Advance in MEIC Cooling Studies

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Outline

1. Introduction
2. MEIC Multi-Staged Cooling Scheme
3. ERL Circulator Cooler
4. Simulations & Technology Development
5. Proof-of-Principle Experiments
6. Summary

Introduction

- JLab has developed a conceptual design of a ***M***edium energy ***E***lectron-***I***on ***C***ollider (***MEIC***) based on the 12 GeV CEBAF recirculating SRF linac
- The machine design of MEIC takes advantages of
  - A high bunch repetition CW electron beam from CEBAF
  - A **proven** luminosity concept but **new** to a collider involving **hadron beams**
  - A new ion complex for producing **high bunch repetition ion beams**
- Cooling of protons/ions is essential for achieving ultra high luminosity
- MEIC design adopted a multi-staged cooling concept
  - Based on ***conventional electron cooling***
  - Cooling at the pre-booster and the collider ring for assisting ion beam formation
  - Continuous cooling during collision to compensate IBS induce beam degradation
- A cooler based on an ERL and a circulator ring has been developed
- A test facility for this ERL-circulator cooler has been proposed

Cooling is Essential for Achieving High Luminosity

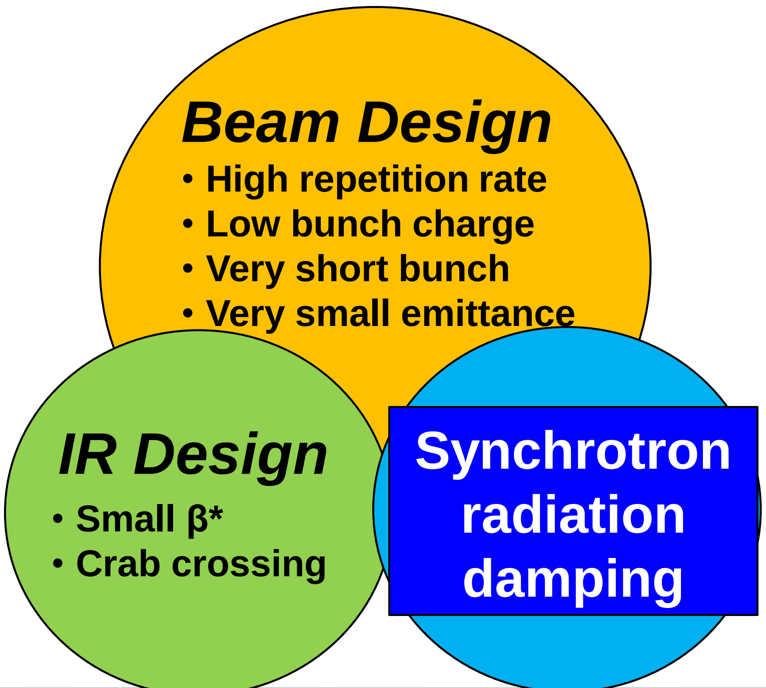
- MEIC design concept for high luminosity is based on ***high bunch repetition rate CW colliding beams***

KEK-B has reached >2x10^{34} /cm^2/s

JLab is poised to replicate the same success in an electron-ion collider:

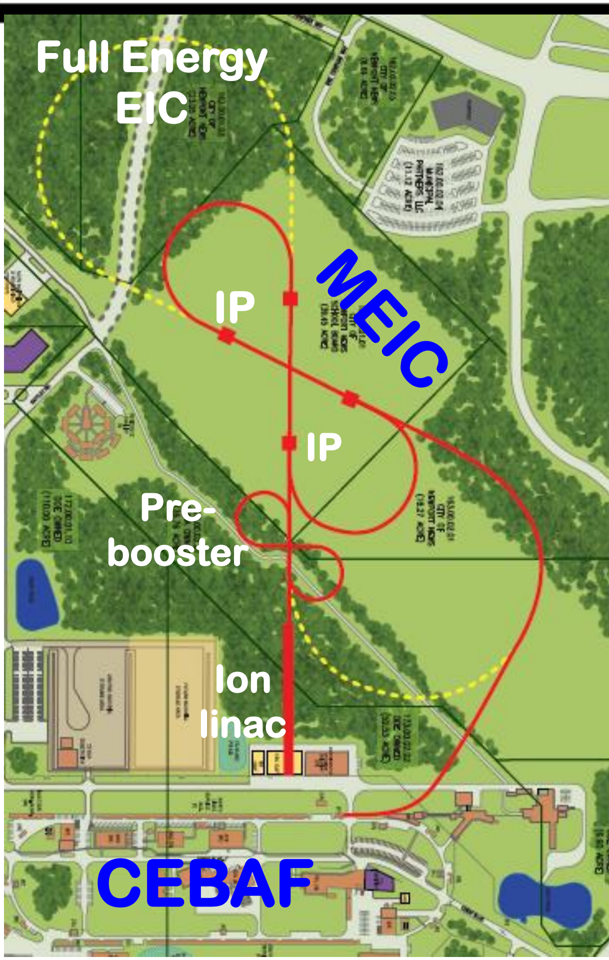
- A high repetition rate electron beam from CEBAF
- A new ion complex specifically designed to match e-beam
- Multi-phase electron cooling of ion beams

