NSAC Sub-Committee Review of the EIC (Electron Ion Collider) Cost Estimates

L Edward Temple, Jr. Chairman

Project Advisor to the Director

Argonne National Laboratory

Review Conducted 1/26-28/2015

Report Given to NSAC 4/3/2015

Committee Members

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- G. Bock, Fermilab
- K. Boudwin, ORNL
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- E. Temple, Argonne
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Guidelines

- Understanding that a detailed conceptual design has not been completed the Sub-committee is asked to provide NSAC with its best current estimate of costs of the projects that will address the physics opportunities identified in the EIC White Paper (arXiv:1212.1701v2), including R&D, construction, pre-operating and operating costs and initial experimental equipment. NSAC is aware that there are uncertainties regarding siting and other issues that limit the precision of such an estimate at this time. Nevertheless, the advice of the Sub-committee will be of great value to NSAC as it evaluates the relative merit of this and other initiatives

eRHIC Cost Estimate Overview

- Design overview
- Performance and performance risks
- R&D requirements
- TPC scope and cost elements
- eRHIC operating cost estimate

Thomas Roser

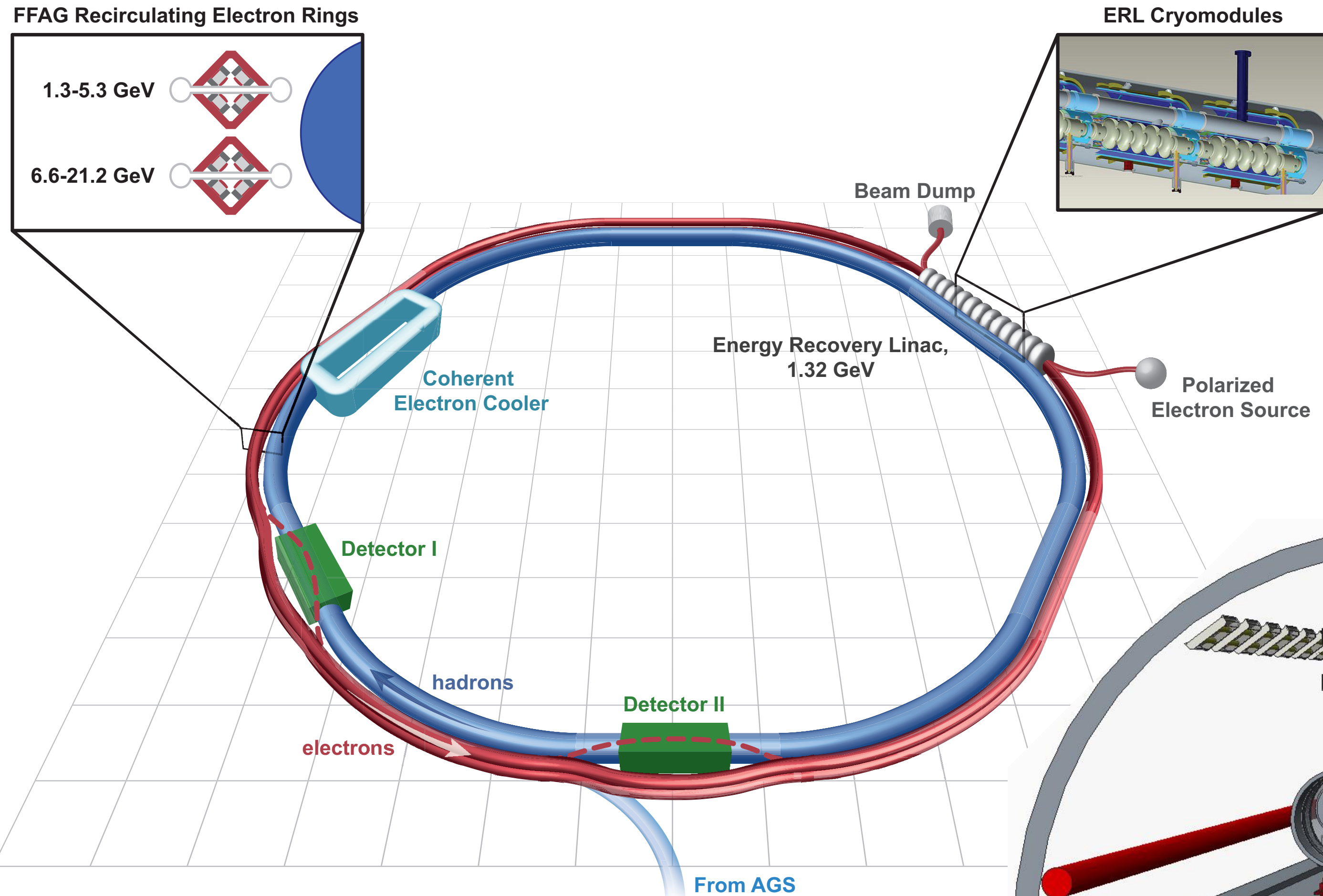
NSAC Subpanel EIC Cost Estimate Review
January 26 – 28, 2015

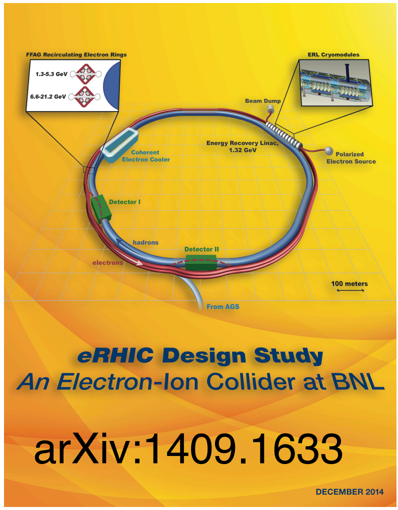
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

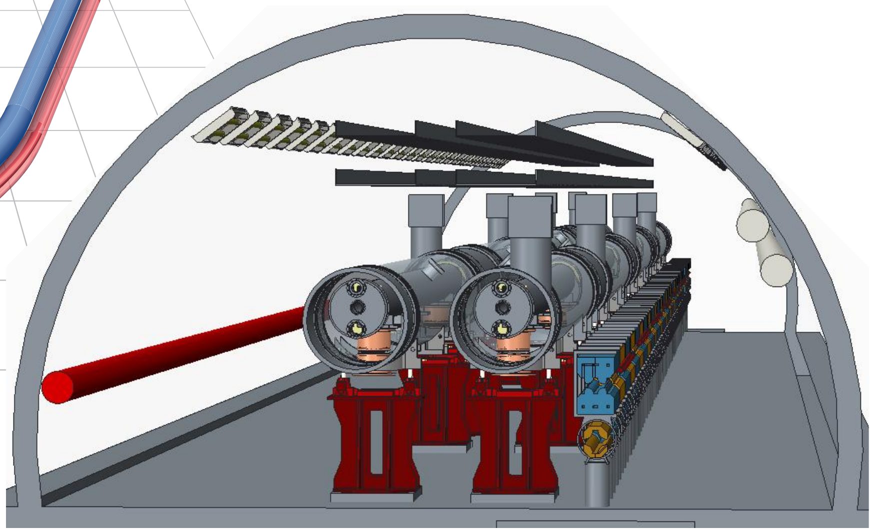
Office of Science
U.S. DEPARTMENT OF ENERGY

