ComPASS Beam Dynamics Work Plan for Jefferson Lab

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Jefferson Lab

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Jefferson Lab
Thomas Jefferson National Accelerator Facility

Outline

- Introduction
- Electron-Ion Collider (ELIC) at JLab
- ELIC Beam-Beam Simulations:
  Progress, Plan and Outlook
- ELIC Electron Cooling Simulations:
  Plan and Outlook
- Summary

Introduction

- Jefferson Lab CASA's objectives closely coincide with those of ComPASS SciDAC-2 project:
  - Developing and utilizing a comprehensive computational infrastructure for accelerator modeling and optimization
  - Taking part in enhancing existing tools to contain new capabilities

- Jefferson Lab's priority is a conceptual design of a next generation ELectron-Ion Collider (ELIC) with high luminosity ($L \sim 10^{34}$ cm^{-2}s^{-1})

High: 0.5-1.5 GHz

$$L = f_c \frac{N_e N_p}{2\pi \sqrt{\sigma_{e,x}^2 + \sigma_{p,x}^2}\sqrt{\sigma_{e,y}^2 + \sigma_{p,y}^2}}$$

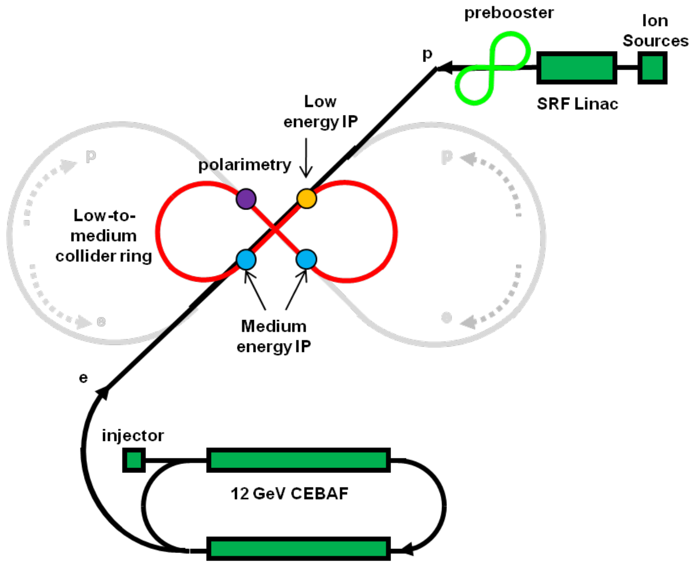
$$\sigma_{p,x} = \sqrt{\beta^*_{p,x}\varepsilon_{p,x}}$$

$$\sigma_{p,y} = \sqrt{\beta^*_{p,y}\varepsilon_{p,y}}$$

Small β* enabled by short ion bunch length, e^--cooling and strong RF bunching

ELectron-Ion Collider at JLab

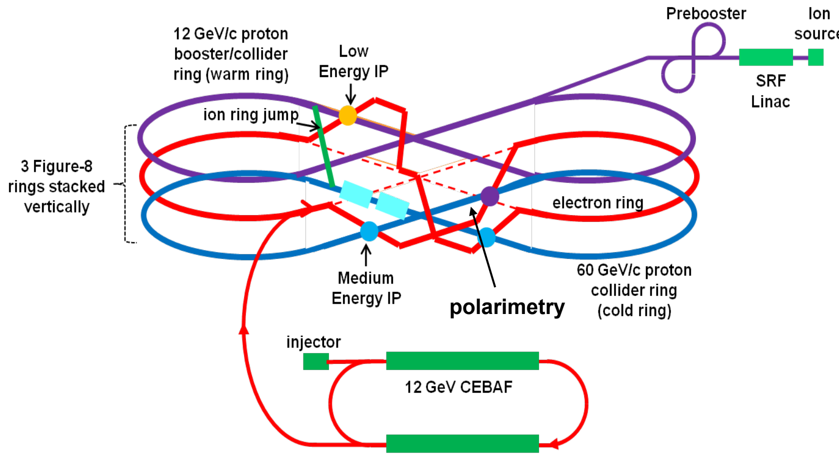
- JLab has been engaged in conceptual design studies of a ring-ring polarized electron-ion collider based on CEBAF recirculated SRF Linac for nearly a decade
- Recent evolution of science programs & design iterations guided us to make a low-to-medium energy collider our immediate project goal and a high energy collider as a future upgrade option
- The design changes have great impact on our R&D, in particularly, beam-beam and electron cooling