Very small bunch charge
8x smaller than KEK-B
20x smaller than HERA



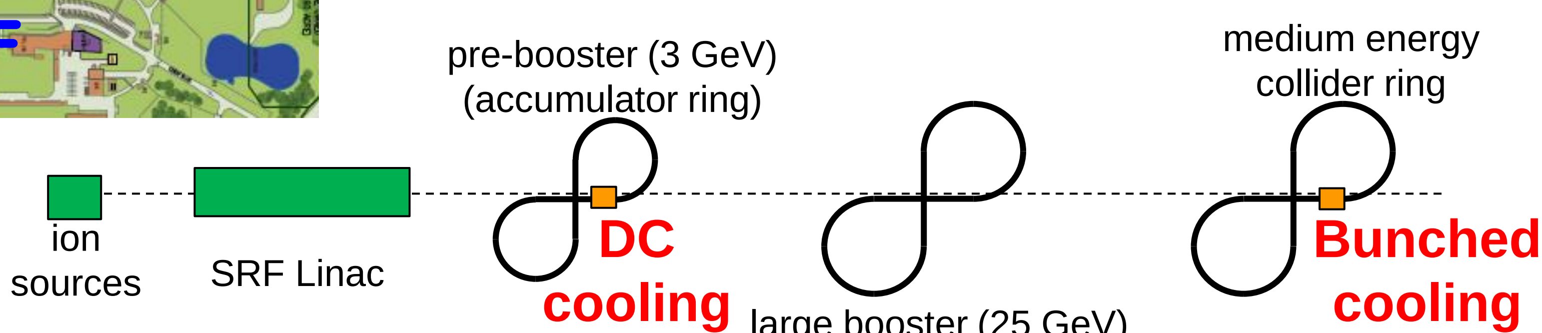
		KEK-B	MEIC
Repetition rate	MHz	509	748.5
Energy (e^-/e^+ or p/e^-)	GeV	8/3.5	60/5
e^-/e^+ or p/e^- per bunch	10^{10}	3.3/1.4	0.42 / 2.5
Beam current	A	1.2/1.8	0.5/3
Bunch length	cm	0.6	1/0.75
Horizontal & vertical β*	cm	56/0.56	10/2~4/0.8
Luminosity/IP, 10^{33}	/cm^{2}s	20	5.6 ~ 14

Multi-Staged Cooling Scheme



	Stage	Ion (GeV/u)	Electron (MeV)	Cooling beam /Cooler
Pre-booster	Assisting accumulation of positive ions	0.1	0.59	DC
	Initial cooling for emittance reduction	3	2.1	DC
Collider ring	Final cooling at top energy for emittance reduction	Up to 100	55	Bunched /ERL
	During collision to suppress IBS emittance growth	Up to 100	55	Bunched /ERL

state-of-art



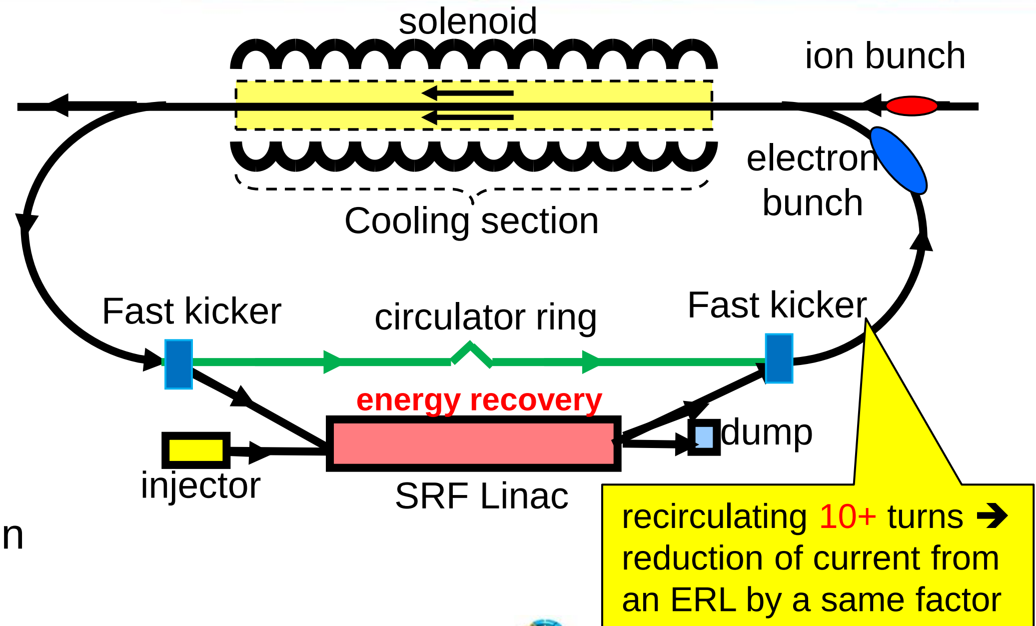
ERL Circulator Cooler Concept

Design Choices

- Energy Recovery Linac (ERL)
- Compact circulator ring

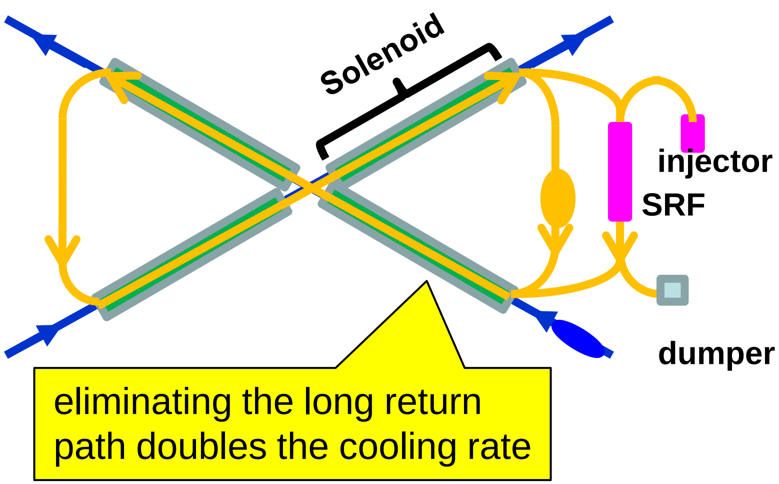
to meet design challenges

- Large RF power (up to 81 MW)
- Long gun lifetime (average 1.5 A)



