# MEIC and Electron Cooling

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**(Presented by Y. Zhang)**

**Jefferson Lab**

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# Outline

1. Introduction
2. Conceptual Design of MEIC
3. Formation of MEIC Ion Beams with Electron Cooling
4. ERL Based Circulator Electron Cooler
5. Future Plan and Summary

**What has changed since COOL09**

- **MEIC baseline has gone through a big change, now is focusing on medium CM energy range**
- **We are also taking a more conservative technical position**
- **Electron cooling concept has remained basically the same**
- **Some design update/optimizations have been achieved.**

# 1. Introduction

## *Nuclear Physics Program at JLab: Through 2025*

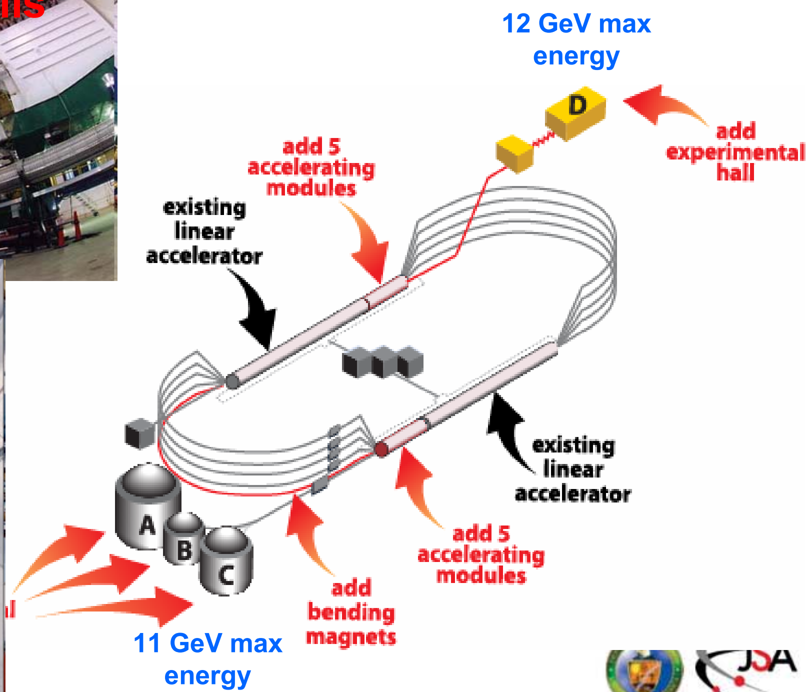
# *CEBAF & 12 GeV Upgrade*

- One of two primary US nuclear science research centers funded by the US DOE
- Operates the world-first **high energy (above 1 GeV) SRF recirculated electron linac**
- CEBAF presently delivers a 6 GeV 1.5 GHz polarized CW beam to 3 experimental halls

### **12 GeV CEBAF Upgrade** *in progress*

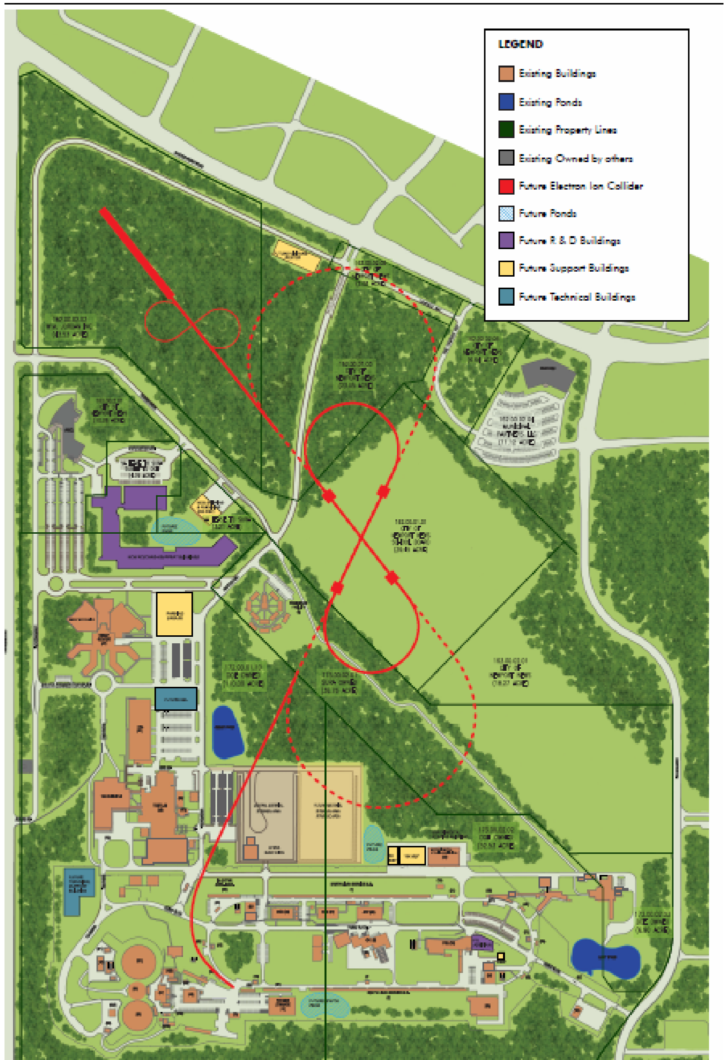
- A $340M upgrade for **energy doubling**, & **a new experimental hall**
- will be completed by 2015, exciting science program through 2025



## *Nuclear Physics Program at JLab: 2025 to 2045*

# *M*edium Energy *E*lectron-*i*on *C*ollider




### MEIC@JLab Proposal

- Add a *modern* ion complex at JLab
- Enable collisions between polarized electrons & polarized light ions or un-polarized heavy ions

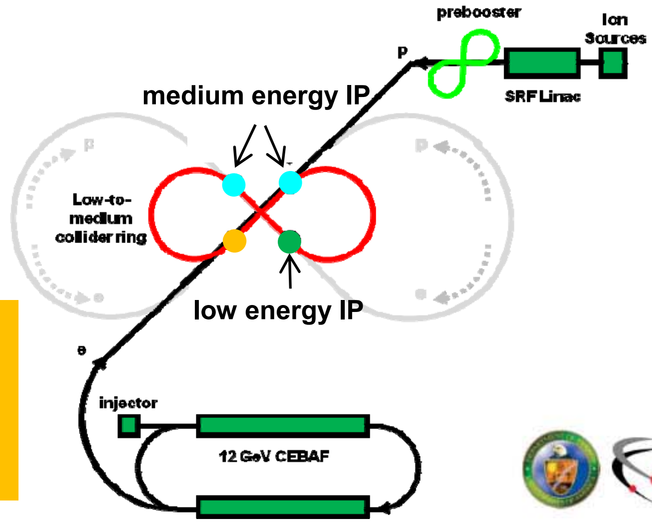
### Science Goal: Explore & Understand QCD

- Map spin & spatial structure of quarks & gluons in nucleons
- Discover the collective effects of gluons in atomic nuclei
- *(Emerging Themes)* Understand emergence of hadronic matter from quarks and gluons & Electro-weak interaction

### Science program driven machine design

- High luminosity per detector, **100 times better than HERA**
- High polarizations (>70%) for both electron and light ions

