Innovative, High-energy, Magnetized Electron Cooling for an EIC

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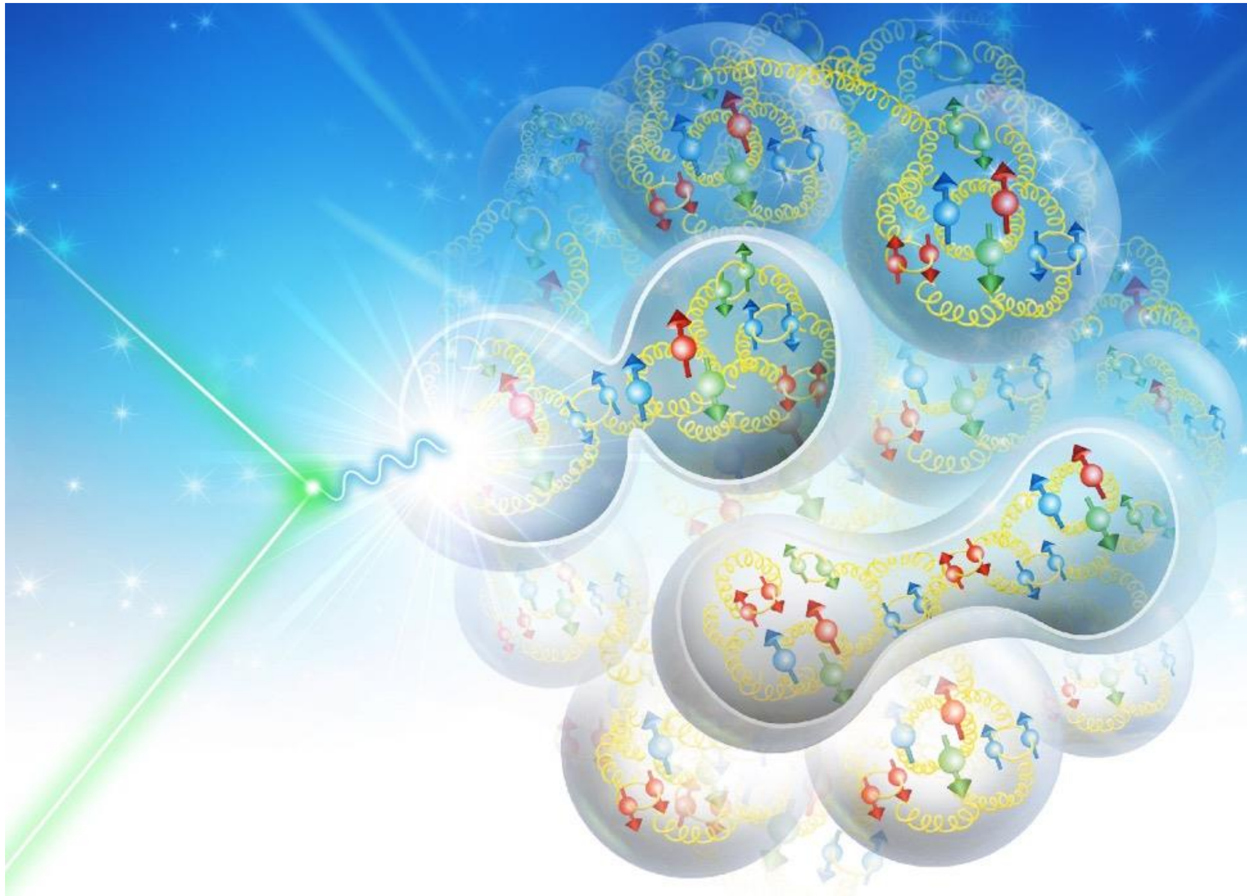


Supported by DoE NP Accelerator R&D funding FOA

2020 NP Accelerator R&D PI Exchange Meeting
December 2, 2020, Virtual meeting

Outline

- General description of the project
- Cooling Simulation codes
- Storage Ring Cooling
  - Single energy
  - Two energy
- Production and Transport of Magnetized bunches
- Novel Cooler Hardware
  - Injector and Linac SRF design
  - Harmonic kicker design
- Bunch beam Cooling experiments

Innovative, High-energy, Magnetized Electron Cooling for an EIC

- Description
  - The EIC at BNL has chosen Coherent electron Cooling for their baseline for the project. This project looks at alternative strategies and technologies for incoherent electron cooling very high energy hadrons.
- Status
  - Several parts of the project are complete or close to complete. Some were delayed by the COVID-19 situation and one changed direction due to the siting decision.
- Main goal
  - Develop concepts and technologies that allow cooling of high-current, high-energy hadron beam in an electron collider using incoherent electron cooling.
- Supported by DoE NP Accelerator R&D funding FOA
- This is the second year of a two year project
- We have extended the scope of the project for two parts and are wrapping up the rest.

Electron Cooler Design Project Budget

	FY'19	FY'20	Totals
a) Allocated (Jlab)	$850,000	$850,000	$1,700,000
b) Costs to date	$850,000	$303,128	$1,153,128
a) Allocated (BNL)	$245,000	$245,000	$490,000
b) Cost to date	$179,513	$130,080	$309,593
a) Allocated (FNAL)	$150,000	$150,000	$300,000
b) Cost to date	$63,921	$26,200	$90,121
a) Allocated (ODU)	$35,000	$35,000	$70,000
b) Cost to date	$28,000	$31,018	$59,018

Deliverables and schedule

Task	FY’19				FY’20			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Codes to predict emittance in SR (BNL)		✓						
Codes to predict heating by hadrons (BNL)				✓				
Cooling with arbitrary electron bunch (JLAB)	✓							
Cooling simulation with dispersion (JLAB)		✓						
Cooling simulation with repeatedly used beams (JLAB)				✓				
Benchmark longitudinal cooling (JLAB)						→	✓	
Integrate JSPEC with other simulation programs								✓
~~Benchmark JLEIC with S2E and imperfections (JLAB)~~							+	
Final software integration, parallelization, and report (JLAB)								→
Benchmark of ion effects on electrons (BNL)			✓					
Model of single energy storage ring cooler (BNL)				✓				

Deliverables and schedule

Task	FY'19				FY'20			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Optimized storage ring cooler (BNL)								✓
Optics for two-energy storage ring cooler (JLAB)				✓				
Initial single particle tracking in 2-energy storage ring				✓				
Estimates of IBS and SC						✓		
Optimization of cooler parameters (JLAB)				→	→	→	✓	
Studies of CSR and BBU (JLAB)							→	→
Magnetized beam transport simulations (NIU)		✓						
Generation of magnetized beams (FNAL)			✓					
LPS diagnostics design				✓				
LPS installation					→	→	→	→
Test of merger					→	→	✓	

Deliverables and schedule

Task	FY'19				FY'20			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Halo tests (FNAL)					→	+		
Magnetized beam simulations in bends (JLAB,NIU)					→	→	→	→
Magnetized beam in bends experiment (FNAL)								→
RF element layouts (JLAB)			✓					
HOM damping requirements (JLAB)				✓				
HOM electromagnetic design (JLAB)				→	→	→	→	→
Thermal and mechanical HOM design (JLAB)					→	→	→	→
Prototype HOM damper bench test						→	→	→
HOM loads tested on cavities								→
Harmonic kicker physics design (JLAB)		→	✓					
Harmonic kicker engineering design (JLAB)			→	✓				

Deliverables and schedule

Task	FY'19				FY'20			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Harmonic kicker fabrication (JLAB)				→	→	→	→	→
Preparations complete for beam test (JLAB)						+		
~~Beam test of harmonic kicker on UITF (JLAB)~~								+
Design and fabricate ion BPM (JLAB, IMP)	✓							
Define HV pulser design (JLAB)	✓							
Initial low energy tests and data analysis (JLAB,IMP)		→	→	✓				
~~Fabricate HV pulser(JLAB)~~				+				
~~Install HV pulser and test (JLAB,IMP)~~					+			
Low energy test with phase dither (JLAB,IMP)					✓			
Analyze final data and produce paper						→	✓	
~~Design 5.5 MeV DC cooler~~								+

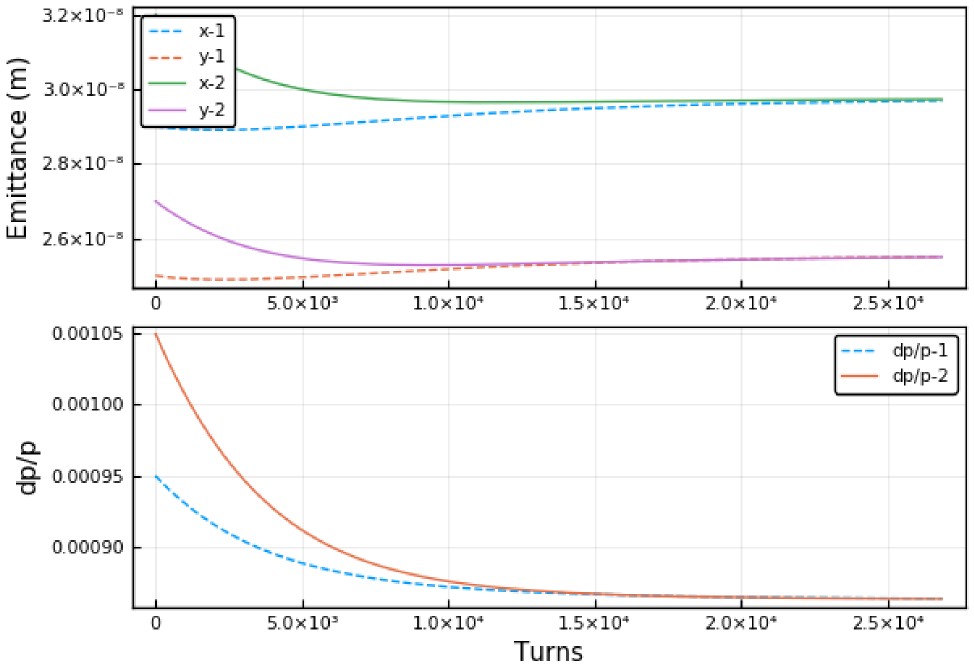
Cooling Simulations

Simulation Tools

- Equilibrium electron beam in cooler

  Particle tracking in the ring cooler with radiation, IBS, BBS and quantum excitation.

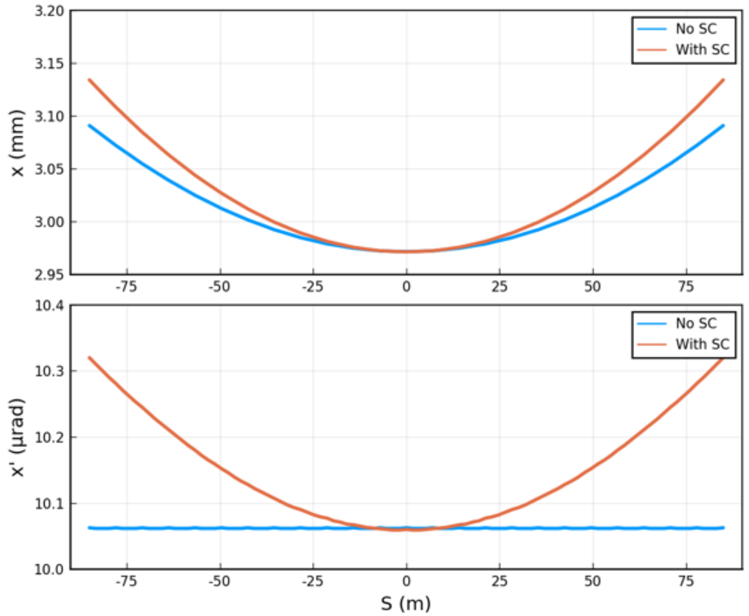
$$\frac{d\epsilon}{dt} = (-2\lambda_{damp} + \lambda_{IBS} + \lambda_{BBS})\epsilon + C_q$$



$$\frac{1}{\tau_{quantum}} = A_x^2 A_z^2 A_p^2 (k_x e^{\frac{-A_x^2}{2}} + k_z e^{\frac{-A_z^2}{2}} + k_p e^{\frac{-A_p^2}{2}}).$$

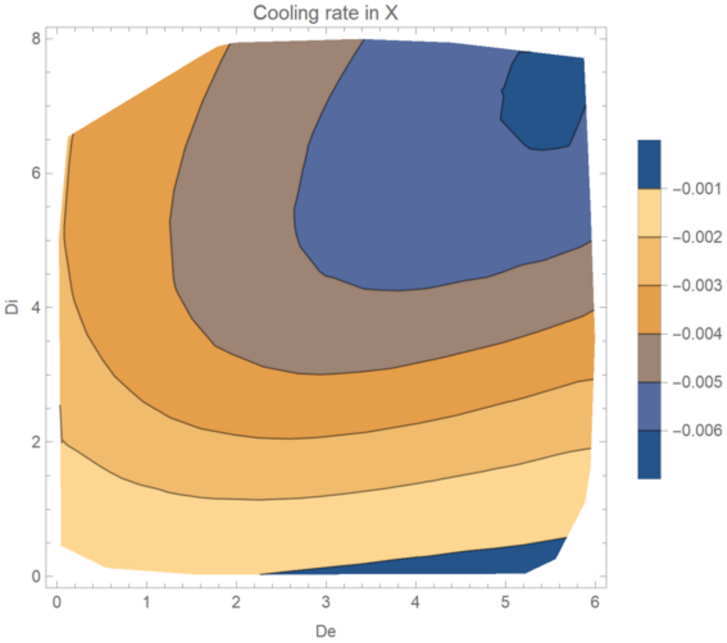
- Space charge in the cooling section.