Required technologies

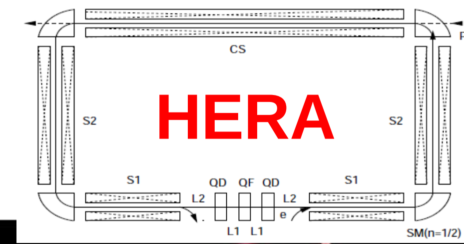
- High bunch charge (2 nC) magnetized gun
- High current ERL (55 MeV, 15 to150 mA)
- Ultra fast kicker



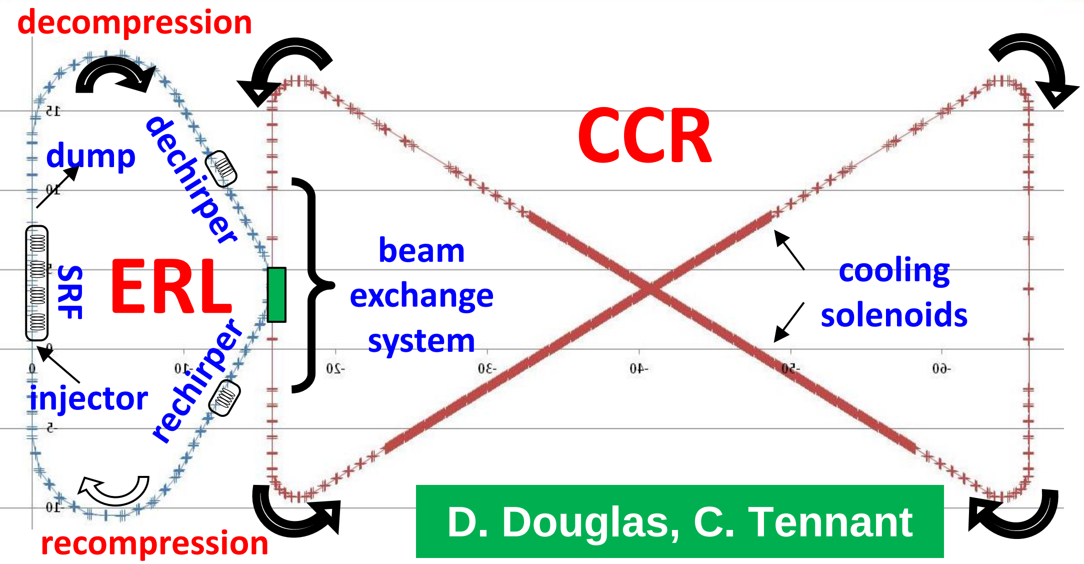
Previous works

- **Using ERL technology**
  (Ben Zvi, *et.al*. 2000~2007)

- **Using circulator ring**
  (Brinkman, *et.al*. ~1997)

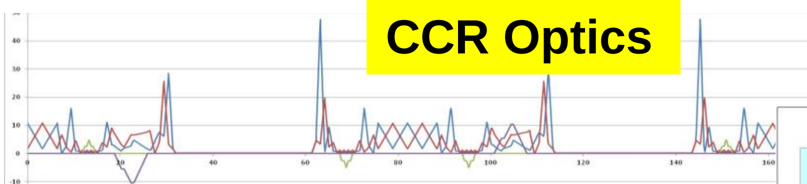


ERL-Circulator Cooler Design



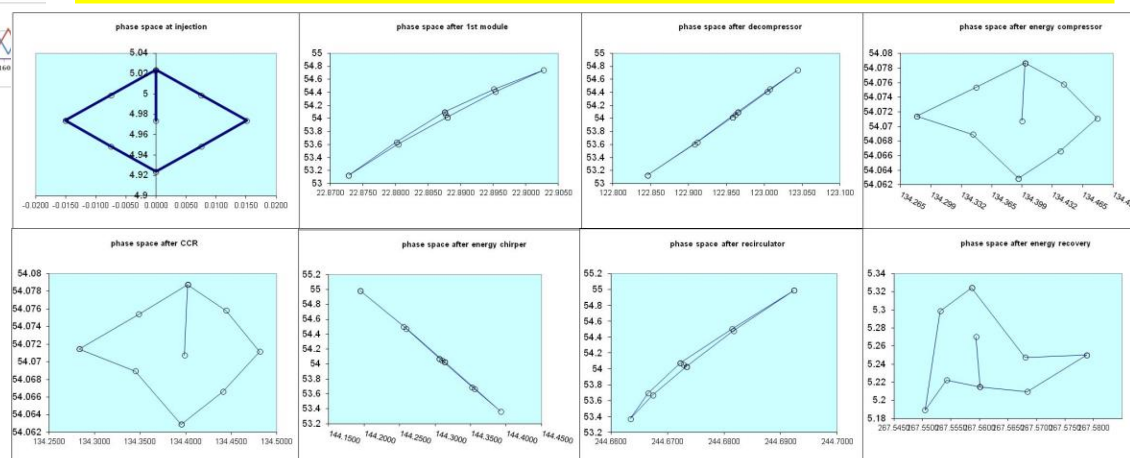
Energy at injection/dump	MeV	5/5.3
Long. emittance at injection	keV-ps	80
RMS bunch length at injection	ps	5
Energy spread at injection		0.003
Linac on-crest energy gain	MeV	50.4
Full energy	MeV	54
Acceleration phase		-13º
Recovery phase		166º
RMS bunch length at CCR	cm	1

