Electron-Ion Collider at Jefferson Lab

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CASA
For the JLAB EIC Study Group

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Outline

- Project Highlights
- Project Status
  - Design
  - Luminosity concepts
  - Key enabling technologies
- Path Forward
  - Feedback Responses
- Summary

Future Electron-Ion Colliders (EICs) for JLAB

- Supporting the NSAC long range plan, JLab has been engaged in conceptual design and R&D activity for an electron-ion-collider based on a new ion complex and on the 12 GeV CEBAF recirculated SRF linac.
- Our design efforts have focused on achieving exceptionally high luminosity (up to 10^{35} $cm^{-2}sec^{-1}$) over multiple detectors & very high polarization (>80%) for both electron and light ion beams, to meet demands of future nuclear science programs.

Since the last EICAC review

- We have made progress on several important issues for producing high collider luminosity on the subjects of beam cooling methods, crab crossing, and interaction point beam physics.

- At present, our design efforts are shifting to a high luminosity low-to-medium energy EIC (up to 60x11 GeV^2), MEIC, as our *near-term goal*, and will keep the full energy EIC (250x11 GeV^2) as an upgrade option.
- MEIC seems to provide not only a rich & broad science program, but also a nicer balance between nuclear science, detector & accelerator R&D, and project cost.
- Since February, we have developed a "first-pass" design for MEIC based on CEBAF, and explored dependences of luminosity on design parameters.
- We are now engaged in development of science cases and key experiments, design optimization, and aggressively pushing R&D.
- The labor pool now devoted to MEIC has expanded.

Science Driven Machine Design

Key issues in nucleon structure & nuclear physics

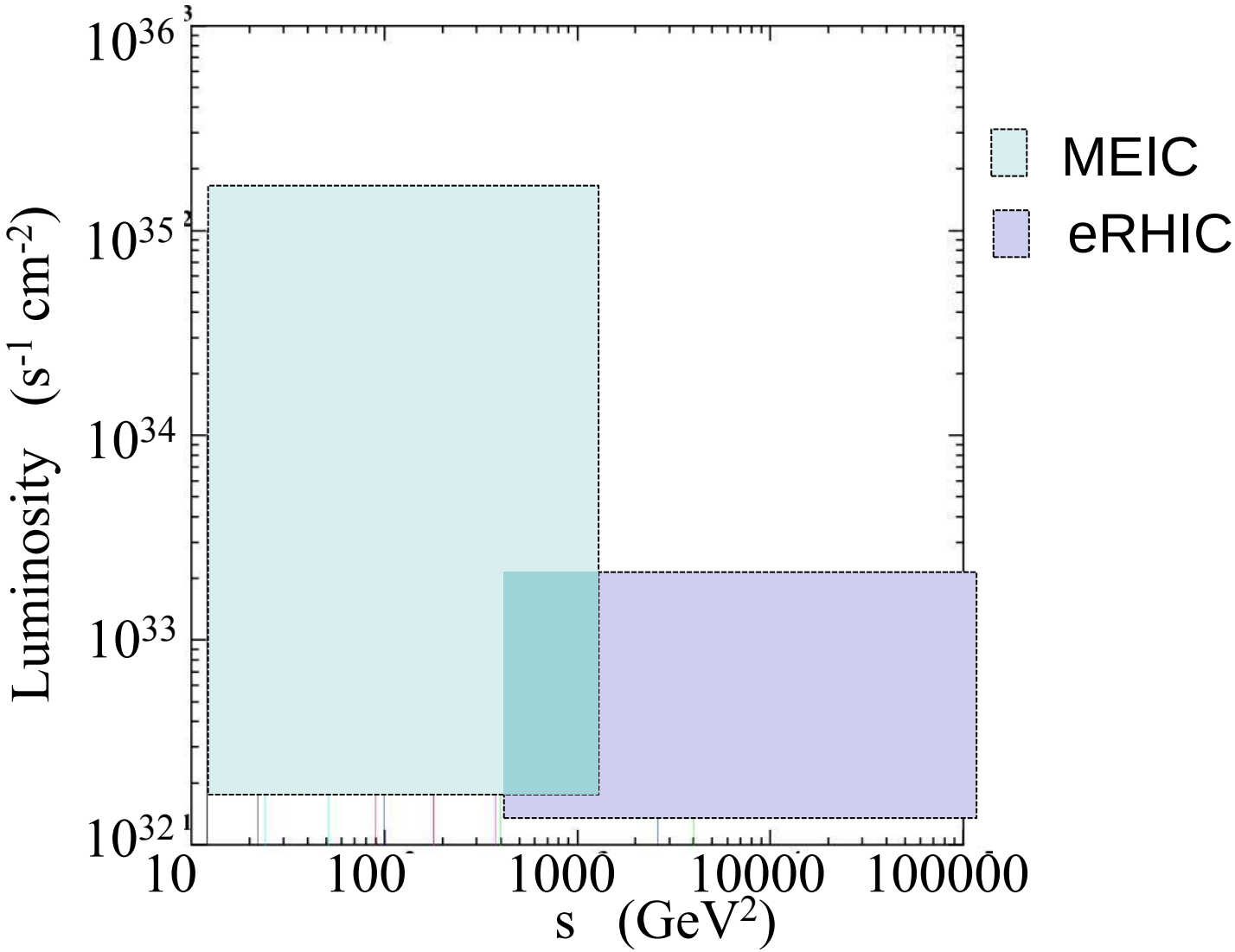
- **Sea quark and gluon imaging of nucleons with GPDs (x >~ 0.01)**
- **Orbital angular momentum, transverse spin, and TMDs**
- **QCD vacuum in hadron structure and fragmentation**
- **Nuclei in QCD: Binding from EMC effect, quark/gluon radii from coherent processes, transparency**

Machine/detector requirements

- Low rates, differential measurements ➔ High luminosity > 10^{34}
- CM energy s~1000 GeV^2: Reach in Q^2, x
- Detectability: Angular coverage, particle ID, energy resolution

➔ favors lower, more symmetric energies!

