A High Luminosity Polarized Medium Energy Electron Ion Collider at JLab

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Outline

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1. Introduction

ELIC: The Primary Future for JLab
World Class Nuclear Science Program

- JLab is developing a preliminary design of an EIC based on the CEBAF recirculating SRF linac for nearly a decade.

- Based on the requirements of the future nuclear science program, design efforts have been focused on achieving:
  - ultra high luminosity (up to 10^{35}) in multiple detector regions
  - very high polarization (>80%) for both electron & light ions

- The ELIC design combines the existing high repetition, high polarization CW electron beam from CEBAF with a new ion complex and new collider rings.

- We have made significant progress on design optimization
  - Investigating a medium-energy (11x60 GeV^2) electron-ion collider (MEIC) as a tentative compromise between science, technology and project cost
  - High luminosity & high polarization continue to be the design drivers
  - A well-defined upgrade capability is maintained

MEIC Science Drivers

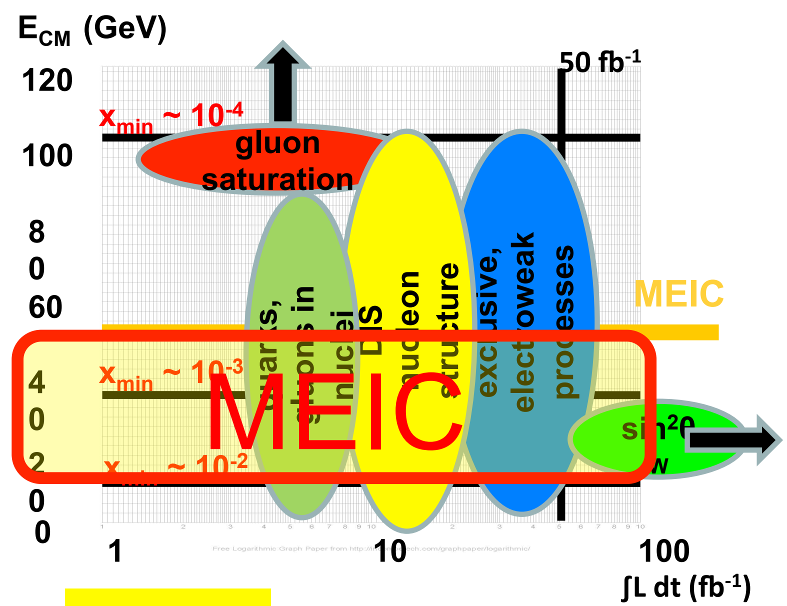
Key issues in nucleon structure & nuclear physics

- 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}:
- CM energy s~3000 GeV^2: Reach in Q^2, x
- Detectability: Angular coverage, particle ID, energy resolution

➔ ***favors lower & more symmetric energies***



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Some example of physics for the EIC

- Tomography of the sea and the glue/ The nucleon spin sum rule; determining J_g
  - Exclusive vector meson production (heavy flavor mesons like the J/psi and the phi). For J_g a transverse polarization of the proton beam is required.
  - Lumi 10^{34} $cm^{-2}.s^{-1}$ and ($s = 100\ GeV^2$ and $s = 4000\ GeV^2$)

- Quark-gluons and gluon-gluon correlations and multiparton parton dynamics.
  - Semi-inclusive production of heavy flavor mesons like D meson production. Investigating the trigluon correlation function and quarks spin-orbit correlations
  - Need: Lumi $>10^{34}$ $cm^{-1}\ s^{-1}$ and ($s = 240\ GeV^2$ to $4000\ GeV^2$)

4000 GeV^2 is 10 GeV e- on 100 GeV protons

2. Design Goal and Consideration

ELIC 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/c p (and ion)
  - Medium energy: up to 11 GeV e on 60 GeV p or 30 GeV/n ion

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

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

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

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

- **Positron Beam** *desirable*

ELIC Design Considerations

- Project goals
  - Luminosity, polarization, energy range, ion species, etc.
  - Cost (construction/operation), technology innovation
  - Future upgrade capability

- Advantages (and a great opportunity)
  - 12 GeV CEBAF
    - High polarization high repetition CW electron beam
    - Full energy injection
  - New Ion Complex
    - High repetition ion beams with short bunch length
  - New collider rings
    - Figure-8 for high polarization

ELIC Design Choices

$$L = f_c \frac{N_h N_e}{4\pi\beta^* \varepsilon}$$

Achieving high luminosity

- Very high bunch repetition frequency (0.5 or 1.5 GHz)
- Very small β* to reach very small spot sizes at collision points
- Short bunch length ($\sigma_z \sim \beta^*$) to avoid luminosity loss due to hour-glass effect (unless other mitigation schemes used)
- Relatively small bunch charge for making short bunch possible
- High bunch repetition restores high average current and luminosity

This luminosity concept has been tested very successfully at two B-factories, reaching luminosity above 2x 10^{34} $cm^{-2}s^{-1}$

ELIC	VS.	eRHIC
High repetition rate		Low repetition rate
Small bunch charge		Super bunch charge
Short bunch length		Long bunch length
Small β*		Large β*

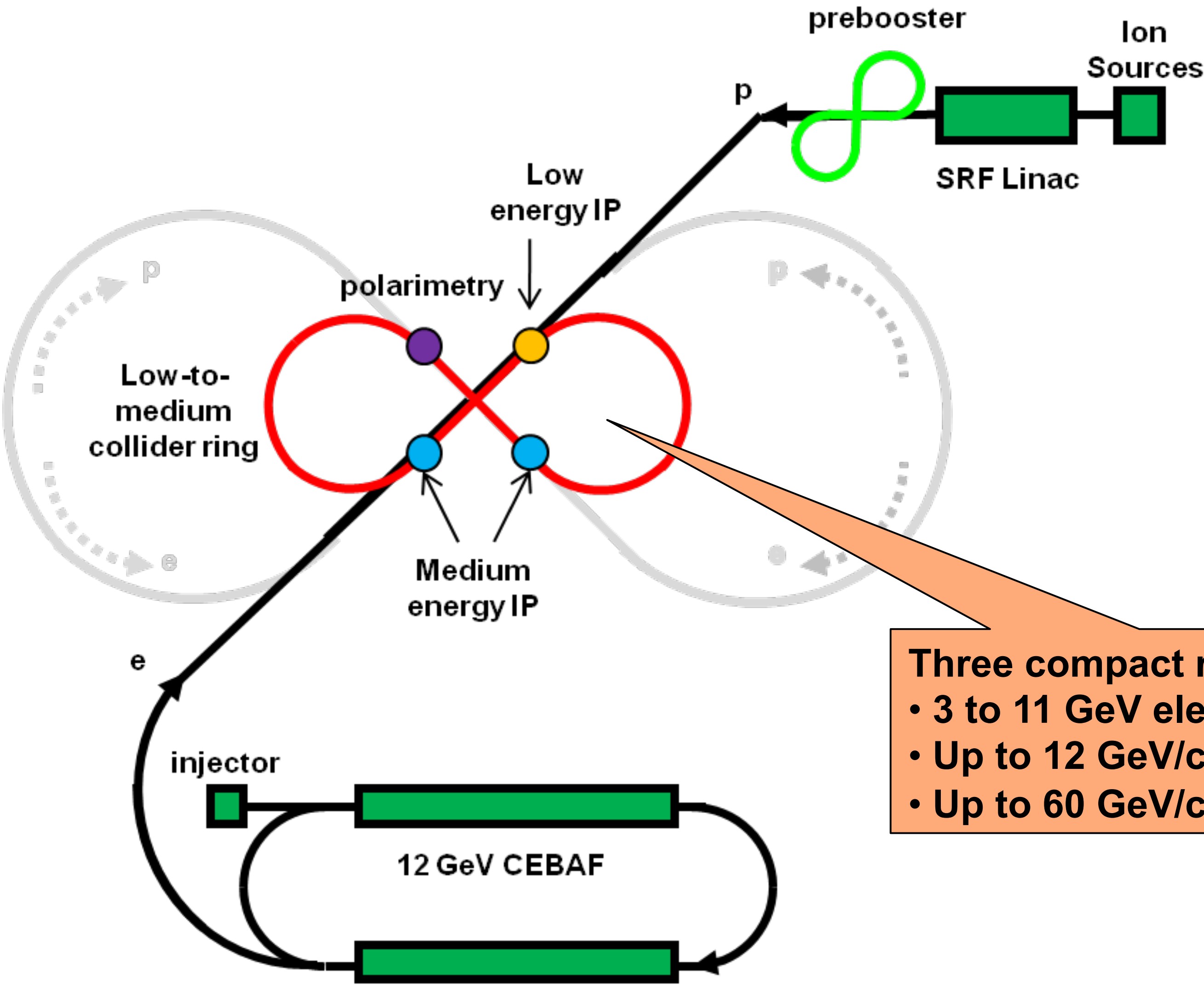
ELIC Design Choice: Figure-8 Ion Collider Rings

