Strong Hadron Cooling for the Electron Ion Collider

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FRIB ACCELERATOR PHYSICS AND ENGINEERING SEMINARS

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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Outline

- Introduction of heating and cooling mechanism
- CeC mechanism
- EIC strong hadron cooling
- Selected design considerations and challenges
- Design progress
- Summary

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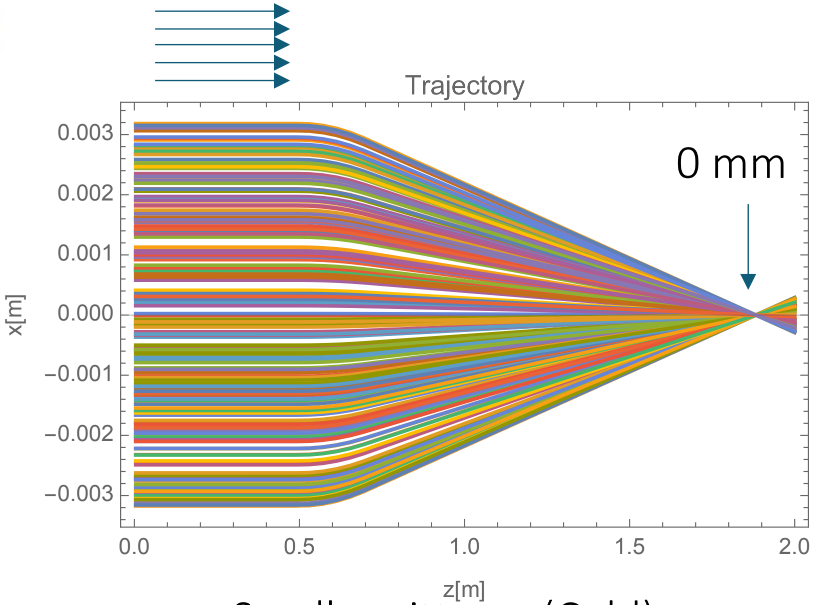
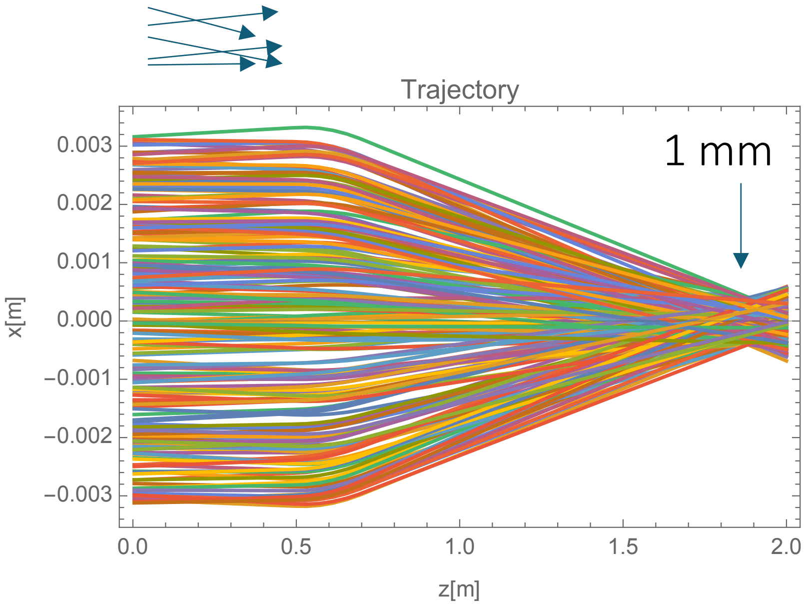
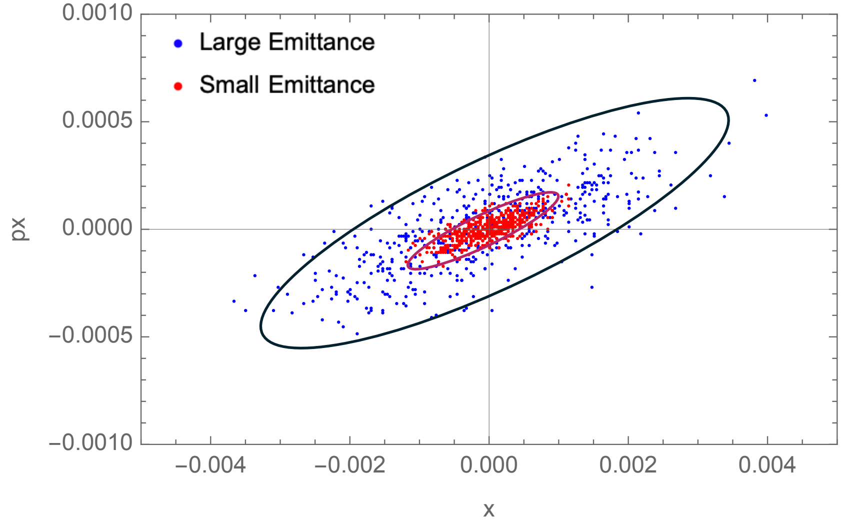
Hot vs cold beam



Small emittance(Cold)



Large emittance (hot)



Beam size(x) & angular spread (y)

Emittance:
the density-weighted area in the projected phase space of the beam $(x\text{-}p_x)$, $(y\text{-}p_y)$ and $(z\text{-}p_z)$

Unfortunately, Cold beam always ***warms up***

Transverse emittance ***Longitudinal emittance***

What is beam cooling

- Cooling is a ***reduction*** of the 6D phase space, occupied by the beam with the same number of particles.

Reduce phase space by non-cooling method:

- Beam scraping: Removing particles with large action
- Accelerating beam
- Coupling between degrees of freedom may lead to a reduction of phase-space.

Why cool beams?

Particle accelerators create a beam with virtually limitless energy in longitudinal direction. This energy can couple randomly and coherently to other directions by various processes, such as:

- Scattering: ***intra-beam, beam-beam***
- Mismatch;
- Wake fields;
- Space-charge effects;

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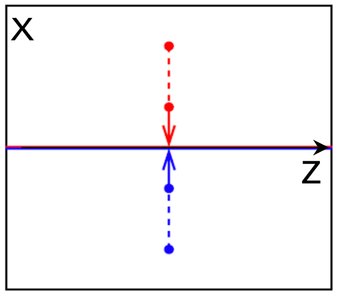
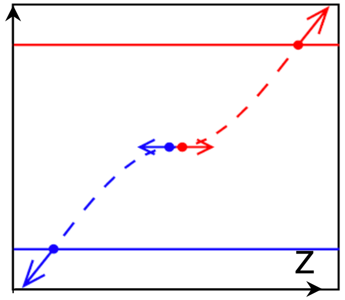
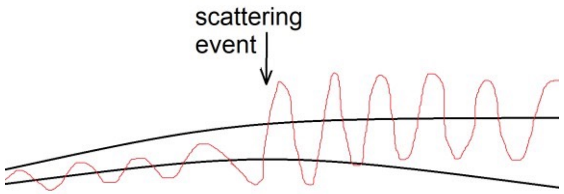
Heating mechanism I: Intra Beam Scattering

- Intra Beam Scattering is caused by Coulomb scattering of high energy particles inside a bunch
- If the particles scatter from the transverse in the longitudinal direction, the momentum transfer as observed in the laboratory frame gets Lorentz boosted by a factor $\boldsymbol{\gamma}$





- This causes a widening of the energy distribution in the beam: ***longitudinal emittance growth***.
- A particle, which experiences a jump in its momentum will oscillate around an equilibrium orbit according to its new momentum. The old and new orbit differ by the dispersion at the location of the scattering: ***transverse emittance growth***



$$x_\beta \to x_\beta - D\Delta p/p$$
$$x'_\beta \to x'_\beta - D'\Delta p/p$$

Effect was discovered by A. Piwinski (1974)
Verified in the Cern-SPS collider (1983)
2017 Wilson Prize together with Bjorken and Mtingwa

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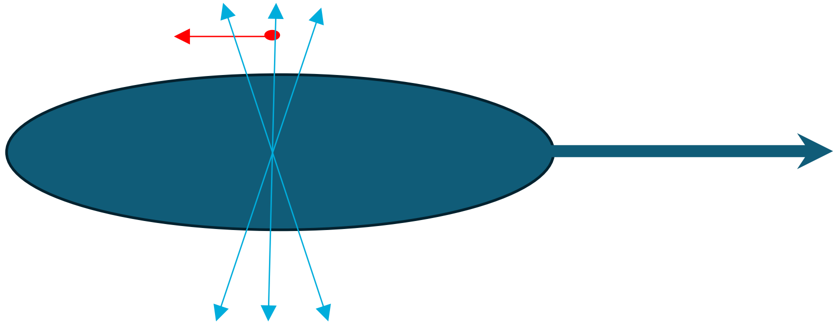
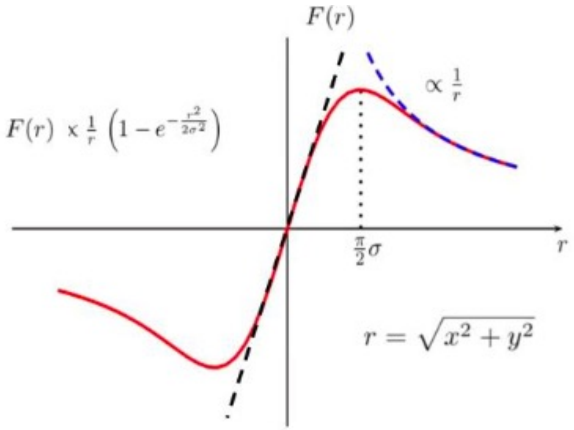
Heating mechanism II: Beam-beam

When two bunches of charged particles collide, particles from one bunch will feel the electrical and magnetic fields of the opposite bunch.

- For charged particles with γ >>1, their electrical and magnetic fields will shrink into a thin disc perpendicular to its velocity.
- When electrons and ions collide at the collision point, the linear beam-beam force acts as a focusing mechanism.
- The presence of ripple in the electron beam can induce changes in the beam-beam force exerted on the hadron beam, thereby resulting in the ***growth of hadron beam emittance*** or ***coupling in different planes***.





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Hadron Cooling Mechanisms

- Radiation damping: particles emit synchrotron radiation which gives rise to radiation damping, Effective for light particles at high energy such as electrons. However, hadrons with mass >2000 times large than the electron mass do not radiate sufficiently.

- There are two main extra mechanisms
  - ***Electron Cooling*** (Budker ,1966):
    Transfer of momentum to light particles (electrons) by scattering

  - ***Stochastic cooling***(Van der Meer, Nobel Prize, 1984)
    The fluctuations of the average beam position can be detected with pickup electrodes, amplify the signal, and place a corresponding correction.

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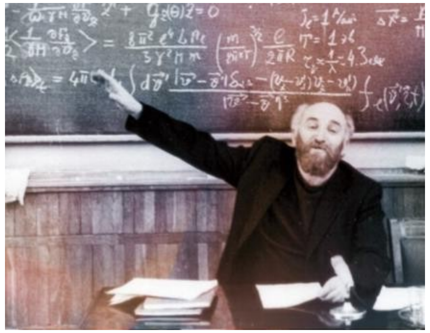
Electron Cooling

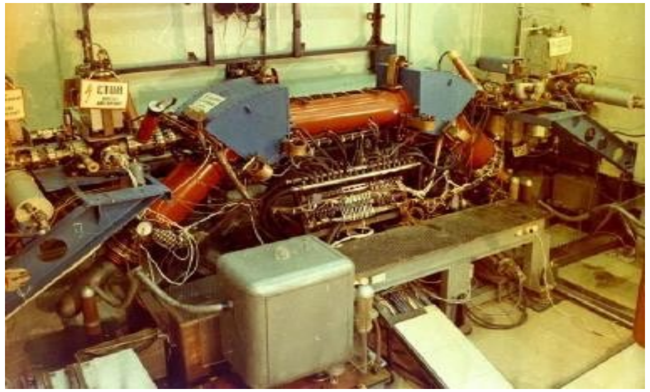
- Electron cooling process is thermalization of two component plasma.
- Hadron and electrons propagate in the same beam pipe with the same velocity.
- Transfer of energy from “hot” hadrons to “cold” electrons by scattering until equilibrium between electron and hadron temperature is reached.

$$\theta_i = \sqrt{\frac{m_e}{m_i}}\theta_e$$

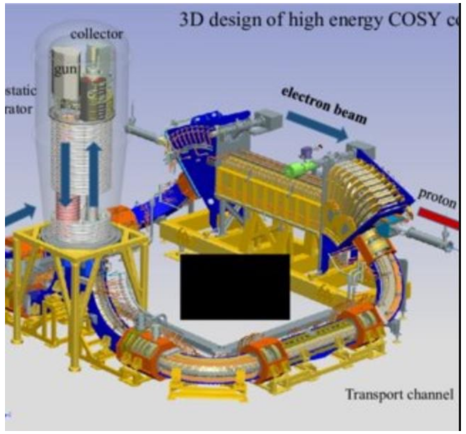
- Always needs to generate new, cold electron beam.



Invented and developed at BINP



NAP-M storage ring cooler (Novosibirsk, 1974)



DC cooler for the COSY proton synchrotron KFZ Juelich

Electron Cooler facilities

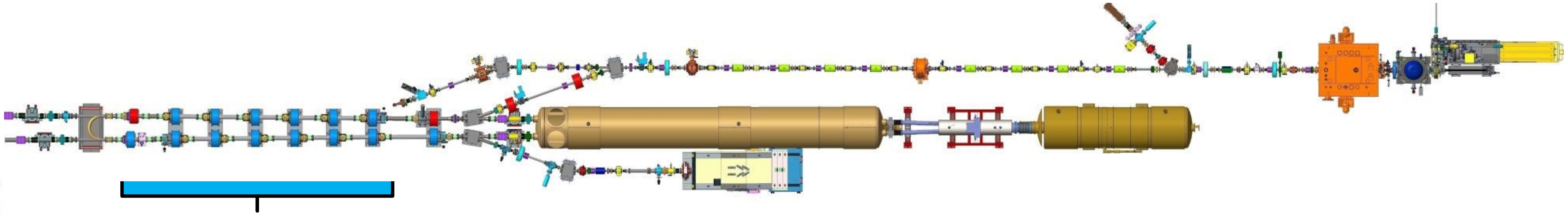
High Voltage DC coolers:

Standard electron coolers (1974-2018): 10's of coolers were constructed and successfully operated– all DC electrostatic accelerators;

- FNAL Recycler cooler (2005-11) :4 MeV electrons, first relativistic electron cooler.

RF acceleration (High Energy approach):

- Electron Cooling in RHIC (LEReC): First RF-linac based electron cooler. Also, the first cooler without any magnetization of electrons (BNL, 2019-2023).



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Electron Cooling Challenges

High energy Challenge: Large proton energies up to 275 GeV

Electron cooling currents in the order of Ampere are required

- There is no electron source which can deliver CW high brightness electron currents ($\varepsilon_N \approx \mu m$, $dE/E \approx 10^{-4}$) in the order of Ampere.
- The power needed to generate ampere beams of up to 150 MeV would exceed what can be considered reasonable by several orders of magnitude.

