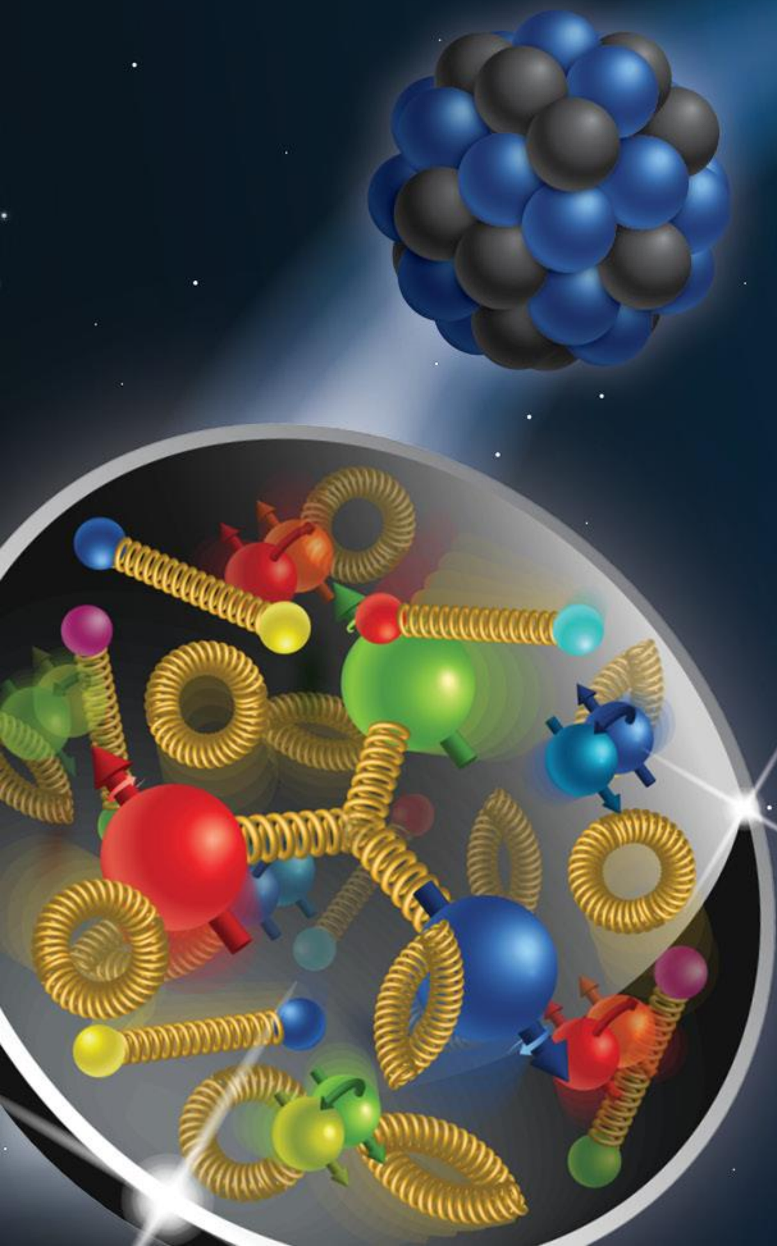
Strong hadron cooling with MBEC for EIC



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Electron Ion Collider – eRHIC

NP R&D PI meeting 2020

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

Project description

- We aim on developing theory of micro-bunched strong hadron cooling, simulation tools, the layout for EIC and preparation for experimental demonstration.
- **Status**: At the second year, we estimated three energy cases for EIC CEC cooler. More theoretical works have been published. Cooling simulation code development is in progress. Increasing plasma frequency by wiggler experiment has been carried out. More detailed injector and ERL studies.
- Monthly collaboration meetings to exchange the progress and discussion. Established cooling design team for EIC.
- This project is tightly aligned with the 2017 Jones EIC R&D task row #2, #3 with panel sub-priority A.

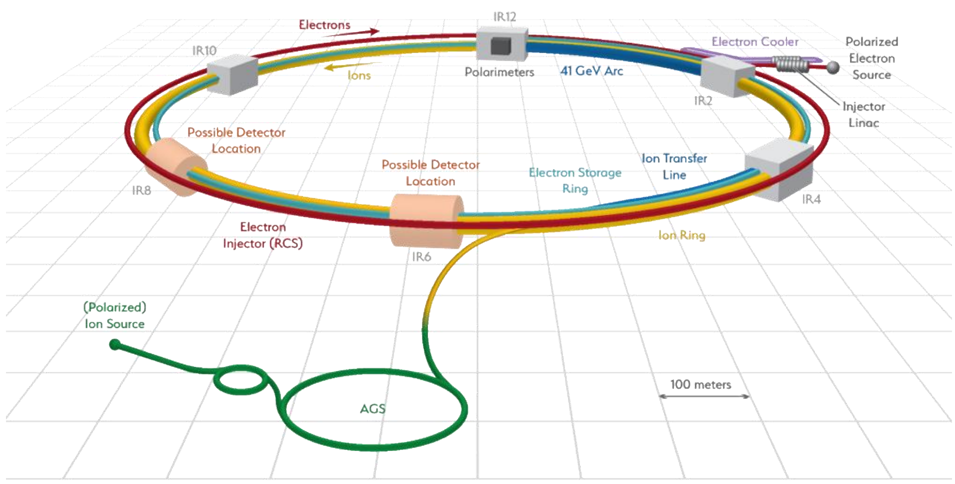
Budget summary

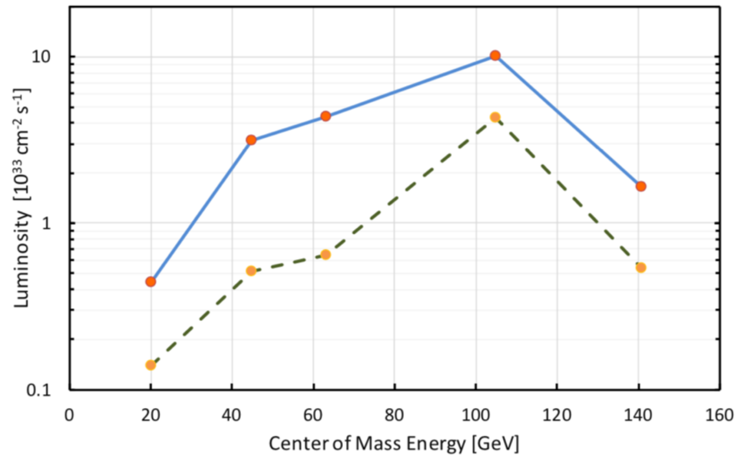
		FY 2018	FY 2019	FY 2020
SLAC	Funds allocated	200,000	382,994	165,339
	Actual costs to date	17,056	217,605	165,339
ANL	Funds allocated	130,000	130,000	260,000
	Actual costs to date	11,552	55,770	253,819
JLAB	Funds allocated	226,000	226,000	452,000
	Actual costs to date	3,626	260,199	437,740
BNL	Funds allocated	300,000	300,000	594,204
	Actual costs to date	0	5,796	119,097

Outlines

- Summary of FY 2018-2019
- Progress of FY 2020
  - SLAC has developed theoretical formulas to describe hadron evolution and diffusion.
  - Jlab has provided ERL design assessment and studied ERL Arc.
  - BNL has worked on cooling code including IBS. And has addressed some of Jlab's recommendation.
  - ANL has carried out an experiment at AWA to speed up conversion of a beam density modulation to energy modulation by a wiggler.

Why need cooling



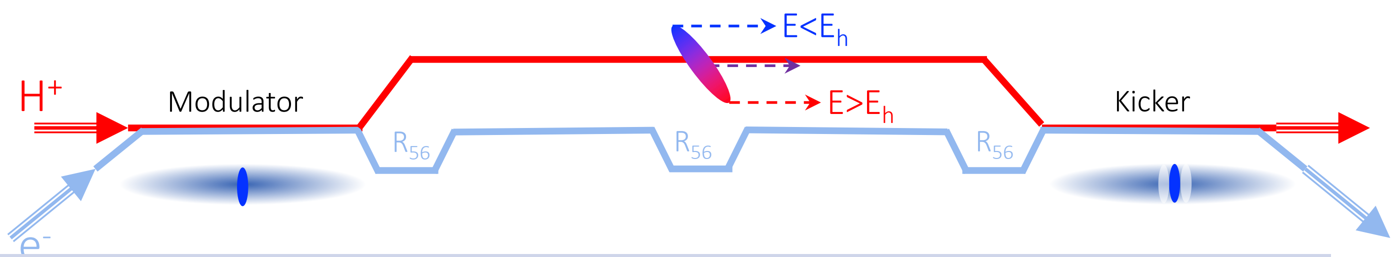


Strong hadron cooling with modest cooling rate of **1h^{-1}**, counteracts IBS

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

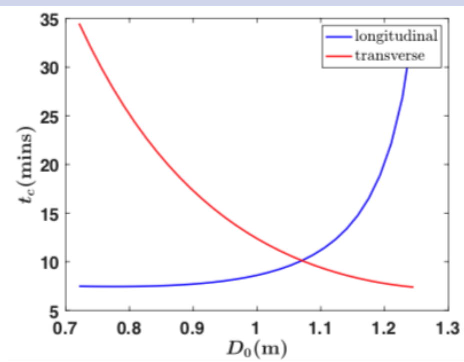
➔ EIC design includes strong hadron cooling

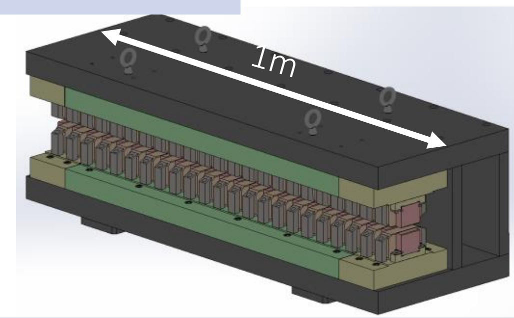
Summary of FY 2018-2019



A 1D theoretical model that describes the MBEC process has been developed.