Figure-8 shape collider ring optimum for polarized ions

- 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
- There are no technical disadvantages

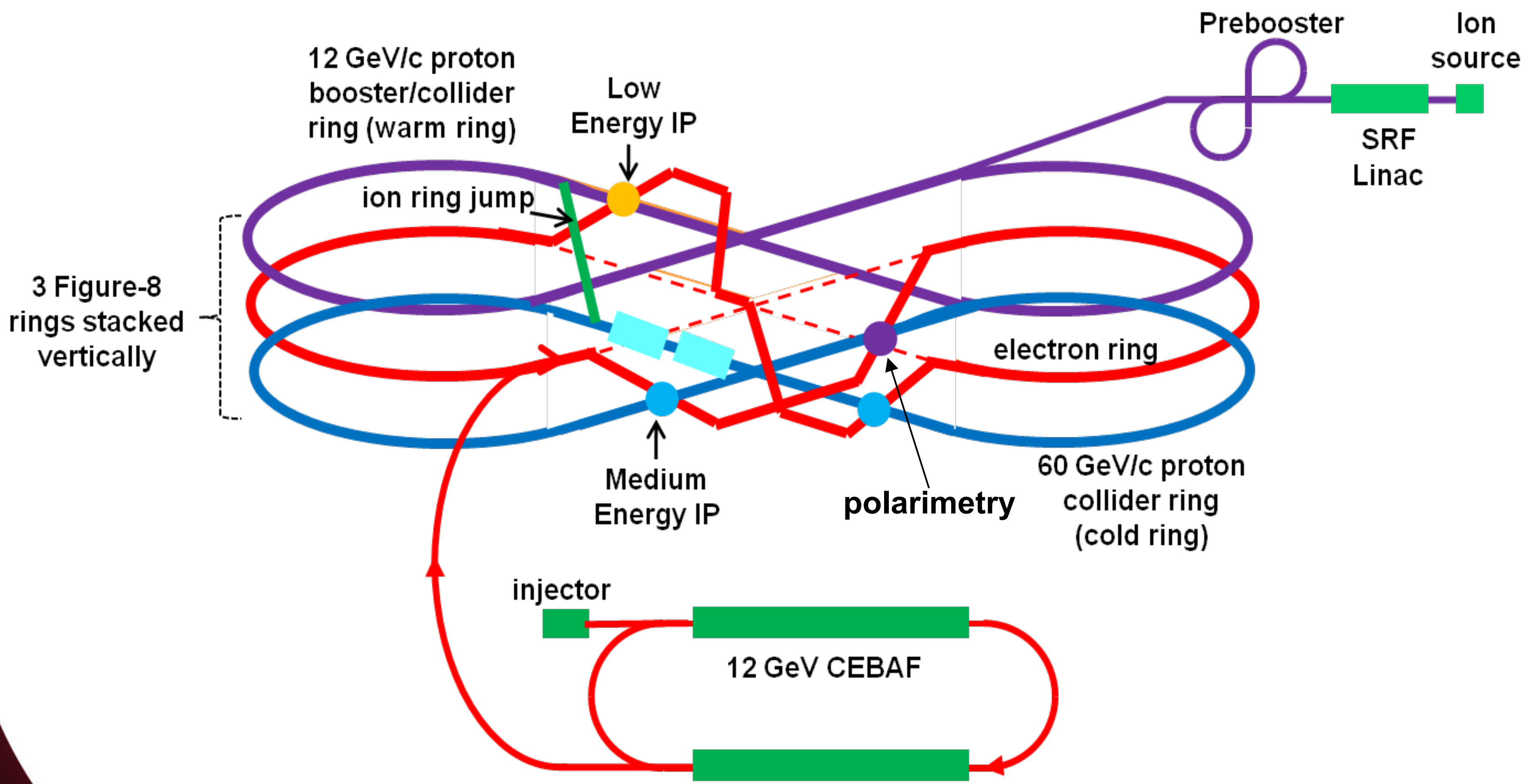
3. Machine Design

MEIC: A Medium Energy EIC

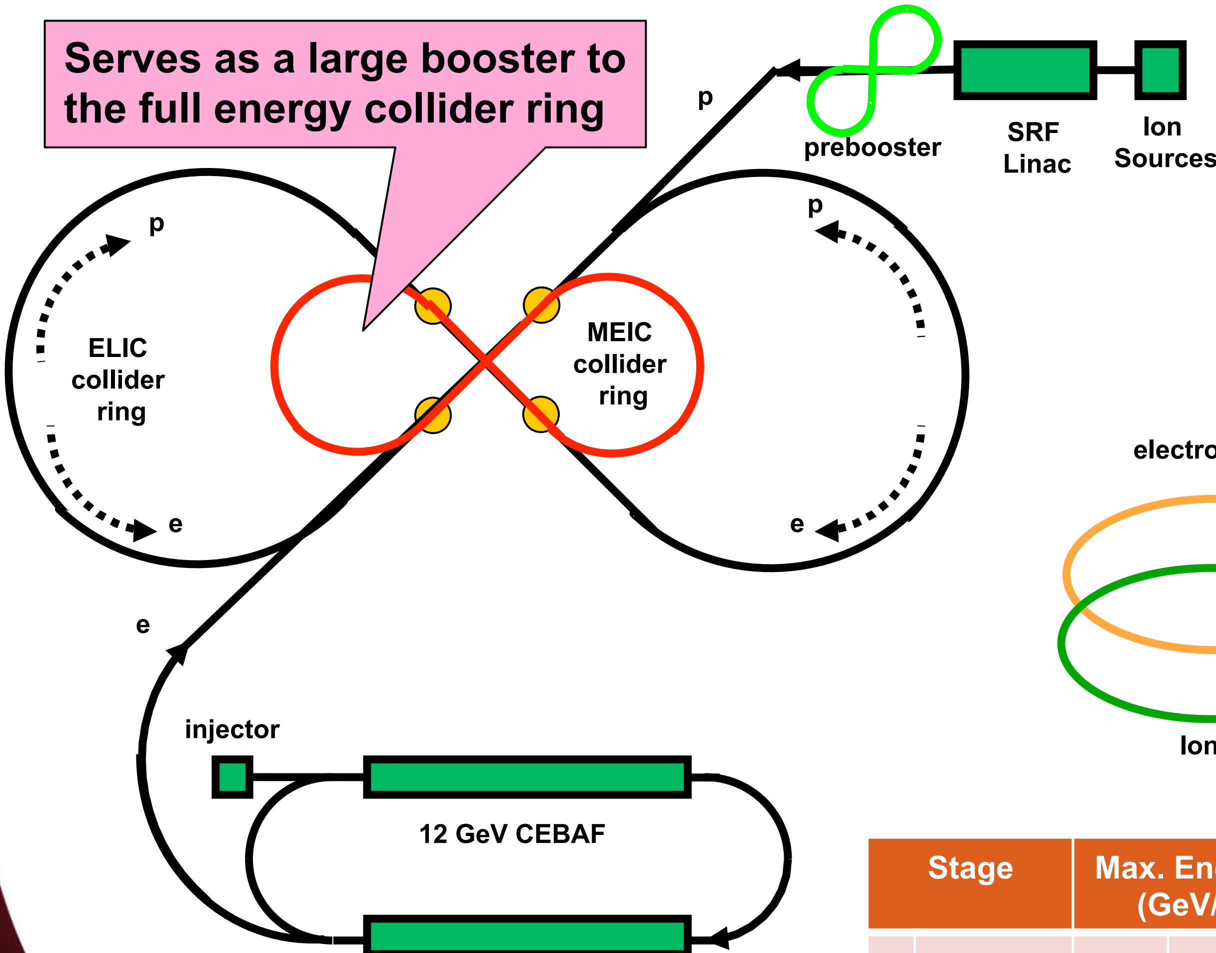


Three compact rings:
- **3 to 11 GeV electron**
- **Up to 12 GeV/c proton (warm)**
- **Up to 60 GeV/c proton (cold)**

