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

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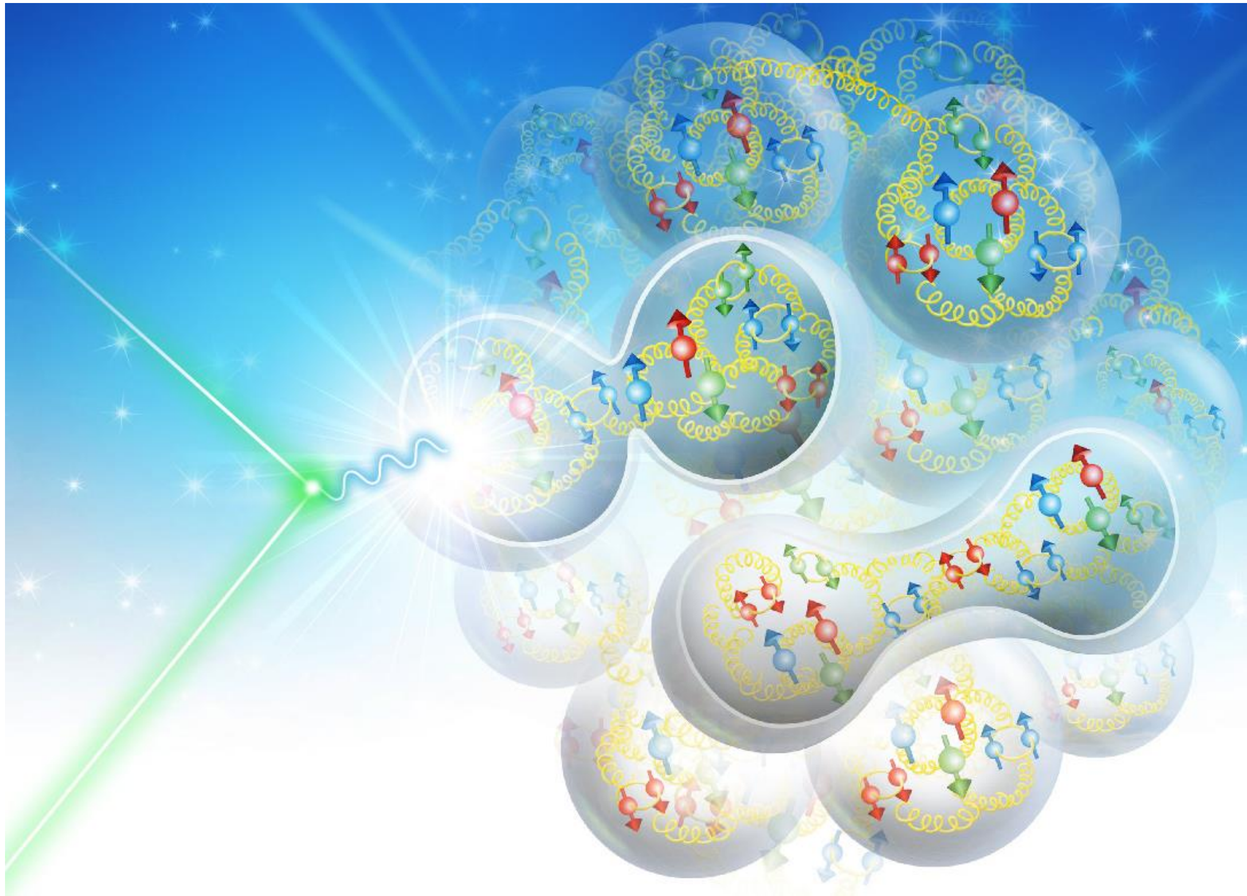


Supported by DoE NP Accelerator R&D funding FOA

Jefferson Lab

2019 NP Accelerator R&D PI Exchange Meeting
November 7, 2019, Gaithersburg, MD

Fermilab · nicadd · U.S. Department of Energy Office of Science · JSA · Brookhaven National Laboratory

Outline

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

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

- Description
  - This project will explore methods to increase the technical readiness levels of electron cooling concepts for an Electron-Ion Collider facility, as well as exploring new methods of cooling. This involves simulations, experimental tests, theoretical studies of new concepts, an development of critical hardware for a cooler.
- Status
  - Good progress on several segments of the program. Some difficulties with experiment logistics.
- Main goal
  - Develop concepts and technologies that allow cooling of high-current, high-energy hadron beam in an electron collider.
- Supported by DoE NP Accelerator R&D funding FOA
- This is the first year of a two year project

Electron Cooler Design Project Budget

	FY'18	FY'19	Totals
a) Allocated (Jlab)	$850,000	$850,000	$1,700,000
b) Costs to date	$564,691	$0.0	$564,691
a) Allocated (BNL)	$245,000	$245,000	$490,000
b) Cost to date	$181,259	$0.0	$181,259
a) Allocated (FNAL)	$150,000	$150,000	$300,000
b) Cost to date	$63,921	$0.0	$63,921
a) Allocated (ODU)	$35,000	$35,000	$70,000
b) Cost to date	$35,302	0.00	$35,302

