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

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**Workshop for *Precision Electron Beam Polarimetry for the Electron Ion Collider*,**
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# Outline

- Science Motivation
- Design Goals
- ELIC Conceptual Design
- Electron Polarization in ELIC
- R&D Requirements and Advances
- Summary

# 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

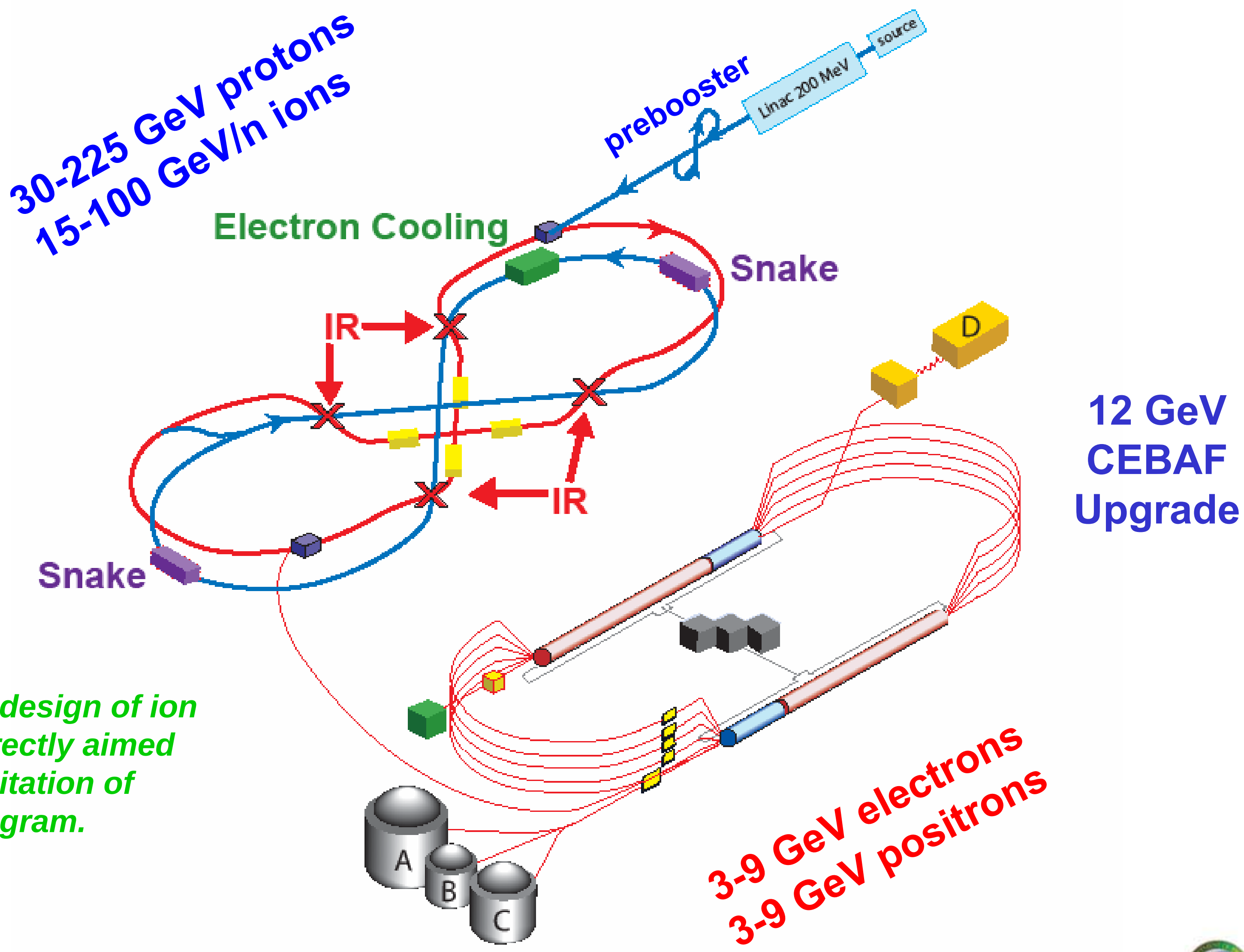
- **How do the gluons and sea-quarks contribute to the spin structure of the nucleon?**
- **What is the spatial distribution of the gluons and sea quarks in the nucleon?**
- **How do hadronic final-states form in QCD?**