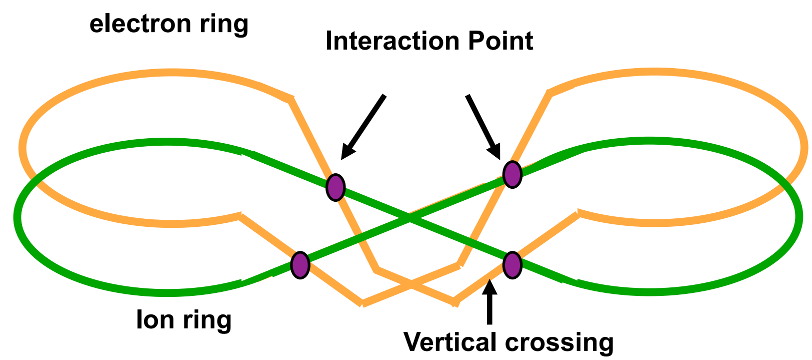
MEIC: Detailed Layout



ELIC: High Energy Upgrade



Circumference	m	1800
Radius	m	140
Width	m	280
Length	m	695
Straight	m	306



Stage	Max. Energy (GeV/c)		Ring Size (m)		Ring Type		IP #
	p	e	p	e	p	e	
Low	12	5 (11)	630		Warm	Warm	1
Medium	60	5 (11)	630		Cold	Warm	2
High	250	10	1800		Cold	Warm	4

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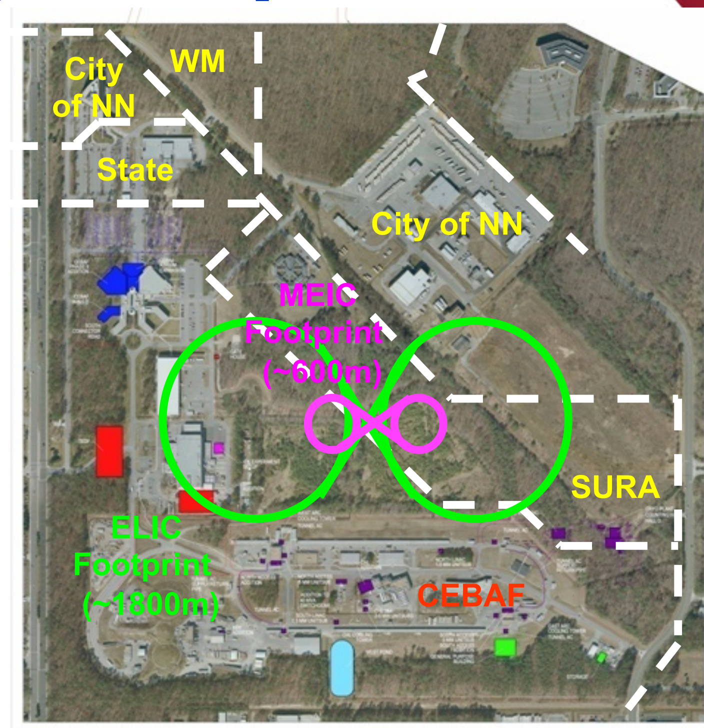
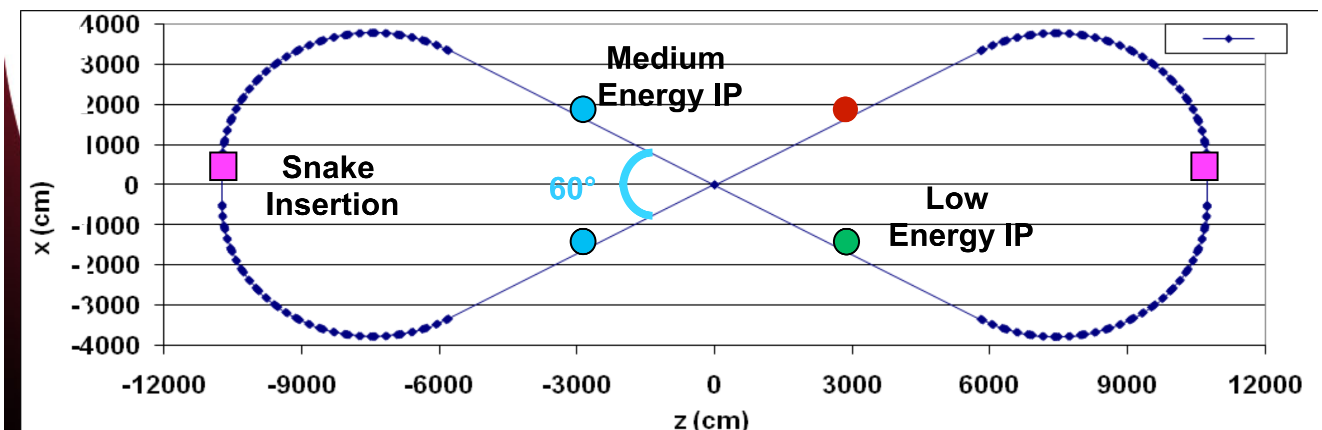
MEIC Figure-8 Ring Footprint

- Ring circumference is a compromise
  - Synchrotron radiation power of e-beam
    - ➔ prefers large arc length
  - Space charge effect of ion beams
    - ➔ prefers small circumference
- Multiple IPs require long straights
- Straights also hold service elements (cooling, injection and ejections, etc.)





Arc	157 m
Figure-8 straight	150 m
Insertion	10 m
Circumference	660 m

ELIC Main Parameters

Beam Energy	GeV	250/10	150/7	60/5	60/3	12/3
CM energy s	GeV^2	10000	4200	1200	720	144
Collision frequency	MHz			499		
Particles/bunch	10^{10}	1.1/3.1	0.5/3.25	0.74/2.9	1.1/6	0.47/2.3
Beam current	A	0.9/2.5	0.4/2.6	0.59/2.3	0.86/4.8	0.37/2.7
Energy spread	10^{-4}			~ 3		
RMS bunch length	mm	5	5	5	5	50
Horiz.. emit., norm.	μm	0.7/51	0.5/43	0.56/85	0.8/75	0.18/80
Vert. emit. Norm.	μm	0.03/2	0.03/2.87	0.11/17	0.8/75	0.18/80
Horizontal beta-star	mm	125	75	25	25	5
Vertical beta-star	mm			5		
Vert. b-b tune shift/IP		0.01/0.1	0.015/.05	0.01/0.03	.015/.08	.015/.013
Laslett tune shift	p-beam	0.1	0.1	0.1	0.054	0.1
Peak Lumi/IP, 10^{34}	cm^{-2}s^{-1}	11	4.1	1.9	4.0	0.59

High energy

Medium energy

Low energy

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Achieving High Luminosity

MEIC design luminosity

$L \sim 4x10^{34}$ cm^{-2} s^{-1} for medium energy (60 GeV x 3 GeV)

Luminosity Concepts

- High bunch collision frequency (0.5 GHz, can be up to 1.5 GHz)
- Very small bunch charge ($<3x10^{10}$ particles per bunch)
- Very small beam spot size at collision points ($\beta^*_y \sim 5$ mm)
- Short ion bunches ($\sigma_z \sim 5$ mm)

Keys to implementing these concepts

- Making very short ion bunches with small emittance
- SRF ion linac and (staged) electron cooling
- Need crab crossing for colliding beams