Jones Report Topics covered

Row No.	Proponent	Concept / Proponent Identifier	Title of R&D Element	Panel Priority	Panel Sub-Priority
3	PANEL	ALL	Strong hadron cooling	High	A
4	PANEL	ALL	Benchmarking of realistic EIC simulation tools against available data	High	A
39	JLAB	ECL1	Electron cooling simulations	High	
40	JLAB	ECL3	ERL Cooler design for single and multi-turn operations	High	C
42	JLAB	ECL5	Fast kicker prototype for multi-turn cooler	High	C
47	JLAB	SRF1	SRF cavity systems	High	
56	JLAB	ECL2	Bunched beam cooling experiment at IMP	Medium	
57	JLAB	ECL6	Fast kicker test with beam	Medium	

Deliverables and schedule

Task	FY'18				FY'19			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Codes to predict emittance in SR (BNL)		✓						
Codes to predict heating by hadrons (BNL)				✓				
Cooling simulation with non-Gaussian beams (JLAB)			✓					
Cooling simulation with repeatedly used beams (JLAB)				✓				
Cooling simulation with imperfections (JLAB)						+		
Final software integration and report (JLAB)								+
Benchmark transverse cooling (JLAB)						+		
Benchmark cooling redistribution methods (JLAB)							+	
Benchmark error tolerances (JLAB)								+
Benchmark of ion effects on electrons (BNL)			✓					
Model of single energy storage ring cooler (BNL)				✓				

Deliverables and schedule

Task	FY'18				FY'19			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Optimized storage ring cooler (BNL)								+
Optics for two-energy storage ring cooler (JLAB)				✓				
Optimization of cooler parameters (JLAB)				→	→	+		
Estimates of IBS and SC				→	→	+		
Initial single particle tracking in 2-energy storage ring				✓				
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'18				FY'19			
	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'18				FY'19			
	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								+

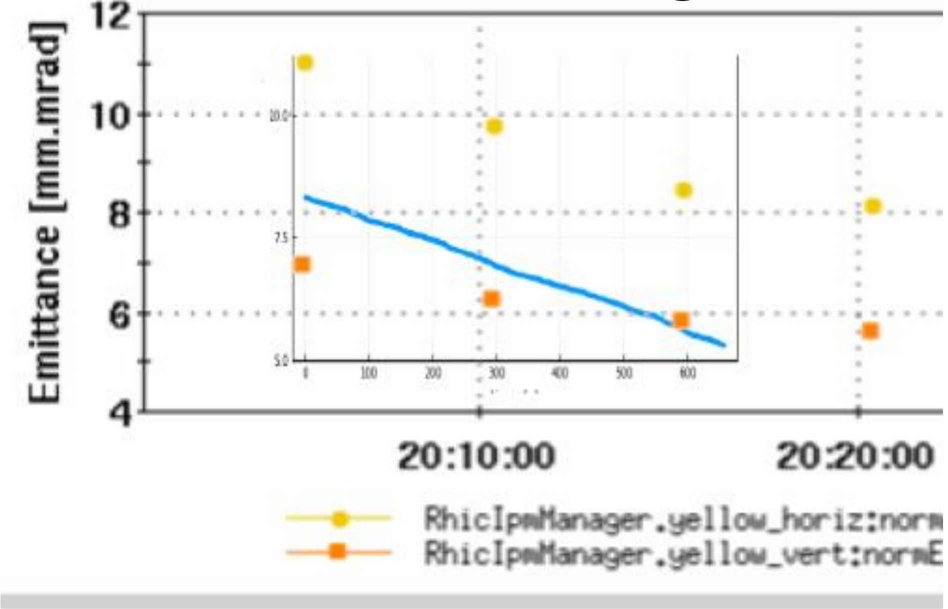
Cooling Simulations

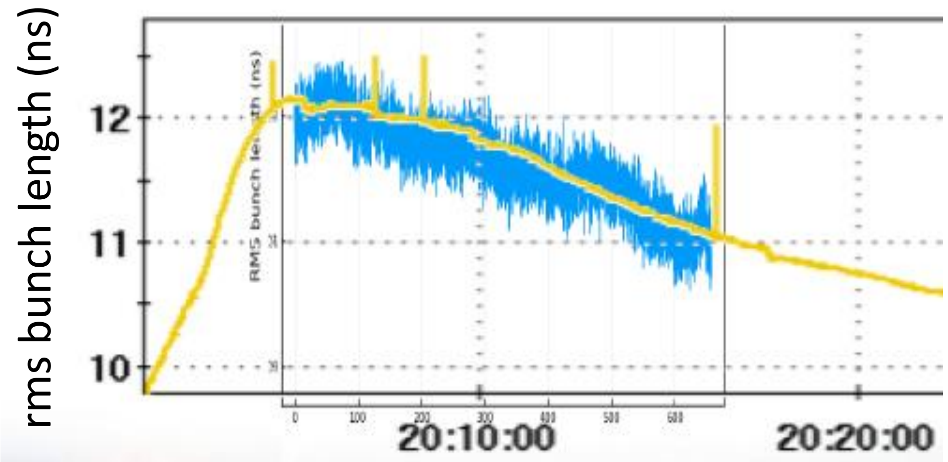
Brookhaven Simulation Effort

- **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.

