Director's Accelerator R&D Review
CASA Summary/ELIC

Geoffrey Krafft

On behalf of the members of the

Center for Advanced Studies of Accelerators

March 20, 2009

OUTLINE

- Introduction to the CASA Department
- CASA Goals and Talks
- ELIC (Goal I)
  - Project
  - Staging
  - Luminosity Studies
  - Cost Estimates
- Compact Sources
  - THz Sources
  - MIT CUBIX
- Education

CASA DEPARTMENT

- **Staff**
  - **10 Scientific Staff (most > 10 years experience) + Director**
  - **7 Graduate Students**
  - **Rough equality between theory and experiment**
- **Clients**
  - **12 GeV Project**
  - **6 GeV Operations**
  - **EIC Project**
  - **FEL Department**
  - **Smaller HEP-funded projects (roughly 15% of effort)**

Five CASA Goals

1. Design a future Electron Ion Collider (EIC) appropriate for Jlab (Krafft)

2. Study current limiting phenomena in SRF Linacs and Energy Recovery Linacs (ERLs), including mitigation techniques (Tiefenback)

3. Develop instrumentation and beam-based measurement procedures for SRF Linacs (Tiefenback)

4. Develop, in collaboration with the FEL Dept, a design for a 4th Generation Light Source based on an SRF Linac

5. Study large-aperture Recirculating Linear Accelerators (RLAs) based on SRF Linacs (Bogacz)

ELIC Study Group & Collaborators

A. Afanasev, A. Bogacz, 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, A. Hutton, C. Hyde, T. Horn, R. Kazimi, G. A. Krafft, F. Klein, R. Li, L. Merminga, J. Musson, P. Nadel-Turonski, M. Poelker, R. Rimmer, Chaivat Tengsirivattana, A. Thomas, H. Wang, C. Weiss, B. Wojtsekhowski, B. Yunn, Y. Zhang - Jefferson Laboratory Staff and Users

W. Fischer, C. Montag - Brookhaven National Laboratory

V. Danilov - Oak Ridge National Laboratory

V. Dudnikov - Brookhaven Technology Group

P. Ostroumov - Argonne National Laboratory

V. Derenchuk - Indiana University Cyclotron Facility

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

V. Shemelin - Cornell University

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

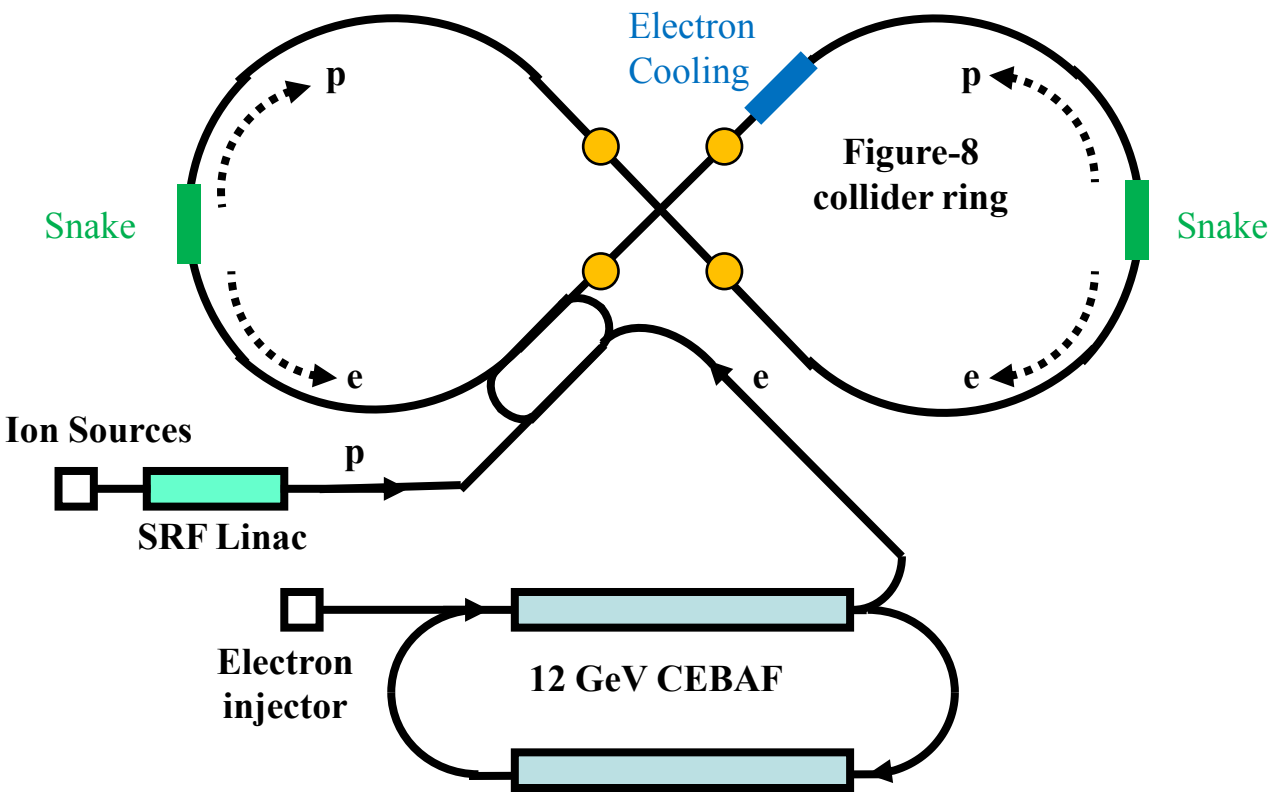
- **Ion Species**
  - Polarized H, D, ^{3}He, possibly Li
  - Up to heavy ion A = 208, fully stripped

- **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 (ERL)-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		

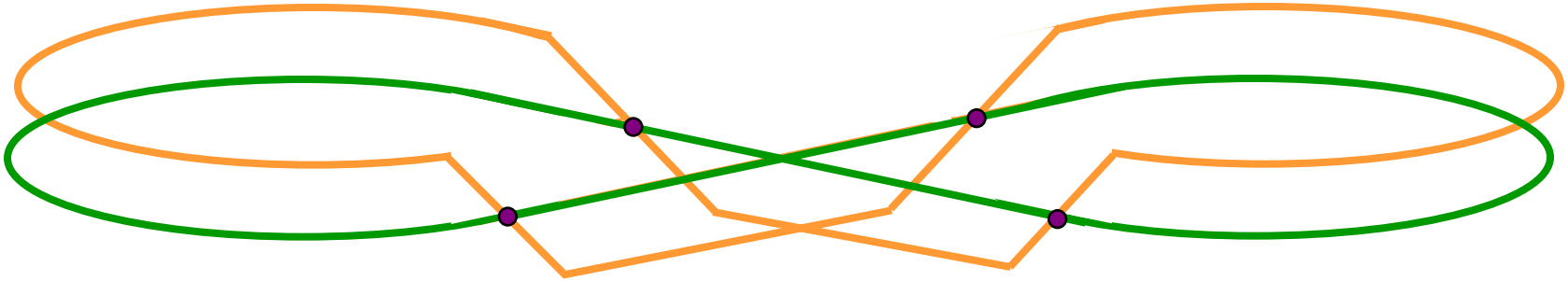
Electron parameters are red

ELIC (A/e) Design Parameters

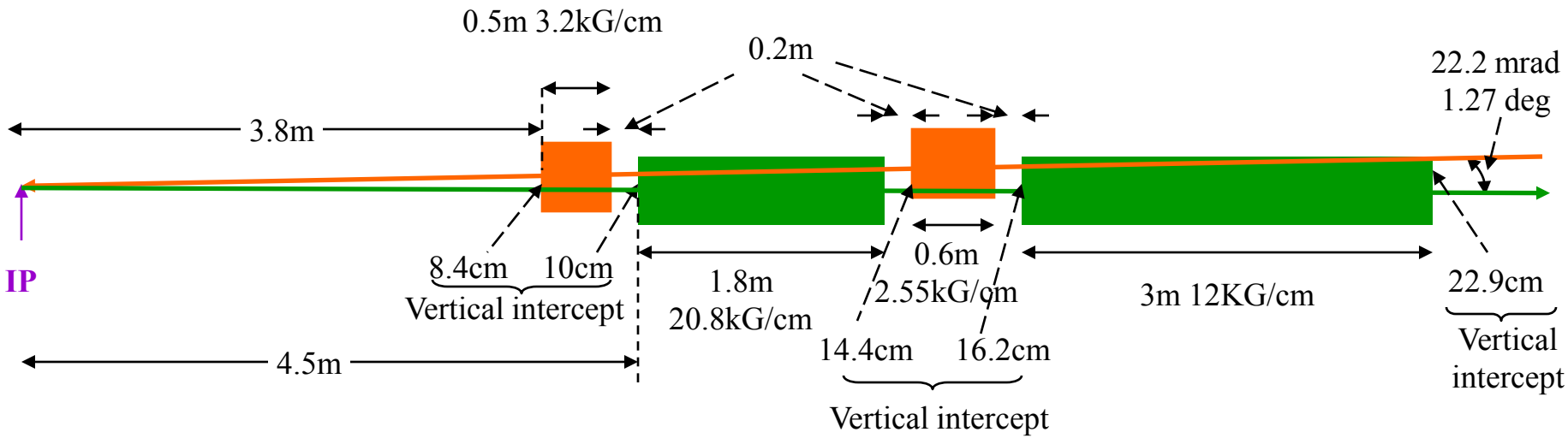
Ion	Max Energy ($E_{i,max}$)	Luminosity / n (7 GeV x $E_{i,max}$)	Luminosity / n (3 GeV x $E_{i,max}$/5)
	(GeV/nucleon)	10^{34} cm^{-2} s^{-1}	10^{33} cm^{-2} s^{-1}
Proton	150	3.0	2.2
Deuteron	75	3.0	2.2
$^{3}He^{+2}$	100	1.3	1.1
$^{4}He^{+2}$	75	1.3	1.1
$^{12}C^{+6}$	75	0.4	0.4
$^{40}Ca^{+20}$	75	0.13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