Project Range



EIC@JLab Design Goals

- **Energy**
  Wide CM energy range between 10 GeV and 100 GeV
  - **Low energy: 3 to 11 GeV *e* on 3 to 12 GeV *p* or 6 GeV/n ion**
  - **MEIC: up to 11 GeV *e* on 60 GeV *p* (and ion equivalent)**

    and *for the future upgrade*
  - **High energy: up to 11 GeV *e* on 250 GeV *p* or 100 GeV/n ion**

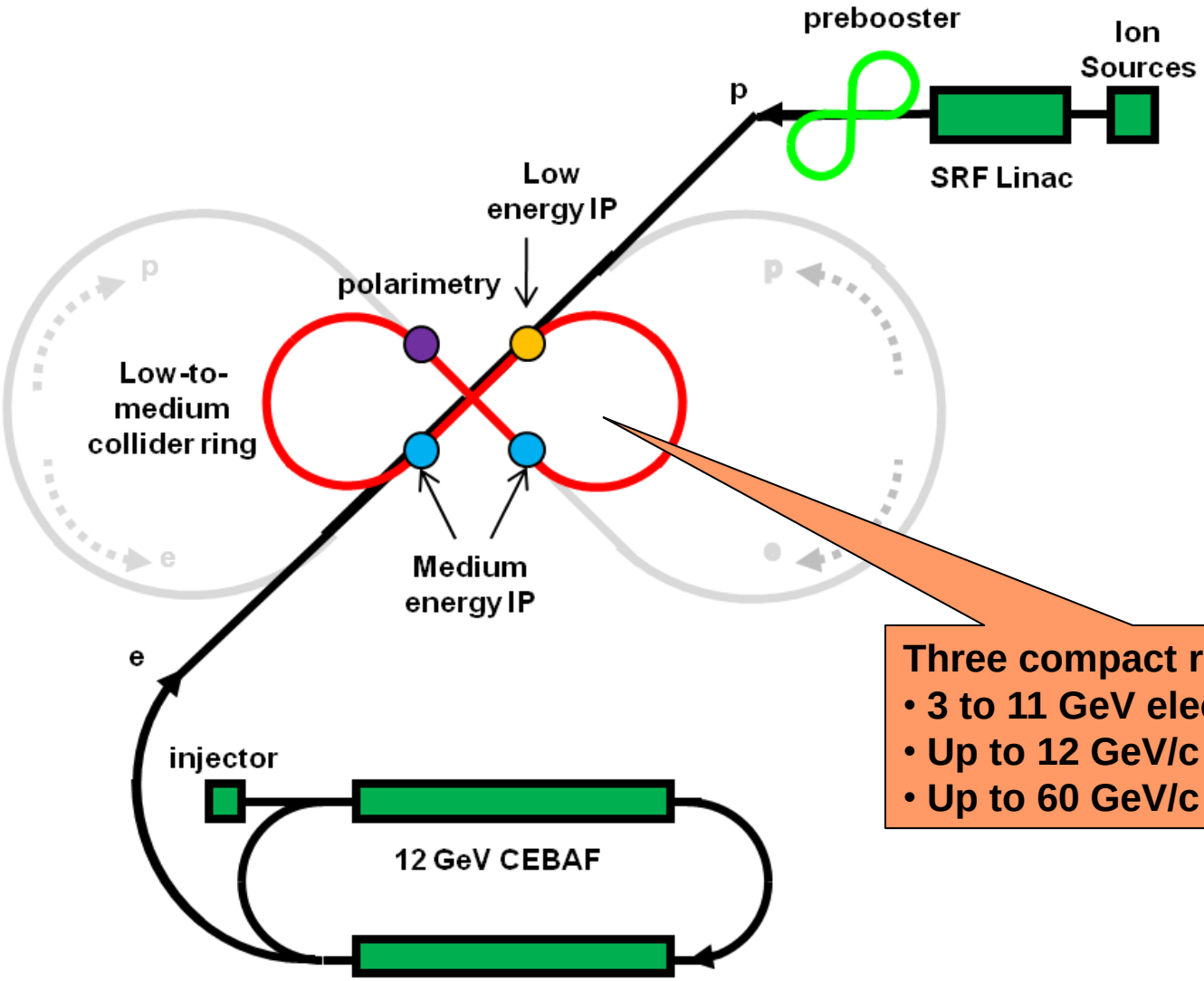
- **Luminosity**
  - **10^{33} to 10^{35} cm^{-2} s^{-1} *per* interaction point**
  - **Multiple interaction points**

- **Ion Species**
  - **Polarized H, D, ^{3}He, possibly Li**
  - **Up to A = 208, all fully stripped**

- **Polarization**
  - **Longitudinal at the IP for both beams, transverse for ions**
  - **Spin-flip of both beams**
  - **All polarizations >70% desirable**