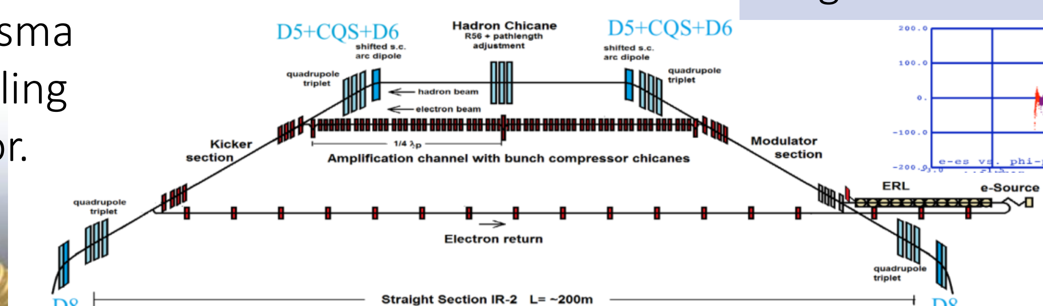
Proton energy [GeV]	275
Electron energy [MeV]	150
Electron relative energy spread	1×10^{-4}
Electron beam charge [nC]	1
Repetition rate [MHz]	112
RMS beam size [mm]	0.7
Modulator and cooler lengths [m]	40
Average electron beam current [A]	0.1
Cooling time [min]	50

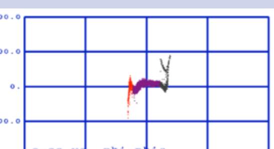




Using the wiggler in amplification section to shorten the drift length has been proposed.

We have developed pre-conceptual design of EIC cooling layout including two plasma amplification stages cooling channel, ERL and injector.





New MBEC kinetic equation

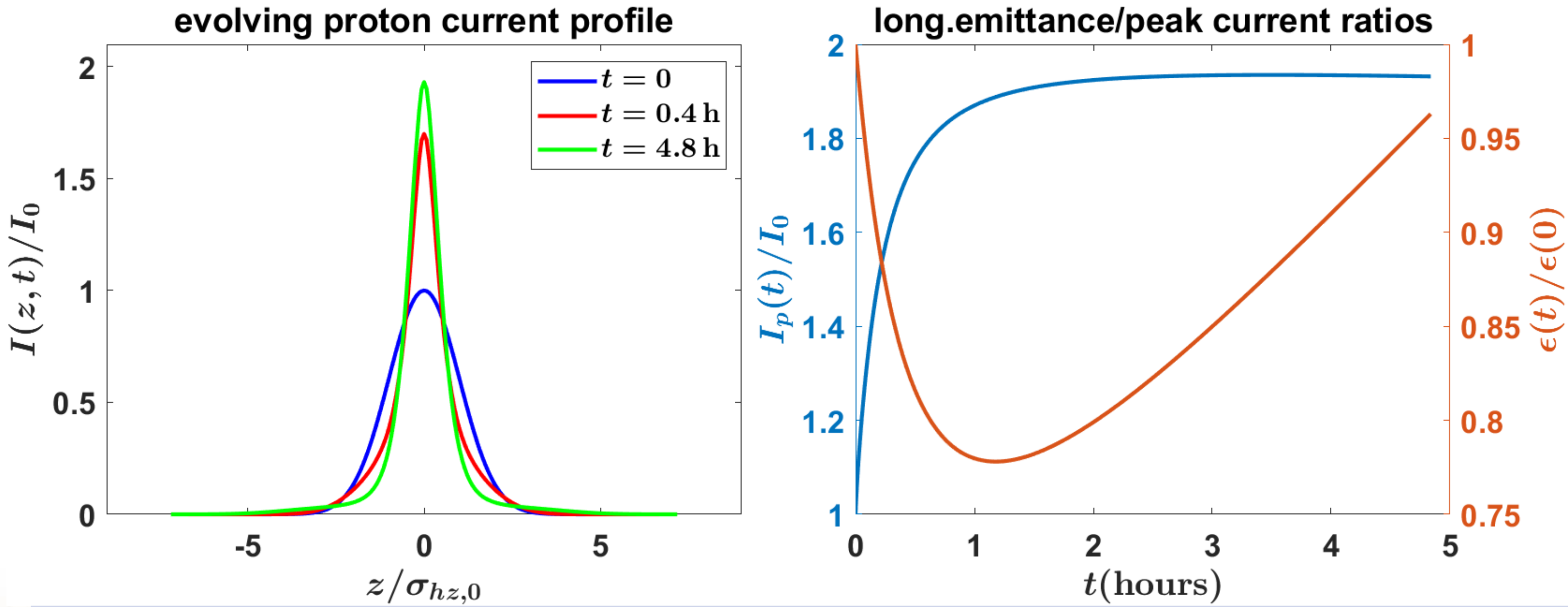
- The hadron distribution function $F(J,t)$ satisfies a kinetic equation

$$\frac{\partial F}{\partial t} = \frac{\partial}{\partial J}\left(\underbrace{J\{\chi(t)D(J) + \overbrace{D_{IBS}(J,t)}^{\text{diffusion term due to IBS}}\}\frac{\partial F}{\partial J}}_{\text{diffusion term}} \right) + \underbrace{\frac{\partial}{\partial J}(\nu(J)F)}_{\text{cooling term}}$$

- Theoretical formulas are derived for the diffusion and cooling terms
- The diffusion and cooling functions depend on the various system parameters (chicane strengths, plasma lengths, etc).
- The diffusion term itself depends on the distribution function, via the peak current ratio
- Computer code was developed for numerical solution of the kinetic equation
- An analytically solvable case was used to test the numerical algorithm

EIC run for 15 m stage with IBS included

Cooling can compensate for IBS, leading to a sharper proton current profile.



Main conclusion: cooling for the proton beam is accompanied by bunch compression (and peak current increase). Moreover, cooling appears to be sufficient to counteract IBS.

Publications related to MBEC studies at SLAC in 2018/2020

1. G. Stupakov, Cooling rate for microbunched electron cooling without amplification, PRAB, 21, 114402 (2018)
2. G. Stupakov, P. Baxevanis, Microbunched electron cooling with amplification cascades, PRAB, 22, 034401, 2019
3. P. Baxevanis and G. Stupakov, Transverse dynamics considerations for microbunched electron cooling, PRAB 22, 081003 (2019).
4. G. Stupakov, Microbunched Electron Cooling (MBEC) for Future Electron-Ion Colliders, in HB2018, paper WEA2WA02, 2018.
5. G. Stupakov, P. Baxevanis, 3D Theory of Microbunched Electron Cooling for Electron-Ion Colliders, IPAC19, p. 814, 2019.
6. P. Baxevanis and G. Stupakov, Tolerances on energy deviation in microbunched electron cooling, NAPAC19, paper WEPLH16, 2019.
7. P. Baxevanis and G. Stupakov, Diffusion and nonlinear plasma effects in microbunched electron cooling, NAPAC19, paper WEPLH17, 2019.
8. P. Baxevanis and G. Stupakov, Transverse dynamics considerations for microbunched electron cooling, PRAB 22, 081003 (7 2019).
9. P. Baxevanis and G. Stupakov, Hadron beam evolution in microbunched electron cooling, PRAB 23, 111001 (2020).

CeC ERL Design Assessment

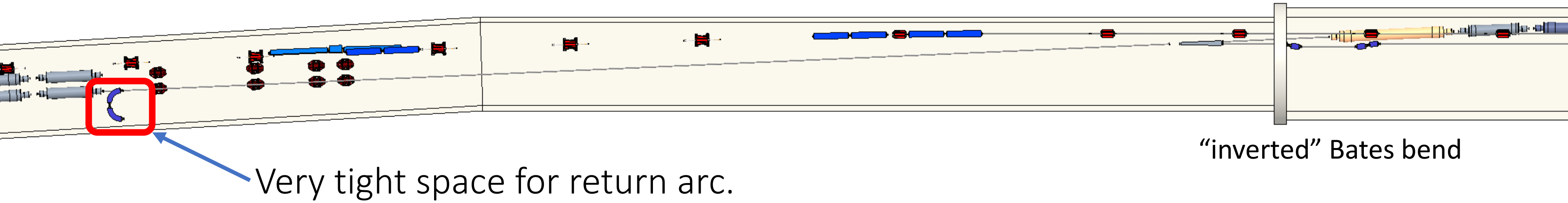
- Jlab reviewed pCDR cooler ERL design.
- Beam requirements at nominal operating point are clear ✓
- System design incomplete but progressing
  - *Injector*: design is quite detailed and increasingly well optimized; appears to provide required beam quality ✓
  - *Linac*: design is detailed and positioned for integration with injector and rest of system; appears to deliver required beam quality ✓
  - *Recirculator*: design concept is clear and transport from linac to cooling system is detailed; notionally provides properly configured beam
    - ***return/recovery transport incomplete***