Additional ideas/concepts

- Relative long bunch (comparing to beta*) for very low ion energy
- Large synchrotron tunes to suppress synchrotron-betatron resonances
- Equal (fractional) phase advance between IPs

MEIC Ring-Ring Design Features

- Ultra high luminosity
- Polarized electrons and polarized light ions
- Up to three IPs (detectors) for high science productivity
- "*Figure-8*" ion and lepton storage rings
  - Ensures spin preservation and ease of spin manipulation
  - Avoids energy-dependent spin sensitivity for all species
- Present CEBAF injector meets MEIC requirements
  - 12 GeV CEBAF can serve as a full energy injector
- Simultaneous operation of collider & CEBAF fixed target program if required
- Experiments with polarized positron beam would be possible

4. Some Design Details

5. Critical R&D and Path Forward

MEIC Enabling Technologies

- Pushing the limits of present accelerator theory
  - Issues associated with short ion bunches (e.g. cooling)
  - Issues associated with small β^* at collision points
    - Focus on chromatic compensation
  - Beam-beam effects
- Development of new advanced concepts
  - Dispersive crabbing
  - Beam-based fast kicker for circulator electron cooler

MEIC Critical Accelerator R&D

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

- Interaction Region design with chromatic compensation
- Electron cooling
- Crab crossing and crab cavity

- Forming high intensity low energy ion beam
- Beam-beam effect
- Beam polarization and tracking

- 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		
Semi Challenging	IR design/chromaticity Electron cooling Traveling focusing (for very low ion energy)	IR design/chromaticity Electron cooling
Likely	Crab crossing/crab cavity High intensity low energy ion beam	Crab crossing/crab cavity High intensity low energy ion beam
Know-how	Spin tracking Beam-Beam	Spin tracking Beam-beam

Near Term Design Work

- ✓ **Design "contract"** : first stage machine parameters (Feb. 2010)
  - ➢ For the near term design work, up to the next EICC AC meeting (Sept. 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 accelerator component 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 four CEBAF 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 reasonable detailed design in the next EICC AC meeting
  - ➢ Produce an intermediate design report
  - ➢ Advance to the next design iteration

Future Accelerator R&D

We will concentrate R&D efforts on the most critical tasks

Focal Point 1: Complete Electron and Ion Ring designs

Led by Slava Derbenev and Alex Bogacz (JLab)

Focal Point 2: IR design and feasibility studies of advanced IR schemes

Led by Mike Sullivan (SLAC)

Focal Point 3: Forming high-intensity short-bunch ion beams & cooling

Led by Peter Ostroumov (ANL)

Focal Point 4: Beam-beam interaction

Led by Yuhong Zhang and Balsa Terzic (JLab)

Additional design and R&D studies

Electron spin tracking, ion source development

Transfer line design

Collaborations Established

- **Interaction region design** M. Sullivan (SLAC)
- **ELIC ion complex front end** P. Ostroumov (ANL)

  (From source up to injection into collider ring)
  - Ion source V. Dudnikov, R. Johnson (Muons, Inc)
    V. Danilov (ORNL)
  - SRF Linac P. Ostroumov (ANL), B. Erdelyi (NIU)
- **Chromatic compensation** A. Netepenko (Fermilab)
- **Beam-beam simulation** J. Qiang (LBNL)
- **Electron cooling simulation** D. Bruhwiler (Tech X)
- **Electron spin tracking** D. Barber (DESY)

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 the polarized high repetition CW electron beam from CEBAF, a new ion storage complex and new figure-8 collider rings, provides opportunity of ultra high luminosity of electron-ion collisions and high beam polarization.
- Present MEIC design covers an energy range matched to the science program proposed by the JLab nuclear physics community (~1000 GeV^2) with luminosity above 10^{34} $cm^{-2}s^{-1}$, but can easily be extended to ~3000 GeV^2 by lengthening the ring if required by the science
- An Upgrade path to higher energies (250x10 GeV^2) has been developed which should provide luminosity of $1x10^{35}$ $cm^{-2}s^{-1}$
- We have identified the critical accelerator R&D topics for MEIC
- Our near term goal is to develop a detailed and creditable machine design, and followed by a long term rigorous R&D program for reaching ultra high luminosity

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, S. De Silva, 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. Krafft, R. Li, L. Merminga, V. Morozov, J. Musson, A. Nadel-Turonski, M. Poelker, F. Pilat, R. Rimmer, Y. Roblin, H. Seyed, M. Spata, C. Tengsirivattana, B. Terzic, A. Thomas, M. Tiefenback, H. Wang, C. Weiss, B. Wojtsekhowski, B. Yunn, Y. Zhang - Jefferson Laboratory staffs and users

W. Fischer, C. Montag - Brookhaven National Laboratory

D. Barber - DESY

V. Danilov - Oak Ridge National Laboratory

V. Dudnikov, R. Johnson - Muons. Inc.

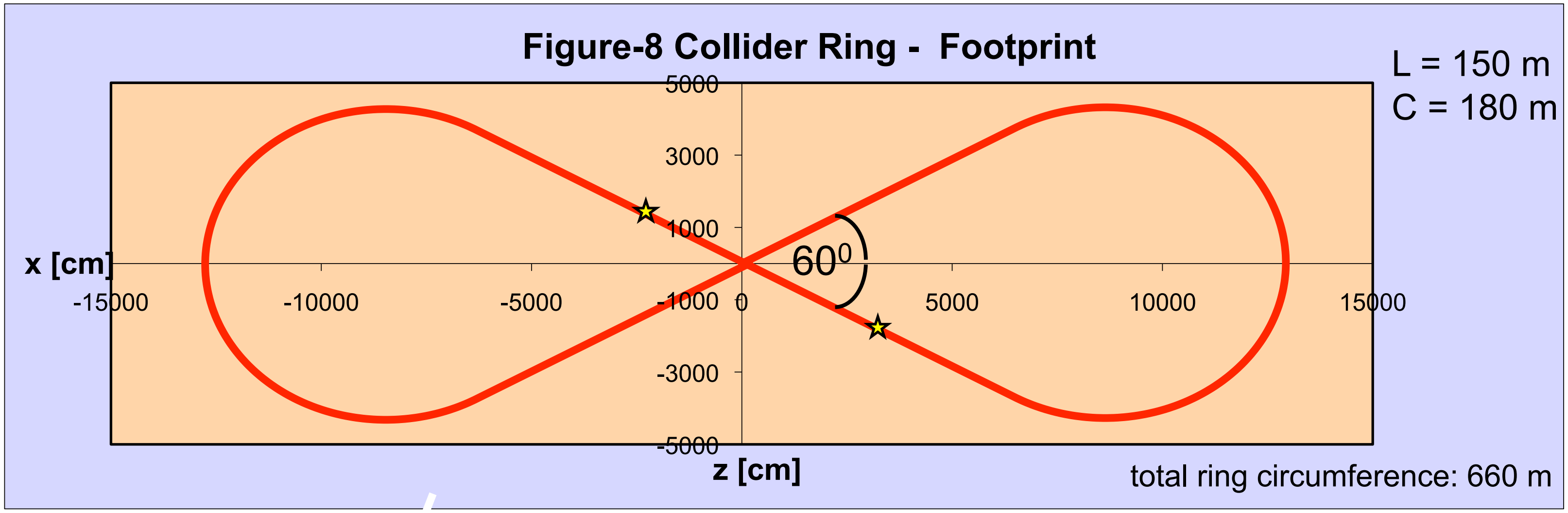
S.. Manikonda, P. Ostroumov - Argonne National Laboratory