CCR Optics



De/Recompression arc: M56 T566 W5666	m	1.615/2.2 -3.3/4 253/250
Dechirper/Rechirper on crest energy gain	MeV	1.8
Dechirper/Rechirper	phase	90º/-90º

Longitudinal matching: short in SRF, long in CCR



MEIC Cooler Design Parameters

- Number of turns allowed in the circulator cooler ring is primarily determined by degradation of beam quality caused by coherent synchrotron radiation (CSR), space charge and inter/intra beam heating up.
- Preliminary simulation studies have shown quality of the beam (and electron cooling efficiency) is still reasonably good after 20 to 50 turns in the circulator ring.
- This leads directly to a 20 to 50 times saving of electron currents from the source/injector and ERL.

Max/min energy of e-beam	MeV	54/11
Electrons/bunch	10^{10}	1.25
bunch revolutions in CCR		~30
Current in CCR/ERL	A	1.5/0.05
Bunch repetition in CCR/ERL	MHz	750/25
CCR circumference	m	~160
Cooling section length	m	30x2
RMS 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

Perspectives of MEIC Cooling R&D

Electron cooling

- High energy (up to 100 GeV *p* / 55 MeV *e*) ← an order of magnitude above the state-of-art
- Bunched cooling electron beam from an SRF linac
- Multi-stage
- Cooling while collisions

Medium energy	**Bunched e-beam**
ERL	**Circulator ring**

Electron cooler

- A magnetized photo-cathode electron gun with long life-time
- High bunch charge (2 nC) ← a significant challenge in injector/ERL
- High Average current and high repetition rate
- High current ERL
- Ultra fast kicker with high repetition rate and short rise/full time
- Transporting a magnetized beam
- Collective beam effects (Coherent synchrotron radiation, space charge)
- Intra and inter beam heating
- Coupling of multiple beams (colliding beams and cooling beam)

Cooling is the No.1 priority of MEIC accelerator R&D!

Cooling Simulations

IBS growth time (BETACOOL & others)

Proton: 60 GeV, 4.16×10⁹ /bunch, Lc=18.75
ε^n=0.35 & 0.07 μm, δE/E=3×10⁻⁴

Model		B-M	Martini
Horizontal	s	20	20
Vertical	s	602	204
Longitudinal	S	28.5	28

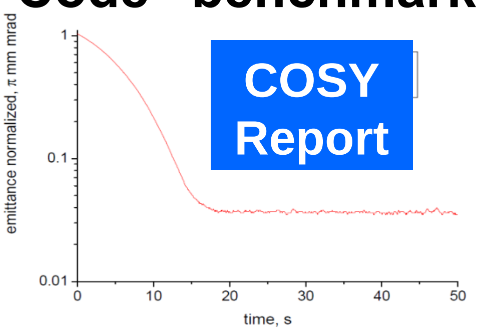
R. Li, L. Mao, H. Zhang

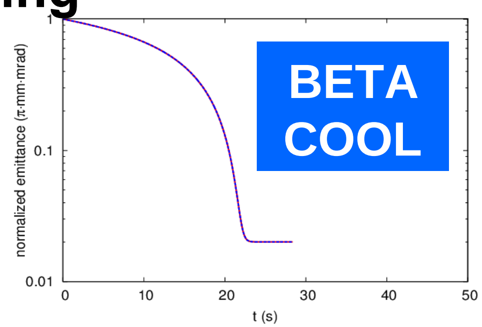
2 MeV DC cooling at the pre-booster

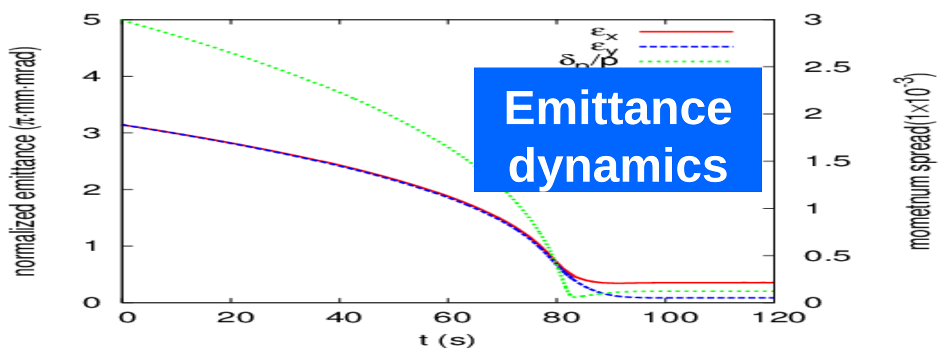
Proton: 3 GeV, 4.16×10⁹ /bunch, Lc=18.75
ε^n=3.15 μm, δE/E=10⁻³
Electron: 2.16 MeV, 3 A, B=0 or 3 kG, length=10m

		IBS	ECOOL	IBS+ECOOL	
R_H	1/s	1.37E-4	-4.77E-3	-4.64E-3	~216 s
R_V	1/s	4.57E-5	-4.77E-3	-4.73E-3	~211 s
R_L	1/s	-7.72E-6	-1.04E-2	-1.04E-2	~96 s

Code "benchmarking"







Code	trub	BETACOOL
Friction force	Parkhomchuk	
IBS	Gas relaxation	
Diffusion (e-p, target)	Included	NOT
Cooling rate	Unknown	Single particle

Further studies

- Magnetized e-beam
- Space charge effect

H. Zhang

Medium energy	Bunched e-beam
ERL	Circulator ring

Cooling Simulations (cont.)