# ELIC Design Goals

- **Energy**
  - Center-of-mass energy between 20 GeV and 90 GeV
  - energy asymmetry of ~ 10,

    ➔ 3 GeV electron on 30 GeV proton/15 GeV/n ion **up to**
    9 GeV electron on 225 GeV proton/100 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

$L \sim 7.7 \times 10^{34}\ cm^{-2}\ sec^{-1}$ (150 GeV protons x 7 GeV electrons)

## ELIC luminosity Concepts

- High bunch collision frequency (f=1.5 GHz)
- Short ion bunches ($\sigma_z \sim 5$ mm)
- Super strong final focusing ($\beta^* \sim 5$ mm)
- Large beam-beam parameters (0.01/0.086 per IP, 0.025/0.1 largest achieved)

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

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

# ELIC (e/p) Design Parameters

| Parameter | Unit | Ring-Ring | | | |
|---|---|---|---|---|---|
| Beam energy | GeV | 225/9 | 150/7 | 100/5 | 30/3 |
| e/A ring circumference | km | 1.5 | | | |
| Bunch collision frequency | GHz | 1.5 | | | |
| Number of particles/bunch | $10^{10}$ | 0.42/.77 | 0.4/1 | 0.4/1.1 | 0.12/1.7 |
| Beam current | A | 1/1.85 | 1/2.4 | 1/2.7 | 0.3/4.1 |
| Energy spread, rms | $10^{-4}$ | 3/3 | | | |
| Bunch length, rms | mm | 5/5 | | | |
| Beta* | mm | 5/5 | | | |
| Horizontal emittance, norm | μm | 1.25/90 | 1/90 | .7/70 | .2/43 |
| Vertical emittance, norm | μm | .05/3.6 | .04/3.6 | .06/6 | .2/43 |
| Beam-beam tune shift (vertical) per IP | | .006/.086 | .01/.086 | .01/.078 | .009/.008 |
| Peak luminosity per IP, $10^{34}$ *(including hourglass effect)* | $cm^{-2} s^{-1}$ | 5.7 | 6.0 | 5.0 | .7 |
| Number of IPs | | 4 | | | |
| Core & lumi. IBS lifetime | hrs | 24 | | | |

# ELIC (e/A) 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 | 7.8 | 6.7 |
| Deuteron | 75 | 7.8 | 6.7 |
| $^{3}H^{+1}$ | 50 | 7.8 | 6.7 |
| $^{3}He^{+2}$ | 100 | 3.9 | 3.3 |
| $^{4}He^{+2}$ | 75 | 3.9 | 3.3 |
| $^{12}C^{+6}$ | 75 | 1.3 | 1.1 |
| $^{40}Ca^{+20}$ | 75 | 0.4 | 0.4 |
| $^{208}Pb^{+82}$ | 59 | 0.1 | 0.1 |

*** Luminosity is given per unclean per IP**

# Evolution of ELIC Conceptual Design

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

- Challenge: high current polarized electron beam
  - ERL-Ring: 2.5 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

- 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
- 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.