eRHIC design

Highly advanced and energy efficient accelerator

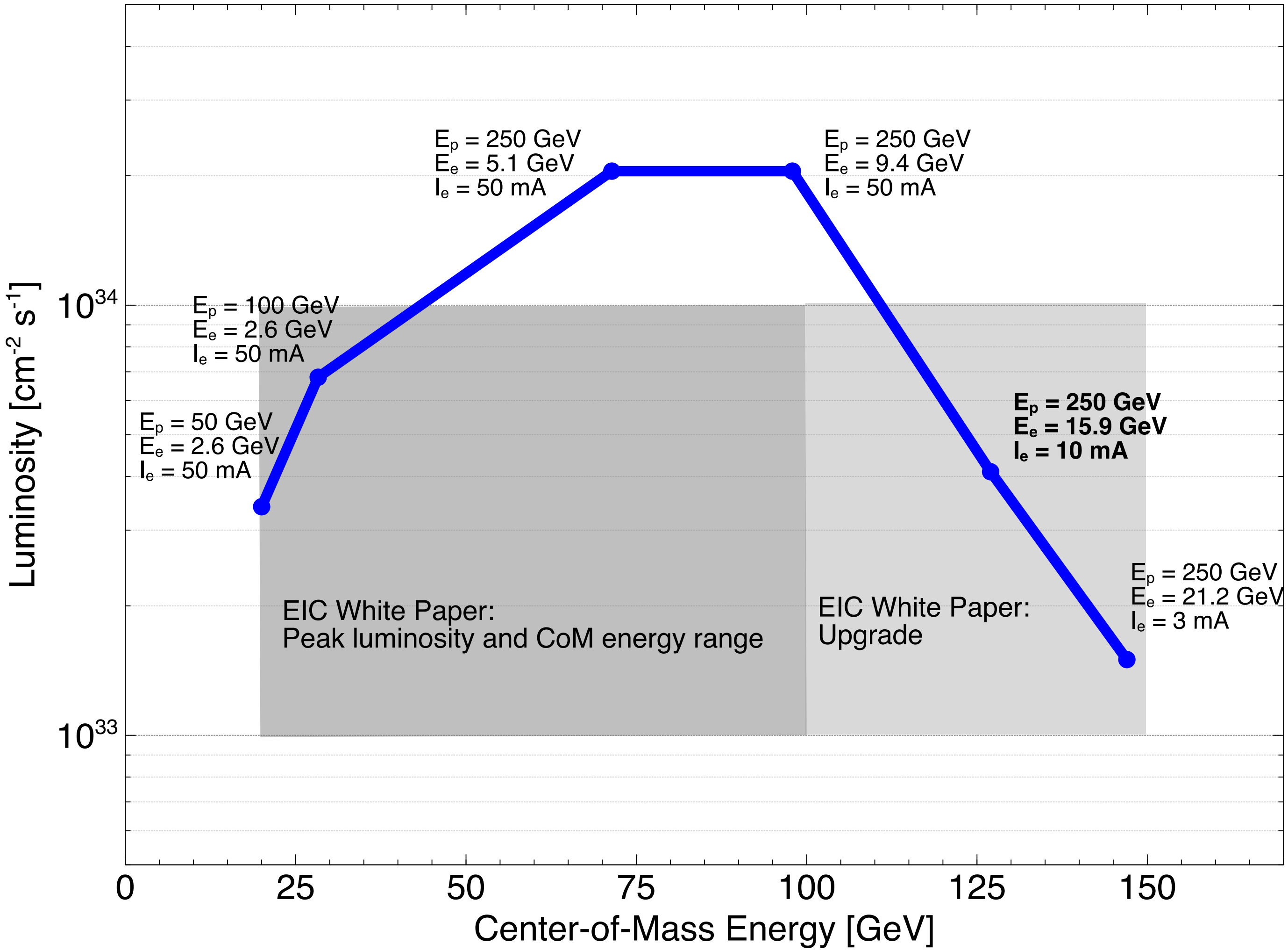






- 4.1×10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 126 GeV (15.9 GeV e ↑ on 250 GeV p ↑)

eRHIC peak luminosity vs. CoM energy



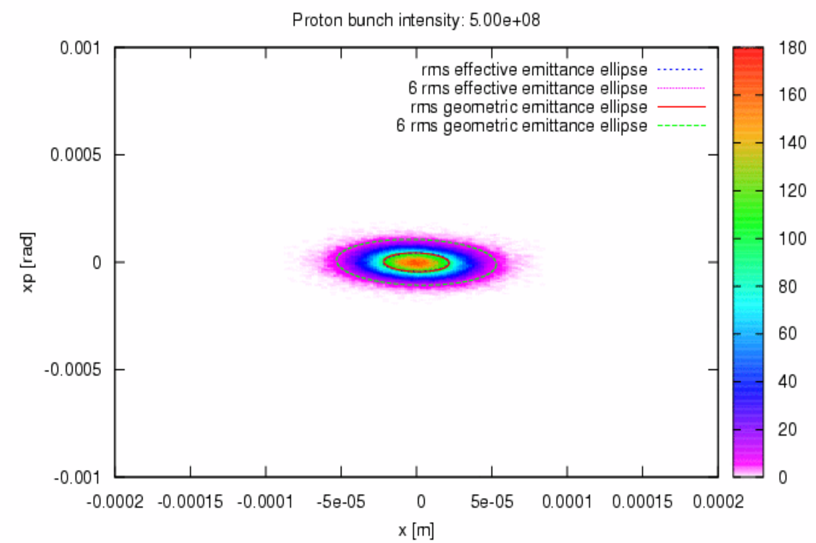
- eRHIC design covers whole Center-of-Mass energy range, including “White Paper Upgrade” region
- Parameters for E_p = 250 GeV, E_e = 15.9 GeV, I_e = 10 mA will be given below

eRHIC parameters for nominal operating energies

	e	p	$^{2}He^{3}$	$^{79}Au^{197}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		126	103	80
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.07	3.0	3.0	3.0
Bunch charge, nC	1.1	48	32	19.6
Beam current, mA	10	415	275	165
Hadron rms normalized emittance, 10^{-6} m		0.2	0.2	0.2
Electron rms normalized emittance, 10^{-6} m		23	35	58
β*, cm (both planes)	5	5	5	5
Hadron beam-beam parameter		0.004	0.003	0.008
Electron beam disruption		36	16	6
Space charge parameter		0.08	0.08	0.08
rms bunch length, cm	0.4	5	5	5
Polarization, %	80	70	70	none
Peak luminosity, 10^{33} cm^{-2}s^{-1}		4.1	2.8	1.7

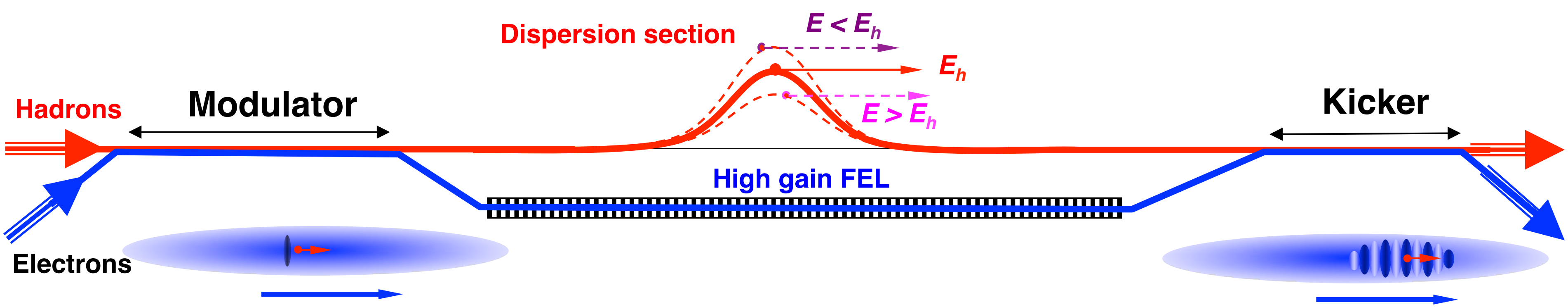
High luminosity with a Linac-Ring collider