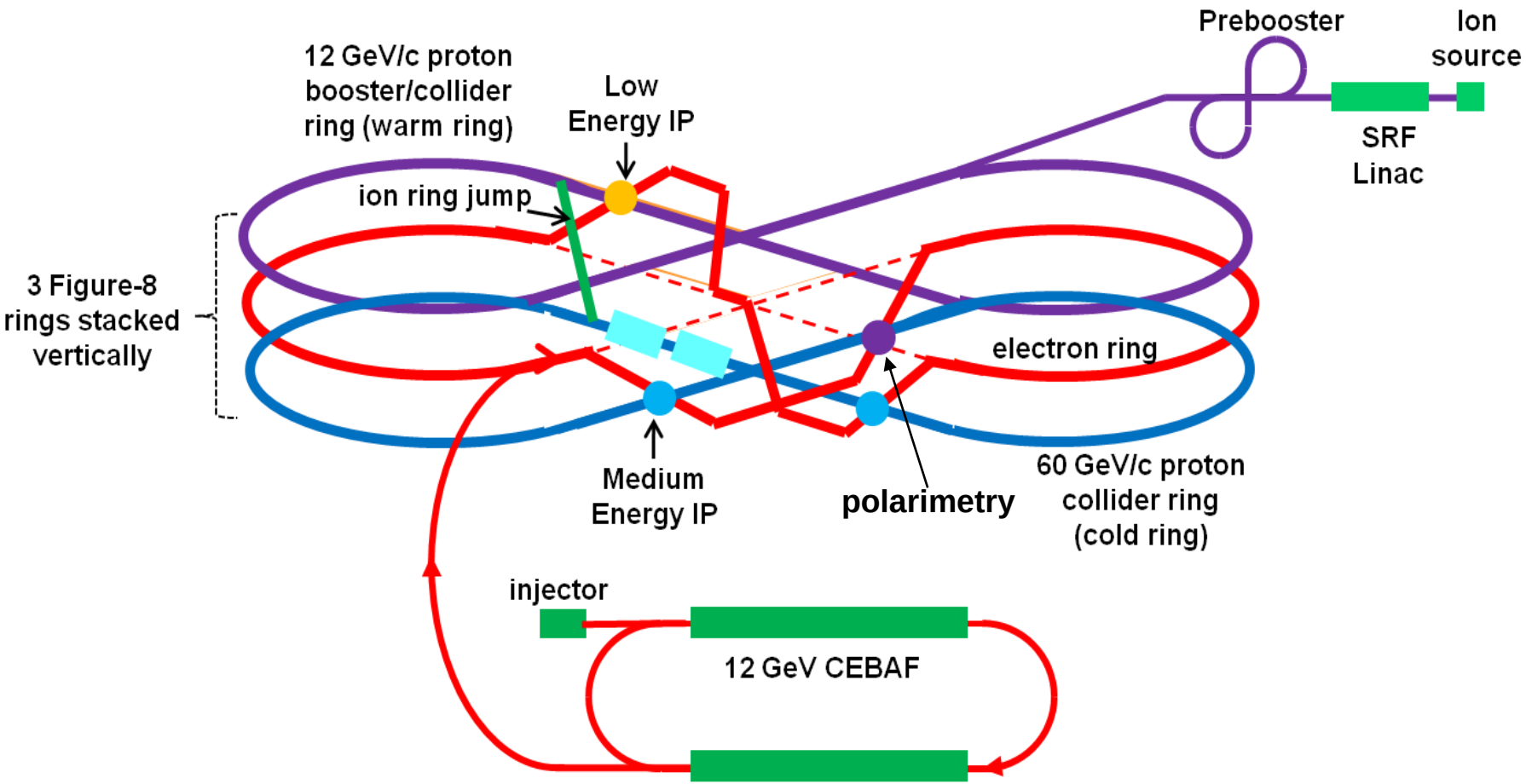
- **Positron Beam *desirable***

MEIC for Jefferson Lab



Three compact rings:
- **3 to 11 GeV electron**
- **Up to 12 GeV/c proton (warm)**
- **Up to 60 GeV/c proton (cold)**

MEIC Detail


Prebooster
Ion source
12 GeV/c proton booster/collider ring (warm ring)
Low Energy IP
SRF Linac
ion ring jump
3 Figure-8 rings stacked vertically
electron ring
Medium Energy IP
polarimetry
60 GeV/c proton collider ring (cold ring)
injector
12 GeV CEBAF

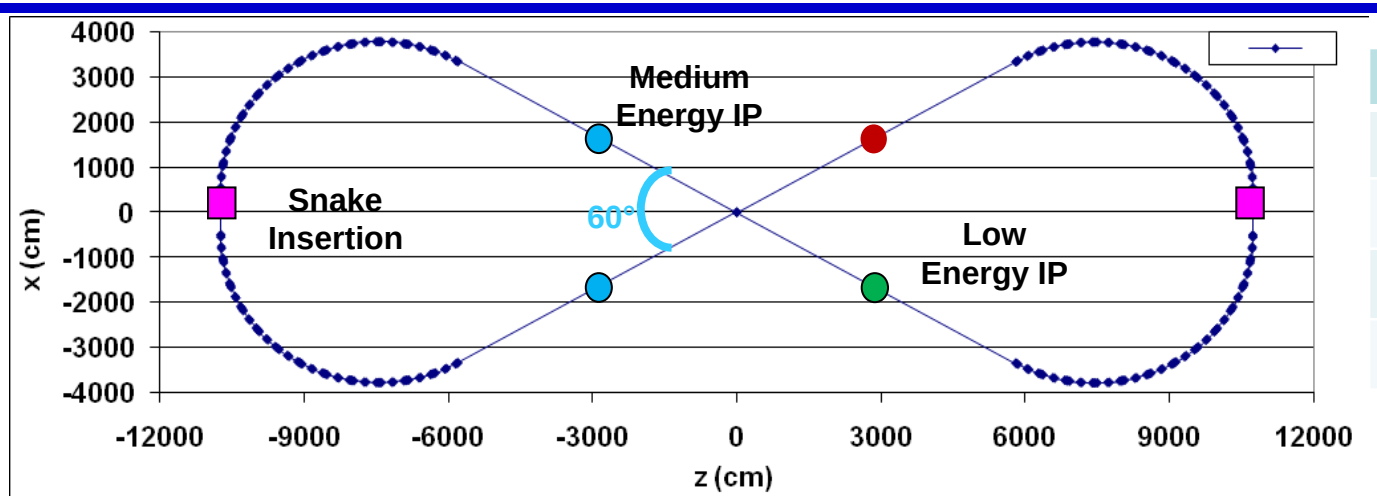
Design Features

- Multiple IPs (detectors) for high science productivity
- Vertically stacked "*Figure-8*" ion and lepton storage rings
- 12 GeV CEBAF serves as a full energy injector to the electron ring
- ***Simultaneous*** operation of the collider & the CEBAF fixed target program is possible
- Experiments with a polarized positron beam are possible with addition of a positron source

Choice of Figure-8 Ion Rings

- Figure-8 optimum for polarized ion beams
  - Simple solution to preserve full ion polarization by avoiding spin resonances during acceleration
  - Energy independence of spin tune
  - g-2 is small for deuterons; a figure-8 ring is the only practical way to arrange for longitudinal spin polarization at interaction point.
  - Allows multiple interactions in the same straight – can help with chromatic correction
- Only disadvantage is small cost increase
  - There are no technical disadvantages

