ELIC

G. A. Krafft for the ELIC Study Group

EICAC Review Talk

Feb 16, 2009

ELIC Study Group & Collaborators

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Topics

- Introduction to ELIC: An Electron-Ion Collider Based on CEBAF
- Medium Energy Colliders and Staging
- R&D Items
- Summary

ELIC Design Goals

- **Energy**
  - **Center-of-mass energy between 20 GeV and 100 GeV**
  - **Energy asymmetry of ~ 10,**

    ➔ **3 GeV electron on 30 GeV proton/15 GeV/n ion up to**
    10 GeV electron on 250 GeV proton/100 GeV/n ion

- **Luminosity**
  - **>10^{33} up to 3×10^{34} cm^{-2} s^{-1} *per* interaction point**

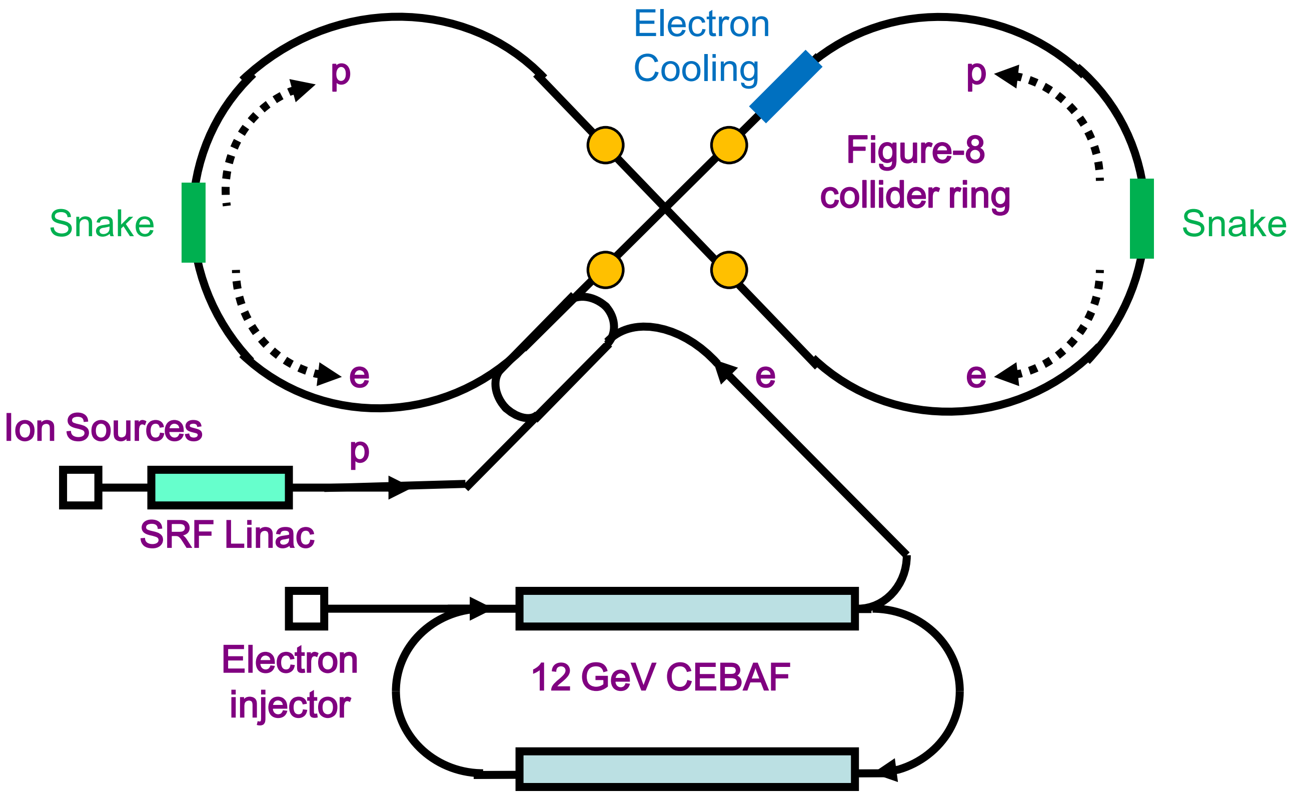
- **Ion Species**
  - **Polarized H, D, ^{3}He, possibly Li**
  - **Up to heavy ion A = 208, fully stripped**

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

Design Choices for ELIC

- **Use a Ring-Ring (R-R) collider design – take advantage of CEBAF as a full energy polarized electron injector**
- Energy Recovery Linac – Ring or Circulator Ring - Ring designs have little luminosity advantage and are challenging: high current polarized electron source
  - ERL-Ring: 2.5 A
  - Circulator ring: 20 mA
  - State-of-art: 1.0 mA
- **12 GeV CEBAF Upgrade polarized source/injector already meets beam requirement of Ring-Ring design**
- **CEBAF-based R-R design has high luminosity and high polarization**

ELIC Conceptual Design



ELIC Ring-Ring Design Features

- Unprecedented high luminosity
  - Enabled by short ion bunches, low *β**, high rep. rate
  - Large synchrotron tune
  - Require crab crossing
- Electron cooling is an essential part of EIC
- 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

Achieving High Luminosity in ELIC

ELIC Design Luminosity

$L \sim 3.0 \times 10^{34}$ cm^{-2} sec^{-1} (250 GeV protons x 10 GeV electrons)

ELIC Luminosity Concepts

- High bunch collision frequency (f=0.5 GHz)
- Short ion bunches ($\sigma_z \sim 5$ mm)
- Super strong final focusing ($\beta^* \sim 5$ mm)
- Large beam-beam parameters (0.01/0.1 per IP,
  0.025/0.1 largest achieved)

- Need high energy electron cooling of ion beams
- Need crab crossing

- Large synchrotron tunes to suppress synchro-betatron resonances
- Equidistant phase advance between four IPs

ELIC (p/e) Design Parameters

Beam energy	GeV	250/10	150/7	50/5
Figure-8 ring	km	2.5		
Collision freq	MHz	499		
Beam current	A	0.22/0.55	0.15/0.33	0.18/0.38
Particles/bunch	10^9	2.7/6.9	1.9/4.1	2.3/4.8
Energy spread	10^{-4}	3/3		
Bunch length, rms	mm	5/5		
Hori. emit., norm.	µm	0.70/51	0.42/35.6	.28/25.5
Vertical emit., norm.	µm	0.03/2.0	0.017/1.4	.028/2.6
β^*	mm	5/5		
Vert. b-b tune-shift		0.01/0.1		
Peak lum. per IP	10^{34} $cm^{-2}s^{-1}$	3.0	1.2	1.1
Number of IPs			4	
Luminosity lifetime	hours	24		

