Electron Cooling for High Luminosity Electron-Ion Collider at JLab

Ya. Derbenev, P. Evtushenko, and Y. Zhang

Cool'09 **Workshop**

Lanzhou, China, August 31 to September 4, 2009

Outline

- Introduction
- Forming and Cooling of High Intensity Ion Beams in ELIC
- Conceptual Design of ERL Based Circulator Electron Cooler
- Key Enabling Technologies and R&D
- Summary

1. Introduction

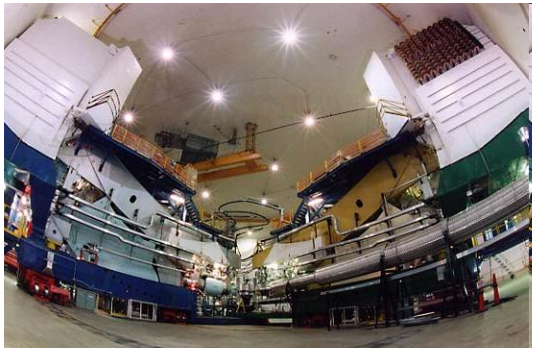
Nuclear Physics Program at JLab

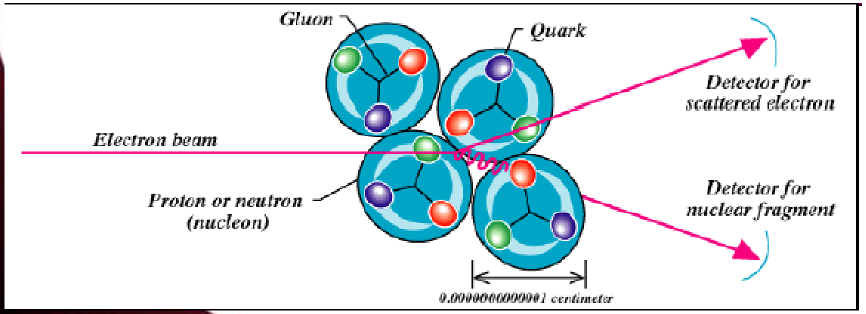
TODAY: 6 GeV CEBAF

25 years Jefferson Lab
Exploring the Nature of Matter

Recirculated Linac

Three Experimental Hall





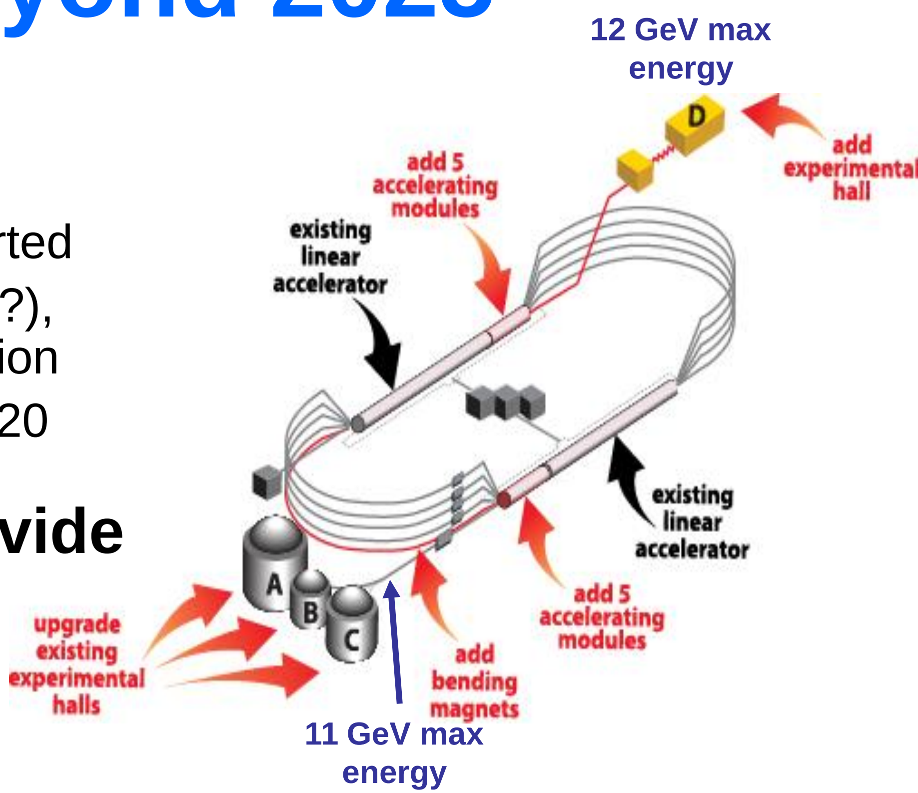
- One of two primary US nuclear science research centers funded by US DOE
- It operates CEBAF, the world-first high energy SRF recirculated electron linac
- CEBAF delivers 6 GeV polarized CW beam to three fixed targets (experimental halls)