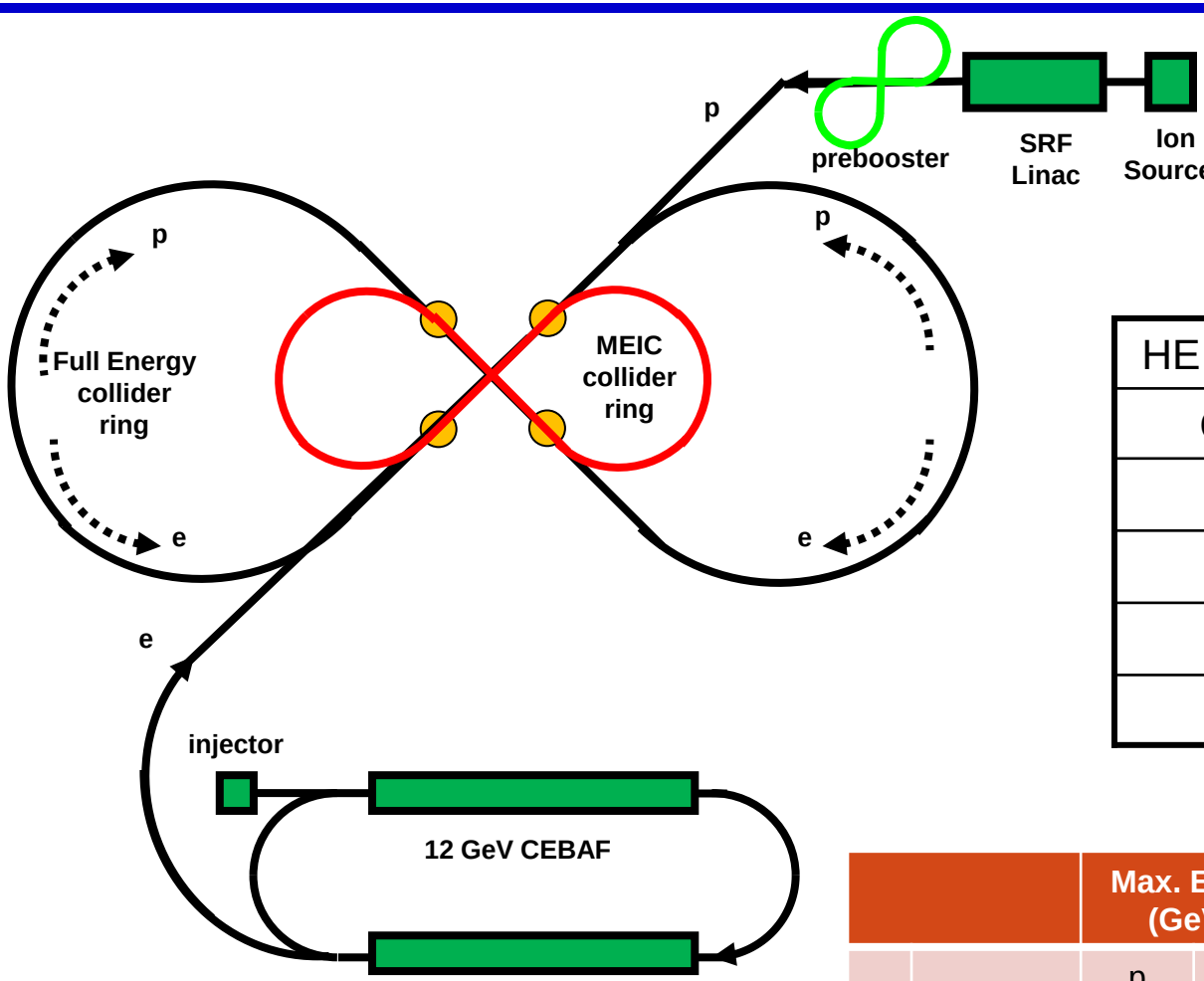
Figure-8 Collider Ring Footprint

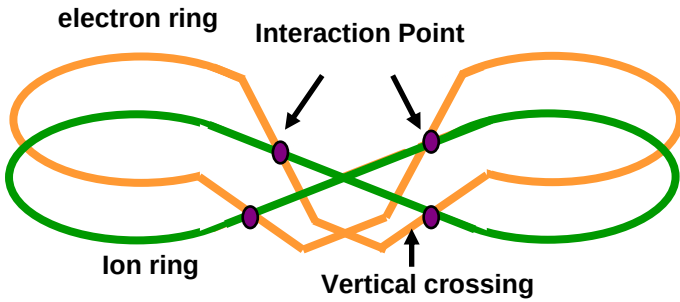


Arc	157 m
Figure-8 straight	150 m
Insertion	10 m
Circumference	634 m

- Ring design is balance between
  - Synchrotron radiation power of e-beam➔ prefers large ring (arc) length (assumed synchrotron radiation power limit is 20 kW/m)
  - Space charge effect of ion beam➔ prefers small ring circumference
- Multiple IPs require long straight sections
- Straight sections also hold required service components (electron cooling, injection and ejection, etc.)

Going to High Energy





HE Ring Dimensions	m
Circumference	1800
Radius	140
Width	280
Length	695
Straight	306

		Max. Energy (GeV/c)		Ring Size (m)		Ring Type		IP #
		p	e	p	e	p	e	
1	Medium	60	5 (11)	630	630	Cold	Warm	2
2	High	250	11	1800	1800	Cold	Warm	4

Achieving High Luminosity

MEIC design luminosity

$L \sim 4 \times 10^{34}$ cm^{-2} s^{-1} for (60 GeV x 3 GeV)

$L \sim 1 \times 10^{35}$ cm^{-2} s^{-1} for high energy (250 GeV x 10 GeV)

Luminosity Concepts *(based on proven technologies)*

- **High bunch collision frequency (0.5 GHz, possibly up to 1.5 GHz)**
- **Bunch charge around 1 nC**
- **Short ion bunches ($\sigma_z \sim 5$ mm)**
- **Strong vertical final focusing ($\beta^*_y \sim 5$ mm)**

Keys to implement these concepts

- **Electron cooling for making short ion bunches with small emittance**
- **Crab crossing of the colliding beams**
- **SRF cavities for bunching and crabbing**

