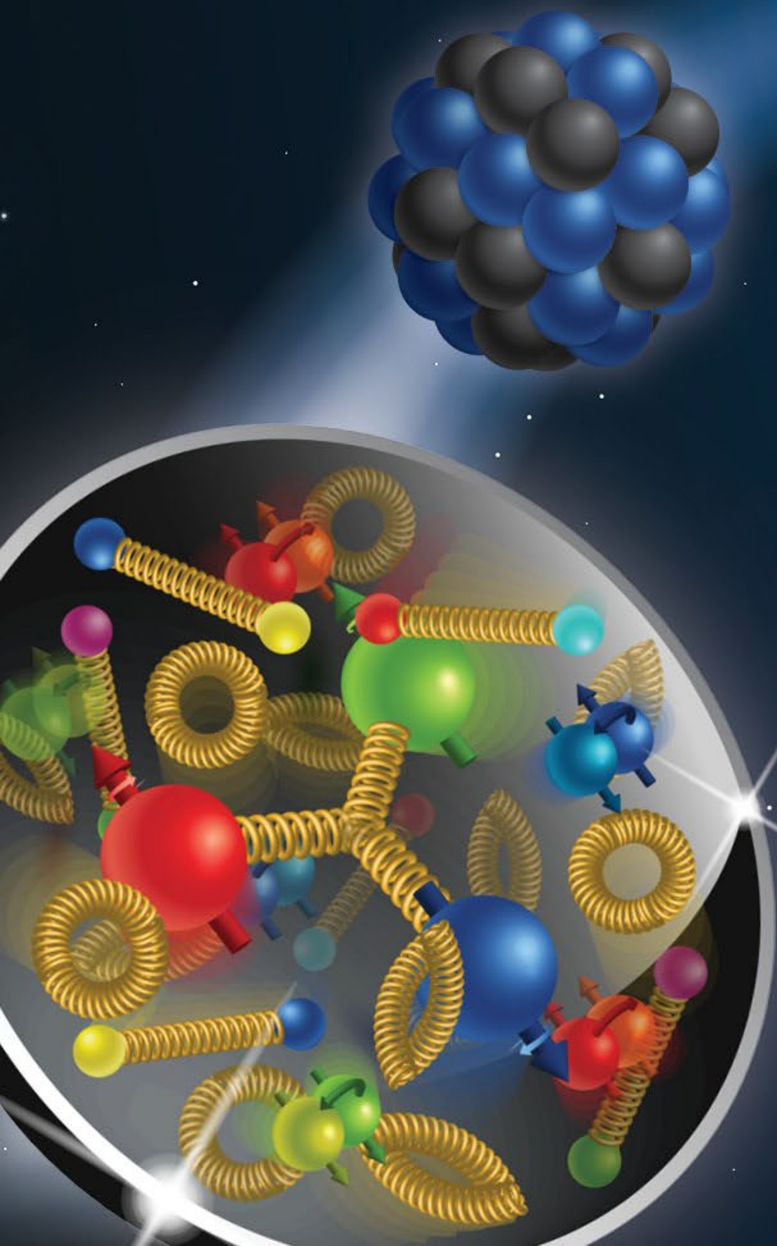

Electron Ion Collider Strong Hadron Cooling Injector and ERL

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Brookhaven National Laboratory

International Linear Accelerator Conference 2022

Aug. 28th-Sep. 2nd 2022

Electron-Ion Collider

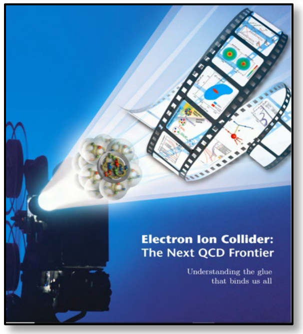
BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY | Office of Science

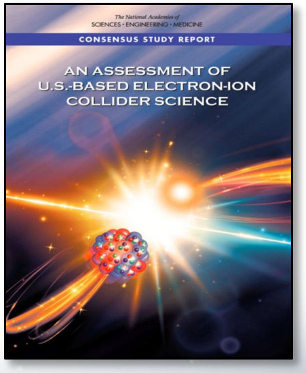
Outline

- EIC overview
- Strong hadron cooling introduction
- Strong hadron cooling accelerator design
  - SHC Injector and Linac
  - Cooling section
  - Beam noise
  - ERL design
  - Proposed SHC+precooler design: injector and Linac
- Summary

EIC Introduction

- Science goals
    - How does the mass of the nucleon arise?
    - How does the spin of the nucleon arise?
    - What are the emergent properties of dense systems of gluons?
- EIC Design Goals
    - High luminosity: $L=(0.1\text{-}1)\times10^{34}\ cm^{-2}\ s^{-1}$ ➔ $10\text{-}100\ fb^{-1}$
    - Collisions of highly polarized +/-70% e, p and light ion beams with flexible spin patterns
    - Large range of center of mass energies: $E_{cm}=(20\text{-}140)$ GeV
    - Large range of ion species: protons–Uranium
    - Ensure accommodation of a second IR
    - Large detector acceptance
    - Good background conditions



