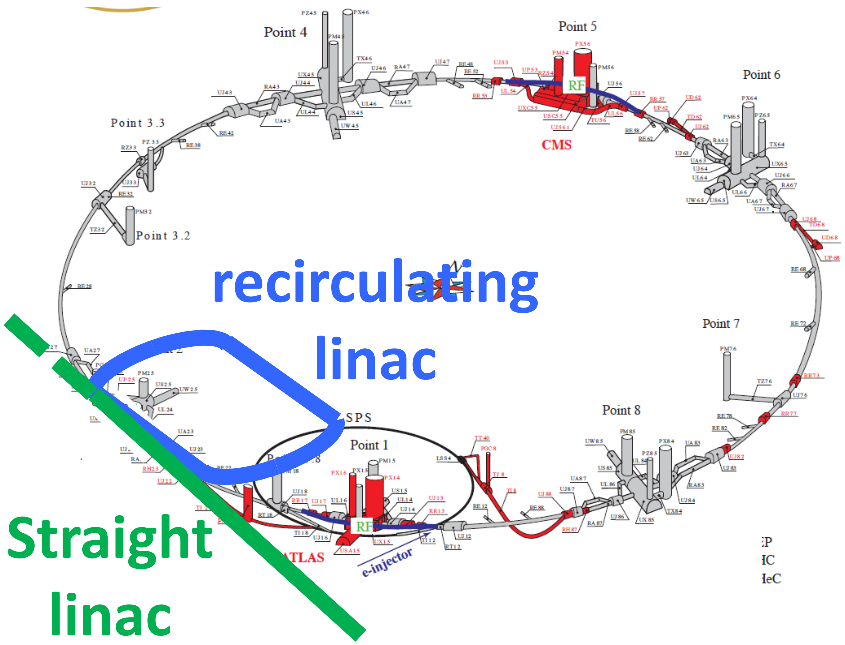
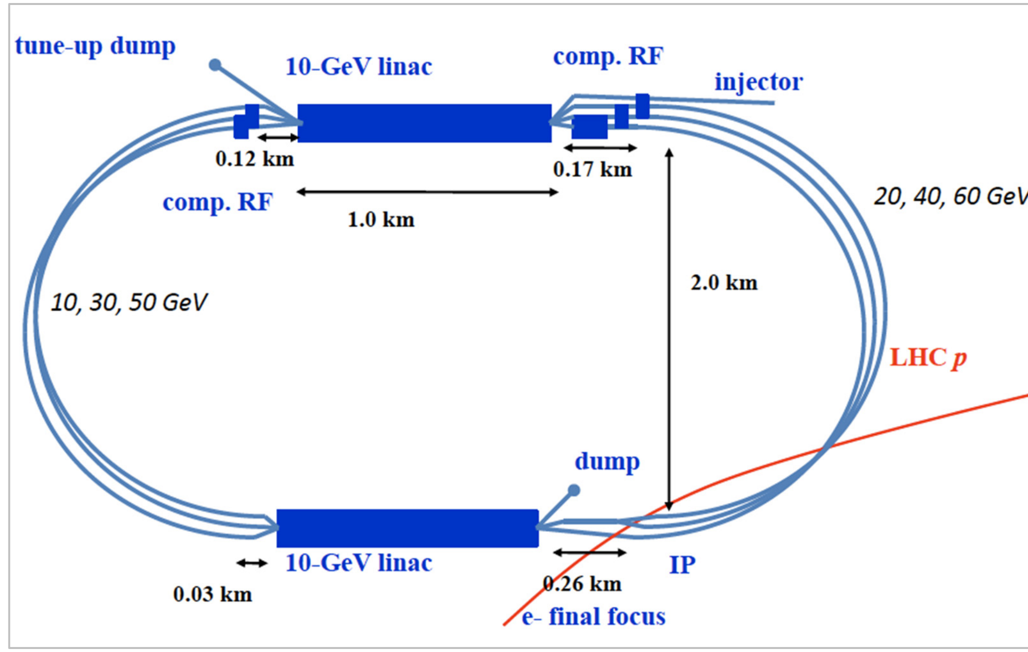


Present Baseline



Why ERL?

- High energy, high current beams require GW-class RF systems in conventional linacs
- ERL alleviates extreme RF power demand ➔ nearly independent of beam current
- ERL maintains superior beam quality: emittance, energy spread, short bunches

LHeC: Linac(ERL)-Ring

Electron beam	LR ERL	LR
e- energy at IP[GeV]	60	140
Luminosity [10^{32} $cm^{-2}s^{-1}$]	**10**	**0.44**
Polarization [%]	90	90
Bunch population [10^9]	2.0	1.6
e- bunch length [mm]	0.3	0.3
Bunch interval [ns]	50	50
Trans. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.12	0.14
Full crossing angle [mrad]	0	0
Geometric reduction H_{hg}	0.91	0.94
Repetition rate [Hz]	N/A	10
Beam pulse length [ms]	N/A	5
ER efficiency	94%	N/A
Average current [mA]	6.6	5.4
Tot. wall plug power [MW]	100	100

Proton beam	RR	LR
Bunch population [10^{11}]	1.7	1.7
Trans. emit. $\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
Spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8, 0.5	0.1
Bunch spacing [ns]	25	25

ERL site power

- Cryo for two 10 GeV SRF Linacs: 28.9 MW
- RF power to control microphonics: 22.2 MW
- Compensation for SR energy loss: 24.1 MW
  - cryo power: 2.1 MW
  - microphonics control: 1.6 MW
- Injector RF: 6.4 MW
- Magnets: 3.0 MW

grand total: **88.3 MW**

Power Limit: 100 MW wall plug!

	ERL 720 MHz	ERL 1.3 GHz	Pulsed
duty factor	cw	cw	0.05
RF frequency [GHz]	0.72	1.3	1.3
cavity length [m]	1	~1	~1
energy gain / cavity [MeV]	18	18	31.5
R/Q [100 Ω]	400-500	1200	1200
Q_0 [10^{10}]	**2.5-5.0**	**2 ?**	**1**
power loss stat. [W/cav.]	5	<0.5	<0.5
power loss RF [W/cav.]	**8-32**	**14-31 ?**	**<10**
power loss total [W/cav.]	13-37 (!?)	14-31	11
"W per W" (1.8 k to RT)	700	700	700
power loss / GeV @RT [MW]	**0.51-1.44**	**0.6-1.1**	**0.24**
length / GeV [m] (*filling*=0.57)	97	97	56

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Bunch spacing [ns]	25	[illegible]

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duty factor	cw	[illegible]	[illegible]
RF frequency [GHz]	0.72	[illegible]	[illegible]
cavity length [m]	[illegible]	[illegible]	[illegible]
energy gain / cavity [MeV]	[illegible]	[illegible]	[illegible]
R/Q [100 Ω]	[illegible]	[illegible]	1200
Q_0 [10^{10}]	[illegible]	[illegible] ?	**1**
power [illegible]	[illegible]	<0.5	<0.5
[illegible]	[illegible]32	**14-31 ?**	**<10**
[illegible]	13-37 (!?)	14-31	11
[illegible]	700	700	700
[illegible]eV @RT [MW]	**0.51-1.4[illegible]**	**0.6-1.1**	**0.24**
[illegible] / GeV [m] (*filling*=0.57)	97	97	56

Post CDR:
choice of frequency (802 MHz) and consideration of increased luminosity for ep→HX

LHeC: Linac(ERL)-Ring

Electron beam	LR ERL	LR
e-		
Lu		
Po		
Bu		
e-		
Bu		
Tr		
rm		
e-		
Fu		
Geometric reduction H_{hg}	[illegible]	[illegible]
Repetition rate [Hz]	N/A	10
Beam pulse length [ms]	N/A	5
ER efficiency	94%	N/A
Average current [mA]	6.6	5.4
Tot. wall plug power [MW]	100	100

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Spot size $\sigma_{x,y}$ [µm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8, 0.5	
Bunch spacing [ns]	25	2

ERL site power

3.9 MW
2.2 MW
4.1 MW
2.1 MW
1.6 MW
6.4 MW
3.0 MW
3.3 MW

ug!

	ERL 720 MHz	ERL 1.3 GHz	
duty factor	cw		
RF frequency [GHz]	0.72		
cavity length [m]			
energy gain / cavity [MeV]			
R/Q [100 Ω]			1200
Q_0 [10^{10}]		?	1
power		<0.5	<0.5
	32	14-31 ?	<10
	13-37 (!?)	14-31	11
	700	700	700
V @RT [MW]	0.51-1.4	0.6-1.1	0.24
/ GeV [m] (*filling*=0.57)	97	97	56

The latest LHeC ERL-ring design assumes the HL-LHC proton beam parameters for further boosting its performance reach (pushing luminosity up to 10^{34} cm^{-2}s^{-1})
→ A serious candidate of Higgs facility

Post CDR:
choice of frequency (802 MHz) and consideration of increased luminosity for ep→HX

LHeC Design Report

Total of ca. 500 pages

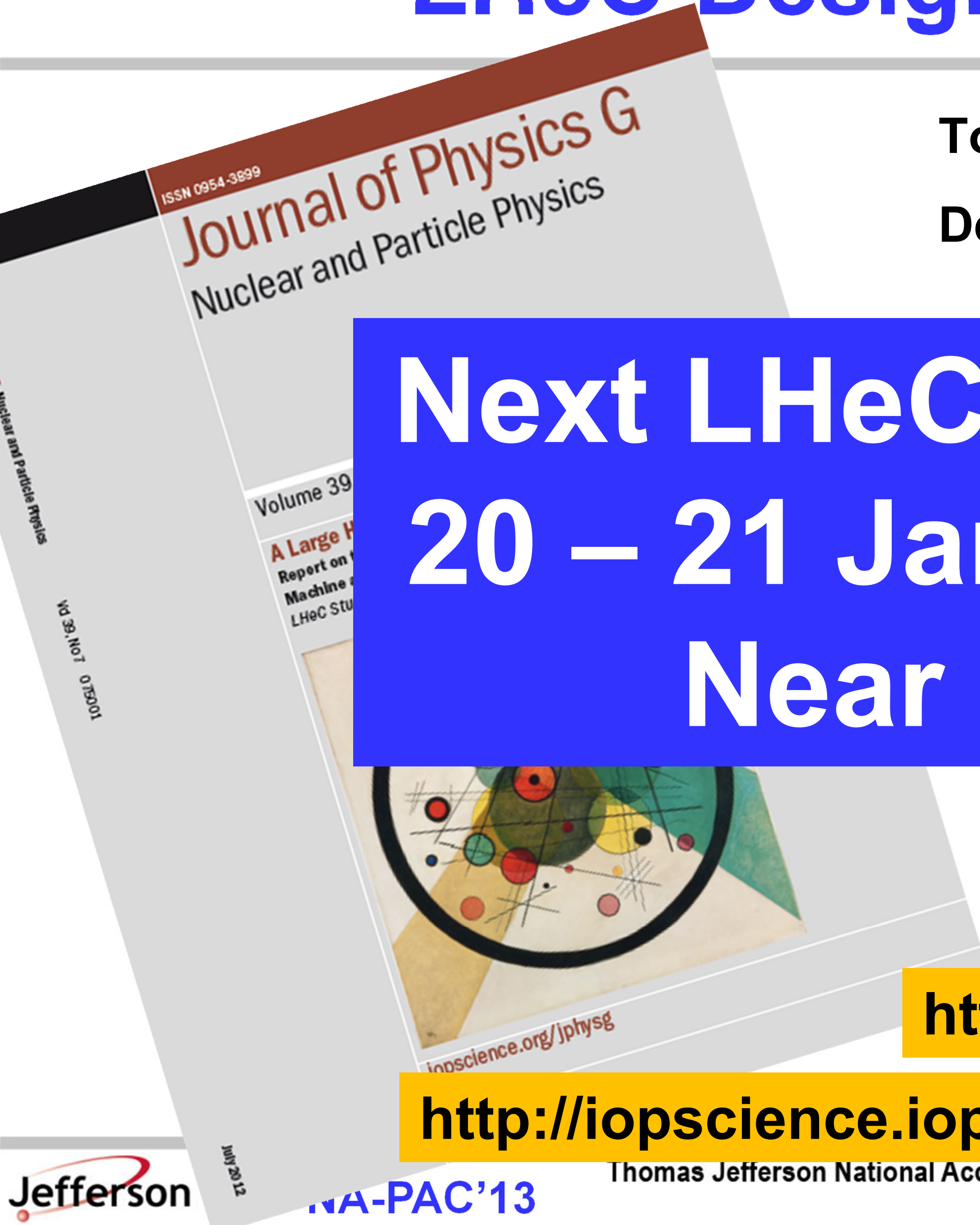
Detailed coverage of many topics:

- Sources
- Damping rings & injector complex
- Injection and injector complex
- Collective effects & Beam-Beam
- Cryogenic system
- Polarization
- Beam Dump
- Vacuum
- Power generation & distribution,

http://arxiv.org/abs/1206.2913

http://iopscience.iop.org/0954-3899/39/7/075001

LHeC Design Report



Total of ca. 500 pages

Detailed coverage of many topics:

- Sources
- ex
- n
- Vacuum
- Power generation & distribution,

Next LHeC Workshop
20 – 21 January 2013
Near CERN

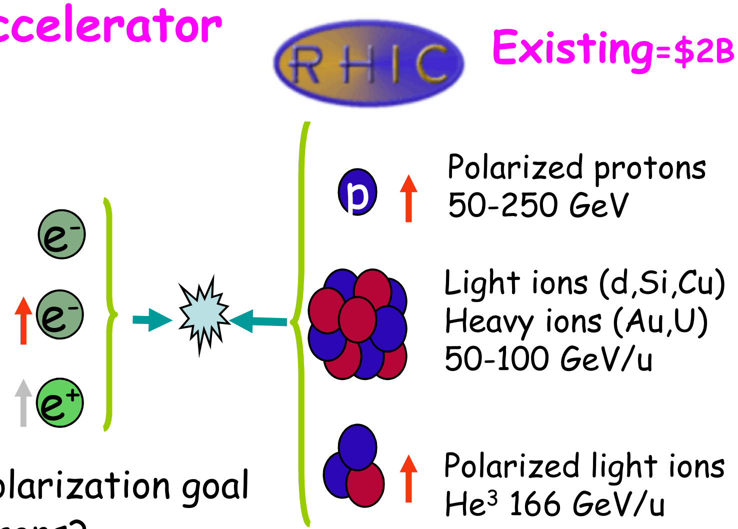
http://arxiv.org/abs/1206.2913

http://iopscience.iop.org/0954-3899/39/7/075001

eRHIC: ERL-Ring

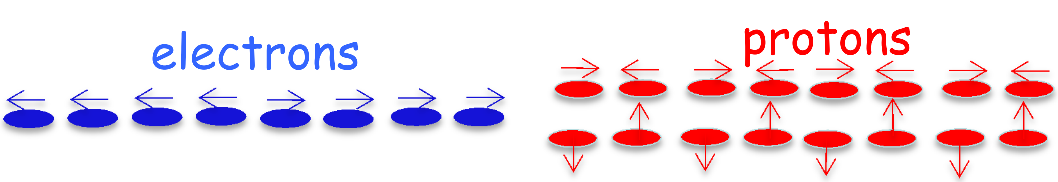
Electron accelerator to be build

Unpolarized and polarized leptons 5-20 (30) GeV



70% e^- beam polarization goal
polarized positrons?

Polarized electrons with $E_e \leq 30$ GeV will collide with either polarized protons with $E_e \leq 325$ GeV or heavy ions $E_A \leq 130$ GeV/u



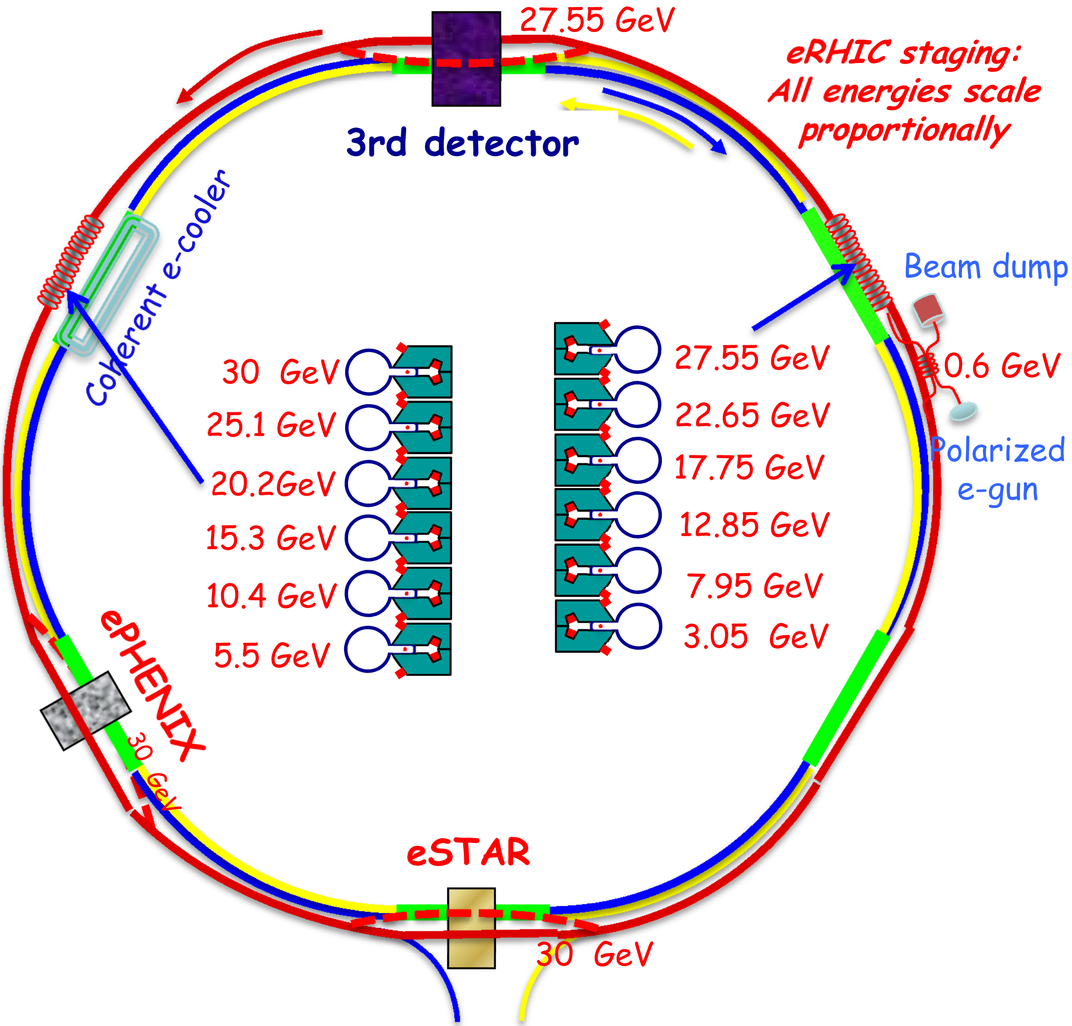
Center mass energy range: $\sqrt{s}$=30-200 GeV;
Luminosity ~ 10^{34}-10^{35} cm^{-2} sec^{-1}

Brief History

- 2000 – 1st eRHIC paper (I. Ben Zvi et al.)
- 2002 – 1st White Paper on eRHIC
- 2003 – eRHIC appears in DoE's "Facilities for the Future Sciences. A Twenty-Year Outlook"
- 2004 – "eRHIC Zeroth-Order Design Report" with <u>cost estimate for Ring-Ring</u>
- 2007 – **Linac-ring became baseline** (~10-fold higher luminosity)
- 2008 – first staging option of eRHIC
- 2009 – completed technical design, dynamics studies and <u>cost estimate</u> for MeRHIC with 4 GeV ERL
- Present - returned to the cost-effective (green) **all in tunnel** high-luminosity eRHIC design with staging electron energy from 10 GeV to 30 GeV

eRHIC: ERL-Ring

BROOKHAVEN NATIONAL LABORATORY



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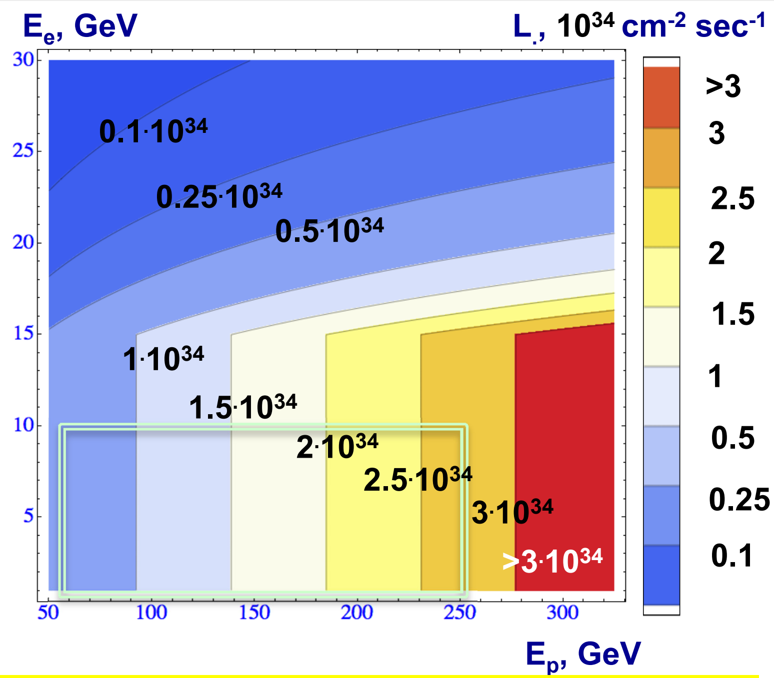
eRHIC: ERL-Ring

	e	p	$^2He^3$	$^{79}Au^{197}$	$^{92}U^{238}$
Energy, GeV	20	250	167	100	100
CM energy, GeV		100	82	63	63
Number of bunches/distance between bunches, ns	107	111	111	111	111
Bunch intensity (nucleons), 10^{11}	0.36	4	6	6	6
Bunch charge, nC	5.8	64	60	39	40
Beam current, mA	50	556	556	335	338
Normalized emittance of hadrons, 95%, mm mrad		1.2	1.2	1.2	1.2
Normalized emittance of electrons, rms, mm mrad		16	24	40	40
Polarization, %	80	70	70	none	None
rms bunch length, cm	0.2	5	5	5	5
β*, cm	5	5	5	5	5
Luminosity per nucleon, $x10^{34}$ cm^{-2} s^{-1} (with hourglass effect)		2.7	2.7	1.6	1.7