Beam Energy	GeV	250/10	150/7	60/5	60/3	12/3
Collision freq.	MHz			499		
Particles/bunch	10^{10}	1.1/3.1	0.5/3.25	0.74/2.9	1.1/6	0.47/2.3
Beam current	A	0.9/2.5	0.4/2.6	0.59/2.3	0.86/4.8	0.37/2.7
Energy spread	10^{-4}			~ 3		
RMS bunch length	mm	5	5	5	5	50
Horz. emit., norm.	µm	0.7/51	0.5/43	0.56/85	0.8/75	0.18/80
Vert. emit. Norm.	µm	0.03/2	0.03/2.87	0.11/17	0.8/75	0.18/80
Horizontal beta-star	mm	125	75	25	25	5
Vertical beta-star	mm			5		
Vert. b-b tuneshift/IP		0.01/0.1	0.015/.05	0.01/0.03	.015/.08	.015/.013
Laslett tune shift	p-beam	0.1	0.1	0.1	0.054	0.1
Peak Lumi/IP, 10^{34}	$cm^{-2}s^{-1}$	11	4.1	1.9	4.0	0.59

High energy | Medium energy | Low energy

Current focus



ELIC Beam-Beam Simulations: Status

- Beam-beam simulations using BeamBeam3D code were performed for ELIC ring-ring design with nominal parameters, single and multiple IP, head-on collision and ideal transport in a Figure-8 ring

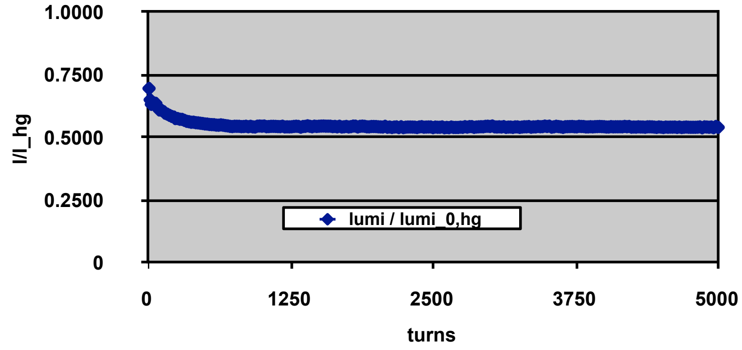
- Simulation results indicated stable operation of ELIC over simulated time scale (10k ~ 25k turns; 0.15s; 12 damping times), with equilibrium luminosity of $4.3 \cdot 10^{34}$ $cm^{-2}s^{-1}$, roughly 25% reduction for each of hour-glass and beam-beam effects

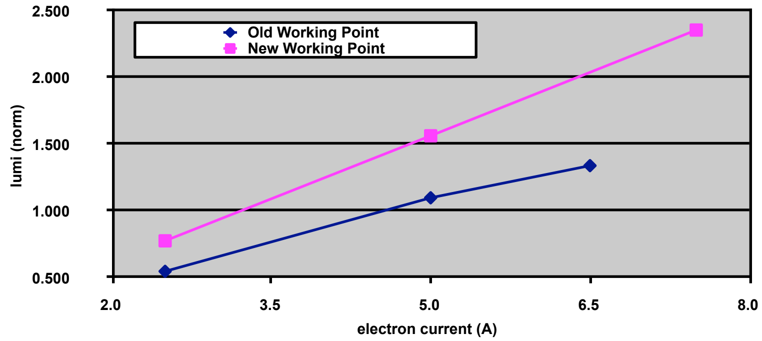
- Studies of dependence of luminosity on electron & proton beam currents showed that the ELIC design parameters are safely away from beam-beam coherent instability

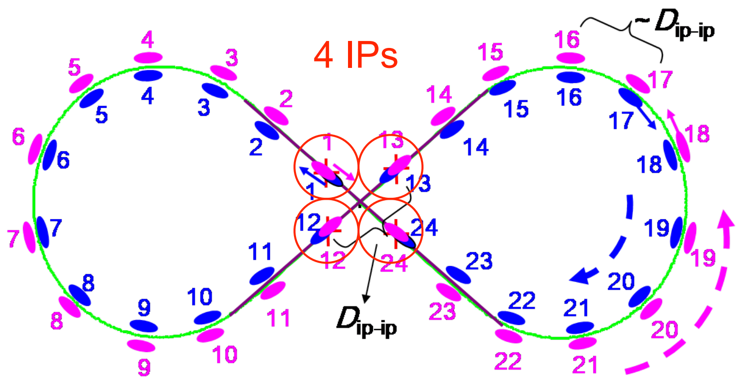
- Search over betatron tune map revealed a better working point at which the beam-beam loss of luminosity is less than 4%, hence an equilibrium luminosity of $5.8 \cdot 10^{34}$ $cm^{-2}s^{-1}$

- Multiple IP and multiple bunch simulations have not shown any new coherent instability. The luminosity per IP suffers only small decay over single IP operation

Normalized Luminosity







ELIC Beam-Beam Simulations: Next Year

- Beam-Beam simulations for the new (revised) ELIC design (low/medium *E*) using BeamBeam3D code
- Need to show that the new design parameter set is viable
- Carefully study the following issues:
  - Onset of beam-beam instability
  - Dependence of beam luminosity on e^- and *p* beam current
  - Single and multiple IP
  - Systematic search for a (near-)optimal betatron tune working point (genetic algorithm?)

ELIC Beam-Beam Simulations: Outlook

Issues beyond next year:

Crab crossing

ELIC design includes a crab crossing, which should be included in beam-beam simulations.