B. Erdelyi - Northern Illinois University

V. Derenchuk - Indiana University Cyclotron Facility

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

Figure-8 Electron Ring



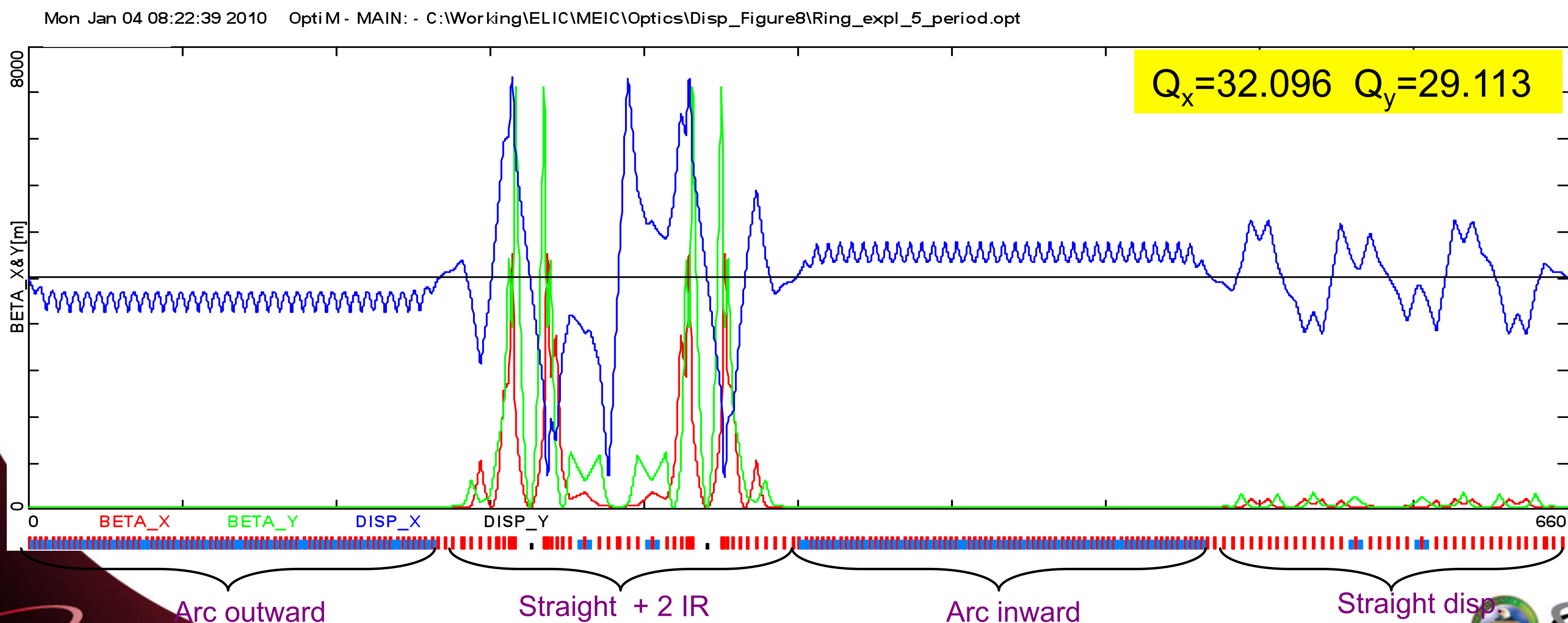
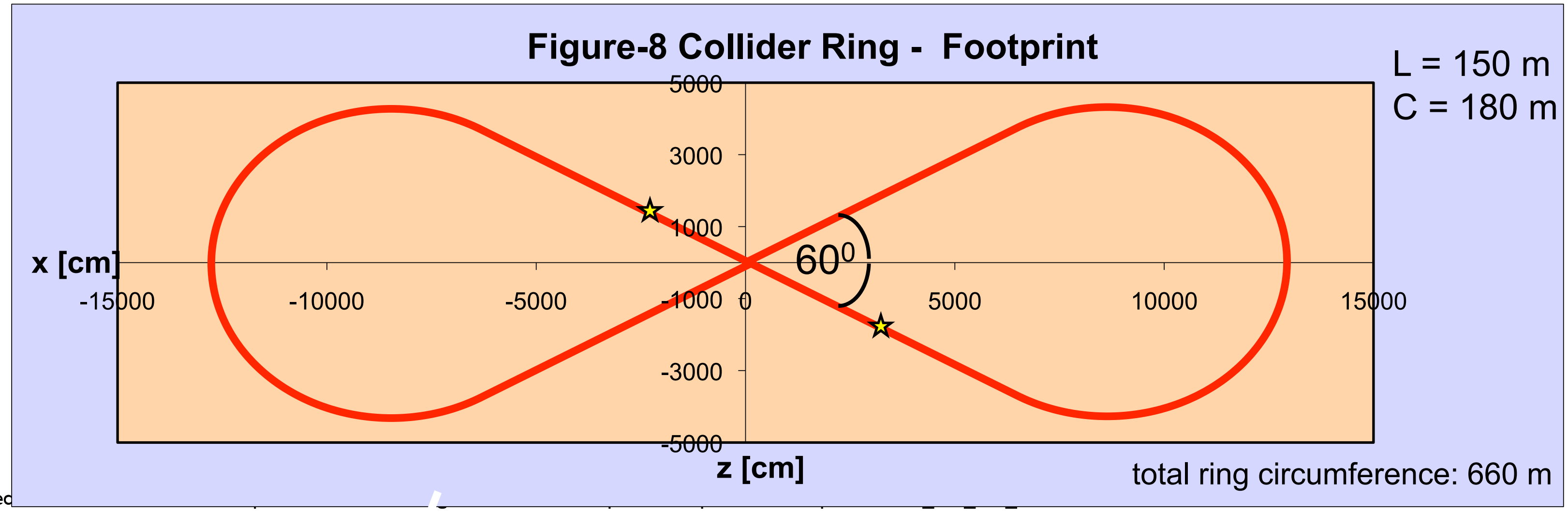
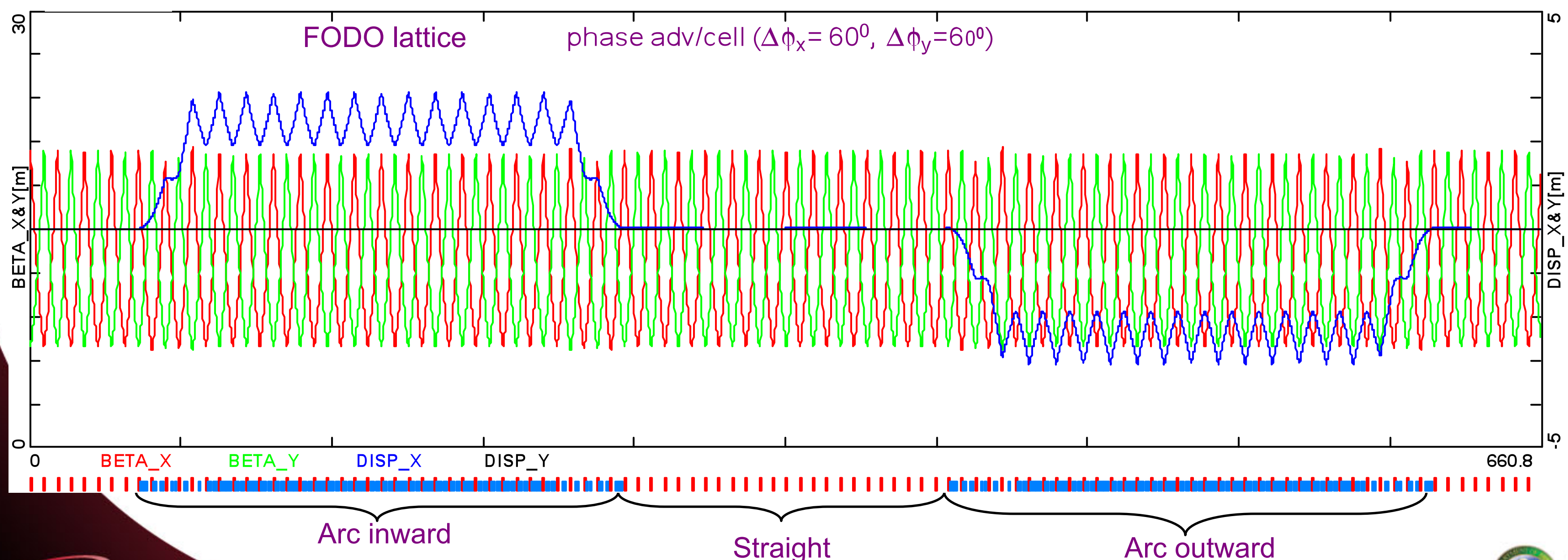