Space charge compensation boosts luminosity with low ion energies

Reaching high luminosity:

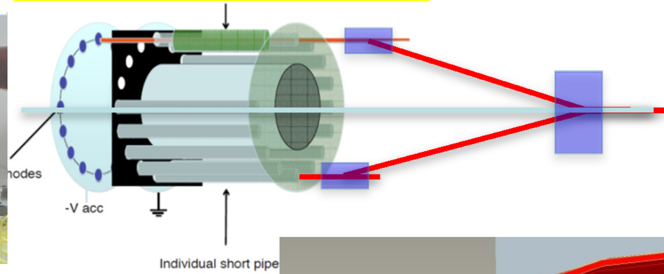
- high average electron current (50 mA = 3.5 nC * 14 MHz)
  - energy recovery linacs; SRF technology
  - high current polarized electron source
- cooling of high energy hadrons (Coherent Electron Cooling)
- β*=5 cm IR with crab-crossing

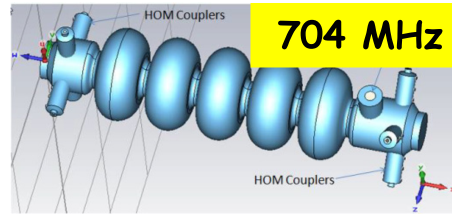
Limiting factors:

- hadron $\Delta Q_{sp} \le 0.035$
- hadron $\xi \le 0.015$
- polarized e current ≤ 50 mA
- SR power loss ≤ 7 MW

eRHIC: Electron ERL Development

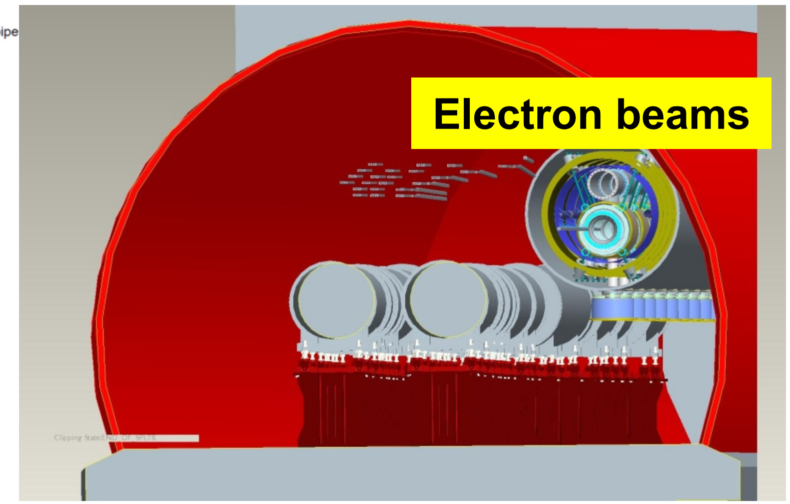
Polarized e-injector

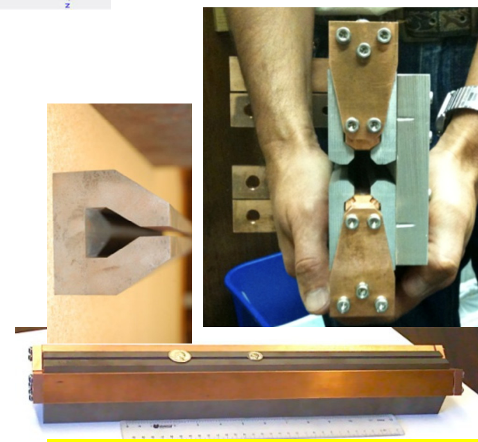




704 MHz SRF cavity

Electron beams

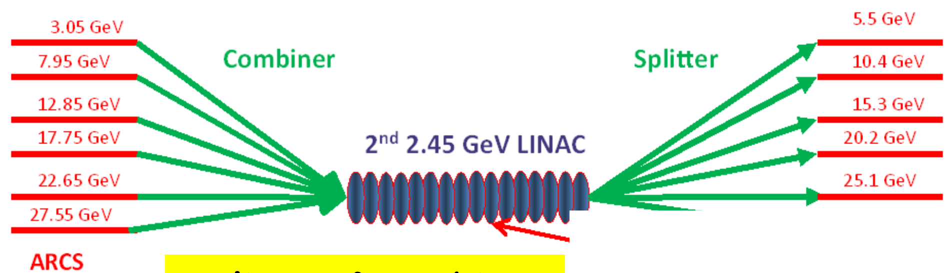




Compact arc magnets

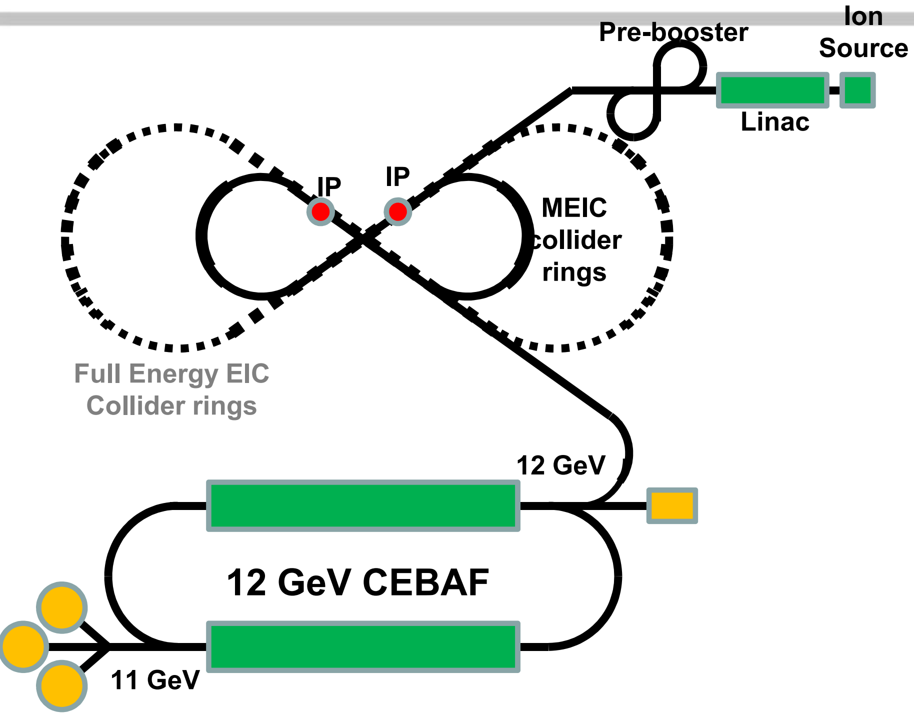
ERL R&D

Heavy ions and polarized protons already there at BNL



Splitter & combiner

MEIC: Ring-Ring



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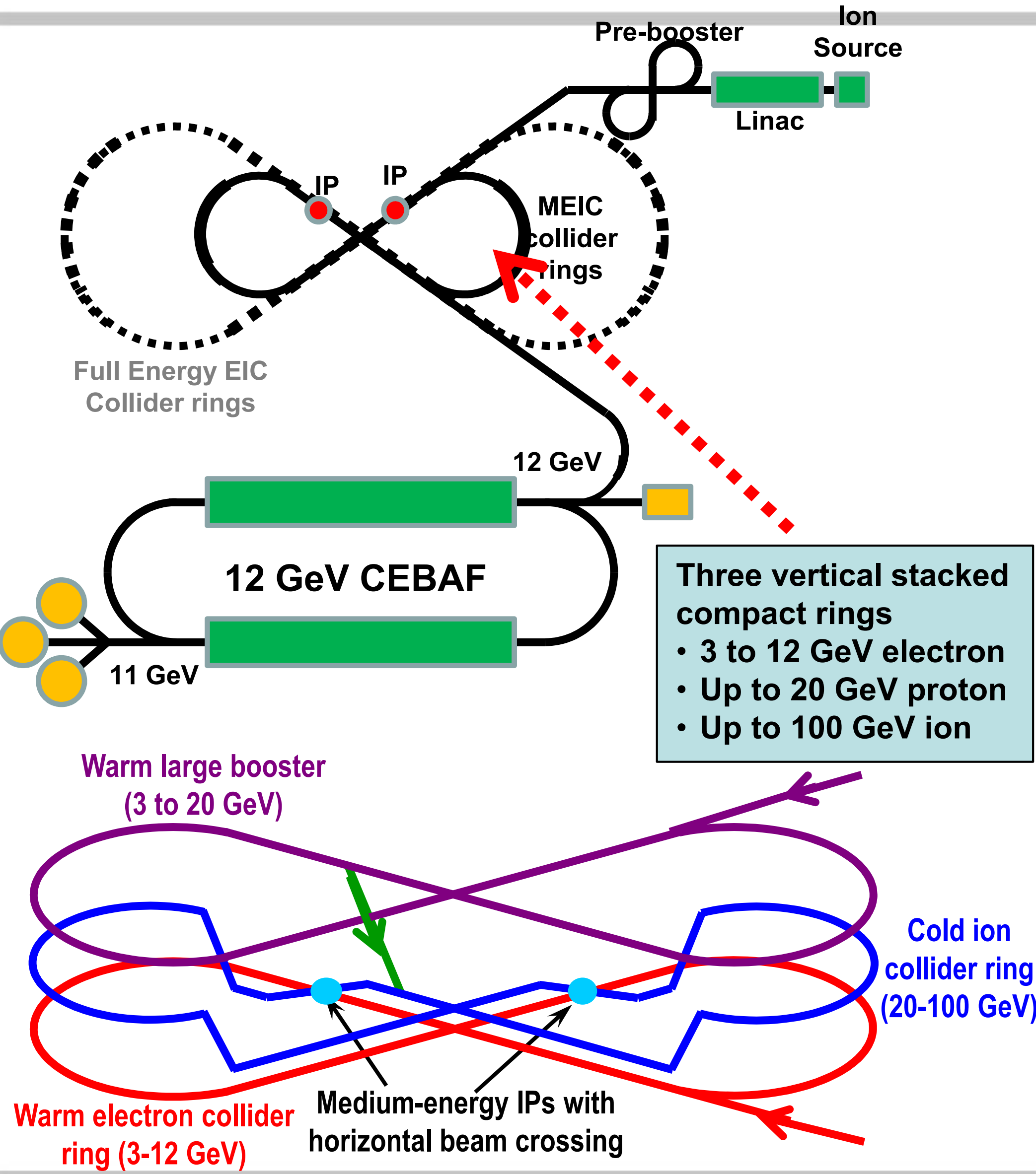
2003 ERL based circulator e-cooler
2006 **Baseline changed to ring-ring**
2007 ELIC 0th Order Design Report
2009 **Medium energy (MEIC) became the baseline** with a future energy upgrade
2012 MEIC Design Report released

Present baseline: Ring-Ring

- Energy: 3-12 GeV e on 20-100 GeV p or up 40 GeV/u ion
- Polarized light ions (p, d, ^{3}He), unpolarized ions up to A=200 (Au, Pb)
- New ion complex & two collider rings
- Up to 3 interaction points
- High polarization for both beams
- Conventional electron cooling
- Upgradable to 20 GeV electron, 250 GeV proton or 100 GeV/u ion

MEIC: Ring-Ring



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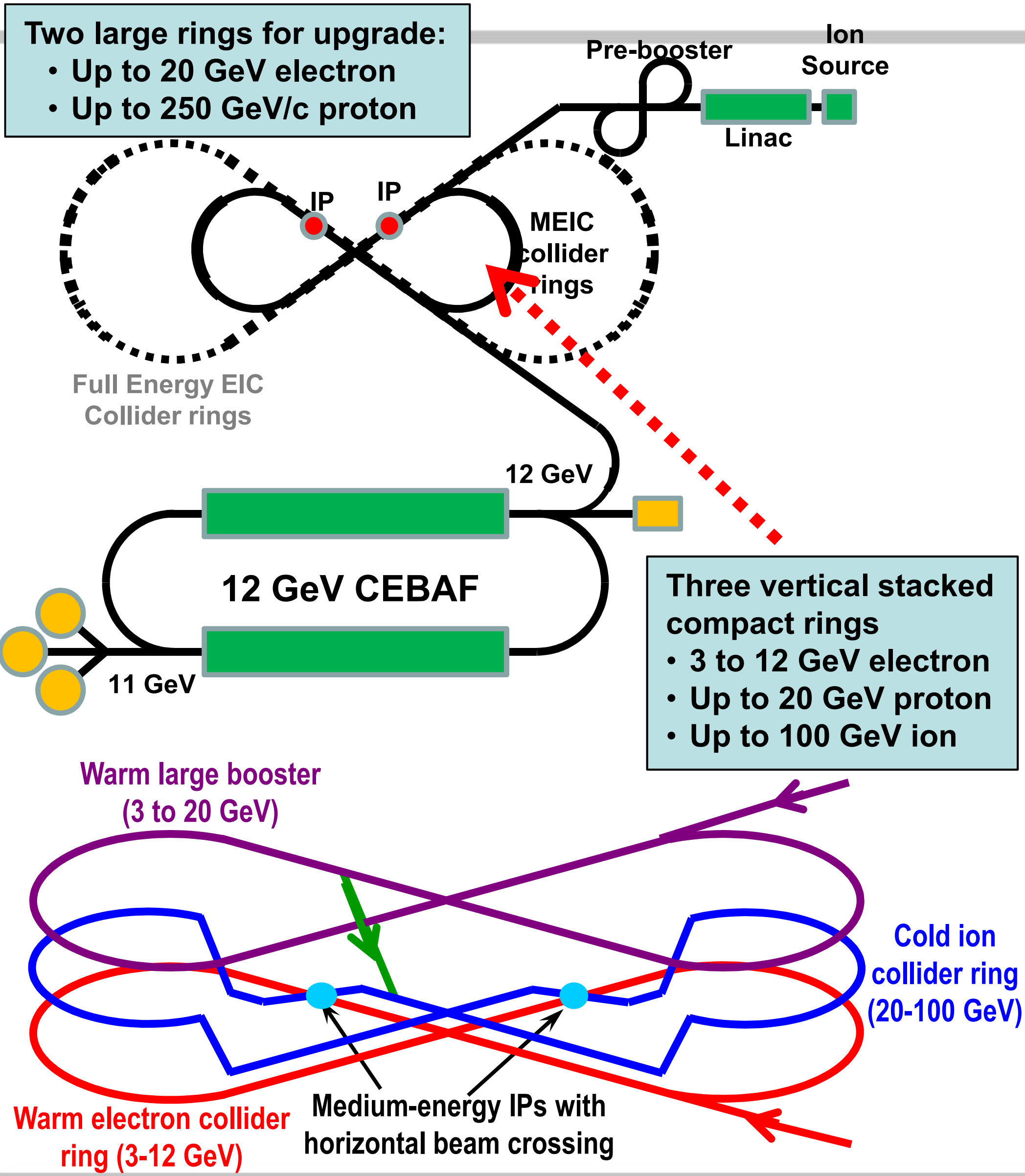

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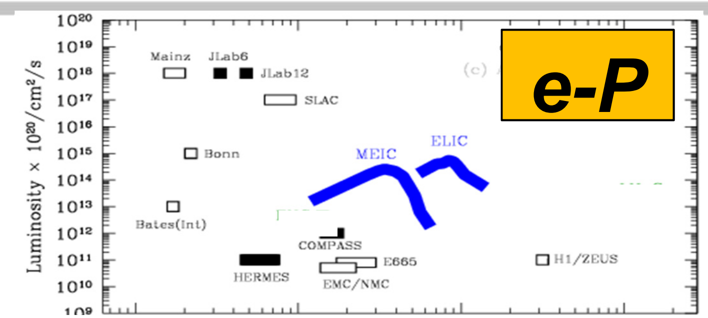
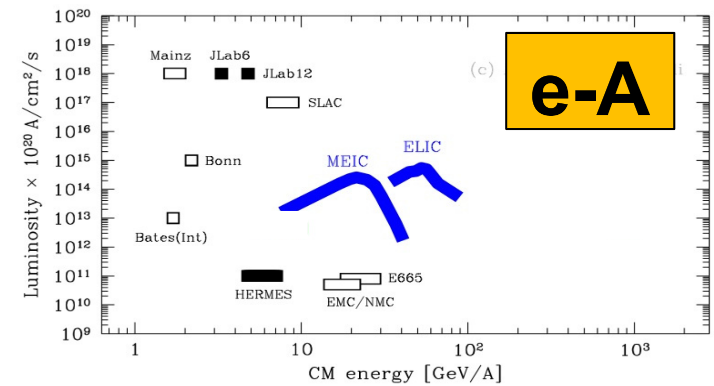
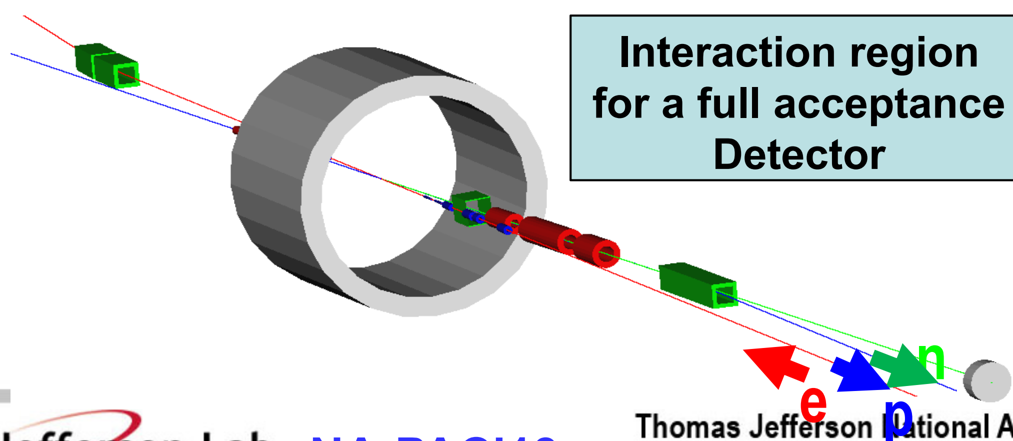
MEIC: Ring-Ring

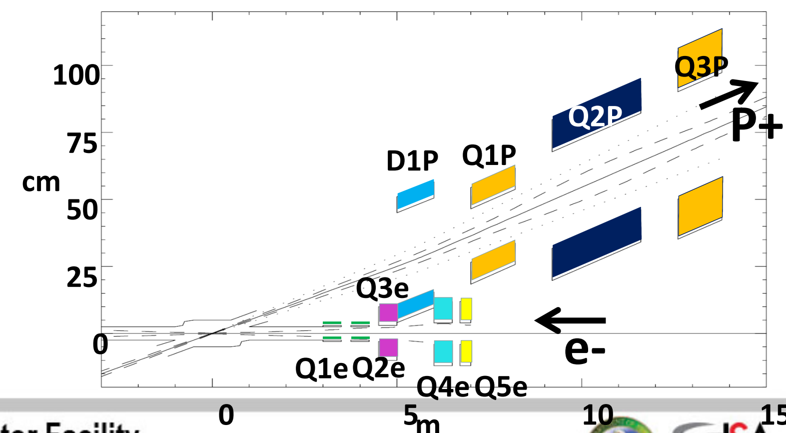
		Proton	Electron
Beam energy	GeV	60	5
Collision frequency	MHz	750	
Beam current / Particles/bunch	A /10[10]	0.5 / 0.416	3 / 2.5
Polarization	%	> 70	~ 80
RMS bunch length	cm	10	7.5
Emittance, norm. (x/y)	µm	0.35 / 0.07	54 / 11
Horizontal and vertical β*	cm	10 / 2 (4 / 0.2)	
Vert. beam-beam tune shift		0.014	0.03
Laslett tune shift		0.06	Small
Dist. from IP to 1st FF quad	m	7 (4.5)	3.5
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	5.6 (14.2)	





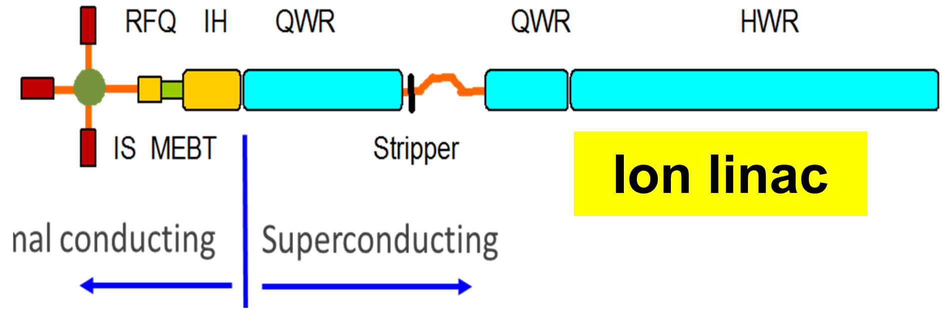
Interaction region for a full acceptance Detector





MEIC: A New Ion Complex

- Generate/accumulate and accelerate ion beams
- Covering all required varieties of ion species
- Matching time, spatial and phase space structure of the ion beam with electron beam

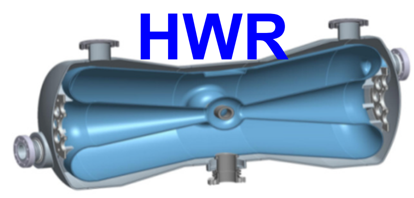


Ion linac

	Length (m)	Max. energy (GeV/c)	Electron Cooling
SRF linac		0.2 (0.08)	
Pre-booster	~300	3 (1.2)	DC
booster	~1300	20 (8 to 15)	
collider ring	~1300	96 (40)	Staged/ERL

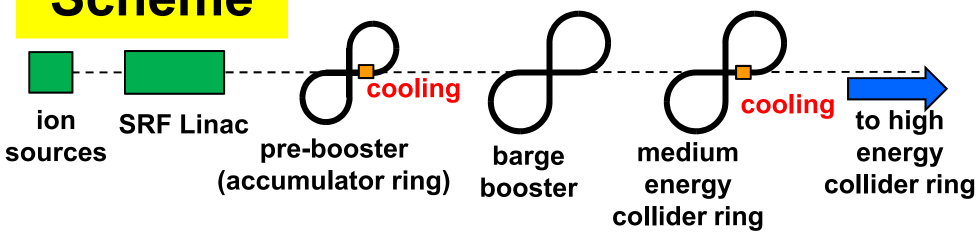
* Numbers in parentheses represent energies per nucleon for heavy ions

Quarter Wave Resonator (QWR)

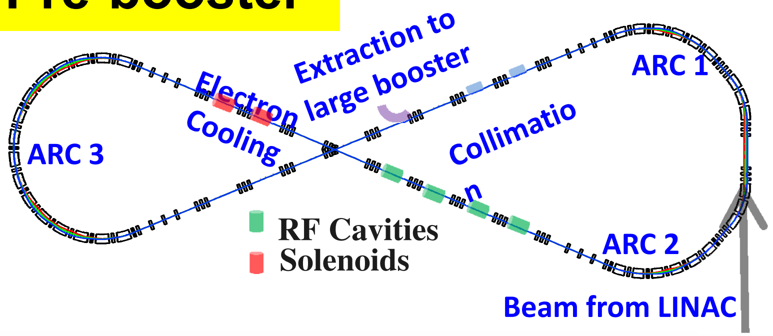


Half-Wave Resonator (HWR)

Scheme



Pre-booster



MEIC Design Report Released!

