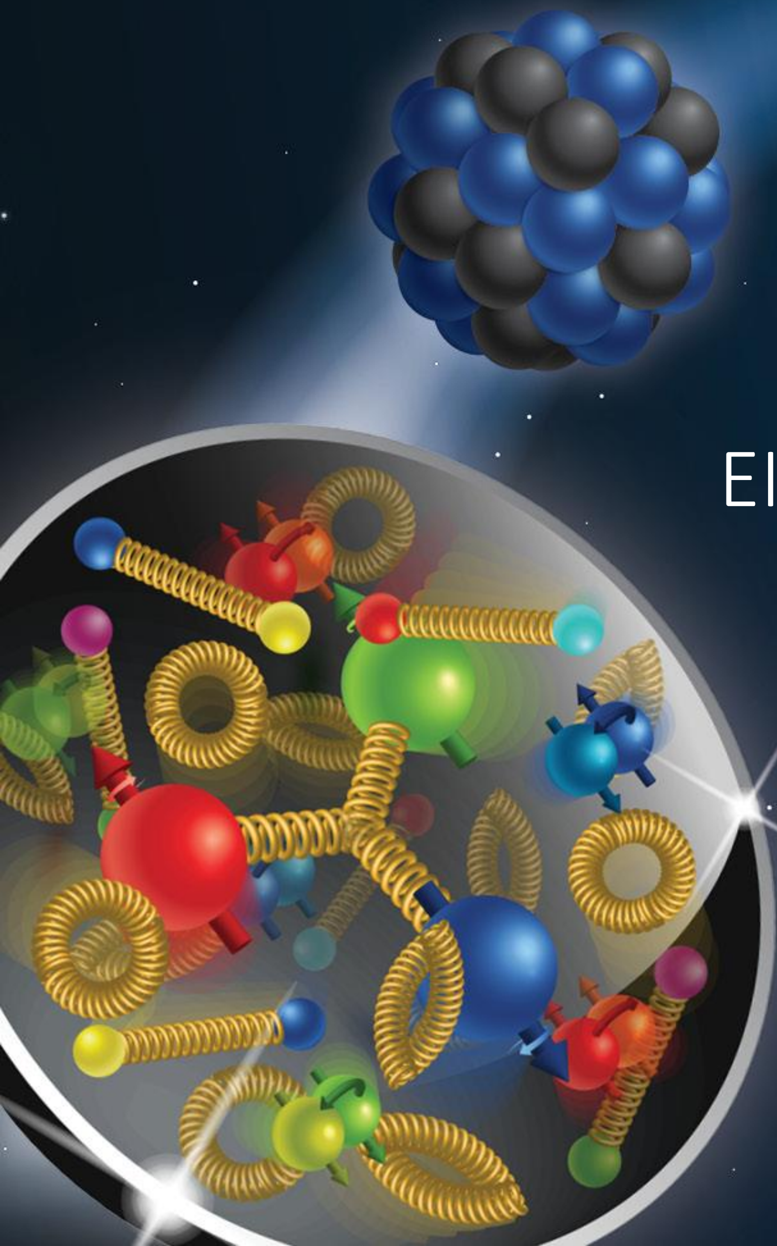

EIC cooling design and R&D status

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Brookhaven National laboratory

EIC Accelerator Collaboration Workshop

October 7-9, 2020

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Motivation
- Cooling Scheme description
- Accelerator design
- Challenges and opportunities
- R&D activities

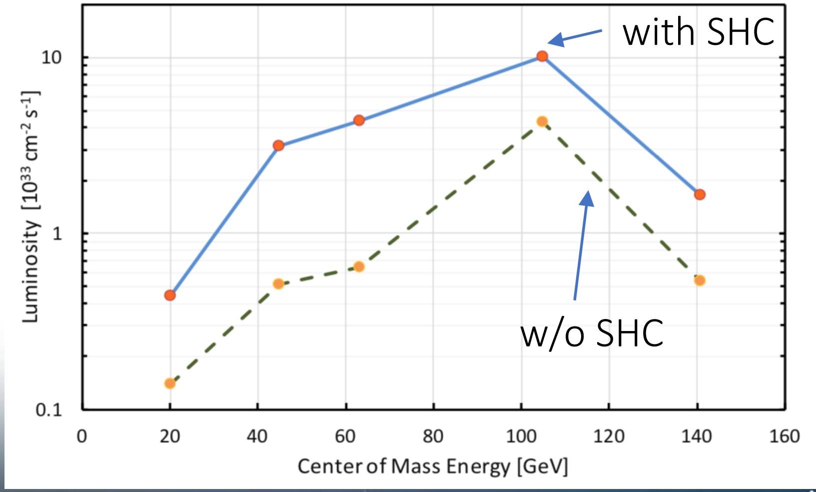
High Luminosity and Strong Hadron Cooling

- Luminosity of lepton-hadron colliders in the energy range of the EIC benefits strongly (factor ≈ 3-10) from cooling the hadron's transverse and longitudinal beam emittance
- Reducing hadron beam emittance with strong hadron cooling enables reaching maximum strength of the beam-beam interaction and therefore achieving a maximum luminosity
- Intra-beam scattering (IBS), a fundamental process prevents small emittance & causes emittance growth.

Strong hadron cooling with modest cooling rate of **$1h^{-1}$**, counteracts IBS

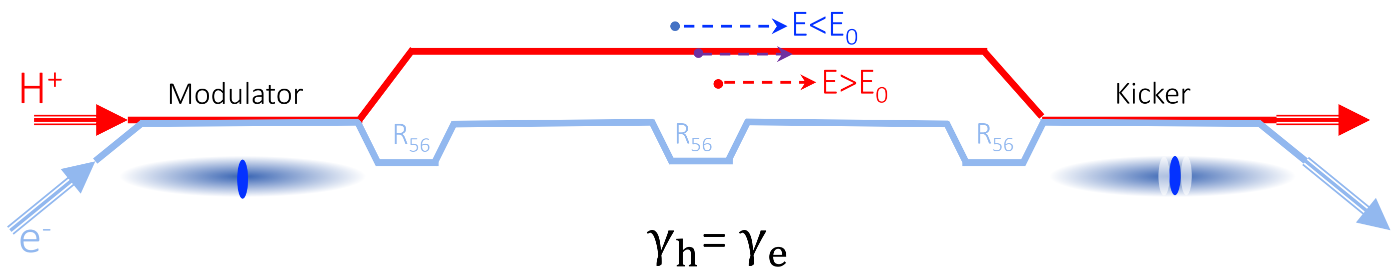
➔EIC design luminosity **$L = 1 \cdot 10^{34} cm^{-2} s^{-1}$ at Ecm=105 GeV** is achieved & full range of EIC physics can be exploited.

➔ EIC design includes strong hadron cooling



Coherent Electron Cooling scheme

Strong Hadron Cooling is based of the principle of well-established stochastic cooling



$$\gamma_h = \gamma_e$$

(Electrons and hadrons have exactly the same speed)

Imprinting: density fluctuation in hadron beam causes **energy modulation** of e-beam
Amplification: e-beam energy modulations are converted **to density fluctuation** by chicane
Hadron chicane: **Controls hadron travel time** with respect to electron path. Transfer to **correlated energy modulation**.
Kicker: longitudinal electric field of electrons **reduces the hadron beam correlated energy spread.**

The baseline design chooses Plasma enhanced micro-bunching
- Very broadband (~THz, slice size ~0.1 mm) amplifier
- Micro-bunching instability was well studied.
- Significant gain without saturation

Various topics were studied in last few years

SLAC/BNL/ANL

- There is a well-developed theory of CeC (published in peer reviewed journals)
  1. The cooling rate is derived in **1D model** for the longitudinal degree of freedom and is optimized with respect to the chicane strength.
  2. One and two **amplification sections** are studied and the cooling rate is obtained as a function of their parameters.
  3. Control of the dispersion in the modulator and kicker re-distributes the cooling rates between **the longitudinal and transverse** degrees of freedom.
  4. **3D effects** in cooling are analyzed. This analysis indicates that 1D model is a good approximation to a more realistic 3D one.
  5. Effects of **energy deviations** in electron and hadron beams is studied and **tolerances** established for various energy profiles.
  6. **Noise effects and the associated heating process** is taken into account. The cooling rate is maximized with account to the noise.
- CeC-Pop experiment has been built and optimized at RHIC 29 GeV aiming to demonstrate strong hadron cooling in FY21-22
- Conceptual design of strong hadron cooler for EIC worked out and published in pCDR and CDR