  The electron beam size at the end of cooling section is increased by about 2% (single pass).



- Cooling simulation

  Cooling evolution with non-magnetized cooling, IBS, dispersion on electron beam and ion beam.



Simulation Codes

JSPEC is a modernized version of Betacool that is more efficient and extensible

Enhancements to JSPEC during the last year:

- Restructured code
  - Old input files can still be used.
  - Modernized the structure to make it more extensible.
- Changes to accommodate EIC simulations
  - Can now use multiple electron bunches per hadron bunch.
  - Have more non-magnetized options now, as well as a single particle model
  - Can use different models for the transverse and longitudinal cooling
  - Saw good agreement with other codes when simulating a low-energy cooler on the EIC
- Improve IBS models
  - Can now include vertical dispersion.
  - Includes Bjorken-Mtingwa and Zimmerman models
- Improvements in User Interface and compatibility with other accelerator codes
  - Can run in a Python environment.
  - Input and output files compatible with SDDS codes.
- Luminosity
  - Calculate the instant luminosity during the evolution of the ion beam under IBS/cooling.

JSPEC Benchmarking

- Introduced turn-by-turn model to allow simulations with synchrotron motion
  - Bunched electron beam is repeated used (~10 times) and may be distorted due to collective effects.
  - Use the user-defined electron model to represent various electron bunches. Calculate the cooling rate for each cases. Since the time for ~10 passes is still much smaller than a simulation time step (~0.1 s), the averaged cooling rate is used for the current time step.
  - Currently works for the RMS dynamic model. We are working on adding it to the particle model.
- Best data is for longitudinal cooling.
  - Some range of input parameters for IMP experiments. Optimize parameters for best fit of all data sets.
  - Can fit transverse data easily but the error bars are large.

Storage Ring Cooler

Storage Ring Cooler: Single Energy

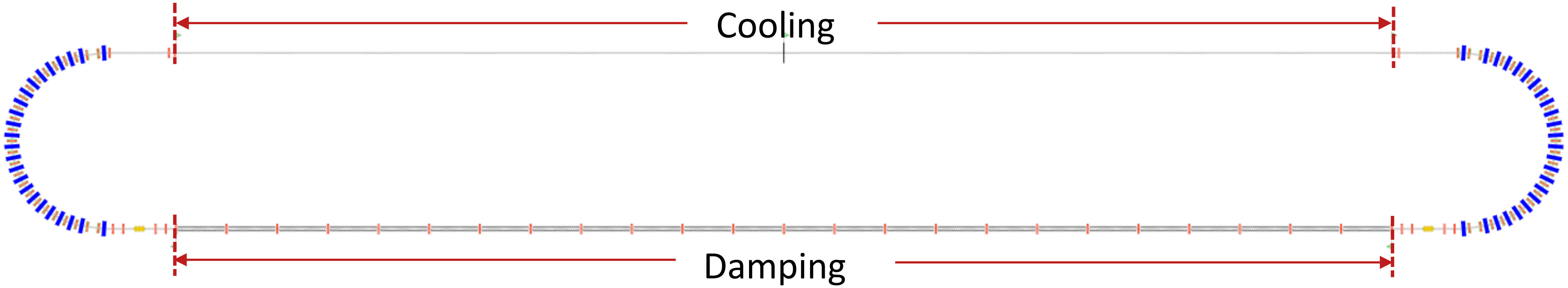
Challenge: Stop the emittance growth due to IBS, and maintain the integrated luminosity.

- Charge = 50nC
- Cooling section: ~200m drift for good cooling
- Wiggler section: strong radiation damping to get a low temperature of e-beam
- Bunch-by-bunch non-magnetized cooling

Mode of operation	Integrated Luminosity [fb^{-1}]
Strong hadron cooling	124
On-energy injection (using Blue Ring)	112
Ring-based electron cooling	87
No cooling	40

Comparison of BNL EIC integrated luminosity for e-p collisions for various cooling options (from pCDR)

- Similar bunch lengths
- E-beam parameters: IBS, heating by the ion and synchrotron radiation.
- Cooling effect: IBS, e-beam temperatures.



Single Energy Storage Ring Optics

The ring uses both horizontal and vertical wigglers with sextupoles built into the wigglers.
It uses dispersion in the cooling section to couple longitudinal and transverse cooling.
Cooling times are useful and allow one to obtain high lluminosity.

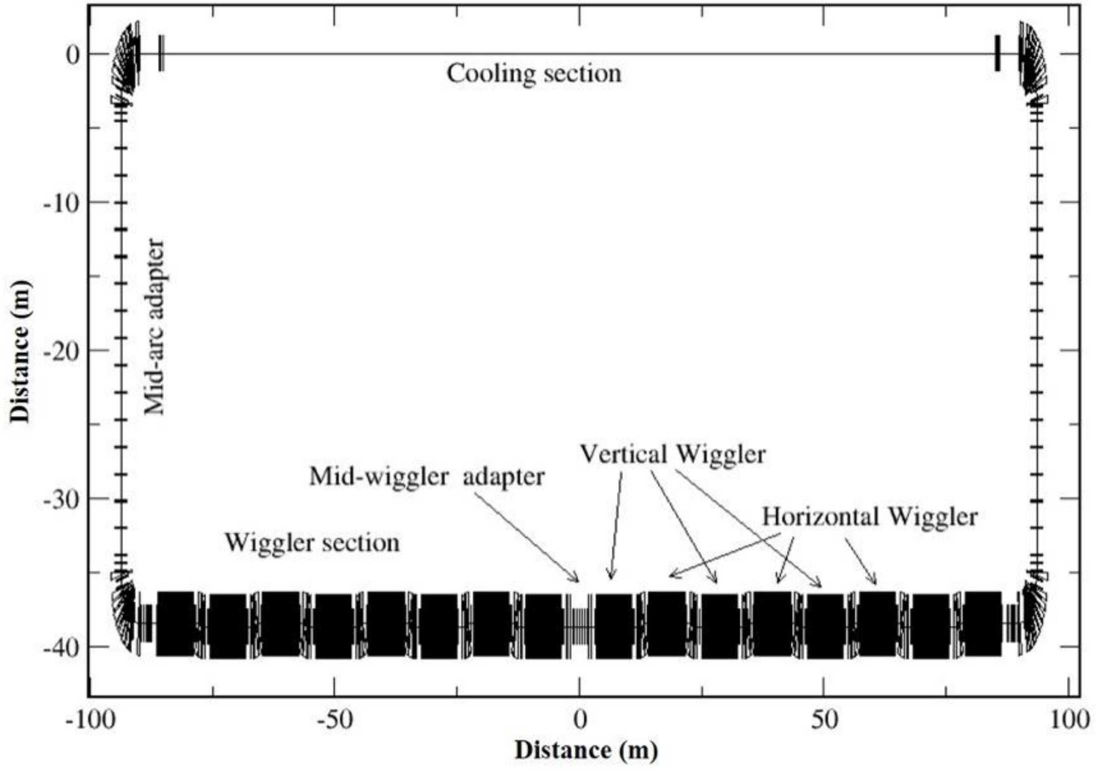
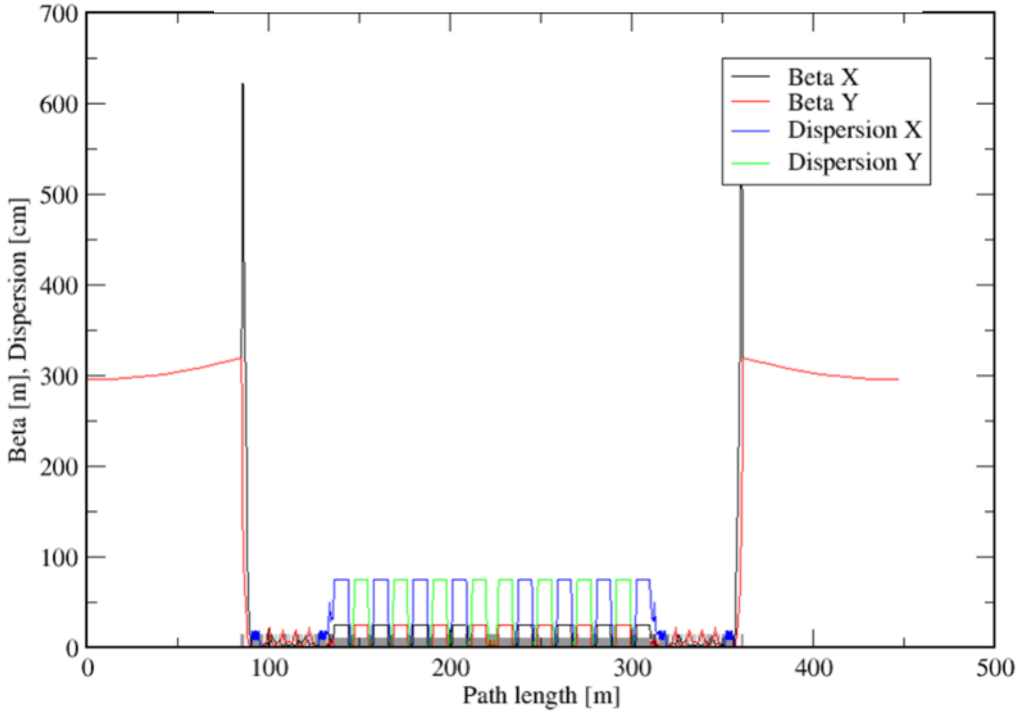


TABLE II. Parameters of the ring cooler

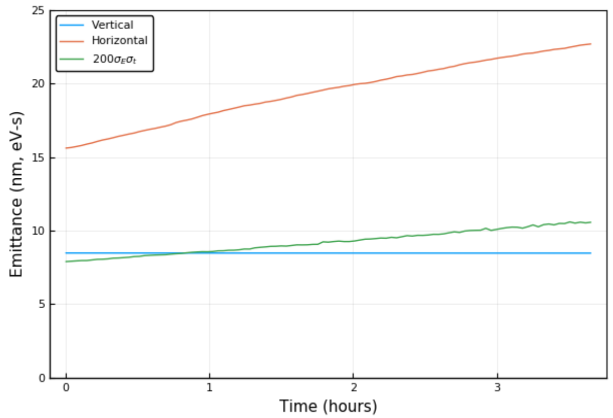
Circumference [m]	446.46
Length of cooling section [m]	170
Average β function in cooling section [m]	300
Bend radius in arc [m]	1.3
Dispersion in acr [cm]	18.5
Wiggler field [T]	1.95
Length of wiggler [m]	7.1
Bend radius of wiggler [m]	0.253
Poles in wiggler	148
Wiggler period [cm]	4.8
β function in wiggler [m]	25
Max. Dispersion in wiggler [cm]	75
Number of wiggler magnets	16
Tune (x/y)	59.96/60.88
Chromaticity (x/y)	-47.0/-30.94

