Electron-Ion Collider – Jefferson Lab Design

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for JLab EIC Study Group

Physics at a High Energy Electron Ion Collider, INT,

Seattle, October 19, 2009

Outline

- Project Highlights
- Project Status

  Design, luminosity concept, key enabling technologies
- Critical R&D

  Issues, state-of-art, program and progress
- Path forward

  Accelerator R&D; Science program; detector & IR
- Summary

EIC: JLab's Future for a World Class Nuclear Science Program

For the last decade…

- JLab has been engaged in a conceptual design and R&D for an EIC based on a green-field ion complex and on the 12 GeV CEBAF (up to 250 x 11 GeV).

- From the very beginning, our design efforts have focused on achieving unprecedently high luminosity (up to **10^{35}**) over multiple detectors and very high polarization (**>80%**) for both electron and light ion beams.

For the last year…

- We have explored a **staged approach** ***to EIC***, *focusing on science cases and accelerator* designs for a **low-to-medium energy EIC** with similar design features (high luminosity, polarization, multiple detectors).

Medium Energy EIC Efforts at JLab

- At present, we regard a high luminosity low-to-medium energy EIC (up to 60 x 11 GeV) as the **next goal** for the EIC project at Jefferson Lab, and will keep the full energy EIC (250 x 11 GeV) as a future upgrade option.

- A low-to-medium energy **staged EIC** provides not only a very rich and broad science program, but also a nicer balance between new science, detector & accelerator R&D, and project cost.

- We have developed a conceptual design of a low-to-medium energy EIC based on CEBAF, and have therefore reduced the detector and accelerator technology R&D significantly, yielding a large cost saving compared to the full energy collider.

- We are now engaged in development of science cases, key experiments, design optimizations and aggressive R&D for enabling technologies.

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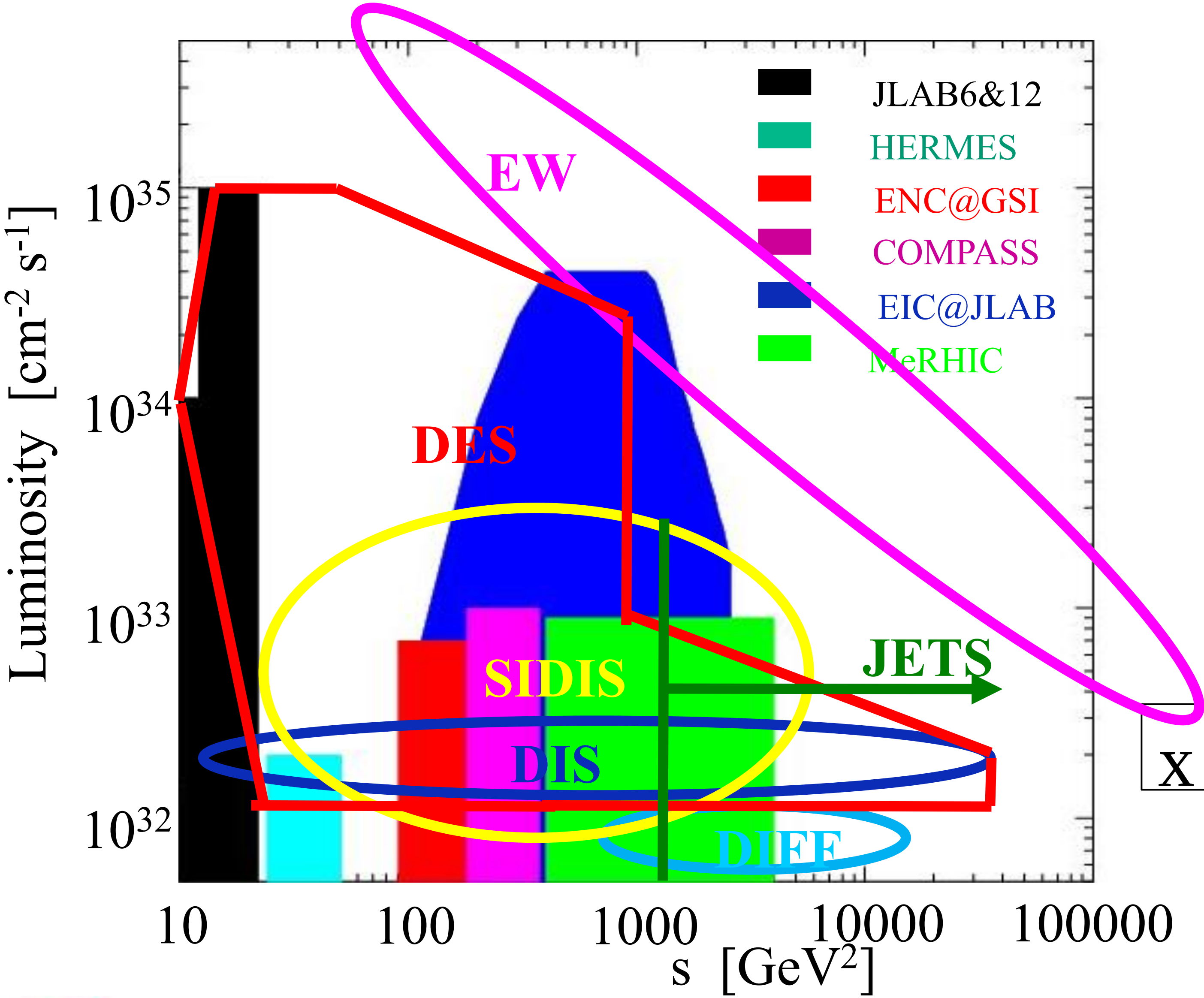
Science Driven Machine Design

- Key issues in **Nucleon Structure** & Nuclear Physics
  - Sea quark and gluon imaging of nucleon 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
  - High luminosity > 10^{34}: Low rates, differential measurements
  - CM energy s~1000 GeV^2: Reach in Q^2, x
  - Detectability: Angular coverage, particle ID, energy resolution

➔ **favors lower, more symmetric energies!**

Science Matrix



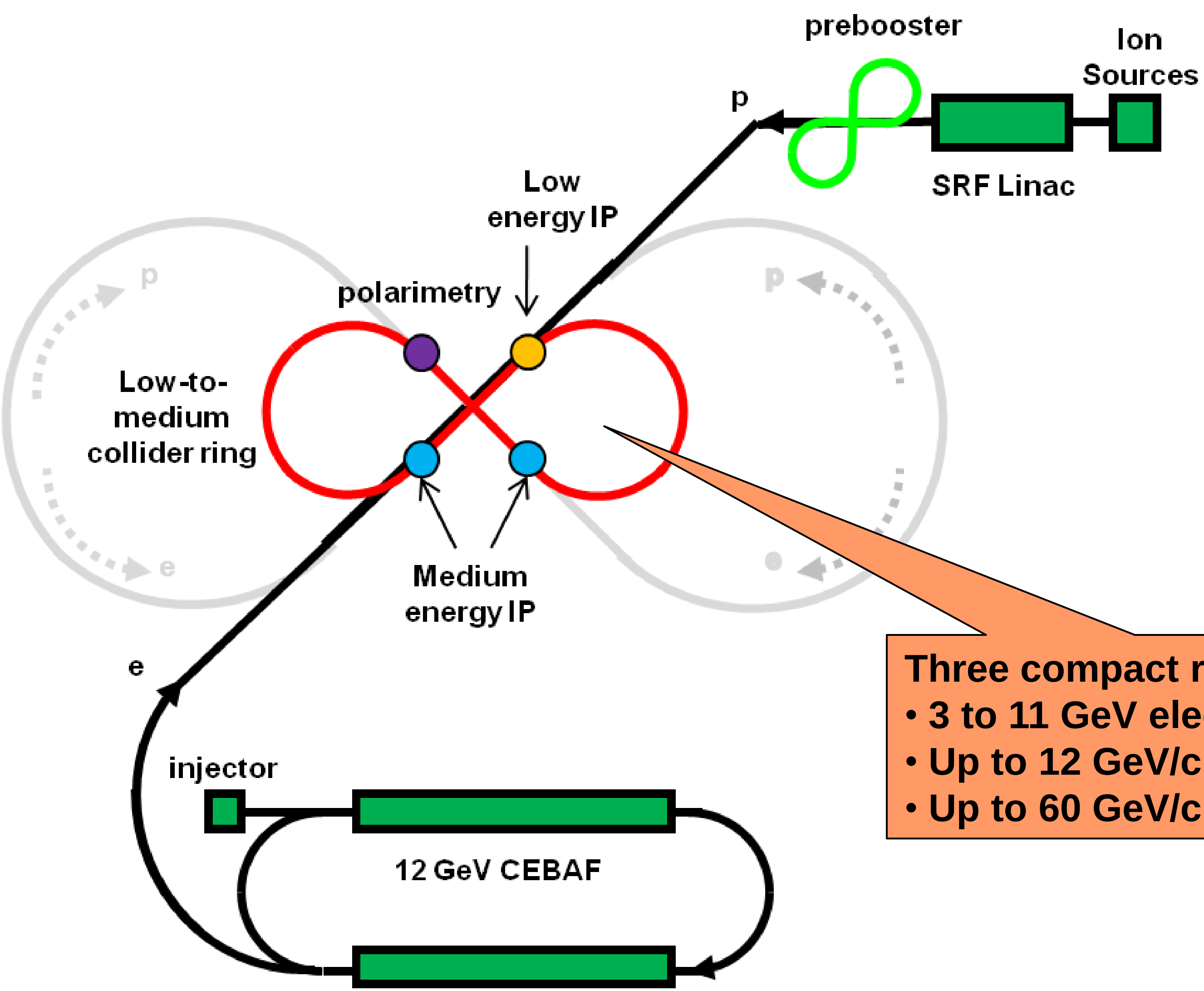
$x \sim Q^2/ys$

R. Ent

EIC@JLab – Design Goals

- **Energy (**wide CM energy range between 10 GeV and 100 GeV)
  - Low energy: 3 to 11 GeV e on 12 GeV/c p (and ion)
  - Medium energy: up to 11 GeV e on 60 GeV p or 30 GeV/n ion
  - High energy: up to 11 GeV e on 250 GeV p or 100 GeV/n ion
- **Luminosity**
  - up to 10^{35} cm^{-2} s^{-1} per interaction point over a wide range of s values
  - 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 for the electron beam:
    - optional flip for the ions – it would require bunched beams from the very source
  - All polarizations >80% desirable
- **Positron Beam** desirable

