Conceptual Design of High Luminosity Ring-Ring Electron-Ion Collider at CEBAF

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For ELIC Design Group

HB2008 **August 26, 2008**

Outline

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- ELIC Conceptual Design
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Science Motivation

A High Luminosity, High Energy Electron-Ion Collider:
A New Experimental Quest to Study the Glue which Binds Us All

How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

Explore the new QCD frontier: strong color fields in nuclei

- How do the gluons contribute to the structure of the nucleus?
- What are the properties of high density gluon matter?
- How do fast quarks or gluons interact as they traverse nuclear matter?

Precisely image the sea-quarks and gluons in the nucleon

- How do the gluons & sea-quarks contribute to spin structure of the nucleon?
- What is the spatial distribution of the gluons and sea quarks in the nucleon?
- How do hadronic final-states form in QCD?

EIC Requirements from NSAC LRP 2007

"… These considerations constrain the basic design parameters to be a **3 to at least 10 GeV** energy electron colliding with a nucleon beam of energy between **25 to 250 GeV** or with nuclear beams ranging from **20 to 100 GeV/nucleon**"

"… the performances needed at an EIC relies on three major advances over HERA: (1) beams of **heavy nuclei, at least up to gold**, are essential at access the gluon saturation regime … (2) collision rates exceeding those at HERA by **at least two orders of magnitude** are required for precise and definitive measurements of the gluon distributions of interest, … and (3) **polarized light-ion beams**, in addition to **polarized electrons** available at HEAR, are mandatory to address central question of the nucleon's spin structure in the gluon-dominated region"

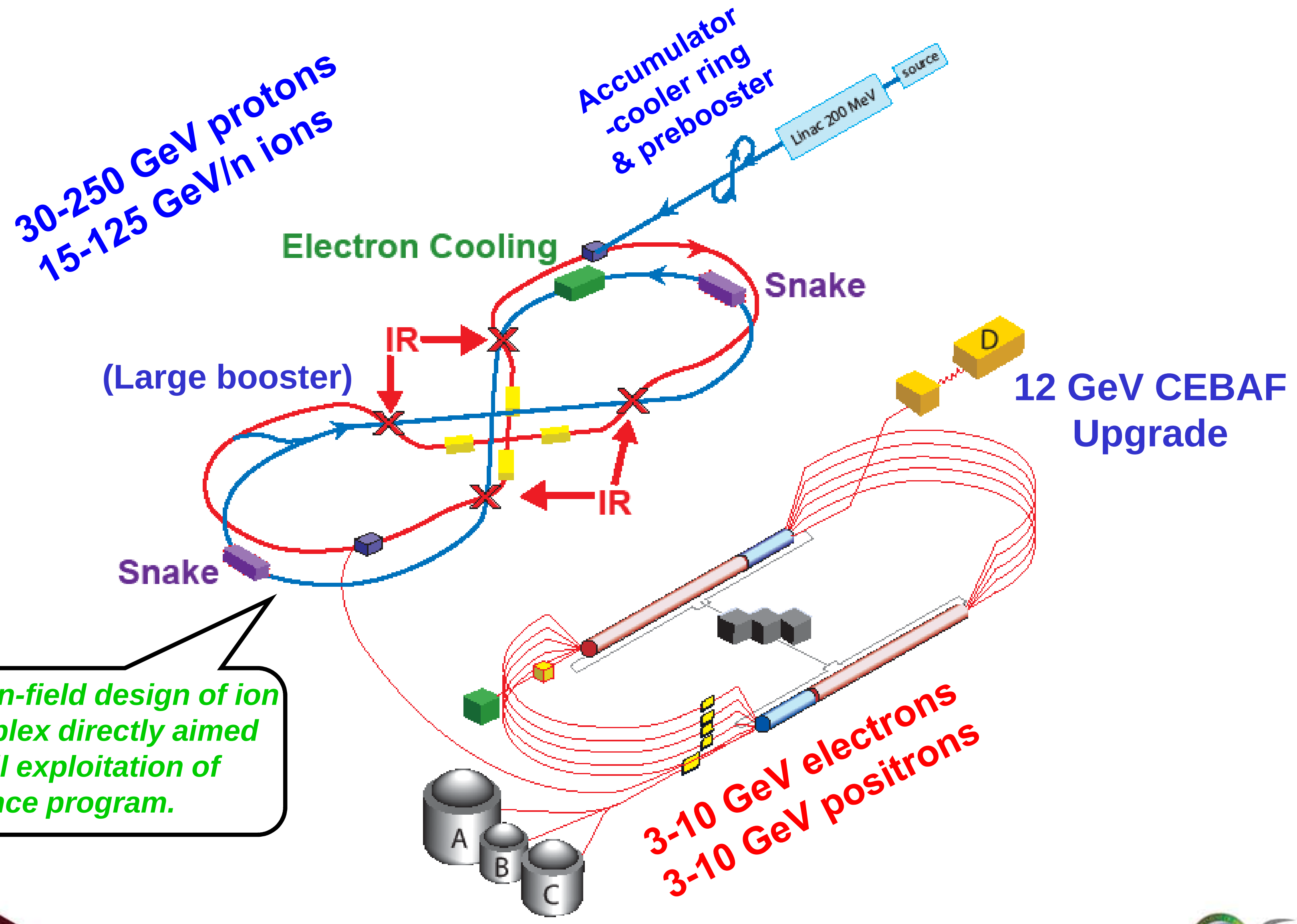
- **Energy**
  - e: 3 GeV to ≥ 10 GeV
  - P: 25 GeV to 250 GeV
  - A: 20 GeV to 100 GeV
- **Ion species**
  - up to gold, A ≥ 197
- **Luminosity**