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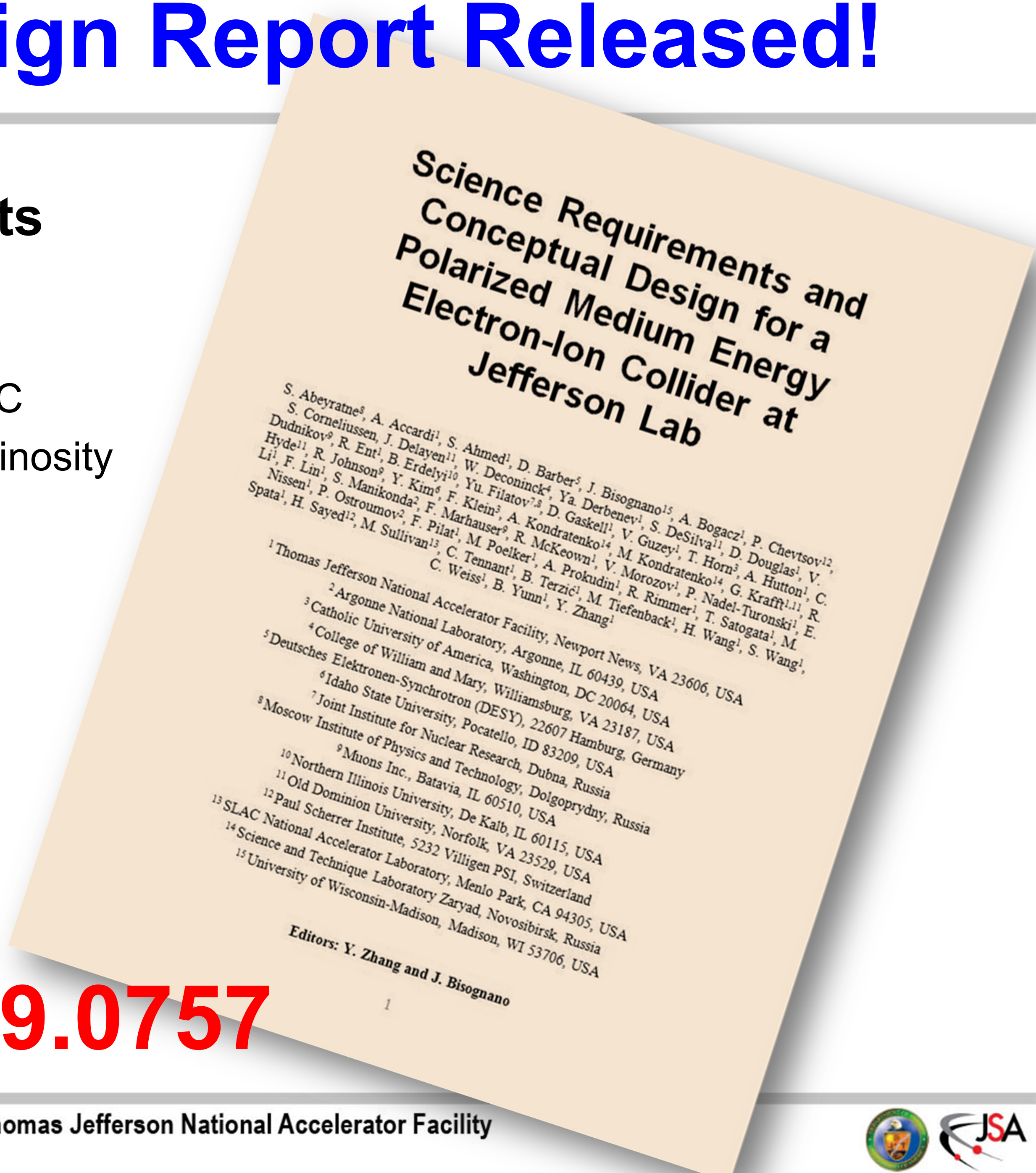

Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

S. Abeyratne[8], A. Accardi[1], S. Ahmed[1], D. Barber[5], J. Bisognano[15], A. Bogacz[1], P. Chevtsov[12], S. Corneliussen, J. Delayen[11], W. Deconinck[4], Ya. Derbenev[1], S. DeSilva[11], D. Douglas[1], V. Dudnikov[9], R. Ent[1], B. Erdelyi[10], Yu. Filatov[7,8], D. Gaskell[1], V. Guzey[1], T. Horn[3], A. Hutton[1], C. Hyde[11], R. Johnson[9], Y. Kim[6], F. Klein[3], A. Kondratenko[14], M. Kondratenko[14], G. Krafft[1,11], R. Li[1], F. Lin[1], S. Manikonda[2], F. Marhauser[9], R. McKeown[1], V. Morozov[1], P. Nadel-Turonski[1], E. Nissen[1], P. Ostroumov[2], F. Pilat[1], M. Poelker[1], A. Prokudin[1], R. Rimmer[1], T. Satogata[1], M. Spata[1], H. Sayed[12], M. Sullivan[13], C. Tennant[1], B. Terzic[1], M. Tiefenback[1], H. Wang[1], S. Wang[1], C. Weiss[1], B. Yunn[1], Y. Zhang[1]

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[10] Northern Illinois University, De Kalb, IL 60115, USA
[11] Old Dominion University, Norfolk, VA 23529, USA
[12] Paul Scherrer Institute, 5232 Villigen PSI, Switzerland
[13] SLAC National Accelerator Laboratory, Menlo Park, CA 94305, USA
[14] Science and Technique Laboratory Zaryad, Novosibirsk, Russia
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Editors: Y. Zhang and J. Bisognano

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arXiv:1209.0757

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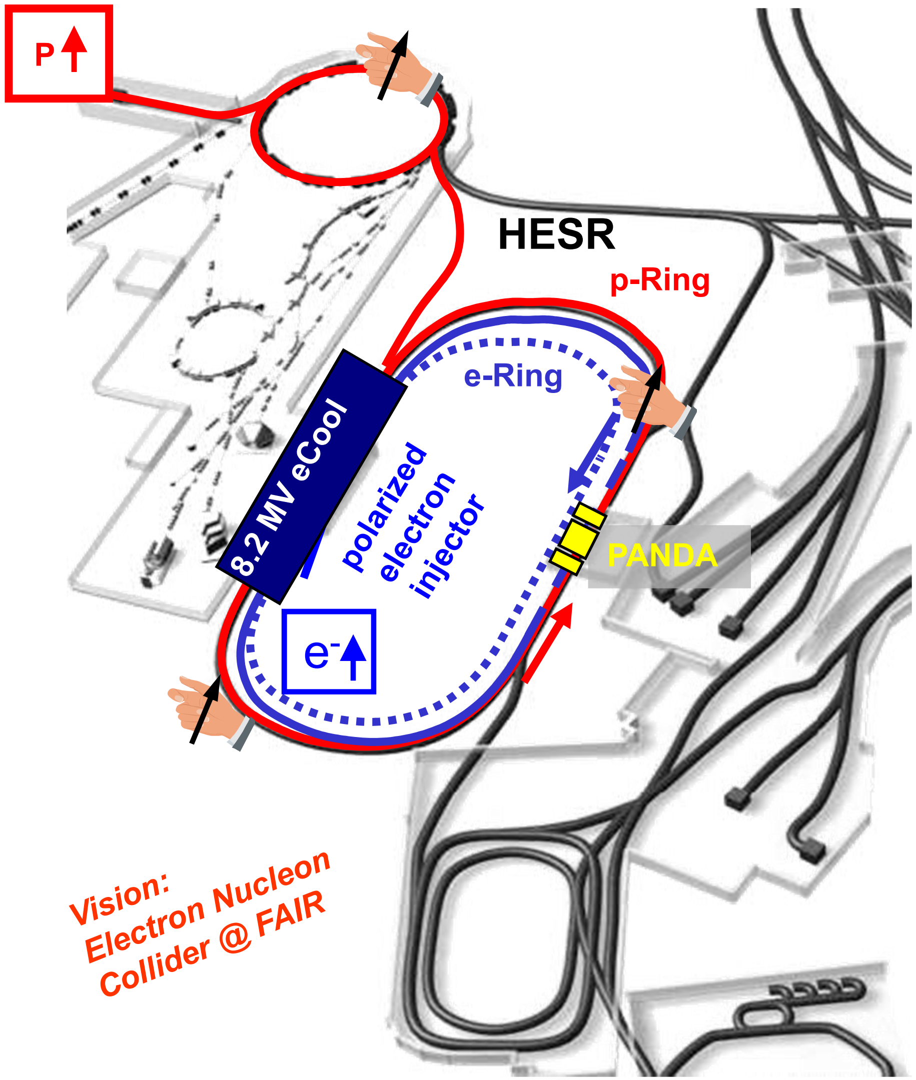


Facility for Antiproton & Ion Research (FAIR@GSI)

- Nuclear structure physics
- Physics with antiprotons
- Nuclear matter physics
- Plasma physics
- Atomic physics

ENC@FAIR

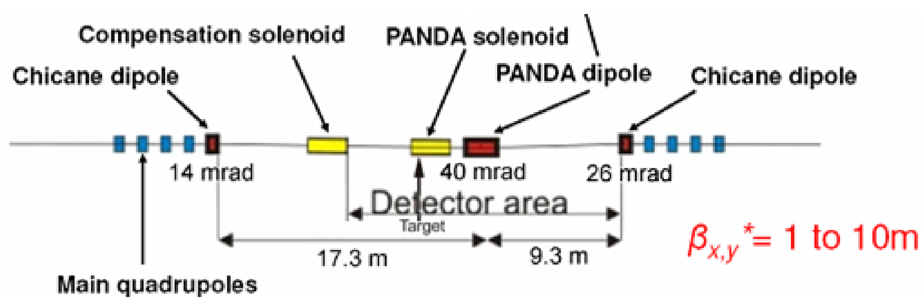
- Use High Energy Storage Ring **(HESR) for storing 15 GeV proton beam**
- Add **an electron storage ring for 3 GeV** 2 A beam
- Share PANDA detector

- Head-on collision
- Baseline: $\beta^*=30$ cm ➔ 2×10^{32} cm^{-2}s^{-1}
- Aggressive: $\beta^*=10$ cm ➔ 6×10^{32} cm^{-2}s^{-1}
- With "traveling focusing" ➔10^{33} cm^{-2}s^{-1}

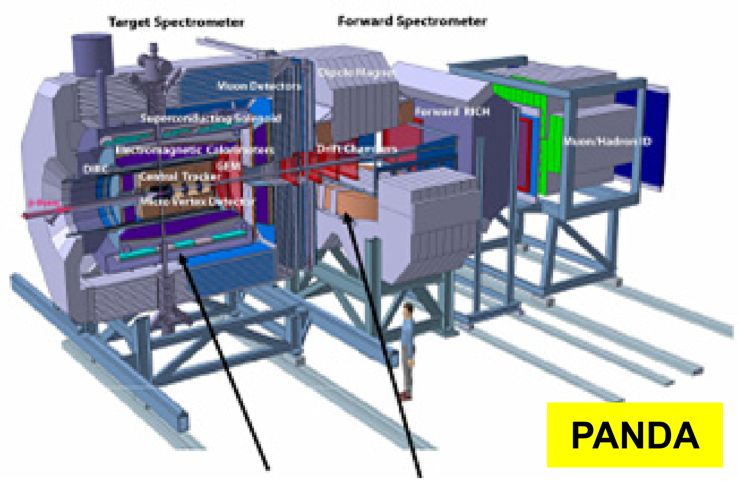
ENC @ FAIR

	HESR / 15GeV p	eRing / 3GeV
L [ring circumference, m]	~ 575	
ε^{norm} / ε^{geo} [mm mrad, rms]	≤ 2.1 / ≤ 0.13	
$\Delta p/p$ (rms)	~ $4 \cdot 10^{-4}$	
β_{IP} [m]	0.3	
r_{IP} [mm, rms]	≤ 0.2	
l (bunch length) [m]	0.27 - 0.35	0.1
n (particle / bunch)	$5.4 \cdot 10^{10}$	$23 \cdot 10^{10}$
h (number of bunches)	100	100
f_{coll} (collision freq) [MHz]	~ 52	
l_{coll} (bunch distance) [m]	~ 5.76	
ΔQ_{sc} (space charge)	≥ 0.05	
ξ (beam-beam parameter)	0.014	0.015
L (luminosity) [$cm^{-2}s^{-1}$]	~ $2 \cdot 10^{32}$	

- Due to availability of HESR storage ring & PANDA detector (from about year 2018 on), an upgrade to collider operation requires only a fraction of the cost of other projects.
- Considerable R&D is required to achieve the parameter set; however there seem to be no issues which are beyond the accepted potential of accelerator physics.
- Physics potential of ENC approaches stage 1 of the EIC concepts at BNL and JLab



$\beta_{x,y}{}^* = 1$ to 10m



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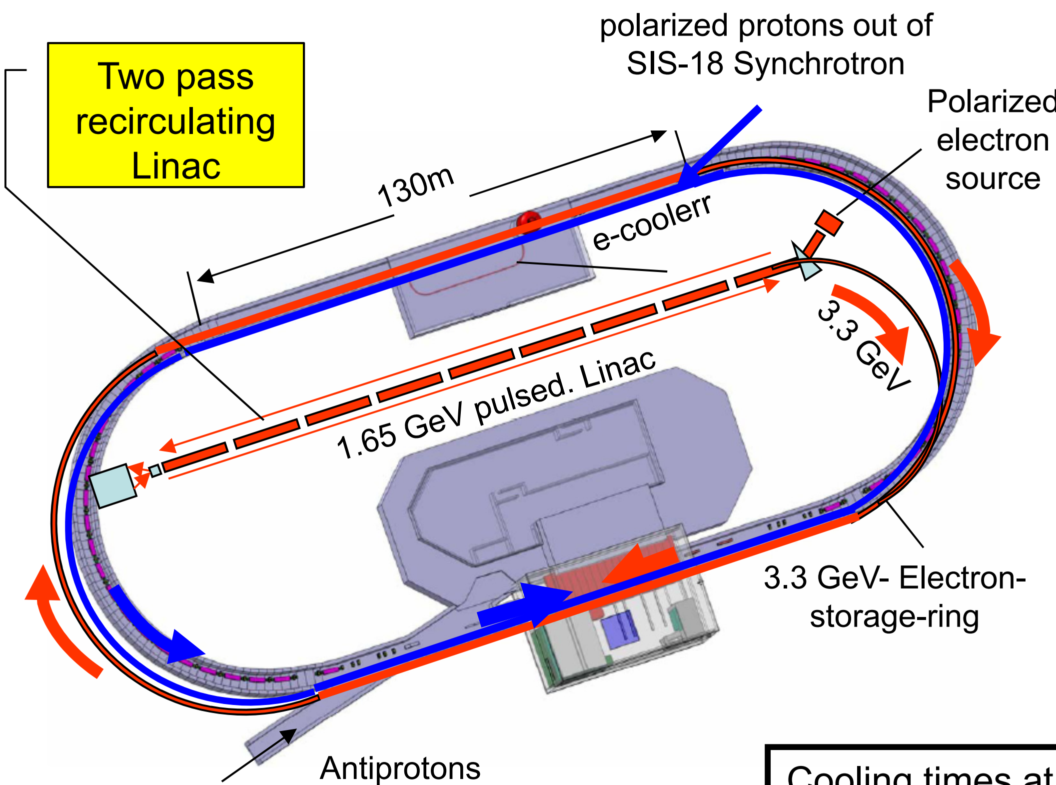
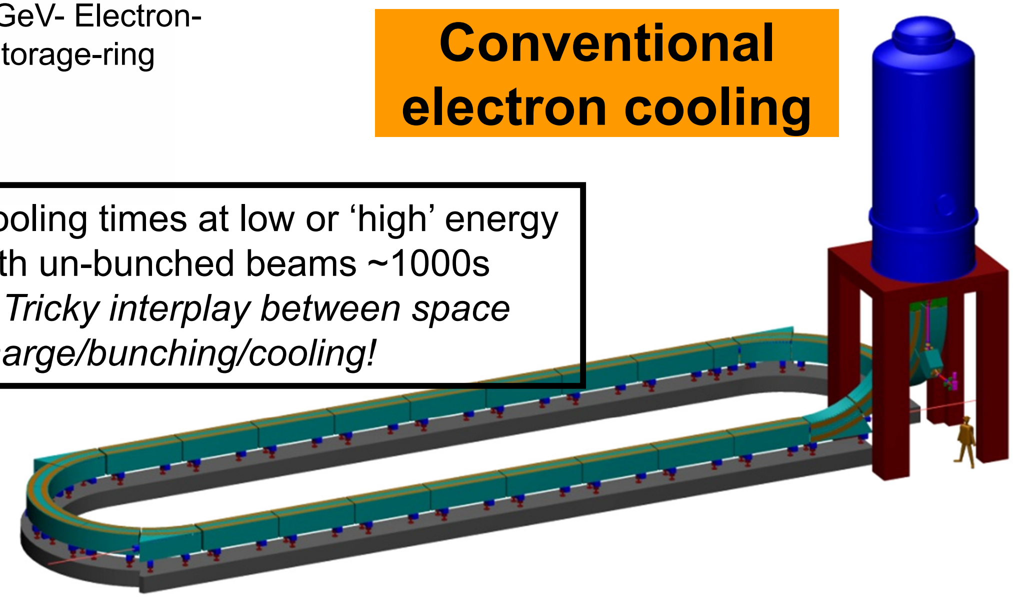


Energy	0.4-8 MeV
Current	1-3 A
Solenoid field	0.07 - 0.2 T
Straightness (rad rms)	$1\cdot10^{-5}$
Interaction length	24 m
Bending radius	4 m

Conventional electron cooling

Cooling times at low or 'high' energy with un-bunched beams ~1000s
➔ *Tricky interplay between space charge/bunching/cooling!*

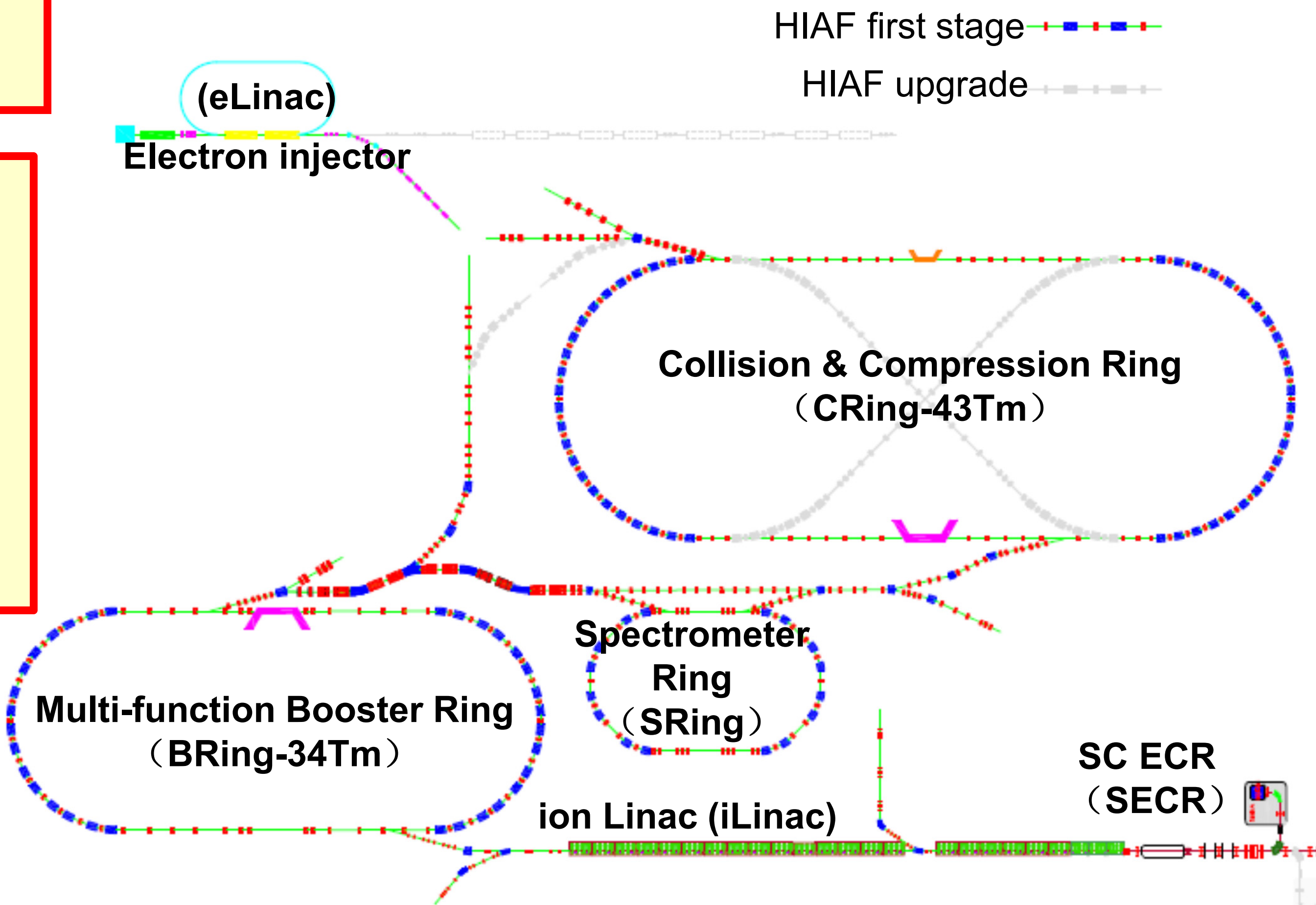


High Intensity Heavy Ion Accelerator Facility (HIAF) at Institute of Modern Physics, CAS

