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

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Outline

- Science Motivation
- Design Goals
- ELIC Conceptual Design
- R&D Requirements and Advances
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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?**

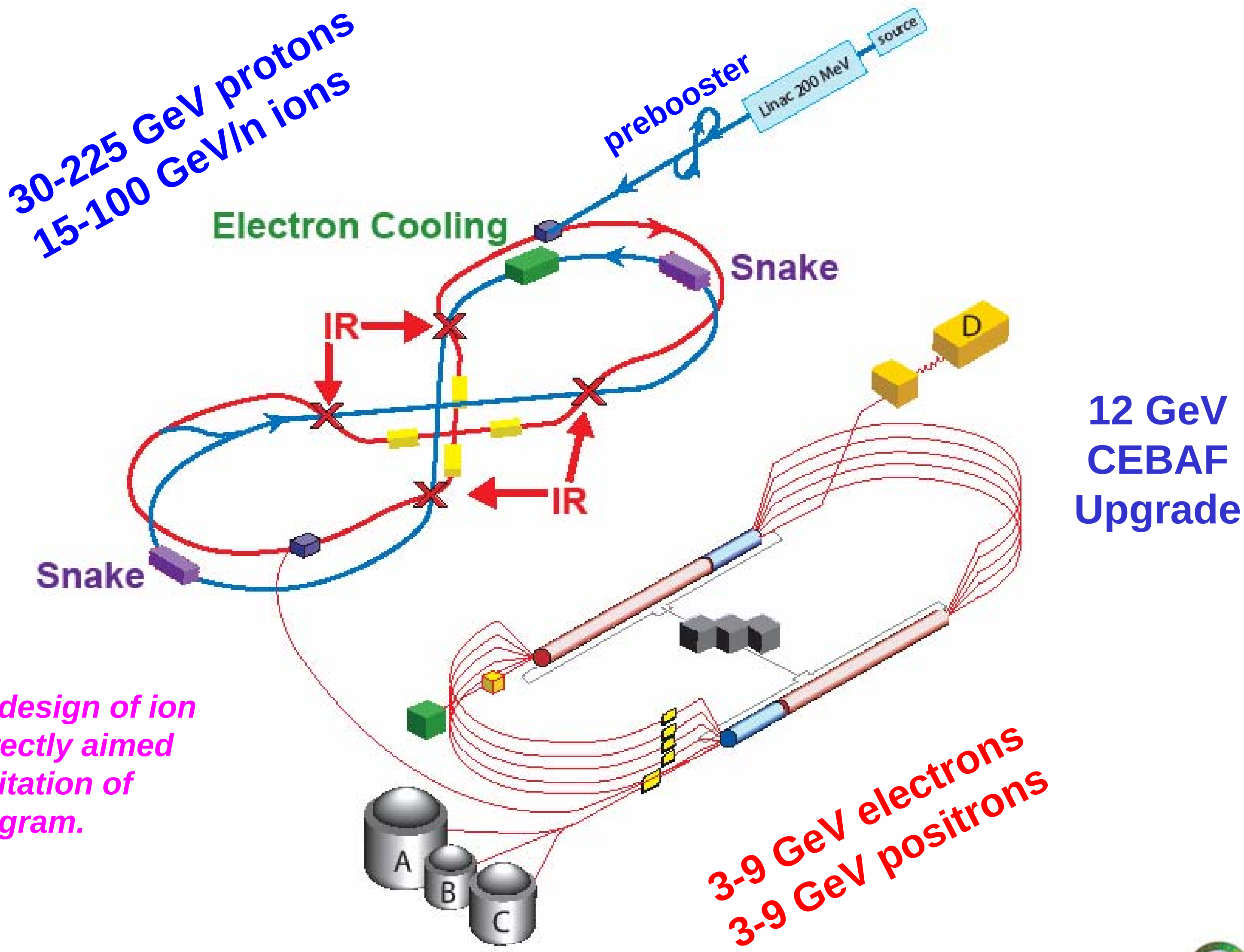
Precisely image the sea-quarks and gluons in the nucleon

- **How do the gluons 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 or 15 GeV/n ion up to 9 GeV electron on 225 GeV proton or 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.