Superconducting Energy Recovery Linac state-of-the-art average current is ~20 mA

Two Possibilities:

- ***Recirculating cooler rings ERL*** to reduce the source requirement. (in consideration)
- Cooling electron beam is provided by ***storage ring*** (alternative solution of EIC hadron cooler)

$$\tau^{-1} \propto \frac{1}{\gamma^2} \frac{Ne}{\varepsilon_{xn}\varepsilon_{yn}\sigma_z\sigma_\delta} L$$

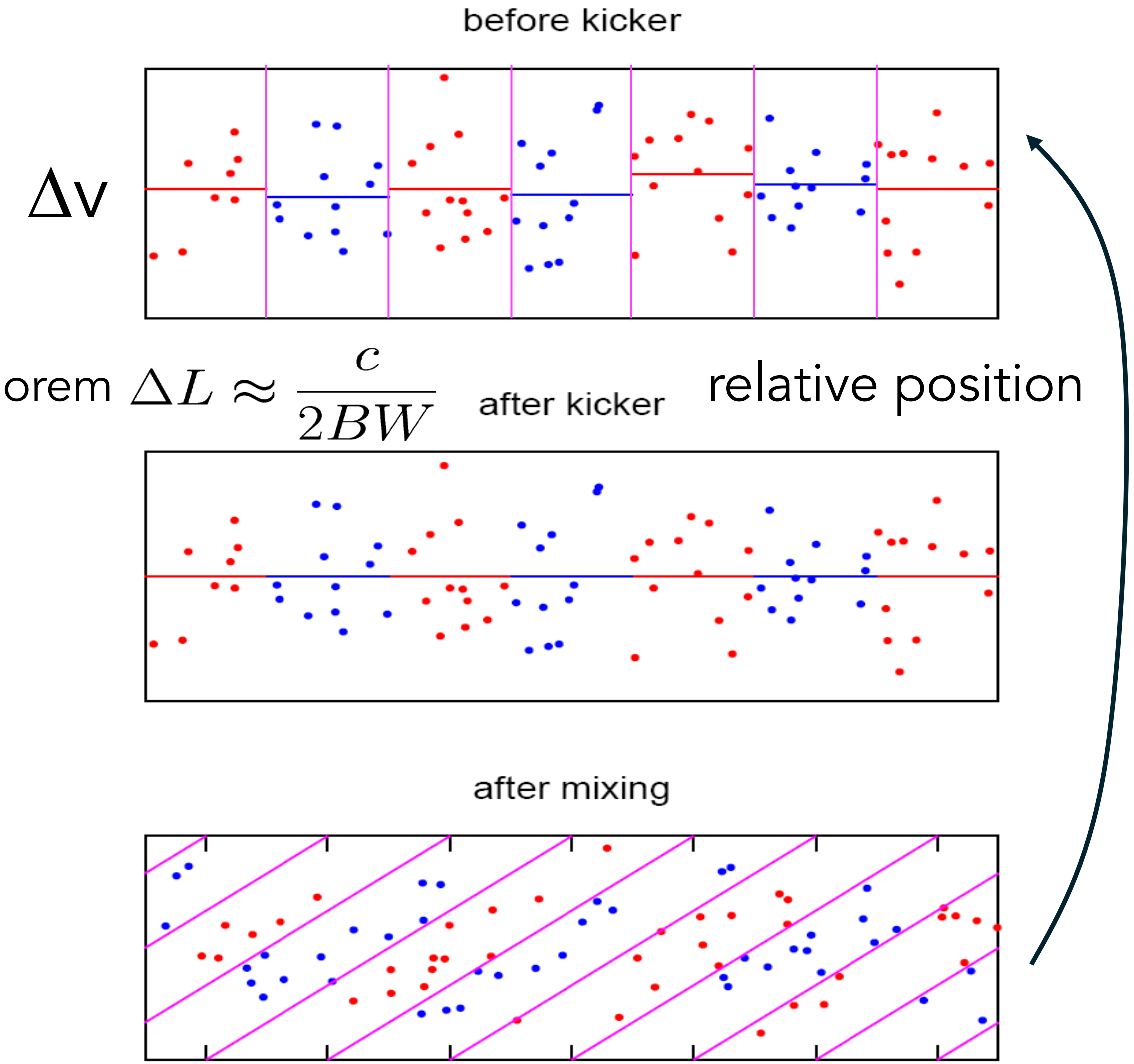
$$\gamma\_eic = 194$$

$$\gamma\_fnal = 8.8$$

$$\gamma\_lerec = 4.9$$

Stochastic Cooling basic idea

- Pickup gets an average velocity error in the sample-each slice.
- With a finite number of particles, the sliced average energy will rarely equal to average from each sample.
- Subtracts the average from each sample.
- The spread is reduced!
- Longitudinal slip mixes into new samples
- Into next iteration



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

Stochastic Cooling Rate

Measure the average sample error and apply a correcting kick, proportional to average sample error:

$$-\Delta x = g \times \langle x \rangle_s$$

$$-\Delta x = \frac{g}{N_s} \sum_{i=1}^{N_s} x_i$$

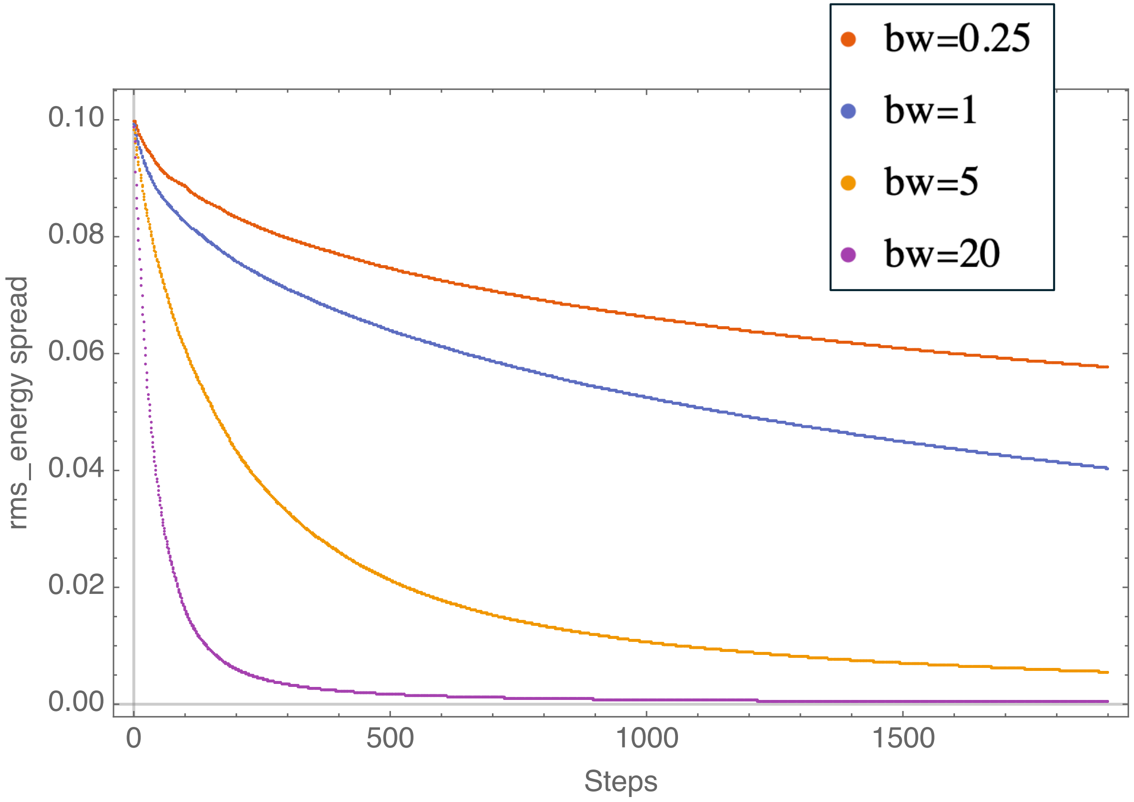
Write number of particles in a sample in term of bandwidth

$$N_s = N\frac{\Delta T}{T_0} = \frac{N}{2BWT_0}$$

Cooling rate per turn

$$\tau^{-1} = T_0^{-1}\frac{\Delta x}{x} = g\frac{2BW}{N}$$

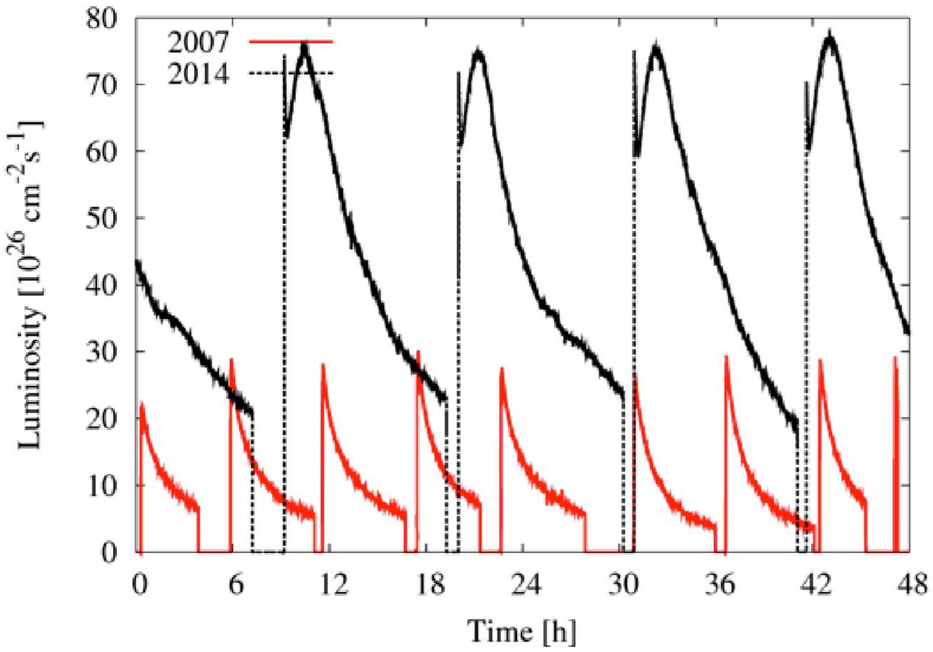
The larger the bandwidth, the higher the cooling rate



Stochastic Cooling at RHIC

Successful cooling of bunched Au beams for Au-Au collision in RHIC for 23GeV-100 GeV Au beams

- Achieved bandwidth of 3 GHz
- ***Cooling reduces the beam emittance initially during the collision run***



If the EIC SHC concept and design is not matured, then the existing stochastic cooling capability will be upgraded for hadron beam cooling (not proton).

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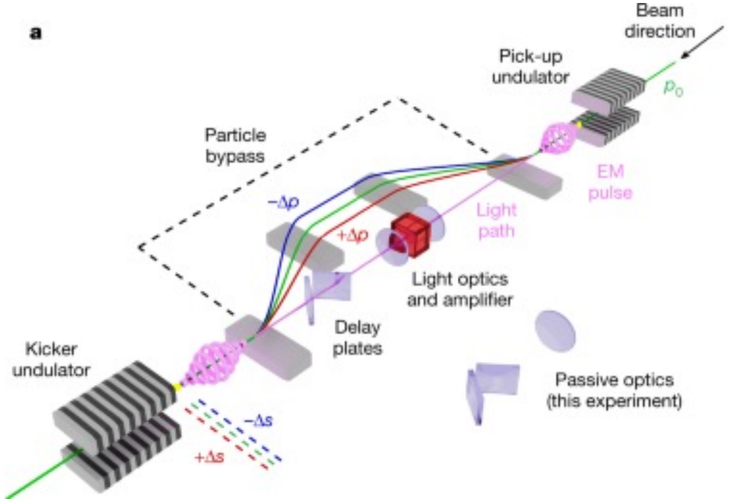
Types of stochastics Cooling

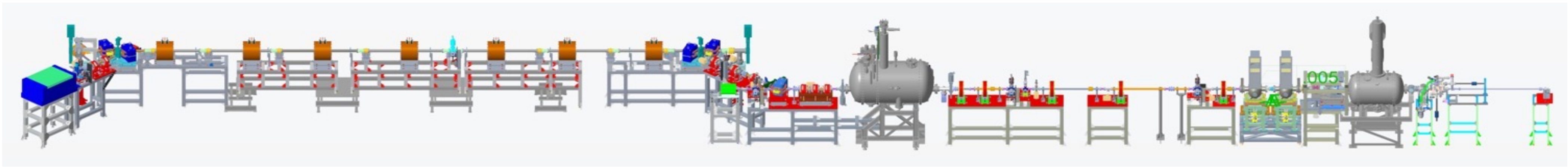
- Conventional microwave (GHz-range bandwidth)
- Optical phonons (10s -100 THz)

Jarvis, J., Lebedev, V., Romanov, A. *et al*. Experimental demonstration of optical stochastic cooling. *Nature* **608**, 287–292 (2022).



- ***Coherent electron (use electron beam as an amplifier, 1-10s THz)***

Vladimir N. Litvinenko and Yaroslav S. Derbenev Phys. Rev. Lett. **102**, 114801



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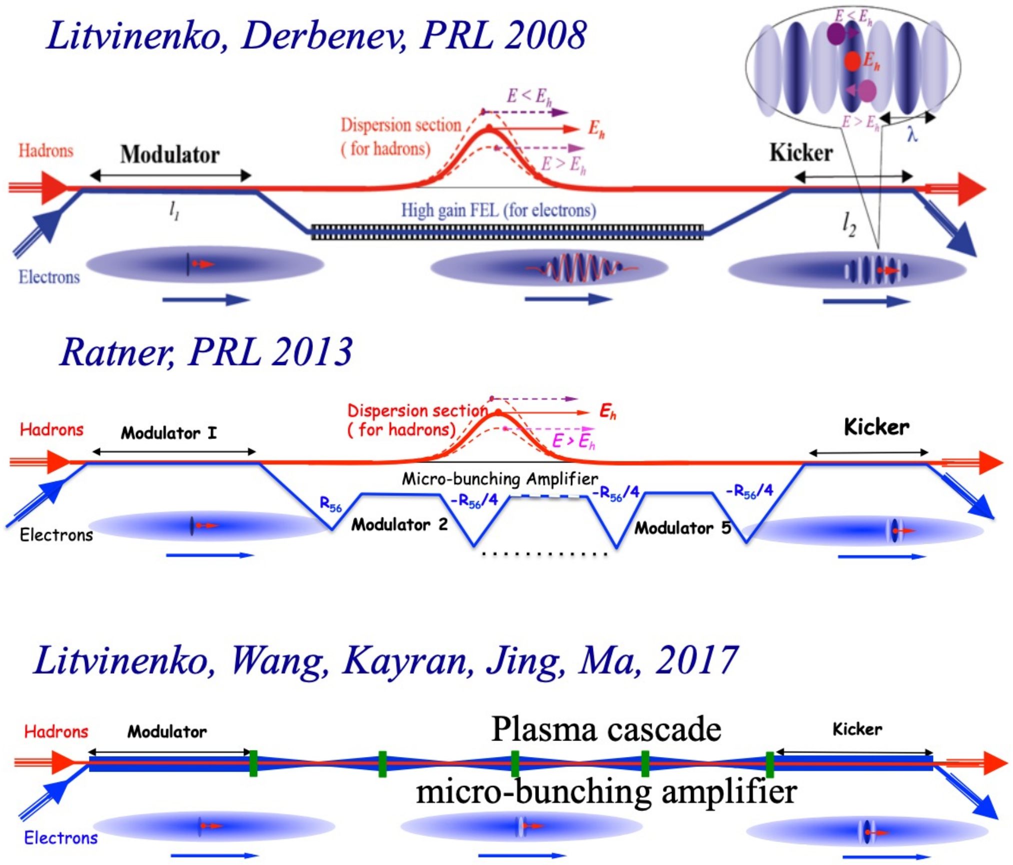
Coherent Electron Cooling proposed schemes

Coherent electron cooling is a variant of the stochastic cooling, use electron beam as signal carrier, with the bandwidth range raised from ~GHz to tens of THz.



High gain FEL amplifier

2012-2018

Multi- Chicane Microbunching amplifier

EIC CDR

Plasma-Cascade Microbunching amplifier

Present test

There are several CeC schemes were proposed. The major difference is the amplification mechanism.