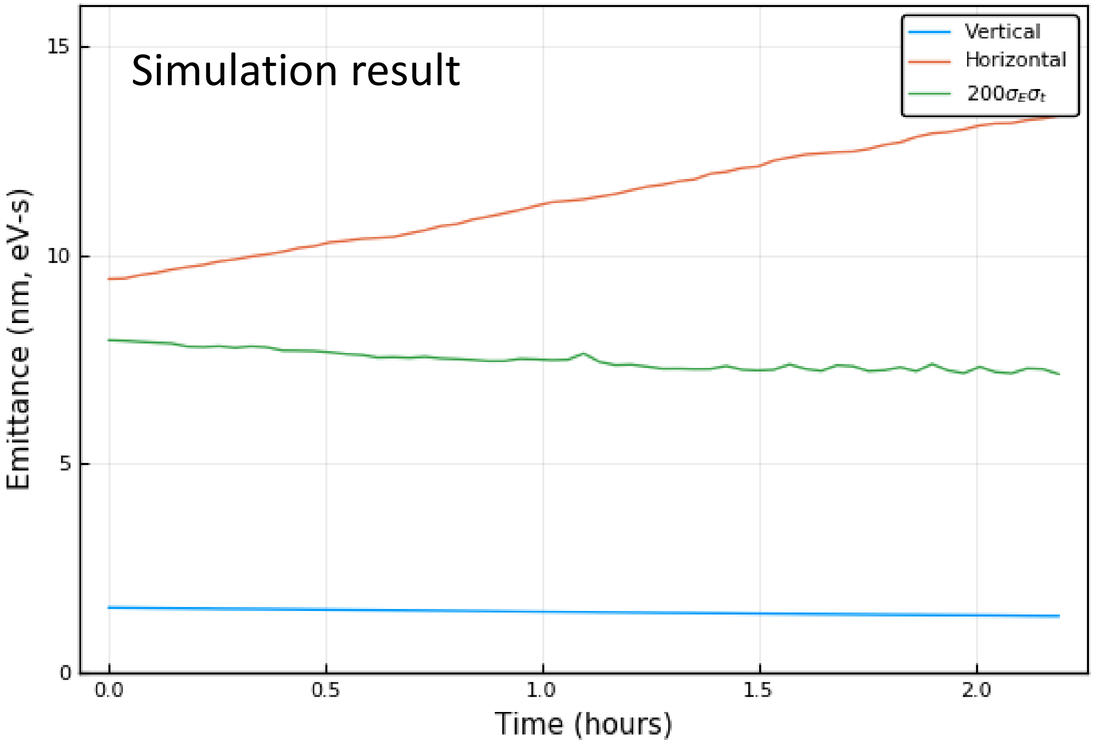


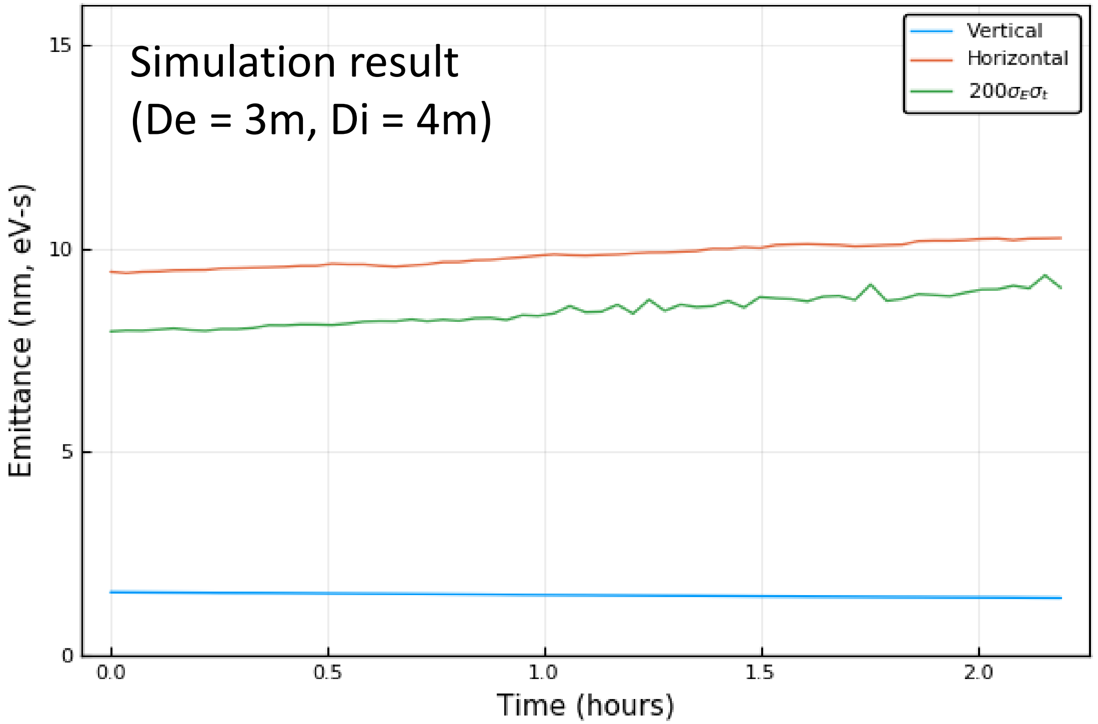
Simulation results on BNL EIC

- With the dispersions, we are close to the cooling requirement..
- The optimum dispersion is related to the beam size. The cooling performance could be better after some optimization on the betafunctions.
- The dispersion will introduce extra IBS heating in the ring cooler and the proton ring. We didn't include that yet.

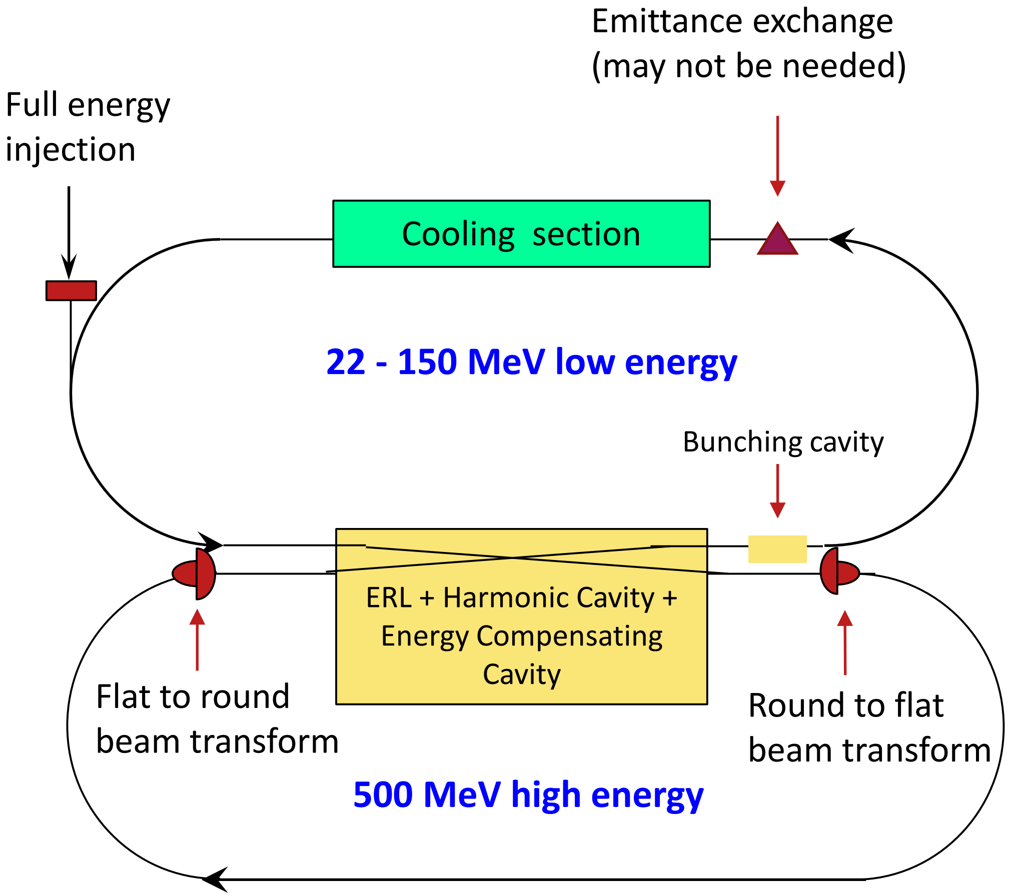
Without-cooling

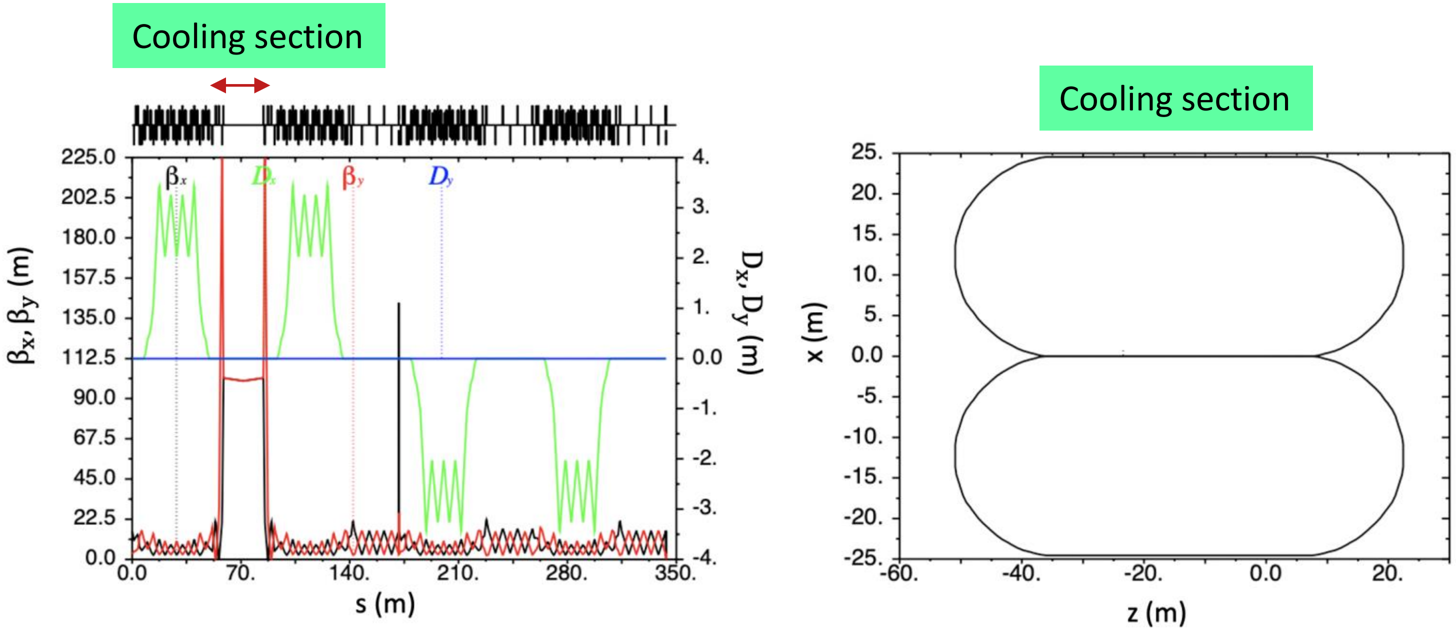






Wiggler-Free Two Storage Ring Cooler





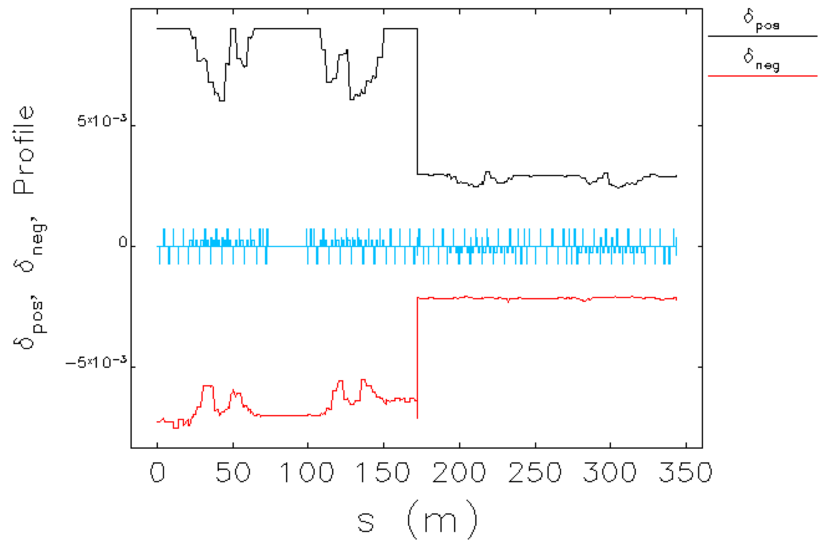
Note that:

- Low energy section can be tuned separately from high energy section, and the low energy varies as the ion energy is varied
- The length of cooling section will be determined by the available space in the machine, ~ 120 m in the EIC

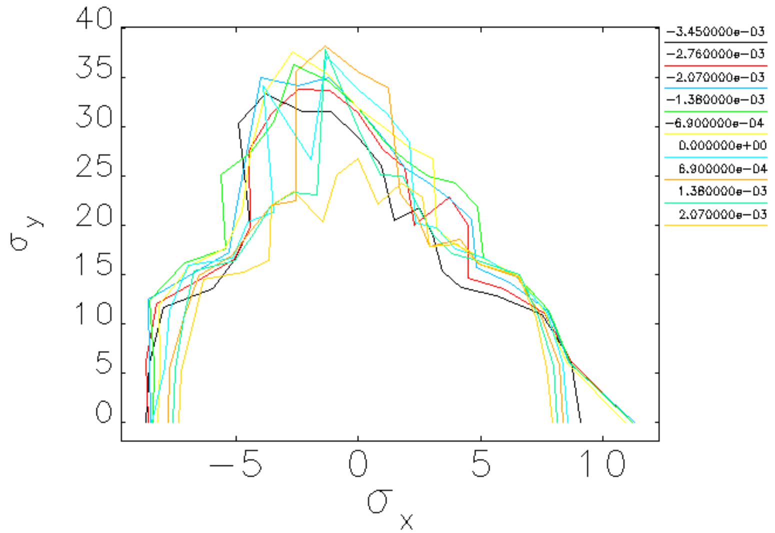
Cooling for the EIC

	Unit	Parameter	
Ion Energy	GeV	275	100
Electron Energy	MeV	150	55
Bunch intensity	10^{10}	6.9	6.9
Bunch charge	nC	11.1	11.1
Normalized emittance h/v	μm	2.8/0.45	4.0/0.22
Energy spread	10^{-4}	6.8	9.7
RMS bunch length	cm	6	7
Cooling channel	m	120	120
Magnetized cooling		Strong	
Cooling solenoid	kG	20	20
IBS time (h/v/l)	h	**2/278/3.4**	**2.4/2.8/2**
Cooling time (h/v/l)	h	**0.4/94/2.0**	**1.2/24/0.5**

Momentum Aperture



Dynamic Aperture

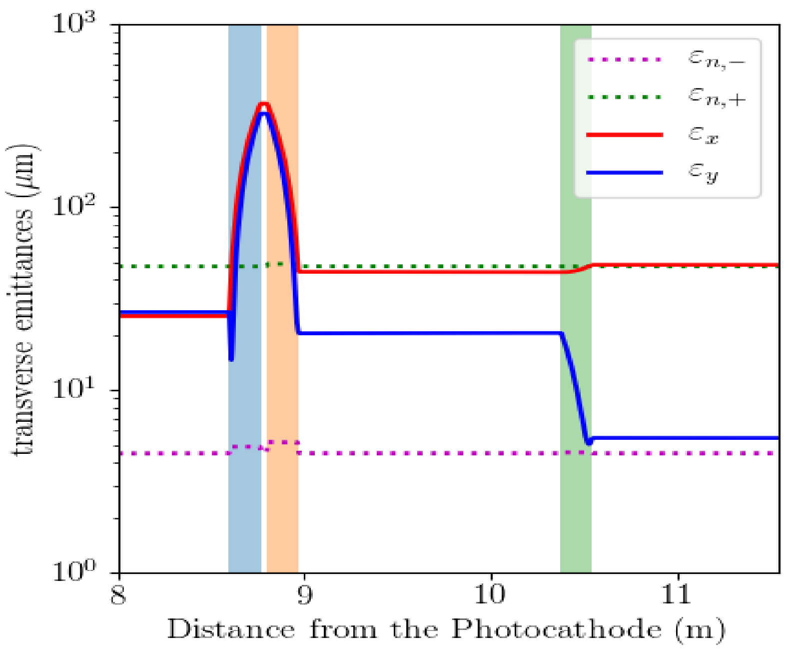


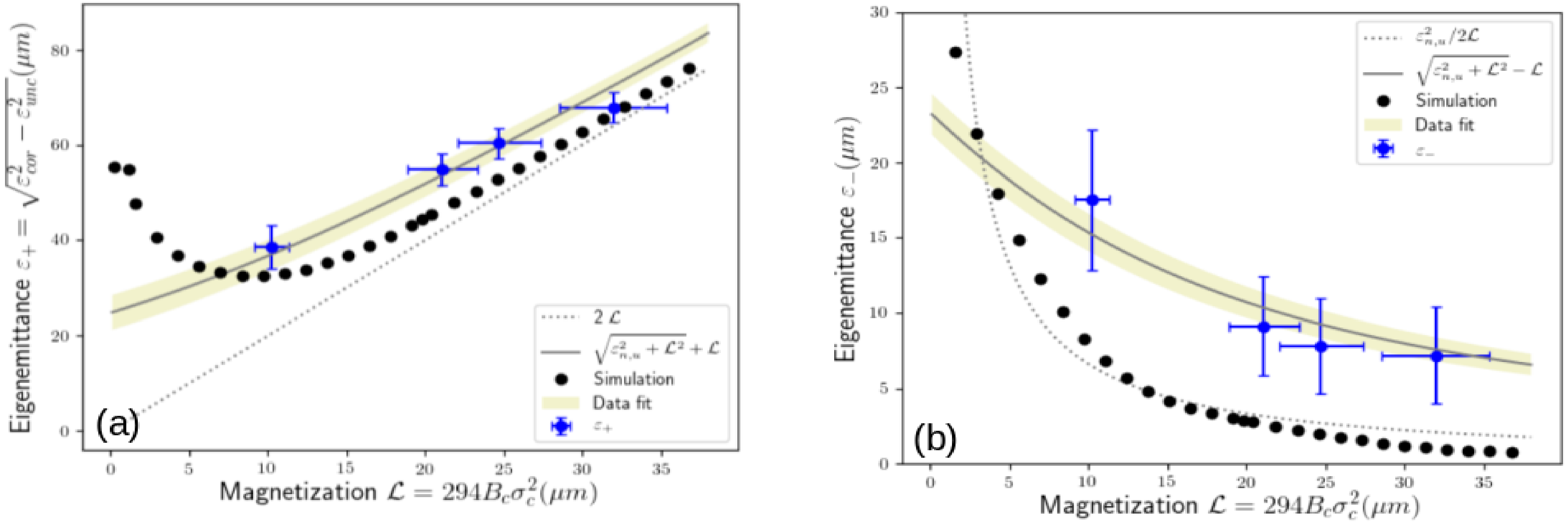
Magnetized Beam Transport

Magnetized beam Simulations

- FAST injector modeled with ASTRA and IMPACT-T
- Transformation to flat beam simulated with ELEGANT and IMPACT-T

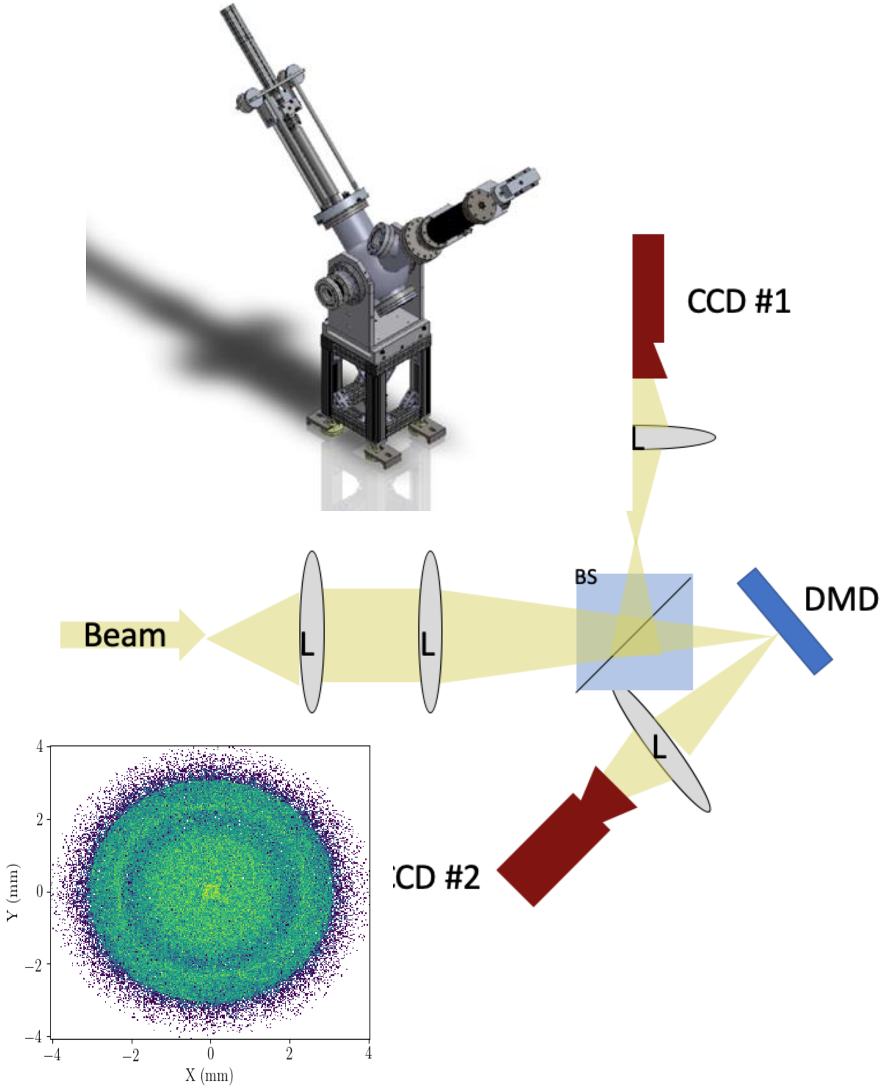
- Simulation of the flat beam conversion demonstrates that eigen emittances are mapped into conventional emittances





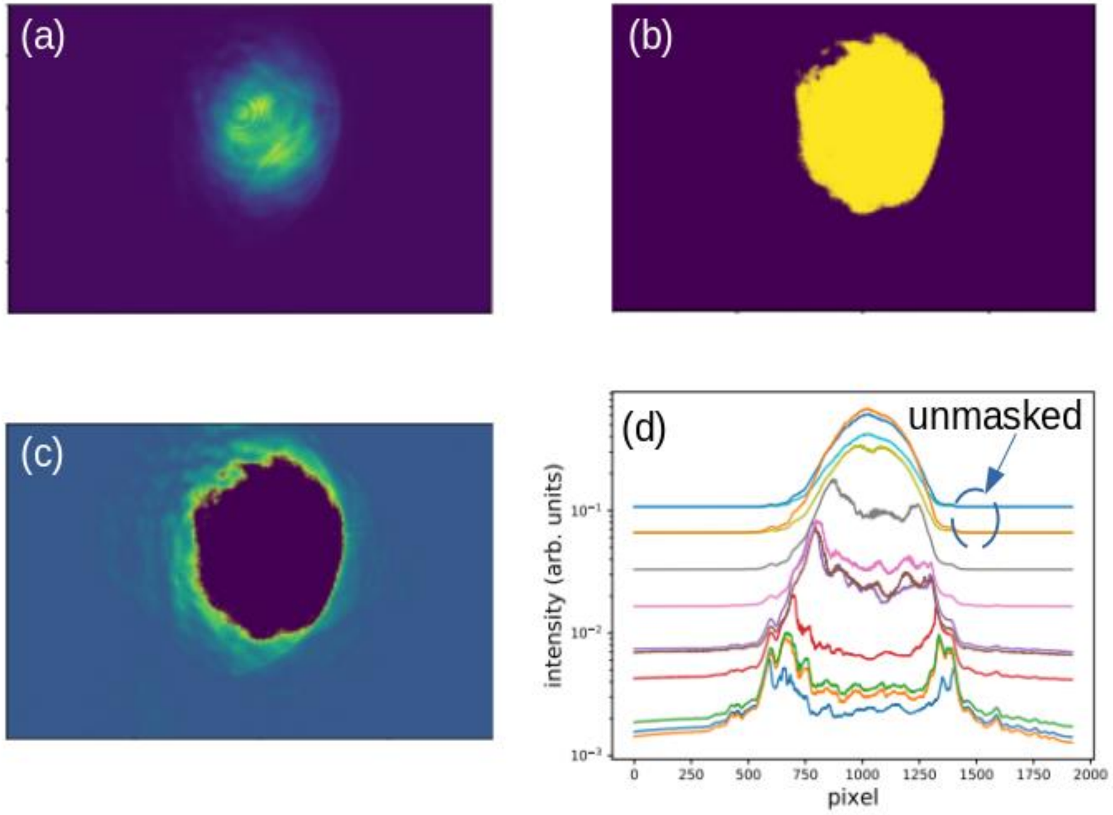
Eigen emittances of the 3.2 nC magnetized beam experimentally measured at FAST (blue circles with error bars) compared with numerical simulations carried out with IMPACT-T.