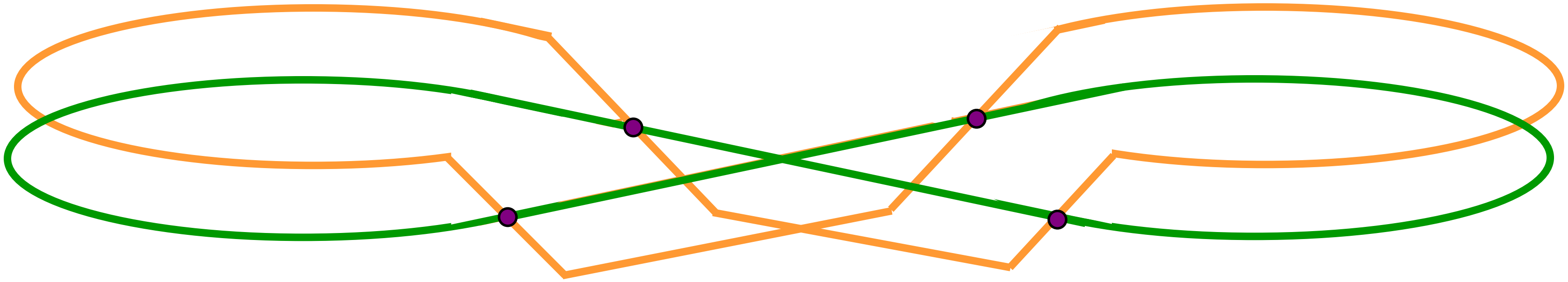
Electron parameters are red

ELIC (A/e) Design Parameters

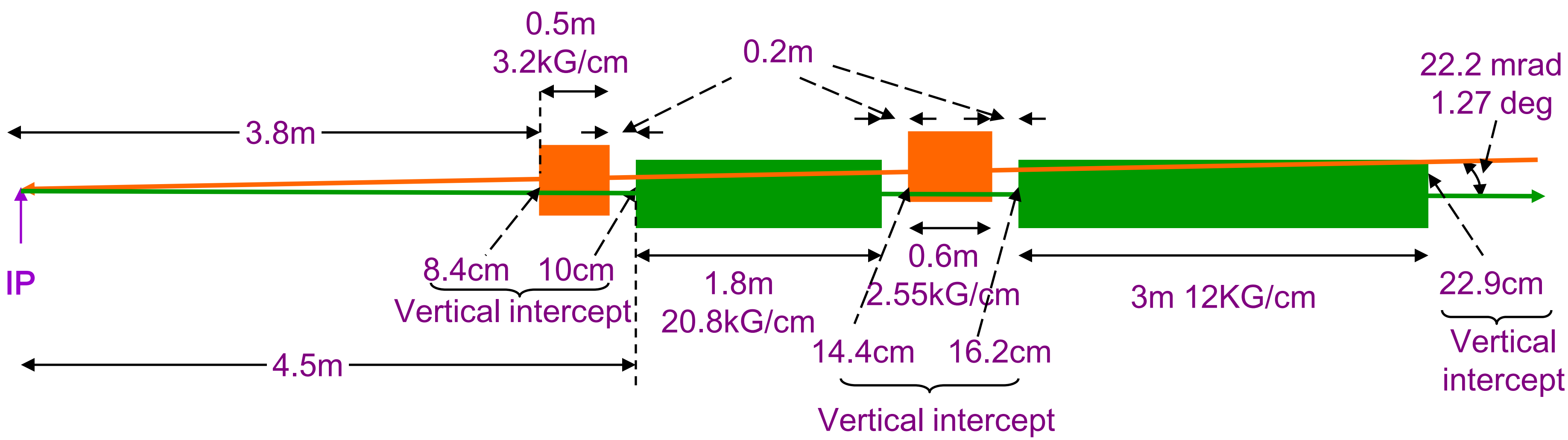
Ion	Max Energy ($E_{i,max}$)	Luminosity / n (7 GeV x $E_{i,max}$)	Luminosity / n (3 GeV x $E_{i,max}$/5)
	(GeV/nucleon)	10^{34} cm^{-2} s^{-1}	10^{33} cm^{-2} s^{-1}
Proton	150	3.0	2.2
Deuteron	75	3.0	2.2
$^{3}He^{+2}$	100	1.3	1.1
$^{4}He^{+2}$	75	1.3	1.1
$^{12}C^{+6}$	75	0.4	0.4
$^{40}Ca^{+20}$	75	0.13	0.13
$^{208}Pb^{+82}$	59	0.04	0.04

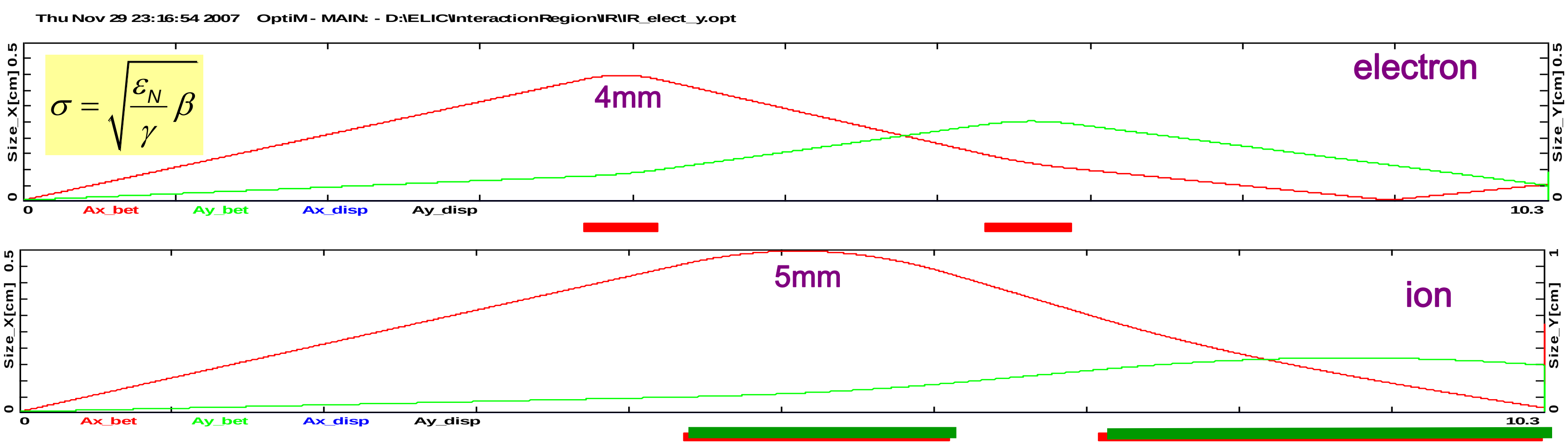
* Luminosity is given per nucleon per IP

Figure-8 Rings – Vertical ‘Stacking’