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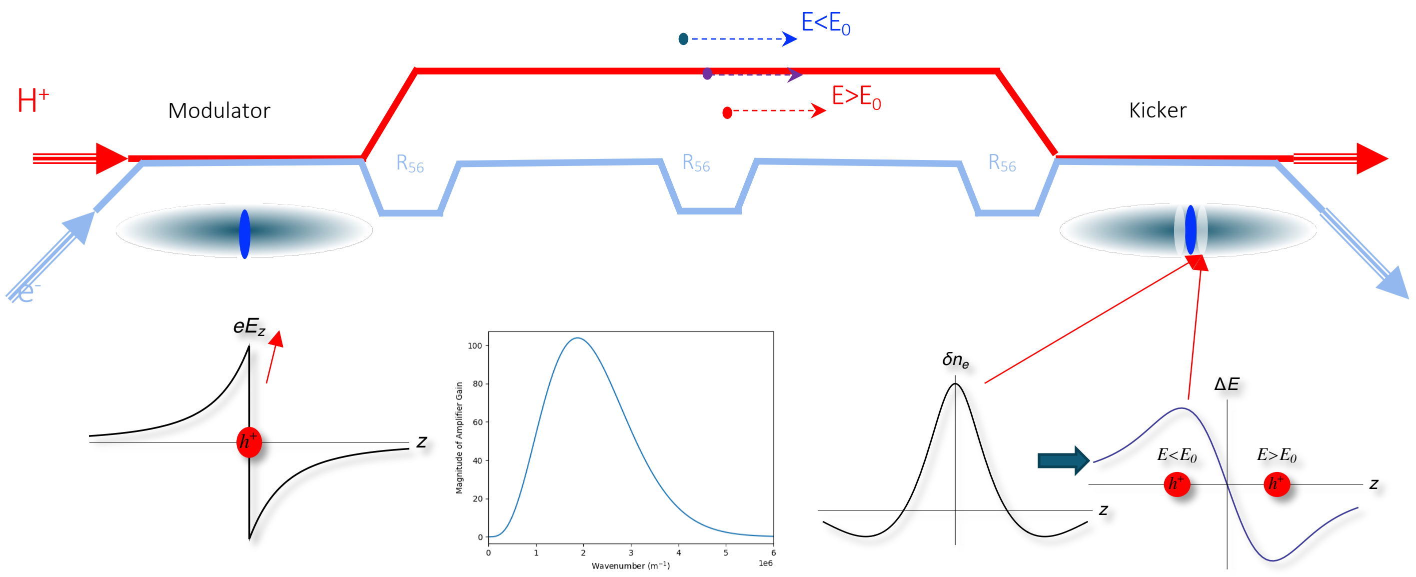
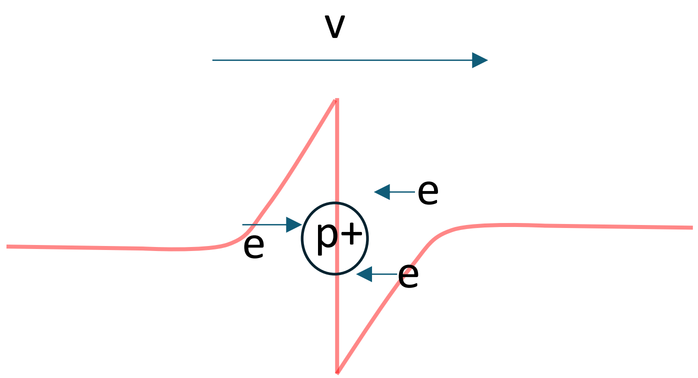
V. Litvinenko EIC cooling(2019)

Coherent Electron Cooling introduction

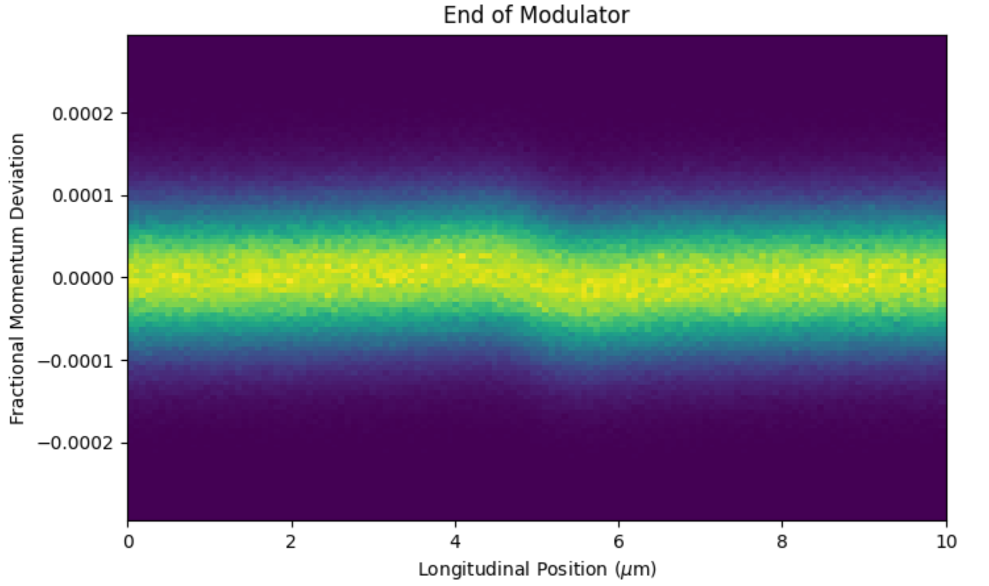


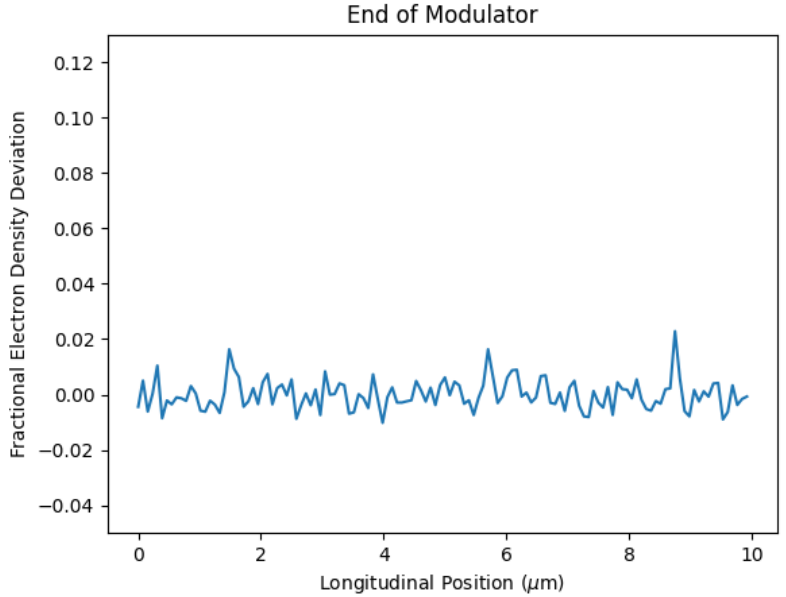
Modulator: density fluctuation in hadron beam causes energy modulation of e-beam
Amplification: e-beam energy modulations are amplified and converted to density fluctuations by chicane and straights
Hadron chicane: Controls hadron travel time with respect to electron path. Transfer to correlated energy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

Modulator section



- The pickup (modulator)are implemented via the Coulomb interaction of the hadrons and electrons when $\gamma_e = \gamma_h$.
- Electrons' momentum is modulated around a proton or hadron density fluctuation.





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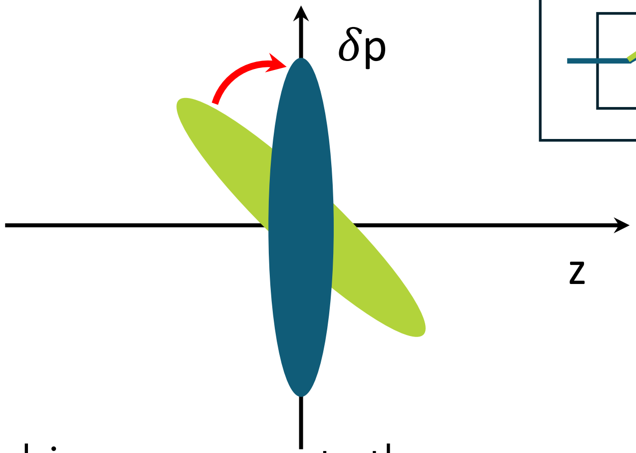
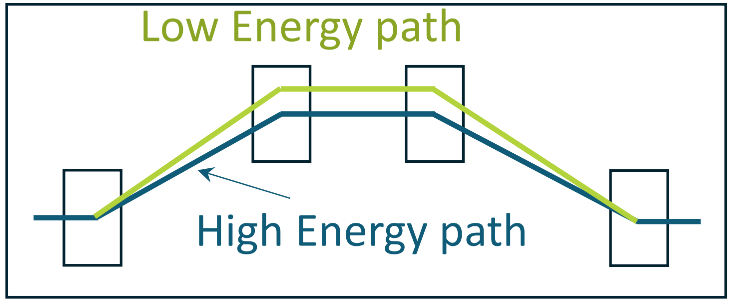
Amplifier section-Chicane

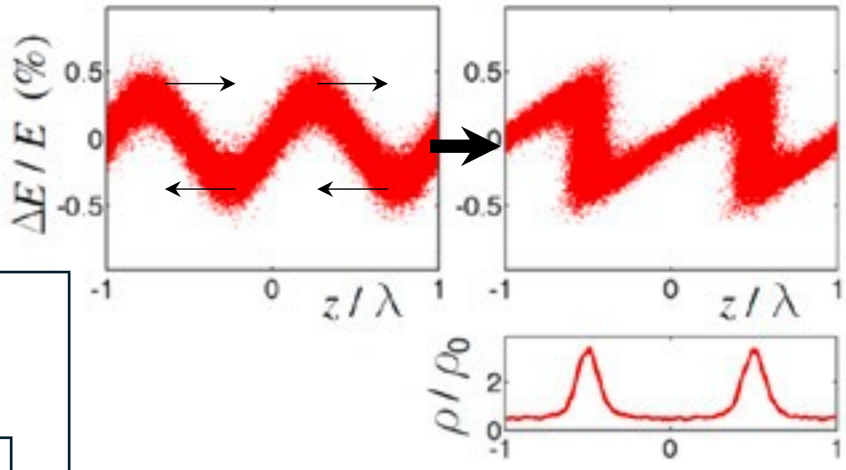
What is chicane: Chicane is one kind of lattice that can provide longitudinal dispersion (R56).

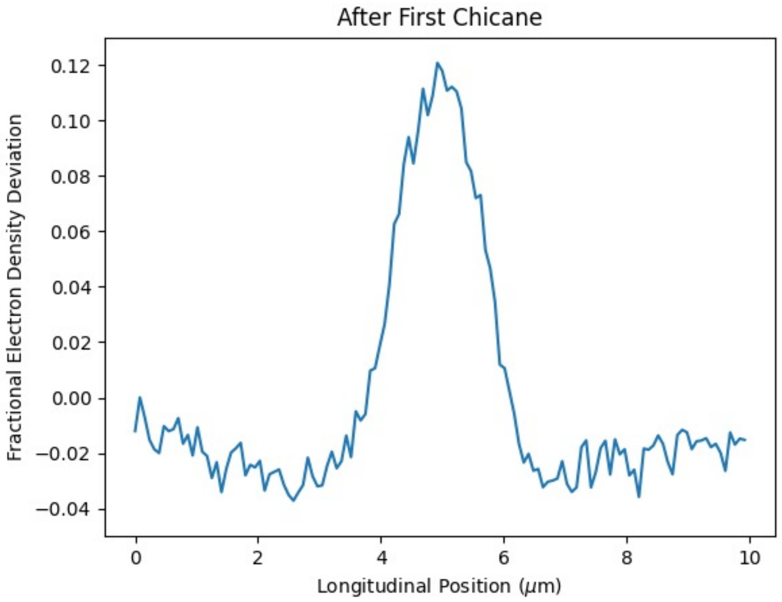
$$\Delta l = R_{56} \frac{\Delta p}{p}$$





Energy modulated beam





The chicane converts the energy-modulated bunch to many micro-bunches.
Micro-bunch has much higher longitudinal space charge.

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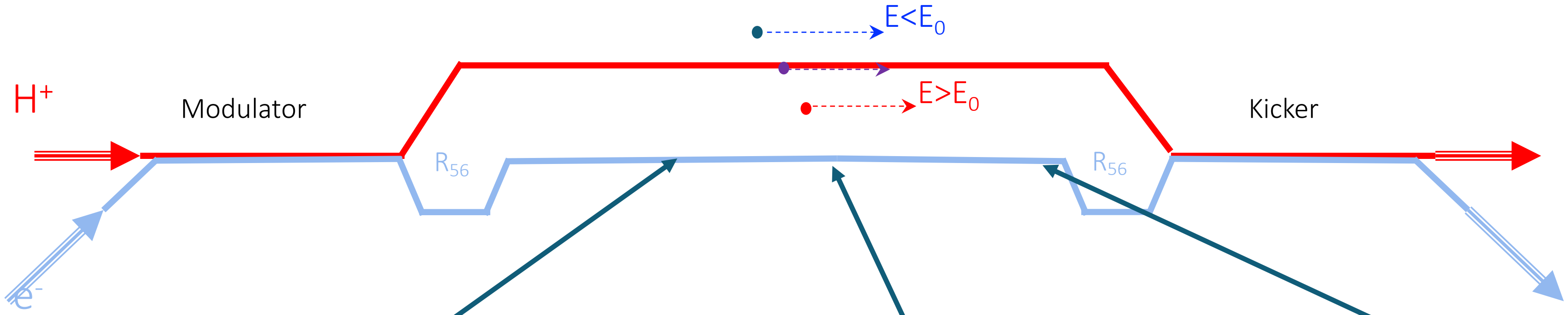
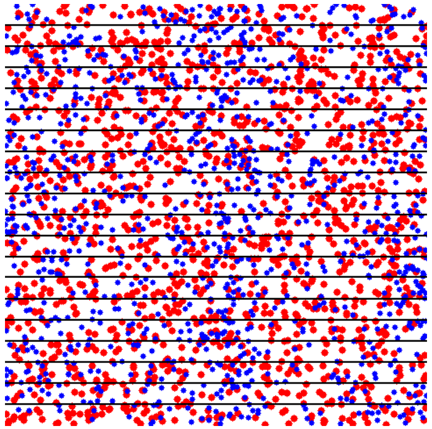
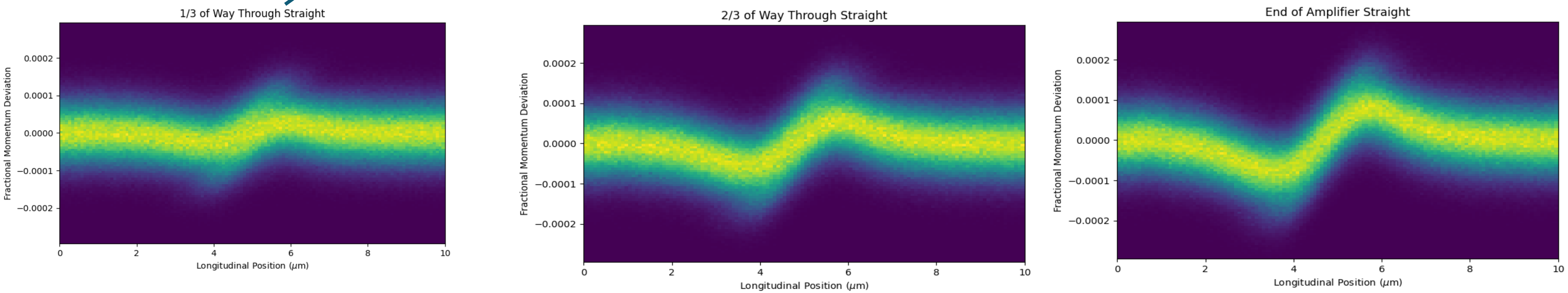
Amplifier section-drift