  $\geq 10 \times 3.8 \cdot 10^{31}\ cm^{-2}s^{-1}$
- **Polarization**
  - electron beam
  - light ion beams

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/125 GeV/n ion
- **Luminosity**
  - 10^{33} up to 10^{35} cm^{-2} s^{-1} *per* interaction point
- **Ion Species**
  - Polarized H, D, ^{3}He, possibly Li
  - Up to heavy ion A = 208, all striped
- **Polarization**
  - Longitudinal polarization at the IP for both beams
  - Transverse polarization of ions
  - Spin-flip of both beams
  - All polarizations >70% desirable
- **Positron Beam** ***desirable***

ELIC Conceptual Design



Green-field design of ion complex directly aimed at full exploitation of science program.

Achieving High Luminosity of ELIC

ELIC design luminosity

$L \sim 8.6 \times 10^{34}\ cm^{-2}\ sec^{-2}$ (250 GeV protons x 10 GeV electrons)

ELIC luminosity Concepts

- High bunch collision frequency (up to 1.5 GHz)
- Short ion bunches ($\sigma_z \sim 5$ mm)
- Super strong final focusing ($\beta^* \sim 5$ mm)
- Large beam-beam parameters (0.01/0.01 per IP,
  0.025/0.1 largest achieved)

- Need High energy electron cooling of ion beams
- Need crab crossing colliding beams

- Large synchrotron tunes to suppress synch-betatron resonances
- Equal betatron phase advance (fractional) between IPs

ELIC (e/p) Design Parameters

Beam energy	GeV	250/10	150/7	50/5
Figure-8 ring circumference	km	2.5		
Bunch collision frequency	MHz	499/1497		
Beam current	A	0.66/1.65	0.46/0.99	0.57/1.15
Particles/bunch	10^9	2.7/6.9	1.9/4.1	2.3/4.8
Energy spread (dp/p)	10^{-4}	3/3		
Bunch length, rms	mm	5/5		
Horizontal emitance, norm.	µm	0.70/51	0.42/35.6	0.28/25.5
Vertical emittance, norm.	µm	0.03/2.0	0.017/1.43	0.028/2.55
Beta*	mm	5/5		
Vertical b-b turn-shift per IP		0.01/0.1		
Peak luminosity per IP	10^{34} $cm^{-2}s^{-1}$	2.9/8.6	1.2/3.6	1.1/3.3
Number of IPs		4		
Luminosity lifetime	hours	24		

Jefferson Lab

ELIC (e/A) Design Parameters

	High Energy (10 GeV electron)		Low Energy (5 GeV electron)	
	Energy/n	Luminosity	Energy / n	Luminosity
	GeV	10^{34} cm^{-2} s^{-1}	GeV	10^{34} cm^{-2} s^{-1}
Proton	250	2.9	100	1.1
Deuteron	125	2.9	50	1.1
Tritium	83.3	2.9	33.3	1.1
$^{3}He^{+2}$	166.7	1.4	66.7	0.55
$^{4}He^{+2}$	125	1.4	50	0.55
$^{12}C^{+6}$	125	0.48	50	0.18
$^{40}Ca^{+20}$	125	0.14	50	0.055
$^{197}Au^{+79}$	100	0.036	40.1	0.014
$^{208}Pb^{+82}$	98.6	0.035	39.4	0.013

- **Luminosity is given per unclean per IP**
- **499 MHz bunch collision frequency**

Evolution of ELIC Conceptual Design

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

  (*by taking advantages of CEBAF high bunch repetition frequency and a green field design of ion complex*)

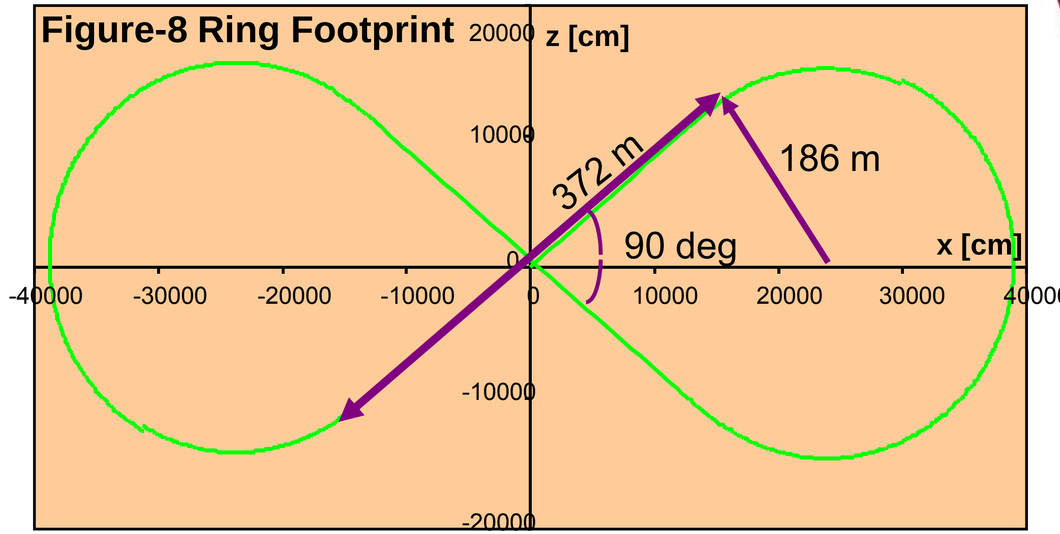
- Challenge: high current polarized electron beam
  - ERL: 2 A
  - Circulator ring: 20 mA
  - State-of-art: 0.1 mA
- 12 GeV CEBAF Upgrade polarized source/injector already meets beam requirement of ring-ring design
- 12 GeV CEBAF will serve as full energy polarized injector to the ring
- ELIC ring-ring design still preserves high luminosity, high polarization