- ***Tech-X*** effort on MEIC cooling simulations is funded by the DOE SBIR program, work is done in collaboration with the Jlab team
- ***Tech-X*** work focuses on developing a hybrid scheme:
  - Detailed dynamical friction simulations that resolve individual ion-electron collisions with VSim (Vorpal) for the MEIC cooler parameter regime
  - Coupled into Fokker-Planck type modeling of electron cooling and competing effects on macroscopic timescales with BETACOOL

"Semi-analytics" w/ modified Coulomb log

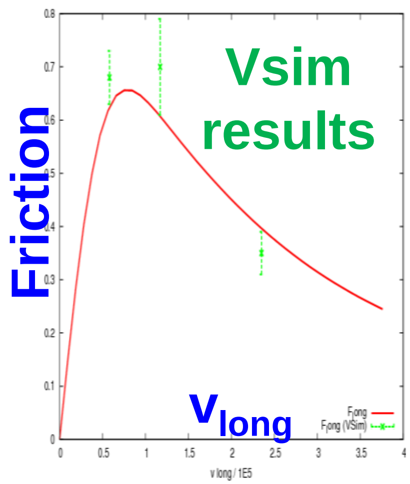
The dynamical friction were calculated by numerical integration over the 3D electron velocity distribution

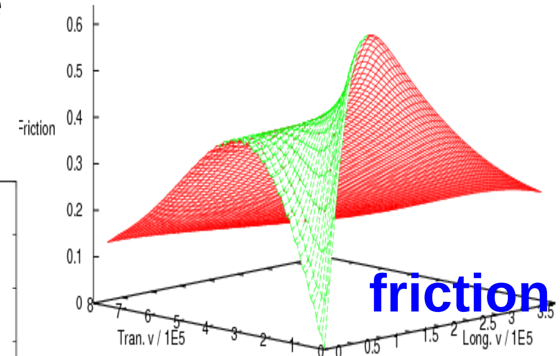
$$\mathbf{F}_{\|} = -\frac{4\pi n_e k^2}{m_e} \int_{-\infty}^{\infty} \Lambda(\mathbf{v}_{rel}) \frac{\mathbf{v}_{rel}}{|\mathbf{v}_{rel}|^3} f(\mathbf{v}_e) d^3\mathbf{v}_e$$

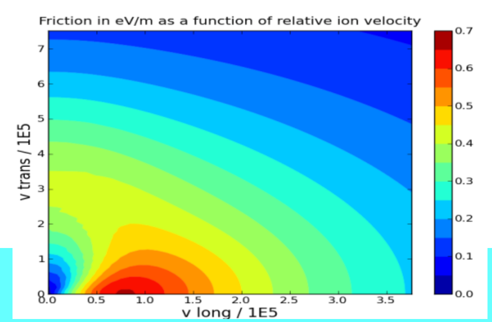
with a modified Coulomb logarithm that accounts for finite-time effects

$$\Lambda_2(\rho_{max}, \rho_{min}, \rho_c, d) = \frac{1}{2} \ln\left[\left(\frac{\rho_{max}^2 + \rho_{min}^2}{\rho_{min}^2 + \rho_c^2}\right)\left(\frac{\rho_c^2 + d^2}{\rho_{max}^2 + d^2}\right)\right]$$

Where $k = Ze^2/(4\pi\varepsilon_0)$, $v_{rel}=v_{ion}-v_e$, ρ_c and ρ_{min} are cutoff impact parameters in a finite time and for 90º scattering, and $\rho_{max}=d=|v_{rel}|\tau/2$







In progress

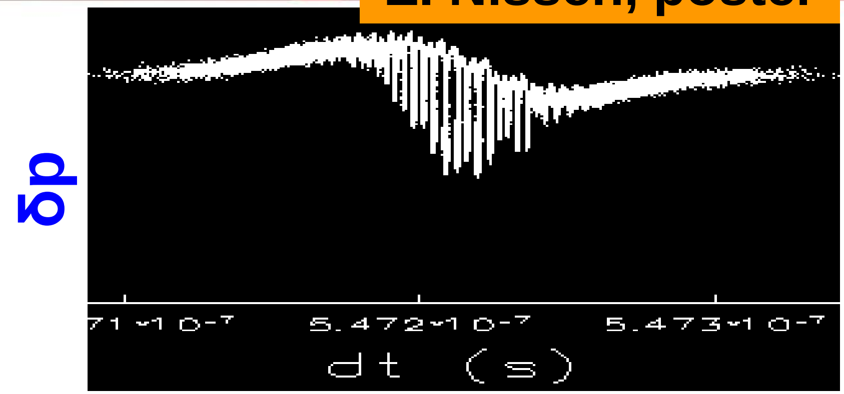
- Developing an interface for coupling VSim-computed dynamical friction data into BETACOOL
- Modifying the binary Coulomb collision algorithm in VSim (Vorpal) to work with δf-PIC macroparticles

