The Use of ERLs to Cool High Energy Ions in Electron-Ion Colliders

Stephen V. Benson, Andrei Seryi, Chris Tennant,
and Yuhong Zhang

*Thomas Jefferson National Accelerator Facility,
Newport News VA, 23606, USA*

Ferdinand Willeke

Brookhaven National Laboratory, Upton NY, 11973, USA

Gennady Stupakov

SLAC National Accelerator Laboratory, Menlo Park CA 94025, USA

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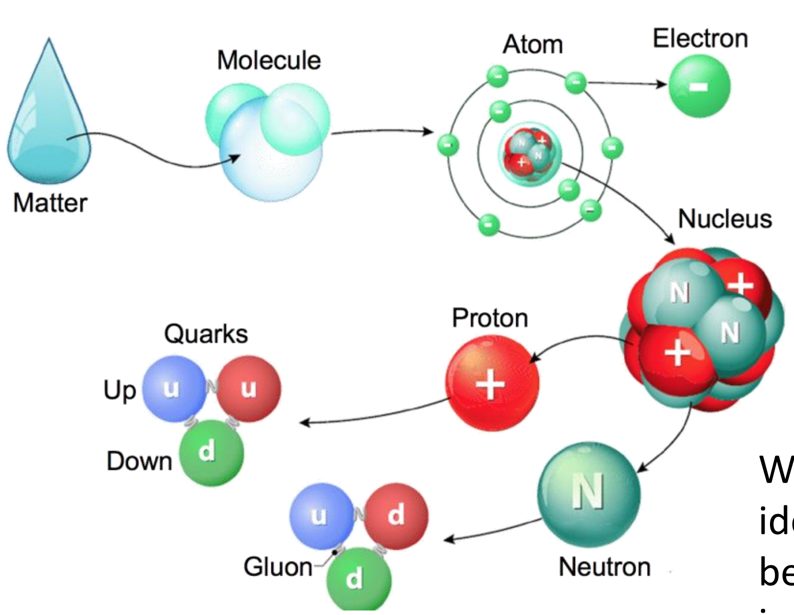
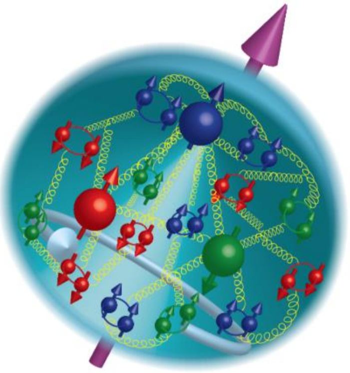
Outline

- Why do we need an ion cooler?
- Electron Ion Cooling
  - Bunched beam incoherent cooling
  - Coherent Cooling
- ERL designs
- Conclusions

Nucleons and Nuclei – fundamental questions

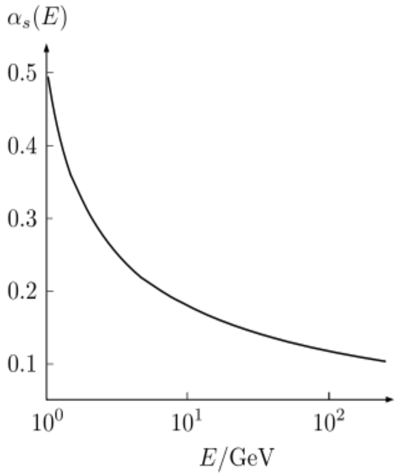




Mass
Spin
Bulk NN interactions
…

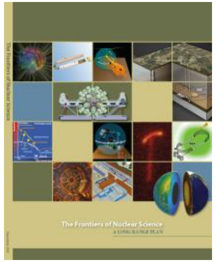
Arise out of quarks and gluons interacting through Quantum Chromodynamics (QCD)

We have limited quantitative idea of how this happens because QCD is strongly coupled in the energy regime of the mass of Nucleons.



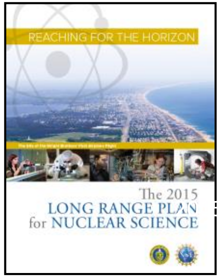
Nucleons and Nuclei and their properties can be thought of as *emergent phenomena* of QCD. We know this happens—the Quest is to understand exactly *How*.

Electron-Ion Collider Planning



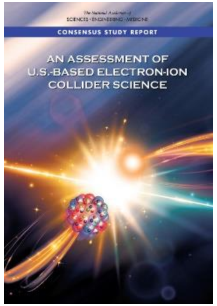
Federal Nuclear Science Advisory Cmte 2007 Long-Range Plan

“An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier”



Federal Nuclear Science Advisory Cmte 2015 Long Range Plan

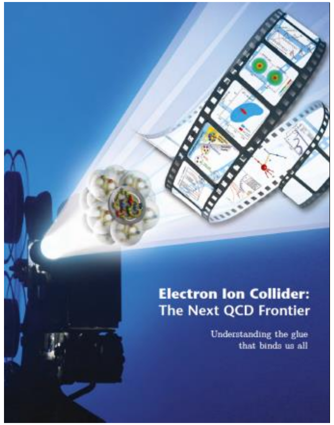
“We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.”

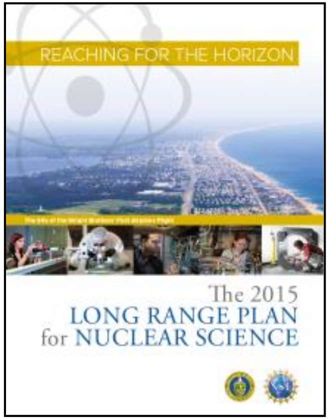


National Academies of Sciences – Assessment of U.S. Based Electron-Ion Collider Science (2018)

“…the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today.”

Electron Ion Collider Requirements





Established in Community White Paper*, re-emphasized in 2015 NSAC LRP, and NAS study

- Polarized (~70%) electrons, protons, and light nuclei
  - High polarization essential to deliver the physics in a timely manner
  - Many measurements go as $\mathcal{L} \times P_e^2 \times P_p^2$
- Ion beams from deuterons to the heaviest stable nuclei
  - Protons, deuterons, light nuclei, through U or Pb
- Variable center of mass energies ~20-100 GeV, upgradable to ~140 GeV
  - Not a collider to achieve highest possible CoM energy
  - Highest luminosity demands in mid energy range
- High collision luminosity $\sim 10^{33\text{-}34}$ cm^{-2} s^{-1}
  - "Factory"-like luminosity, factor of 100-1000 beyond HERA
- Possibly have more than one interaction region

*A. Accardi et al. , "Electron Ion Collider: The Next QCD Frontier - Understanding the Glue that Binds Us All", Eur. Phys. J. A52 , p. 268 (2016), https://doi.org/10.1140/epja/i2016-16268-9

