Electron-Ion Collider at JLab: Opportunities, Designs, Optimization, Staging and R&D

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For

ELIC/MEIC Study Group, Jefferson Lab

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Outline

- Introduction
- ELIC Nominal Design update
- Reaching Ultra High Energy
- Supporting Low to Medium Energy
- Charting A Staging Path
- Parade of R&D
- Conclusions

Introduction: Opportunities Ahead of Us

- 12 GeV upgraded CEBAF fixed target program
  - CD3 recently approved, construction begins next year
  - Exciting fixed target program utill 2020
- What CEBAF will provide
  - Up to 11 GeV high repetition rate CW electron beam
  - High polarization
  - Very good beam quality from the recirculated SRF linac
- Opportunity: Making an electron-ion collider
  - Add a modern ion complex with a *Green Field* design
  - Expand science program beyond 12 GeV CEBAF fixed target physics
  - Open up new science domain with high CM energy

Question: ***What kind of Electron-Ion Collider?***

Science Driven Accelerator Design

- High Energy EIC (CM energy: 20 ~ 100 GeV)
  - First in discussion, endorsed by NSAC LRP
  - Colliding beam energies: 30 to 250 GeV/u ions x 3 to 10 GeV electrons
  - Explore the new QCD frontier: strong color fields in nuclei
  - Precisely image the sea-quarks and gluons in the nucleon
- Ultra High Energy EIC (CM energy: 115 ~ 160 GeV)
  - Colliding beam energies: 325 GeV/u ions x 10 to 20 GeV electrons
  - There are science cases calling even high energy
- Low to Medium Energy EIC (CM Energy: 8 ~ 20 GeV)
  - Colliding beam energies: up to 15 GeV/u ions x up to 10 GeV electrons
  - Gluons via J/ψ production
  - Higher CM in valence region
  - Study the asymmetric sea for $x \approx m_\pi/M_N$

Design Challenges

Design an Electron-Ion Collider that satisfies

- NSAC LRP requirements as a baseline (at high energy)
- Covers very wide CM energy range (10 to 160 GeV) in a ***unified & coherent*** way for highest science productivity
- Deliver best collider quality in terms of high luminosity, high polarization, maximum flexibility and reliability
- Take maximum advantage of existing CEBAF
- Offer a good path for future upgrade
- Realize in a cost effective way, staging if possible

Expanding ELIC Baseline Design Scope

- ELIC was presented originally as a collider for electrons and light ions with low maximum energy, up to 150 GeV for protons and 7 GeV for electrons.

- As NSAC LRP has already standardized requirements for beam energies and ion species, we have adjusted the design to follow these requirements.

- With expansion of ELIC storage rings from to 1.5 km to ~2.5 km, we are able to extend beam energies up to 250 GeV for protons, 100 GeV/u for ions respectively (superconducting magnet capability) and up to 10 GeV for electrons (within synchrotron radiation power limit)

ELIC New Nominal Parameters

Beam energy	GeV	250/10	150/7	100/5
Figure-8 ring	km	2.5		
Collision frequency	MHz	499		
Beam current	A	0.22/0.55	0.15/0.33	0.19 /0.38
Particles/bunch	109	2.7/6.9	1.9/4.1	2.4/4.8
Energy spread	10^{-4}	3/3		
Bunch length, rms	mm	5/5		
Horizontal emit., norm.	µm	0.7/51	0.42/35.6	0.28/25.5
Vertical emit., norm.	µm	0.03/2.0	0.017/1.42	0.028/2.6
Beta*	mm	5/5		
Vert. b-b tune-shift		0.01/0.1		
Peak lumi. per IP	10^{34} cm^{-2}s^{-1}	2.9	1.2	1.1
Luminosity lifetime	hours	24		

- These parameters are derived assuming a 6 m detector space, 27 mrad crab crossing angle, 10 to 14 sigma radius for aperture, 10 kW/m synchrotron radiation power density limit
- Collision frequency has been reduced to 499 MHz as suggested by EICC Steering Committee

ELIC at Ultra High Energy

• As a potential future upgrade option, ELIC rings can accommodate proton beam with energy up to 325 GeV, electron beam with energy up to 20 GeV.

