Electron-Ion Collider at Jefferson Lab

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For the JLAB EIC Study Group

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Rutgers University/Jefferson Lab
Electron-Ion Collider Workshop

Outline

- Collider Accelerators
  - Collider Luminosity
  - Luminosity-tune shift relationship
- Electron-Ion Collider Accelerator Project Status
  - Design
  - Luminosity concepts
- Recent Activity
- 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 the 12 GeV CEBAF recirculated SRF linac and a new ion complex at Jefferson Lab.

- Our design efforts have focused on achieving exceptionally high luminosity (above $5\ 10^{33}$ $cm^{-2}sec^{-1}$) over multiple detectors & very high polarization (>80%) for both electron and light ion beams, to meet demands of future nuclear science programs.

- At present, our design efforts are concentrating on a high luminosity medium energy EIC (up to 60x11 GeV^2), **MEIC**, as our ***near-term goal***, and will work to keep a full energy site filling EIC (250x11 GeV^2) as an upgrade option.
- MEIC seems to provide not only a rich & broad science program, but also a good balance between nuclear science, detector & accelerator R&D, and project cost.
- We have developed a "first-pass" design for MEIC based on CEBAF, and explored dependences of luminosity on design parameters, and would like **additional user input regarding design parameters leading to particularly strong science cases.**

Collider Luminosity

- Probability an event is generated by a Beam 1 bunch with Gaussian density crossing a Beam 2 bunch with Gaussian density

$$P = \frac{N_1 N_2}{2\pi \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}}\sigma$$

- Event rate with equal transverse beam sizes

$$\frac{dN}{dt} = \frac{f N_1 N_2}{4\pi \sigma_x \sigma_y}\sigma = \mathcal{L}\sigma$$

- Linear beam-beam tune shift

$$\xi_x^i = \frac{N_{\bar{i}} r_i}{2\pi\gamma_i}\frac{1}{\varepsilon_x^i\left(1+\sigma_y/\sigma_x\right)} \qquad \xi_y^i = \frac{N_{\bar{i}} r_i}{2\pi\gamma_i}\frac{1}{\varepsilon_y^i\left(1+\sigma_y/\sigma_x\right)\left(\sigma_x/\sigma_y\right)}$$

Luminosity beam-beam tune-shift relationship

- **Express Luminosity in terms of the (larger!) vertical tune shift (*i* either 1 or 2)**

$$\mathcal{L} = \frac{f N_i \xi_y^i \gamma_i}{2 r_i \beta^*}\left(1 + \sigma_y / \sigma_x\right) = \frac{I_i}{e} \frac{\xi_y^i \gamma_i}{2 r_i \beta^*}\left(1 + \sigma_y / \sigma_x\right)$$

- **Necessary, but not sufficient, for self-consistent design**

- **Expressed in this way, and given a known limit to the beam-beam tune shift, the only variables to manipulate to increase luminosity are the stored current, the aspect ratio, and the *β** (beta function value at the interaction point)**

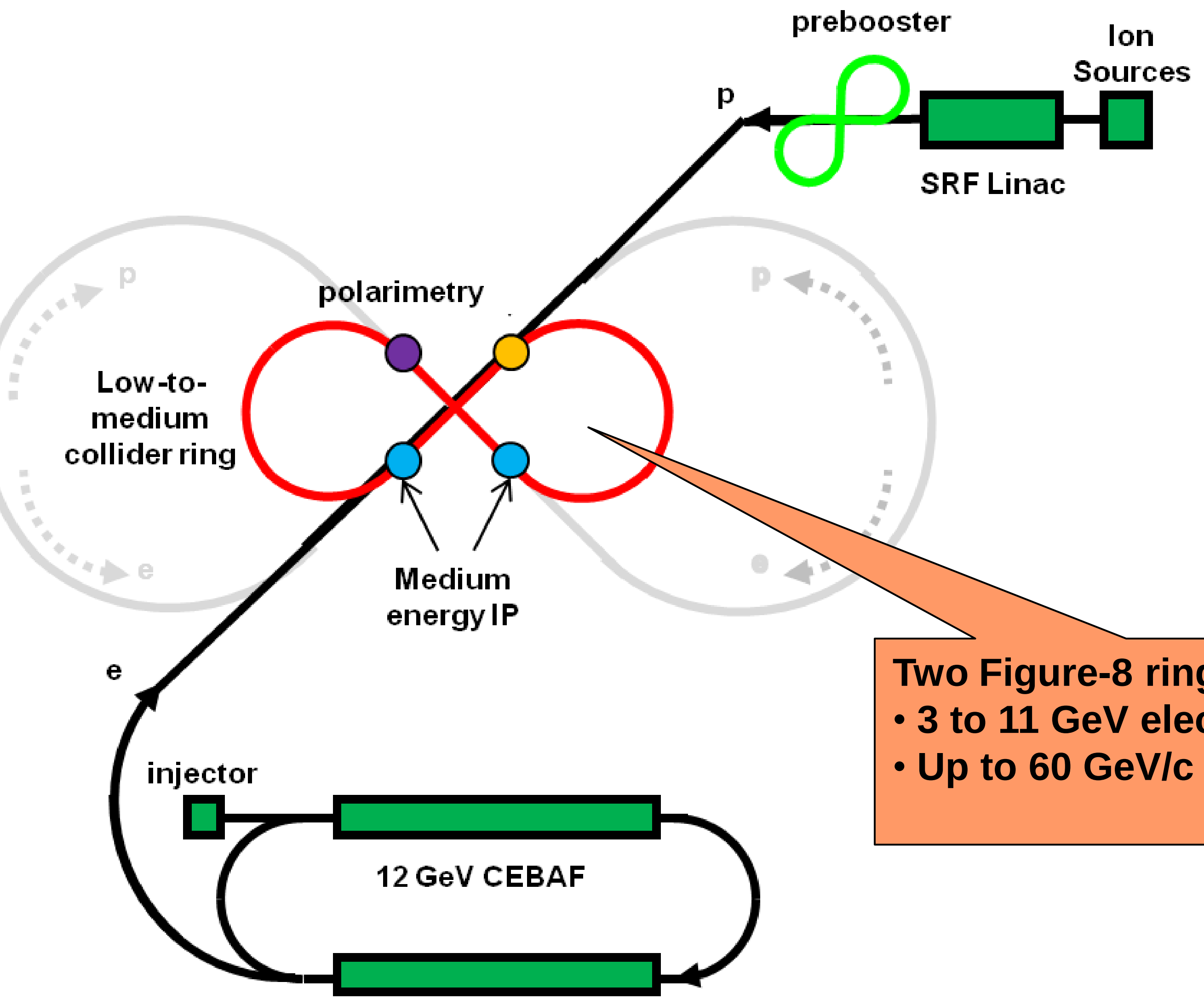
- **Applies to ERL-ring colliders, stored beam (ions) only**

Draft EIC Design Goals

- Energy
  - MEIC: up to 11 GeV *e* on 60 GeV *p* (and ion equivalent)