**For global EIC effort: Y. Zhang: “EIC as A Gluon Microscope”, COOL11, Sept. 15, 2011**

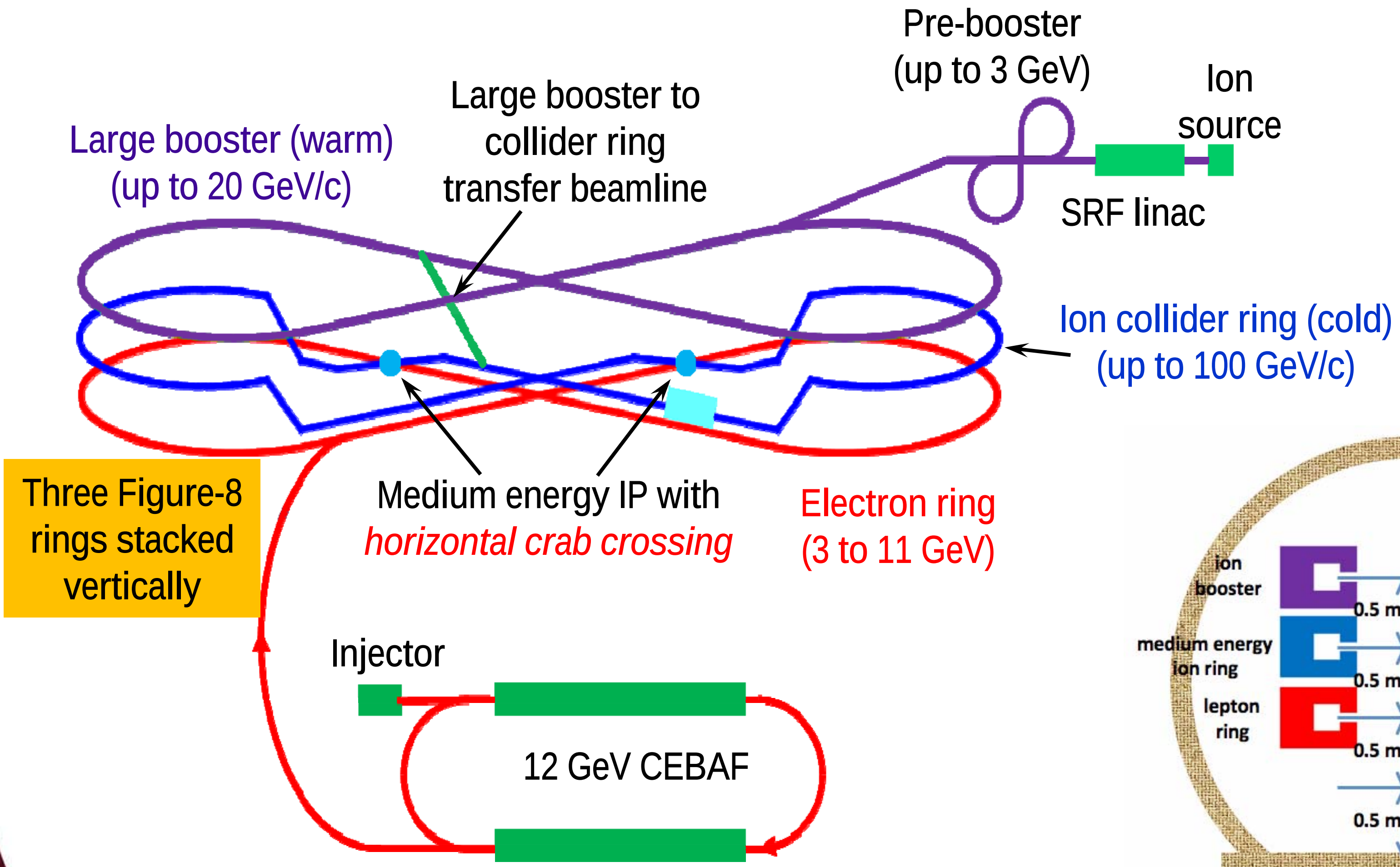


# MEIC at JLab & Electron Cooling

- Over the last decade, JLab has been developing a conceptual design of an EIC based on CEBAF
- The future science program drives the MEIC design, focusing on:
  - Medium CM energy range ➔ *e*: 3-11 GeV, *p*: 20-100 GeV, *i*: up to 50 GeV/u
  - High luminosity (above $10^{34}$ $cm^{-2}s^{-1}$) per detector over multiple collision points
  - High polarization (>80%) for both electrons & light ions
- The JLab EIC machine design takes full advantage of
- A high bunch repetition CW electron beam from the CEBAF
- A **proved** luminosity concept but **new** to a collider involving **proton/ion beams**
- A new ion complex for producing a high bunch repetition ion beams
- **Staged electron cooling**
  - Assisting formation of high bunch repetition CW ion beams with short bunch (~1 cm), small emittance, high average current, however, modest bunch intensity
  - Continuous beam cooling at collision mode to compensate IBS
- **ERL based circulator cooler ring**
  - Designed to deliver a high current (1.5 A) and high power (85 MW) electron beam with state-of-the-art accelerator technologies

# 2. Conceptual Design of MEIC

# A Polarized Ring-Ring MEIC at JLab



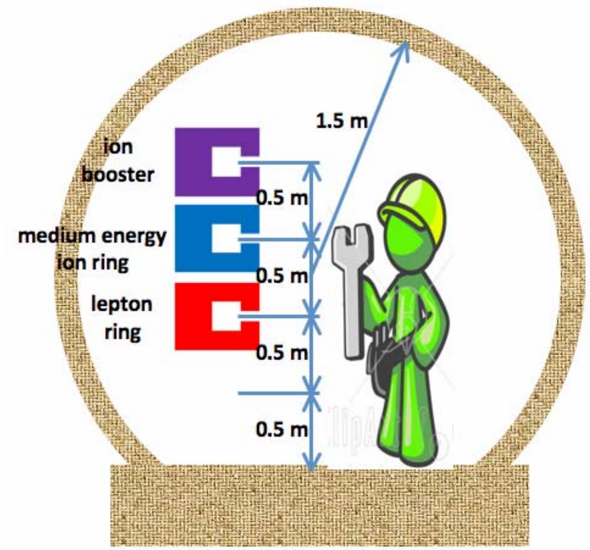




**Figure-8 shape is adopted for**
- **preservation of ion polarization**
- **polarized deuterons**

**Future energy/luminosity upgrade possible (250 GeV proton, 100 GeV/u ion, $10^{35}$ cm$^{-2}$s$^{-1}$)**

# MEIC Nominal Design Parameters

| | | Full Acceptance | | High Luminosity | |
|---|---|---|---|---|---|
| | | Proton | Electron | Proton | Electron |
| Beam energy | GeV | 60 | 5 | 60 | 5 |
| Collision frequency | MHz | 750 | | | |
| Particles per bunch | $10^{10}$ | 0.416 | 2.5 | 0.416 | 2.5 |
| Beam Current | A | 0.5 | 3 | 0.5 | 3 |
| Polarization | % | > 70 | ~ 80 | > 70 | ~ 80 |
| Energy spread | $10^{-4}$ | ~ 3 | 7.1 | ~ 3 | 7.1 |
| RMS bunch length | cm | 10 | 7.5 | 10 | 7.5 |
| Hori. & vert. emitt., normalized | µm rad | 0.35/0.07 | 54/11 | 0.35/0.07 | 54/11 |
| Horizontal & vertical β* | cm | 10 / 2 | 10 / 2 | 4 / 0.8 | 4 / 0.8 |
| Vertical beam-beam tune shift | | 0.014 | 0.03 | 0.014 | 0.03 |
| Laslett tune shift | | 0.06 | Very small | 0.06 | Very small |
| Distance from IP to 1st FF quad | m | 7 | 3.5 | 4.5 | 3.5 |
| Luminosity per IP, $10^{33}$ | $cm^{-2}s^{-1}$ | 5.6 | | 14.2 | |