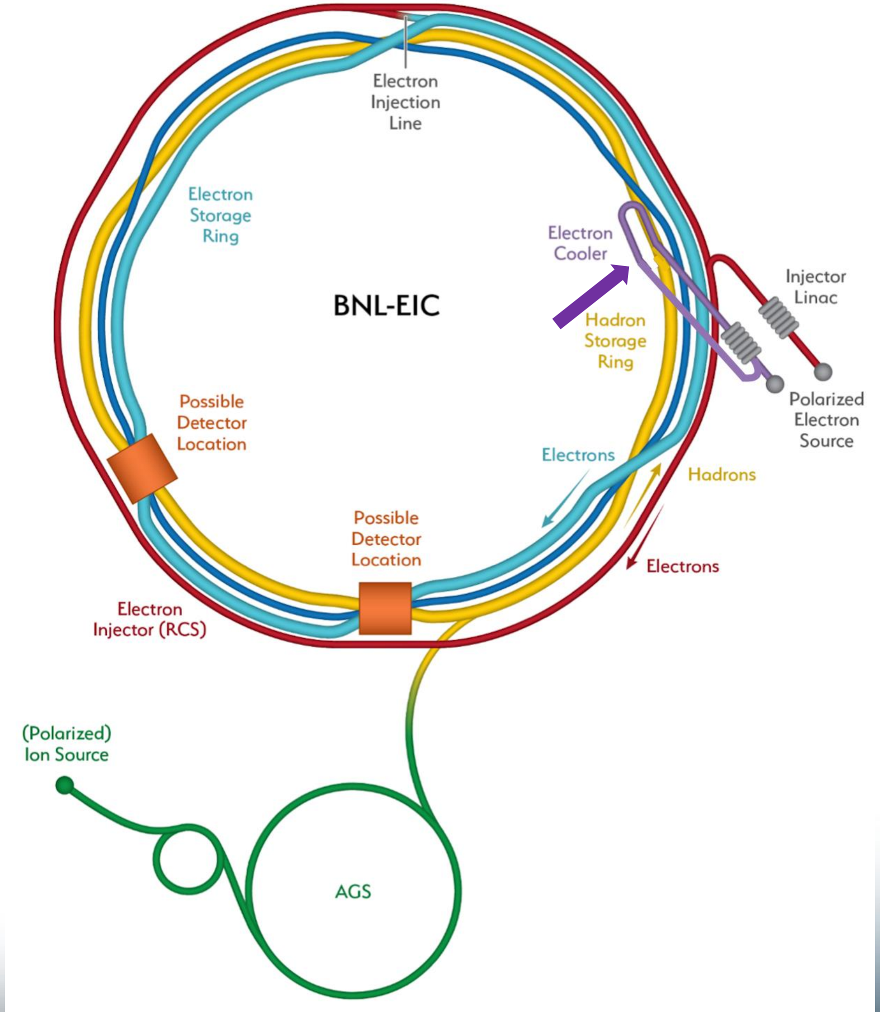
EIC Coherent Electron Cooling parameters

	Value
e-beam energy [MeV]	150
e-beam normalized emittance [mm-mrad]	2.8
e-beam energy spread	10^{-4}
RMS beam size[mm]	0.7
Average electron beam current [mA]	120
e-beam bunch charge [nC]	1
Cooling time [min]	50

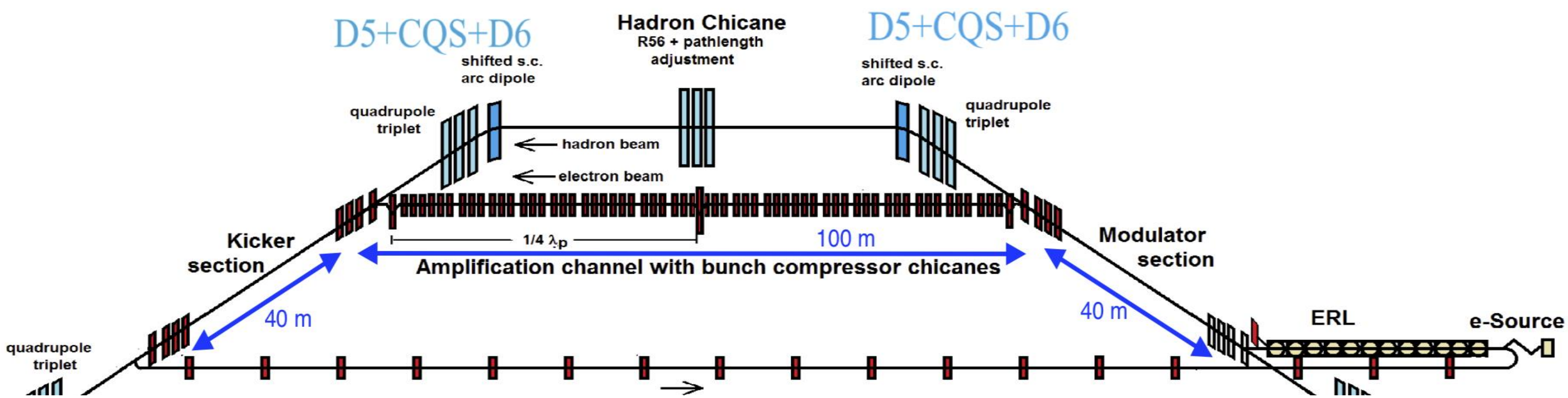
Two amplification sections.

e-cooler facility layout

- Share the same Linac tunnel and electron source building of EIC pre-injector
- Hadron chicane for pathlength and R56 adjustment using displaced s.c. dipole magnets at IR2 straight section.