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

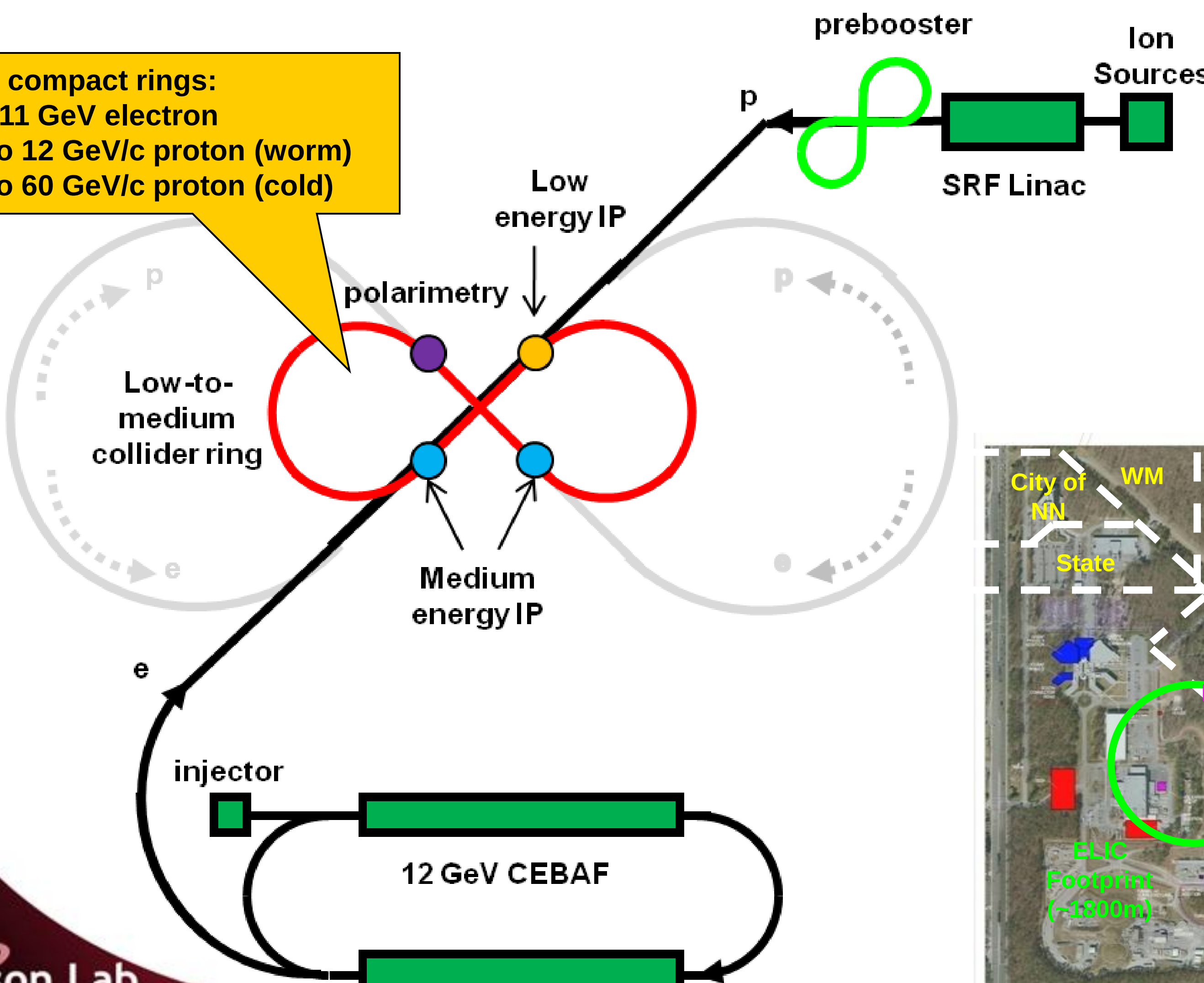
Opportunity: *Electron-Ion Collider* on CEBAF

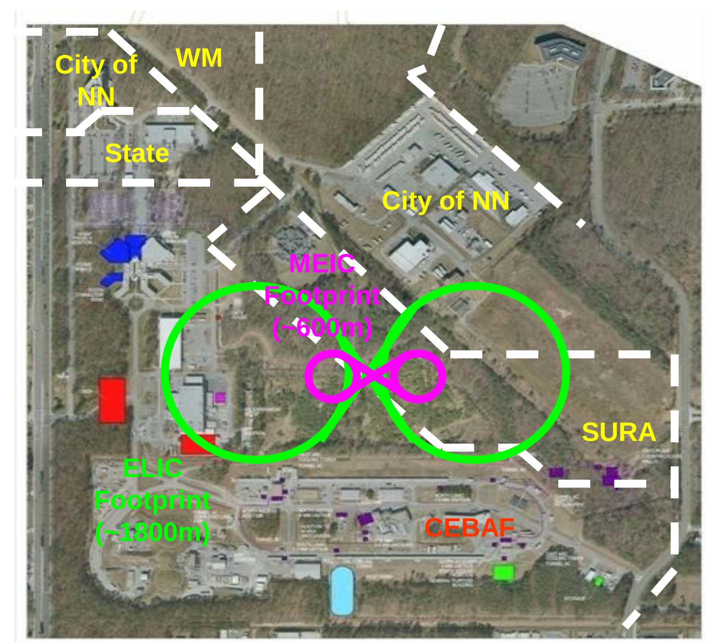
- Add a *modern* ion complex with a ***Green Field*** design
- Expand science program beyond 12 GeV CEBAF fixed target
- Open up new science domain with higher CM energy