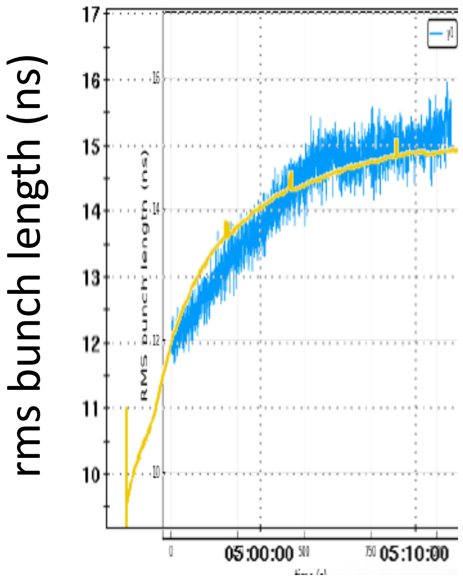
LEReC simulation (blue) and data

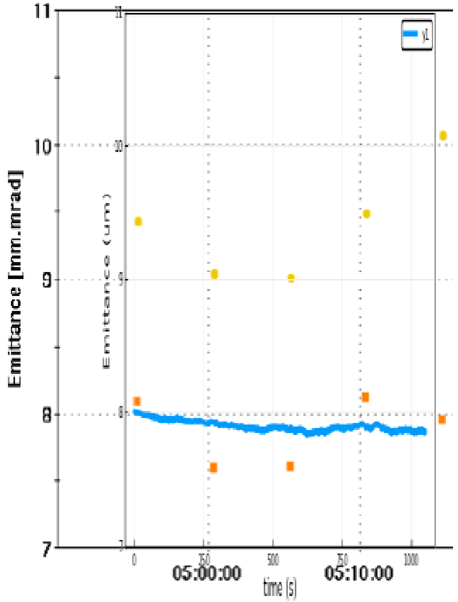
With Cooling





No Cooling





These are preliminary results.

Simulation Codes

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

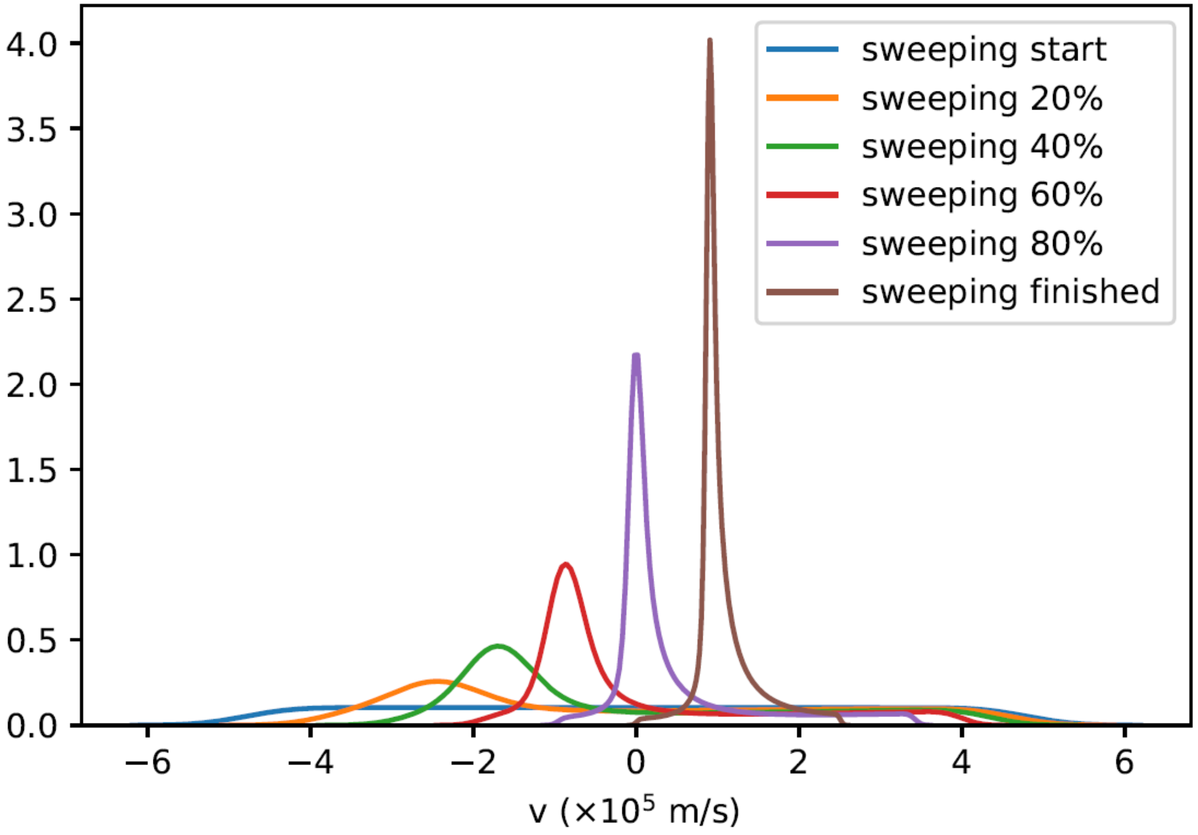
Enhancements to JSPEC in the previous year:

- User-defined electron beam
  - Allow users to define arbitrary electron bunch for cooling using particles.
  - Use tree structure to organized the particles and generate the position to density/temperature map.
- Improved IBS model (Nagaitsev formulas)
  - Calculate and output IBS contribution of individual element for detailed IBS analysis.
- Maintain constant ion bunch length during cooling
- Dispersive cooling
  - Make the average velocity of the ion slightly different from that of the electron bunch and introduce dispersion at the cooler and using Gaussian bunch.
  - A module is developed to model the synchrotron and betatron motion of ions and calculate the average dynamic invariant change over the oscillations, which, averaged over all particles, is the cooling rate.
- Luminosity
  - Calculate the instant luminosity during the evolution of the ion beam under IBS/cooling.

JSPEC Enhancements (cont.)

- Enhanced UI for multi-step simulation
  - Allow users to set up multiple simulations in a single input script.
  - Key results, eg. cooling rate, emittances, etc., from the previous simulations can be used as inputs of the following ones.

- Sweeping effect
  - Change the electron beam velocity to "sweep" from the lower end of the ion velocity to the higher end of the ion beam velocity, which increases the longitudinal cooling.
  - A module is developed to simulate this process with n steps, where n is the user defined value. The "sweeping" speed of the electron beam is calculated by the program automatically.



JSPEC Enhancements (cont.)

- Cooling with repeatedly-used electron beam
  - 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.

Storage Ring Cooler

Storage Ring Cooler: Single Energy

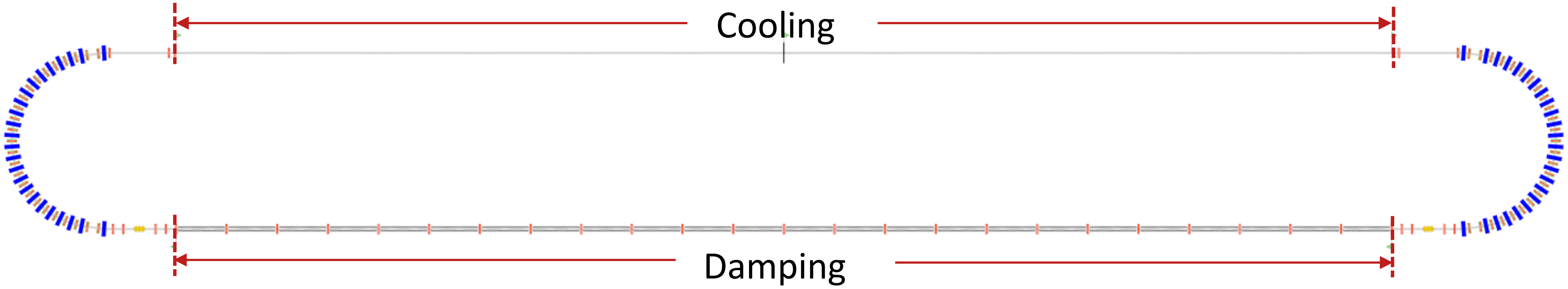
Challenge: Stop the emittance growth due to IBS, and maintain the integrated luminosity.

- 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.