Beam Halo Measurements



- Using a Digital Micromirror Device (DMD) the beam core can be blocked to show just a halo.
- Combining the two pictures reconstruct

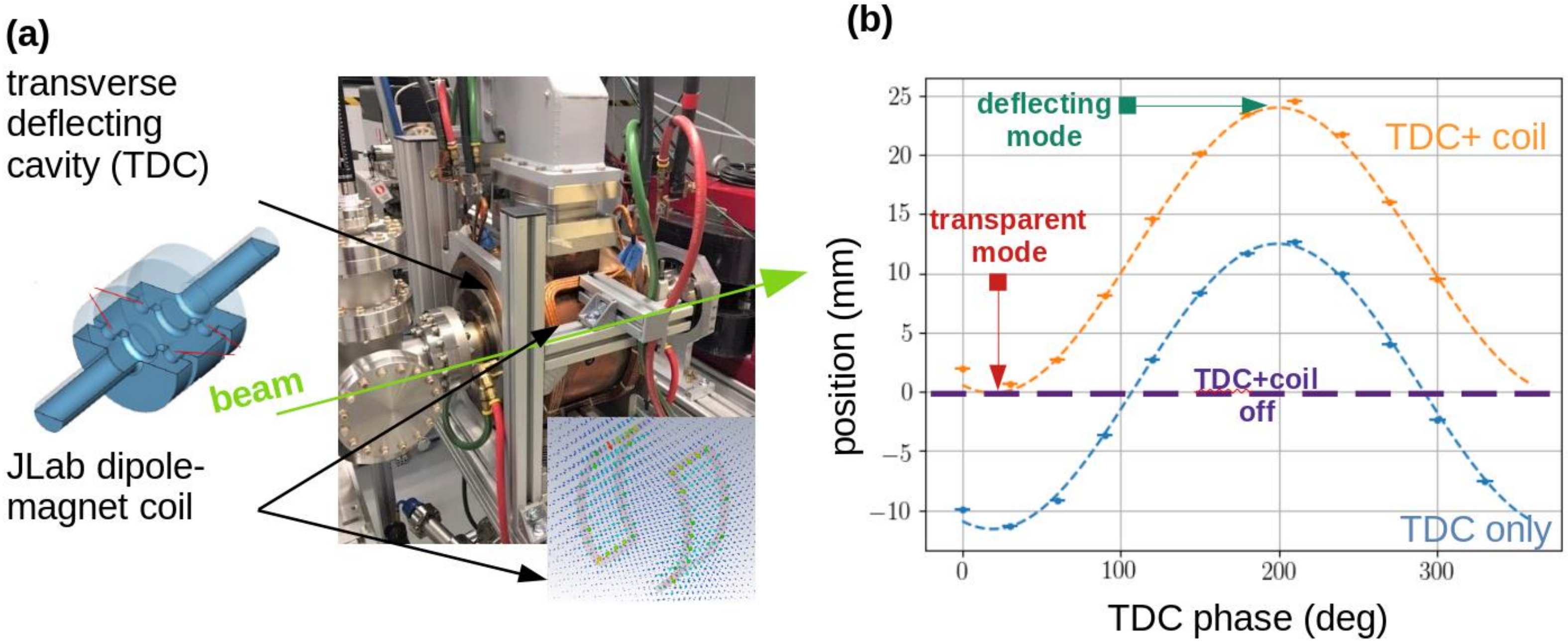
1080p Resolution

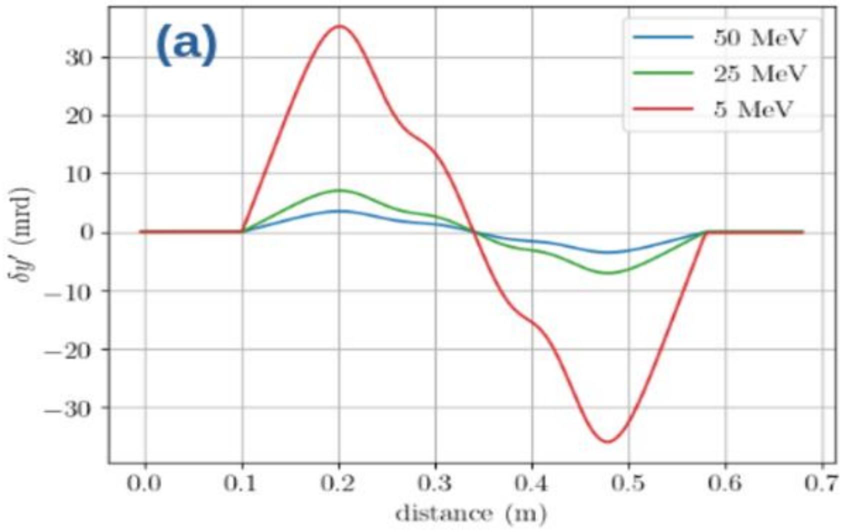


C. Marshall, *Design and Analysis of a Halo-Measurement Diagnostics,* NAPAC2019

Straight merger

- Have tested RF merger concept at AWA





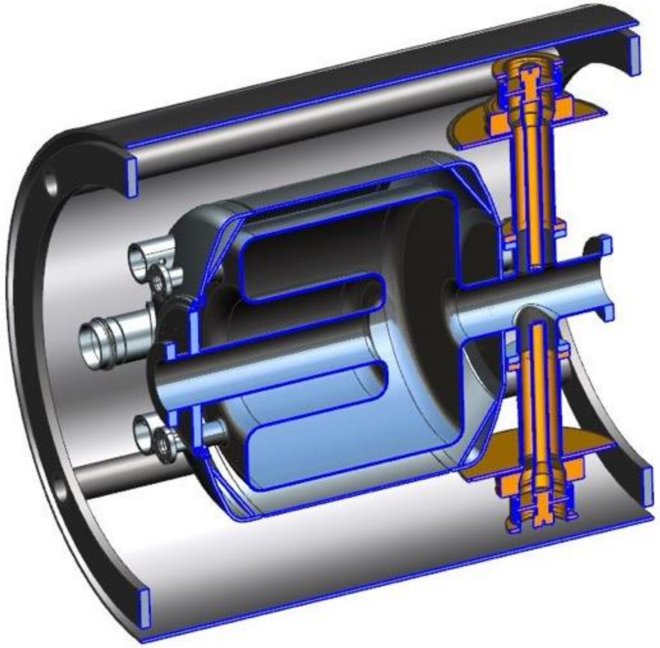
Overview of the straight-merger configuration (a) and simulated kick as a function of phase (b). The simulations are performed using the AWA TDC powered for a maximum kick of 20 mrad.

Deflection along the straight-merger for different injection energies.

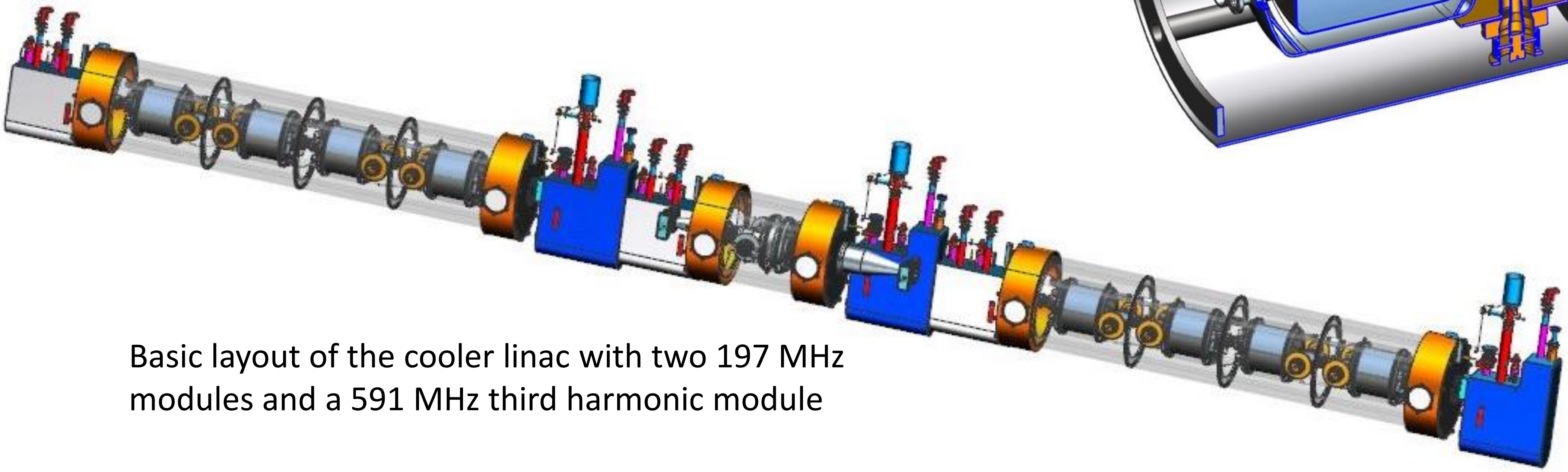
Cooler Hardware

New EIC Cavity Designs

197 MHz QWR concept for EIC cooler



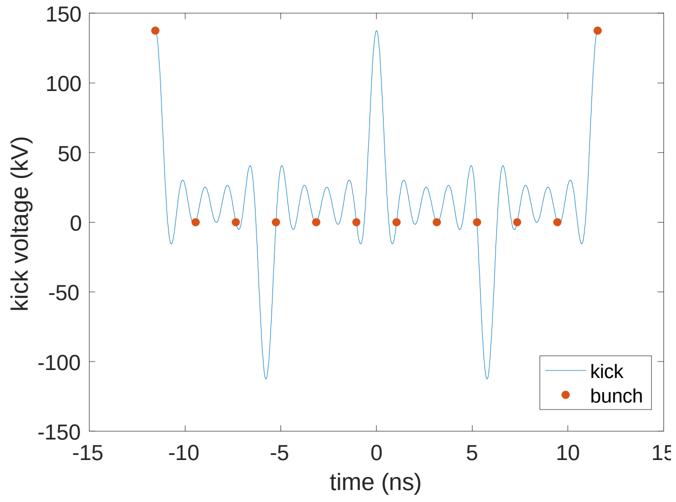
The EIC requires very long bunches for cooling the EIC hadron bunches. Lower frequencies plus harmonic cavities can provide 250 psec window of RF voltage flat to 10^{-4}
CeC ERL also needs a 197 MHz cavity and 5-cell linac modules.