**Design constraints:**
- maximum betatron function < 2 km
- maximum SC dipole field: 6 T
- Bunch frequency: < 1 GHz

# Achieving High Luminosity: *Following the Leader*

## KEK B-factory e+e- collider

- High bunch repetition rate (509 MHz)
- Very large bunch numbers
- Very small β* (~6 mm)
- Very short bunch length ($\sigma_z$~ β*)
- Modest bunch charge (~$10^{10}$, 5.3 nC)
- Crab crossing of colliding beam

➔ **over 2x$10^{34}$ /cm$^2$/s**

## HERA (traditional hadron collider)

- Low bunch repetition rate (10.4 MHz)
- small bunch numbers (180)
- Large β* (~700 mm)
- Long bunch length (~50 cm)
- Large bunch charge (8.75·$10^{10}$, 14 nC)
- No crab crossing

➔ **2x$10^{31}$ /cm$^2$/s**

**JLab is poised to replicate same success in electron-ion collider:**
- **A high repetition rate electron beam from CEBAF**
- **A new ion complex (so can match e-beam)**

| | | KEK B | MEIC |
|---|---|---|---|
| Repetition rate | MHz | 509 | **750** |
| Particles/bunch | $10^{10}$ | 3.3 / 1.4 | **0.4 /** 2.5 |
| Bunch charge | nC | 5.3 / 2.2 | **0.67** / 4 |
| Beam current | A | 1.2 / 1.8 | 0.5 / 3 |
| Bunch length | cm | 0.6 | **1** / 0.75 |
| Hori. & vert. β* | cm | 56 / 0.56 | **10 / 2** |
| Luminosity/IP | $10^{33}$ cm$^{-2}$s$^{-1}$ | 20 | 5.6~14 |

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

Jefferson

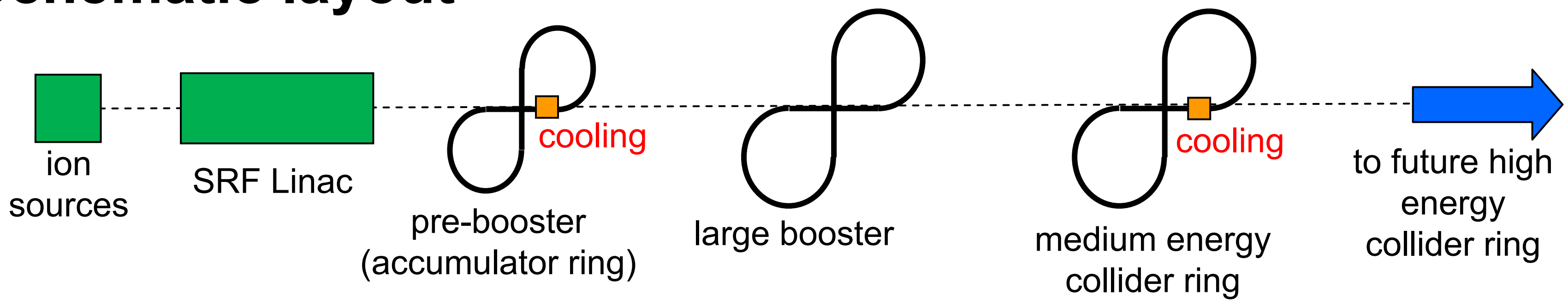
# 3. Formation of Ion Beams with Electron Cooling

# MEIC Ion Complex

## MEIC ion complex design goal

- Be able to generate/accumulate and accelerate ion beams for collisions
- Cover all required ion species
- Match time, spatial and phase space structure of the electron beam (bunch length, transverse emittance and repetition frequency)

## Schematic layout

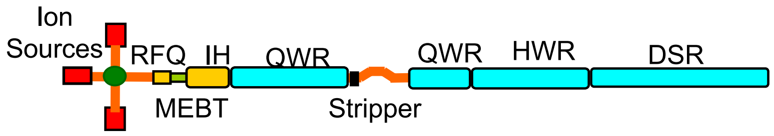


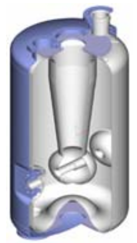

| | Length (m) | Max. energy (GeV/c) | Electron Cooling | Cooling Electron energy (MeV) | Process |
|---|---|---|---|---|---|
| SRF linac | | 0.285 (0.1) | | | |
| Pre-booster | ~300 | 3 (1.2) | **DC** | 0.054 – 0.077 | Accumulation |
| Large booster | ~1300 | 20 (8) | | | Filling (5x) |
| collider ring | ~1300 | 100 (40) | **Staged/Bunched** | 11 & 54 | |

* Numbers in parentheses represent energies per nucleon for heavy ions

# Ion Linac & Pre-booster

## on Linac



Quarter Wave Resonator (QWR)

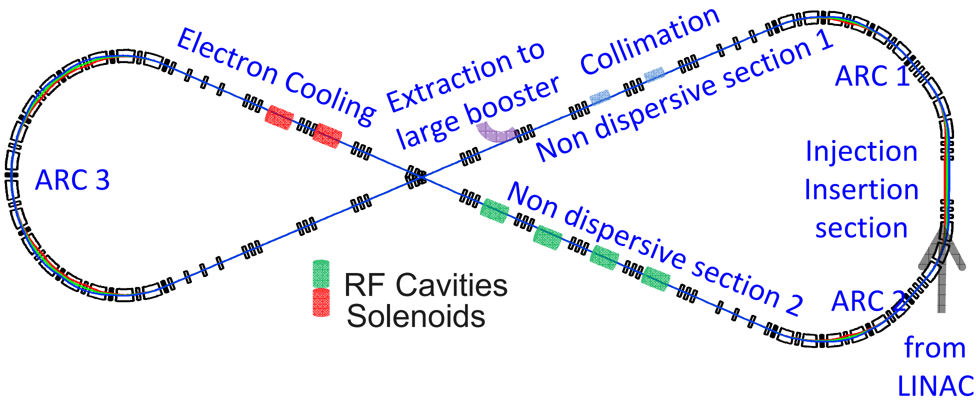
Half-Wave Resonator (HWR)

Double Spoke Resonator (DSR)

| Species | | p to lead |
|---|---|---|
| Kinetic energy | MeV/u | 100 @ $^{208}$Pb |
| Pulse current | mA | 2 |
| Pulse repetition | Hz | 10 |
| Pulse length | ms | 0.25 |
| Pulsed power | kW | 680 |
| Frequency | MHz | 115 |
| Total length | m | 150 |