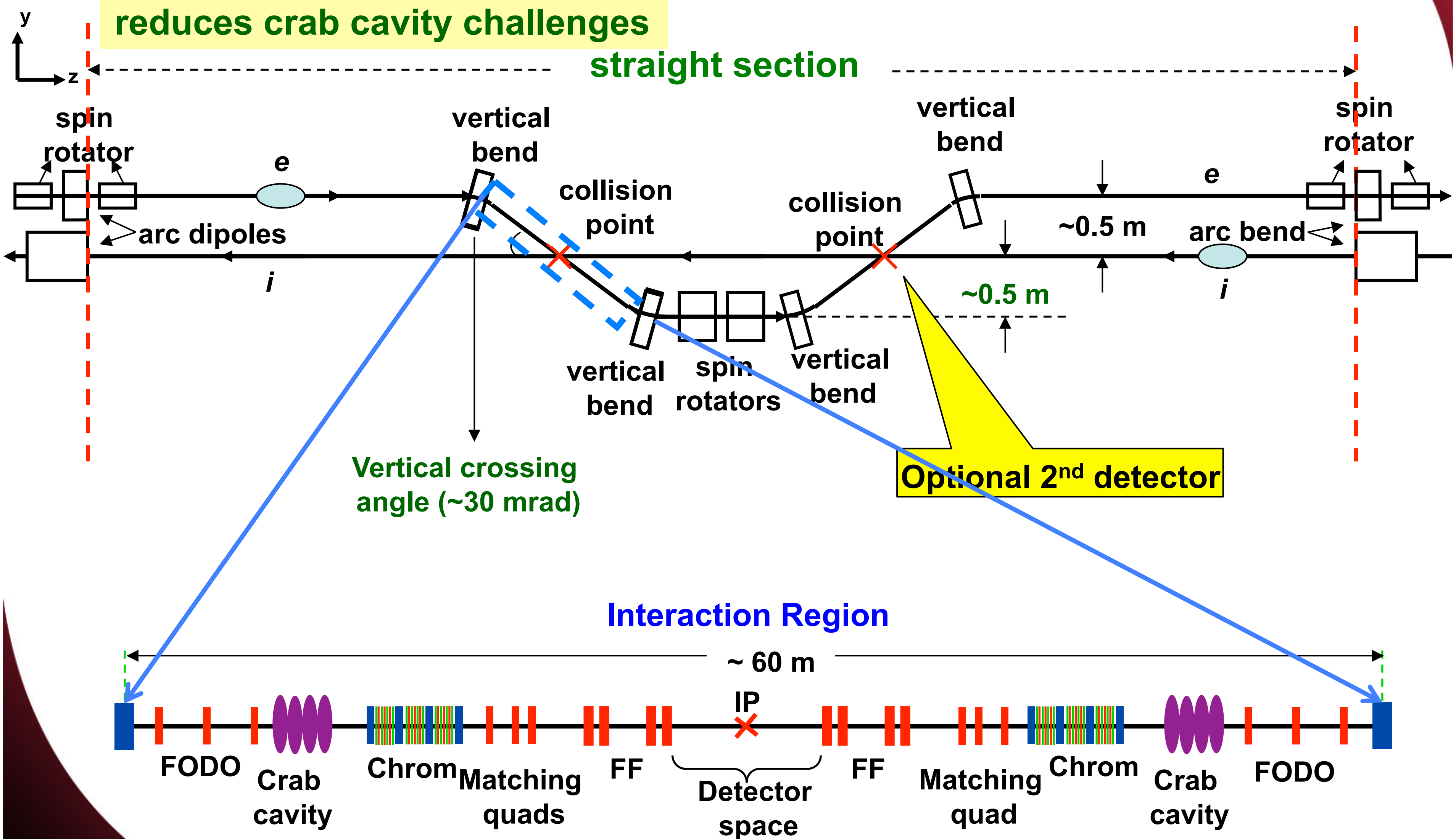
Figure-8 Ion Ring





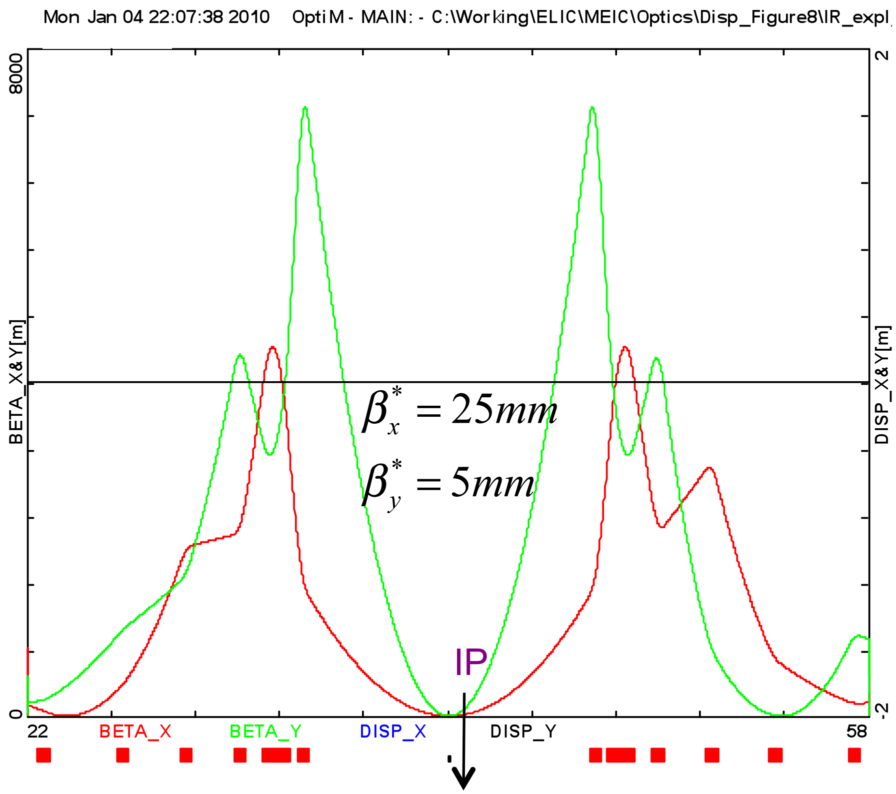
Straight Section Layout

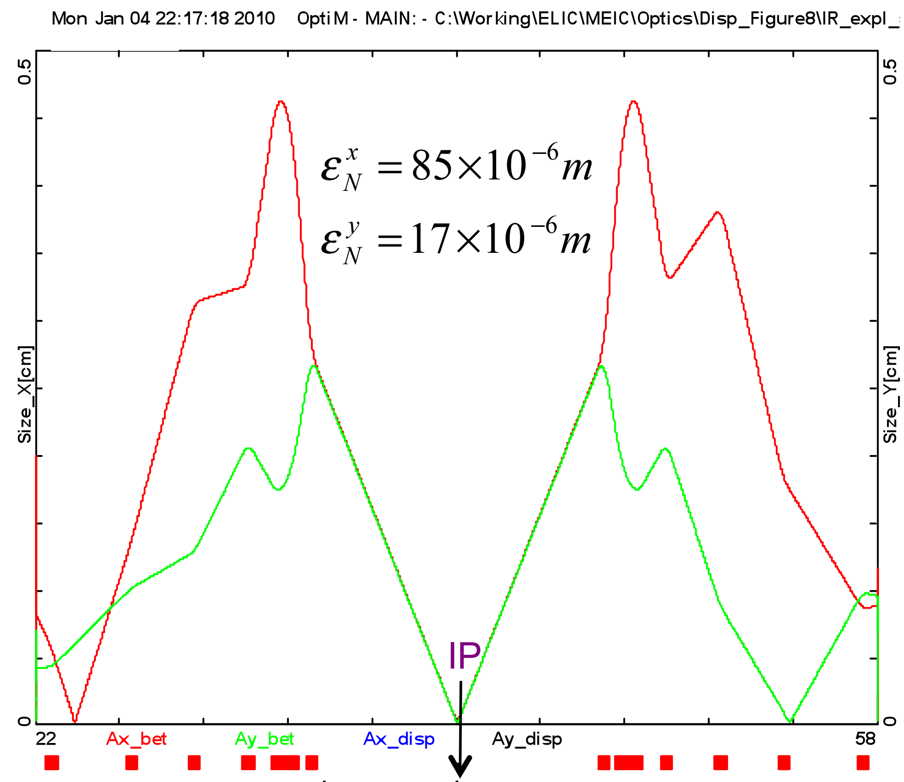
Minimizing crossing angle reduces crab cavity challenges



