Progress on EIC Strong Hadron Cooling

Erdong Wang, William Bergan

Combined slides from:

G. Stupakov MAC review

E. Wang MAC review

S. Benson OPA review

E. Wang OPA review

CeC-EIC Meeting Oct. 15th

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab

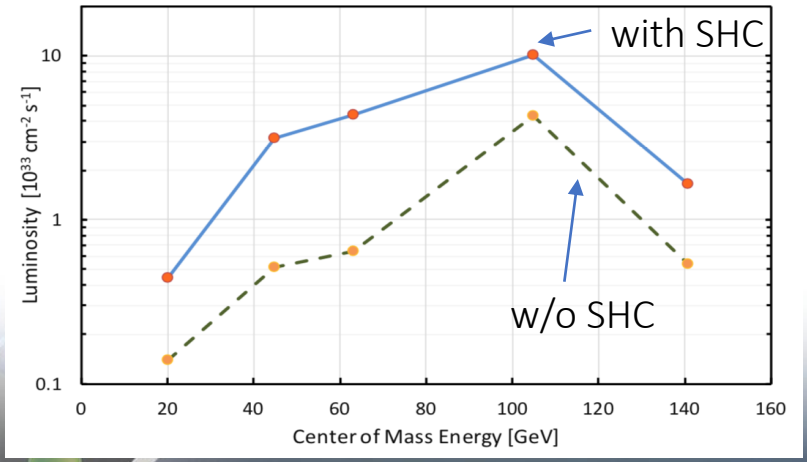
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Scope Overview
- Progress on SHC code development
- Progress on accelerator design
- Progress on infrastructure and layout

EIC cooling requirements

- 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.
- Cool the proton beam at 275 GeV and 100 GeV , need for 41 GeV under study.
- 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.
  - Pre-cooling at injection (24GeV) with electron cooling is desired.
- The cooling section must fit in the available IR 2 space.



Progress on cooling analysis and optimization tools

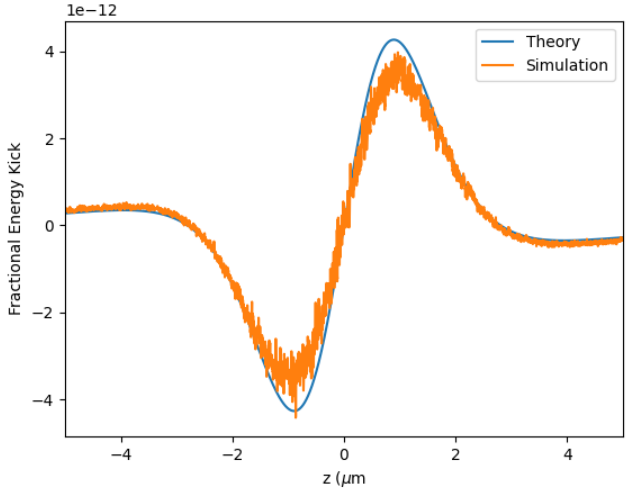
1. G. Stupakov and P. Baxevanis developed MBEC theories(based on D. Ratner's original paper) including:
   1D model, 2 amplification stages, transverse cooling and noise effects.

1. W. Bergan developed two 1D-codes:
   a) Obtain saturation information and determine impact on the wake.
   b) If the saturation is acceptable, simulate turn by turn hadron performance, interplay between cooling, diffusion and IBS in longitudinal and horizontal direction

Two methods have been compared. Now, W. Bergan's codes are used for optimizing the cooling performance and providing beam requirements.

Progress on computer simulations of MBEC

W. Bergan wrote (in C++/Python) a cloud-in-cell computer code that simulates the cooling process through macro-particle tracking*. First, a small fraction (~50 µm) of the two beams is simulated to find the wake. This wake is then used to calculate the cooling over many (~10^9) passages through the cooling section.

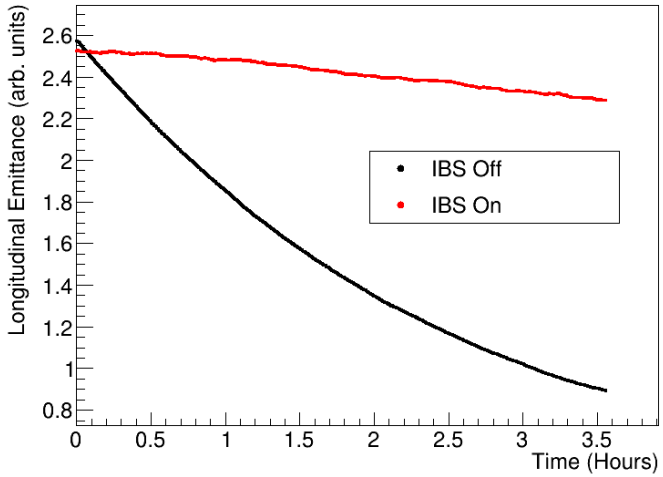


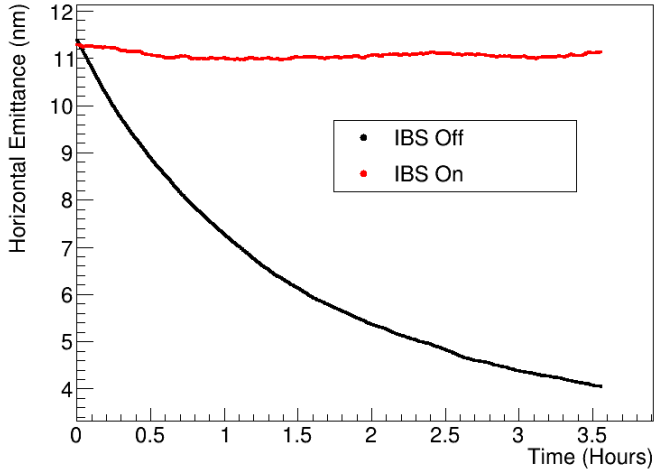
Wake for the case of one amplifier for 275 GeV protons, both from the linear theory and the average of 10 runs of the simulation. Good agreement is observed.

- Synchrotron motion of the ions is included.
- The code allows the horizontal dispersion D (and D') in the modulator and kicker and simulates horizontal cooling of hadrons together with the longitudinal cooling.
- It includes diffusion due to the noise in the hadron and electron beams, and IBS.
- The cooling time is averaged over the longitudinal distribution of the e-bunch

*) W. Bergan. Paper TUPAB179, IPAC 2021; W. Bergan et al. Paper TUPAB180, IPAC 2021.

Simulations of cooling time for EIC

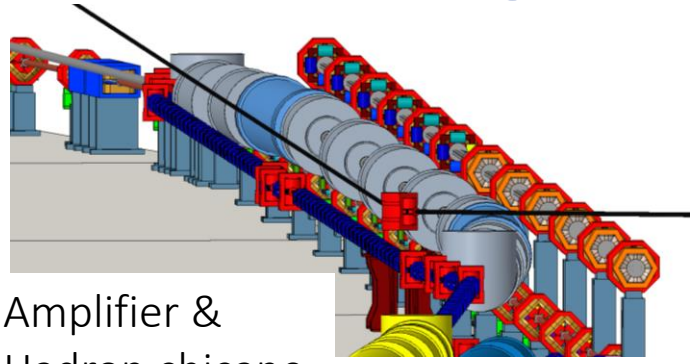




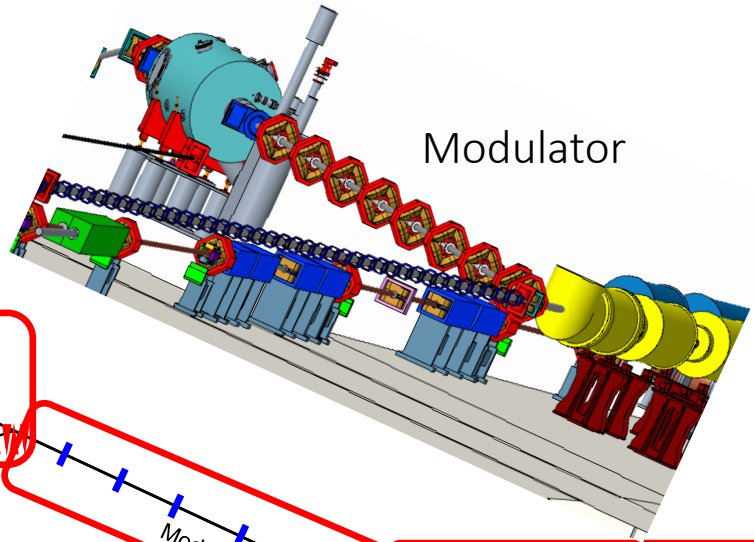
Cooling needs a low-noise electron beam

At 275 GeV, increasing the Poisson noise by a factor of 1.5 increases the cooling times to 2 hours horizontally and 3.1 hours longitudinally, close to the IBS limit. At 100 GeV, the noise in the electron beam is limited to 3 times the Poisson random noise.