• Electron current is severely limited by synchrotron radiation power, it must be reduced to 0.1 A at 20 GeV, however, luminosity is still at a level above 10^{34} $cm^{-2}s^{-1}$

Beam energy	GeV	325/10	325/20
Figure-8 ring	km	2.5	
Collision freq	MHz	499	
Beam current	A	0.22/0.71	0.44/0.1
Particles/bunch	109	2.8/8.9	5.4/1.3
Energy spread	10^{-4}	3/3	
Bunch length, rms	mm	5/5	
Horizontal emit., norm.	µm	0.9/50.9	0.9/102
Vertical emit., norm.	µm	0.036/2.0	0.036/4.1
Beta*	mm	5/5	
Vert. beam-beam tune-shift		0.01/0.1	0.0014/0.1
Peak lumi. per IP	10^{34} $cm^{-2}s^{-1}$	3.7	1.0

Low to Medium Energy EIC at JLab

- Recently, significant effort has been made at JLab through a very fruitful collaboration between nuclear & accelerator scientists for a conceptual design of a low to medium electron-ion collider, mEIC, based on CEBAF

- Motivations
  - ➢ Science (started by several groups *independently*) (See T. Horn's Talk)
  - ➢ Accelerator
    - ❖ Bring ion beams and associated technologies to JLab (a lepton lab)
    - ❖ Have a ring-ring collider at JLab
    - ❖ Provides a test bed for new technologies required by ELIC
    - ❖ Develop expertise and experience, acquire/train technical staff
  - Staging possibilities of ELIC (suggested by EICC Steering Committee)

- Presentation scope
  - Will not present mEIC baseline design (See G. Krafft's talk)
  - Will discuss how we have came to this final (?) design, what issues, scenarios and energy range we have considered

MEIC: Scenario, Type, Energy Range

- Scenarios
  - ERL-ring
    - A storage-collider ring for protons/ions and a recirculated arc for electrons
    - Minimum hardware requirement, possibility of fitting ion complex inside an CEBAF experiment hall and share same detector considered
    - Low luminosity (~10^{30}) due to small polarized electron beam current (~8 mA)
  - Ring-ring
    - Standard, with multiple booster-collider ring
    - Delivers high luminosity
- Type and Energy Range
  - "Inverted": 2 to 4 GeV/c proton x 9 to 11 GeV electron
  - Symmetric: 4 to 11 GeV/c proton x 4 to 11 GeV electron
  - "Normal": 15 GeV/c proton x 5 GeV electron (close to MANUEL)
    30 GeV/c proton x 10 GeV electron (Close to low end of ELIC)

All above scenarios/cases are science driven

Beam Physics Considerations

Limiting Factors

- Space charge effect for low ion energy (5 to 7 GeV/c and below)
- Electron current due to synchrotron radiation power (6 GeV and up)
- Beam-beam effect
- Aperture size due to large ion emittance

Colliding energy luminosity optimization

– High proton energy (>10 GeV/c), low electron energy (<3 GeV or < 6 GeV)
– Can reach luminosity above 10^{34} $cm^{-2}s^{-1}$
– But not necessarily delivering best science

Luminosity Concepts

- High bunch collision frequency (up to 0.5 GHz)
- Long ion bunches with respect to β^* for high bunch charge (σ_z ~ 5 cm)
- Super strong final focusing (β^* ~ 2.5 mm to 5 mm)
- Large beam-beam parameters (0.015/0.1 per IP for *p* and *e*)

