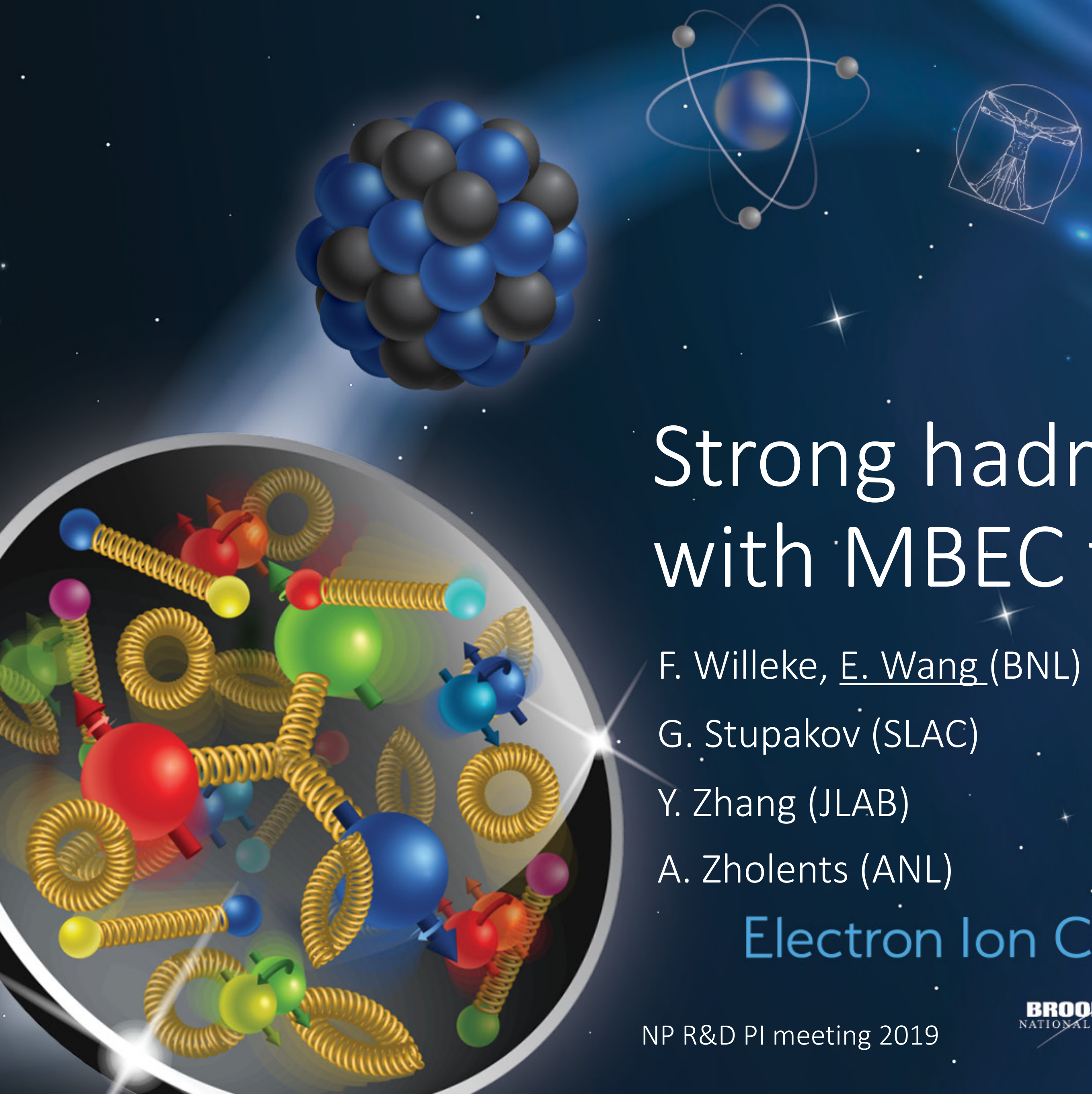

Strong hadron cooling with MBEC for EIC

F. Willeke, E. Wang (BNL)

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Y. Zhang (JLAB)

A. Zholents (ANL)

Electron Ion Collider – eRHIC

NP R&D PI meeting 2019

BROOKHAVEN NATIONAL LABORATORY

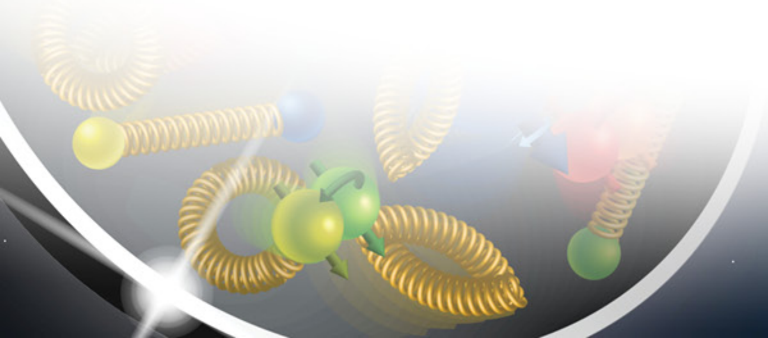
U.S. DEPARTMENT OF ENERGY | Office of Science

Project description

- We aim on developing theory of micro-bunched strong hadron cooling, simulation tools, the layout for EIC and preparation for experimental demonstration.
- **Current Status**: At the first year, we concentrated on theory /simulation tools development and cost efficiency layout development. The progress meets and slightly beyond the planned milestones.
- Monthly collaboration meetings to exchange the progress and discussion.
- 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	YF 2019
SLAC	Funds allocated	200,000	382,994
	Actual costs to date	17,056	217,605
ANL	Funds allocated	130,000	130,000
	Actual costs to date	11,552	55,770
JLAB	Funds allocated	226,000	226,000
	Actual costs to date	3,626	260,199
BNL	Funds allocated	300,000	300,000
	Actual costs to date	0	5,796

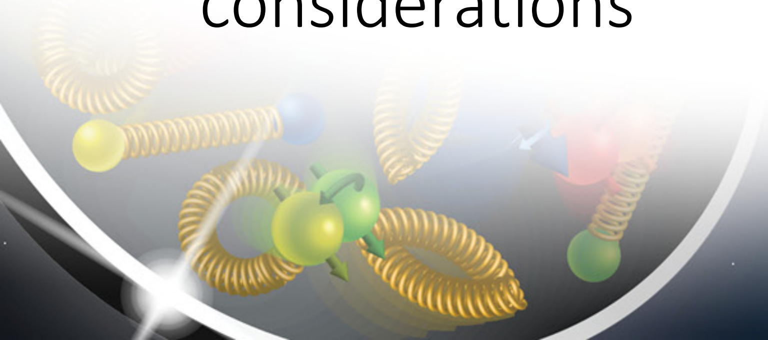


Deliverable and schedule

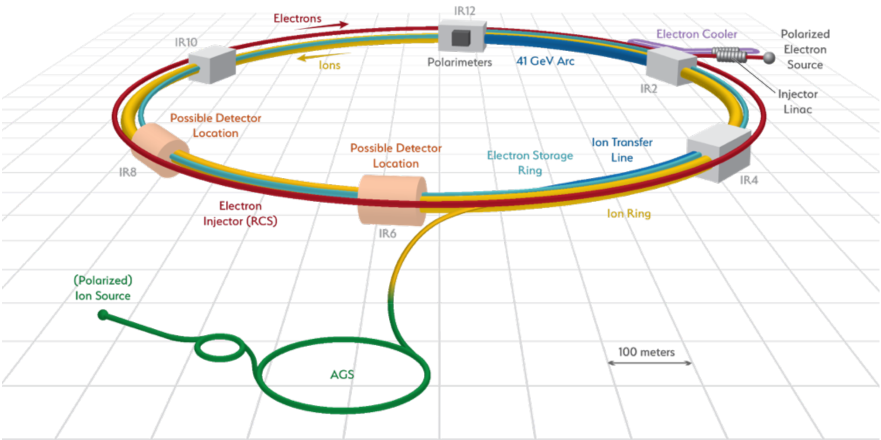
Activities	Schedule	Status
Theoretical analysis: 1D model; analytical formula for cooling rate with/ without amplification, publish paper	Y1: Q1-Q4	Done
Physical model: Noise effect, 3D effect, energy deviation, heating process	Y1: Q1-Q4 Y2: Q1	3D in preliminary
Layout of the cooling channel for EIC: pre-conceptual layout; beam parameter, magnets	Y1: Q1-Q4 Y2:Q1	90% Done
Preconceptual layout of ERL: Electron source, RF accelerator, HOMs, Merger, return loop	Y1: Q3-Q4 Y2:Q1	80% Done
Preconceptual layout of entire cooling facility: Injector, Linac, Merger, dump with optimization	Y2:Q3-Q4	10%
Simulation code: Develop Matlab code, Impact-T, bench marking	Y2: Q1-Q4	1D Matlab code
Start to end simulation	Y2:Q3-Q4	Not start
Experimental methods to verify MBEC: diagnostic	Y2:Q3-Q4	Not start
Ring based microbunching cooler	Y1Q1-Y2Q4	Terminated

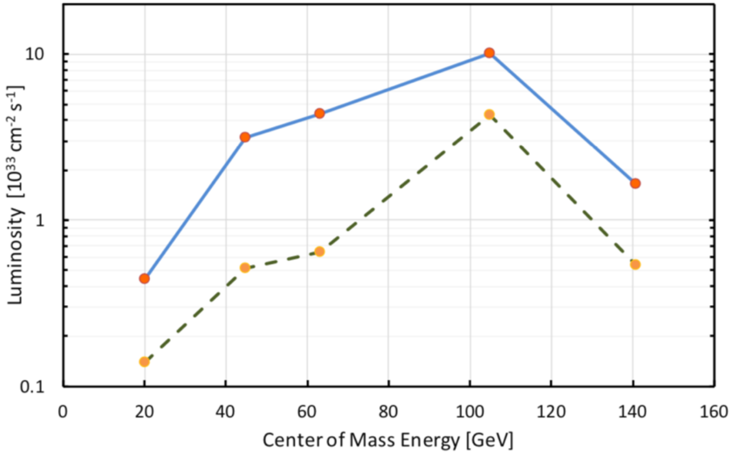
Outlines

- Why need cooling
- Theoretical analysis of MBEC
- Conceptual parameters of the hadron cooler for eRHIC
- Preconceptual Layout development: Cooling channel and ERL
- Optics simulation and major components considerations



Why need cooling

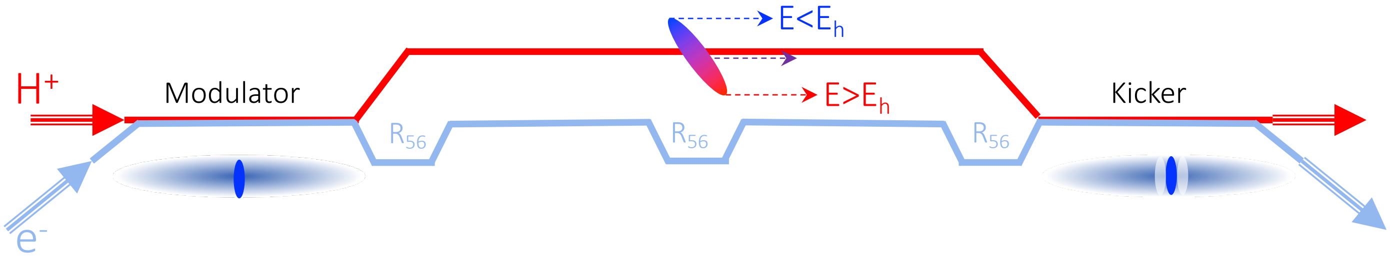




E_{cm} = 20 GeV -141 GeV
High luminosity goal: L = 10^{34}cm^{-2}s^{-1}
IBS time: longi.~ 3.4 h, transv.~ 2 h