EIC@Jlab – Conceptual Layout



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

EIC@Jlab – Collider Rings

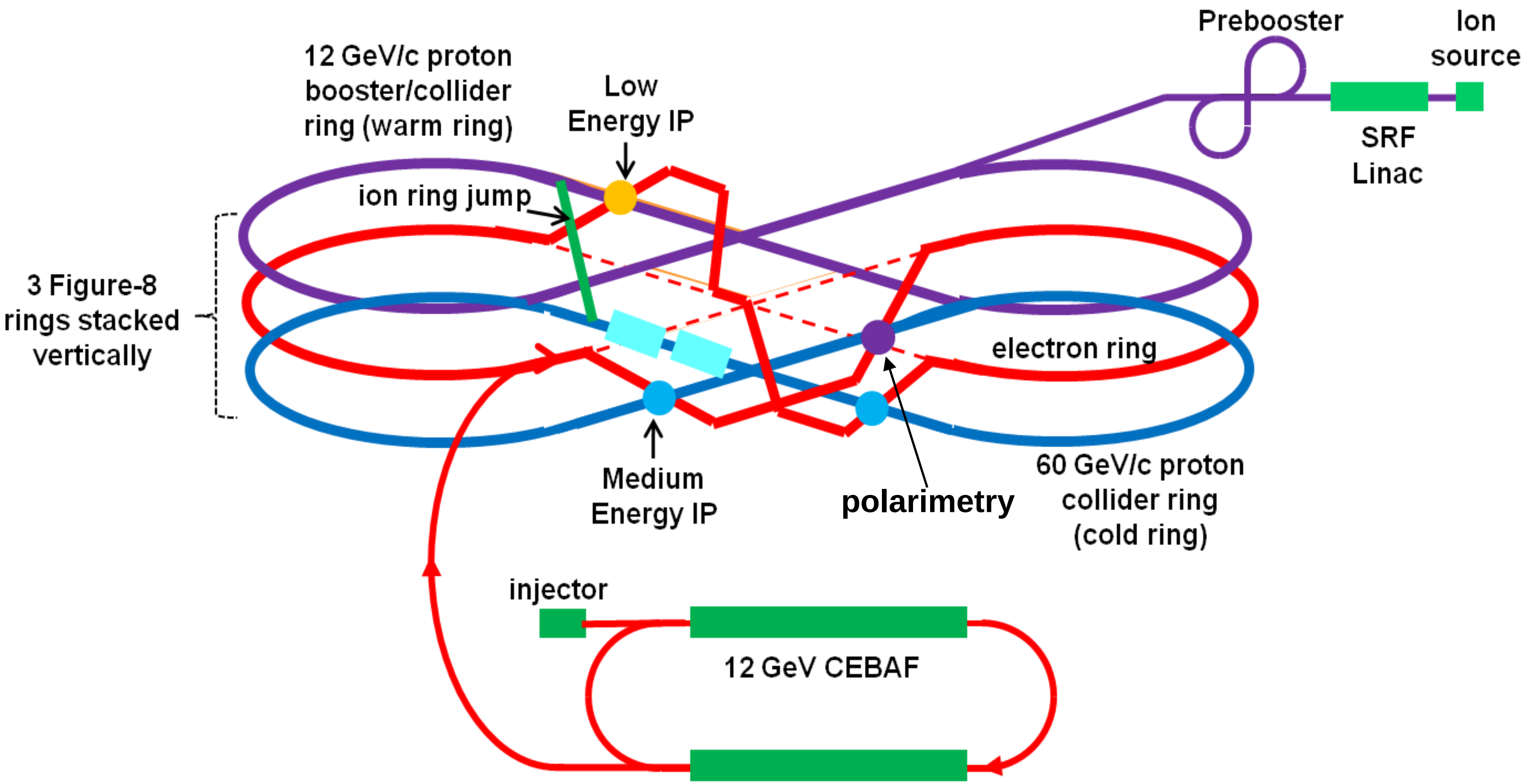
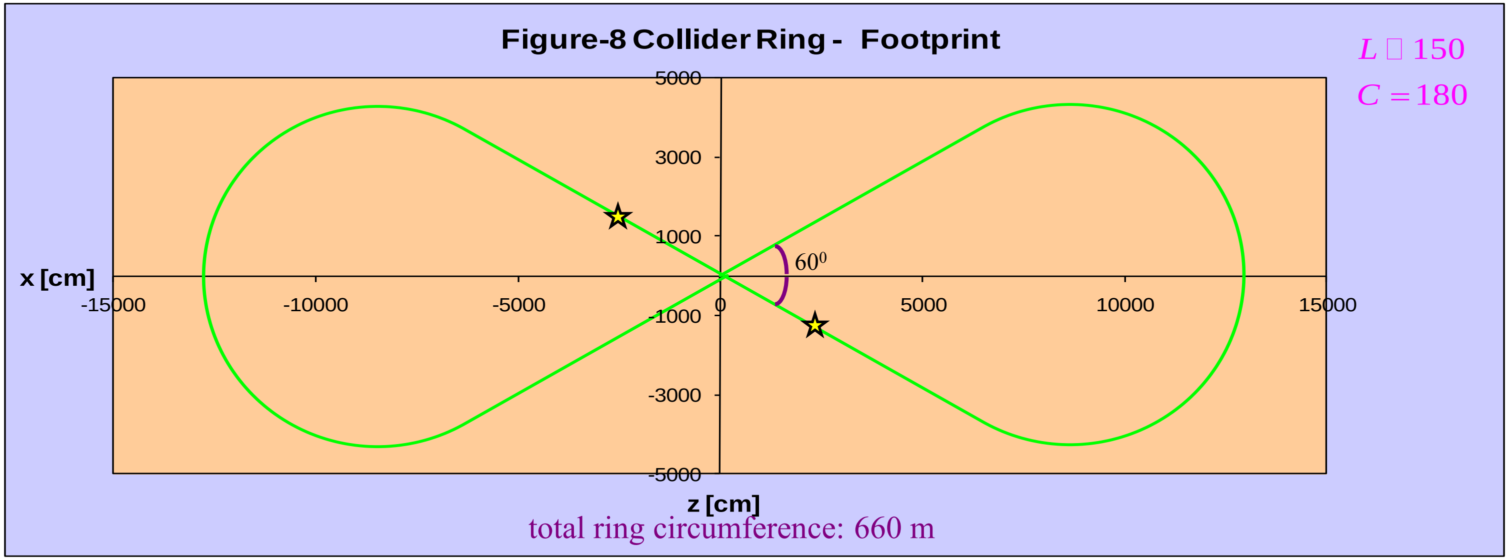
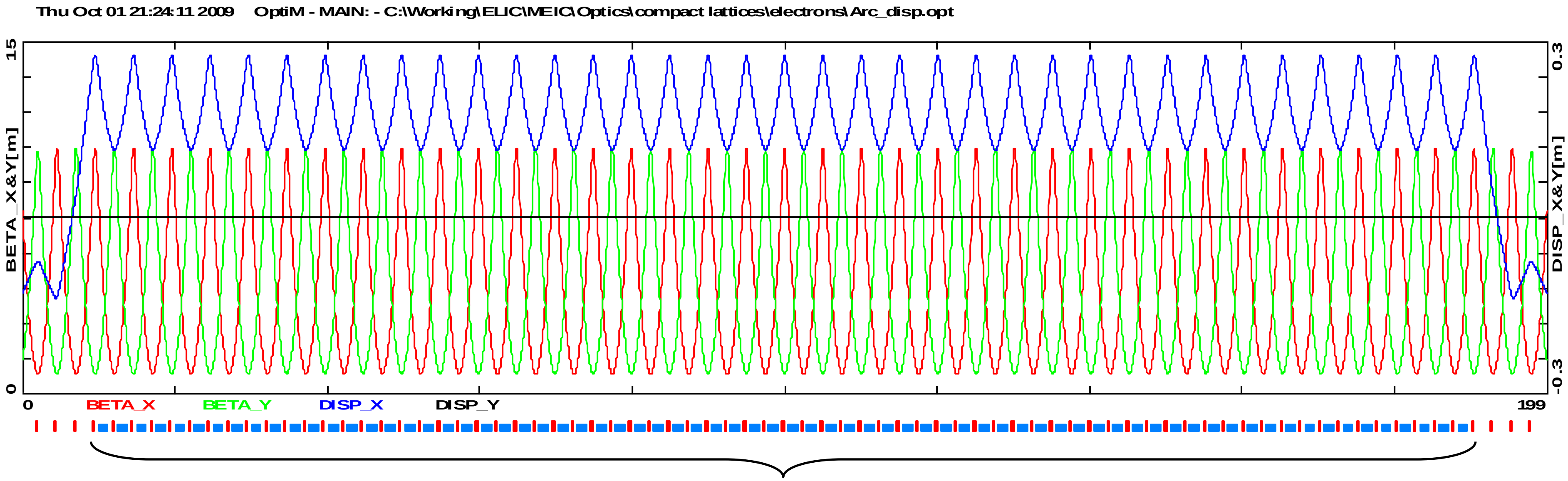


Figure-8 Compact Collider Ring



- Collider Ring design is a compromise between:
  - Minimizing synchrotron radiation effects ➔ prefers a large size ring
  - Space charge effect of ion beam ➔ prefers a compact ring
- Multiple IPs require long straight sections to hold required functional components, such as: matching quads, electron cooling, injection and ejection inserts, etc.

MEIC Figure-8 Electron Ring Optics



36 FODO cells, B, total arc length: 180 m
phase adv./cell ($\Delta\phi_{x,y}$= 120^0)

11 GeV

Dipoles

$Lb=150 cm

$B=**11.6** kG.