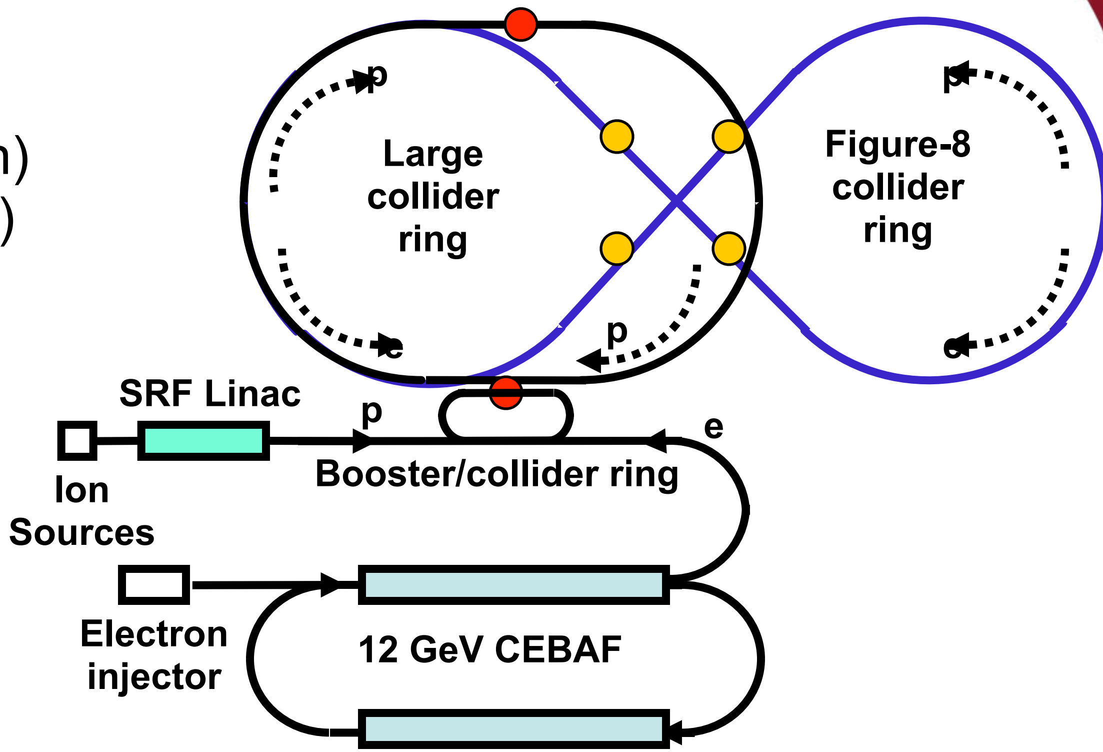
Schemes and technologies

- Staged cooling for ion beams
- Crab crossing colliding beams

MEIC and Staging of ELIC

Coherent picture

- Energy range (physics domain)
- Project Staging (energy boost)
- simultaneous operation
- Technology staging
- Product/cost optimization

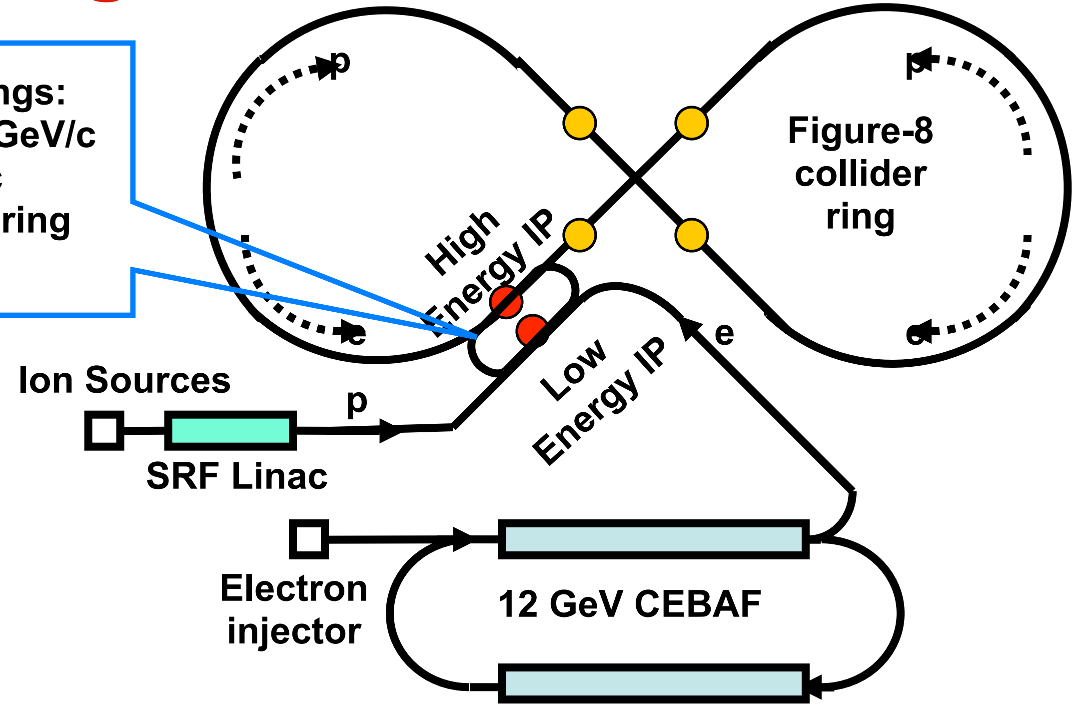


(see G. Krafft's talk)

- Low Energy Collider (stage 1)
  - Both *e* and *p* in a compact ring (320 m)
- Medium Collider (stage 2)
  - Large warm ion ring (1400 m)/Compact superconducting ion ring (320 m)
  - Large electron ring (1400 m)
- High Energy Collider (stage 3) (Full ELIC)

MEIC & Staging of ELIC: Alternative Pass

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



(Ya. Derbenev, etc.)

- Low energy collider (stage 1) → (up to 5GeV/c for both *e* and *i*)
  - Both *e* and *p* in compact ring (~ 300 m)
- Medium energy collider (stage 2) → (up to 5GeV/c for *e*, 30 GeV/c for *i*)
  - Compact superconducting ion ring (~ 300 m)
- Medium energy collider (Stage 3) → (up to 11 GeV/c for *e*, 30 GeV/c for *i*)
  - Large Figure-8 electron ring (1500 m to 2500 m)
- High energy collider (stage 4) → (up to 11 GeV/c for *e*, 250 GeV/c for *i*)
  - Large Figure-8 super conducting ion ring (Full ELIC)