Nuclear Physics Program at JLab

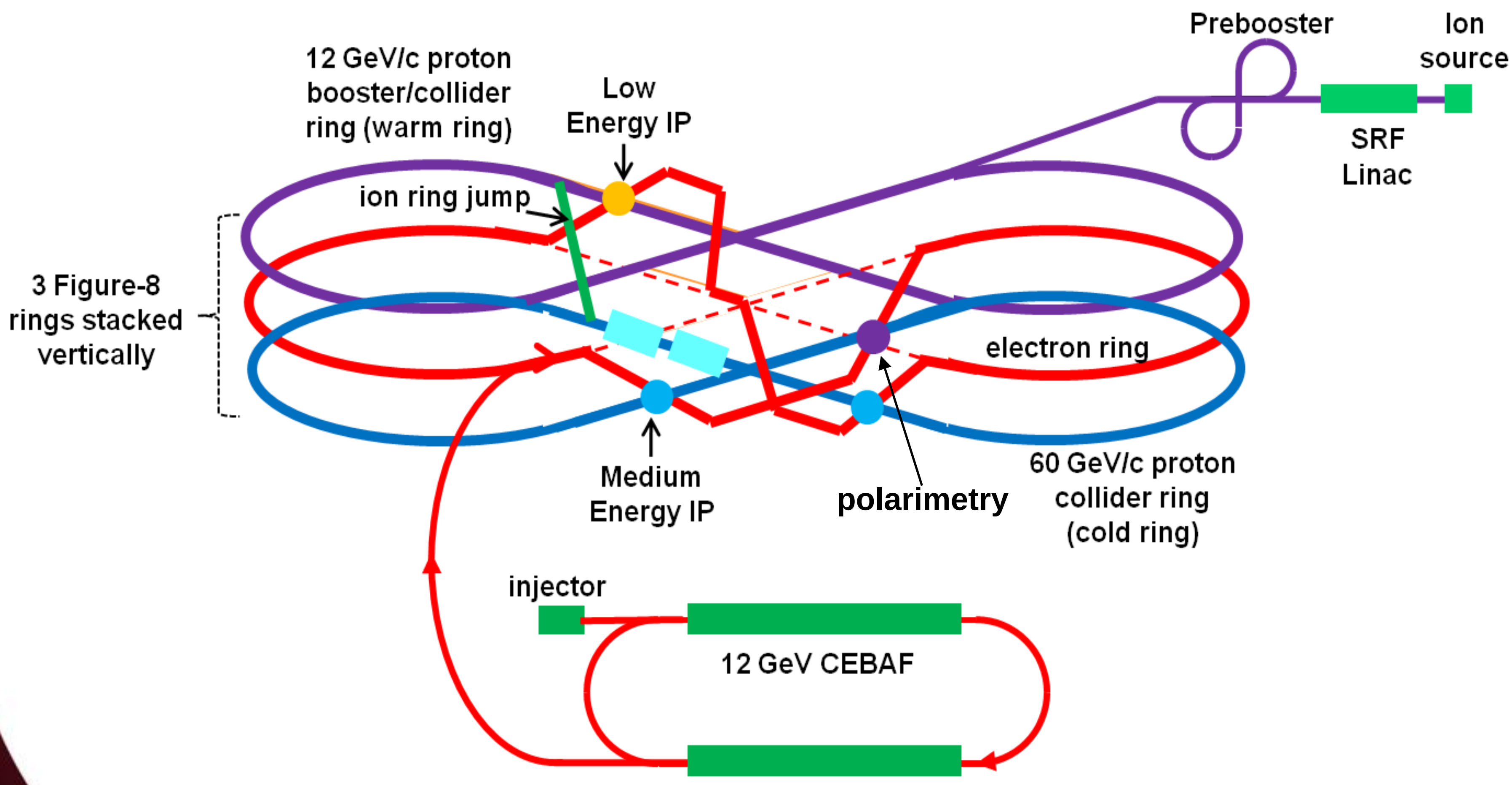
Day After Tomorrow: Electron-ion Collider at JLab & Science Beyond 2040

Three compact rings:
- 3 to 11 GeV electron
- Up to 12 GeV/c proton (worm)
- Up to 60 GeV/c proton (cold)