Chromaticity

Because of strong focusing (small β^*), chromaticity is a serious issue. Needs to be properly addressed in simulations.

Tolerance of Imperfect Ring Optics

How sensitive is the beam stability to imperfections in the optics? Determine the range of beam stability.

Space Charge

Low energy ELIC design *may be* sensitive to space charge.

If so, space charge capabilities should be included in simulation code.

ELIC Electron Cooling

Issues

- Essential for delivering ion bunches with small emittances and short length for ELIC
- Cooling electron energy
  - up to 33 MeV for medium energy ELIC
  - up to 136 MeV for high energy
- Up to 3 A CW unpolarized beam (~nC bunch charge)
- Up to 400 MW beam power

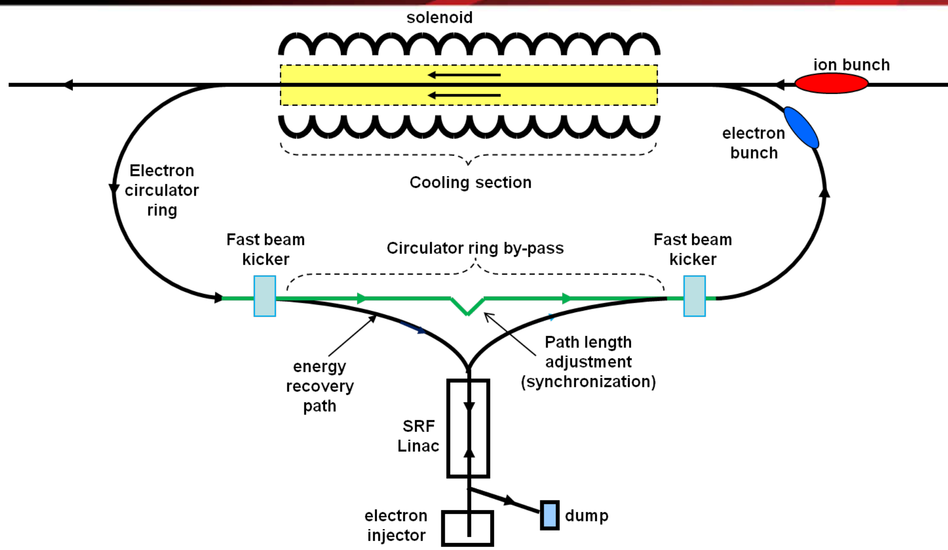
ERL Based Circulator Cooler

- SRF ERL able to provide high average current CW beam with minimum RF power
- Circulator ring for reducing average current from source/ERL

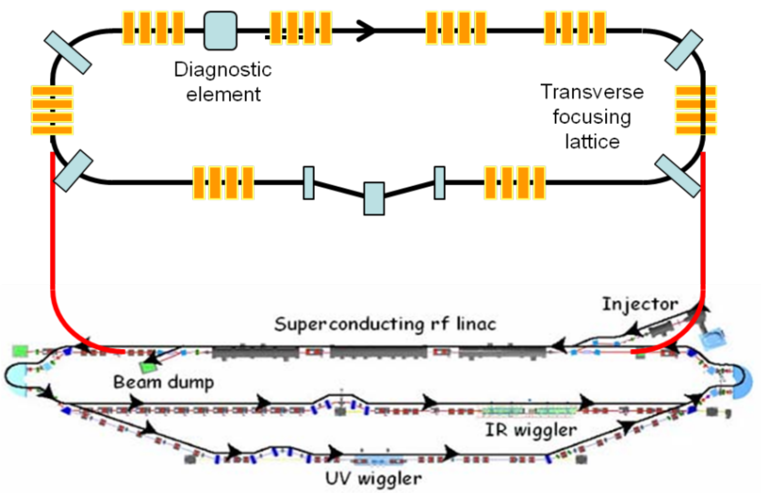
ERL Key technologies

- High intensity unpolarized electron source/injector
- Energy Recovery Linac (ERL)
- Fast kicker

Beam Dynamics R&D



Test Facility for Circulator Cooling Ring



ELIC Electron Cooling: Plan and Outlook

- Prioritize our efforts:
  - **Level 1:** e^- beam stability
    - Space charge, collective effects
  - **Level 2:** Two beam stability
    - e^- heating
    - Inter- and intra-beam scattering
  - **Level 3:** e^- cooling
    - Rates
- After careful investigation of these issues, we will proceed with numerical simulation to validate our design (VORPAL, BETACOOL,…?)