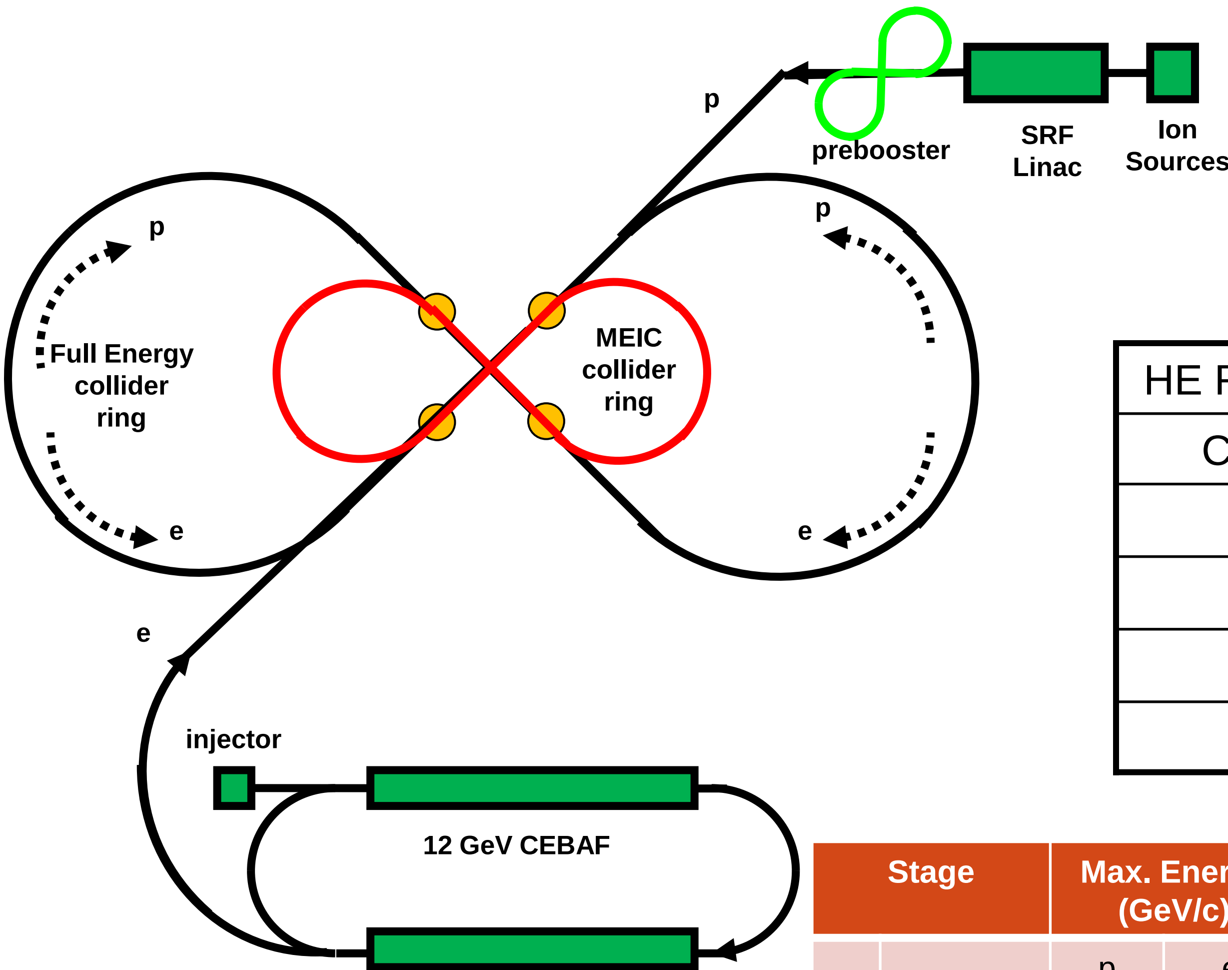
Quadrupoles

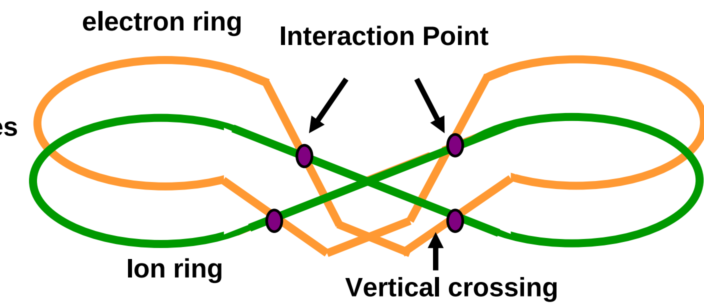
$Lq=50 cm

$G= **4.5** kG/cm

- Minimized emittance dilution due to quantum excitations
- Limited synchrotron radiated power (14.3MW (total) @ 1.85A)
- Quasi isochronous arc to alleviate bunch lengthening (α~10^{-5})
- Dispersion pattern optimized for chromaticity compensation with sextupoles

Going to High Energy





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

Stage		Max. Energy (GeV/c)		Ring Size (m)		Ring Type		IP #
		p	e	p	e	p	e	
1	Low	12	5 (11)	630	630	Warm	Warm	1
2	Medium	60	5 (11)	630	630	Cold	Warm	2
3	High	250	11	1800	1800	Cold	Warm	4

Achieving High Luminosity

EIC at JLab design luminosity

$L \sim 4 \times 10^{34}\ cm^{-2}\ s^{-1}$ for (60 GeV x 3 GeV at 0.5 GHz)

$L \sim 1 \times 10^{35}\ cm^{-2}\ s^{-1}$ 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)
- Short ion bunches ($\sigma_z \sim 5$ mm)
- Strong final focusing ($\beta^*_x \sim 25$ mm, $\beta^*_y \sim 5$ mm)
- Large beam-beam parameters
- Need for crab crossing of colliding beams (dispersive crabbing)

Keys to implement these concepts

- Making very short ion bunches with small emittance (but small bunch charge)
- **SRF ion linac** (a la ProjectX) and **electron cooling**

Additional ideas/concepts

- Long bunch, compared to β^*, for very low ion energy – travelling focusing
- Large synchrotron tunes to suppress synchrotron-betatron resonances
- Global chromaticity compensation for a pair of IPs via highly symmetric Optics

EIC@JLab Parameters

		Low energy	Medium energy		High energy
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	0.8/75	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 Lumi/IP, 10^{34}	$cm^{-2}s^{-1}$	0.59	1.9	4.0	11

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EIC@JLab Accelerator R&D

We have identified the following critical R&D for EIC at JLab

- Electron cooling
- IR chromaticity corrction
- Crab crossing and crab cavity (dispersive crabbing)
- Forming high intensity low energy ion beam
- Beam-beam effect
- Traveling focusing for very low energy ion beam

Level of R&D	Low-to-Medium Energy (12x3 GeV/c) & (60x5 GeV/c)	High Energy (up to 250x10 GeV)
Challenging	Traveling focusing (for very low i energy)	Electron cooling
Semi Challenging	Electron cooling IP design/chromaticity compensation	Crab crossing/crab cavity
Likely	Crab crossing/crab cavity High intensity low energy i beam Beam-beam	High intensity low energy i beam Beam-beam
Know-how	Spin tracking	Spin tracking IP design/chromaticity

ERL Circulator Cooler

Issues

- Essential for delivering ion bunches with small emittances and short length.
- Cooling electron energy
  - up to 6.5 MeV for low energy EIC
  - up to 33 MeV for medium energy EIC
  - up to 136 MeV for high energy
- Up to 3 A CW un-polarized beam (~nC bunch charge)

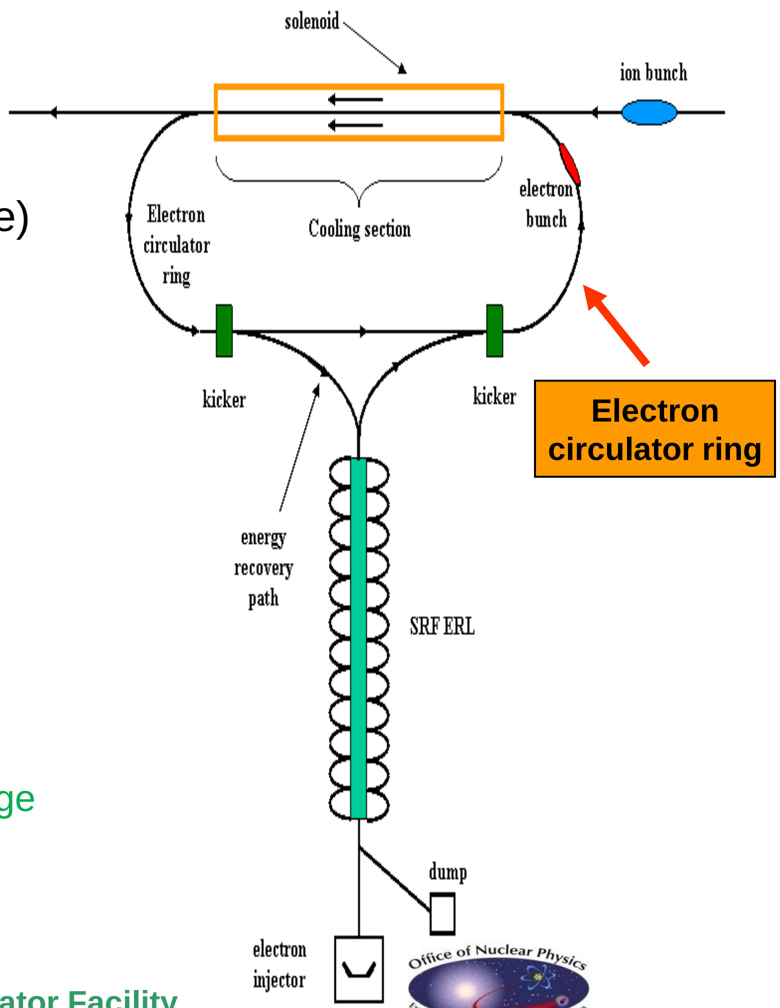
State-of-Art
Fermilab electron cooling demo. (4.34 MeV, 0.5 A DC)

ERL Based Circulator Cooler

- SRF ERL able to provide high average current CW beam with minimum RF power
- Circulator ring for reducing average current from source/ERL