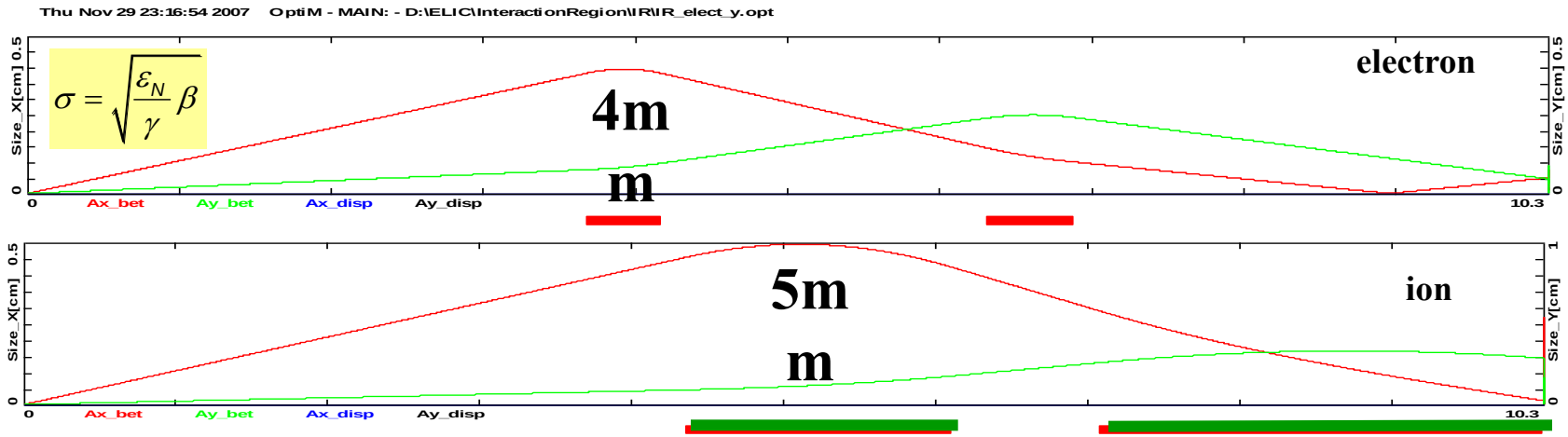
*** Luminosity is given per nucleon per IP**

Figure-8 Rings – Vertical 'Stacking'