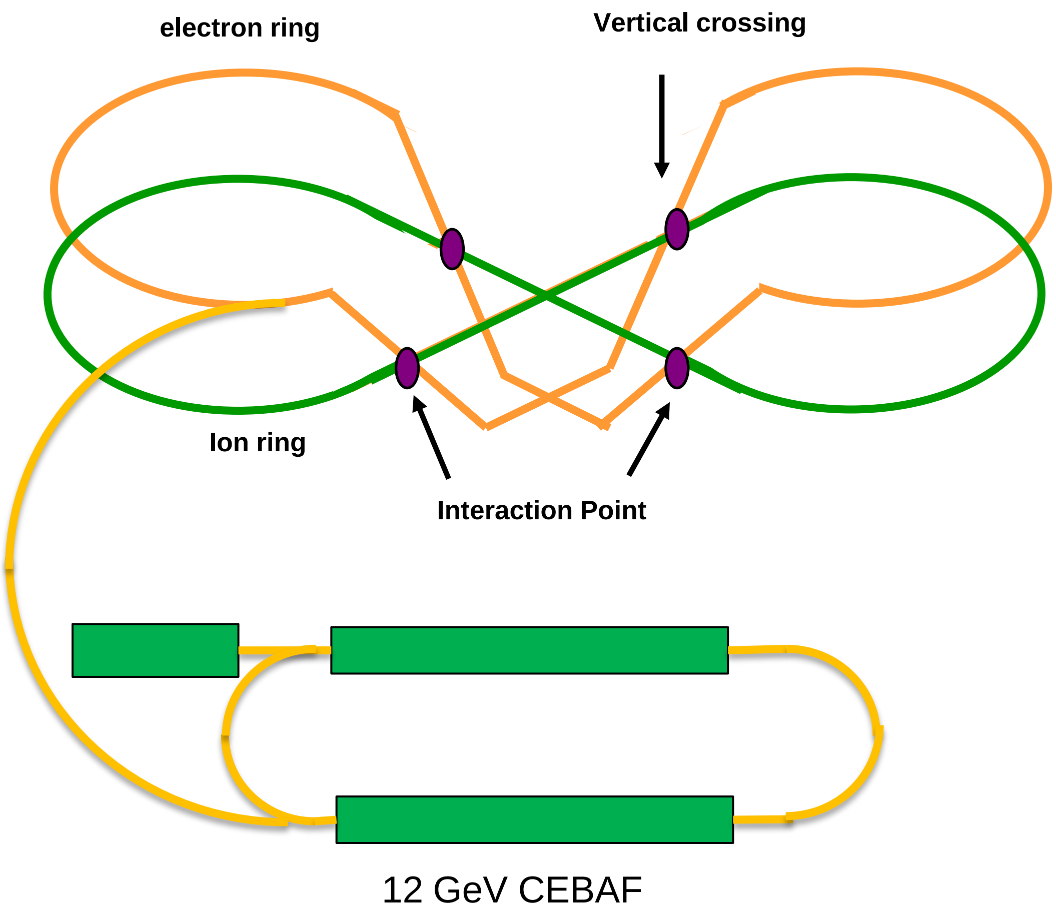
    and *for the future upgrade*
  - High energy: up to 11 GeV *e* on 250 GeV *p* or 100 GeV/n ion
- Luminosity
  - Above 5×10^{33} cm^{-2} s^{-1} *per* interaction point for some operating conditions
  - Multiple interaction points
- Ion Species
  - Polarized H, D, ^{3}He, possibly Li
  - Up to A = 208, 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



Two Figure-8 rings:
- 3 to 11 GeV electron
- Up to 60 GeV/c proton (cold)

MEIC Detail


electron ring
Vertical crossing
Ion ring
Interaction Point
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 & a CEBAF fixed target program is possible
- Experiments with a polarized positron beam are possible with addition of a positron source

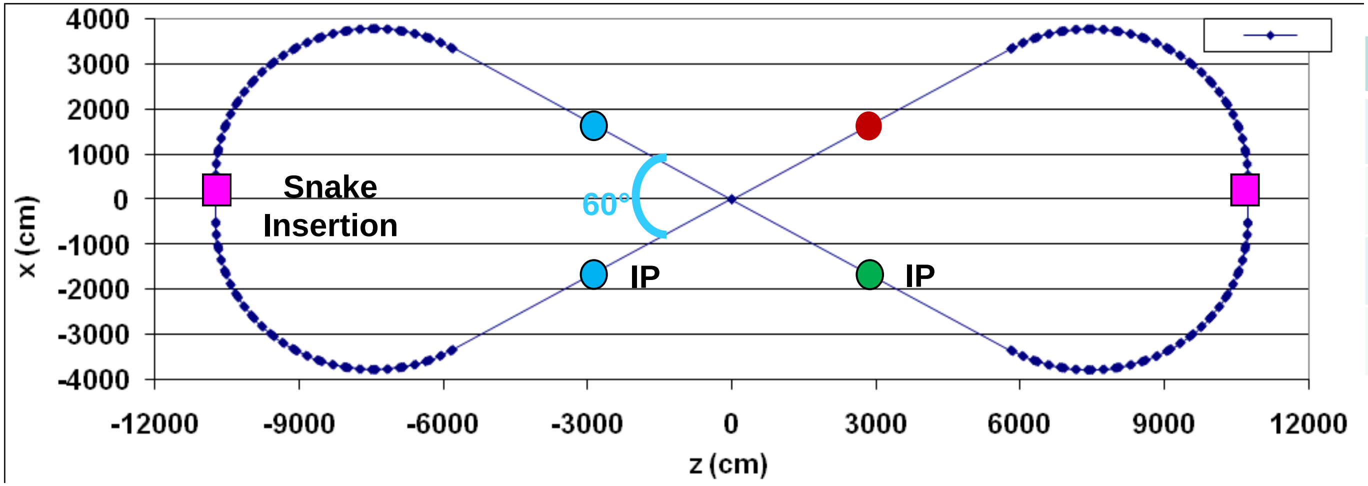
Choice of Figure-8 Ion Rings

- 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
- Needs further evaluation
  - Incremental cost increase: more bends and tunnel
  - Recent review mentions only possible backgrounds between IPs on same straight

Evolution of the Design

- Energy Recovery Linac-Storage-Ring (ERL-R)
- ERL with Circulator Ring – Storage Ring (CR-R)
- **Back to Ring-Ring (R-R) – by using CEBAF as full energy polarized injector**
- Overcomes problem making the polarized electron source
  - ERL-Ring: 2.5 A
  - Circulator ring: 20 mA
  - State-of-art: 0.1 mA
- **12 GeV CEBAF Upgrade polarized source/injector already meets beam requirements of ring-ring design**
- **CEBAF-based R-R design still preserves high luminosity, high polarization (+polarized positrons…)**