Absent full layout, simulation-based beam dynamics validation is TBD

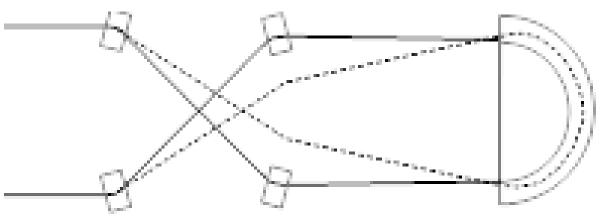
Observations/Recommendations

- **Return/recovery transport** very high priority
  - Return arc designs being studied
- **Operational requirements** (tuning, stability, reproducibility, beam property tolerances, …) need clarification
  - Machine tuning requirements and ranges not specified
  - Hardware "knobs" not designated
- There is no **start-to-end (S2E) model**; this is necessary to
  - Validate beam dynamics performance
    - BBU, CSR, mBI, … not yet studied in detail
    - Space charge effects explored through accelerating pass of linac only
  - Assess impact of errors
  - Generate hardware specifications
  - Simulate operational processes
- **RF drive requirements** unclear (see Powers/Tennant, ERL2007)
- **Halo is a major problem at high current**; provisions for halo control/mitigation are needed

Bates Recirculation Arc Studies

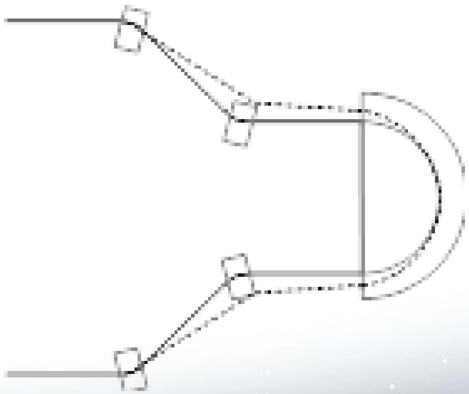


“inverted” Bates bend



- Comprises 4 “reverse” bends (actually, a segmented chicane) and a 180º dipole (“p-bend”),Multiple variations possible
- Longitudinal motion readily controllable operationally through very high order

ERLs are time of flight spectrometers, use an arc derived from a time-of-flight spectrometer



“conventional” Bates bend

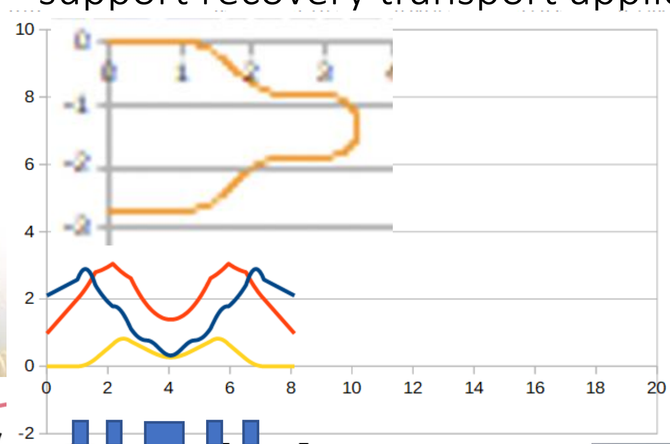
Preliminary Studies

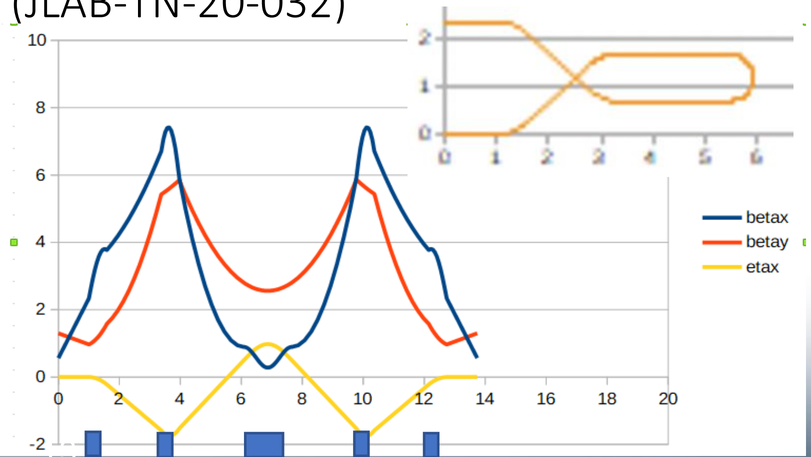
Initial study:

- Determine if Bates/"inverted" Bates bend would fit in 2-3 m wide footprint
- Compare properties/performance of the two geometries
- Conclusion: Bates geometries potentially offer suitable footprint and performance (JLAB-TN-20-024)

Follow-on study:

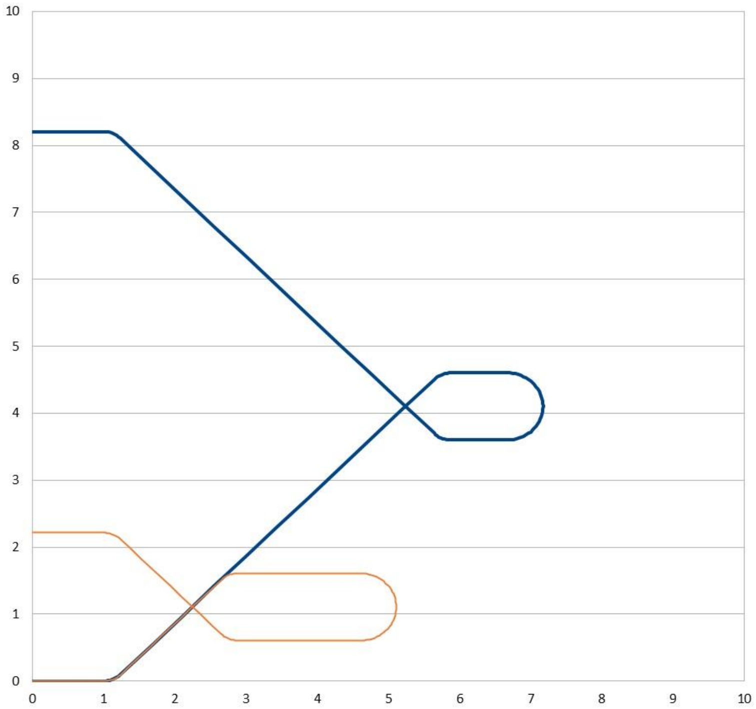
- Explore performance/sensitivity in greater detail over larger range of parameters by implementing chromatic correction/comparing several solutions
- Conclusion: the same – Bates bends offer potential size and dynamics to support recovery transport application (JLAB-TN-20-032)





Work Forward

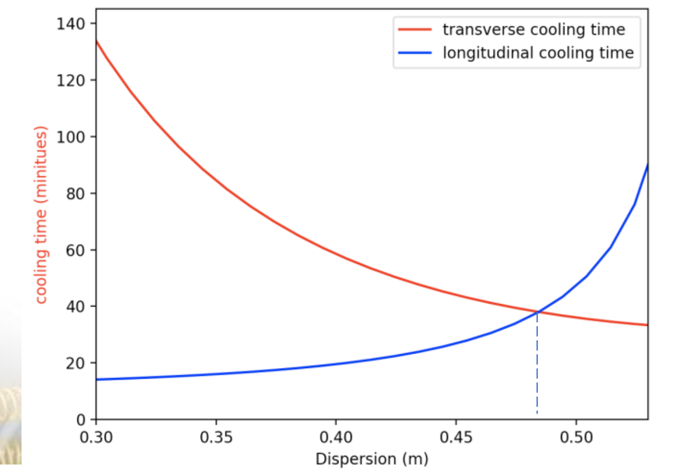
- Need to
  - Open up parameter space
    - Explore dependences on reverse bend angles
  - Optimize solutions by modulating entry/exit angles
    - This may hold particular promise for inverted Bates geometries, particularly if focusing (pole face rotations) are introduced on the π-bends (at right)
  - Decide if detailed design is warranted

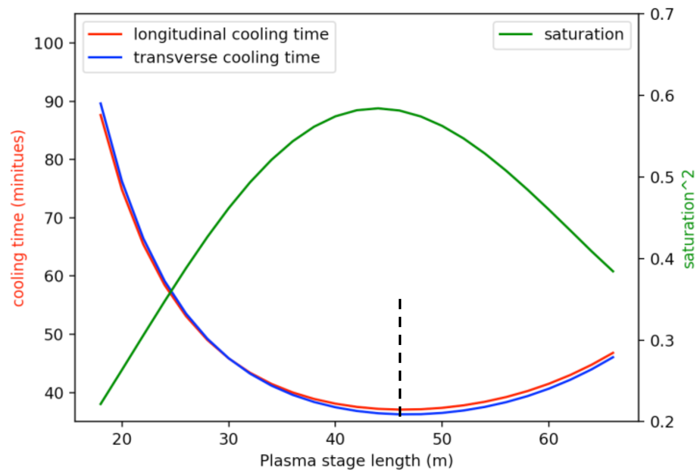


Cooling time optimization

The analytical formulas and optimization methods are encoded in Python.(Panos PRAB 22 081003(2019) including transverse cooling, diffusion and evaluate saturation)

- Using the realistic tunnel geometry parameters: Total IR2 size, hadron energy, charge, bunch length, emittance and energy spread, electron charge, emittance and energy spread
- Maximum the transverse cooling rate by varying hadron dispersion, phase advance, plasma stage length and hadron, electron R56
- Fine tune the hadron dispersion to get same longitudinal and horizontal cooling rate
- Scan the plasma stage length, check the saturation rate.