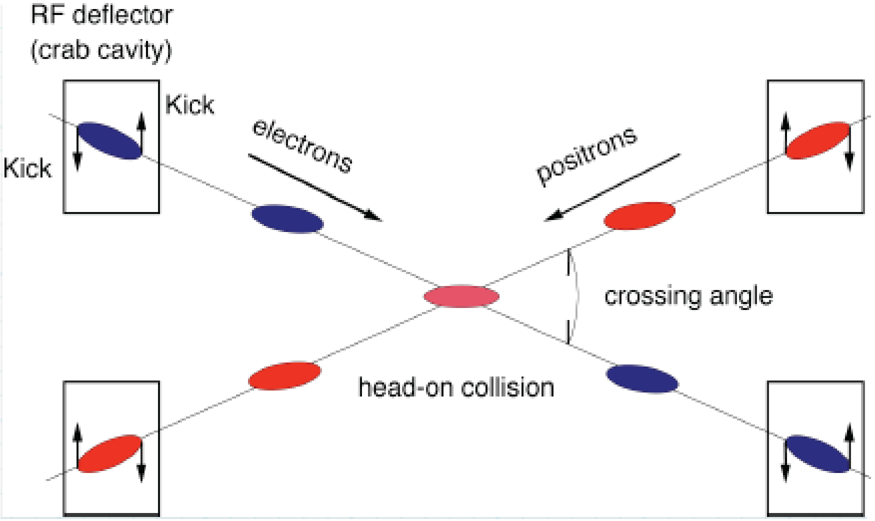
ERL Key technologies

- High intensity un-polarized electron source/injector
  - Jlab FEL gun: 30 mA, up to 33 MeV, 1 nC bunch charge
- Energy Recovery Linac (ERL)
- Fast kicker



Crab Crossing and 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: ~ 2x12 mrad



R. Palmer

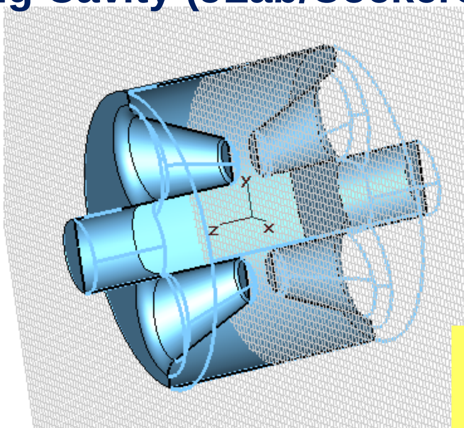
Stage	Beam Energy (GeV/c)	Integrated Kicking Voltage (MV)	R&D
electron	10	~ 1	State-of-art
Proton	12	~ 1	State-of-art
Proton	60	5	Not too far away
Proton	250	21	

State-of-art:

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

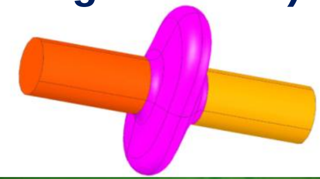
JLab Crab Cavity Development

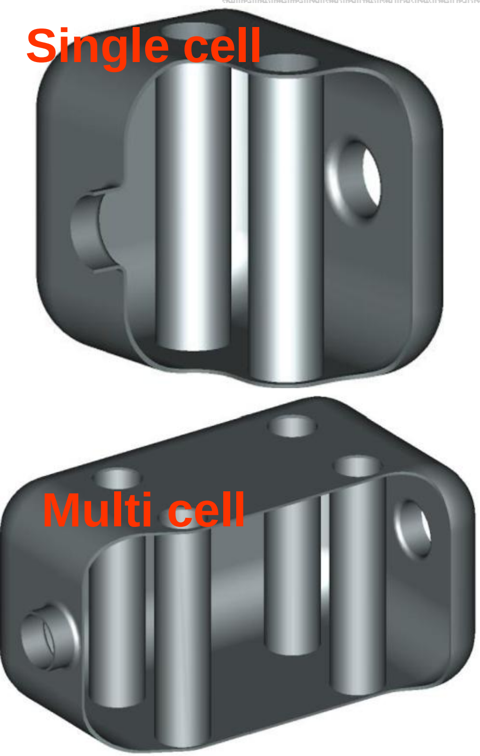
Multi-cell TM110 and Loaded Structure of Crabbing Cavity (JLab/Cockcroft/Lancaster)



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

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



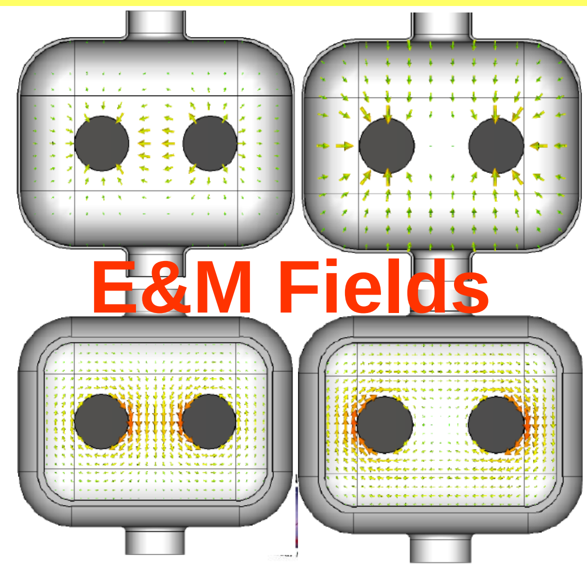


New (Innovative) Program

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

Single cell: 37x50cm, **4 MV@500MHz**

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



Forming High Intensity Ion Beams

	Length (m)	Energy (GeV/c)	Cooling Scheme	Process
Source/SRF linac		0.2		Full stripping
Accumulator-cooler Ring /prebooster	100	3	DC Electron	Stacking/accumulating Energy booster
Low energy ring (booster)	630	12	Electron	Fill ring/Energy boosting RF bunching (for collision)
Medium energy ring (large booster)	630	60	Electron	Energy boosting RF bunching (for collision)
High energy ring	1800	250	Electron	Fill ring/energy boosting RF bunching

Stacking/accumulation process

- Multi-turn (~20) pulse injection from SRF linac into an accumulator-cooler ring
- Damping/cooling of injected beam
- Accumulation of 1 A coasting beam at space charge limited emittence
- Fill prebooster/large booster, then accelerate
- Switch to collider ring for energy booster, RF bunching and initial/continuous cooling

Stacking proton beam in ACR

Circumference	M	100
Arc radius	M	3
Crossing straights length	M	2 x 15
Energy/u	GeV	0.2 -0.4
Electron current	A	1
Electron energy	keV	100-200
Cooling time for protons	Ms	10
Stacked ion current	A	1
Norm. emit. After stacking	µm	16

In addition to simulation studies, we are considering team up with ORNL to study space charge effect at SNS

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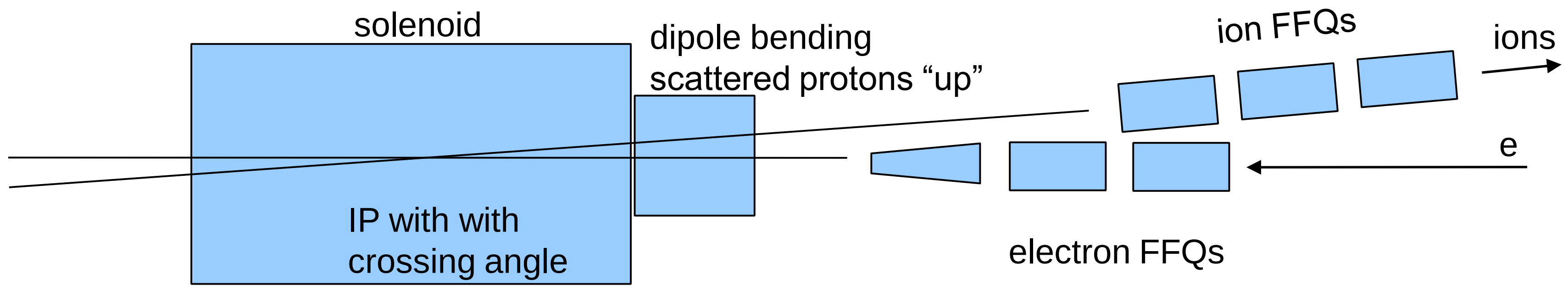
Detector – Interaction Region Layout