ELIC Ring-Ring Design Features

- Unprecedented high luminosity
  - Enabled by short ion bunches, low β*, high rep. rate, large synchrotron tune
  - Require crab crossing colliding beam
- Electron cooling is an essential part of ELIC
- 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 gun/injector meets electron storage-ring requirements
- The 12 GeV CEBAF can serve as a full energy injector to electron ring
- *Simultaneous* operation of collider and CEBAF fixed target program.
- Experiments with polarized positron beam are possible.

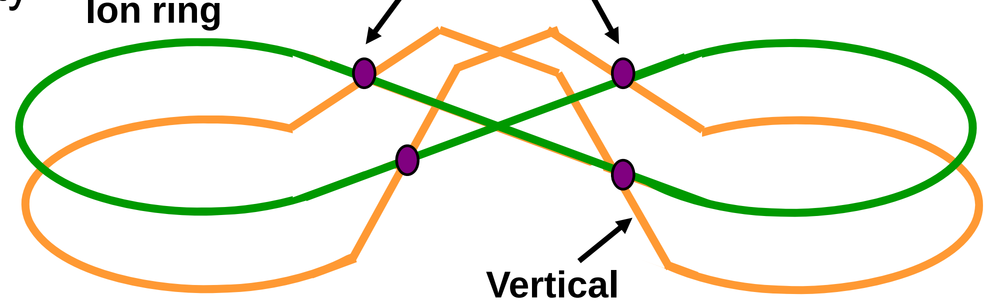
Figure-8 Ring

		Small Ring	Large Ring
Circumference	m	2100	2500
Radius	m	152	180
Width	m	304	360
Length	m	776	920
Straight	m	362	430



Design is determined by

- Synchrotron radiation power & density
- Arc bending magnet strength
- Length of crossing straights
- Cost and fit to site