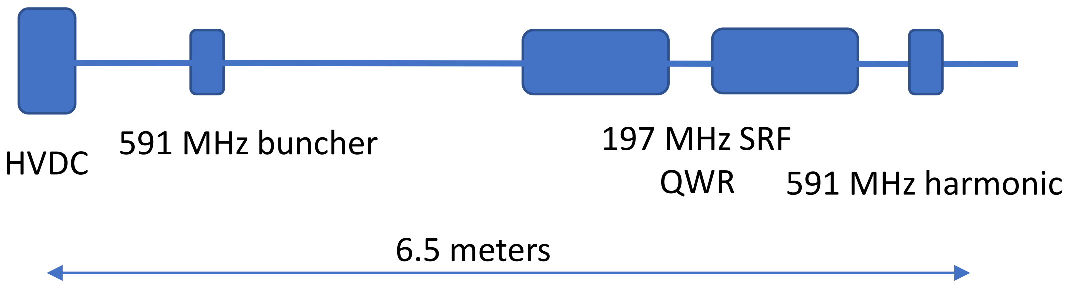


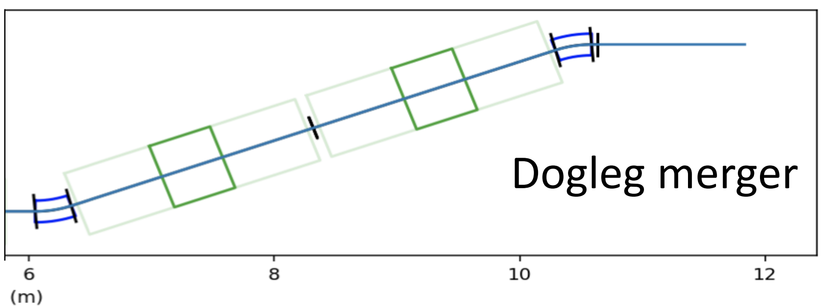
EIC Strong Hadron Cooling Facility

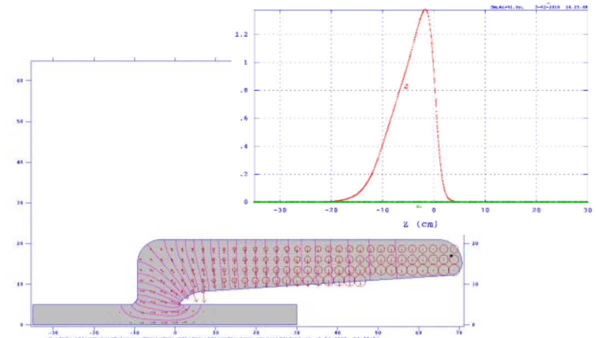


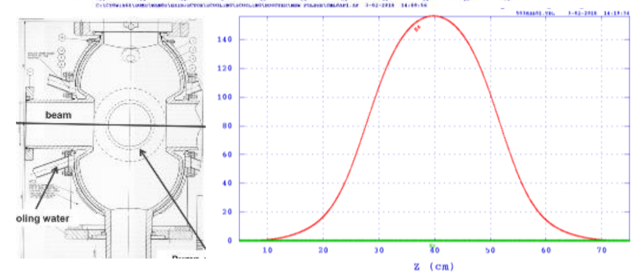
- 400kV DC gun for 100 mA of beam and 4 MeV SRF injector
- Dogleg ERL merger
- 149 MeV Super conducting Energy Recovery LINAC (in existing tunnel)
- e Beam transport to merge hadron beam
- Amplification section with chicanes for electrons
- Hadron chicane (existing magnets) path length matching & R_{56} adjust
- Return transport of electron beam to ERL
- 2 K He sub cooler station, RF and power infrastructure
- Electron beam instrumentation and diagnostics

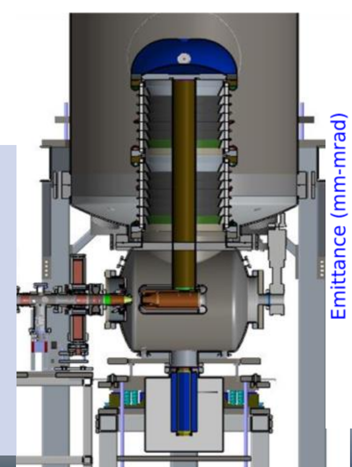
6.5.8.2 Electron source_injector

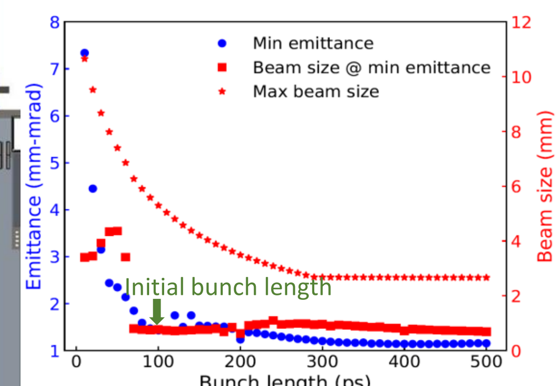






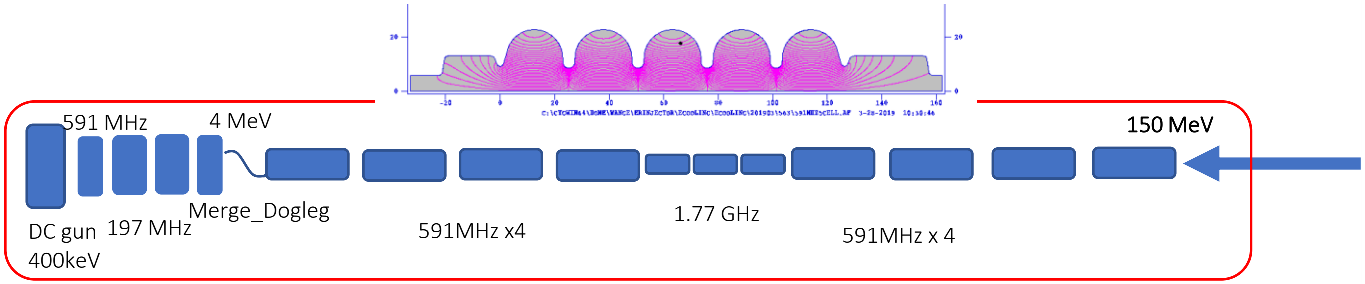




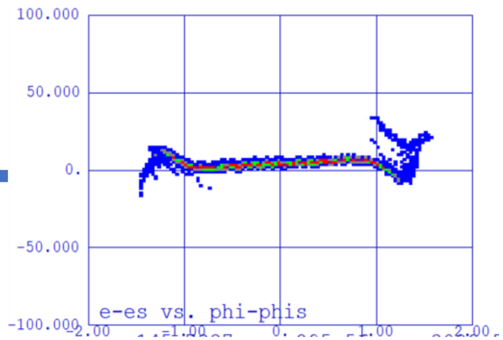


- The ERL injector includes 400 kV HVDC gun and SRF boosters.
- The goal is 100 mA average beam with 1 nC bunch charge.
- Normalized Emittance ~2mm-mrad

ERL_injector and Linac



Longitudinal phase space

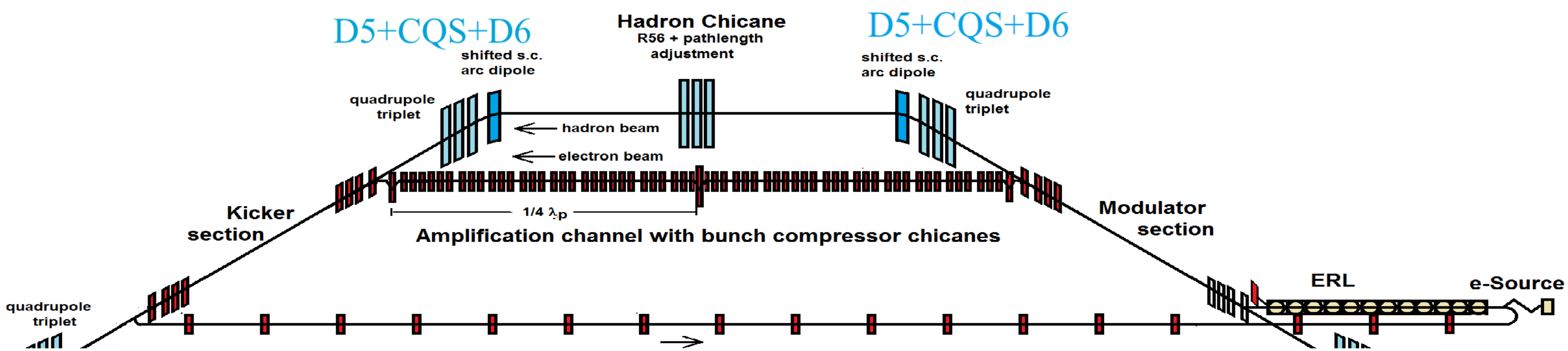


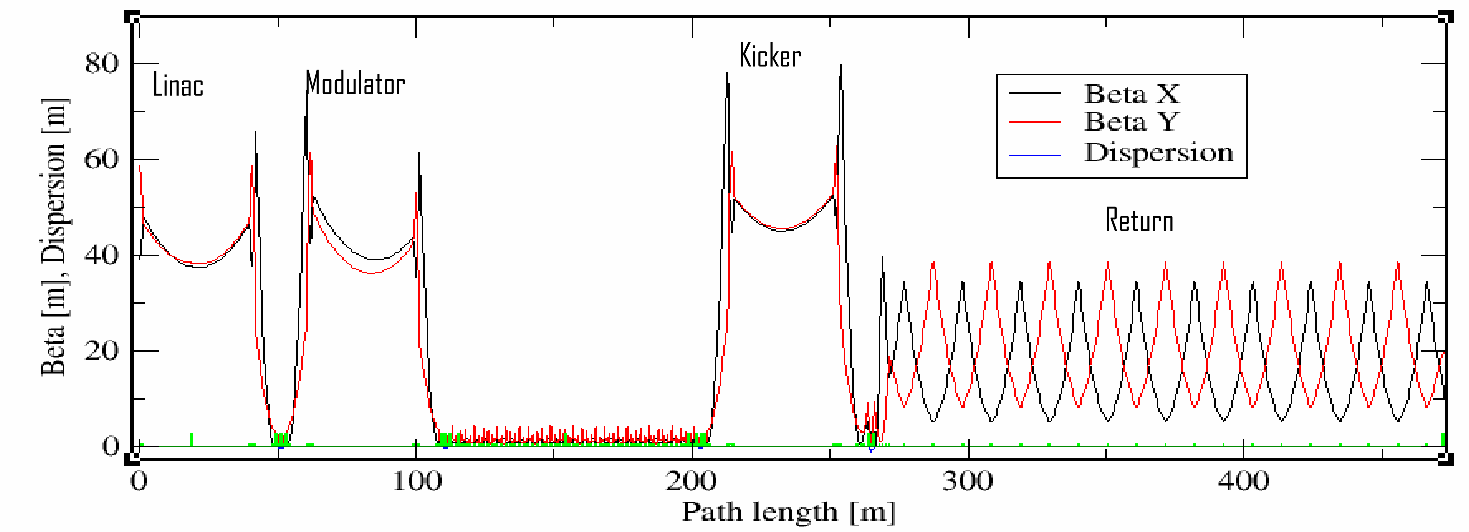
Injector and Linac are simulated by Parmela with space charge effect. Verified with advanced 3D space charge code (CSR and wakefield yet to be included).