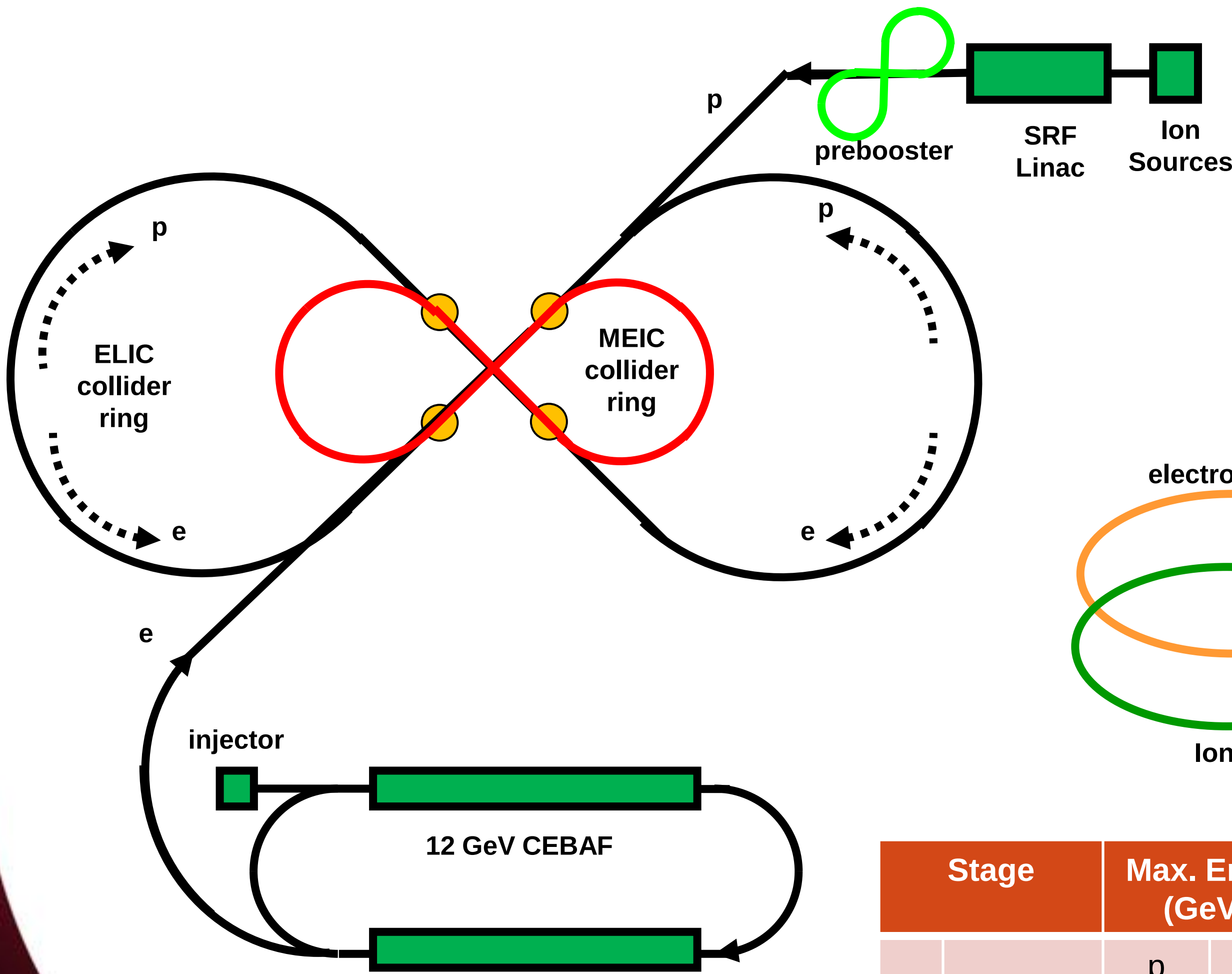




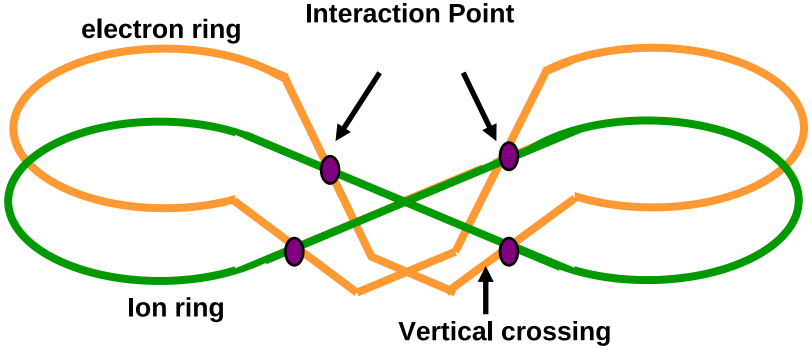
EIC@JLab: Low to Medium Energy



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

EIC@JLab Parameters

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

Achieving High Luminosity

ELIC design luminosity

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

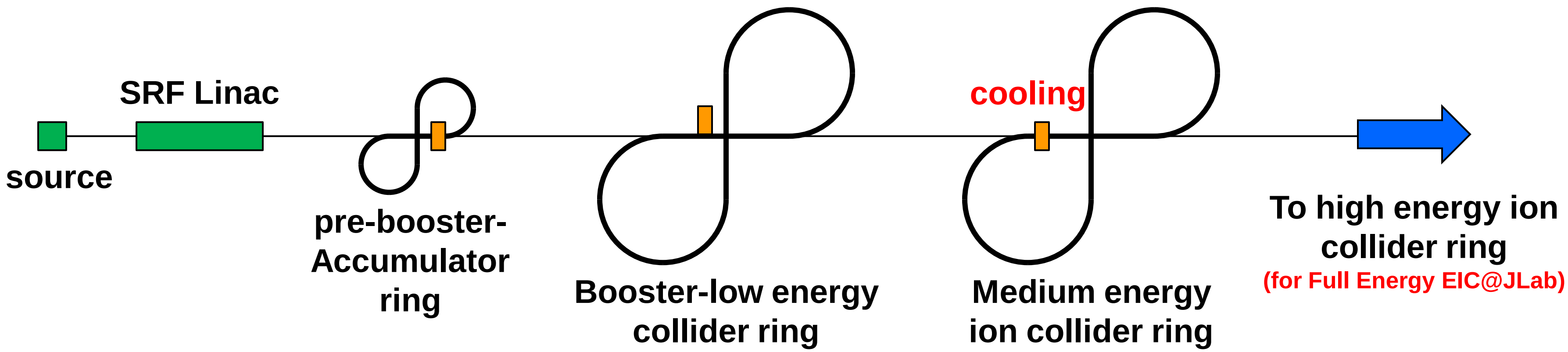
$L \sim 4 \times 10^{34}$ cm^{-2} s^{-1} for medium energy (60 GeV x 3 GeV)

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

2. Forming and Cooling of High Intensity Ion Beams in ELIC

Forming High Intensity Ion Beam With Staged Cooling



	Length (m)	Max. Energy (GeV/c)	Cooling Scheme	Process
Source/SRF linac		0.2		Full stripping
Accumulator-Cooler Ring (Pre-booster)	~100	3	DC electron	Stacking/accumulating Energy boosting
Low energy ring (booster)	~630	12	Electron (ERL)	Fill ring/Energy boosting RF bunching (for collision)
Medium energy ring (large booster)	~630	60	Electron (ERL)	Energy boosting RF bunching (for collision)
High energy ring	~1800	250	Electron (ERL)	Fill ring/energy boosting RF bunching