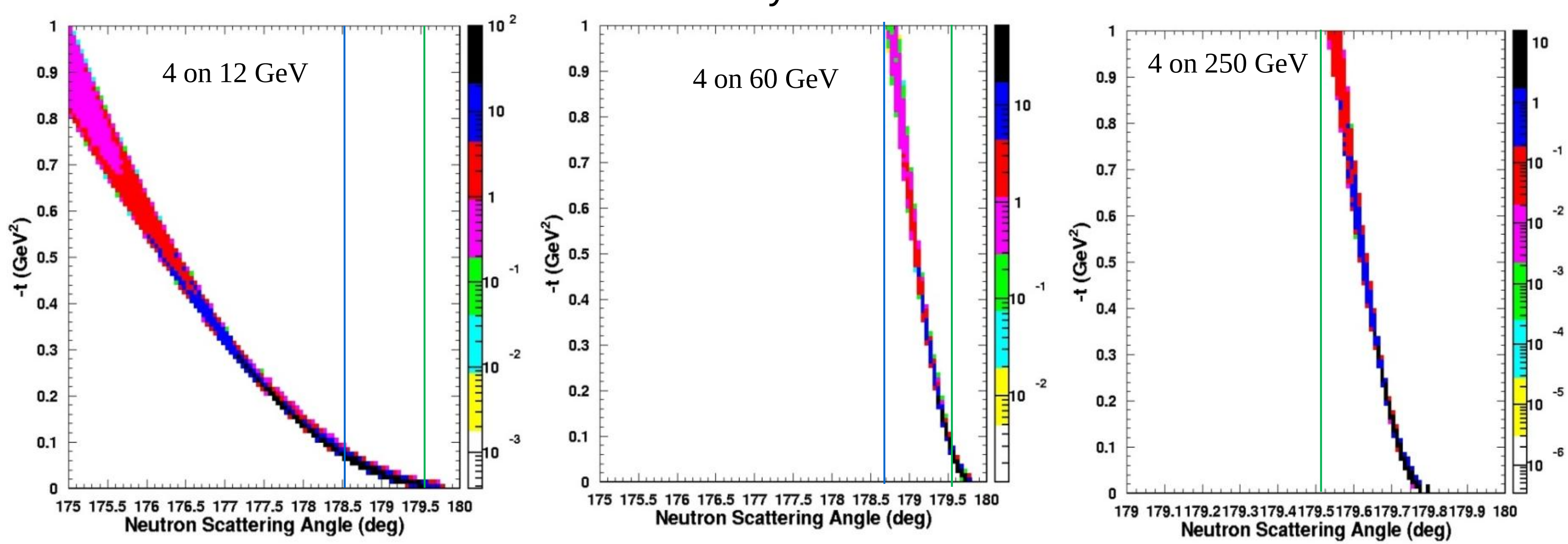
P. Nadel-Turonski



Distance from IP to electron FFQ: 6 m, to ion FFQ: 9m

T. Horn

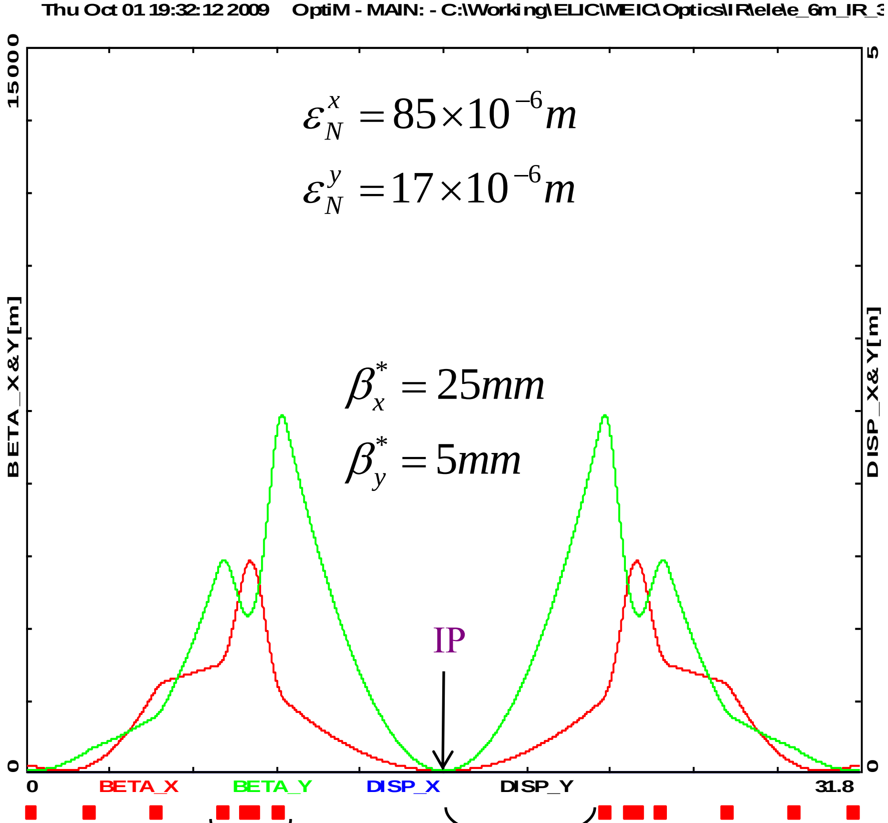
Recoil baryon kinematics



$$ep \rightarrow e'\pi^{+}n$$

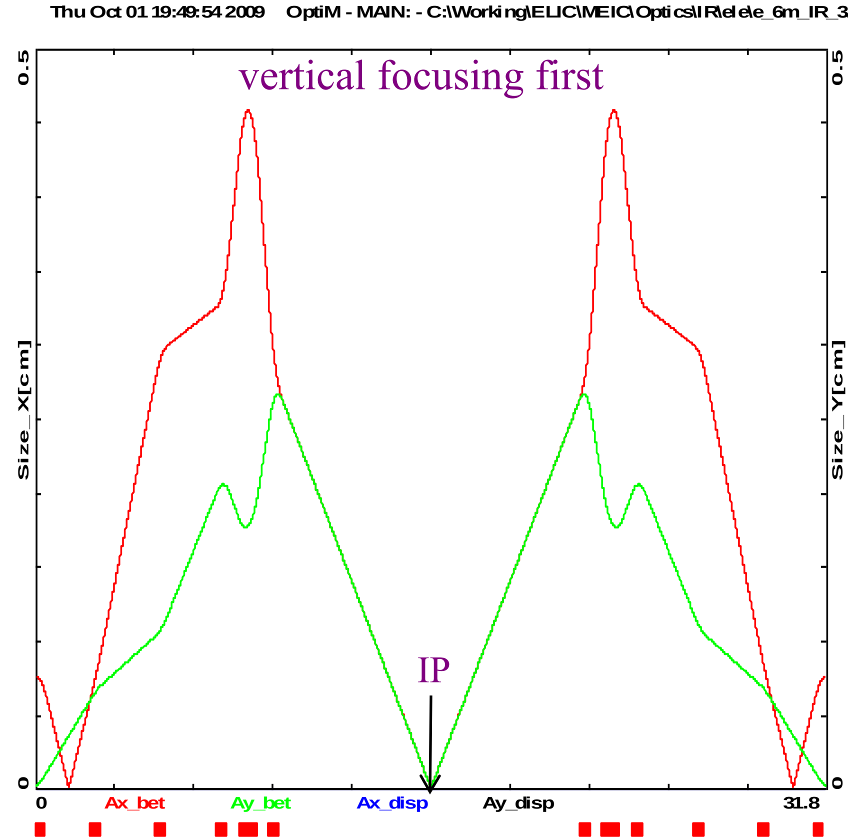
Interaction Region Optics

vertical focusing first



FF triplet : Q3 Q2 Q1

$\ell^* = 6\text{m}$



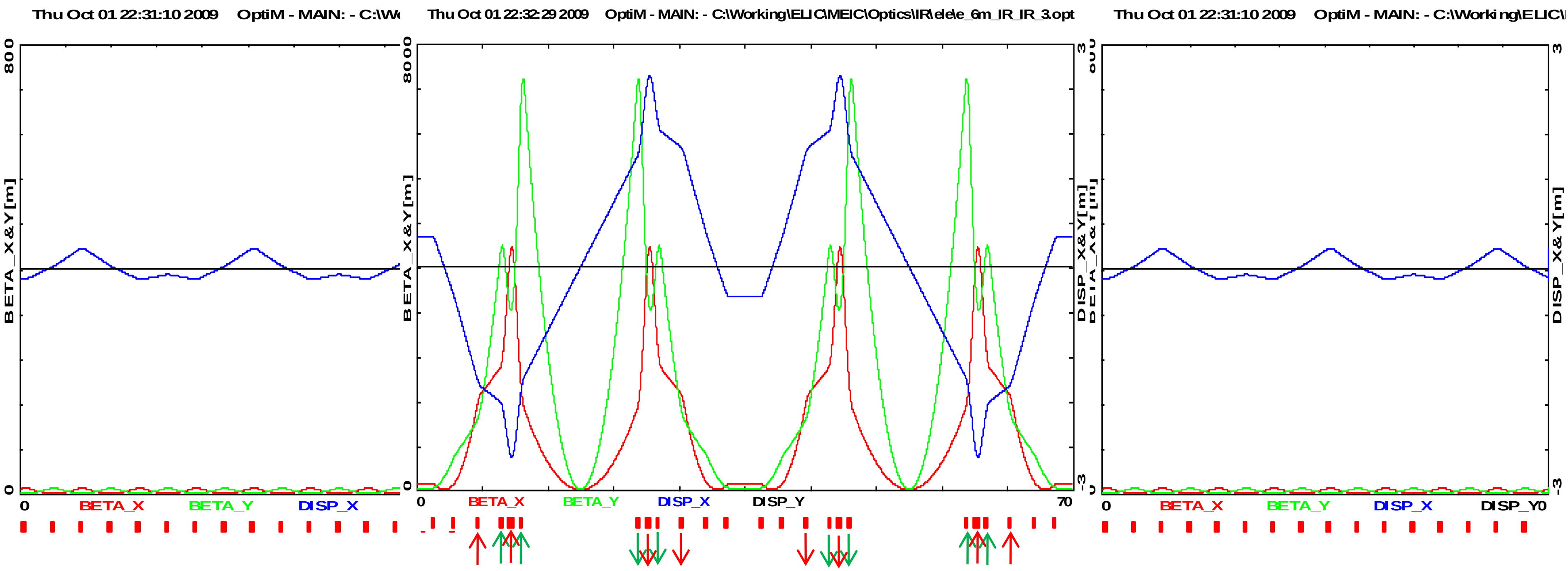
$\ell^* = 6\text{m}$

Q1	G[kG/cm] = -3.4
Q2	G[kG/cm] = 3.1
Q3	G[kG/cm] = -2.6

Natural Chromaticity: ζ_x=-299 ζ_y=-448

IR – Chromaticity Compensation

Uncompensated dispersion pattern coming out of the Arc



$$\zeta^{IR}_{x,y} \approx -\frac{1}{4\pi}\sum_i \beta^i_{x,y}\int g^i_0\, ds = -\frac{1}{4\pi}\sum_i \beta^i_{x,y} k^i_1$$

$$k_1 = \frac{1}{B\rho}\int \frac{\partial B_y}{\partial x}\, dl = \frac{e}{pc}\int \frac{\partial B_y}{\partial x}\, dl\ [m^{-1}]$$