EIC at JLab: R&D Overview

	High to Ultra high (CM energy 20~160)		Medium (CM energy ~20)		Low (CM energy ~10)	
	critical	challenging	critical	challenging	critical	challenging
Space charge & stability	x		x		x	
Electron cooling	x	x	x		x	
Crab cavity development	x	x	x		x	
Beam dynamics with crab	x		x		x	
Beam-beam interaction	x		x		x	?
IP Chromatic Compensation	x		x		x	
Traveling focusing			x		x	x
Detector	x		x		x	

- Provide good staging approach for key technologies
- Process of gaining experiences/expertise

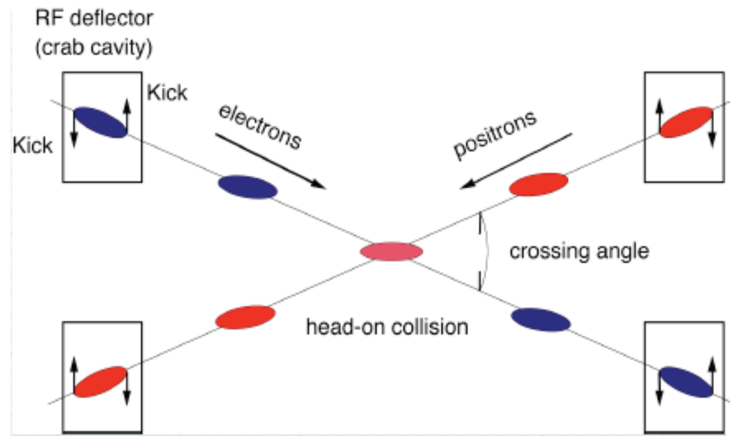
Crab Cavity Development

Issue

- High bunch repetition rate requires crab crossing colliding beams to avoid parasitic beam-beam
- Crab cavities needed to restore head-on collision and avoid luminosity reduction

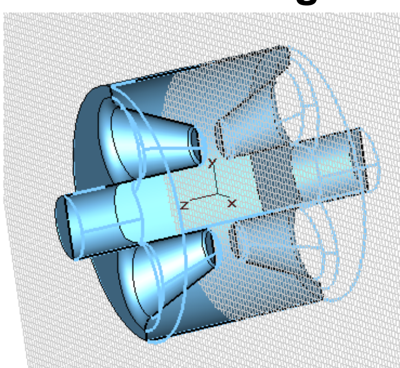
Staging

- Low (1 to 2 MV) integrated crab cavity voltage for MEIC is within present state-of-art. Development is not an issue, beam dynamics with crab crossing is. Lessons can be learnt in MEIC.
- High voltage (up to 24 MV) crab cavity is required for high energy ELIC



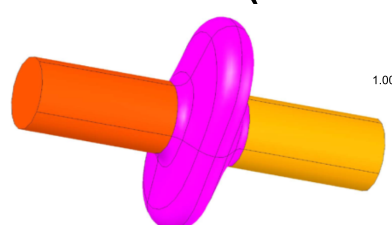
H. Wang, R. Rimmer, Moun Collider Design Workshop, 12/10/2008

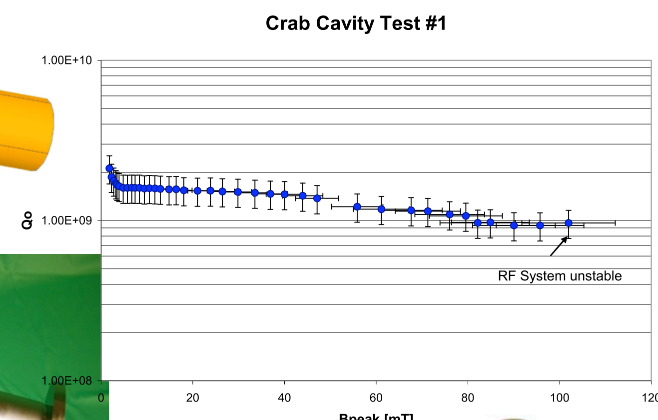
Multi-cell TM110 and Loaded Structure of Crabbing Cavities



200MHz for LHC LC scheme by JLab/Cockcroft Inst./Lancaster Univ. UK

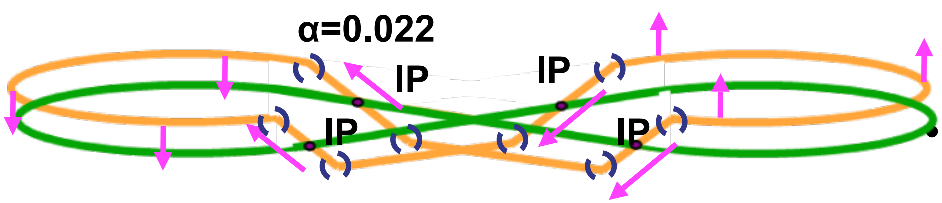
Elliptical squashed SRF cavity R&D for APS (JLab/LBNL/AL/Tsinghua Univ.)