Science goals of HIAF
- Nuclear physics
- High energy density physics
- Science based on the EIC
- Atomic physics
- Application

Main Components
- High intensity ion source
- High intensity pulsed SC-Linac
- Multi-function booster and collector ring
- Long straight ion collider
- Figure-8 electron collider
- Large acceptance RIBs line

- **A multi-purpose science complex w/ a green field design**
- **Already approved (2013) by Chinese central government** (total $2.3B RMB (~$380M) plus labors)
- **Electron-ion Collider is likely in the 2nd stage**



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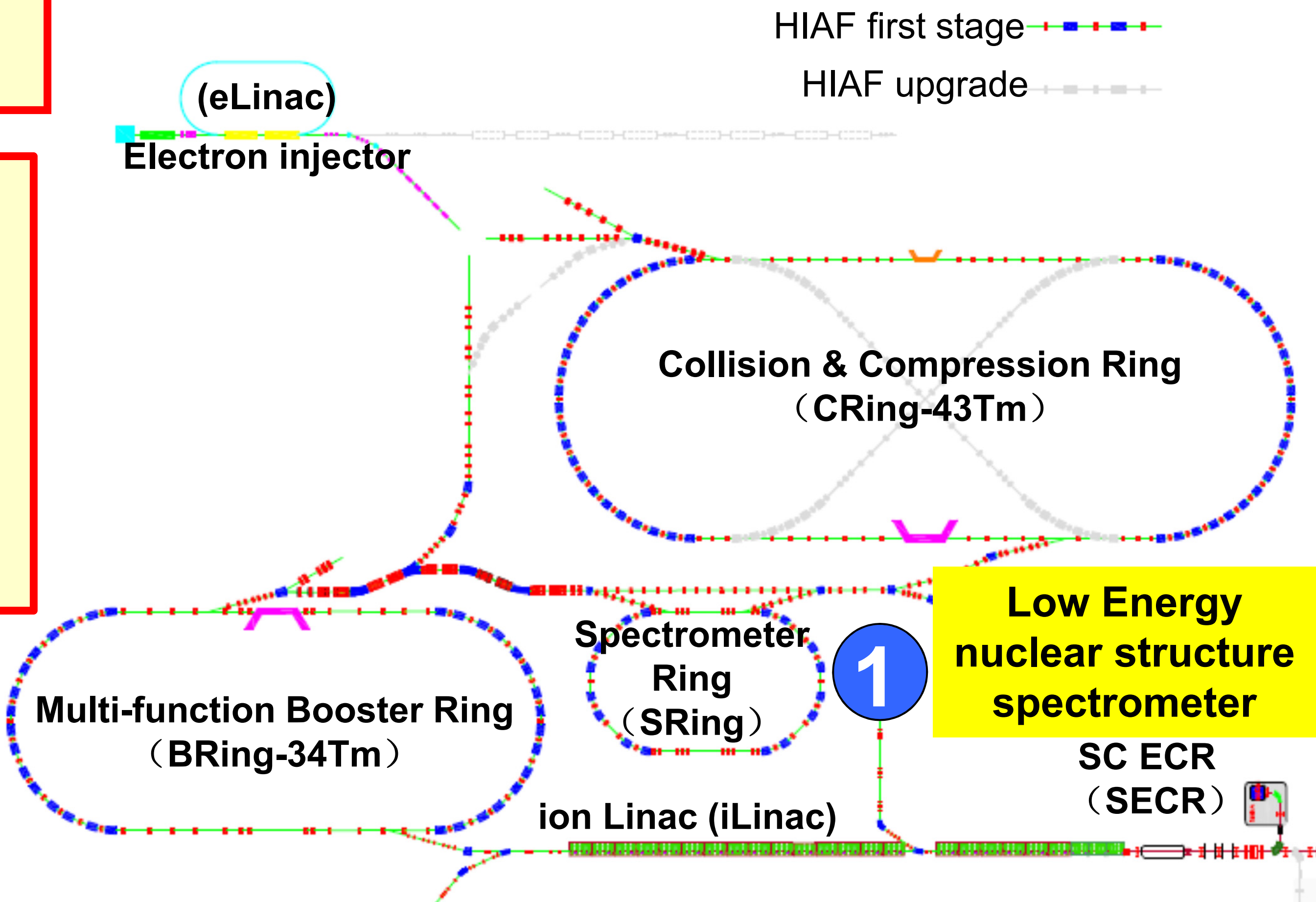

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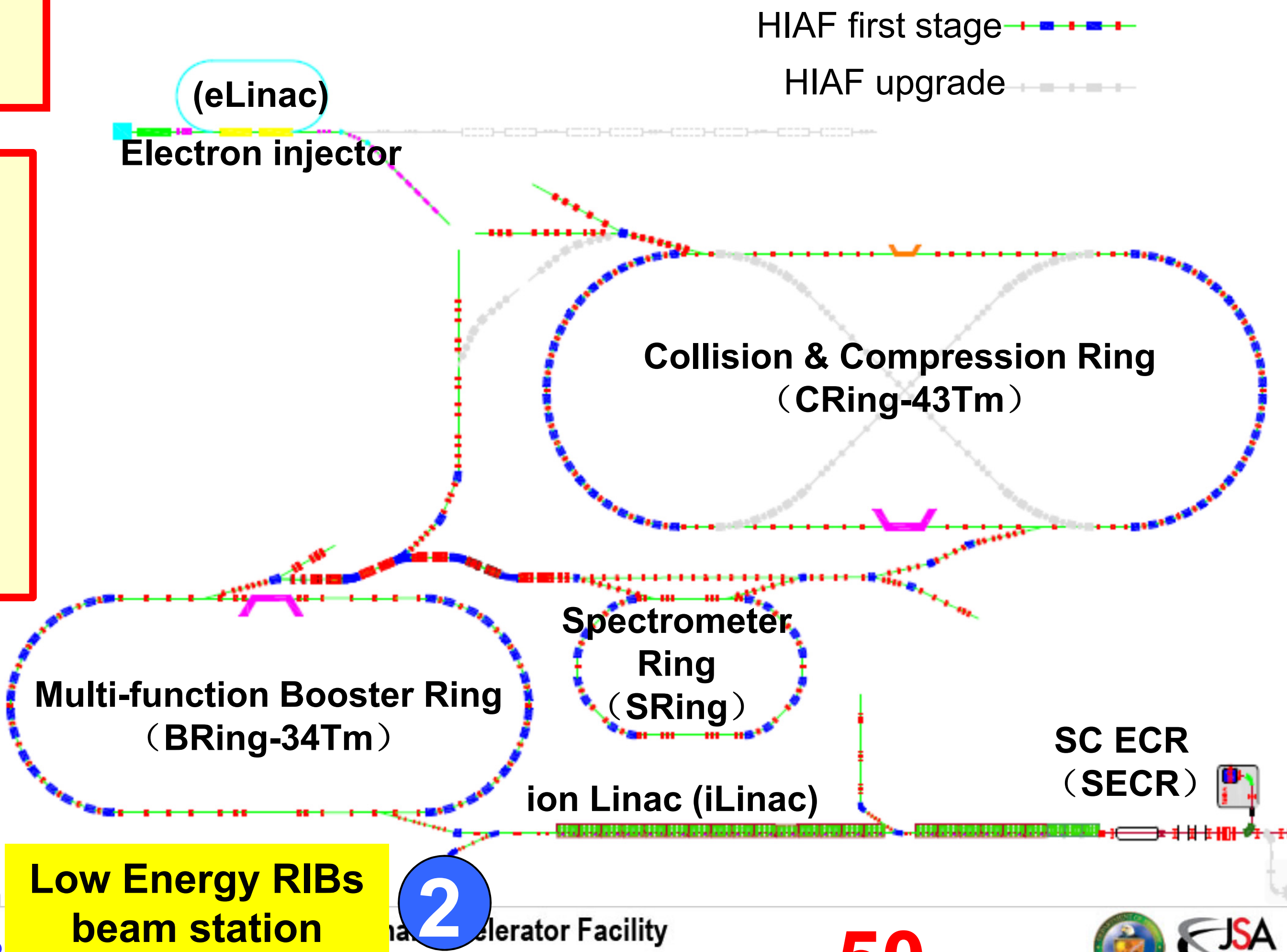

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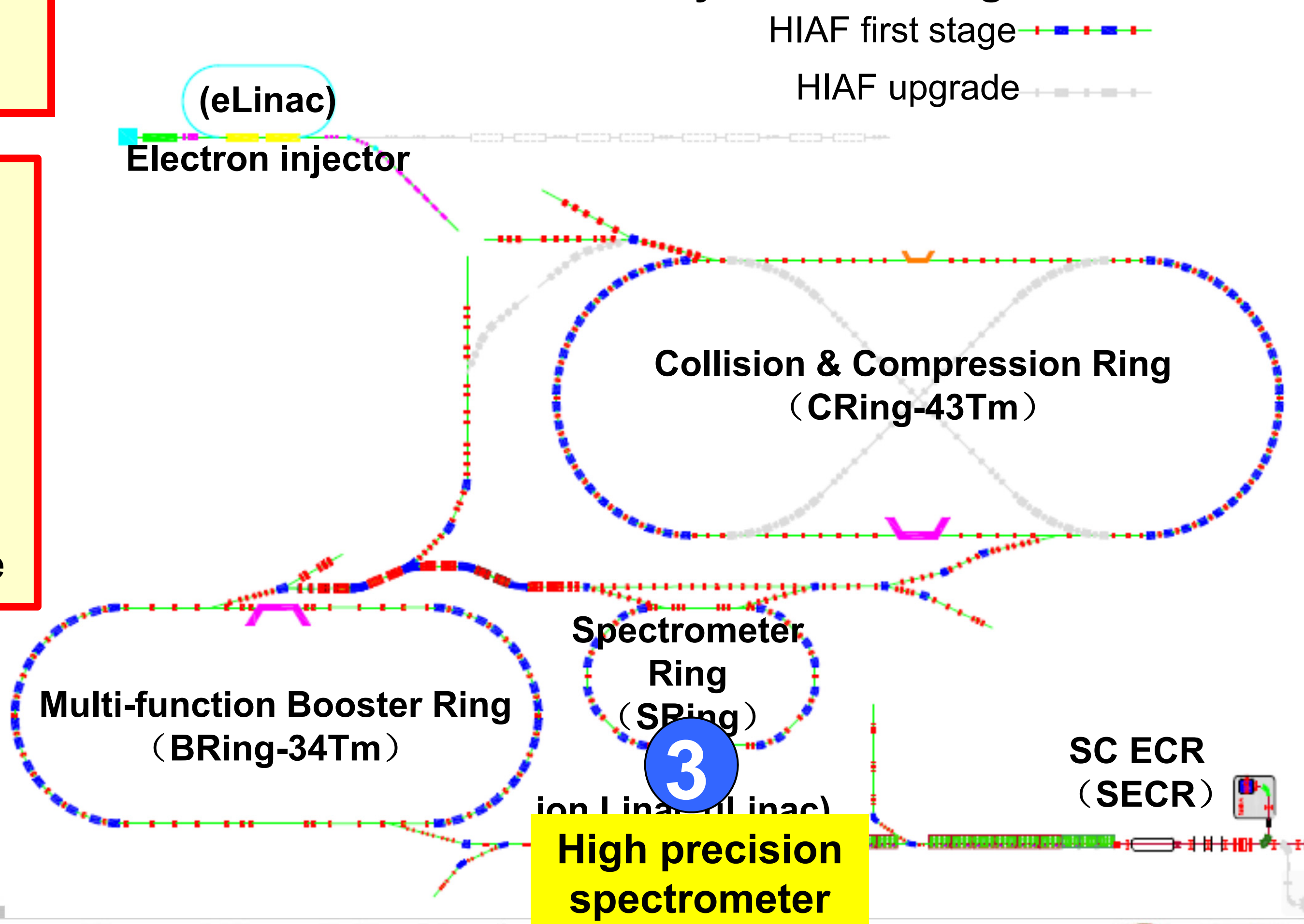

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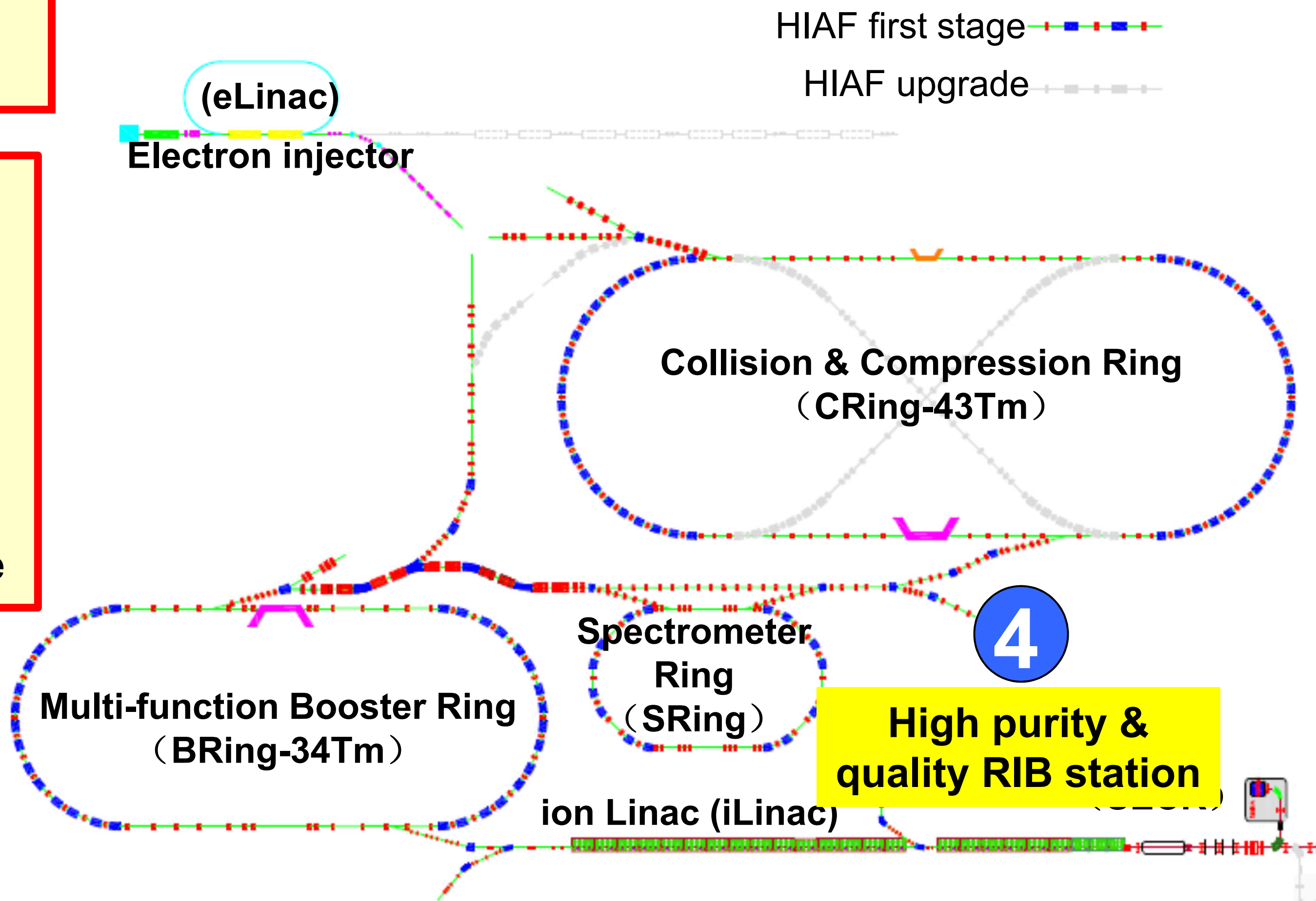

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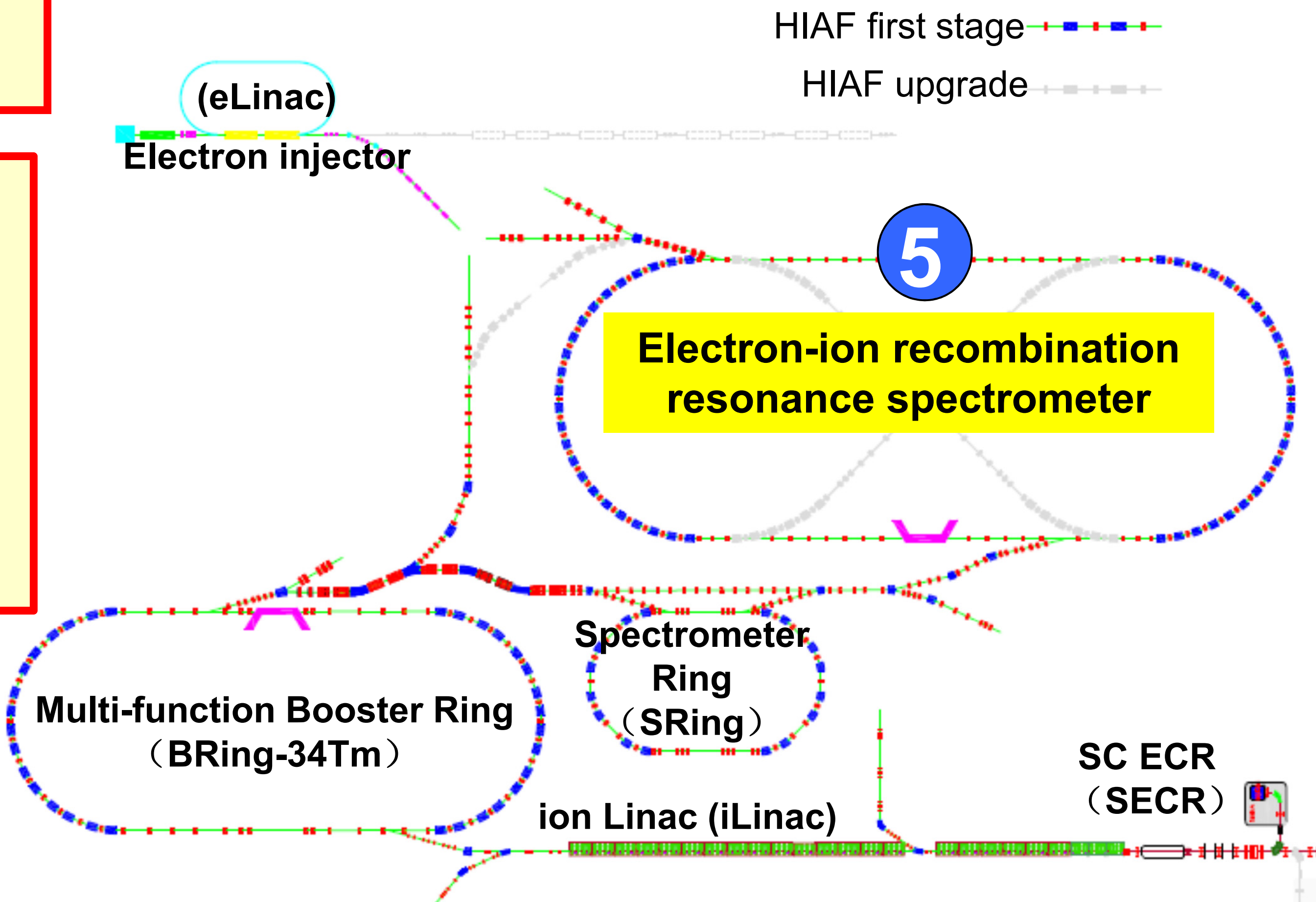

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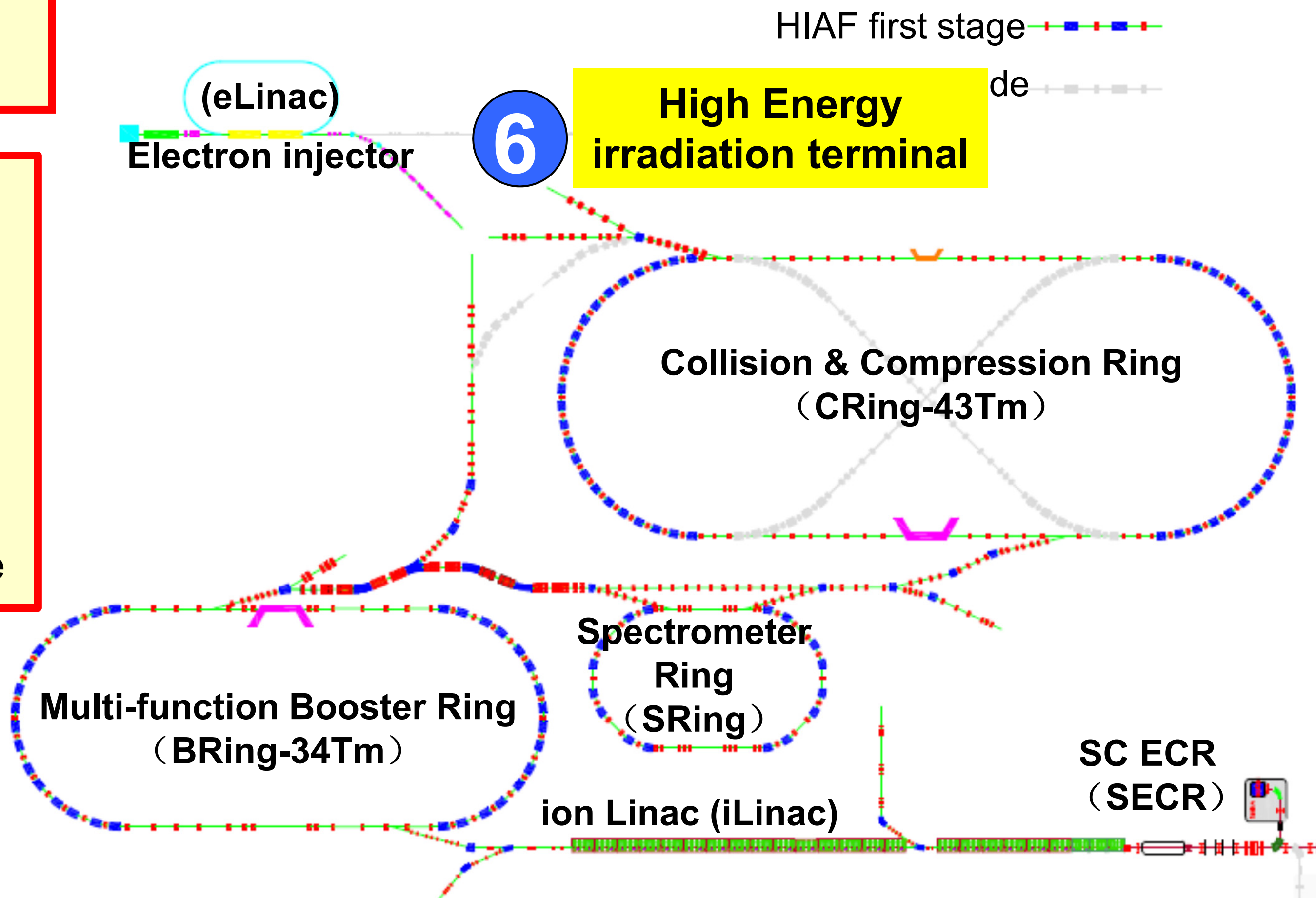