P. Ostroumov, ANL

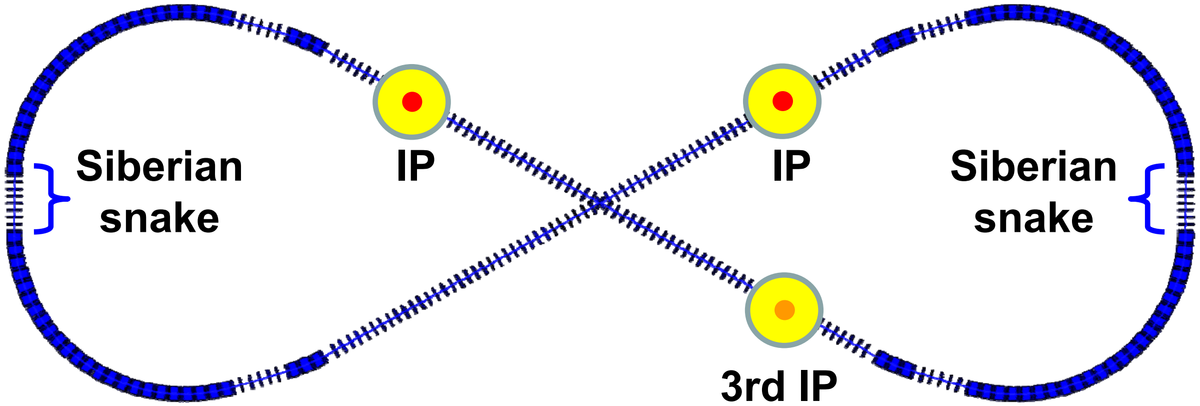
## Pre-booster




| | | |
|---|---|---|
| Circumference | m | 234 |
| Angle at crossing | deg | 75 |
| Dispersive FODO cells (Type I & 2) | | 6 & 9 |
| Triplet cells & # of matching cells | | 10 & 4 |
| Minimum drift between magnets | cm | 50 |
| Injection insertion & between triplets | m | 5 |
| Beta maximum in X and Y | m | 16 & 32 |
| Maximum beam size | cm | 2.3 |
| Max. vertical beam size in dipoles | cm | 0.5 |
| Tune in X and Y | | 7.96 & 6.79 |
| Transition gamma and energy | | 5 & 4.22 |
| Momentum compaction | | 0.04 |

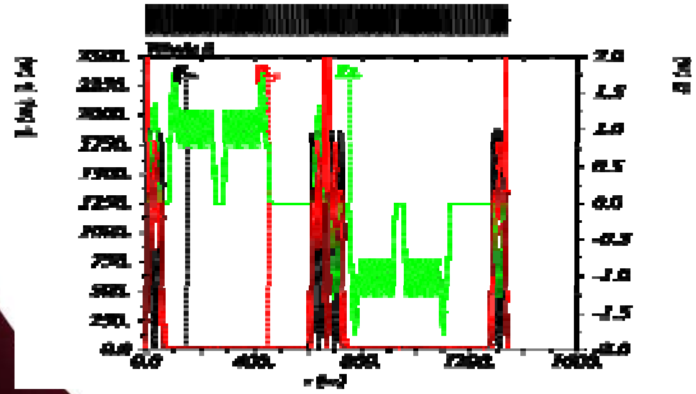
B. Erdelyi, NIU

# MEIC Ion Collider Ring




| | | |
|---|---|---|
| **Dipoles** | | 144 |
| Length | m | 3 |
| Bending radius | M | 53.1 |
| Bending Angle | deg | 3.2 |
| Field @ 60 GeV | T | 3.8 |
| **Quads** | | 298 |
| Length | M | 0.5 |
| Strength @ 60 GeV | T/m | 92/89 |

| Circumference | m | 1340.92 |
|---|---|---|
| Total bend angle/arc | deg | 240 |
| Figure-8 crossing angle | deg | 60 |
| Arc length / radius | m | 391 / 93 |
| Long & short straight | m | 279.5 / 20 |
| Lattice & phase advance | | FODO / 60 deg |
| Cells in arc / straight | | 52 / 20 |
| Arc/straight cell length | m | 9 / 9.3 |
| Betatron tunes ($\nu_x, \nu_y$) | | 25.501 /25.527 |
| Momentum compaction | $10^{-3}$ | 5.12 |
| Transition gamma | | 13.97 |
| Dispersion suppression | | Adjusting quad strength |