Additional ideas/concepts

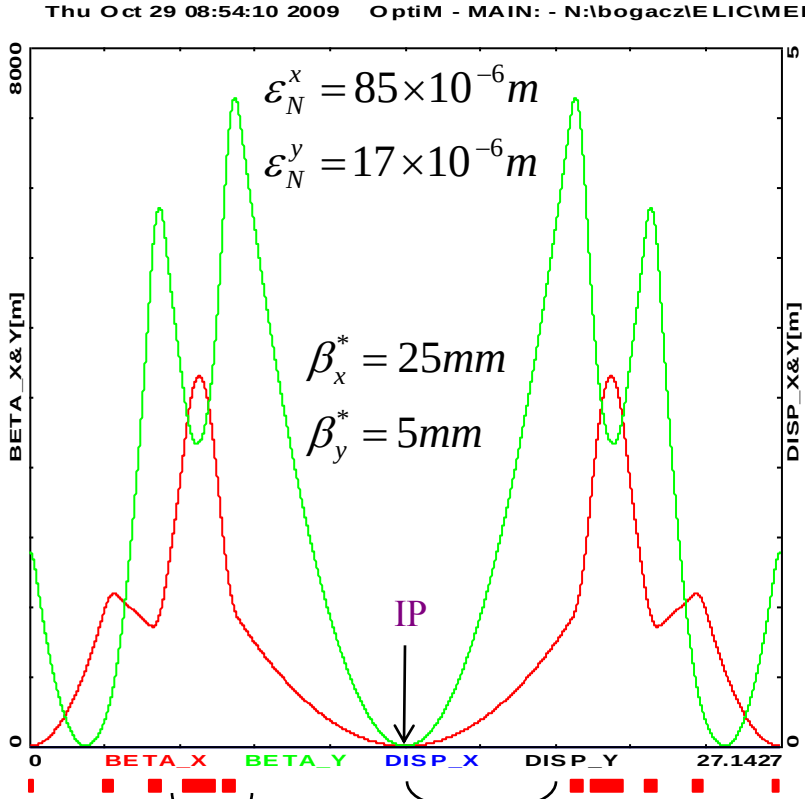
- **Parameters limited by the beam-beam effect**
- **Hour-glass correction for very low ion energy (bunches longer than β^*)**
- **Large synchrotron tunes to suppress synchrotron-betatron resonances**
- **Equal (fractional) betatron phase advance between IP**
- **Advanced achromatic IP region focusing**

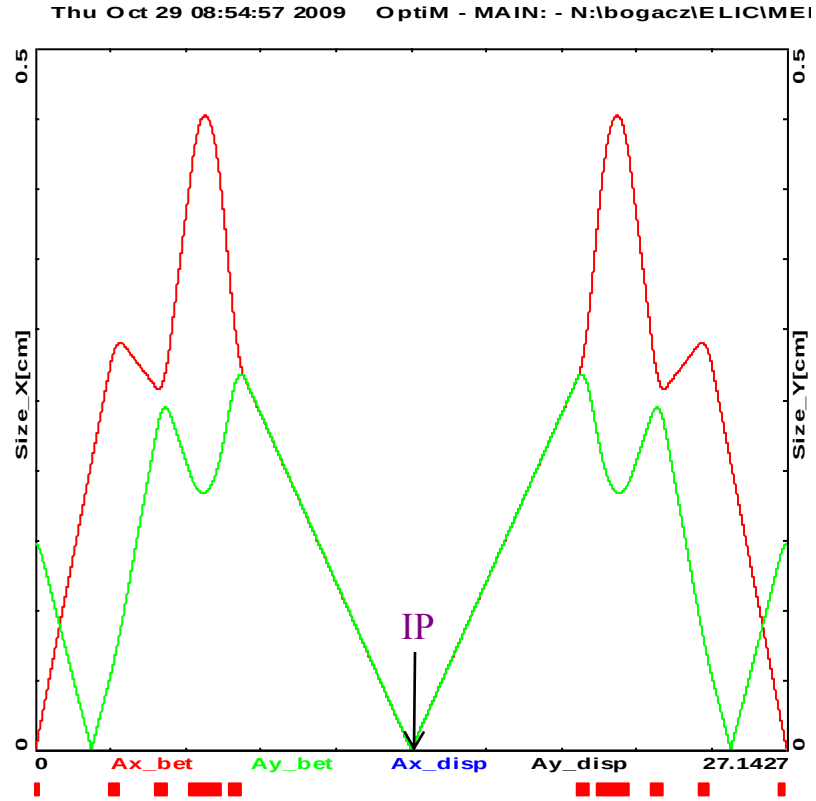
EIC Parameters

Beam Energy	GeV	12/3	60/5	60/3	250/10
Collision freq.	MHz		499		
Particles/bunch	10^{10}	0.47/2.3	0.74/2.9	1.1/6	1.1/3.1
Beam current	A	0.37/2.7	0.59/2.3	0.86/4.8	0.9/2.5
Energy spread	10^{-4}		~ 3		
RMS bunch length	mm	50	5	5	5
Horz. emit., norm.	μm	0.18/80	0.56/85	0.8/75	0.7/51
Vert. emit. Norm.	μm	0.18/80	0.11/17	0.16/15	0.03/2
Horizontal β^*	mm	5	25	25	125
Vertical β^*	mm		5		
Vert. b-b tuneshift/IP		.015/.013	0.01/0.03	.015/.08	0.01/0.1
Laslett tune shift	p-beam	0.1	0.1	0.054	0.1
Peak Luminosity/IP, 10^{34}	$cm^{-2}s^{-1}$	0.59	1.9	4.0	11
		Low energy	MEIC		High energy