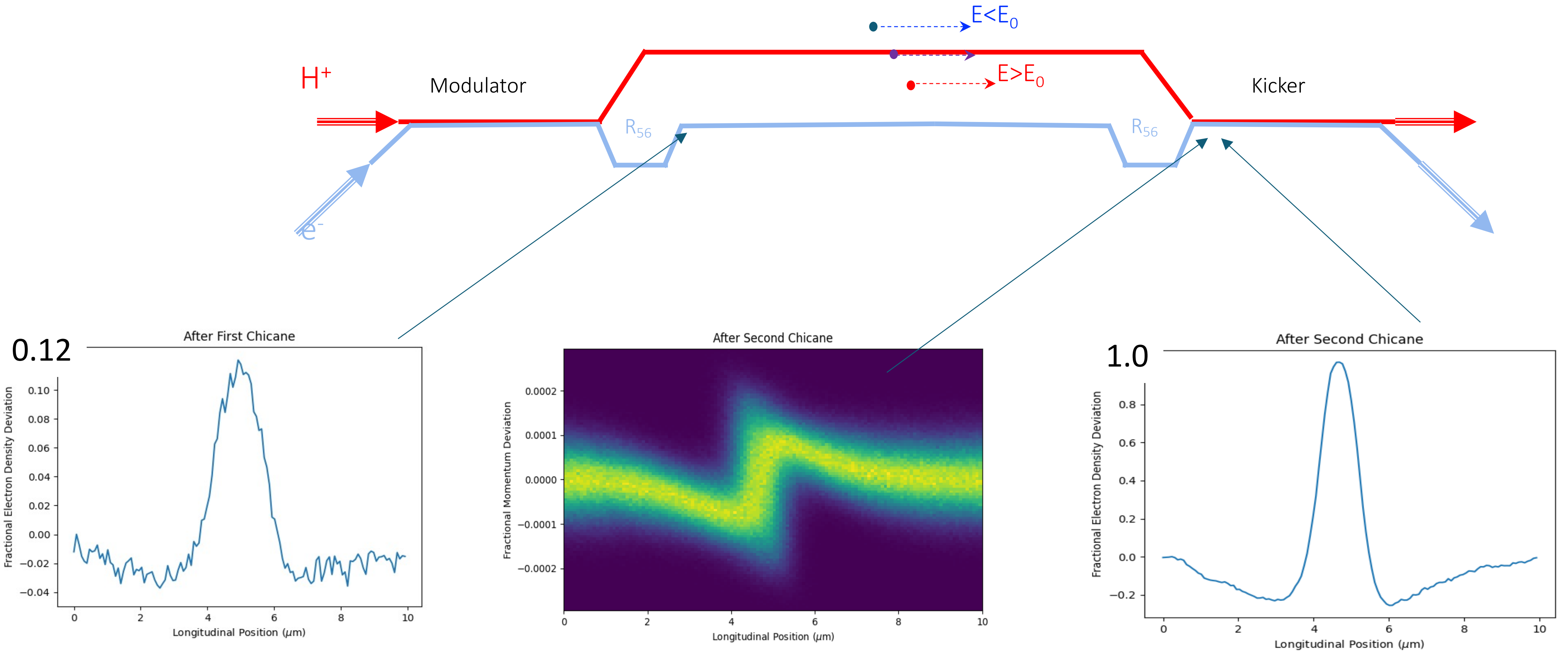
Longitudinal plasma oscillation in a neutral plasma (from the internet, only for illustration)







Amplifier second chicane



Micro bunch density is increased ~ 8X

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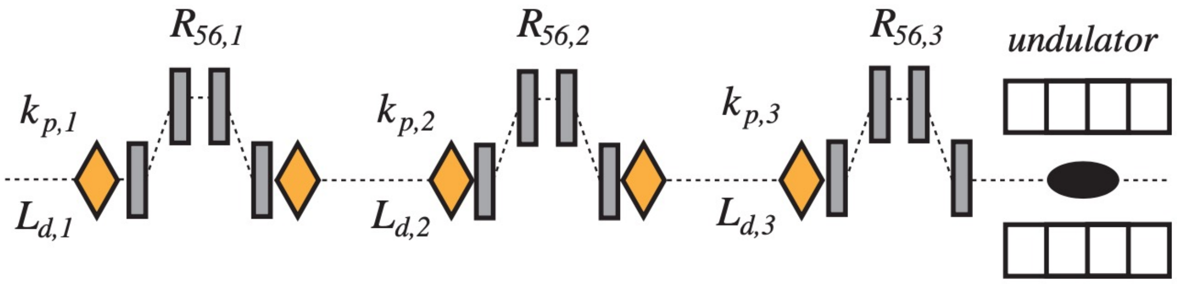
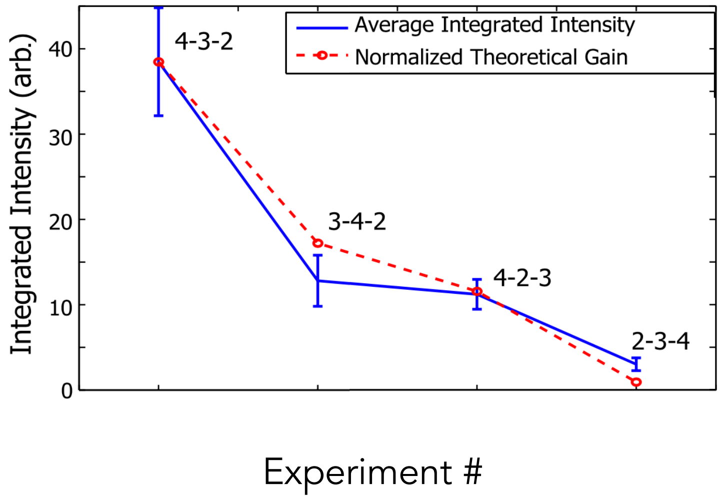
Chicane-drift amplifier was tested experimentally

Micro-bunched amplification is well known in FELs [Schneidmiller&Yurkov PRAB **13**, 110701 (2010); Dohlus et al. PRAB **14**, 090702 (2011)]. It has been tested experimentally at NLCTA facility at SLAC [Marinelli et al. PRL **110**, 264802 (2013)].



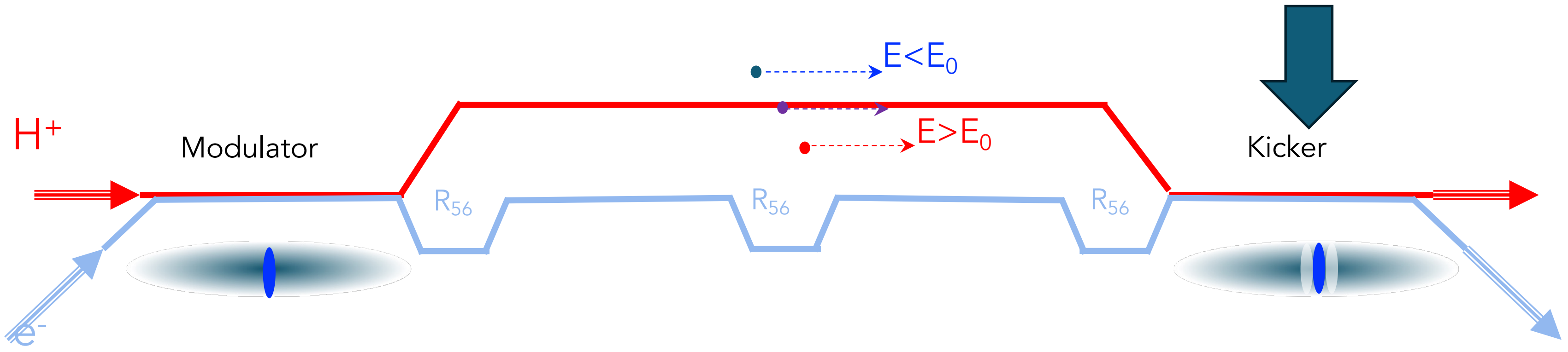
Beam line for the NLCTA experiment.
Beam energy is 72 MeV.
The amplification was inferred from the beam radiation in the undulator

Estimated intensity amplification ~ 3000

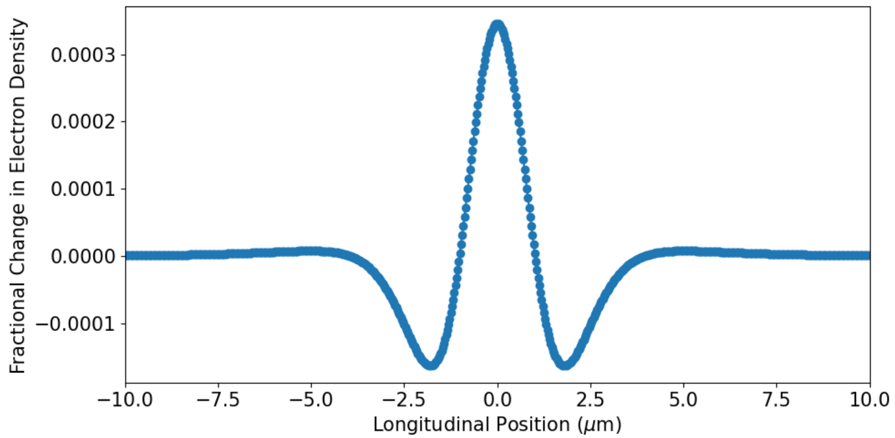


Signal intensity increases when the chicane strength is optimized. Good agreement with theory.

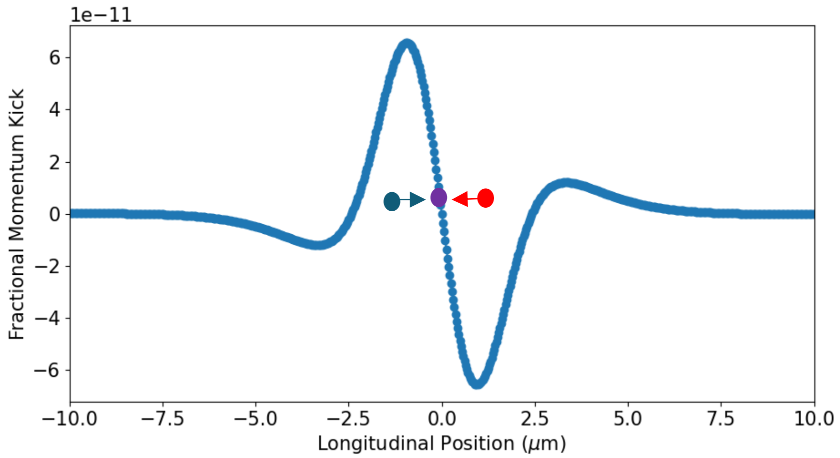
Kicker section



if one amplifier is not enough, we can have a second amplifier to get a higher gain.



Electron density in kicker



Micro bunched electron wake in kicker

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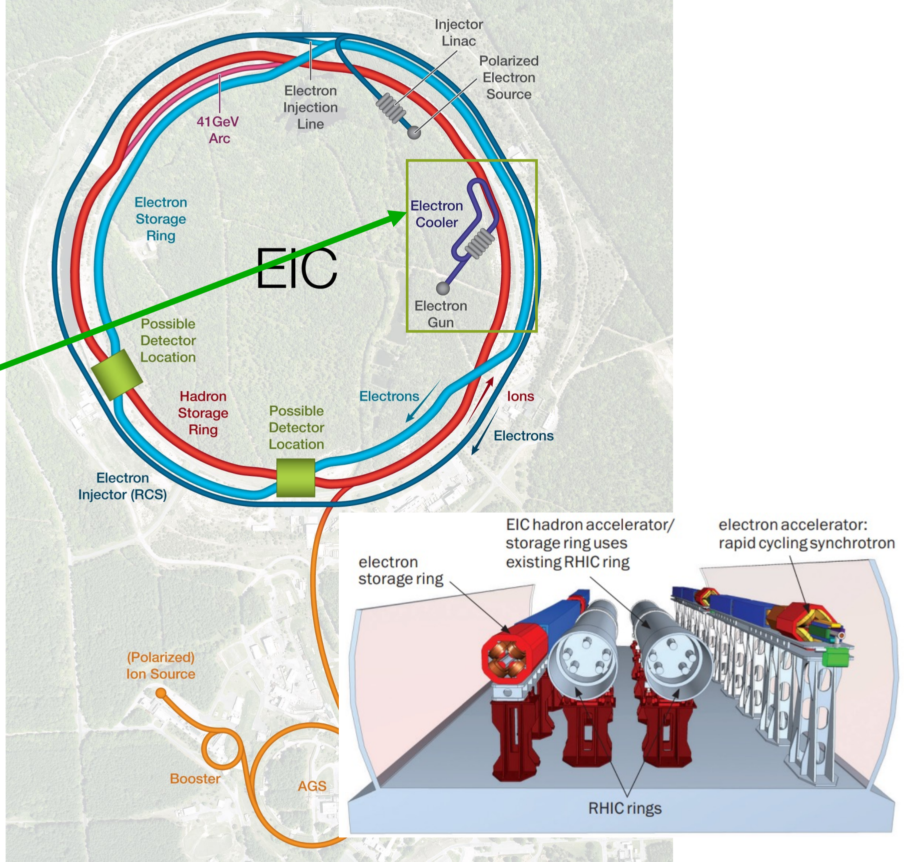
EIC accelerator introduction

Electron Ion collider design based on existing RHIC.

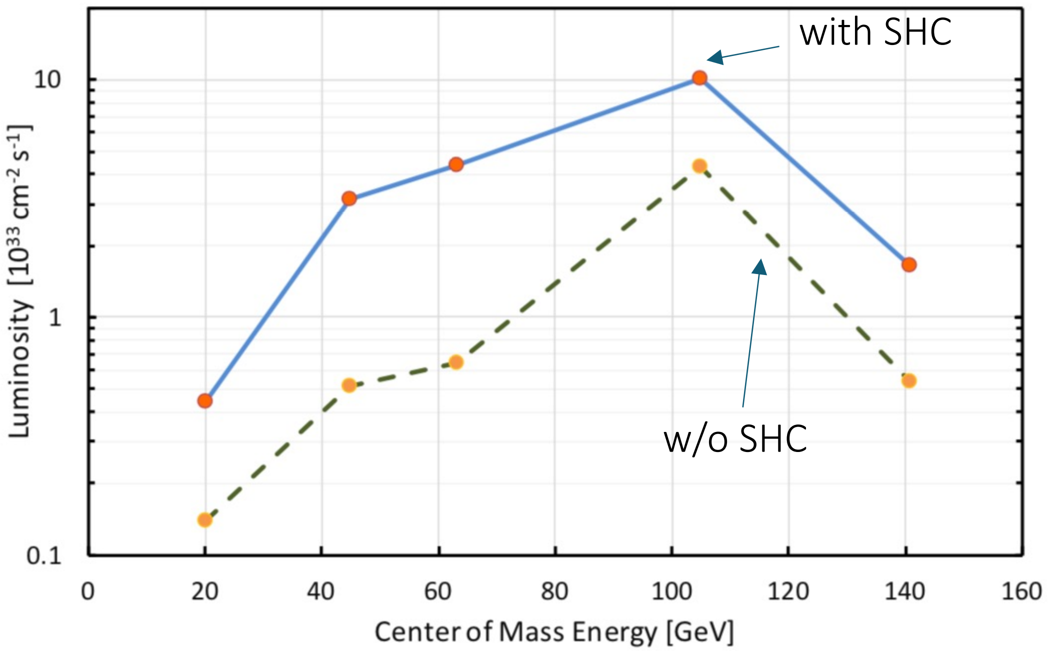
- Hadron storage ring 40-275 GeV (existing)
  - ~10 hour lifetime
  - 70% polarization
  - Bright beam
  - ***Strong hadron cooling (new)***
- Electron storage ring (2.5–18 GeV, new)
- Electron Injector(new)

E_{cm} = 20 GeV -141 GeV
High luminosity goal: $L = 10^{34} cm^{-2}s^{-1}$



EIC cooling requirements

- Luminosity of lepton-hadron colliders in the energy range of the EIC benefits strongly (factor ≈ 3-10) from cooling the transverse and longitudinal hadron beam emittance.
- Cool the proton beam at 275 GeV and 100 GeV ;
- ***IBS*** longitudinal and transverse(h) growth time is 2-3 hours. ***Beam-beam*** growth time(v) is > 5 hours. The cooling time shall be equal to or less than the diffusion growth time from all sources.
- Must cool the hadron beam normalized rms vertical emittance at injection from 2.5 um to 0.3 um in 2 hours.