Stacked vertically

ELIC at JLab Site

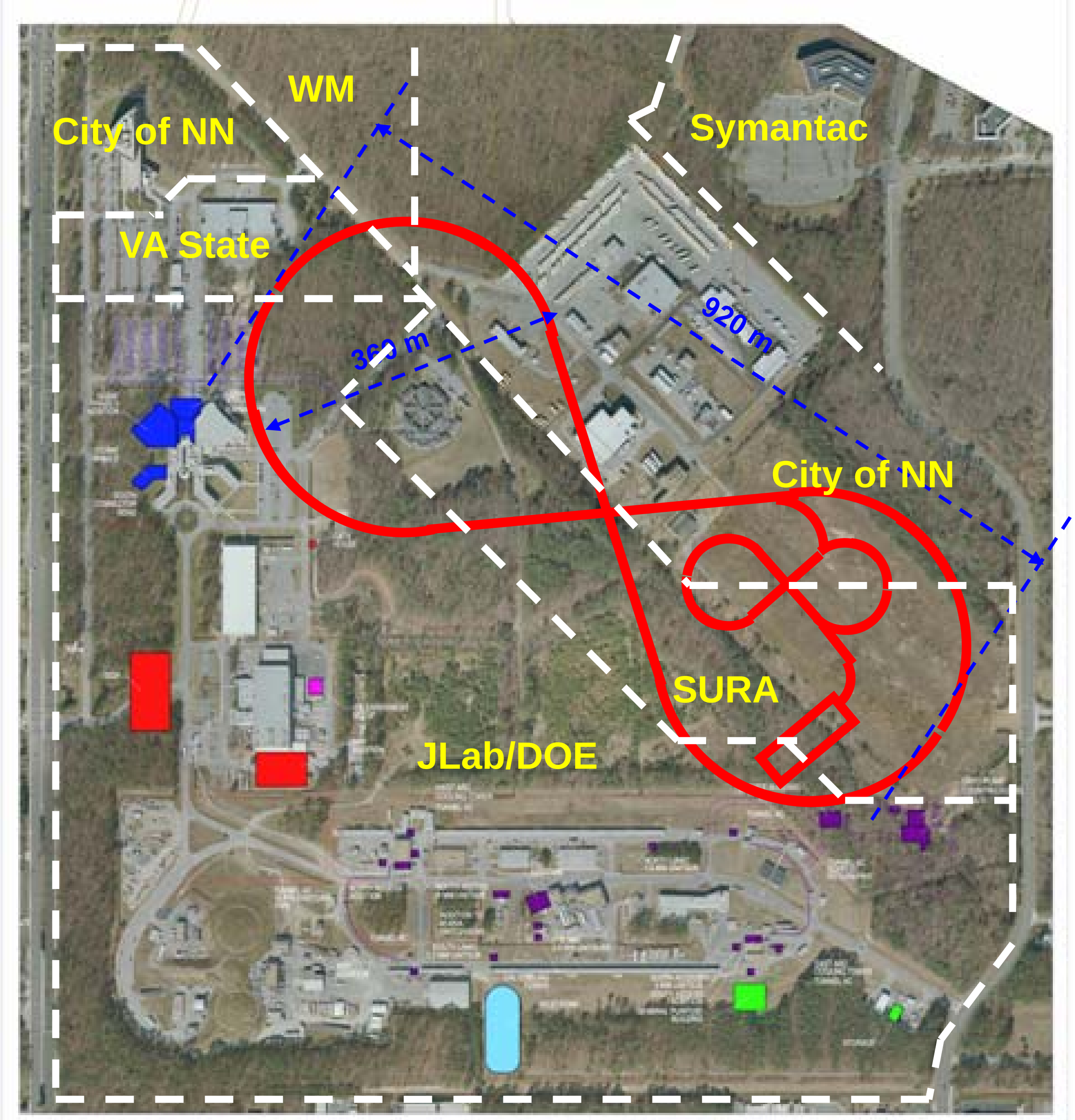
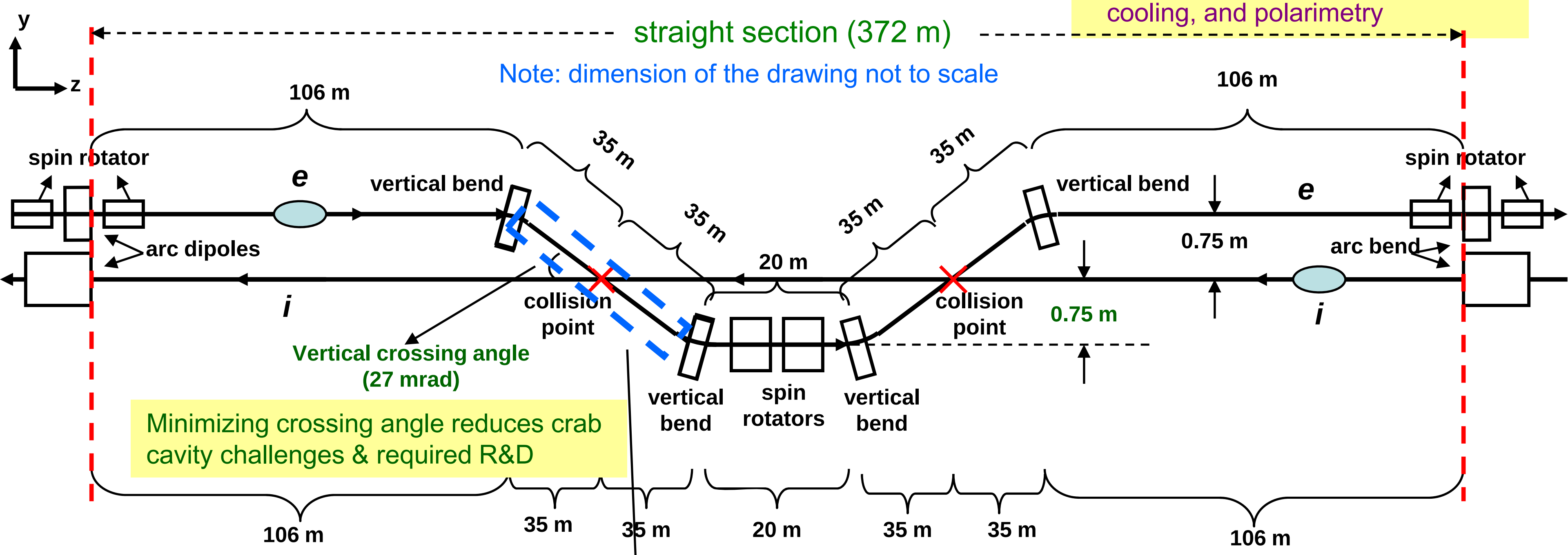


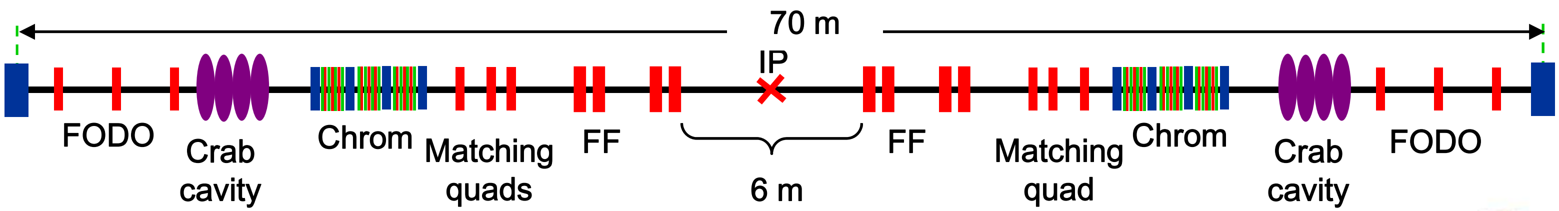
Figure-8 Straight Sections and IPs

- 106 m space to accommodate e/p injection/ejection, SRF cavity, e-cooling, and polarimetry