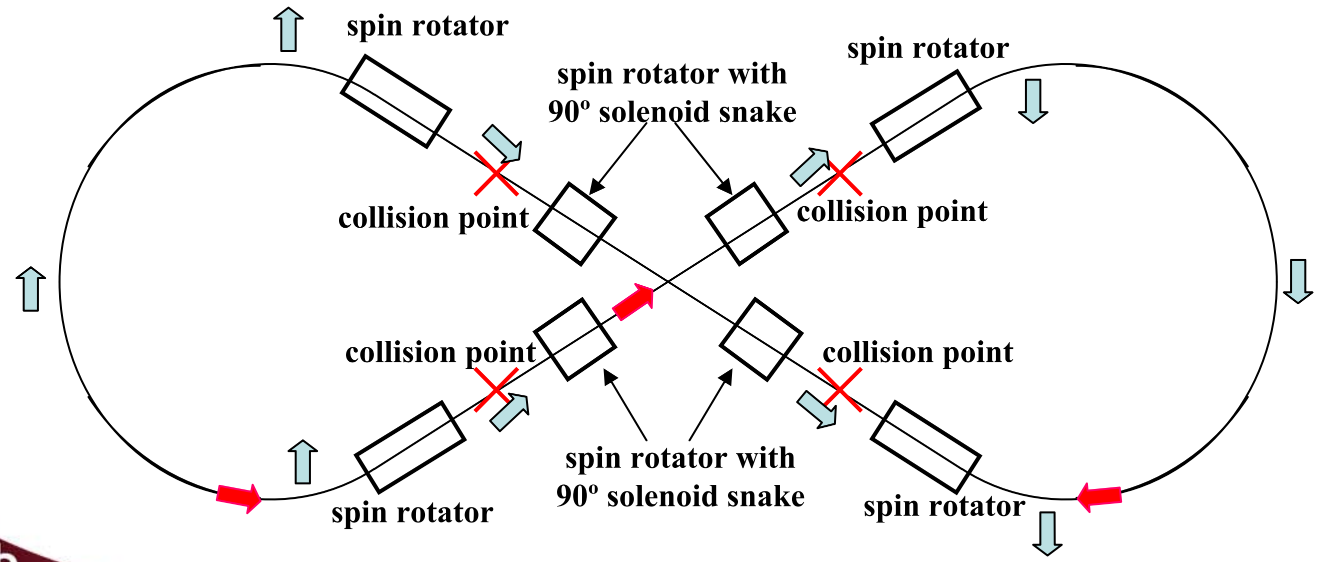
# ELIC Ring-Ring Design Features (cont)

- **Present CEBAF gun/injector meets 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.**

# Electron Polarization in ELIC

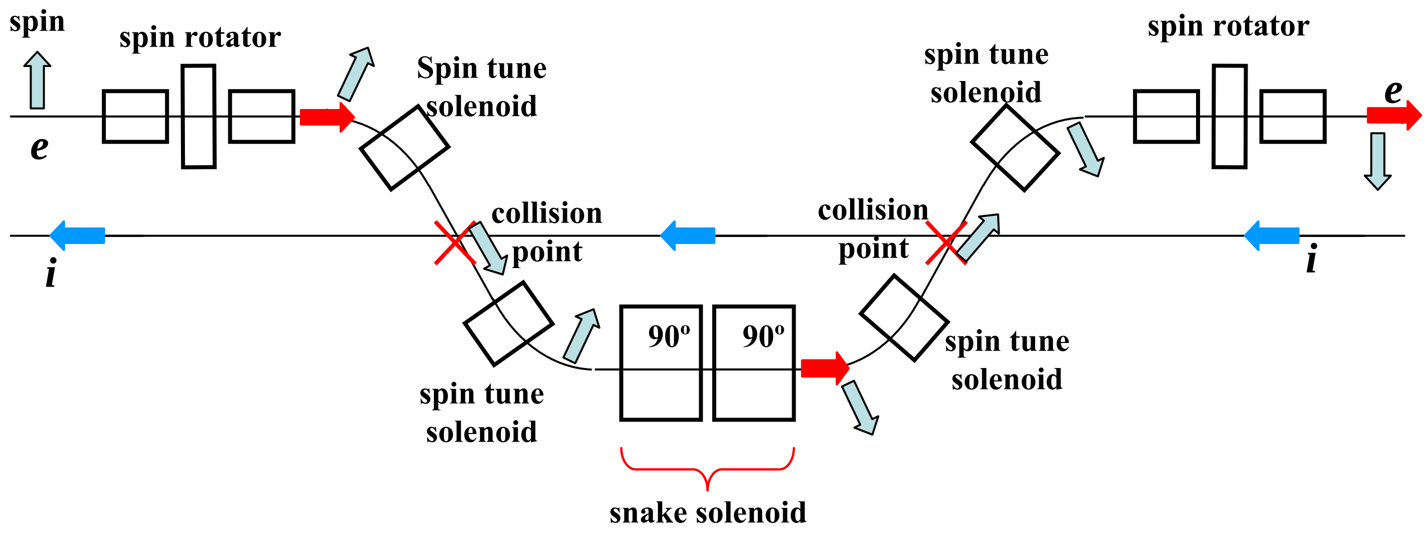
- **Producing at source**
  - **Polarized electron source of CEBAF**
  - **Preserved in acceleration at recirculated CEBAF Linac**
  - **Injected into Figure-8 ring with vertical polarization**