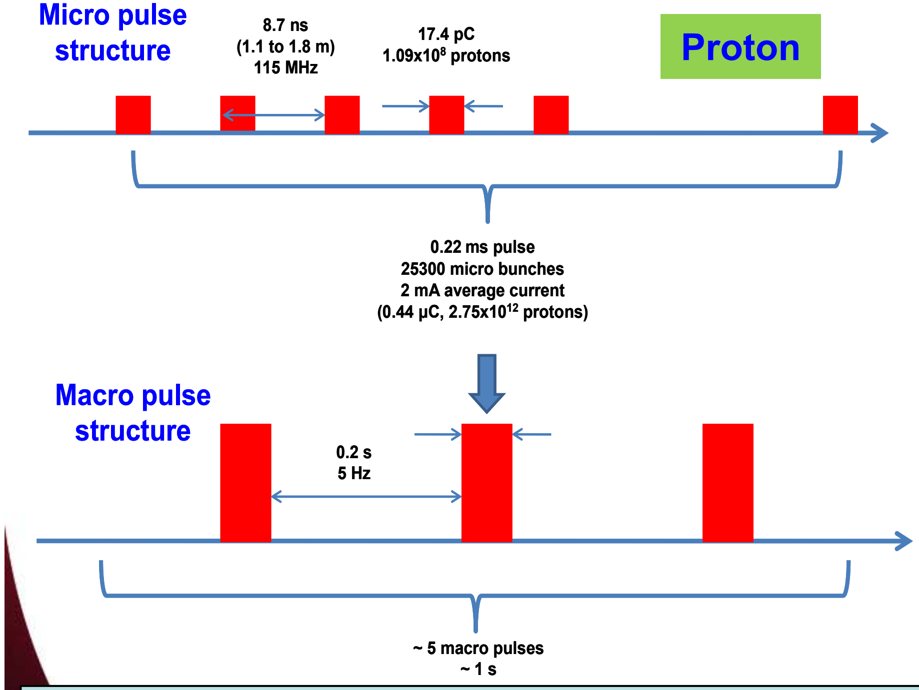


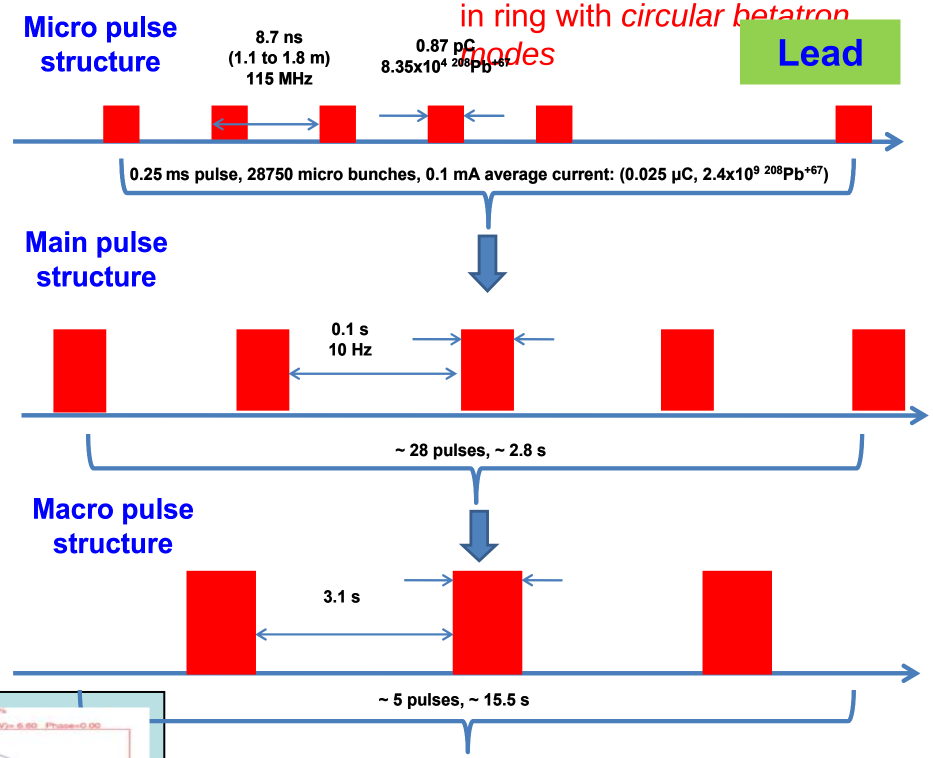
V. Morozov

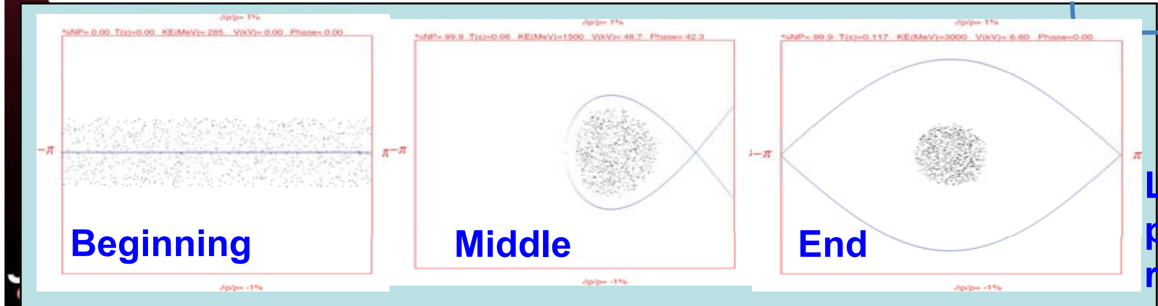
# Accumulating Ion Beams in Pre-booster

- Polarized p, d: stripping injection of negative ions ($H^-$, $D^-$)
- 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

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




Longitudinal dynamics of protons during accelerating ramp in pre-booster

# Stacking of Polarized Proton beam with an ABPIS Source

| | | Source | Linac | Pre-booster | | Large booster | Collider ring |
|---|---|---|---|---|---|---|---|
| | | ABPIS | exit | At Injection | After boost | After boost | After boost |
| Charge status | | -1 | -1 | +1 | +1 | +1 | +1 |
| | | $H^-$ | $H^-$ | $H^+$ | $H^+$ | $H^+$ | $H^+$ |
| Kinetic energy | MeV/u | ~0 | 13.2 | 285 | 3000 | 20000 | 60000 |
| γ and β | | | | 1.3 / 0.64 | 4.2 / 0.97 | 22.3 / 1 | 64.9 / 1 |
| Pulse current | mA | 2 | 2 | 2 | | | |
| Pulse length | ms | 0.5 | 0.5 | 0.22 | | | |
| Charge per pulse | μC | 1 | 1 | 0.44 | | | |
| Ions per pulse | $10^{12}$ | 3.05 | 3.05 | 2.75 | | | |
| # of pulses | | | | 1 | | | |
| Efficiency | | | | 0.9 | | | |
| Total stored ions | $10^{12}$ | | | 2.52 | 2.52 | 2.52x 5 | 2.52x5 |
| Stored current | A | | | 0.33 | 0.5 | 0.5 | 0.5 |
| Reason of current change | | | | | Change of velocity | Change of velocity | |

# Stacking of Fully Stripped Lead Ions with an ECR Source

| | | Source | Linac | Pre-booster | | Larger booster | | Collider ring |
|---|---|---|---|---|---|---|---|---|
| | | ECR | After stripper | At Injection | After boost | Stripping before injection | After Boost | After boost |
| Charge status | | 30 | 67 | 67 | 67 | 82 | 82 | 82 |
| | | $^{208}Pb^{30+}$ | $^{208}Pb^{67+}$ | $^{208}Pb^{67+}$ | $^{208}Pb^{67+}$ | $^{208}Pb^{82+}$ | $^{208}Pb^{82+}$ | $^{208}Pb^{82+}$ |
| Kinetic energy | MeV/u | ~0 | 13.2 | 100 | 670 | 670 | 7885 | 23653 |
| γ | | | | 1.11 | 1.71 | 1.71 | 9.4 | 26.2 |
| β | | | | 0.43 | 0.81 | 0.81 | 0.99 | 1 |
| Velocity boost | | | | | 1.88 | | 1.22 | 1 |
| Pulse current | mA | .5 | 0.1 | | | | | |
| Pulse length | ms | 0.25 | 0.25 | | | | | |
| Charge per pulse | μC | 0.125 | 0.025 | | | | | |
| ions per pulse | $10^{10}$ | 1.664 | 0.332 | | | | | |
| Number of pulses | | | | **28** | | | | |
| efficiency | | | 0.2 | 0.7 | | 0.75 | | |
| Total stored ions | $10^{10}$ | | | 4.5 | 4.5 | 3.375x5 | 3.375x5 | 3.375x5 |
| Stored current | A | | | 0.26 | 0.5 | 0.447 | 0.54 | **0.54** |
| Reason of current change | | | stripping | Multi-pulse injection | Change of velocity | stripping | Change of velocity | |

# Cooling in Ion Collider Ring

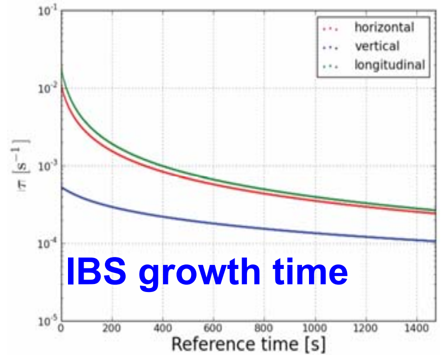
- Initial cooling after ions injected into the collider ring for reduction of longitudinal emittance before acceleration
- After boost & re-bunching, cooling for reaching design values of beam parameters
- Continuous cooling during collision for suppressing IBS, maintaining luminosity lifetime

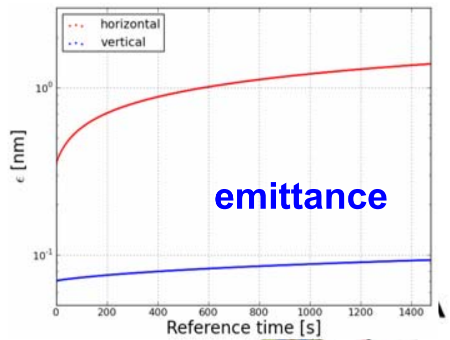
| | | Initial | after boost | Colliding Mode |
|---|---|---|---|---|
| Energy | GeV/MeV | 15 / 8.15 | 60 / 32.67 | 60 / **32.67** |
| proton/electron beam current | A | 0.5 / 1.5 | 0.5 / 1.5 | 0.5 / **1.5** |
| Particles/Bunch | $10^{10}$ | 0.416 / 2 | 0.416 / 2 | 0.416 / 2 |
| Bunch length | mm | (coasted) | 10 / 20~30 | 10 / **20~30** |
| Momentum spread | $10^{-4}$ | 10 / 2 | 5 / 2 | 3 / 2 |
| Hori. & vert. emittance, norm. | μm | 4 / 4 | | 0.35 / 0.07 |
| Laslett's tune shift (proton) | | 0.002 | 0.005 | 0.06 |