Low Beta Focusing

vertical focusing first





FF triplet : Q3 Q2 Q1

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

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

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

Natural Chromaticity: $\xi_x = -278$ $\xi_y = -473$

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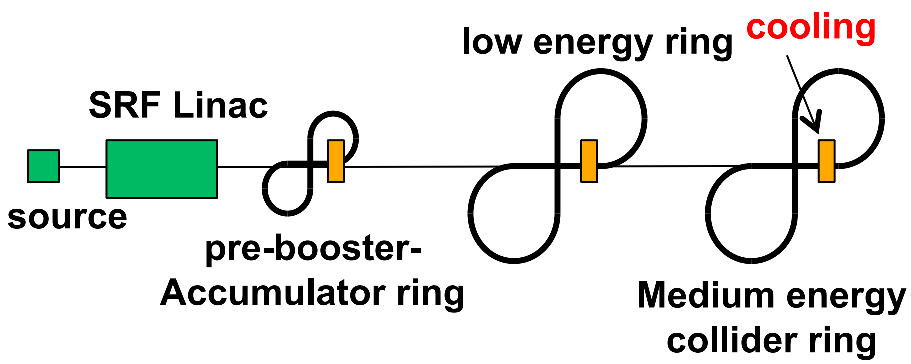
Forming a High-Intensity Ion Beam



Stacking proton beam in ACR

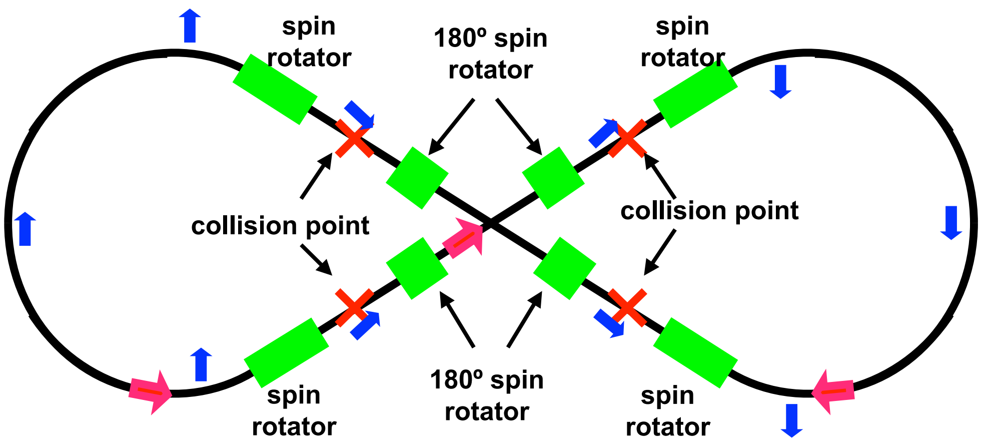
Circumference	m	100
Energy/u	GeV	0.2 -0.4
Cooling electron current	A	1
Cooling time for protons	ms	10
Stacked ion current	A	1
Norm. emit. After stacking	μm	16

	Energy (GeV/c)	Cooling	Process
Source/SRF linac	0.2		Full stripping
Prebooster/Accumulator-Ring	3	DC electron	Stacking/accumulating
Low energy ring (booster)	12	Electron	RF bunching (for collision)
Medium energy ring	60	Electron	RF bunching (for collision)

Stacking/accumulation process

- Multi-turn (~20) pulse injection from SRF linac into the prebooster
- Damping/cooling of injected beam
- Accumulation of 1 A coasting beam at space charge limited emittance
- Fill prebooster/large booster, then acceleration
- Switch to collider ring for booster, RF bunching & staged cooling

Electron Polarization



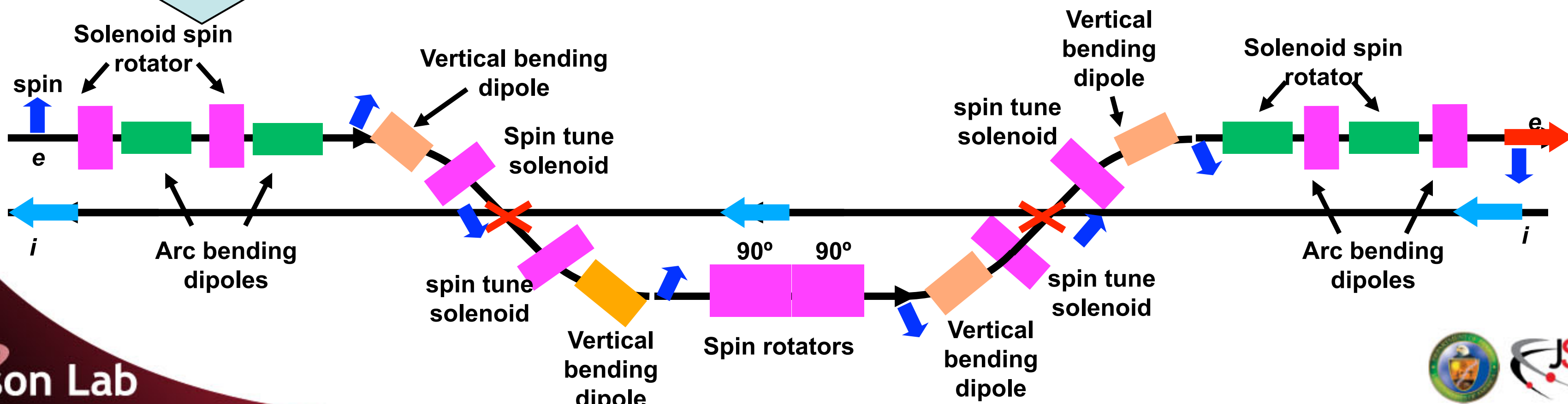
Producing/matching

- CEBAF polarized electron source
- Injected into Figure-8 ring with vertical polarization
- Turn to longitudinal direction at IPs using vertical crossing bends and solenoid spin rotators