JLEIC Layout

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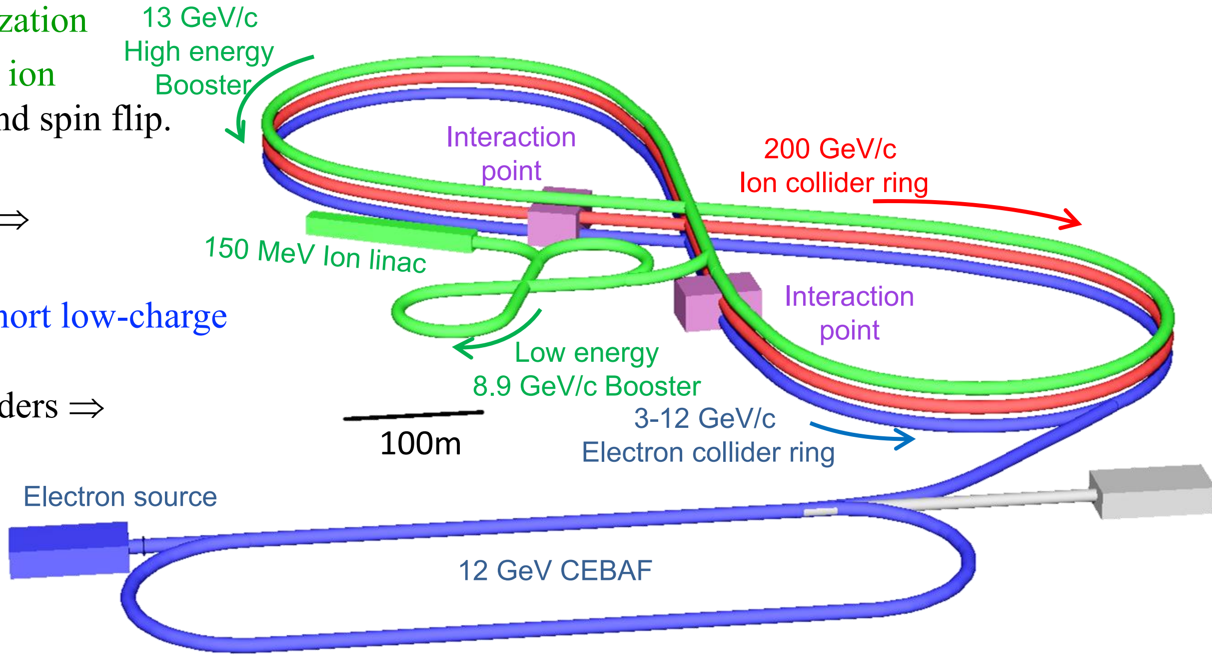
- Full-energy top-up injection of highly polarized electrons from CEBAF
  ⇒ High stored electron current and polarization
- Figure-8 ring design ⇒ High electron and ion polarizations, polarization manipulation and spin flip.
- Full-size high-energy booster ⇒
  Quick replacement of colliding ion beam ⇒
  High average luminosity
- High-rate collisions of strongly-focused short low-charge low-emittance bunches
  similarly to record-luminosity lepton colliders ⇒
  High luminosity
- Multi-stage electron cooling using demonstrated magnetized cooling mechanism ⇒ Small ion emittance ⇒
  High luminosity



- Integrated full acceptance detector with far-forward detection sections.
- Upgradable to 140 GeV CM by replacing the ion collider 6T NbTi cosΘ bending dipoles only with 12 T Nb_3Sn magnets.

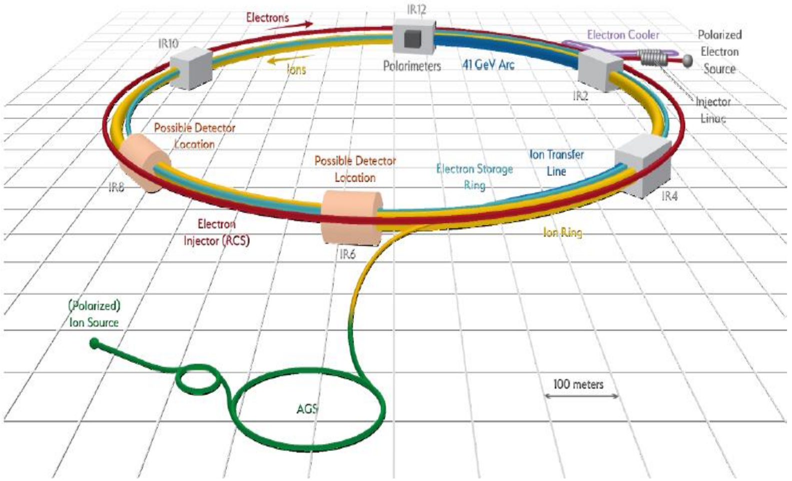
- Design meets the high luminosity goal of **$L = 10^{34} cm^{-2}s^{-1}$**

eRHIC Layout

- **Hadrons up to 275 GeV**

eRHIC is using the existing RHIC complex: Storage ring (Yellow Ring), injectors, ion sources, infrastructure

- Need only few modifications for eRHIC
- Todays RHIC beam parameters are close to what is required for eRHIC



- **Electrons up to 18 GeV**

- Electron storage ring with up to 18GeV ➔ E_{cm} = 20 GeV -141 GeV installed in RHIC tunnel. Beam current are limited by the choice of installed RF power 10 MW
- Electron beams with a variable spin pattern accelerated in the on-energy, spin transparent injector: Rapid Cycling Synchrotron with 1-2 Hz cycle frequency in the RHIC tunnel
- Polarized electron source and 400 MeV s-band injector linac in existing tunnel
- Design meets the high luminosity goal of **$L = 10^{34} cm^{-2} s^{-1}$**

High Luminosity Implementation

As both designs, JLEIC and eRHIC are storage ring designs, the same ingredients are required for large luminosity