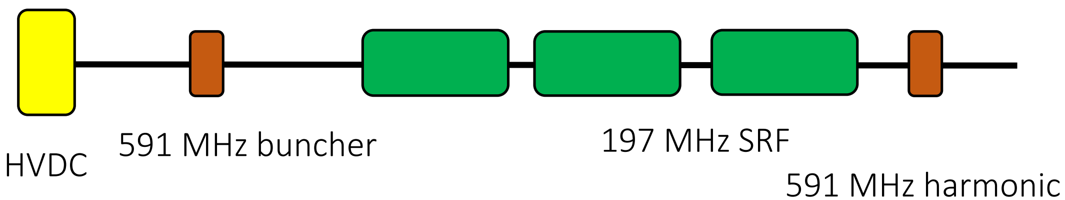
EIC CeC parameters

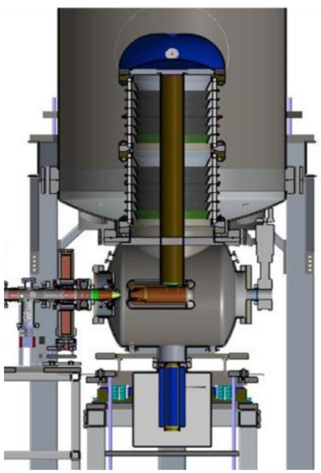
	Value		
e-beam normalized emittance [mm-mrad]	2.8		
e-beam energy spread	10^{-4}		
Average electron beam current [mA]	100		
e-beam bunch charge [nC]	1		
e-beam energy [MeV]	22.3	54.1	150
Electron R56 [cm]	1.26	0.652	0.68
Hadron R56 [cm]	0.3	0.15	0.16
Dispersion [m]	0.33	0.21	0.442
Amplification length*[m]	46	44	96
Modulator, Kicker length [m]	30	40	50
Cooling time [min]	91	46	38

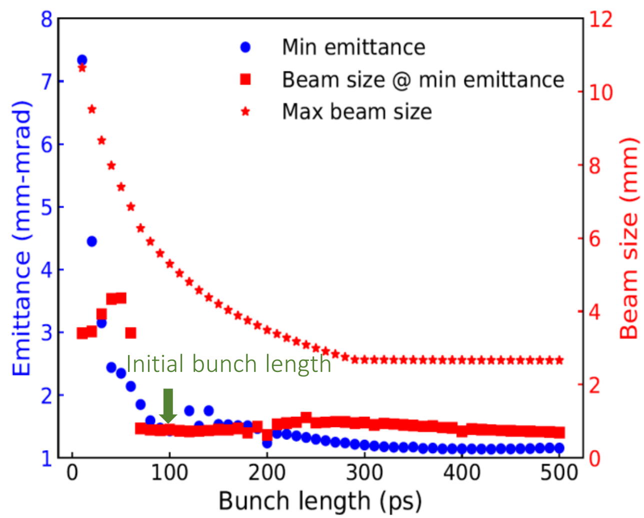
Two amplification sections.

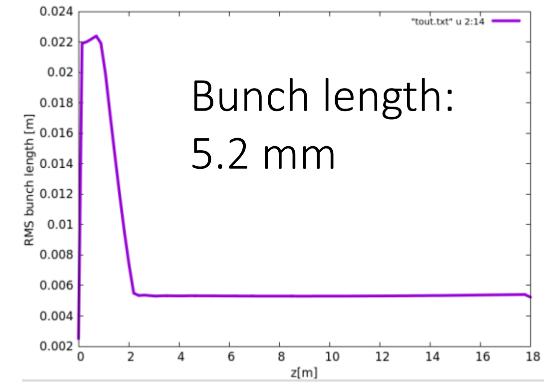
* Assume same beta function

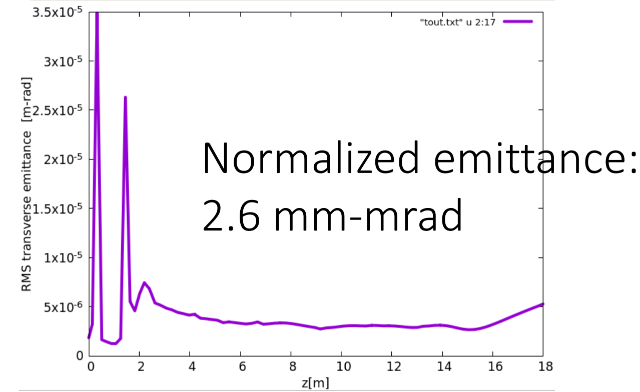
DC gun + SRF booster Injector

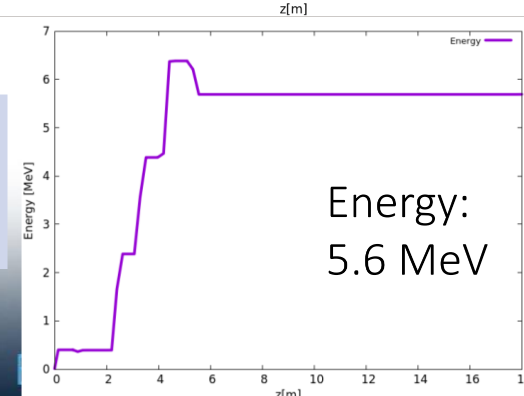






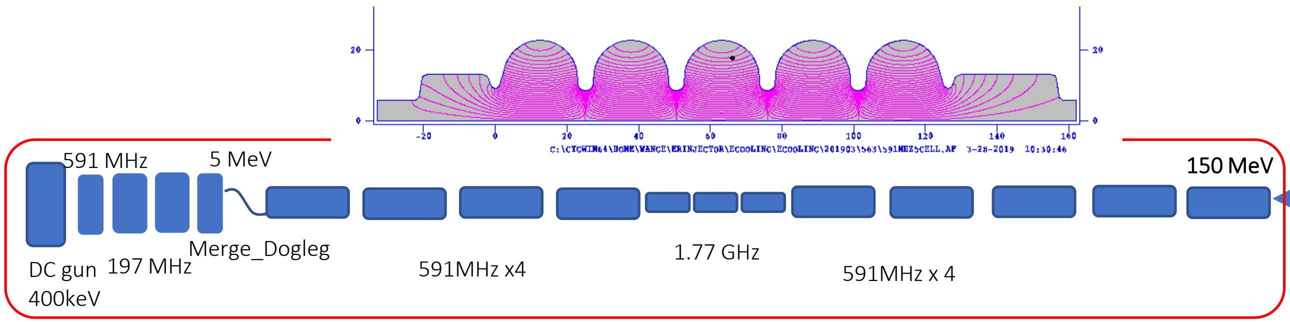




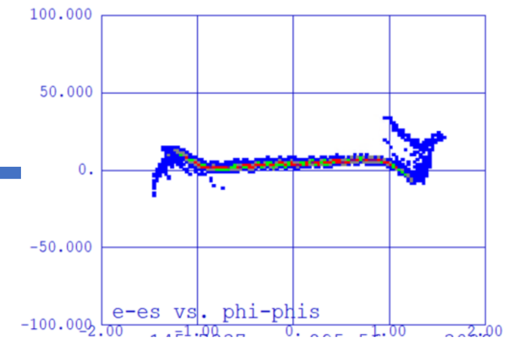


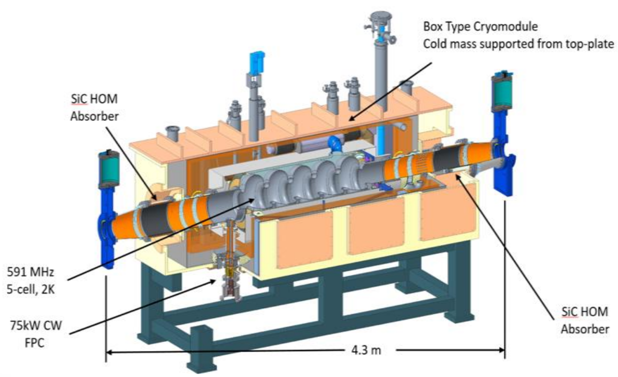
- We studied 5.6 MeV injector and simulated by 3D space charge code GPT.
- HVDC gun and 197 MHz SRF booster with harmonic cavity.

