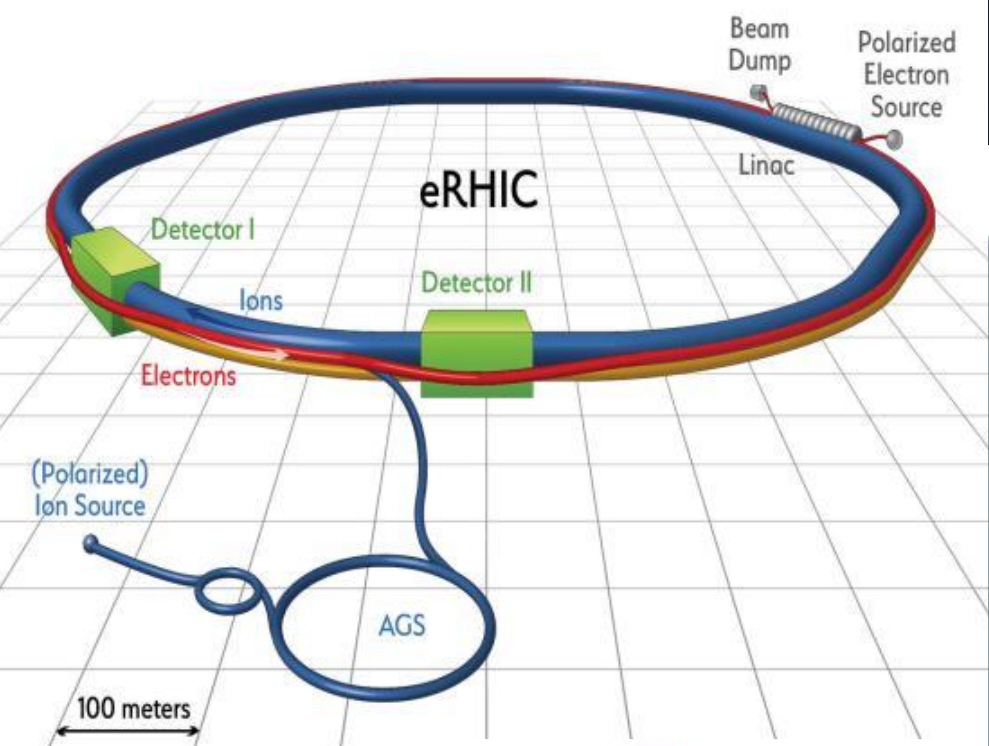
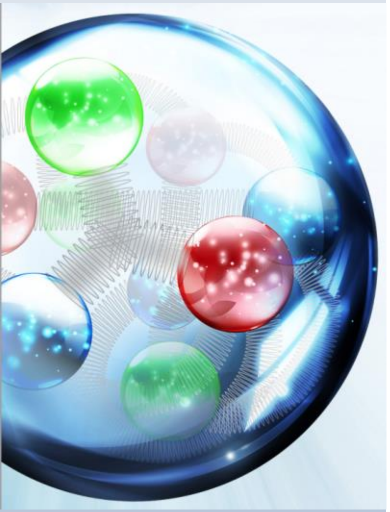
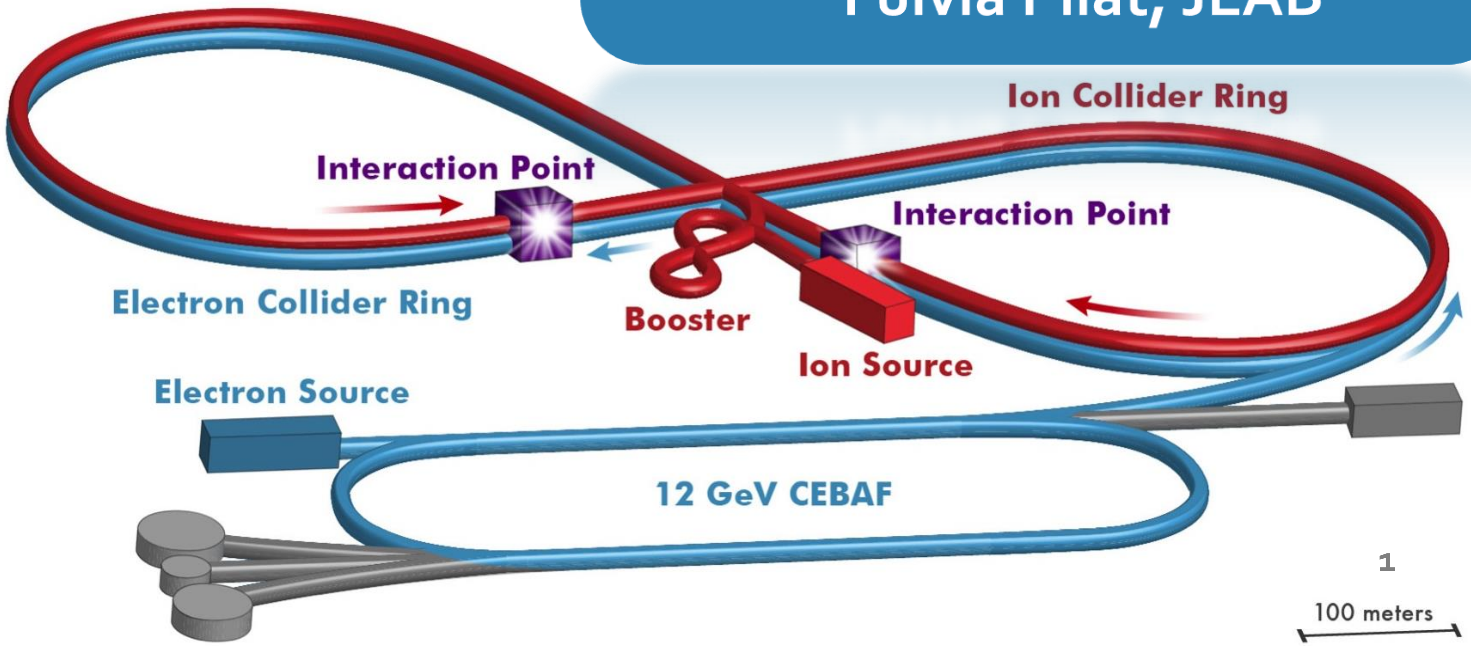
EPS Conference on High Energy Physics
Venice, Italy 5-12 July 2017

Accelerator designs and R&D for the Electron-Ion Collider

Fulvia Pilat, JLAB





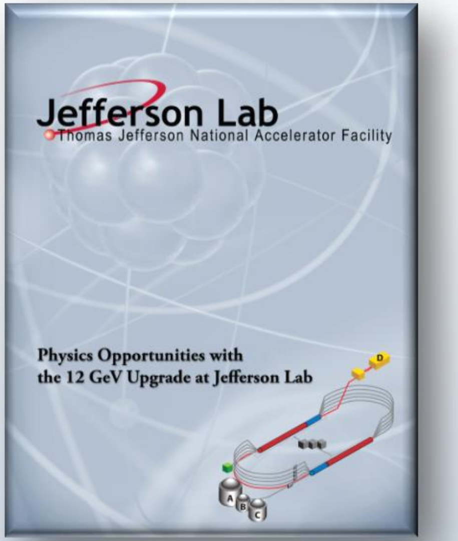


Outline

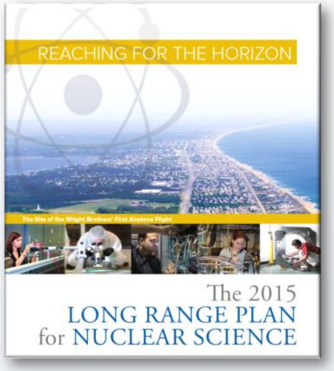
- EIC: an introduction
- EIC accelerator challenges and parameters
- EIC concepts:
  - JLEIC: **figure-8 ring-ring** (JLAB)
  - eRHIC **ring-ring** (BNL)
  - *eRHIC ERL-ring (BNL)*
- EIC accelerator R&D: common and design specific
- Collaborative frame, US and international
- Outlook

An electron-Ion collider is the highest priority for new construction in Nuclear Physics

Decade of Experiments Approved
First 12 GeV Science Experiments Complete

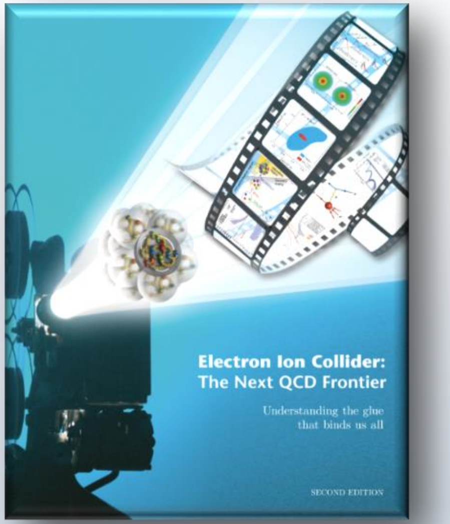


- **Confinement**
- **Hadron Structure**
- **Nuclear Structure and Astrophysics**
- **Fundamental Symmetries**



2015 NSAC Long Range Plan
Strong support for JLAB program

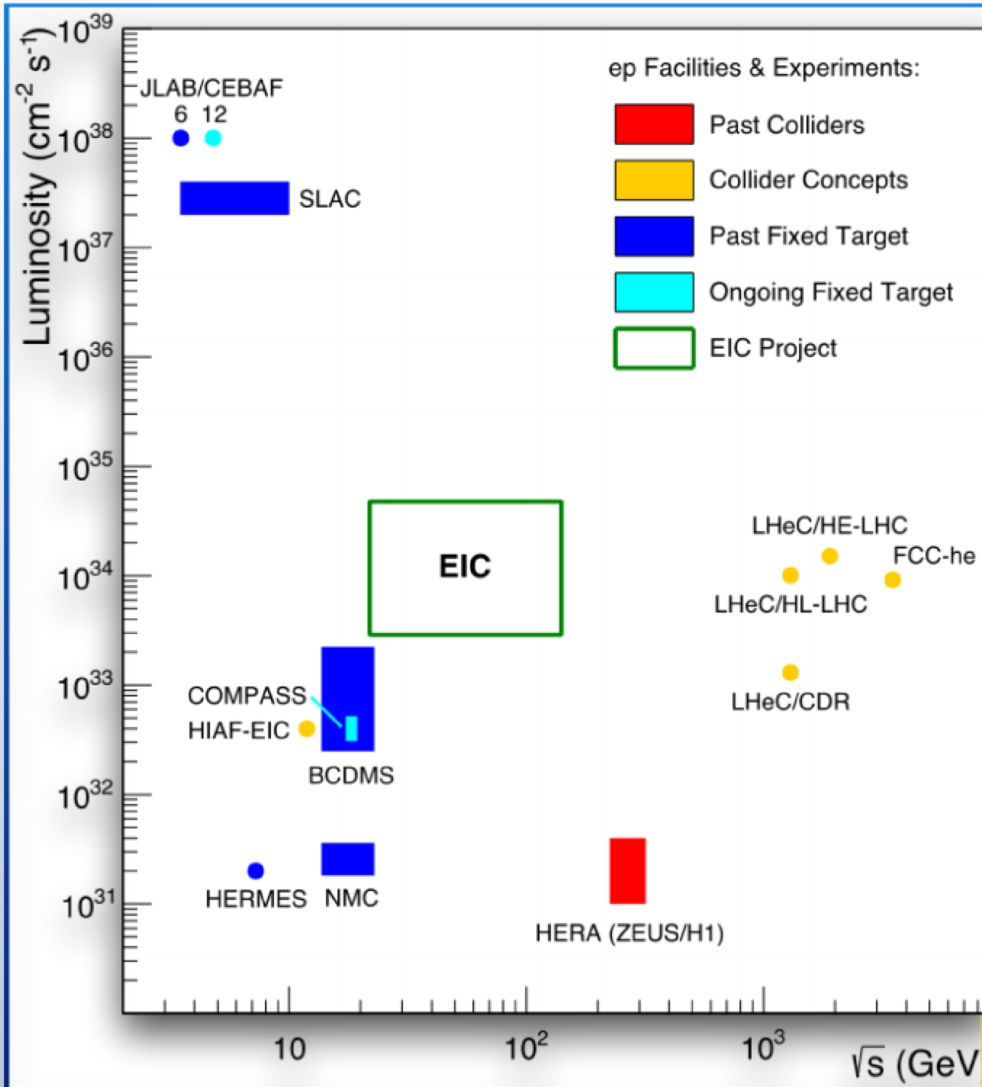
Electron Ion Collider
The Next QCD Frontier



- **Role of Gluons in Nucleon and Nuclear Structure**

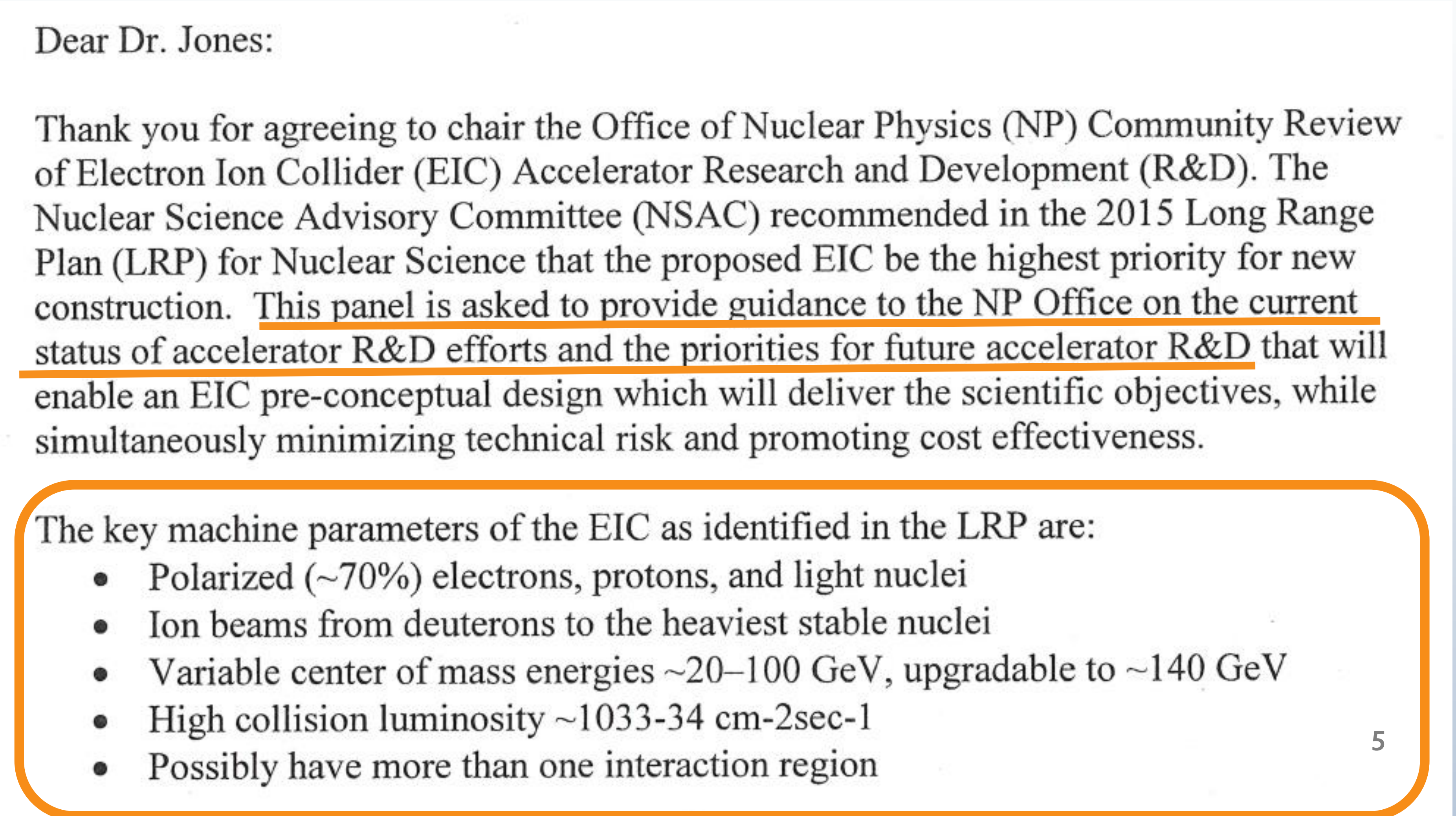
EIC unique characteristics and challenge