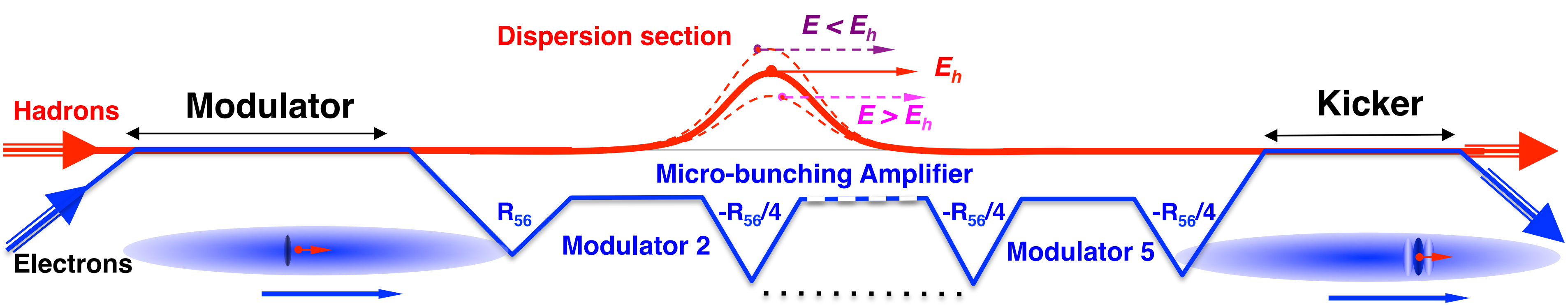
- For Linac-Ring collider the single collision of electron bunch removes the limitation of the beam-beam effect of the high energy hadron beam on the lower energy electron beam
- Can reach high luminosity with high intensity, low emittance hadron beam and lower intensity electron beam
- Disruption of electron beam by hadron beam is large (similar to ILC) but emittance growth is limited due to the focusing by the hadron beam (pinch effect)
- Need strong hadron beam cooling (10 times in transverse and longitudinal direction) for highest luminosities, small vertex distribution, and small forward divergence
- Novel cooling method:
  - Coherent electron Cooling (CeC)
  - Required performance demonstrated in extensive simulations
  - Proof-of-Principle test underway at RHIC



Coherent electron Cooling

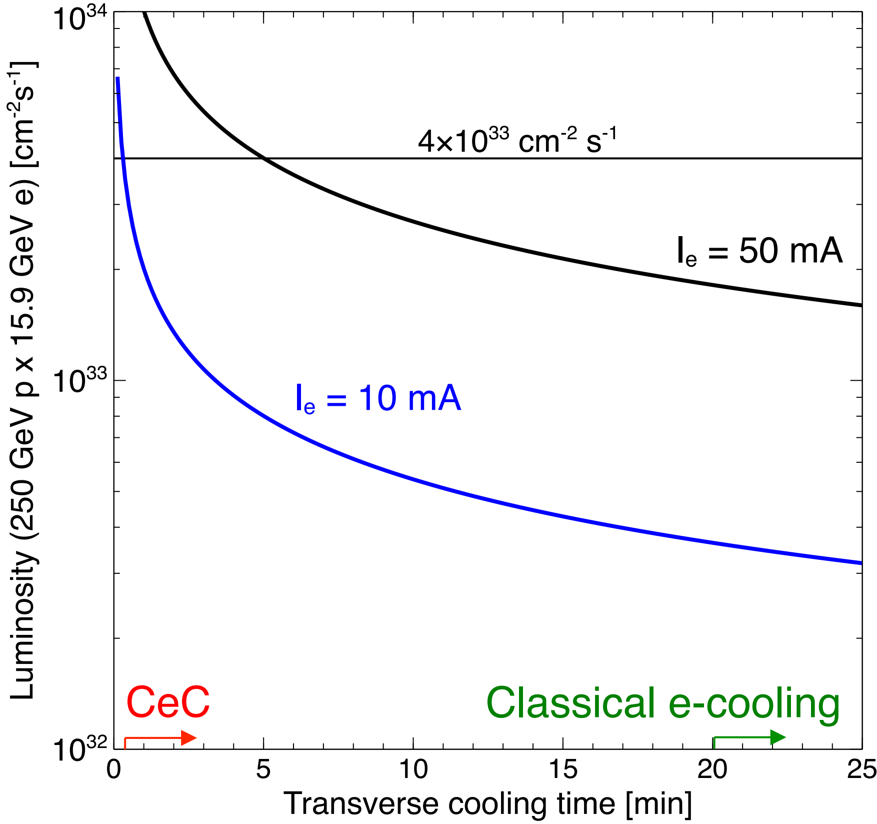
- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Very high bandwidth (~ 10 - 100 THz) stochastic cooling using electron beam as medium
- Made possible by high brightness electron beams and FEL technology
- Proof-of-principle demonstration planned with 40 GeV/n Au beam in RHIC (2016)
- Micro-bunching amplifier test also planned with same set-up





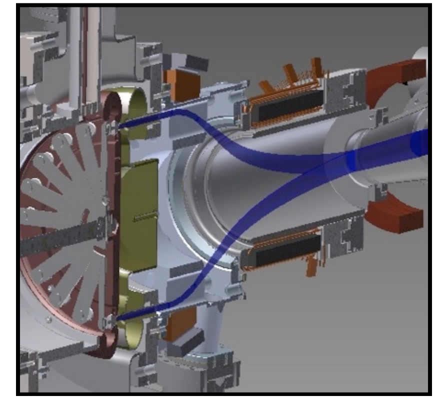
Performance risk: fast hadron cooling

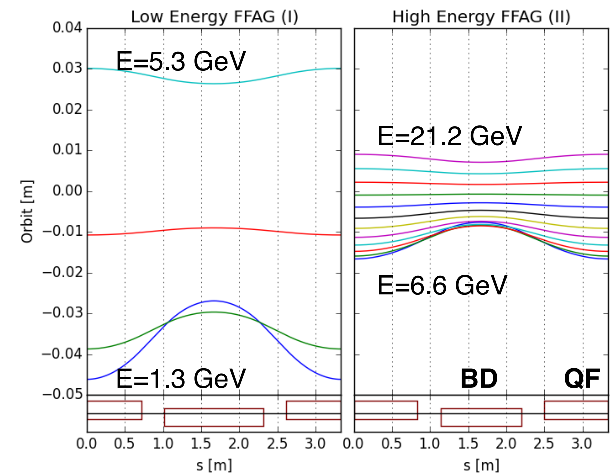
- At maximum luminosity (4×10^{33} cm^{-2} s^{-1}) the transverse IBS growth time of 250 GeV proton beam (3×10^{11} ppb, 0.2 μm, 5 cm bunch length) is about 20 seconds
- Only CeC with enhancements such as micro-bunching and with a 50mA, 125 MeV electron beam can reach this cooling time
- However, luminosity doesn't depend strongly on cooling time ($L \propto \tau^{-4/7}$)
- Less efficient cooling up to 5 minute cooling time can be fully compensated with increased eRHIC electron current (50 mA)
- Enhanced classical electron cooling with 3 A, 125 MeV electron beam, as being developed at JLab, can support ~ 20 minutes cooling time or ~ 2×10^{33} cm^{-2} s^{-1} with 50 mA electron current.