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



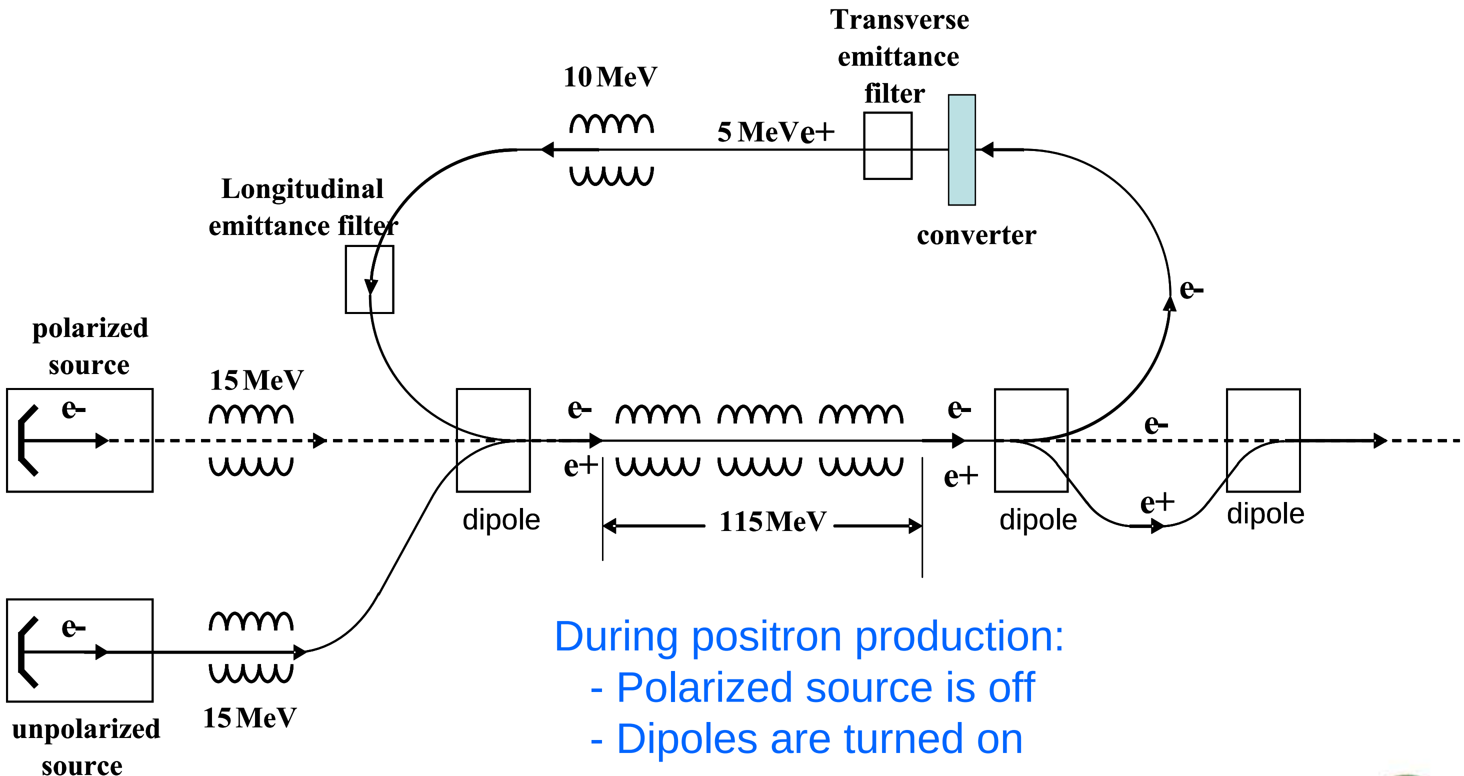
# Electron Polarization in ELIC (cont.)