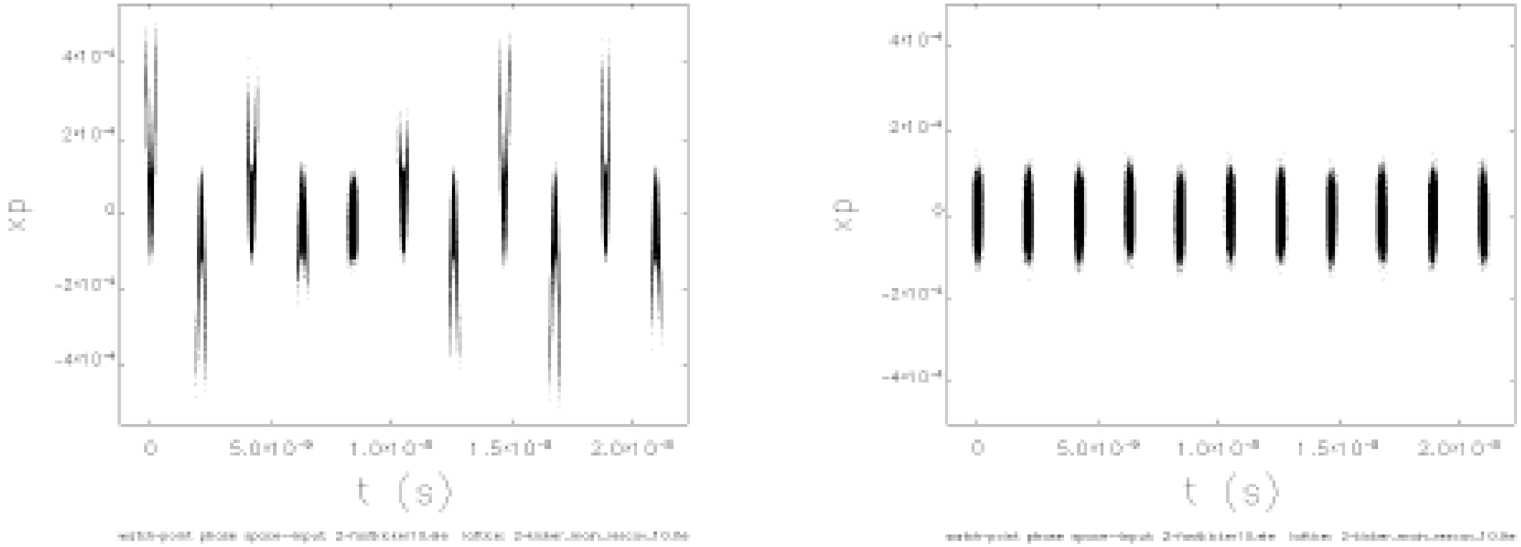


Basic layout of the cooler linac with two 197 MHz modules and a 591 MHz third harmonic module

Harmonic Kicker Design

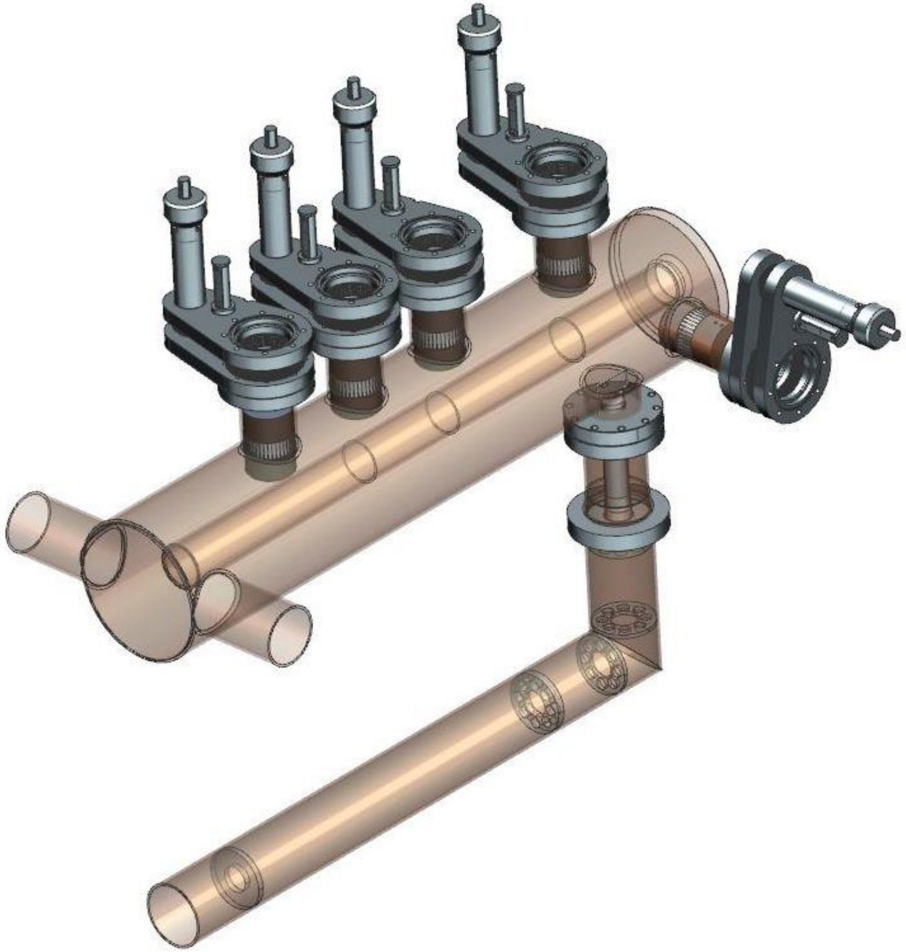
Harmonic Beam Kicker. A first 952.6 MHz copper cavity has been prototyped, bench measured, and satisfies beam dynamic requirements for a Circulating Cooler Ring design for the bunched electron cooler.
The EIC Rapid Cycling Synchrotron can use the same technology to fill the electron storage ring.





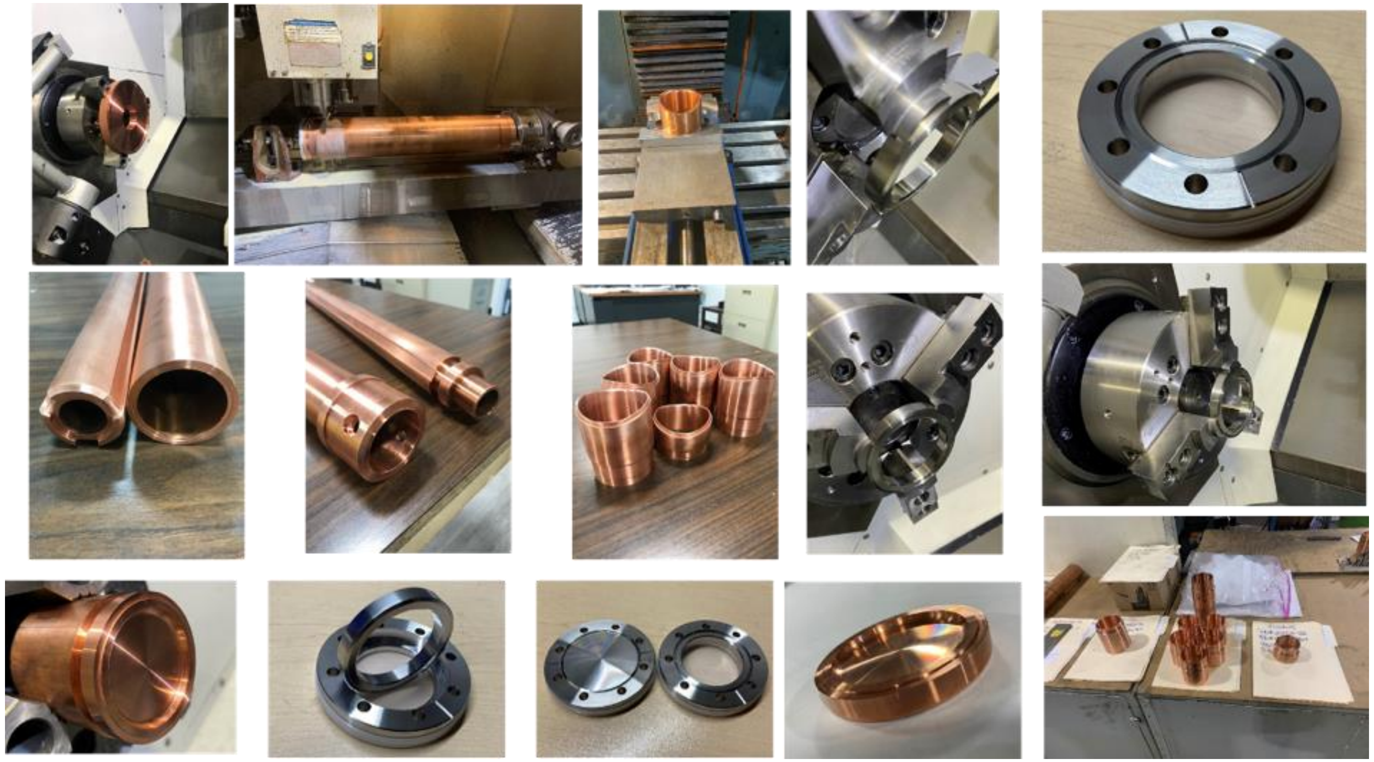
(a) Harmonic kicker only (without pre-kicker).

(b) With pre-kicker.



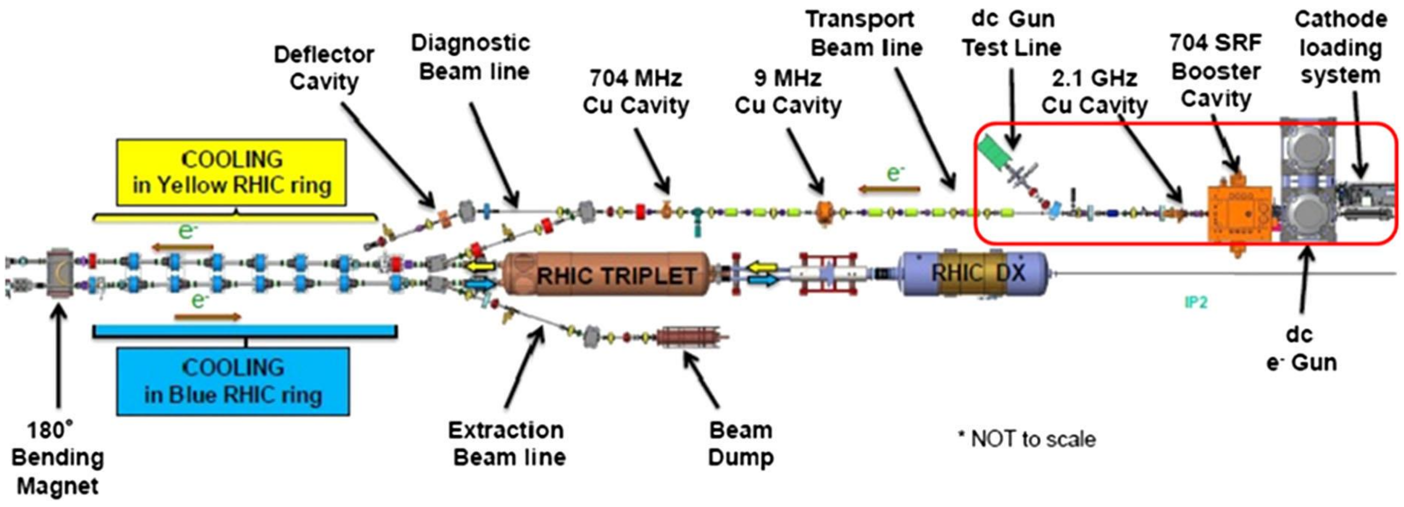
Fabrication Status

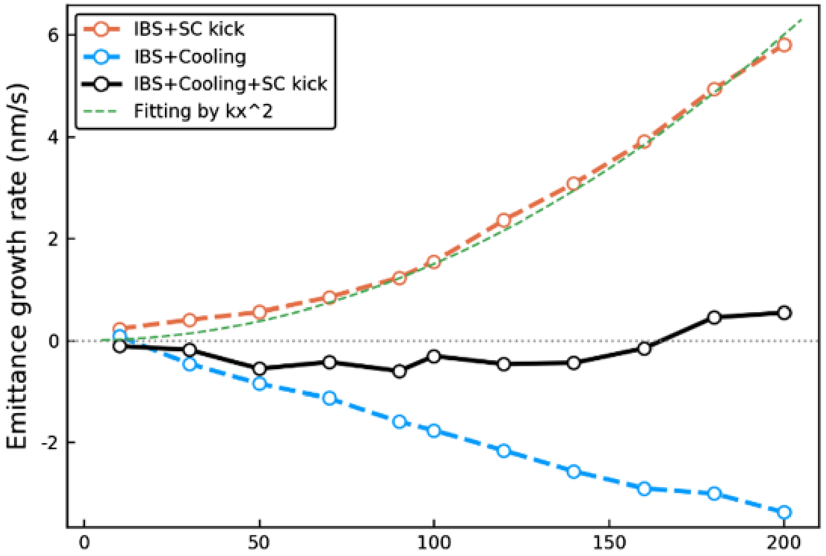
- All parts machined and QC'd.
- Getting brazing and electron beam welding recipes qualified before final brazing and welding.