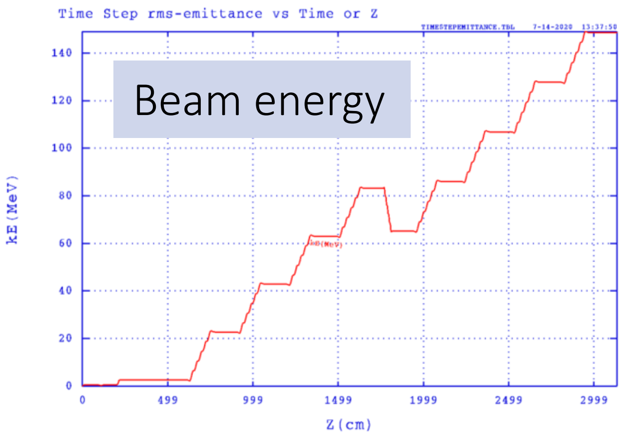
ERL_injector and Linac

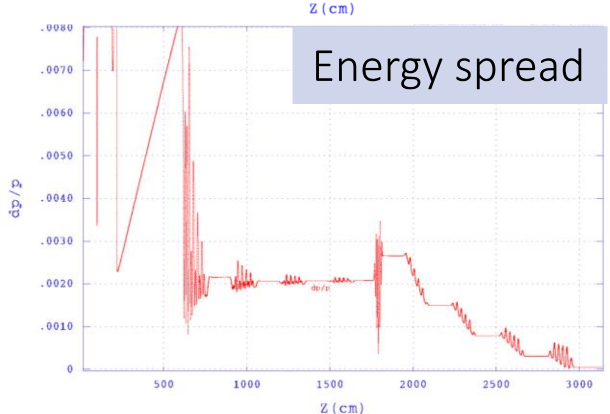


Longitudinal phase space





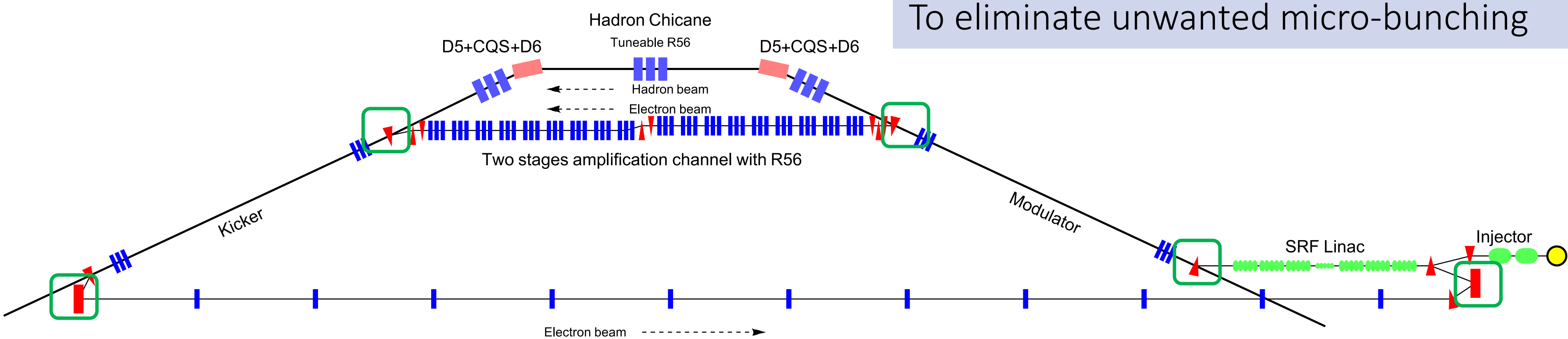


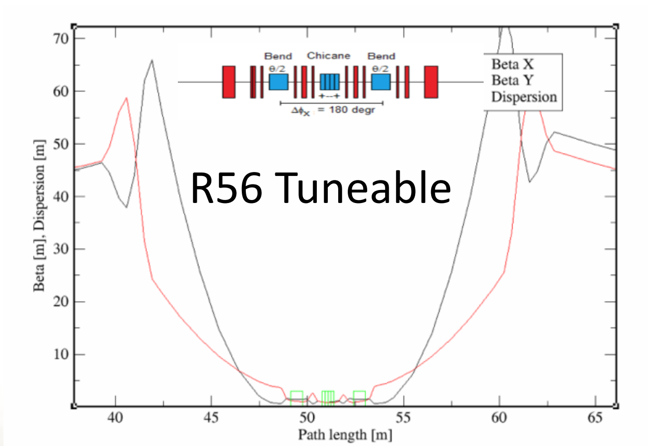


- Developed a 150 MeV linac using 591 MHz 5 cell SRF.
- 1.77 GHz 3[rd] harmonic to reduce the energy spread.
- Space charge is included. Simulation shows the beam parameters meets the requirements.

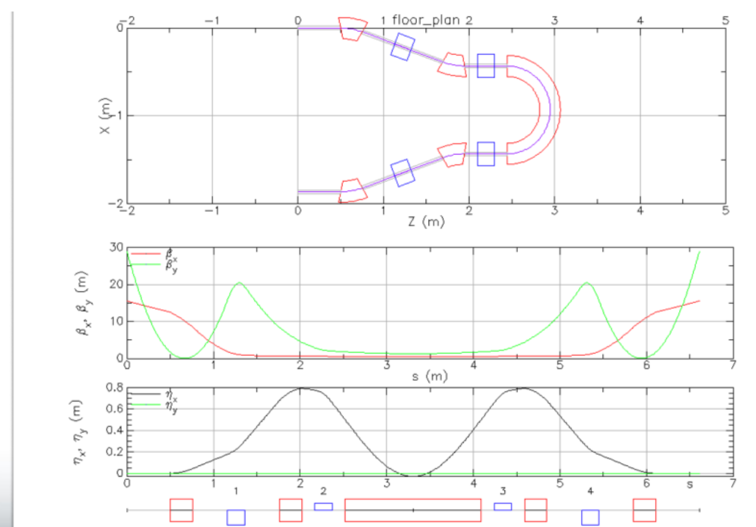
R56 canceled bending

To eliminate unwanted micro-bunching





Bates bending for 180 return



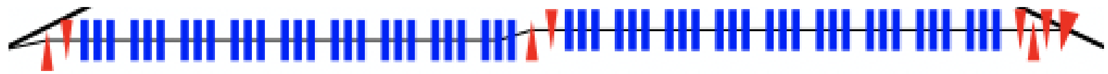
16 deg bending:

- Place a Chicane at center cancel out R_{56}
- Two quads triplets: achromatic bend

180 deg bending:

- Bates bending to cancel out R_{56}

R56 canceled along the cooling stage



Two stages amplification channel with R56

- The longitudinal space charge causes longitudinal kick. The microbunches slips due to R56 of drift and chicanes

Energy	R56 drift+Chicane	Slips at one sigma	Slips using dogleg/chicane
150 MeV	-2.3mm -20.4 mm	175 nm ✓	-35 nm ✓
54.1 MeV	-17 mm -19.56 mm	3.8 um ?	1.57 um ✓
22.3 MeV	-100 mm -37.8 mm	105 um ✗	1.9 um ✓

- Solution:

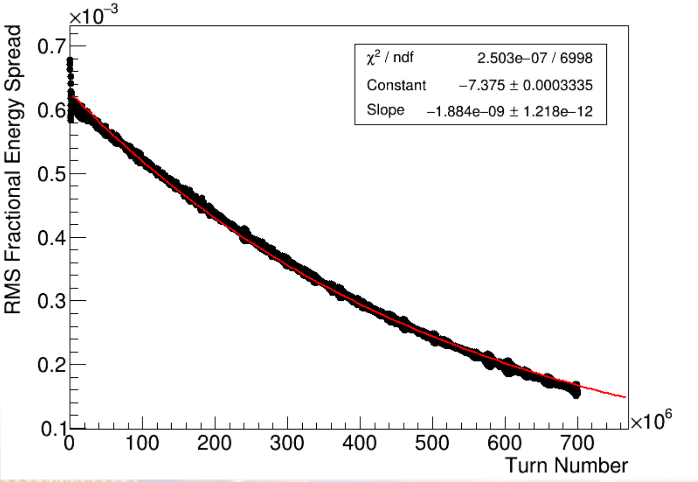
We use two dogleg and one chicane to compensate R56.

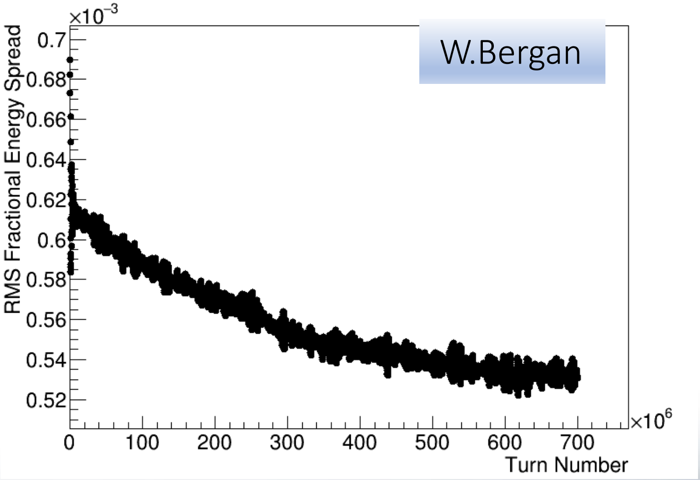
$R_{56}1*R_{56}2*R_{56}3 < 0$(negative means higher momentum particles move forward)

E. Wang # EIC-ADD-TN-011

Multi-Turn Simulation

- Developing a C++ cooling tracking code
- Do turn-by-turn tracking of hadrons, applying kicks from CeC process as well as IBS and synchrotron motion to verify achievable cooling rates.
- Can also simulate the electron beam directly to determine the regime in which saturation of electron beam becomes important.
- Will optimize parameters, include transverse motion, and study the effects of noise in the electron beam

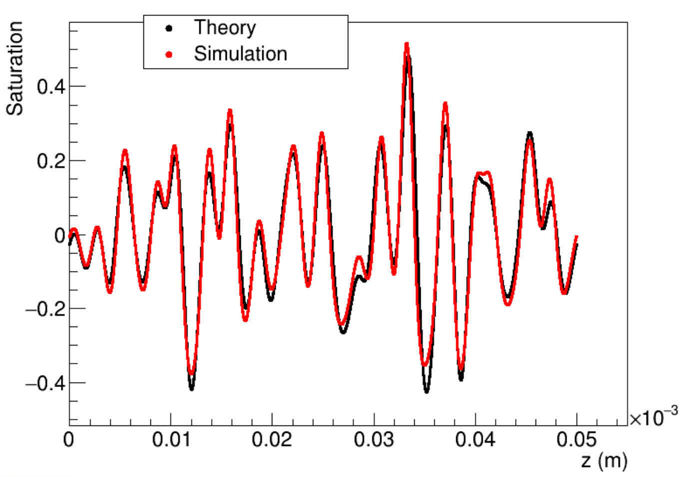


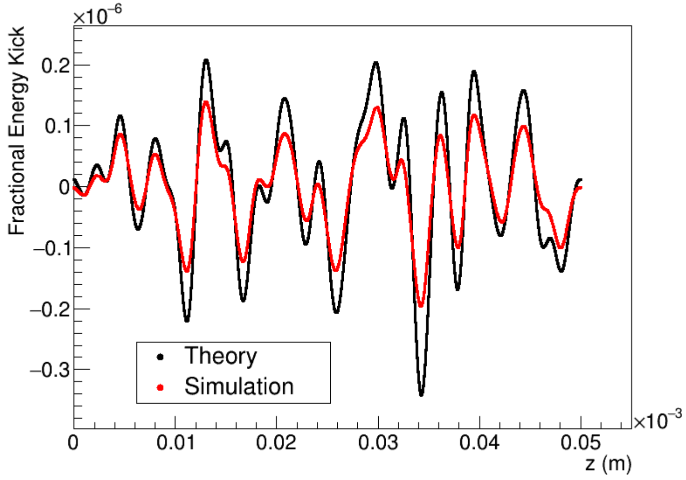


W.Bergan

Saturation Studies

- Model proton macroparticles and a background electron fluid, with realistic shot noise
- Simulate the plasma dynamics through the cooling section to understand the nonlinear effects in the cooling process