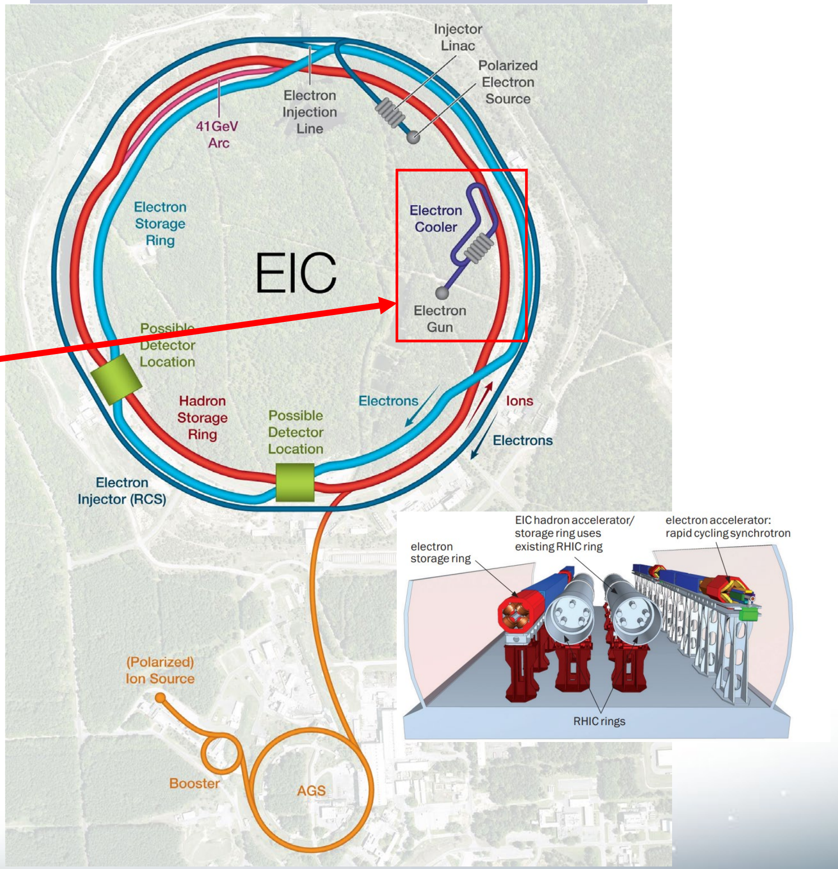


EIC Accelerators

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

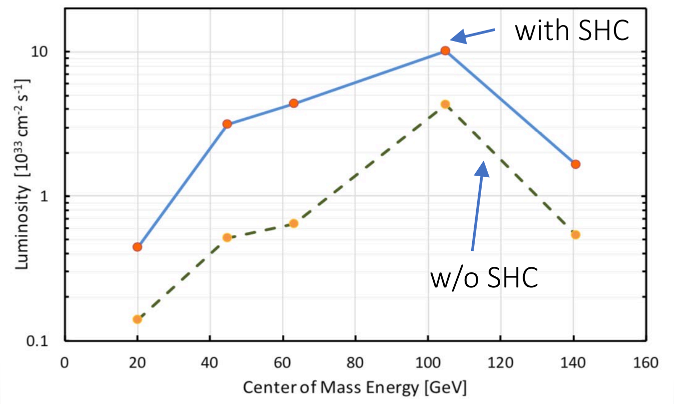
Design based on existing RHIC,
RHIC is well maintained, operating at its peak

- Hadron storage ring 40-275 GeV (existing)
  - RHIC Yellow(Blue) Ring
  - Many bunches, 1160 @ 1A beam current
  - Bright beam emittance
  - Strong hadron cooling (new)
- Electron storage ring (2.5–18 GeV, new)
  - Many bunches,
  - Large beam current (2.5 A) 10 MW S.R. power
  - s.c. RF cavities
- Electron rapid cycling synchrotron (new)
  - High charge polarized pre-injector
  - Spin transparent due to high periodicity



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,100 GeV ,and 41 GeV.
- IBS longitudinal and transverse(h) growth time is 2-3 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 from 2.5 um(from injector) to 0.3 um in 2 hours.
- The cooling section must fit in the available IR 2 space.



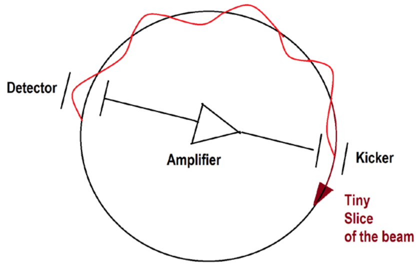
Using SHC
Using precooler

SHC: Strong Hadron Cooling, the cooling technique that provides strong cooling rate at high energies
Precooler: Cool proton at injection energy(24 GeV) using electron cooling

SHC: Coherent Electron Cooling (CEC)

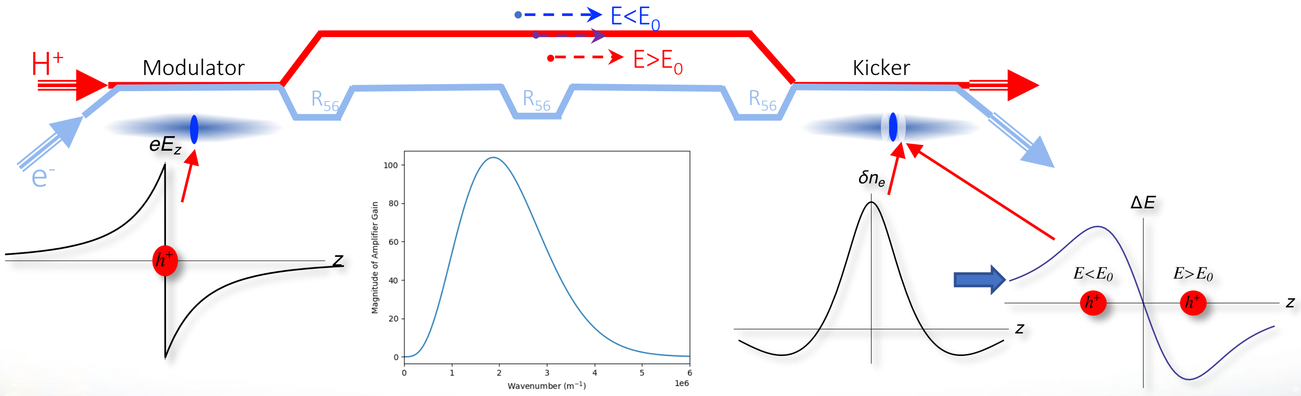
Similar to stochastic cooling, tiny fluctuations in the hadron beam distribution (which are associated with larger emittance) are **detected, amplified and fed back** to the hadrons thereby reducing the emittance in tiny steps on each turn of the hadron beam

- High bandwidth (small slice size)
- Detector(Modulator), amplifiers and fed back (kicker)