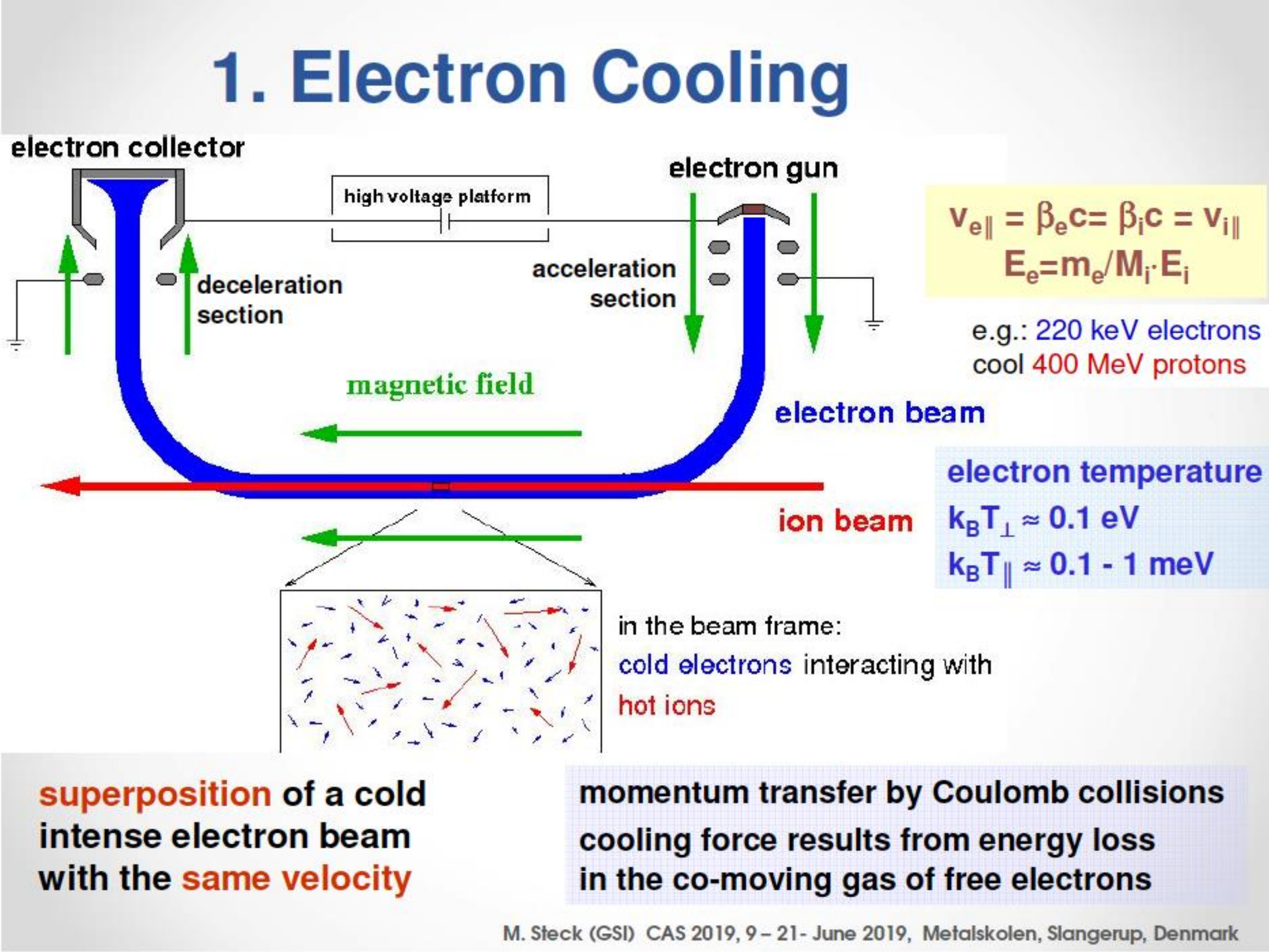
- **Large bunch charge** (yet small in comparison with hadron colliders)
- **Many bunches** ➔ large total beam currents
  ➔ crossing angle collision geometry
- **Small beam size** at collision point achieved by
  * **small emittance**
    ➔ small hadron emittance
  * **and strong focusing at IR** (small β)
    ➔ required short bunches

➔ requires strong hadron cooling **or** frequent injection of pre-cooled beam

- Luminosity limits vs E: **Space Charge, Beam-Beam Limits, Synchrotron Radiation**

Cooling Schemes

Incoherent Electron Cooling



Multi-Phase Electron Cooling for High Luminosity

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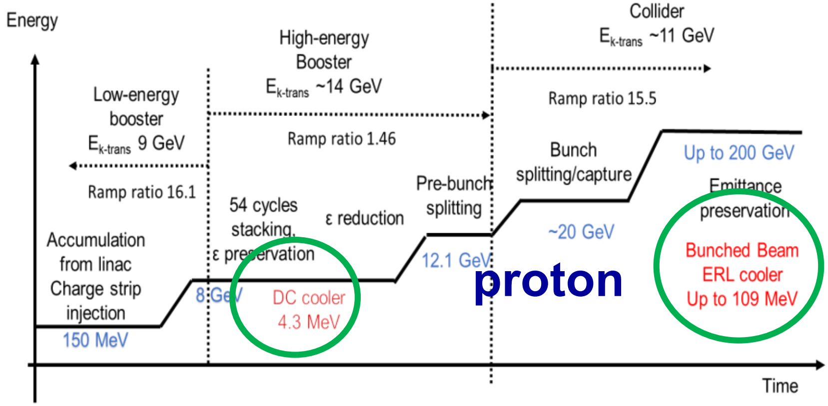
- JLEIC choice: conventional electron cooling and multi-phase
- Achieving very small emittance (up to **~10 times** reduction) and very short bunch (**~2 cm**) with SRF
- Assisting injection/accumulation of heavy ions
- Suppressing IBS induced emittance growth during beam store
- High cooling efficiency at low energy & small emittance
- Requires high peak currents at high energy

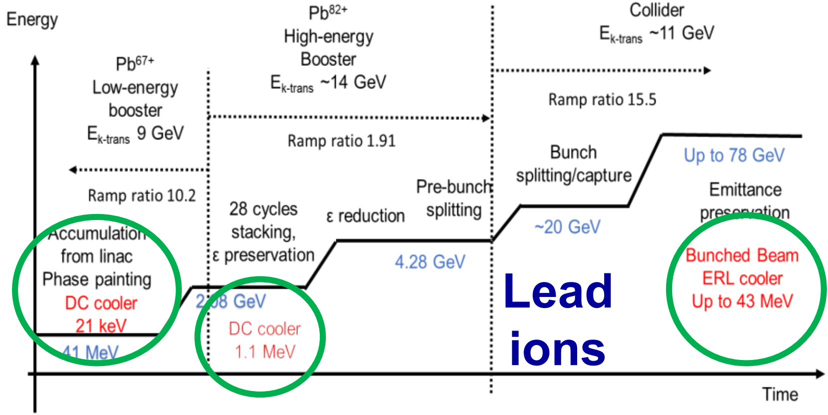
$$\tau_{cool} \sim \gamma^2 \frac{\Delta\gamma}{\gamma} \sigma_z \varepsilon_{4d}$$

Pre-cool when energy is low

Cool after emittance is reduced (after pre-cool at low energy)

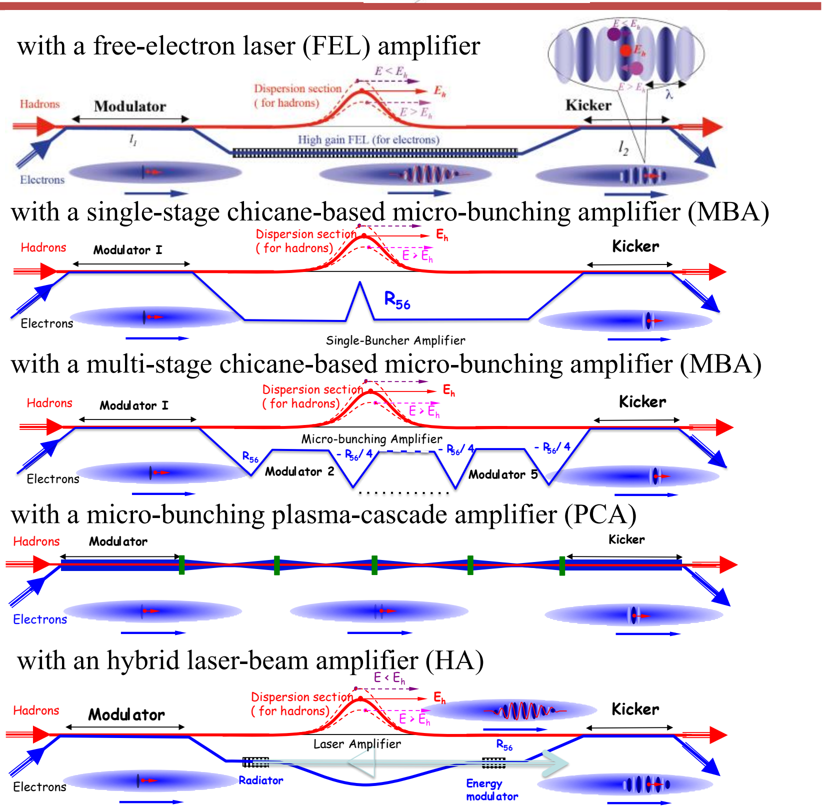
Ring	Functions	Kinetic energy (GeV / MeV)			Cooler type
		Proton	Lead ion	Electron	
Low Energy Booster	Accumulation of positive ions		0.1 (injection)	0.054	DC
High Energy booster	Maintain emitt. during stacking	7.9 (injection)	2 (injection)	4.3 (proton) 1.1 (lead)	DC
	Pre-cooling for emitt. reduction	7.9 (injection)	7.9 (ramp to)	4.3	
collider ring	Maintain emitt. during collision	Up to 150	Up to 78	Up to 109	ERL