- High **luminosity** (50 x Hera)
- High **polarization: first ever fully polarized collider**
- Wide range of **collision energies and** collision energy ratios
- **Many species** (polarized p, e- and light nuclei, d to heaviest nuclei)
- **Large detector acceptance**: first ever e-p and e-A studies with ~100% reconstruction of nuclei in the final state



EIC parameters

From the charge letter to the NP Panel Review of EIC design and R&D, December 2016:



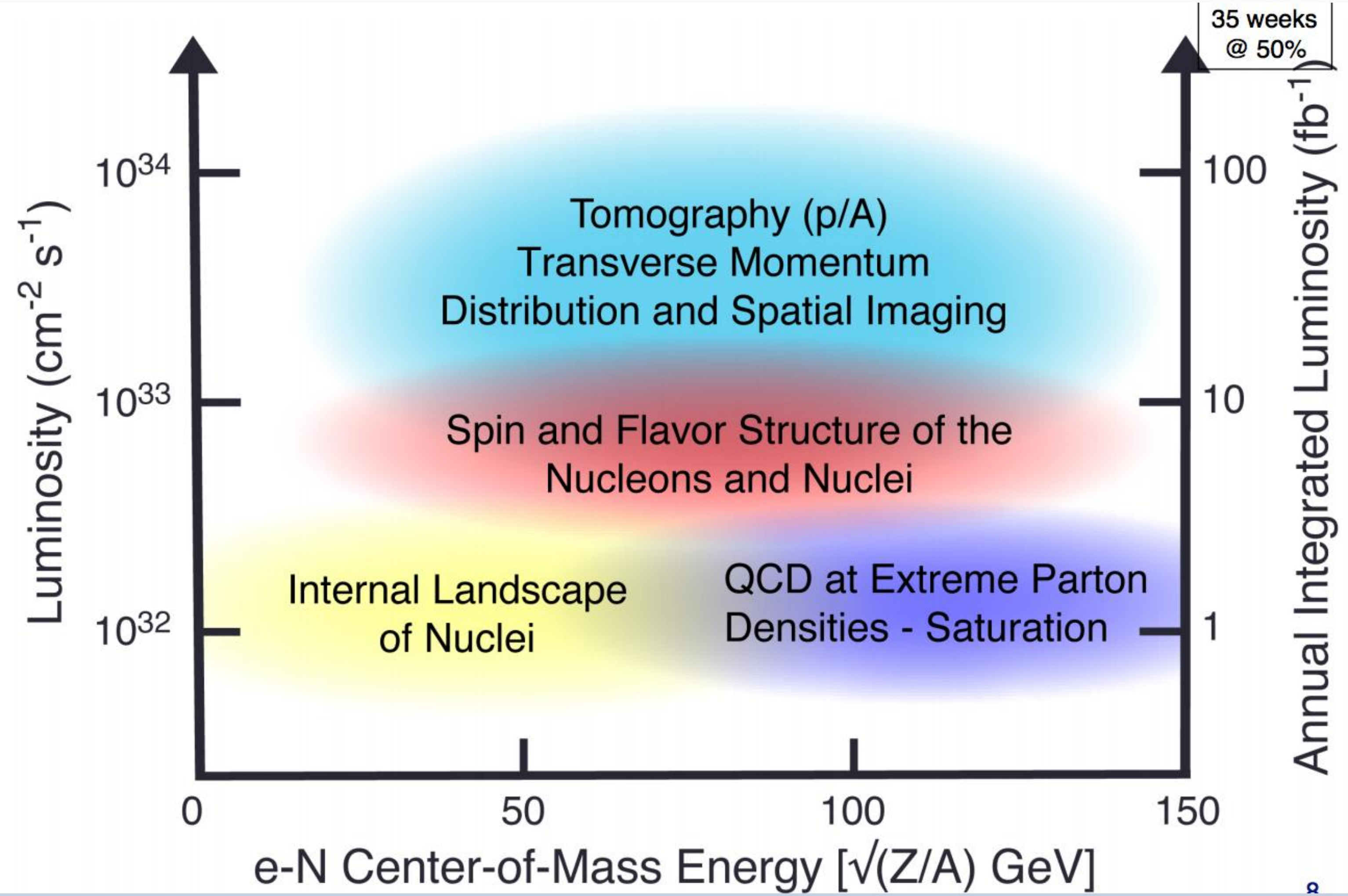
Dear Dr. Jones:

Thank you for agreeing to chair the Office of Nuclear Physics (NP) Community Review of Electron Ion Collider (EIC) Accelerator Research and Development (R&D). The Nuclear Science Advisory Committee (NSAC) recommended in the 2015 Long Range Plan (LRP) for Nuclear Science that the proposed EIC be the highest priority for new construction. This panel is asked to provide guidance to the NP Office on the current status of accelerator R&D efforts and the priorities for future accelerator R&D that will enable an EIC pre-conceptual design which will deliver the scientific objectives, while simultaneously minimizing technical risk and promoting cost effectiveness.

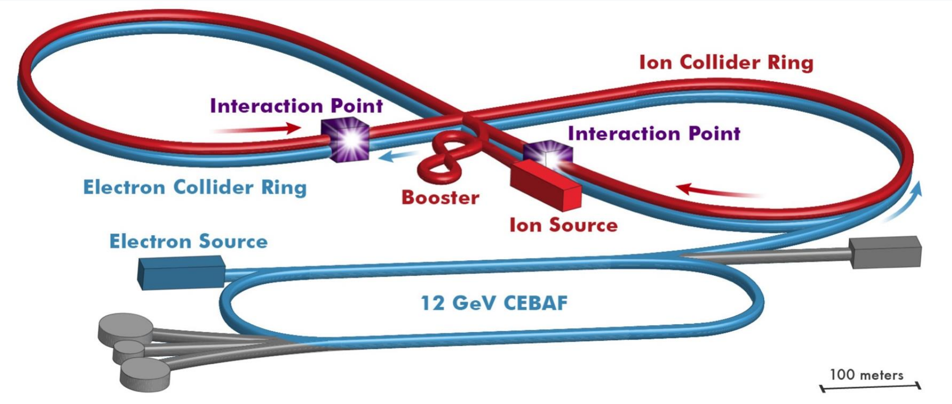
The key machine parameters of the EIC as identified in the LRP are:

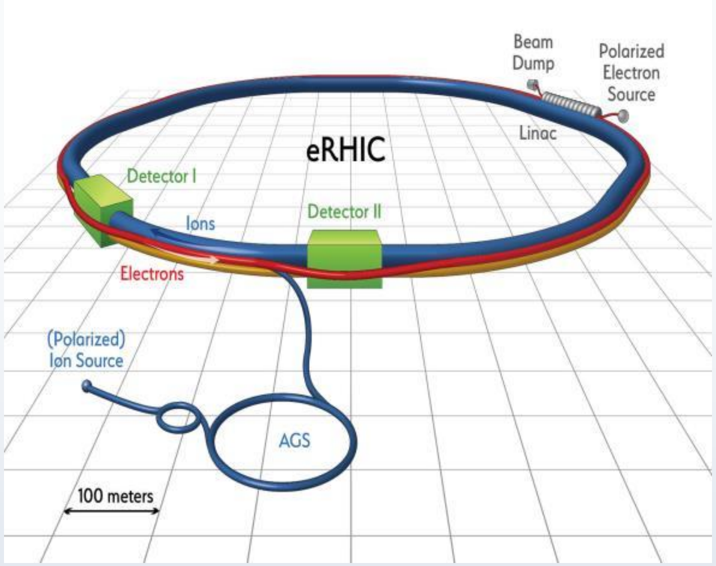
- Polarized (~70%) electrons, protons, and light nuclei
- Ion beams from deuterons to the heaviest stable nuclei
- Variable center of mass energies ~20–100 GeV, upgradable to ~140 GeV
- High collision luminosity ~1033-34 cm-2sec-1
- Possibly have more than one interaction region

EIC Physics


35 weeks
@ 50%
Luminosity (cm^{-2} s^{-1})
10^{34}
10^{33}
10^{32}
Annual Integrated Luminosity (fb^{-1})
100
10
1
Tomography (p/A)
Transverse Momentum
Distribution and Spatial Imaging
Spin and Flavor Structure of the
Nucleons and Nuclei
Internal Landscape
of Nuclei
QCD at Extreme Parton
Densities - Saturation
0
50
100
150
e-N Center-of-Mass Energy [√(Z/A) GeV]

EIC accelerator designs



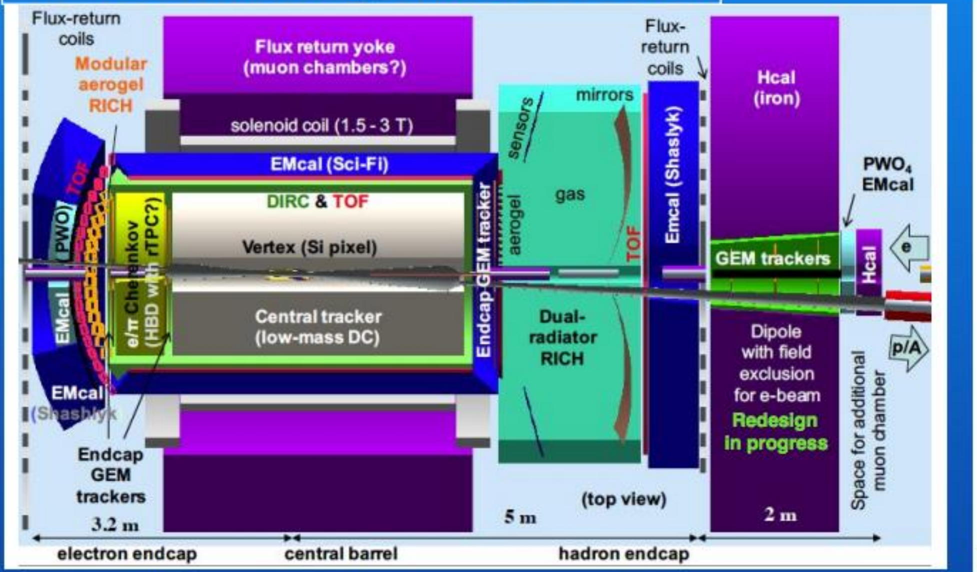


- New e-ring and ion complex
- CEBAF full e-energy injector
- High initial luminosity
- Increase energy reach

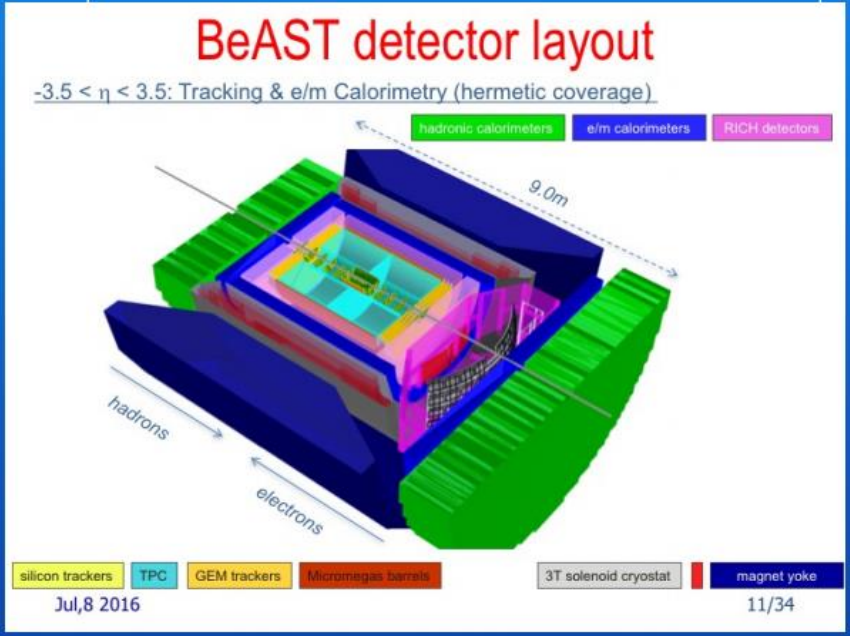
- New e-ring (or e-ERL)
- RHIC ion complex
- High initial collision energy
- Increase luminosity

EIC detector designs

JLEIC Full Acceptance Detector



Brookhaven *eA* Solenoidal Tracker

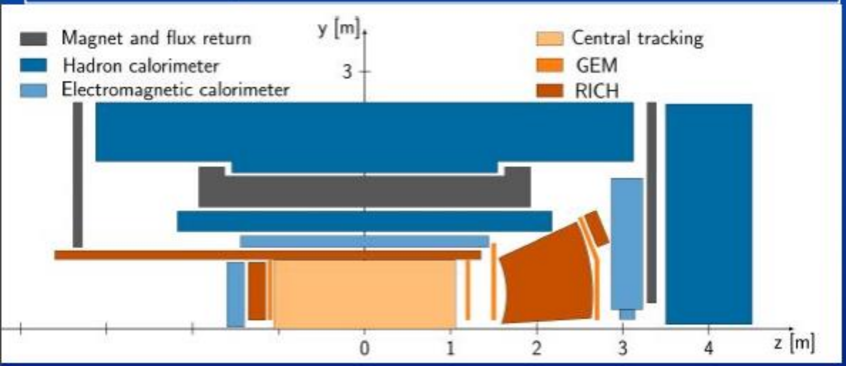

BeAST detector layout

-3.5 < η < 3.5: Tracking & e/m Calorimetry (hermetic coverage)