Balance IBS: $\tau_{\text{cooling}} < \tau_{\text{IBS}}$
Decrease β^* needs to decrease σ_s

Micro-bunched cooling



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

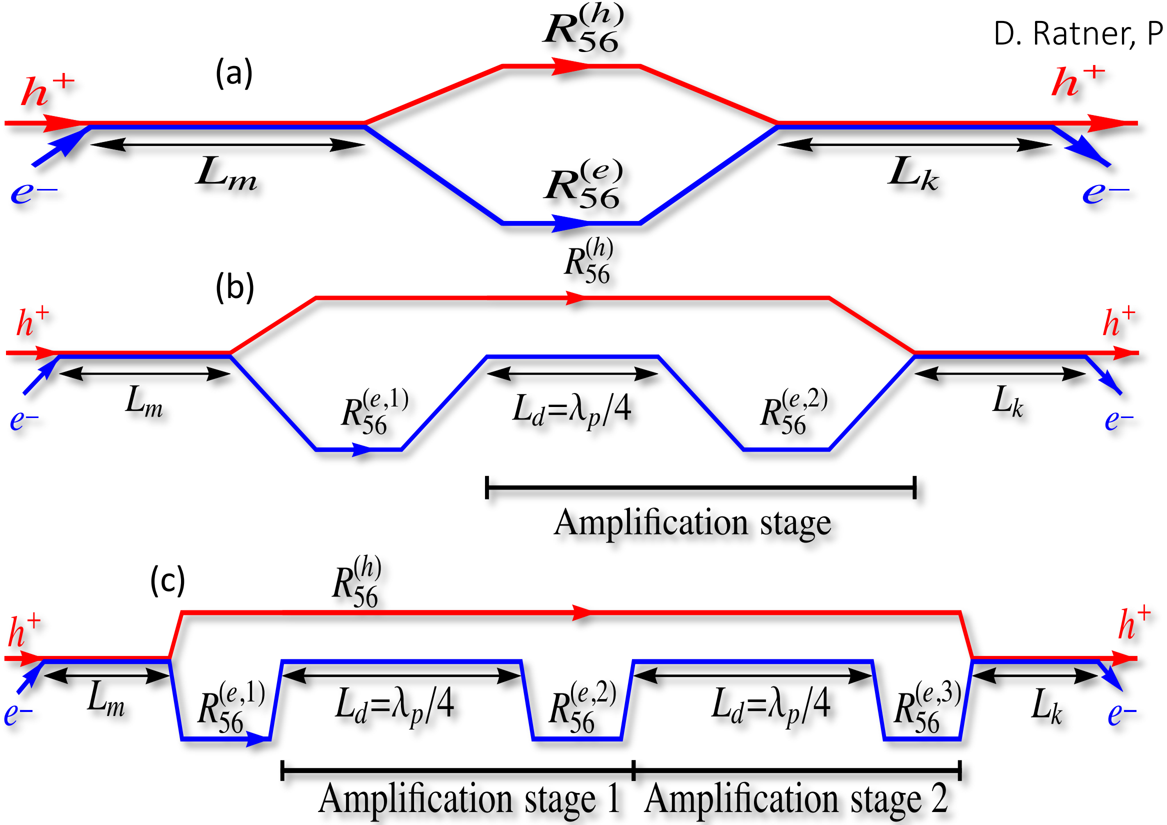
Advantages:

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

High cooling rates

Micro-bunched electron cooling (MBEC) for EIC

D. Ratner, PRL, 111, 084802 (2013)



Too weak

Strong

Imprinting: $\gamma_h = \gamma_e$,electrons energy is perturbed by hadron

Amplification: e-beam energy perturbations are converted to density fluctuation by chicane

Hadron chicane: Controls hadron travel time with respect to electron path.

Kicker: longitudinal electric field of electrons reduces the hadron beam correlated energy spread.

Scaling of the cooling rate with beam parameters in 1D model

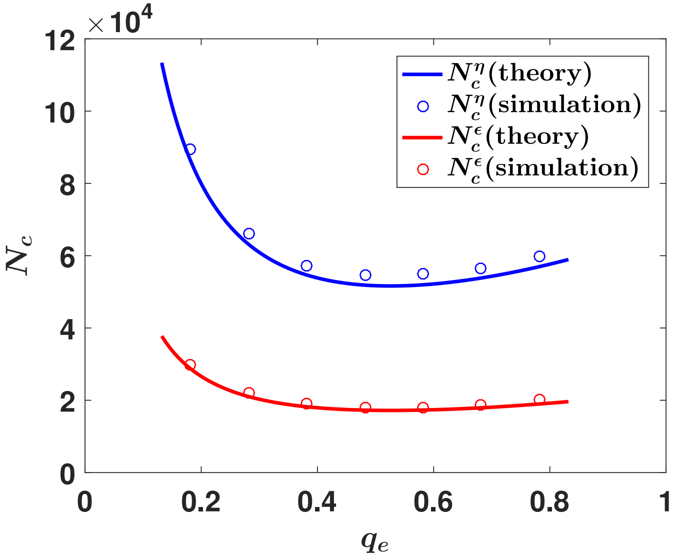
- Scaling of the cooling rate N_c^{-1} provides critical information about the feasibility of MBEC for cooling high-energy hadron beams and sets requirements for the parameter choice of the cooling sections,

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

- Gain factor G to the cooling rate :

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

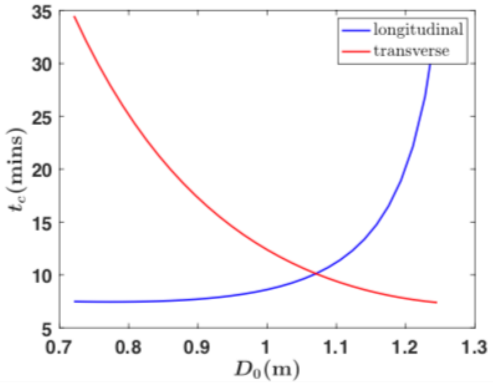
Our theoretical formulas are benchmarked against computer simulations

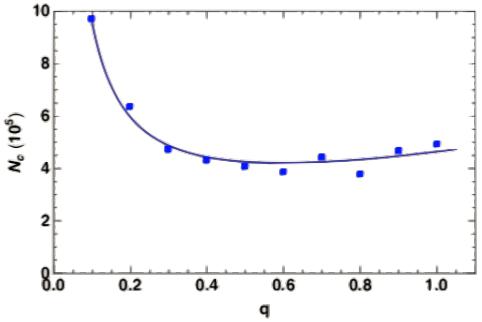


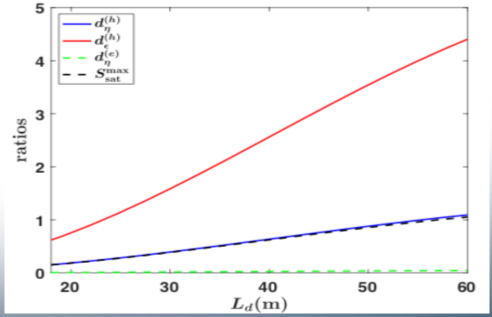
Transverse (N_c^ε) and longitudinal (N_c^η)cooling rates versus dimensionless chicane strength

Various topics are addressed in theory

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





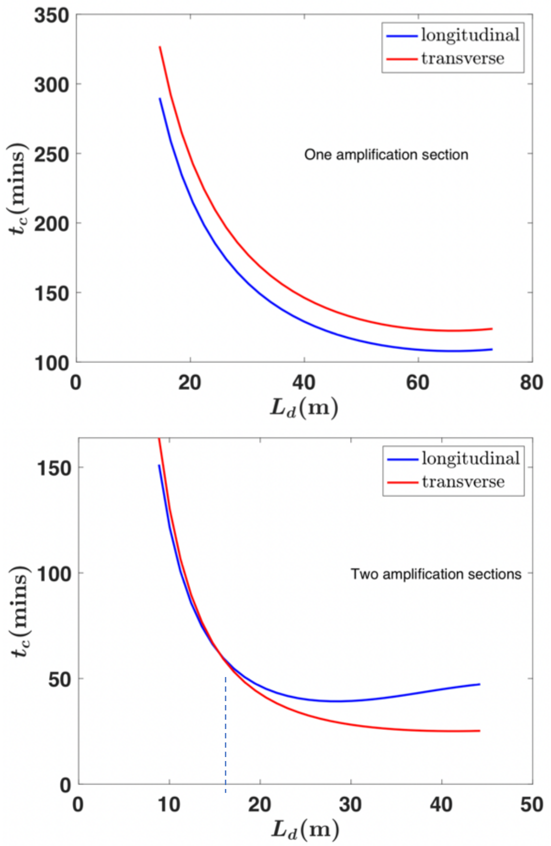


Conceptual parameters of the hadron cooler for eRHIC

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

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

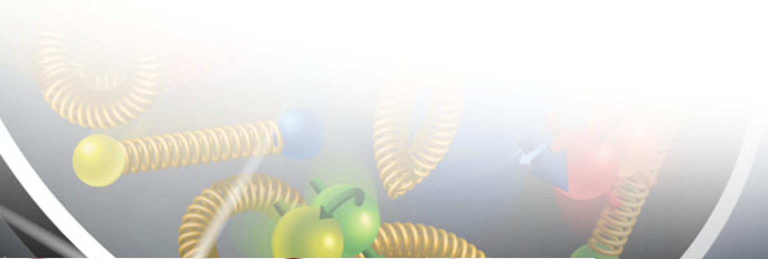
Two amplification sections, 20 m of each.