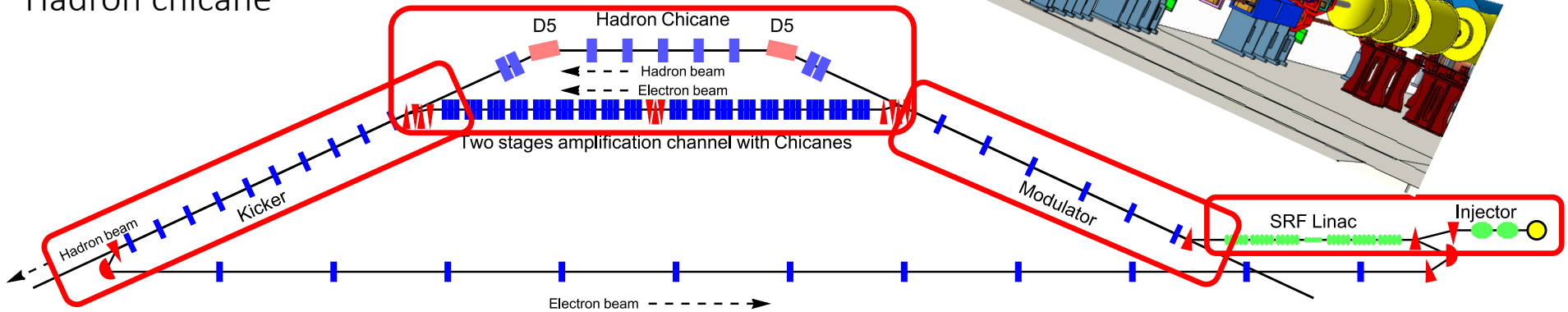
EIC Strong Hadron Cooling Facility

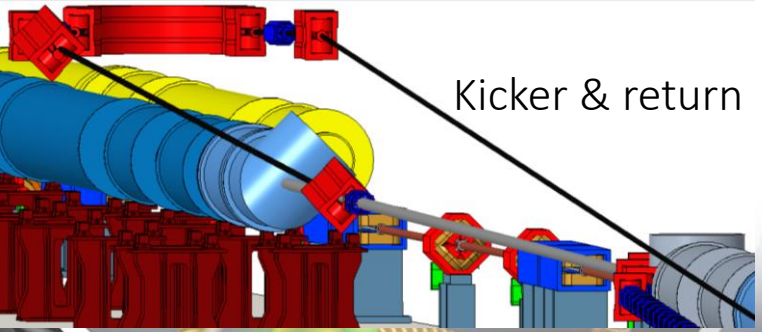


Amplifier &
Hadron chicane

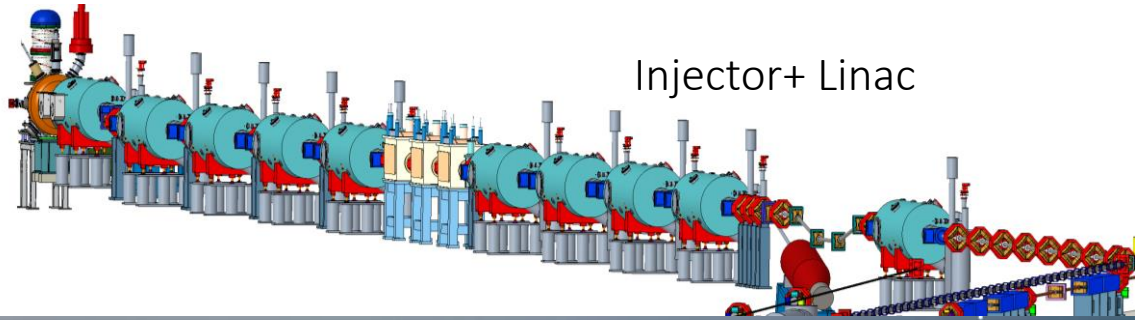


Modulator





Kicker & return



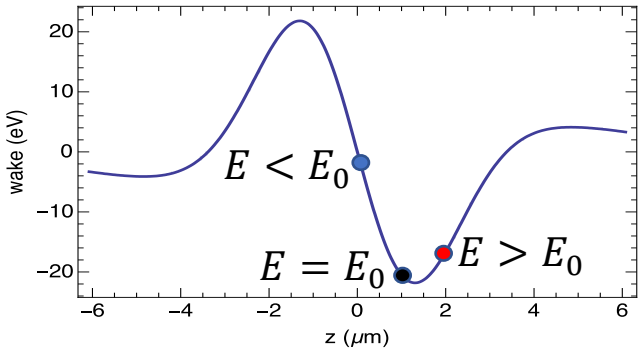
Injector+ Linac

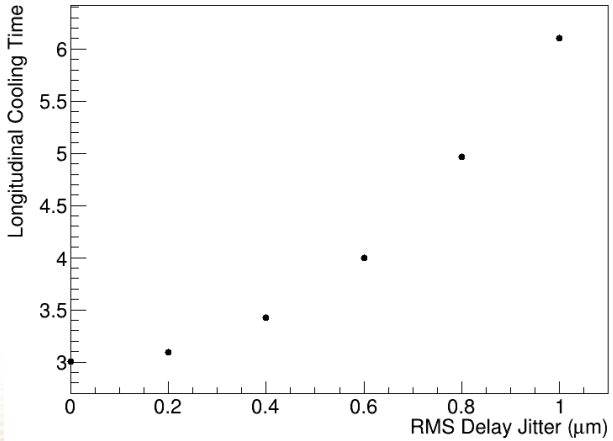
Optimized SHC parameters

Case	100 GeV	275 GeV
Protons per Bunch	6.9e10	6.9e10
Proton Bunch Length (cm)	7	6
Proton Emittance (x/y) (nm)	30 / 2.7	11.3 / 1
Proton Fractional Energy Spread	9.7e-4	6.8e-4
Electron Normalized Emittance (x/y) (mm-mrad)	2.8 / 2.8	2.8 / 2.8
Electron Bunch Charge (nC)	1	1
Electron Bunch Length (mm)	14	7
Electron Peak Current (A)	8.5	17
Electron Fractional Energy Spread	1e-4	1e-4
Horizontal/Vertical Proton Betas in Modulator (m)	40 / 44	40 / 60.2
Horizontal/Vertical Electron Betas in Modulator (m)	40 / 35	40 / 25
Horizontal/Vertical Proton Betas in Kicker (m)	40 / 44	40 / 60.2
Horizontal/Vertical Electron Betas in Kicker (m)	10 / 10	4 / 4
Modulator Length (m)	39	39
Number of Amplifier Drifts	2	2
Amplifier Drift Lengths (m)	43	43
Kicker Length (m)	39	39
R56 in First Two Electron Chicanes (cm)	1.86	0.50
R56 in Third Electron Chicane (cm)	-4.82	-1.15
R56 in Proton Chicane (cm)	-0.635	-0.226
Proton Horizontal Phase Advance (rad)	5.055	5.446
Proton Horizontal Dispersion in Modulator & Kicker (m)	1.108	1.36
Proton Horizontal Dispersion Derivative in Modulator/Kicker	-0.0177 / 0.0177	-0.0146 / 0.0146
Electron Betas in Amplifiers (m)	5.45	1.00
Horizontal / Longitudinal IBS Times (hours)	2.0 / 2.5	2.0 / 2.9
Horizontal / Longitudinal Cooling Times (hours)	1.8 / 2.3	1.9 / 3.0

- The 275 GeV and 100 GeV cases have been optimized.
- 41 GeV case will be studied later.

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 SC → ~56 nm
- CSR wake → ~140nm
- Hadron chicane contribution is being studied.

A feedback system for the path control seems necessary.

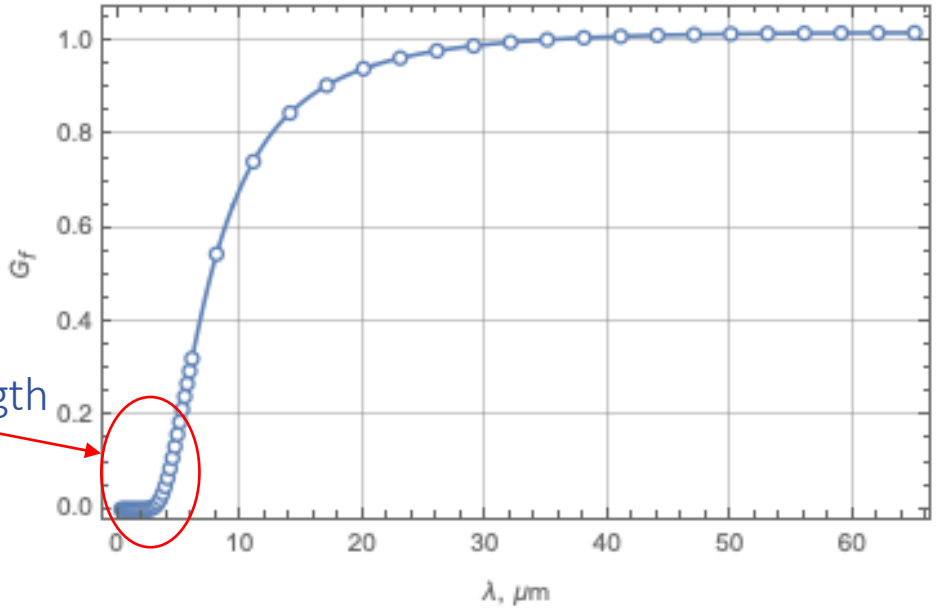
*) S. Seletskiy, A. Fedotov, D. Kayran. “Effect of coherent excitation in coherent electron cooler”, arXiv:2106.12617 (2021).

No CSR microbunching in electron chicanes

CSR wake can lead to amplification of microbunching in chicanes*.

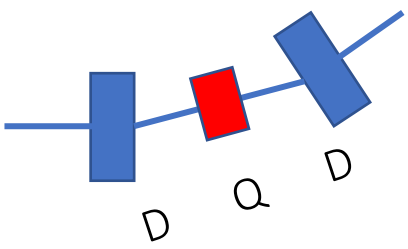
- Send a small density perturbation in the beam with the wavenumber k.
- Calculate the ratio G of its amplitude at the exit to the amplitude at the entrance.

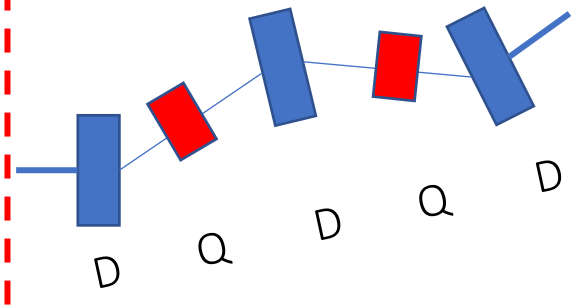
Cooling wake wavelength

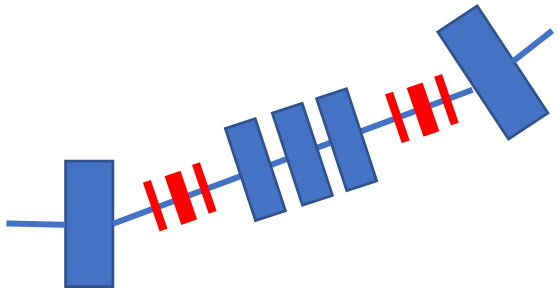


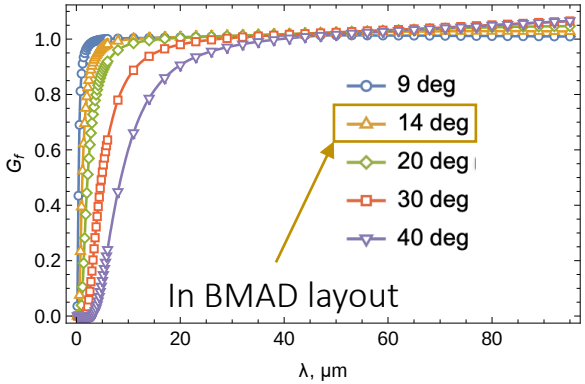
*)S. Heifets, G. Stupakov and S. Krinsky. “Coherent synchrotron radiation instability in a bunch compressor”, PRAB,5,064401 (2002).