IP Magnet Layout and Beam Envelopes



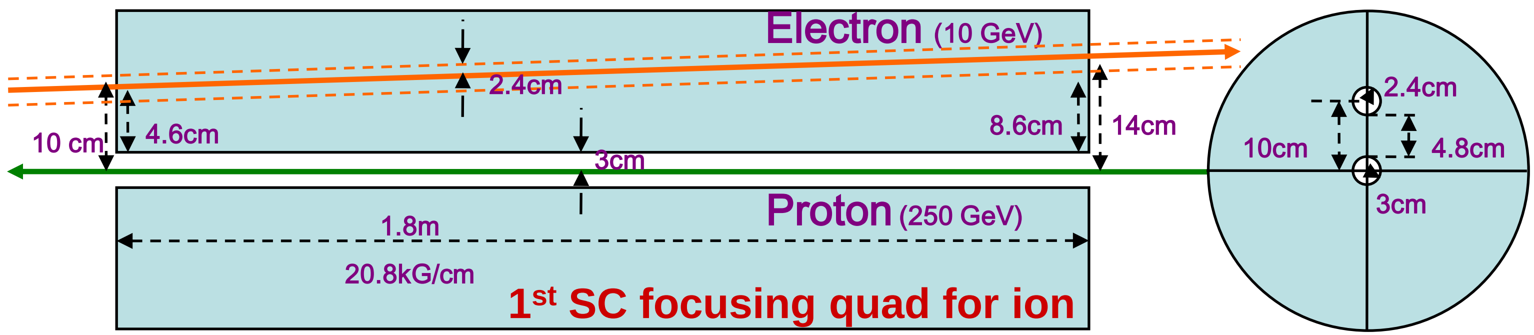


β^* OK

IR Final Quad

Optimization

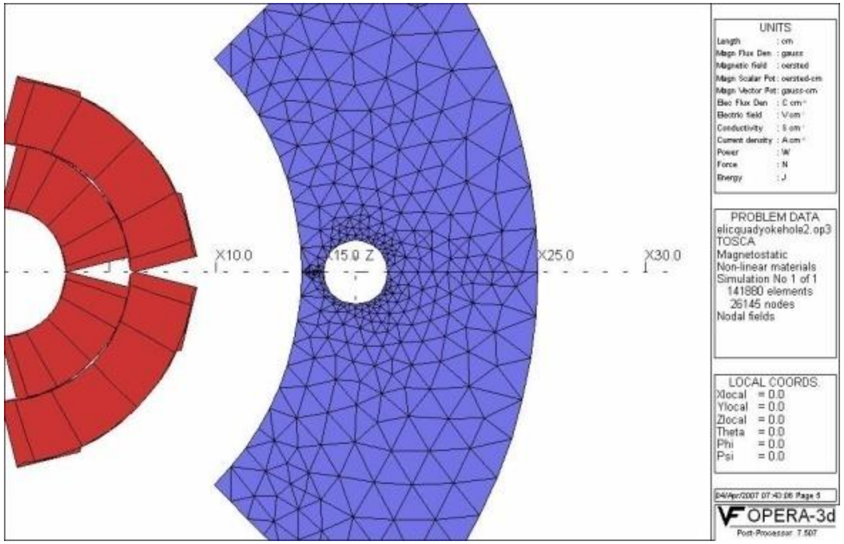
- IP configuration optimization
- "Lambertson"-type final focusing quad
- Crab crossing angle ➔ **22** *mrad*

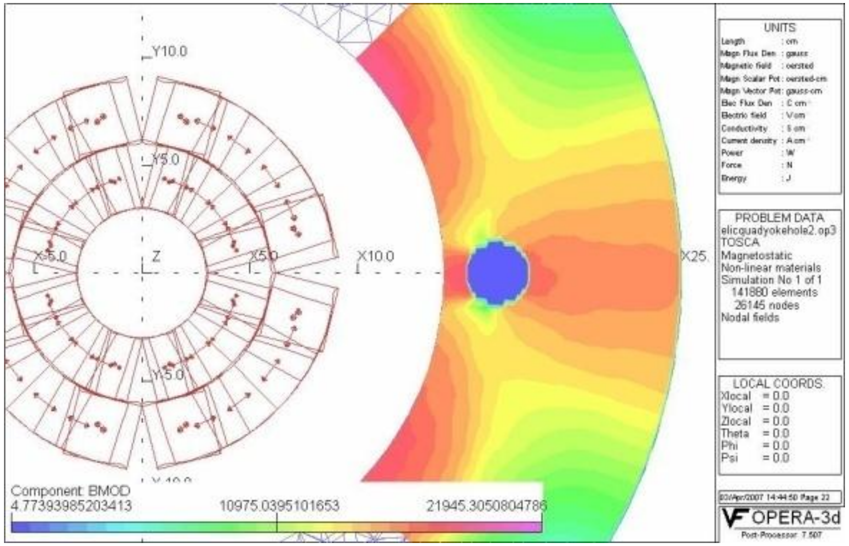


Lambertson Magnet Design

Cross section of quad with beam passing through

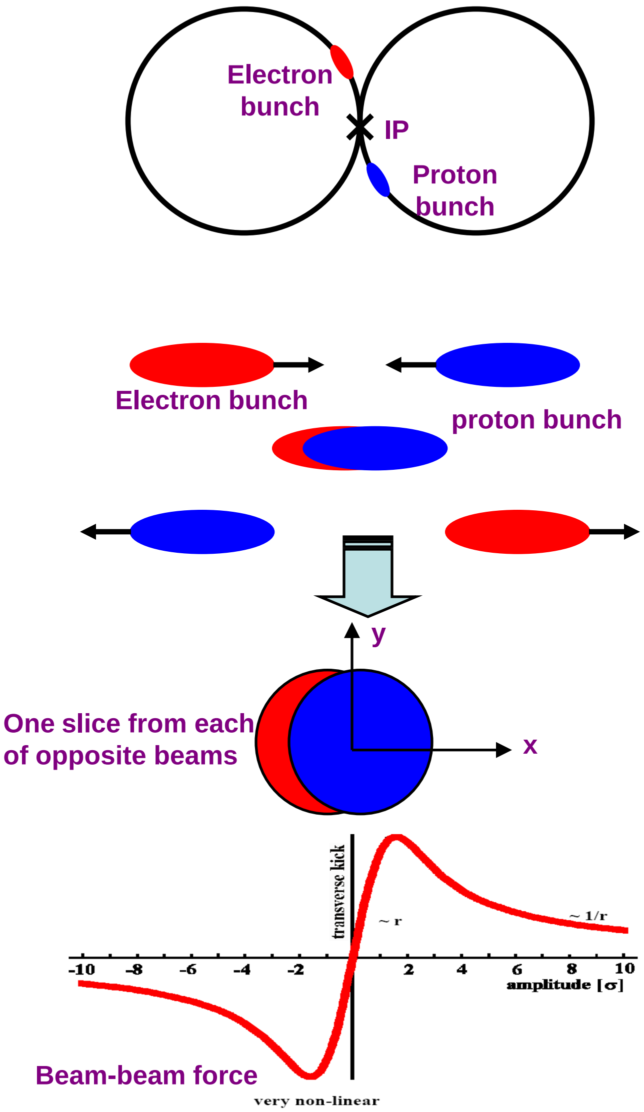
Magnetic field in cold yoke around electron pass.





Paul Brindza

Beam-Beam Effect in ELIC



Transverse beam-beam force

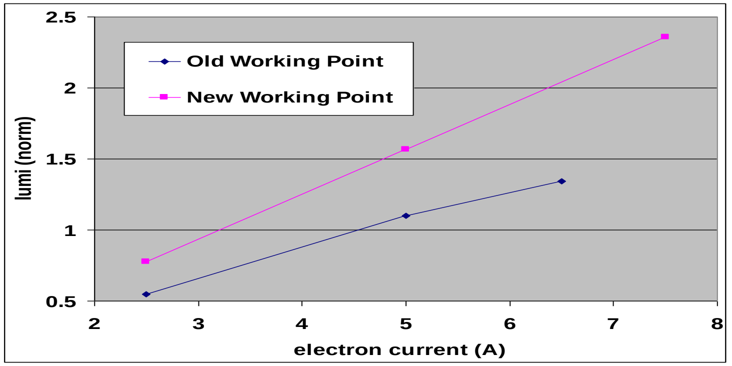
- **Highly nonlinear forces**
- **Produce transverse kicks between colliding bunches**
- **Can cause size/emittance growth or blowup**
- **Can induce coherent beam-beam instabilities**
- **Can decrease luminosity and its lifetime**

ELIC Case

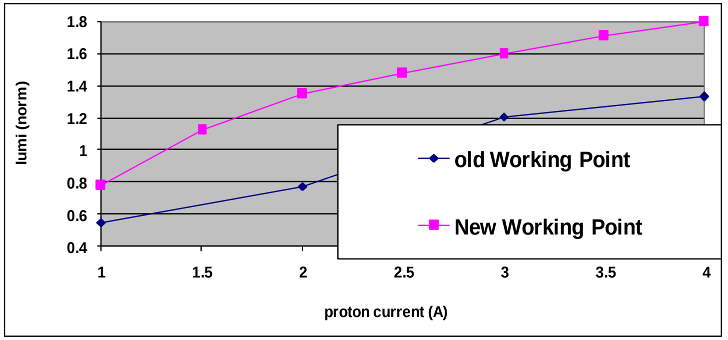
- **Highly asymmetric colliding beams (10 GeV/2.5 A on 250 GeV/1 A)**
- **Four IPs and Figure-8 rings**
- **Strong final focusing (β* 5 mm)**
- **Short bunch length (5 mm)**
- **Employs crab cavity**
- **vertical b-b tune shifts are 0.087/0.01**
- **Very large electron synchrotron tune (0.25) due to strong RF focusing**
- **Equal betatron phase advance (fractional part) between IPs**