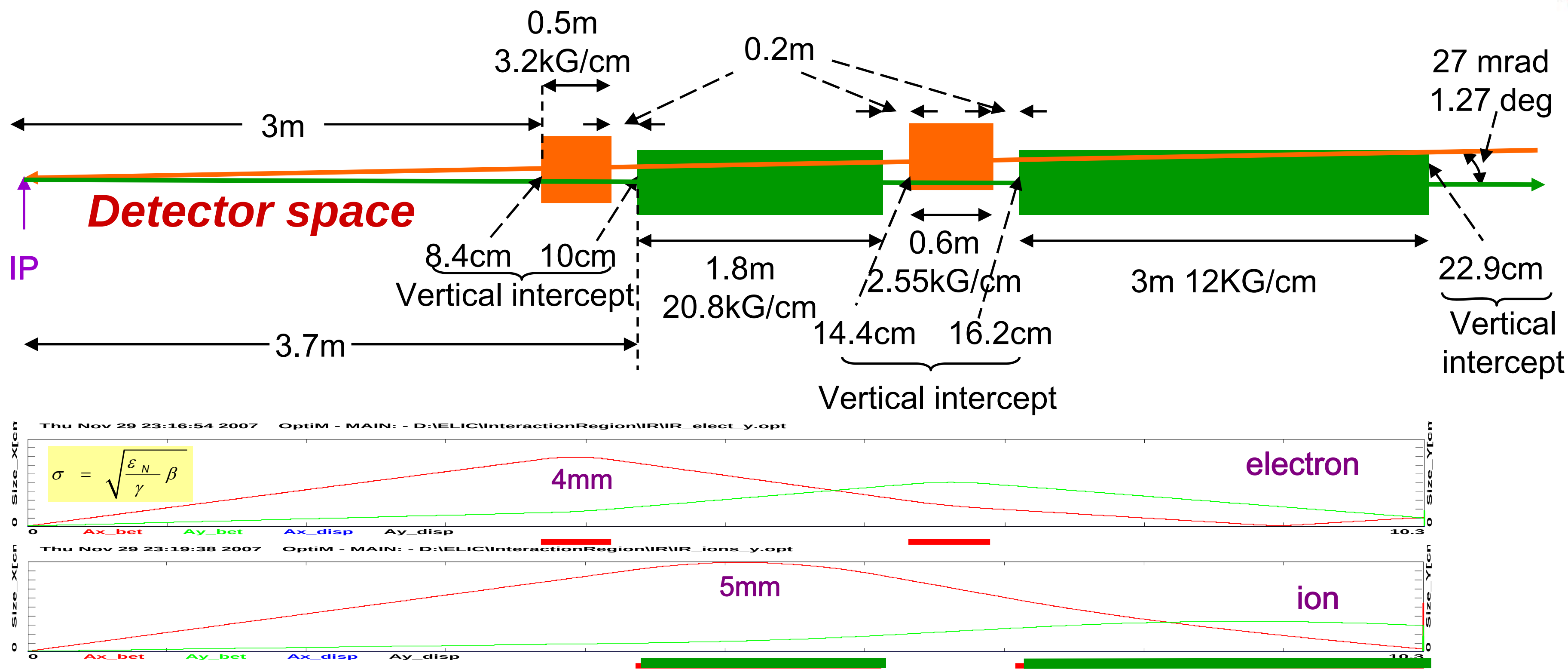


Minimizing crossing angle reduces crab cavity challenges & required R&D

Interaction Region



IR Layout and Beam Envelopes



- Magnet free space (for detector) is +/- 3 m
- Final focusing achieved by quad doublet for both beams
  250 T/m peak field gradient (7.5 T over 3 cm aperture radius)
- Electron & ion doublets "Interleave" to avoid physical magnet overlap
- Quad design calls for a "pass through" hole through a magnet yoke
- Chromatic aberration compensation by two families of sextupoles

ELIC R&D Requirements

To achieve luminosity at 10^{33} cm^{-2} sec^{-1} and *up*

- High energy electron cooling

To achieve luminosity at ~ 10^{35} cm^{-2} sec^{-1}

- Crab crossing and crab cavity
- Forming and stability of intense ion beams
- Beam-beam interactions
- Detector R&D for high repetition rate (>0.5 GHz)

  - *What is the problem?*
  - *How does it affect the ELIC design?*
  - *How these R&D topics are selected and prioritized?*
  - *What is our approach to these topics?*

ELIC R&D: Electron Cooling

Issue

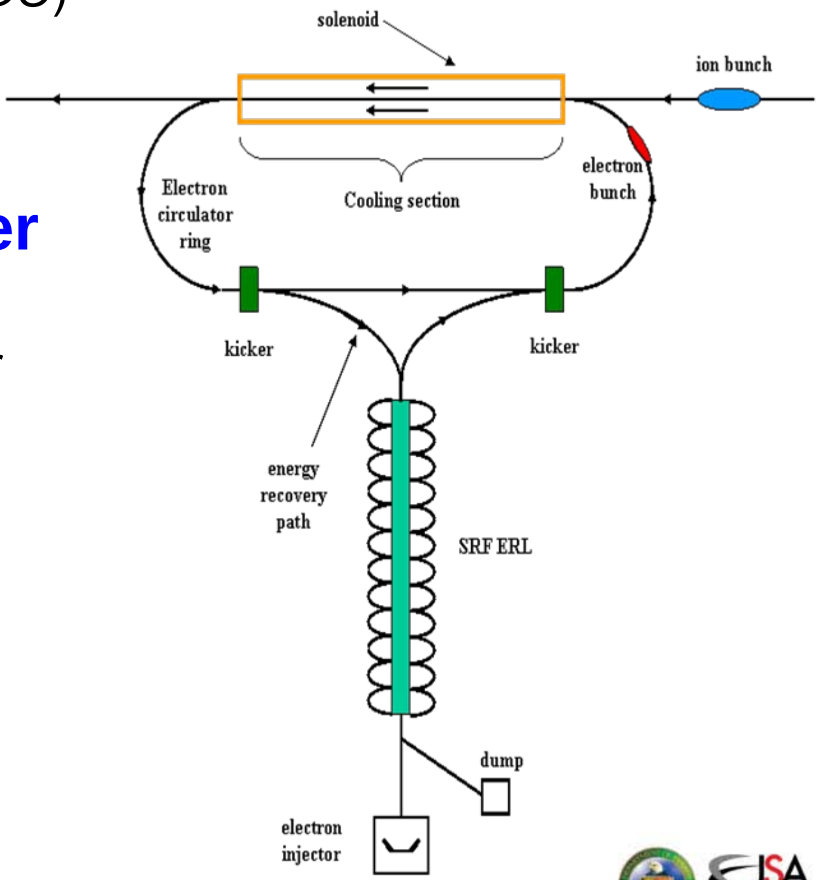
- To suppress IBS, reduce emittances, provide short ion bunches.
- Effective for heavy ions (higher cooling rate), difficult for protons.