	parameter
Bunch charge	1 nC ✓
Peak current	30 A ✓
RMS Bunch length	5.1 mm ✓
RMS Normalized emittance	2.8 mm-mrad ✓
Energy	150 MeV ✓
RMS dp/p	5.5 e-5 ✓

- High brightness injector for 120 mA CW
- Dogleg merger scheme
- 150 MeV 591 MHz superconducting Energy Recovery LINAC

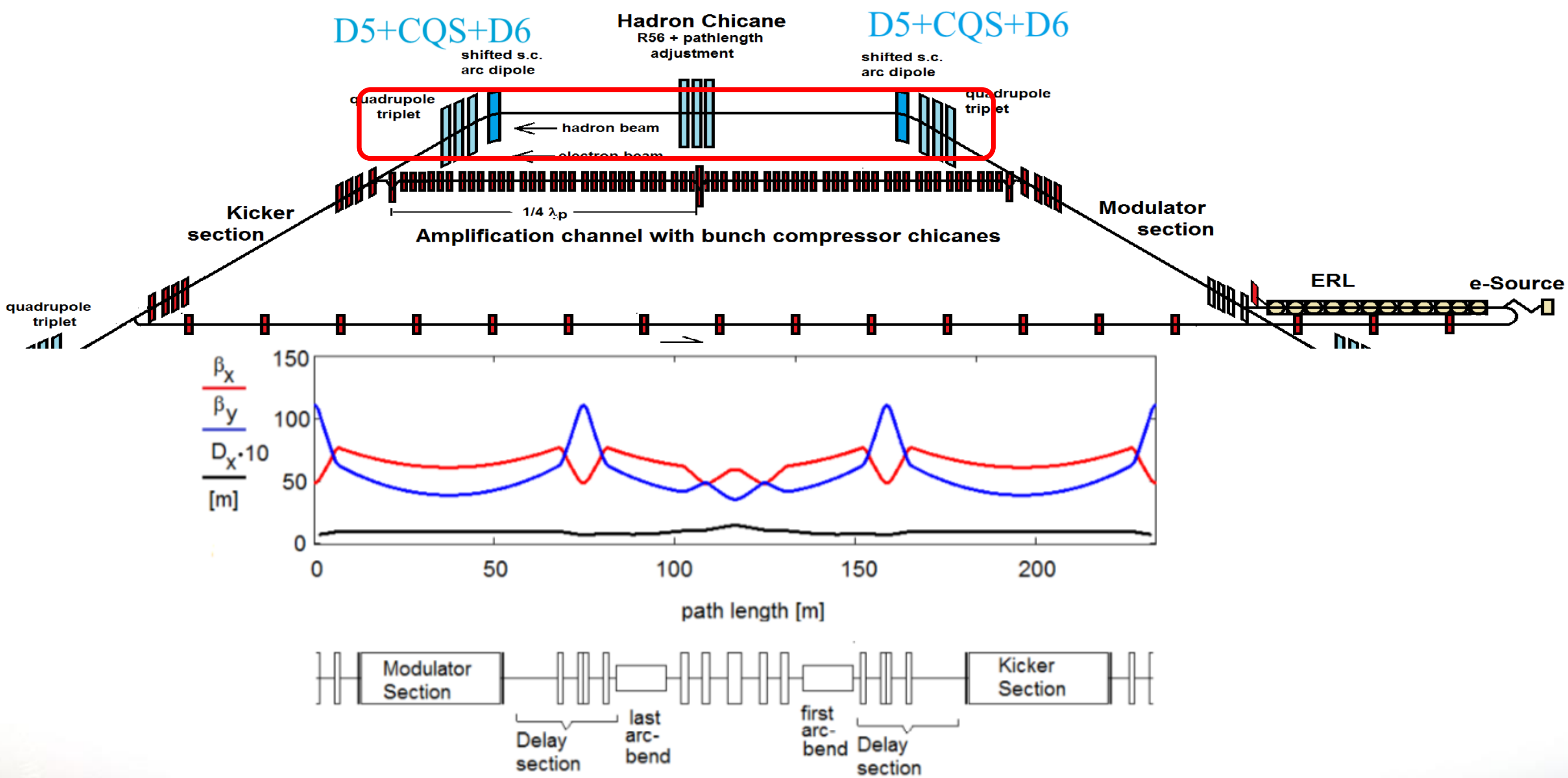
Electron lattice





Total 20 quads triplets and 3 chicane (R_{56}=23mm)
Chicanes lengthen the pathlength by 45 mm

Hadron lattice



Proton R_{56}=4 mm

Transfer to correlated energy modulation

Lengthens the path by 45 mm matching to electrons chicanes length

In detailing the hadron lattice design now.

EIC strong hadron cooling activities

High current ERL
- 4 MeV injector
- 150 MeV Linac
- CSR
- Wake field
- Shot noise
- Lattice in tight tunnel
- Beam dump

Hadron modifications
- Hadron Chicane

Diagnostics/Controls
- Beam noise
- Phase
- Energy spread
- e-h alignment

Theory and simulation
- Develop a cooling tracking code
- 3D PIC tracking

Components R&D

Electron source
- Active cooling
- Enlarge cathode/anode size
- Better vacuum
- High power , stable laser

SRF accelerator
- High gradient and voltage
- HOM absorber
- Fundamental power coupler

Challenges and opportunities

- CeC has not been experimentally demonstrated ← RHIC CeC experiment
- Very low energy spread is required ← GPT/Bmad simulation

Require: $<10^{-4}$

- 2e-4 at LEReC; 1e-4 PAL XFEL

- Very low shot noise from electron beam ← IMPACT-T simulation

- Laser heater LCLS; by optimizing optics at BNL

- High current ERL

Require: 120 mA and 150MeV

- Jlab FEL 8 mA; Novo FEL 30 mA (normal conducting)

- High current high charge electron source ← EIC components R&D

Require: 120 mA @1nC

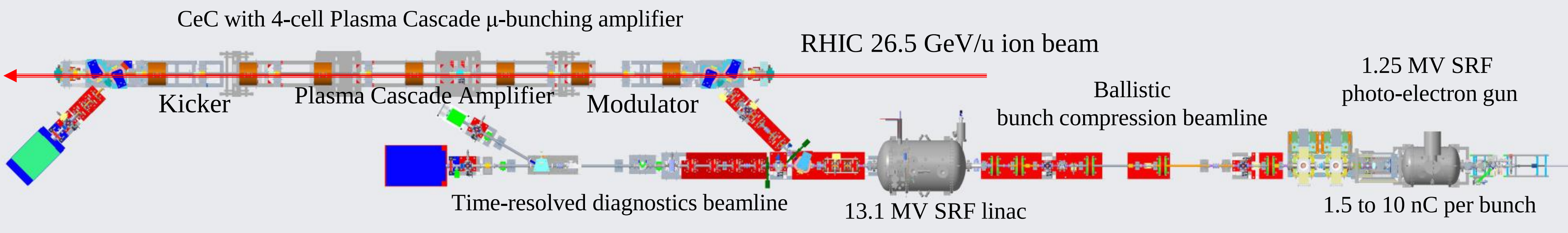
- Cornell 65 mA@ 60 pC; BNL 30 mA@100 pC

- Beam diagnostics: beam noise, e-h alignment, energy spread measurement.