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

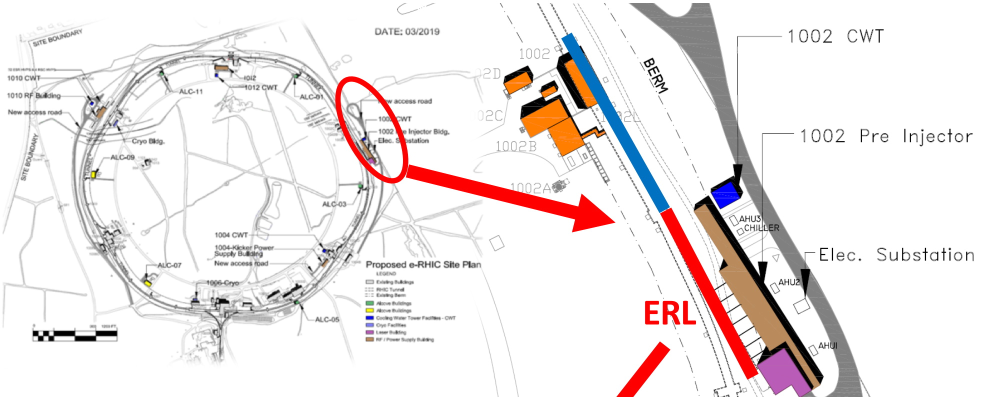
Publications related to MBEC studies at SLAC in 2018/2019

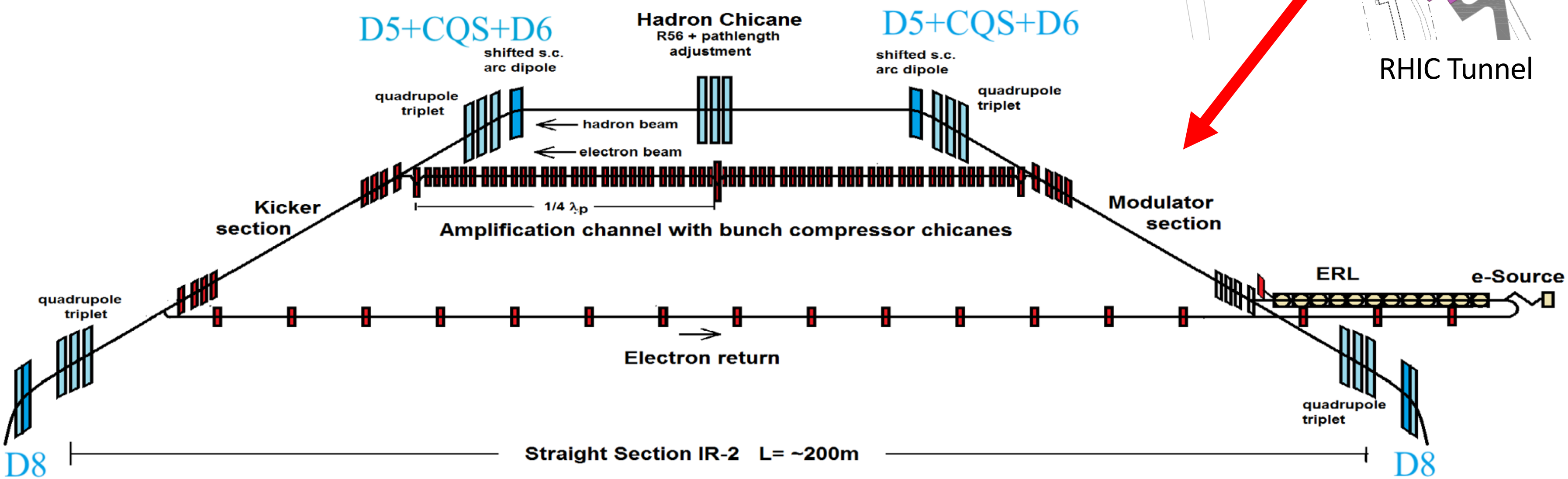
1. G. Stupakov, Cooling rate for microbunched electron cooling without amplification, PRAB, 21, 114402 (2018)
2. G. Stupakov, P. Baxevanis, Microbunched electron cooling with amplification cascades, PRAB, 22, 034401, 2019
3. P. Baxevanis and G. Stupakov, Transverse dynamics considerations for microbunched 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.



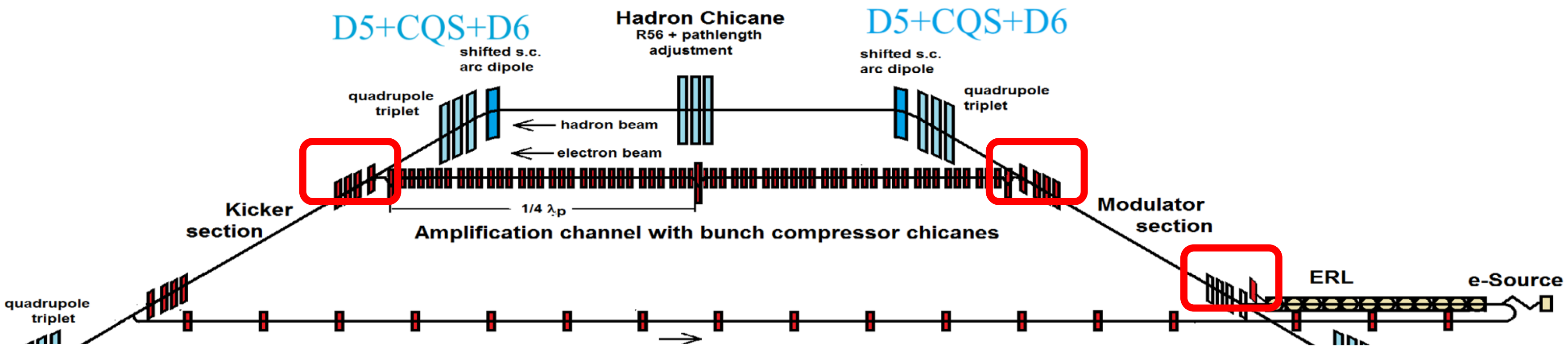
Cost saving e-cooling layout

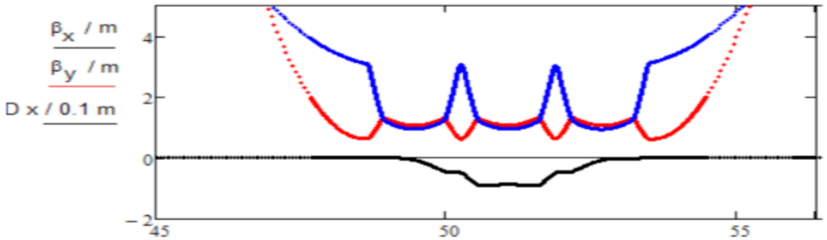
- HV DC electron photoinjector, buncher and SRF booster with round-to-flat beam transformation.
- 150 MeV superconducting Energy Recovery Linac with 591 MHz 5-cell SC accelerator.
- Strongly focusing micro-bunching channel
- Hadron chicane for pathlength and R56 adjustment using displaced s.c. arc magnets

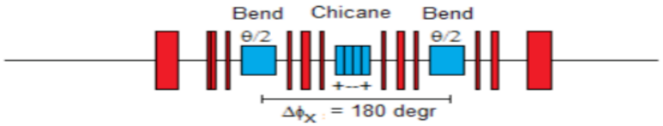


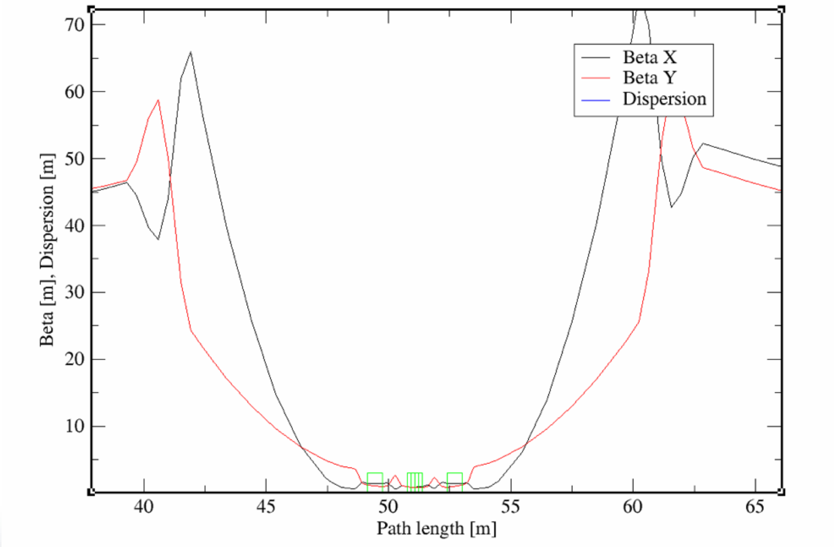


Mitigate residual energy spread



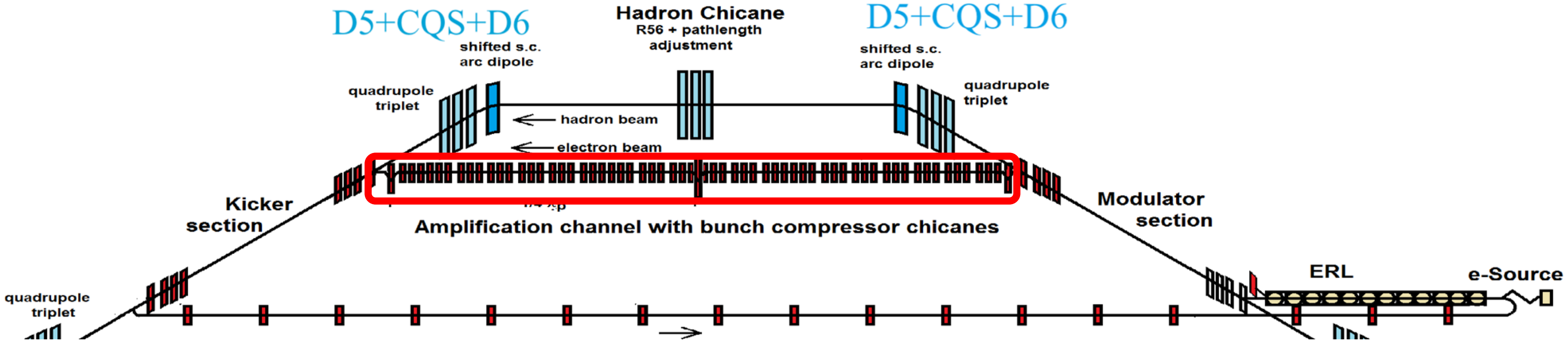


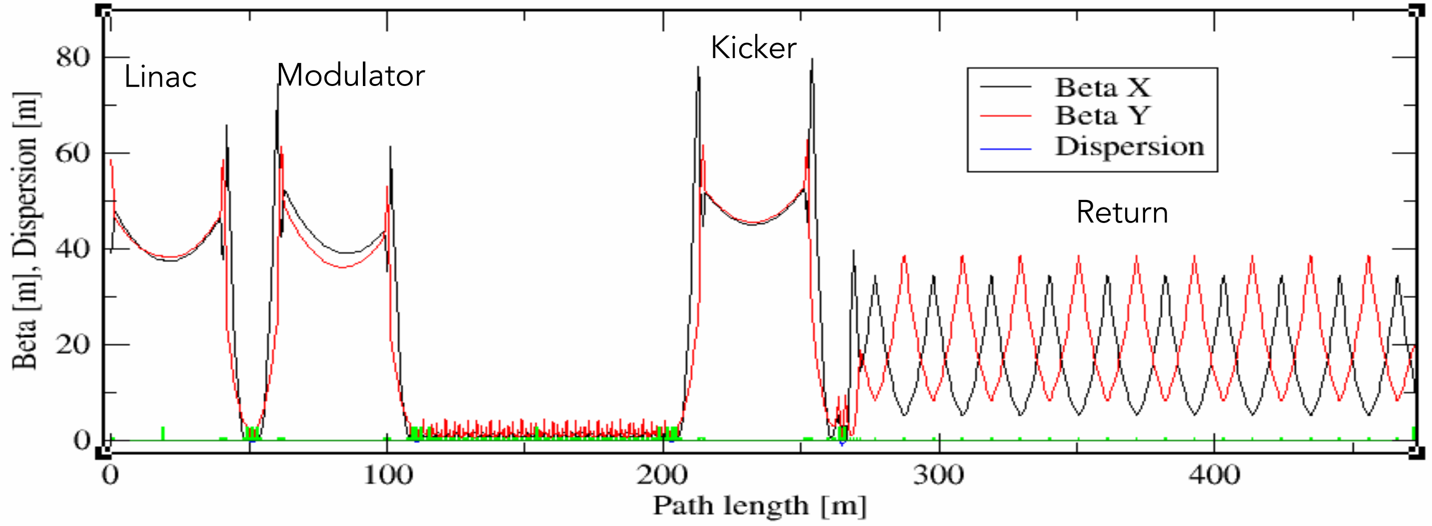




- Place a Chicane at center compensate R_{56}
- Two quads triplets: achromatic bend