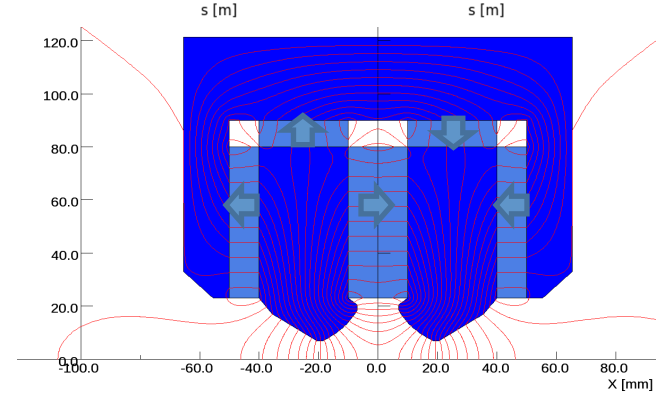


Innovations and challenges of eRHIC accelerator design

- High intensity (10 - 50mA) polarized electron source using multi-cathode gun (“Gatling Gun”)
- Energy Recovery Linac with 99% recovery efficiency (energy loss from synchrotron radiation)
- Up to 16 re-circulations of the electron beam through the same 1.32 GeV Linac
- Novel FFAG lattice allows 16 beam re-circulations using only two beam transport loops
- Permanent magnet technology is used for the FFAG beamline magnets eliminating the need for power supplies, power cables and cooling.
- Strong cooling of hadron beams gives high luminosity while minimizing electron beam current and synchrotron radiation loss.







Pre-project R&D to mitigate technical risk

- Prototyping of Gatling Gun polarized electron source (BNL LDRD, DOE NP mid-term accel. R&D)
  - First beam from two cathodes in one gun, prototype supports full tests with 20 cathodes
- Coherent electron Cooling (DOE NP COMP, BNL PD)
  - CeC PoP in 2016 using 40 GeV/n Au beams in RHIC; micro-bunching technique test also possible
  - Same set-up allows test of e-p collisions with high disruption parameter
- High average current ERL to support operation with high current e-beam (NAVY, DOE NP mid-term accel. R&D)
  - Results from test-ERL in 2015/16
- Development of high gradient crab cavities for HL-LHC upgrade (LARP)
- Development of polarized He-3 underway in collaboration with MIT (DOE NP mid-term accel. R&D)
- 422 MHz elliptical 5-cell cavity (BNL LDRD)
  - Test of 4 K operation with N_2 doping
- Possible multi-pass ERL beam dynamics studies at BINP ERL, CEBAF, or a future Cornell multi-pass test-ERL

eRHIC TPC cost elements

#	WBS	eRHIC	FY15 M$ Burdened				
			Burdened Labor	Burdened Material	Cont. $	Total	Cont. %
#	1.1	Civil Construction/Infrastructure	7.3	40.8	18.9	**67.0**	39%
#	1.2	Cryogenic Systems	12.2	47.5	16.0	**75.7**	27%
#	1.3	CW SRF Linac	23.4	69.6	36.8	**129.8**	40%
#	1.4	RF Power Amplifiers and LLRF	3.2	47.9	15.6	**66.7**	30%
#	1.5	Magnets	22.8	66.7	27.7	**117.3**	31%
#	1.6	Vacuum	9.9	45.3	11.0	**66.2**	20%
#	1.7	Magnet PS	3.1	31.6	11.5	**46.1**	33%
#	1.8	Instrumentation	13.8	23.2	10.0	**47.0**	27%
#	1.9	Controls	9.8	7.3	5.4	**22.4**	31%
#	1.10	Electron Injector and Abort	8.8	16.1	8.4	**33.3**	34%
#	1.11	RHIC Modifications	6.7	6.2	4.0	**17.0**	31%
#	1.12	Commissioning/Pre-Operations	6.9	7.8	4.3	**18.9**	29%
#	1.13	Project Management/Control	21.3	2.4	4.7	**28.4**	20%
#	1.14	Project R&D	10.0	5.4	4.6	**20.0**	30%
		TPC Total	**159.3**	**417.7**	**178.9**	**755.9**	**31%**

- Full bottom-up cost and contingency estimate of eRHIC conceptual design
- WBS elements 1.1 to 1.11 all include PED, construction, assembly, and installation
- Based on extensive experience from RHIC and RHIC upgrades, and also information from other projects (Cryo: FRIB, CEBAF 12 GeV; CW SRF Linac: FRIB, LCLS II, CEBAF 12 GeV; Magnets: FNAL Recycler, NSLS II)