SHC R&D will push the frontier of accelerator science

Coherent electron Cooling experiment at RHIC

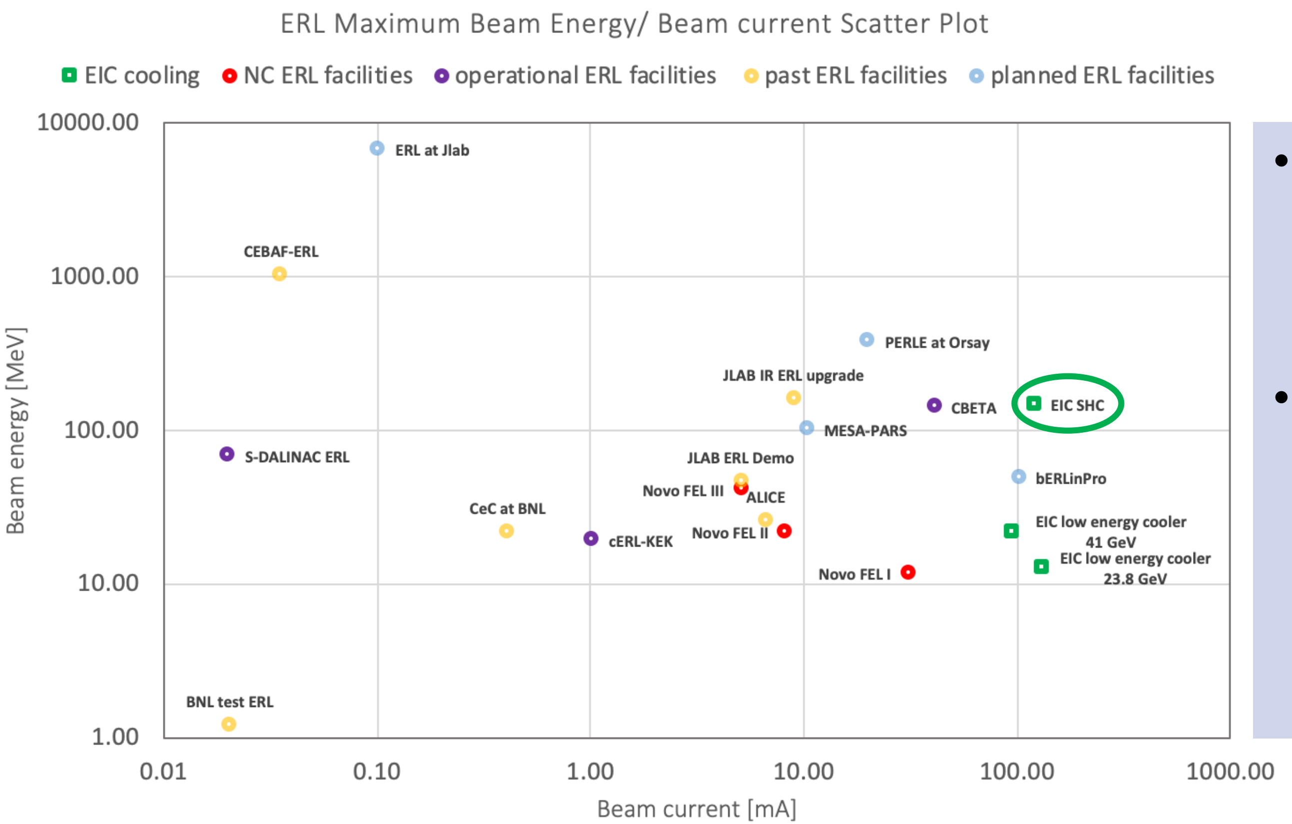
Courtesy V.N. Litvinenko



- The 14.5 MeV CW SRF accelerator has unique SRF electron gun generating record-low emittance with beam quality sufficient for current experiment and for future IEC cooler.
- Electron bunches are compressed to peak current of 50-100 , the e-beam is accelerated to energy of 14.5 MeV and merged with RHIC 26.5 GeV/u ion beam in the CeC system
- Current CeC system has seven high field solenoids, five of which serve as a 4-cell Plasma-Cascade µ-bunching amplifier with 15 THz bandwidth and amplitude gain exceeding 100.
- All necessary electron beam parameters – the beam energy, peak current, the beam emittances, energy spread, the low noise in the beam - had been demonstrated. The full CW beam was propagated with low losses through the newly built PCA CeC
- The CeC run was completed in mid-September and preliminary analysis is that all goals for this run have been achieved.
- The project plans are to demonstrate longitudinal CeC in 2021 and 3D (both longitudinal and transverse) CeC in 2022.
- The CeC group invites all interested parties to collaborate on this incredibly challenging project in any of relevant areas: CeC theory, CeC and beam dynamics simulations, CeC experiment and diagnostics….

Details will be presented in the "Coherent Electron Cooling: talk by V.N. Litvinenko this Friday, October 9, 2020, in Europe/Africa Focus: Session 6.1, 13:10 London time/ 8:10 am New York time

High current ERL



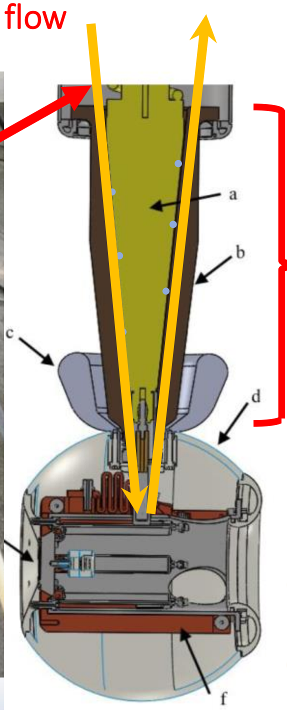
- Many success facilities: Jlab- FEL, CBETA, cERL-KEK, ALICE, Novo-FEL et,al
- Remain researches for high current ERL:
  - Halo
  - CSR
  - Beam loading
  - BBU

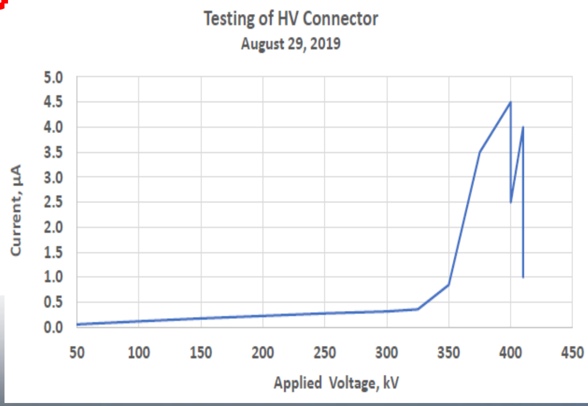
- High current tests of cERL in KEK and potential research for EIC (Tsukasa Miyajima Thursday 22:25 GMT-4)
- Cornell University contribution for EIC (G. Hoffstaetter Thursday 22:50 GMT-4)

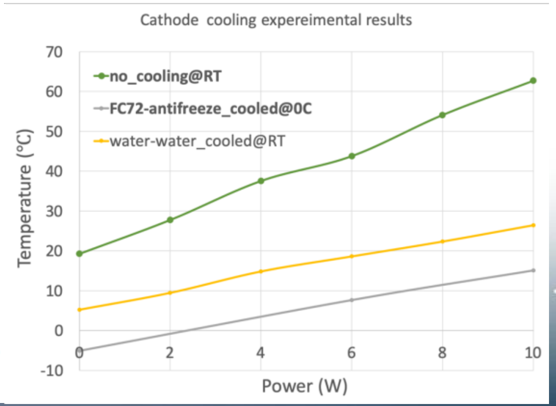
HVDC gun R&D_ active cooling

Cool the cathode:
Aiming to absorb the laser power up to 10 W. We are collaborating with Dielectric Sci. developed the active cooling HV feedthrough.