Summary

- Presented JLab's status and plans for the next 12 months and beyond for ComPASS SciDAC-2 project:
  - Beam-Beam simulations for new ELIC design
    - Use BeamBeam3D code
    - Investigate the need for new functionalities
  - Electron cooling for ion bunches in ELIC
    - Current issues still conceptual (beam stability)
    - Computer simulations will be needed for conceptual design and proof-of-concept

Auxiliary Slides

ELIC Design Goals

- **Energy**

  Wide CM energy range between 10 GeV and 100 GeV
  - High energy: up to 10 GeV *e* on 250 GeV *p* or 100 GeV/n *ion*
  - Medium energy: up to 11 GeV e on 60 GeV p or 30 GeV/n ion
  - Low energy: 3 to 10 GeV e on 3 to 12 GeV/c p (and ion)

- **Luminosity**
  - 10^{33} up to 10^{35} cm^{-2} s^{-1} *per* interaction point
  - Multiple interaction points

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

- **Polarization**
  - Longitudinal at the IP for both beams, transverse of ions
  - Spin-flip of both beams
  - All polarizations >70% desirable

- **Positron Beam** *desirable*

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Design Challenges

Design an Electron-Ion Collider that

- Covers a very wide CM energy range (10 to 100 GeV) in a ***unified & coherent*** way for highest science productivity
- Deliver best collider quality in terms of high luminosity, high polarization, multiple interaction points, maximum flexibility and reliability
- Takes maximum advantage of existing CEBAF
- Offers a good path for staging and future upgrade
- Requires minimum R&D
- Realizes in a most cost effective way

ELIC Ring-Ring Design Features

- Unprecedented high luminosity
- Electron cooling is an essential part of ELIC
- Up to 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 injector meets storage-ring requirements
- 12 GeV CEBAF can serve as a full energy injector to electron ring
- *Simultaneous* operation of collider & CEBAF fixed target program.
- Experiments with polarized positron beam are possible.

Nuclear Physics Program at JLab

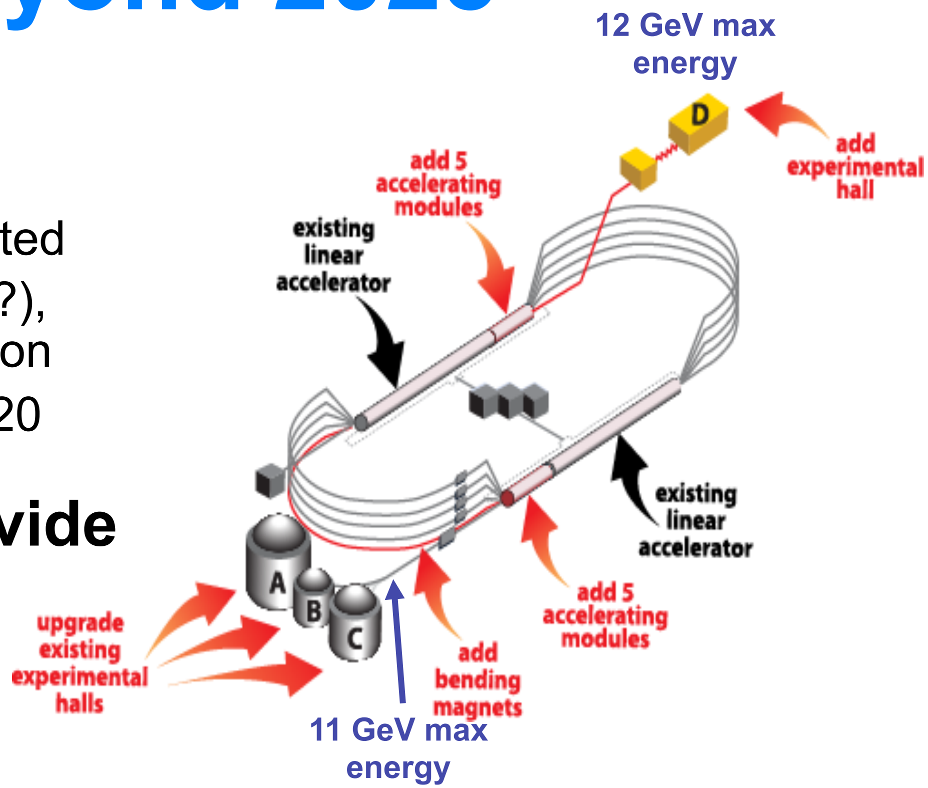
Tomorrow: CEBAF Energy Upgrade & Science Beyond 2025

12 GeV CEBAF Upgrade

- A $340M energy doubling
- CD3 approved, construction already started
- Construction will be completed by 2014(?), science will start after 6 month commission
- Exciting fixed target program beyond 2020

What upgraded CEBAF will provide

- Up to 12 GeV CW electron beam
- High repetition rate (3x499 MHz)
- High polarization (>80%)
- Very good beam quality