Natural Chromaticity: ζ_x=-592 ζ_y=-881

horizontal

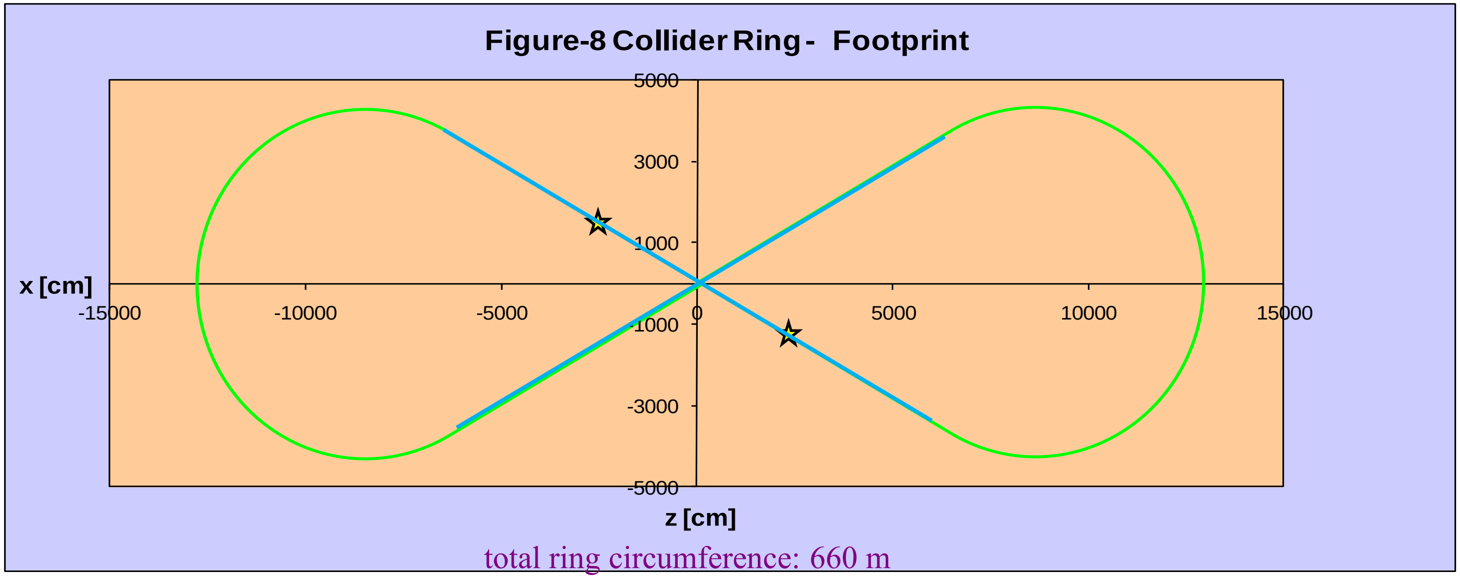
N	Beta [m]	Disp[m]
4.00	4360.00	2.80
4.00	1850.00	1.50

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

vertical

N	Beta [m]	Disp[m]
4.00	7400.00	1.00
4.00	4400.00	2.00

Natural Chromaticity Compensation



Natural Chromaticity: ζ_x=-649 ζ_y=-959

horizontal

N	Beta [m]	Disp[m]	g1 [m-2]	ksi
4.00	4360.00	2.80	0.14	544.05
4.00	1850.00	1.50	0.11	98.93
36.00	10.00	0.28	0.30	2.41
26.00	10.00	0.30	0.30	1.86
				649.65

vertical

N	Beta [m]	Disp[m]	g1 [m-2]	ksi
4.00	7400.00	1.00	0.19	447.56
4.00	4400.00	2.00	0.18	508.98
36.00	10.00	0.12	0.30	1.03
26.00	10.00	0.10	0.30	0.62
				959.22

Summary

- An electron-ion collider at JLab promises to accelerate and store a wide variety of polarized light ions and un-polarized heavy ions in collision with polarized electron or positron beam 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 50 GeV) is our **immediate goal & R&D focus.**

- The collider luminosity for *e-p* collisions should reach **4×10^{34} cm^{-2}s^{-1} at (60x3~5^2 GeV^2),** and 6×10^{33} cm^{-2}s^{-1} at lower energies (12x3 GeV^2).

- 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 a key in order to implementing these advanced concepts, and electron cooling is absolutely essential for cooling and bunching the ion beams.

- We have identified the critical accelerator R&D topics for our project. R&D for the medium energy EIC is usually much easy than for the high energy one, providing a nice staging for R&D work too. We are aggressively pushing R&D programs to complete, validate, and optimize our design.

EIC is the future of nuclear physics at JLab!

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, M. Tiefenback, H. Wang, C. Weiss, B. Wojtsekhowski, B. Yunn, Y. Zhang - Jefferson Laboratory staffs and users

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V. Dudnikov - Brookhaven Technology Group

P. Ostroumov - Argonne National Laboratory

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V. Shemelin - Cornell University

Backup Slides

EIC Ring-Ring Design Features

- Up to four IPs (detectors) for high science productivity
- "*Figure-8*" ion and lepton storage rings
  - Ensure spin preservation and ease of spin manipulation
  - No spin sensitivity to energy for all species.
- Present CEBAF injector meets storage-ring requirements
- 12 GeV CEBAF can serve as a full energy injector to electron ring
- *Simultaneous* operation of collider & CEBAF fixed target program.
- Experiments with polarized positron beam are possible with addition of positron source.

ELIC Baseline Design Choice

- Energy Recovery Linac-Storage-Ring (ERL-R)
- ERL with Circulator Ring – Storage Ring (CR-R)
- Back to Ring-Ring (R-R)

  by taking CEBAF advantage as full energy polarized injector

- Reason of design change:

  High current polarized electron/positron source R&D too challenging

  - ERL-Ring: 2.5 A
  - Circulator ring: 20 mA
  - State-of-art: 0.1 mA

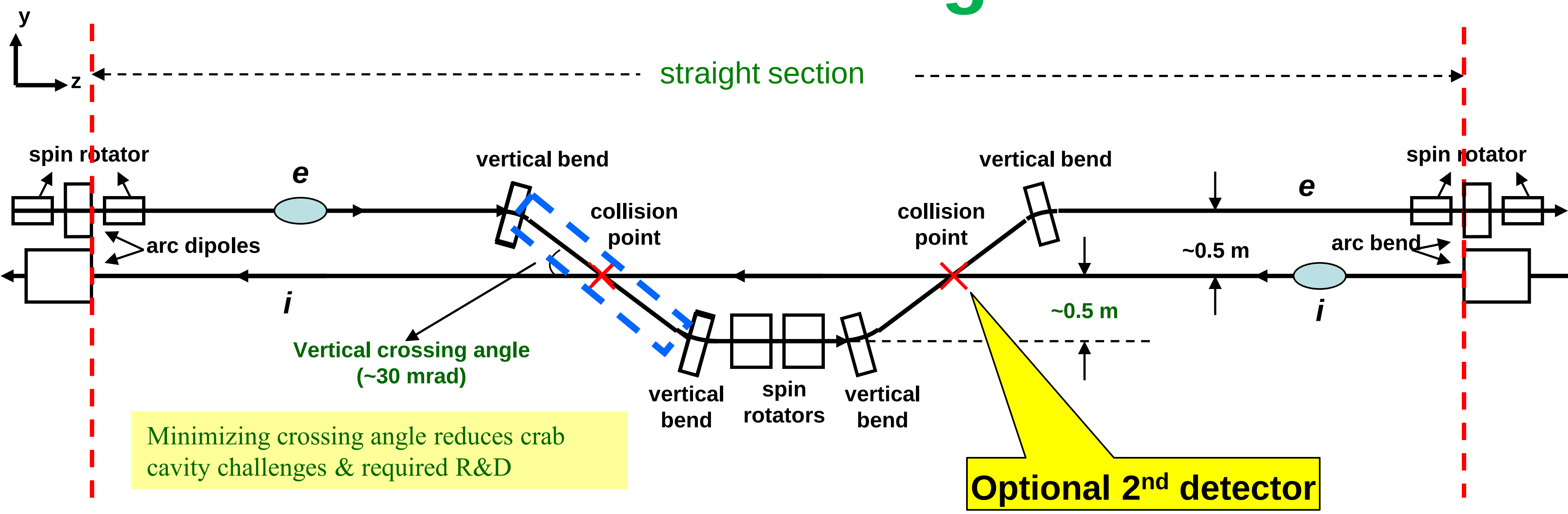
  → Note we don't have to have ERL in order to delivering high luminosity

  → Key for high luminosity is *high repetition, small beta* & short bunch*

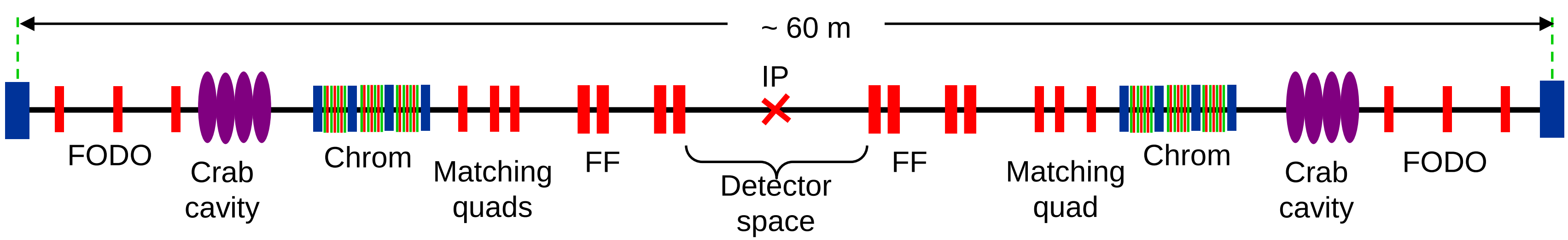
- 12 GeV CEBAF Upgrade polarized source/injector already meets beam requirement of ring-ring design

- CEBAF-based R-R design still preserves high luminosity, high polarization (+polarized positrons…)

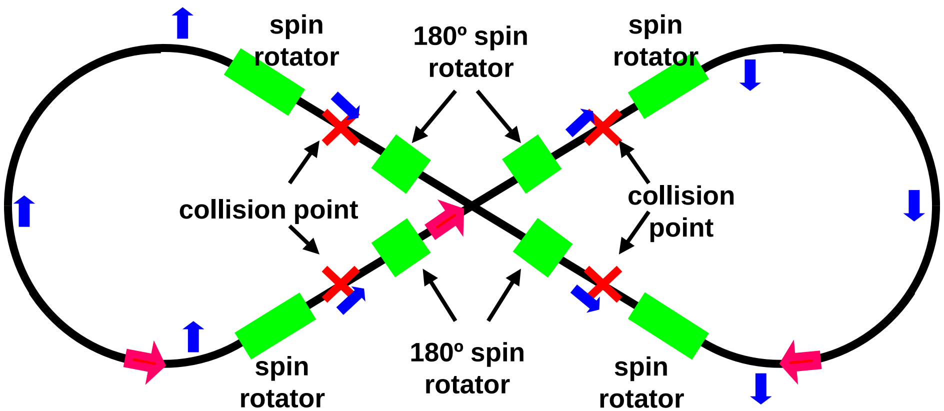
Figure-8 Straight Sections and Interaction Regions