IP Magnet Layout and Beam Envelopes



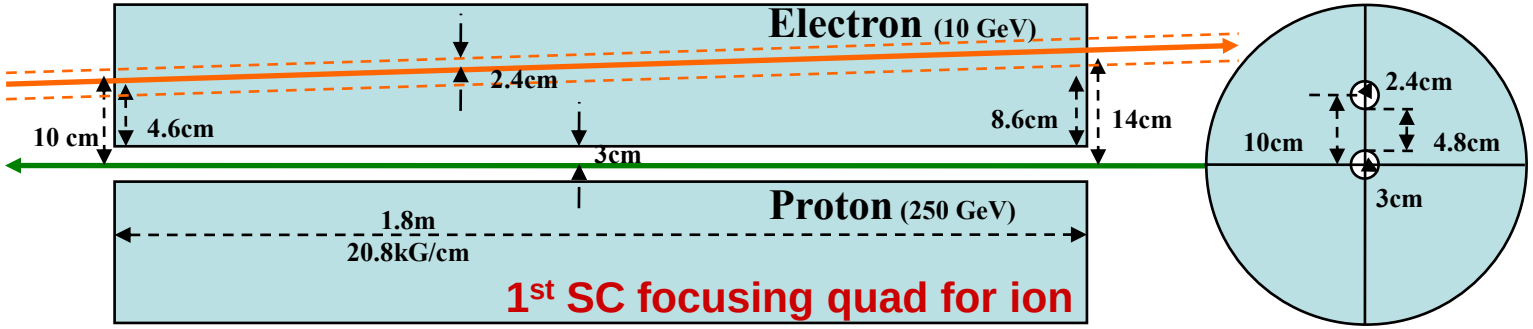


β^* OK

IR Final Quad

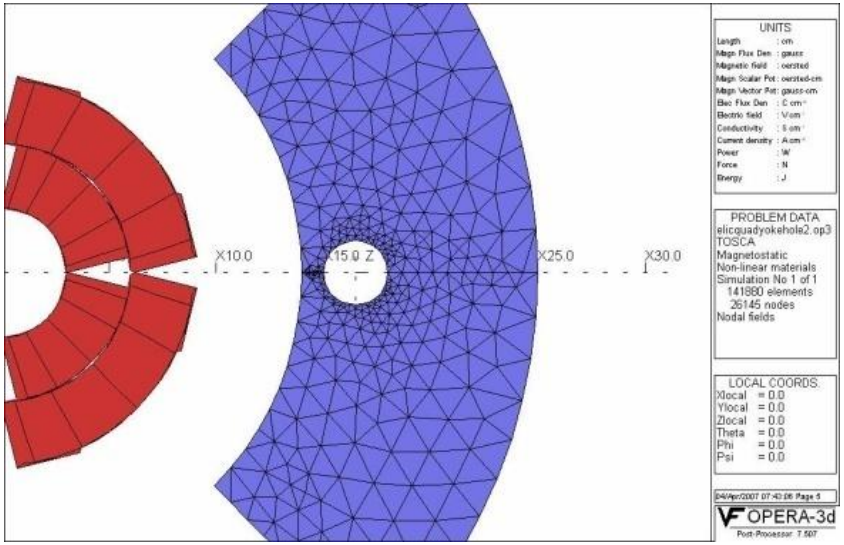
Optimization

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

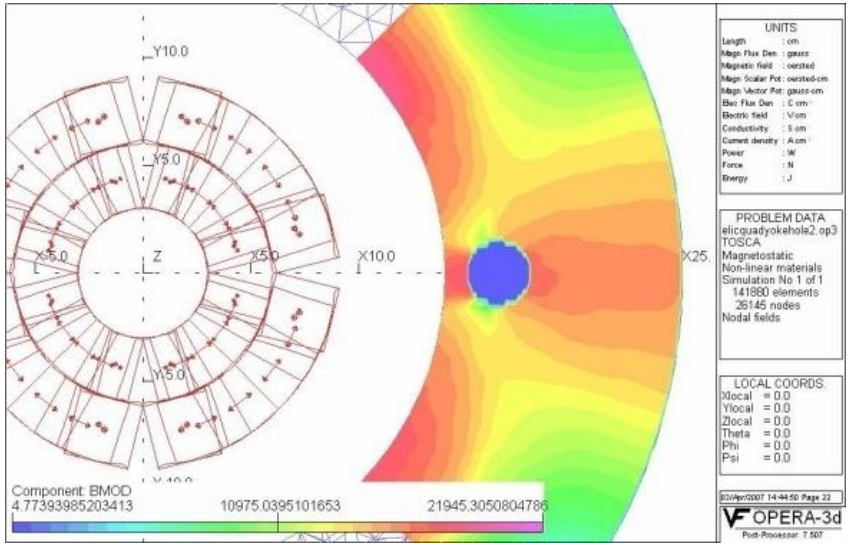


Lambertson Magnet Design

Cross section of quad with beam passing through

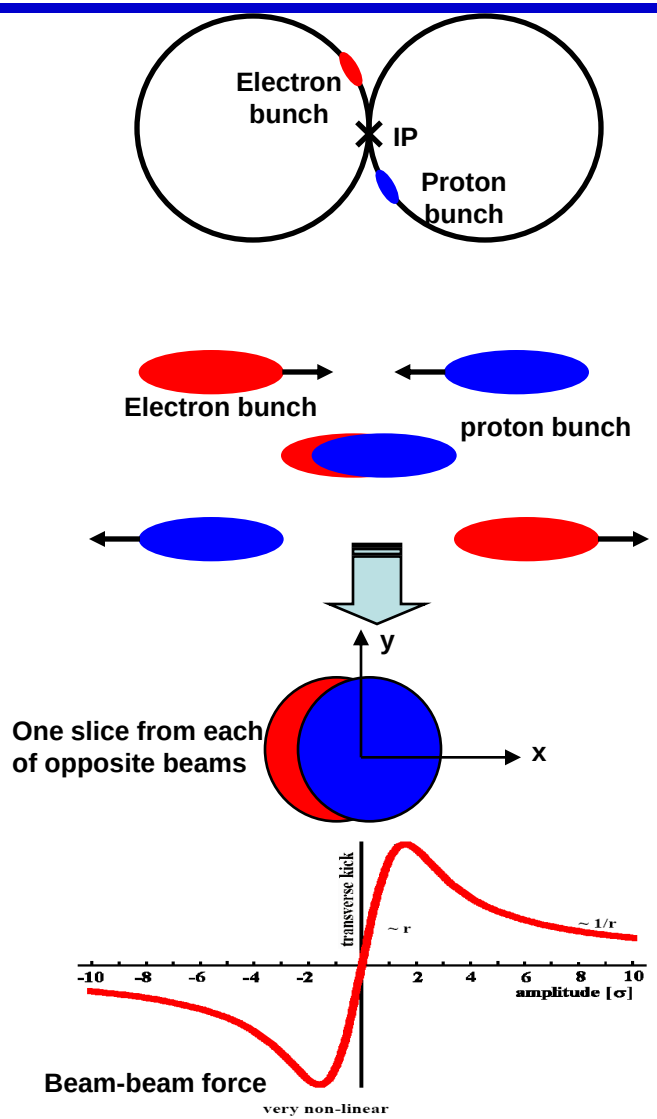


Magnetic field in cold yoke around electron pass.



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

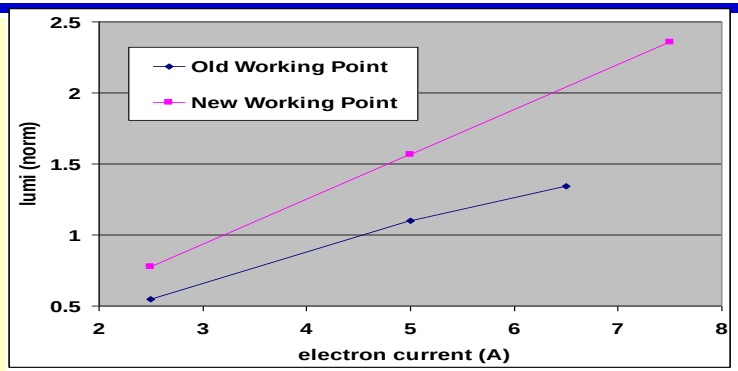
ELIC Case

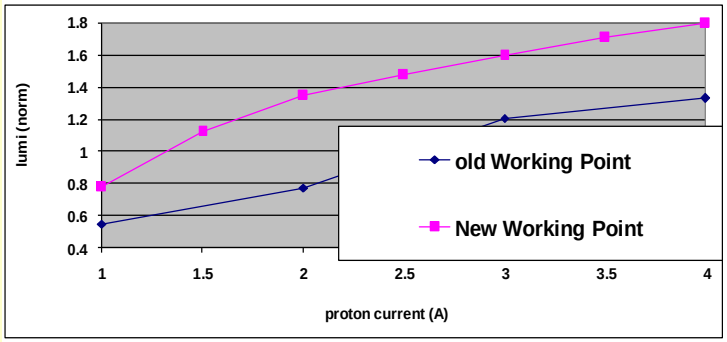
- Highly asymmetric colliding beams (10 GeV/2.5 A on 250 GeV/1 A)
- Four IPs and Figure-8 rings
- Strong final focusing (β^* 5 mm)
- Short bunch length (5 mm)
- Employs crab cavity
- vertical b-b tune shifts are 0.087/0.01
- Very large electron synchrotron tune (0.25) due to strong RF focusing
- Equal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

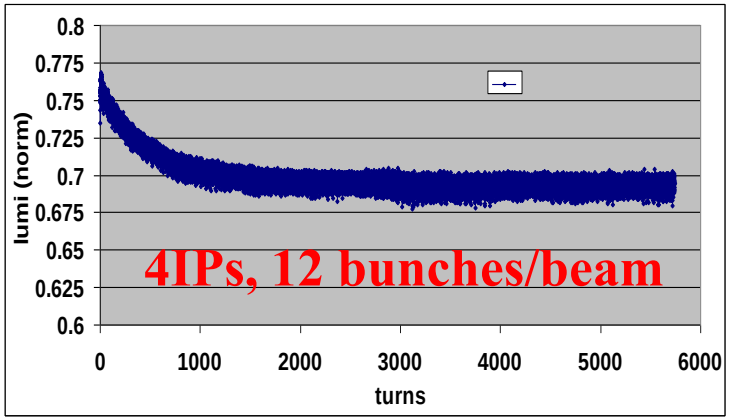
Beam-Beam Simulations

- **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:

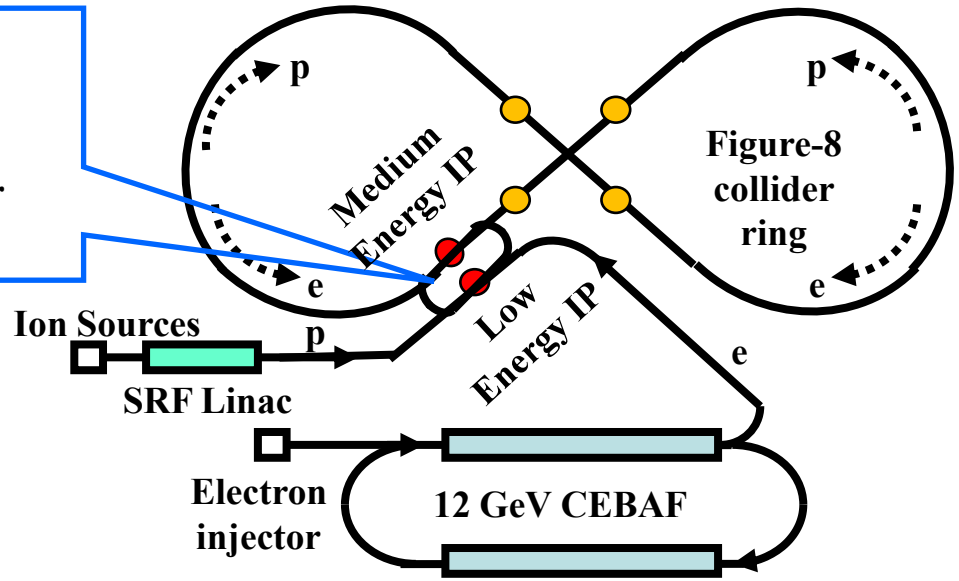
- **Valence quarks/gluon structure beyond JLab 12 GeV**
- **Asymmetric sea for $x \sim M_\pi / M_N$**
- **GPDs, transverse spin at x ~ 0.1**

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

The tunnel houses 3 rings:
Electron ring up to 5 GeV/c
Ion ring up to 5 GeV/c
Superconducting ion ring for up to 30 GeV/c