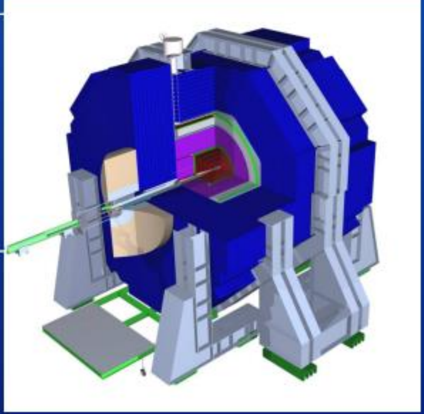
Jul,8 2016

11/34

ePHENIX, based on BaBAR Solenoid



ANL
SiEIC
Particle FLow
HCal

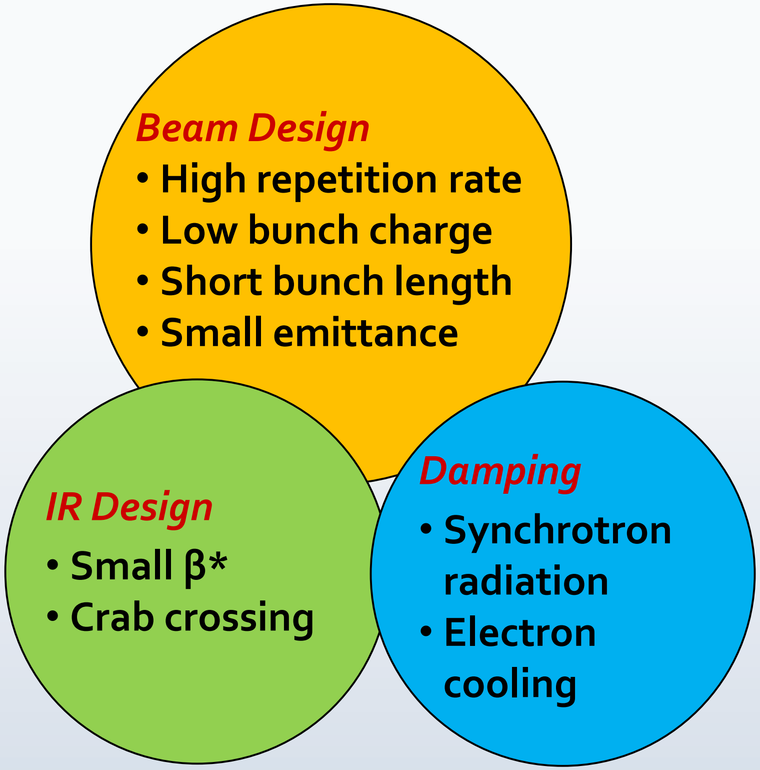


JLEIC design strategy

- **High luminosity**: **high collision rate** of short low-charge low-emittance bunches
  - Small **beam size**
    - Small β* ⇒ Short bunch length
      Low bunch charge, high repetition rate
    - Small emittance ⇒ Cooling
  - Similar to **lepton colliders** such as KEK-B with L > 2×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

$$L = f\,\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*} \sim f\,\frac{n_1 n_2}{\varepsilon\beta_y^*}$$

- **High polarization**: **Figure-8** rings
  - Net spin precession zero
  - Spin easily controlled by small magnetic fields for any particle species



Beam Design
- **High repetition rate**
- **Low bunch charge**
- **Short bunch length**
- **Small emittance**

IR Design
- **Small β***
- **Crab crossing**

Damping
- **Synchrotron radiation**
- **Electron cooling**

- **Optimal integration IR and total acceptance detector** (including far-forward acceptance)

- **Technical risk minimization**

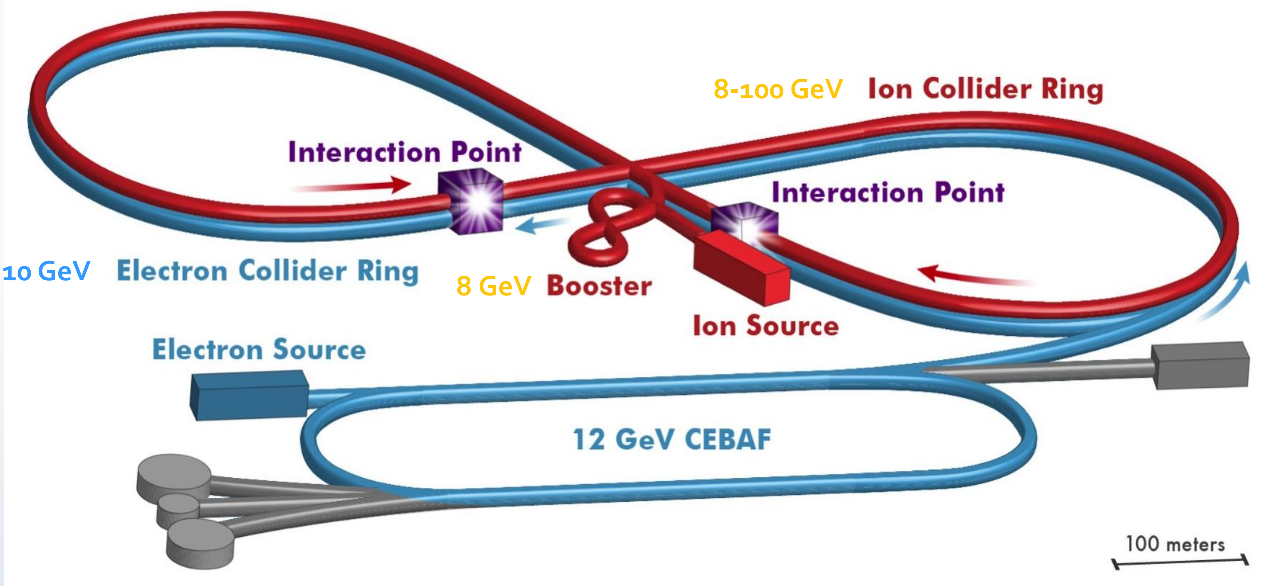
  adopt established technology where possible, focus technology demonstration in few selected areas

JLEIC design

energy range:
e-: **3-10** GeV
p : **20-100** GeV
√s: up to **65 GeV**

Range to to √s=**100 GeV** and √s=**140 GeV** possible

- **Electron complex**
  - CEBAF
  - Electron collider ring
- **Ion complex**
  - Ion source
  - SRF linac
  - Booster
  - Ion collider ring
- Fully integrated IR and **detector**
- DC and bunched beam **coolers**




MEIC Design Summary

January 20, 2015

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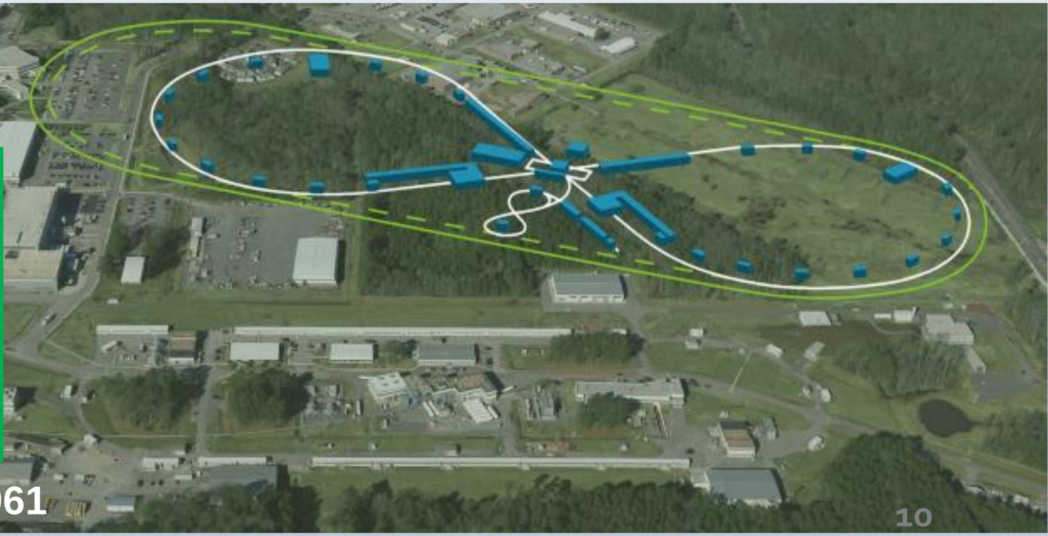
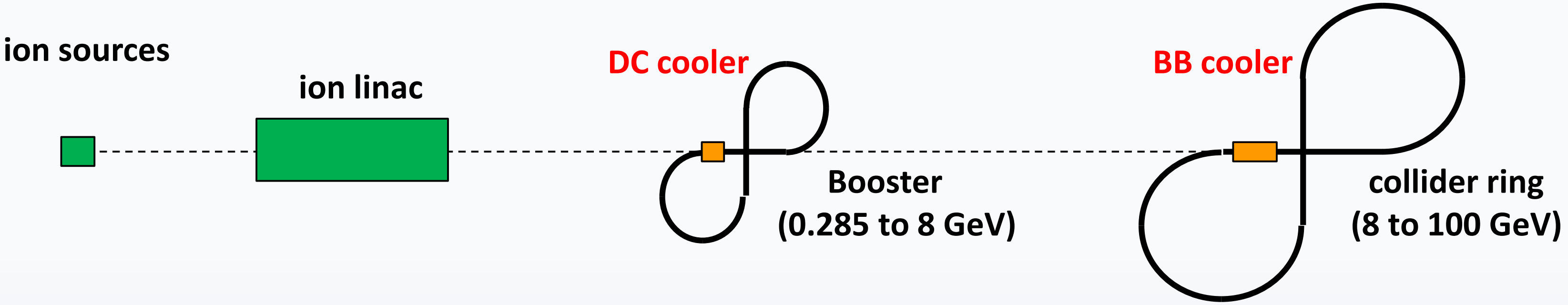
2015



arXiv:1504.07961

High luminosity: electron cooling



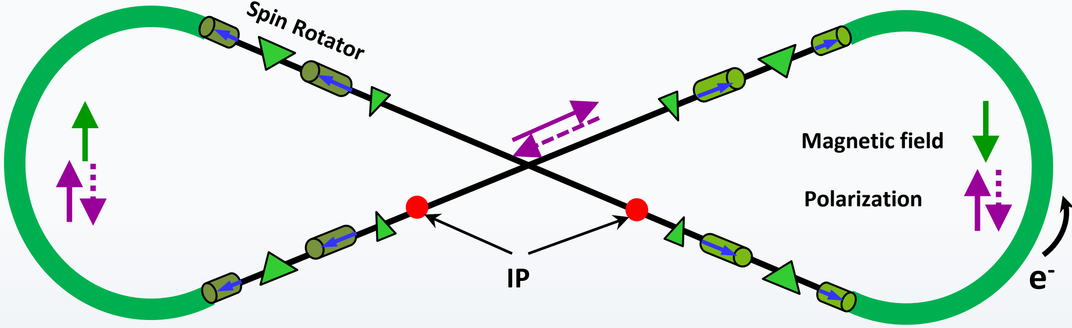
Ring	Cooler	Function	Ion energy	Electron energy
			GeV/u	MeV
Booster ring	DC	Injection and accumulation of positive ions	**0.11 ~ 0.19** (injection)	**0.062 ~ 0.1**
		Emittance reduction	**2**	**1.1**
Collider ring	Bunched Beam Cooling (BBC)	Maintain emittance during stacking	**7.9** (injection)	**4.3**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

- **DC cooling for emittance reduction**
- **BBC cooling for emittance preservation** against intra-beam scattering

High polarization: Figure-8

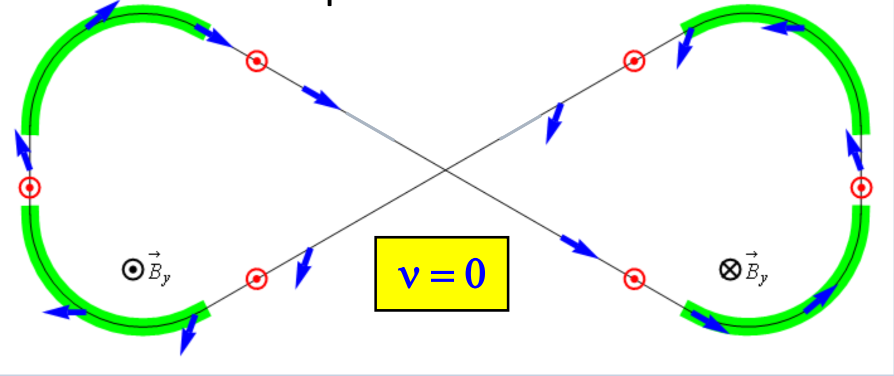
- **Figure-8** concept: spin precession in one arc is exactly cancelled in the other
- **Spin stabilization by small fields**: ~3 Tm vs. ~ 400 Tm for **deuterons** at 100 GeV
  - Criterion: induced spin rotation >> spin rotation due to orbit errors
- **Polarized deuterons possible**
- **3D spin rotator**: combination of small rotations about different axes provides **any polarization orientation** at any point in the collider ring
- No effect on the orbit
- Adiabatic spin flips
- **Spin tracking** in progress