Stacking/cooling Ion Beam in Pre-booster/Accumulator Ring

- Accumulation of 1 A coasted beam in pre-booster
    - Polarized p, d: stripping injection from negative ion source after linac
    - Other ions: must use DC electron cooling
  - Multi-turn (~10) pulse injection from linac
  - Damping/cooling of injected pulse
  - Accumulating beam at space charge limited emittance
- Accelerating to 3 GeV/c
- Fill large booster/low energy collider ring, then accelerate
- Switch to collider ring for energy booster,
- RF bunching and initial/continuous cooing

<u>An advanced concept</u>
Overcoming space charge by accumulating low temperature, large area beam in ring with *circular betatron modes*

Pre-booster/Accumulator-ring

Circumference	M	~80
Arc radius	M	~3
Crossing straight length	M	2 x 15
Energy/u	GeV	0.2 -0.4
Electron current	A	1
Electron energy	MeV	0.1 - 0.2
Cooling time for protons	ms	10
Stacked ion current	A	1
Norm. emit. After stacking	µm	16

Initial, Final and Continuous Cooling of Ion Beam in Collider Ring

	GeV/MeV	Initial Cooling	after bunching & boost	Colliding Mode
Momentum	GeV/MeV	12 / 6.55	60 / 32.67	60 / 32.67
Beam current	A	0.6 / 3	0.6 / 3	0.6/ 3
Particles/Bunch	10^{10}	0.74 / 3.75	0.74 / 3.75	0.74 / 3.75
Bunch length	mm	200 / 200 (coasted)	10 / 30	5 / 15
Momentum spread	10^{-4}	5 / 1	5 / 1	3 / 1
Horizontal emittance, norm.	µm	4	1	0.56
Vertical emittance, norm.	µm	4	1	0.11
Laslett's tune shift (proton)		0.002	0.006	0.1
Cooling length/circumference	m/m	15 / 640	15 / 640	15 / 640
Cooling time	s	92	162	0.2
IBS growth time (longitudinal)	s			0.9

Advanced Concepts of Electron Cooling

- **Staged cooling**
  - Start (longitudinal) electron cooling at injection energy in collider ring
  - Continue electron cooling after acceleration to high energy
- **Sweep cooling**
  - After transverse stochastic cooling, ion beam has a small transverse temperature but large longitudinal one.
  - Use *sweep cooling to* gain a factor of longitudinal cooling time
- **Dispersive cooling**
  - compensates for lack of transverse cooling rate at high energies due to large transverse velocity spread compared to the longitudinal (in rest frame) caused by IBS
- **Flat beam cooling** (for high energies)
  - based on flattening ion beam by reduction of coupling around the ring
  - IBS rate at equilibrium reduced compared to cooling rate
- **Matched cooling** (low energies)
  - based on use of circular modes optics of ions matched with solenoid of cooling section
  - separates cooling of beam temperature from cooling (round) beam area
  - results in removal temperature limit due to space charge (strong reduction of achievable 4D emittance)

Flat-to-Round Beam Transform and Reduction of Space Charge

- Flat colliding ion beam and space charge
  - Colliding ion beam should be flat at interaction point in order to match flat electron beam (due to synchrotron radiation)
  - Space charge tune shift is a leading limiting factor for low energy ion beam, and it further effect luminosity of the collider
  - Flat beam enhances space charge tune-shift . i.e., Laslett tune-shift is determined by smaller transverse dimension
- Luminosity optimization: flat-to-round transform
  if colliding ion beam can be arranged as
  - flat at interaction point ➔ matching flat electron beam
  - Round in the storage ➔ maintaining large transverse beam area for overcoming space charge
- Technical feasibility
  - *circular (100% coupled) optics* (ring) under *matched cooling*
  - Special adapters to converting round beam to flat beam and back to round beam at collision point