Amplification



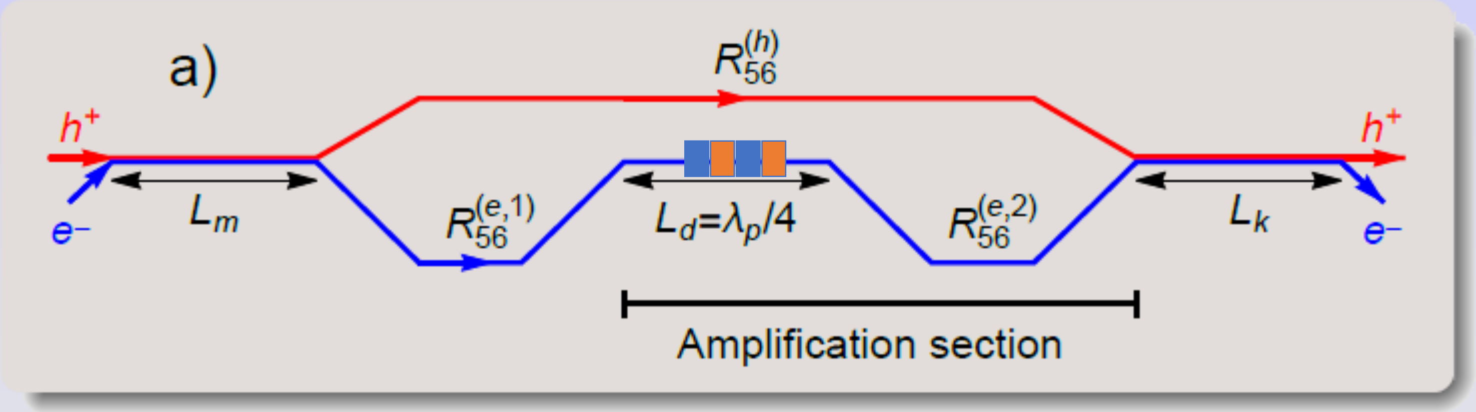


Total 20 quads triplets and 3 chicane (R_{56}=23mm)
Chicanes lengthen the pathlength by 45 mm

Using wiggler to shorten the amplification stages

MBEC amplification using plasma oscillations[4]

Figure is courtesy of G. Stupakov



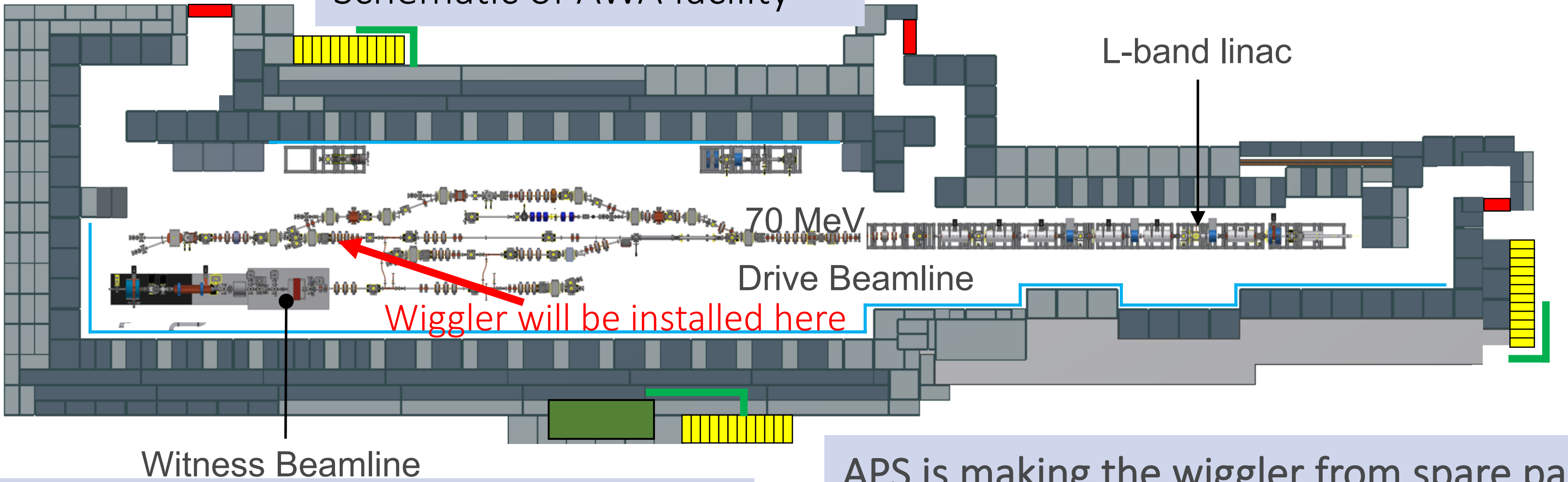
Space charge force is much stronger if the beam follows a wiggling trajectory

$$\gamma_{e_z} = \frac{\gamma_e}{\sqrt{1+K_e^2}} \quad K_e = (eB_w\lambda_w)\,/\,(2\pi m_e c) \qquad \gamma_{e_z} = \left(1-\beta_{e_z}^2\right)^{-1/2}$$

For $K_e >> 1$, $\Delta\gamma_w / \Delta\gamma = (\Delta\gamma_{drift} / \Delta\gamma)\,(K_e)^a$ where $a \simeq 1$

Experimental verification of the idea

Schematic of AWA facility



Goal:

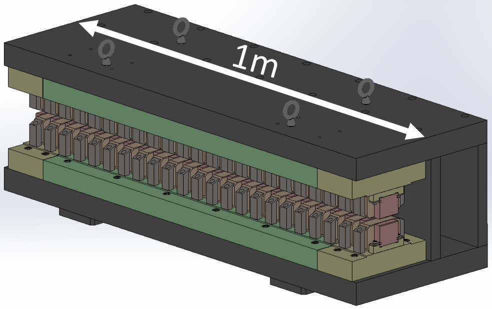
Measure the modulation amplification with and without the wiggler, and compare it to simulations (OPAL and GPT) and theory in different beam conditions:

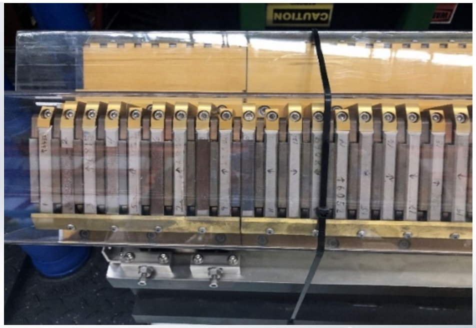
-different transverse beam sizes

-different initial density modulations

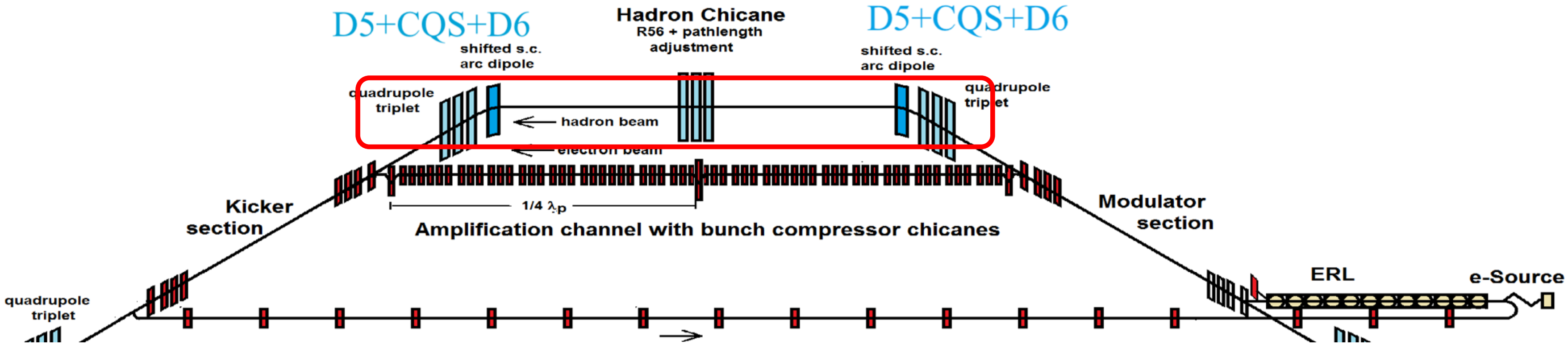
-different peak current

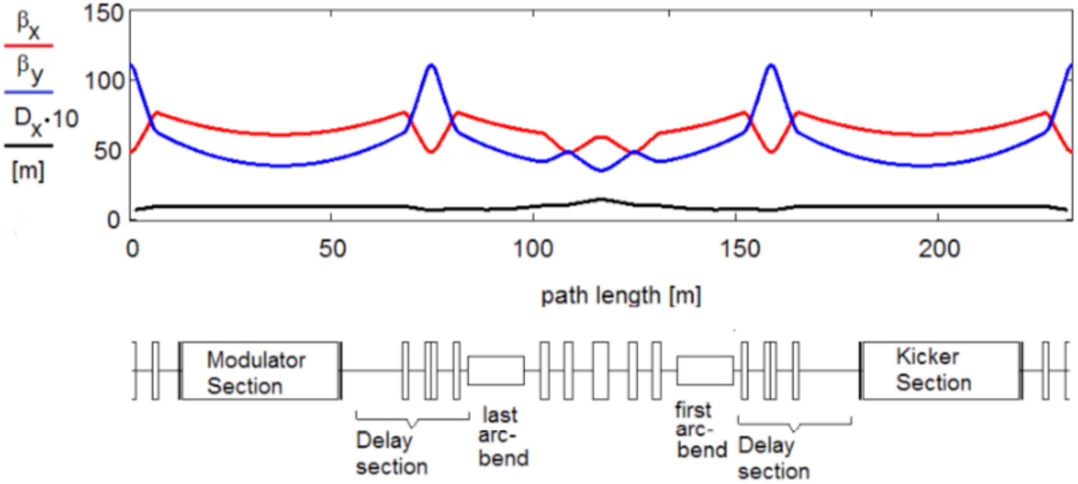
APS is making the wiggler from spare parts