Beam-Beam Simulations

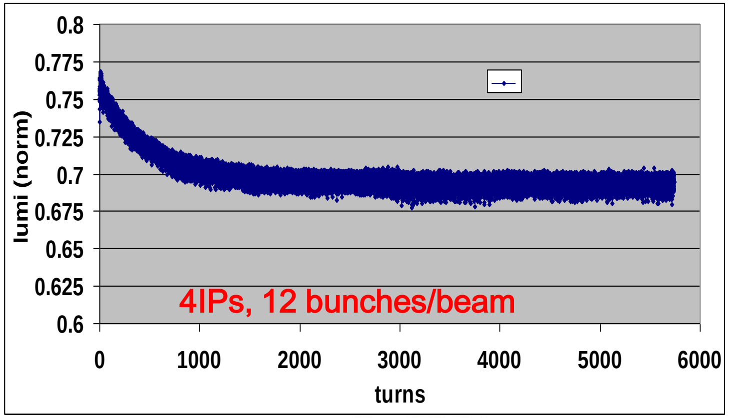
- Simulation Model
  - Single/multiple IPs, head-on collisions
  - Strong-strong self consistent Particle-in-Cell codes, developed by J. Qiang of LBNL
  - Ideal rings for electrons & protons, including radiation damping & quantum excitations for electrons



- Scope
  - 10k ~ 30k turns
  - 0.05 ~ 0.15 s of stored time (12 damping times)
    → reveals short-time dynamics with accuracy



- Simulation results
  - Equilibrium at 70% of peak luminosity, 1.9×10^{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
  - Simulations with 4 IPs and 12-bunch/beam showed stable luminosity and bunch sizes after one damping time, saturated luminosity is 1.8×10^{34} $cm^{-2}s^{-1}$ per IP, very small loss from single IP and single bunch operation



Supported by SciDAC

Opportunities for Staging

A medium energy EIC becomes the low energy ELIC ion complex

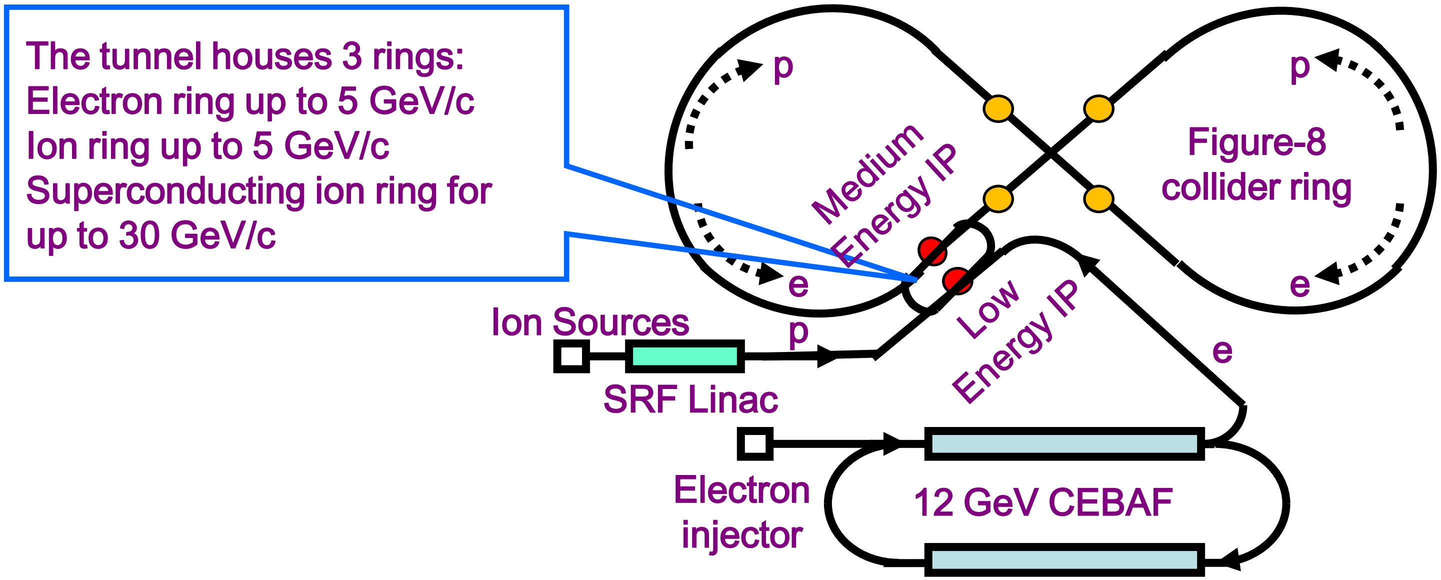
Lower energies and symmetric kinematics provide new science opportunities complementary to ELIC/eRHIC:

- Valence quarks/gluon structure beyond JLab 12 GeV
- Asymmetric sea for $x \sim M_\pi / M_N$
- GPDs, transverse spin at $x \sim 0.1$

Accelerator Advantages/Benefits

- Bring ion beams and associated technologies to JLab
- Have an early ring-ring collider at JLab
- Provides a test bed for new technologies required by ELIC
- Develop expertise and experience, acquire/train technical staff

MEIC & Staging of ELIC



Stage		Maximum Momentum (GeV/c)		Ring Size (m)		Ring Type	
		Proton	Electron	Ion	Electron	Ion	Electron
1	Low Energy	5	5	400	400	Warm	Warm
2	Medium Energy (MEIC)	30	5	400	400	SC	Warm
3	Medium Energy	30	10	400	1800	SC	Warm
4	High Energy (ELIC)	250	10	1800	1800	SC	Warm

Medium Energy EIC Features

- High luminosity near-symmetric collider
- CM energy region up to 24.5 GeV (30x5 GeV)
- High polarization for both electron and light ion beams
- Natural injection path to high energy ELIC
- Minimal R&D required
  - Space charge effect for low ion energy
  - Beam-Beam effect