3. Conceptual Design of ERL Based Circulator Electron Cooler

Design of e-Cooler for EIC@JLab

Design Requirements and Challenges

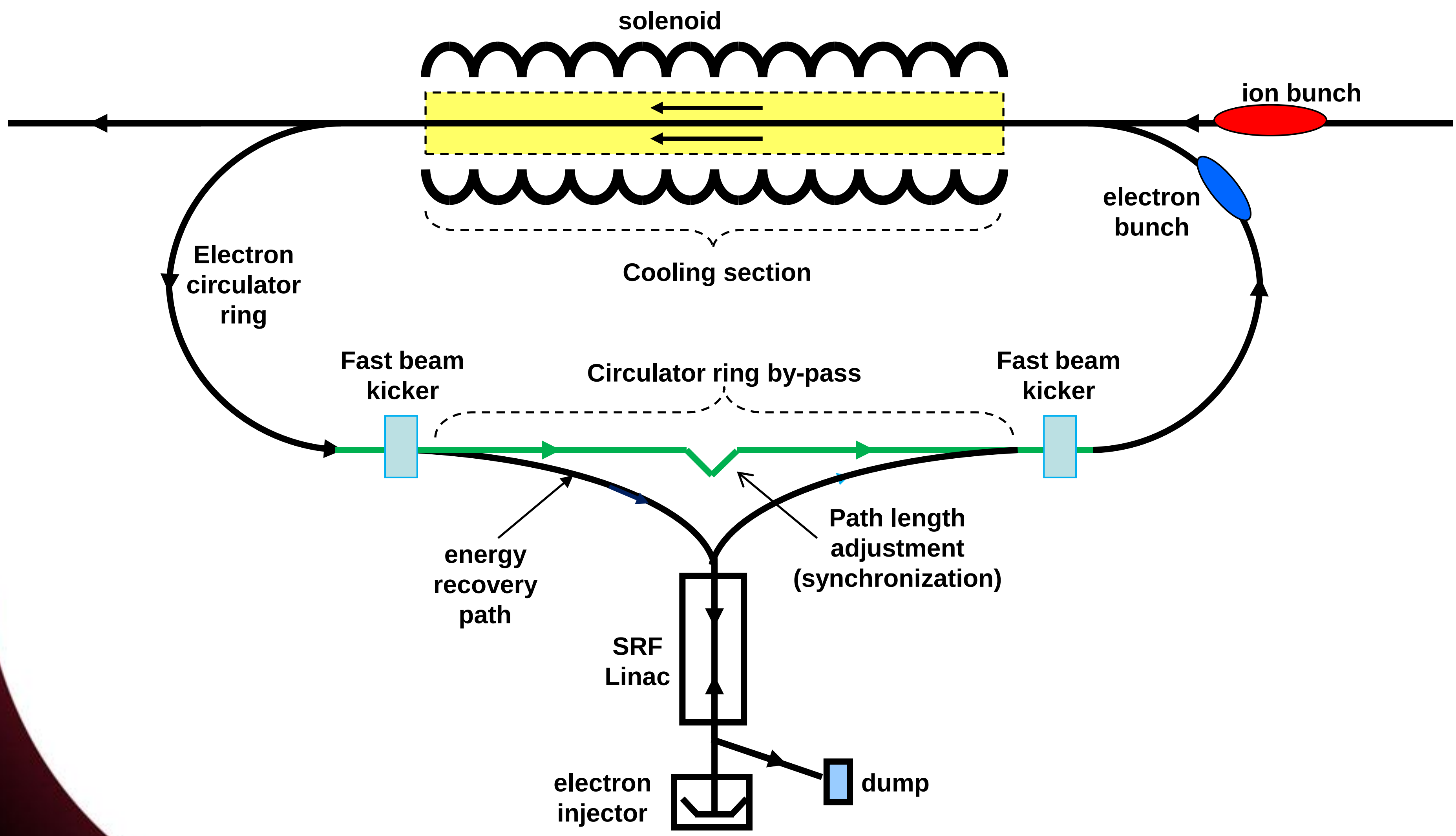
- Electron beam current
  - up to 3 A CW beam at 499 MHz repetition rate
  - About 5 nC bunch charge (possible space charge issue at low energy)
  - About 260 kC per day from source/injector (state-of-art is 0.2 kC per day)
- Energy of cooling electron beam
  - up to 6.7 MeV for cooling low energy (12 GeV/c) ELIC
  - up to 33 MeV for cooling medium energy (60 GeV/c) ELIC
  - up to 136 MeV for cooling high energy (250 GeV/c) ELIC
- Beam power
  - Need 100 to 400 MW for cooling 60 to 250 GeV/c ELIC

Design Choice: ERL Based Circulator Cooler (ERL-CCR)

- Energy Recovery SRF Linac (ERL) to solve RF power problem
- Circulator-cooler ring (CCR) for reducing average current from source/ERL

ERL-CCR can provide the required high cooling current while consuming fairly low RF power!

Conceptual Design of Circulator e-Cooler



ELIC e-Cooler Design Parameters

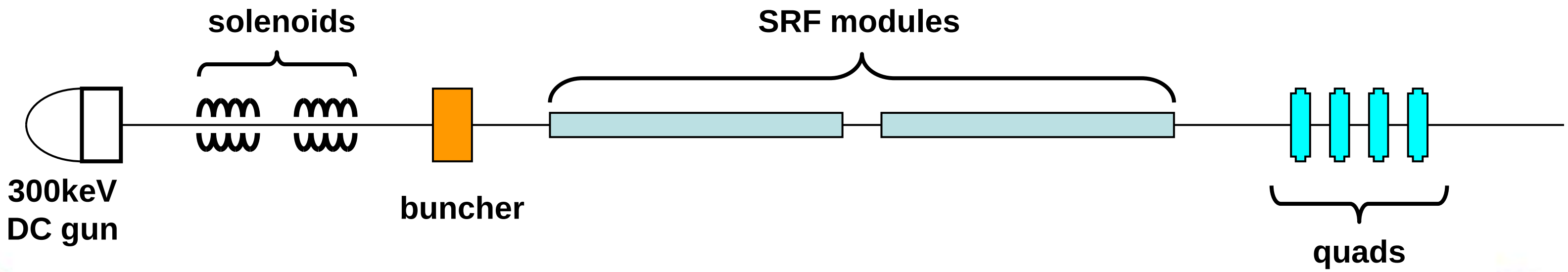
- Number of turns in circulator cooler ring is determined by degradation of electron beam quality caused by inter/intra beam heating up and space charge effect.
- Space charge effect could be a leading issue when electron beam energy is low.
- It is estimated that beam quality (as well as cooling efficiency) 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 heating	**μs**	**200**