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			

Evolution of ELIC Conceptual Design

- Energy-Recovery-Linac-Ring
- Linac-Circulator-Ring-Storage-Ring
- Ring-Ring

- Challenge: polarized high current 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

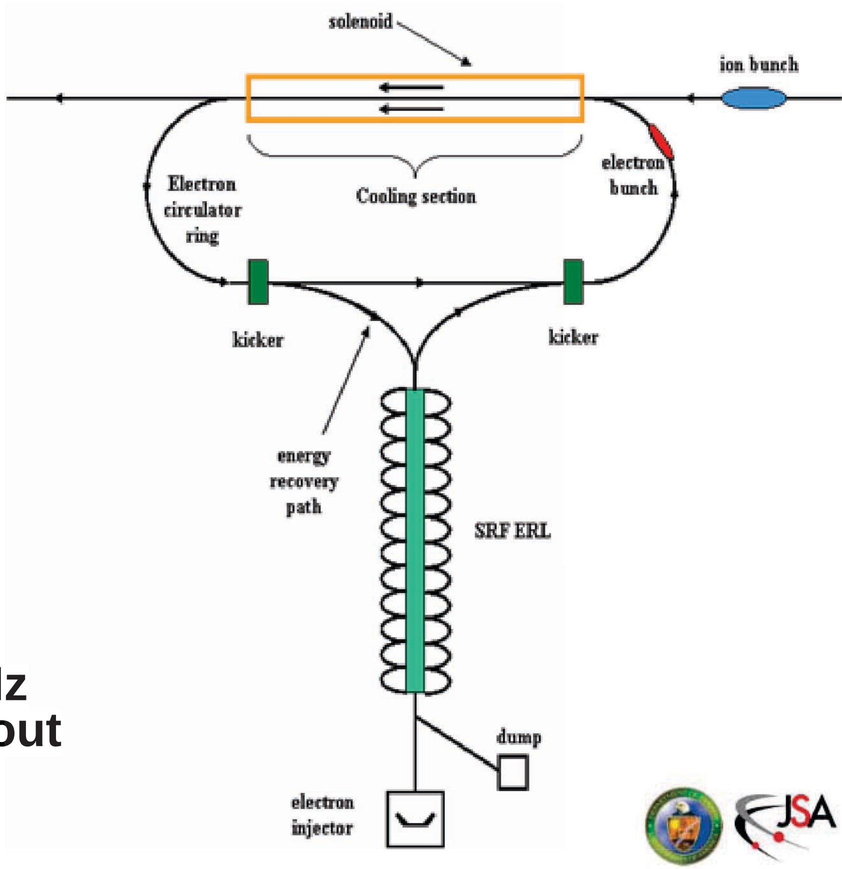
- **Unprecedented high luminosity**
  - **Enabled by short ion bunches, low β*, high rep. rate**
  - **Require crab crossing**
- **Electron cooling is an essential part of ELIC**
- **Four interaction regions (detectors) for high productivity**
- **"*Figure-8*" ion and lepton storage rings**
  - **Ensure spin preservation and ease of spin manipulation.**
  - **No spin sensitivity to energy for all species.**
- **Present CEBAF gun/injector meets storage-ring requirements**
- **The 12 GeV CEBAF can serve as a full energy injector to e-ring**
- ***Simultaneous* operation of collider and CEBAF fixed target program.**
- **Experiments with polarized positron beam are possible.**

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 cavity needed to avoid luminosity reduction
- Minimizing crossing angle reduces crab cavity challenges and required R&D

- Routes of optimization
  - IP configuration optimization
  - "Lambertson"-type final focusing quad
  - ➔ angle reduction: 100 *mrad* ➔ 30 *mrad*