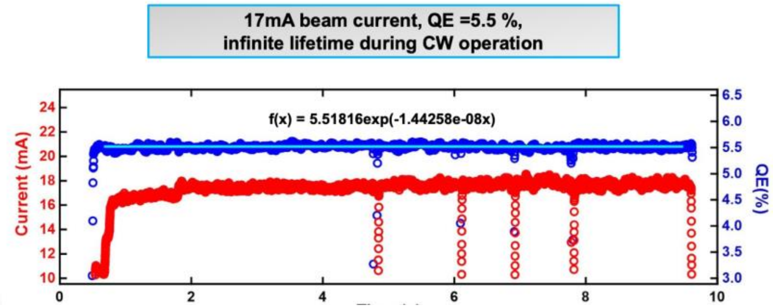
Tested up to 410 kV with flow







Electron source R&D_ Photocathode

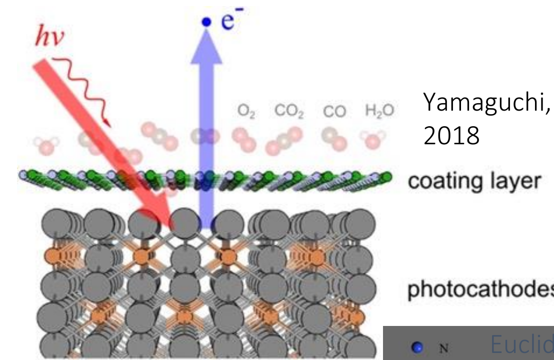


	parameters
Cathode QE(%)	1%-8%
Average current [mA]	120
Average laser power [W]	23-3
Pulse energy [nJ]	230-30
Charge lifetime [C/mm]	20000/2.5
Extrapolated Cl [C/mm]	80000/5~ 9 days

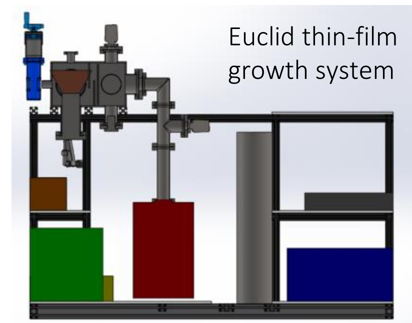
- By increasing the multilakali cathode area, it looks promising to get reasonable charge lifetime with good vacuum
- R&D focus on demonstration of high charge/ high current e-beam

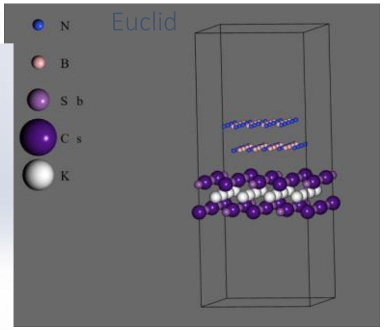
Multialkali photocathode R&D

- BNL is working with Euclid Techlabs, LLC on investigating thin-film protection schemes for bi-alkali antimonide photocathodes
  - Hexagonal boron nitride (hBN) are top candidates of materials
  - Reject detrimental molecules such as H_2O, O_2, etc.
  - Transparent to photoelectrons
  - Investigating novel laser oscillator deposition enhancement system (LODES) based on existing sputtering chamber



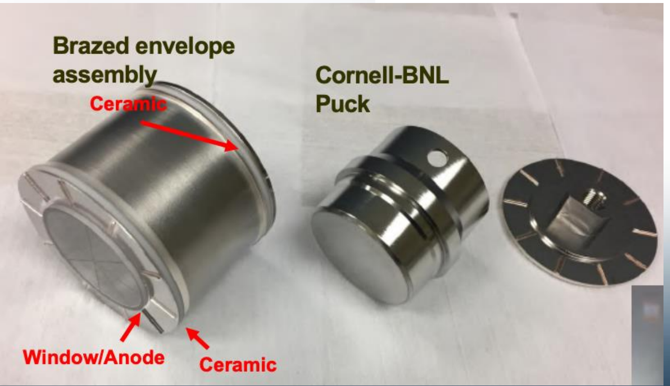
Yamaguchi, et al, NPJ, 2018





- BNL is working with Photonics and RMD on developing capsule sealed multialkali photocathode
  - Outsourcing cathode production for alkali antimonides
  - Overnight shipping /longterm storage;

Both cathode R&Ds benefit to EIC cooler



SRF cavities R&D

	Buncher	Booster	3^{rd} Harmonic Injector	5 cell main Linac	3^{rd} Harmonic
Freq. (MHz)	591	197	591	591	1773
Gap voltage (MV)	0.2	2	0.5	18.78	6.3

- High accelerator voltage
- 200 kW Fundamental power coupler
- HOM absorber

Summary

- We have developed a cooler conceptual design for EIC.
- The Strong hadron cooler would establish a major advance in accelerator science and technology.
- The challenges have been identified and components R&D are planned.
- The potential broad collaboration topics are discussed. Welcome to collaborate on EIC cooling R&D.

Thanks for your attention!

Welcome to have collaborations!

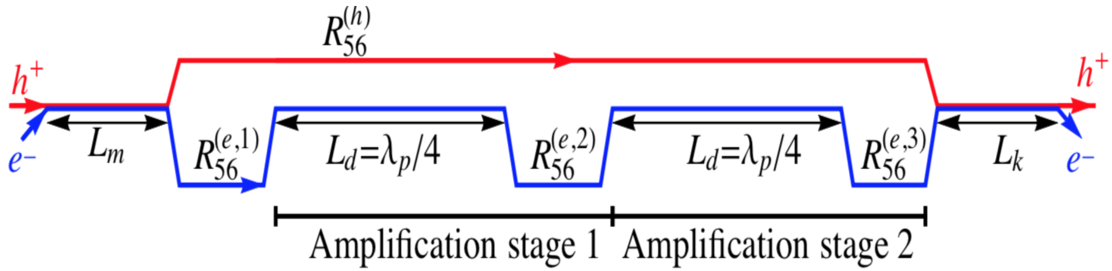
Backup

Strong Hadron Cooling for EIC

Requirements: eRHIC Peak Luminosity of $10^{34} cm^{-2} s^{-1}$ requires $6 \cdot 10^{10}$ protons per bunch, 6 cm bunch length and small emittances of e_x= 9.2 nm, e_y = 1.3 nm ➔ beam subject to IBS, initial growth time of >2h in the hor. and long. direction

Method: Strong Hadron Cooling using coherent electron cooling with micro-bunched beams, bunching enhancement with 2 plasma amplification sections with a total of 3 bunching chicanes. Quarter of plasma wavelength as low as l_p =40 m

- Cooling rate for short flat bunches ~1 h for longitudinal and transverse oscillations (theory & simulations)
- Need an electron beam with 1nC bunches (100 mA CW) , dp/p~10^{-4} , normalized horizontal emittance ~2.5 mm-mrad

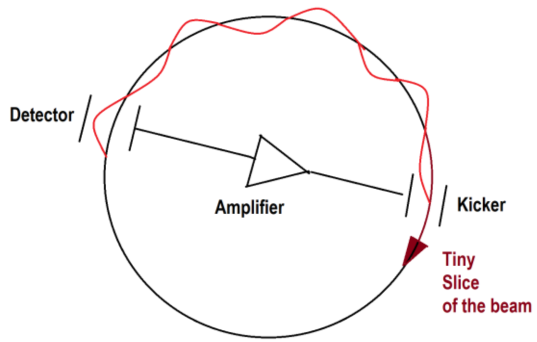


Electron-Ion Collider

Coherent Electron Cooling

Like stochastic cooling, tiny fluctuations in the hadron beam distribution (which are associated with larger emittance) are detected, amplified and fed back to the hadrons thereby reducing the emittance in tiny steps on each turn of the hadron beam

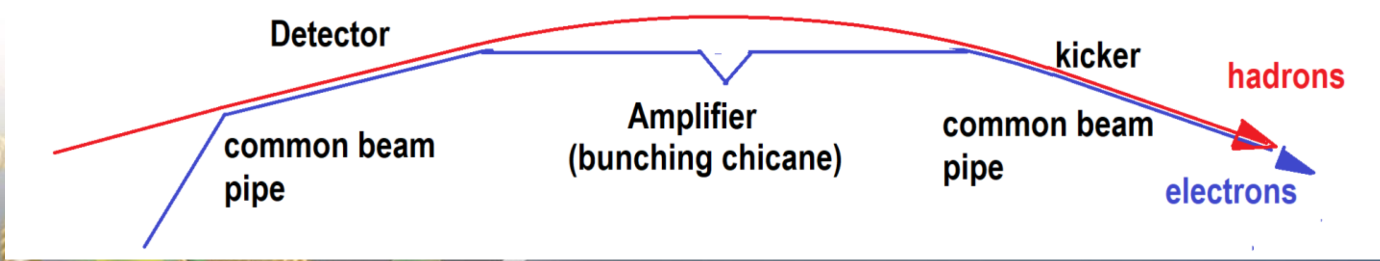
- High bandwidth (small slice size)
- Detector, amplifiers and kickers