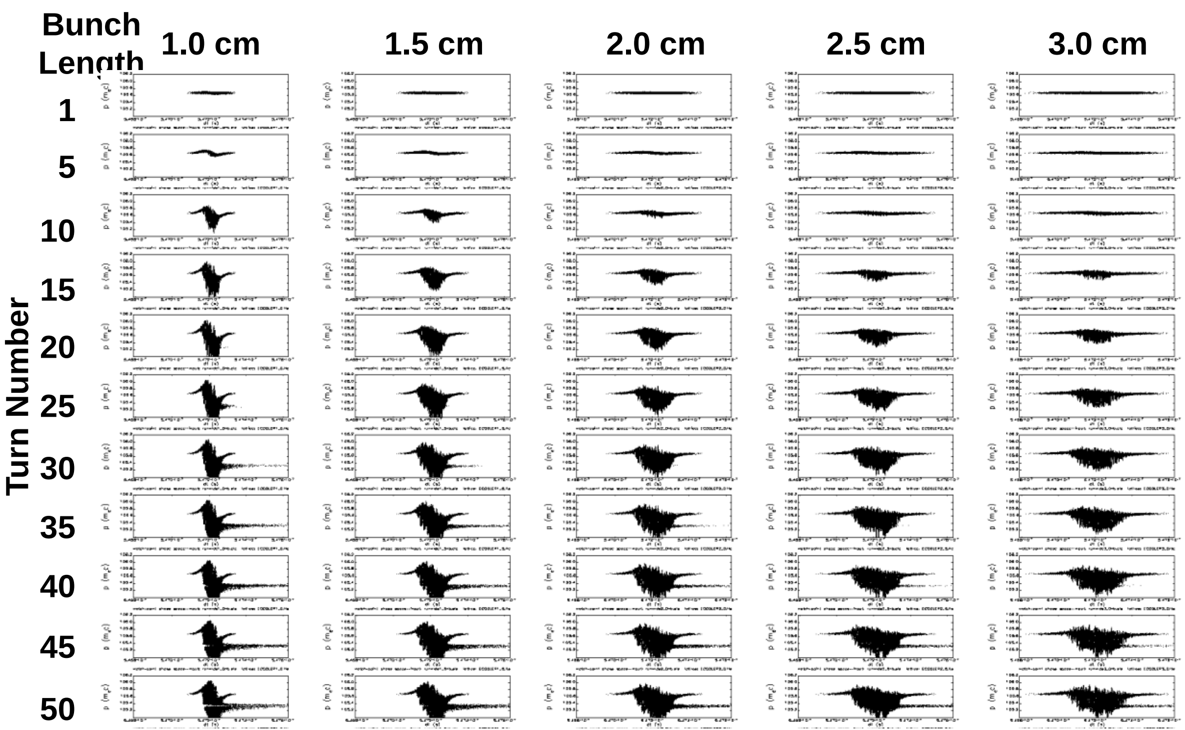
G. Bell, I. Pogorelov (Tech-X)

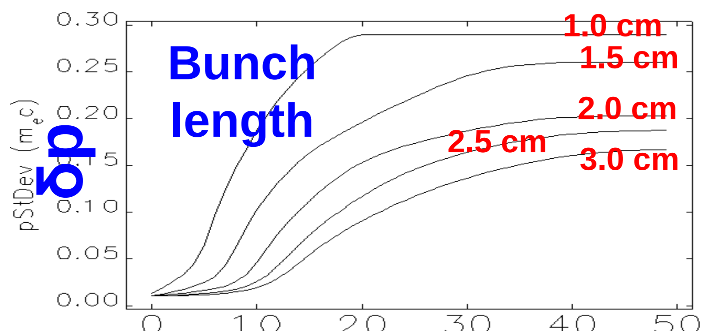
Beam Dynamics in an ERL-Circulator Cooler

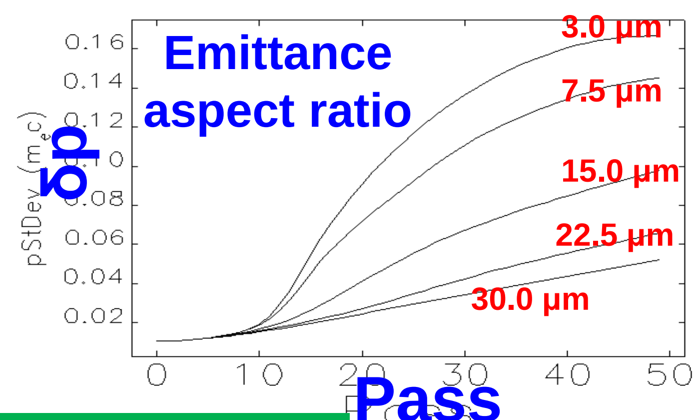
E. Nissen, poster

- Particle tracking was performed for a circulating electron bunch in a CCR using Elegant
- Coherent synchrotron radiation (CSR) is included first, the space charge will be added later
- It is found the CSR causes micro-bunching
- Study of parameter dependence (bunch length & emittance aspect ratio)