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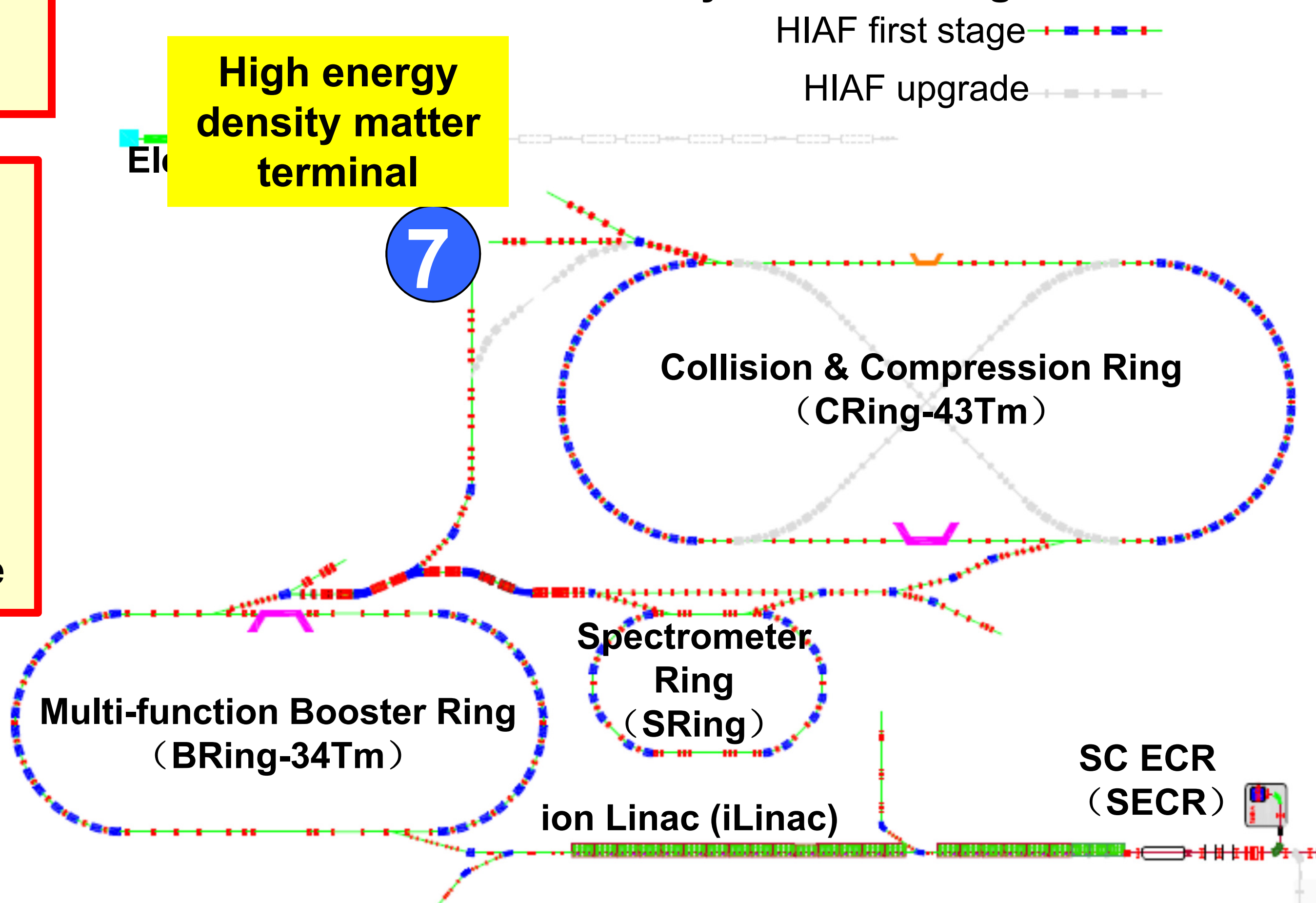

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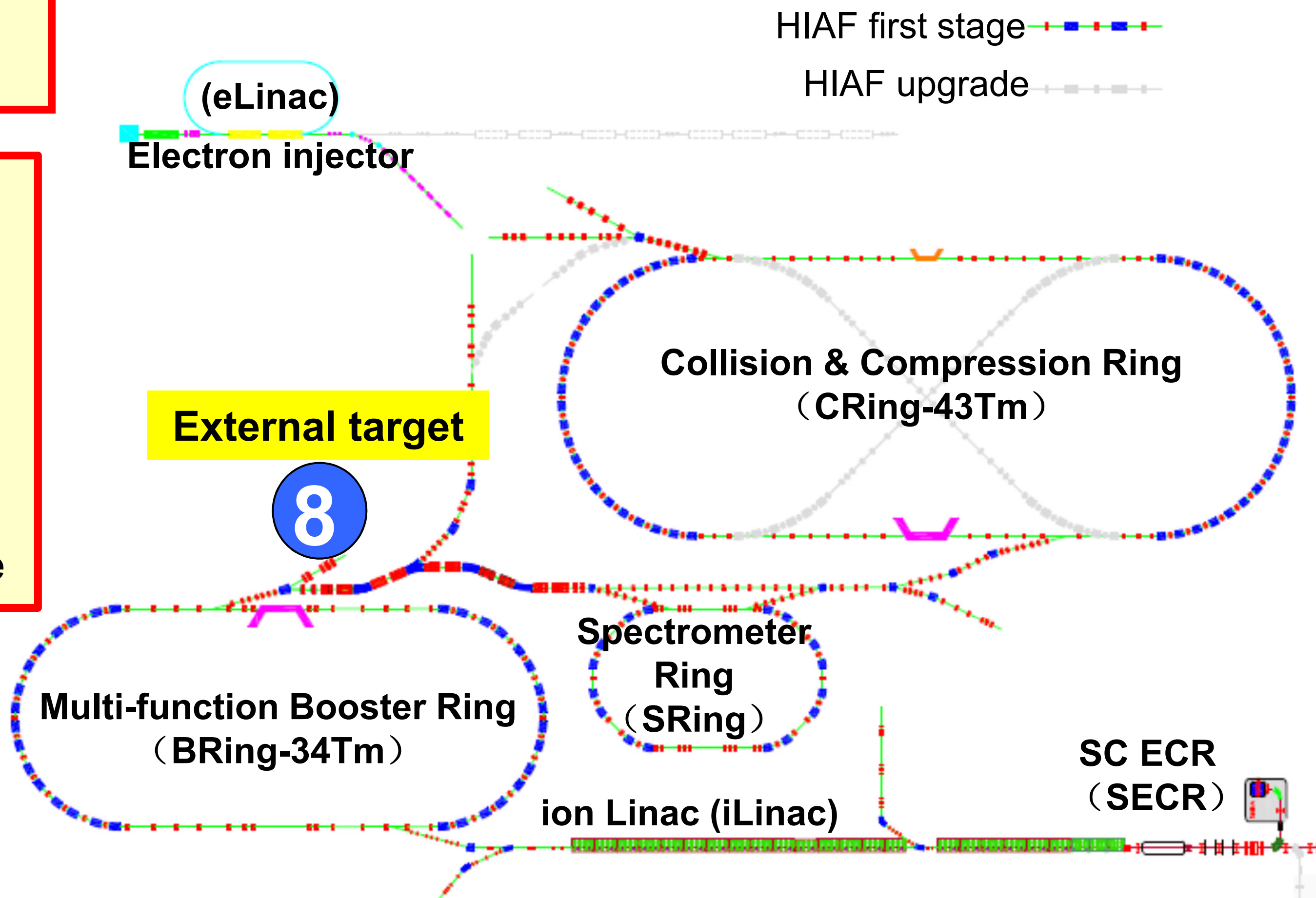

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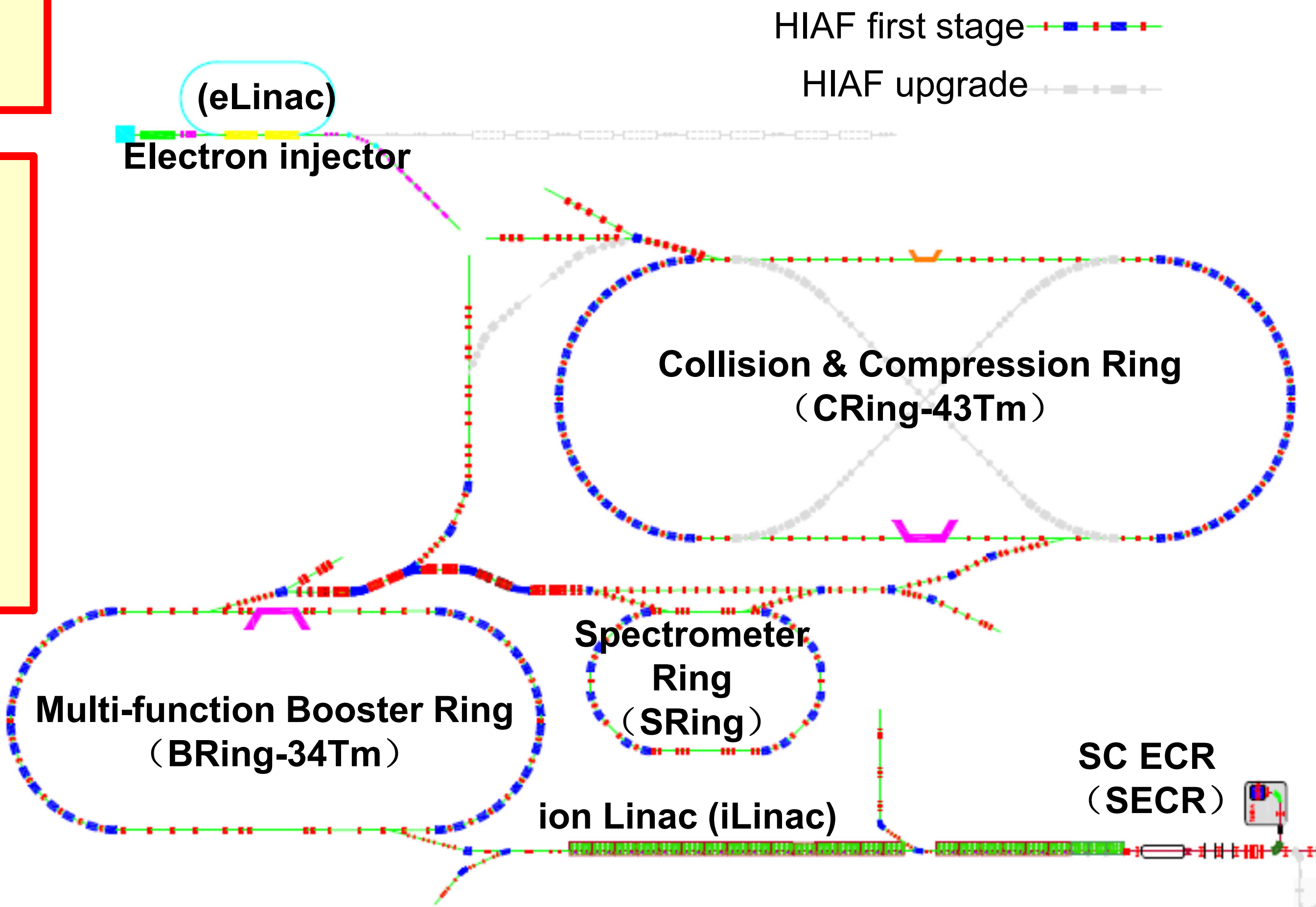

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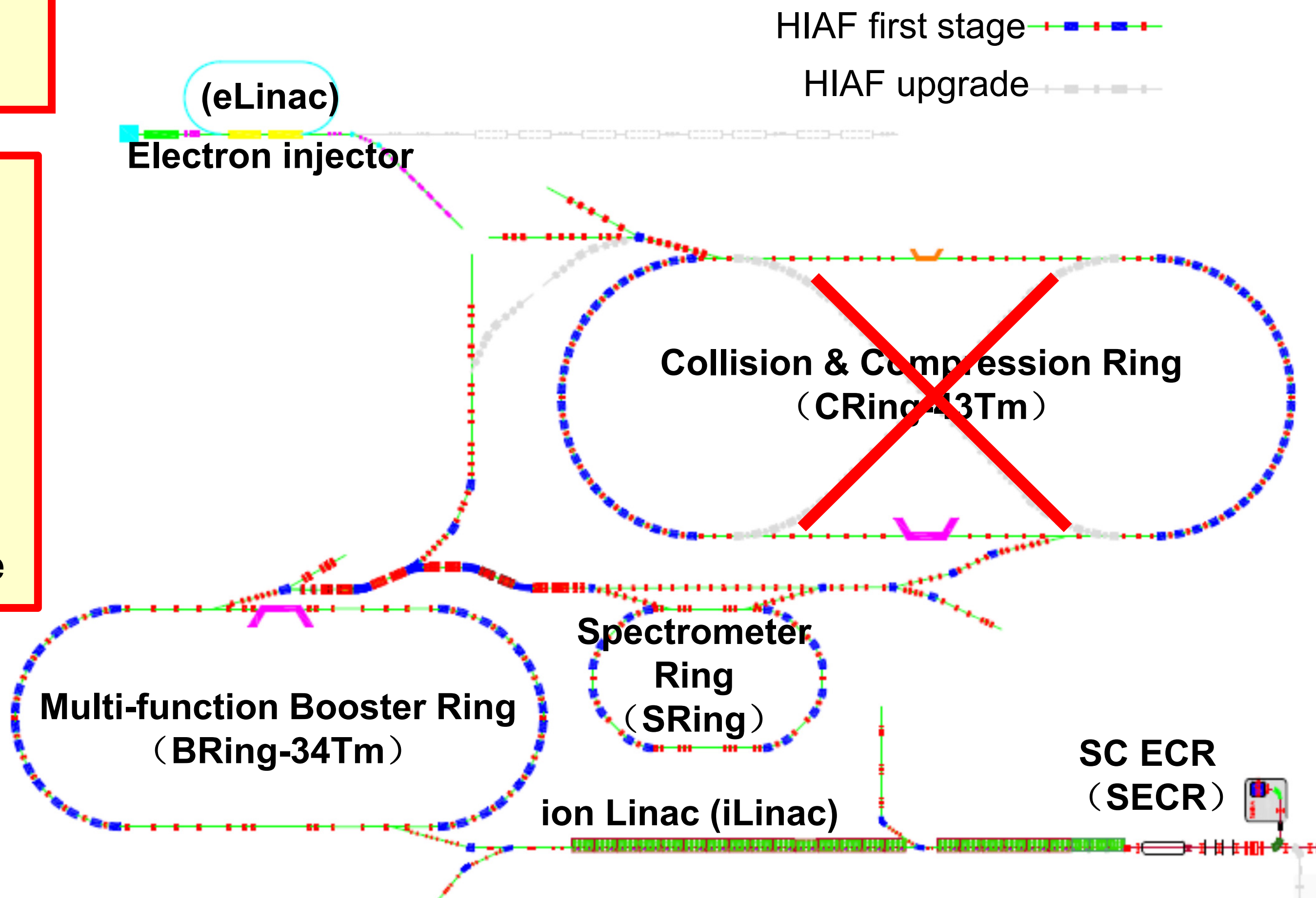

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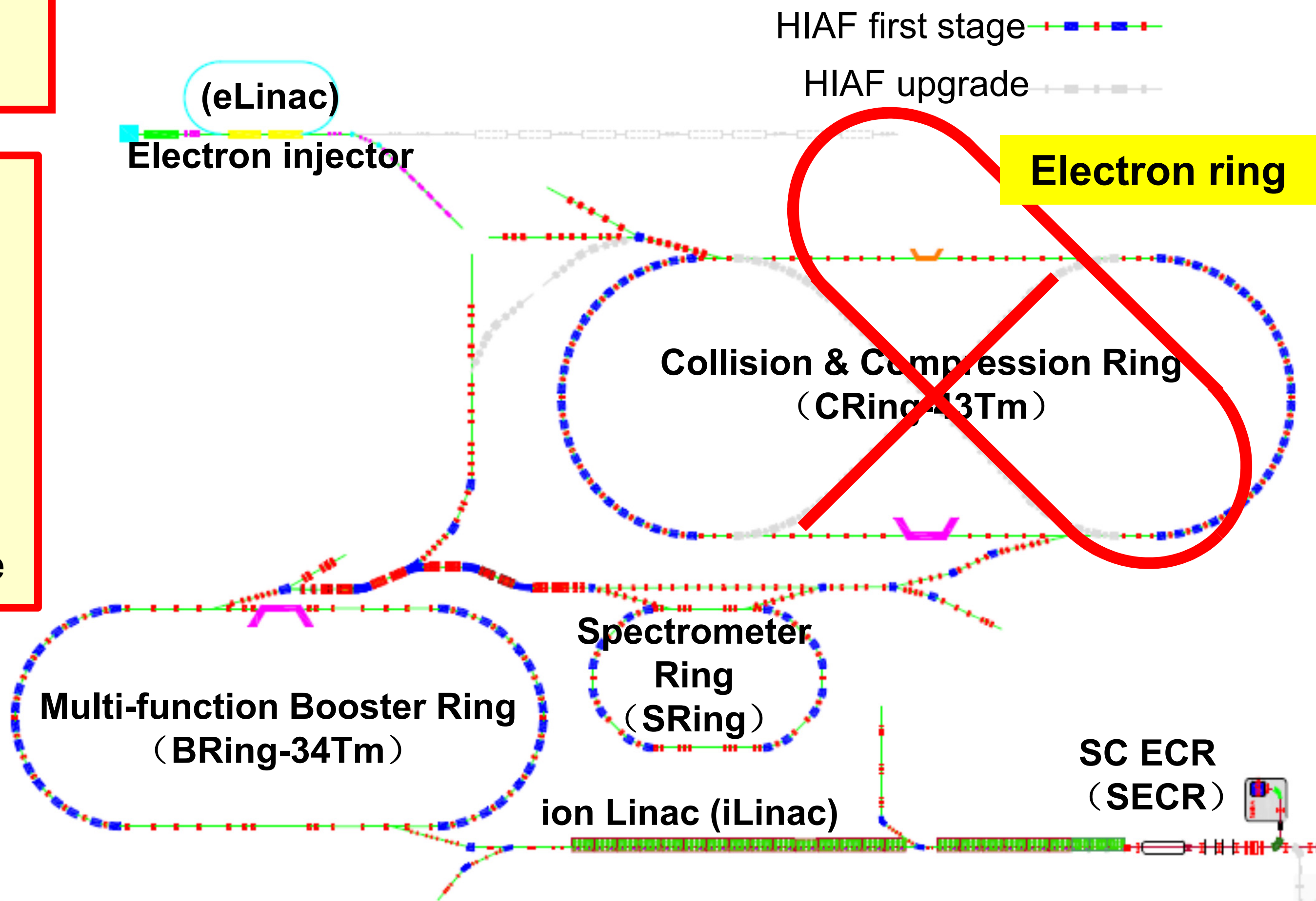