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

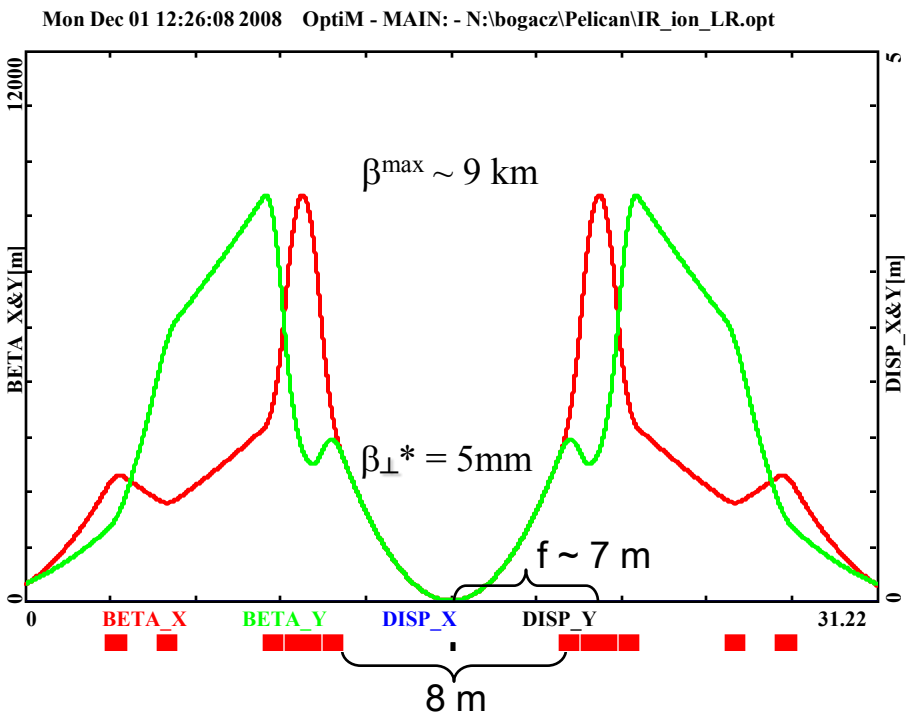
MEIC Parameter Table

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

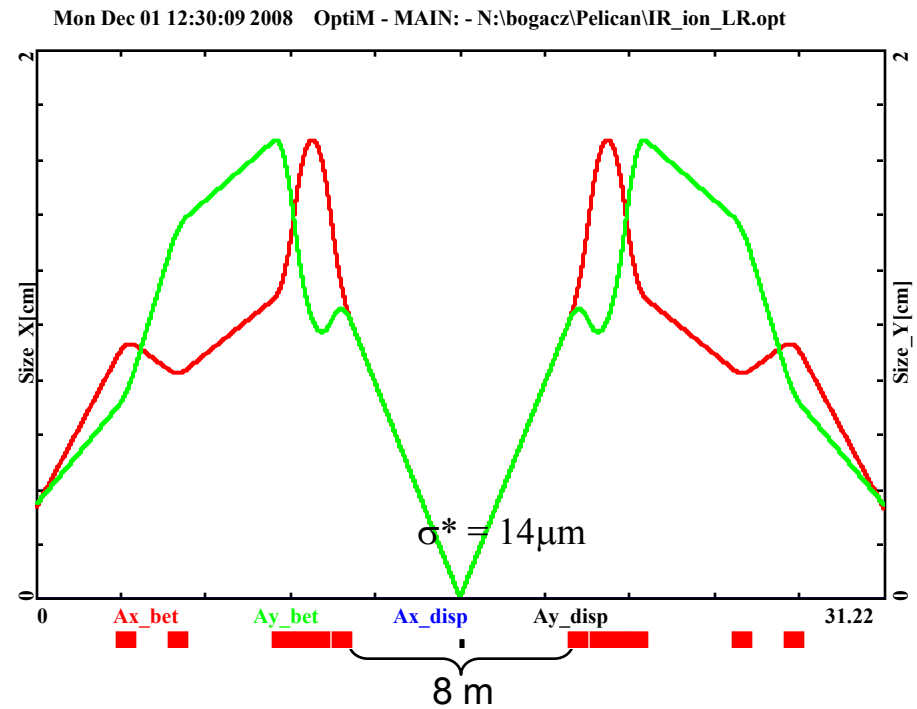
Electron parameters are red

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**

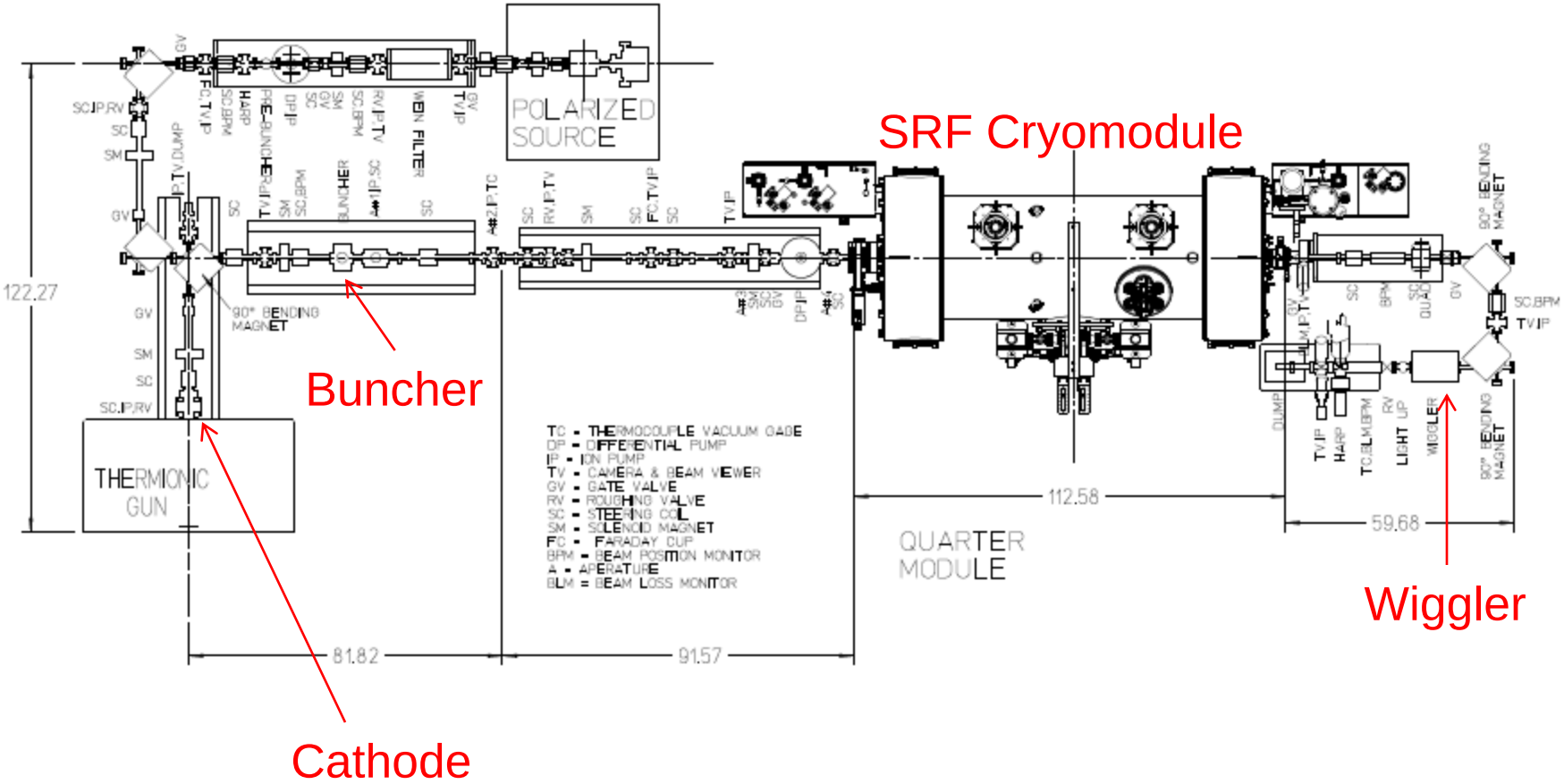
  Issue: Use simulations to evaluate electron-ion beam-beam effects, including the kink instability, e-beam disruption and beam emittance growth in the collider. Investigate conventional electron cooling for both magnetized and non-magnetized schemes. For electron cooling based on a circulator ring, investigate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