Electron polarization



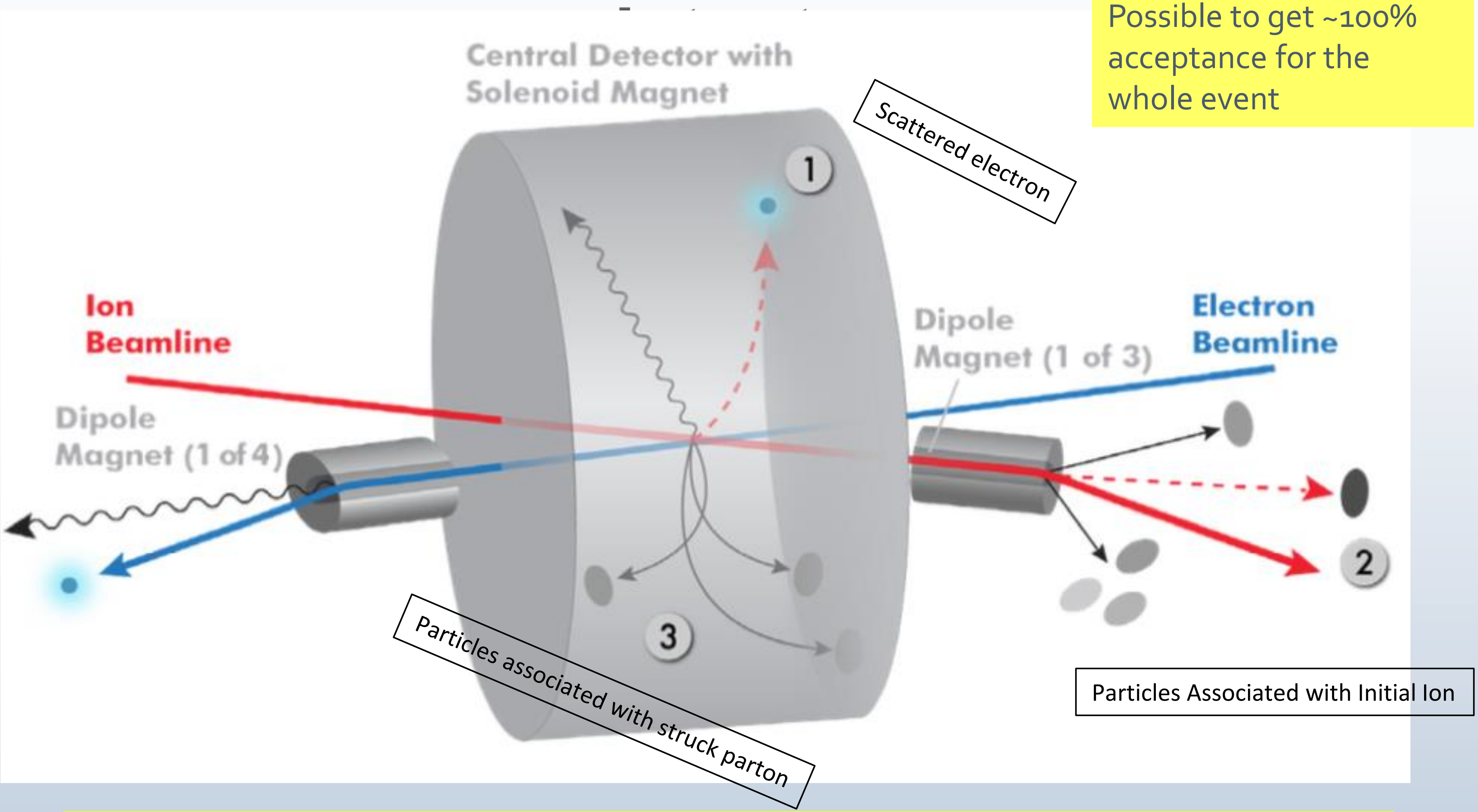
E- energy (GeV)	3	5	7	9	10
Estimated Pol. Lifetime (hours)	66	5.2	2.2	1.3	0.8

Ion polarization



Integration IR: total acceptance

Possible to get ~100% acceptance for the whole event



Scattered electron

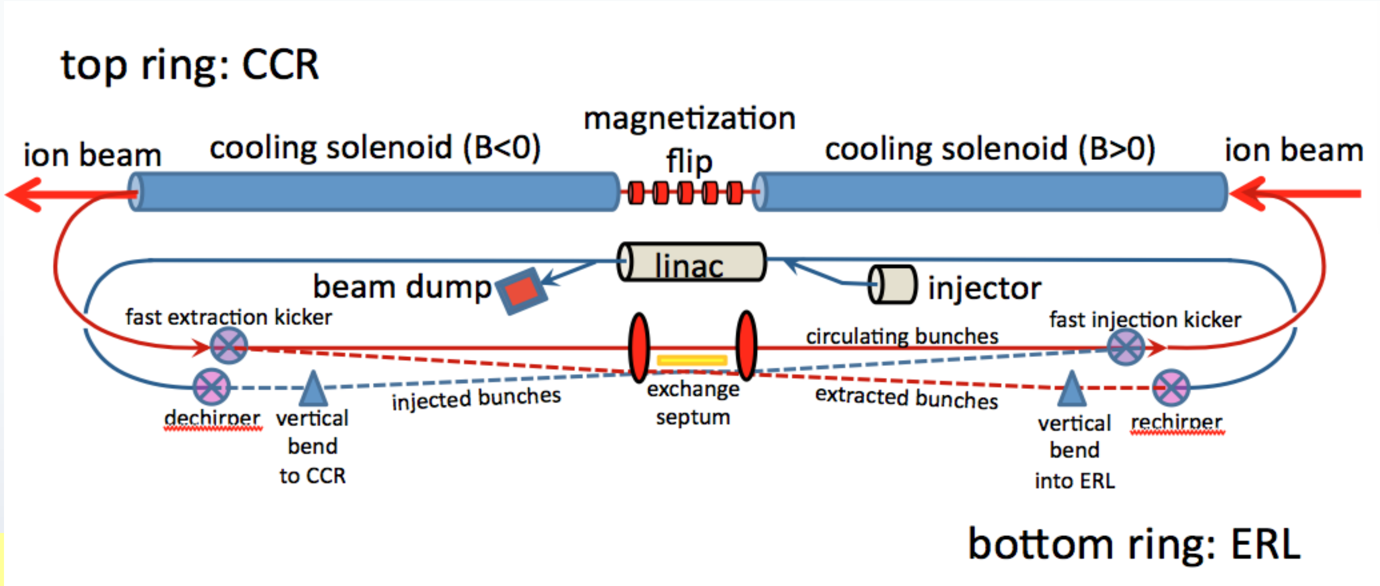
Particles associated with struck parton

Particles Associated with Initial Ion

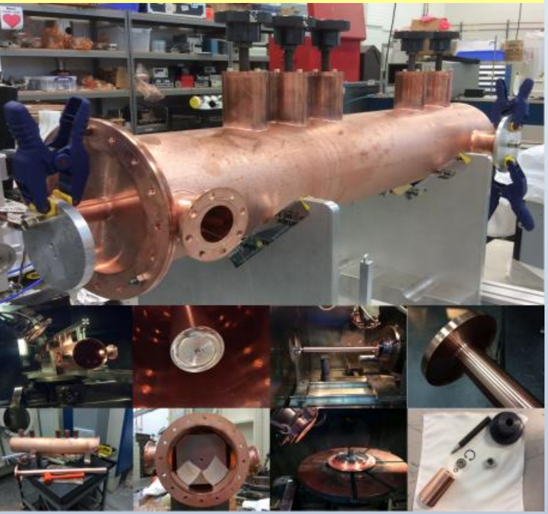
Relatively **large crossing angle** (**50 mr**) combined with **large aperture final focus magnets**, and forward dipoles are keys to this design.

Baseline: strong cooling

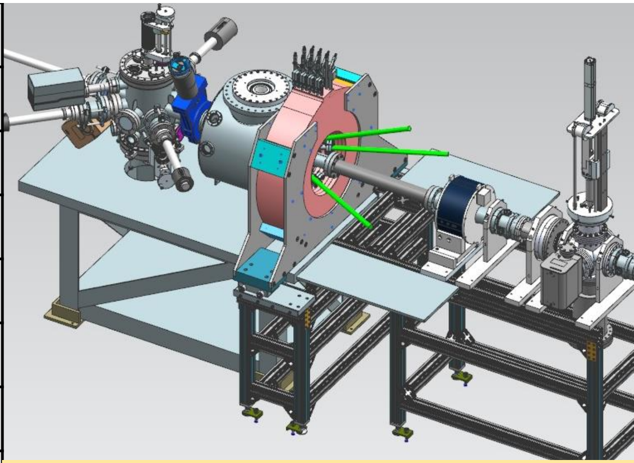
ERL cooler +
Multi-turn circulator ring



Enabling technologies :
Fast kickers, risetime <1 nsec



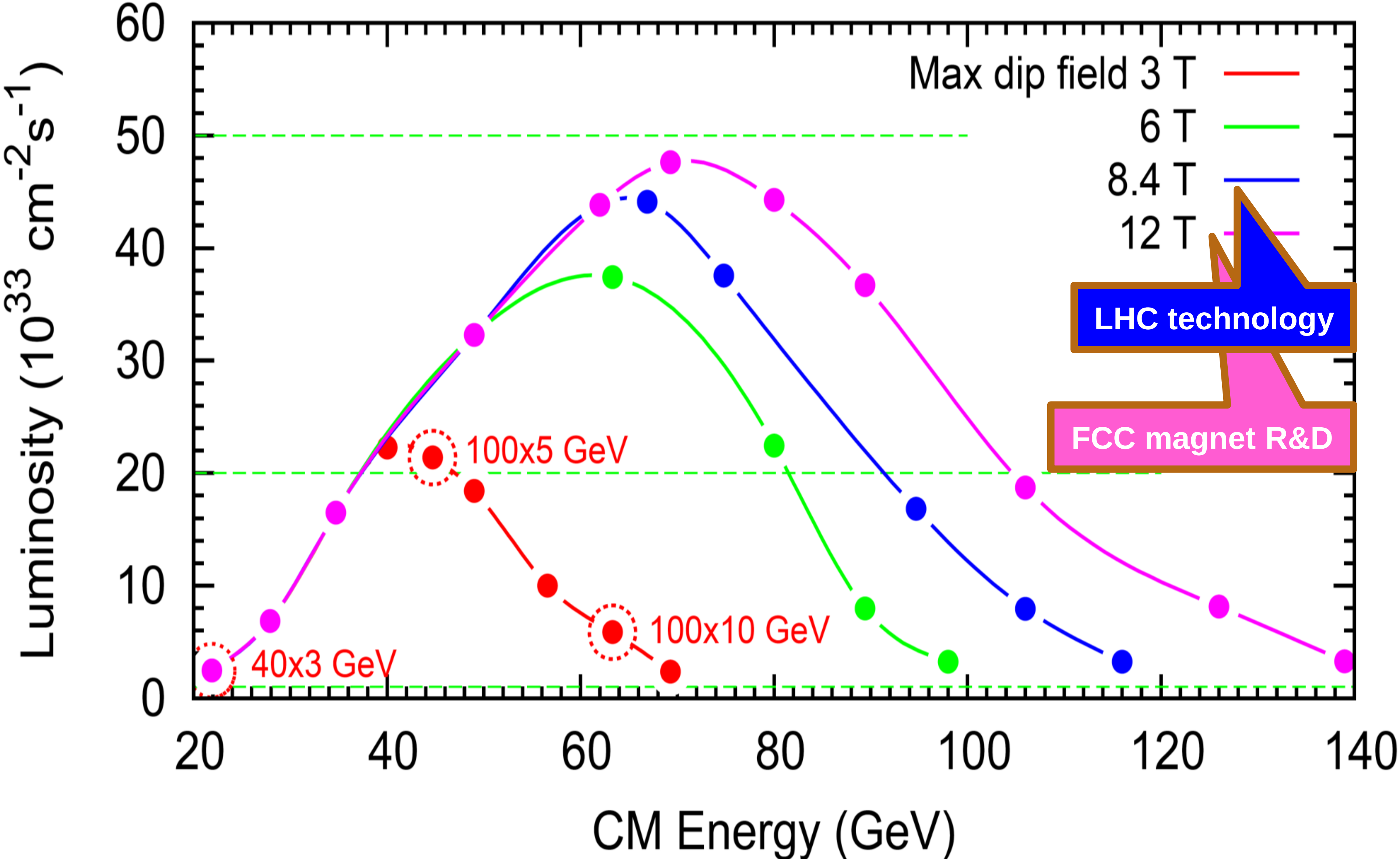
Electron energy	MeV	up to 55
Bunch charge	nC	3.2
Turns in circulator ring	turn	~20
Current in CCR/ERL	A	1.5/0.075
Bunch repetition	MHz	476
Cooling section length	m	60
RMS Bunch length	cm	3
Energy spread	10^{-4}	3
Cooling solenoid field	T	1
Cooling section length	m	2x30



Magnetized source ~75mA

JLEIC Luminosity and Energy

technical choice



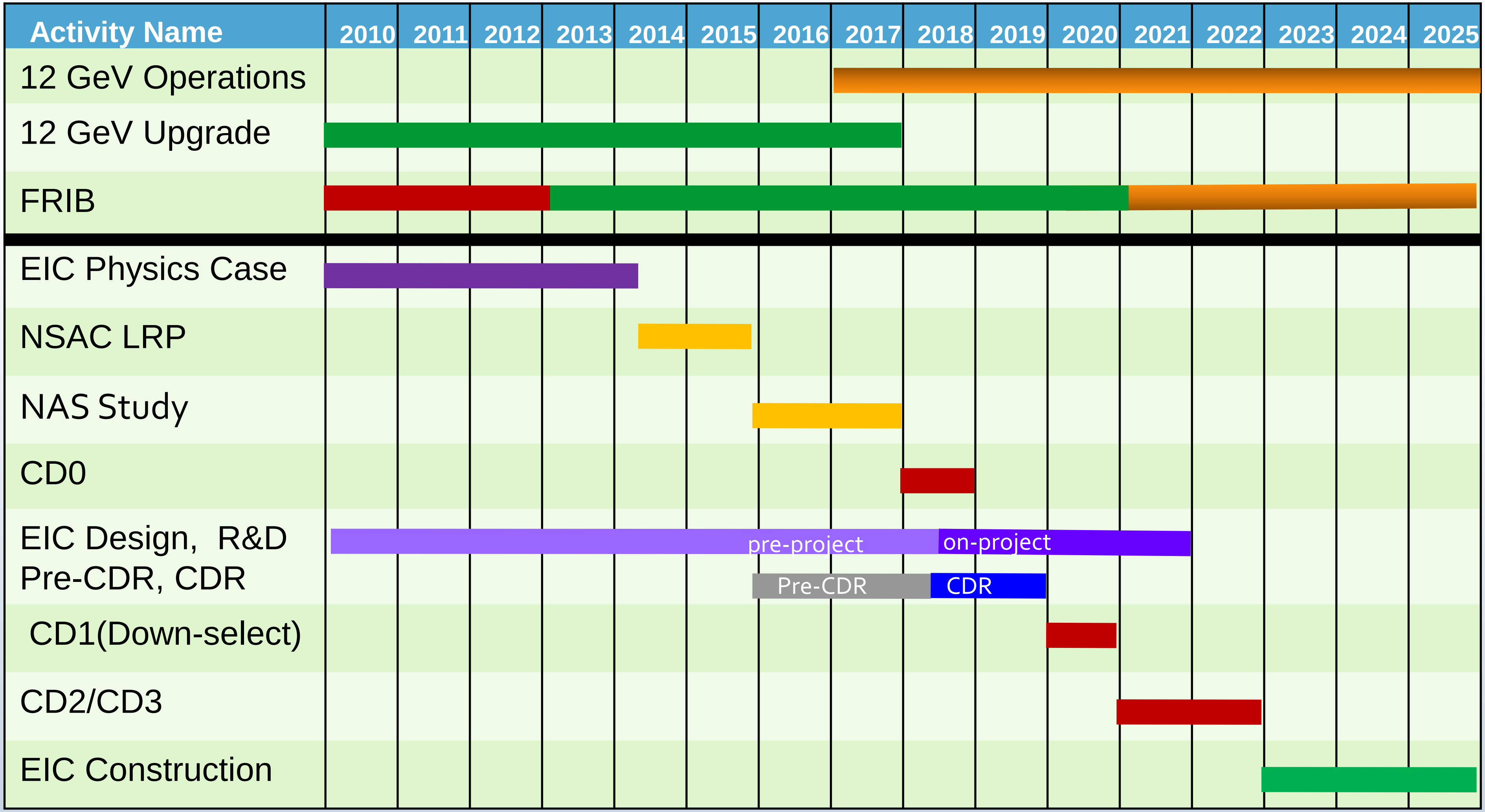
LHC technology

FCC magnet R&D

JLEIC Parameters (3T)