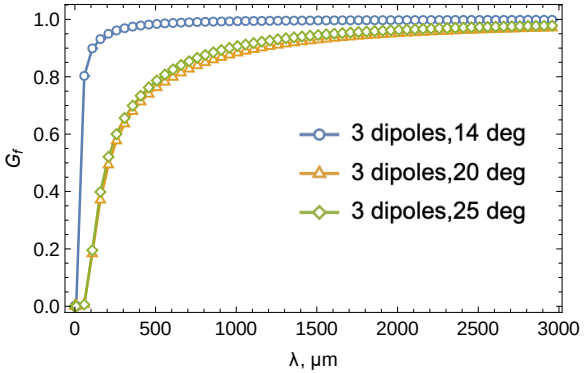
Comparison of different bends

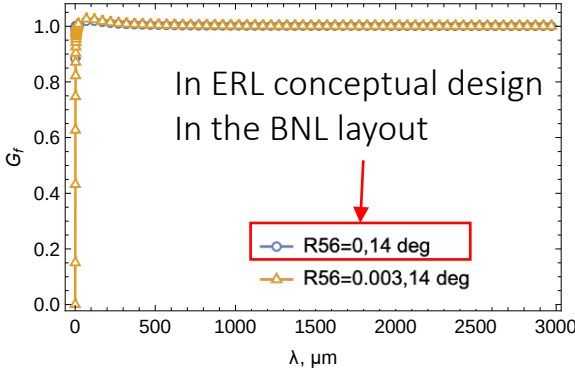


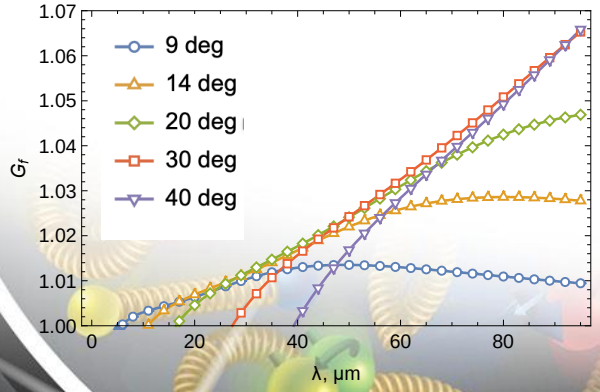


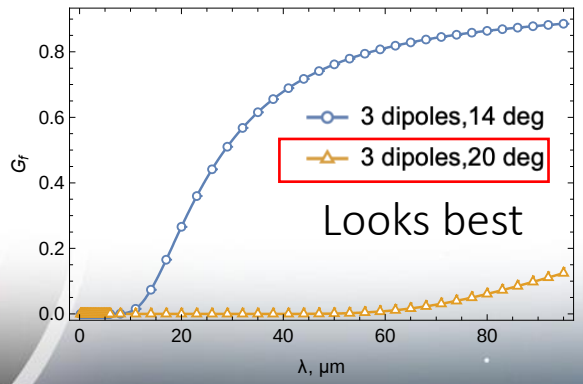


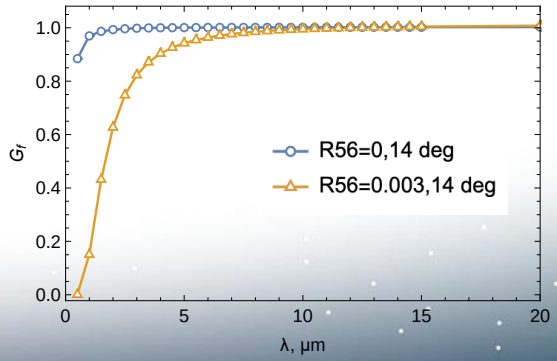




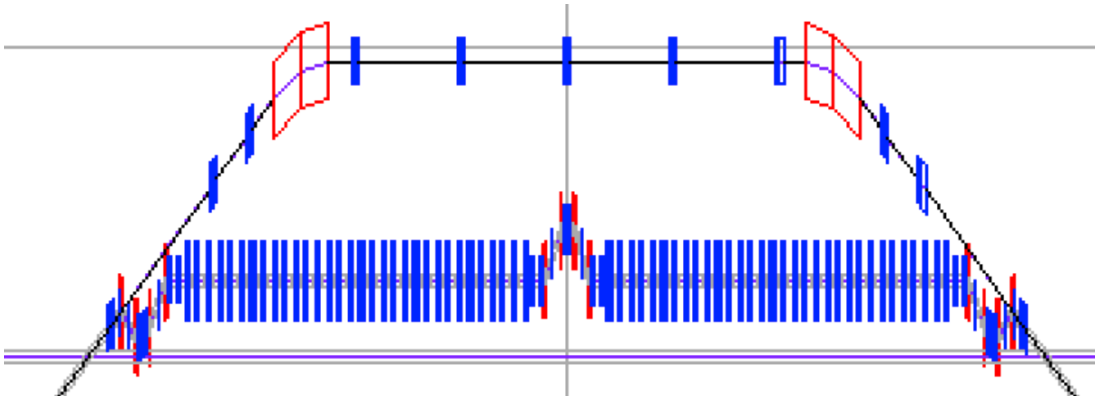


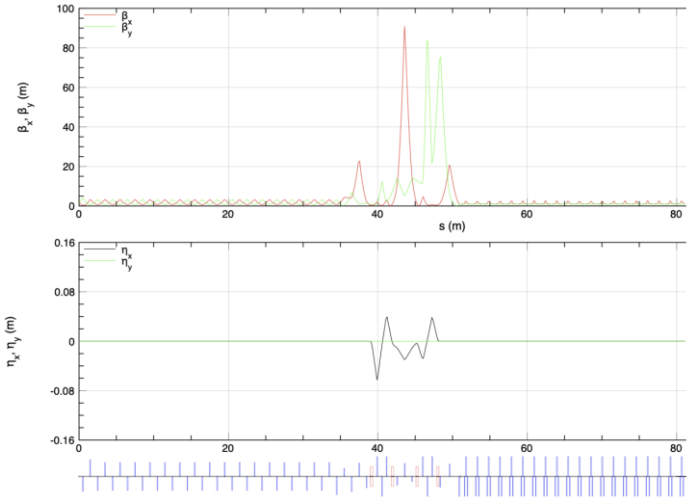






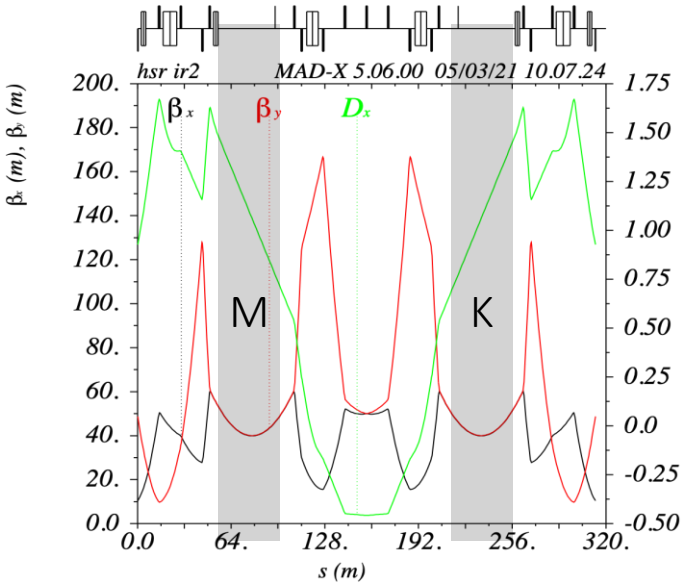
Progress on cooling section lattice

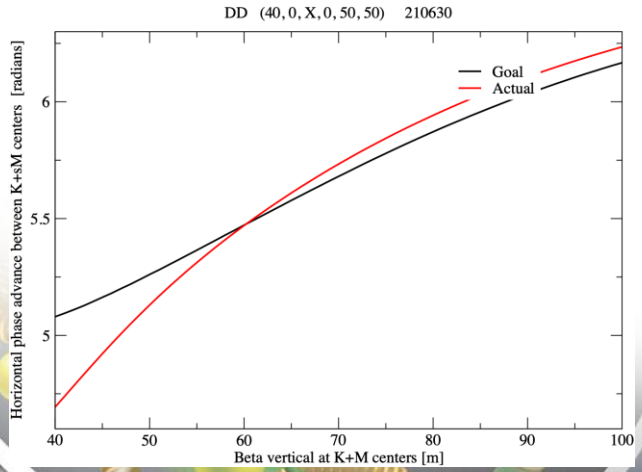


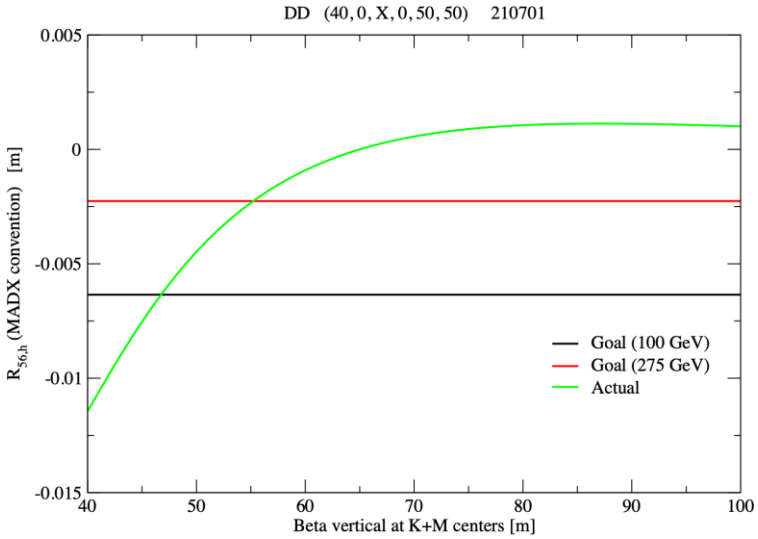


- Cooling section includes 39 m of modulator(M), 100 m of amplification and 39 m kicker (k).
- FODO cells are used for M and K section, the beta can be tuned from 4- 10 m for K and 25-40 for M.
- Triplets are used for amplification section, the beta is 1-2 meters.
- R56 tunable chicanes are designed as shown before.

Progress on hadron Lattice at cooling section







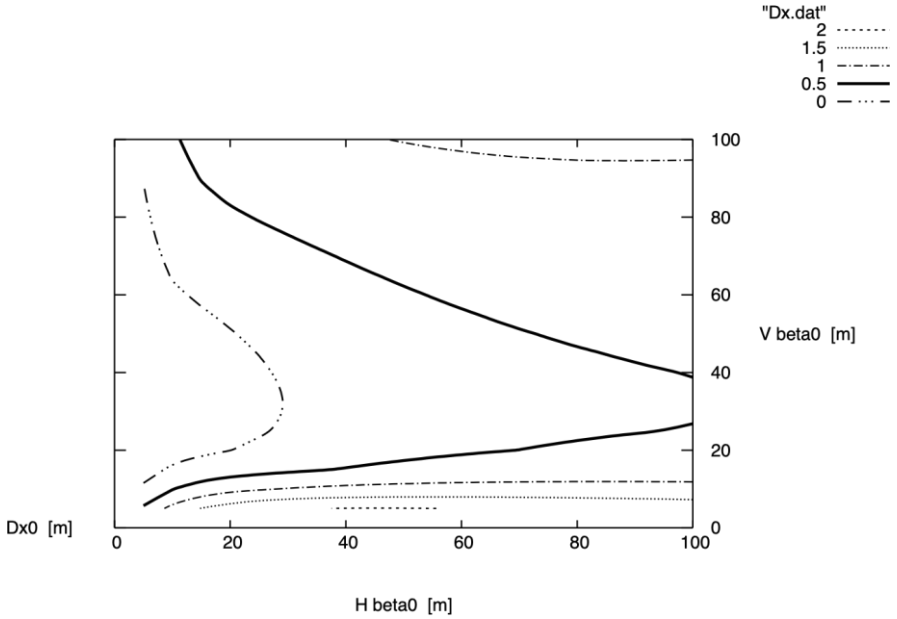
@ S. Peggs

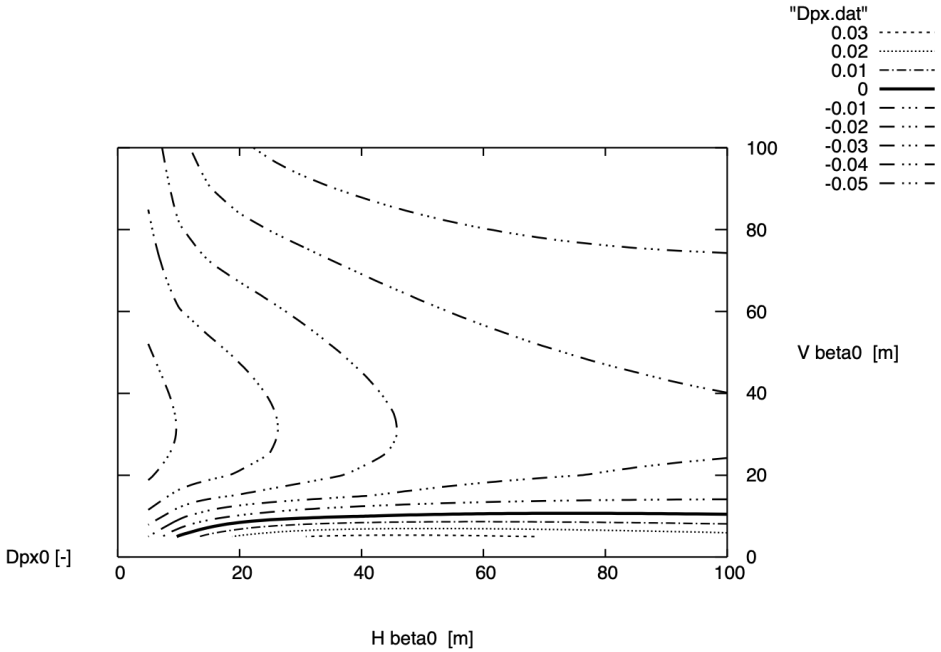
	100 GeV	275 GeV
H/V proton R56 (m)	-0.635	-0.226
proton H phase advance (rad)	5.055	5.446

- All quads except for the 4 doublets are spaced by the nominal half-cell in the RHIC arcs.
- Need these quads for dispersion and R56h tuning.
- The M/K common section are filled with regularly-spaced quadrupoles that control the electron optics but which have little effect on the protons.
- D and D' at M/K can be controlled by the beta function to meet the transverse cooling parameters.