CeC – Stochastic Cooling at Optical Frequencies

- All proposed CeC systems are based on the same basic scheme
- In modulator electron beam picks-up density modulation ("imprint") from individual ions
- This modulation is amplified in a broad-band high frequency amplifier (instability)
- In a kicker, ion's momentum is corrected by electric field induced in the electron beam
- Important feature of an amplifier– its frequency bandwidth
- CeC with two amplifiers: FEL and PCA does not require separating electron and hadron beams.



PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

Coherent Electron Cooling

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]

Features of CeC

- Requires a very low noise input electron beam
  - Try to get as close to shot noise floor as possible
  - Microbunching gain must be small
- Want to avoid saturation (broad bandwidth is preferable)
- Want higher peak current
  - Still have to meet energy spread specification
  - Bunch can be much shorter than the ion bunch
- eRHIC has chosen the microbunching option.

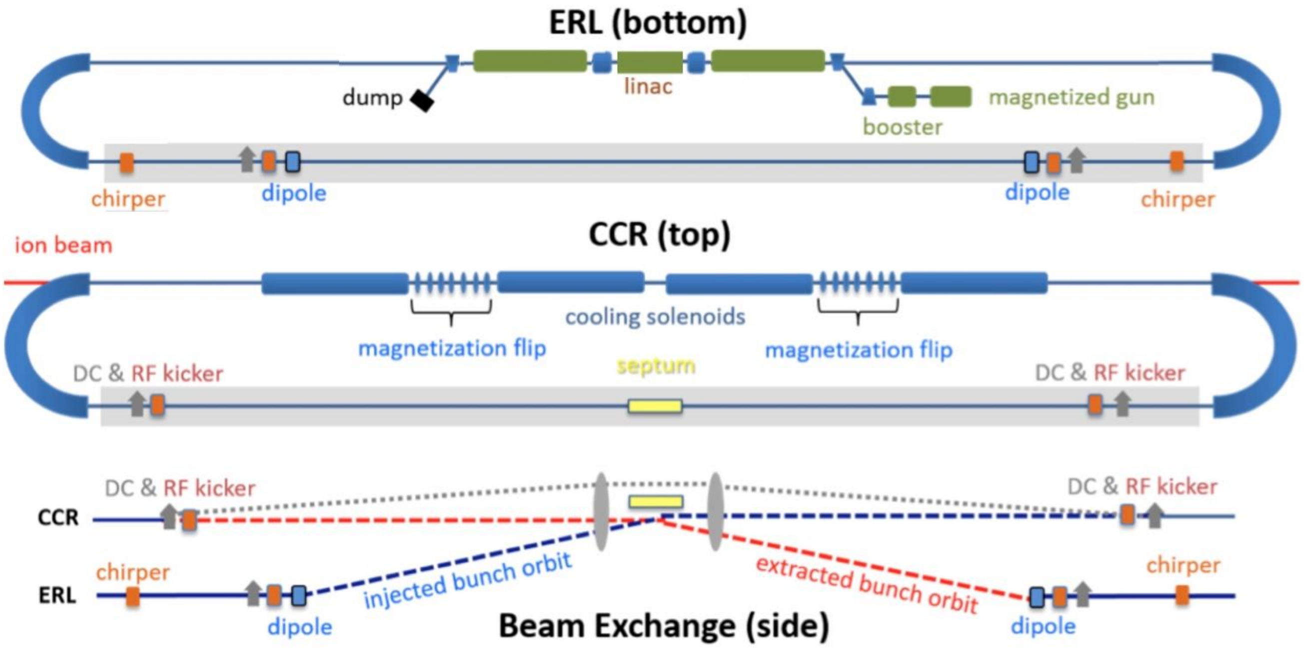
ERL Designs

JLEIC BBU Cooler Specifications

Energy	20–110 MeV
Charge	3.2 nC
CCR pulse frequency	476.3 MHz
Gun frequency	43.3 MHz
rms Energy spread (uncorr.)	3×10^{-4}
Energy spread (p-p corr.)	$<6 \times 10^{-4}$
Bunch length (tophat)	3 cm (17°)
Thermal (Larmor) emittance	<19 mm-mrad
Cathode spot radius	3.1 mm
Cathode field	0.05 T
Normalized hor. drift emittance	36 mm-mrad
Solenoid field	1 T
Electron beta in cooler	37.6 cm
Solenoid length	4x15 m
Bunch shape	beer can

Baseline Design – Cooling Ring Fed by ERL

- Use Circulating Cooling Ring (CCR) to enhance current by 11X.
- Magnetized electron beam for higher cooling efficiency
- Same-cell energy recovery in 476.3 MHz SRF cavities with Harmonic linearizer
- Assumes high charge, low rep-rate injector (w/ harmonic linearizer acceleration)
- Use magnetization flips to compensate ion spin effects



Circulating Cooler Ring Specifications

The proposed design is to use a Circulating Cooling Ring (CCR) to provide high current in the cooler (~1 A) without requiring such high current in the electron source.

- The CCR has the following requirements:
  - Isochronous.
  - Achromatic
  - Need RF compensation to counter SC and CSR
  - High periodicity with rational tune
  - Moderate size
  - Local axial symmetry
  - Local isochronicity ⇔small compaction oscillations (for μBI)
  - Local dispersion suppression
  - No tune resonances except for coupling resonance
- We would also like the ring to use conventional magnet and vacuum chamber technology as far as possible. Should take advantage of CSR shielding.