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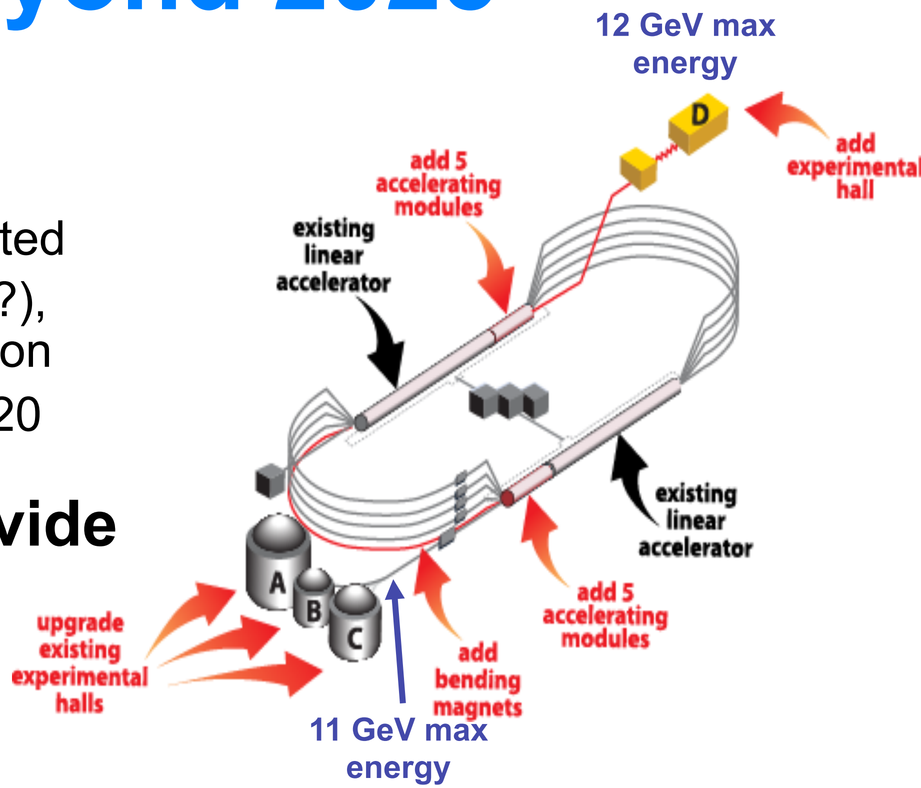

Opportunity: ***Electron-Ion Collider*** on CEBAF

- Add a *modern* ion complex with a ***Green Field*** design
- Expand science program beyond 12 GeV CEBAF fixed target
- Open up new science domain with higher CM energy

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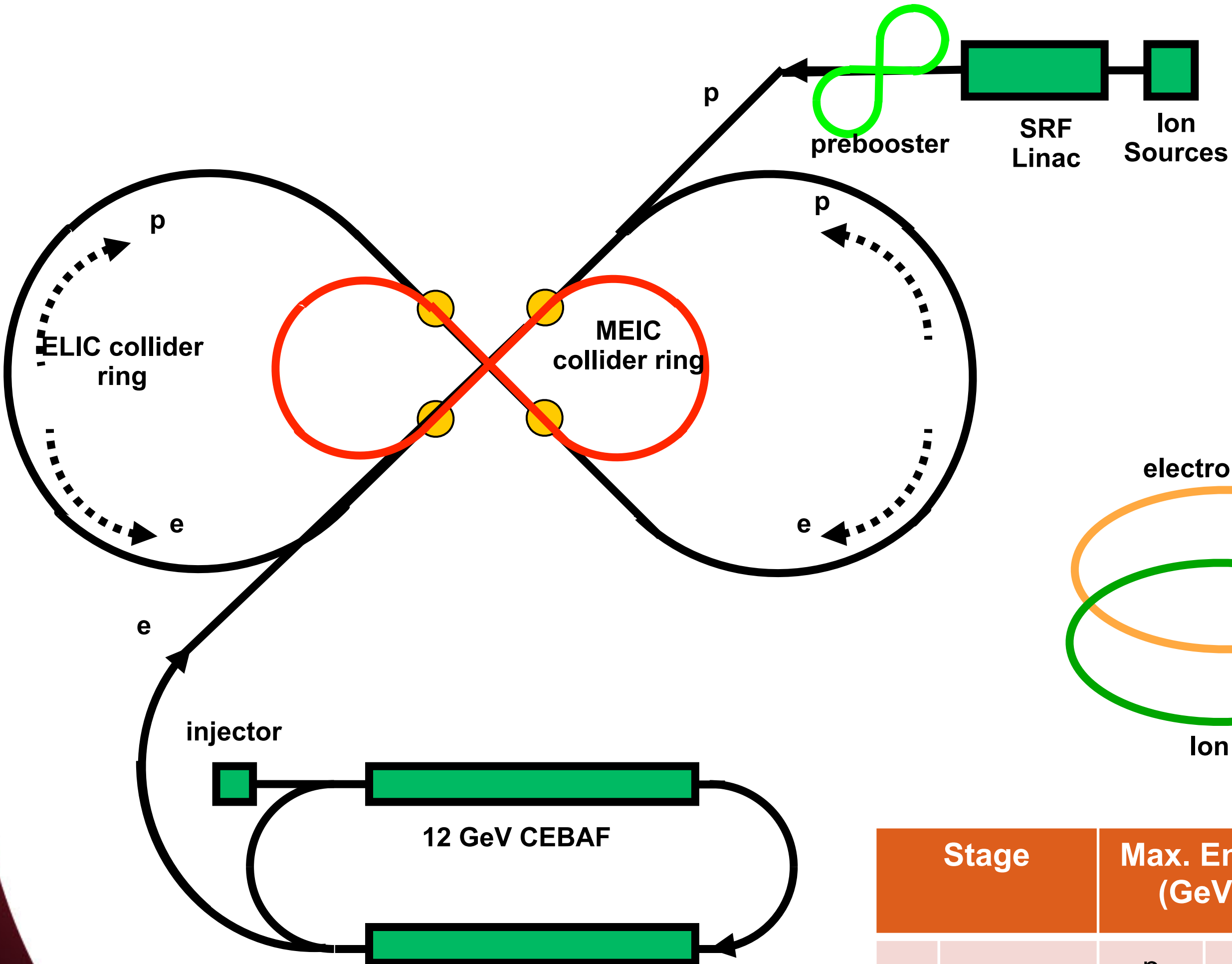
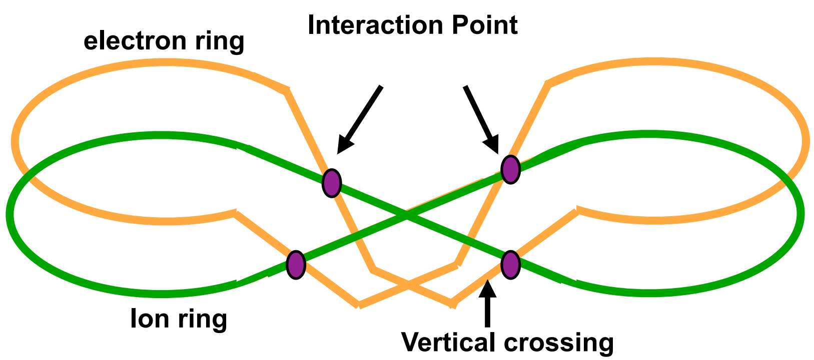
EIC @ JLab: High Energy & Staging