CM energy	**GeV**	**21.9 (low)**		**44.7 (medium)**		**63.3 (high)**	
		p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		476		476/4=119	
Particles per bunch	10^{10}	0.98	3.7	0.98	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	**80%**	**80%**	**80%**	**80%**	**80%**	**75%**
Bunch length, RMS	cm	3	1	1	1	2.2	1
Norm. emittance, hor / ver	µm	0.3/0.3	24/24	0.5/0.1	54/10.8	0.9/0.18	432/86.4
Horizontal & vertical β*	cm	8/8	13.5/13.5	6/1.2	5.1/1.0	10.5/2.1	4/0.8
Ver. beam-beam parameter		0.015	0.092	0.015	0.068	0.008	0.034
Laslett tune-shift		0.06	7×10^{-4}	0.055	6×10^{-4}	0.056	7×10^{-5}
Detector space, up/down	m	3.6/7	3.2/3	3.6/7	3.2/3	3.6/7	3.2/3
Hourglass(HG) reduction		1		0.87		0.75	
Luminosity/IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	**2.5**		**21.4**		**5.9**	

JLEIC possible timeline

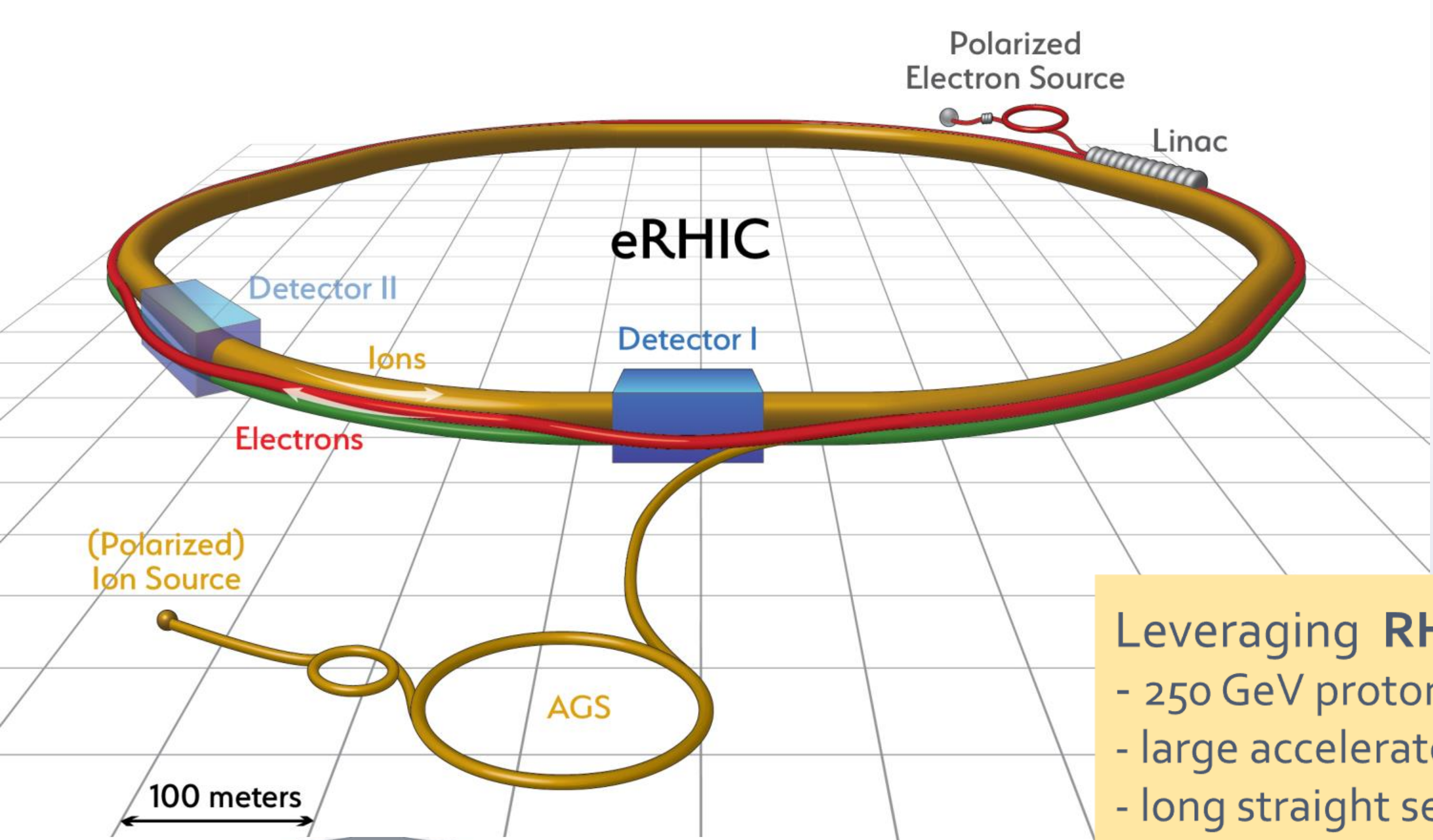


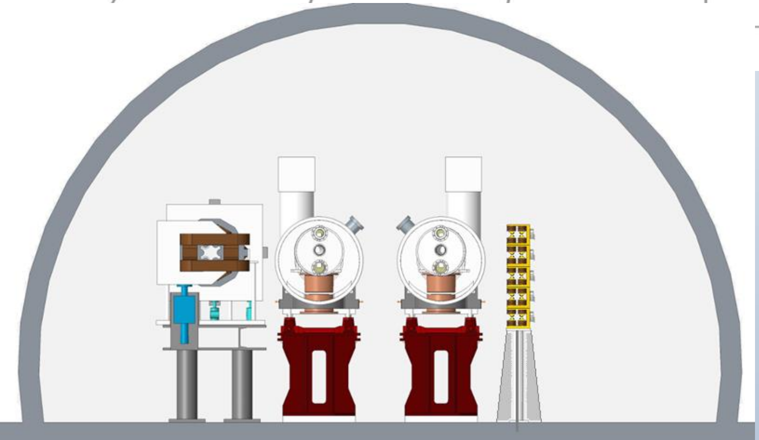
CD0 = DOE "Mission Need" statement; **CD1** = design choice and site selection (VA/NY)

CD2/CD3 = establish project baseline cost and schedule

eRHIC design

From F. Willecke, BNL





Leveraging **RHIC** with its

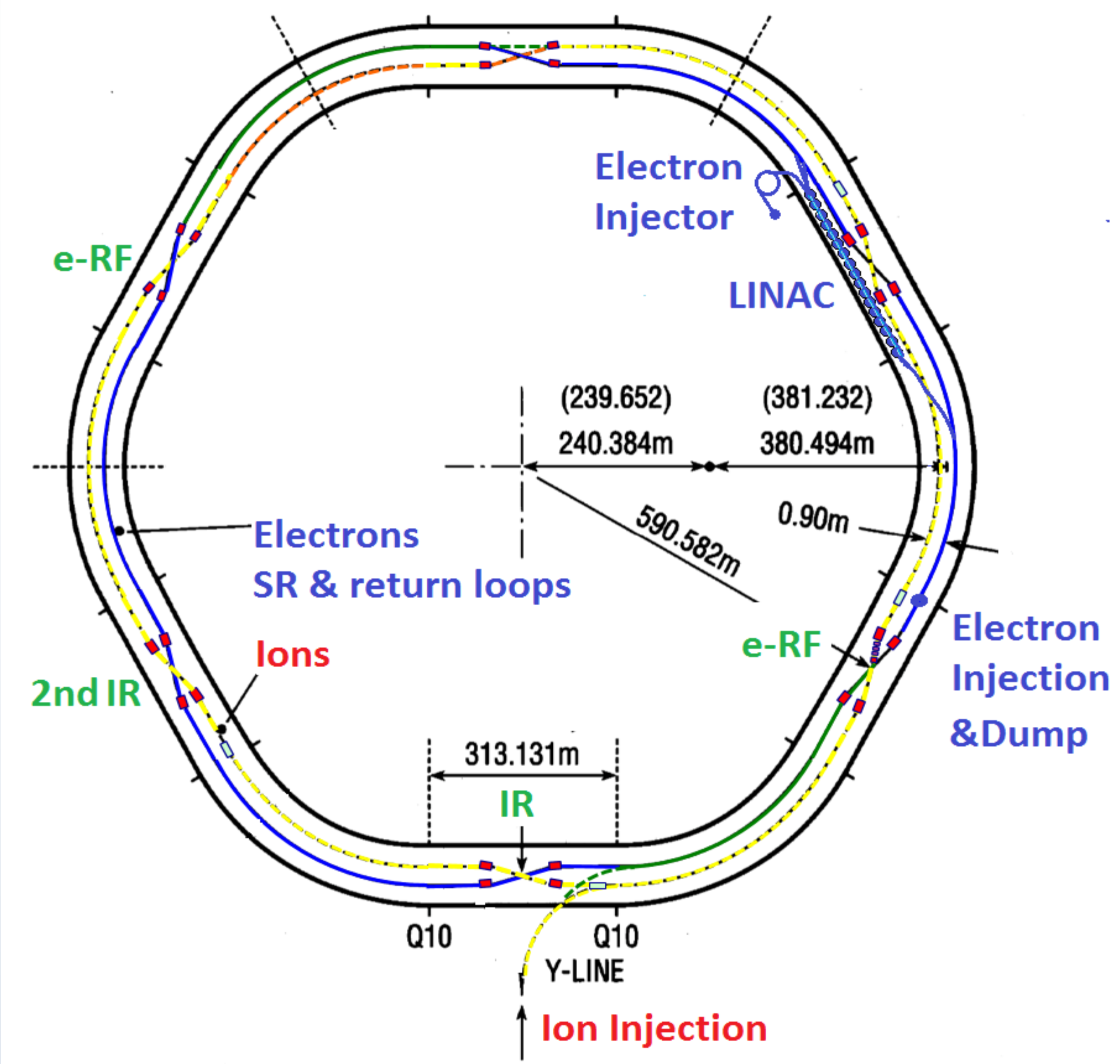
- 250 GeV protons
- large accelerator tunnel
- long straight sections
- Hadron injector complex

by

adding an electron accelerator of 18 GeV in the <u>same</u> tunnel

- high energy reach
- modest synchrotron radiation
- an electron storage ring (or a ERL)

Overall Facility Layout



Issue with large E_{cm} range:

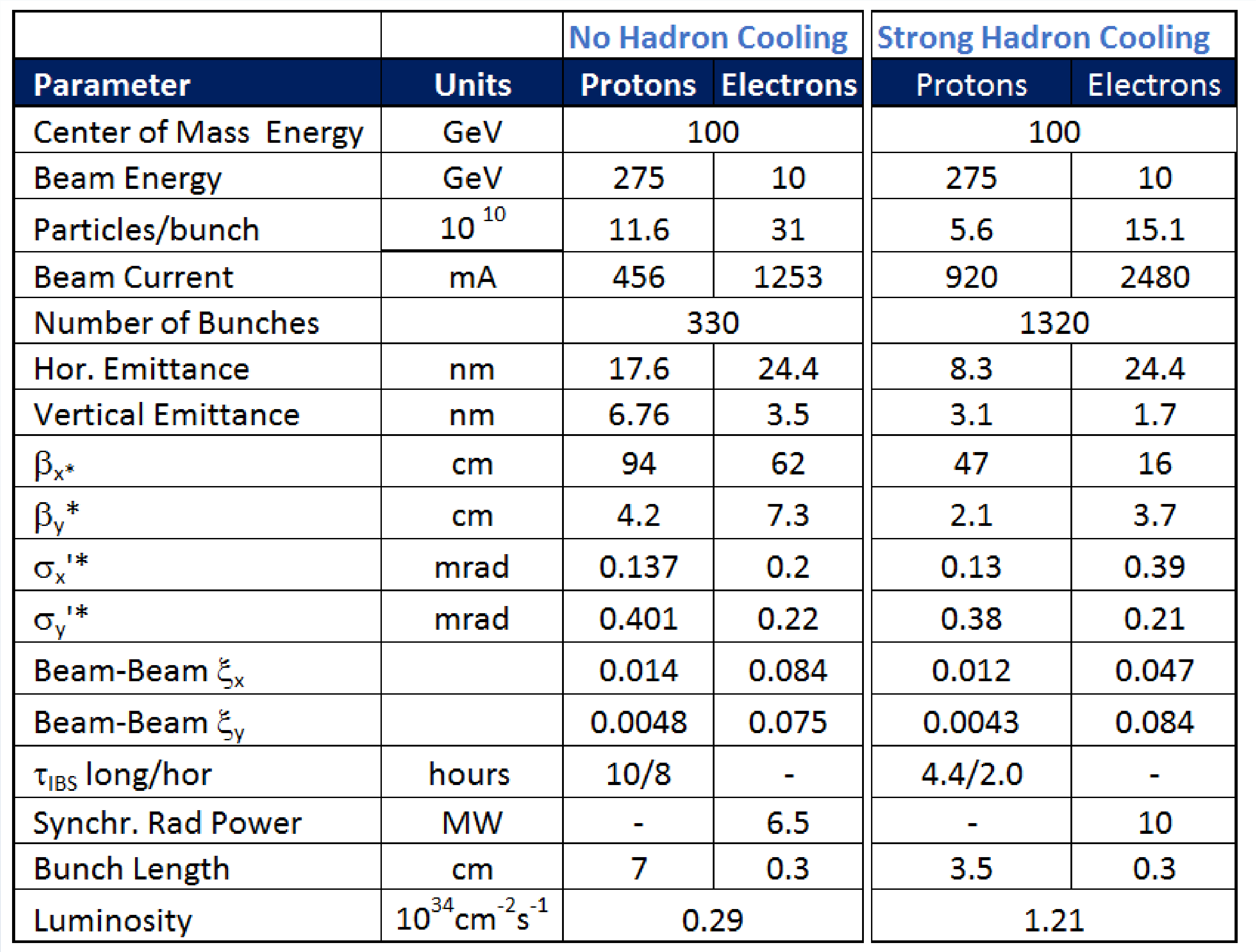
Matching **hadron and e revolution times** for low hadron energies:

<u>Achieved by:</u>

- Increasing the path length for 275 GeV by a combination of going through 4 outer and 2 inner arcs and using nominal for 50GeV
- Plus modifying the entrance into straight sections for fine tuning