State-of-Art

- Fermilab demonstration (4.34MeV, 0.5A *DC*)
- Feasibility of EC with bunched beams remains to be demonstrated.

ELIC ERL Based Circulator Cooler

- 2 A CW electron beam, up to 137 MeV
- Non-polarized electron source (present or under developing) can deliver nC bunch
- SRF ERL able to provide high average current CW beam
- Circulator cooler for reducing average current from source/ERL
- Electron bunches circulate 100 times in a ring while cooling ion beam



Cooling Time and Ion Equilibrium

Multi-stage cooling scenario in the collider ring

- 1st stage: longitudinal cooling with SRF bunching at injection energy
- 2nd stage: initial cooling after acceleration to top energy
- 3rd stage: continuous cooling in collider mode

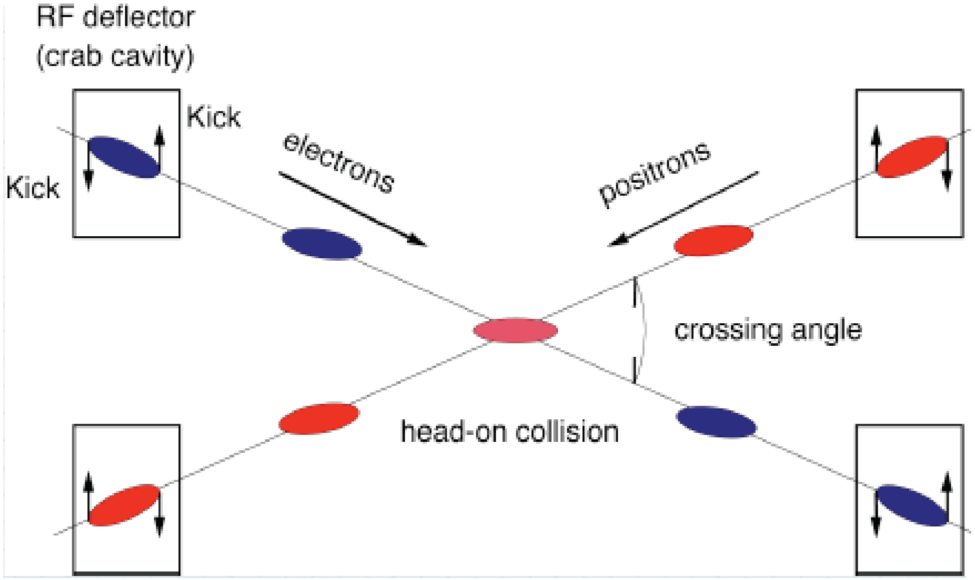
Cooling rates and equilibrium of proton beam

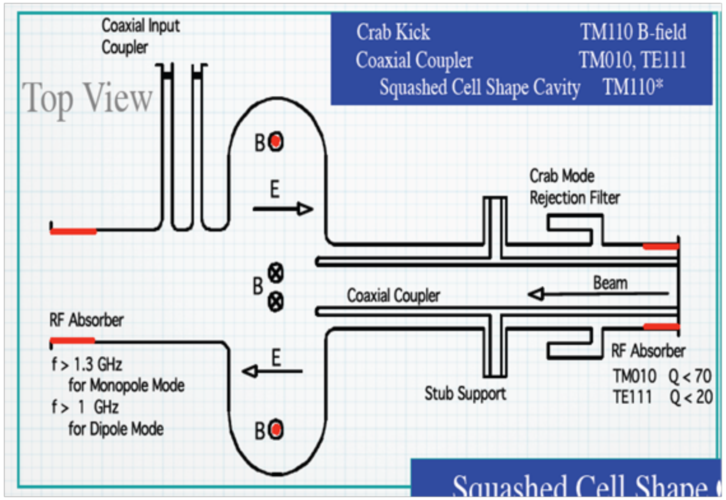
Parameter	Unit	Value	Value
Energy	GeV/MeV	50/25	250/127
Particles/bunch	10^{10}	0.23/1	0.26/1.2
Initial energy spread*	10^{-4}	30/3	1/2
Bunch length*	cm	20/3	1
Proton emittance, norm*	μm	1	1
Cooling time	min	1	1
Equilibrium emittance	μm	1/1	1/0.04
Equilibrium bunch length**	cm	2	0.5
Cooling time at equilibrium	min	0.1	0.3
Laslett's tune shift (equil.)		0.04	0.02