Hadron Lattice design to get transverse cooling

@ S. Peggs



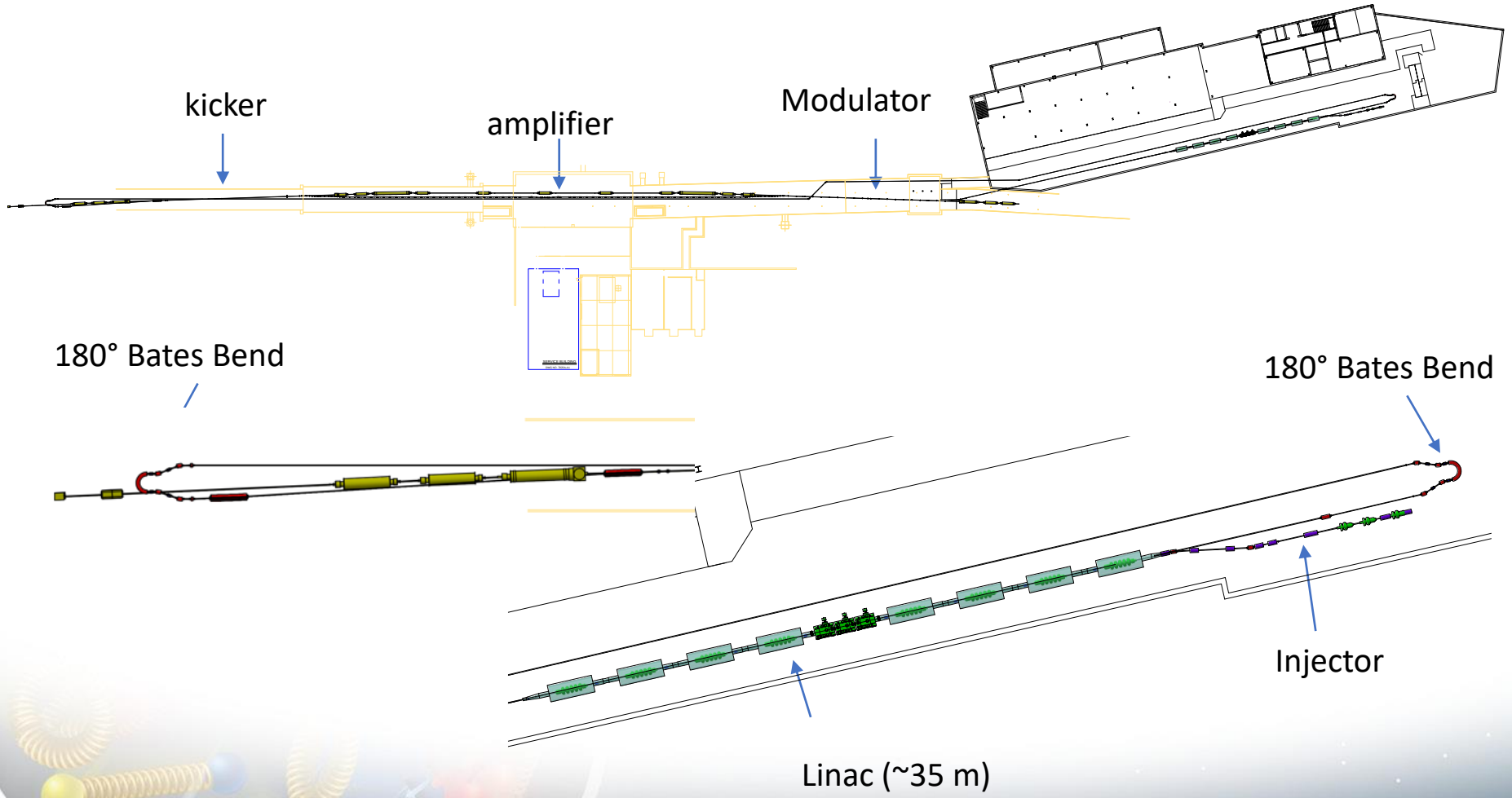


	100 GeV	275 GeV
Proton H D in M/K (m)	1.108	1.36
Proton H D' in M/K (m)	-0.0177/0.0177	-0.0146/0.0146

Current ERL Physical Layout

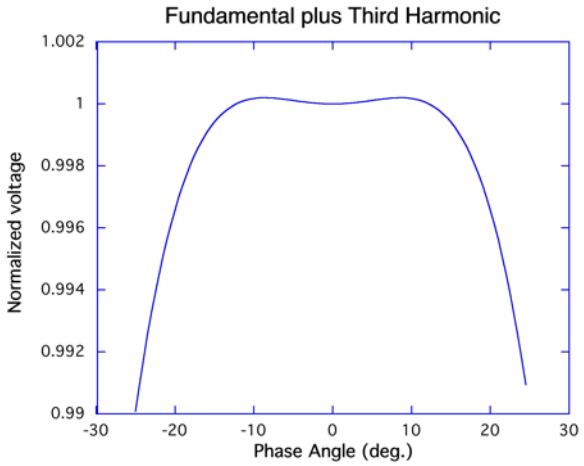
@ Xelera

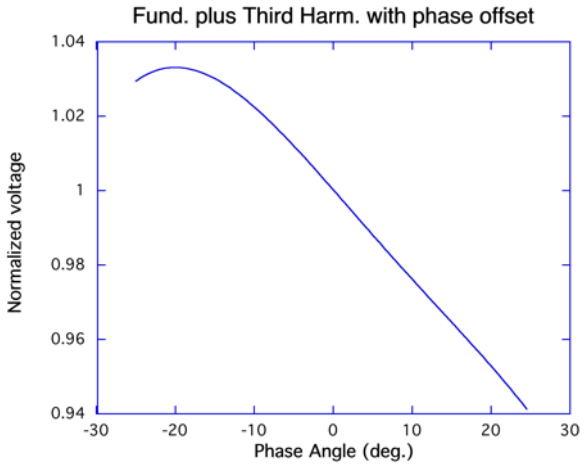
Note: This configuration will probably change.

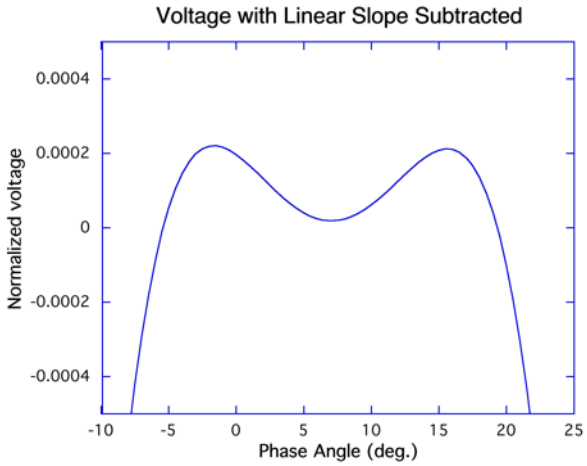


How to get long bunches (using 3rd harmonic RF)

- Can get 3.5 cm flat top with +/- 10^{-4} p-p energy variation.
- Accelerate 3.5 cm FW bunch in linac with 3rd harmonic cavity 7 degrees off crest from the fundamental.
  - This produces an energy slew of 6.14% (FW)
  - Need R_{56} of 57 cm to stretch 3.5 cm bunch to 7 cm (a BIG chicane)
  - For a 55 MeV beam, need 7.9 MeV in dechirper at 591 MHz to take out the slope
  - This has to be done in the return loop in reverse
  - Relative RF gradient at the linac exit is shown below

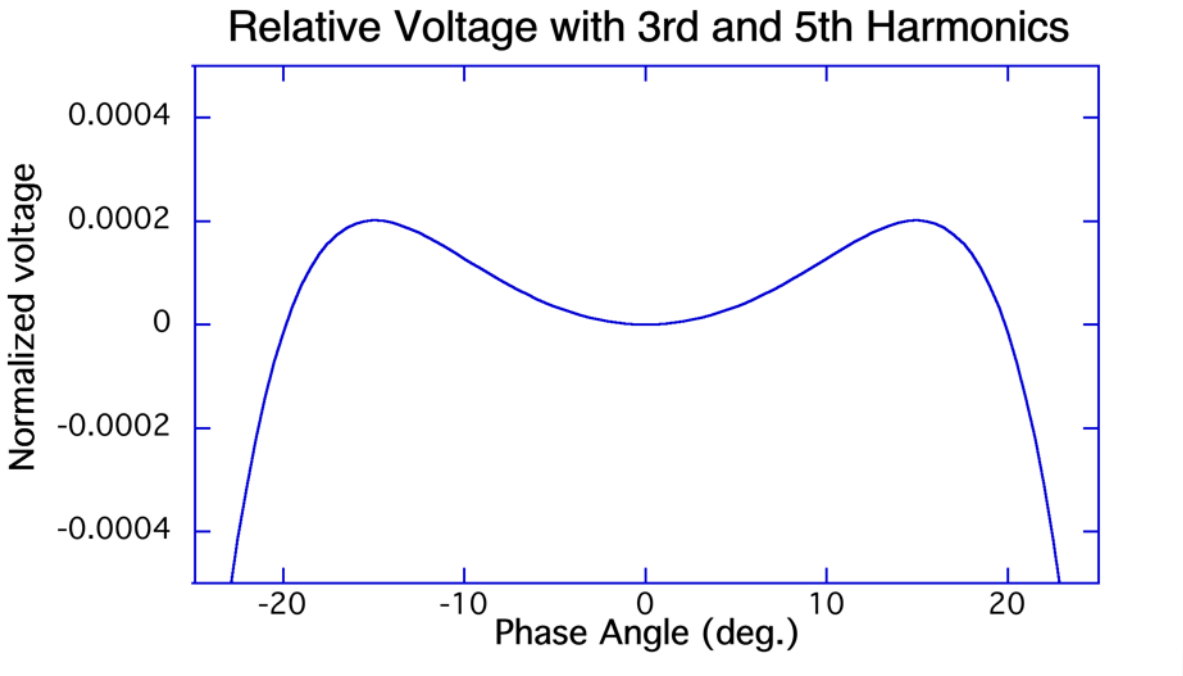




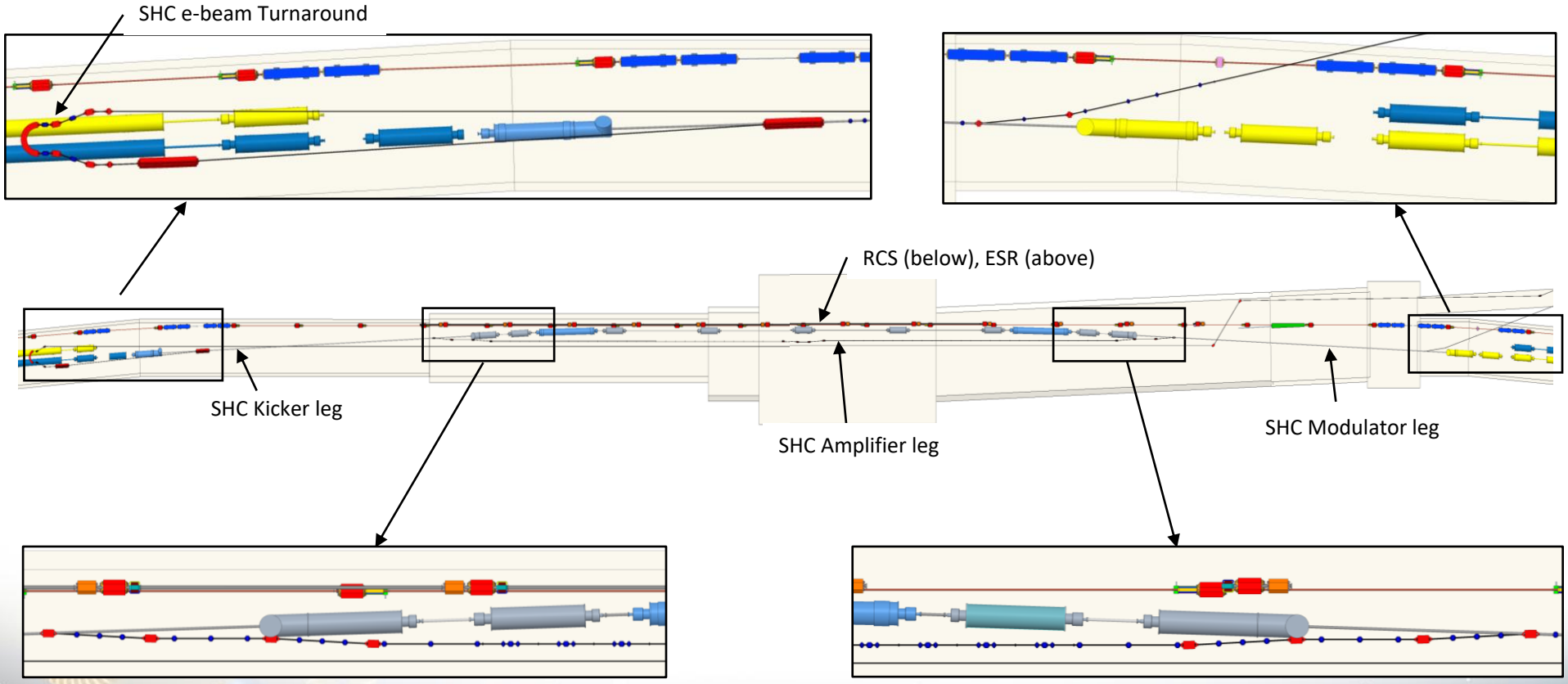


Another way to get long bunches (Use 5th harmonic RF)

- Assume a more compact bunch [<5.6 cm FW, (187 psec).] Peak current is still 8.5 A.
- Accelerate 5 cm FW bunch in linac with 3rd harmonic cavity on crest but 1/6 the fundamental amplitude and 5th harmonic 2% of the fundamental.
  - No chicane needed. RF flat to +/- 1e-4 over 40° of 591 MHz phase.
  - 5th harmonic cavity should be large aperture.



IR2 Configuration



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Jlab: S. Benson

Xelera: C. Mayes, C. Gulliford

FNAL: S. Nagaitsev, V. Lebedev

Thanks for your attention!

SHC diagnostics

- *Emittance measurement*
  - X,Y slit with YAG crystal at injector (emittance: 2-3 mm-mrad, resolution: <0.5 mm-mrad)
  - Quad scan method at the end of Linac (resolution: <0.5 mm-mrad) with wire scanner.
- *Beam profile*
  - YAG– plunging transverse profiles.
  - SLM (streak camera – longitudinal profile – expect 4-14 mm bunch length), resolution at 1 mm
  - Halo scrapers at injector.
- *Slice energy spread measurement* at 150 MeV (ensure $<10^{-4}$), use transverse deflecting cavity
- *Charge measurement*
  - DCCT, to measure 100 mA at injector and in the recirculating part of the ERL.
  - FCT measures bunch pattern and differential current for MPS
  - ICT measure 1nC bunch charge
  - Faraday Cups: Dump beam and measure charge: at injector, diagnostic line, dump de-acc beam and at re-injection point.
- Beam position monitor
  - 10 – 100 µm resolution, 100 pC – 1.2 nC bunch charge range (average position measurement of CW beams)
  - Large bandwidth position monitor between the tanks at the Linac. To see individual ac and de-acc beam position.
  - Co-propagation e-ion transverse alignment <5% of ~0.7 mm RMS beam size in modulator and kicker.
- Beam Loss Monitors
  - PMT/Scintillators (fiber optic cables) & Pin Diodes (resolution: ~1uA)
  - Beam pipe temperature
- *Electron & Ion bunch longitudinal* relative alignment < 300 nm stability of the longitudinal alignment. Synchrotron radiation, Smith-Purcell radiation…

Challenges and opportunities

- CeC has not been experimentally demonstrated
- Very low energy spread is required

Require: $<10^{-4}$

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

- Very low shot noise from electron beam

- 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

Require: 120 mA @1nC

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

- Beam diagnostics: beam noise, e-h alignment (~250 nm), energy spread measurement(<1e-4).