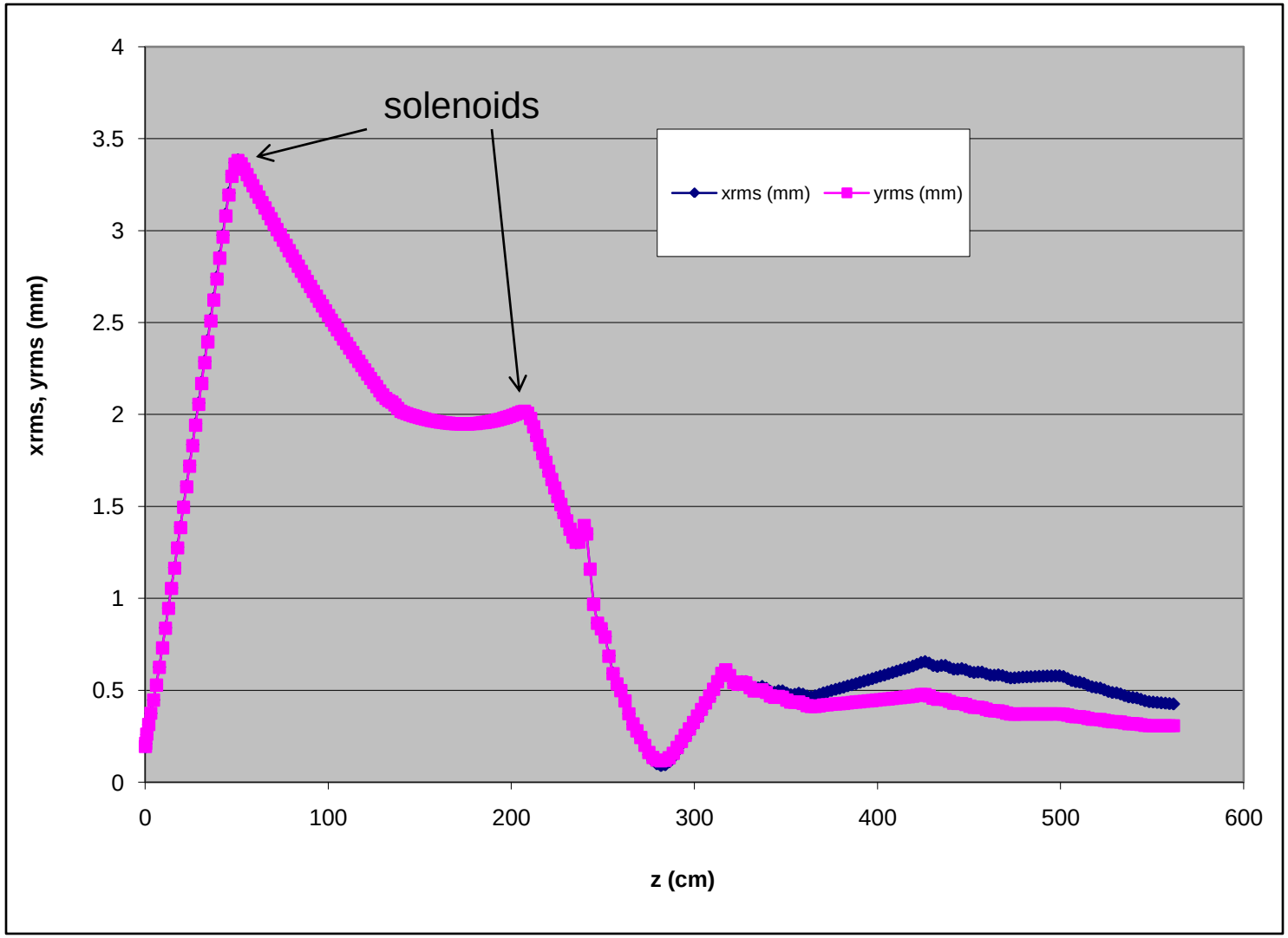
THz Source Layout



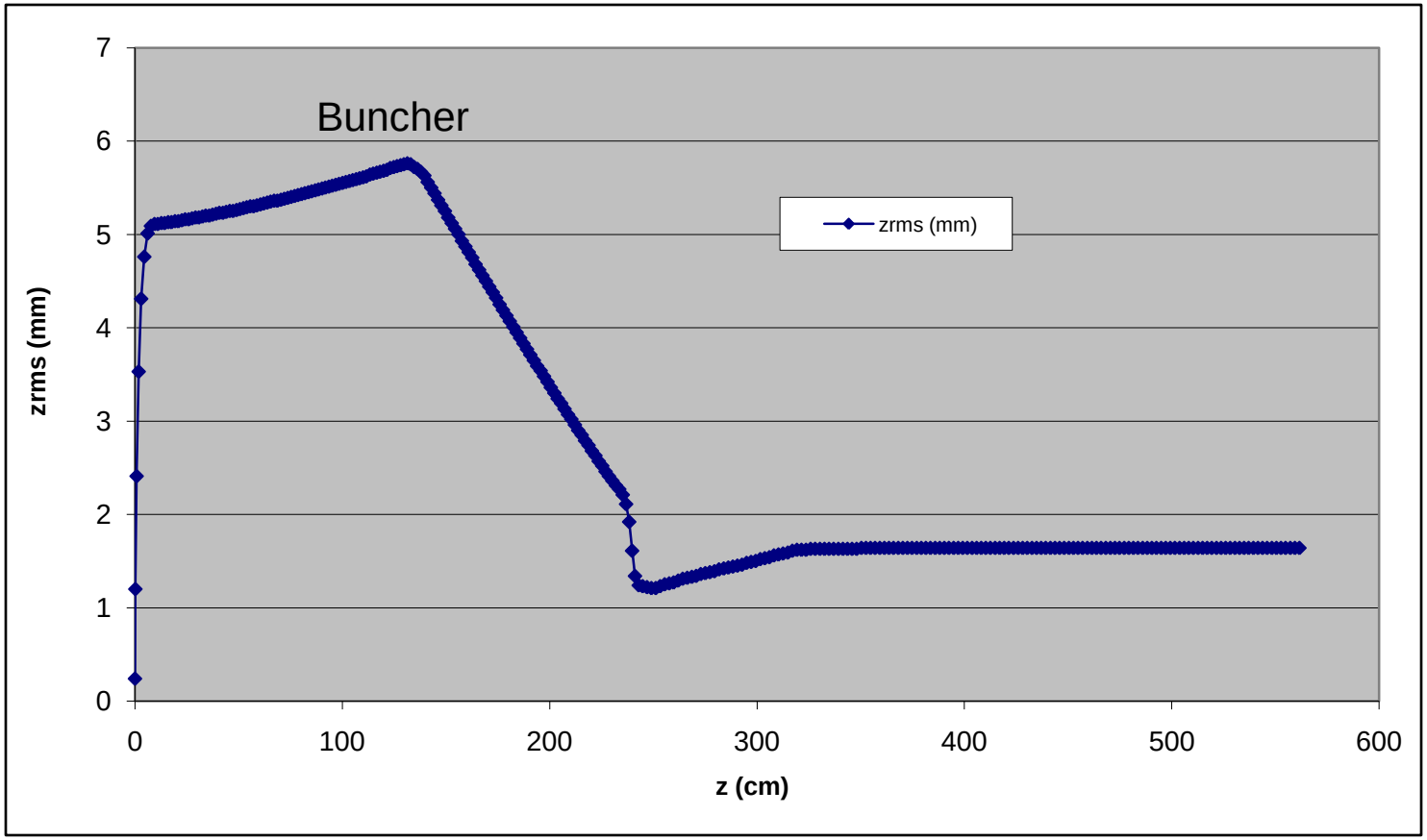
Compact Linac Parameters

Parameter	Value	Unit
Gun Voltage	250	kV
Bunch Charge	<10	pC
Drive Laser Pulse Length (σ)	22	psec
Beam Current	100	μA
Buncher Amplitude	9	kV
SRF Amplitude	25	MV
SRF Frequency	1497	MHz
Extracted Energy	48	MeV