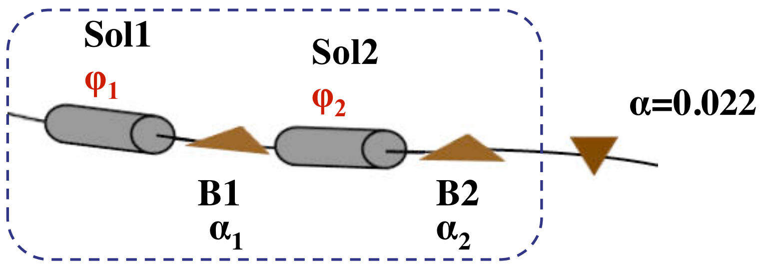


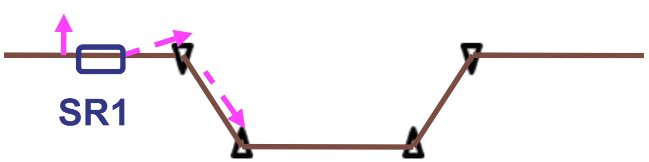


Jefferson Lab

Electron Polarization Matching & Tracking







Issues

- Found a good way to manipulate spins in rings to satisfy polarization requirement of experimentals
- Equilibrium electron polarization in a ring is determined by
  - ➢Sokolov-Ternov self-polarization
  - ➢Depolarization (quantum, vertical betatron oscillation, orbit distortion and beam-beam interaction)
- To remove spin resonances, superconducting solenoids are used in straight sections
- Additional solenoids at the end sectors of arcs (acting together with arc bends) provide spin rotators, which do not change the beam orbit at all available beam energies

Matching and Tracking

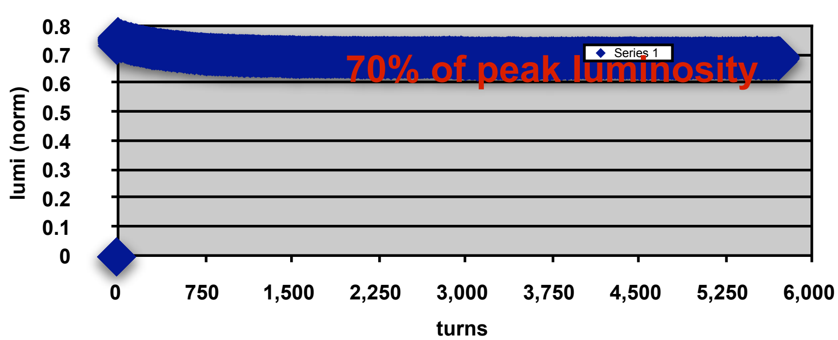
- Simulation study is in progress, in colloboration with D. Barber of DESY

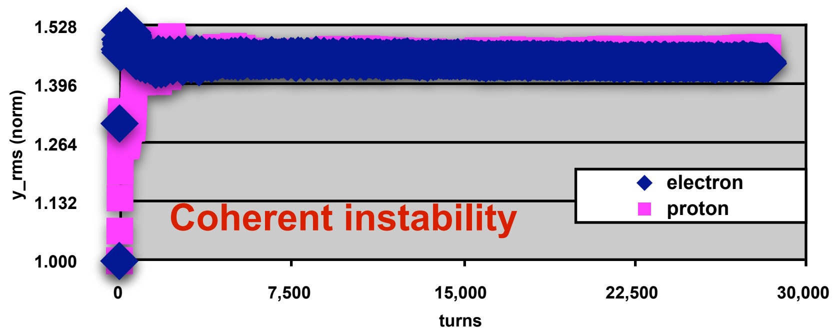
Beam-Beam Interactions

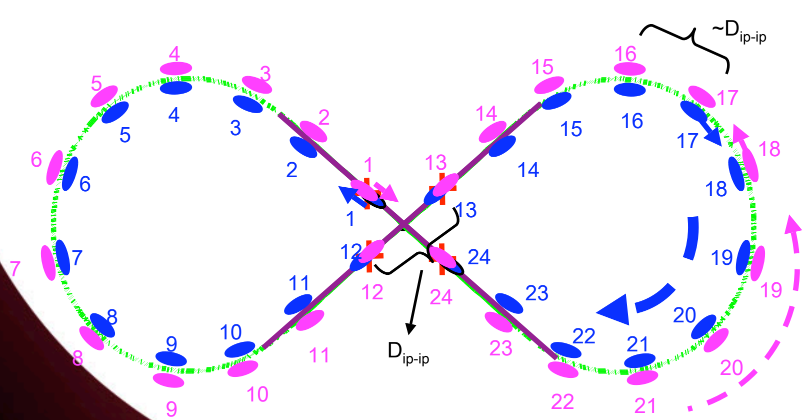
Simulation Model
- Single/multiple IP, head-on collisions
- Ideal rings for e & p, a linear one-turn map
- Radiation damping & quantum excitations