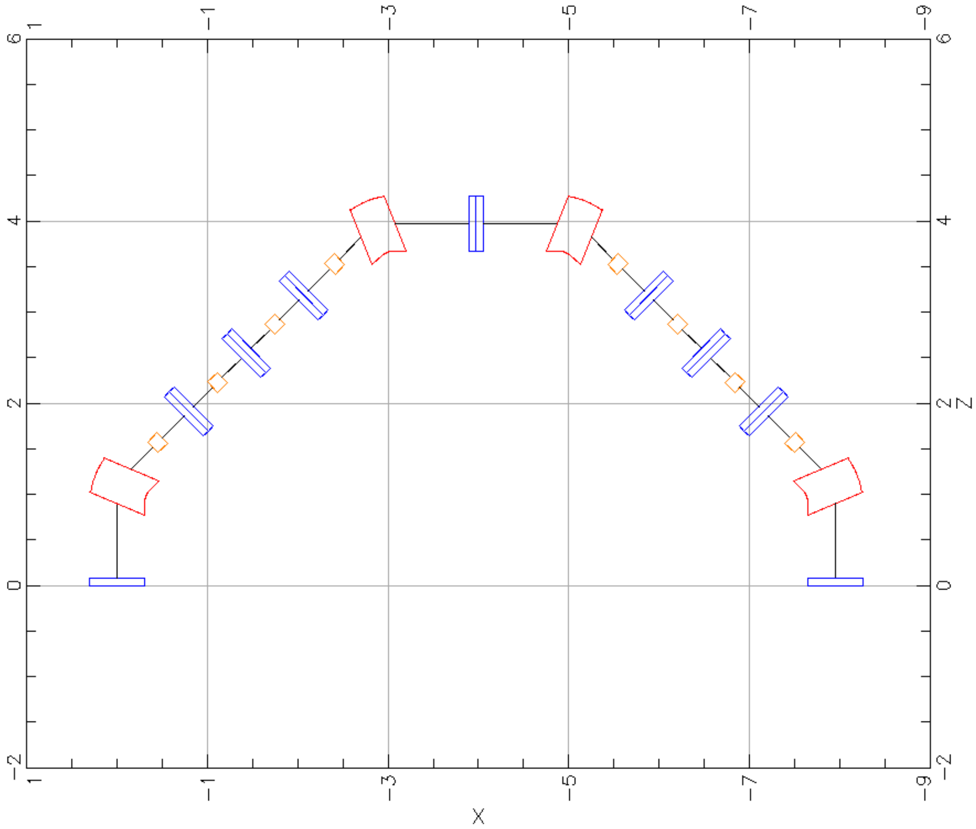
Simple Arc Layout

- design by D. Douglas

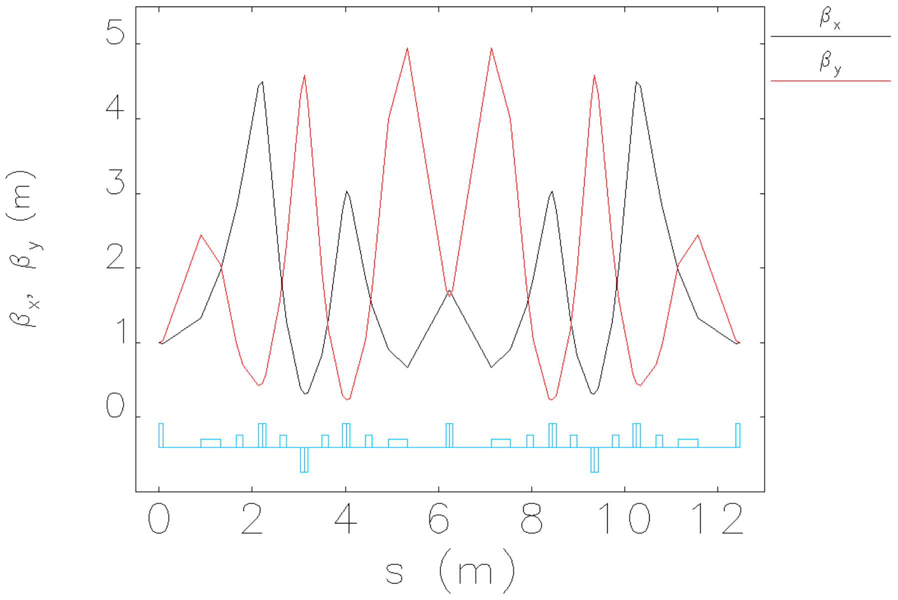
dipole

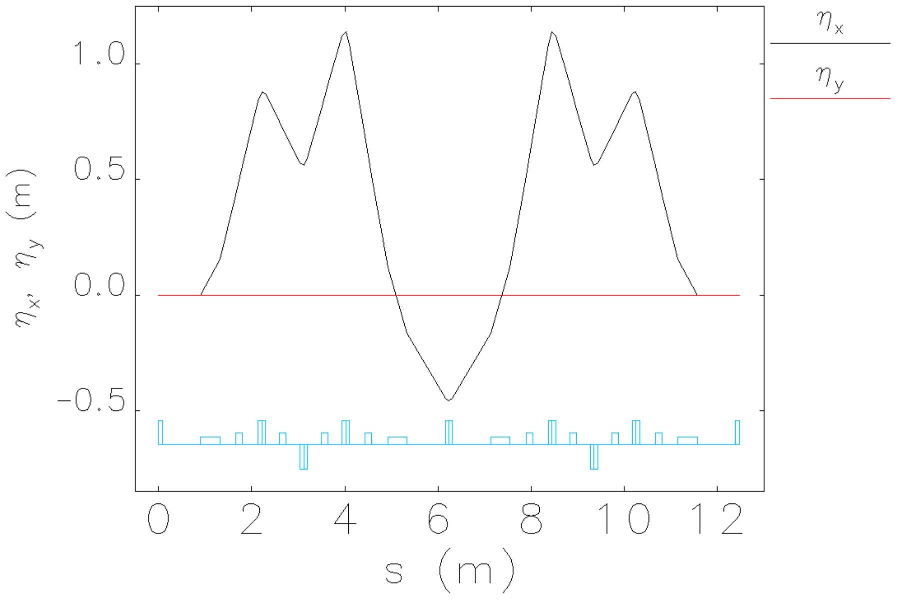
quadrupole

sextupole



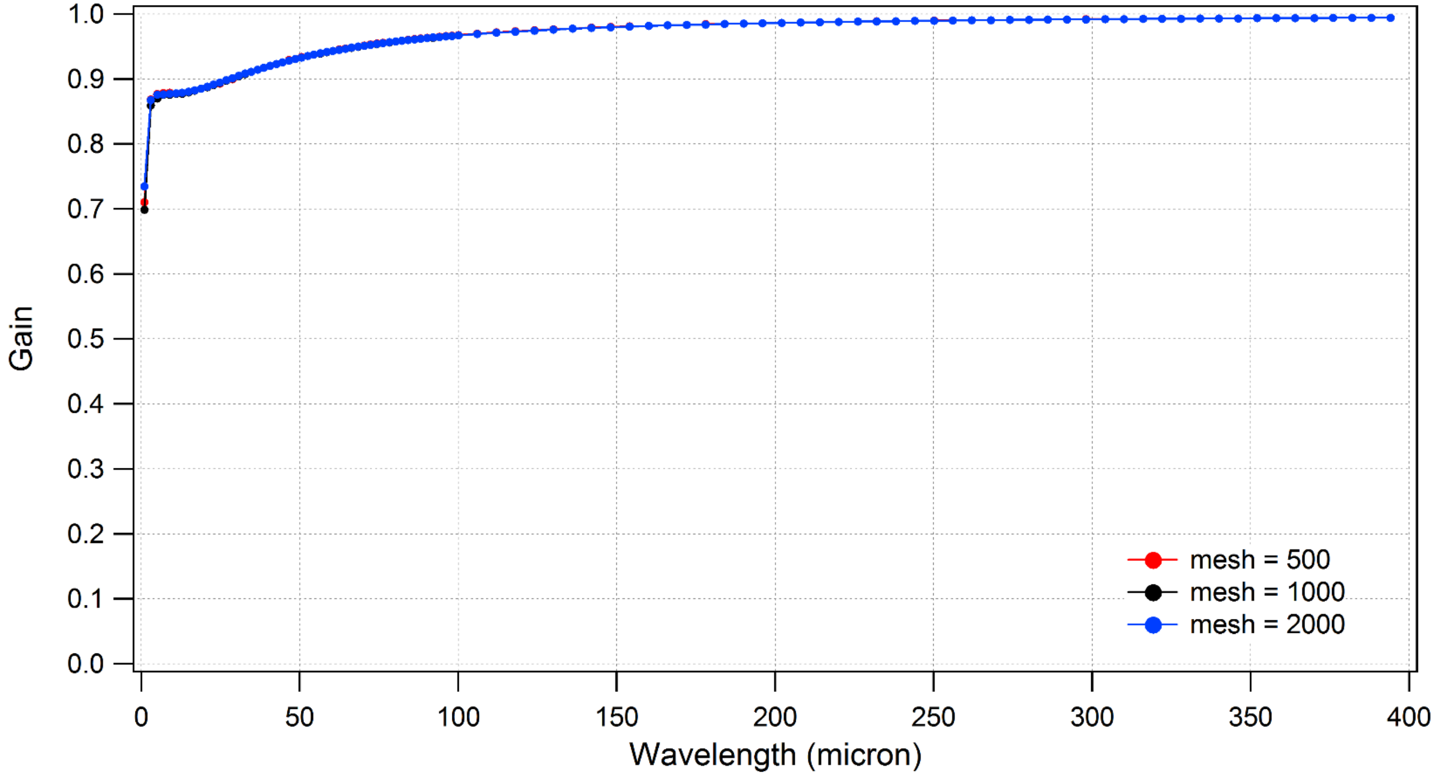
Lattice Functions





Microbunching Gain for Simple Bend

- μBI gain is ≤ unity
- <u>needs</u> to be less than unity for multiple passes (gain grows exponentially)