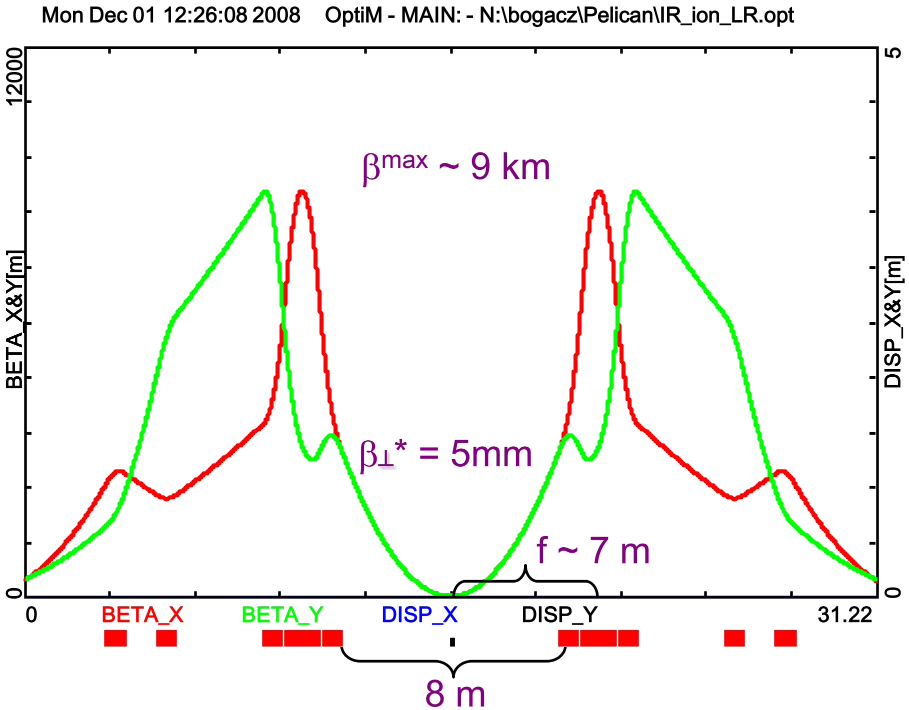
MEIC Parameter Table

Beam Momentum	GeV/c	5/5	10/5	30/5
Circumference	m	407	407	407
Beam Current	A	0.16/1	0.42/1	0.43/1
Repetition Rate	GHz	0.5	0.5	0.5
Particles per Bunch	10^{10}	0.2/1.25	0.52/1.25	0.54/1.25
Bunch Length	cm	5/0.25	5/0.25	5/0.25
Normalized Hori. Emittance	mm mrad	0.27/120	0.26/120	0.39/120
Normalized Vert. Emittance	mm mrad	0.27/12	0.26/12	0.39/12
Horizontal β^*	cm	0.5/2	0.5/1	0.5/0.5
Vertical β^*	cm	0.5/20	0.5/10	0.5/5
Beam Size at IP (x/y)	μm	15.7/15.7	11/11	7.8/7.8
Horizontal B-B Tune Shift		0.006/0.004	0.006/0.006	0.004/0.01
Vertical B-B Tune Shift		0.006/0.37	.01/0.1	0.004/0.1
Laslett Tune Shift		0.1/small	0.07/small	0.05/small
Luminosity	$10^{33} s^{-1} cm^{-2}$	0.4	2.1	4.4

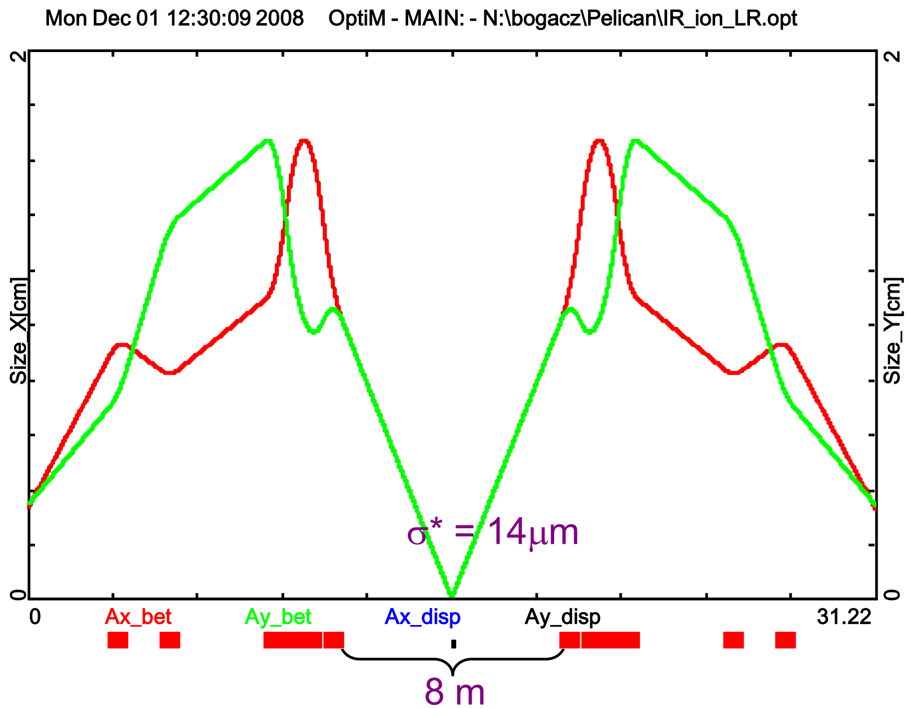
Electron parameters are red

Interaction Region: Simple Optics

Beta functions



Beam envelopes (σ_{RMS}) for ε_N = 0.2 mm mrad



$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

$$\beta^{max} = \beta^* + \frac{f_{tripl}^2}{\beta^*}, \quad f_{tripl}^2 \approx \beta^{max}\beta^*$$

Triplet based IR Optics

- first FF quad 4 m from the IP
- typical quad gradients ~ 12 Tesla/m for 5 GeV/c protons
- beam size at FF quads, σ_{RMS} ~ 1.6 cm

MEIC and ELIC Costs (2009 M$)

	MEIC	ELIC
Energy (GeV/c)	30x5	250x10
Peak luminosity ($10^{33}s^{-1}cm^{-2}$)	4.4	30
IPs and Detectors	1/1	4/1
Ring Size	400	1800
Ion injector (source, RFQ, Linac, LEBT, MEBT, civil, etc.)	74.5	74.5
Prebooster/Low energy collider (including civil)	23.8	23.8
Large booster/Medium energy collider (no civil)	32	
Small electron ring (for low & medium EIC)	14	
Storage-collider ring		
Civil		79.9
Electron ring (including RF, spin rotators)		125.7
Ion ring (including CLH, snakes)		210.1
Electron cooler	16	19.5
Others (IP beamline, experiment Halls, transport line from CEBAF)	42.6	89.6
Labor	22.5	67.6
Total	225.4	690.6
With PED, overhead (15%) and contingency (30%)	395.6	1209.4
Detector allowance	75	100
Pre-ops, R&D	26.7	89.1
Total Project Cost (TPC)	497.3	1398.5

Key R&D Issues

Item	Task	Comment
Forming the Ion Beam	Choose/optimize ion injection scheme	No new hardware development
Cooling of Ion Beams	Develop circulator cooler	ERL/Circulator Ring/Kicker development
Crab Cavity Development	Single and Multi-cell RF deflectors	KEK cavity OK for MEIC
Traveling Focusing Scheme	Choose scheme, optimize, and simulate	Needed only for lowest energy stage (15 GeV/c or lower)
Beam-Beam Effect	Expand existing simulations	Better simulations require more machine bunches
Beam Dynamics of Crab Crossing Beams	Simulations	

ELIC Research Plans

- Recently submitted to DOE, in conjunction with BNL, for inclusion as "stimulus" funding (15.4 M$ over 5 year grant period)
- Items
  - Common Items
    - Coherent Electron Cooling (BNL) 8.0 M$
    - ERL Technology (JLAB) 8.5 M$
    - Polarized ^{3}He Source (BNL) 2.0 M$
    - Crab Cavities (JLAB) 2.8 M$
  - ELIC Specific Items
    - Space Charge Effects Evaluation 0.9 M$
    - Spin Tracking Including Beam-Beam Force 1.6 M$
    - Simulations and Traveling Focus Scheme 1.6 M$

JLAB "Common" Items

- **Energy Recovery Technology for 100 MeV level electron beam.**
  - Demonstrate beam properties and robust sustainability at high electron current for a device compatible with circulator cooling ring
  - Conduct experiments at JLAB FEL

  Total labor: 20 FTE – years ($ 4.0 M)

  M&S: $4.5 M

  Duration: 5 years

  Subtotal: $8.5M

- **Crab cavities**

  Issue: The ELIC design is based on the use of crab cavities to reach luminosity at the 10^{35} cm^{-2} sec^{-1} level. Multi-cell crab cavities at 1.5 GHz have not been designed yet, and their effect on the electron and ion beam dynamics needs to be quantified.