SHC R&D will push the frontier of accelerator science
Welcome to collaboration!

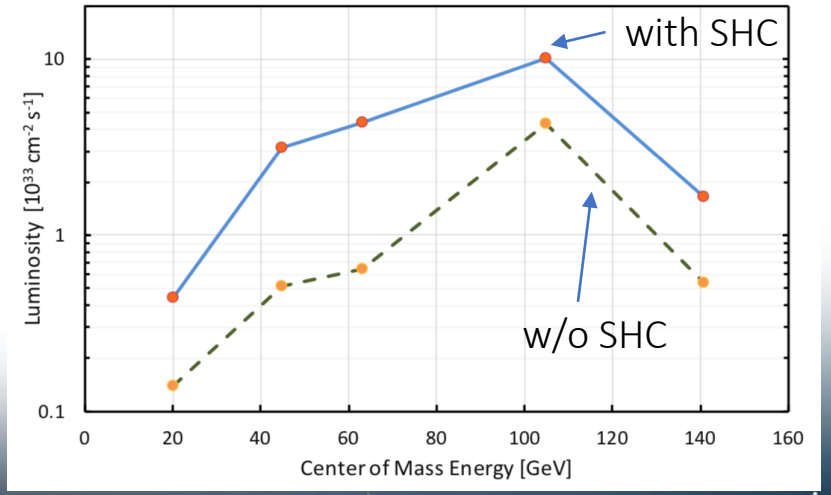
High Luminosity and Strong Hadron Cooling

- 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 **2-3 h^{-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 CeC as optimum strong hadron cooling scheme.



Base selections of ERL

			Reasons
ERL	Multi turns	Single turn ✓	No large bending before cooling: eliminate CSR, large R56
Electron source	HVDC gun ✓	SRF gun	HVDC gun achieved 65 mA / 2 nC
LINAC fundamental frequency	591 MHz ✓	197 MHz	591MHz is matured.>18 MV, reasonable cost

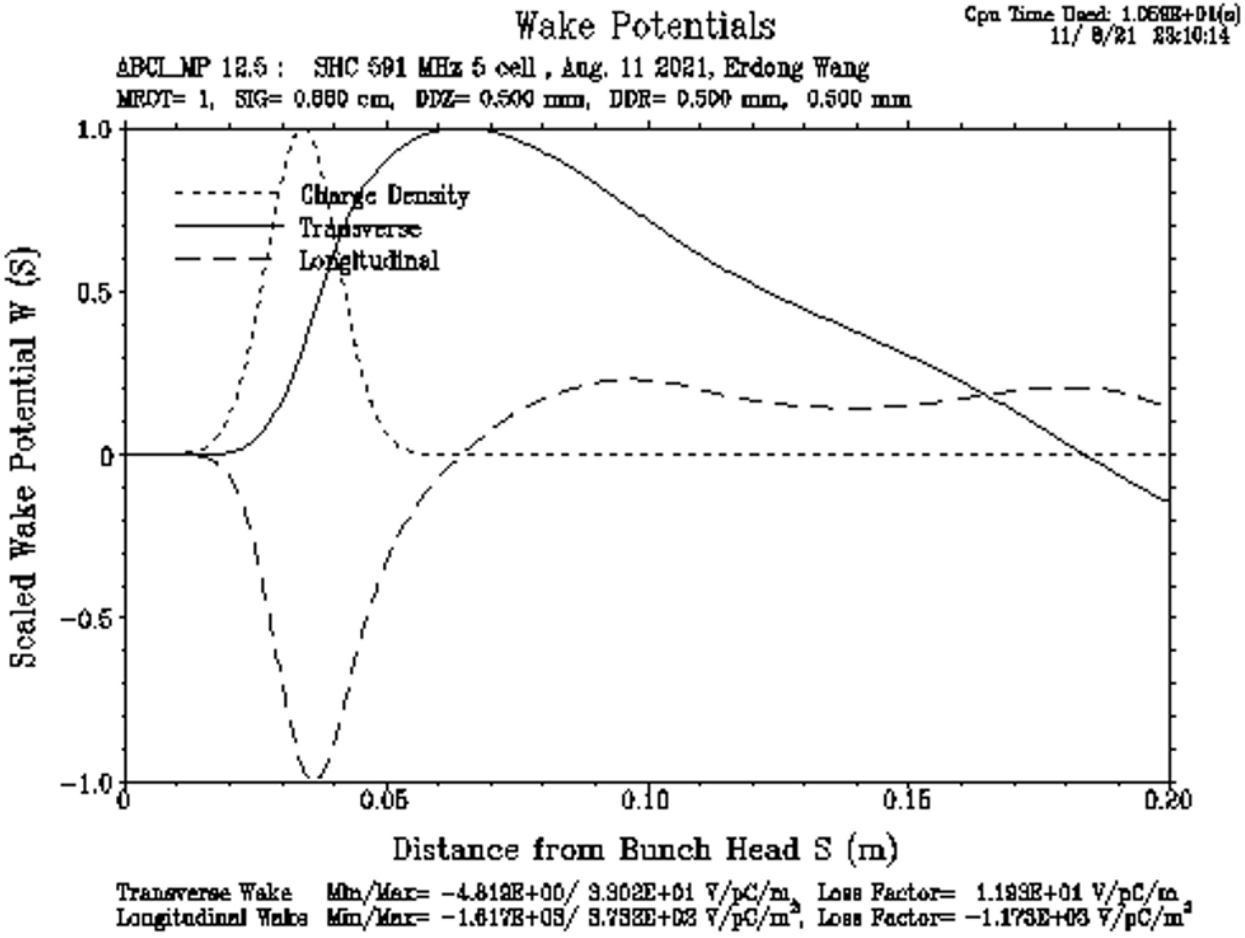
Summary of completed and ongoing tasks

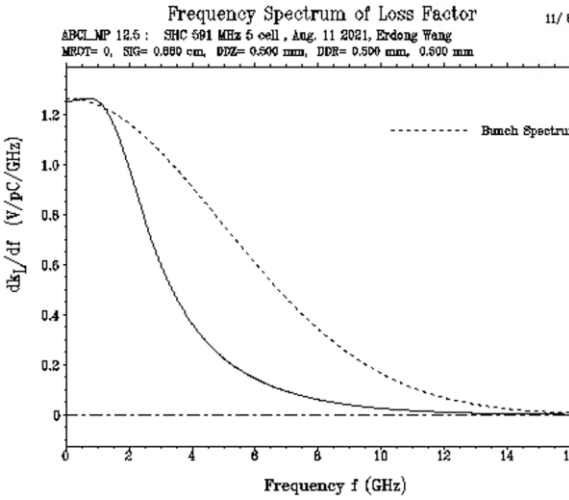
- MBEC theoretical study ✓
- 1D cooling simulation tools development ✓
- Optimized cooling parameters V1 ✓
- ERL and cooler conceptual lattice . ✓
- Gun to cooling section detailed design, full 3D simulation ✓
- Hadron lattice V1 ✓
- Detailed cooler common section lattice
- Layout in IR2 and new source building

Summary of completed and ongoing tasks II

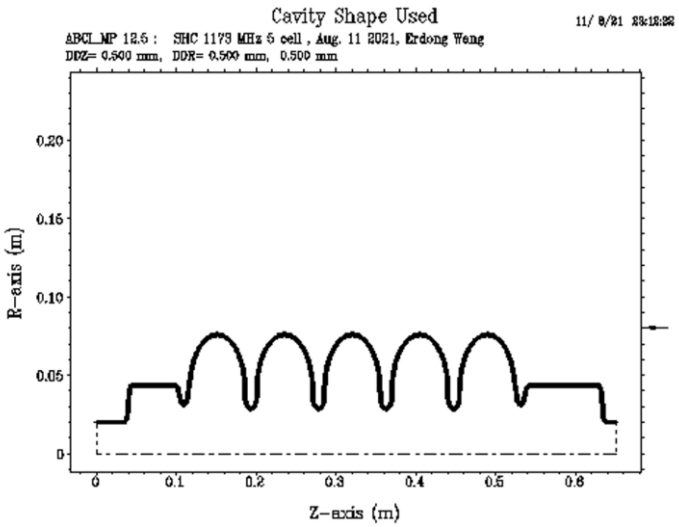
- 3D cooling simulation. Planned to be continued in FY22
- Cooling diagnostics
- ERL design:
  - Detail lattice design in Bmad: transverse/longitudinal matching, BBU, wake impedance, tolerances
  - Impact T/Z : Halo, beam noise Planned to be continued in FY22
  - CST, Omega3P: Detail RF design, RF kick, HOM, Qext
  - Engineering: Infrastructure, PS, Vacuum, Cryo