Hadron lattice



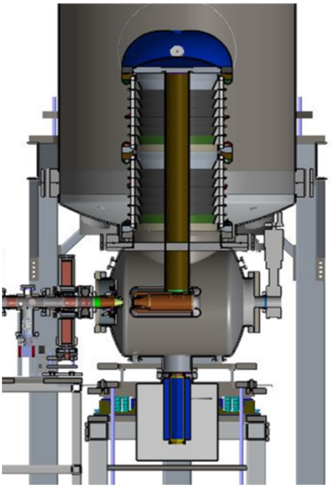


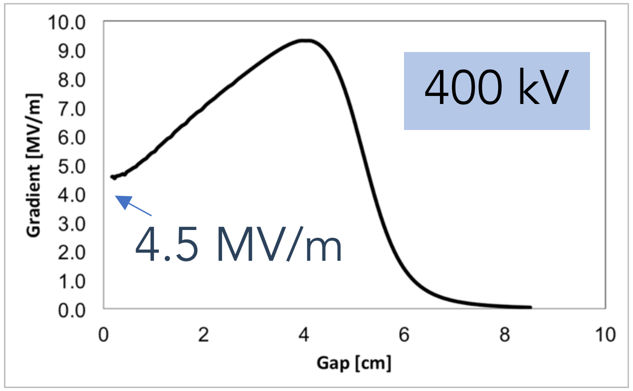
Proton R_{56}=4 mm

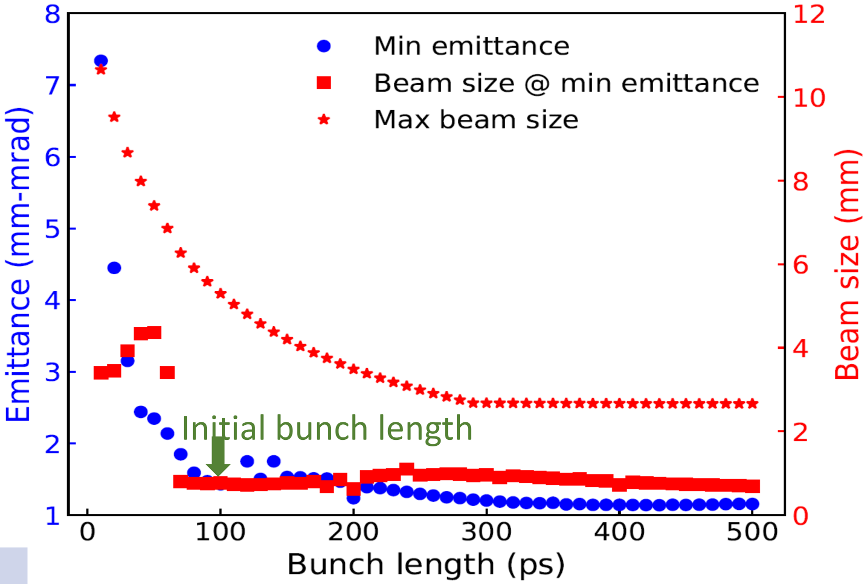
Transfer to correlated energy modulation

Lengthens the path by 45 mm matching to electrons chicanes length

HV DC gun



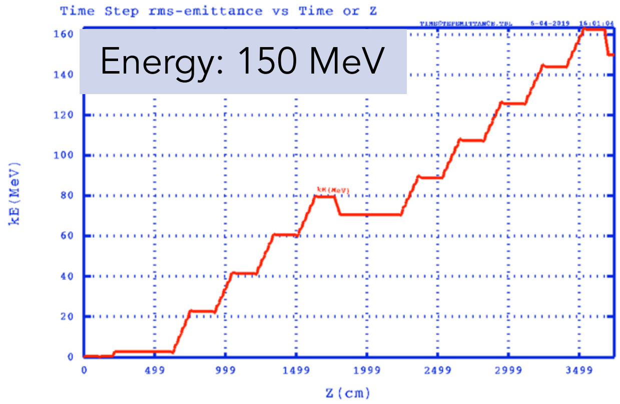


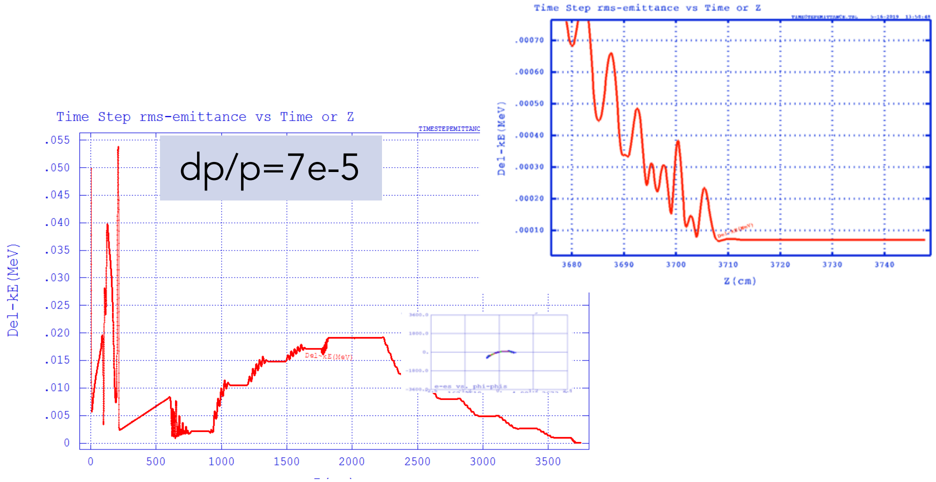


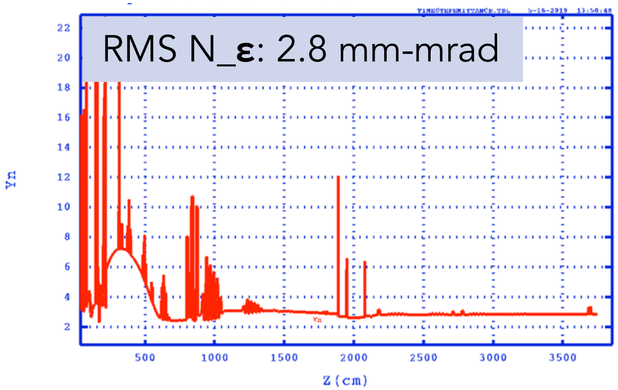
- Will use LEReC HVDC gun and HVPS
(BNL has purchased most of the parts).

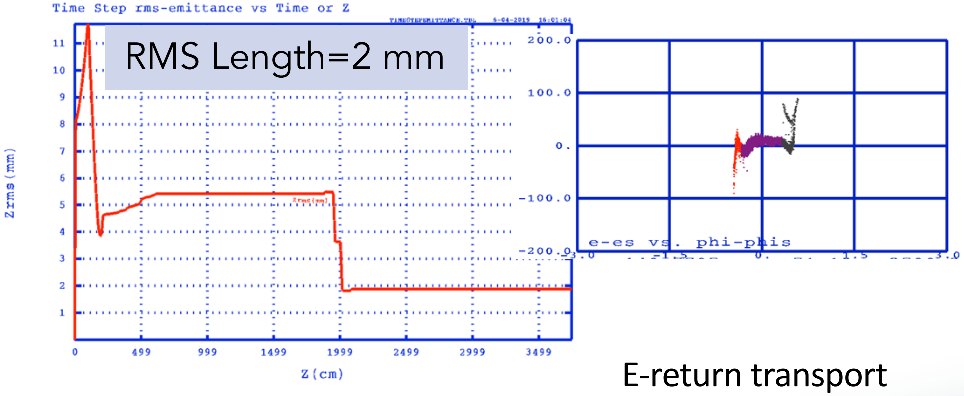
	LEReC	Cornell		eRHIC cooling
Voltage [kV]	400	450		400 ✓
Bunch charge [nC]	0.3	2	0.06	1
Ave. current [mA]	30	0.002	75	100

Gun-Linac

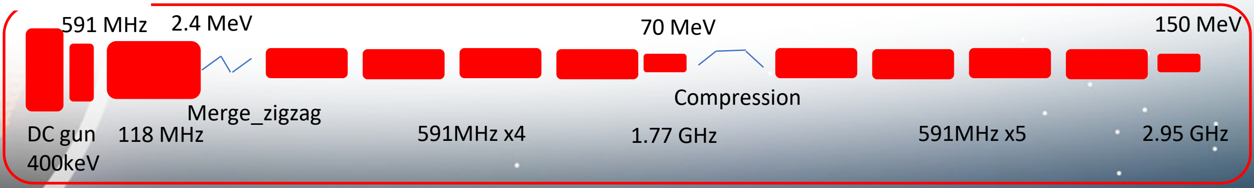

Energy: 150 MeV


dp/p=7e-5


RMS N_**ε**: 2.8 mm-mrad


RMS Length=2 mm

E-return transport

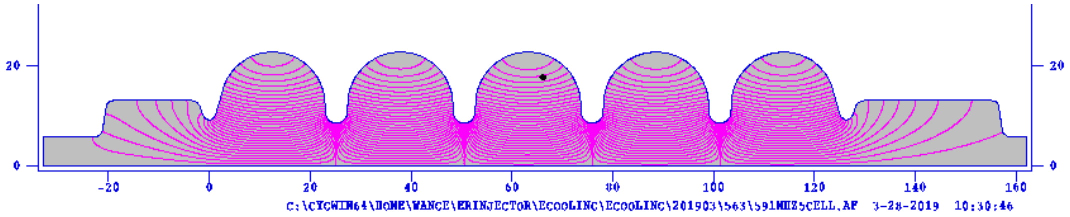

591 MHz
2.4 MeV
70 MeV
150 MeV
Merge_zigzag
Compression
DC gun
400keV
118 MHz
591MHz x4
1.77 GHz
591MHz x5
2.95 GHz

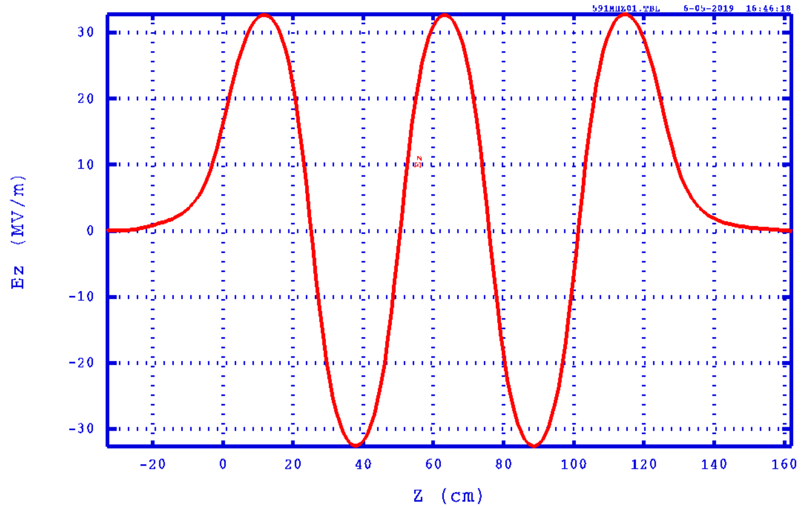
Beam parameters (Parmela simulation results)