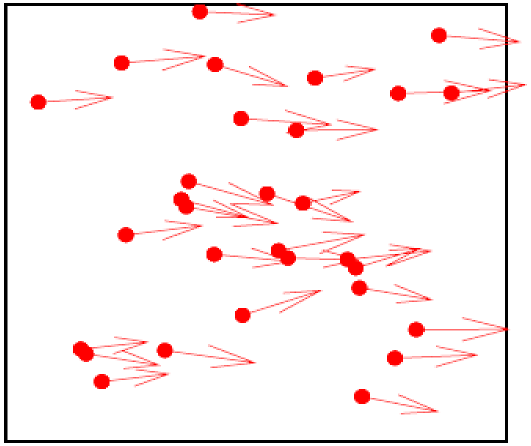
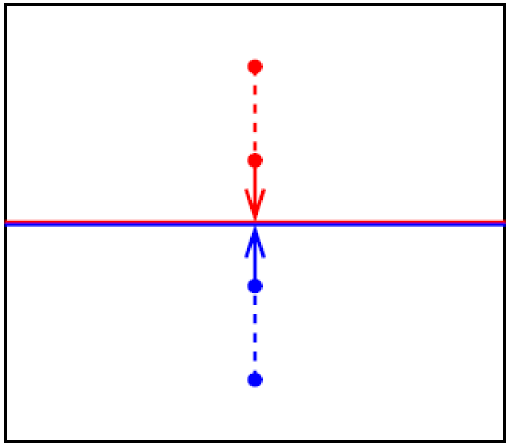
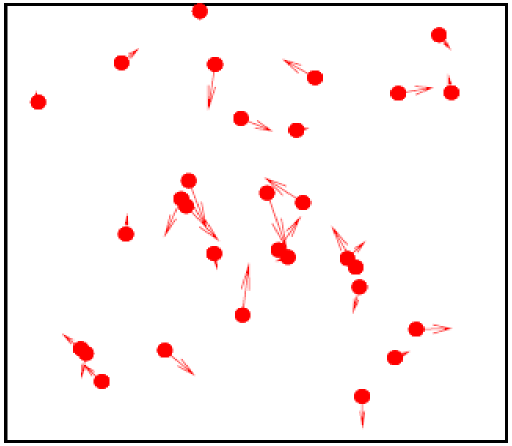
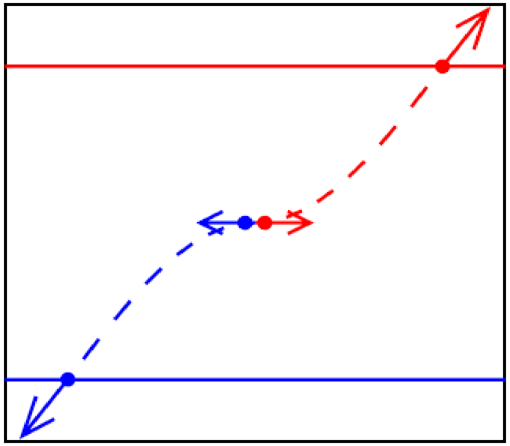
For high energy protons required bandwidth (is much larger than possible with cables amplifiers and kickers

➔ Use an electron beam instead to detect fluctuations, to amplify and to kick

Electrons vastly increase the bandwidth.

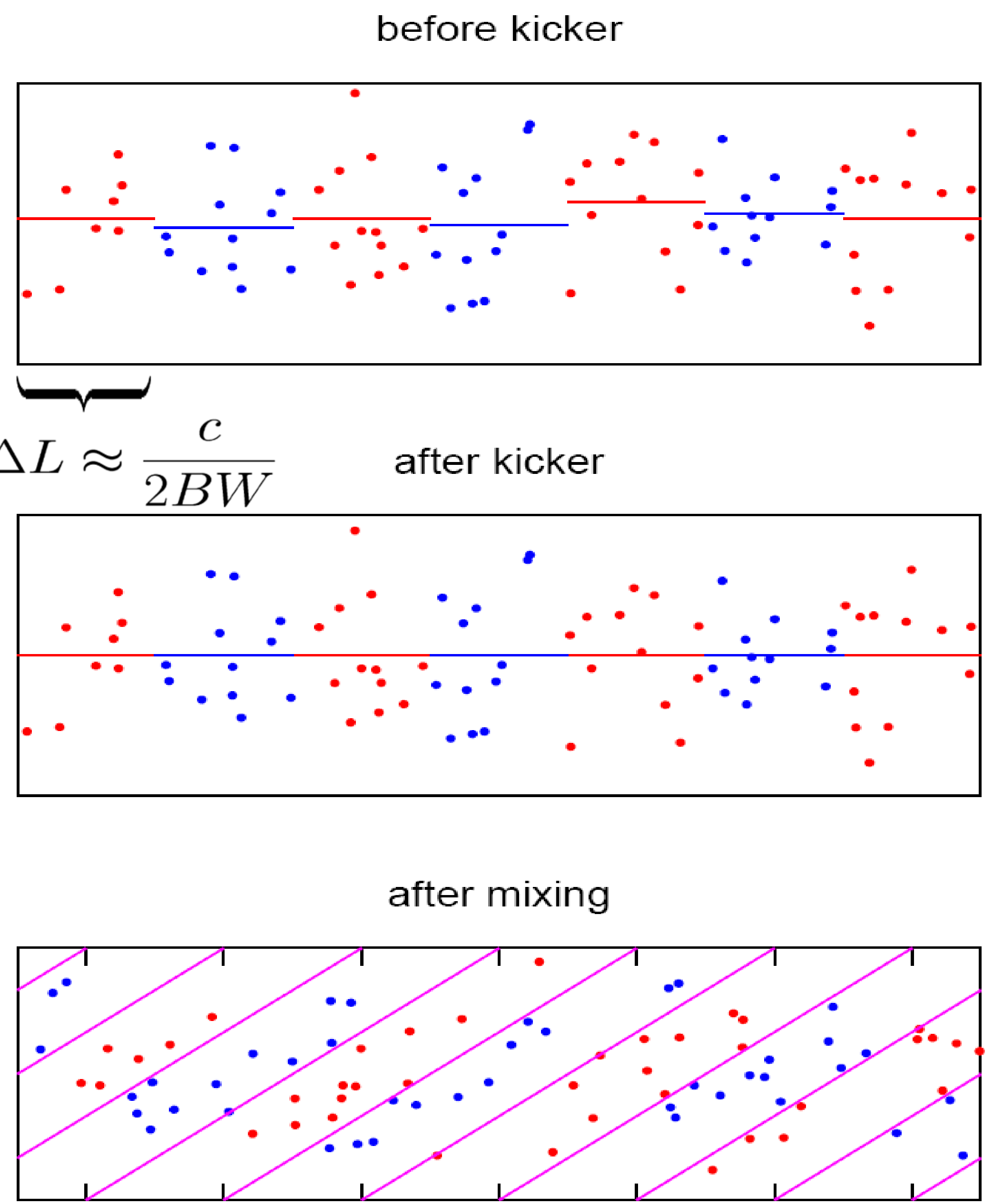


Why does the beam heat up?