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Plasma frequency in the beam moving in vacuum and in wiggler

Conversion of a beam density modulation to energy modulation dramatically speeds up in a wiggler with K>>1

$$\omega_{p(wiggler)} \simeq \omega_{p(drift)} \frac{K}{\sqrt{2}}$$

Comparing plasma frequencies in the electron beam propagating the wiggler and a drift*)

*) G. Geloni, E. Saldin, E. Schnedmiller, M. Yurkov, Preprint DESY 07-087, June 2007

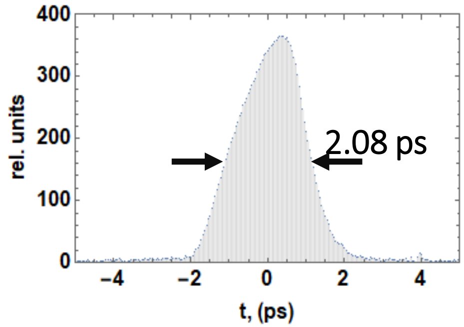
A proof-of-principle experiment at Argonne Wakefield Accelerator (AWA) facility

S. Lee, E. McCarthy, M. Qian, E. Trakhtenberg, I. Vasserman, J. Xu prepared the wiggler including the design of a strong back, wiggler assembly, magnetic measurement and tuning; **S. Doran** designed the wiggler support and the vacuum chamber, assembled the beamline and installed the wiggler; **G. Ha, J. Seok** conducted the experiment and analyzed the data; **A. Adelmann, A. Alba, R. Bellotti** carried out the simulations and analyzed the data; **J. Power** provided the oversight of the experiment and data analysis; **A. Zholents** proposed the experiment and led the activity.

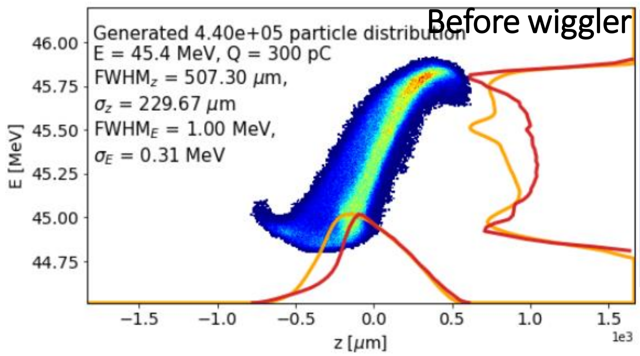
Beam parameters and experimental setup

Beam energy = 45.4 MeV, bunch charge = 300 pC

Peak current distribution

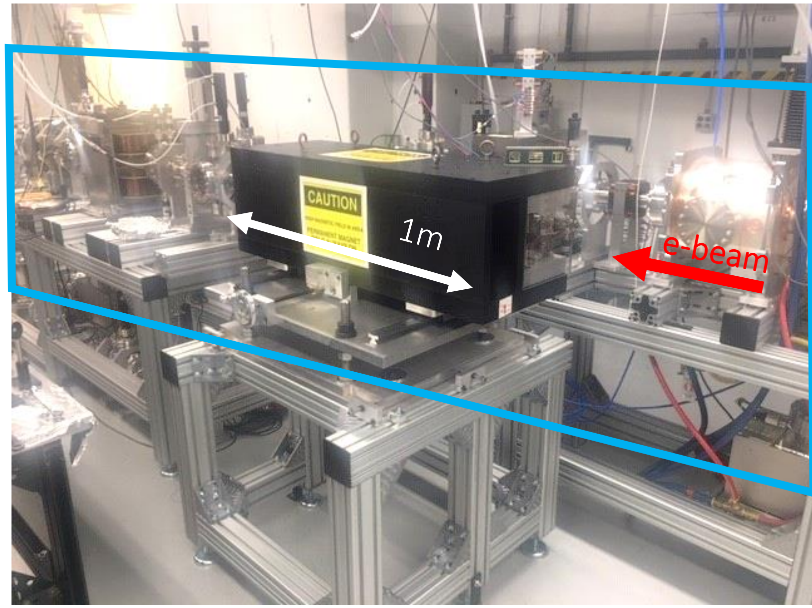


Beam longitudinal phase space upstream of the wiggler



Red : simulations. Orange: measurements. Discrepancies are due to a second low intensity "ghost" bunch

Reconstruction from measurements

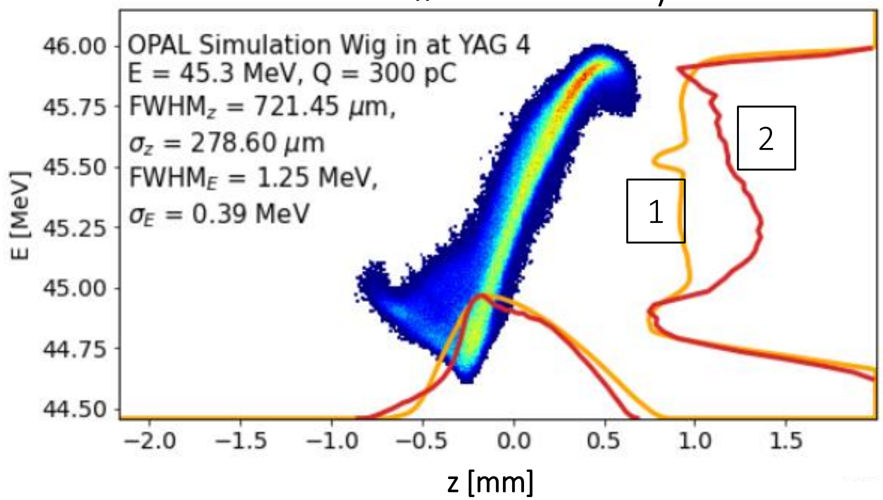


Section of AWA beamline used in the experiment. Wiggler was assembled using spare magnetic structures and a new strong back frame and a new vacuum chamber. Wiggler period = 8.5 cm, K=10.8

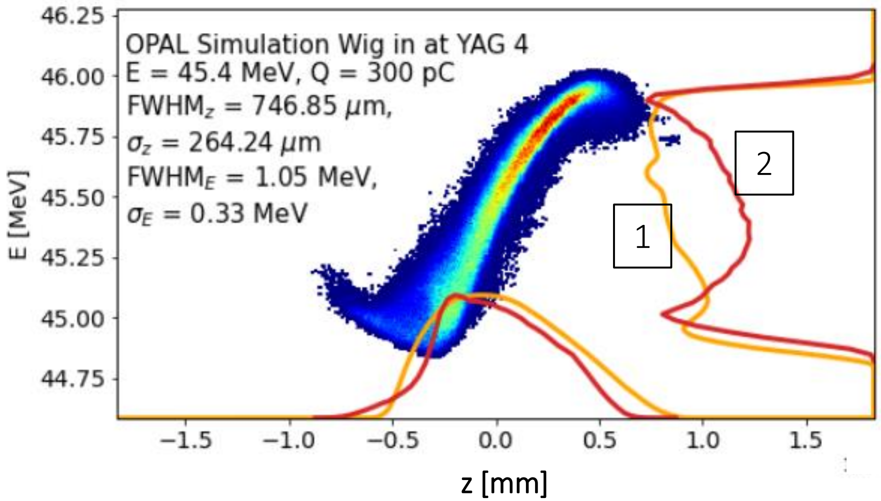
Experimental result: observed space charge and radiation interactions of electrons

Measured (1) wiggler impact on the beam longitudinal phase space and compared it with simulations (2) using round and elliptical beams

Round beam case: s_x=0.6 mm, s_y=0.4 mm



Elliptical beam case: s_x=2.6 mm, s_y=0.4 mm



Space charge and radiation interactions of electrons in the wiggler were modeled using OPAL+ MITHRA

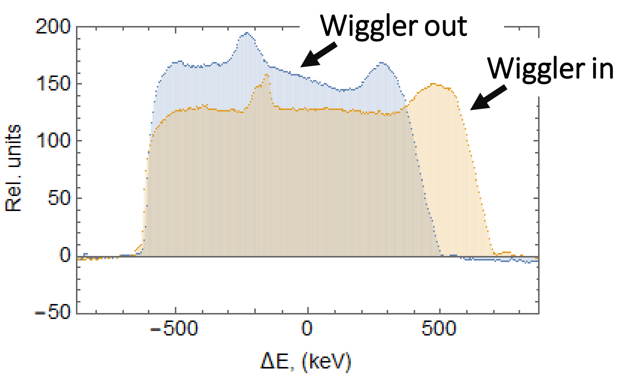
A. Adelmann et al., **OPAL a Versatile Tool for Charged Particle Accelerator Simulations**, 2019, arXiv:1905.06654; A. Fallahi, A. Yahaghi, and F. Kärtner, **MITHRA 1.0: A Full-Wave Simulation Tool for Free Electron Lasers**, Computer Physics Communications, 228, pp.192-208, 2018.