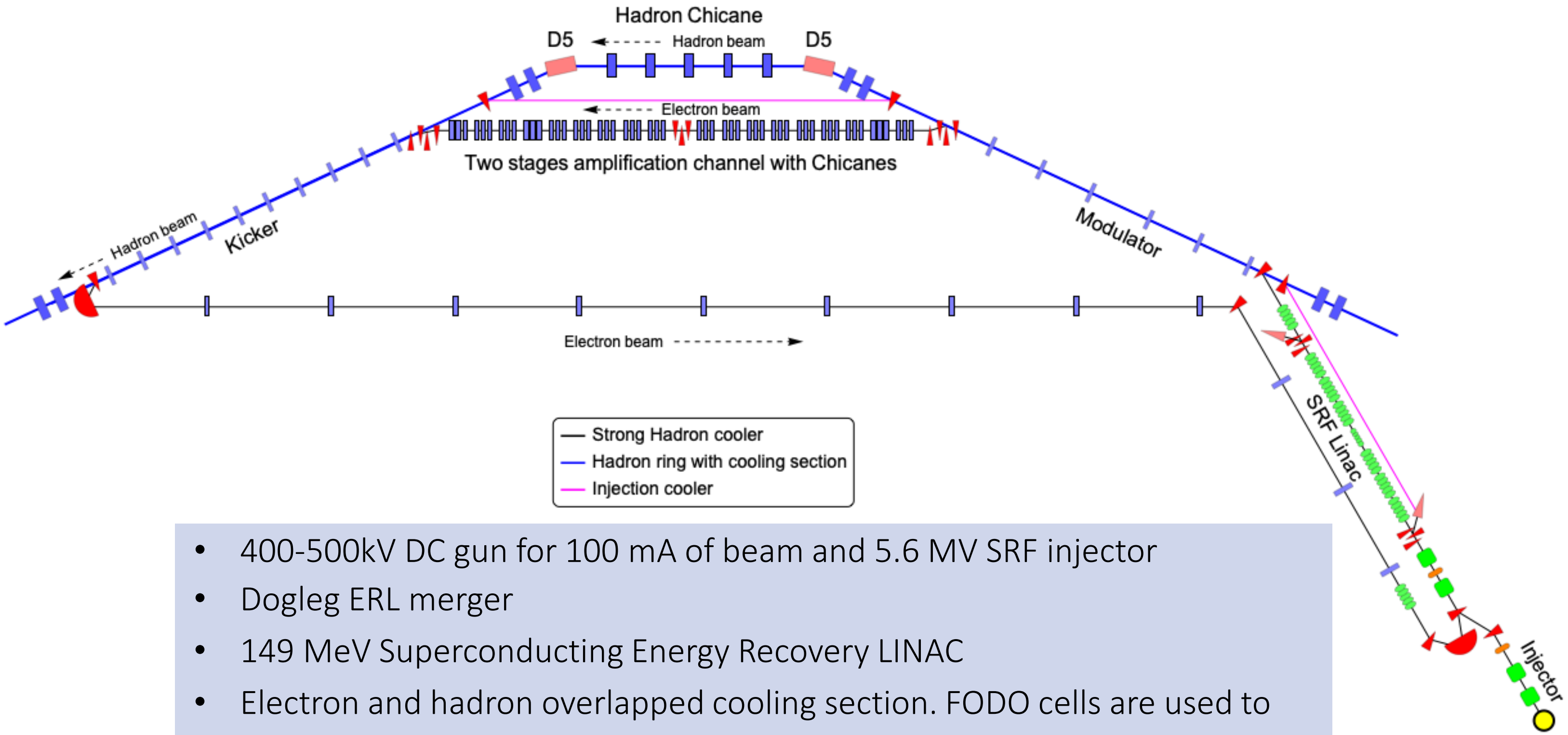
For high energy protons, a large bandwidth(tens of THz) is required:
➔ Using an electron beam to detect fluctuations, to amplify and to kick.

CDR baseline Amplification: micro-bunching amplifier(MBEC)



The pickup and the kicker are implemented via the Coulomb interaction of the hadrons and electrons, $\gamma_e = \gamma_h$. The electron modulated signal has to be amplified.

SHC schematic layout



- 400-500kV DC gun for 100 mA of beam and 5.6 MV SRF injector
- Dogleg ERL merger
- 149 MeV Superconducting Energy Recovery LINAC
- Electron and hadron overlapped cooling section. FODO cells are used to control ebeam size
- Amplification section with chicanes and triplets for electrons
- Hadron chicane path length matching & R_{56} adjust
- Return of electrons to ERL
- Electron beam instrumentation and diagnostics

Strong Hadron Cooler ERL Specifications

The EIC cooler ERL features unprecedented large beam current and small energy spread.
The 1D cooling simulation yields a cooling rate higher than the IBS heating.

Case	100 GeV	275 GeV
Electron Energy (MeV)	55	150
Electron Norm. Emit. (x/y) (mm-mrad)	2.8 / 2.8	2.8 / 2.8
Repetition rate (MHz)	98.5	98.5
Electron Bunch Charge (nC)	1	1
Electron Peak Current (A)	8.5	17
Electron Bunch Length (mm, rms)*	14	7
Electron Fractional Energy Spread	10^{-4}	10^{-4}
Hor./Vert. Elec. Betas in Modulator (m)	86.6 / 14.1	64/ 11
Hor./Vert. Electron Betas in Kicker (m)	49.7 / 10	16 / 2
Modulator Length (m)	55	55
Kicker Length (m)	55	55
H/V/L Cooling time(hr)	1.3/2.5/1.7	0.8/2.1/1.2

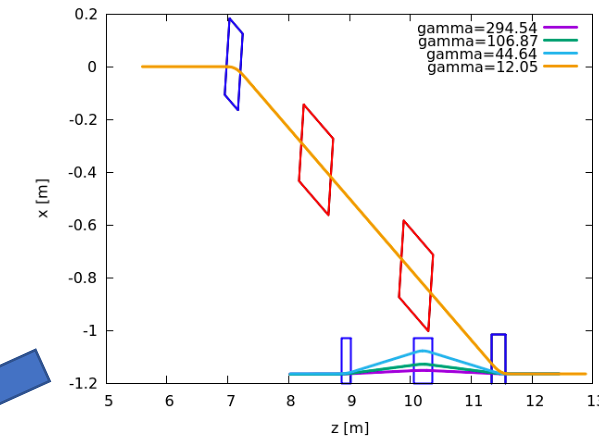
* *Gaussian bunch assumed*

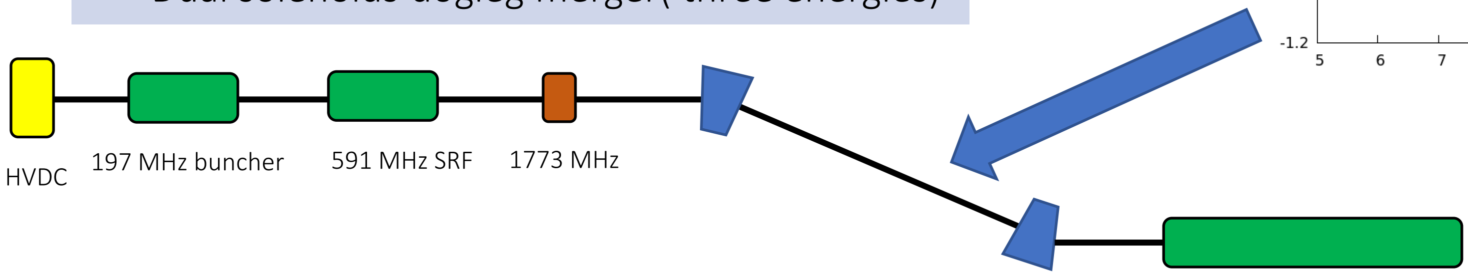
ERL Longitudinal matching

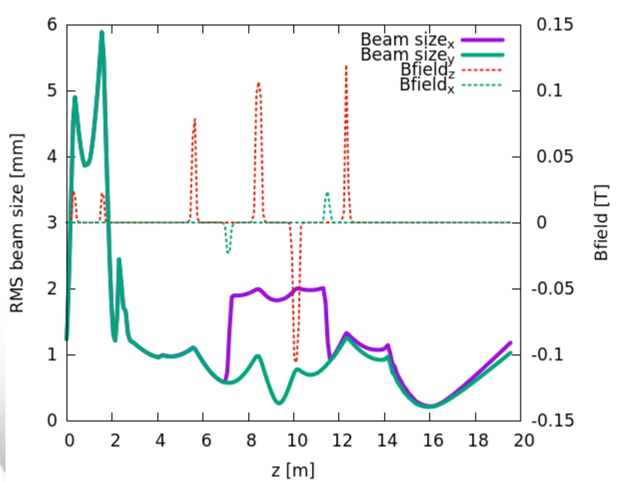
- Due to the long proton bunches, we need very long electron bunches with very small energy spread.
- We use the 5 cell 591 MHz SRF cavity as the main linac
- At 7 mm *rms*, the 6σ full bunch length is 30° of RF phase. We have to cancel the RF curvature using third harmonic cavity.
- Take space charge and CSR into account to minimize any energy slew or curvature in the bunch.
- A 14 mm rms bunch is 60° so it must be stretched.
  - Need R_{56} of 57 cm to stretch 3.5 cm bunch to 7 cm
  - For a 55 MeV beam, need 7.9 MeV in de-chirper at 591 MHz to take out the slope
- The return beam has to be chirped and compressed before back to the Linac