Interaction Region Optics

vertical focusing first





FF triplet : Q3 Q2 Q1

$\ell^* = 6$ m

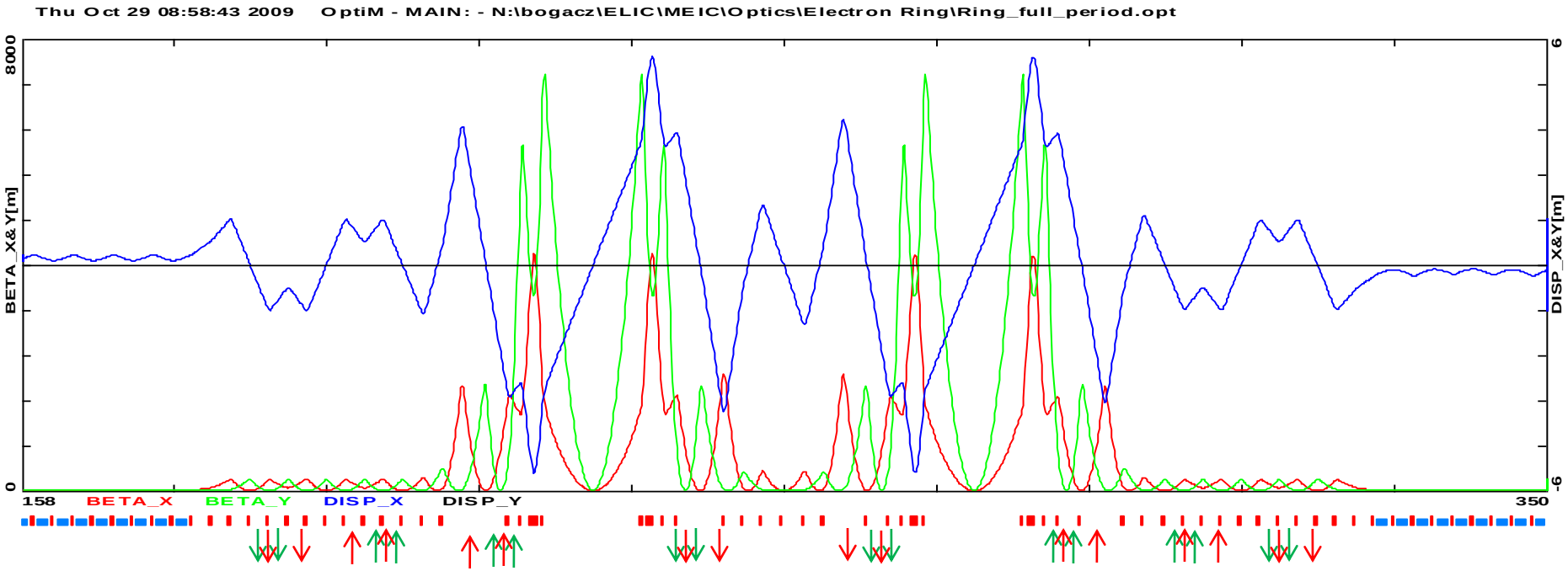
Q1	G[kG/cm] = -3.4
Q2	G[kG/cm] = 2.1
Q3	G[kG/cm] = -4.1

$\ell^* = 6$ m

Natural Chromaticity: ζ_x=-305 ζ_y=-425

IR – Chromaticity Compensation

Uncompensated dispersion pattern coming out of the Arc



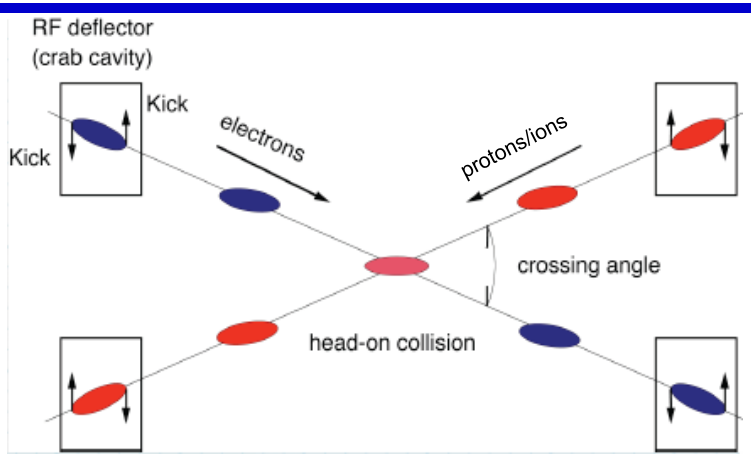
Natural Chromaticity: $\zeta_x = -650$ $\zeta_y = -990$

$$\zeta_{sext} = \frac{1}{4\pi} \sum_{sext} \beta \, \eta_0 \, g_1^{sext}$$

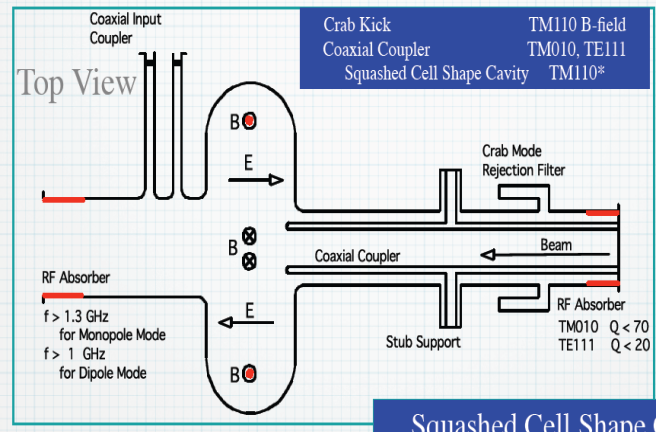
Compensating sextupole strength: $g_1 = 0.15\ m^{-2}$

Crab Crossing & Crab Cavity

- **High repetition rate requires crab crossing beams to avoid parasitic beam-beam collisions**
- **Crab cavities are needed to restore head-on collision and avoid luminosity reduction**
- **ELIC crossing angle: ~ 2x25 mrad (6+6 m IR)**



Stage	Beam Energy (GeV/c)	Integrated Kick Voltage (MV)	R&D
electron	10	~ 1	State-of-art
Proton	12	~ 1	State-of-art
Proton	60	10	Not too far away



Issues

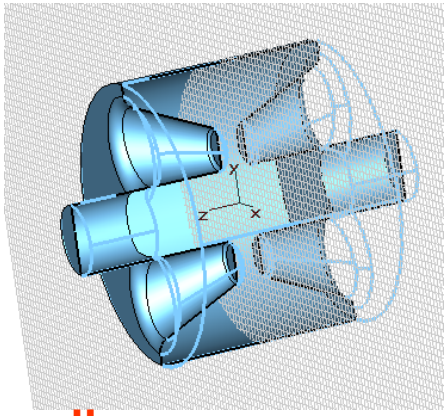
- Crab cavity development & gradient limits
- Phase & amplitude stability requirements
- Beam dynamics/luminosity dependence of crab crossing

State-of-the-art:

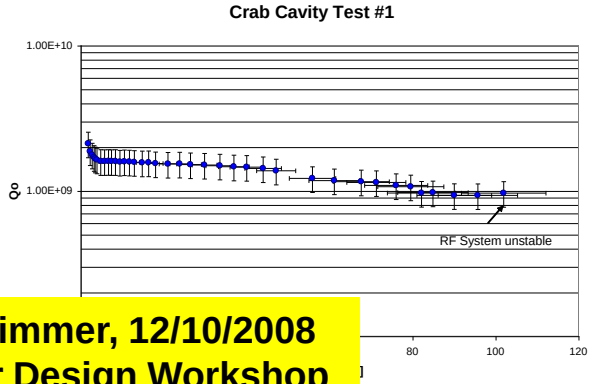
KEKB Squashed cell@TM110 Mode
Crossing angle = 2 x 11 mrad
V_{kick}=1.4 MV, E_{sp}= 21 MV/m