  A. Prototype two 1500 MHz crab cavities

  B. Develop and test phase and amplitude stability scheme(s).

  A. Labor: 4 FTE – year ($ 0.8 M)

  M&S: $200K

  B. Labor: 4 FTE – year ($ 0.8 M)

  M&S: $1.0M

  Subtotal: $2.8M

"ELIC Specific" Items

- **Ion Space charge simulations (in collaboration with SNS)**
  - Explore "painting" technique for stacking via simulations
  - Experimental investigation in SNS.

    A. Total labor: 1.5 FTE – years ($ 0.3 M)
    Duration: 1 year
    B. Labor: 0.5 FTE – year ($ 0.1 M)
    M&S: $500K for diagnostics development

  Subtotal: $0.9M
- **Spin Track Studies for ELIC**

  - A. Full electron and ion spin tracking/including vertical bend in electron ring
  - B. Beam-beam effect on spin depolarization

  A. Total labor: 2.0 FTE – years ($ 0.4 M)
  Duration: 2 years
  B. Labor: 6 FTE – year ($ 1.2 M)
  Duration: 5 years

  Subtotal: $1.6M
- **Studies Traveling Focus Scheme**

  - Feasibility studies for the scheme (essential for ELIC staging)
  - Develop experimental proof-of-principle program

  Total labor: 3 FTE – years ($ 0.6 M)
  Duration: 2 years
  Subtotal: $0.6M
- **Simulation studies supporting ELIC project**

  Issue: Use simulations to evaluate electron-ion beam-beam effects, including the kink instability, e-beam disruption and beam emittance growth in the collider. Investigate conventional electron cooling for both magnetized and non-magnetized schemes. For electron cooling based on a circulator ring, investigate beam cooling interactions and space charge stability of the electron beam in the circulator ring.

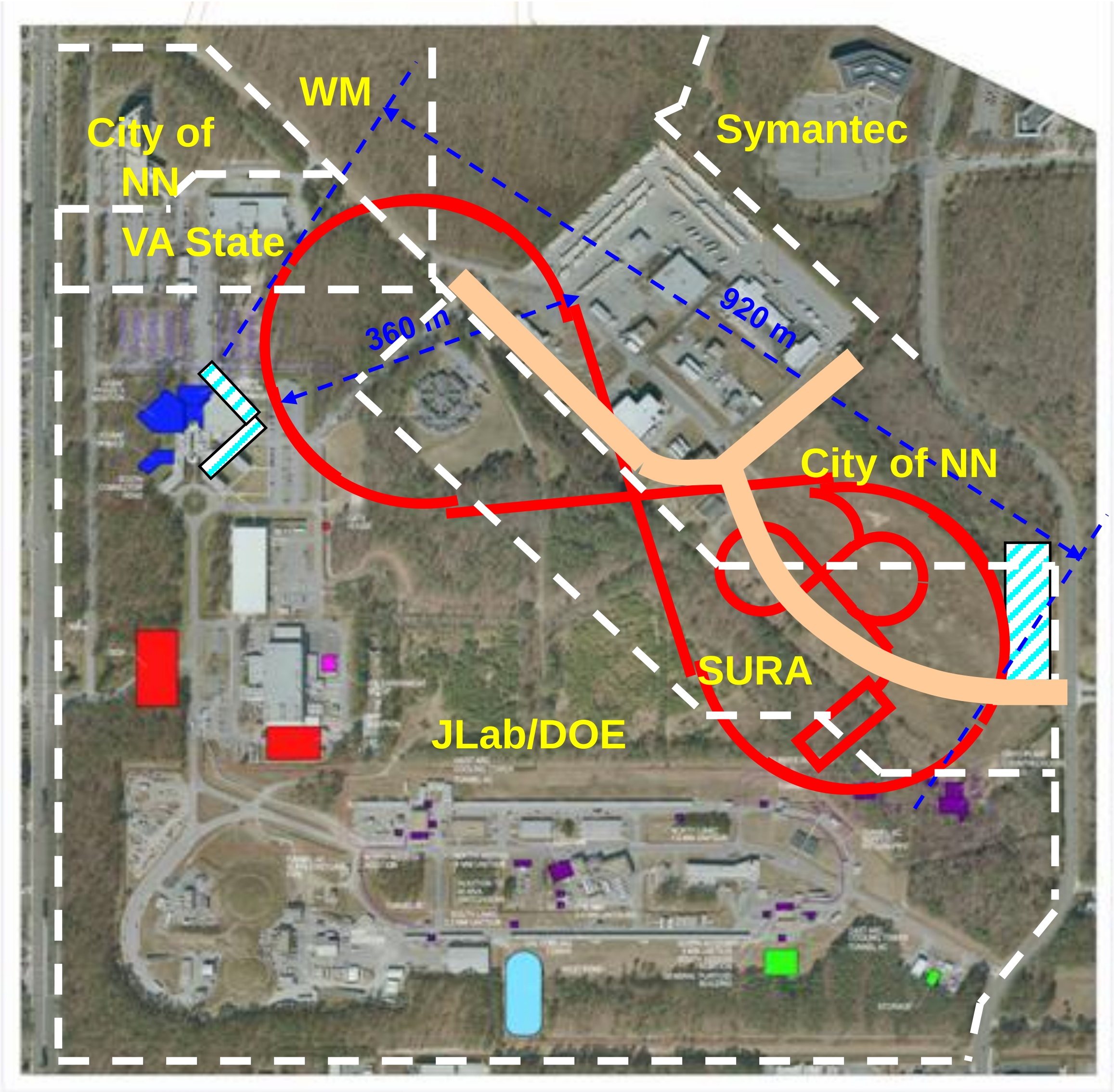
  Total labor: 5 FTE-years ($ 1.0 M)
  Duration: 5 years
  Subtotal: $1.0M

Summary

- The ELIC collider promises to accelerate a wide variety of polarized light ions and unpolarized heavy ions to high energy, enabling a unique physics program.
- The final ELIC luminosity should comfortably exceed 1×10^{34} $cm^{-2}s^{-1}$ for protons.
- Low/medium energy stages enable a rich physics program not covered by a high-energy collider.
- The initial design studies indicate that luminosity of the intermediate colliders can exceed 1×10^{33} $cm^{-2}s^{-1}$. This luminosity utilizes staged ion beam cooling and crab crossing.
- The R&D plans supporting ELIC have been recently updated and re-submitted.

BACKUP SLIDES

ELIC at the JLab Site



ELIC Cost Estimate (2009 M$)

	Stage 1	Stage 2	Stage 3	Full ELIC
Energy (GeV/c)	5x5	30x5	30x10	250x10
Peak luminosity ($10^{33}s^{-1}cm^{-2}$)	0.4	4.4	7	30
IPs and Detectors	1/1	1/1	1/1	4/1
Ring Size	400	400	400x1800	1800
Ion injector (source, RFQ, Linac, LEBT, MEBT, civil, etc.)	74.5	74.5	74.5	74.5
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Electron ring (including RF, spin rotators)			125.7	125.7
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Labor	18.2	22.5	45.5	67.6
Total	185.1	225.4	440.0	690.6
With PED, overhead (15%) and contingency (30%)	324	395.6	778	1209.4
Detector allowance	50	75	100	100
Pre-ops, R&D	22.2	26.7	44.9	89.1
Total Project Cost (TPC)	396.8	497.3	916.4	1398.5