EIC Cooling methods

Pre-cooler@24 GeV cooling time <1 hr
SHC time@100, 275 GeV ~2 hrs

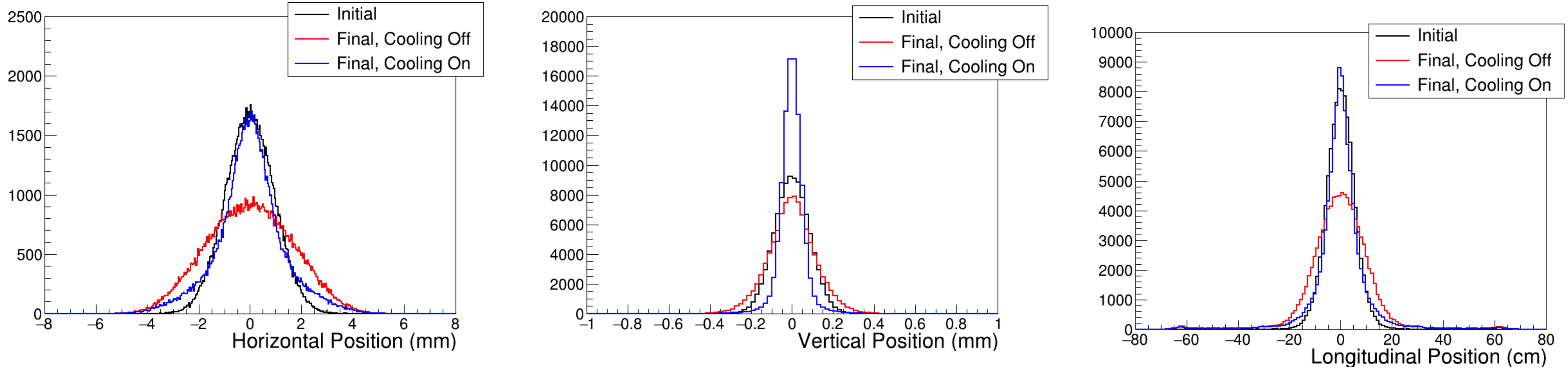
- Use a precooler(***electron cooling***) with bunched beam electron cooling at injection energy to reduce the vertical hadron RMS normalized emittance from 2.5 um to 0.3 um within 2 hours or less of storage time at the injection energy of 24 GeV. Achieve the hadron collision emittance.(Flat beam experimental test is being started at RHIC run.)
- Maintaining high beam brightness counteracting intra-beam scattering and beam-beam by cooling at high energy(***Coherent electron Cooling***)

SHC Parameters table

	100 GeV	275 GeV
Modulator/Kicker length [m]	33	33
Amplification length [m]	49 x 2	
e bunch charge [nC]	1	
e RMS Bunch length[mm]	9	7
e slice energy spread(dp/p)	1e-4	5.9e-5
e normalized emittance [mm-mrad]	2.8	
R56_*e* of 1st , 2nd and 3rd chicane [mm]	23/-17/-18	12./-6.7/-6.8
Proton Energy spread	9.7e-4	6.8e-4
R56 of proton chicane [mm]	4.2	1.3
Proton H/V phase advance [rad]	3.2/4.7	3.2/4.8
Proton H/V dispersion in M&K [m]	0.0036/0.096	0.0019/0.067
H/V/L IBS time [hrs]	***2/4/2.5***	***2/7/2.9***
H/V/L cooling time [hrs]	***1.7/3.9/2.4***	***0.9/1.9/1.2***

- 1D/3D Cooling code has been developed.
- The cooler parameters are optimized by a genetic algorithm on the cluster.

Initial and final hadron’s spatial distributions after 10 hours



Track 10 hr with IBS and beam-beam emittance growth

Selected SHC design consideration and challenges

- A ***high current ERL*** to generate uniform energy spread, super gaussian distribution beam
- A high-quality electron beam with ***high current***, ***small energy spread***, and ***small noise*** in the beam.
- Total R56 to be zero to avoid slice slippage.
- Path length control for electrons and hadrons with sub-micron accuracy. An exquisite stability of the system.

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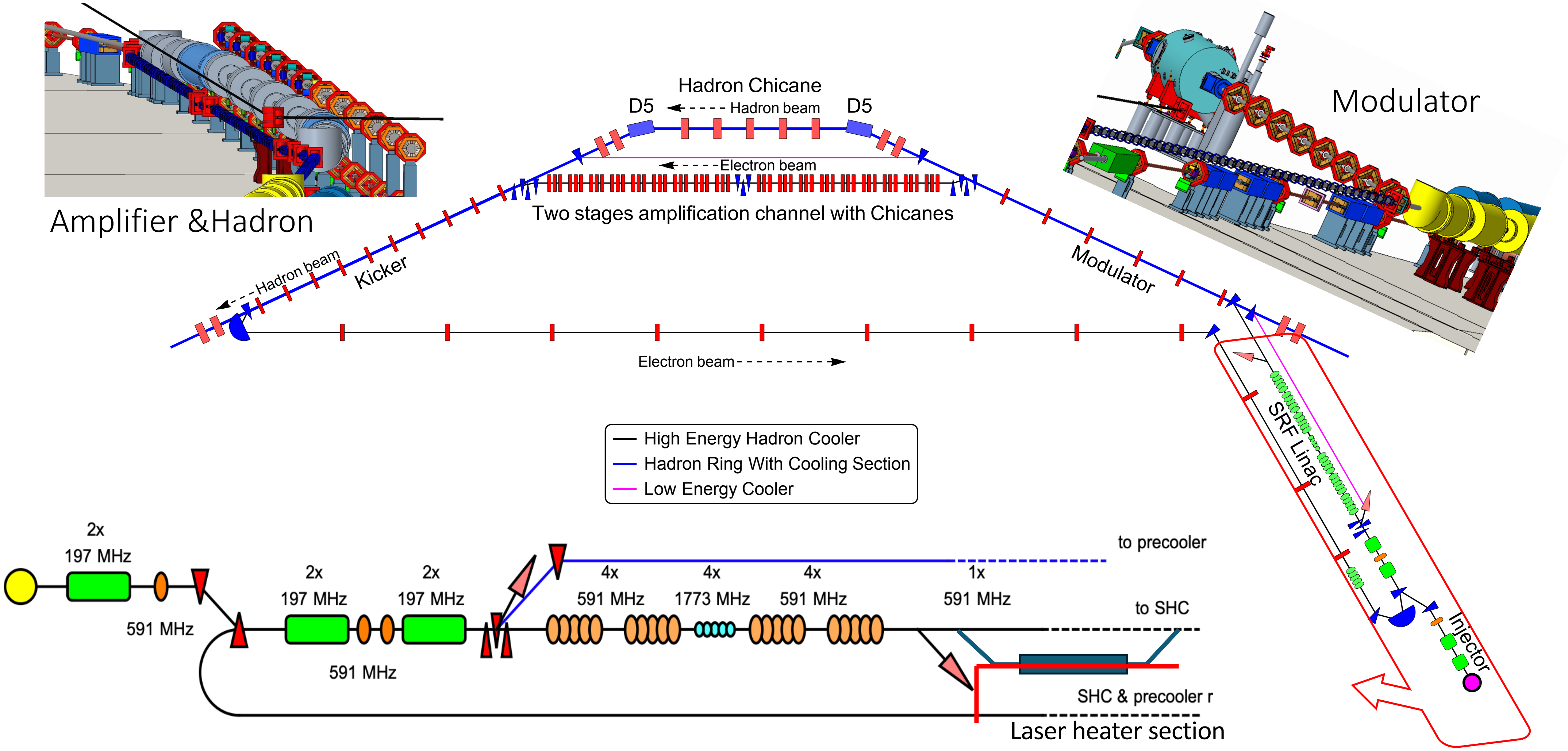
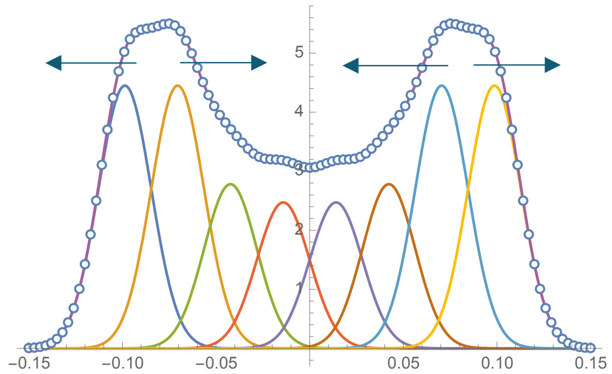
SHC/precooler facility layout

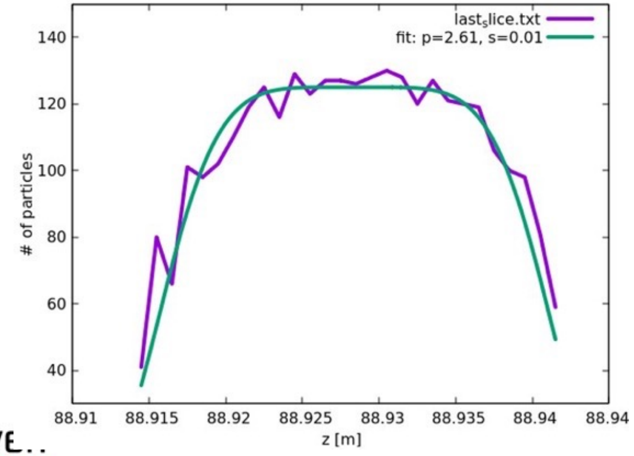


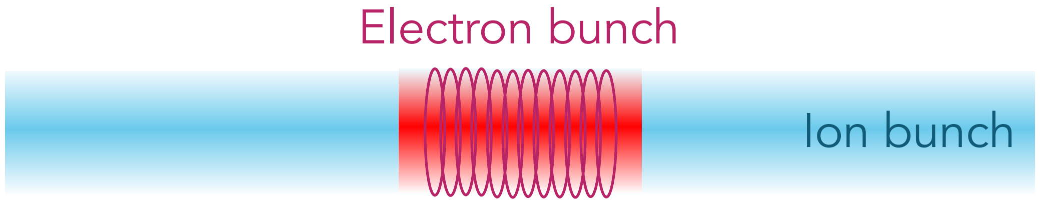
Make a SuperGaussian bunch in the Cooler

Initial Laser distribution in the gun



SuperGaussian distribution at the end of Linac





In amplifier: $G \propto \boxed{\sqrt{I_e}} sin(\frac{\omega_p \boxed{(I_e)} L}{c})$

3D GPT simulation	Beam parameters
Bunch charge	1 nC
RMS emittance x/y	2.6 mm-mrad
rms dp/p	5e-5
Slice dp/p	< 3e-5
rms Bunch length	7 mm

- Uniform current along the bunch provides higher cooling rate
- Chicane's T_{566} compensated here using 3rd harmonic RF gradient

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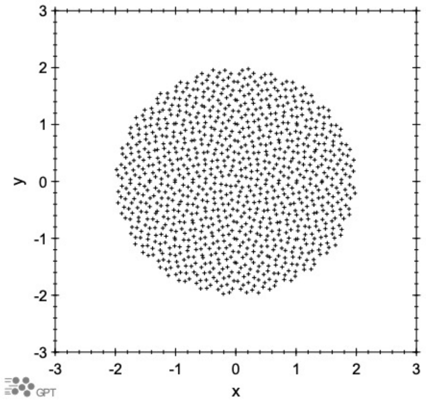
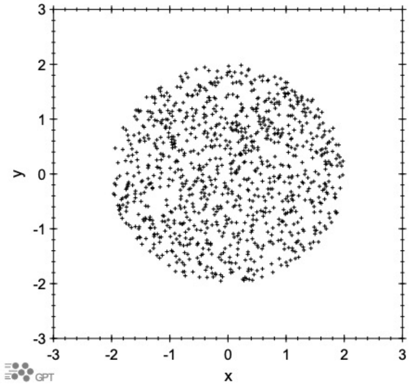
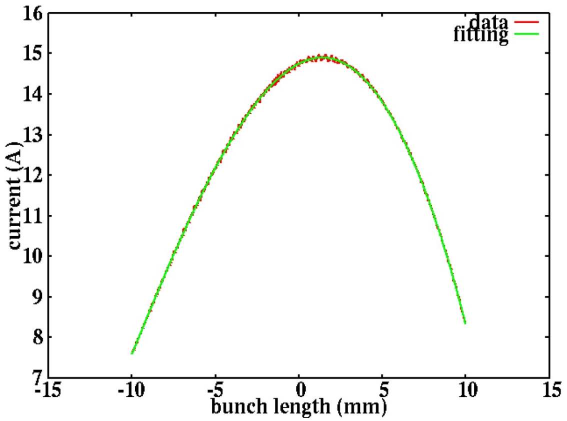
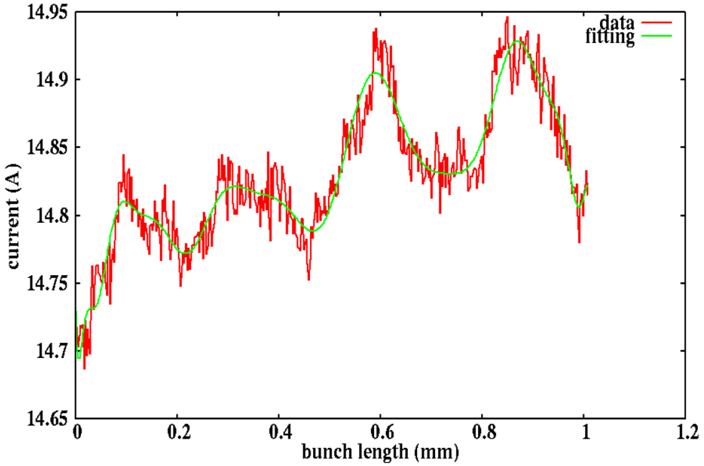
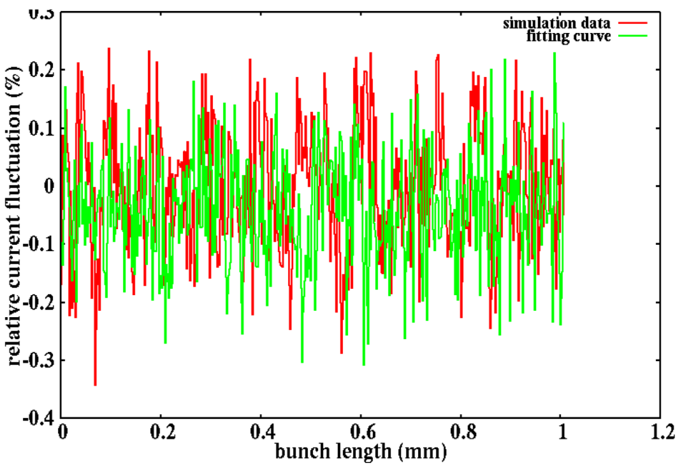
Beam noise simulation











- Beam shot noise is created initially. The question is how to avoid noise increasing.
- Observed > 250 um modulation with noise amplitude 2x shot noise. It will not be amplified in the cooler. (The typical amplified signal is ~40 THz(3 um)).
- 250 um modulation will ***not affect the cooling rate***.
- current fluctuation through the linac and the merger is ***close to the shot noise level***.