		Small
Circumference	m	1800
Radius	m	140
Width	m	280
Length	m	695
Straight	m	306



Stage		Max. Energy (GeV/c)		Ring Size (M)		Ring Type		IP#
		p	e	p	e	p	e	
1	Low	12	5 (11)	630	630	Warm	Warm	1
	Medium	60	5 (11)	630	630	Cold	Warm	2
2	Medium	60	10	600	1800	Cold	Warm	4
3	High	250	10	1800	1800	Cold	Warm	4

Achieving High Luminosity

ELIC design luminosity

$L \sim 10^{35}\ cm^{-2}\ s^{-1}$ for high energy (250 GeV x 10 GeV)

$L \sim 4 \times 10^{34}\ cm^{-2}\ s^{-1}$ for medium energy (60 GeV x 3 GeV)

ELIC luminosity Concepts

- High bunch collision frequency (0.5 GHz, can be up to 1.5 GHz)
- Short ion bunches ($\sigma_z \sim 5$ mm) ***(also much smaller bunch charge)***
- Relative long bunch (comparing to beta-star) for very low ion energy
- Strong final focusing ($\beta^*_y \sim 5$ mm)
- Large beam-beam parameters (~0.01/0.1, 0.025/.1 largest achieved)
- **Need electron cooling of ion beams**
- Need crab crossing colliding beams
- Large synchrotron tunes to suppress synchrotron-betatron resonances
- Equal (fractional) betatron phase advance between IPs

ELIC e-Cooler Design Parameters

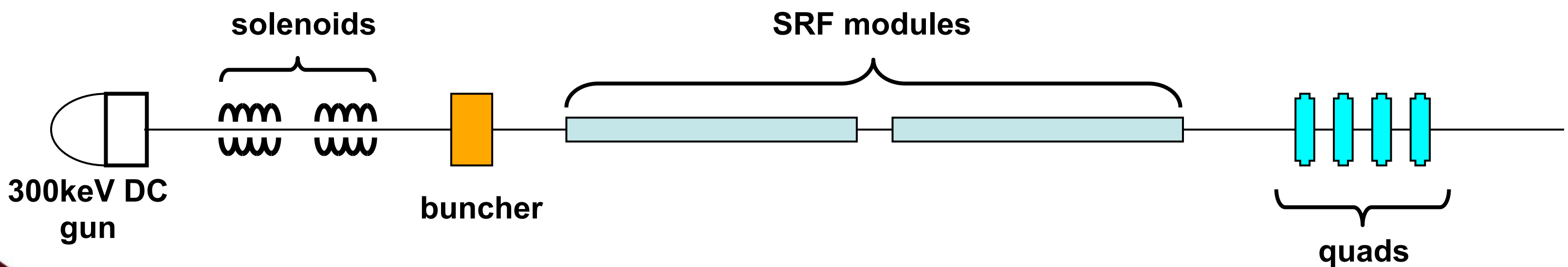
- Number of turns in circulator cooler ring is determined by degradation of electron beam quality caused by inter/intra beam heating up and space charge effect.
- Space charge effect could be a leading issue when electron beam energy is low.
- It is estimated that beam quality (as well as cooling efficiency) is still good enough after 100 to 300 turns in circulator ring.
- This leads directly to a 100 to 300 times saving of electron currents from the source/injector and ERL.