Main Parameters for Maximum Luminosity

E_p = 275 GeV, E_e= 10 GeV



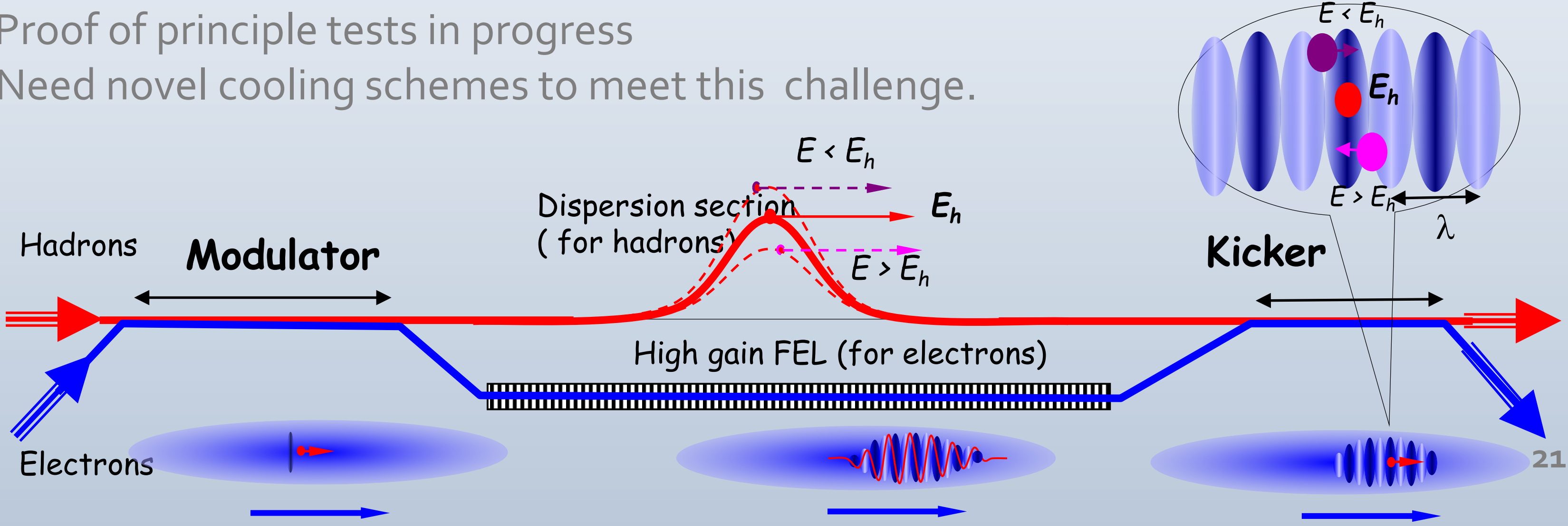
		No Hadron Cooling		Strong Hadron Cooling	
Parameter	**Units**	**Protons**	**Electrons**	Protons	Electrons
Center of Mass Energy	GeV	100		100	
Beam Energy	GeV	275	10	275	10
Particles/bunch	10^{10}	11.6	31	5.6	15.1
Beam Current	mA	456	1253	920	2480
Number of Bunches		330		1320	
Hor. Emittance	nm	17.6	24.4	8.3	24.4
Vertical Emittance	nm	6.76	3.5	3.1	1.7
β_{x*}	cm	94	62	47	16
$\beta_y{}^*$	cm	4.2	7.3	2.1	3.7
$\sigma_x{}'^*$	mrad	0.137	0.2	0.13	0.39
$\sigma_y{}'^*$	mrad	0.401	0.22	0.38	0.21
Beam-Beam ξ_x		0.014	0.084	0.012	0.047
Beam-Beam ξ_y		0.0048	0.075	0.0043	0.084
τ_{IBS} long/hor	hours	10/8	-	4.4/2.0	-
Synchr. Rad Power	MW	-	6.5	-	10
Bunch Length	cm	7	0.3	3.5	0.3
Luminosity	$10^{34}cm^{-2}s^{-1}$	0.29		1.21	

Small Hadron Emittance – Strong cooling

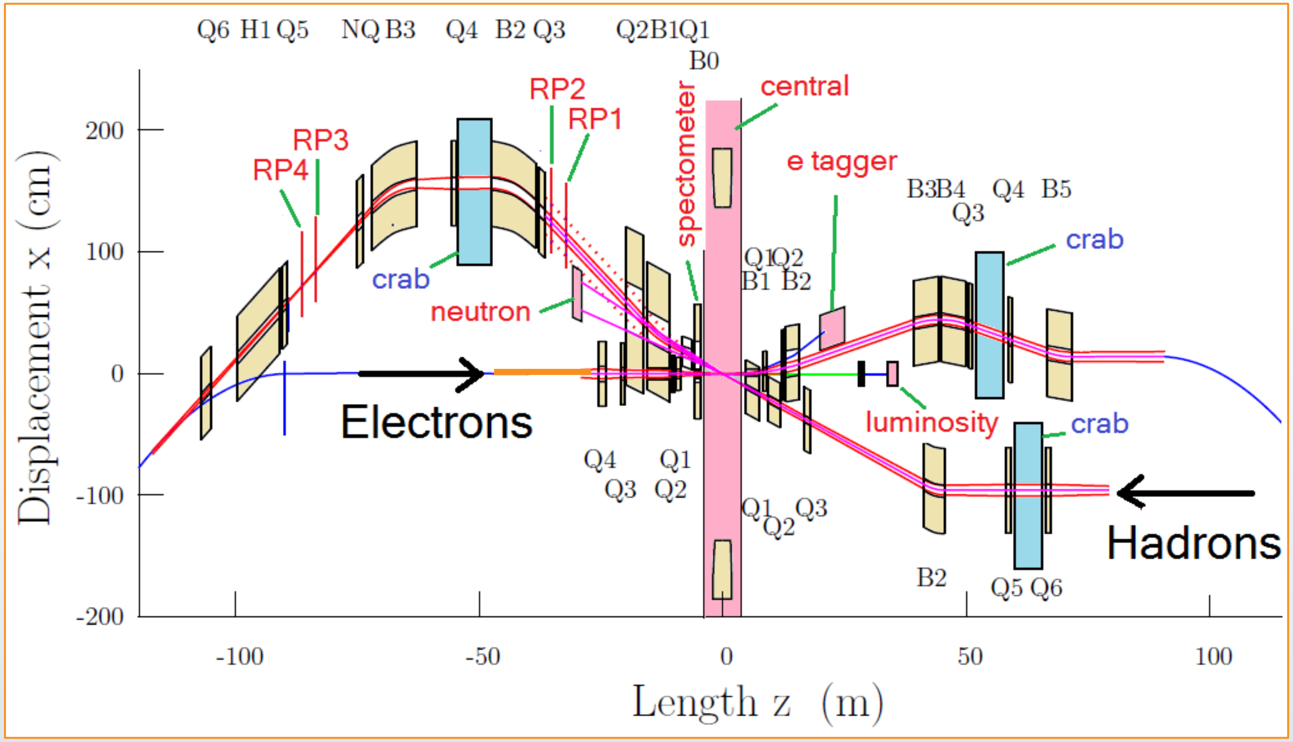
$L = 1.2 \cdot 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ requires vertical normalized proton emittance **3.1 μm rad, $I_{bp} = 0.7$ mA, bunch length 7 cm.**
These hadron beam parameters are subjected to **strong IBS** and can be achieved and maintained only be **strong active cooling of the Hadron beams** with cooling times in the order of minutes.
MAJOR TECHNICAL CHALLENGE FOR ANY EIC

➔ Cooling time < IBS growth time only **0.5 hours**
- This exceeds the cooling rates possible with stochastic cooling by several orders of magnitude
- **Coherent Electron Cooling** promises to provide required cooling rates
- **Novel scheme**, never implemented
- Proof of principle tests in progress

➔ Need novel cooling schemes to meet this challenge.

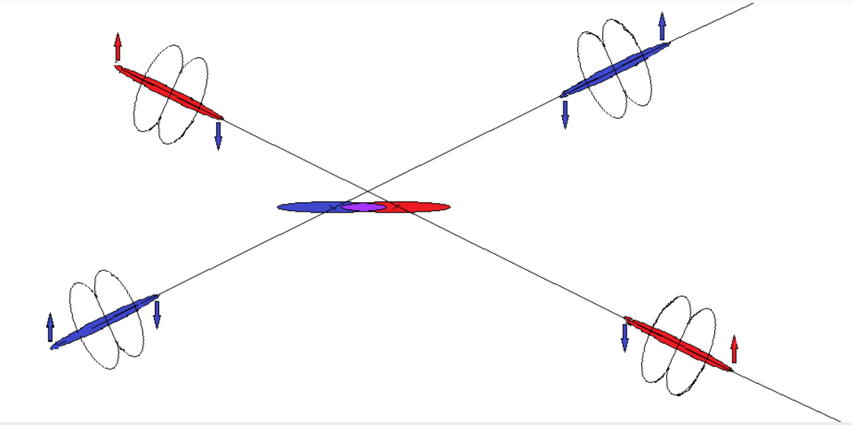


Interaction Region Layout



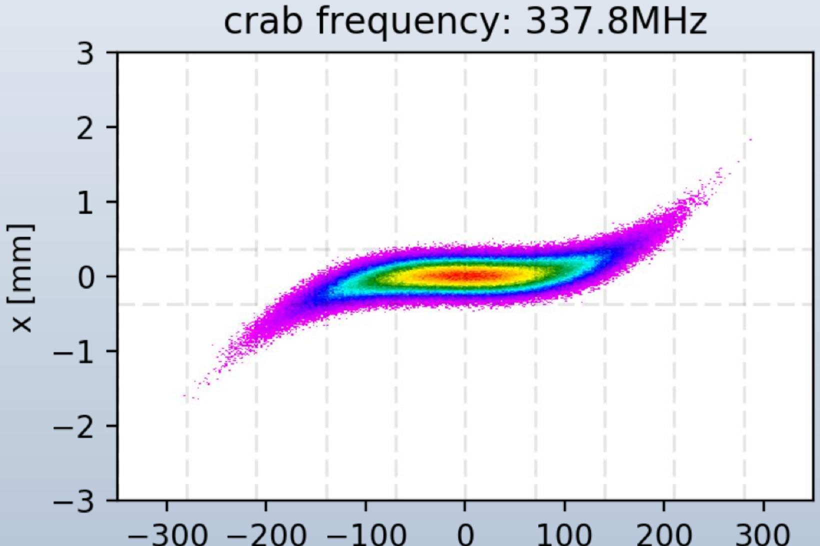
- Interleaved arrangement of electron and hadron quadrupoles
- **22 mrad total crossing angle, using crab cavities**
- Beam size in crab cavity region independent of energy – crab cavity apertures can be rather small, thus allowing for higher frequency
- Forward spectrometer (B0) and Roman Pots (R1-R4) for full acceptance

Crossing Angle Geometry and Crab Cavities



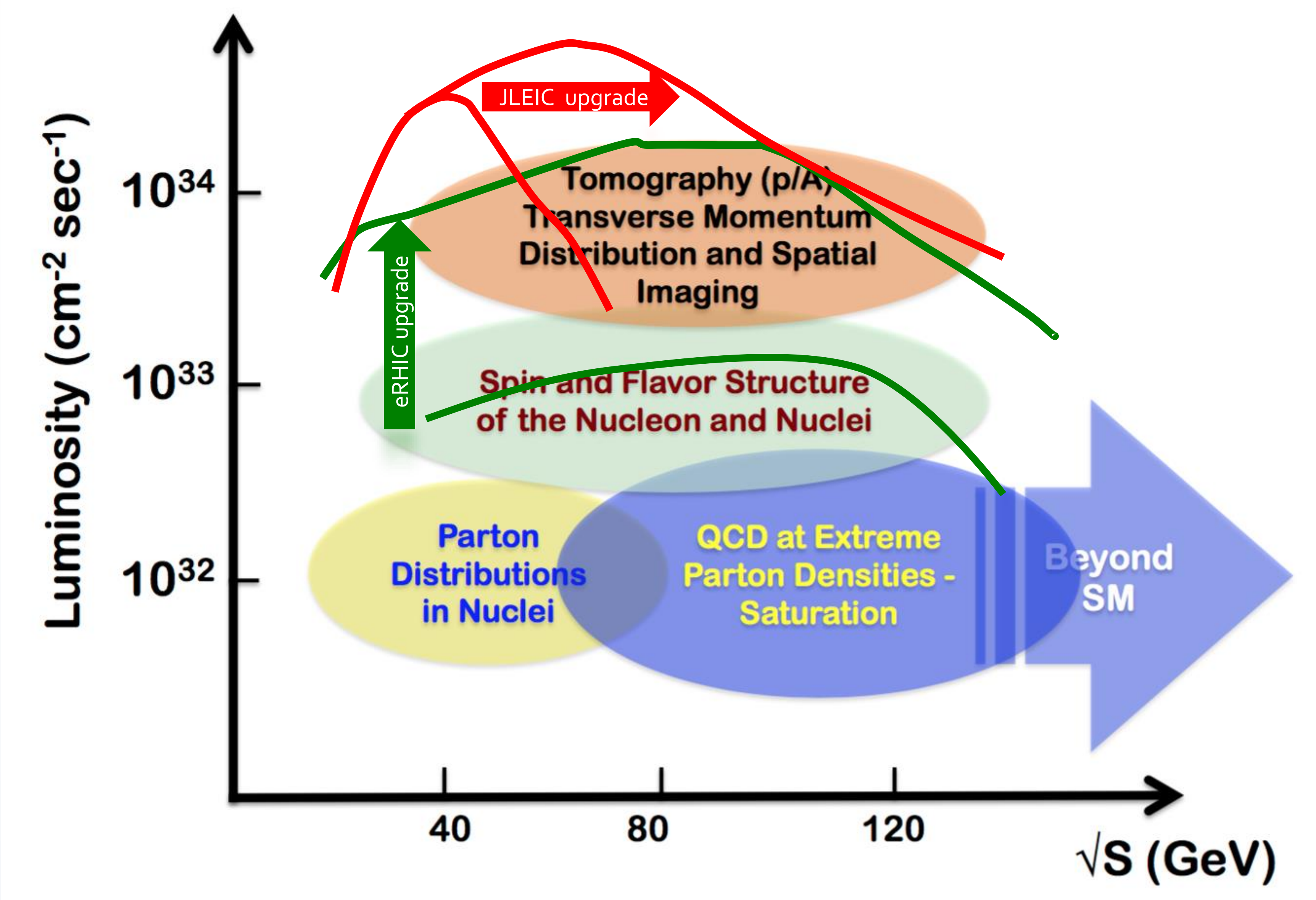
Prototype of a double quarter wave length s.c. crab cavity
(father of the prototype to be installed in SPS for the **LHC crab cavity test**)

Simulation of crabbing and crab cavity effects just started ➔ needs more effort
Example: Results on the quest of Higher Harmonic Crab Cavities