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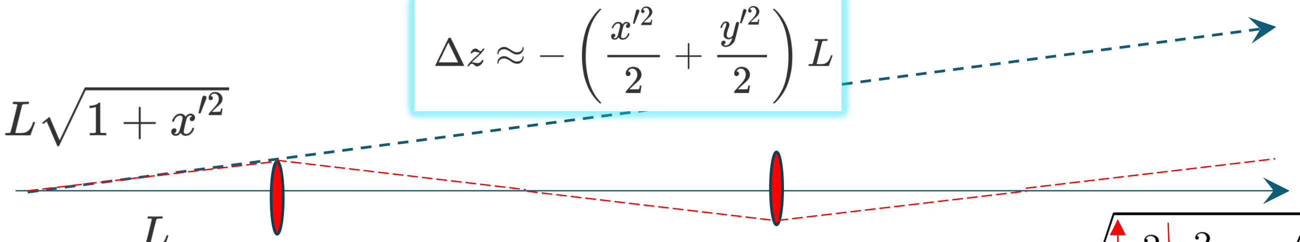
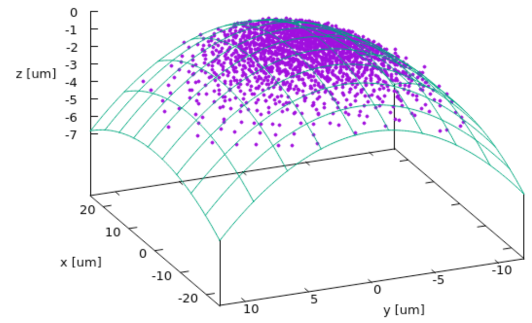
Electron beam divergence

$$\Delta z \approx -\left(\frac{x'^2}{2} + \frac{y'^2}{2}\right) L$$

$$L\sqrt{1 + x'^2}$$

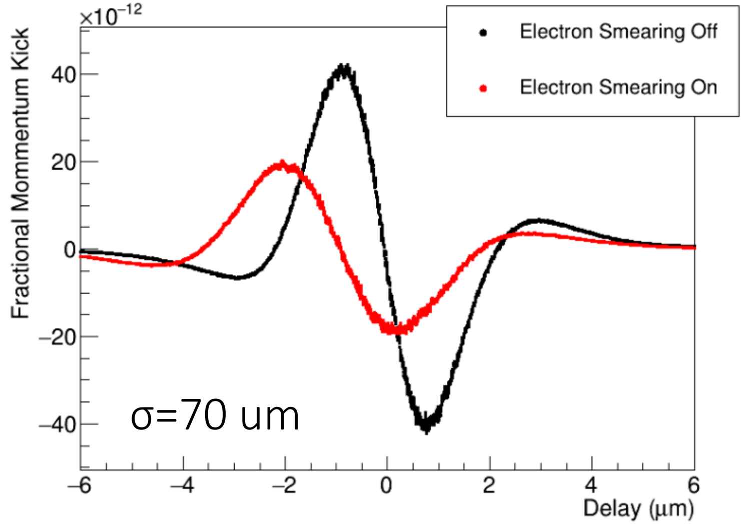
$$L$$

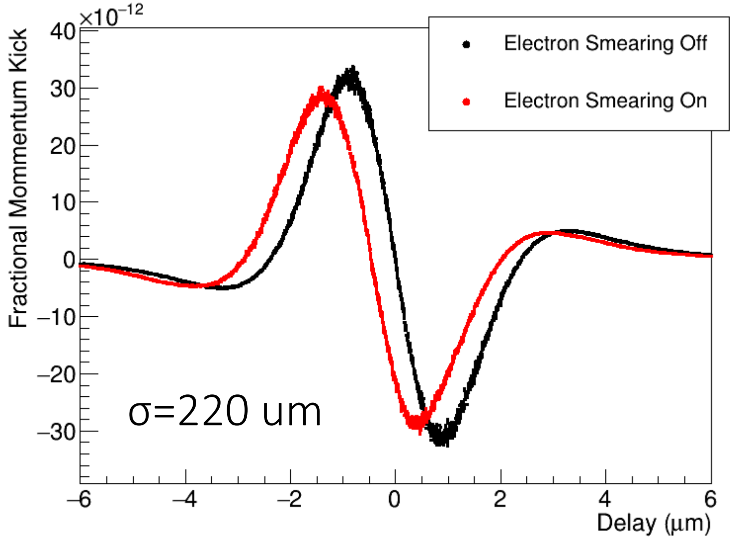




$$\epsilon_x = \sqrt{\sigma_x^2 \sigma_{x'}^2 - \langle x x' \rangle^2}$$

- Electron divergence causes path length change which can accumulate over long distance with small beam sizes. It will smear out the wake.
- By ***increasing the beam size*** at the amplifier section one can reduce the impact on wake.





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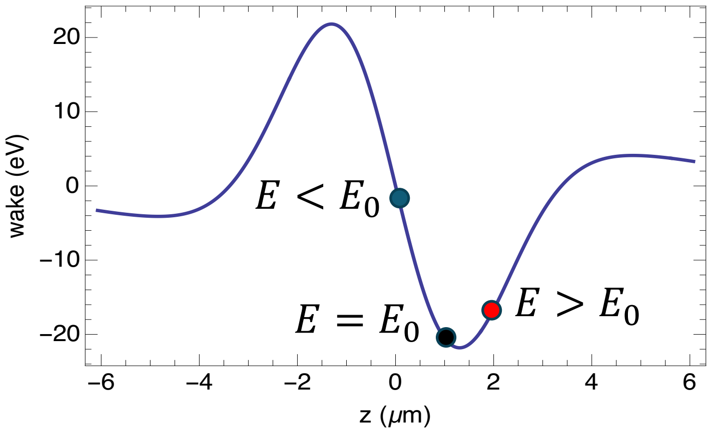
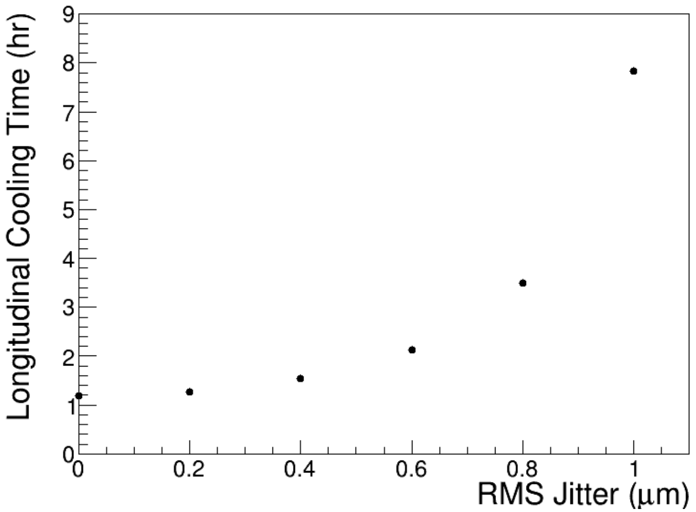
Unequal path-length of electrons and protons





Jitter of the path-length of electrons and ions leads to ***deterioration of cooling***. Simulations show that the rms pathlength jitter ~0.5 μm noticeably increases the cooling time.

Contributions to the jitter:

- Cooling section electron beamline PS stabilization ~ 3 ppm → longitudinal shift ~200nm
- Longitudinal Space charge→ ~56 nm
- CSR wake → ~140nm
- Hadron bypass → ~um

Getting path length identical is crucial

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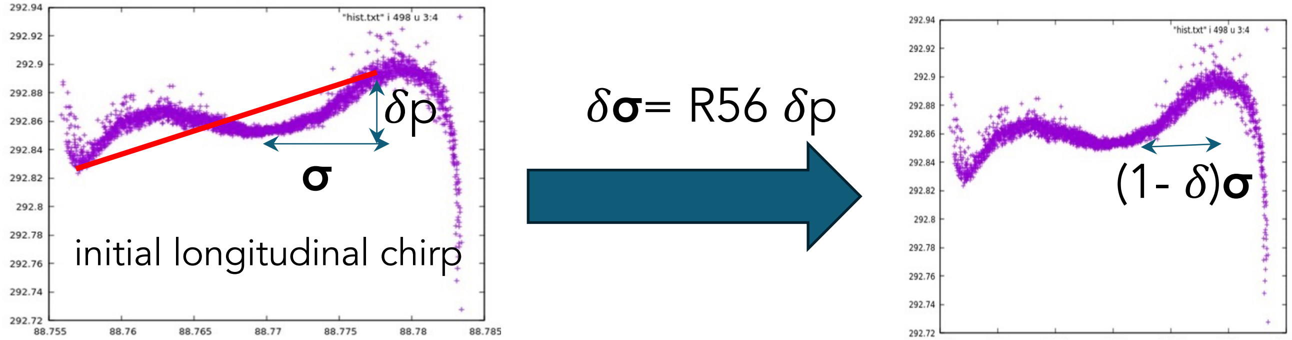
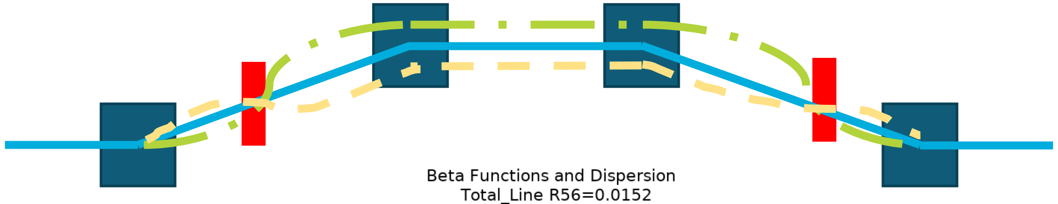
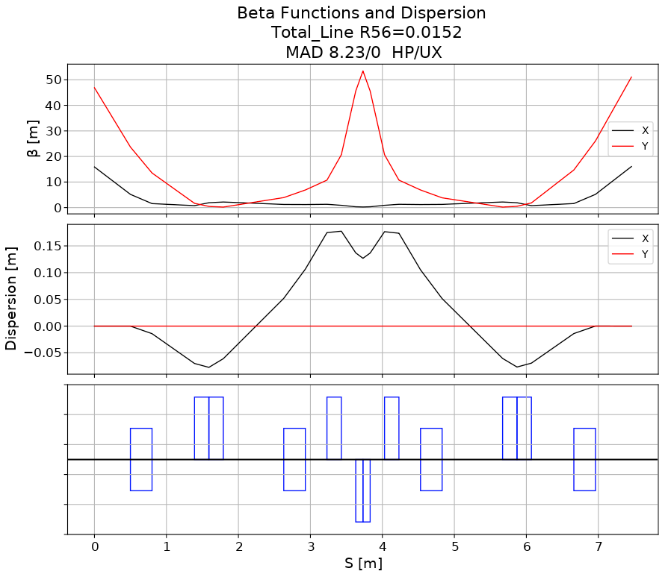
S. Seletskiy, A. Fedotov, D. Kayran. "Effect of coherent excitation in coherent electron cooler", arXiv:2106.12617 (2021).

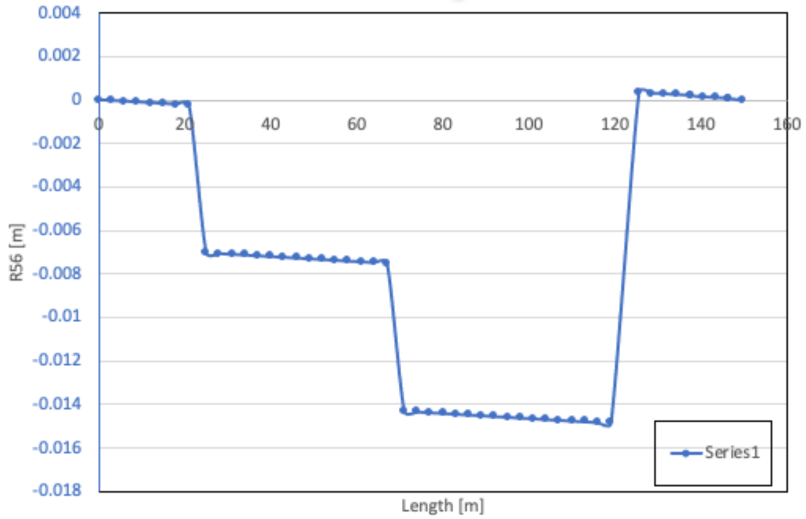
Chicanes of the amplification section



- The micro-bunched amplification has three chicanes.
- To avoid slippage:
    - R56_e from Mid M to K is ***zero***.
    - R56_e ***tunable*** for each chicane.