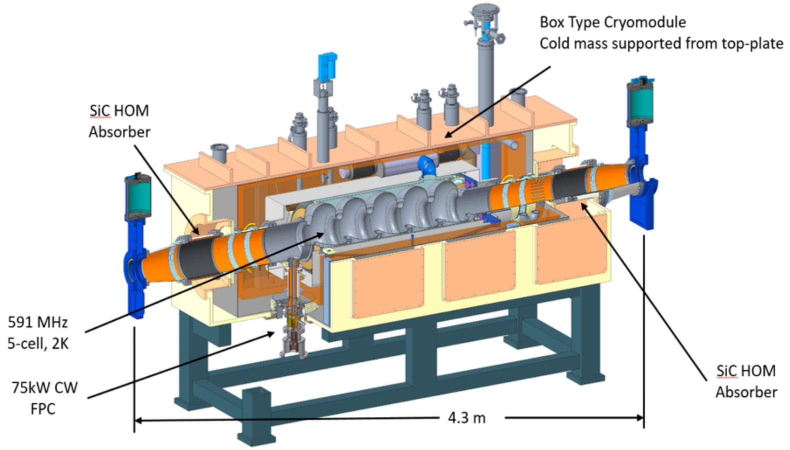
	parameter
Bunch charge	1 nC ✓
Bunch length	7 mm ✓
Normalized emittance	2.8 mm-mrad // round beam
Energy	149.77 MeV ✓
Energy spread	7e-5 ✓
Rep. Freq	98.7 MHz
Average current	98.7 mA ✓

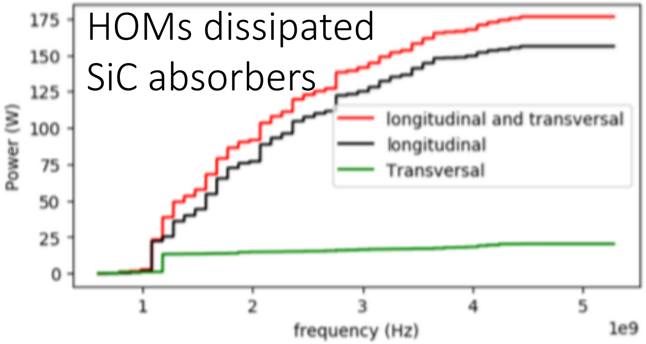
Next Step: Will use Impact-T and Elegant to consider Wakefield, CSR and flat beam

591 MHz SRF Linac





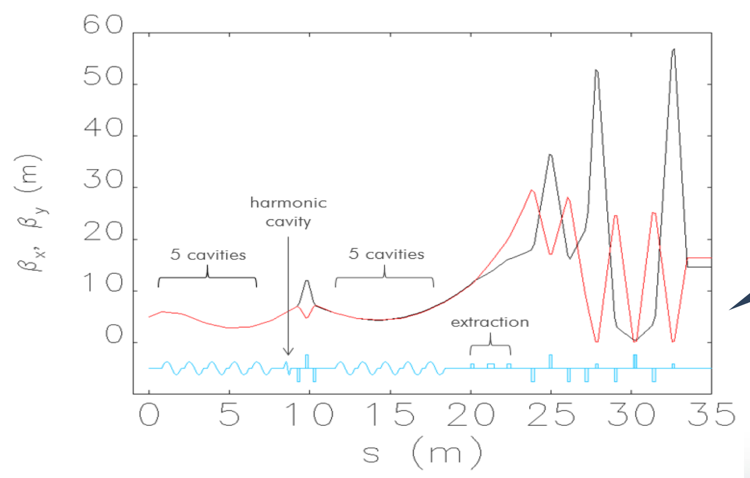


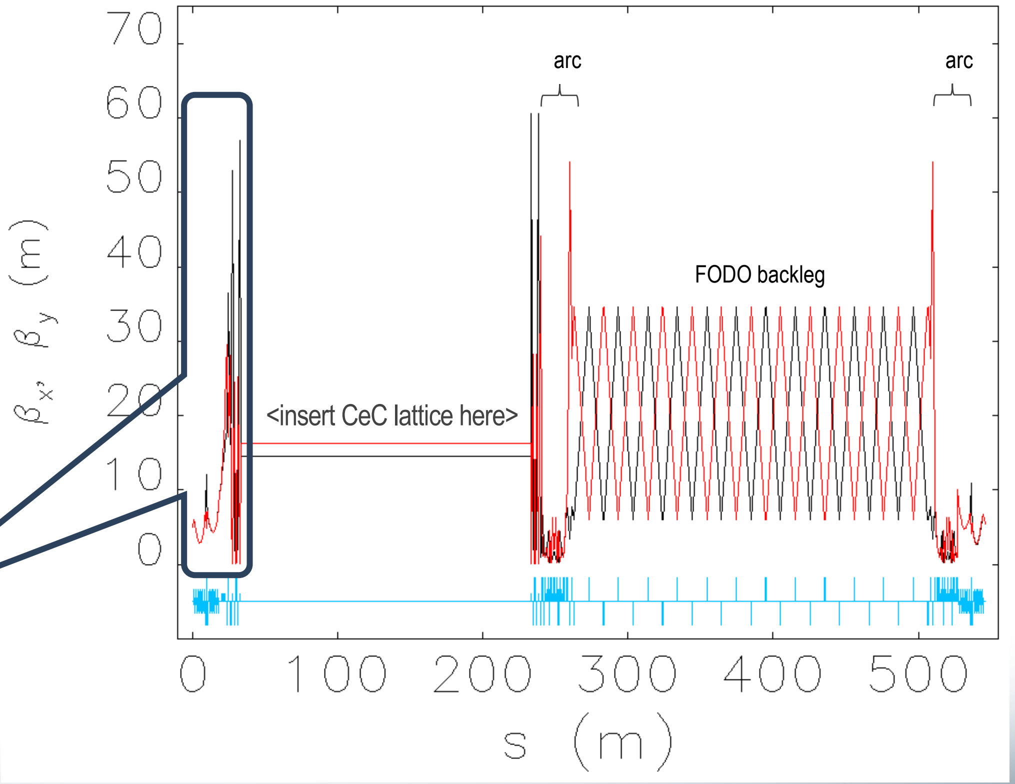

HOMs dissipated
SiC absorbers

- Gap voltage limited at 20 MV
- 65 kW IOT amplifier
- SiC HOMs absorber up to 20 kW
- Other harmonic cavities are considered to be scaled from 591 MHz cavity

ERL Beta Functions

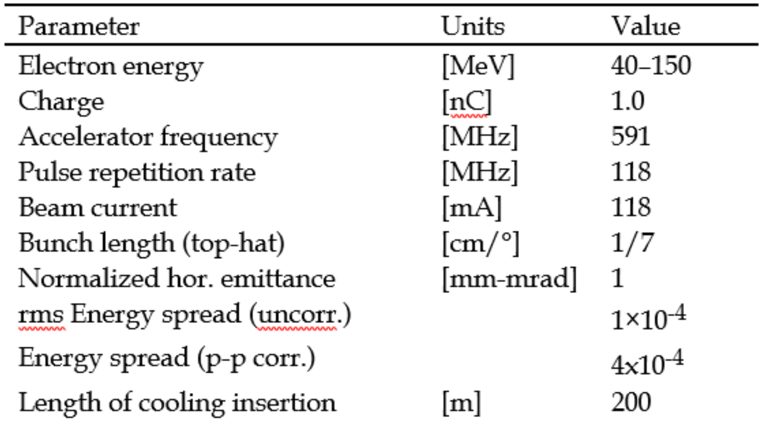
- linac region consists of:
  - ✓ cryomodule (5 cavities, 591 MHz)
  - ✓ third harmonic cavity
  - ✓ quadrupole triplet
  - ✓ cryomodule (5 cavities, 591 MHz)
- followed by extraction (to dump)
- stair-step and matching section to CeC



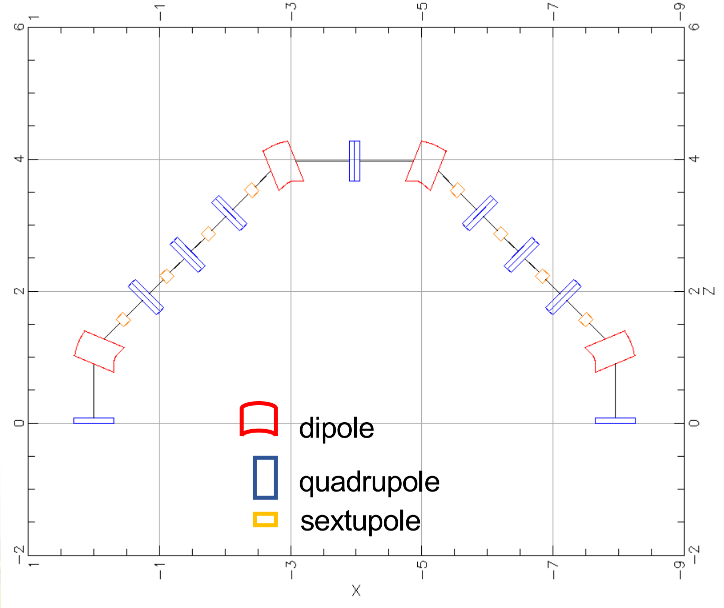


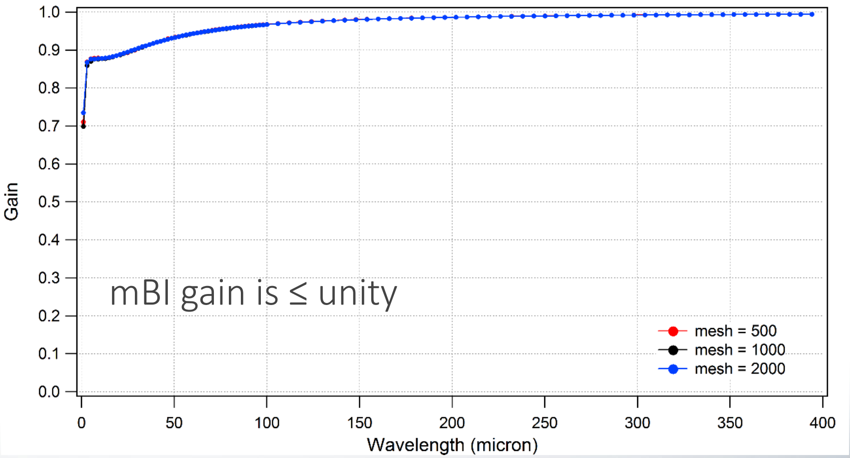
Parameters and Recirculation Arc Layout

- assume DC gun that generates
  - ✓ 1 nC, 1 mm-mrad, 7 ps × 10 keV
- to avoid beam degradation:
  - ✓ assume straight merger
  - ✓ assume cooling insertion before arc



Parameter	Units	Value
Electron energy	[MeV]	40–150
Charge	[nC]	1.0
Accelerator frequency	[MHz]	591
Pulse repetition rate	[MHz]	118
Beam current	[mA]	118
Bunch length (top-hat)	[cm/°]	1/7
Normalized hor. emittance	[mm-mrad]	1
rms Energy spread (uncorr.)		1×10^{-4}
Energy spread (p-p corr.)		$4\text{x}10^{-4}$
Length of cooling insertion	[m]	200





mBI gain is ≤ unity

Use of Synchrotron radiation damping in storage ring

Synchrotron radiation damping using wigglers *)