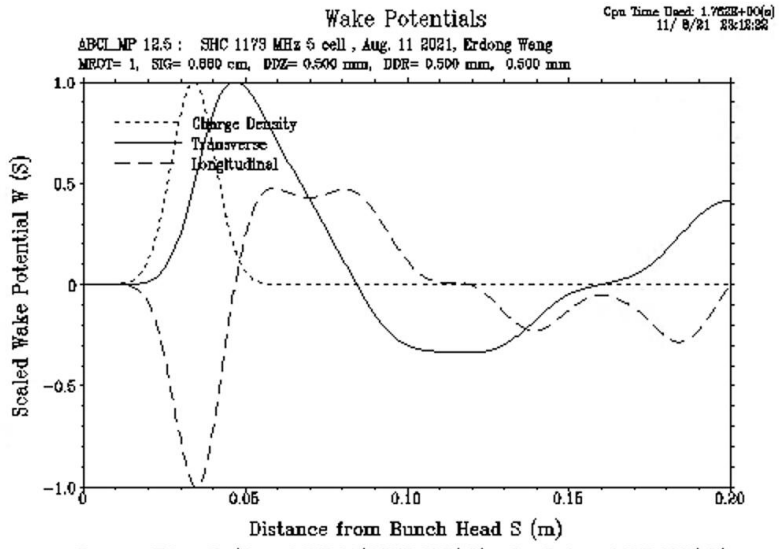
591 Short range wake

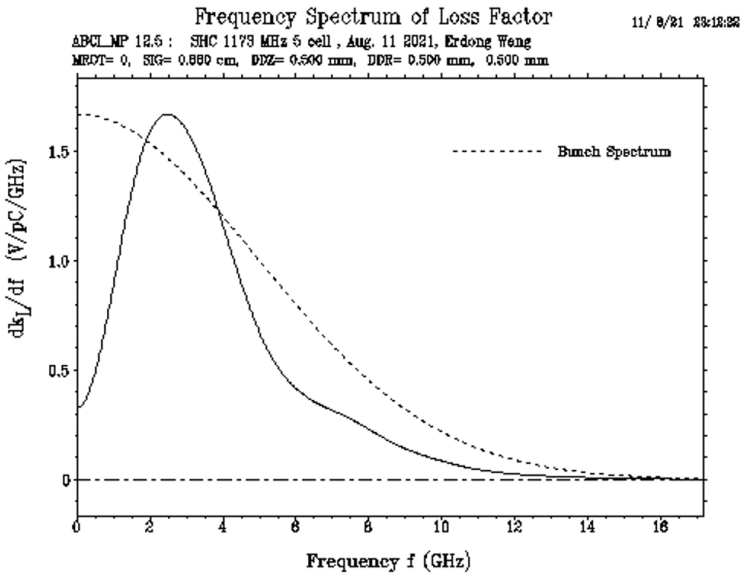




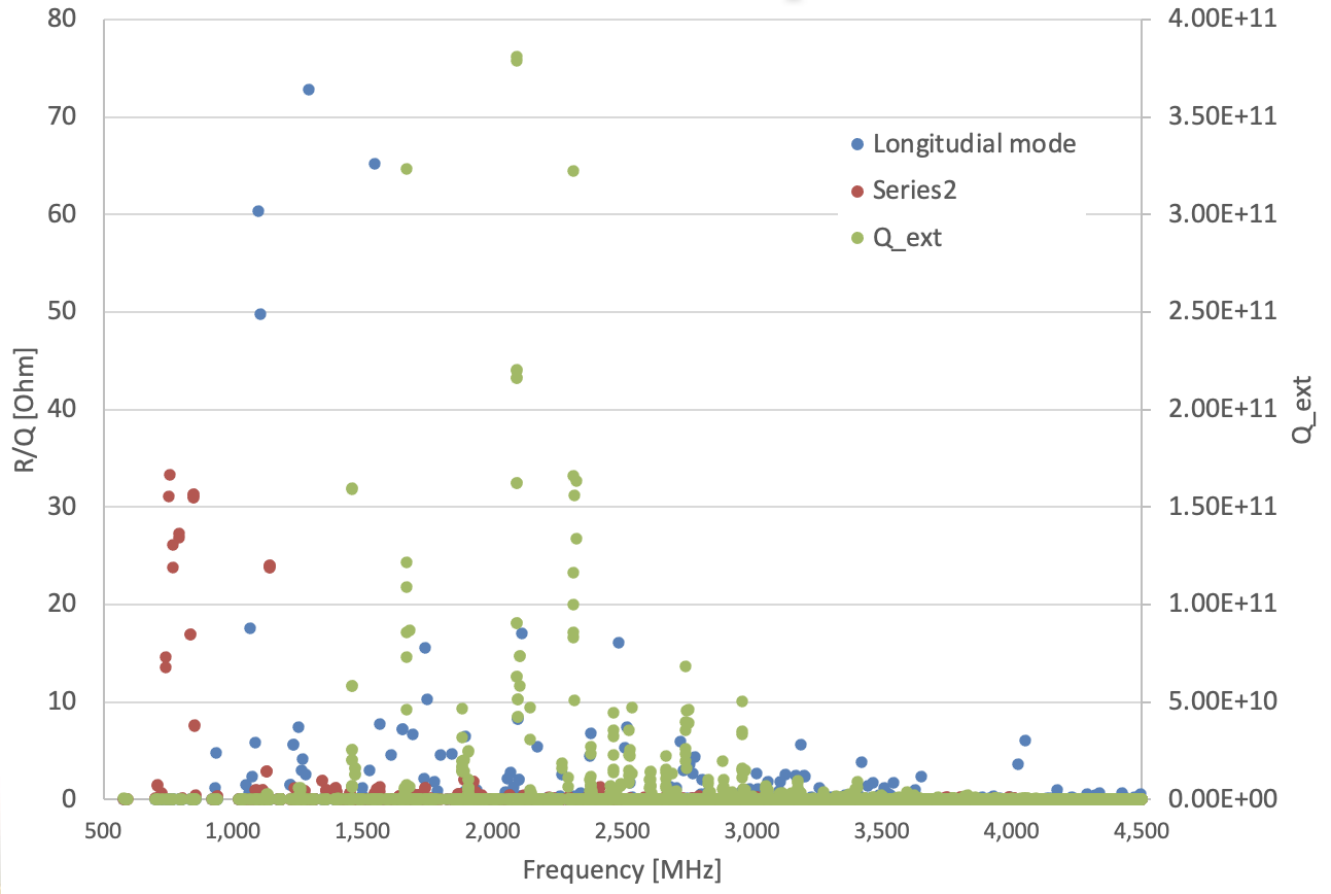
1773 short range wake



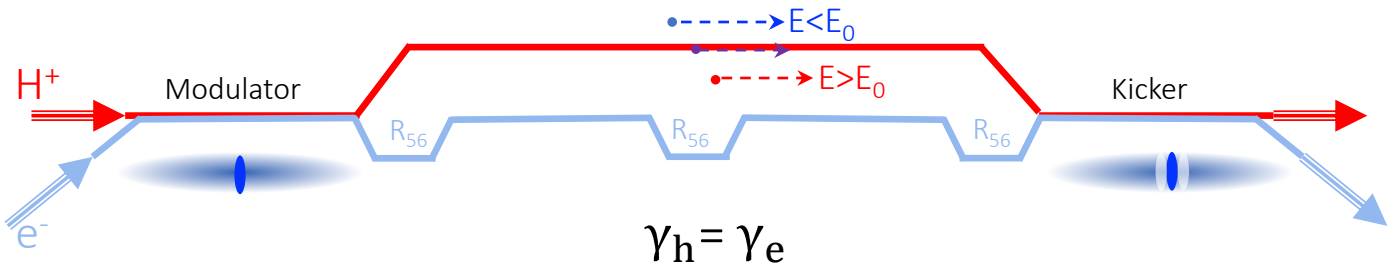




Long range wake of 5 cell



Coherent Electron Cooling Scheme



$\gamma_h = \gamma_e$

(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

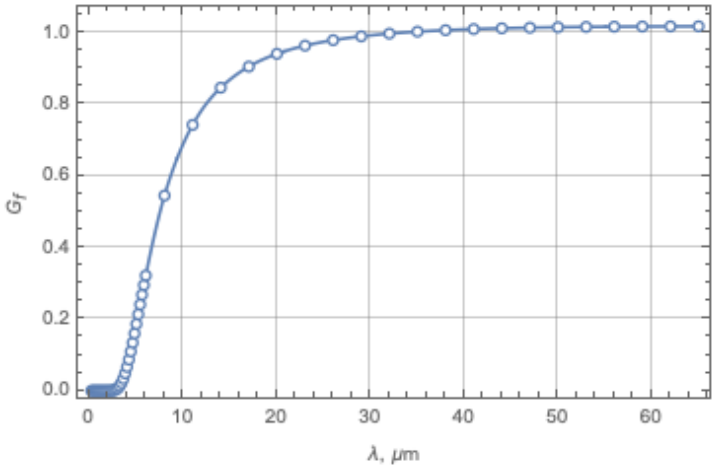
- Very broadband (~THz, slice size ~0.1 mm) amplifier
- Micro-bunching instability was well studied.
- Significant gain without saturation

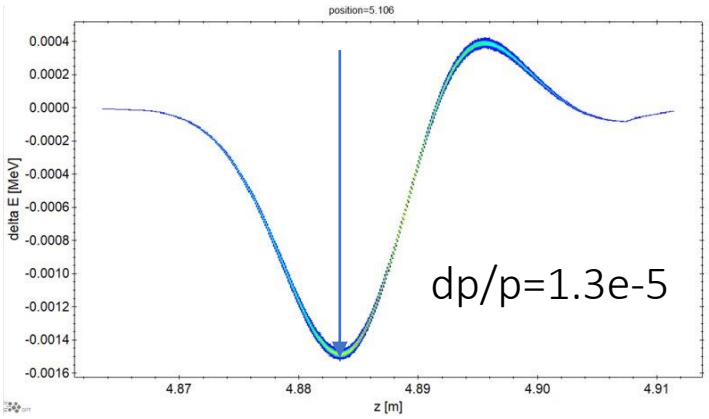
41 GeV case_start

Table 1: Parameters for Longitudinal and Transverse Cooling

Energy	41 GeV	41 GeV
Protons per Bunch	2.6e10	2.6e10
Proton Bunch Length (cm)	7.5	7.5
Proton Emittance (x/y) (nm)	44 / 10	44 / 10
Proton Fractional Energy Spread	10.3e-4	10.3e-4
Electron Normalized Emittance (x/y) (mm-mrad)	2.8 / 2.8	2.8 / 2.8
Electron Bunch Charge (nC)	**1**	**0.667**
Electron Bunch Length (mm)	**24**	**16**
Electron Peak Current (A)	5.0	5.0
Electron Fractional Energy Spread	1e-4	1e-4
Horizontal/Vertical Proton Betas in Modulator (m)	40 / 60.2	40 / 60.2
Horizontal/Vertical Electron Betas in Modulator (m)	40 / 40	40 / 40
Horizontal/Vertical Proton Betas in Kicker (m)	40 / 60.2	40 / 60.2
Horizontal/Vertical Electron Betas in Kicker (m)	40 / 40	40 / 40
Modulator Length (m)	39	39
Number of Amplifier Drifts	2	2
Amplifier Drift Lengths (m)	43	43
Kicker Length (m)	39	39
R56 in First Two Electron Chicanes (cm)	8.50	8.50
R56 in Third Electron Chicane (cm)	-23.546	-23.546
R56 in Proton Chicane (cm)	-2.25	-2.25
Proton Horizontal Phase Advance (rad)	5.203	5.203
Proton Horizontal Dispersion in Modulator & Kicker (m)	1.36	1.36
Proton Horizontal Dispersion Derivative in Modulator/Kicker	-0.0146 / 0.0146	-0.0146 / 0.0146
Electron Betas in Amplifiers (m)	30	30
Horizontal / Longitudinal IBS Times (hours)	3.4 / 3.8	3.4 / 3.8
Horizontal / Longitudinal Cooling Times (hours)	**2.2 / 2.7**	**3.2 / 3.6**

CSR in chicane



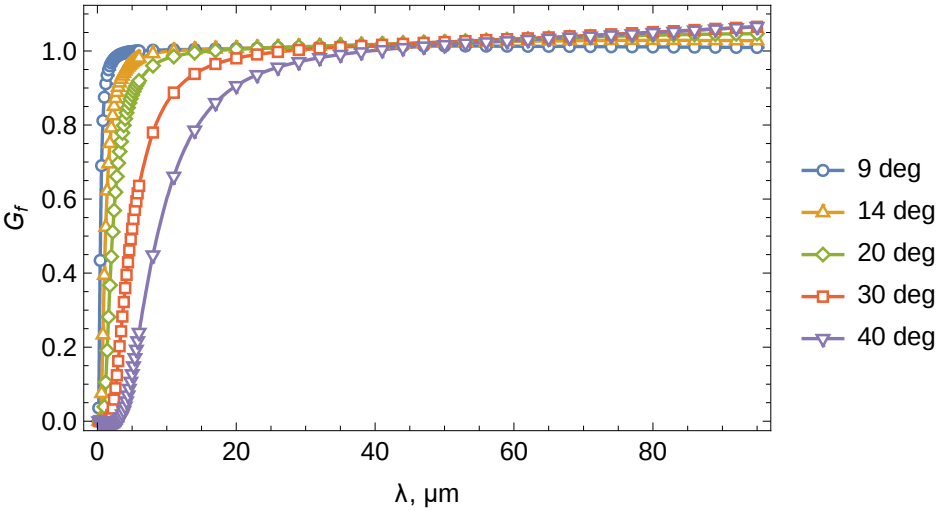


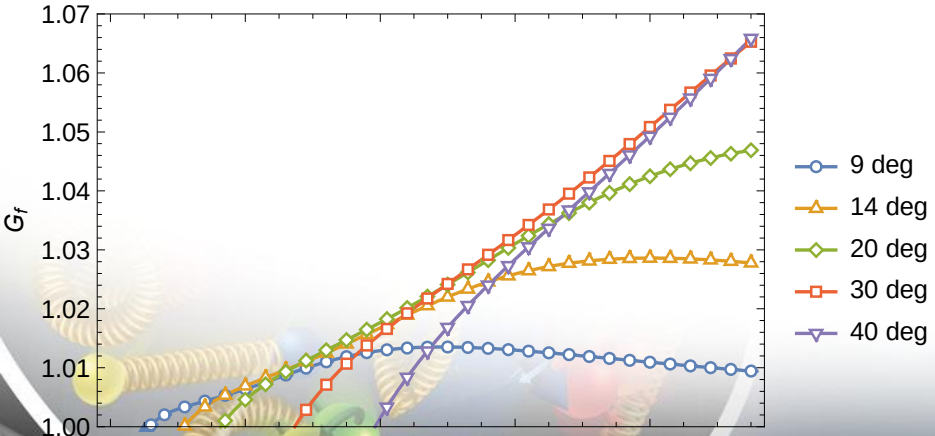
- Send a small density perturbation in the beam with the wavenumber k.
- Calculate the ratio(G) of its amplitude at the exit to the amplitude at the entrance.
- The CSR microbunch is eliminated in the amplification chicanes.