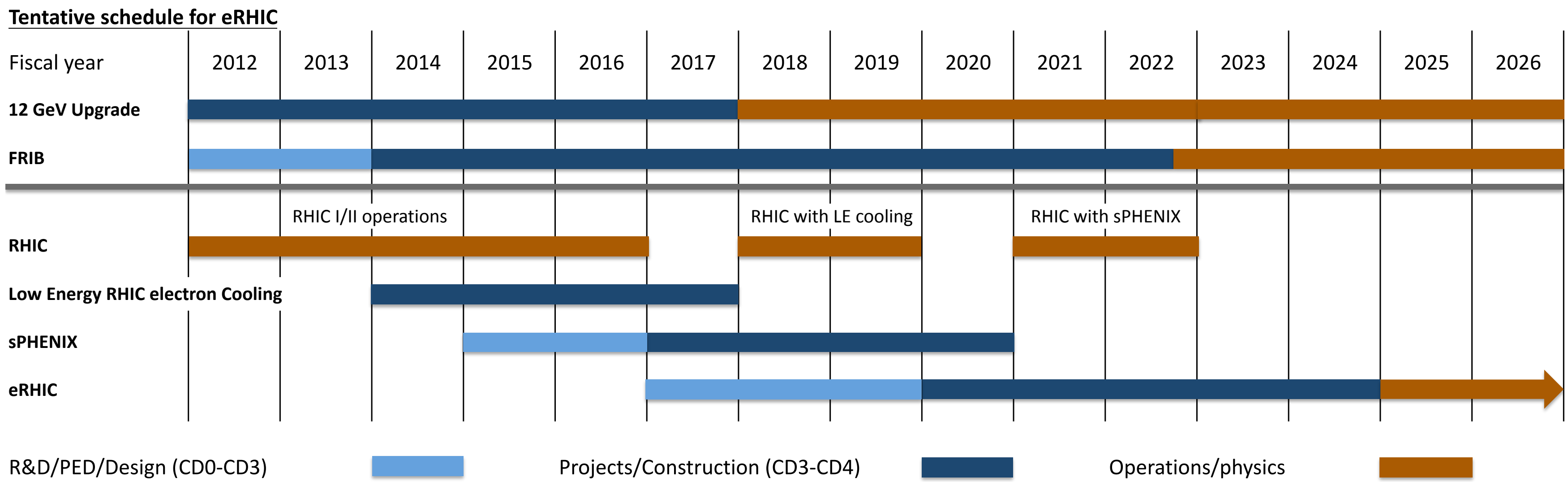
Main cost drivers

- CW SRF Linacs
  - 140 m long 1.32 GeV Linac with 20 MeV energy loss compensation and 53 MeV energy spread compensation
    - *Total for elliptical cavities, cryo-modules and RF: TPC cost $122.9M*
  - 50 m long 52 MeV Linac with 6 MeV energy spread compensation for CeC
    - *Total for quarter-wave cavities, cryo-module and RF: TPC cost $50.2M*
- FFAG arcs
  - 4264 permanent magnet quadrupoles, each with two electrically powered correctors and one dual plane BPM for every 4 magnets
    - *Total, incl. corrector and PS, vacuum chamber and BPMs: TPC cost $175.0M Average cost per magnet: TPC cost $41.2k*
- Spreader/combiner beamlines on either side of main linac
  - Each with 16 beam lines with total of 218 magnets
    - *Total, incl. vacuum chamber, BPMs, PS: TPC cost $35.2M*

eRHIC operating costs

- Based on RHIC operating cost with incremental cost for the operation of the electron machine
- Present RHIC operating costs (FY14, escalated to FY15):
  - RHIC accelerator operations: FY15$ 132.6M
  - RHIC detector operations (2 detectors): FY15$ 37.5M
  - RHIC total operating costs: FY15$ 170.1M
- Accelerator operations of the electron machine adds about 12% for increased manpower and increased electric power consumption to the RHIC accelerator operations:
  - eRHIC accelerator operations: FY15$ 148.3M
  - eRHIC detector operations (1 detector): FY15$ 25.0M
  - eRHIC total operating costs: FY15$ 173.3M
- Details in Wolfram's talk

RHIC and possible eRHIC schedule



eRHIC Summary Cost Data

- The accelerator total project cost was presented to be \$755.9M in FY15\$ including 31% contingency.
- An on-going pre-project R&D program that has been underway for several years would continue into project approval when a \$20M on-project R&D program would begin.
- An initial detector might cost about \$100M for hardware with a rough estimate including full effort costs bringing the total to \$237M. Much of the effort is anticipated to be contributed by collaborators.
- Finally accelerator pre-operations activities are estimated at \$18.9M and annual operations costs, including experimental support are estimated slightly up from those of RHIC, at \$173.3M/yr.

eRHIC Committee Summary

- Will work if the unproven or demanding technical components can be shown to meet the demanding technical specifications
- They present both technical and costs risks and will require substantial R&D to be proven reliable and cost effective
- The sub-committee believes the resources required to demonstrate component successes at the performance levels required to begin production have been seriously underestimated both at the ongoing pre-project level and the $20M on-project level. The cost estimate was considered reasonable for the well understood technical and civil components.

MEIC Design Overview

Fulvia Pilat

EIC Cost Review January 26-28 2015

Jefferson Lab
Thomas Jefferson National Accelerator Facility

MEIC Design Goals

Energy

Full coverage of √**s** from **15** to **65** GeV

Electrons **3-10** GeV, protons **20-100** GeV, ions **12-40** GeV/u (lower than White Paper)

Ion species

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

Un-polarized light to heavy ions up to A above 200 (Au, Pb)

Space for at least 2 detectors

Full acceptance is critical for the primary detector

Luminosity

10^{33} to 10^{34}cm^{-2}s^{-1} per IP in a *broad* CM energy range

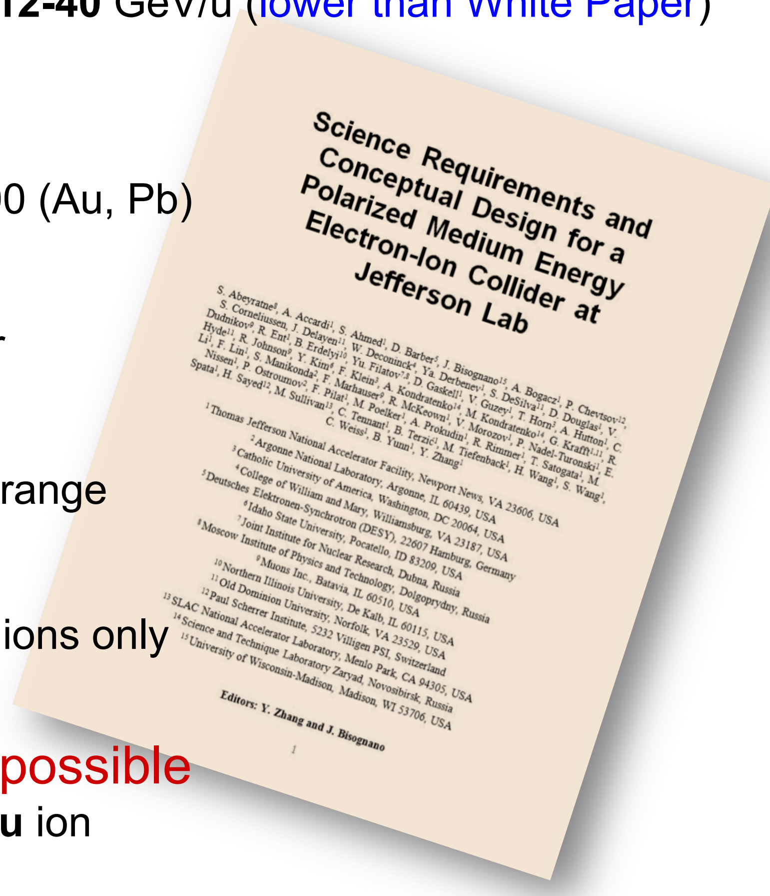
Polarization

At IP: longitudinal for both beams, transverse for ions only

All polarizations >70%

Upgrade to higher energies and luminosity possible

20 GeV electron, **250 GeV** proton, and **100 GeV/u** ion



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. Terzić[1], M. Tiefenback[1], H. Wang[1], S. Wang[1], C. Weiss[1], B. Yunn[1], Y. Zhang[1]

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[15] University of Wisconsin-Madison, Madison, WI 53706, USA