## In collision mode of MEIC, 60 GeV proton

| | formula | | Long. | Hori. | Vert. |
|---|---|---|---|---|---|
| IBS | Piwinski | s | 66 | 86 | |
| IBS | Martini (BetaCool) | s | 50 | 100 | 1923 |
| Cooling | Derbenev | s | ~24 | | |

## BetaCool Simulations



# 4. ERL Based Circulator Electron Cooler

# Low Energy DC Electron Cooler for MEIC Pre-booster

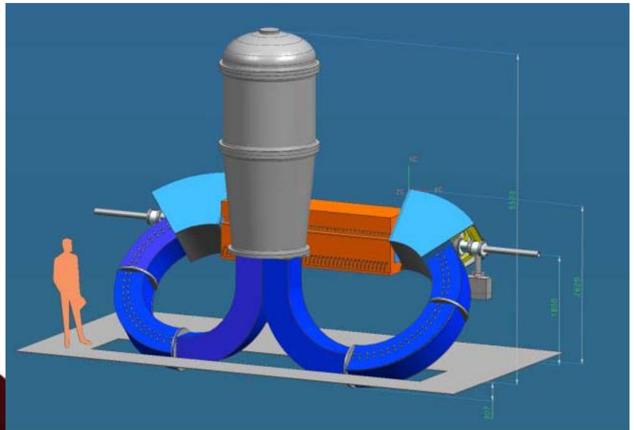
What we need for MEIC pre-booster for assisting accumulation:

- A conventional DC electron cooler
- Ion energy from 100 MeV/u (lead ion) to 145 MeV/u light ions
- Electron energy is 54 to 77 keV

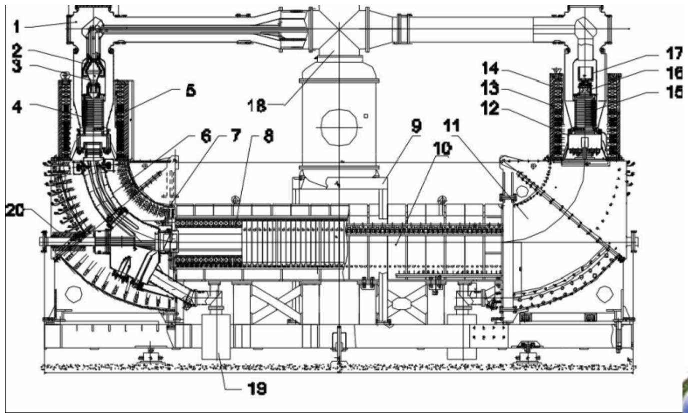
Technology is mature & successfully demonstrated in many facilities

Our collaborator at ANL & NIU. will lead an initial conceptual design

**COSY electron cooler**



**HIRFL-CSR electron cooler @ IMP, Lanzhou**



# High Energy e-Cooler for Collider Ring

## Design Requirements and Challenges

- Electron beam current
  - up to 1.5 A CW beam at 750 MHz repetition rate
  - About 2 nC bunch charge (possible space charge issue at low energy)
  - About **173 kC/day** from source (state-of-art photo-cathode source ~0.2 kC/day)
- Energy of cooling electron beam in MEIC
  - up to 10.8 MeV for cooling injection energy (20 GeV/c)
  - up to **54 MeV** for cooling top proton energy (100 GeV/c)
- Beam power
  - Need 16 to **81 MW** for cooling 20 to 100 GeV/c protons

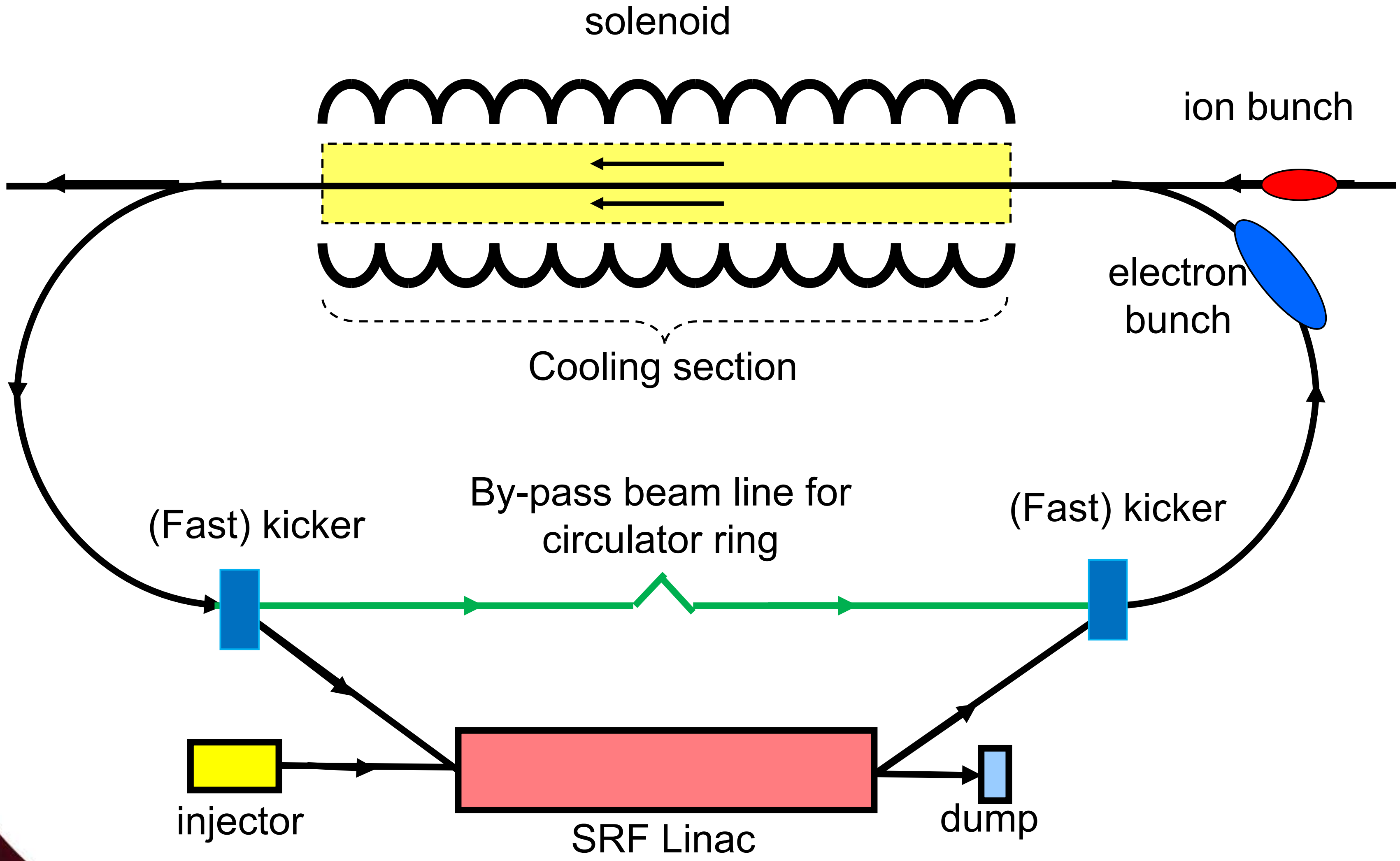
## Design Choice: ERL Based Circulator Cooler (ERL-CCR)