Max/min energy of e-beam	MeV	33/8
Electrons/bunch	10^{10}	3.75
bunch revolutions in CCR		~300
Current in CCR/ERL	A	3/0.01
Bunch repetition in CCR/ERL	MHz	500/1.67
CCR circumference	m	80
Cooling section length	m	15
Circulation duration	μs	27
Bunch length	cm	1-3
Energy spread	10^{-4}	1-3
Solenoid field in cooling section	T	2
Beam radius in solenoid	mm	~1
Beta-function	m	0.5
Thermal cyclotron radius	μm	2
Beam radius at cathode	mm	3
Solenoid field at cathode	KG	2
Laslett's tune shift @60 MeV		0.07
Longitudinal inter/intra beam	μs	200

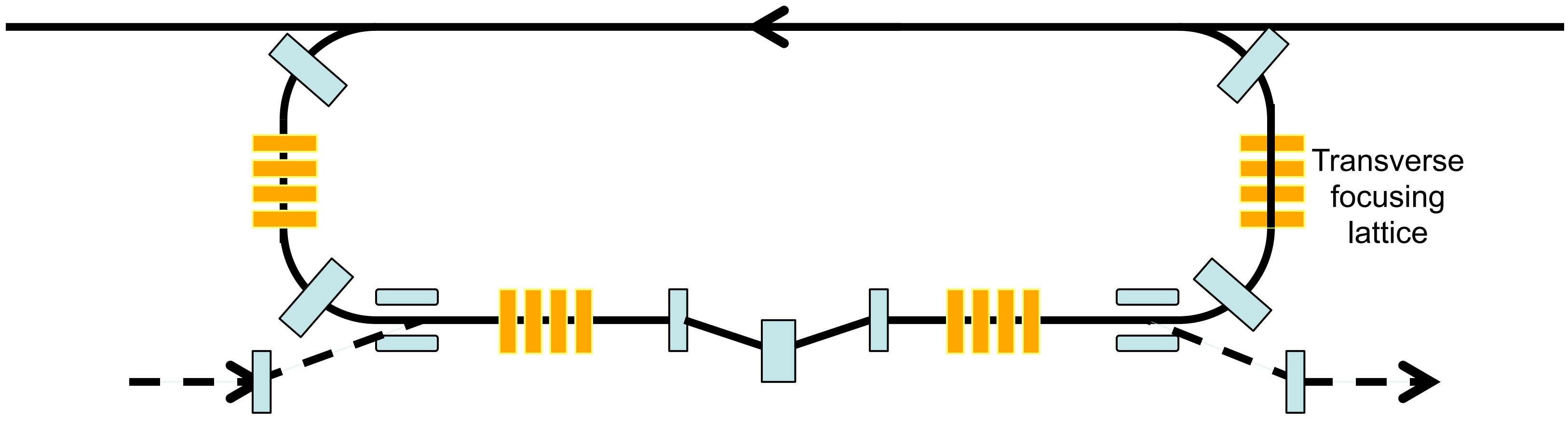
Electron Source/Injector

- ELIC CCR driving injector
  - 10 mA@1.667 MHz, up to 33 (125) MeV energy
  - 5 nC bunch charge, magnetized
- Challenges
  - Source life time: 0.86 kC/day (state-of-art is 0.2 kC/day)

    → source R&D, & exploiting possibility of increasing evolutions in CCR
- Conceptual design
  - High current/brightness source/injector is a key issue of ERL based light source applications, much R&D has been done
  - We adopt light source injector as a baseline design of CCR driving injector
- Beam qualities should satisfy electron cooling requirements (based on previous computer simulations/optimization)
- Bunch compression may be needed.



Circulator Ring & Synchronization



Kicker Parameter

energy	MeV	33
Kick angle		0.04
Integrated BDL	GM	400
Frequency BW	GHz	2
Kicker aperture	cm	2
Repetition Rate	MHz	1.67
Power	kW	13