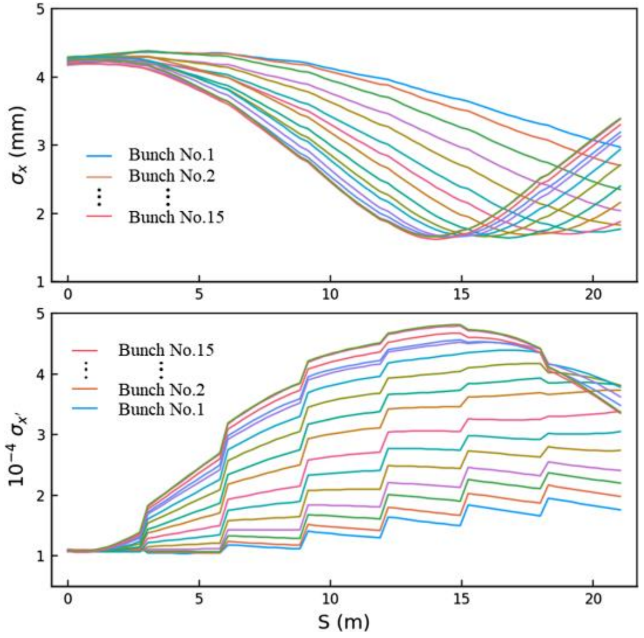


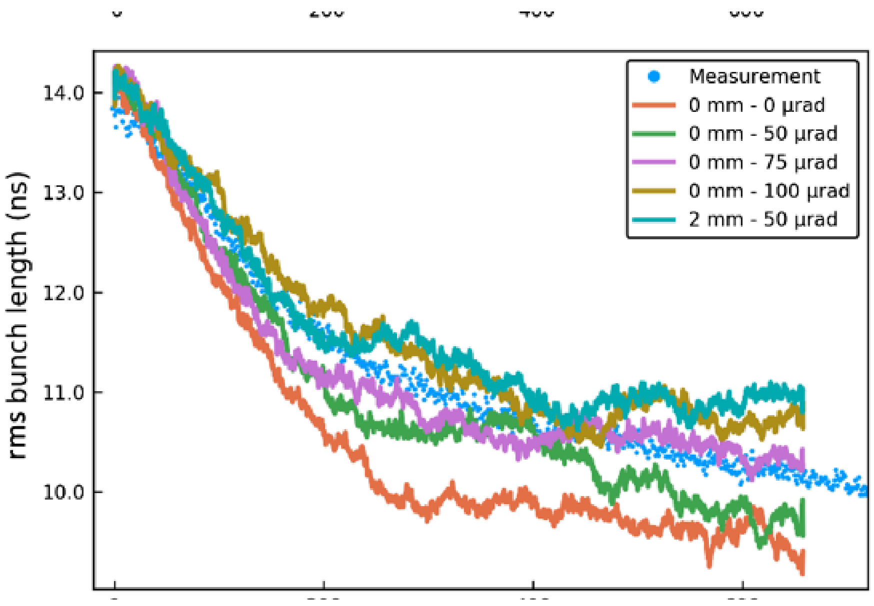
Bunched Beam
Cooling Experiments

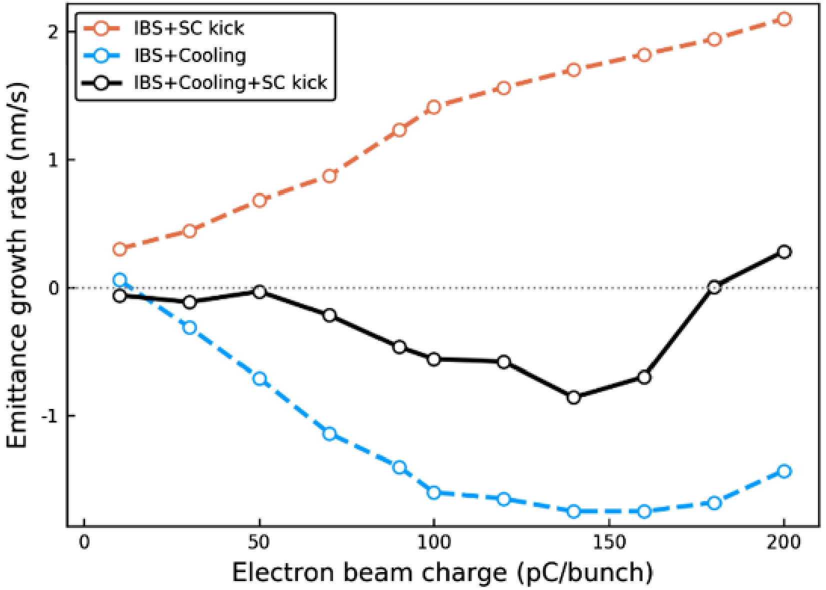
LEReC simulation (blue) and data









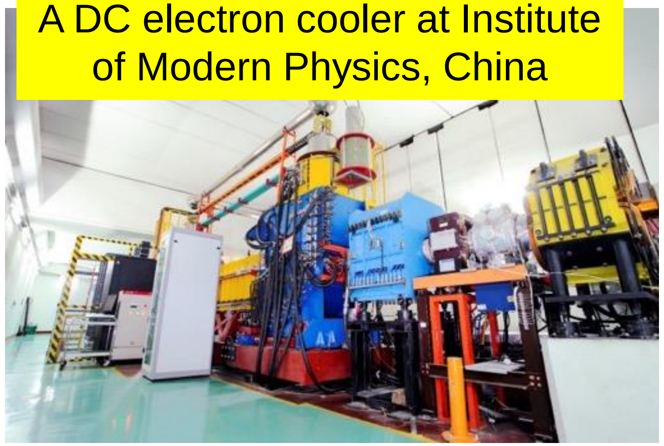


Bunched Beam Cooling Experiment

- Using a DC cooler to demonstrate cooling by a bunched electron beam
- Pulsed electron beam from a thermionic gun by switching on/off the grid electrode
- 1st Experiments performed on 4/2016, follow-up experiment on 4/2017, 12/2018

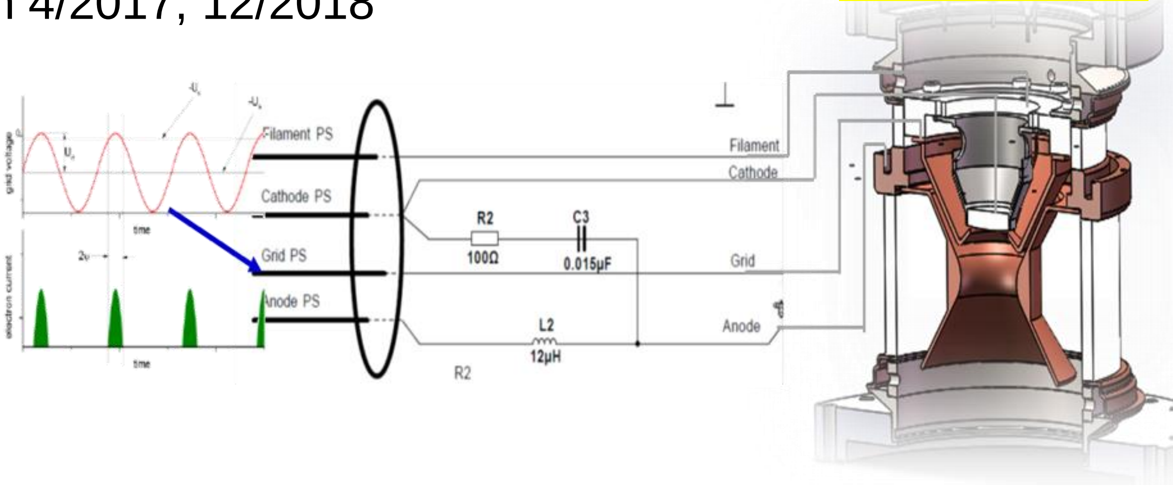
JLab-IMP Collaboration

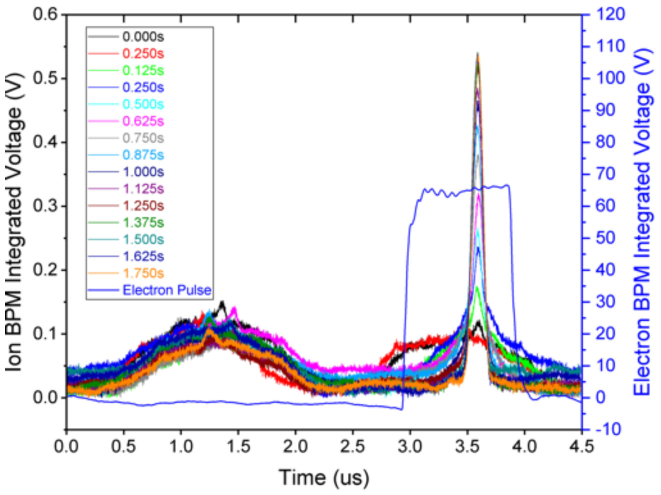
A DC electron cooler at Institute of Modern Physics, China

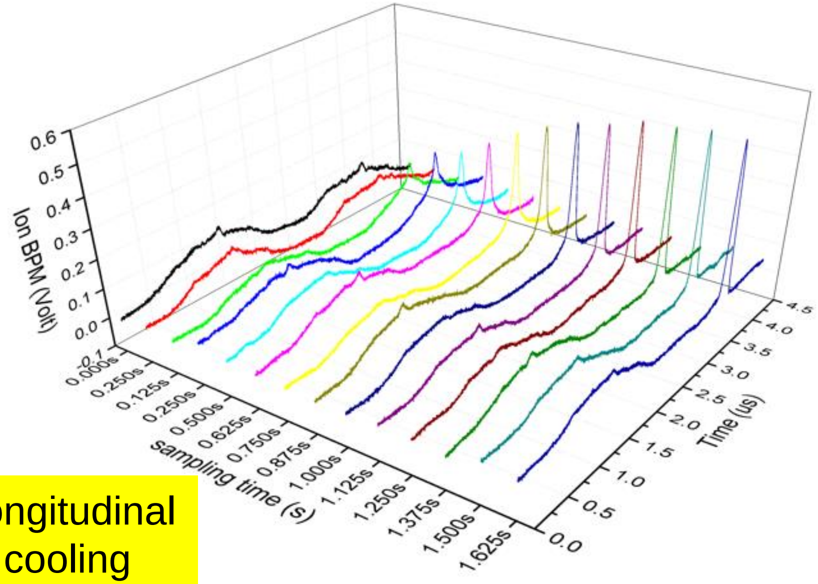


Ion	$^{86}Kr^{25+}$
Energy (i/e)	5 MeV/u & 2.7 KeV
Ion bunches	2
RF voltage	600 V
Stored ions	~10^8
Anode voltage	400 V, 600 V, 800 V
Pulse width	300 ns to 1200 ns