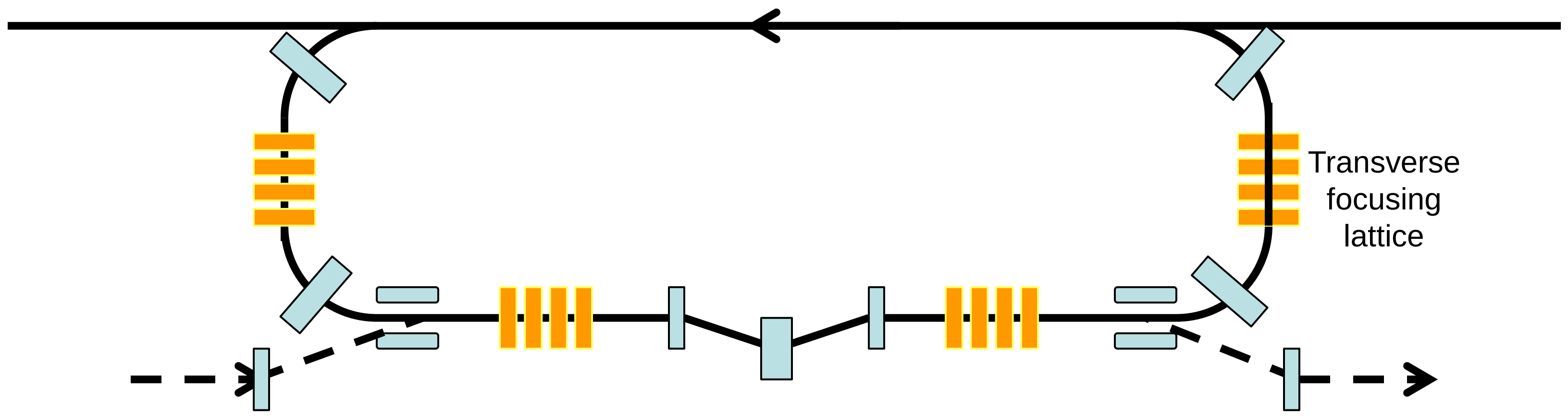
Electron Source/Injector

- 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)

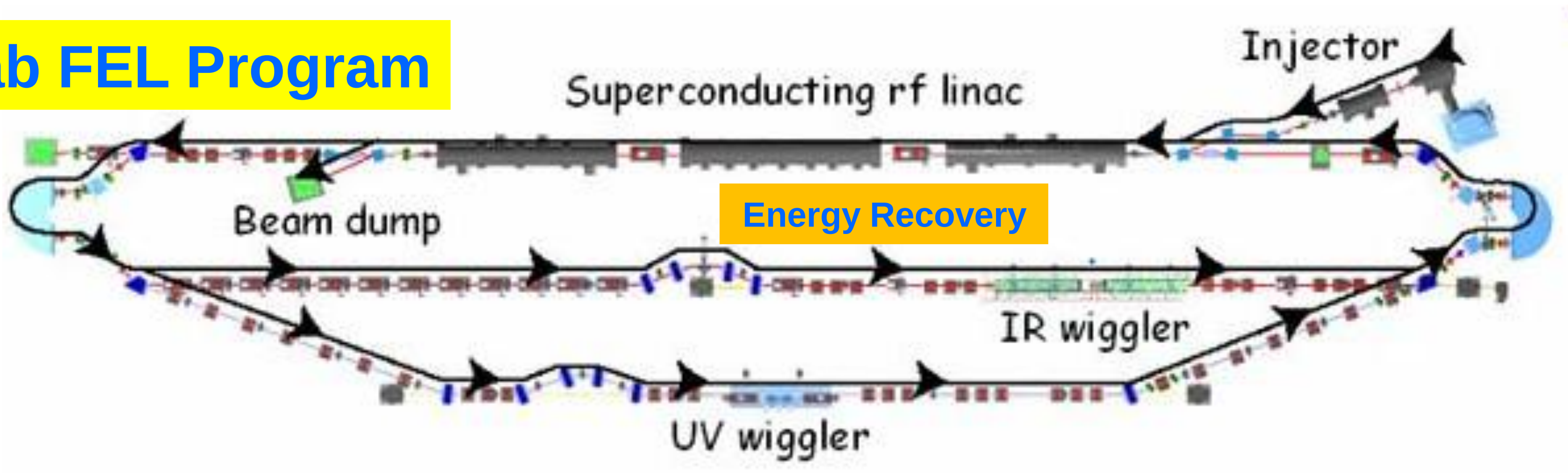
Synchronization

- 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 13^{o}, providing total 26cm path length adjustment.