- **Matching at IP**
  - vertical in arc, longitudinal at IP
  - Vertical crossing bend causing energy-dependent spin rotation
  - Spin rotators with vertical crossing bends of IP



# Positrons in ELIC

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




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

# Electron Polarization in ELIC (cont.)

## Electron/positron 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.

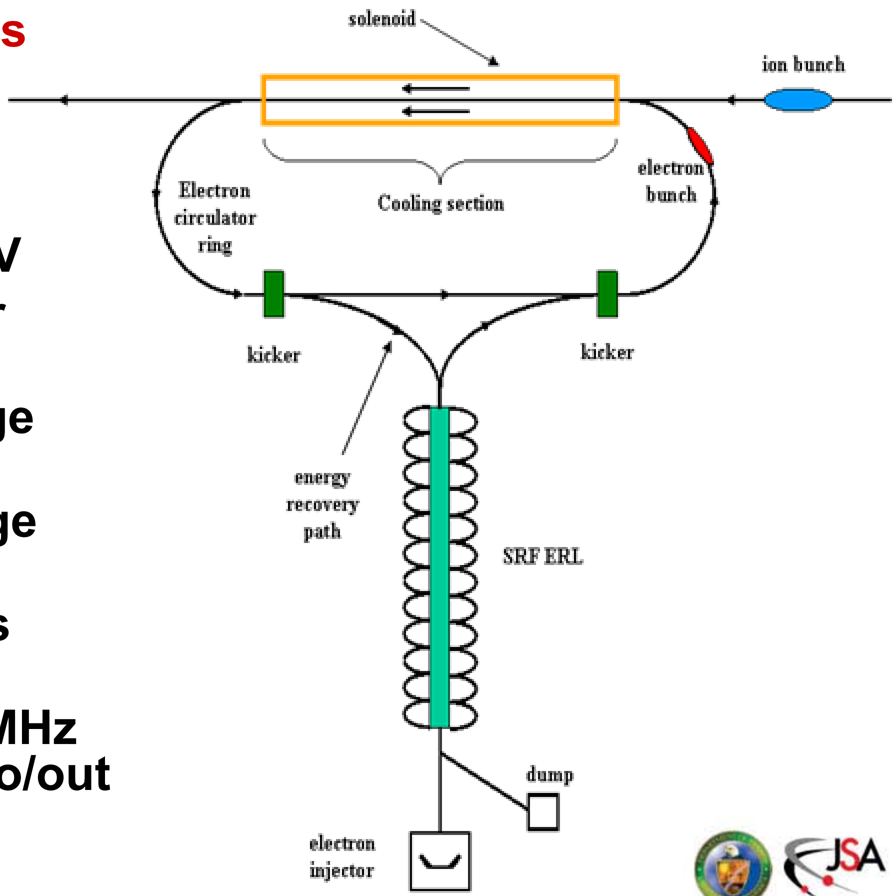
# ELIC R&D Requirements

- To achieve luminosity at $10^{33}$ $cm^{-2}$ $sec^{-1}$ and *up*
  - High energy electron cooling with or without circulator ring

- To achieve luminosity at ~ $10^{35}$ $cm^{-2}$ $sec^{-1}$
  - Crab cavity
  - Stability of intense ion beams
  - Beam-beam interactions
  - Detector R&D for high repetition rate (1.5 GHz)

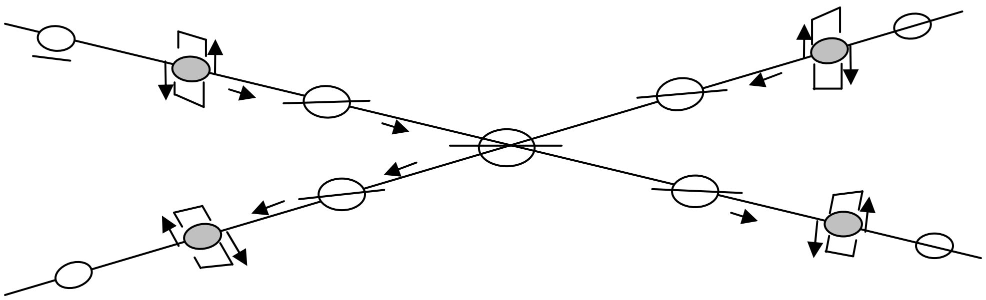
# ELIC R&D: Electron Cooling

- **Issue**
  - To suppress IBS, reduce emittances, provide short ion bunches.
  - Effective for heavy ions (higher cooling rate), difficult for protons.
- **State-of-Art**
  - Fermilab electron cooling demonstration (4.34 MeV, 0.5 A DC)
  - Magnetic field in the cooling section - 100 G
  - Feasibility of EC with bunched beams remains to be demonstrated.
- **ELIC Circulator Cooler**
  - 3 A CW electron beam, up to 125 MeV
  - Non-polarized source (present/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
  - Fast (300 ps) kicker operating at 15 MHz rep. rate to inject/eject bunches into/out circulator-cooler ring