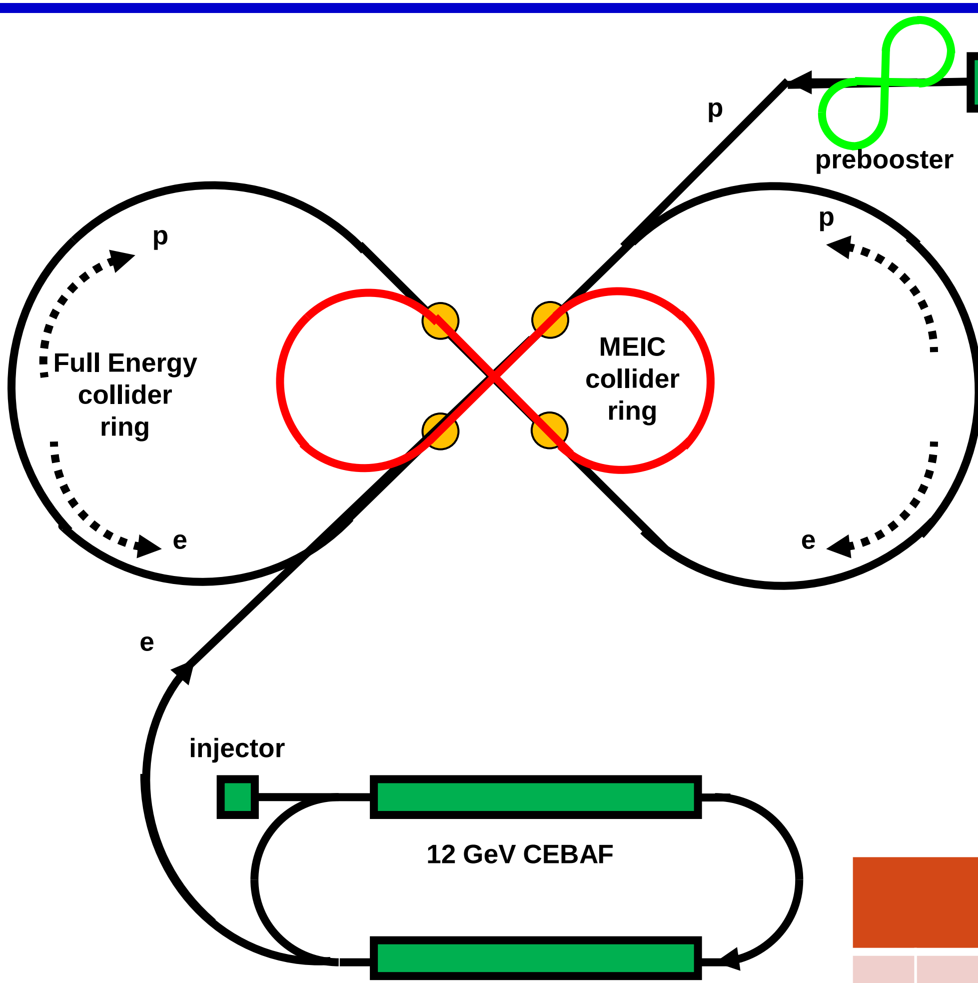
Figure-8 Collider Ring Footprint

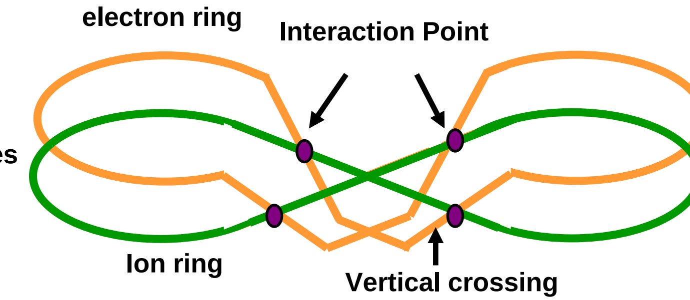


Arc	157 m
Figure-8 straight	150 m
Insertion	10 m
Circumference	634 m

- 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 up to L ~ 10^{34} cm^{-2} s^{-1} for (60 GeV x 5 GeV)

L~ 1×10^{35} cm^{-2} s^{-1} for high energy (250 GeV x 10 GeV)

Luminosity Concepts

- High bunch collision frequency (0.5 GHz, possibly up to 1.5 GHz)
- Small bunch charge (<3×10^{10} particles per bunch)
- Short ion bunches (σ_z ~ 10 mm)
- Strong vertical final focusing (β^*_y ~ 20 mm)

Keys to implement these concepts

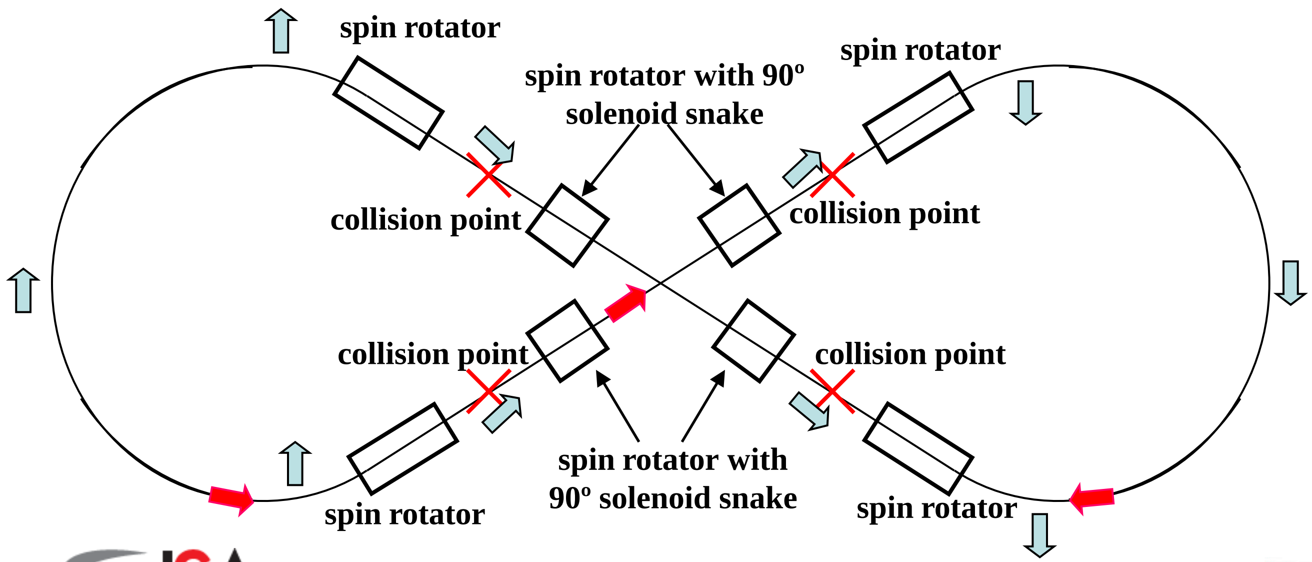
- Electron cooling for making short ion bunches with small emittance
- Crab crossing of the colliding beams
- SRF cavities for bunching and crabbing

Additional ideas/concepts

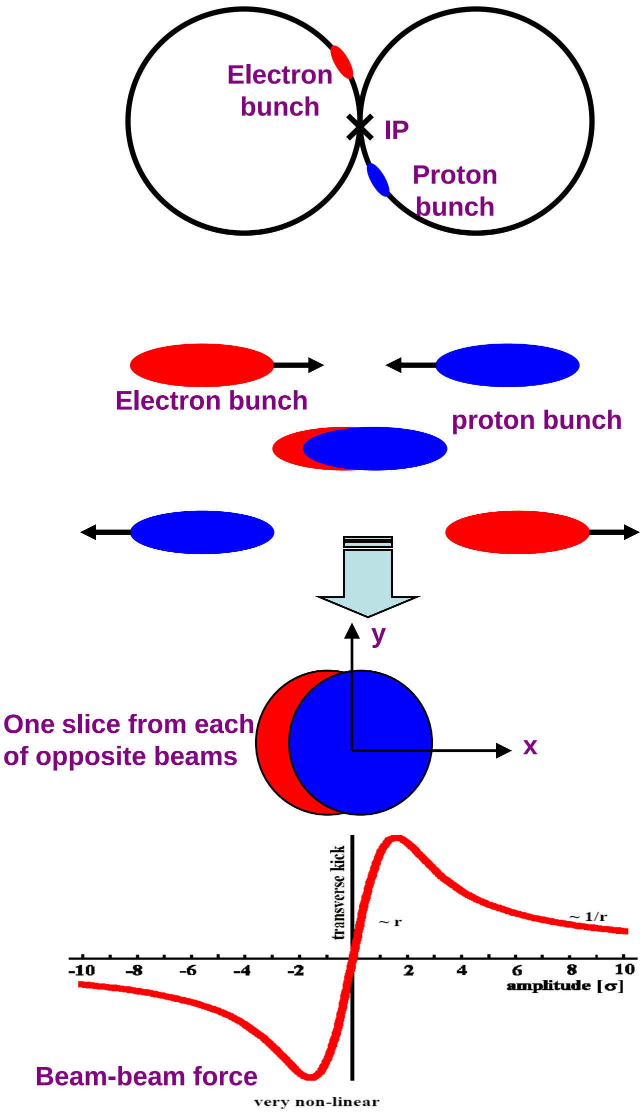
- Parameters limited by the beam-beam effect
- Hour-glass correction for very low ion energy (bunches longer than β^*)
- Large synchrotron tunes to suppress synchrotron-betatron resonances
- Equal (fractional) betatron phase advance between IP
- Advanced achromatic IP region focusing

Electron Polarization in ELIC

- Produced at electron source
  - Polarized electron source of CEBAF
  - Preserved in acceleration at recirculated CEBAF Linac
  - Injected into Figure-8 ring with vertical polarization
- Maintained in the ring
  - SC solenoids at IPs removes spin resonances and energy sensitivity.