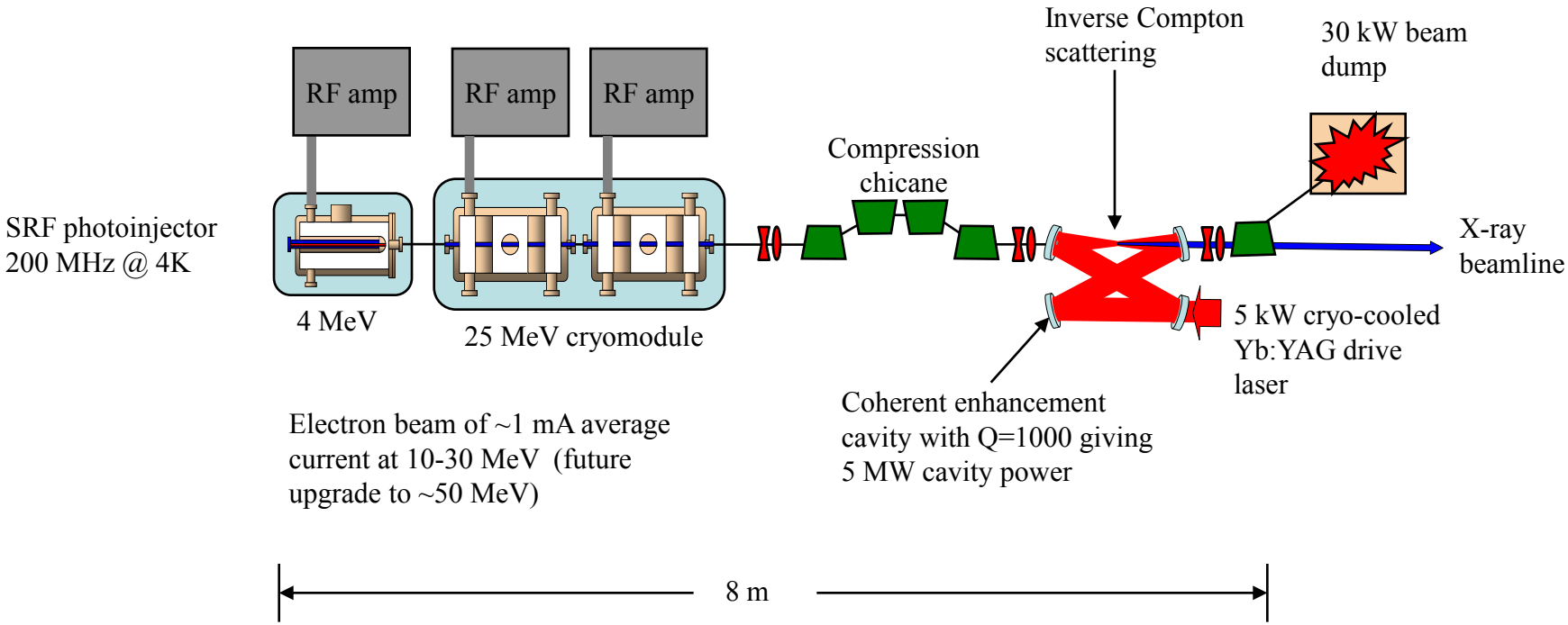
Transverse Beam Size @ 10 pC



Longitudinal Beam Size @ 10 pC



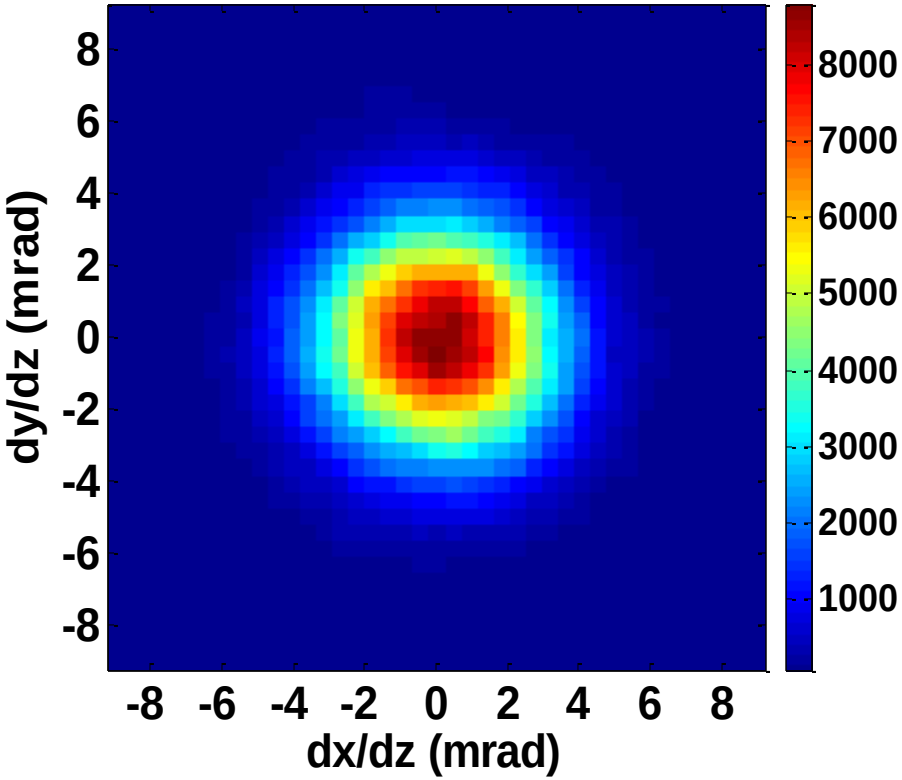
Photoinjector and linac with 1 beamline

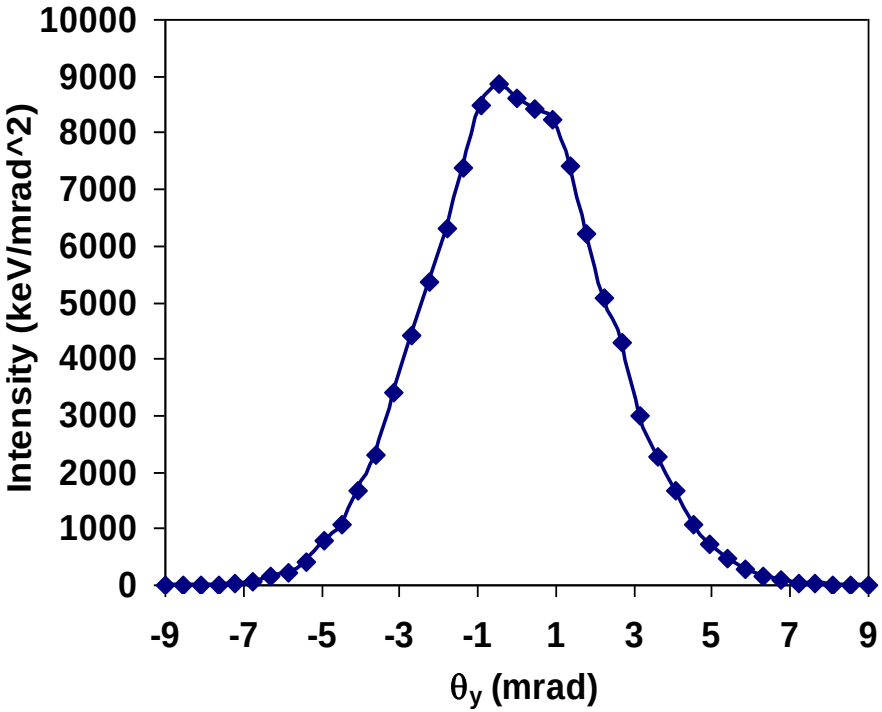


Courtesy: William Graves

Intensity Profile of 12 keV X-rays with 0.1% bw

Emittance = 0.7 mm-mrad





~10^{12} photons/sec @ 100 MHz in 0.1% BW

Courtesy: William Graves

Electron Beam Parameters

Parameter	**Single-shot**	**High average flux**
Tunable energy [MeV]	4 – 30 (~50 MeV upgrade)	
Bunch charge [pC]	1000	10
Repetition rate [Hz]	1-10	10^8
Average current [mA]	10^{-5}	1
Normalized emittance [mm-mrad]	2	0.1
FWHM bunch length [ps]	2	0.3
RMS energy spread [keV]	4	1

Courtesy: William Graves

EDUCATION EFFORTS

- Two Jefferson Lab Professors at Old Dominion University
  - 2 USPAS Courses
    - Recirculated and Energy Recovered Linacs
    - Introduction to SRF
  - 2 Old Dominion University Courses
    - Introduction to Accelerator Physics (1 semester)
    - Low Temperature Physics (1 semester)
- 2 CASA staff are undergraduate student advisors (REU and SULI)
- 7 CASA Staff are graduate student advisers for students from 4 different institutions
- With H. Areti, J. Delayen, and A. Hutton, working to create a Center for Accelerator Science and Technology (CAST) at ODU

CASA GRADUATE STUDENTS

M. Spata	ODU	Krafft	Nonlinear Beam Optics in the Spreaders/Recombiners
Alicia Hofler	ODU	Evtushenko	SRF Gun and Injector Optimization
Chuyu Liu	Peking	Krafft	Electron Beam Diagnostics
Hisham Sayed	ODU	Bogacz	Chromatic Correction of Low β* Collider Optics
Ryan Bodenstein	UVA	Tiefenback	Operational Diagnostics Development at CEBAF*
Ilkyung Shin	UConn	Yunn	Multipass BBU and Feedback

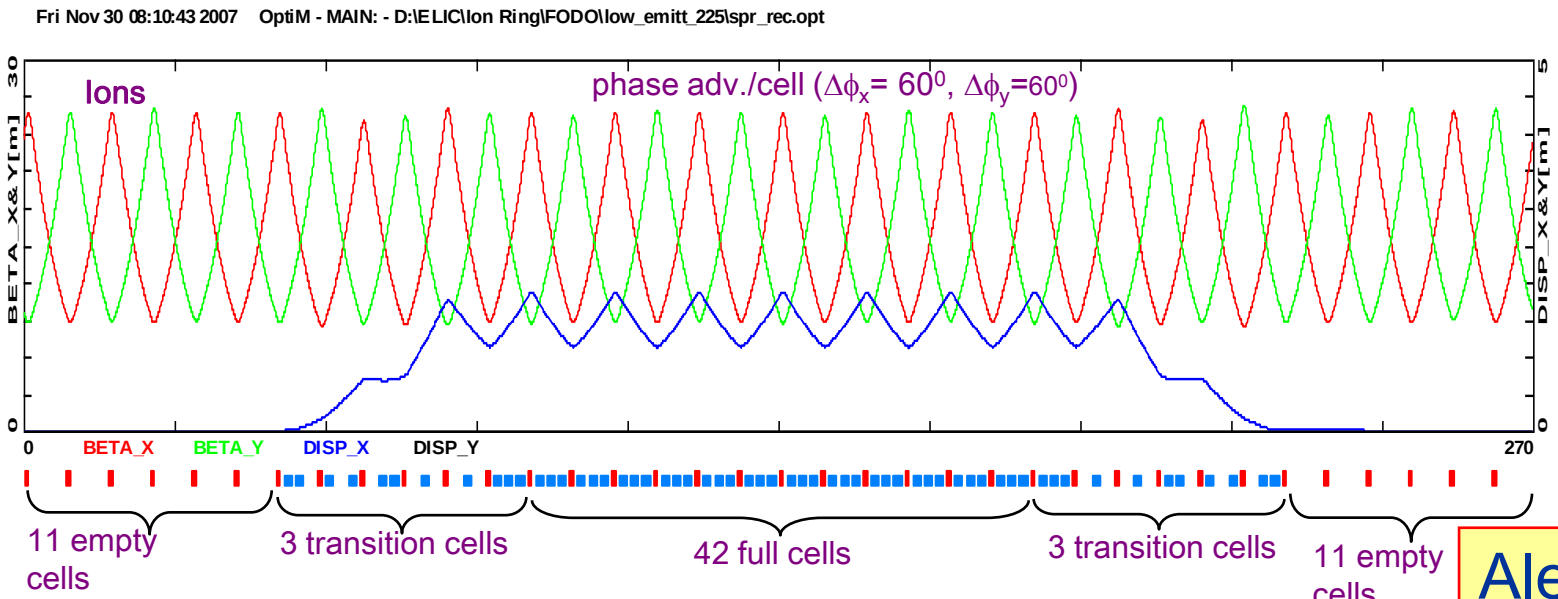
CASA is training the next generation of Accelerator Scientists