4. Key Enabling Technologies and Critical R&D

Energy Recovery Linac

JLab FEL Program

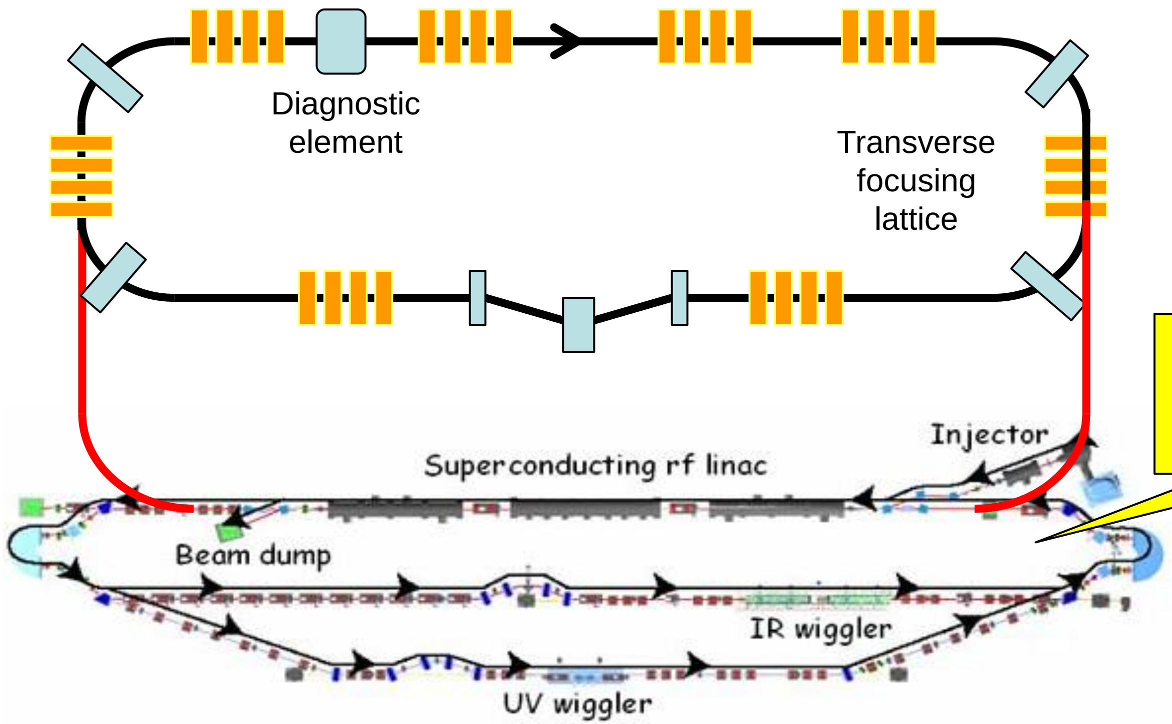


Energy	MeV	80-200
Charge/bunch	pC	135
Average current	mA	10
Peak current	A	270
Beam power	MW	2
Energy spread	%	0.5
Normalized emittance	µm-rad	<30

- 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 !

Test Facility for Circulator Cooling Ring

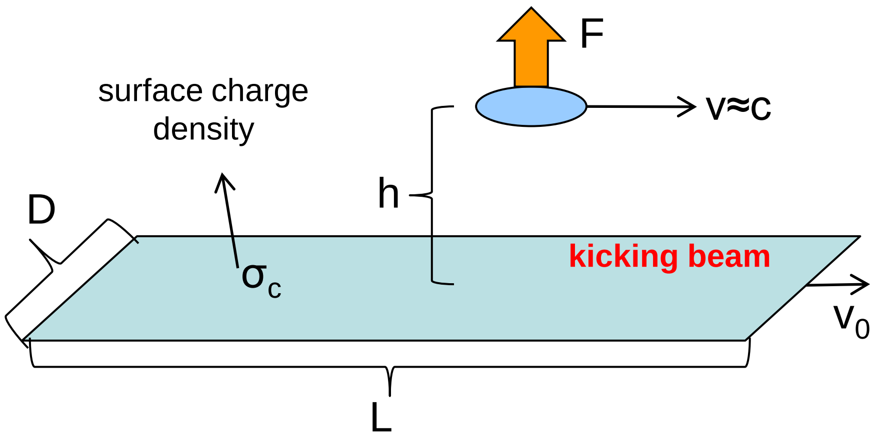


Using JLab FEL ERL facility or a new SRF module

- Proposal for a test facility of a ERL based circulator cooler utilizing existing JLab FEL facility is under consideration. Additional hardware cost is moderate.
- Focusing of this test facility will be studies of
  - Lifetime of driving high peak current/bunch charge source/injector
  - beam dynamics of high bunch charge electron beam in the circulator ring (space charge effect, IBS heating up, etc.)
  - test of fast kicker.

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.

Summary

- EIC@JLab promises to accelerate a wide variety of ions to collider with electron/positron beam with a CM energy range from 10 to 100 GeV, enabling a unique physics program in a coherent way.
- ELIC Luminosity should be able to reach 4×10^{34} $cm^{-2}s^{-1}$ at medium energy (60x3~5 GeV^2) for e-p collisions, achieved through a very strong vertical final focusing (β^*=5mm) of a high repetition CW ion beam of very short bunch length (~5mm) and very small transverse emittance.
- Electron cooling is essential for forming (through stacking & accumulating) and cooling of the high intensity ion beam for ELIC.
- Conceptual design of an ERL circulator-ring based electron cooler has been proposed to provide high intensity (3 A) and high energy (up to 137 MeV) cooling electron beam.
- Key enabling technologies and critical RD on ERL, circulator ring, high bunch charge electron source and ultra-fast kicker are also discussed and planed.

Backup Slides

ELIC Study Group

A. Afanasev, A. Bogacz, J. Benesch, P. Brindza, A. Bruell, L. Cardman, Y. Chao, S. Chattopadhyay, E. Chudakov, P. Degtiarenko, J. Delayen, Ya. Derbenev, R. Ent, P. Evtushenko, A. Freyberger, D. Gaskell, J. Grames, L. Harwood, T. Horn, A. Hutton, C. Hyde, R. Kazimi, F. Klein, G. A. Krafft, R. Li, L. Merminga, J. Musson, A. Nadel-Turonski, M. Poelker, R. Rimmer, C. Tengsirivattana, A. Thomas, M. Tiefenback, H. Wang, C. Weiss, B. Wojtsekhowski, B. Yunn, Y. Zhang - Jefferson Laboratory staffs and users

W. Fischer, C. Montag - Brookhaven National Laboratory

V. Danilov - Oak Ridge National Laboratory

V. Dudnikov - Brookhaven Technology Group

P. Ostroumov - Argonne National Laboratory

V. Derenchuk - Indiana University Cyclotron Facility

A. Belov - Institute of Nuclear Research, Moscow, Rssia

V. Shemelin - Cornell University

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*

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.