- **Must be** a RF Linac for accelerating electron beam
- **Must be** Energy Recovery SRF Linac (ERL) to solve RF power problem
- **Must be** Circulator ring (CCR) for reducing average current from source/ERL

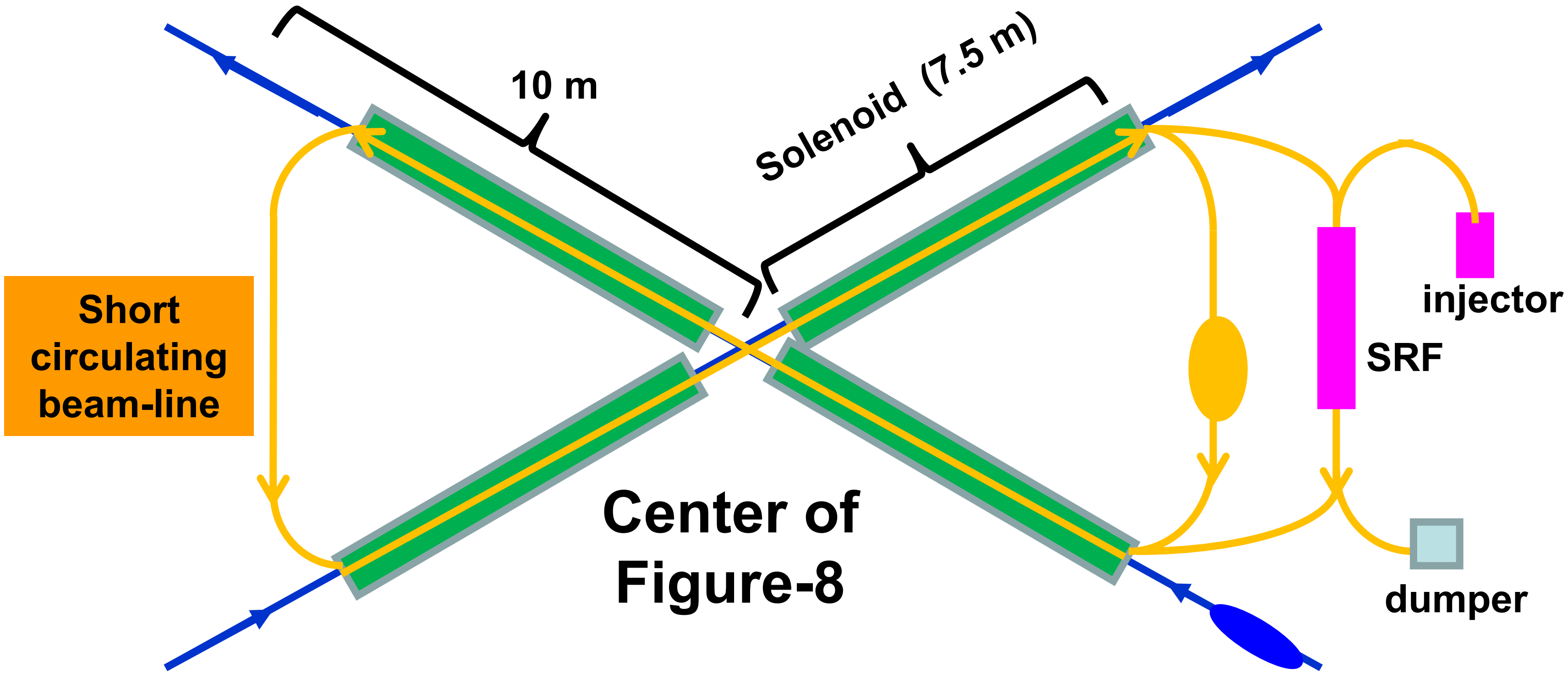
***ERL-CCR can provide the required high cooling current while consuming fairly low RF power!***

**Other option (thermionic gun + circulator ring) also under evaluation**

# ERL Circulator Electron Cooler



# Optimized Location of Cooling Channel




**Eliminating a long circulating beam-line could**

- cut cooling time by half, or
- reduce the cooling electron current by half, or
- reduce the number of circulating by half

# MEIC Electron Cooler Design Parameters

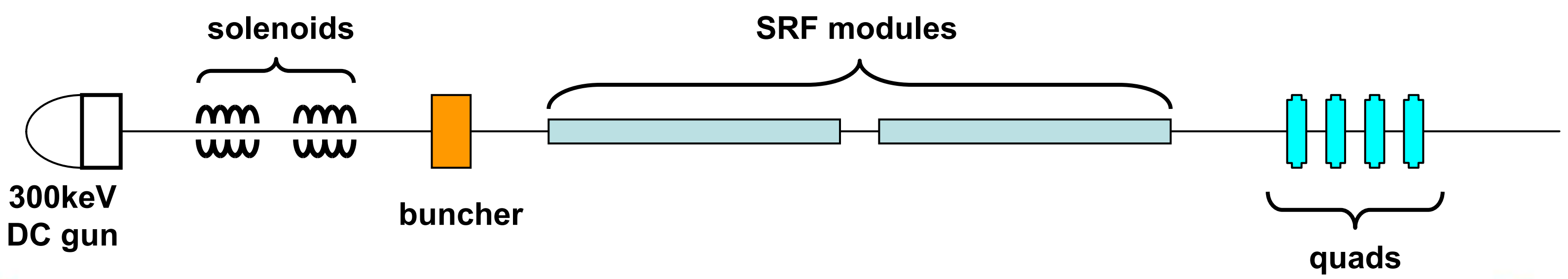
- Number of turns in circulator cooler ring is determined by degradation of electron beam quality caused by inter/intra beam heating up and space charge effect.
- Space charge effect could be a leading issue when electron beam energy is low.
- It is estimated that beam quality (as well as cooling efficiency) 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 | 54/11 |
| Electrons/bunch | $10^{10}$ | 1.25 |
| bunch revolutions in CCR | | ~100 |
| Current in CCR/ERL | A | 1.5/0.015 |
| Bunch repetition in CCR/ERL | MHz | 750/7.5 |
| CCR circumference | m | ~80 |
| Cooling section length | m | 15x2 |
| Circulation duration | μs | 27 |
| 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 |