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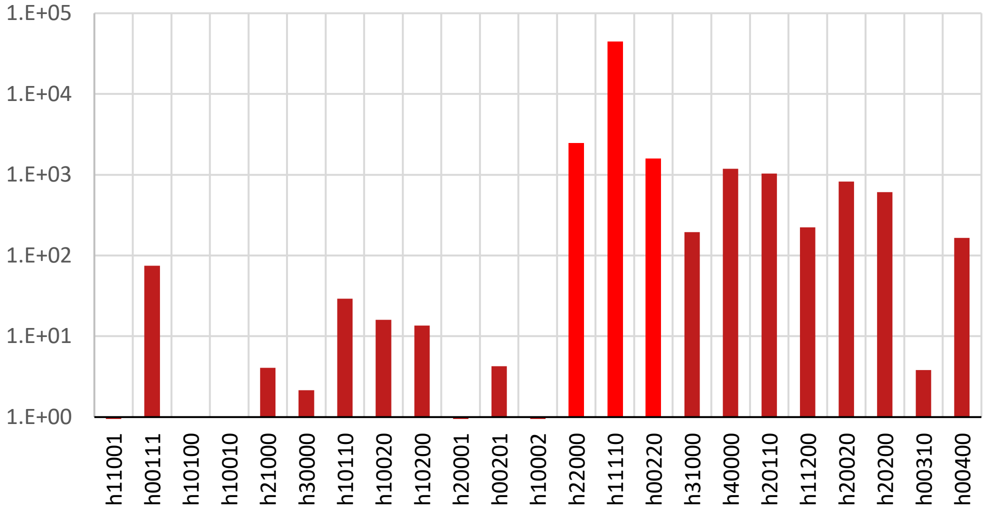
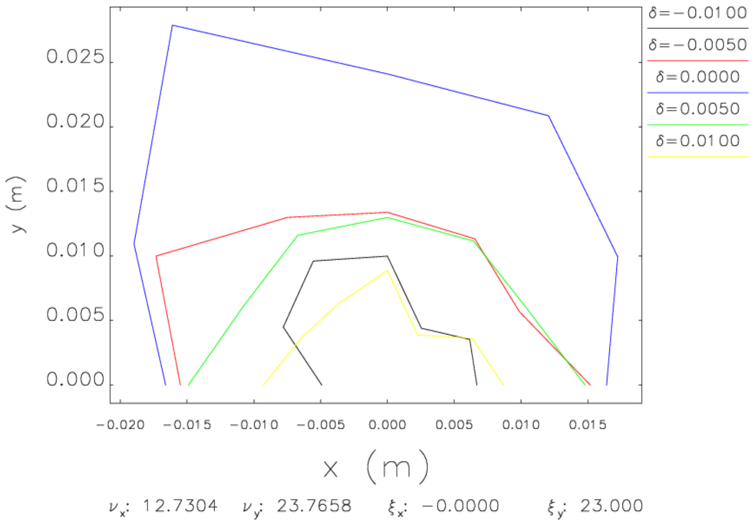
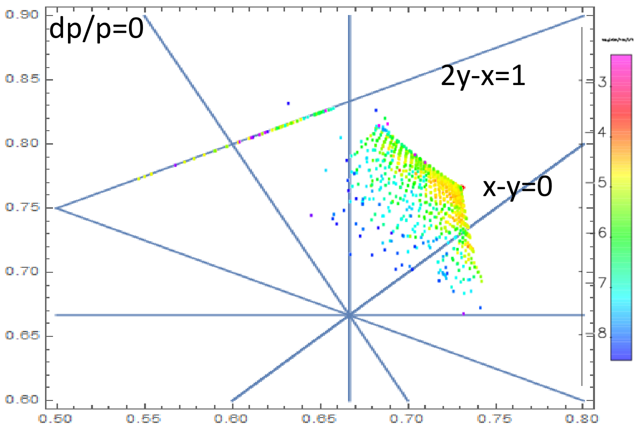
Dynamic Aperture

- The amplitude-dependent tune will strongly affect the dynamic aperture of the cooler ring.
  - The wiggler period and magnetic field need to be carefully optimized.
  - Several single dipoles instead of wigglers may be better for dynamic aperture.







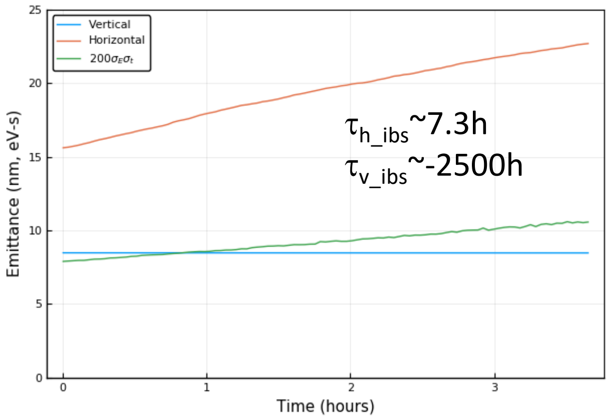
M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation, "Advanced Photon Source LS-287, September 2000.

Simulation results on BNL EIC

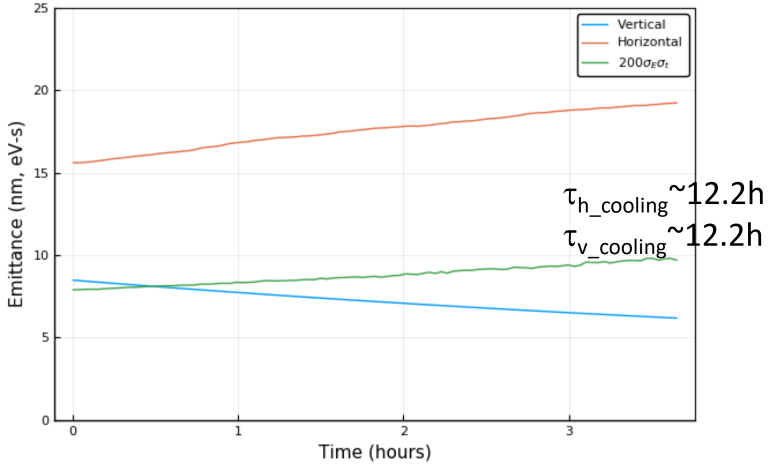
- A complicated optics of the cooler is needed for a good cooling effect, and the lattice must be well optimized.