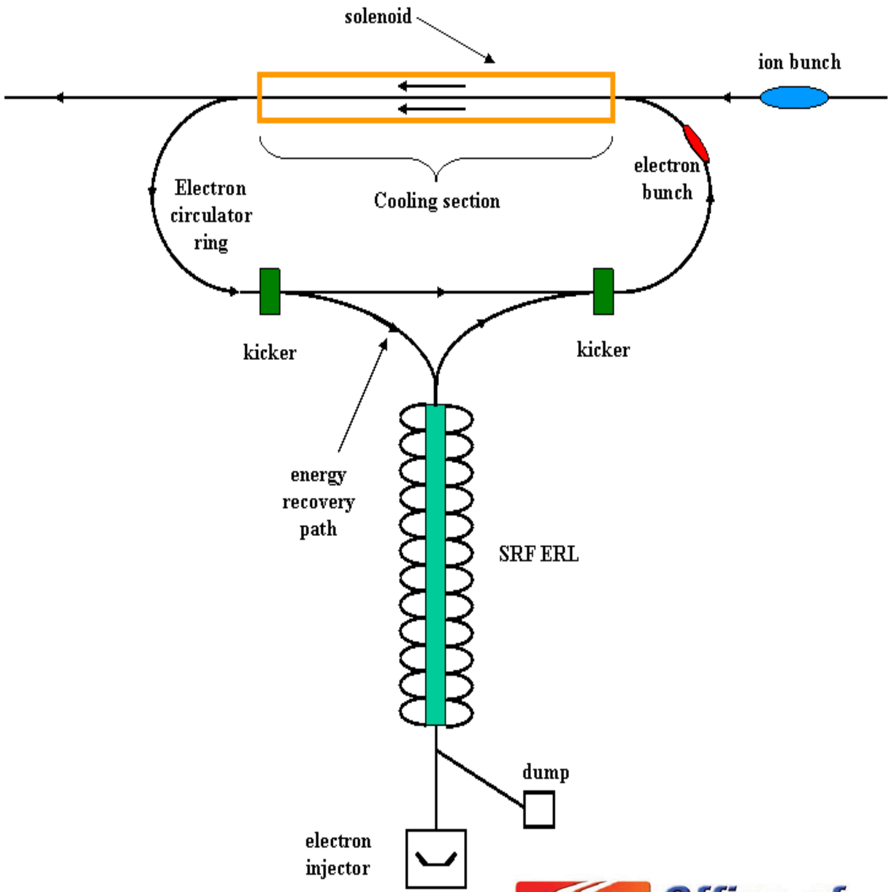
Production of Ion Beam

- One Idea
  - SRF to 50 to 300 MeV/c
  - Accumulate current in Low Energy Ring
  - Accelerate to final energy
  - Store in Low Energy Ring or send on to next ring
- Another Idea
  - Accelerate to ~ 2 GeV/c in an SRF linac
  - Accumulate current in Low Energy Ring
  - Accelerate to final energy
  - Store in Low Energy Ring or send on to next ring

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

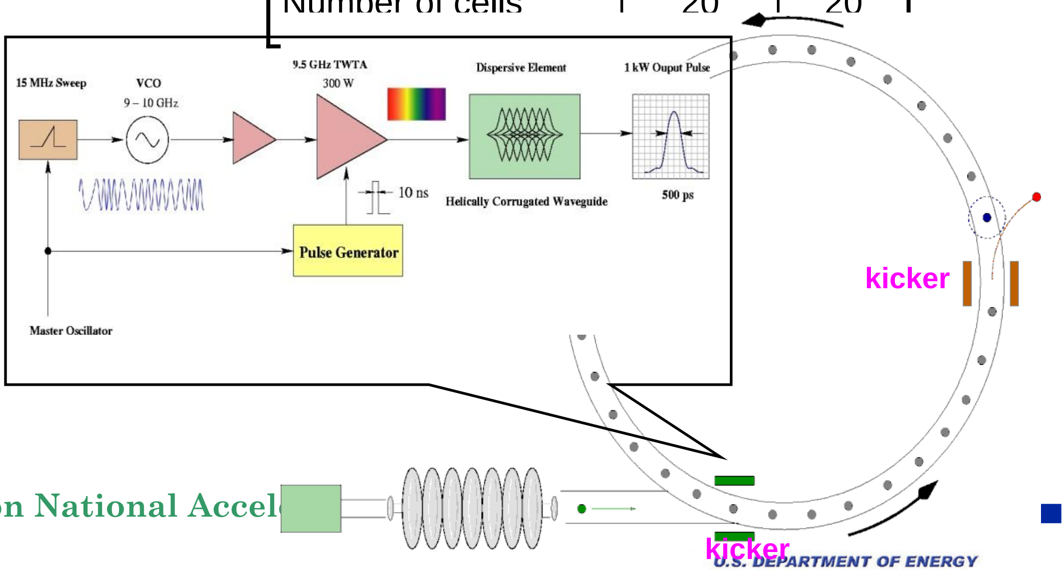


Fast Kicker for Circulator Cooling Ring

- Sub-ns pulses of 20 kW and 15 MHz are needed to insert/extract individual bunches.
- RF chirp techniques hold the best promise of generating ultra-short pulses. State-of-Art pulse systems are able to produce ~2 ns, 11 kW RF pulses at a 12 MHz repetition rate. This is very close to our requirement, and appears to be technically achievable.
- Helically-corrugated waveguide (HCW) exhibits dispersive qualities, and serves to further compress the output pulse without excessive loss. Powers ranging from up10 kW have been created with such a device.
- Collaborative development plans include studies of HCW, optimization of chirp techniques, and generation of 1-2 kW peak output powers as proof of concept.
- Kicker cavity design will be considered

Estimated parameters for the kicker

Beam energy	MeV	125
Kick angle	10^{-4}	3
Integrated BdL	GM	1.25
Frequency BW	GHz	2
Kicker Aperture	Cm	2
Peak kicker field	G	3
Kicker Repetition Rate	MHz	15
Peak power/cell	KW	10
Average power/cell	W	15
Number of cells	20	20



Cooling Time and Ion Equilibrium

Multi-stage cooling scenario:

- 1st stage: longitudinal cooling at injection energy (after transverses stochastic cooling)
- 2nd stage: initial cooling after acceleration to high energy
- 3rd stage: continuous cooling in collider mode

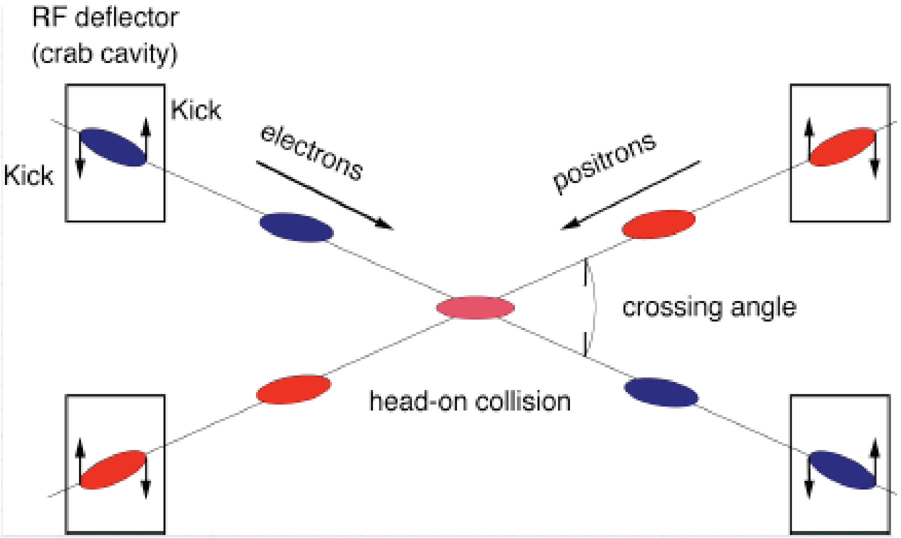
Cooling rates and equilibrium of proton beam