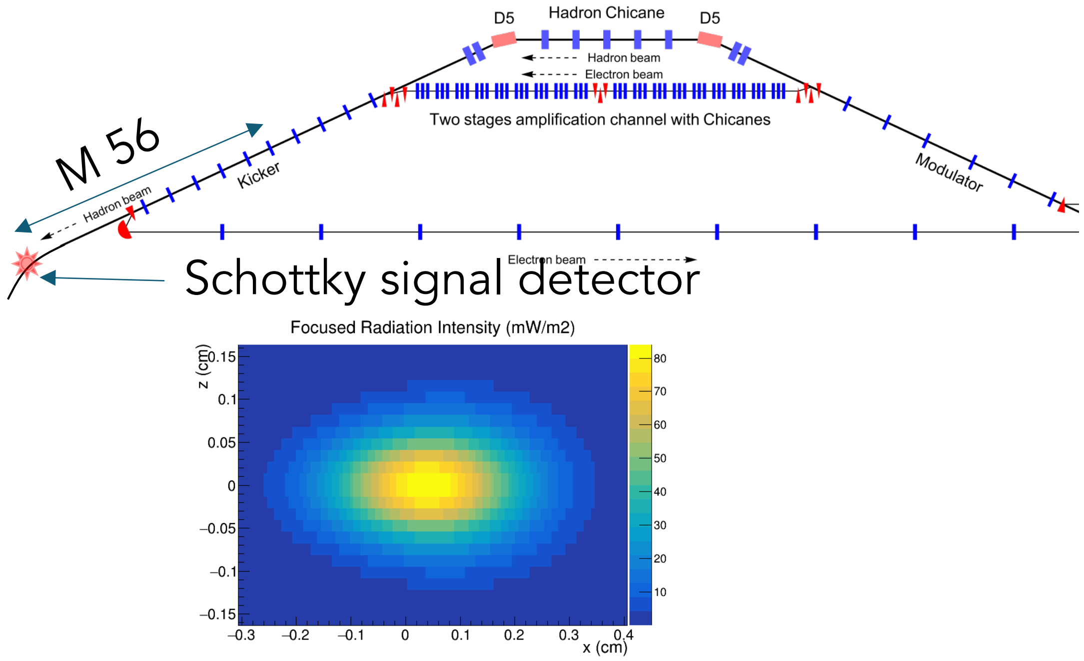


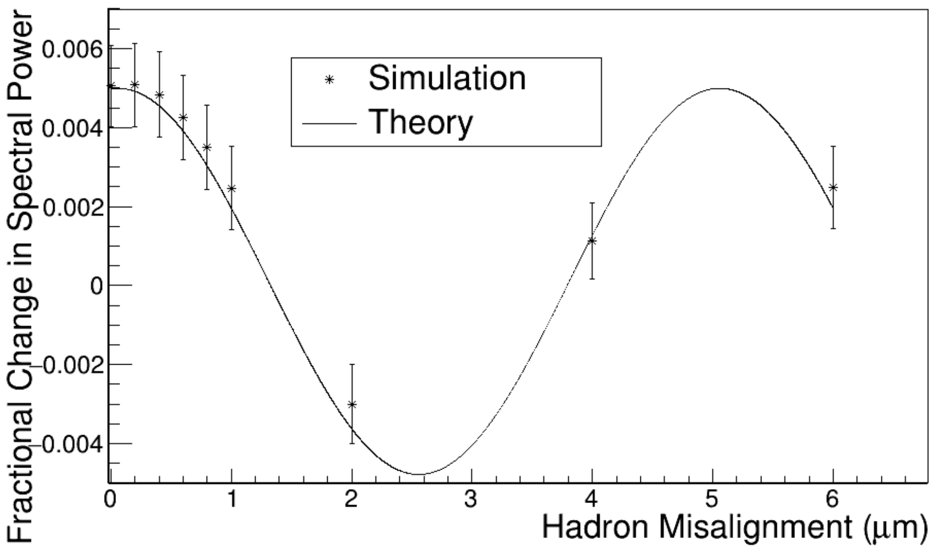




W. Bergan , et,al. PRAB 25.094401 (2023)

e-h longitudinal alignment



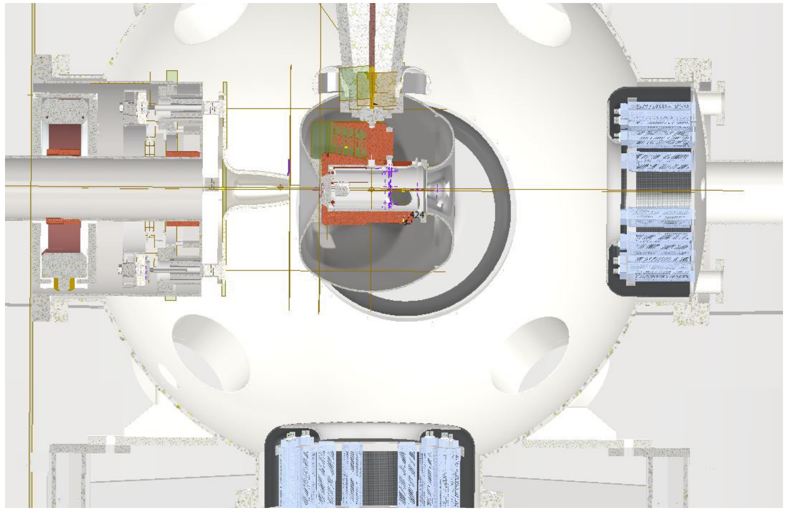


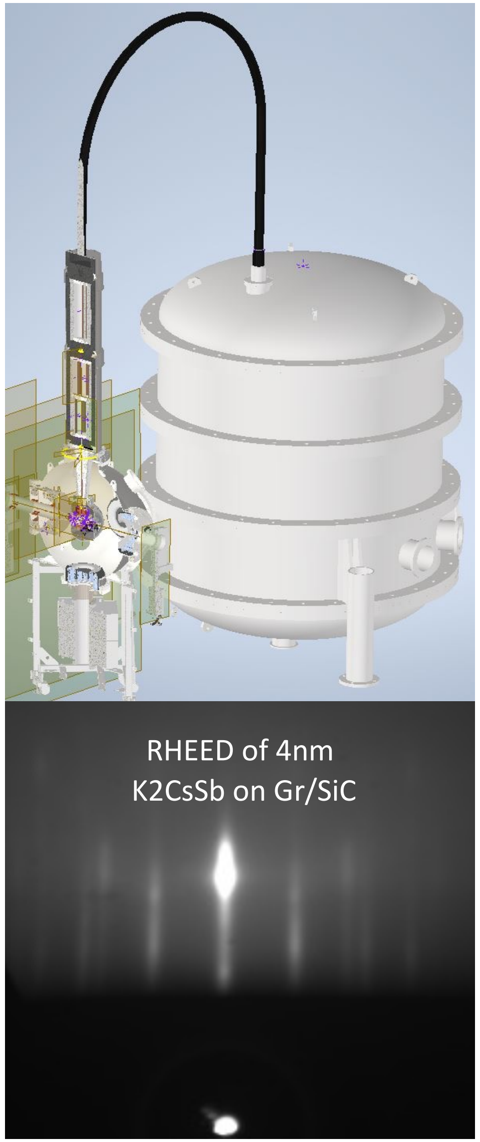
- Electron and hadron beams must be aligned longitudinally on ***sub-um scale***.
- Correction feedback will be needed to stabilize the path length
- At "detector" element downstream of kicker, the fractional change in hadron noise at wavenumber k is ***A cos(kΔz),*** where Δz is the electron/hadron misalignment, and A is some amplitude
- Signal modification amplitude at 275 GeV and 5 um wavelength using synchrotron radiation from dipole placed ~10 meters behind the kicker.

Strong Hadron Cooler e-source R&D

	World record	Goal
Voltage [kV]	550 (KEK)	550
Average current [mA]	65 (Cornell) 50(BNL)	100

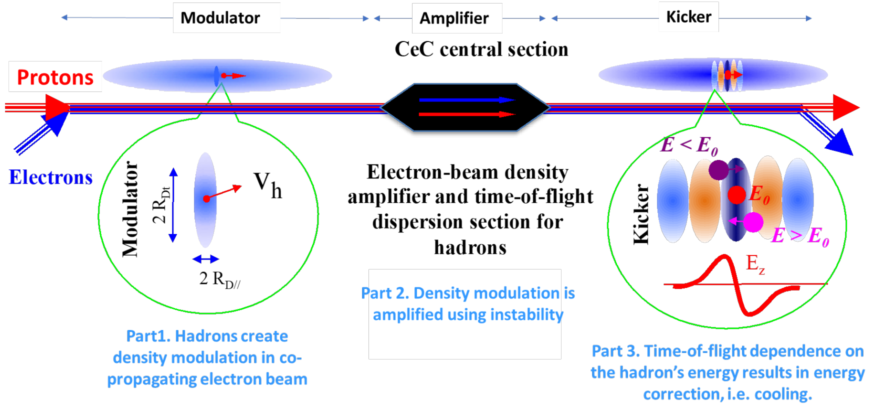
- Leveraging polarized gun design/commissioning and LEReC gun operation experience, we are developing an SHC R&D gun. Novel features:
  - 150 mA, 600 kV high voltage power supply.
  - A 600 kV HV cable and gun-attached resistor network can prevent cable storage energy from hurting the gun.
  - ***Cathode heat sink with cooling FC62 feedthrough can hold up to 20 W laser.***
  - The success of ***epitaxial growth*** of K2CsSb on Gr/4H-SiC (9% QE), gave us the chance to generate a much smaller initial emittance and longer lifetime.

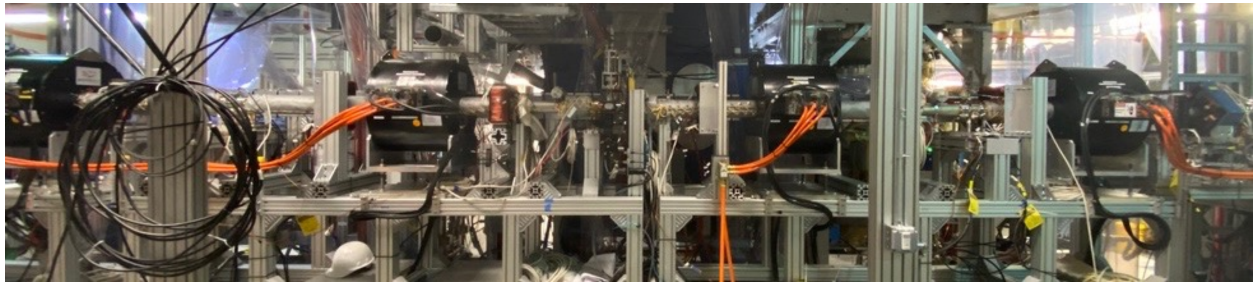




CeC experiment

Experimental study for cooling at BNL: Coherent Electron Cooling Experiment (CeC-X)





Solenoids for Plasma-Cascade Amplifier

- The experiment of demonstrating PCA-amplification is ongoing at each RHIC run.
- We observed
  - PCA-amplified imprint of ion beam in the electron beam radiation
  - Observed high PCA gain at frequencies between 5 and 10 THz
  - Regular electron cooling – albeit very weak – of 26.5 GeV/u ion beam
- CeC-X has many challenges. It has been improved year by year. And will continue with this and the next RHIC run.

G. Wang, EIC Machine Advisory Review, July 2022
V. Litvinenko et. al., Coherent Electron Cooling Experiment at RHIC: Status and Plans,

Summary

- SHC will boost EIC luminosity by a factor of 3-10.
- The Strong hadron cooler will establish a major advance in accelerator science and technology.
- We developed CeC theory, models, and cooling code. Now have a preliminary design of SHC based on CeC.
- SHC needs a high-quality electron beam. It requires the development of an ERL with parameters beyond the state of the art.
- Challenges exist, but many have already been removed, and there are promising avenues to mitigate others.

Acknowledgment

- BNL: W. Bergan, M. Blaskiewicz, D. Holmes, P. Baxevanis, S. Peggs, F. Willeke, V. Ptitsyn, G. Wang, V. Litvinenko, J. Ma, A. Fedotov
- SLAC: G. Stupakov
- Jlab: S. Benson, K. Deitrick, D. Douglas
- LBNL: J.Qiang
- Xelera: C. Mayes, C. Gulliford, N. Taylor


Thanks!
Questions?
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Back up

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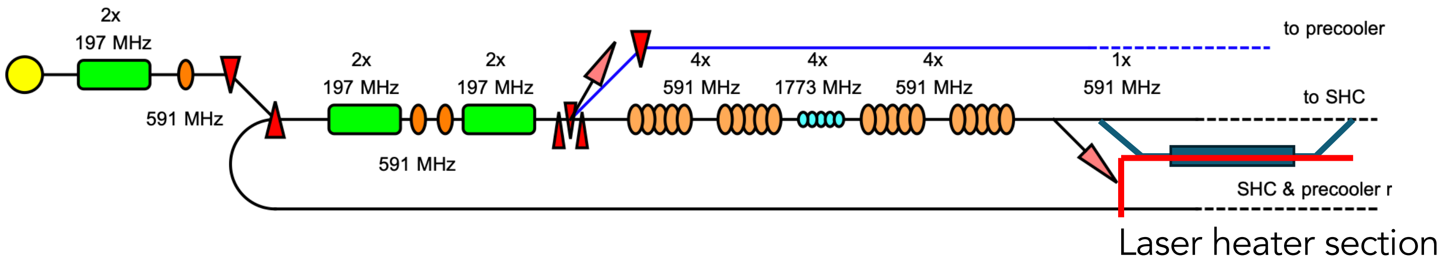
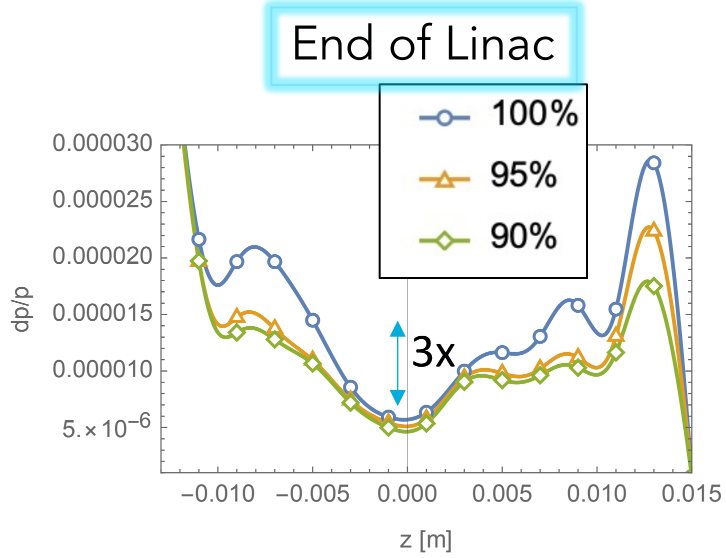
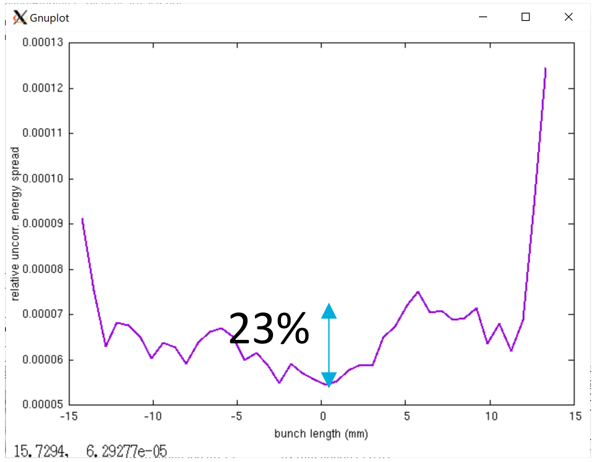
Using laser heater to get uniform slice energy spread





	Estimate parameters
Beam rms size	150 um
Laser rms size	210 um
Beam energy	150 MeV
Full bunch length	200 ps
Laser average power	1.1 kW



- Small energy spread caused saturation in the amplifier.
- At the end of Linac(150 MeV), propagate 98.5 MHz beam with laser in an undulator
- Increase in slice energy spread by 7.5 keV(5e-5).

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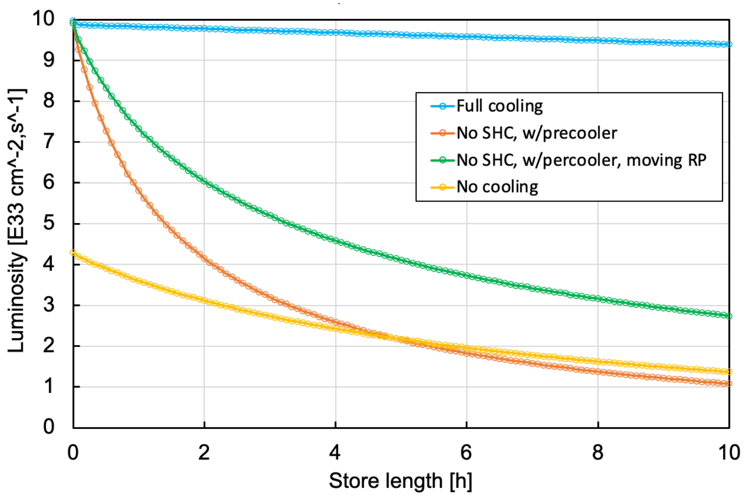
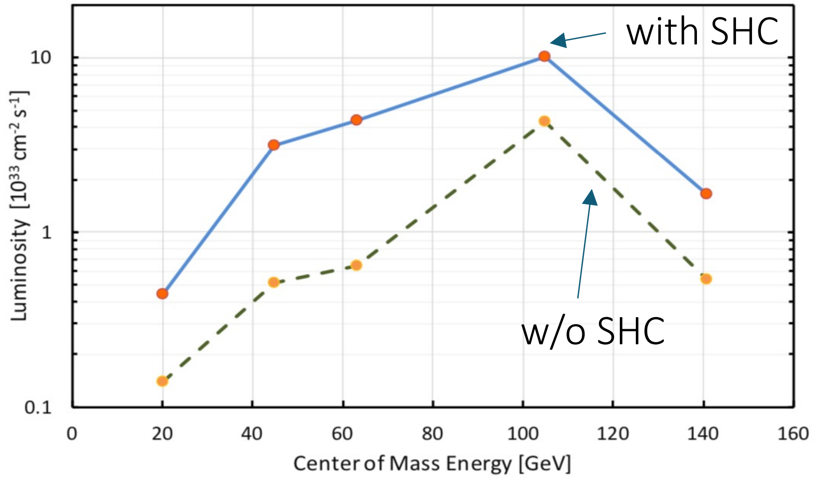
EIC cooling requirements

- Luminosity of lepton-hadron colliders in the energy range of the EIC benefits strongly (factor ≈ 3-10) from cooling the transverse and longitudinal hadron beam emittance.
- Cool the proton beam at 275 GeV and 100 GeV ;
- ***IBS*** longitudinal and transverse(h) growth time is 2-3 hours. ***Beam-beam*** growth time(v) is > 5 hours. The cooling time shall be equal to or less than the diffusion growth time from all sources.
- Must cool the hadron beam normalized rms vertical emittance at injection from 2.5 um to 0.3 um in 2 hours.





Integrated luminosity with cooling is > 3 x larger than without SHC.