Basic Idea of Longitudinal Cooling

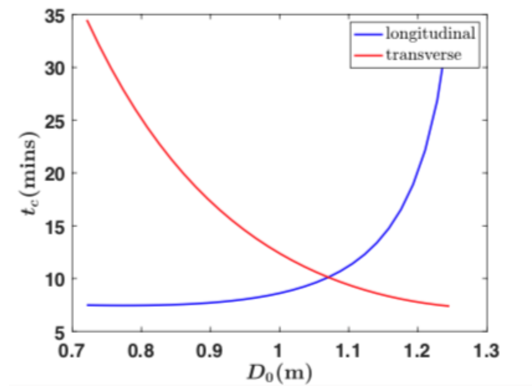
- Pickup gets average velocit
  error in sample with respect to synchronous particle.
- Flipping a coin 100 times rarely gives exactly 50 heads
- Kicker is broad band RF
- Subtracts the average from each sample.
- The spread is reduced!
- Longitudinal slip mixes into new samples

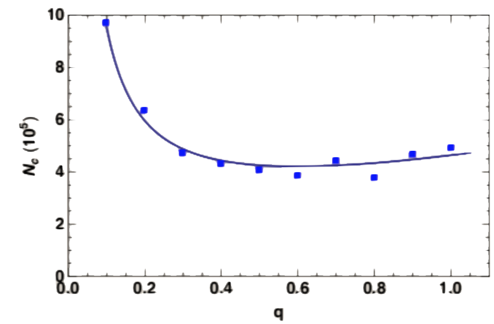


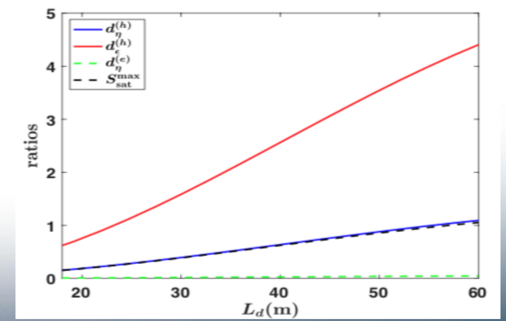
$$\Delta L \approx \frac{c}{2BW}$$

Various topics are addressed in theory

1. The cooling rate is derived in **1D model** for the longitudinal degree of freedom and is optimized with respect to the chicane strength.
2. One and two **amplification sections** are studied and the cooling rate is obtained as a function of their parameters.
3. Control of the dispersion in the modulator and kicker re-distributes the cooling rates between **the longitudinal and transverse** degrees of freedom.
4. **3D effects** in cooling are analyzed. This analysis indicates that 1D model is a good approximation to a more realistic 3D one.
5. Effects of **energy deviations** in electron and hadron beams is studied and **tolerances** established for various energy profiles.
6. **Noise effects and the associated heating process** is taken into account. The cooling rate is maximized with account to the noise.
7. 1D cooling simulation code is implemented in Matlab. **Theoretical formulas are benchmarked against computer simulations**.





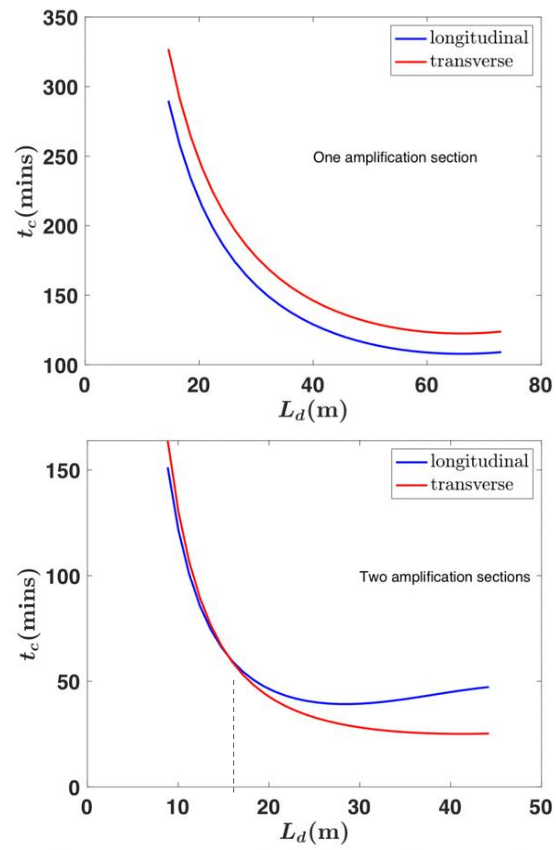


Conceptual parameters of the hadron cooler for EIC

Proton energy [GeV]	275
Electron energy [MeV]	150
Electron relative energy spread	1×10^{-4}
Electron beam charge [nC]	1
Repetition rate [MHz]	112
RMS beam size [mm]	0.7
Modulator and cooler lengths [m]	40
Average electron beam current [A]	0.1
Cooling time [min]	50

The electron bunch length, σ_{ze} =4mm, is much shorter than the proton bunch length, σ_{zh} =5 cm.

Two amplification sections, 20 m of each.



Cooling time as a function of the length of the amplification sections L_d for one (top) and two (bottom) amplification sections in the system.

1D model developed

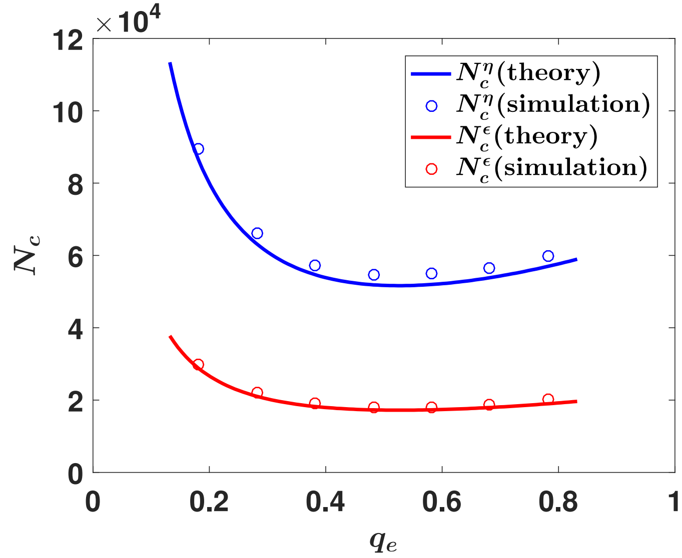
- Scaling of the cooling rate N_c^{-1} provides critical information about the feasibility of MBEC for cooling high-energy hadron beams and sets requirements for the parameter choice of the cooling sections,

$$N_c^{-1} \equiv \frac{T}{t_c} \approx \frac{0.3}{\sigma_{\eta h}\sigma_{\eta e}} \frac{1}{\gamma^3} \frac{Q_e c/\sigma_{zh}}{\sqrt{2\pi} I_A} \frac{r_h L_m L_k}{\Sigma_x^3}$$

- Gain factor G to the cooling rate :

$$G \sim \frac{1}{\sigma_{\eta e}} \sqrt{\frac{I_e}{\gamma I_A}} \quad \sim 10\text{-}20$$

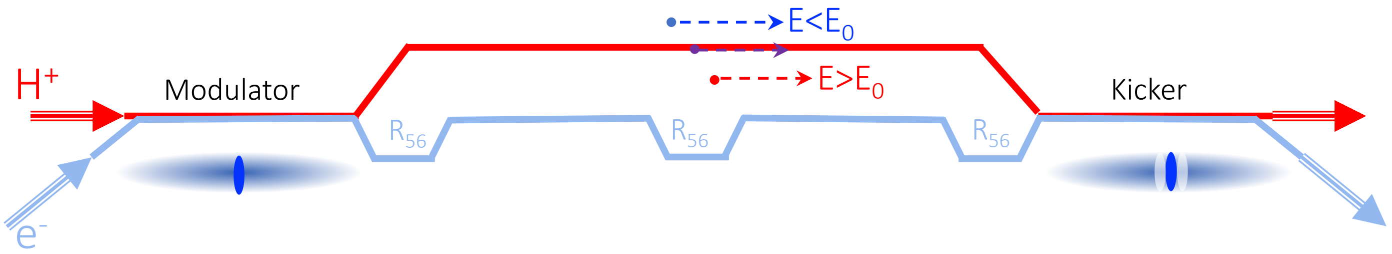
Our theoretical formulas are benchmarked against computer simulations



Transverse (N_c^ε) and longitudinal (N_c^η)cooling rates versus dimensionless chicane strength

Various topics are addressed in theory

Micro-bunched cooling enhanced by plasma oscillations



- Density modulated electron beam subject to **plasma oscillations** while drifting
- (drift quarter of electron beam plasma wavelength)
- **➔More energy modulation ➔ another chicane ➔ more micro-bunching**
- EIC Strong hadron cooler: 2 such plasma amplification stages

Features of Plasma enhanced micro-bunching

- Very broadband (~THz, slice size ~0.1 mm) amplifier
- Micro-bunching instability was well studied.
- Significant gain without saturation

High cooling rates