- Obtaining fast electron cooling and maintaining a low energy spread in the electron beam requires a long wiggler

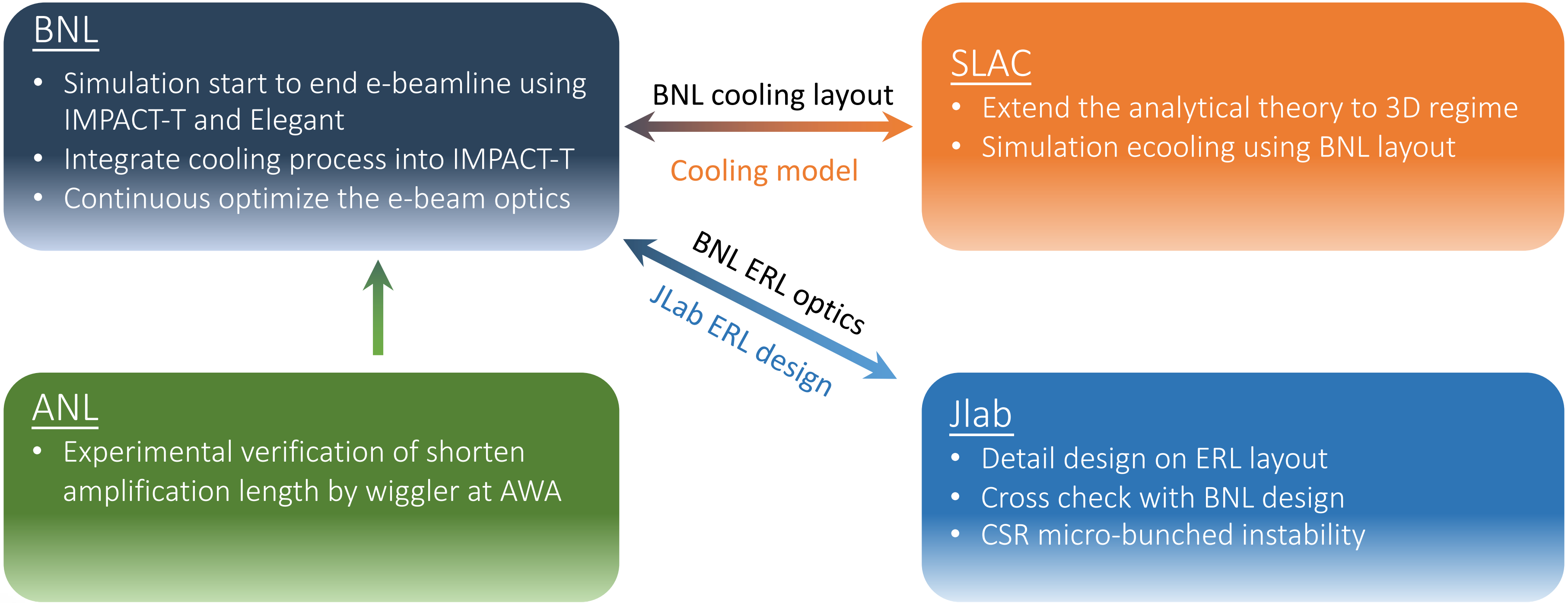
- Require ~600 m total length of wigglers with a peak magnetic field of 1.6 T 10^{-4} energy spread and 300 eV energy transferring

- Conclusion:
  Technique doable for slow proton cooling of the order of 50 hours at the cost of a long wiggler.

Not practical for eRHIC

*) M. Gentner, R. Brinkmann, Ya. Derbenev, D. Husmann, C. Steier, ``On the possibilities of electron cooling for HERA'', NIM A vol. 424, pp. 277-295, 1999.

Next year plan



BNL

- Simulation start to end e-beamline using IMPACT-T and Elegant
- Integrate cooling process into IMPACT-T
- Continuous optimize the e-beam optics

BNL cooling layout

Cooling model

SLAC

- Extend the analytical theory to 3D regime
- Simulation ecooling using BNL layout

BNL ERL optics

JLab ERL design

ANL

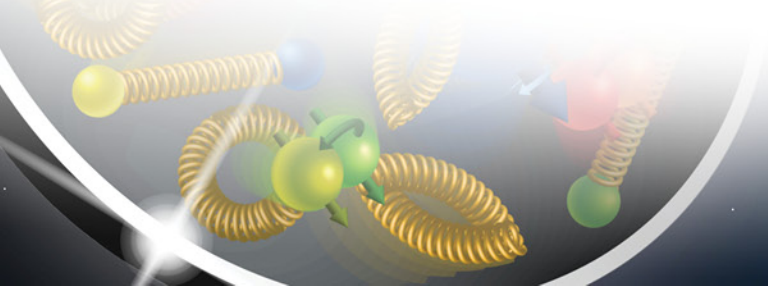
- Experimental verification of shorten amplification length by wiggler at AWA

Jlab

- Detail design on ERL layout
- Cross check with BNL design
- CSR micro-bunched instability

Summary

- A theoretical model that describes the MBEC process has been developed. The derivation is based on 1D Vlasov technique.
- The analysis is benchmarked via comparison with 1D simulation and simple formulas are obtained. The 3D study confirms results of 1D model.
- Based on the above analytical results, we have developed pre-conceptual design of eRHIC cooling layout including two plasma amplification stages cooling channel, ERL and injector.
- Using the wiggler in amplification section to shorten the drift length has been proposed. Experiments are in preparation.
- The plan for next year is well defined.



Thanks for your attention!

Acknowledgements:

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

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BROOKHAVEN NATIONAL LABORATORY

Argonne NATIONAL LABORATORY

Jefferson Lab
Thomas Jefferson National Accelerator Facility

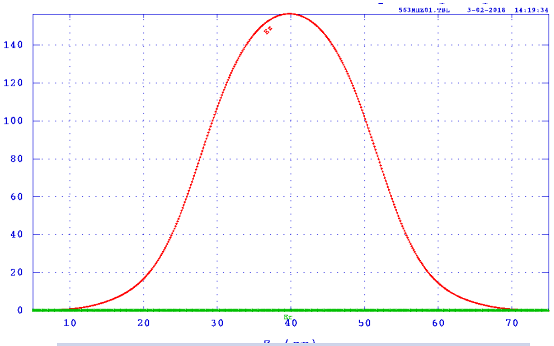
Back up

Strong hadron cooling parameter

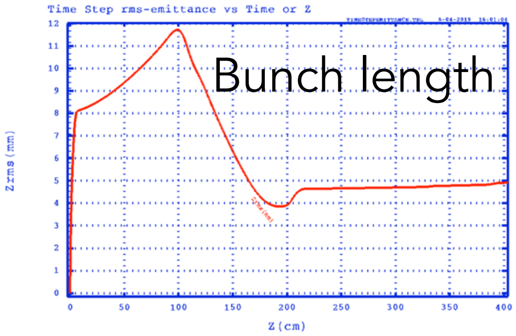
	Value
e-beam energy [MeV]	149.8
e-beam normalized emittance [mm-mrad]	2.8
e-beam current [mA]	110
e-beam charge [nC]	1
e-beam energy spread	10^{-4}
e-p beam $\beta_{x,y}$ [m]	40
e-p beam size σ_x; σ_y[mm]	0.49-0.69; 0.23-0.32
Modulator section length [m]	40
Cooling section length [m]	40
Amplification section length [m]	100
Electron chicane R_{56} [cm]	2.3
Proton chicane R_{56} [cm]	0.4
Cooling time [min]	50

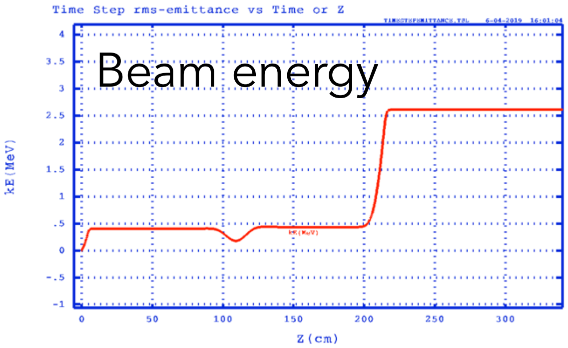
Injector and Merger

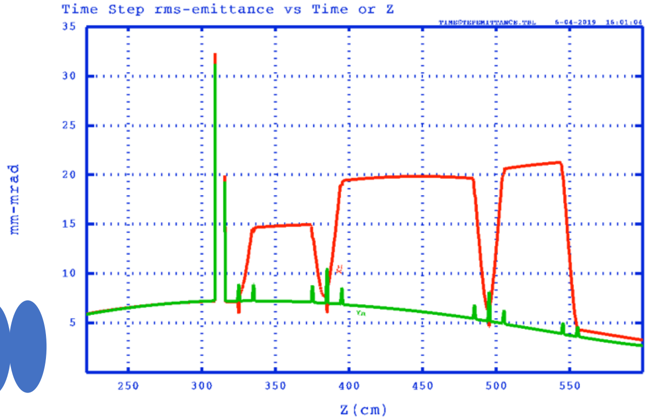
591 MHz NC buncher

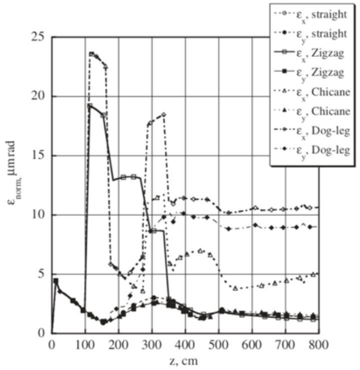


Scaled from 563 single cell
Gap voltage 200 kV

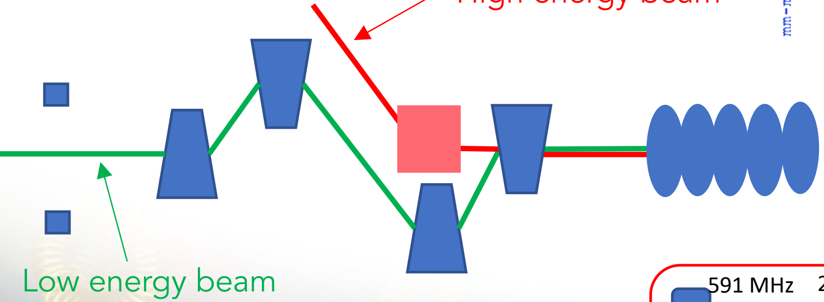








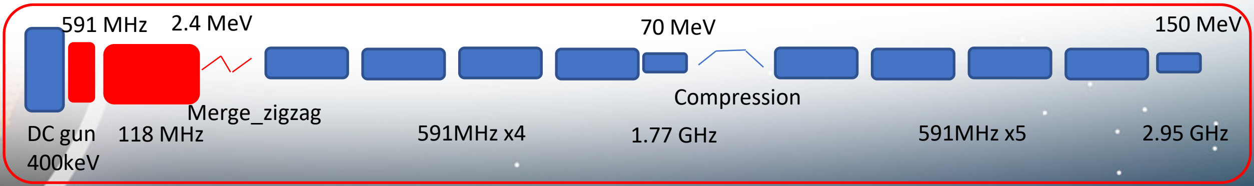
NIM A557 (2006)