Interaction Region



Electron Polarization

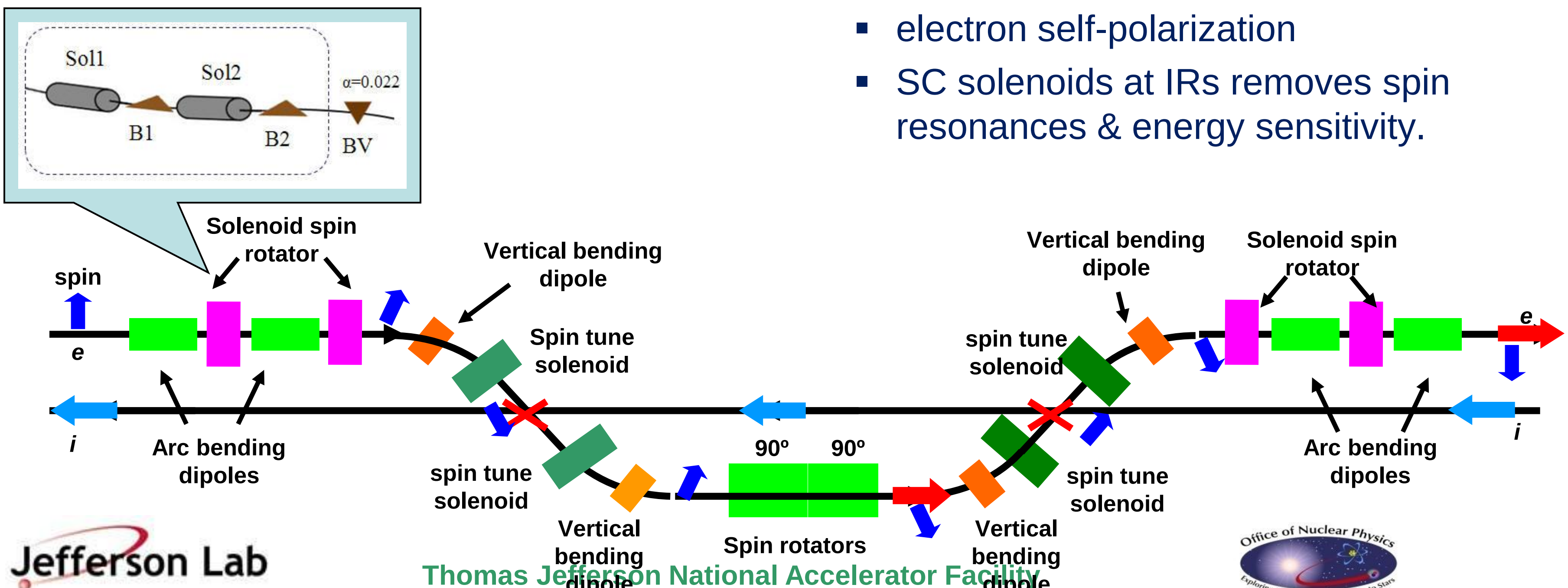


Producing/matching

- Polarized electron source of CEBAF
- Preserved in recirculated CEBAF
- Injected into Figure-8 ring with vertical polarization
- Turn to longitudinal polarization at IP using vertical crossing bends and solenoid spin rotators

Maintaining in the ring

- electron self-polarization
- SC solenoids at IRs removes spin resonances & energy sensitivity.



Beam-Beam Interactions

Issue

• Nonlinear b-b force can cause incoherent & coherent instability, reduce luminosity

• The most important limiting factor

Simulation Model

• Single/multiple IP, head-on collisions

• Ideal rings for e & p, a linear one-turn map

• Radiation damping & quantum excitations

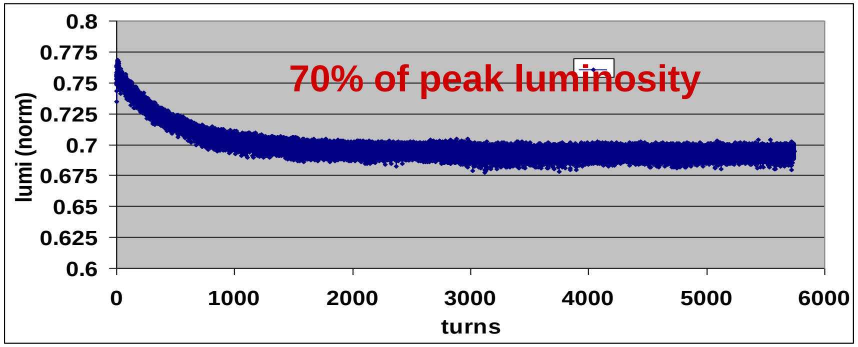
• Code: BeamBeam3D by LBNL

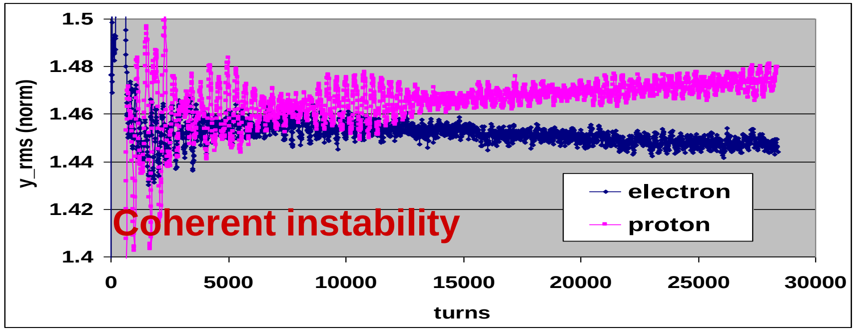
Simulation Scope & Limitations

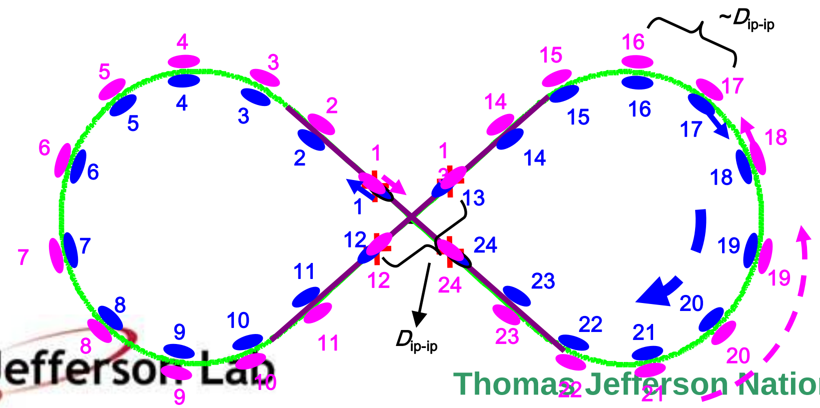
• Typical run corresponds to 0.1s of storing time (12 damping times)

• reveals short-time dynamics with accuracy

• can't predict long term (>min) dynamics







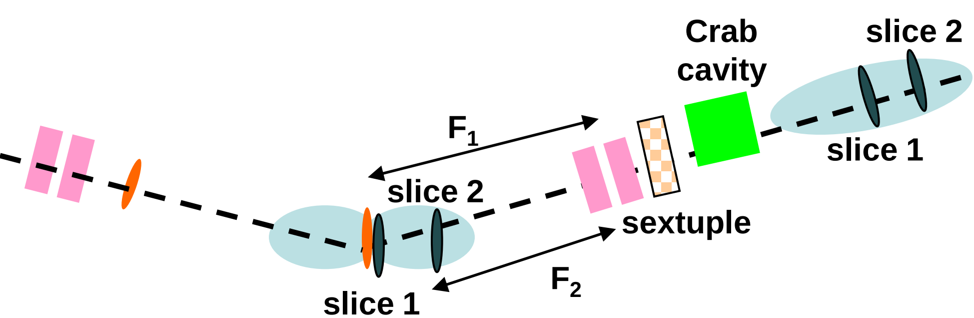
Low-to-medium energy b-b problem

- Non-relativistic, space charge dominated
- Ring transport can't be treated as a one-turn map, coupling everywhere
- Long ion bunch (up to 20 x β*), longitudinal dynamics important
- Traveling focusing scheme introduces non-linear optics

Boosting luminosity at low ion energy: Traveling Final Focusing/Crab Waist

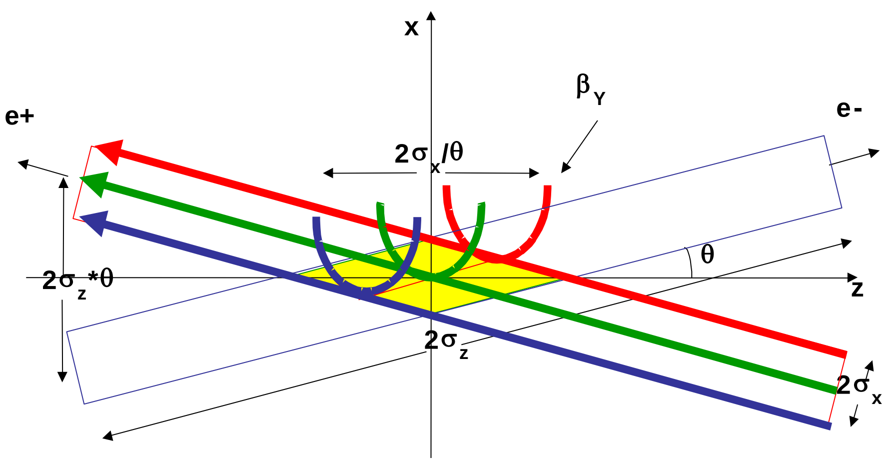
Traveling Final Focusing

- Laslett tune-shift limits bunch charge for very low energy ions (space charge dominated)
- Long bunch length enables more bunch charge, therefore high luminosity
- Hour glass effect could kill luminosity if bunch length is much large than beta*
- "Traveling Focusing" (Brinkmann/Dohlus), can mitigate hour-glass effect
- New realization: crab crossing beam with sextupoles