Beam-Beam Effect



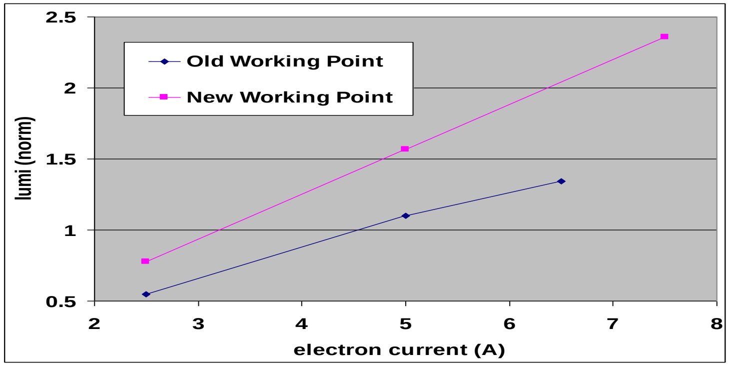
Transverse beam-beam force
- Highly nonlinear forces
- Produce transverse kicks between colliding bunches

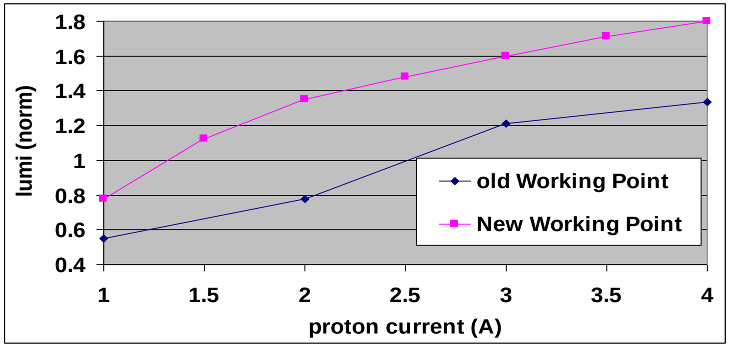
Beam-beam effect
- Can cause size/emittance growth or blowup
- Can induce coherent beam-beam instabilities
- Can decrease luminosity and its lifetime

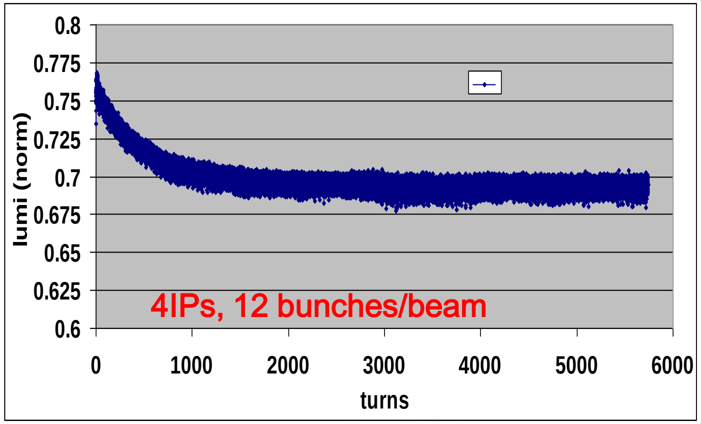
Impact of ELIC IP design
- Highly asymmetric colliding beams
  (9 GeV/2.5 A on 225 GeV/1 A)
- Four IPs and Figure-8 rings
- Strong final focusing (β^* 5 mm)
- Short bunch length (5 mm)
- Employs crab cavity
- vertical b-b tune shifts are 0.087/0.01
- Very large electron synchrotron tune (0.25) due to strong RF focusing
- Equal betatron phase advance (fractional part) between IPs

Beam-Beam Simulations

- **Simulation Model**
  - Single/multiple IPs, head-on collisions
  - Strong-strong self consistent Particle-in-Cell codes, developed by J. Qiang of LBNL
  - Ideal rings for electrons & protons, including radiation damping & quantum excitations for electrons
- **Scope and Limitations**
  - 10k ~ 30k turns for a typical simulation run
  - 0.05 ~ 0.15 s of storing time (12 damping times)
    → reveals short-time dynamics with accuracy
    → can't predict long term (>min) dynamics
- **Simulation results**
  - Saturated at 70% of peak luminosity, $5.8 \cdot 10^{34}$ $cm^{-2}s^{-1}$, the loss is mostly due to the hour-glass effect
  - Luminosity increase as electron current linearly (up to 6.5 A), coherent instability observed at 7.5 A
  - Luminosity increase as proton current first linearly then slow down due to nonlinear b-b effect, electron beam vertical size/emittance blowup rapidly
  - Simulations with 4 IPs and 12-bunch/beam showed stable luminosity and bunch sizes after one damping time, situated luminosity is $5.5 \cdot 10^{34}$ $cm^{-2}s^{-1}$ per IP, very small loss from single IP and Single bunch operation







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Charge to JLab Machine Study Group

Report of the last EICC Advisory Committee meeting

Highest priority

- **Design of JLab EIC (Backup Plan?)**
- **High current (e.g. 50 mA) polarized electron gun**
- **Demonstration of high energy – high current recirculation ERL**
- **Beam-beam simulations for EIC**
- **Polarized 3He production and acceleration**
- **Coherent electron cooling**

Mont's Slide at Stony Brook EICC Meeting (01/11/2010)

It is clearly important to produce a complete Jefferson Lab machine design over the next 9 months

--- This will be our main thrust

Recent Activity

- We are charged to deliver a ***detailed*** accelerator design of the medium energy ELIC in the next 6 months (by the next meeting of the EIC Advisory Committee), a specific requirement from the last advisory committee meeting and JLab management.
- Scaling down ELIC machine parameters for the ***near term*** to make this design possible
  - Choosing key parameters within the state-of-art of existing colliders
  - Utilize as many existing technologies and experiences of other colliders as possible
  - Keeping minimum (absolute required) R&D issues for this version
- It is an excellent time for broader input from the Jefferson Lab user community. **What sort of collider best extends the studies completed in the 12 GeV era?**

Near Term (Scaled Down) Parameters

		Electron	Proton	
Collision energy	GeV	3 – 11	20 - 60	Booster 3–12 GeV, ring accepts 12 GeV injection
Max dipole field	T		6	
Max SR power	kW/m	20		
Max current	A	2	1	~ max B-factory current, HOM in component HERA 0.15 A (?) RHIC 0.3 A
RF frequency	GHz	1.5	1.5	Needs gap?
Bench length	mm	5	5	6 mm demonstrated in B-factory, 10 cm in RHIC (?)
IP to front face of 1st quad	m	+/- 3 to 4	+/- 7	
Vertical β*	cm	2	2	Keep β_{max} below 2 km
Crossing angle	mrad	100		50 to 150 desired for detector advantages