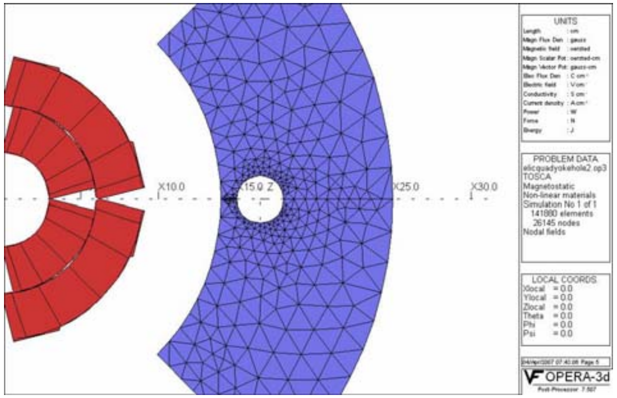
- Crab cavity Development

  Electron: 1.2 MV – within state of art (KEK, single Cell, 1.4 MV)

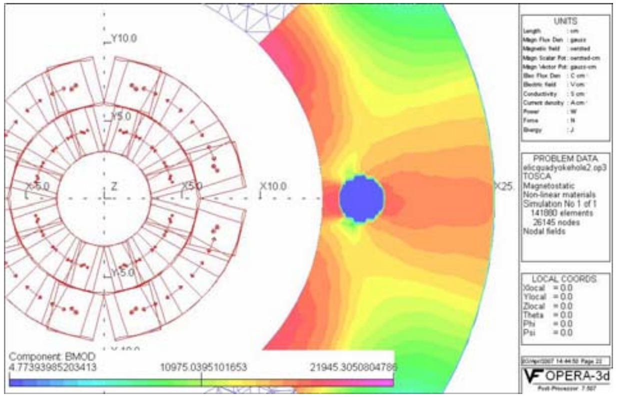
  Ion: 24 MV (Integrated B field on axis 180 G / 4 m)

- Crab Crossing R&D program planned
  - Understand gradient limit, 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

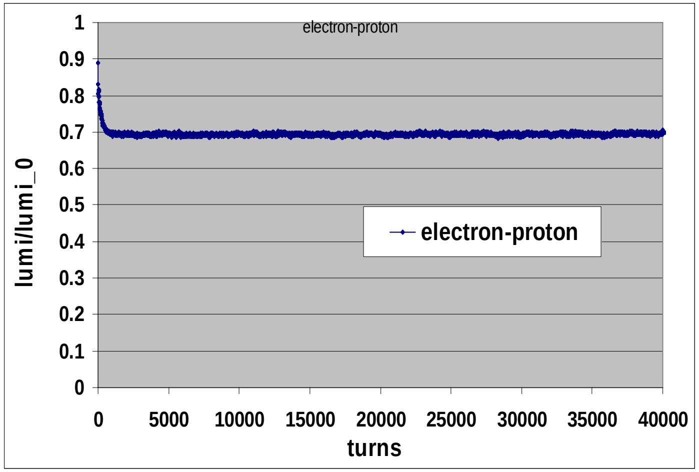
Beam-beam features

- 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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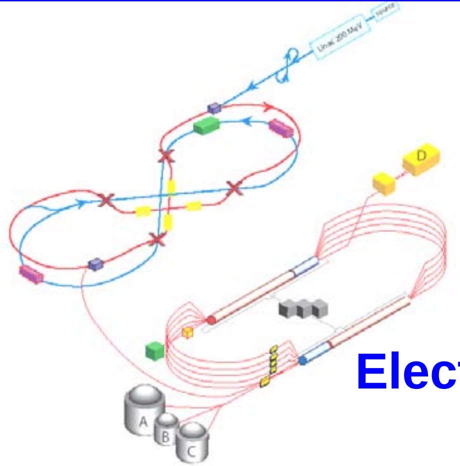

Zeroth–Order Design Report for the Electron-Ion Collider at CEBAF

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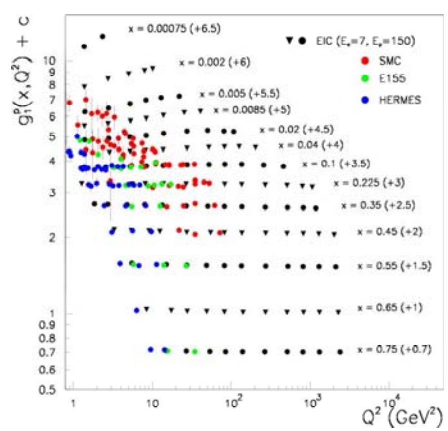

http://casa.jlab.org/research/elic/elic_zdr.doc