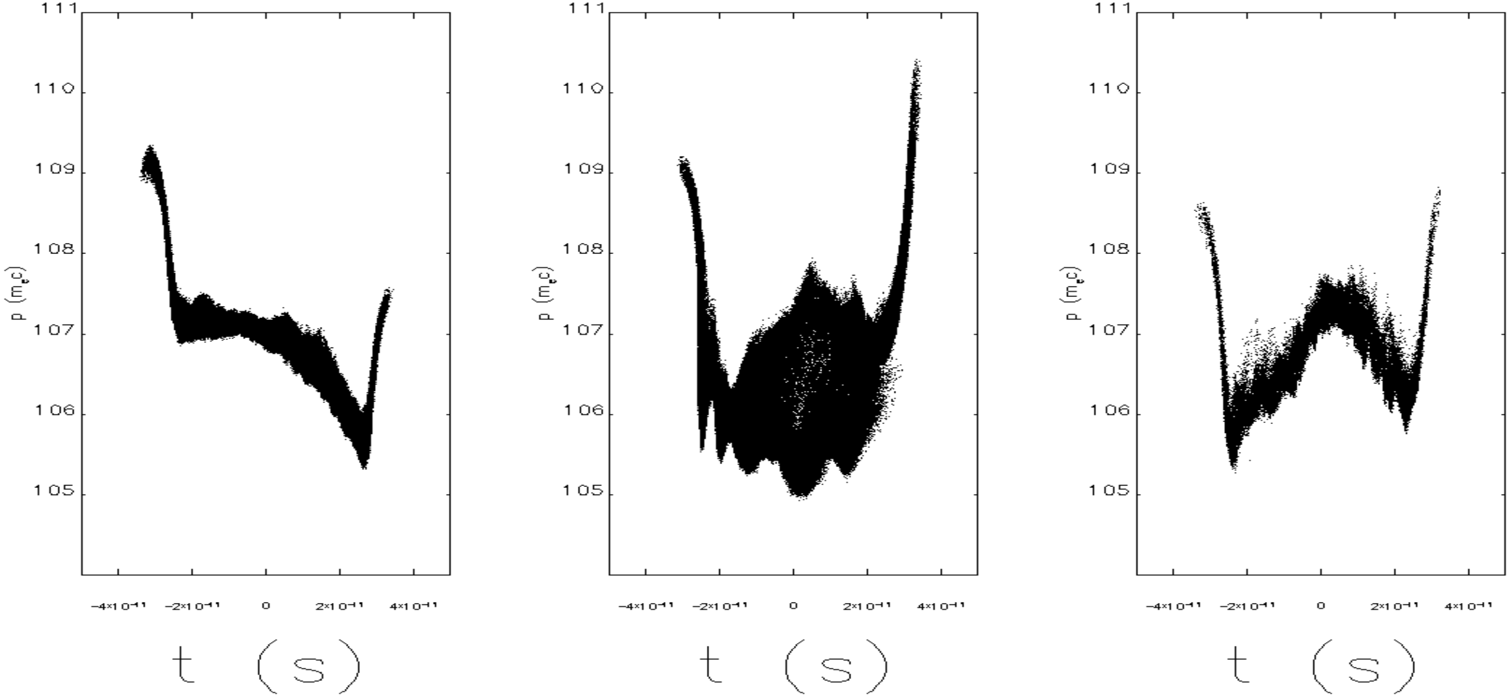


Longitudinal Phase Space Comparison: After 10-Turns

elegant – Stupakov + RF correction

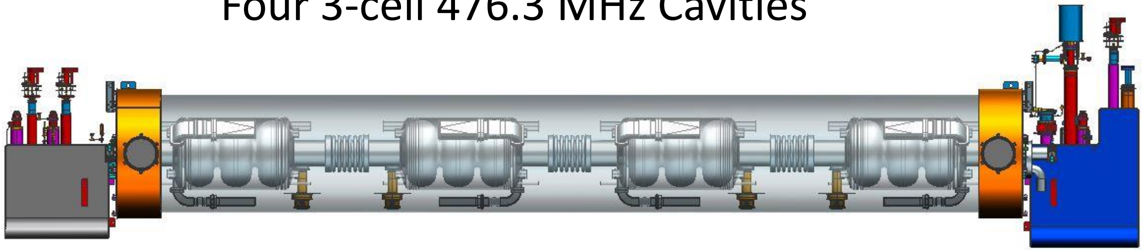
elegant – without csrdrifts

Bmad – with shielding

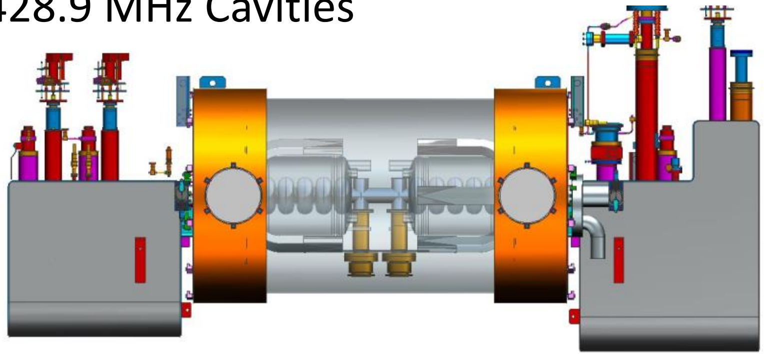


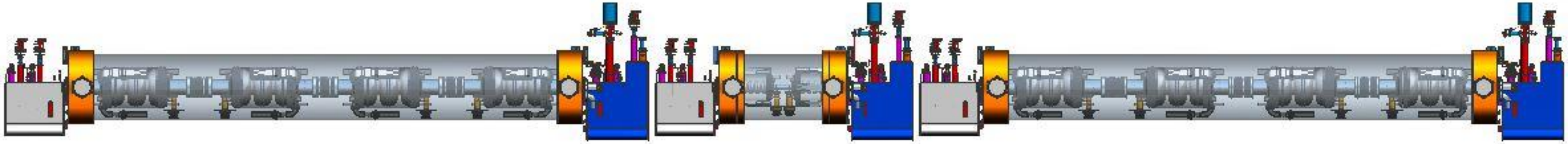
ERL Linac

Four 3-cell 476.3 MHz Cavities



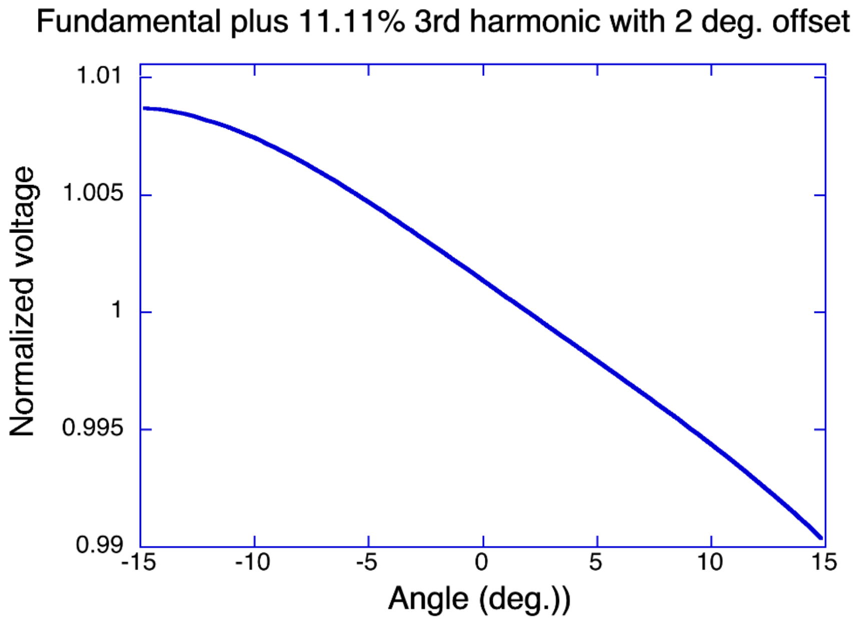
Two 5-cell 1428.9 MHz Cavities