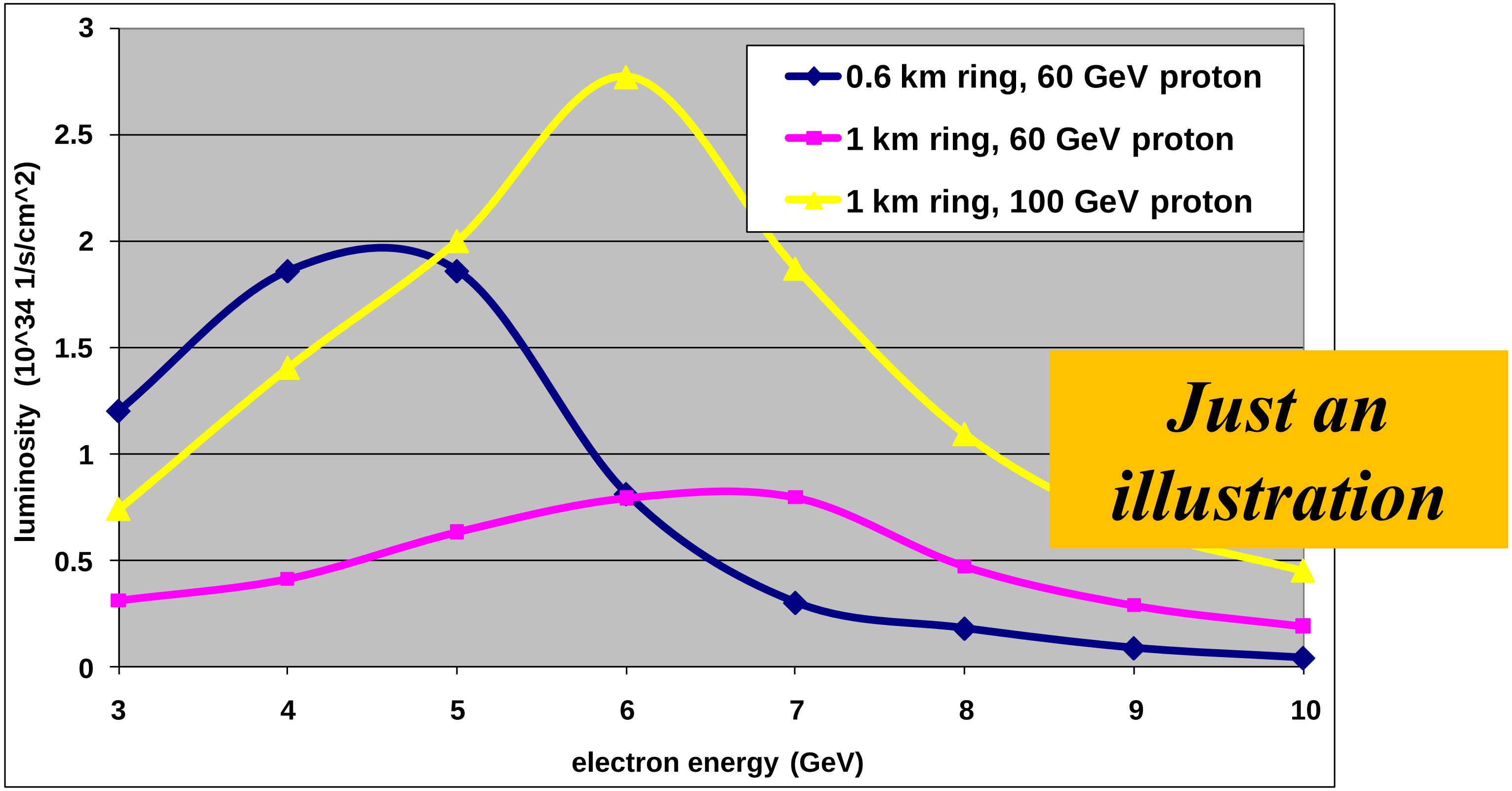
Luminosity can reach up to 0.5 ~ 1 x 10^{34} s^{-1} cm^{-2} around 60x5 GeV^2

MEIC Machine Design Path Forward

- Design "contract" : Scaled down parameters (Feb. 2010)
- Collider Design Review Retreat (March 2, 2010)
- Design Week (March 4, 5 & 7, 2010)
  - Identify major components and determine level of details
  - Farm out tasks and set up collaborations
  - Produce a design manual
- Next level design (By June 1, 2010)
  - Complete the optics design (base for many simulations)
  - Conceptual design of major components (and parameter)
  - Design modification with input from User Workshops
- JLab internal reviews (around June 1, 2010)
  - Accelerator design review (3 to 5 expert panel)
  - Machine cost review
- First round detailed studies with simulations (By Sept. 1, 2010)
  - Present a reasonably detailed design in the next EICC AC meeting
  - Produce an intermediate design report
  - Advance to the next design iteration

MEIC Luminosity

- Back-of-envelope calculation, based on three main parameter limits
- Luminosity of 60 GeV protons in 1 km ring is lower than that in 0.6 km ring, since space charge effect is more servere in a large ring
- Luminosity of 100 GeV protons is much better since space charge effect is reduced with higher energy



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

- ELIC is designed to collide a wide variety of polarized light ions and unpolarized heavy ions with polarized electrons (or positrons).
- The conceptual design takes advantages of a polarized high repetition CW electron beam from CEBAF, a new ion storage complex and new collider rings, provides opportunity of ultra high luminosity of electron-ion collisions and high beam polarization.
- Present ELIC version covers an energy range up to s~1000 GeV^2 with luminosity up 10^{34} $cm^{-2}s^{-1}$. An upgrade path to higher energies (up to 250 GeV protons and associated energy for ions) has been developed which should provide luminosity close to 10^{35} $cm^{-2}s^{-1}$
- MEIC design is very flexible in matching the physics requirements on energy range. The associated machine cost adjustment is moderate.
- A scaled down version of MEIC parameters has been developed recently as the near term design goal, using as much as possible state-of-art technologies, thus requiring minimum R&D efforts. It was estimated that MEIC with this scaled down parameters is still able to deliver maximum luminosity above $5x10^{33}$ $cm^{-2}s^{-1}$.

EIC Parameters (Nov. 2, 2010)

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

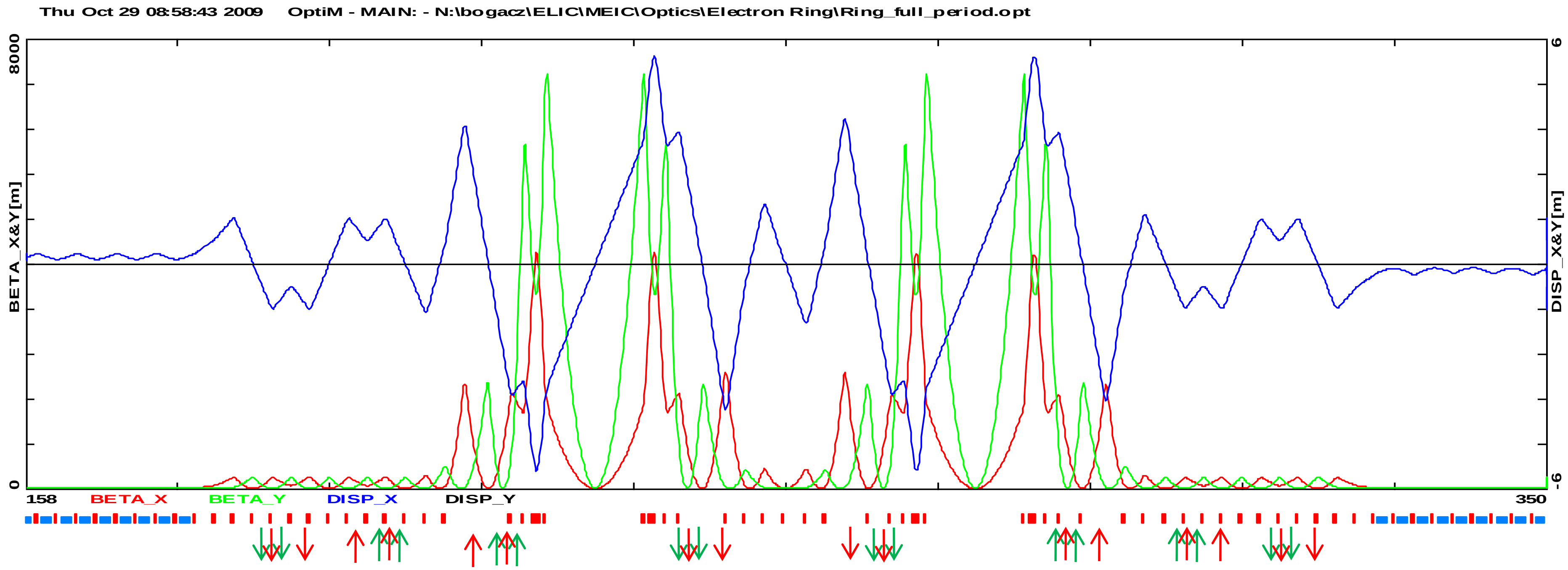
MEIC (e/A) Design Parameters

Ion	Max Energy ($E_{i,max}$)	Luminosity (3 GeV x $E_{i,max}$)	Luminosity (3 GeV x $E_{i,max}$/5)
	(GeV/nucleon)	10^{34} cm^{-2} s^{-1}	10^{33} cm^{-2} s^{-1}
Proton	60	4.0	8.0
Deuteron	30	4.0	8.0
$^{3}H^{+1}$	20	4.0	8.0
$^{3}He^{+2}$	40	2.0	4.0
$^{4}He^{+2}$	30	2.0	4.0
$^{12}C^{+6}$	30	0.67	1.3
$^{40}Ca^{+20}$	30	0.2	0.4
$^{208}Pb^{+82}$	24	0.05	0.1