# ELIC R&D: Crab Crossing

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




**State-of-art:** KEKB

Crossing angle = 2 x 11 mrad

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

# ELIC R&D: Crab Crossing (cont.)

## Routes of optimization

- IP configuration optimization
- "Lambertson"-type final focusing quad

➔ angle reduction: 100 *mrad* ➔ 30 *mrad*

## Crab cavity

Electron: 1.2 MV – within state of art

(KEK, single Cell, 1.8 MV)

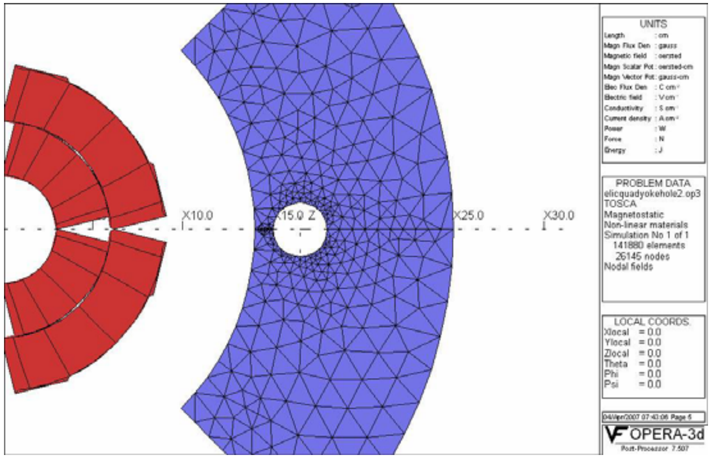
Ion: 24 MV

(Integrated B field on axis 180G/4m)

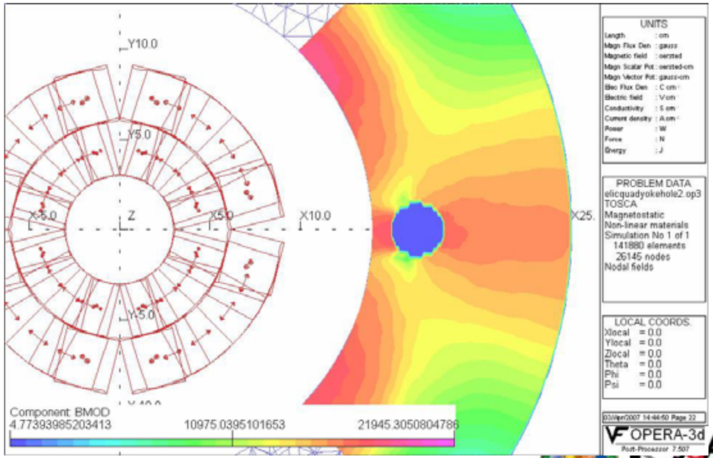
## Crab Crossing R&D program

- 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

Cross section of quad with beam passing through




magnetic Field in cold yoke around electron pass.



# ELIC R&D: Instability of Ion Beam

## Stacking of ion beam

- Stacking/accumulation process
  - Multi-turn (10 – 20) injection from SRF linac to pre-booster
  - Damping of injected beam
  - Accumulation of 1 A coasted beam at space charge limited emittence
  - RF bunching/acceleration
  - Accelerating beam to 3 GeV, then inject into large booster
- Ion space charge effect dominates at low energy region
- Method: stochastic cooling

## Pre-cooling in collider ring (30 GeV)

- stochastic cooling

**Stacking proton beam in pre-booster with stochastic cooling**

| Parameter | Unit | Value |
|---|---|---|
| Beam Energy | MeV | 200 |
| Momentum Spread | % | 1 |
| Pulse current from linac | mA | 2 |
| Cooling time | s | 4 |
| Accumulated current | A | 0.7 |
| Stacking cycle duration | Min | 2 |
| Beam emittance, norm. | μm | 12 |
| Laslett tune shift | | 0.03 |