Simulation taking into account
- linear BB,
- Energy pick up in the cavity
- Path length and orbit effects due to dispersion in the crab
- Crab dispersion effect
- Nonlinear BB with crab: in progress

EIC luminosity summary



EIC accelerator R&D

R&D Timeline

- Pre-project R&D ongoing since 10+ years
- JLEIC R&D overview was presented at the NP EIC Community Review Panel (a.k.a. “Jones Panel”) in November 2017
- Final Review Panel Report and R&D Priorities released in March 2017
- Identified EIC JLAB-BNL Common R&D at JLEIC April Collaboration Meeting
- NP EIC R&D FoA was tabled for FY’2017
- NP asked for a plan for Accelerator R&D to be submitted by May 31 2017
- Plans submitted by May 31 2017

JLEIC R&D areas

R&D activities **Higher priority topical areas for EIC R&D funding**	**Electron Cooling** **ECL** **8 CTE**	**Magnets** **MAG** **6 CTE**	**SRF R&D** **SRF** **3 CTE**

Bridge design and R&D **Executed on base, LDRD and selected EIC R&D funding**	**Injectors R&D** **INJ** **6 CTE**	**Interaction Regions** **IRS** **3 CTE**	**Beam dynamics and diagnostics** **BDD** **8 CTE**

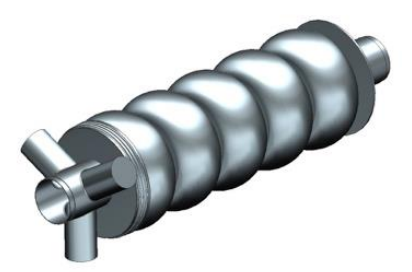
Guiding principles

- Adopt **mature technology** where applicable
- Focus R&D in **critical areas** (i.e electron cooling)
- look at a 4-5 years timeline
- move **technical readiness** from "low" to "medium" in critical areas
- properly identify **high priority R&D** (judgment call based on technology readiness and impact on performance and cost)

JLEIC R&D progress

- e-cooling simulation, beta-cool and new code development
- bunched beam electron cooling at IMP
- cooler design, preliminary design single-turn cooler
- magnetized source, first magnetized beam in spring 2017
- fast harmonic kicker – ½ size prototype tested successfully

- short SF prototype, mock up winding for 1.2m
- IR magnets, initial designs started



- ERL cavity, design done, prototype in progress
- crab cavity, design started

- spin tracking, p and e simulations validating Figure-8
- beam beam, GHOST code development progressing

Project development and collaborations

- JLAB and BNL have been developing their designs in close collaboration with other US laboratories and Universities for **10+ years**
- The **Long Range Plan** endorsement of the EIC has motivated an increased collaboration in the US and a reach to expand the collaboration internationally
- An 800+ member international EIC Users Group has been established, next meeting in Trieste in **July 18-22 2017**
- The EIC accelerator community is encouraging **national and international collaboration**

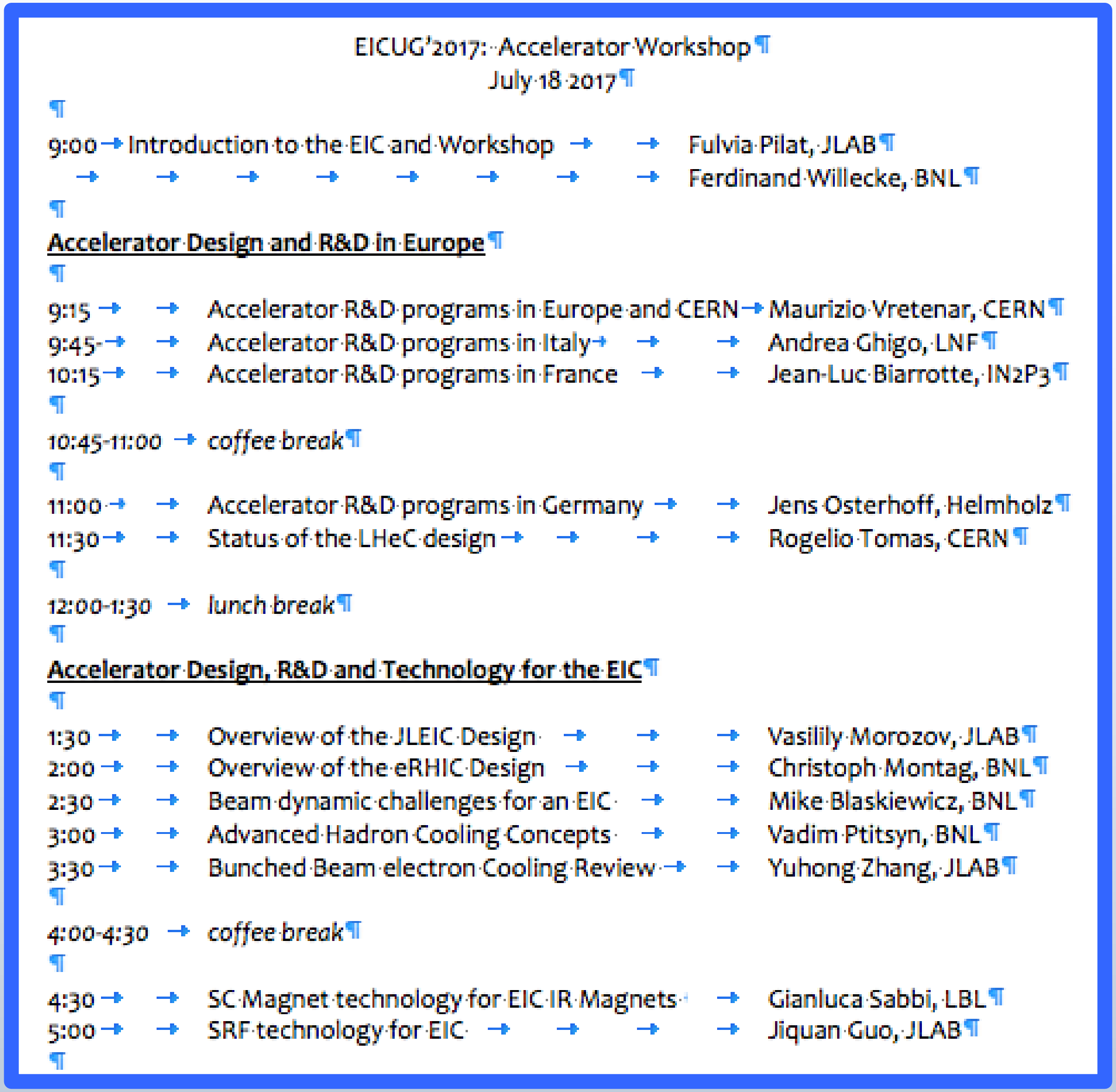
EIC Users Group

EIC Users Group Meeting 18—22 July 2017
Trieste Italy
https://agenda.infn.it/conferenceDisplay.py?confId=13037

157 Institutions
(50 JLab users)
693 Members
29 countries

EIC Accelerator outreach

- Outreach to EU institutions/funding agencies
- EIC event at INFN Genova in January 2017
- EIC event at LNF Frascati in March 2017
- Presence at EPS high energy physics conference in July 2017
- Accelerator workshop at the EICUG in Trieste
- Planned outreach in Asia in 2018-19



EICUG'2017: Accelerator Workshop
July 18 2017

9:00	Introduction to the EIC and Workshop	Fulvia Pilat, JLAB Ferdinand Willecke, BNL

Accelerator Design and R&D in Europe

9:15	Accelerator R&D programs in Europe and CERN	Maurizio Vretenar, CERN
9:45	Accelerator R&D programs in Italy	Andrea Ghigo, LNF
10:15	Accelerator R&D programs in France	Jean-Luc Biarrotte, IN2P3
10:45-11:00	*coffee break*	
11:00	Accelerator R&D programs in Germany	Jens Osterhoff, Helmholz
11:30	Status of the LHeC design	Rogelio Tomas, CERN
12:00-1:30	*lunch break*	

Accelerator Design, R&D and Technology for the EIC

1:30	Overview of the JLEIC Design	Vasilily Morozov, JLAB
2:00	Overview of the eRHIC Design	Christoph Montag, BNL
2:30	Beam dynamic challenges for an EIC	Mike Blaskiewicz, BNL
3:00	Advanced Hadron Cooling Concepts	Vadim Ptitsyn, BNL
3:30	Bunched Beam electron Cooling Review	Yuhong Zhang, JLAB
4:00-4:30	*coffee break*	
4:30	SC Magnet technology for EIC IR Magnets	Gianluca Sabbi, LBL
5:00	SRF technology for EIC	Jiquan Guo, JLAB

Conclusions

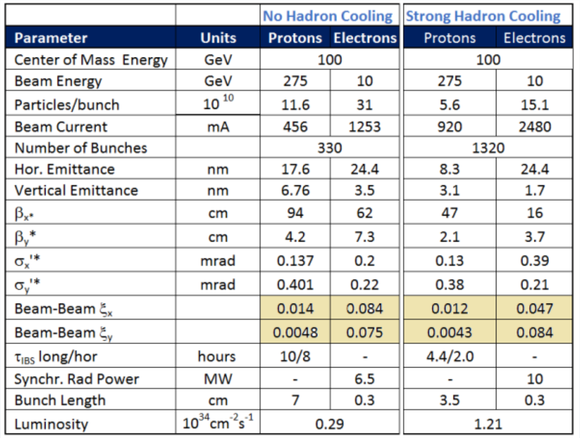
- The recognition in the US of the EIC as the highest priority for new construction in nuclear physics has set firm foundations to build this challenging accelerator
- We are looking forward to engaging the national and international scientific communities
- Contact info for Fulvia and Ferdinand

Fulvia Pilat, JLAB, pilat@jlab.org

Ferdinand Willecke, willecke@bnl.gov

Backup

Beam-Beam Parameters Electrons

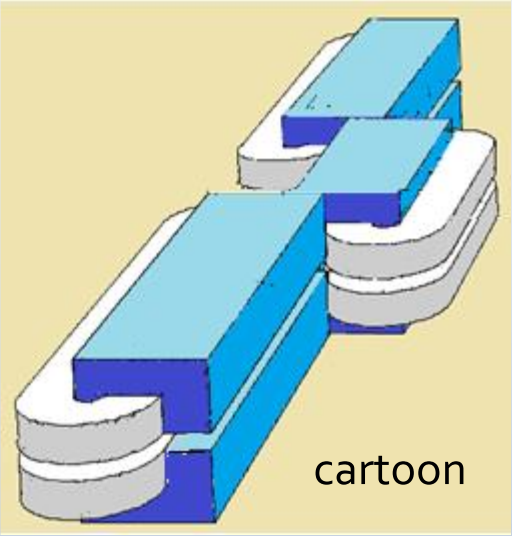


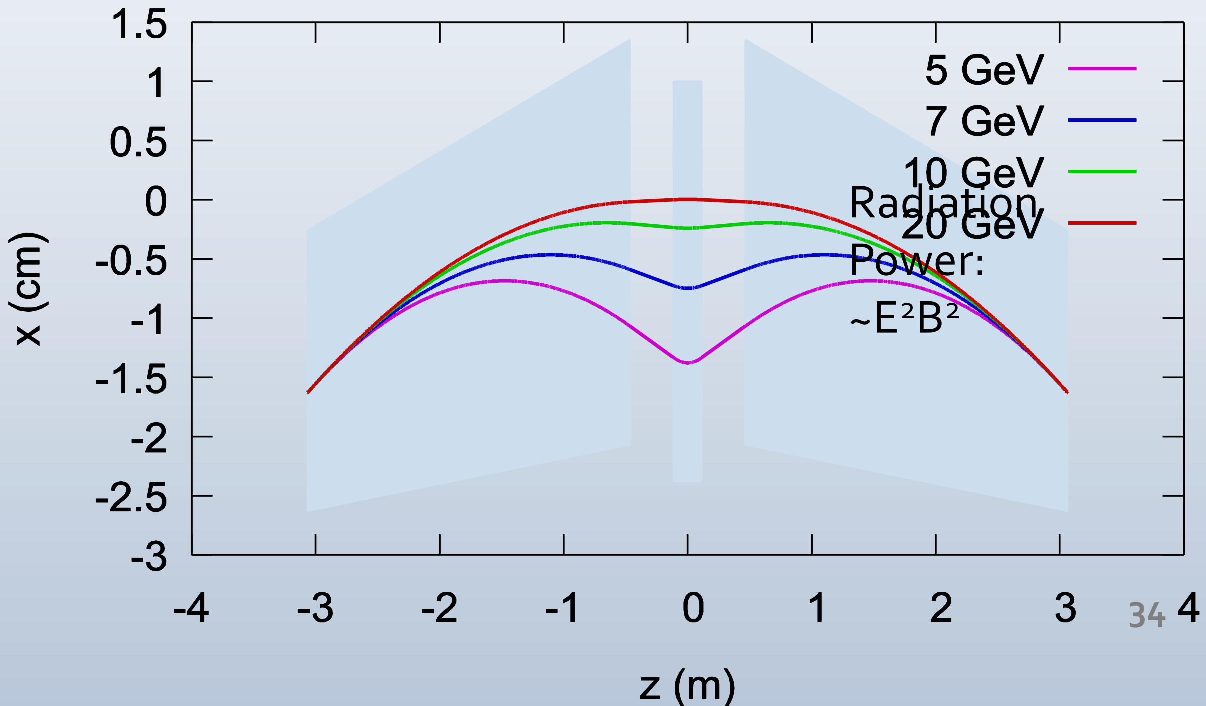
		No Hadron Cooling		Strong Hadron Cooling	
Parameter	**Units**	**Protons**	**Electrons**	**Protons**	**Electrons**
Center of Mass Energy	GeV	100		100	
Beam Energy	GeV	275	10	275	10
Particles/bunch	10^{10}	11.6	31	5.6	15.1
Beam Current	mA	456	1253	920	2480
Number of Bunches		330		1320	
Hor. Emittance	nm	17.6	24.4	8.3	24.4
Vertical Emittance	nm	6.76	3.5	3.1	1.7
β_{x^*}	cm	94	62	47	16
$\beta_y{}^*$	cm	4.2	7.3	2.1	3.7
$\sigma_x{}'^*$	mrad	0.137	0.2	0.13	0.39
$\sigma_y{}'^*$	mrad	0.401	0.22	0.38	0.21
Beam-Beam ξ_x		0.014	0.084	0.012	0.047
Beam-Beam ξ_y		0.0048	0.075	0.0043	0.084
τ_{IBS} long/hor	hours	10/8	-	4.4/2.0	-
Synchr. Rad Power	MW	-	6.5	-	10
Bunch Length	cm	7	0.3	3.5	0.3
Luminosity	$10^{34}cm^{-2}s^{-1}$	0.29		1.21	

Large Beam-beam Parameters at 5GeV:

Strong electron Beam-Beam effects require strong radiation damping. Between 5 and 18 GeV τ_x changes by a factor **50** without further measures. (11GeV gives KEK-B damping decrement)

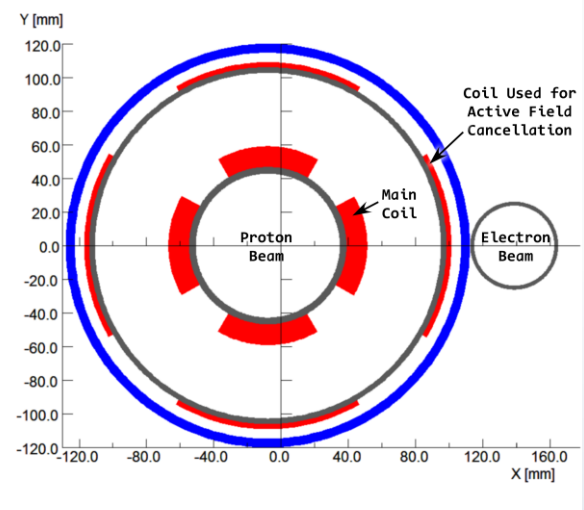
➔ With" super-bend" lattice achieve 11 GeV damping time at 5GeV to match KEK-B damping decrement (overcomes as well the E² scaling of beam emittance, helps with polarization)





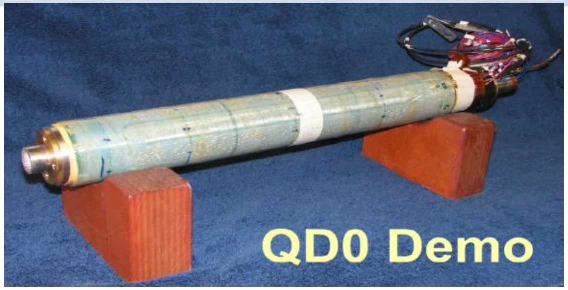
Radiation Power: ~E²B²

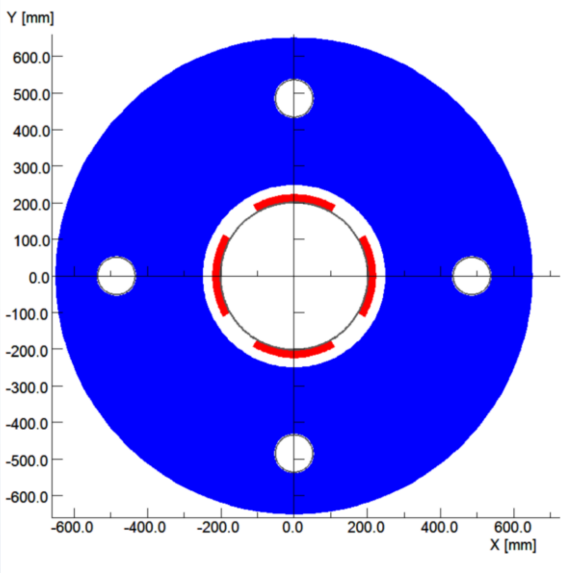
Conceptual Layout of IR Magnets with active shielding



magnets with direct-wound coil including cancelling dipole to shield electron

Prototype for actively shielded quadrupole Q1 already exists as part of ILC work





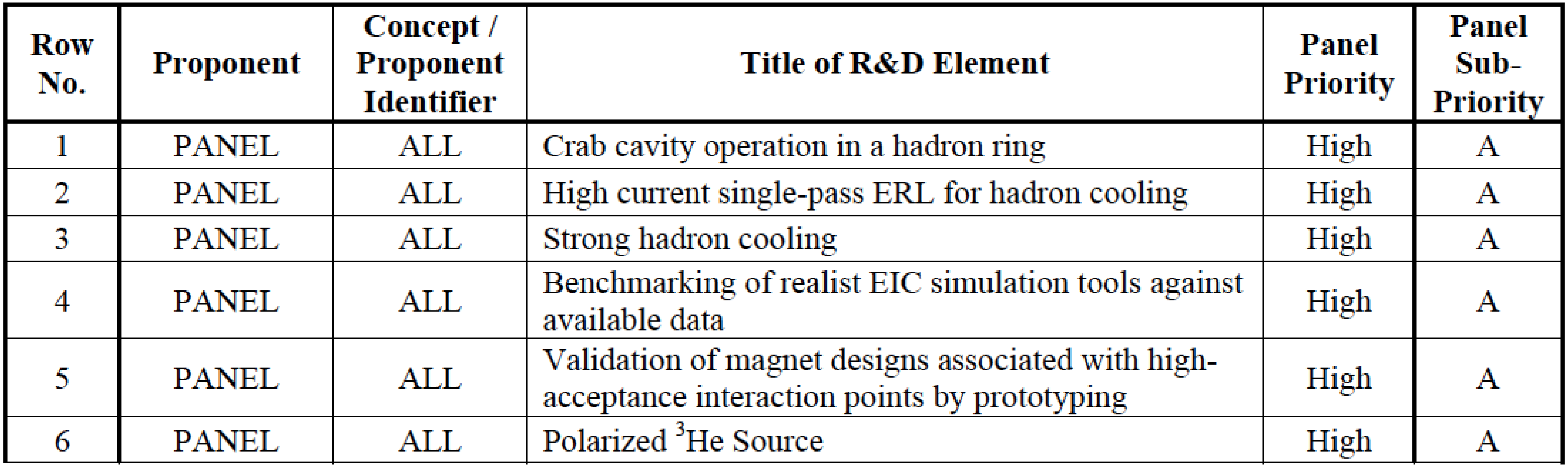
Hadron superconducting quadrupole with hoses in the return yoke for electrons

Spectrometer magnet in the Hadron line close to detector: detection of forward scattered Hadron
Generation of dispersion downstream for increased p_t acceptance
Conceptual design for super-ferric dipole
With actively shielded pipe for electrons

The panel reviewed all Critical Technology Elements presented by JLAB and BNL and compiled prorities for :

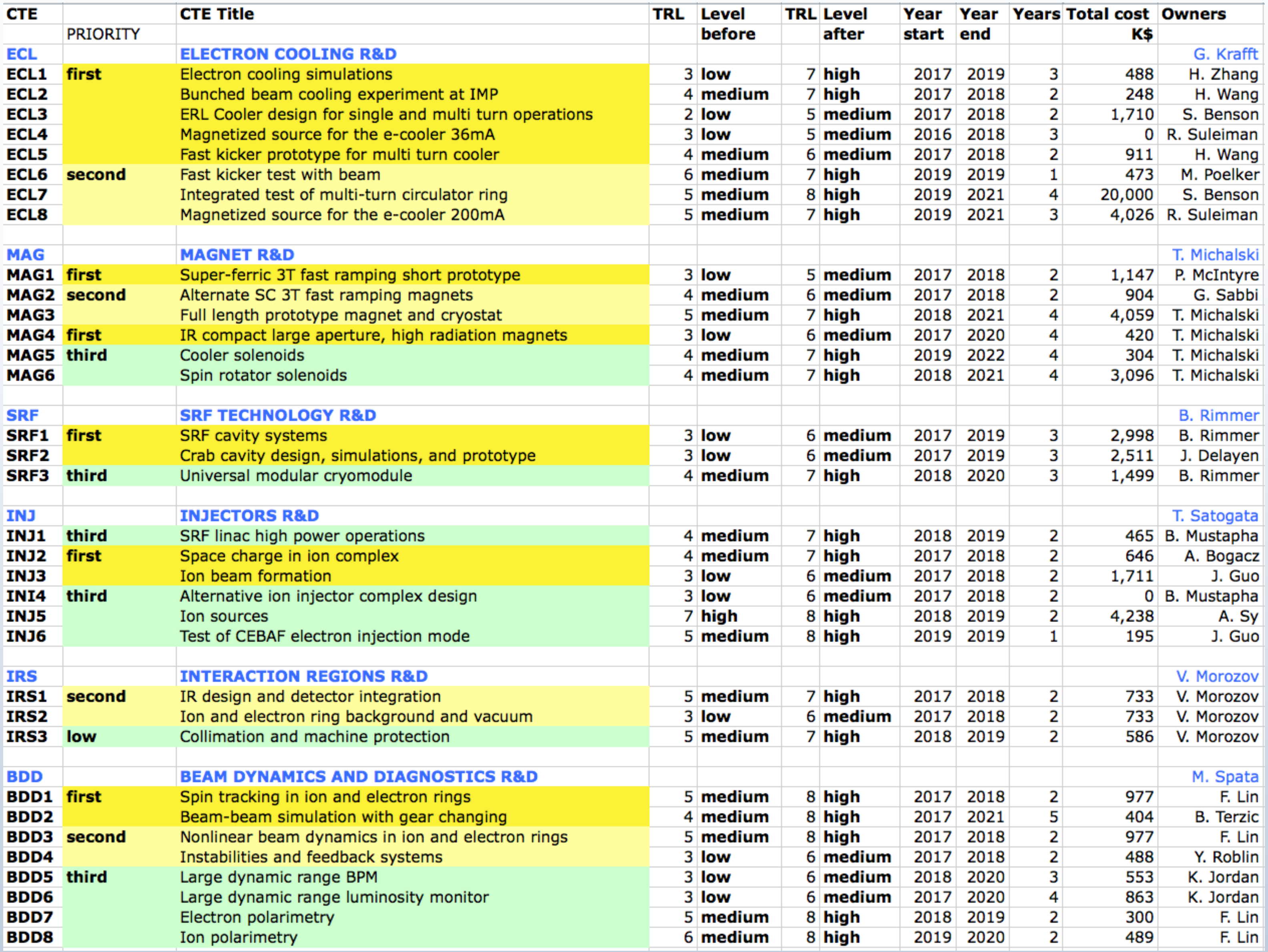
- R&D common to all designs
- Project-specific R&D

Panel priorities for R&D common to all EIC designs:



Row No.	Proponent	Concept / Proponent Identifier	Title of R&D Element	Panel Priority	Panel Sub-Priority
1	PANEL	ALL	Crab cavity operation in a hadron ring	High	A
2	PANEL	ALL	High current single-pass ERL for hadron cooling	High	A
3	PANEL	ALL	Strong hadron cooling	High	A
4	PANEL	ALL	Benchmarking of realist EIC simulation tools against available data	High	A
5	PANEL	ALL	Validation of magnet designs associated with high-acceptance interaction points by prototyping	High	A
6	PANEL	ALL	Polarized ^{3}He Source	High	A

Overview of JLEIC R&D



CTE		CTE Title	TRL	Level	TRL	Level	Year	Year	Years	Total cost	Owners
	PRIORITY			before		after	start	end		K$	
ECL		ELECTRON COOLING R&D									G. Krafft
ECL1	first	Electron cooling simulations	3	low	7	high	2017	2019	3	488	H. Zhang
ECL2		Bunched beam cooling experiment at IMP	4	medium	7	high	2017	2018	2	248	H. Wang
ECL3		ERL Cooler design for single and multi turn operations	2	low	5	medium	2017	2018	2	1,710	S. Benson
ECL4		Magnetized source for the e-cooler 36mA	3	low	5	medium	2016	2018	3	0	R. Suleiman
ECL5		Fast kicker prototype for multi turn cooler	4	medium	6	medium	2017	2018	2	911	H. Wang
ECL6	second	Fast kicker test with beam	6	medium	7	high	2019	2019	1	473	M. Poelker
ECL7		Integrated test of multi-turn circulator ring	5	medium	8	high	2019	2021	4	20,000	S. Benson
ECL8		Magnetized source for the e-cooler 200mA	5	medium	7	high	2019	2021	3	4,026	R. Suleiman
MAG		MAGNET R&D									T. Michalski
MAG1	first	Super-ferric 3T fast ramping short prototype	3	low	5	medium	2017	2018	2	1,147	P. McIntyre
MAG2	second	Alternate SC 3T fast ramping magnets	4	medium	6	medium	2017	2018	2	904	G. Sabbi
MAG3		Full length prototype magnet and cryostat	5	medium	7	high	2018	2021	4	4,059	T. Michalski
MAG4	first	IR compact large aperture, high radiation magnets	3	low	6	medium	2017	2020	4	420	T. Michalski
MAG5	third	Cooler solenoids	4	medium	7	high	2019	2022	4	304	T. Michalski
MAG6		Spin rotator solenoids	4	medium	7	high	2018	2021	4	3,096	T. Michalski
SRF		SRF TECHNOLOGY R&D									B. Rimmer
SRF1	first	SRF cavity systems	3	low	6	medium	2017	2019	3	2,998	B. Rimmer
SRF2		Crab cavity design, simulations, and prototype	3	low	6	medium	2017	2019	3	2,511	J. Delayen
SRF3	third	Universal modular cryomodule	4	medium	7	high	2018	2020	3	1,499	B. Rimmer
INJ		INJECTORS R&D									T. Satogata
INJ1	third	SRF linac high power operations	4	medium	7	high	2018	2019	2	465	B. Mustapha
INJ2	first	Space charge in ion complex	4	medium	7	high	2017	2018	2	646	A. Bogacz
INJ3		Ion beam formation	3	low	6	medium	2017	2018	2	1,711	J. Guo
INI4	third	Alternative ion injector complex design	3	low	6	medium	2017	2018	2	0	B. Mustapha
INJ5		Ion sources	7	high	8	high	2018	2019	2	4,238	A. Sy
INJ6		Test of CEBAF electron injection mode	5	medium	8	high	2019	2019	1	195	J. Guo
IRS		INTERACTION REGIONS R&D									V. Morozov
IRS1	second	IR design and detector integration	5	medium	7	high	2017	2018	2	733	V. Morozov
IRS2		Ion and electron ring background and vacuum	3	low	6	medium	2017	2018	2	733	V. Morozov
IRS3	low	Collimation and machine protection	5	medium	7	high	2018	2019	2	586	V. Morozov
BDD		BEAM DYNAMICS AND DIAGNOSTICS R&D									M. Spata
BDD1	first	Spin tracking in ion and electron rings	5	medium	8	high	2017	2018	2	977	F. Lin
BDD2		Beam-beam simulation with gear changing	4	medium	8	high	2017	2021	5	404	B. Terzic
BDD3	second	Nonlinear beam dynamics in ion and electron rings	5	medium	8	high	2017	2018	2	977	F. Lin
BDD4		Instabilities and feedback systems	3	low	6	medium	2017	2018	2	488	Y. Roblin
BDD5	third	Large dynamic range BPM	3	low	6	medium	2018	2020	3	553	K. Jordan
BDD6		Large dynamic range luminosity monitor	3	low	6	medium	2017	2020	4	863	K. Jordan
BDD7		Electron polarimetry	5	medium	8	high	2018	2019	2	300	F. Lin
BDD8		Ion polarimetry	6	medium	8	high	2019	2020	2	489	F. Lin

JLAB LDRD

ANL LDRD