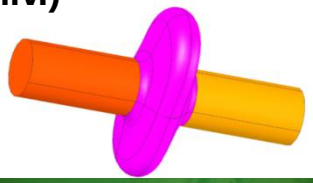
JLab Crab Cavity Development

Multi-cell TM110 and Loaded Structure of Crabbing Cavity (JLab/Cockcroft/Lancaster)



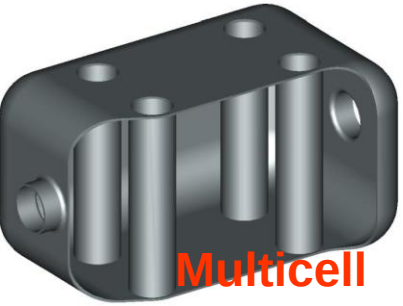
Elliptical squashed SRF cavity R&D for APS (JLab/LBNL/AL/Tsinghua Univ.)





H. Wang, R. Rimmer, 12/10/2008
Moun Collider Design Workshop

Single cell



Multicell

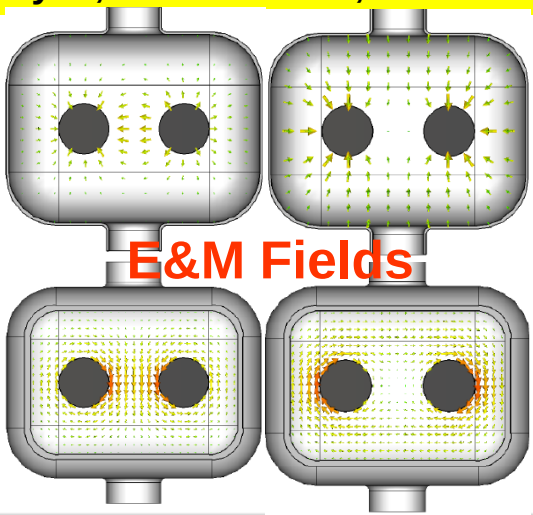
New (Innovative) Program

- Compact TEM-type, parallel-bar
- Deflecting ➔ 12 GeV CEBAF
- Crabbing ➔ MEIC, ELIC
- Providing high transverse kick

Single cell: 37x50cm, 4 MV@500MHz

Multi-cell: ~ n x (37 cm), n x (4 MV)

J. Delayen, H. Wang, PRST 2009
J. Delayen, JLab seminar, 02/19/09



E&M Fields

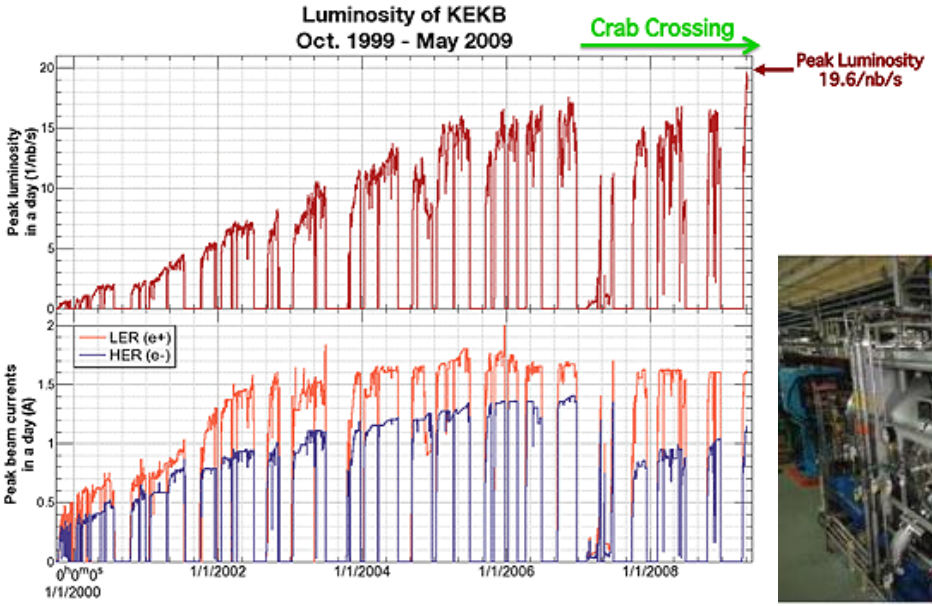
News From KEK

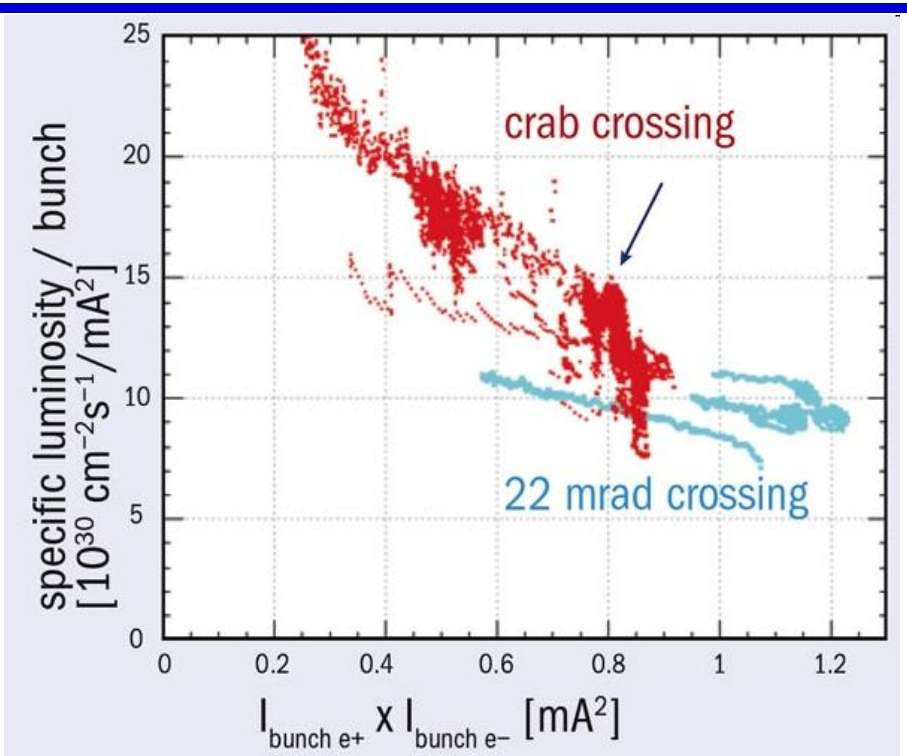
KEK Press Release (05/11/09)