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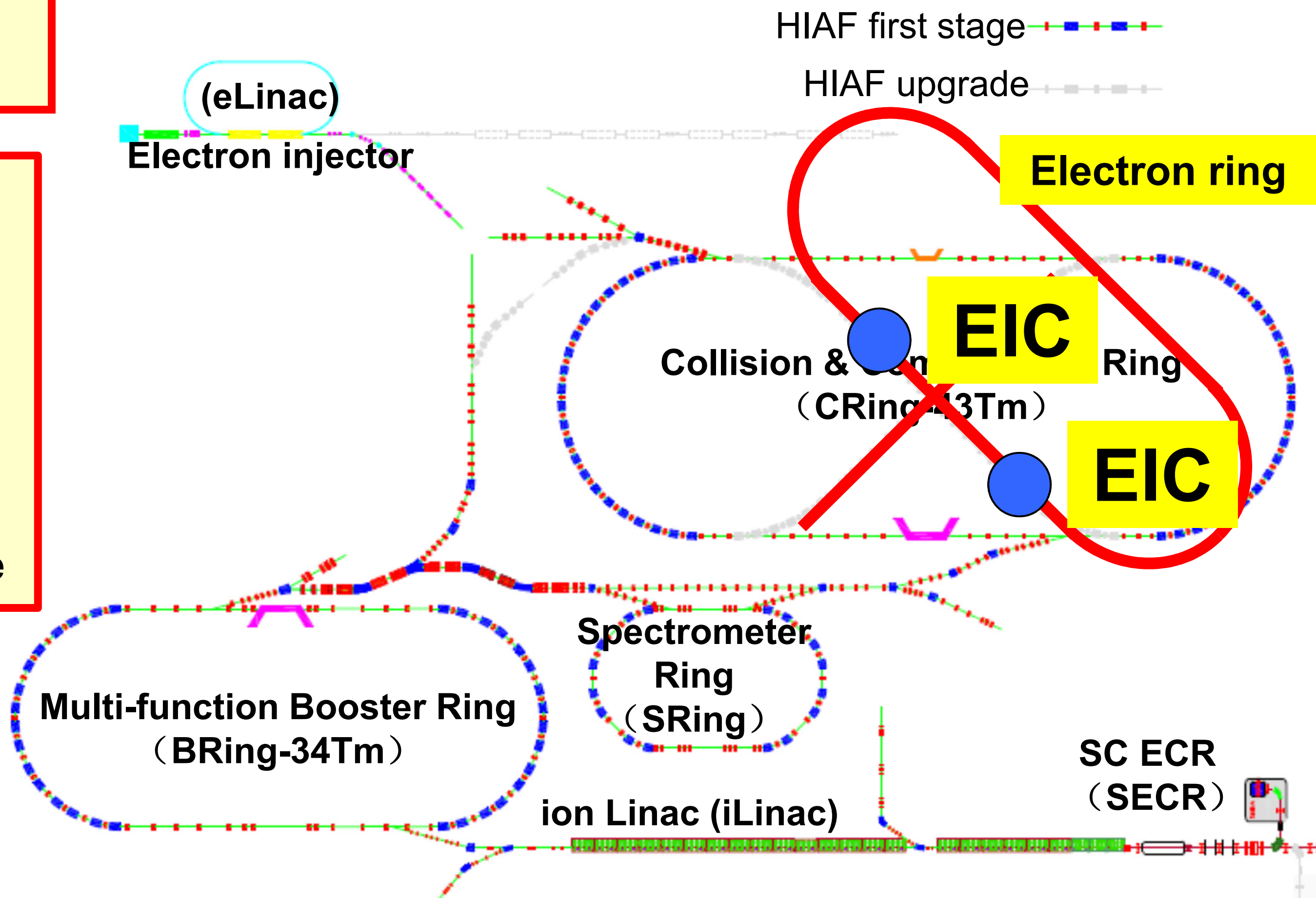
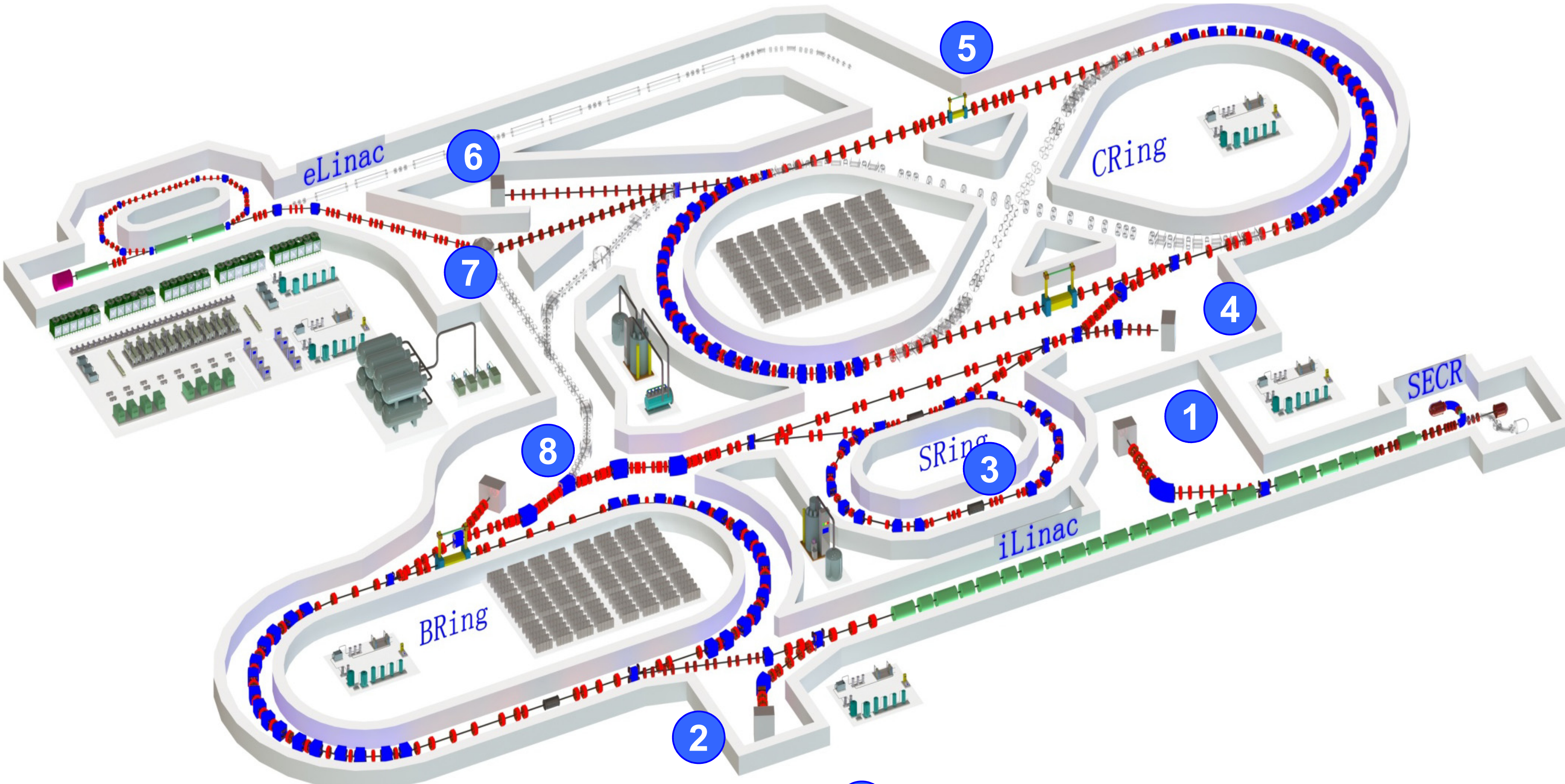
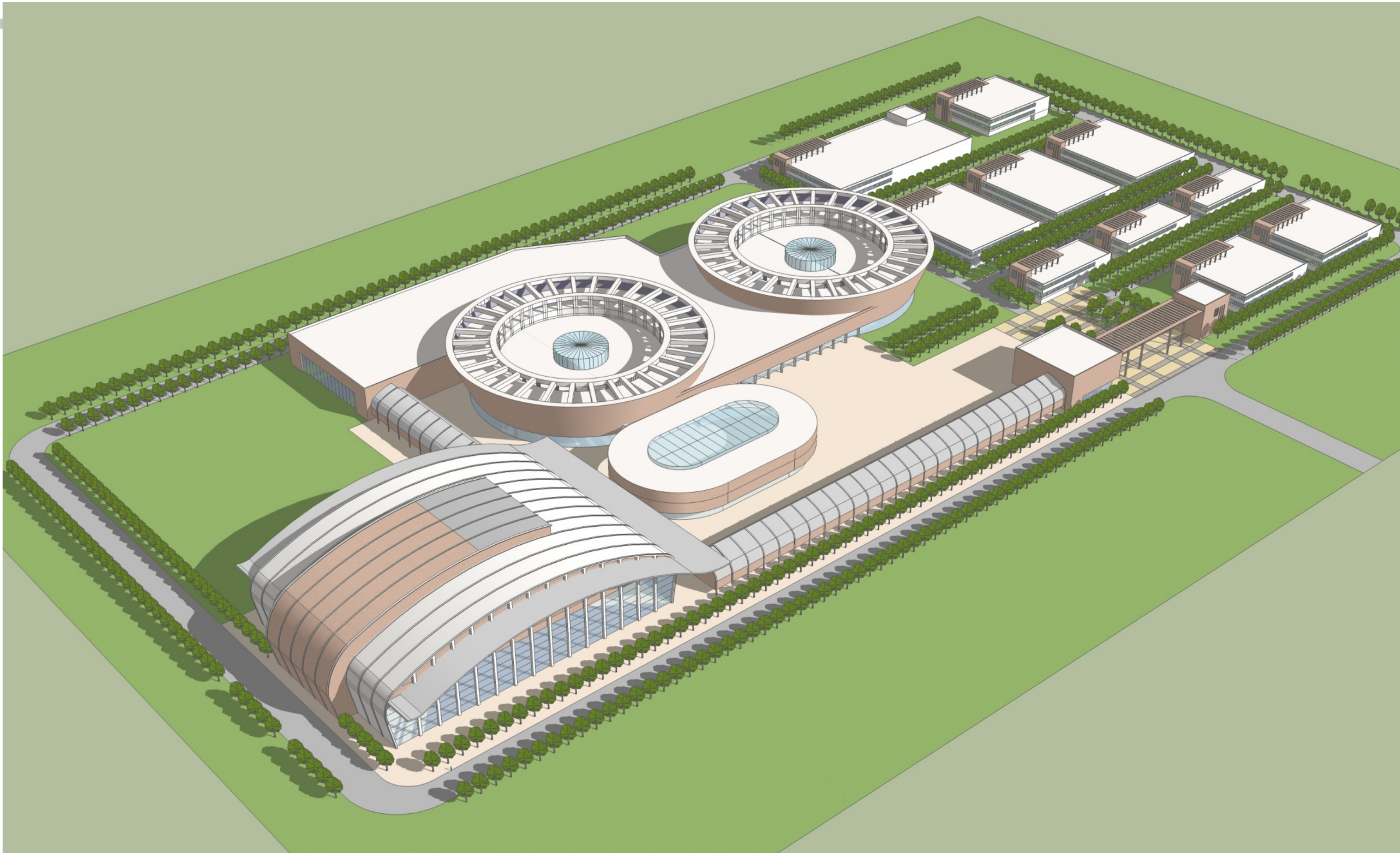


HIAF @ IMP, A Green Field Project



1. Low energy nuclear structure spectrometer
2. Low energy RIBs beam station
3. High precision spectrometer
4. High purity & quality RIBs station
5. Electron-ion recombination resonance spectrometer
6. High energy irradiation terminal
7. High-Energy-Density Matter terminal
8. External target station

HIAF @ IMP, A Green Field Project

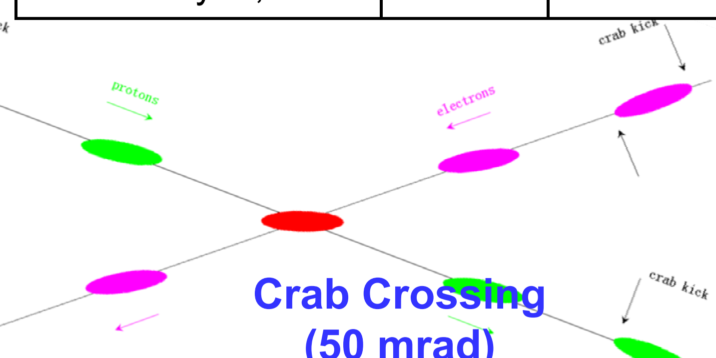


HIAF @ IMP, CAS

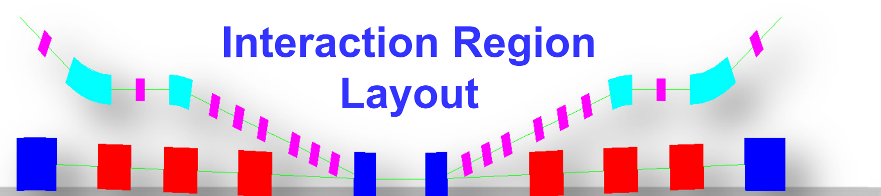
		Proton	Electron	$^{238}U^{92+}$	Electron
Beam energy	GeV	12	3	0.769	0.5
Collision frequency	MHz	500		54.6	
Particles per bunch	10^{10}	0.54	3.7	0.00032	5
Beam Current	A	0.43	3	0.0026	0.437
Polarization	%	> 70	~ 80		
Energy spread	10^{-4}	3	3	3	4
RMS bunch length	cm	2	1	15	4
Horiz. Emitt., geom.	nm•rad	150	30	50	50
Vert. emitt., geom.	nm•rad	50	10	50	50
Horiz. & vert. β*	cm	2	10	100 / 15	100 / 15
Vert. b-b tune shift		0.0048	0.015	0.018	0.008
Laslett tune shift		0.045	small	0.1	Small
Luminosity/IP, 10^{32}	$cm^{-2}s^{-1}$	4.0		$2.9•10^{-5}$	

HIAF Low energy DC electron cooling

Expected to use the similar cooler for the existing HIREL



Crab Crossing (50 mrad)



Interaction Region Layout

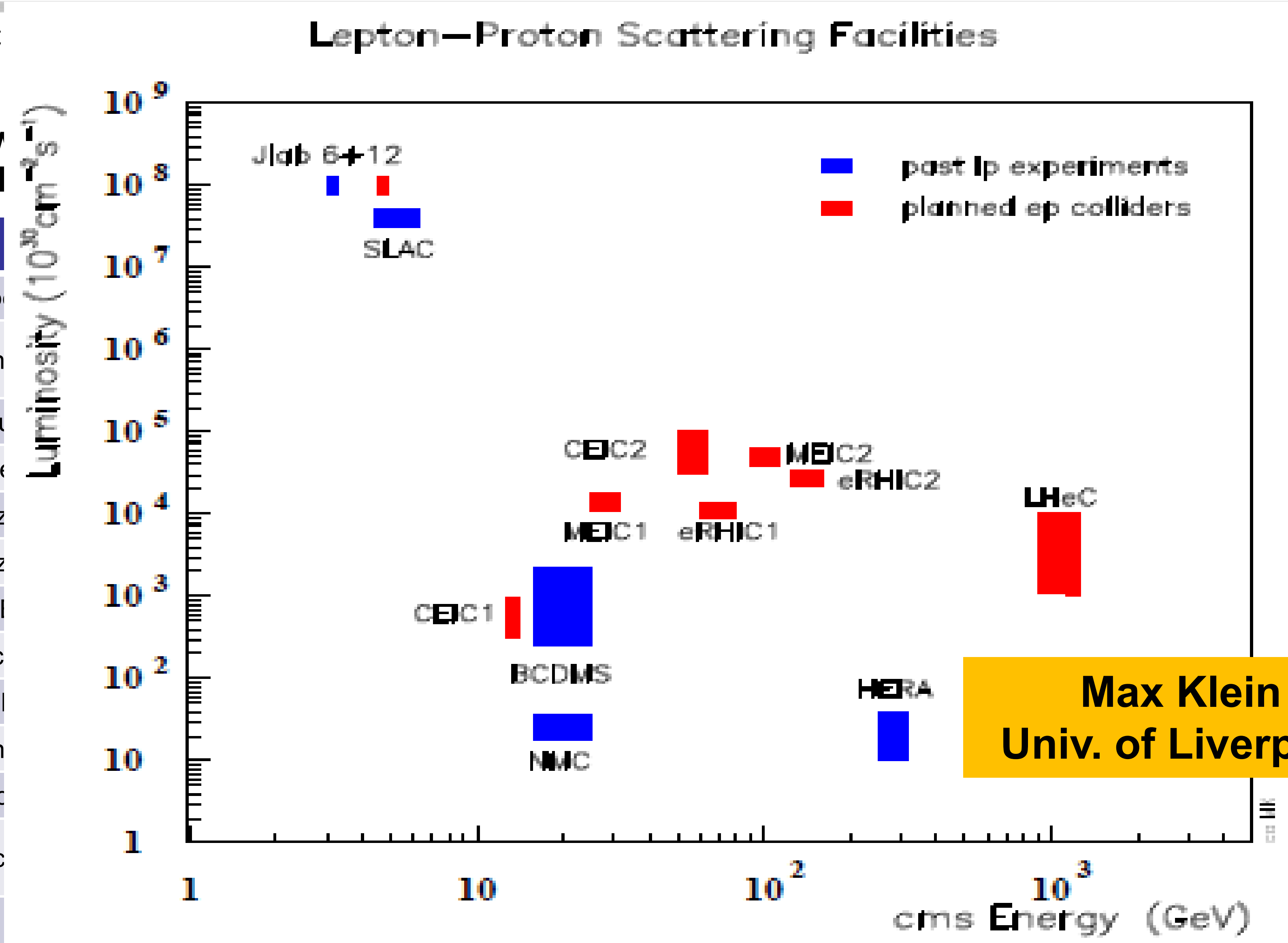
General Design Trends

- **EIC machine design aims for high performance to meet science needs**
  NSAC Long Range Plan (2007): **eRHIC/MEIC 100x higher luminosity than HERA**
- **New concepts and technologies have been incorporated into the designs, and shared by multiple proposals**

	LHeC R-R	LHeC L-R	eRHIC	MEIC	ENC	HIAF
New beam facility	Electron	Electron	Electron	Ion	Electron	Both
CM energy range, up to (GeV)	1296	1296	81@stage 1 161@stage 2	66@stage 1 141@stage 2	13.4	12
Max. luminosity (10^{33} $cm^{-2}s^{-1}$)	1.3	1 ➔ 10	14.6	14.2	0.2	0.4
Ion species	p & lead	p & lead	p to uranium	p to lead	p	p to uranium
Polarized lepton	Yes	Yes	Yes	Yes	Yes	Yes
Polarized hadron			Yes	Yes	Yes	Yes
Linac(ERL)-Ring		Yes	Yes			
Reduction of ion emittance	High energy	High energy	Cooling	Cooling	Cooling	Cooling
Small beta-star of e / p (cm)	18 / 50	12 / 10	5	10 (x), 2 (y)	30	10 (x), 2 (y)
Proton beam-beam tune-shift	Very small	Very small	0.015 x 3 IP	0.015 x 2 IP	0.015	0.0048
Electron beam-beam disruption		6	0.2 to 140			
Crab crossing	Small angle, no crab cavity		Yes	Yes		Yes
Advanced IR Scheme		Detector-integrated dipole			Traveling focus	

General Design Trends

- EIC
- New ... red by mul



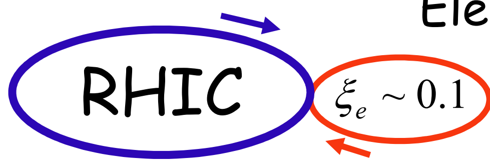
Max Klein
Univ. of Liverpool

	HIAF
New b	Both
CM en	12
Max. l	0.4
Ion spe	to uranium
Polariz	Yes
Polariz	Yes
Linac(l	
Reduc	Cooling
Small	(y)
Proton	
Electr	
Crab c	Yes
Advanced IR Scheme ... integrated dipole ... focus	

LHeC/eRHIC Approach: Linac(ERL)-Ring

- Ring-ring:

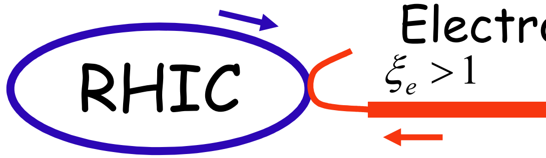
$$L = \left(\frac{4\pi\gamma_h\gamma_e}{r_h r_e} \right) (\xi_h \xi_e) (\sigma'_h \sigma'_e) f$$



Electron storage ring

- Linac-ring:

$$L = \gamma_h f N_h \frac{\xi_h Z_h}{\beta^*_h r_h}$$



Electron linear accelerator

✔ L x 50

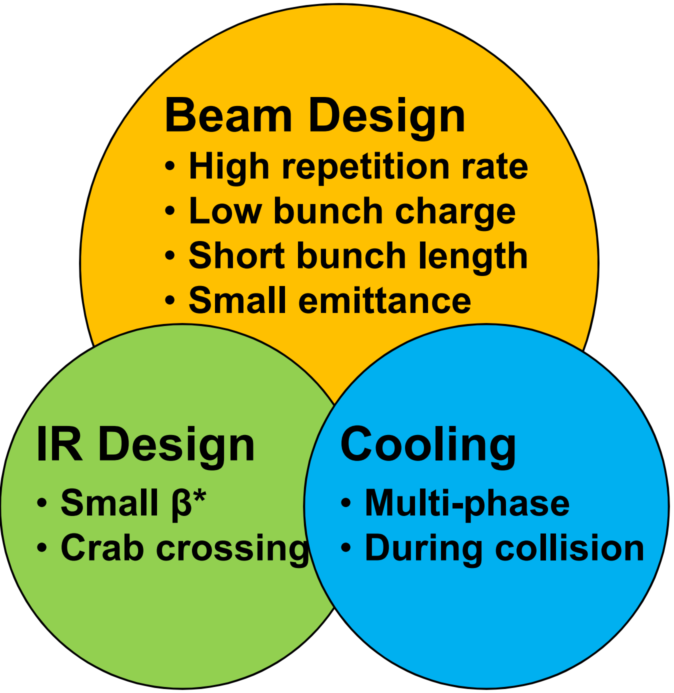
Natural staging strategy

- In a linac-ring collider, a lepton beam can tolerate much higher non-linear beam-beam perturbations since it is not stored in a ring, thus leading to a higher luminosity than a ring-ring collider of same collision frequency and other beam parameters
- ERL provides a practical way to accelerate high current lepton beam with a low RF power

MEIC Approach to High Luminosity

- MEIC design concept for high luminosity is based on *high bunch repetition rate CW colliding beams*, specifically

KEK-B already reached above 2x10^{34} /cm^2/s



MEIC is designed to replicate same success in EIC:
- **A high repetition rate electron beam from CEBAF**
- **A new ion complex (so can match e-beam)**

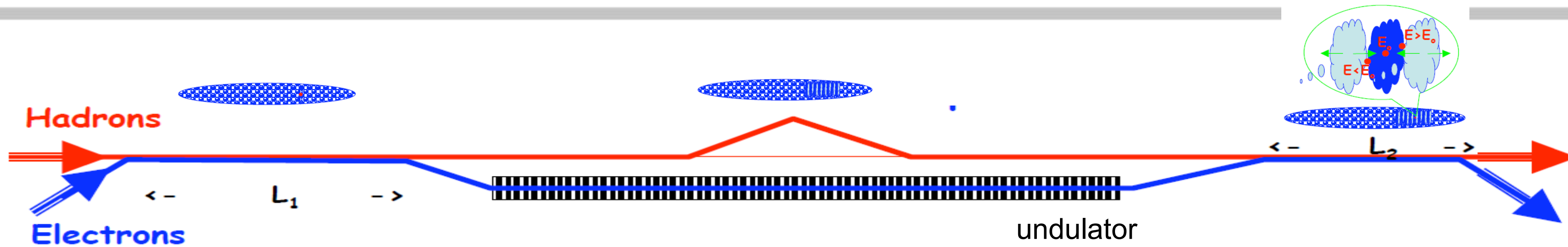
		KEK-B	MEIC	eRHIC ring-ring
Repetition rate	MHz	**509**	**748.5**	**13.1**
Energy (e^-/e^+ or p/e^-)	GeV	8/3.5	60/5	250/10
Particles/bunch (e^-/e^+ or p/e^-)	10^{10}	3.3/1.4	**0.42** 2.5	**10**/10
Beam current	A	1.2/1.8	0.5/3	0.42/0.42
Bunch length	cm	0.6	1/0.75	?/0.2
Horiz. & vert. β*	cm	56/0.56	10/2 ~ 4/0.8	108/27
Luminosity/IP, 10^{34}	/cm^{2}s	2	0.56 ~ 1.4	0.044