Proton
(without strong hadron cooling)
ε_x=16.1nm, ε_y=8.5nm
dp/p=6.6e-4
length=0.07m
N=10.3e10

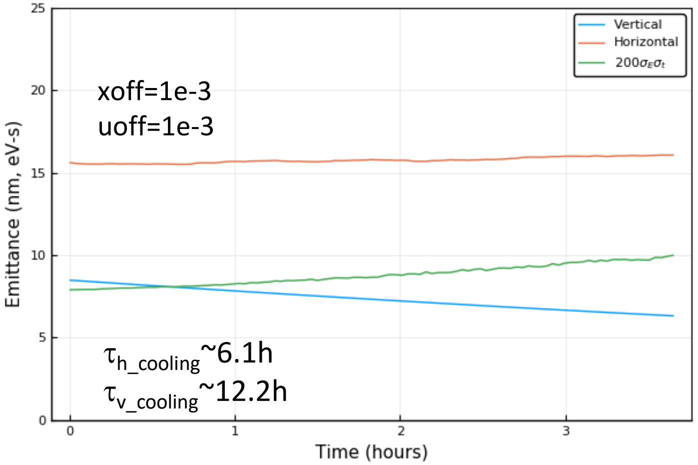
Without-cooling



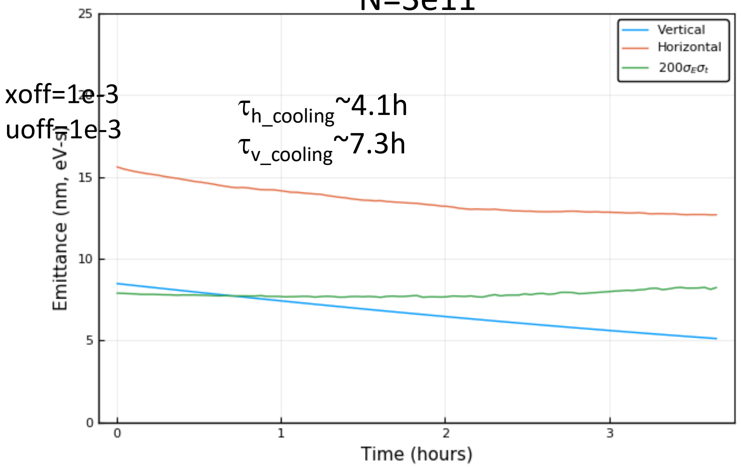
Cooler-1 (H-Wiggler)
ε_x=11.8nm, ε_y=2.7nm
dp/p=1.78e-3
length=0.375m
N=3e11