Maintaining in the ring

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

Energy independent spin rotation - vertical to longitudinal



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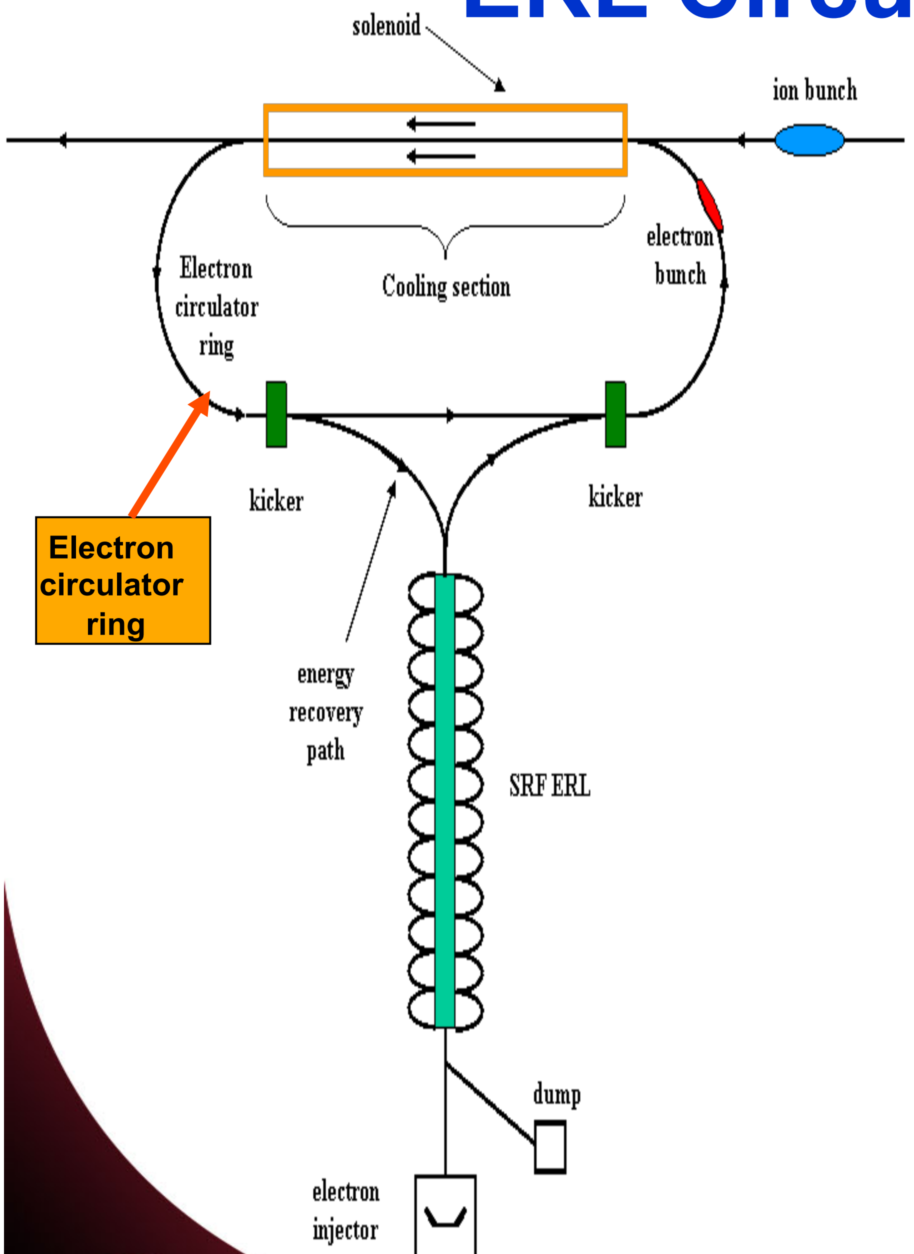
ERL Circulator Cooler



Design goal

- Up to 33 MeV electron energy
- Up to 3 A CW unpolarized beam
  (~nC bunch charge @ 499 MHz)
- Up to 100 MW beam power!

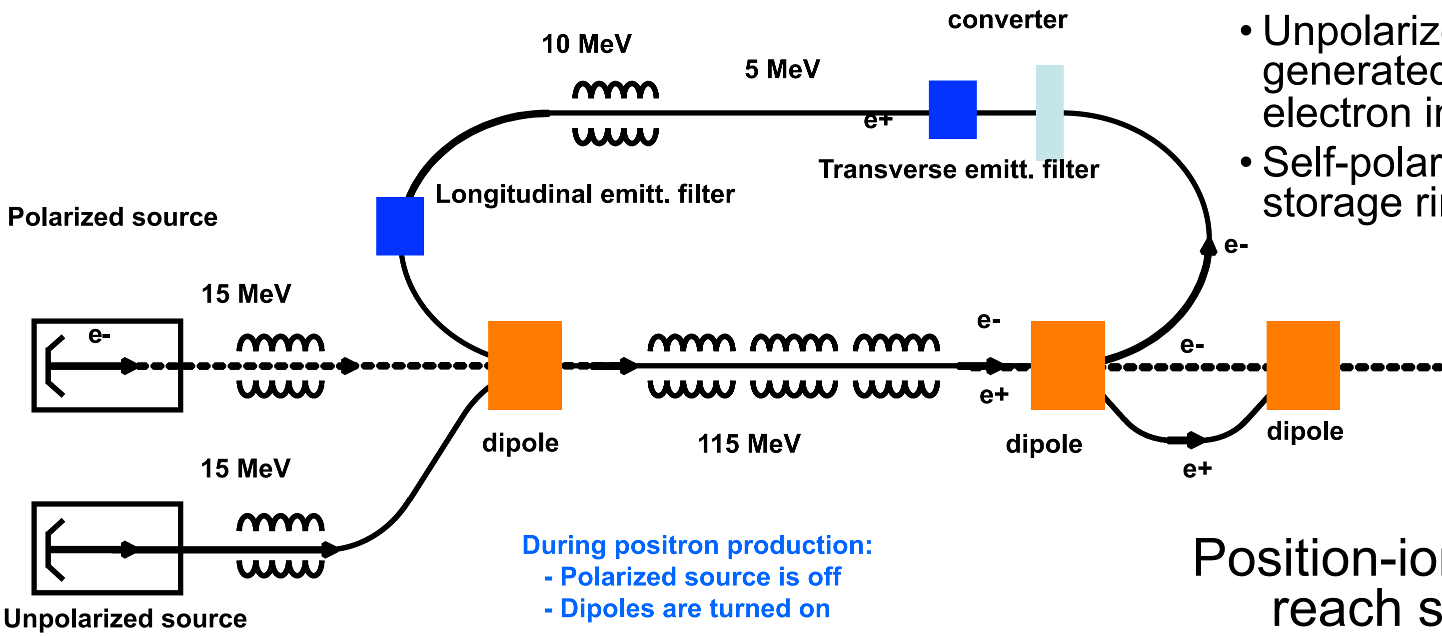
Solution: ERL Circulator Cooler

- ERL provides high average current CW beam with minimum RF power
- Circulator ring for reducing average current from source and in ERL
  (# of circulating turns reduces ERL current by same factor)

Technologies

- High intensity electron source/injector
- Energy Recovery Linac (ERL)
- Fast kicker

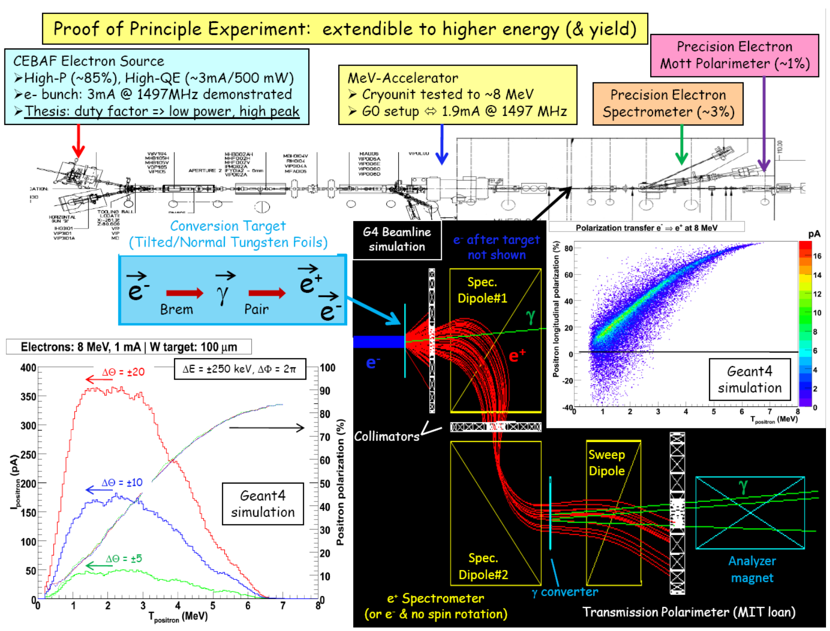
Positrons in CEBAF/MEIC



- Unpolarized positrons generated from the modified electron injector by a converter
- Self-polarization in the lepton storage ring

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

Position-ion collisions should reach same luminosity as electron-ion collisions



Positron source development at JLab

- **"CEPBAF", S. Golge (Ph. D thesis)**
- **Polarized e+ Source, J. Dumas (PhD thesis)**
- **Joint JLab/Idaho Univ. Positron Program**

(M. Poelker)

International Workshop on Positrons at Jefferson Lab

March 25-27, 2009