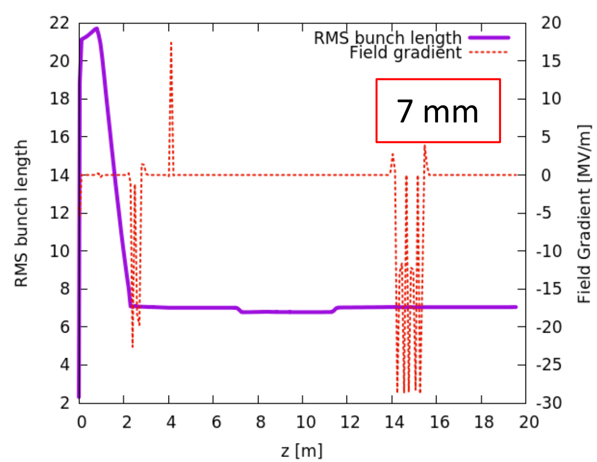
Injector

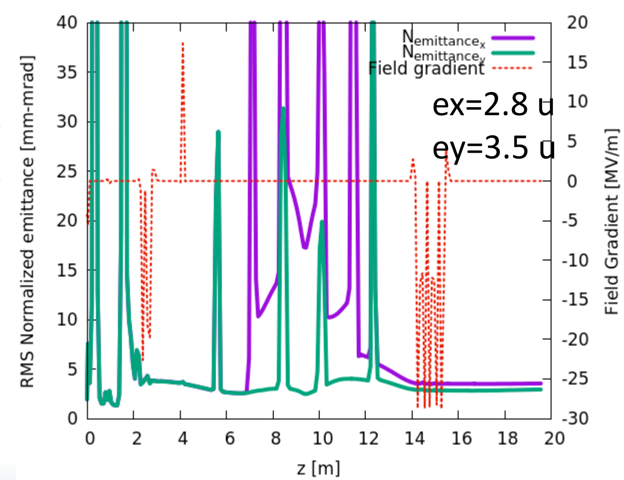
- HVDC gun with multi-alkali photocathode
- Ballistic compression
- Injector(buncher+booster) energy 5.6 MeV
- Dual solenoids dogleg merger(three energies)



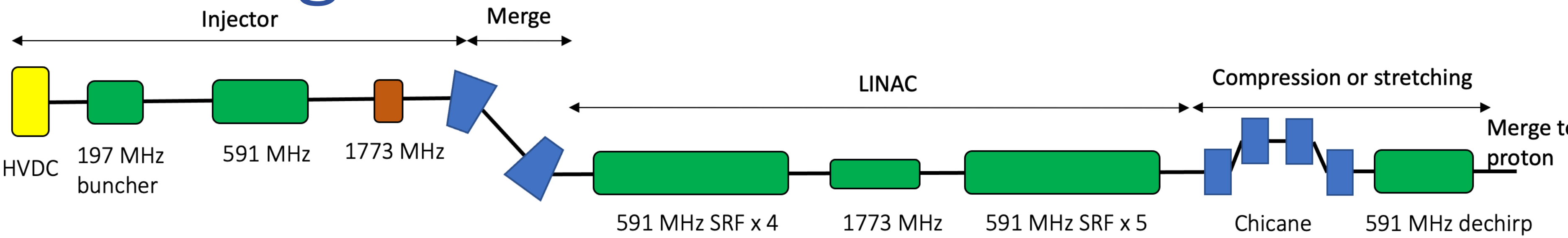




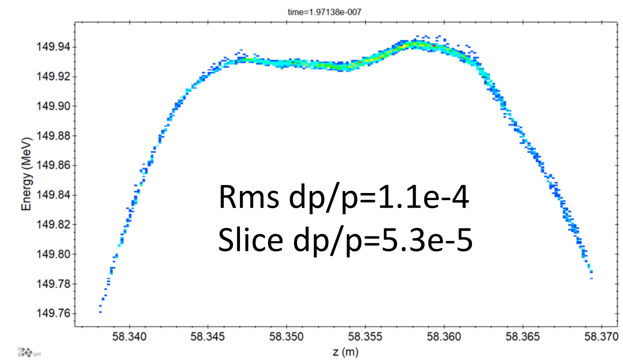


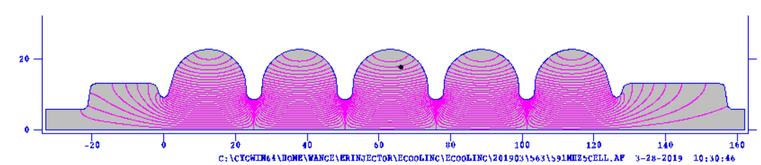


e-beam quality before entering cooling section



	parameter
Bunch charge	1 nC
Peak current	8.5-34 A
RMS Bunch length	14-3.4 mm
RMS Normalized emittance	3 mm-mrad
Energy	150 MeV
RMS dp/p	<1 e-4

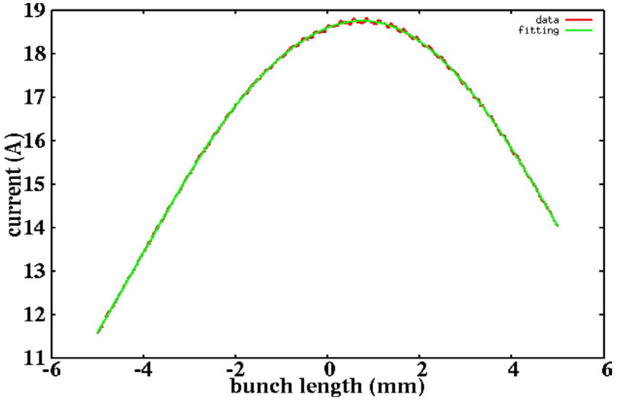




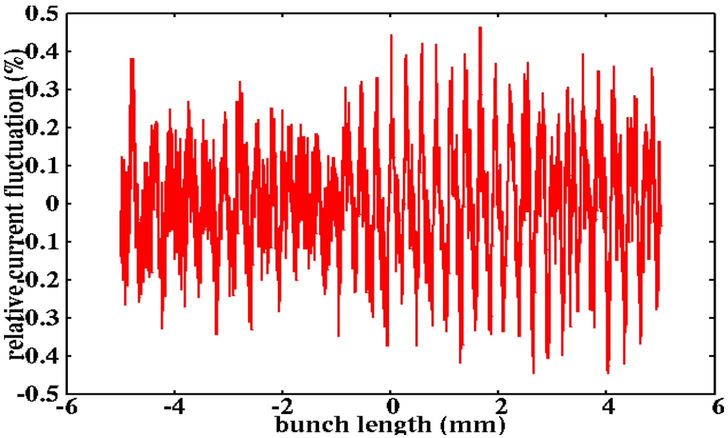
Injector and Linac up to cooling section are simulated by advanced 3D space charge code GPT 3.4.