*MS Student

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.
- 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.
- CASA is strongly committed to education in Accelerator Physics

Optimization of Figure-8 Rings Lattices



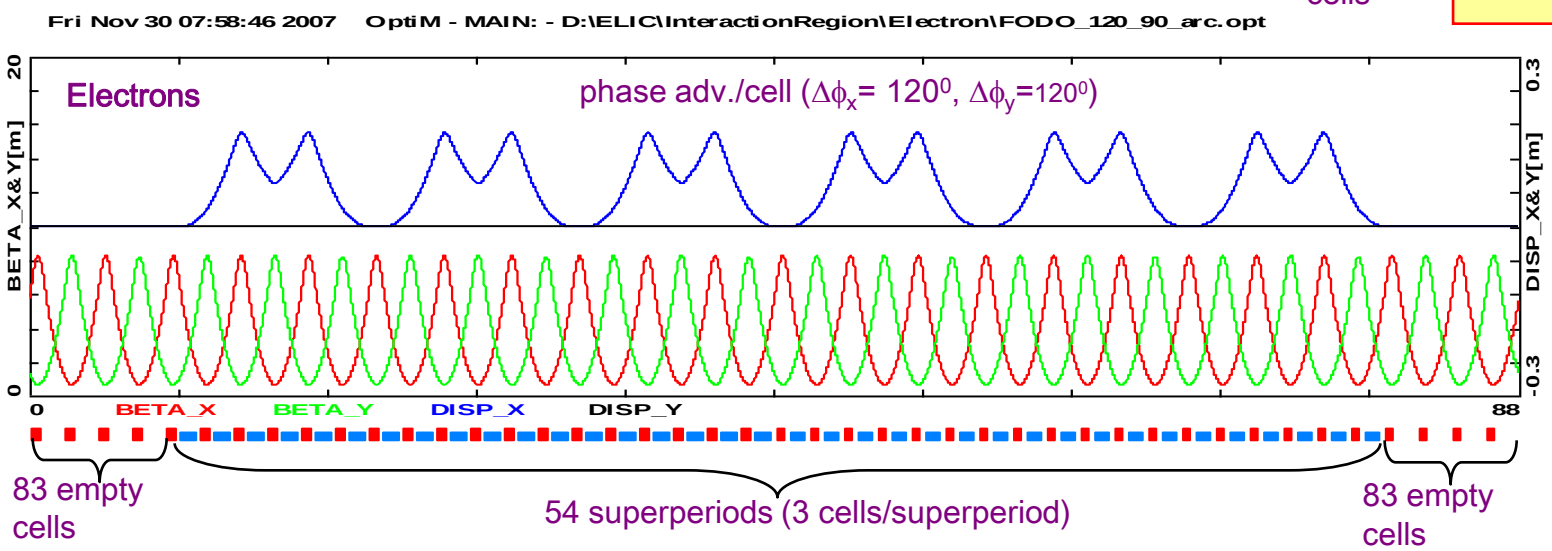
Dipoles::

$Lb=170 cm
$B=73.4 kG
$rho =102 m

Quadrupoles:

$Lb=100 cm
$G= 10.4 kG/cm

Alex Bogacz



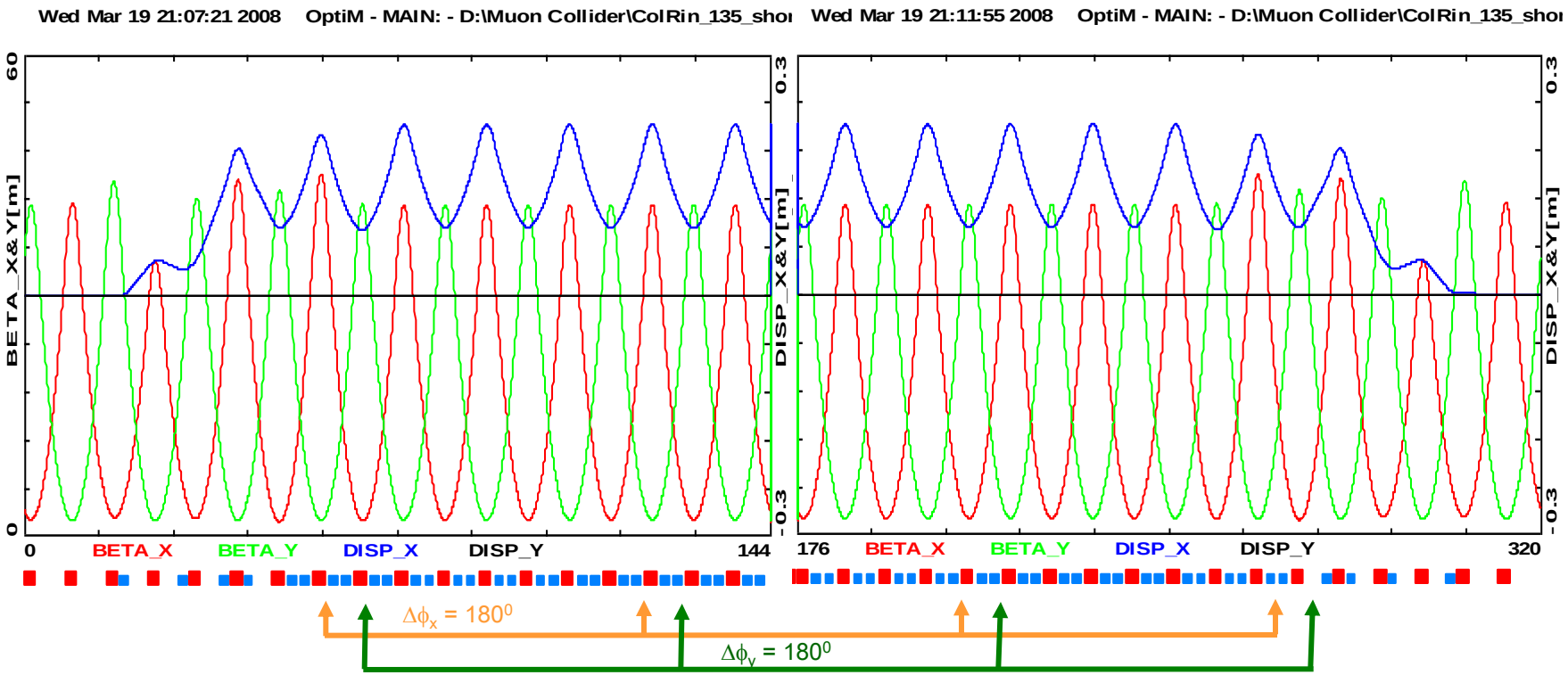
Dipoles::

$Lb=100 cm
$B=3.2 kG
$rho =76 m

Quadrupoles:

$Lb=60 cm
$G= 4.1 kG/cm

Chromatic Correction with families of Sextupoles



Cancellation of geometric aberrations generated by sextupoles through 'pairing' them with a minus identity transformation between them

Alex Bogacz and Hisham Sayed Thesis

HAMPTON08 Contributions

Author	Talk
Krafft	ELIC Overview
Bogacz	ELIC Optics
Derbenev	Cooling Methods
Sayed	Chromaticity Correction
Brindza	Interaction Region Magnet Design
Musson	Fast Kickers
Zhang	Beam-Beam Interaction
Grames	Polarized Electron Sources

Users recommend go to 0.5 GHz bunch repetition rate
(Peak Luminosity to 2.6×10^{34} $cm^{-2}sec^{-1}$)