Cooler-1 (+Skew Q)
ε_x=2.7nm, ε_y=11.8nm
dp/p=1.78e-3
length=0.375m
N=3e11



Cooler-2 (H&V-Wiggler)
ε_x=26nm, ε_y=14.7nm
dp/p=0.725e-3
length=0.1m
N=3e11



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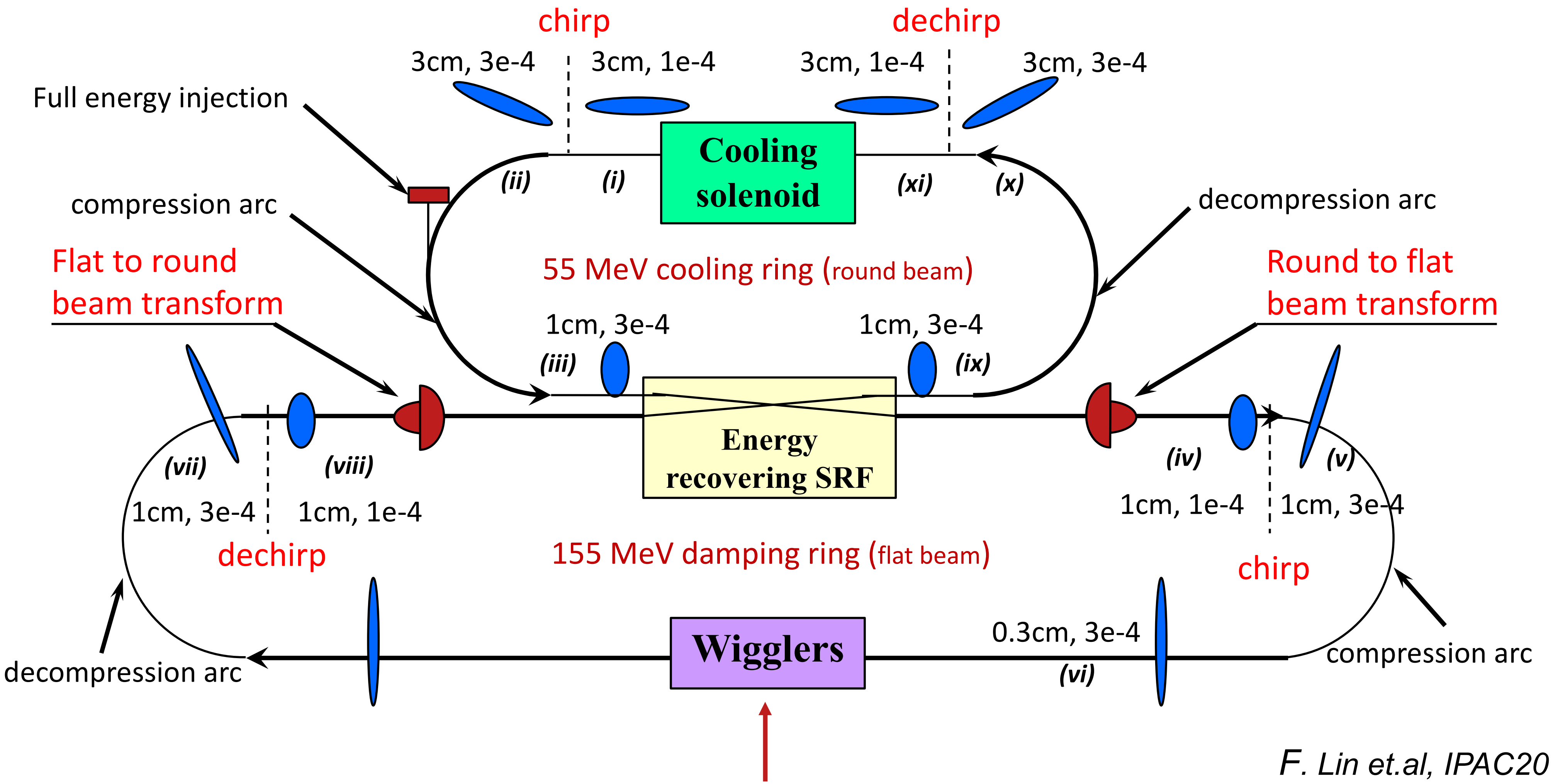
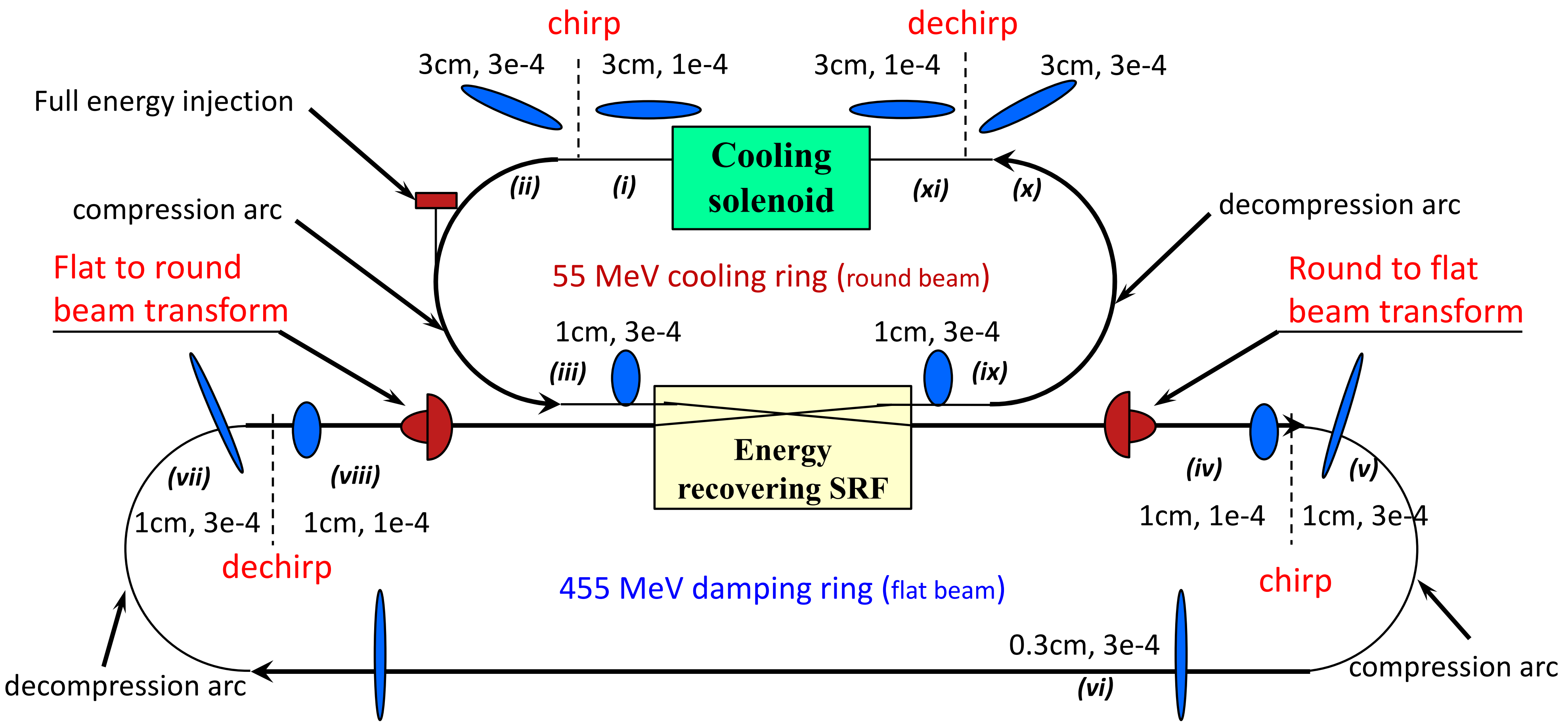
Two Energy Storage Ring