Full number particles simulation

Before beam getting into cooling section

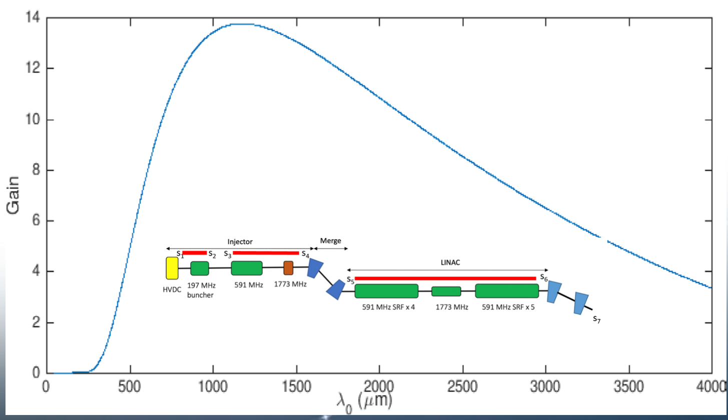


Relative Current Fluctuation $(I_d-I_{fit})/I_{fit}$



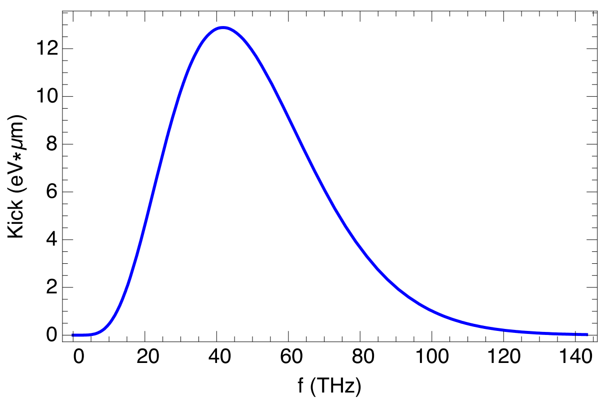
- Beam noise is extremely important for the SHC. Only allow 2x Possion noise.
- IMPACT simulation: energy spread, emittance, and bunch length are well matched to GPT results.
- Using the full number of particles can study the beam noise at the cooling entrance.
- Observed 280 um noise.

longitudinal space-charge gain

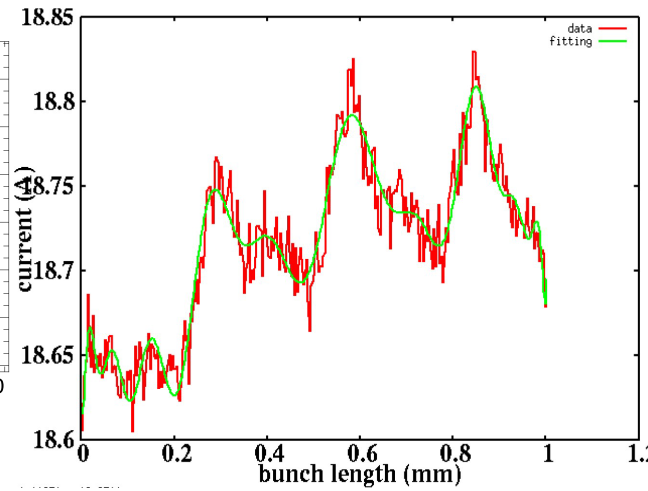


Shot noise simulation

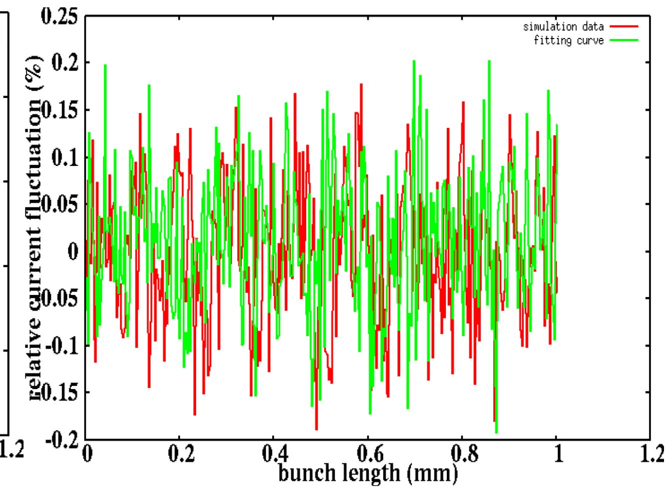
The kick generated by one proton in the kicker section



Zoom in current profile



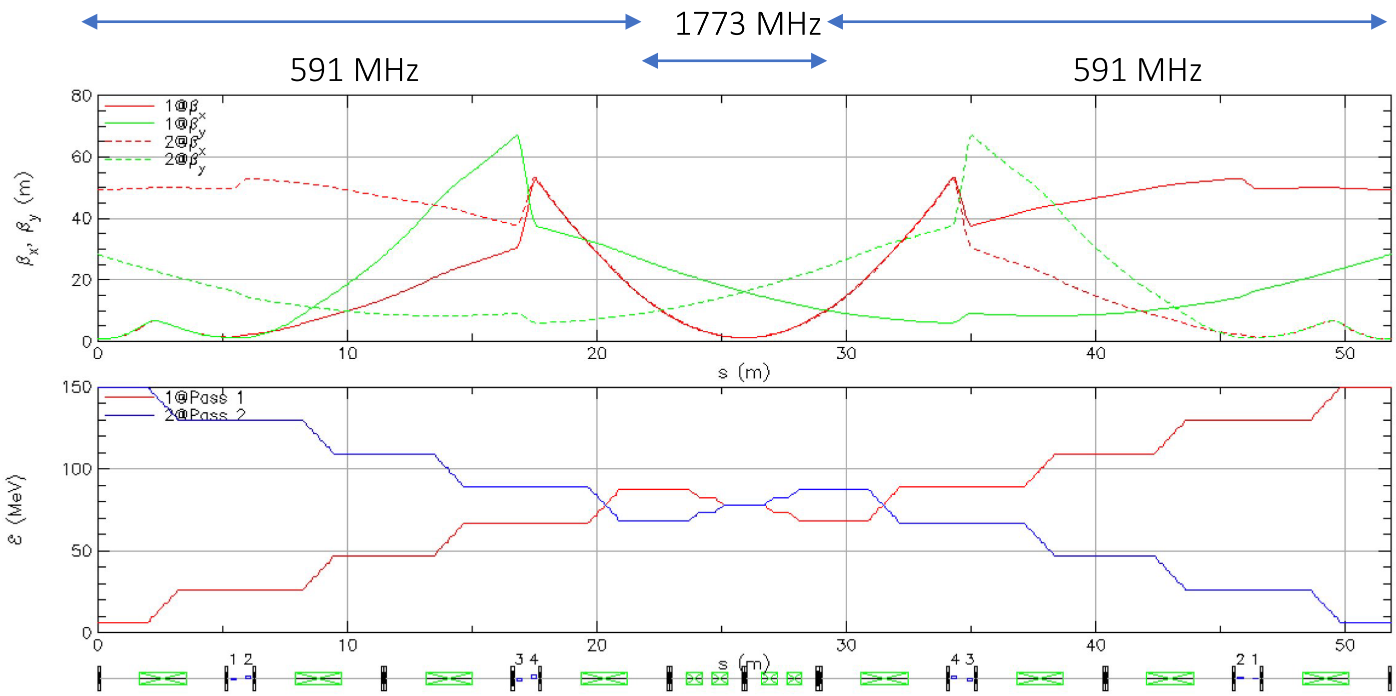
Compare simulation and directly sampled shot noise