thermionic gun

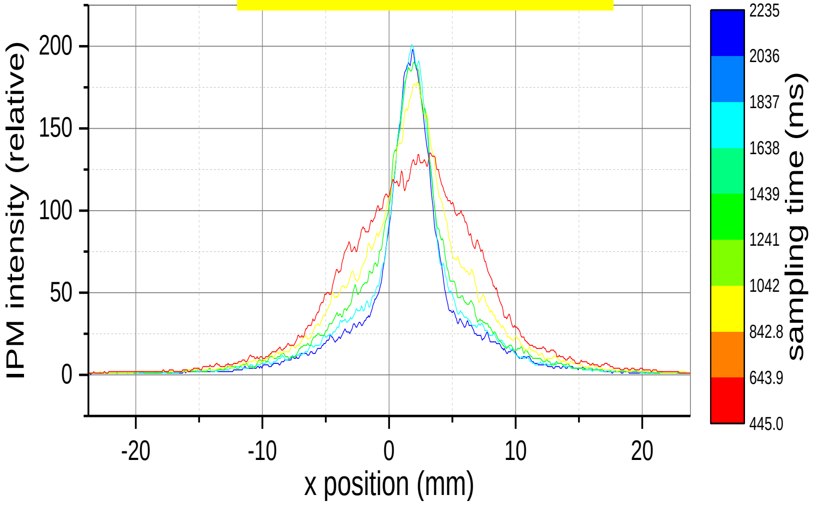




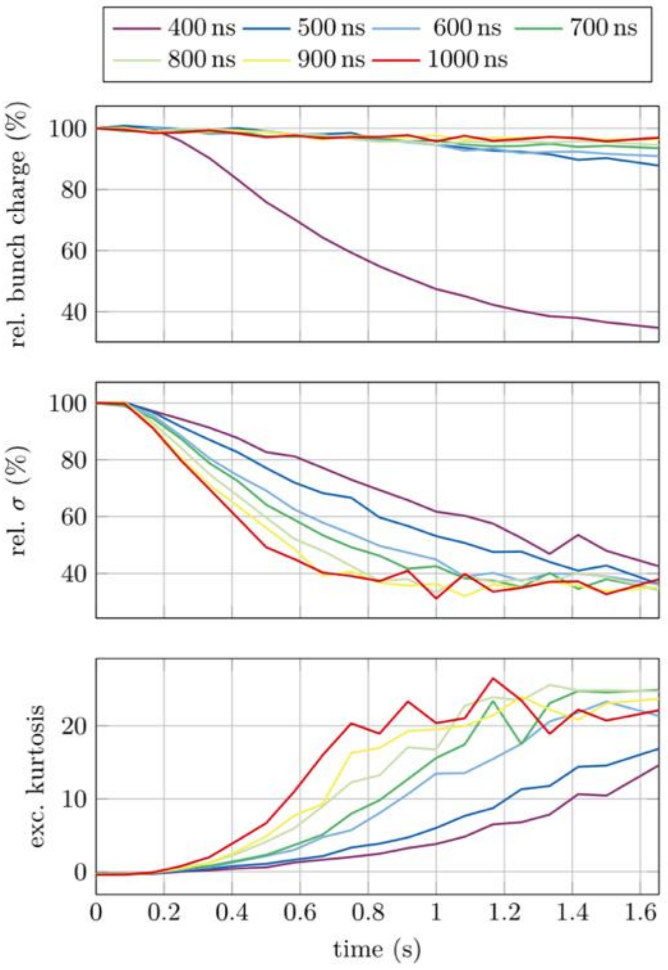


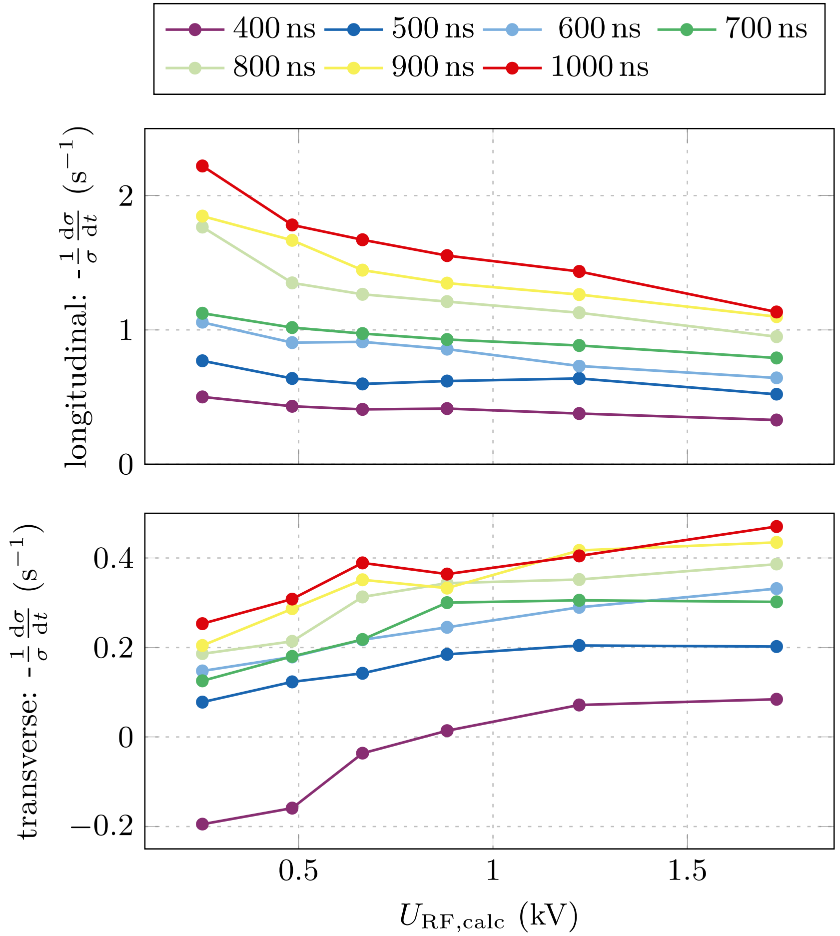
Longitudinal cooling

Transverse cooling



IMP Cooling Results

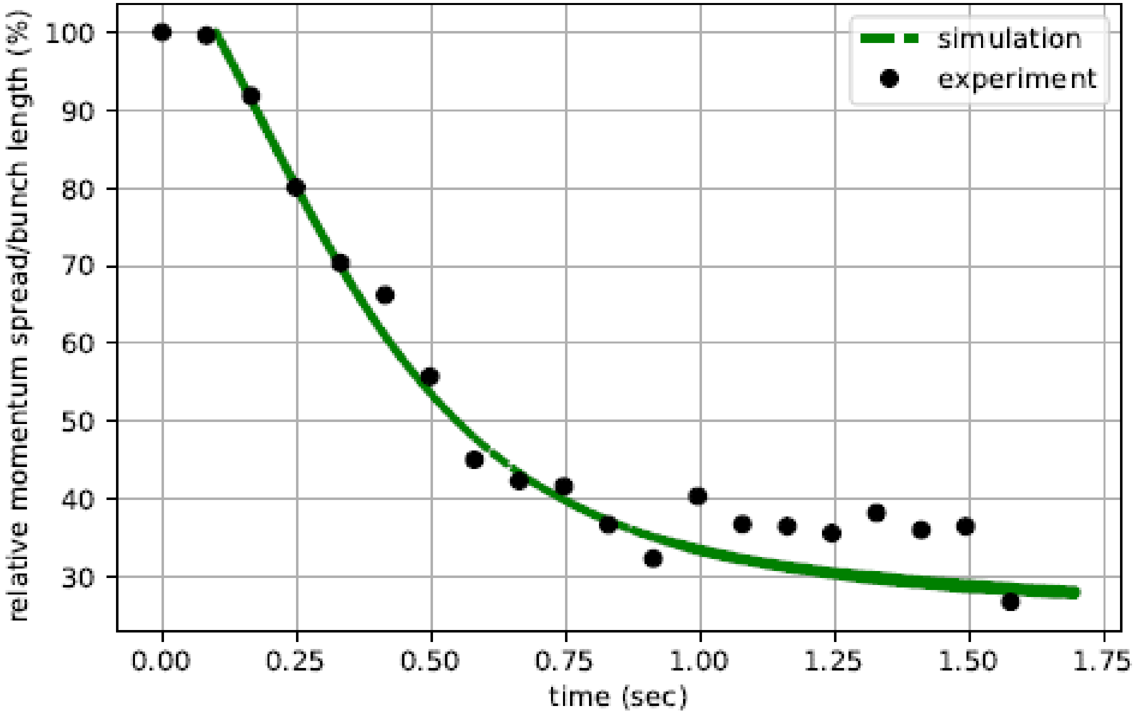




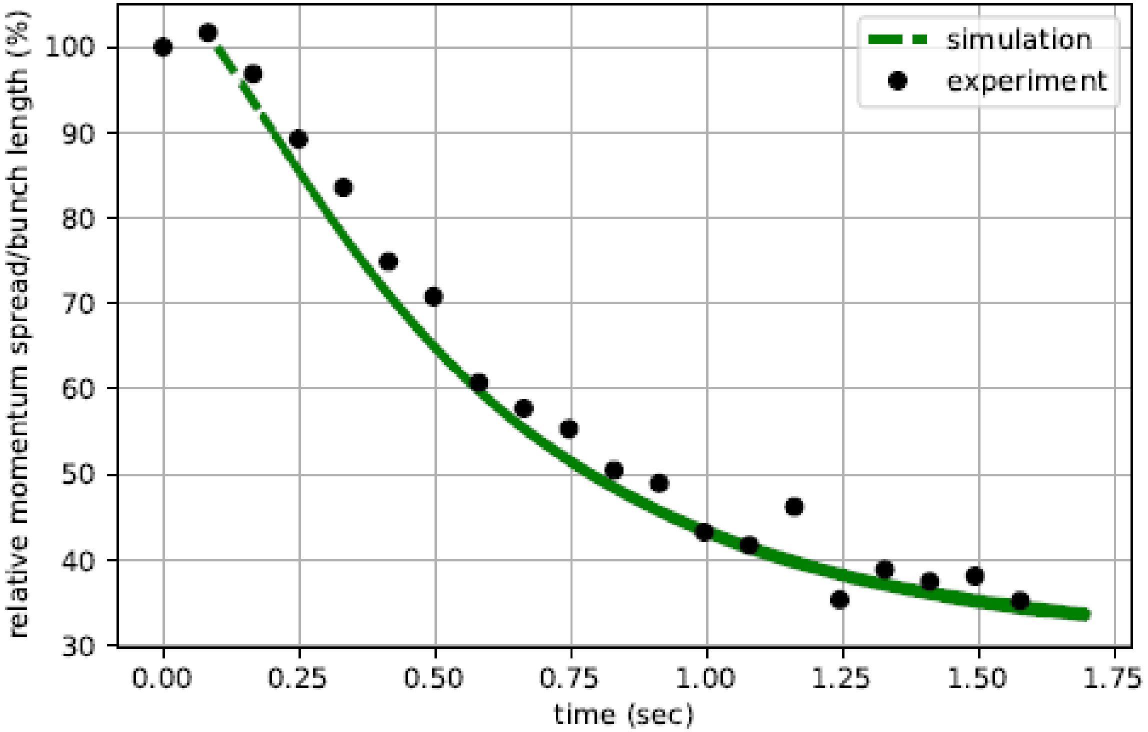
- Evolution of the statistical properties of the longitudinal ion bunch profile as a function of time.

Longitudinal and transverse cooling rates as a function of electron bunch length and RF voltage. The interpolating lines on both sides are meant to guide the eye.

JSPEC Benchmarking



Cooling of krypton ion bunch with 900 ns electron bunch



Cooling of krypton ion bunch with 500 ns electron bunch

Summary

Many different threads to the research:

✓Cooling Simulations

- Good advances in both capability and usability.
- Are using the codes now for design

✓ Storage Ring Coolers

- Rings designs are maturing and starting to look feasible.
- Dynamic aperture is still a challenge due to wigglers and low energy.
- Both designs see net cooling at peak luminosity.

✓Bunch beam cooling experiment

- Have published cooling results with good agreement between experiment and simulations.

✓Magnetized beam transport

- AWA is providing new experimental capability.
- Good agreement between simulations and experiment
- First test of RF merge idea complete.

○ Cooler Hardware

- Designs for EIC frequencies in progress
- Harmonic kicker parts are fabricated

Brookhaven Simulation Effort

- **E-beam tracking (after dynamic aperture work)**
  - Radiation damping and quantum excitation
  - IBS with H and V dispersion
  - Heating by the ions assuming Gaussian distributions and using Landau collision integral.
  - Track rms emittances using a large time step
  - Space charge and Z/n limits tested after the run
- **Hadron beam cooling**
  - Non-magnetized cooling with 3 different electron temperatures
  - IBS, space charge
  - Beta function variation in the cooling section
  - Ion dispersion, electron position and energy offsets in the cooling section
  - Use particle tracking and scale cooling and IBS to allow a large time step, as was done for stochastic cooling.

Thank You