"Using Crab Cavities, KEKB Breaks Luminosity World Record"

Symmetry *Breaking* (05/11/09)

"Record luminosity collisions due to "crab" crossing,





Conceptual Progress

- Dispersive crab crossing for MEIC/ELIC
  - Dispersive crabbing (Jackson): Phase-correlated energy difference causes transverse oscillation. After the kick, dispersion is compensated at star-point, but the excitation remains. Tilt mechanism looks the same at IP as a transverse kick by deflecting cavity.
- Beam-beam kicker for electron cooling
  - Problem: beam injection and extraction from circulator cooling ring, must be very fast
  - Proposed solution: use two-beam kick between co-propagating electron beams
  - Average current for "deflector" beam close to JLAB FEL beam parameters

Accelerator R&D (Roser Talk)

We have identified the following critical R&D for our plans

- Electron cooling
- Crab crossing and crab cavity
- Forming high intensity low energy ion beam
- Beam-beam effect
- Traveling focusing for low energy ion beam

Will discuss issues/requirements/state-of-art/challenges/activities

Level of R&D	Low-to-Medium Energy (12x3 GeV/c) & (60x5 GeV/c)	High Energy (up to 250x10 GeV)
Challenging		
Semi Challenging	Electron cooling Traveling ion focus (low energy) Round to flat ion beam IP design/chromaticity	Electron cooling/fast kicker IP design/chromaticity
Likely	Stacking high intensity ion beam Beam-beam	Stacking high intensity ion beam Beam-beam
Know-how	Spin manipulation/tracking Crab crossing Clocking	Spin manipulation/tracking Crab crossing Clocking

EICAC Issues Summary

Question	Assessment	Status
Ultra short ion bunch	• Forming ultra-short ion bunch • Beam dynamics and instability	Have a workable concept Checked cooling & IBS rates
Ion beam lifetime	General question (also beam instabilities)	Checked leading causes (Byung Yunn)
Figure-8 ion ring choice		Closed
Luminosity lifetime reduction due to beamsstrahlung at IP		Checked (Slava Derbenev)
5 mm β^* in x and y	Good observation	β^* in x changed to 25 mm Electron linear optics complete Ion ring will be similar
Lattice design with sufficient dynamical aperture	Needs linear lattices, chromatic correction, and tracking studies	In progress. Tracking studies will start (Alex Bogacz, Yves Roblin)
CSR effect for unusually short ion bunch		Effects are small. Closed (Rui Li)

Labor Pool Expanded

- Increased CASA Scientist Commitment (JLAB Staff)
  - Slava Derbenev
  - Rui Li
  - Byung Yunn
  - Balsa Terzic (partial SciDac support)
- Visiting Scientists (NP Supplemental Funds)
  - Peter Ostroumov (ANL)
  - Michael Sullivan (SLAC National Lab)
  - Vadim Dudnikov (Muons, Inc.)
  - Vasiliy Morozov (Old Dominion University)
  - Jie Wei was first “official” visitor visiting early last month

Priorities for Future Work

- Complete ring optics designs, chromaticity correction, and dynamic aperture for MEIC parameters
- Preliminary design of ion complex up to collider ring
  - Ion sources
  - SRF Accelerator
  - Ion Booster
- Beam-beam simulations with new parameters
  - Stability
  - Working point optimization
  - Luminosity vs. current
- Spin tracking

ELIC Study Group

A. Afanasev, A. Bogacz, J. Benesch, P. Brindza, A. Bruell, L. Cardman, Y. Chao, S. Chattopadhyay, E. Chudakov, P. Degtiarenko, J. Delayen, Ya. Derbenev, R. Ent, P. Evtushenko, A. Freyberger, D. Gaskell, J. Grames, L. Harwood, T. Horn, A. Hutton, C. Hyde, R. Kazimi, F. Klein, G. A. Krafft, R. Li, L. Merminga, J. Musson, P. Nadel-Turonski, M. Poelker, R. Rimmer, C. Tengsirivattana, A. Thomas, B. Terzic, M. Tiefenback, H. Wang, C. Weiss, B. Wojtsekhowski, B. Yunn, Y. Zhang - Jefferson Laboratory staff and users

W. Fischer, C. Montag - Brookhaven National Laboratory

D. Barber - DESY

V. Danilov - Oak Ridge National Laboratory

V. Dudnikov – Muons, Inc.

P. Ostroumov - Argonne National Laboratory

V. Derenchuk - Indiana University Cyclotron Facility

A. Belov - Institute of Nuclear Research, Moscow, Russia

V. Shemelin - Cornell University

Summary

- An electron-ion collider at JLab promises to accelerate and store a wide variety of polarized light ions and un-polarized heavy ions, and bring them into collision with polarized electron beams enabling a unique physics program.

- The project covers a wide CM energy range (10 to 100 GeV) in a coherent way. In the immediate future, a low-to-medium energy collider (CM energy 10 to 55 GeV) is our near-term goal and R&D focus.

- The collider luminosity for *e-p* collisions should reach 4×10^{34} $cm^{-2}s^{-1}$ at (60×3 GeV^2), and 6×10^{33} $cm^{-2}s^{-1}$ at lower energies (12×3 GeV^2).

- By shifting towards lower energy, the project is now based on mostly *proven* accelerator technologies. Making a high intensity ion beam with high repetition rate, small emittance, and short bunch length is key in order to implement the collider, and deploying ion beam cooling is absolutely essential to obtain ion beams with the proper beam properties.

- We have identified the critical accelerator R&D topics for our project. Some topics are easier for MEIC than for the full energy collider, providing nice staging for such R&D. Work on R&D programs to complete, validate, and optimize our designs continues.