Simulation Codes and Supports
- BeamBeam3D by LBNL
- SciDAC support

Simulation Scope and Limitations
- 10k ~ 30k turns for a typical simulation run (multi-days of NERSC supercomputer)
- 0.15 s of storing time (12 damping times)
- reveals short-time dynamics with accuracy
- can't predict long term (>min) dynamics





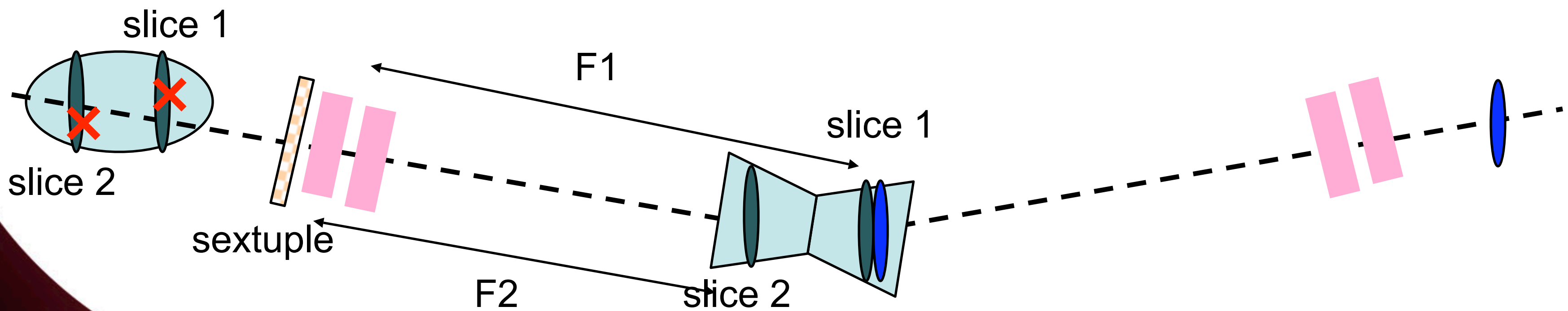


MEIC Beam-beam problem

- Very low ion energy, non-relativistic, space charge dominated
- Ring transport can't be treated as a one-turn map, coupling everywhere
- Long ion bunch (up to 20 x β*), longitudinal dynamics
- Traveling focusing scheme introduces non-linear optics

Traveling Final Focusing

- Under same space charge Lastett tune-shift limit, we must increase ion bunch length in order to increase bunch charge, and hence increase luminosity
- Hour glass effect would kill collider luminosity if ion bunch length is much large than beta-star
- “Traveling Focusing”, first proposed by R. Brinkmann and M. Dohlus, can mitigate hour-glass effect.
- The scheme effectively moves final focusing point along the ion bunch longitudinally, enabling the short electron bunch to collide with different slices of the long ion bunch at their relative focusing points.
- Nonlinear elements (sextuples, etc.) working with a linear final focusing block produce non-uniform focus length for different slices of a long bunch
- This scheme is needed only for very low ion energy (space charge dominated)



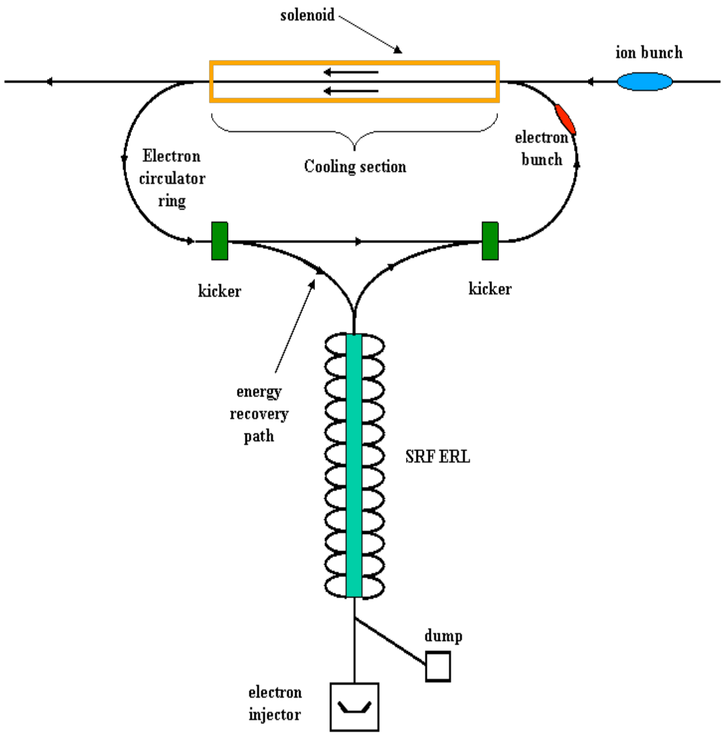
Electron Cooling

Issue

- To suppress IBS, reduce emittances, provide short ion bunches.