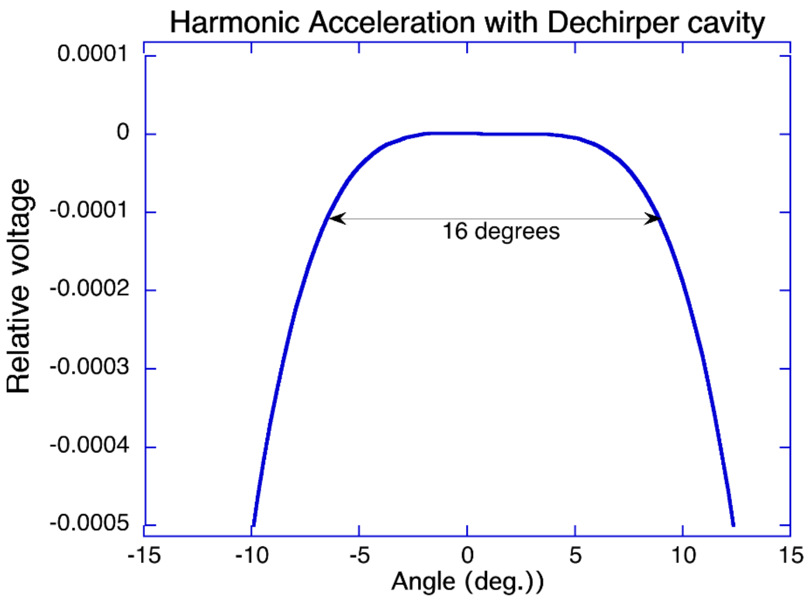




Voltage with 3rd Harmonic and Phase Offsets

If we want to accelerate a very long bunch and then stretch it out even more we can use 3rd harmonic cavities in the linac.





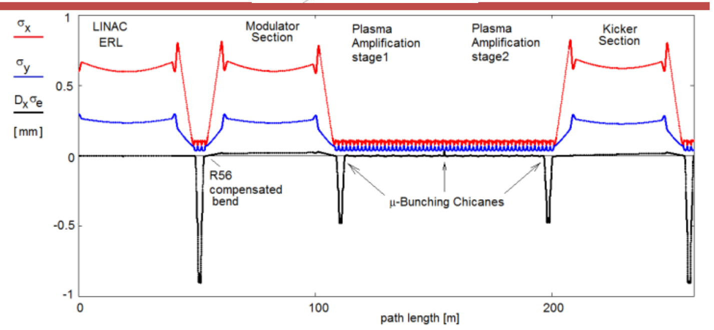
Before going into the CCR, take out the slope using a 952.6 MHz de-chirper.
We can also put in a quartic correction if necessary by changing the amplitude