ELIC Low Beta Optics with Chromatic Corrections

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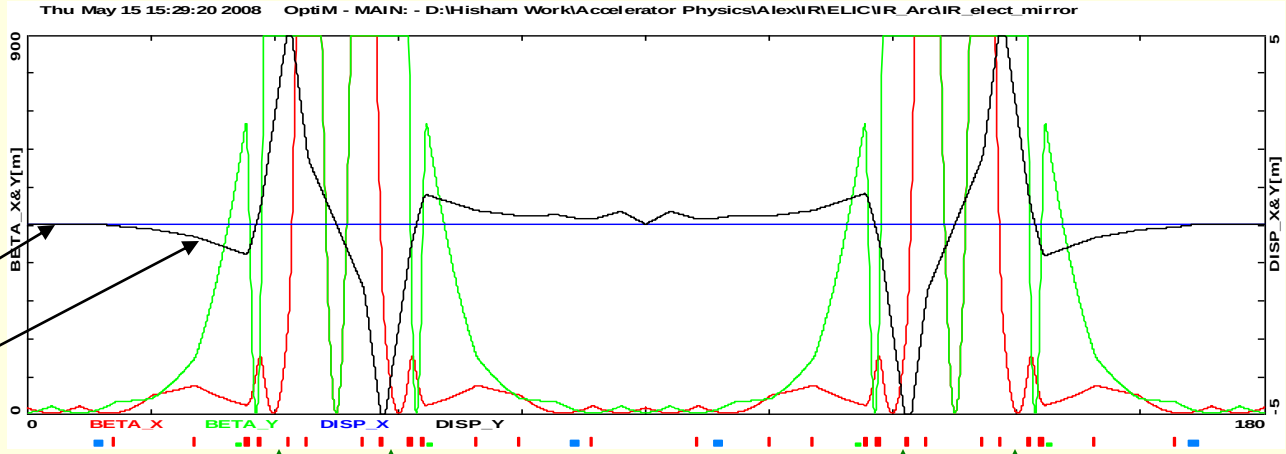
Alex Bogacz[1]
1 Jefferson Lab
2 Old Dominion University

β Chromaticity correction with sextupoles

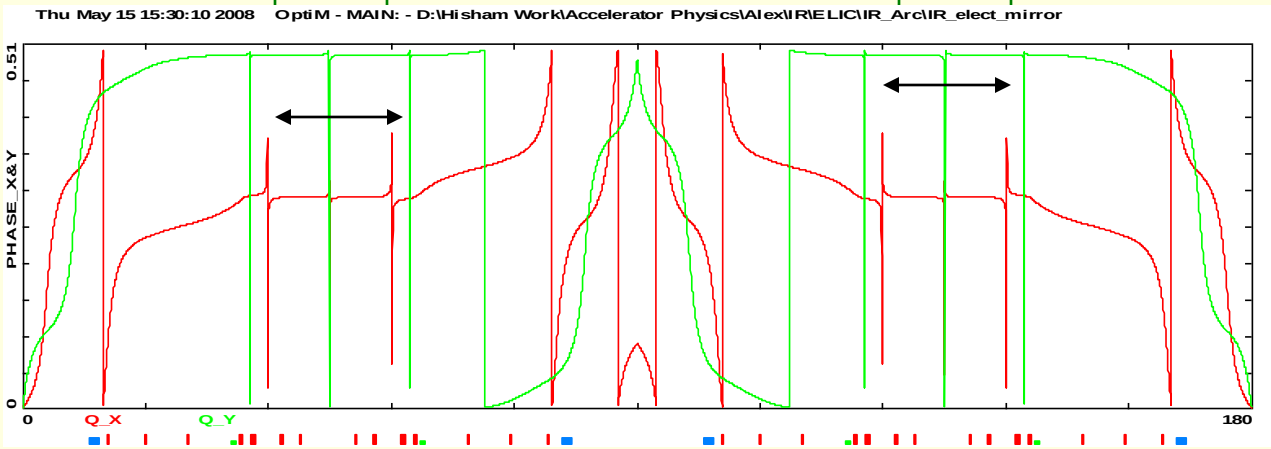
β- functions around the interaction region, the green arrows represent the sextupoles pairs.

Horizontal dispersion

Vertical dispersion



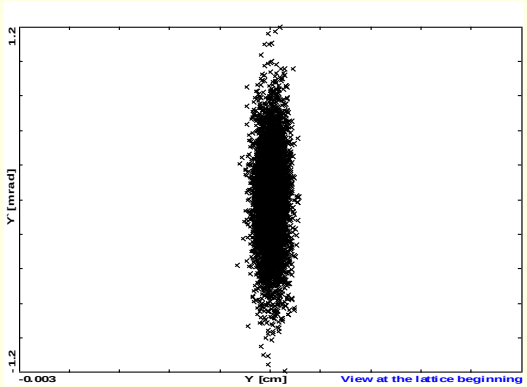
The phase advance, showing the –I transformation between the sextupoles pairs



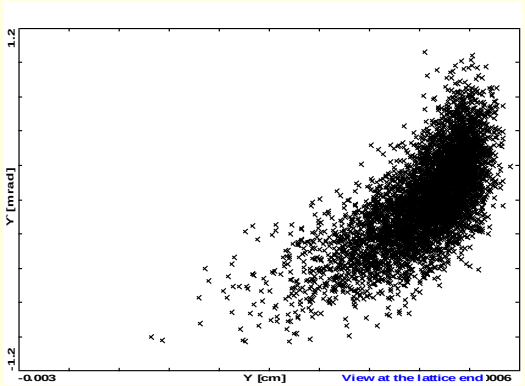
Phase space in vertical plane before and after applying the correction scheme

Vertical plane $\Delta p/p \sim 0.0006$

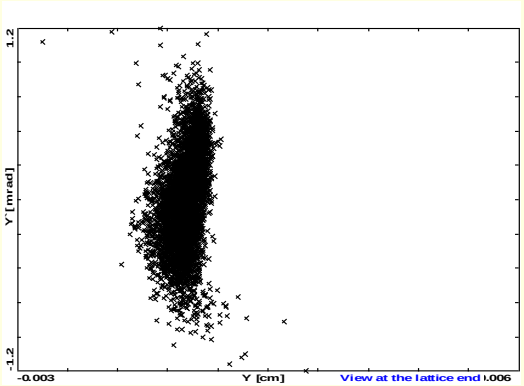
Initial phase space



phase space after two pass through 2 IR's No correction



phase space after two pass through 2 IR's after correction



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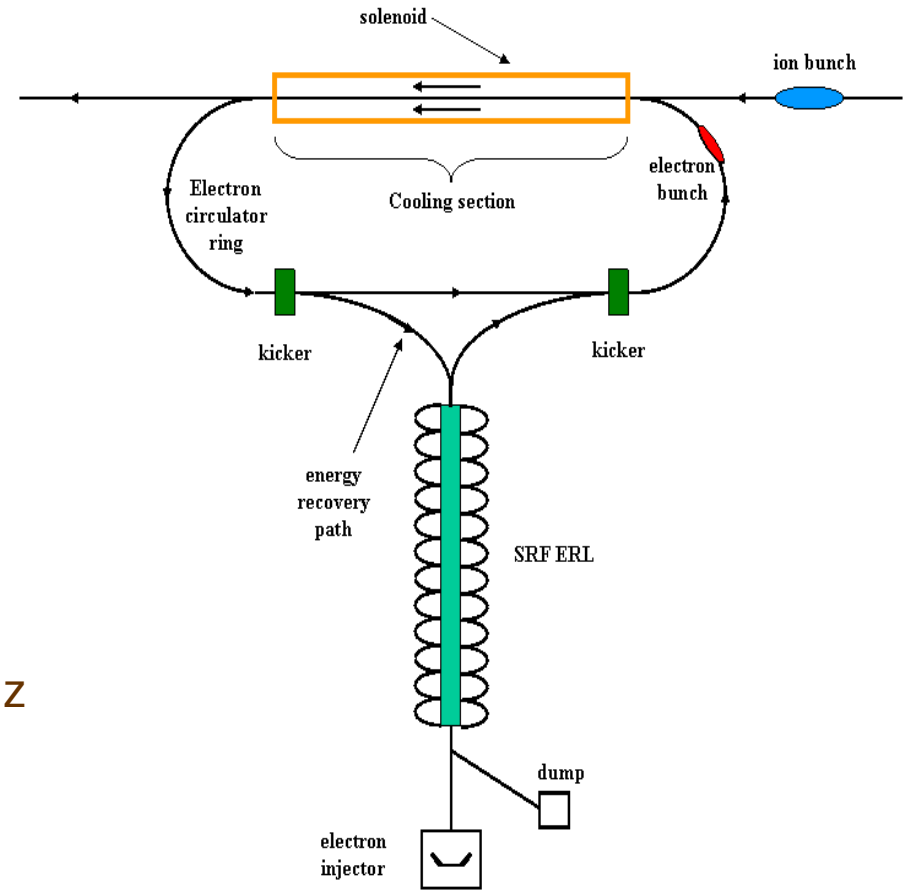
Electron Cooling with a Circulator Ring

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.

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

- 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