*** Luminosity calculated by nucleus number, per IP**

IR – Chromaticity Compensation

Uncompensated dispersion pattern coming out of the Arc



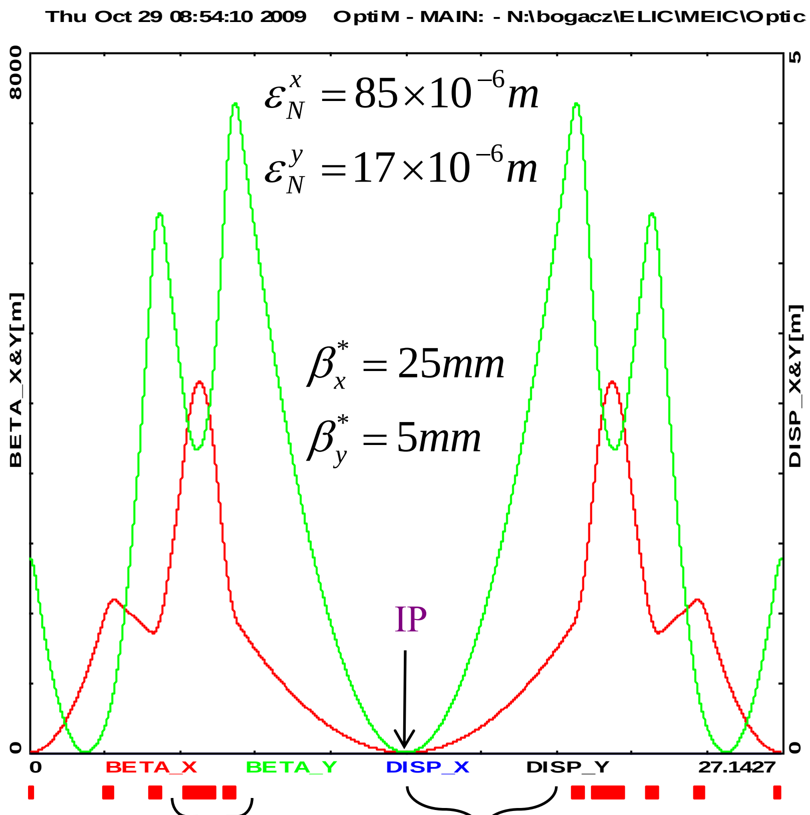
Natural Chromaticity: $\zeta_x = -650$ $\zeta_y = -990$

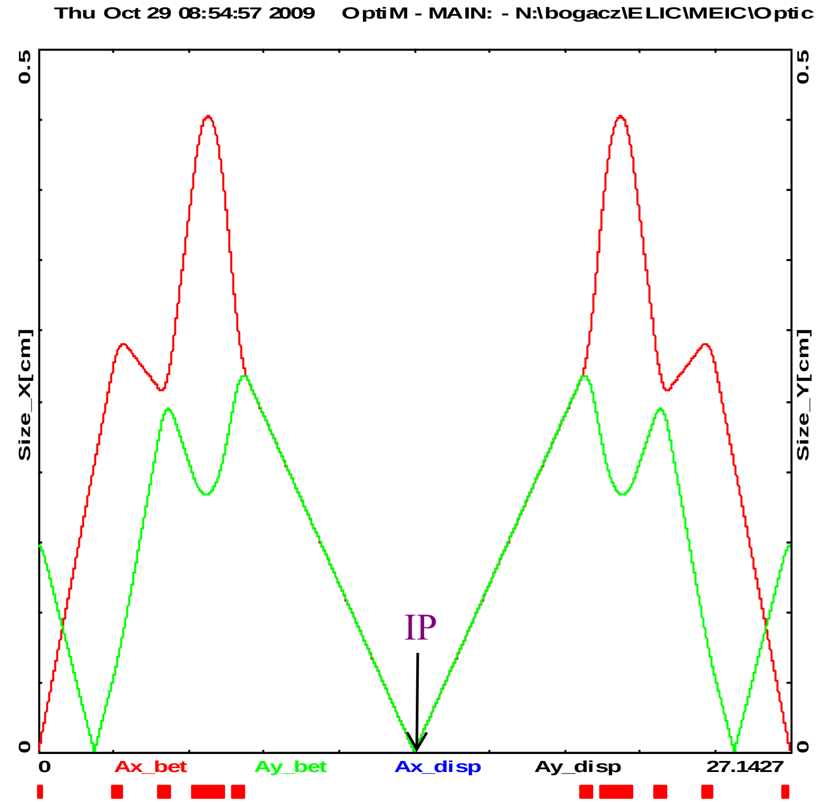
$$\zeta_{sext} = \frac{1}{4\pi} \sum_{sext} \beta\ \eta_0 g_1^{sext}$$

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

Interaction Region Optics

vertical focusing first





FF triplet : Q3 Q2 Q1

$\ell^* = 6$ m

$\ell^* = 6$ m

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

Natural Chromaticity: ζ_x=-305 ζ_y=-425

Accelerator R&D

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

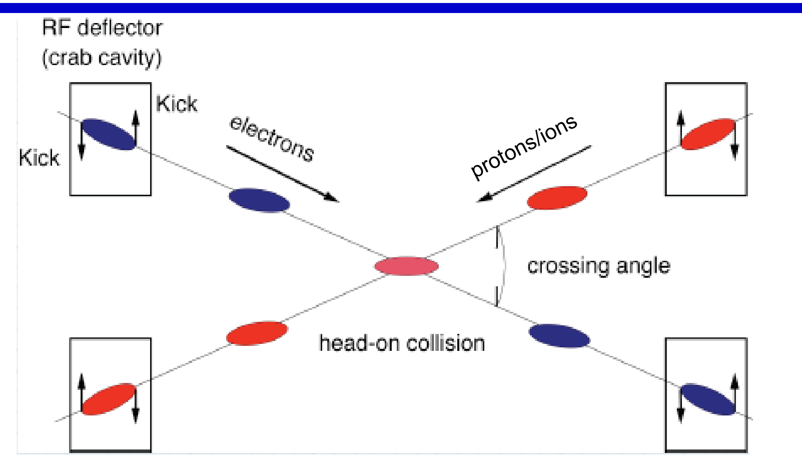
Crab Crossing & Crab Cavity

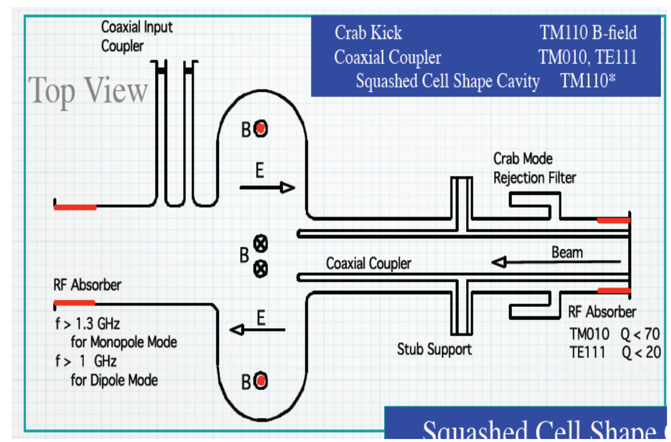
- High repetition rate requires crossing beams to avoid parasitic beam-beam collisions
- Crab crossing is needed to restore head-on collision and avoid luminosity reduction
- ELIC crossing angle: ~ 2x25 mrad (6+6 m IR)
- Dispersive crabbing is another possibility

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

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



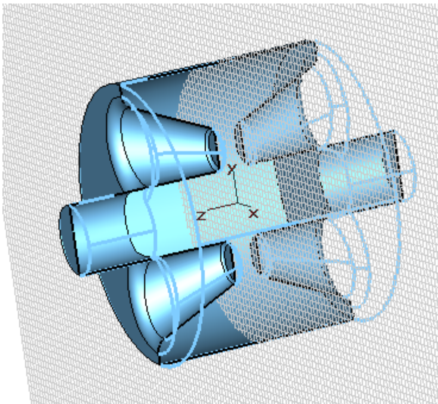


State-of-the-art:

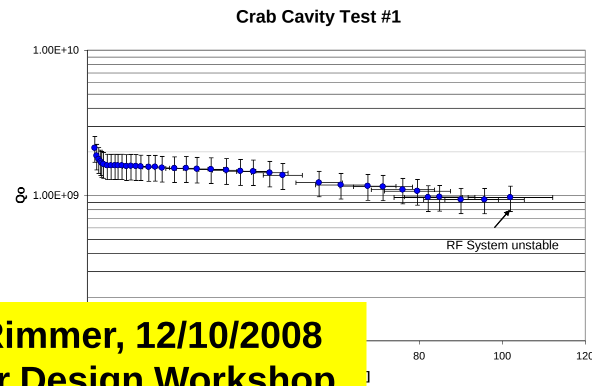
KEKB Squashed cell@TM110 Mode
Crossing angle = 2 x 11 mrad
V_{kick}=1.4 MV, E_{sp}= 21 MV/m

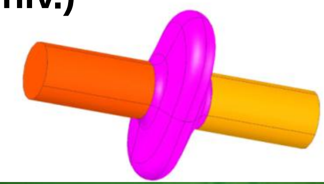
JLab Crab Cavity Development

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

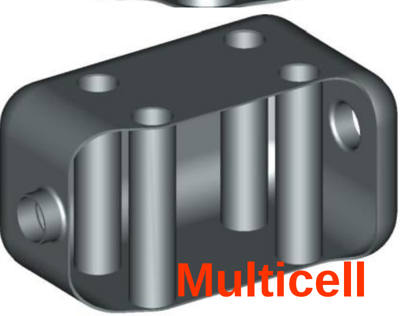


Elliptical squashed SRF cavity R&D for APS (JLab/LBNL/AL/Tsinghua Univ.)





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



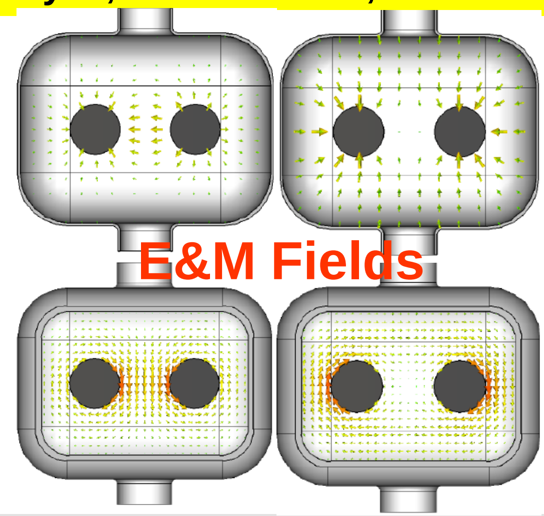
New (Innovative) Program

- 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



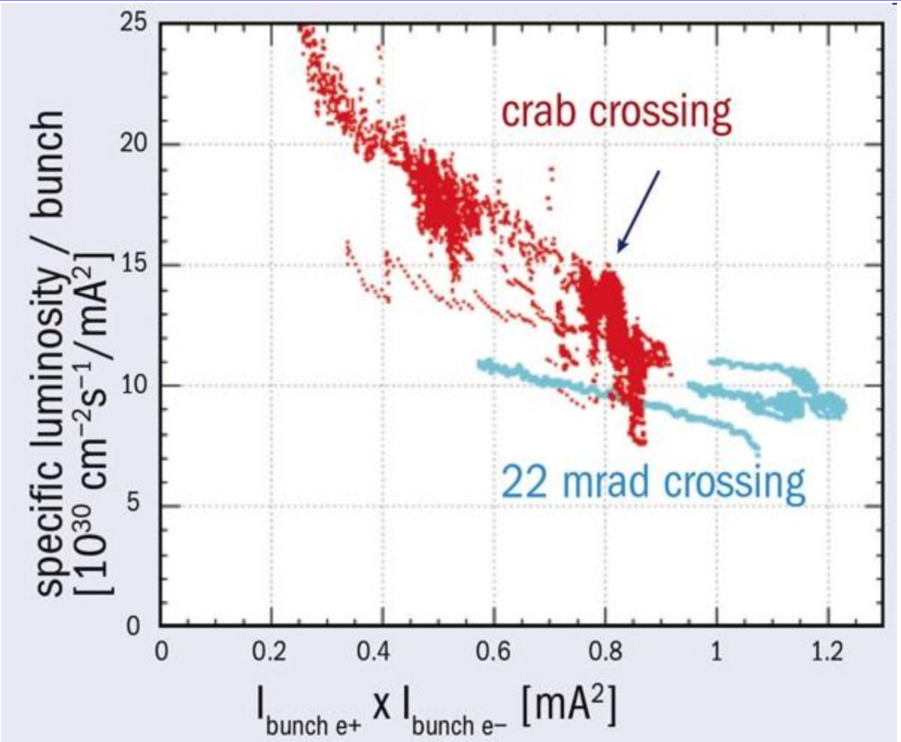
News From KEK

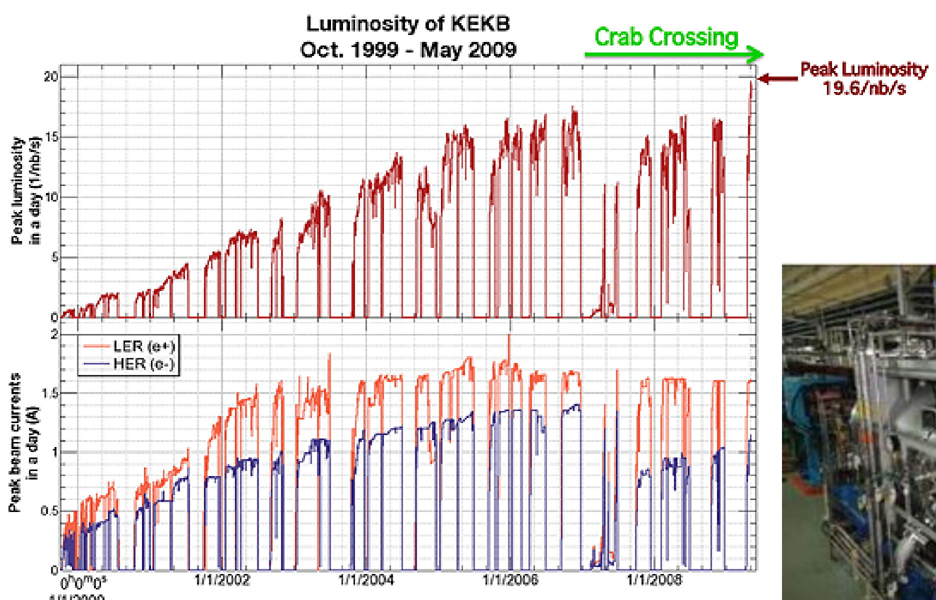
KEK Press Release (05/11/09)

"Using Crab Cavities, KEKB Breaks Luminosity World Record"

Symmetry *Breaking* (05/11/09)