High energy beam

Low energy beam

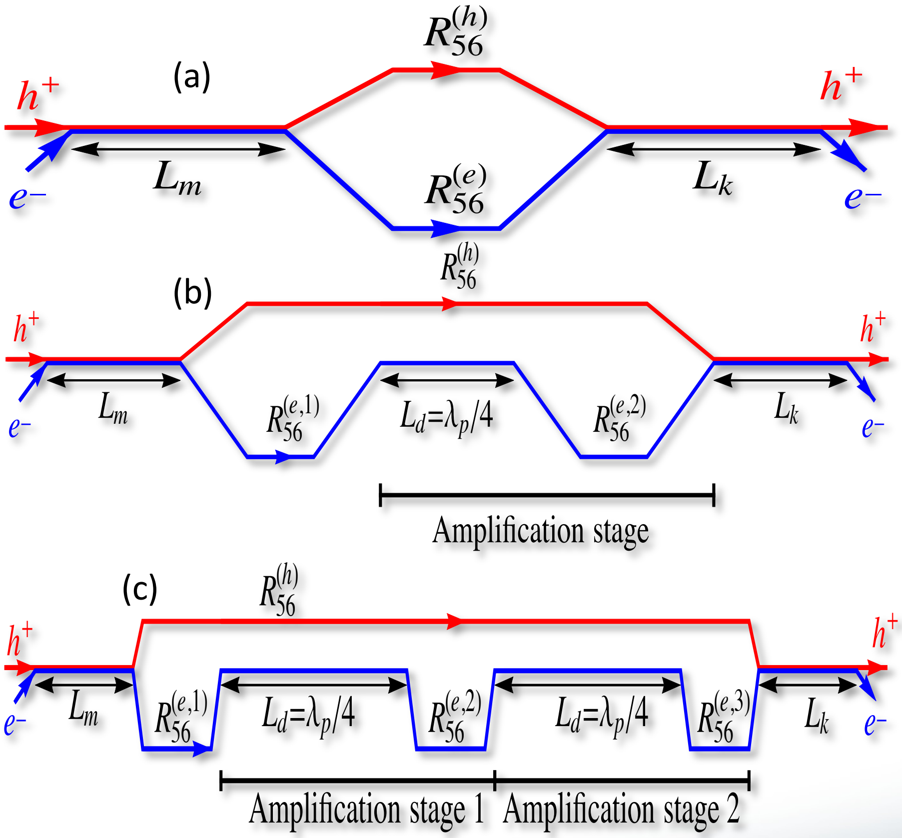
E-return transport



591 MHz
2.4 MeV
70 MeV
150 MeV
DC gun
400keV
118 MHz
Merge_zigzag
591MHz x4
Compression
1.77 GHz
591MHz x5
2.95 GHz

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)).



Use of Synchrotron radiation damping in storage ring

Synchrotron radiation damping using wigglers *)

- Obtaining fast electron cooling and maintaining a low energy spread in the electron beam requires a long wiggler
- I found that a ring with ~600 m total length of wigglers with a peak magnetic field of 1.6 T can maintain 10^{-4} energy spread in the electron beam when rms energy transfer from protons to each electron per turn is of the order of 300 eV

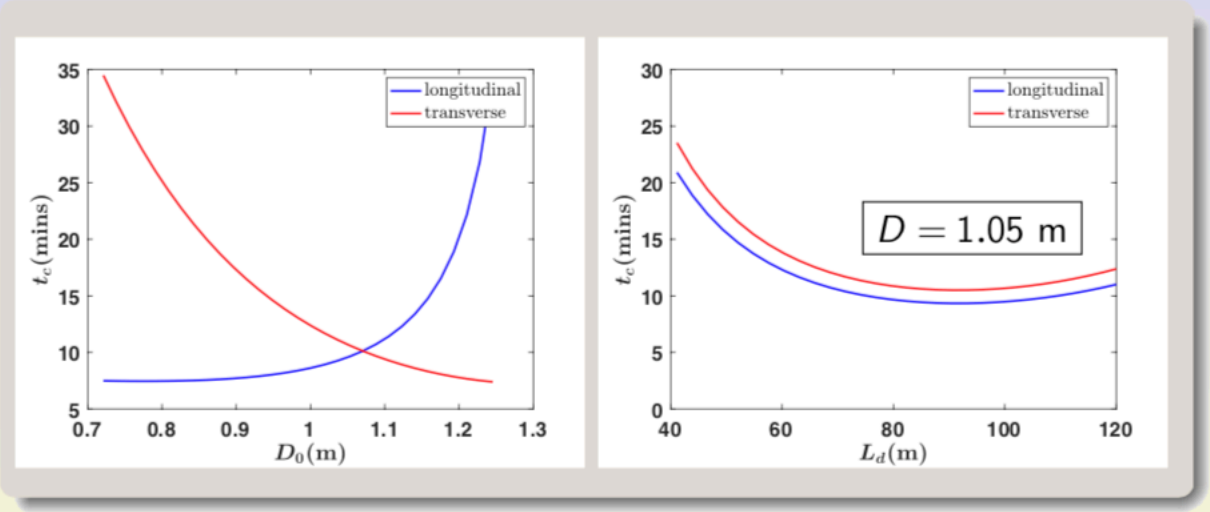
- Conclusion:

  Technique doable for slow proton cooling of the order of 50 hours at the cost of a long wiggler, but for proton cooling under one hour afforded by amplification of electron microbunching, "there is simply no chance to use synchrotron radiation for cooling since the rms energy transfer from protons to each electron per turn approaches 20000 eV".

*) M. Gentner, R. Brinkmann, Ya. Derbenev, D. Husmann, C. Steier, ``On the possibilities of electron cooling for HERA'', NIM A vol. 424, pp. 277-295, 1999.

Optimization of the cooling rate, two ampl. stages

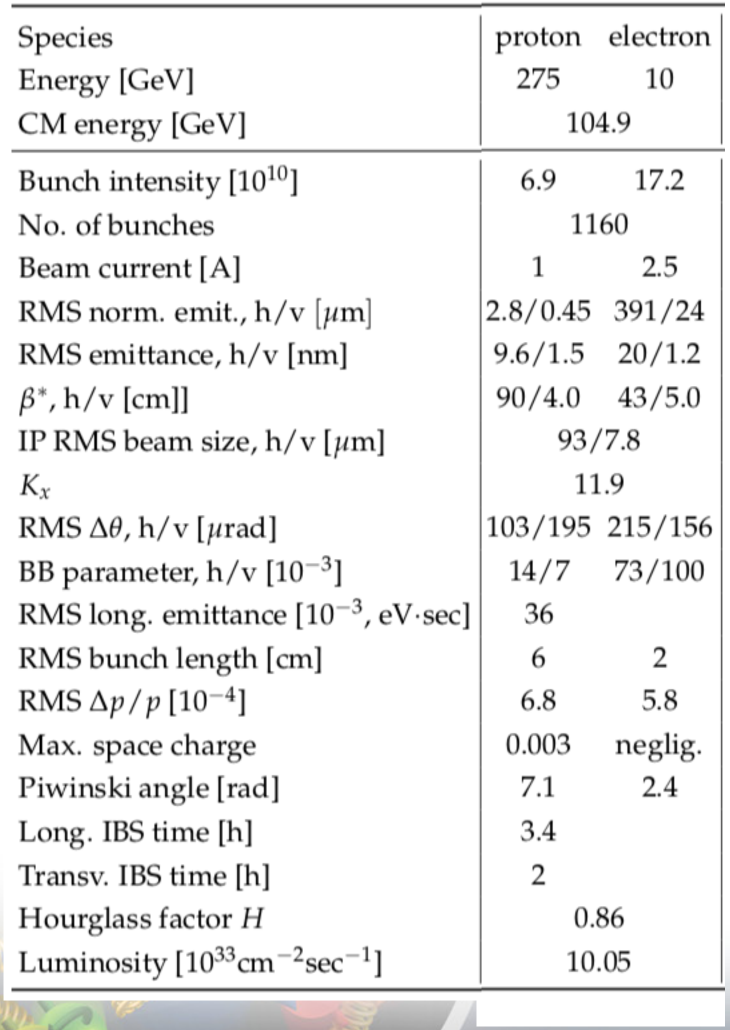
Optimized parameters for two amplification stages: $D = 1.31$ m, phase advance $= 0.38$ rad (modulo 2π), plasma stage length $= 82.2$ m, $R_{56}^{h} = 1.26$ cm, $R_{56}^{(e,1)} = R_{56}^{(e,2)} = R_{56}^{(e,3)} = 2.54$ cm.



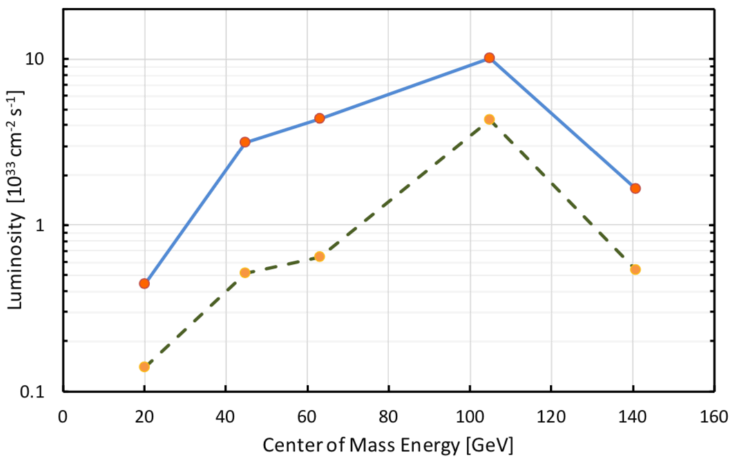
$D = 1.05$ m

Note relatively weak dependence of t_c on the length of the amplification section.

eRHIC High luminosity parameters



Species	proton	electron
Energy [GeV]	275	10
CM energy [GeV]	104.9	
Bunch intensity [10^{10}]	6.9	17.2
No. of bunches	1160	
Beam current [A]	1	2.5
RMS norm. emit., h/v [μm]	2.8/0.45	391/24
RMS emittance, h/v [nm]	9.6/1.5	20/1.2
β^*, h/v [cm]]	90/4.0	43/5.0
IP RMS beam size, h/v [μm]	93/7.8	
K_x	11.9	
RMS $\Delta\theta$, h/v [μrad]	103/195	215/156
BB parameter, h/v [10^{-3}]	14/7	73/100
RMS long. emittance [10^{-3}, eV·sec]	36	
RMS bunch length [cm]	6	2
RMS $\Delta p/p$ [10^{-4}]	6.8	5.8
Max. space charge	0.003	neglig.
Piwinski angle [rad]	7.1	2.4
Long. IBS time [h]	3.4	
Transv. IBS time [h]	2	
Hourglass factor H	0.86	
Luminosity [10^{33}cm^{-2}sec^{-1}]	10.05	



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