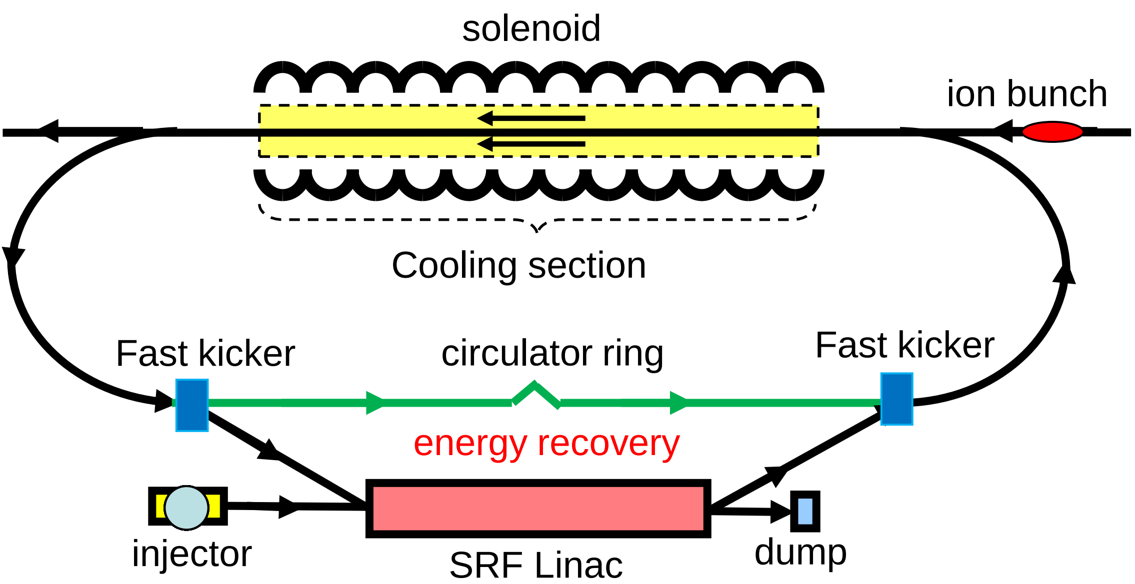






E. Nissen, C. Tennant, D. Douglas, R. Li

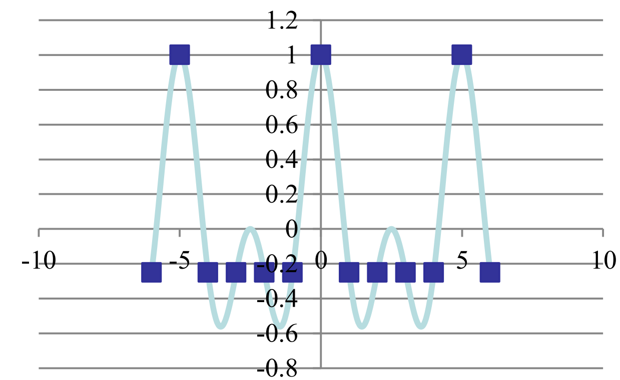
Accelerator technology for ERL-CCR



- It requires an ultra fast kicker for switching bunches in/out of a CCR
- The kicker must be able to operate at a high repetition rate (25~75 MHz)
- Rise/full time must be shorter than sub ns to avoid disturbing the neighboring bunches

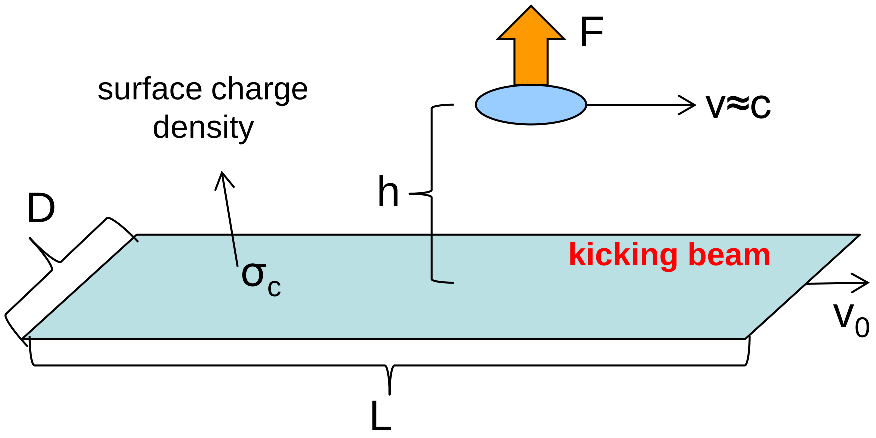
RF kicker

- Like an RF separator, a strip-line kicker driven by a waveform which is a superposition of multi harmonic waveforms
- Very high duty factor, especially with a small number of survivable turns.
- Low power requirements
- Requires a multi-harmonic signal amplifier
- Engineering design & proto-typing are underway



A. Hutton, A. Kimber, E. Nissen

Beam-Beam Kicker



V. Shiltsev, NIM 1996

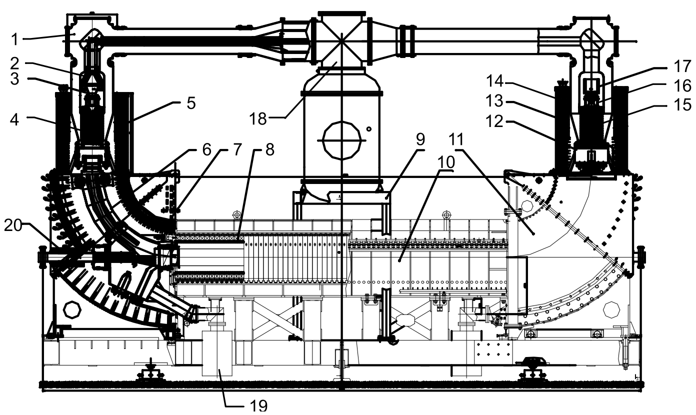
- A short (1~ 3 cm) target electron bunch passes through a long (15 ~ 50 cm) low-energy flat bunch at a very close distance, receiving a transverse kick
- The kicking force is $F = \frac{e\sigma_e}{2\xi_0}(1-\beta_0)$

  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.