RMS Fluc_simulation ~ 7.5e-4
RMS Fluc_analytical ~ 7.3e-4

- Observed > 280 um modulation;
- Noise amplitude is 2x shot noise.
- Cooling frequency bandwidth is 40 THz(3 um), which is far away from 280 um.
- The rest noise is at the same level as the shot noise
- Should not affect cooling performance

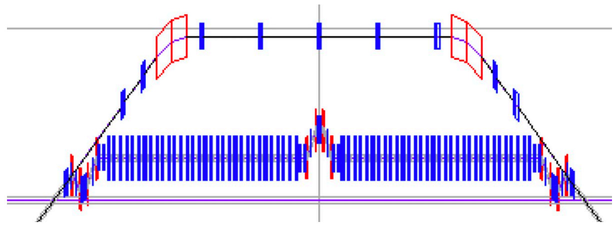
Energy recovery lattice

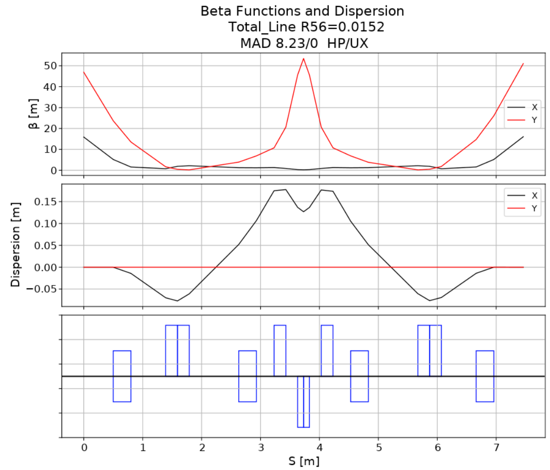


1st and 2nd passes of the electron beam matched transversely in the Linac section using BMAD.