Experimental results cont'd

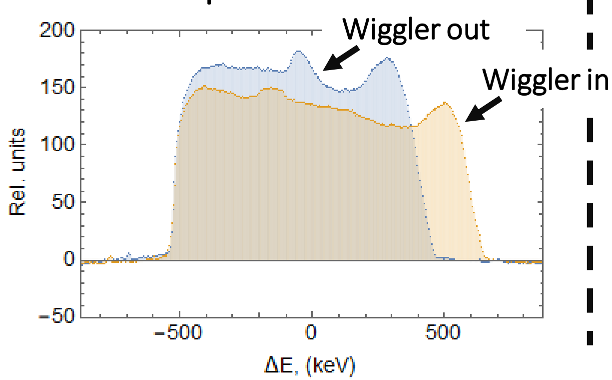
Beam energy distribution measured with wiggler rolled out of the beam line (blue colored histogram) and with wiggler rolled on the beam line (yellow colored histogram)

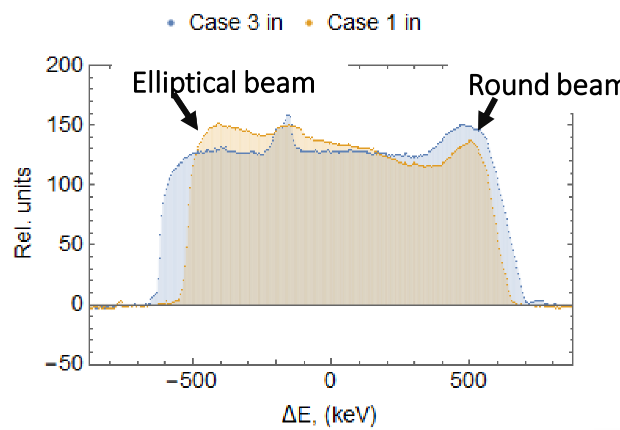
Comparing wiggler impact on round (blue colored histogram) and elliptical beams (yellow colored histogram)

Round beam



Elliptical beam





Data analysis is in progress

Summary

- We have evaluated three energy cases for EIC CEC cooler.
- Theoretical formulas has been derived for the diffusion and cooling terms. More theoretical works have been published.
- Cooling simulation C++ code development is in progress. The code includes IBS, incoherent heating due to wakes of nearby protons and e- noise and synchrotron motion.
- The pCDR ERL has been assessed. More detail injector, arc, amplification R56 and ERL design have been studied.
- Increasing plasma frequency by wiggler experiment has been carried out.

Thanks for your attention!

Acknowledgements:

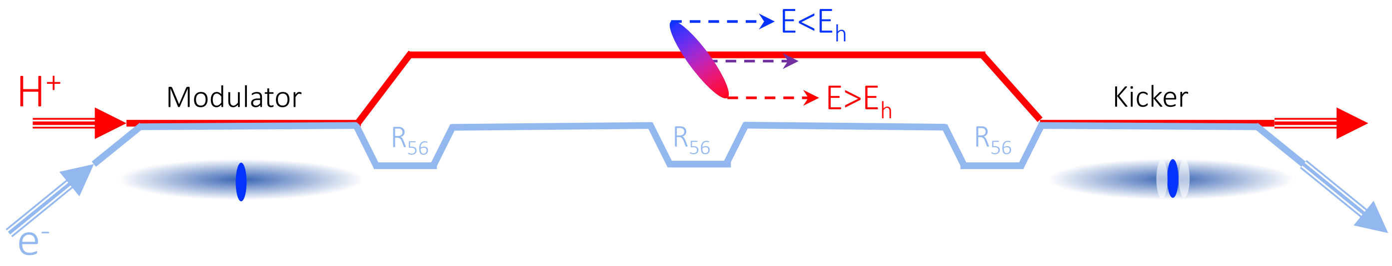
Coherent electron cooling with ERL electron beam and multi-stage micro-bunching amplifier FOA 19 B&R #KB0202011

Collaborators:

ANL: A. Zholents, G. Ha, J. Power, J. Xu
JLab : S. Benson, D. Douglas and Y. Zhang
SLAC: G. Stupakov and P. Baxevanis
BNL: F. Willeke, W. Bergan, M. Blaskiewics, E. Wang

Back up

Micro-bunched cooling



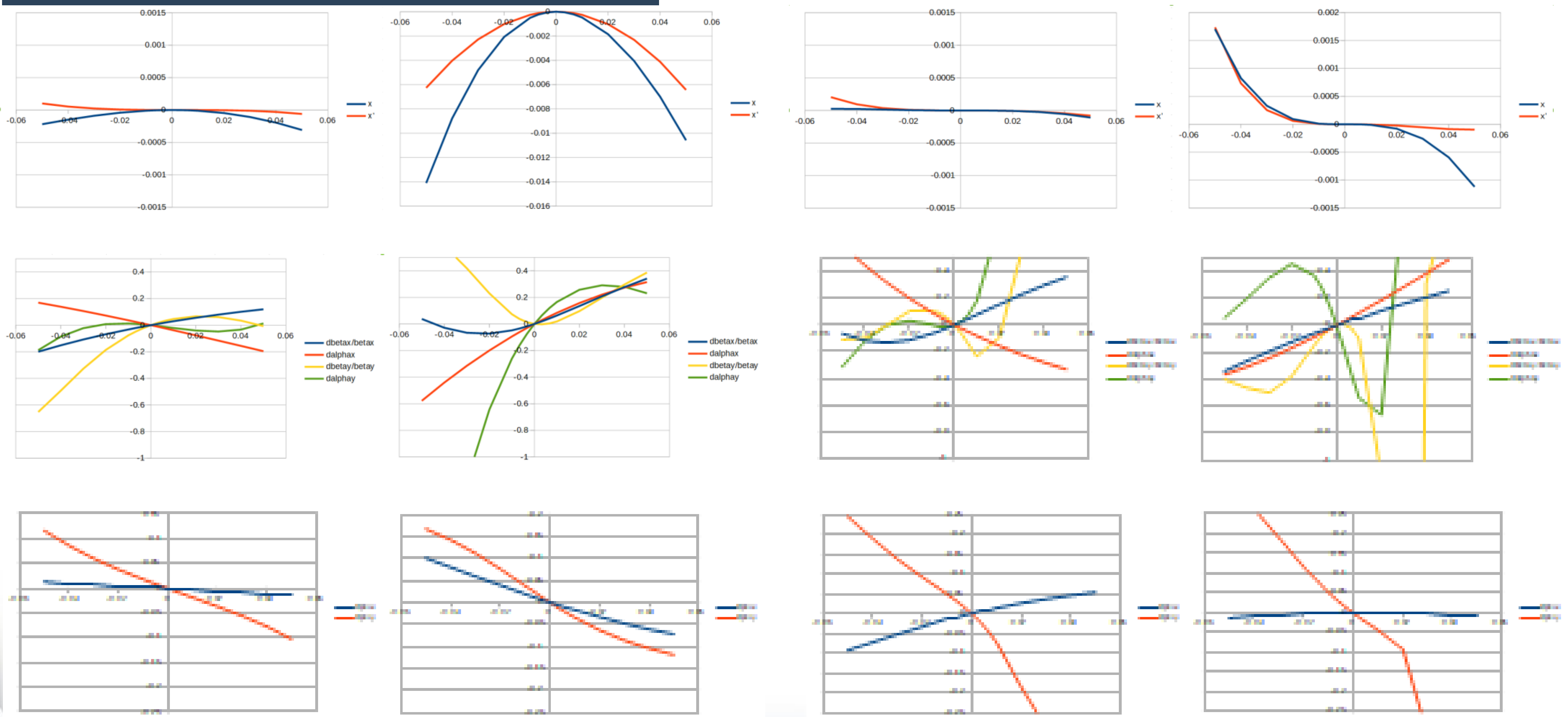
Drift quarter of electron beam plasma wavelength, could be multiple stages.

Advantages:

- Very broadband (~THz) amplifier
- Micro-bunching instability was well studied.
- Significant gain without saturation