Bunch In/out kicking

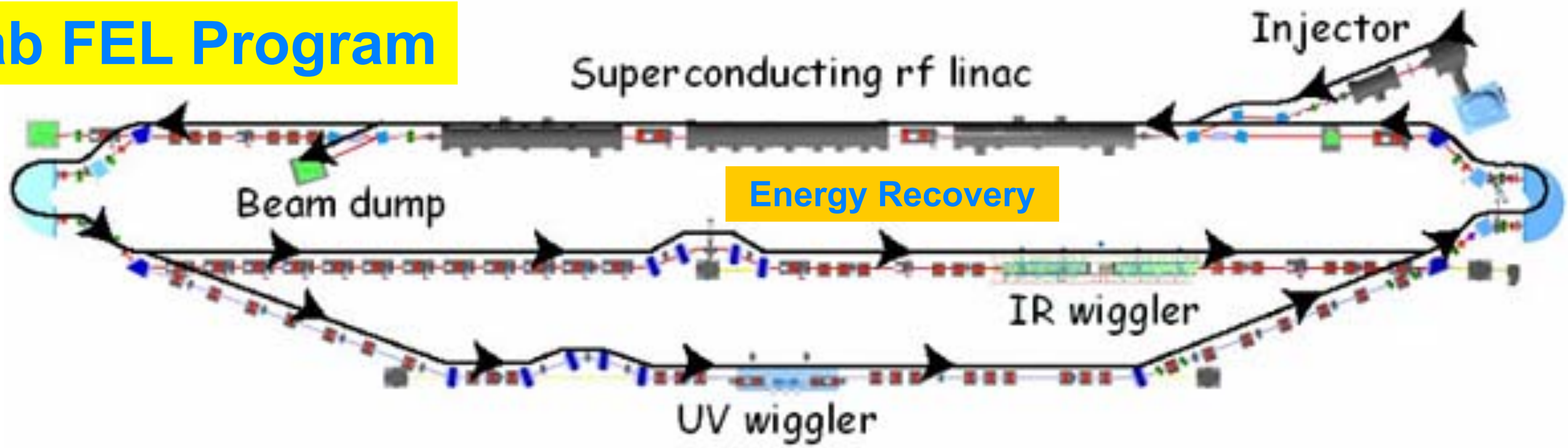
- An ultra fast kicker switches electron bunches in and out circulator ring.
- Deflecting angle should be large enough to separate outgoing bunches from circulating bunches and be further deflected by a dipole
- Duration of kicking should be less than bunch spacing (~1/500MHz = 2 ns)

Synchronization

- Bunch spacing depends on beam energy. There is about 1.8 mm difference when energy is boosted from 12 to 60 GeV/c
- A 10m dog-lag lattice or loops in arc must be introduced to ensure electron-ion synchronization at cooling section.
- Maximum deflecting angle is 13º, providing total 26cm path length adjustment.

Energy Recovery Linac

JLab FEL Program



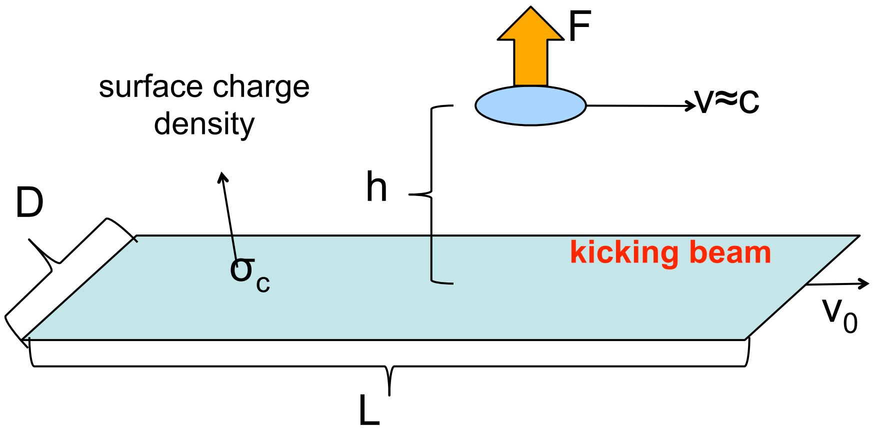
Energy	**MeV**	**80-200**
Charge/bunch	**pC**	**135**
Average current	**mA**	**10**
Peak current	**A**	**270**
Beam power	**MW**	**2**
Energy spread	**%**	**0.5**
Normalized emittance	**µm-rad**	**<30**

- SRF ERL based FEL
- High average power, up to14 kW (*world record*)
- mid-infrared spectral region
- Extension to 250 nm in the UV is planned
- Photocathode DC injector, 10 mA class CW beam, sub-nC bunch charge
- Beam energy up to 200 MeV, energy recovery
- **Next proposal: 100kW average power, 100 mA CW beam. ERL, nC-class bunch charge**

JLab is world leader in ERL technology !

Ultra-Fast Kicker based on a Flat Kicking Beam

V. Shiltsev, NIM 1996



Circulating beam energy	**MeV**	**33**
Kicking beam energy	**MeV**	**~0.3**
Repetition frequency	**MHz**	**5 -15**
Kicking angle	**mrad**	**0.2**
Kinking bunch length	**cm**	**15~50**
Kinking bunch width	**cm**	**0.5**
Bunch charge	**nC**	**2**

- A short (1~ 3 cm) target electron bunch passes through a long (15 ~ 50 cm) low-energy flat bunch at a very close distance, receiving a transverse kick
- The kicking force is $F = \frac{e\sigma_e}{2\xi_0}(1-\beta_0)$

  integrating it over whole kicking bunching gives the total transverse momentum kick
- Proof-of-principle test of this fast kicker idea can be planned. Simulation studies will be initiated.

An ultra-fast RF kicker is also under development.