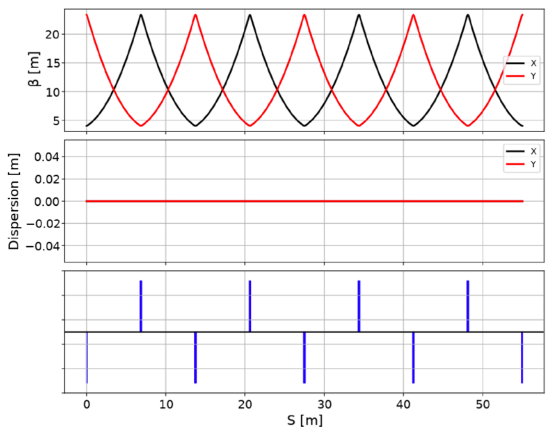
Cooling section lattice

Amplifier section

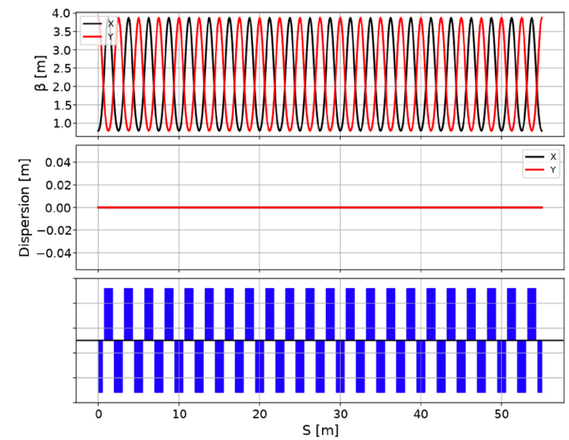




Modulator section

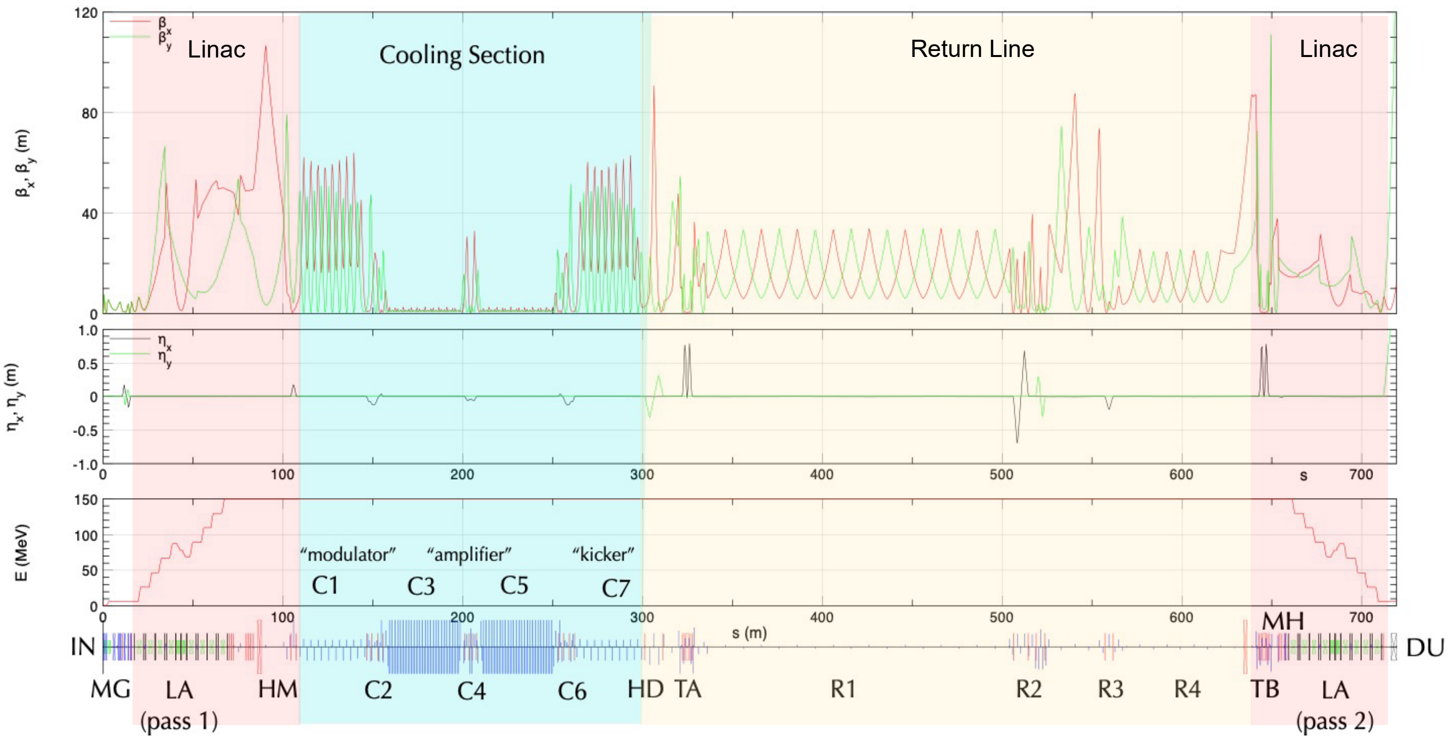


Kicker section



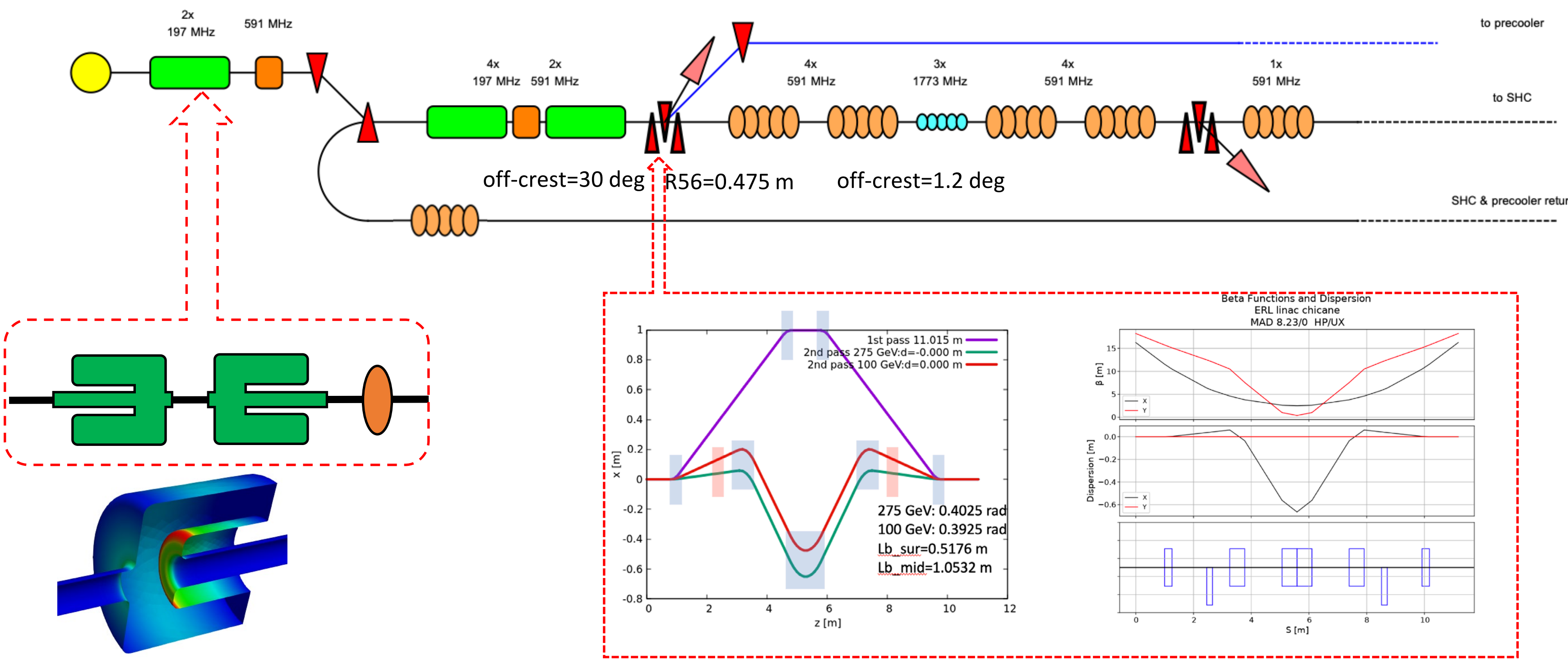
- Cooling section includes 55 m of modulator(M), 100 m of amplification and 55 m kicker (k).
- FODO cells are used for K and M section, the beta function can be tuned from 2.5 to 50 m for K and 11 to 85 for M.
- Triplets are used for the amplification section; the beta function is 1-2 meters.
- (-+)R56 tunable chicanes are designed for amplification section.
- Total R56 from M to K has to be zero

ERL optics: closed lattice



Electron-Ion Collider

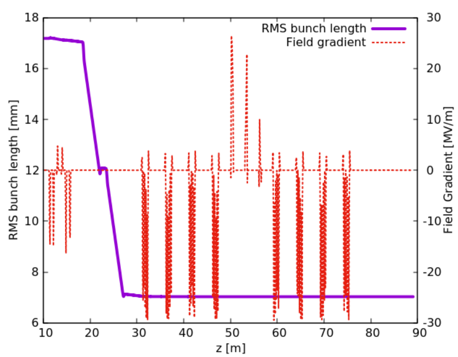
New design: SHC+pre-cooler injector and Linac



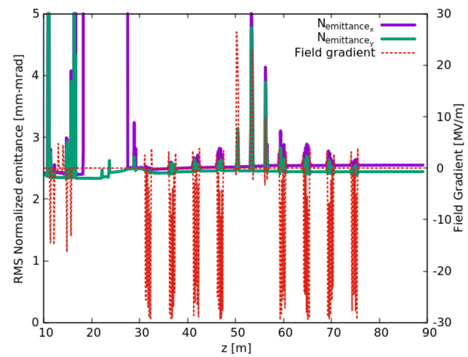
- Precooler bunch charge is 2 nC for 10^{-4} dp/p, 197 MHz cavities will be needed.
- SHC takes advantage of using 197 MHz and compresses the beam at 14 MeV using chicane.
- The chicane has four dipoles for 14 MeV beam and other three dipoles for high energy return beam. They have the same time of flight.
- Using 591 MHz+1774 MHz cavity to accelerate beam to the cooling energy.