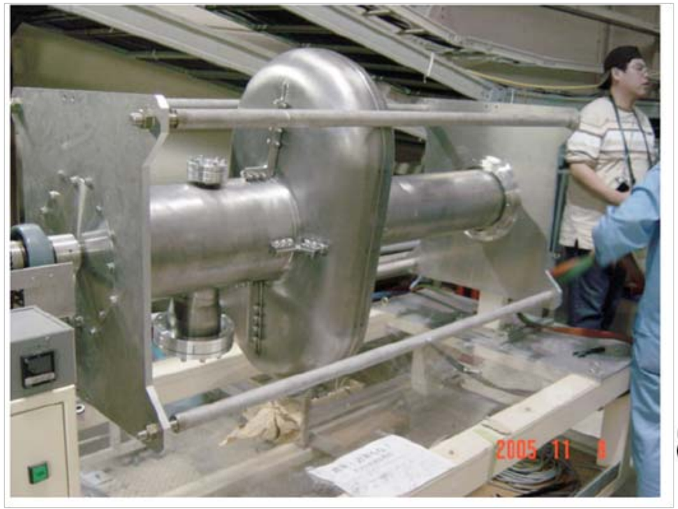
* max.amplitude
** norm.,rms

ELIC R&D: Crab Crossing

- High repetition rate requires crab crossing colliding beam 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







State-of-art:

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 (cont.)

ELIC Crab cavity Requirements

(Based on 27 mrad crossing angle)

Electron: 1.5 MV – within state of art (KEK, single Cell, 1.8 MV)

Ion: 30 MV (220G/4m integrated B field on axis)

Crab Crossing R&D program

- Cavity development
  - 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
  - Effect on collider luminosity
  - Effect on synchrotron-betatron motion and instability

ELIC R&D: Forming High Intensity Ion Beam

	Length (m)	Energy (GeV)	Cooling Scheme	Process
Source/SRF Linac		0.2		Full stripping
Accumulator-Cooler Ring	50	0.2	DC electron	Stacking/accumulating
Prebooster	200	3	(Stochastic??)	Energy booster
Big Booster (using electron ring)	2500	30		Filling large ring Energy booster
Collider Ring	2500	30	(Stochastic??) Electron	Injection energy cooling RF bunching
		250	Electron	Initial/continuous cooling

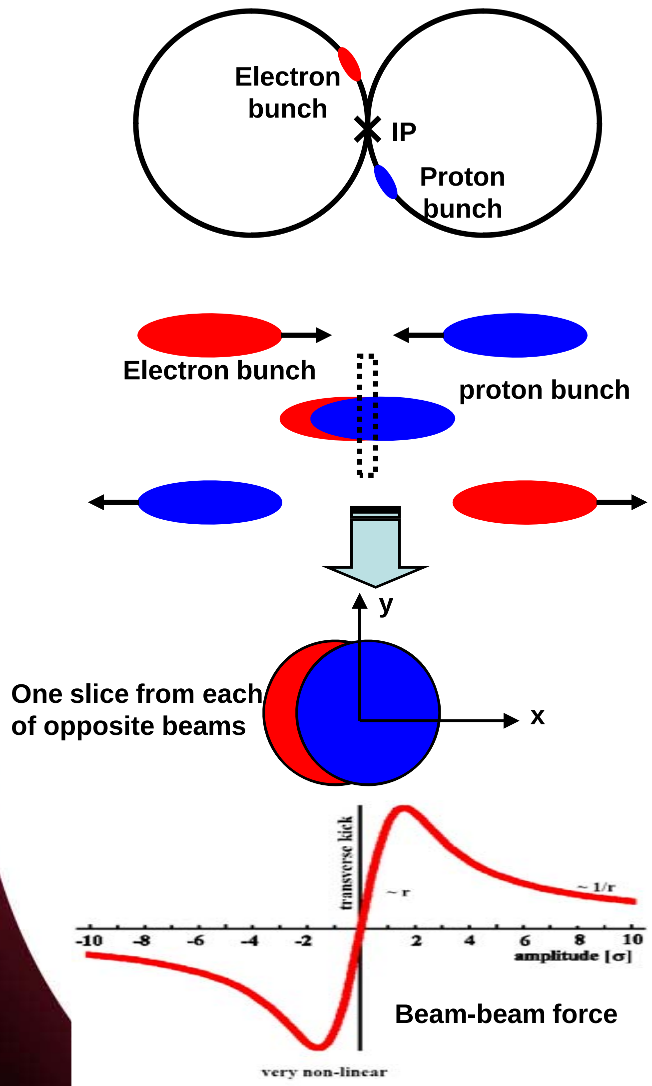
Stacking/accumulation process

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

Stacking proton beam in ACR

Circumference	M	50
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

ELIC R&D: Beam-Beam Interaction



Transvers beam-beam force

- Highly nonlinear forces
- Produce transverse kickers between colliding bunches

Beam-beam effect

– Can cause emittance growth or blowup
– Can induce coherent beam-beam instabilities
– Can decrease luminosity and its lifetime

Most important limiting factor of collider luminosity !

Impact on ELIC IP design

– Highly asymmetric colliding beams (10 GeV/1.65 A on 250 GeV/0.66 A)
– Four IPs and Figure-8 rings
– Strong final focusing (beta* 5 mm)
– Short bunch length (5 mm)
– Crab crossing colliding beam
– Large synchrotron tune required by RF bunching
– Near-limit vertical b-b parameters (0.1/0.01)
– Equal (fractional part) betratron phase advance between IPs

ELIC R&D: Beam-Beam (cont.)