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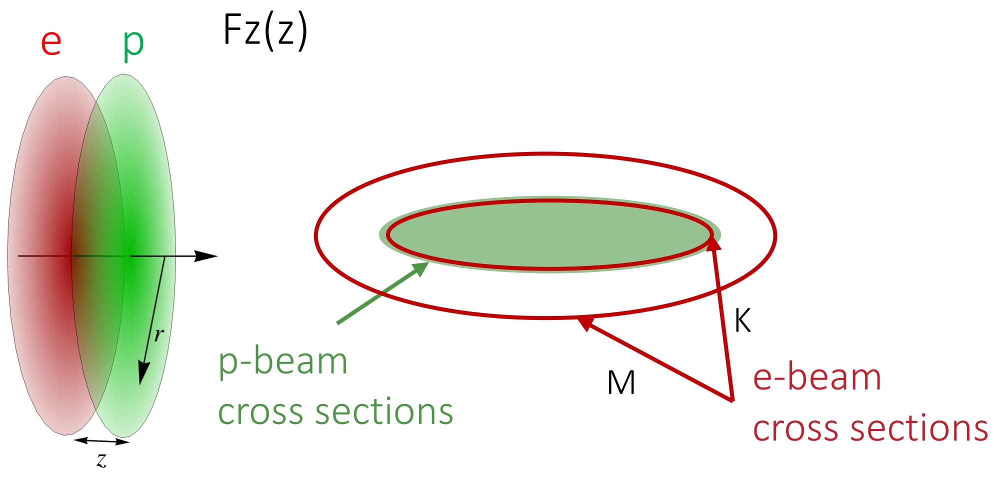
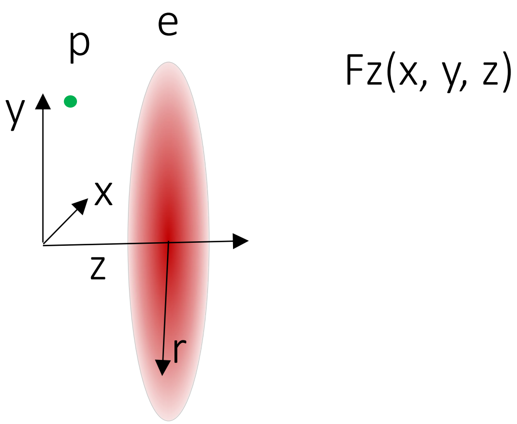
Cooling code using hybrid model





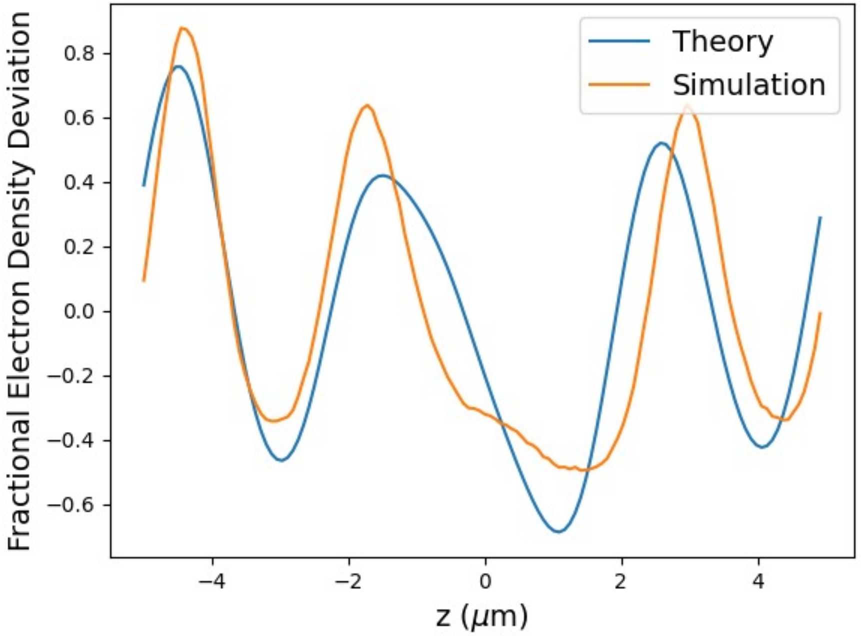
At CD1, quasi-1D model(G.S and P.B) :
A *quasi-1D* model was used to simplify analysis – p- and e-point charges are replaced by ***elliptical disks with 2D Gaussian distribution*** of charge over the surface of the slice.

Now, hybrid model(W.B):
Treat electrons as discs; Treat hadrons as ***point charges*** within modulator and kicker. Wake function W(xm,ym,xk,yk,dz)

With new hybrid model, the ***cooling time increased ~x1.7***

Saturation

- Finite electron current
  - Cannot create arbitrarily large electron density fluctuations



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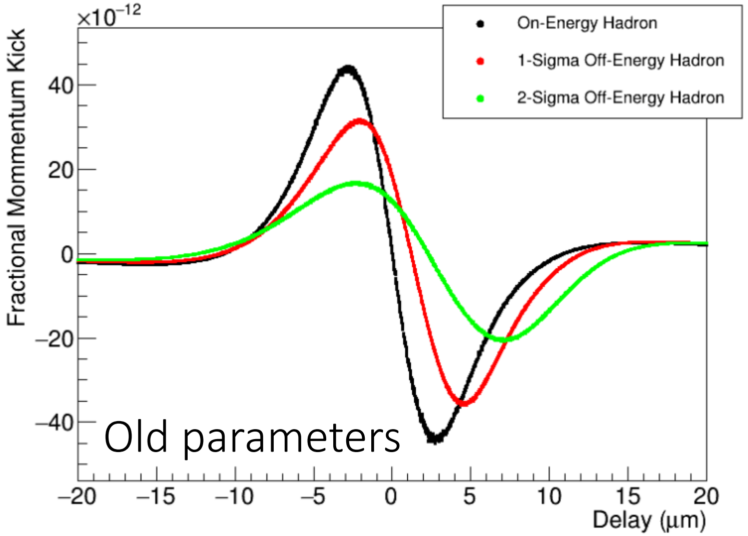
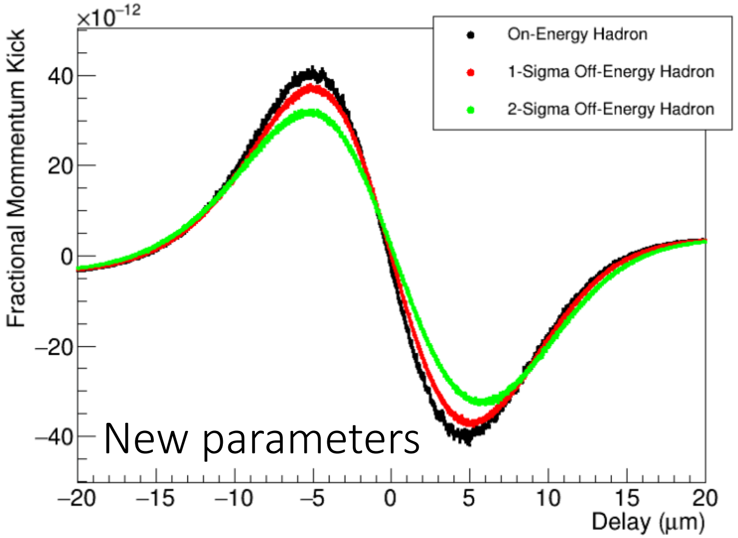
Hadron energy Drift

Off-energy hadron drifts are relative to the electrons in the modulator and kicker

$$\Delta z = \frac{L}{\gamma^2}\delta$$

By ***shortening the modulator and kicker length*** and lengthening wake wavelength by ***strengthening electron chicanes***, we can reduce the impact on the wake.





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3D cooling codes development and comparison

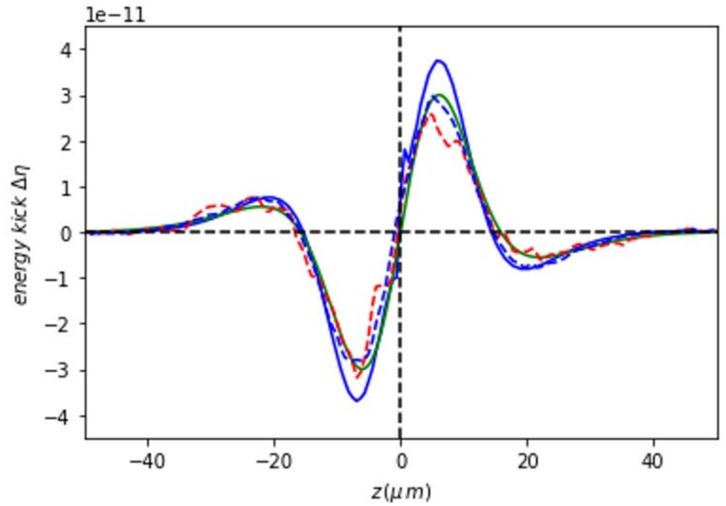
3D theory (solid): a frequency-domain approach based on the linearized Vlasov equation

3D simulation(dash): macroparticles with space charge force.

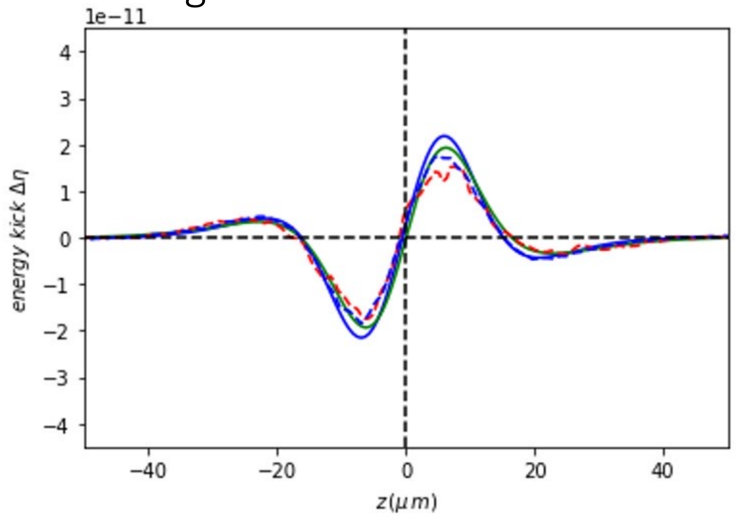
3D SPACE simulation(dash): parallel, relativistic PIC (used in CeC-X design)

Hybrid model(solid)

2-stages kicker ion at x=y=0

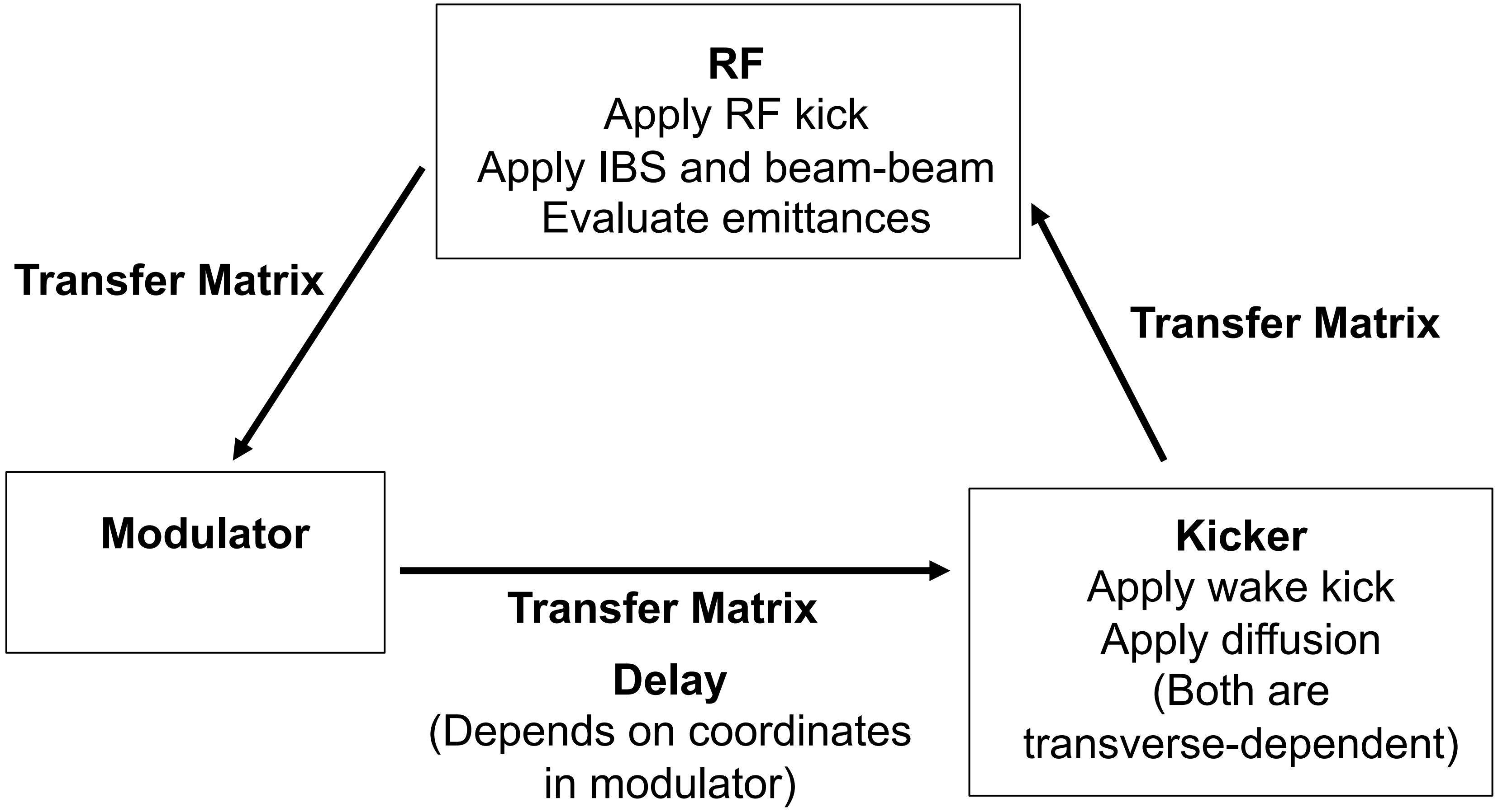


2-stages kicker ion at x=1.07σ

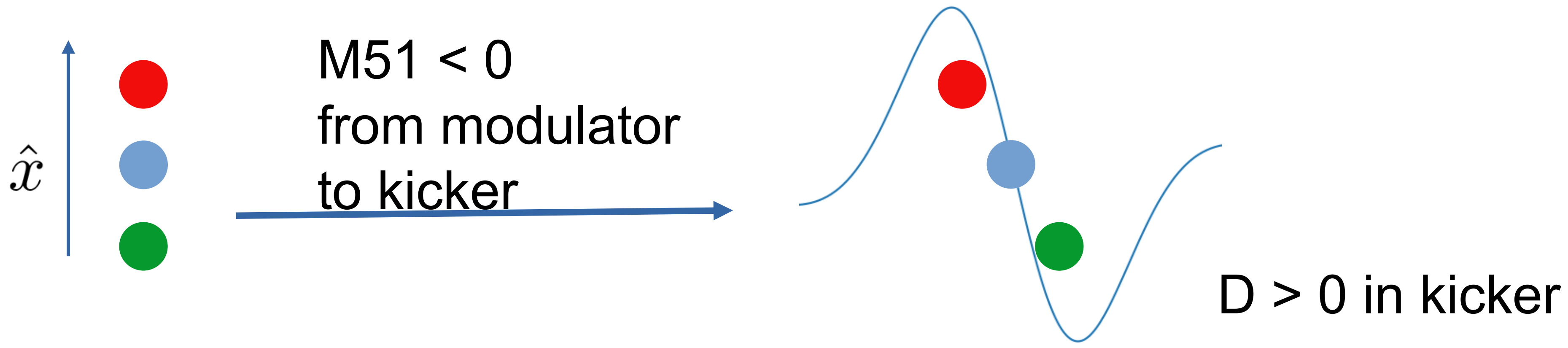


Four approaches give good agreement. The hybrid model used to design SHC can be trusted. The final cooling parameters will be checked by the 3D codes.

Multi-Turn Tracking



Transverse Cooling (x' = D' = 0)



$$J = \frac{1}{2}\gamma(x - D\delta)^2 \qquad \Delta J = -\gamma x D \Delta\delta$$

If x > 0, then Δz < 0 and Δδ > 0, so ΔJ < 0.
If x < 0, then Δz > 0 and Δδ < 0, so ΔJ < 0.
Either way, transverse action is reduced.

Details for more realistic case in PRAB 22, 081003 (2019).