**Transverse stochastic cooling of coasted proton beam after injection in collider ring**

| Parameter | Unit | Value |
|---|---|---|
| Beam Energy | GeV | 30 |
| Momentum Spread | % | 0.5 |
| Current | A | 1 |
| Freq. bandwidth of amplifiers | GHz | 5 |
| Minimal cooling time | Min | 8 |
| Initial transverse emittance | μm | 16 |
| IBS equilibrium transverse emitt. | μm | 0.1 |
| Laslett tune shift at equilibrium | | 0.04 |

# ELIC R&D: Beam-Beam

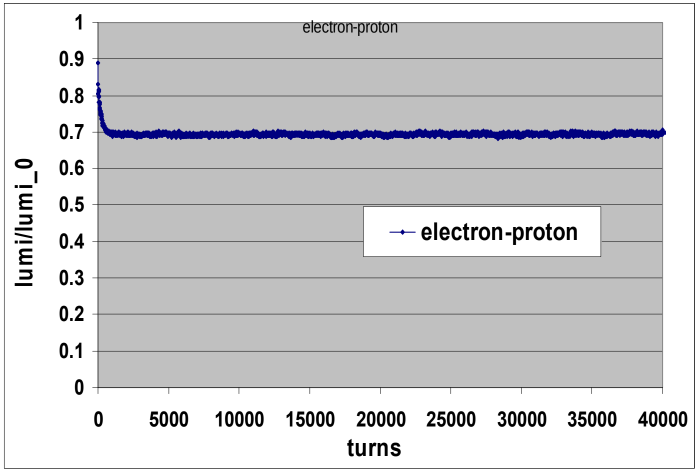
## Beam-beam features

- Asymmetric colliding beams (9 GeV/2.5 A on 225 GeV/1 A)
- IP design
  - Short ion bunch (5 mm), strong final focusing (β*=5 mm)
  - High repetition rate (up to 1.5 GHz)
  - Large synchrotron tune (up to 0.25/0.06)
- Multiple IPs
- Crab crossing

## Simulation studies

- PIC code *BeamBeam3d* (LBL)
- Single IP, no crossing, 7/150 GeV ,
- Working point: e(0.91, 0.88, 0.25), p(0.71, 0.7, 0.06)
- Saturated at 70% of peak luminosity $4.2 \cdot 10^{34}$ $cm^{-2}s^{-1}$

$L/L_0$



# Summary

## ELIC Conceptual Design provides

- CM energy up to 90 GeV, light to heavy ions (A=208)
- *Unprecedented high* luminosity (up to $6 \cdot 10^{33}$ $cm^{-2}$ $sec^{-1}$ for e-p)
- High spin polarization for both electron & light ion beams
- *Simultaneous* operation of collider and CEBAF fixed target

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

## Recent R&D Advances

- Electron cooling and circulator cooler
- Crab crossing and crab cavity
- Instability of intense ion beam
- Beam-beam effects

## Continue design optimization

## We have developed a detailed Pre-R&D program

# ELIC Study Group & Collaborators

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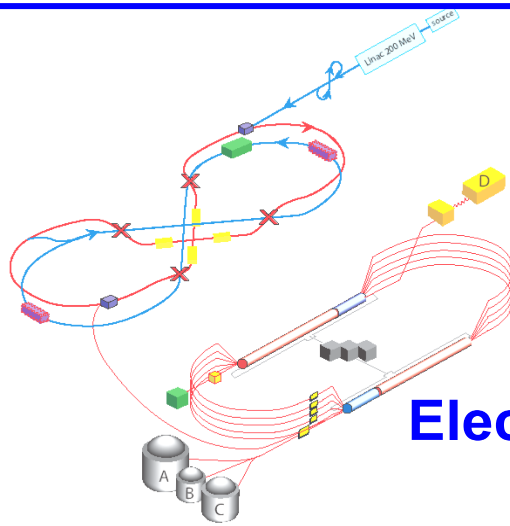


# Zero$^{th}$–Order Design Report for the Electron-Ion Collider at CEBAF

http://casa.jlab.org/research/elic/elic_zdr.doc


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