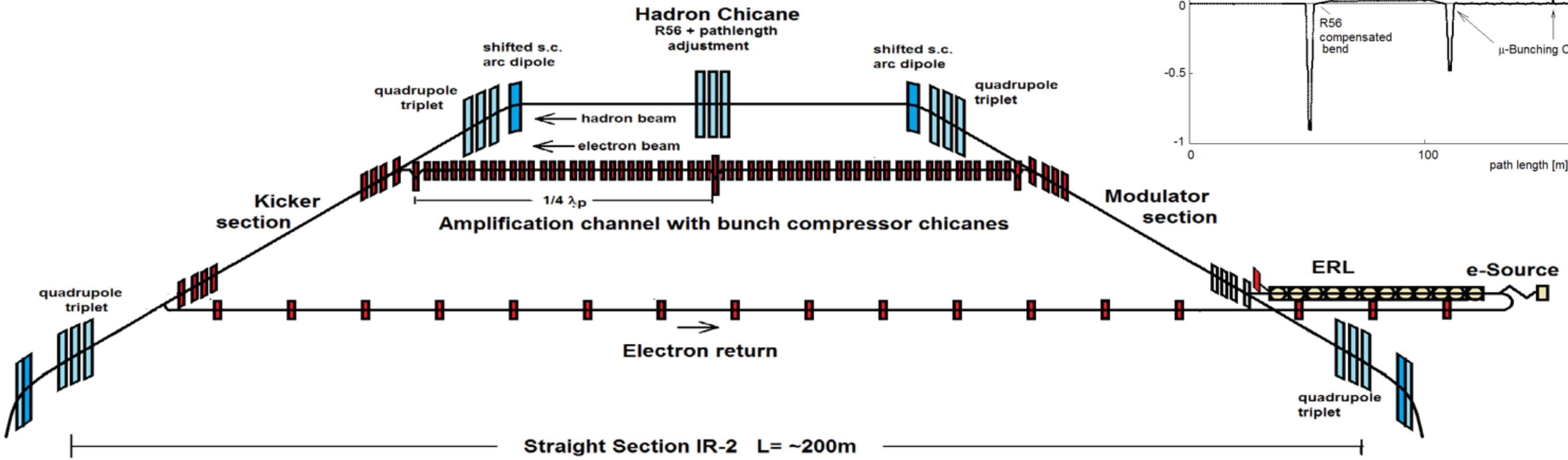
eRHIC BBU Cooler Specifications

Energy	40–150 MeV
Accelerator frequency	591 MHz
Charge	1.0 nC
Pulse frequency	118 MHz
Gun current	118 mA
rms Energy spread (uncorr.)	1×10^{-4}
Energy spread (p-p corr.)	4×10^{-4}
Bunch length (tophat)	1 cm (7°)
Transverse emittance	1 mm-mrad
Electron beta in cooler	37.6 cm
Cooling Insertion length	200 m

Strong Coherent Hadron Cooling for eRHIC

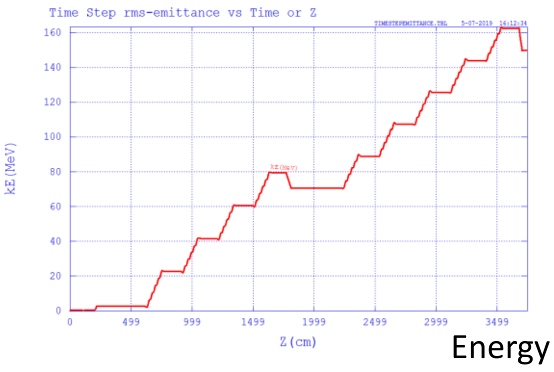
Coherent Electron Cooling with micro-bunching amplification

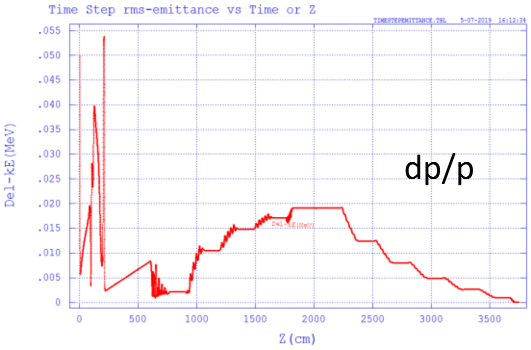


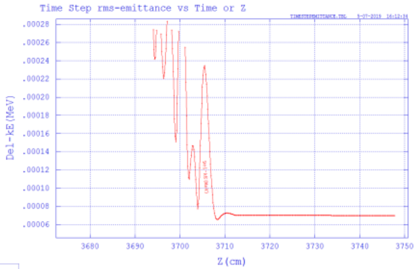


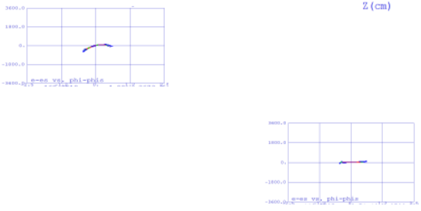
- Micro-bunched cooling is a novel scheme based on available technology
- Similarly as for the JLEIC scheme, this option requires electron cooling at low energy
- Also similar to JLEIC, harmonic RF used to reduce the correlated energy spread.
- Almost no transport between ERL and modulator to reduce microbunching gain
- Strong cooling is not absolutely necessary since the hadron beam could be replaced frequently on-energy using the existing second ring of present RHIC.

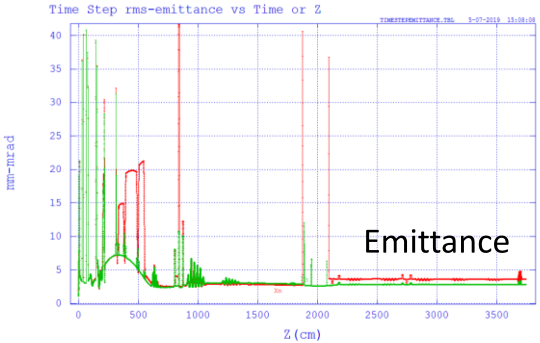
CeC ERL Design

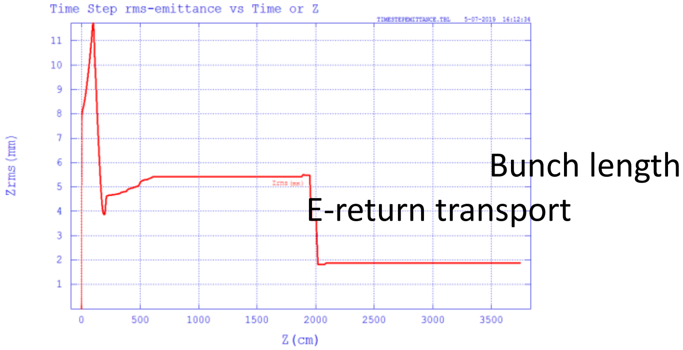


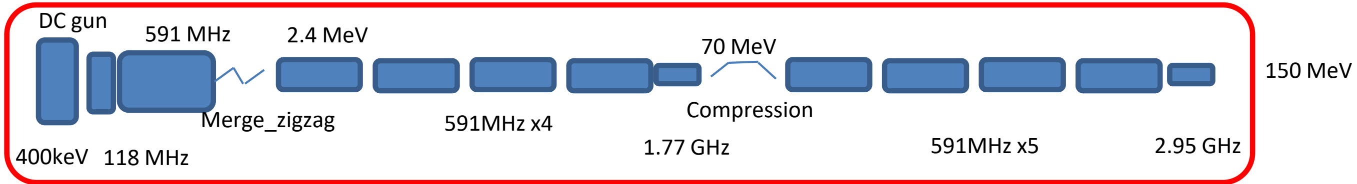












Conclusions

- Electron Ion Colliders are the highest construction priority in U.S. Nuclear Physics today.
- The high luminosity demanded in the EIC design can be reached using strong hadron cooling.
- The conventional cooling solution is incoherent cooling.
  - At the lowest energies DC incoherent cooling is a good choice
  - But medium energies need very high current so CCR is required.
  - Requires high charge so CSR is a challenge.
- A new approach at higher energies is coherent cooling.
  - Essentially stochastic cooling at very high frequencies
  - Lower current and charge due to higher gain.
  - Very stringent requirements for the electron beam.
- Good progress has been made in the designs but further optimization is still necessary.