ELIC ERL Based Circulator Cooler

- 2 A CW electron beam, up to 137 MeV
- Non-polarized source (present/under development) can deliver nC bunch
- SRF ERL able to provide high average current CW beam
- Circulator cooler for reducing average current from source/ERL



R&D

- Cooling theoretic study
- Simulation study supported by SciDAC, in corroboration with Tech-X
- Exploring new idea, coherent electron cooling, in corroboration with BNL

MEIC electron cooling assessment

- Low electron beam energy
- Low electron current
- Closed to Fermilab e-cooling demo (4 MeV, coast beam), state-of-art

Conclusions

- We continue to push design optimization and studies of a polarized electron-ion collider based on CEBAF. The CM energy range of this collider has been expanded greatly to support wide science programs
- The present ELIC nominal design covers CM energy from 20 to 100 GeV, i.e., 30 on 3 GeV up to 250 GeV on 10 GeV, consistent with the NSAC LRP, and reaches a luminosity above 10^{34} $cm^{-2}s^{-1}$.
- ELIC can also accommodate colliding beam energies up to 325 GeVs for protons and 20 GeV for electrons with a similar high luminosity.
- Recently, a feasibility study and initial design of a low to medium energy electron collider based on CEBAF has been carried out for new science programs, and also as a staging option for the high energy ELIC.
- We continue to actively pursue R&D programs and have made significant progress for several key technologies required by ELIC/MEIC. We have initiated collaborations with various national labs and universities.