Not current eRHIC baseline

HIAF e-p collision also adopts this high luminosity concept

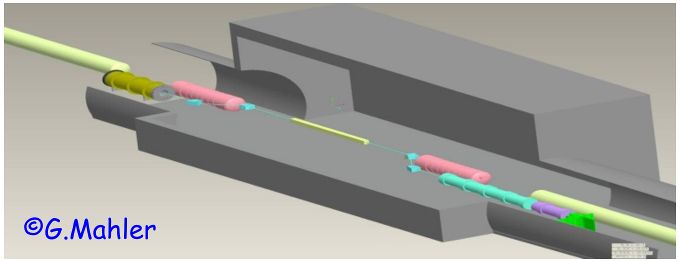
3. Technology Innovations

Coherent Electron Cooling for eRHIC



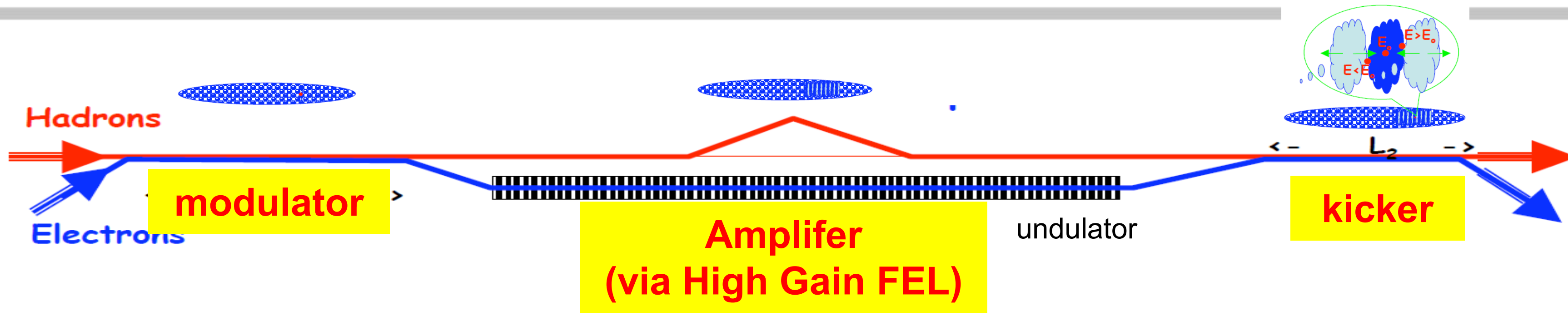
- First suggested by Y. Derbenev, 1980, further development, 1991 & 1995
- Recent development, V. Litvinenko & Y. Derbenev, PRL 2009
- A promising scheme for efficient cooling of high energy hadron beam, orders of magnitude reduction of cooling time
- Important application in hadron-hadron & lepton-hadron colliders
- **Potential luminosity increase: RHIC polarized *pp* ~ 6 fold, eRHIC ~ 5–10 fold, LHC ~ 2 fold**

Machine	Species	Energy GeV/n	Synchrotron radiation, hrs	Electron cooling, hrs	CEC, hrs
RHIC	Au	100	20,961 ∞	~ 1	0.03
RHIC	protons	250	40,246 ∞	> 30	0.8
LHC	protons	450	48,489 ∞	> 1,600	0.95
LHC	protons	7,000	13/26	∞ ∞	< 2



Proof-of-Principle experiment in RHIC IR 2
Collaboration between BNL, JLab & Tech-X

Coherent Electron Cooling for eRHIC



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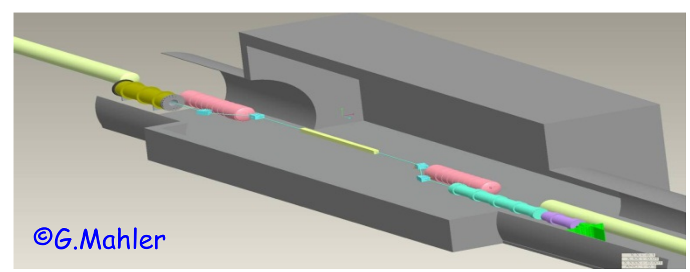

Proof-of-Principle experiment in RHIC IR 2
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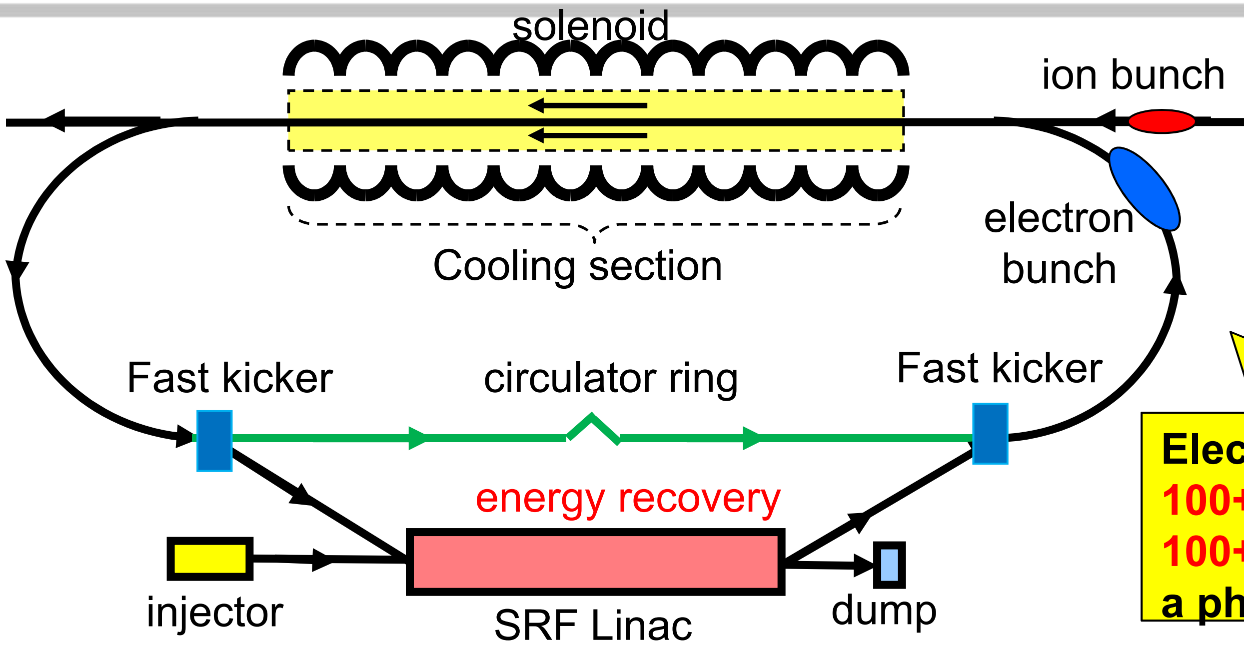
ERL Circulator Electron Cooler for MEIC



Earlier proposals:
RHIC: ERL
HERA: circulator ring

Electron bunches circulate 100+ times, leads to a factor of 100+ reduction of current from a photo-injector/ERL

Design choice

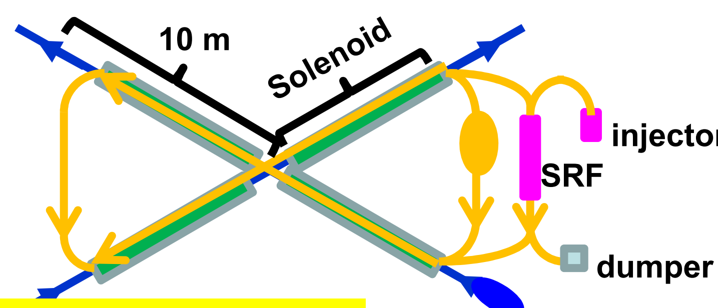
to meet design challenges

- RF power (up to 50 MW)
- Cathode lifetime (130 kC/day)

Required technology

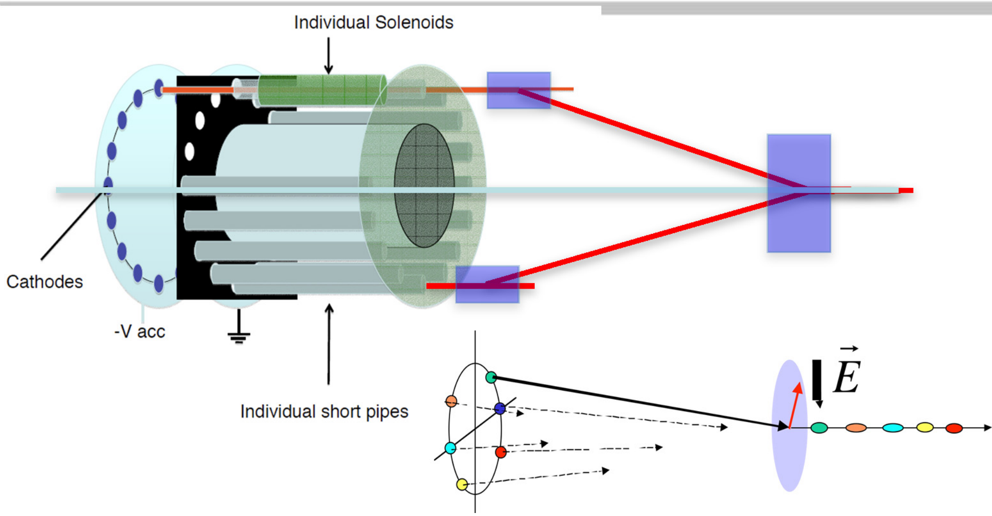
- High bunch charge gun (ok)
- ERL (50 MeV, 15 mA) (ok)
- Ultra fast kicker

Cooling section at the center of Figure-8



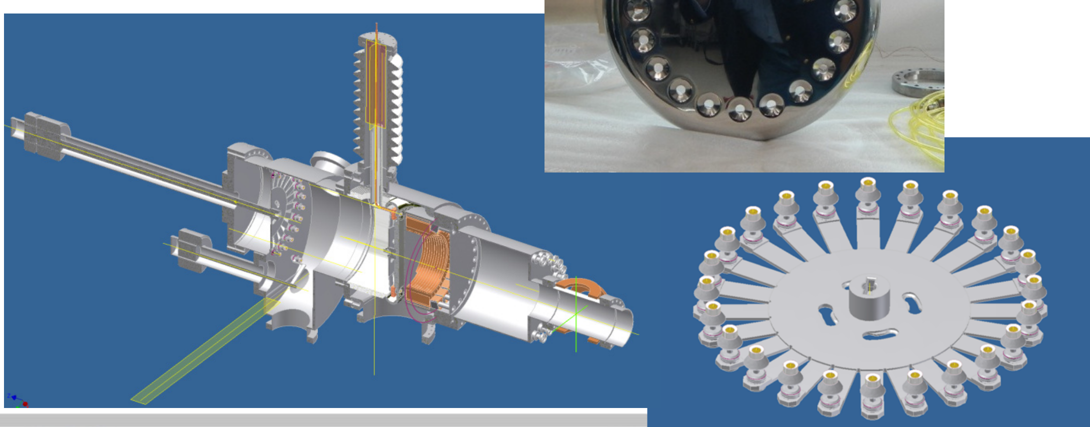
- **cut cooling time by half, or**
- **reduce cooling current by half, or**
- **reduce number of circulations by half**

eRHIC Gatling Electron Gun Concept



- Bunches from ***multiple photo-cathodes*** of a ***single gun*** merge together to form one high average current beam
- BNL Gatling gun requires 20 cathodes (each delivering 2.5 mA polarized electron current) to meet 50 mA current requirement of present ERL-ring baseline design
- A recent JLab breakthrough pushed single gun polarized current to 4 mA. This could reduce number of cathodes down to 12 in the BNL Gatling gun design concept

First gun prototype testing is scheduled at the end of 2014



JLab 200kV inverted polarized gun recently reached 4 mA

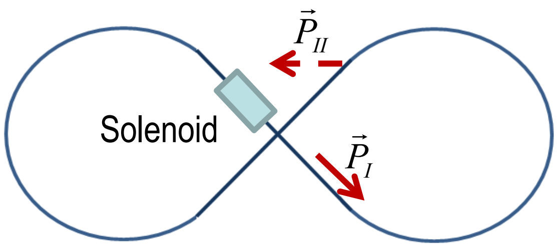
MEIC Figure-8 Ring for Achieving High Ion Polarization

Figure-8 optimum for polarized ion beams

Ya. Derbenev 1993

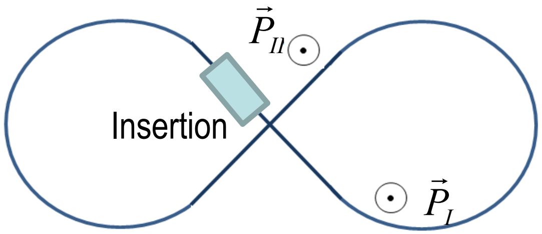
- Simple solution to preserve ion polarization by avoiding spin resonances during acceleration
- Energy independence of spin tune
- A figure-8 ring is the ***only practical way*** for accelerating, storing and colliding polarized deuterons (g-2 is small for deuterons)

Case 1: Achieving longitudinal polarization of deuterons at one IP



- Magnetic inserts provide small spin rotation, thus shift the spin tune sufficiently away from 0
- Polarization is stable as long as additional spin rotation exceeds perturbations of spin motion

Case 2: Achieving transverse polarization of deuterons at all IP's



- Magnetic insert(s) in straight(s) rotating spin by relatively small angle around vertical axis (A. Kondratenko)

MEIC Figure-8 Ring for Achieving High Ion Polarization

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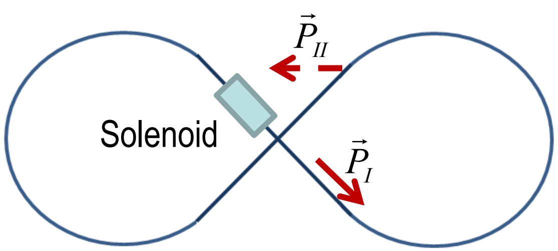

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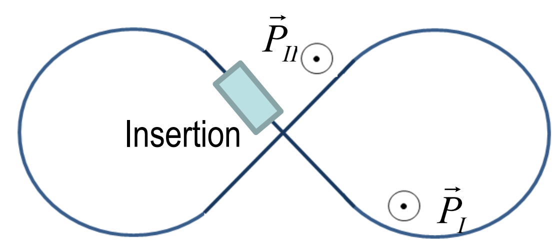
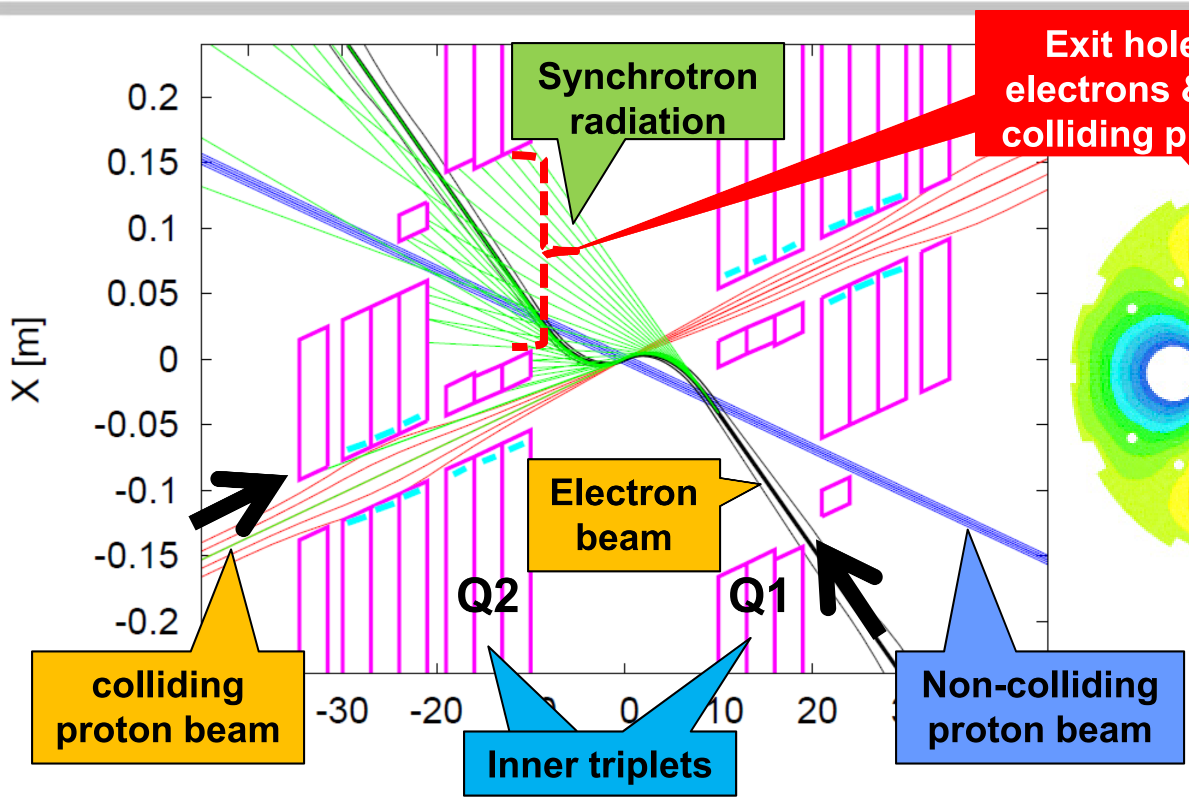


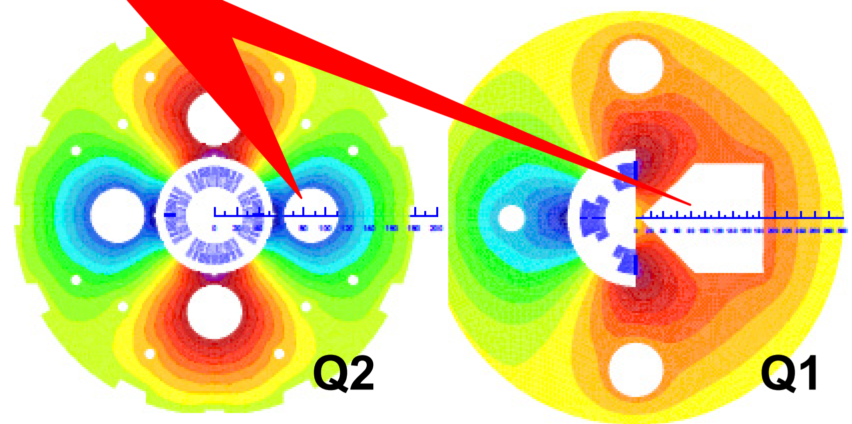
- Magnetic insert(s) in straight(s) rotating

HIAF ion ring now also adopts a figure-8 shape

LHeC High-Gradient SC IR Quadrupoles



S. Russenschuck



Type		Ring-ring single aperture	Ring-ring half-quad	Linac-ring single aperture	Linac-ring half-quad
Function		Q2	Q1	Q2	Q1
SC		Nb-Ti at 1.8 K			
R	mm	36	35	23	46
I_{nom}	A	4600	4900	6700	4500
g	T/m	137	137	248	145
B_0	T	-	2.5	-	3.6
LL	%	73	77	88	87
S_{beam}	mm	107	65	87	63
B_{fringe}	T	0.016	0.03	0.03	0.37
g_{fringe}	T/m	0.5	0.8	3.5	18
SC		Nb_3Sn at 4.2 K			
I_{nom}	A			6700	4500
g	T/m			311	175
B_0	T			-	4.7
LL	%			83	82
B_{fringe}	T			0.09	0.5
g_{fringe}	T/m			9	25

High-gradient SC IR quadrupoles based on Nb3Sn for colliding proton beam with common low-field **exit hole for electron beam and non-colliding proton beam**.