Editors: Y. Zhang and J. Bisognano

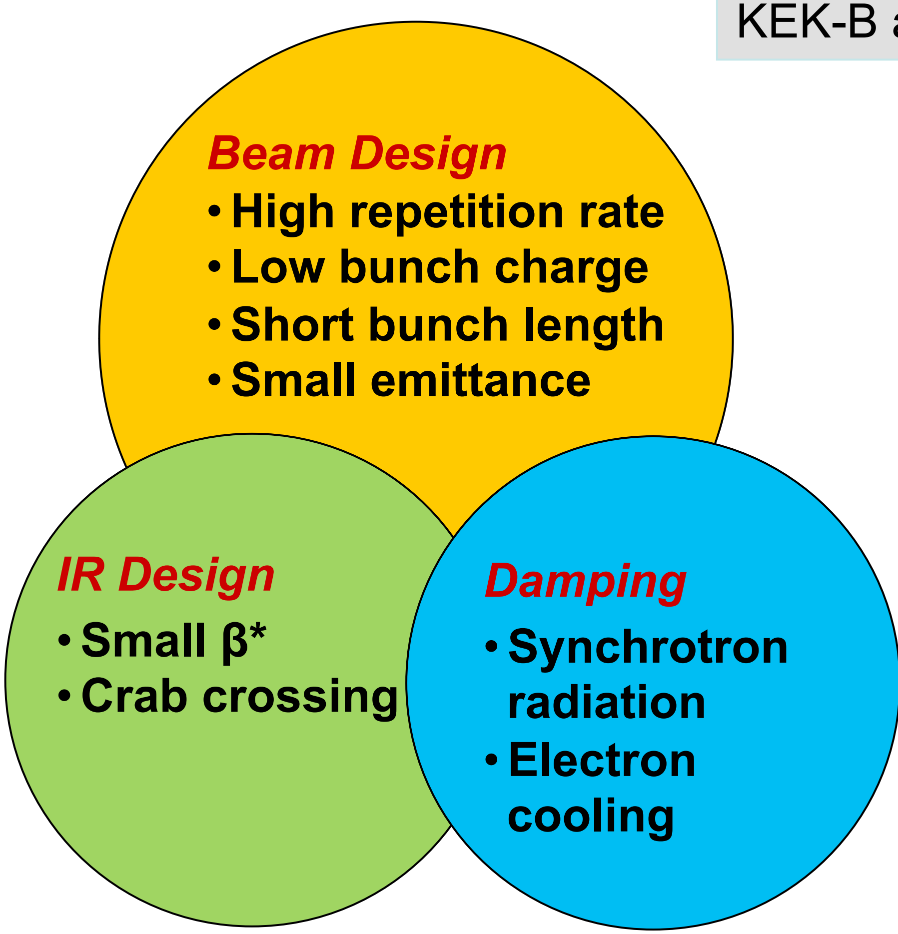
1

Design goals consistent with the White Paper requirements

Design Strategy: High Luminosity

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

KEK-B already reached above 2x10[34] /cm[2]/s



$$L = f\frac{n_1 n_2}{4\pi\sigma^*_x\sigma^*_y} \sim f\frac{n_1 n_2}{\varepsilon\beta^*_y}$$

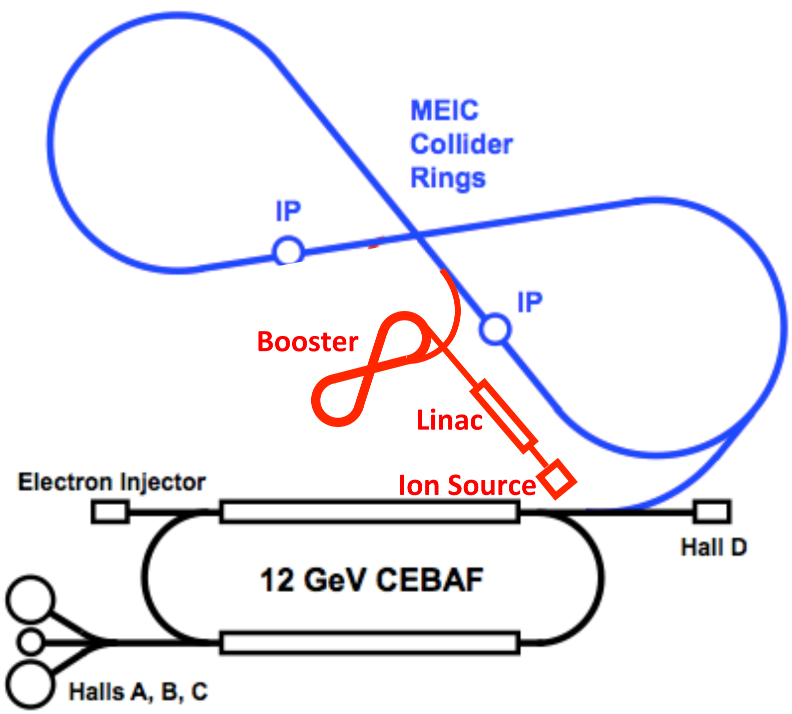
"Traditional" hadrons colliders

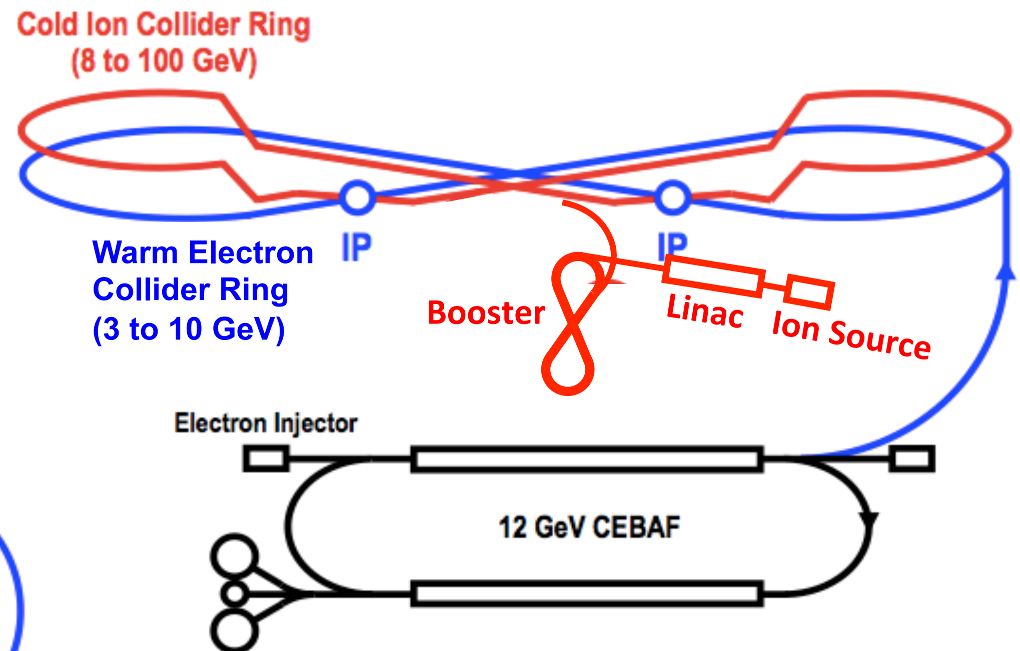
Small number of bunches
→ Small collision frequency *f*
→ Large bunch charge n_1 and n_2
→ Long bunch length
→ Large beta-star

Linac-Ring colliders

- Large beam-beam parameter for the electron beam
- Need to maintain high polarized electron current
- High energy/current ERL