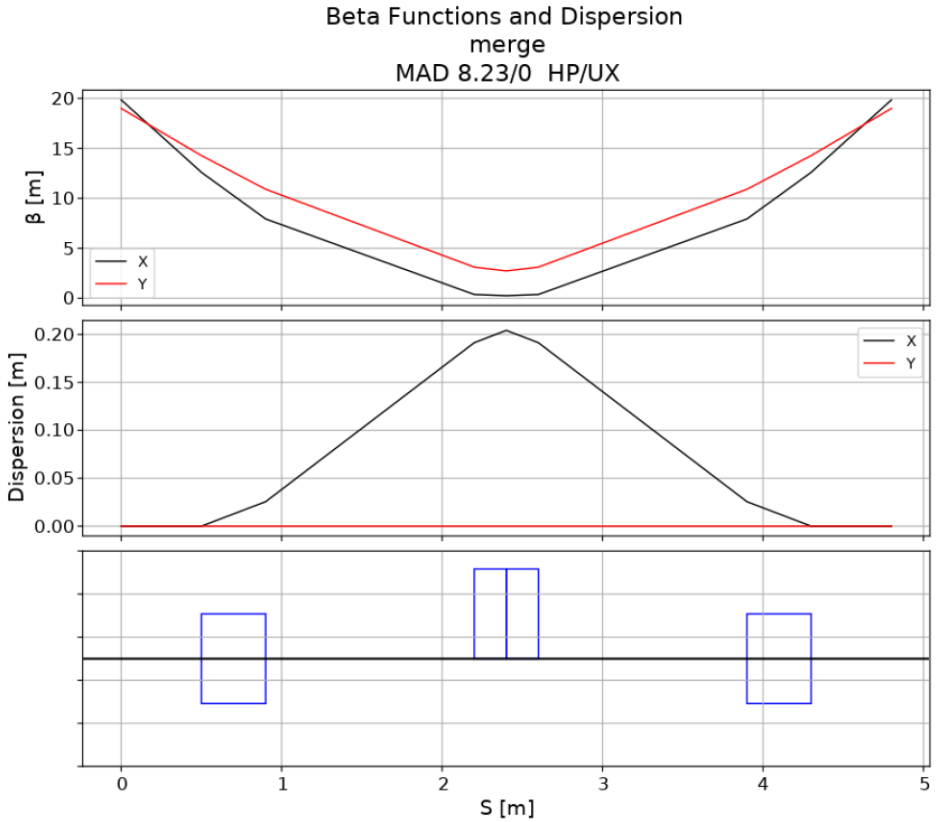
- CSR caused energy spread increasing is much smaller than sliced dp/p
- Micro bunch shift~ R56_local x R56~140nm.

S. Heifets, G. Stupakov and S. Krinsky. “Coherent synchrotron radiation instability in a bunch compressor”, PRAB,5,064401 (2002).

CSR microbunch enhancement before into cooling







Longitudinal space charge

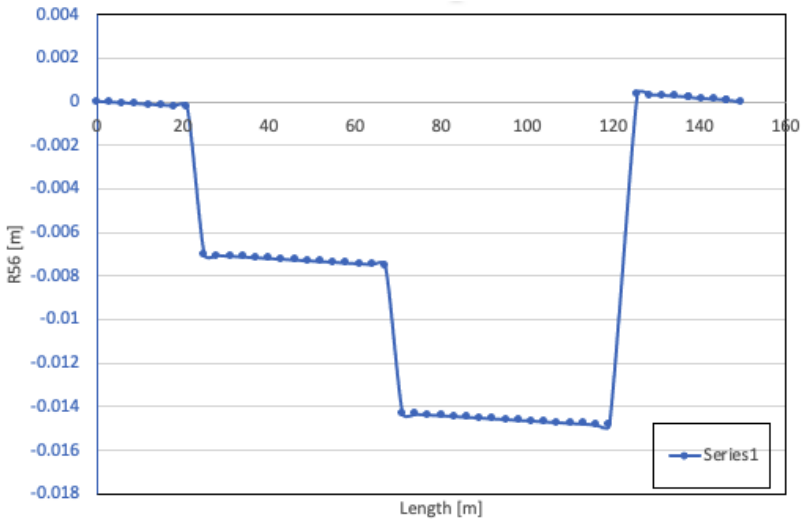
- The longitudinal space charge causes longitudinal kick. The microbunches slips due to R56 of drift and chicanes
- The slippage is significantly reduced by the choice of positive and negative R56 of chicane in amplification.
- Considering the beam pipe, assume a round Gaussian beam: Longitudinal space charge field is

$$\langle E_z \rangle = \frac{Z}{n}\frac{z-vt}{2\pi\sigma_z^2} I_{peak} e^{-\frac{(z-vt)^2}{2\sigma_z^2}}$$

$$\frac{Z}{n} = \frac{Z_0}{\beta\gamma^2} ln(\frac{b}{1.5\sigma_r})$$

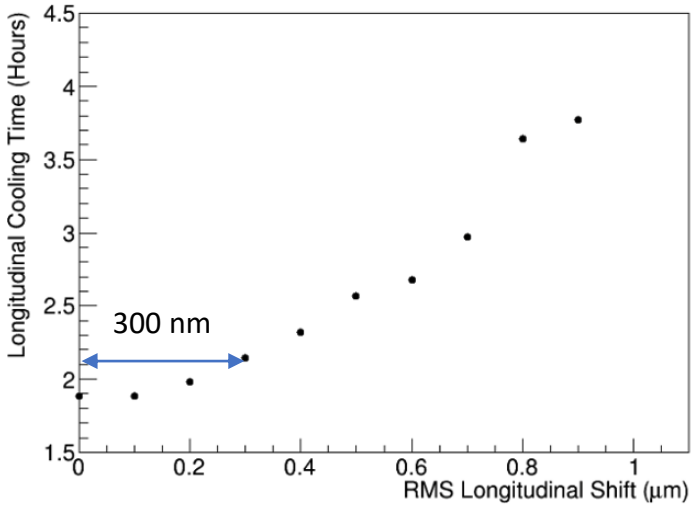
LSC force is $F = q\langle E_z \rangle$

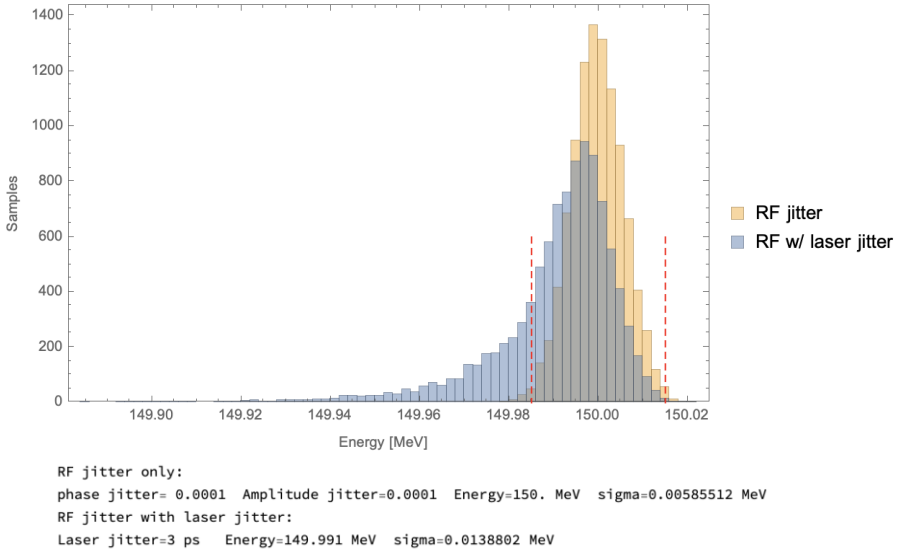
	$\delta l@1\sigma$
150 MeV	56 nm
54.1 MeV	67 nm



E. Wang, et.al Longitudinal space charge kick in CeC NL-220638-2020-TECH. EIC-ADD-TN-011

Longitudinal slippage summary






```
RF jitter only:
phase jitter= 0.0001  Amplitude jitter=0.0001  Energy=150. MeV  sigma=0.00585512 MeV
RF jitter with laser jitter:
Laser jitter=3 ps   Energy=149.991 MeV  sigma=0.0138802 MeV
```

- Cooling section electron beamline PS stabilization ~ 3 ppm, longitudinal shift ~200nm
- CSR caused longitudinal shift ~140nm
- Longitudinal SC caused shift ~56 nm
- Hadron chicane still in study. A feedback system looks necessary.

$$\Delta s1 = R_{51}x_{err} + R_{52}x'_{err} + \frac{R_{56_err}dp}{p}$$

$$\Delta s2 = \frac{1}{2} < x'^2 > s0$$

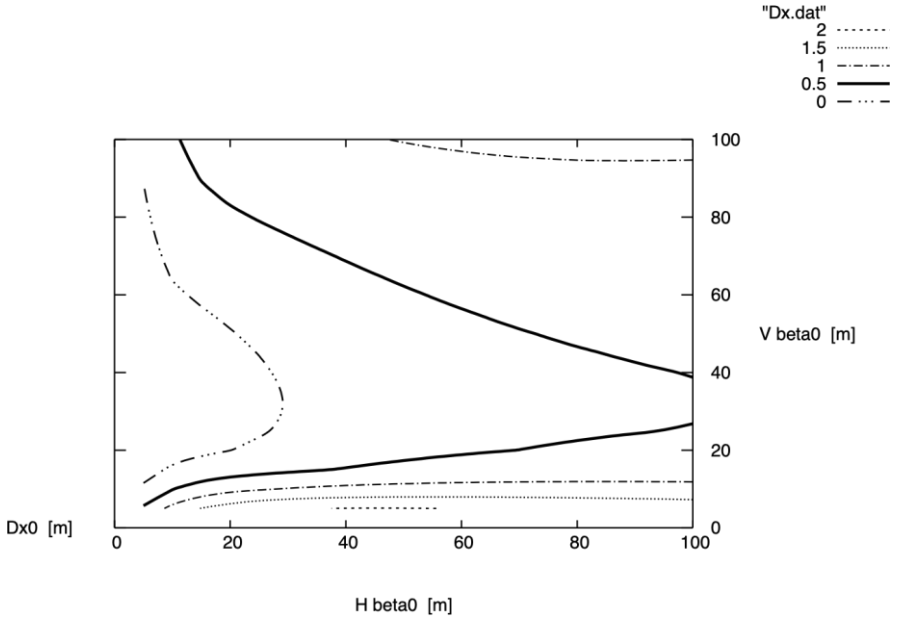
dominated :$\Delta s3 = (\rho + \rho_{err})(\theta + \theta_{err}) - \rho\theta$

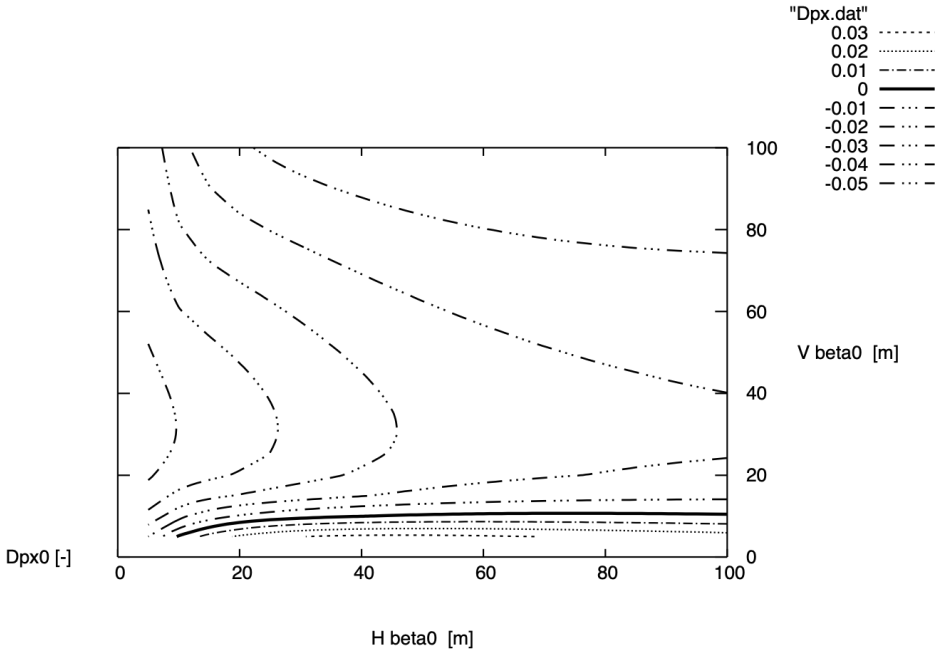
- R56_err,dp
- ρ_{err}, θ_{err}

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

Hadron Lattice design to get transverse cooling

@ S. Peggs





	100 GeV	275 GeV
Proton H D in M/K (m)	1.108	1.36
Proton H D' in M/K (m)	-0.0177/0.0177	-0.0146/0.0146

CEC Experiment

RHIC Experiment

- Proof of principle experiment to demonstrate coherent electron cooling, underway since 2016
- Use a 28 GeV/n RHIC Gold ion beam
- First attempts (2016-2018) with seeded FEL amplification scheme not completed because of unforeseen effects and lack of time to deal with them (2018), because RHIC low energy program required larger aperture than provided by the wiggler magnets
- New amplification scheme was proposed which is based on excitation of unstable plasma oscillation.
- Test in 2020 and 2021. Coherent electron cooling could not be demonstrated because of energy fluctuation in the electron beam, presumable due to timing jitter of the gun laser pulses.
- Observed weak cooling is compatible and is attributed to bunched beam electron cooling.
- Simulations indicate that with observed energy fluctuation, coherent electron cooling should not occur.
- Next Steps: Fix the stability of the laser beam and try for cooling again