# Technology: Electron Source/Injector

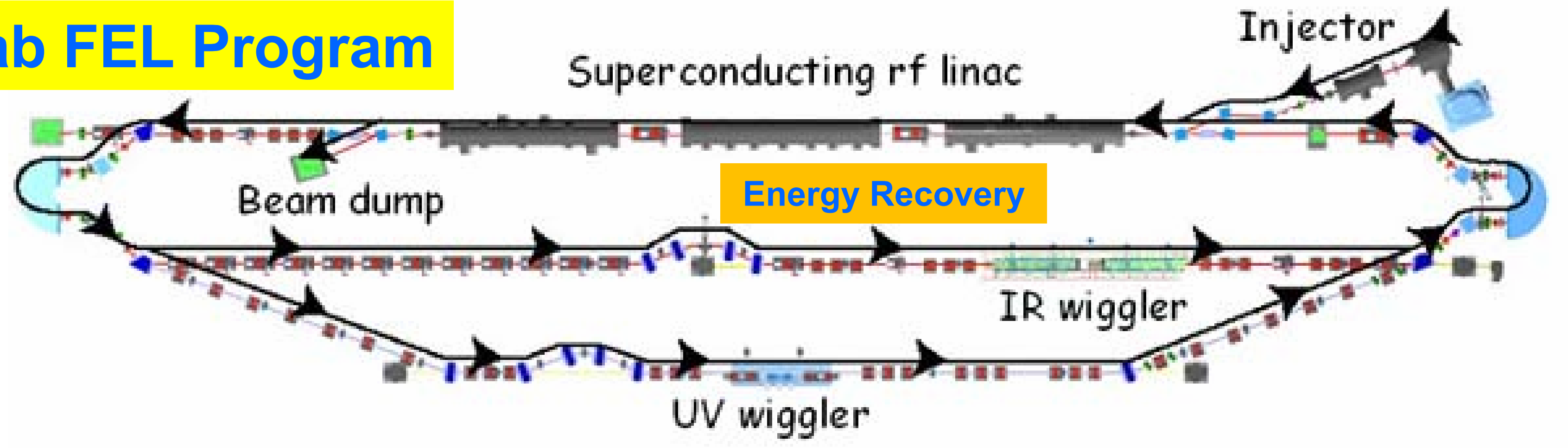
- ELIC CCR driving injector
  - 15 mA@7.5 MHz, up to 54 MeV energy
  - 2 nC bunch charge, magnetized
- Challenges
  - Source life time:  1.7 kC/day (state-of-art is 0.2 kC/day)

    → 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.



# Technology: Energy Recovery Linac

## JLab FEL Program

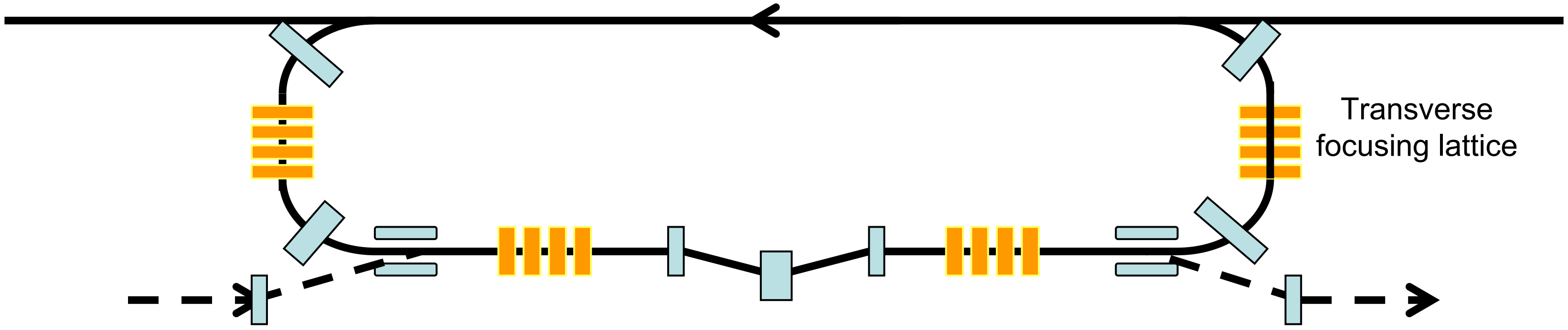



| | | |
|---|---|---|
| Energy | MeV | 80-200 |
| Charge/bunch | pC | 135 |
| Average current | mA | 10 |
| Peak current | A | 270 |
| Beam power | MW | 2 |
| Energy spread | % | 0.5 |
| Normalized emittance | µm-rad | <30 |

- 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 a world leader in ERL technology!***

# Technology: Circulator Ring




**Kicker Parameter**

| | | |
|---|---|---|
| energy | MeV | 54 |
| 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 one bunch spacing (~1/750MHz = 1.3 ns)

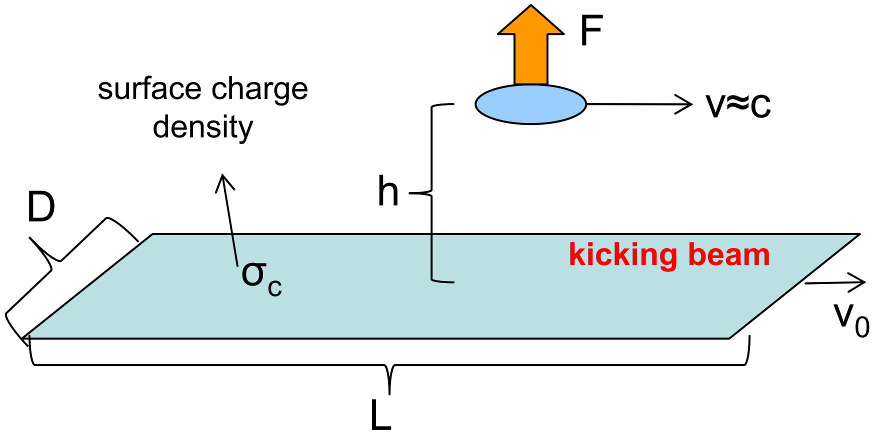
## Synchronization

- Bunch spacing depends on beam energy. There is about 1.8 mm difference when energy is boosted from 20 to 100 GeV/c
- A 10 m 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.

**Ultra fast kicker may not be required if a gap of bunch train is introduced in the circulator cooler**

# Technology: Ultra-Fast Kicker

## Beam-beam kicker




| | | |
|---|---|---|
| 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 |

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.

**An ultra-fast RF kicker is also under development.**

# 5. Future Plan and Summary

# MEIC EC R&D Challenges

## Electron Cooling

*Beyond the state-of-art*

- Much higher energy, up to 100 GeV/u
- Cooling of a bunched beam
- Continuous cooling during collisions

## ERL based Circulator Cooler

Also beyond the state-of-art

- High current from source (lifetime)
- Linac instead of electrostatic machine
- High average current ERL (BBU)
- Two cooling channels

## Beam Dynamics

Reuse of a cooling bunch hundred times introducing many instability issues

- Electron beam stabilities
- Long term space charge effect
- Coupled beam instabilities

## JLab EC Study Group

JLab staffs and **two new postdocs** will work on design and R&D, focusing on

- Electron cooling simulations
- Circulator Cooler design and beam dynamics in cooler

## Aiming for a design report

(by 2013)

### Design Report Outline

- Introduction
- Electron Cooling Concept for MEIC
- MEIC Electron Cooling Simulations
- ERL Based Circulator Cooler
  - Electron Source/Injector
  - Energy Recovery Linac
  - Circulator Ring
  - Cooling Channel
- Beam Dynamics in Circulator Cooler
  - Single Beam Effect
  - Coupled Beam Effect
- Technical Design and R&D
  - Electron Source and Lifetime
  - SRF linac
  - Magnets, Solenoids and Kicker
- Conclusion

***JLab is seeking collaborations with world experts in electron cooling.***

Jefferson Lab

# Summary

- MEIC is considered a primary future of JLab nuclear physics program. It promises to accelerate a wide variety of ions to collide with electrons beam with a CM energy range up to 65 GeV
- MEIC can reach up to $1.4 \times 10^{34}$ $cm^{-2}s^{-1}$ luminosity for e-p collisions based on a luminosity concept of high bunch repetition CW beams
- Electron cooling is essential for forming (through stacking & accumulating) 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 high intensity (1.5 A) and high energy (up to 54 MeV) cooling electron beam.
- Key enabling technologies and critical RD on ERL, circulator ring, high bunch charge electron source are also discussed and planed.
- A conceptual design report will be produced by 2013

# MEIC Accelerator Design Study Group

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# Backup Slides

# 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