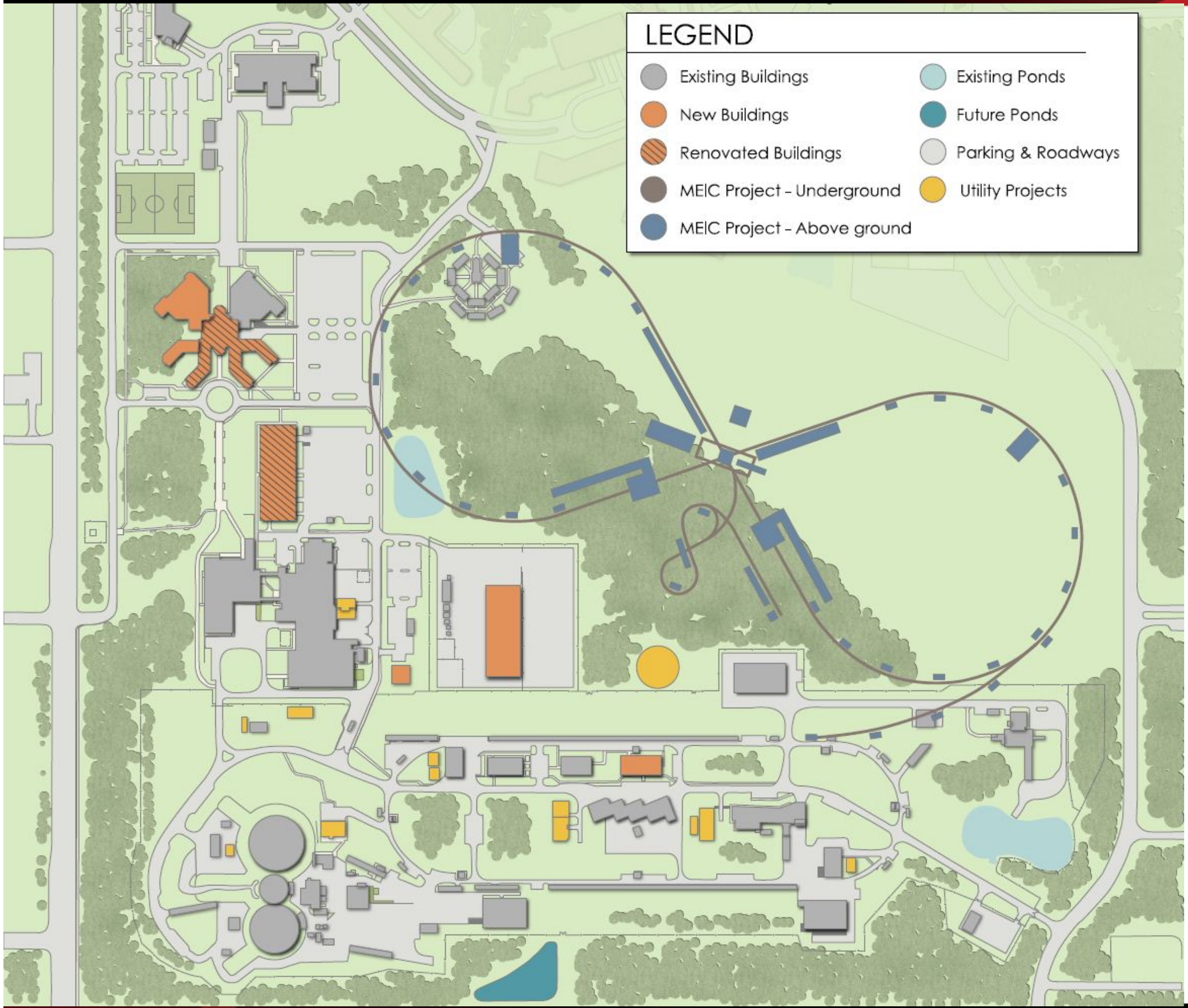
Baseline Layout





CEBAF is a full energy injector.
Only minor gun modification is needed

Campus Layout



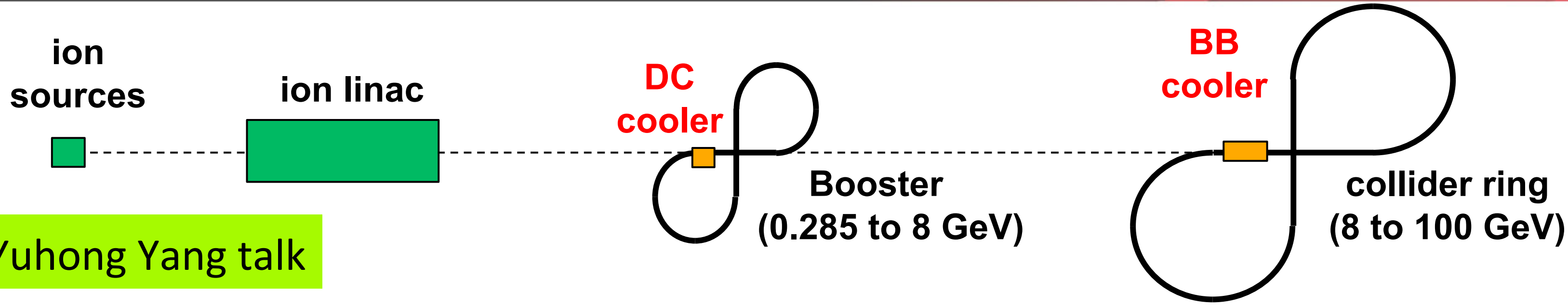
~2.2 km circumference

E-ring from PEP-II

Ion-ring with super-ferric magnets

Tunnel consistent with a 250+ GeV upgrade

MEIC Multi-Step Cooling Scheme



Yuhong Yang talk

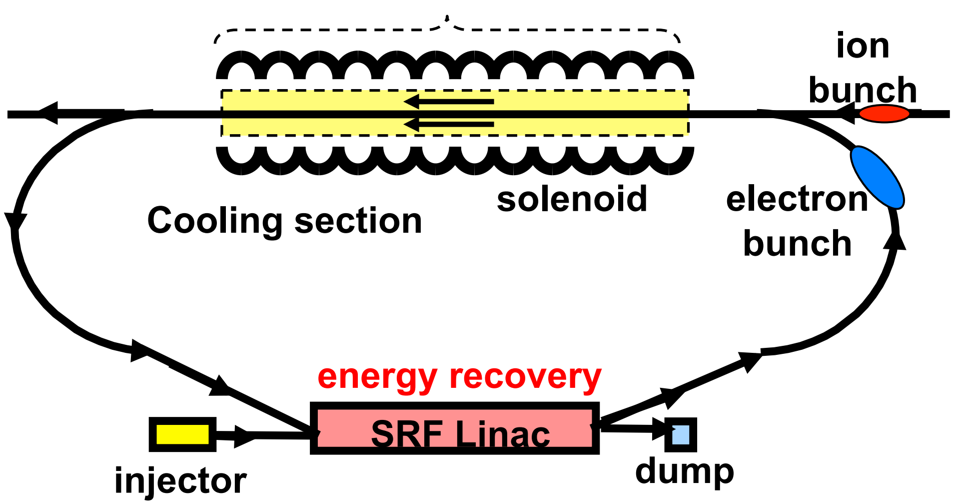
Ring	Cooler	Function	Ion energy	Electron energy
			GeV/u	MeV
Booster ring	DC	Injection/accumulation of positive ions	0.11 ~ 0.19 (injection)	0.062 ~ 0.1
		Emittance reduction	2	1.1
Collider ring	Bunched Beam Cooling (BBC)	Maintain emittance during stacking	7.9 (injection)	4.3
		Maintain emittance	Up to 100	Up to 55