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

Experiment to Demonstrate Cooling with a Bunched Electron Beam

Institute of Modern Physics, Chinese Academy of Science



- Modulated the DC beam into a bunched beam with a high repetition rate by applying a pulsed voltage to the bias-electrode of the electron gun (*Hongwei Chao, IMP*)
- Replacing the existing thermionic gun by a JLab photo-cathode gun (Matt *Poelker, JLab*)
- Low cost, non-invasive experiment, as early as 08/2013

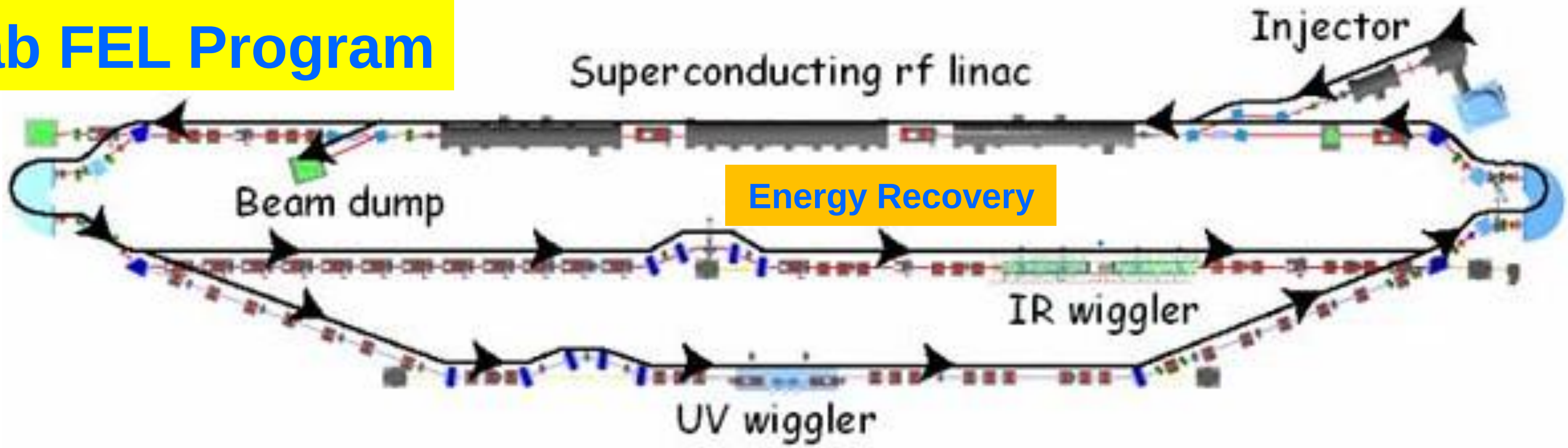
Phase II: adding an RF cavity for bunching the ion beams) testing a bunched electron beam to cool a bunched ion beam

Medium energy	**Bunched e-beam**
ERL	**Circulator ring**

A. Hutton (JLab), H. Zhao (IMP)

Energy Recovery Linac

JLab FEL Program

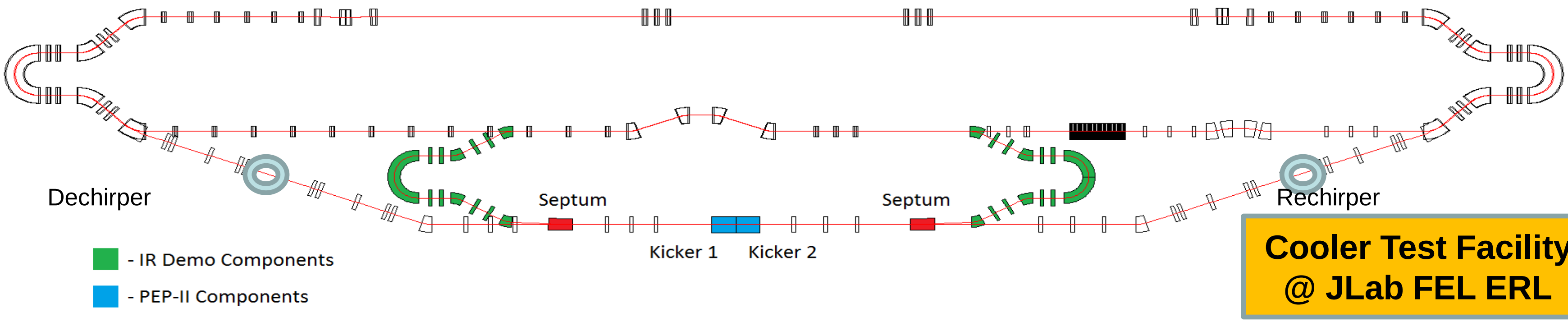


Energy	MeV	80-200
Charge/bunch	pC	135
Average current	mA	10
Peak current	A	270
Beam power	MW	2
Energy spread	%	0.5
Normalized emittance	µm-rad	<30

- 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

A world leader in ERL technology!

ERL-Circulator Cooler Proof-of-Concept Experiment at JLab FEL-ERL



Cooler Test Facility @ JLab FEL ERL

Purpose

- ***Demonstrate the cooler design concept***
- Develop/test key accelerator technologies (faster beam kickers, etc.)
- Study dynamics of the cooling electron bunches in a circulator ring

Medium energy	Bunched e-beam
ERL	Circulator ring

Phase 1 scope

- Using the existing ERL without new upgrade except two 180° beam lines (available at JLab)
- Supporting MEIC to deliver the high luminosity (5.6~14 x 10^{33} 1/cm^2/s),
- To be completed before 2016

Summary

- MEIC is considered the primary future of the JLab nuclear physics program. A comprehensive design report was released in Aug. 2012
- Multi-staged (conventional) electron cooling is essential for formation and cooling of the high intensity ion beam for MEIC.
- Conceptual design of an ERL circulator-ring based electron cooler has been proposed to provide a high intensity (1.5 A) and high energy (up to 54 MeV) cooling electron beam.
- Simulation studies of MEIC electron cooling and dynamics of the cooling electron beam in ERL-CCR are in progress
- Key enabling technologies and critical RD on ERL, circulator ring, high bunch charge electron source are also discussed and planed.
- A test facility for the ERL-circulator cooler concept and proof-of-principle experiments are under development.