LHeC is designed to run synchronous to LHC

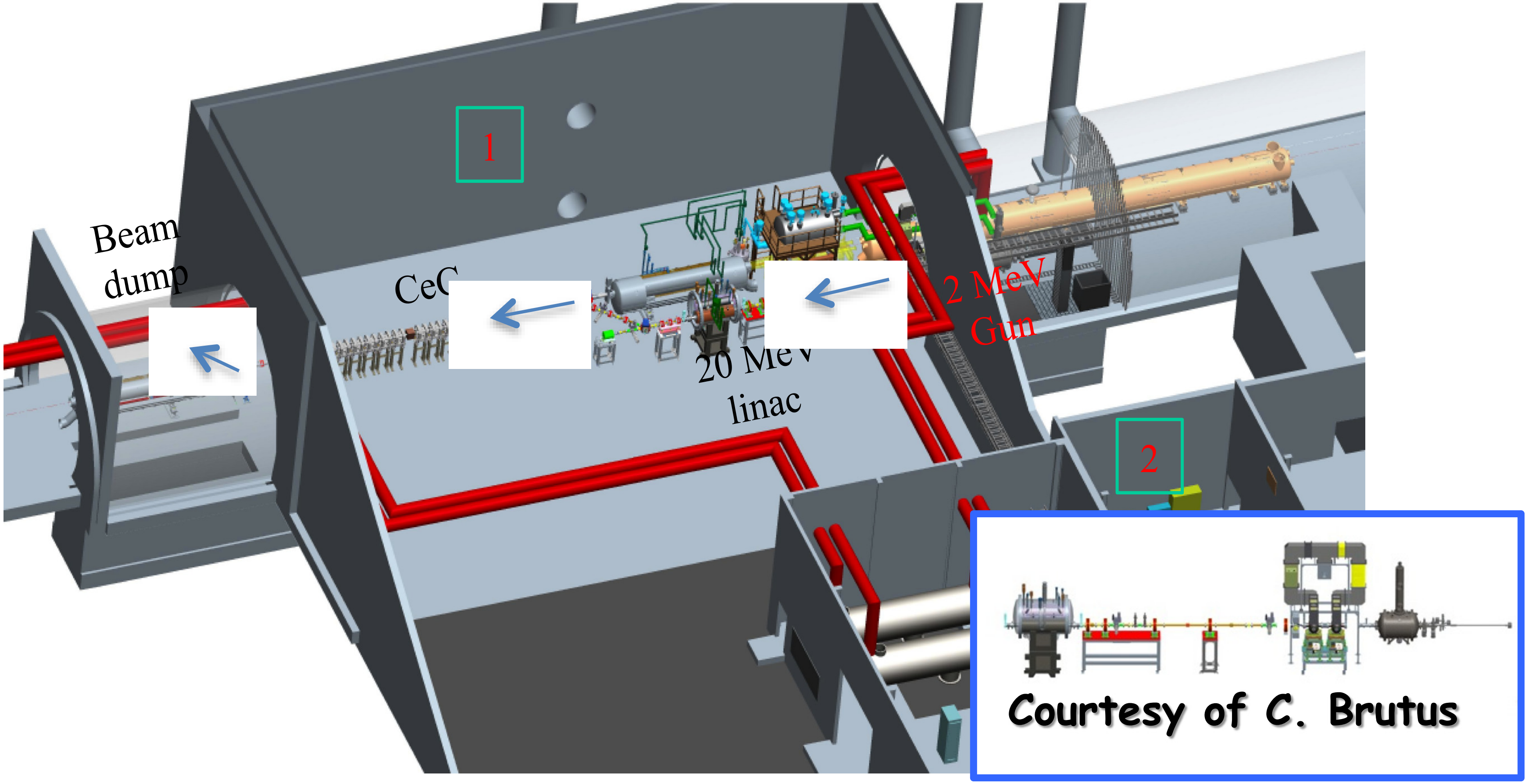
4. Outlook and Summary

Accelerate R&D Needs for EIC

V. Ptitsyn, O. Bruning, R. Ent and R. Roser for Snowmass 2013

	LHeC RR	LHeC LR	eRHIC	MEIC	ENC	HIAF
Cooling of hadron beams			Yes	Yes	Yes	Yes
Low β^* interaction regions	Yes	Yes	Yes	Yes	Yes	Yes
Crab crossing			Yes	Yes		Yes
High beam power ERL and High current SRF cavities		Yes	Yes			
Preserving electron beam polarization in ring-ring colliders	Yes			Yes	Yes	Yes
Proton and light ion polarization			Yes	Yes		Yes
High current polarized electron source		Yes	Yes			
Beam-beam effects in the linac-ring scheme		Yes	Yes			
Intense positron beam in the linac-ring		Yes				
Matching electron and hadron bunch frequencies at different hadron energies				Yes	Yes	Yes

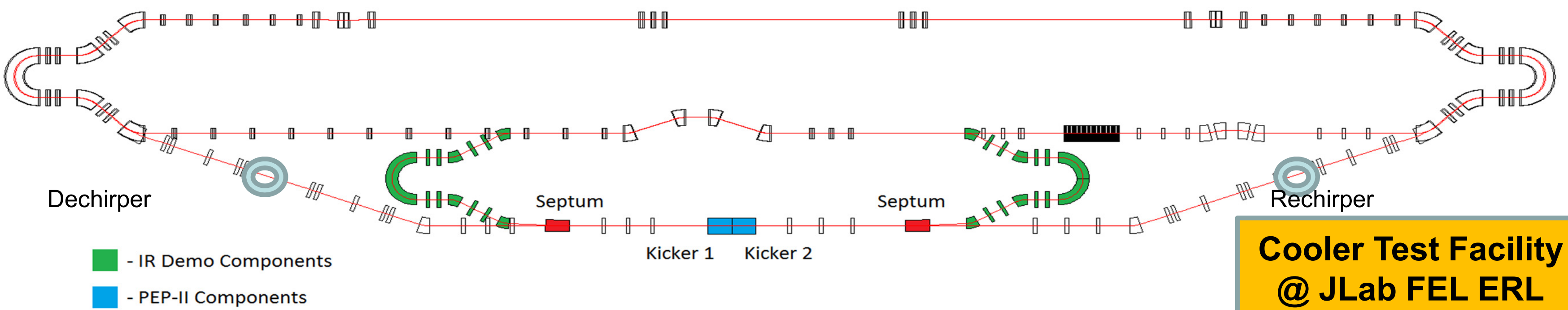
Coherent Electron Cooling Proof-of-Principle Experiment at RHIC



V. Litvinenko, POETIC 2013

Start of commissioning - 2015

ERL-Circulator Cooler Proof-of-Concept Experiment at Jefferson Lab FEL-ERL



Cooler Test Facility @ JLab FEL ERL

Purpose

- ***Demonstrate the cooler design concept***
- Develop/test key accelerator technologies (faster beam kickers, etc.)
- Study dynamics of the cooling electron bunches in a circulator ring

Medium energy	Bunched e-beam
ERL	Circulator ring

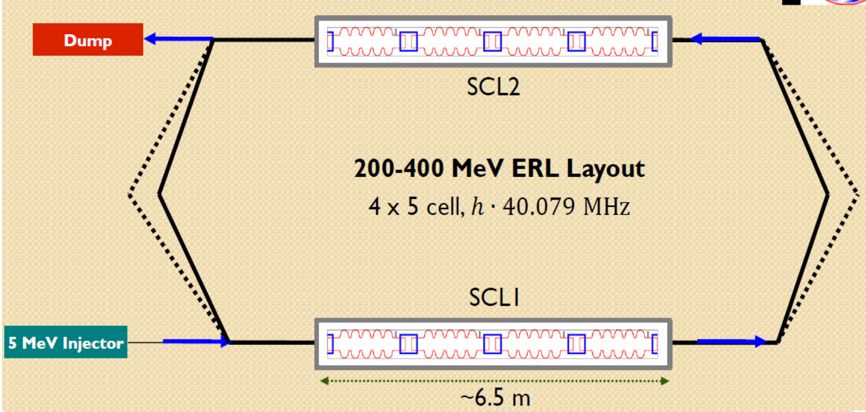
Phase 1 scope

- Using the existing ERL without new upgrade except two 180° beam lines (available at JLab)
- Supporting MEIC to deliver the high luminosity (5.6~14 x 10^{33} 1/cm^2/s),
- To be completed before 2016

ERL Test Facility for LHeC

E. Jensen, LHeC Meeting 22-23/01/2013

ERL-TF @ CERN



	units	1-CM	2-CM
Energy	[MeV]	100	200-400
Frequency	[MHz]	$h \cdot 40.079$	$h \cdot 40.079$
Charge	[pC]	~500	~500
Rep. rate		CW	CW

A multi-purpose test facility

- SC magnet development
  - A test stand for quenching magnets with beam in cryogenic environment
  - Provide a irradiation test facility for detector component development

Why ERL TF @ CERN?

- Physics motivation
  - ERL demo, FEL, γ-source, e-cooling demo!
  - Ultra-short electron bunches
- The 1st low-freq. multi-pass SC-ERL
  - synergy with SPL/ESS & BNL activities
- High energies (200 to 400 MeV) & CW
- Multi-cavity cryomodule layout – validation and gymnastics
- Two-Linac layout (similar to LHeC)
- MW class power coupler tests in non-ER mode
- Complete HOM characterization and instability studies
- Cryogenics & instrumentation test bed

ERL Test Facility for LHeC

E. Jensen, LHeC Meeting 22-23/01/2013

ERL TF @ CERN?

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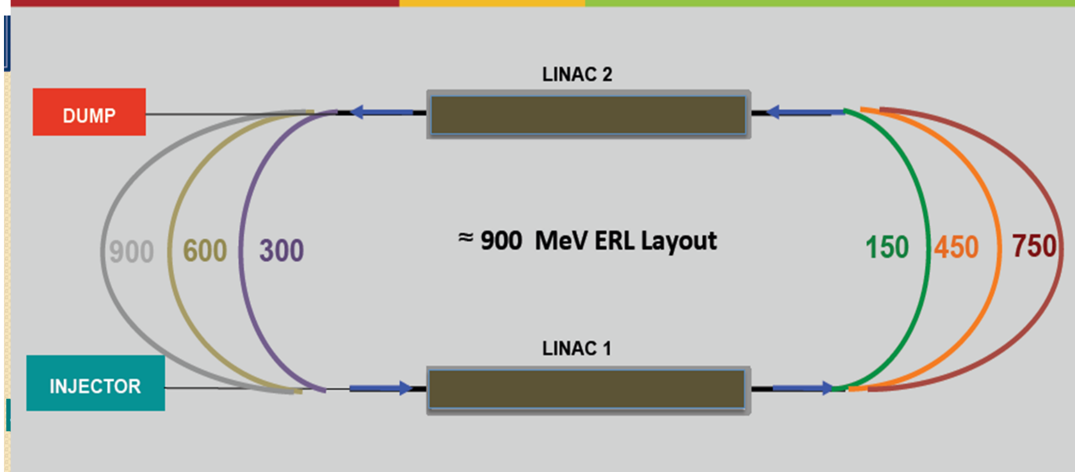


	units
Energy	[MeV]
Frequency	[MHz]
Charge	[pC]
Rep. rate	

CERN is looking into an ultimate test facility which allows a complete beam dynamics and RF analysis for a three recirculation ERL with a maximum beam energy up to 0.5 - 1 GeV

(*Alessandra Valoni's talk*)

A multi-purp
- SC magnet dev
  - A test stand for quenching magnets with beam in cryogenic environment
  - Provide a irradiation test facility for detector component development

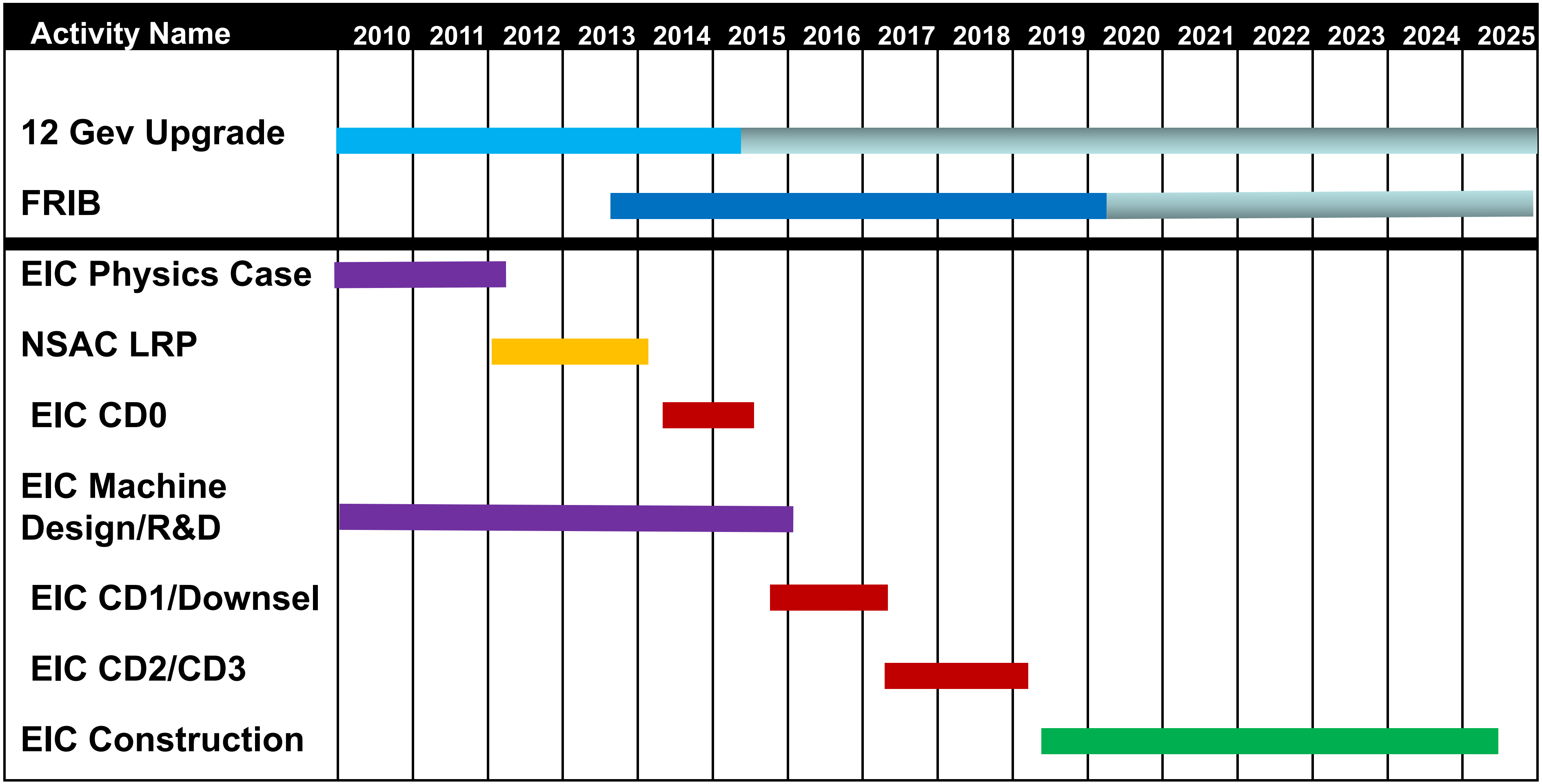
- Cryogenics & instrumentation test bed

NuPECC Roadmap: New Large-Scale Facilities

(12/2010)

		2010	2015	2020	2025
FAIR	PANDA	R&D Construction Commissioning		Exploitation	
	CBM	R&D Construction Commissioning		Exploitation	SIS300
	NuSTAR	R&D Construction Commissioning		Exploit.	NESR FLAIR
	PAX/ENC	Design Study R&D Tests	Construction/Commissioning		Collider
SPIRAL2		R&D Constr./Commission.	Exploitation		150 MeV/u Post-accelerator
HIE-ISOLDE		Constr./Commission.	Exploitation		Injector Upgrade
SPES		Constr./Commission.	Exploitation		
EURISOL		Design Study R&D	Preparatory Phase / Site Decision	Engineering Study	Construction
LHeC		Design Study R&D	Engineering Study	Construction/Commissioning	

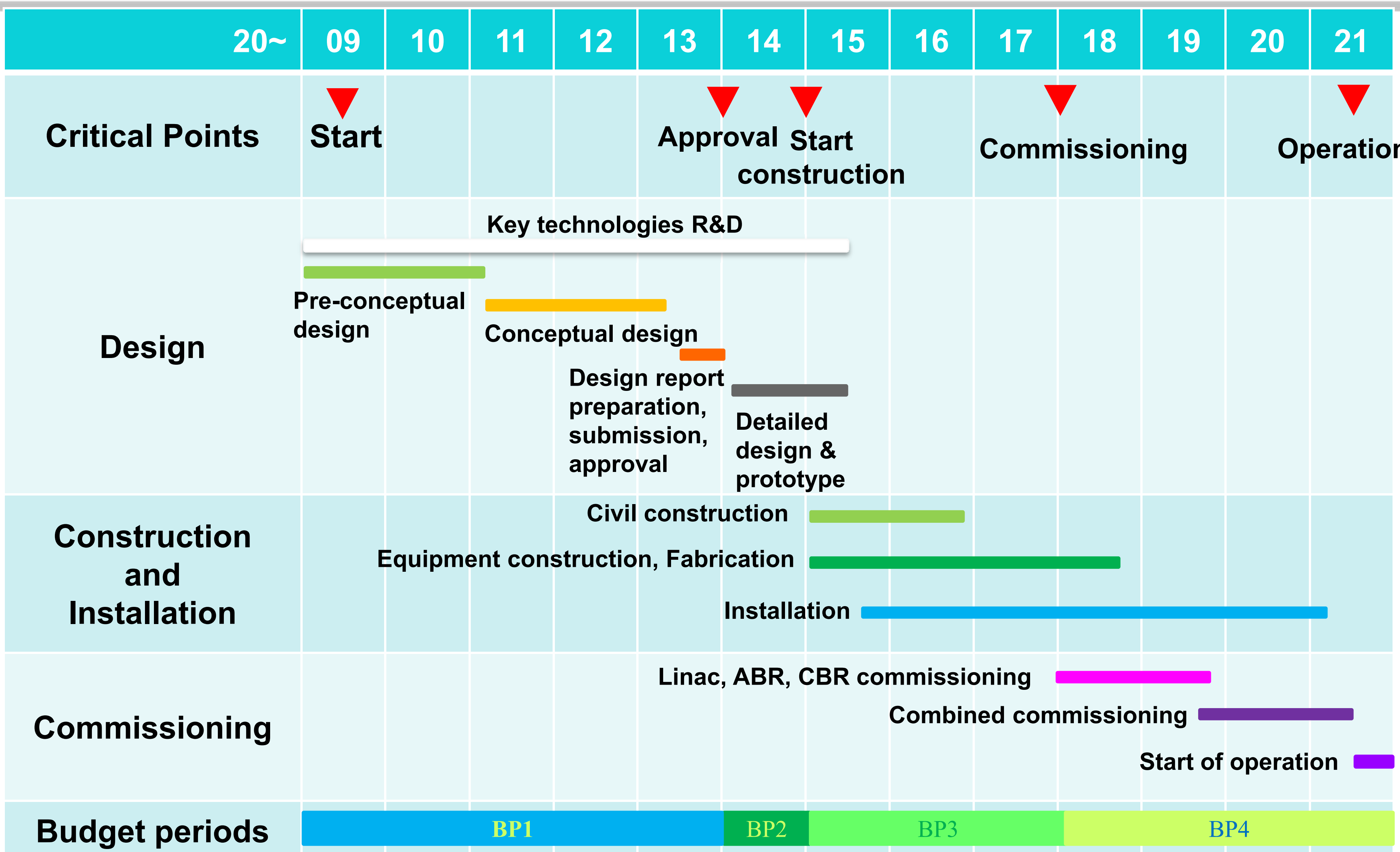
US EIC Realization Imagined



Note: 12 GeV LRP recommendation in 2002 – CD3 in 2008

(H. Montgomery @ INT)

HIAF Project Schedule



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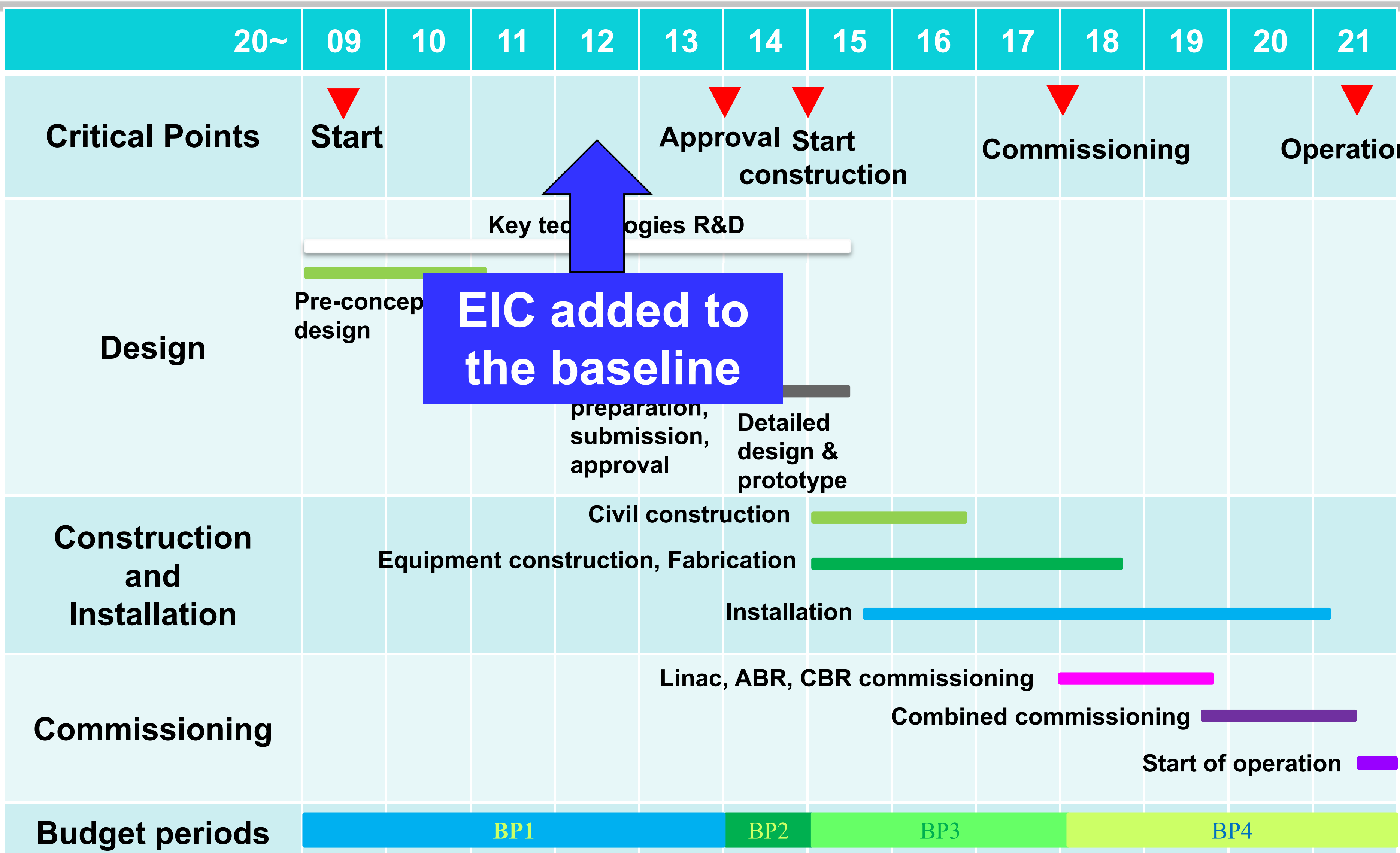

Summary

- A class of new electron-ion colliders have been proposed worldwide for future high energy and nuclear physics research. Both the science programs and the accelerator designs are under active development.
- All new electron-ion collider accelerator designs aim for high performance, orders of magnitude better than HERA, to meet science needs.
- In order to deliver the high performance, a class of new technologies have been integrated into the conceptual designs; some are adopted from other facilities; others are very forward looking, resulting in high demands on technology R&D.
- All machine designs are still at relatively early stages of their evolutions, either some baseline design decisions have not been made yet, or key design parameters are still in dynamic evolution, driven by both science and accelerator technology development.


EIC 14
An International Workshop on Accelerator Science and Technology for Electron-Ion Colliders
Jefferson Lab
Newport News, Virginia, USA
March 17-21, 2014
topics
-Beam physics including beam dynamics and collective effects, beam polarization, and cooling
-Interaction region, detector integration and background
-Superconducting RF technology and energy recovery linac
-Electron/positron sources, proton/ion sources
Contact:
eic14@jlab.org

Acknowledgement

I would like to thank all the following colleagues for helping me to prepare this talk

LHeC: Oliver Bruning, Max Klein

eRHIC: Vadim Ptitsyn, Thomas Roser

ENC: Kurt Aulenbacher

HIAF: Jiangchen Yang

I would also like to thank Rolf Ent of Jefferson Lab for preparing the science slides