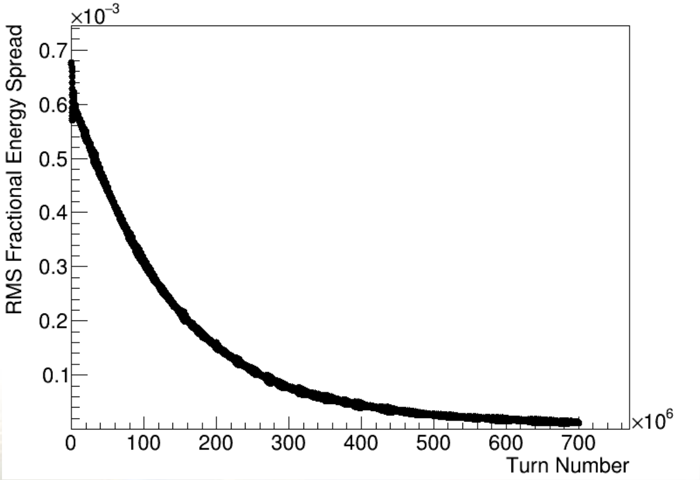
High cooling rates

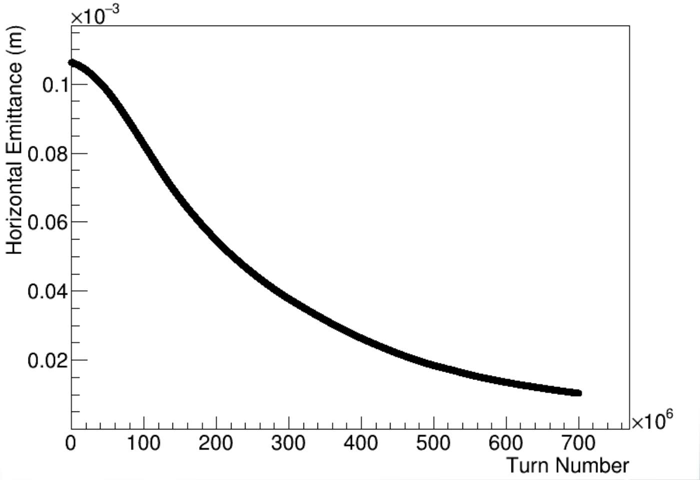
Chromatic properties



Transverse Cooling

- Work is ongoing to add transverse dynamics to the cooling code





Core bunch and full bunch w cooling on/off

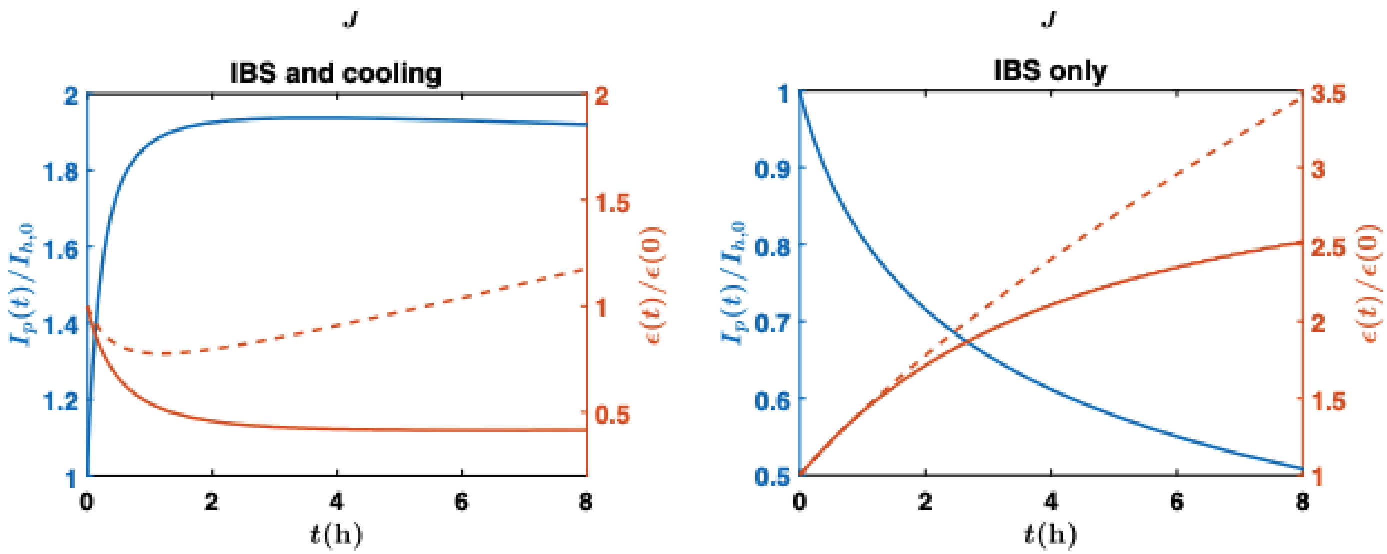
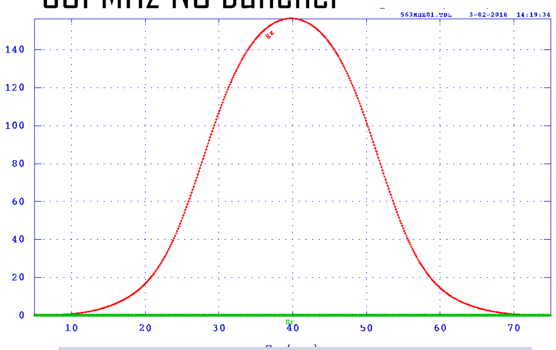


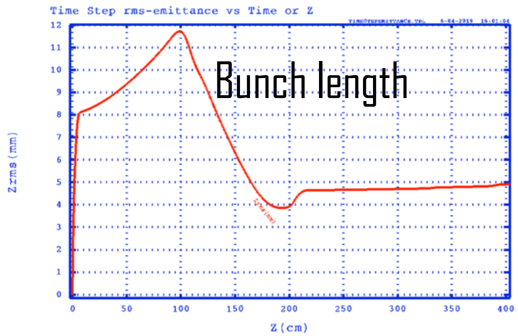
FIG. 6. Upper panel: hadron distribution function at selected times during the cooling process. Lower panel: hadron peak current (blue curve), total longitudinal emittance (dashed brown curve) and core part (95%) emittance (solid brown curve) versus time. The data shown compare and contrast the cases with and without cooling.

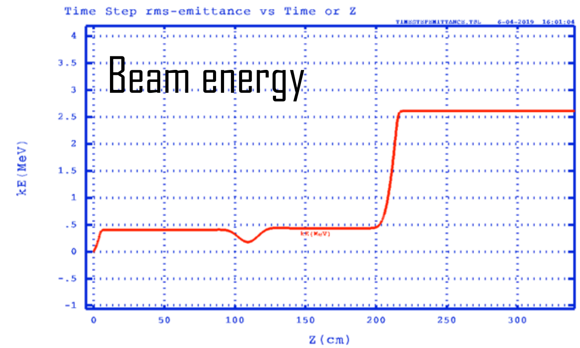
Injector and Merger

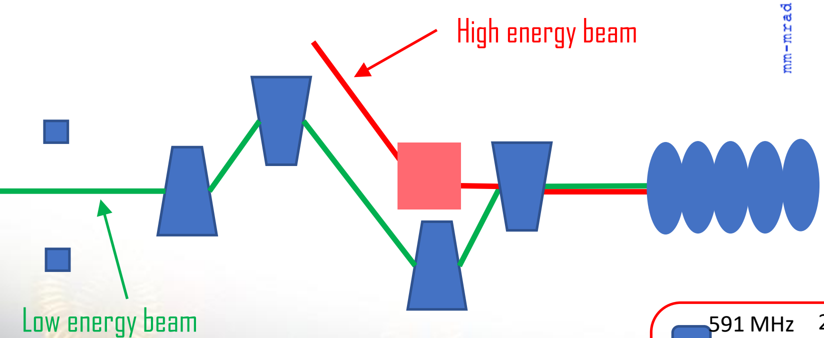
591 MHz NC buncher

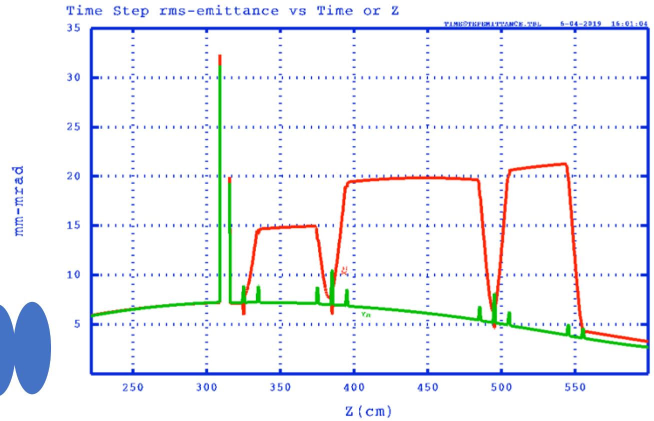


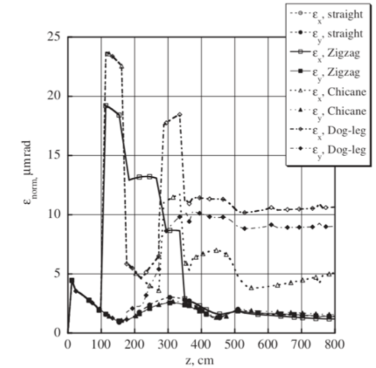
Scaled from 563 single cell
Gap voltage 200 kV





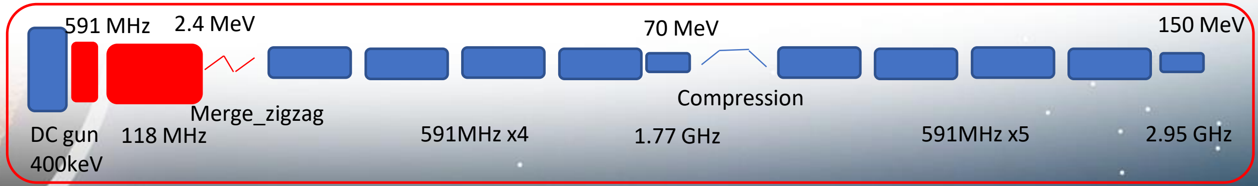






NIM A557 (2006)

E-return transport



Micro-bunched electron cooling (MBEC) for EIC

- Electrons of the cooler beam with $\gamma_e = \gamma_h$ first interact with the hadron beam in a short modulator where their energy is perturbed by hadrons. The energy perturbations in the electron beam are then converted to density modulation in the chicane $R_{56}^{(e)}$. The longitudinal electric field of these density perturbations acts back on hadrons in the kicker. High-energy hadrons passing through $R_{56}^{(h)}$ move ahead and get a negative kick, low-energy move back and get a positive kick. Over many passages, this decreases the energy spread of the hadron beam.
- This scheme (a) is typically too weak to provide an adequate cooling and should be supplemented by an amplification of the signal in the electron beam in one (b) or two (c) stages (D. Ratner, PRL, **111**, 084802 (2013)).