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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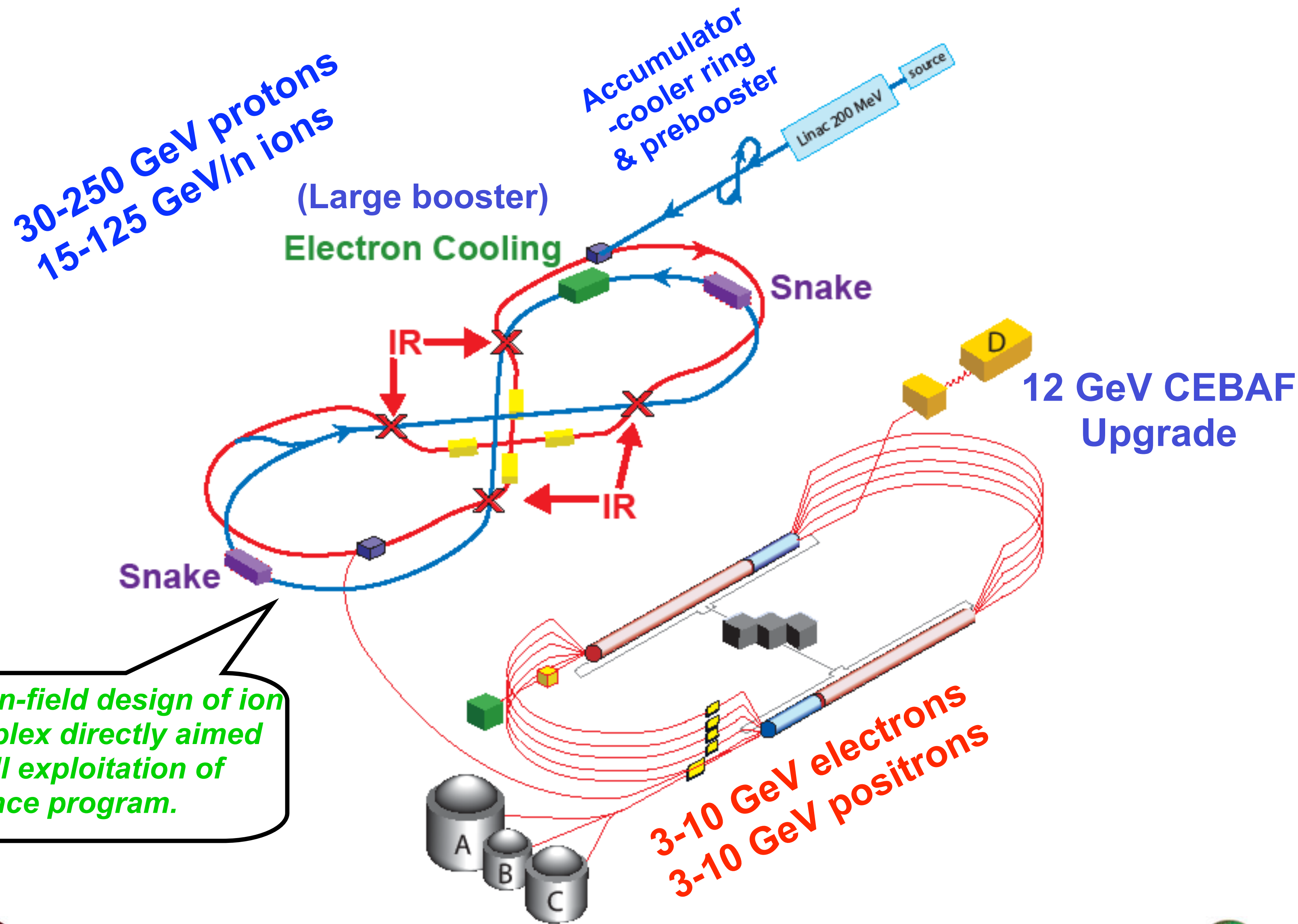
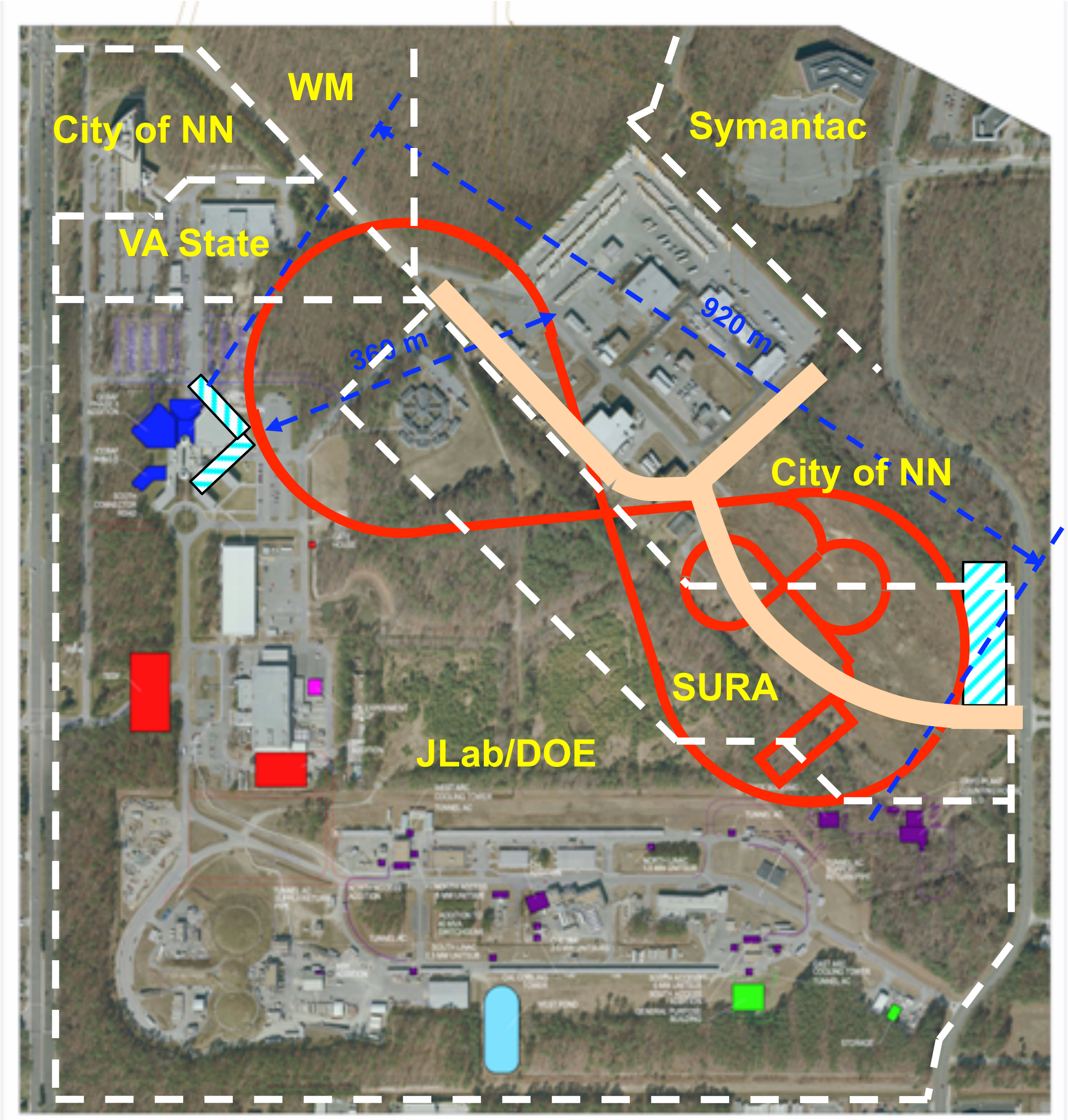
ELIC Conceptual Design



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

ELIC at JLab Site



Chromatic aberration compensation