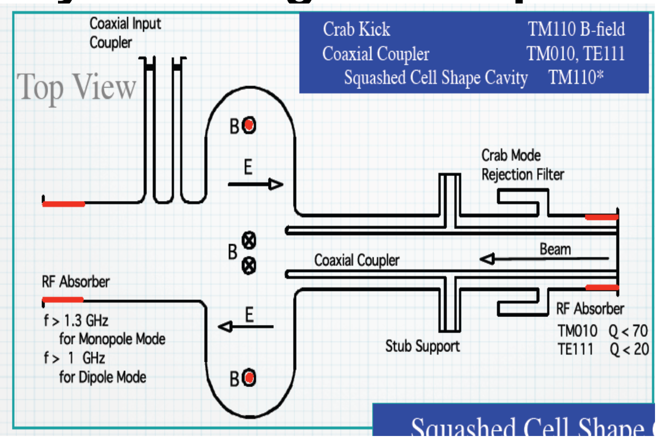
Parameter	Unit	Value	Value
Energy	GeV/MeV	30/15	225/123
Particles/bunch	10^{10}	0.2/1	
Initial energy spread*	10^{-4}	30/3	1/2
Bunch length*	cm	20/3	1
Proton emittance, norm*	μm	1	1
Cooling time	min	1	1
Equilibrium emittance $\varepsilon_x/\varepsilon_y$ **	μm	1/1	1/0.04
Equilibrium bunch length**	cm	2	0.5
Cooling time at equilibrium	min	0.1	0.3
Laslett's tune shift (equil.)		0.04	0.02

* max.amplitude
** norm.,rms

Crab Crossing

- **High repetition rate requires crab crossing to avoid parasitic beam-beam interaction**
- **Crab cavities needed to restore head-on collision & avoid luminosity reduction**
- **Minimizing crossing angle reduces crab cavity challenges & required R&D**





KEKB Squashed cell@TM110 Mode

Crossing angle = 2 x 11 mrad

V_{kick}=1.4 MV, E_{sp}= 21 MV/m

ELIC R&D: Crab Crossing

Crab cavity development

Electron: 1.2 MV – within state of art
(KEK, single Cell, 1.8 MV)

Ion: 24 MV
(Integrated B field on axis 180G/4m)

Crab Crossing R&D program

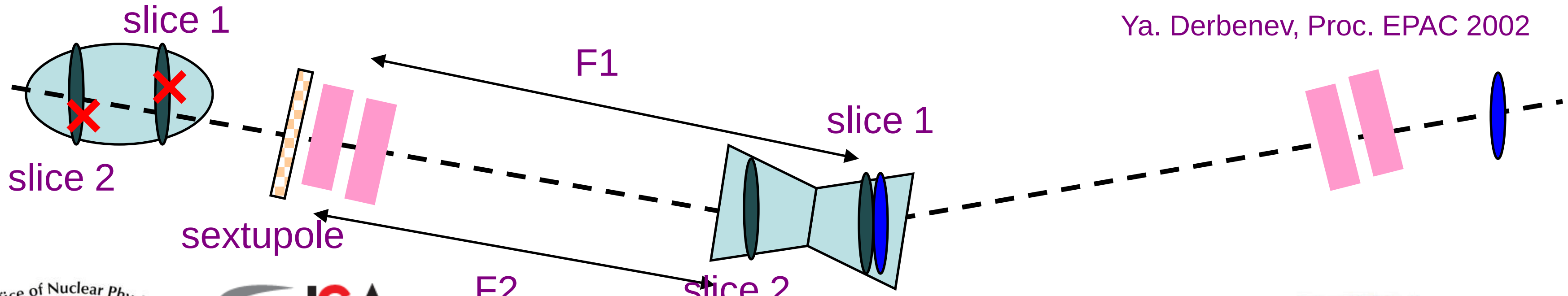
- Understand gradient limit and packing factor
- Multi-cell SRF crab cavity design capable for high current operation.
- Phase and amplitude stability requirements
- Beam dynamics study with crab crossing

Interaction Region: Traveling Focusing

- Under same space charge tune-shift limit, we need to increase ion bunch length in order to increase bunch charge, and hence increase luminosity (p < 15 GeV/c)
- Hour glass effect would normally kill collider luminosity if ion bunch length is much larger than β^*
- The "Traveling Focusing" scheme can mitigate hour-glass effect by moving the final focusing point along the long ion bunch. This setup enables the short electron bunch to collide with different slices of the long ion bunch at their relative focusing points
- Nonlinear elements (sextupoles) working with linear final focusing block produce non-uniform focus length for different slices of a long bunch

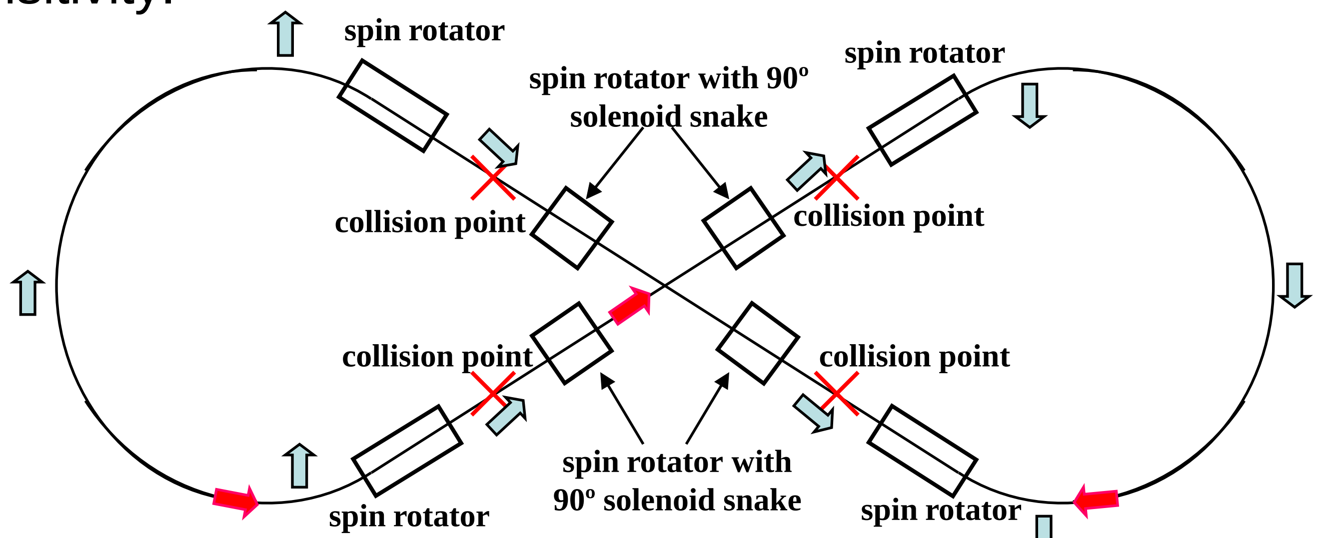
Brinkmann and Dohlus,

Ya. Derbenev, Proc. EPAC 2002



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
  - High polarization in the ring by electron self-polarization
  - SC solenoids at IPs removes spin resonances and energy sensitivity.



Electron polarization parameters

Parameter	Unit			
Energy	GeV	3	5	7
Beam cross bend at IP	mrad	70		
Radiation damping time	ms	50	12	4
Accumulation time	s	15	3.6	1
Self-polarization time *	h	20	10	2
Equilibrium polarization, max **	%	92	91.5	90
Beam run time	h	Lifetime		

* Time can be shortened using high field wigglers.

** Ideal max equilibrium polarization is 92.4%. Degradation is due to radiation in spin rotators.

COSY as Pre-Booster/Collider Ring

- COSY complex provides a good solution for the EIC pre-booster/low energy collider ring
- Adding 4 dipoles on each arc can bring maximum momentum of COSY synchrotron from 3.7 GeV/c to 5 GeV/c, while still preserving its optics
- COSY existing cooling facilities can be reused