EIC Project involvement

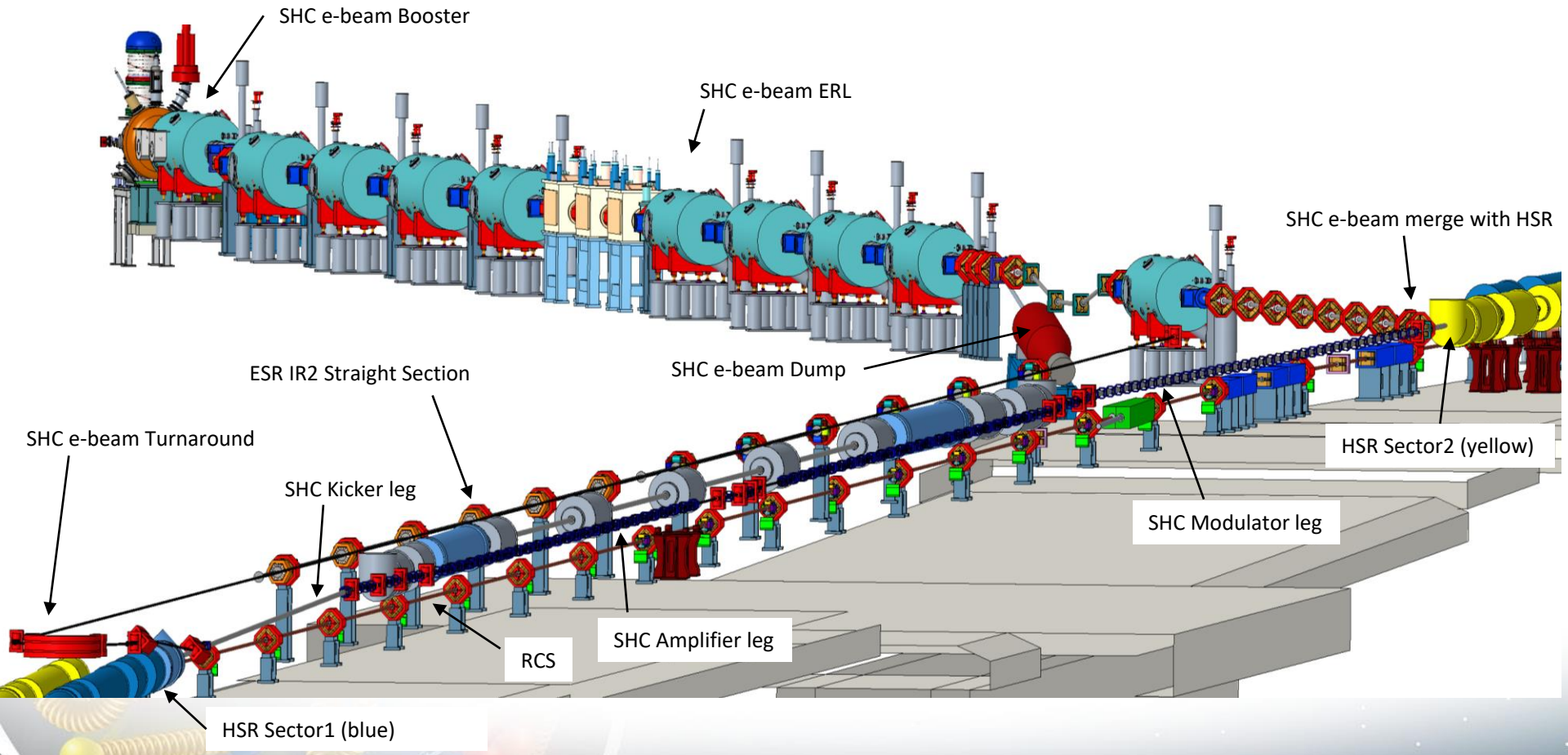
Weekly meeting to

- Review status of experiment
- Discuss whether plasma amplification scheme would be a viable or even better scheme for EIC. No reason why plasma amplification would not work in principle for EIC, so far inconclusive.
- No direct EIC oversight of CEC experiment, but indirect since CEC-experiment reports to BNL project oversight board on a regular base.

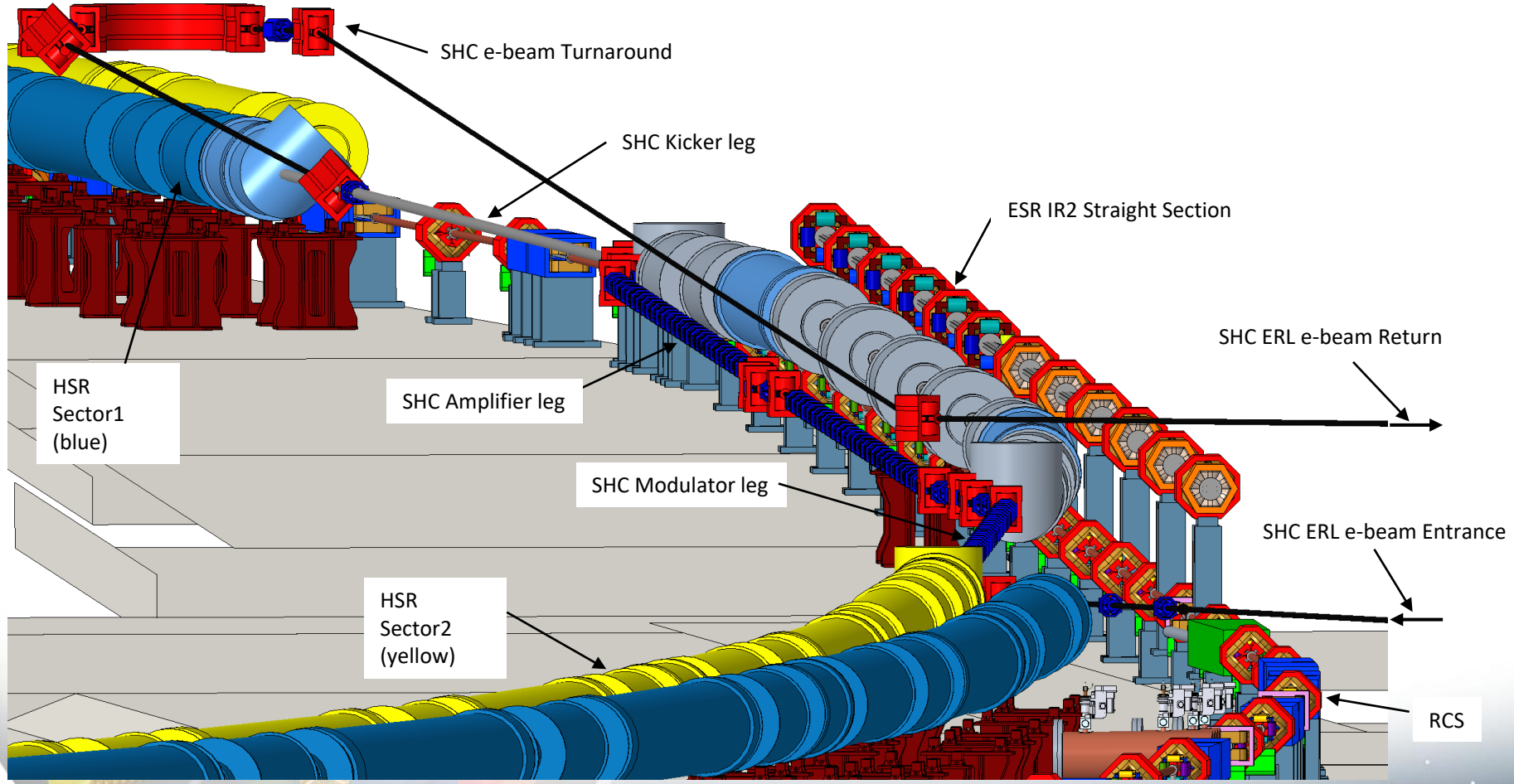
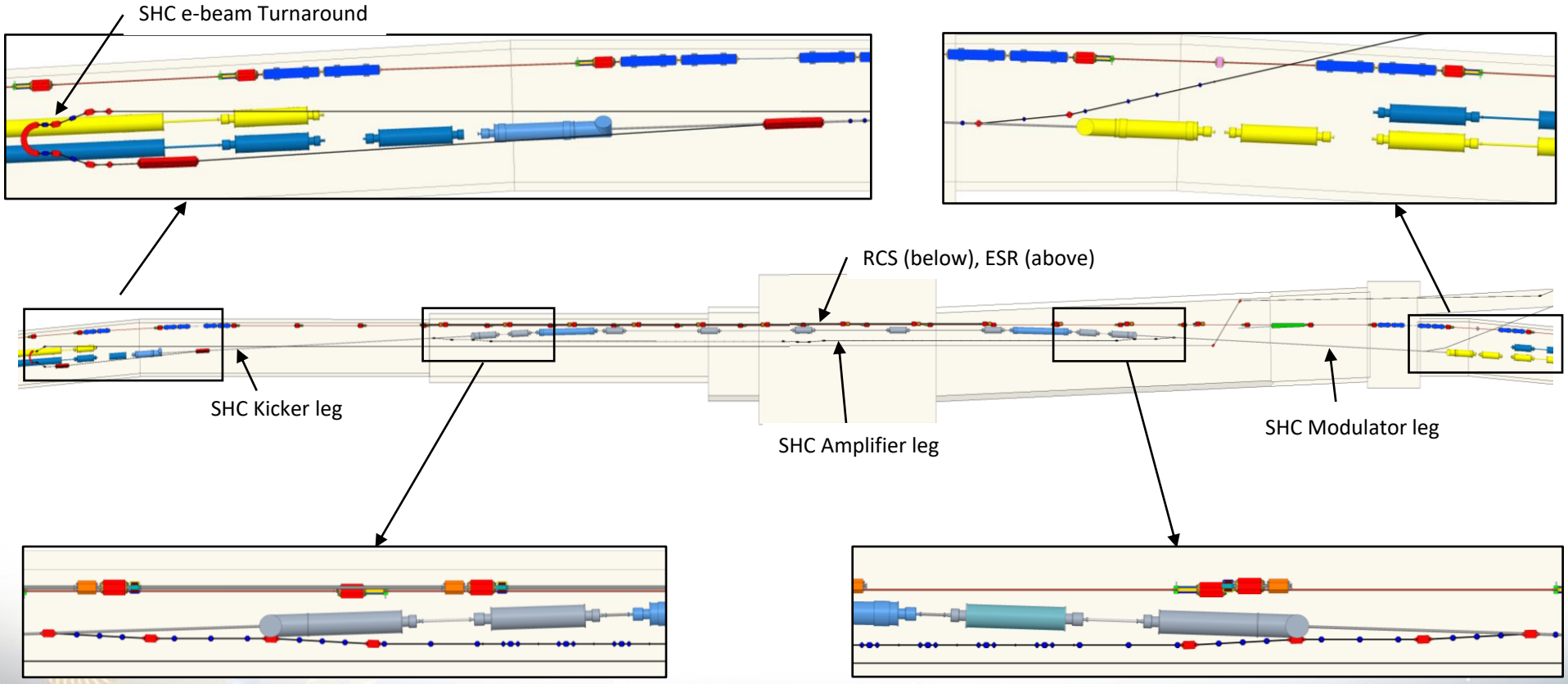
SHC Value Engineering and Risk Mitigation

- Because of the difficulties to demonstrate coherent electron cooling experimentally
- While the ability to cool does not impact the threshold or objective KPP but only the ultimate EIC KPPs, we nevertheless treat SHC as a performance risk
- Without invalidating the AoA, we are considering **alternative ways to cool the hadron with SHC.**
- Several schemes have been studies:
  - Strong hadron cooling using electron beams provided by an induction linac
  - Strong hadron cooling by bunched beam electron cooling using a ring with an ERL integrate to change the energy before and after cooling by a large factor
  - Using a storage ring to provide a strong electron cooling beam (amp class) and integrating wigglers in the lattice and have the photon carry away the energy transferred from the hadron beam
- While none of these schemes has sufficient maturity to be considered as an alternative to coherent electron cooling, the last of the three option appears to be the most feasible. It has been described in an appendix of the EIC pCDR and published in a peer reviewed journal.
- We decided to spend some effort to further mature the ring-based electron cooler as a **value engineering** and **risk mitigation/handling** activity which is deemed promising as a possible alternative.

IR2 SHC Configuration



IR2 Configuration



IR2 Configuration