Simulation Model

- Single/multiple collision points, head-on collision
- Strong-strong self-consistent Particle-in-Cell codes
- Ideal rings for electrons & protons, but include synchrotron radiation damping & quantum excitations for electrons

Scope and Limitations

- 20k turns (0.15s of storing time) for a typical simulation run
  - ➢ Reveals short-time dynamics with accuracy
  - ➢ Can't predict long term (>min) dynamics

Simulation results

- Single IP case

  Reach equilibrium luminosity, $6.1 \cdot 10^{34}$ $cm^{-2}s^{-1}$, after one damping time, loss mainly due to the hour-glass effect
- Parameter dependence of ELIC luminosity

  Coherent beam-beam instabilities and emittance blow-up observed at electron beam above 6.5 A, however away from ELIC design point
- 4 IP with two sets of 12 bunches

  Reach equilibrium luminosity $5.9 \cdot 10^{34}$ $cm^{-2}s^{-1}$, after one damping time

It is the first phase of a long-term research plan

Summary

ELIC Conceptual Design provides

- CM energy up to 100 GeV, light to heavy ions (A=208)
- *Unprecedented high* luminosity (up to $2.9 \cdot 10^{34}$ cm^{-2} s^{-1} @499MHz or $8.6 \cdot 10^{34}$ cm^{-2} s^{-1} @1497MHz, for e-p)
- High polarization for both electron & light ion beams
- *Simultaneous* operation of collider and CEBAF fixed target program

- Design evolution towards more robust
- Increase using existed and proved technologies
- Reduces technology challenges and required R&D effort

Recent R&D Advances

- Complete ring and IP beam optics with chromaticity correction
- Electron cooling and circulator cooler conceptual design
- Crab crossing and crab cavity scheme
- Forming and instability studies of intense ion beam
- Beam-beam effects

Continue design optimization and carry out key R&D

ELIC Study Group & Collaborators

A. Afanasev, E. Aschenauer, J. Benesch, A. Bogacz, P. Brindza, A. Bruell, L. Cardman, Y. Chao, S. Chattopadhyay, P. Chevtsov, E. Chudakov, P. Degtiarenko, J. Delayen, Ya. Derbenev, R. Ent, P. Evtushenko, A. Freyberger, D. Gaskell, J. Grames, A. Hutton, R. Kazimi, G. Krafft, R. Li, L. Merminga, J. Musson, M. Poelker, R. Rimmer, A. Thomas, H. Wang, C. Weiss, B. Wojtsekhowski, B. Yunn, Y. Zhang - Jefferson Laboratory

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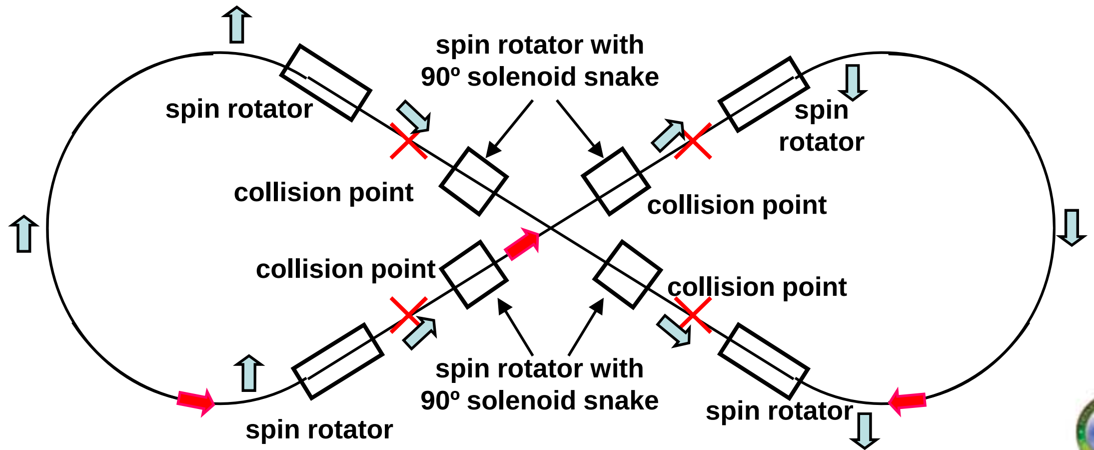
Electron Polarization in ELIC

- **Producing polarization at CEBAF**
  - Polarized source, preserved in acceleration at CEBAF recirculated linac
  - Injected into Figure-8 ring with vertical polarization
- **Maintaining polarization in the ring**
  - Equilibrium polarization in the ring determined by
    - Sokolov-Ternov self-polarization
    - Depolarization (quantum, vertical betatron oscillation, orbit distortion and beam-beam interaction)
  - SC solenoids at IPs removes spin resonances and energy sensitivity



Electron Polarization in ELIC (cont.)

Polarization manipulation

- Vertical polarization in arc, but longitudinal at IP required by physics
- Use vertical crossing bend to rotate spin, but energy-dependent
- Combination of vertical crossing bend, two arc bending dipoles and two superconducting solenoids for energy independent spin rotation
- 180° snake solenoid & symmetry principle ensure longitudinal polarization at 2nd IP & vertical polarization in the other arc of Figure-8 ring