e-beam quality evaluation

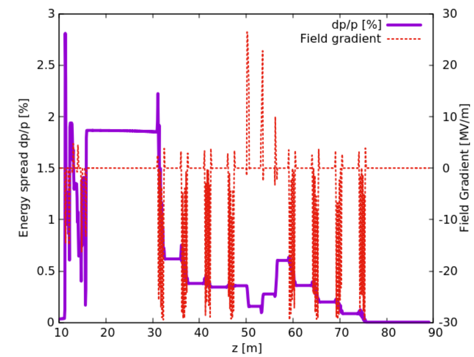
Bunch length

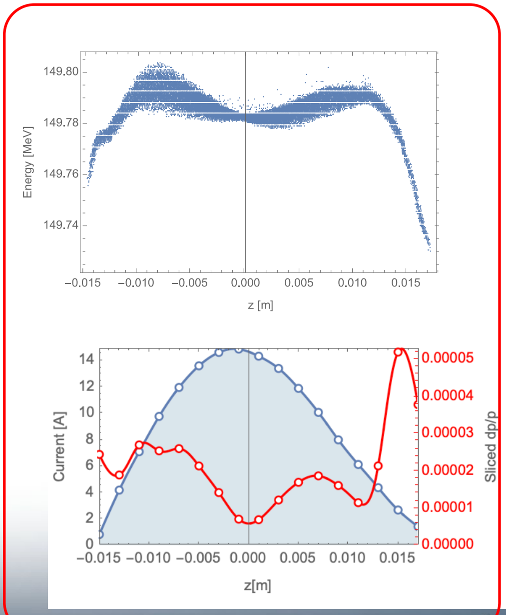


Emittenace



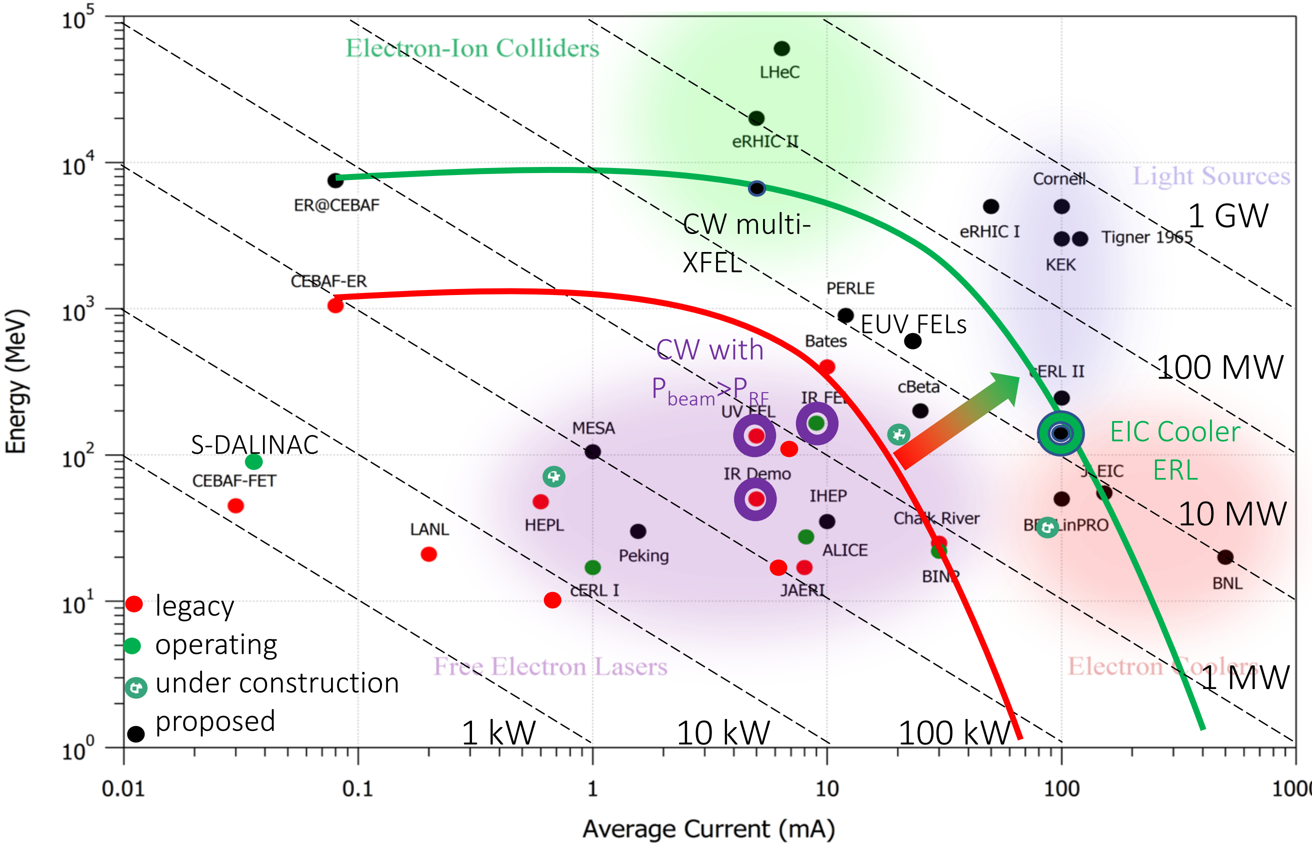
Energy spread





	SHC only	SHC+ precooler
Bunch charge	1 nC	
Energy	150	
RMS emittance x/y	3.1/2.8 mm-mrad	2.4/2.5 mm-mrad
rms dp/p	1.1e-4	4e-5
Slice dp/p	5.3e-5	2e-5
rms Bunch length	6.9 mm	7 mm

ERL Challenges



- Low noise electron beam
- High current ERL
  - ➢ Beam halo
  - ➢ BBU
  - ➢ Ion trapping
- High current high charge electron source (EIC R&D)
- Beam diagnostics: beam noise, beam halo, e-h alignment (~250 nm), energy spread measurement(<1e-4).

Summary

- SHC will boost EIC luminosity by factor of 3-10.
- The Strong hadron cooler will establish a major advance in accelerator science and technology.
- SHC needs a high-quality electron beam with high current, small energy spread, and small noise in the beam. It requires development of an ERL with parameters beyond the state of the art.
- A SHC baseline design has been developed that meets the beam requirements for the SHC.
- A SHC and precooler hybrid ERL has been proposed. ERL design is in progress.
- The ERL challenges have been evaluated and are being addressed with our detailed design and R&D.

Acknowledgements

BNL: W. Bergan, M. Blaskiewicz, D. Holmes, S. Peggs, F. Willeke, V. Ptitsyn, J. Skaritka, D.Xu, W. Xu, A. Fedotov, D. Kayran

SLAC: G. Stupakov

Jlab: S. Benson, Shaohen Wang, K. Deitrick

Xelera: C. Mayes, D. Douglas, C. Gulliford, N. Taylor