- DC cooling for emittance reduction
- BBC cooling for emittance preservation

MEIC Bunched Beam Electron Cooler

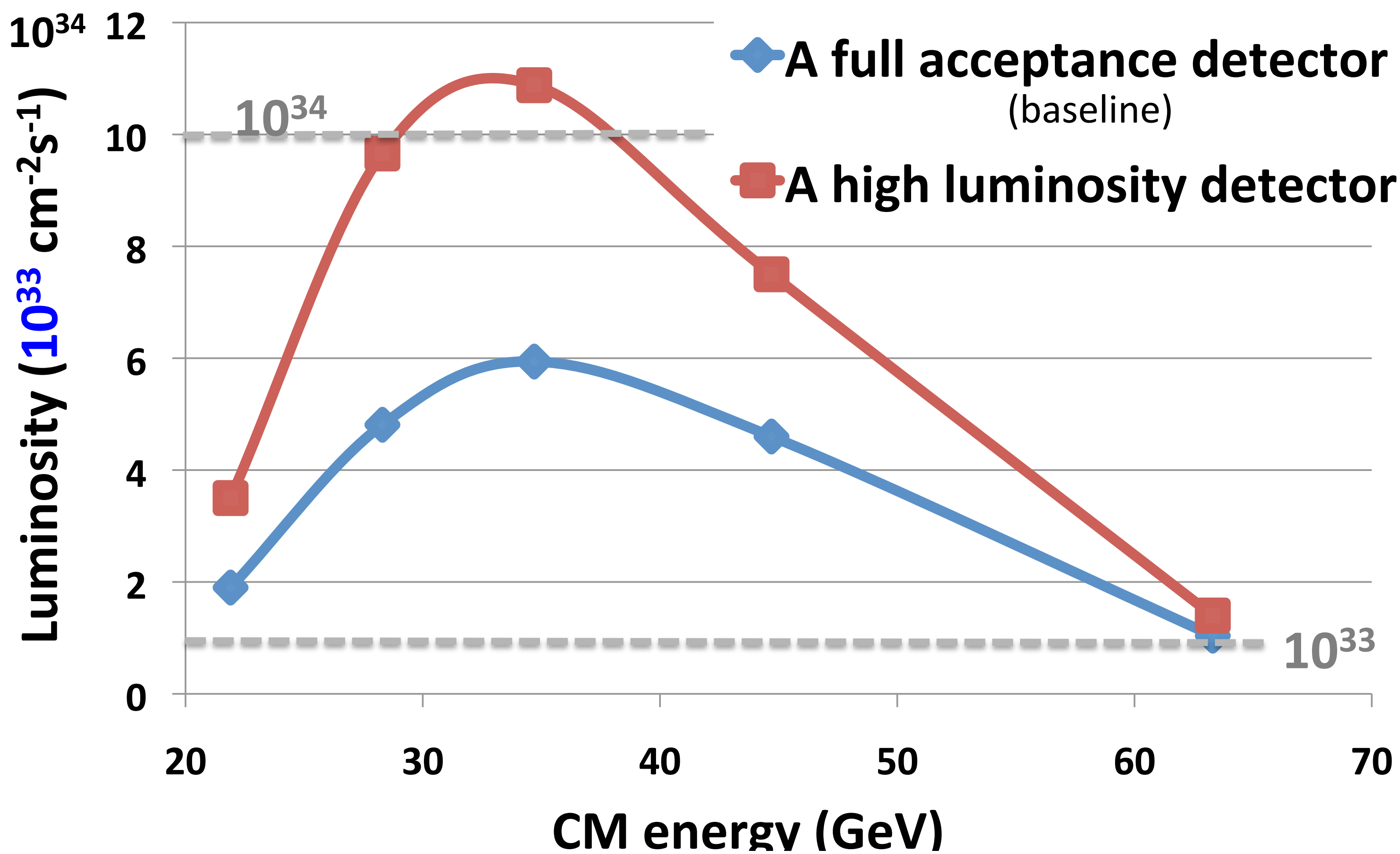
Baseline cooling requirements and solution

- Emittance 0.5 to 1 mm mrad → reduced IBS effect
- Magnetized beam, up to 55 MeV energy, and 200 mA current
- Need linac for acceleration
- Must utilize energy-recovery-linac (beam power is 11 MW)
- Cooling by a bunched electron beam



Electron energy	MeV	up to 55
Current and bunch charge	A / nC	0.2 / 0.42
Bunch repetition	MHz	476
Cooling section length	m	60
RMS Bunch length	cm	3
Electron energy spread	10^{-4}	3
Cooling section solenoid field	T	2
Beam radius in solenoid/cathode	mm	~1 / 3
Solenoid field at cathode	KG	2

e-p Luminosity



The baseline performance requires a **ERL bunched beam cooler** but no circulator cooler

Overview R&D for the MEIC baseline

Needed R&D	Risk level	Mitigating strategies	Mitigated risk level
Bunched beam electron cooling ERL only	MEDIUM	▪ Test of bunched beam cooling at IMP (LDRD) ▪ Experience from RHIC low energy cooling ▪ Development of a 200 mA unpolarized e- gun	LOW
Low β^* ion ring	MEDIUM	▪ Chromatic and IR nonlinear correction schemes ▪ DA tracking with errors and beam beam ▪ Operational experience at hadron colliders	LOW
Space charge dominated beams	MEDIUM	▪ Simulation ▪ DC cooling in Booster ▪ Operational experience at UMER and IOTA rings ▪ Study of space charge compensation at eRHIC	LOW
Figure 8 layout	MEDIUM	▪ Spin tracking simulations	LOW
Super ferric magnets	MEDIUM	▪ Existing prototypes (SSC, GSI) ▪ Early MEIC prototype (FY15-16) ▪ Operational experience at GSI ▪ Alternative cosθ designs	LOW
Crab cavities	MEDIUM	▪ Prototypes ▪ Operational experience at KEK-B and LHC ▪ Test of crab cavity in LERF (FEL)	LOW
SRF R&D	LOW	▪ 952 MHz RF development	LOW

Total

(k$, FY15, w/OH)

		Scope	Contingency
1.1.	CDR	4,656	1,629
1.2.	Accelerator	692,285	271,740
1.4.	Conv. Facilities	210,349	42,070
1.5.	Integrated comm.	37,327	13,064
1.6.	Management -Project	13,411	4,694
	Total	1,291,255	
1.3.	Exp. Systems	126,639	61,418
		188,056	
		1,479,311	

MEIC Summary Cost Data

- Total Project Cost without detector of $1.29B in FY15$ and a TPC with detector of $1.48B.
- Pre-operations (included in the TPC) are estimated at $37.3M and the annual MEIC operating cost is estimated at $117M for 26 weeks of operations

MEIC Committee Summary

- This ring-ring design concept is largely based on conventional technologies and can be expected to perform as planned. There are a modest number of higher risk components that the R&D program should address.
- Several parts of the cost estimate were prepared on a parametric basis which is typical at this early stage of project development. The extensive cavity and cryomodule experience at JLab lends credence to these estimates. The recent experience from the 12 GeV Upgrade project is a benefit to the team as well.
- Overall the cost estimate of the chosen technical scope was reasonable. The TPC is reasonable, although R&D and Pre-ops funds are marginal. The 35% overall contingency is marginally appropriate.

Overall Review Committee Summary

- eRHIC incorporates certain technical advances which are beyond the state of the art; the 31% contingency is, in the opinion of the subcommittee insufficient.
- MEIC is based on largely conventional technology with fewer technical risks; the proposed 35% contingency is marginally sufficient.
- An EIC could be built for about $1.5B in FY15$.
    - This is equal to the MEIC TPC and $0.5B higher than the eRHIC TPC to account for the higher technical risk.
- The total on-project cost may potentially be reduced as technical risk is retired, by off-project funds especially for the detectors from international sources, by redirection of operating funds at the host laboratory or by reducing the design requirements.