Crab Waist

- Proposed by P. Raimondi for Super-B factory for luminosity enhancement
- It deals with large Piwinski angle and low vertical beat-star
- Current Super-B design calls 0.2 mm beta-star while bunch length is 6 mm
- Recent proof-of-principle experiment done at DAΦNE very positive



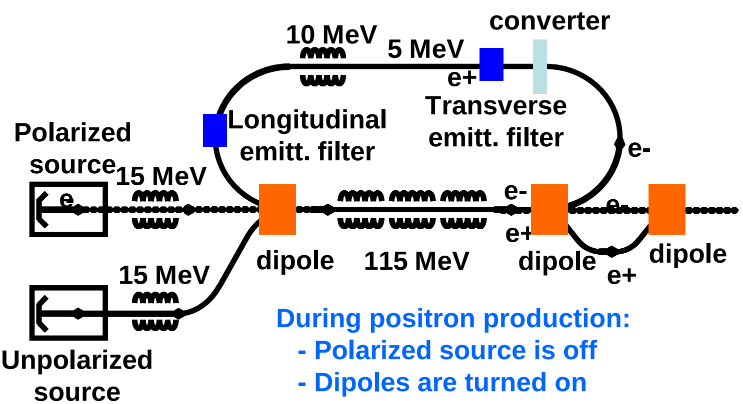
Crabbed waist can be realized with a sextupole in with IP in x and at π/2 in y

Positrons in CEBAF/ELIC

International Workshop on Positrons at Jefferson Lab

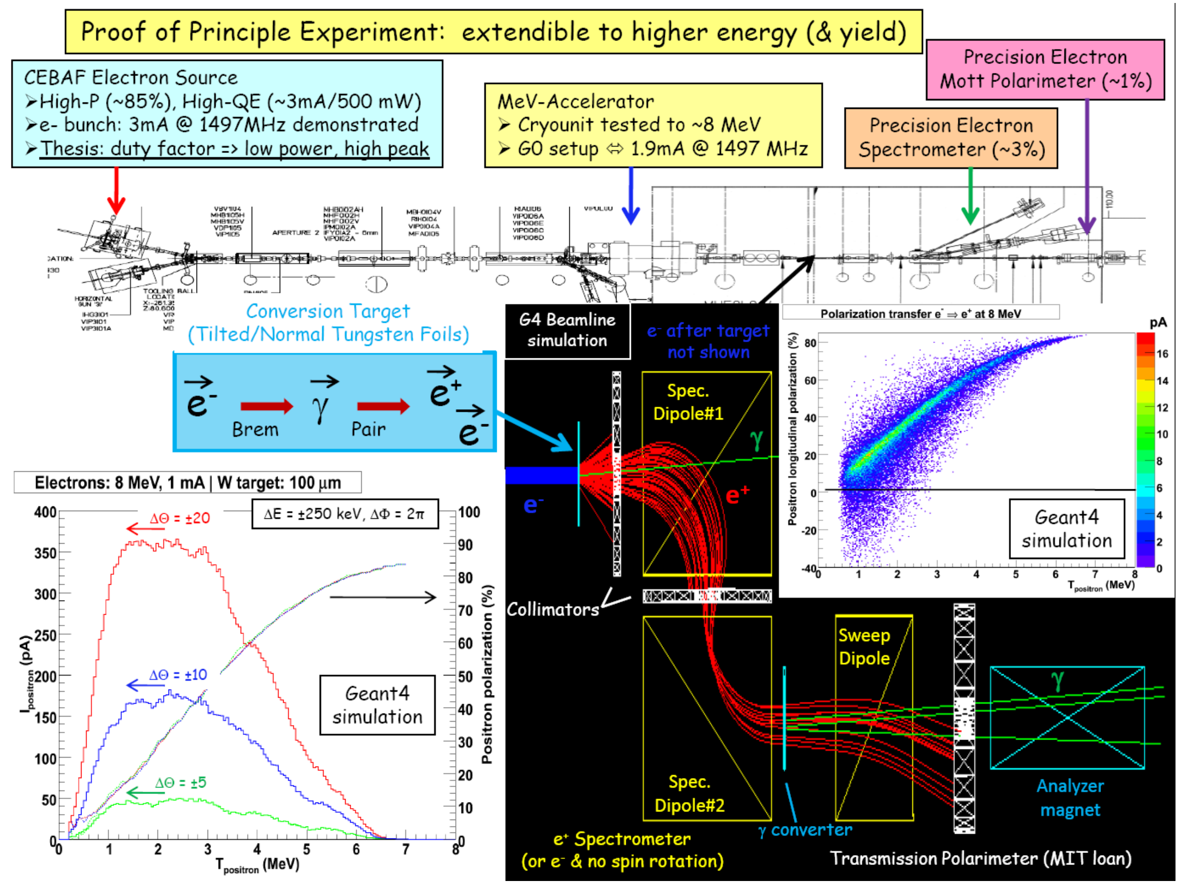
March 25-27, 2009

- **"CEPBAF", S. Golge (Ph. D thesis) / A. Freyberger**
- **Polarized Positron Source, J. Dumas (Ph.D thesis) /J. Grames**
- **Joint JLab/Idaho Univ. Position Program**



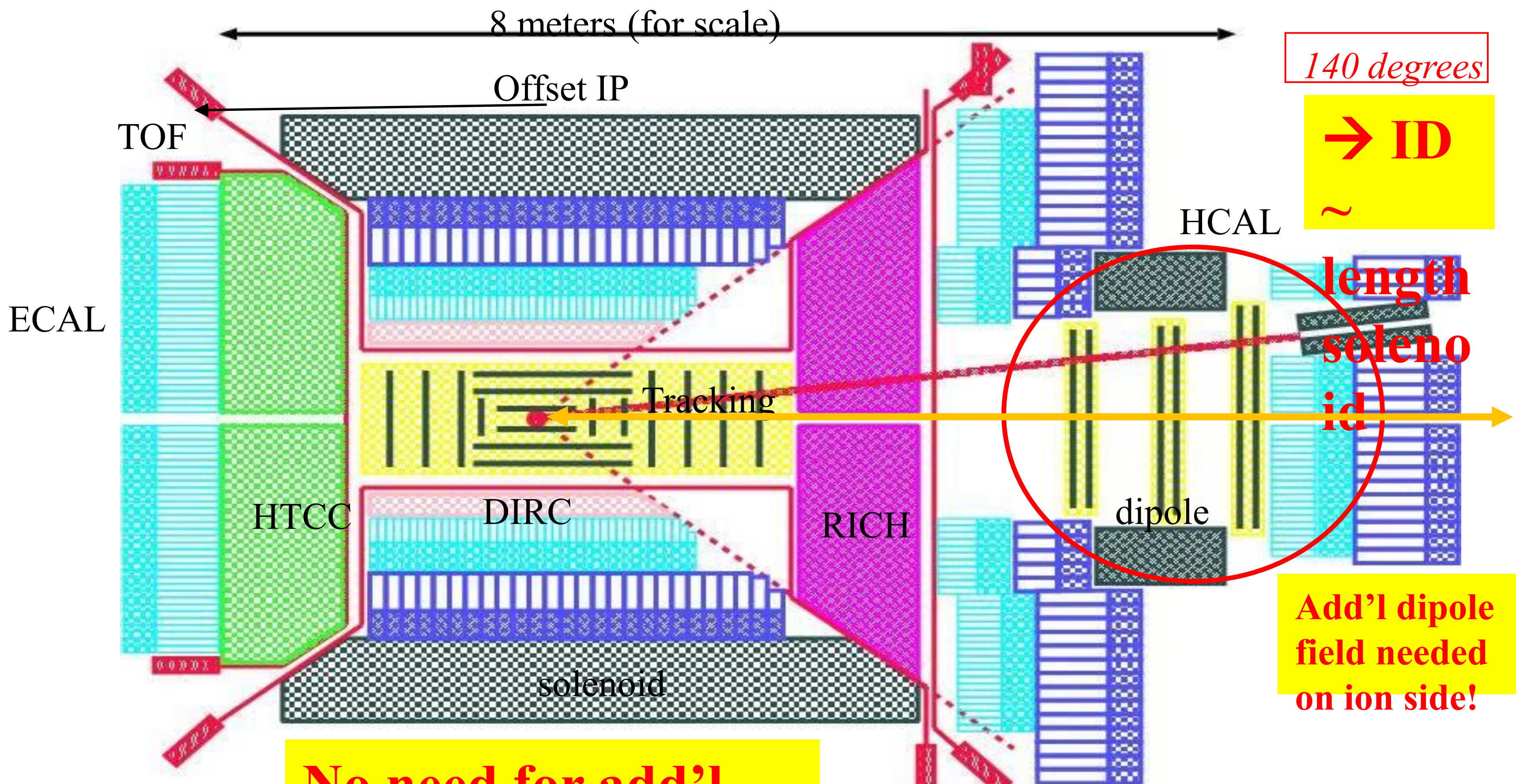
During positron production:
- Polarized source is off
- Dipoles are turned on

- Non-polarized positron bunches generated from modified electron injector through a converter
- Polarization realized through self-polarization at ring arcs



(M. Polker)

ELIC Detector – Conceptual Design



Ion beam

No need for add'l dipole if non-diffractive, non-low-Q^2 detector: $\Theta > 10^o$

But, 9 m space exists → add dipole, HCAL?

e beam

R. Ent

EIC@JLab Parameters: High Energy

Beam Energy	GeV	250/10	150/7
Collision freq.	MHz	499	
Particles/bunch	10^{10}	1.1/3.1	0.5/3.25
Beam current	A	0.91/2.5	0.4/2.6
Energy spread	10^{-4}	3	
RMS bunch length	mm	5	
Horz. beta-star	mm	125	75
Vert. beta-star	mm	5	
Horz. emit., norm.	µm	0.7/51	0.5/43
Vert. emit. Norm.	µm	0.03/2	0.03/2.87
B-B tune shift per IP		0.01/0.1	0.015/0.05
Laslett tune shift (p-beam)		0.1	0.1
Lumi. per IP, 10^{34}	$cm^{-2}s^{-1}$	11	4.1

Major design change: symmetric IR → asymmetric IR