"Record luminosity collisions due to "crab" crossing,



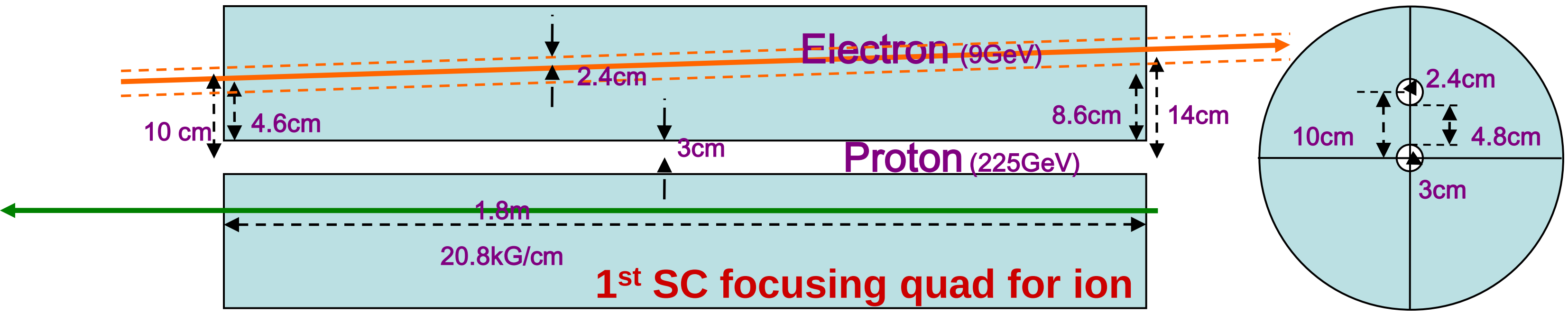


IR Final Quad

Optimization

- IP configuration optimization
- "Lambertson"-type final focusing quad

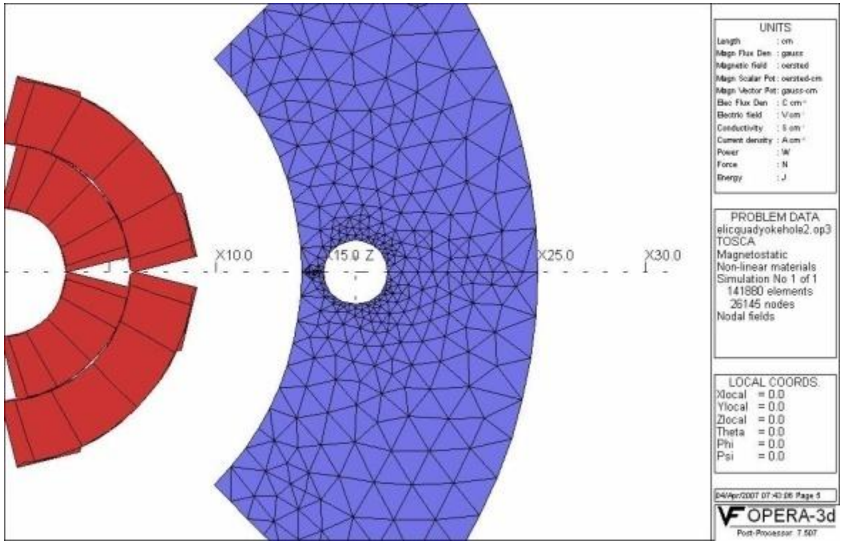
➔ angle reduction: 100 *mrad* ➔ 22 *mrad*



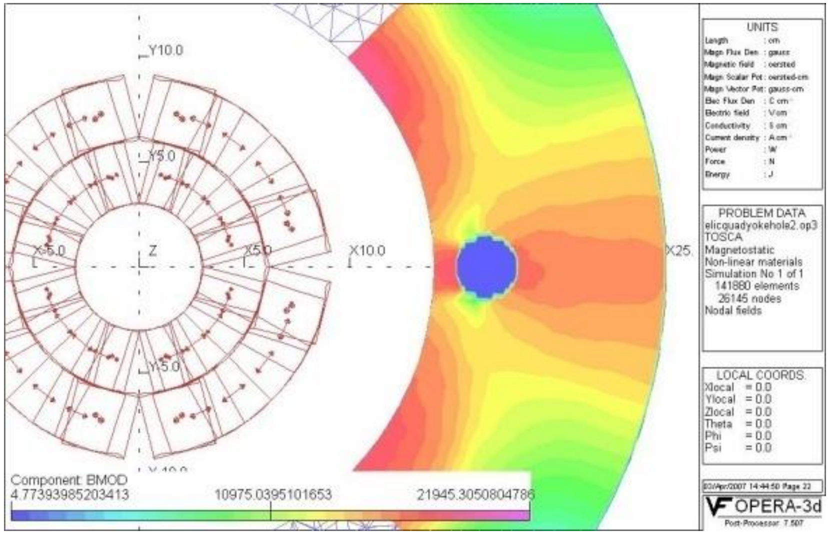
Paul Brindza

Lambertson Magnet Design

Cross section of quad with beam passing through



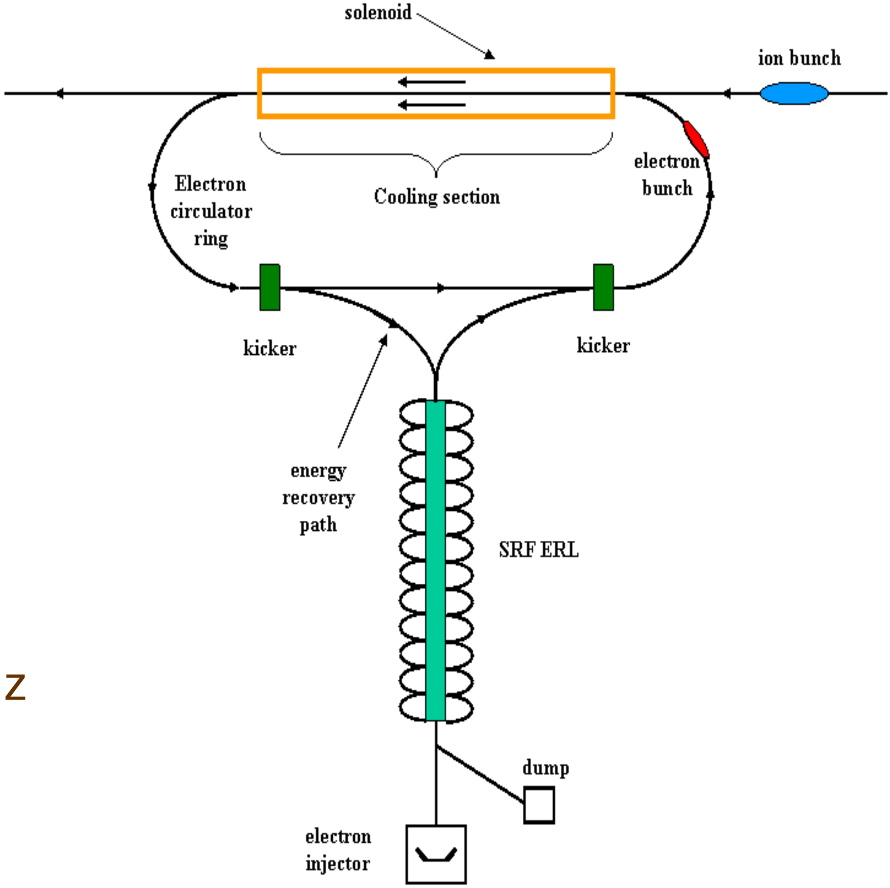
magnetic Field in cold yoke around electron pass.



Circulator Ring Electron Cooling

.Effective for heavy ions (higher cooling rate), difficult for protons.

- State-of-Art
  - Fermilab electron cooling demonstration (4.34 MeV, 0.5 A DC)
  - Feasibility of EC with bunched beams remains to be demonstrated



- ELIC Circulator Cooler
  - 3 A CW electron beam, up to 125 MeV
  - SRF ERL provides 30 mA CW beam
  - Circulator cooler for reducing average current from source/ERL
  - Electron bunches circulate 100 times in a ring while cooling ion beam
  - Fast (300 ps) kicker operating at 15 MHz rep. rate to inject/eject bunches into/out circulator-cooler ring

Luminosity for 11 GeV electrons

- **Present ELIC design**
  - Energy range: up to 11x60 GeV
  - 640 m ring (170 m per arc, 150 m par straight)
  - Luminosity peaks at 3GeV electron energy

- **This new exercise**
  - Energy range: up to 11x115 GeV
  - 988 m ring (330m pare arc, 150 m par straight)
  - Luminosity peaks at 6 GeV electron energy

- **Cost impact**
  - Present design: $650M (2009), with roughly $150M for collider rings
  - New exercise, doubled arc length, so add another $100M to $120M, making total cost $750M to $800M, to the first order

MEIC Luminosity