F. Lin et.al, IPAC2016, Busan, Korea

Proposed Idea: Add wigglers to decrease damping time

Avoid Wigglers?

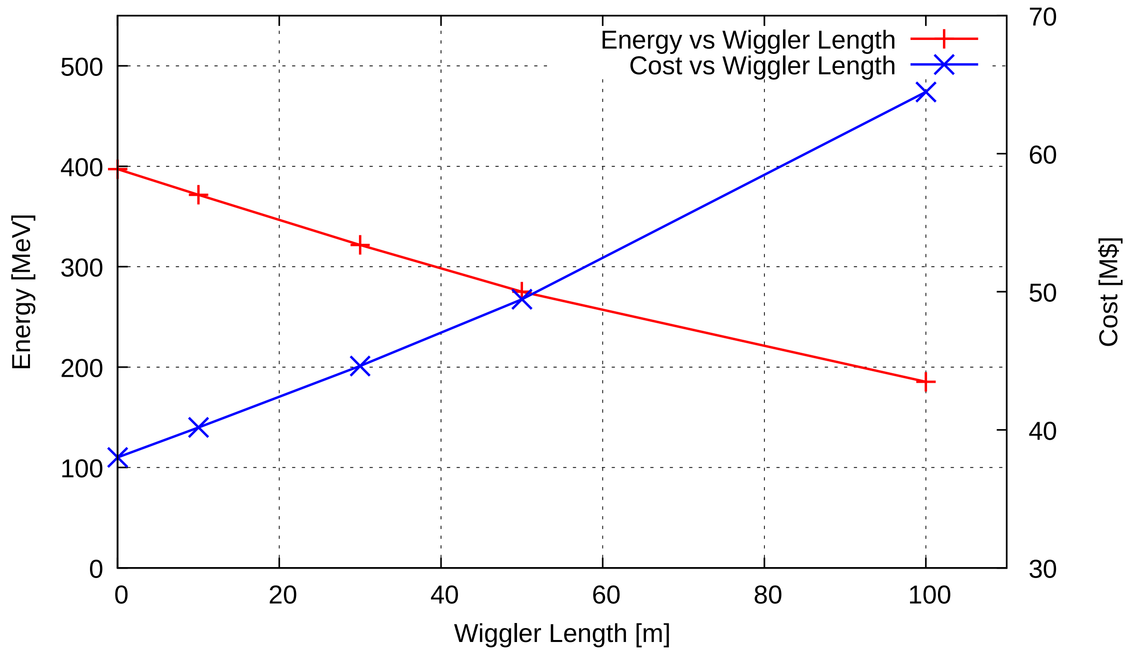


New Idea: increase beam energy in the damping ring to decrease damping time

Parameter Choices to Reach 600ms Damping Time

- Damping time for a two-energy ring: $\frac{t_{rev}}{\tau_{rad}} = \frac{t_{rev,LE}}{\tau_{rad,LE}} + \frac{t_{rev,HE}}{\tau_{rad,HE}} \approx \frac{t_{rev,HE}}{\tau_{rad,HE}} \sim \frac{\Delta E_{rad}}{E} = \frac{4\pi r_e}{3\rho_H}\gamma_H^3 + \frac{2\pi}{3}\alpha K^2 \frac{L_W}{\lambda_{ID}} \frac{2\gamma_H}{1+K^2/2} \frac{\lambda_c}{\lambda_{ID}}$

- Simple cost model: $C(\gamma_H, L) = \frac{511kV}{0.9}\left(\frac{10\$}{100V}\right)\left(\gamma_H + \frac{CL_W}{\lambda_{ID}}\right) - \frac{511kV}{0.9}\left(\frac{10\$}{100V}\right)\gamma_L$



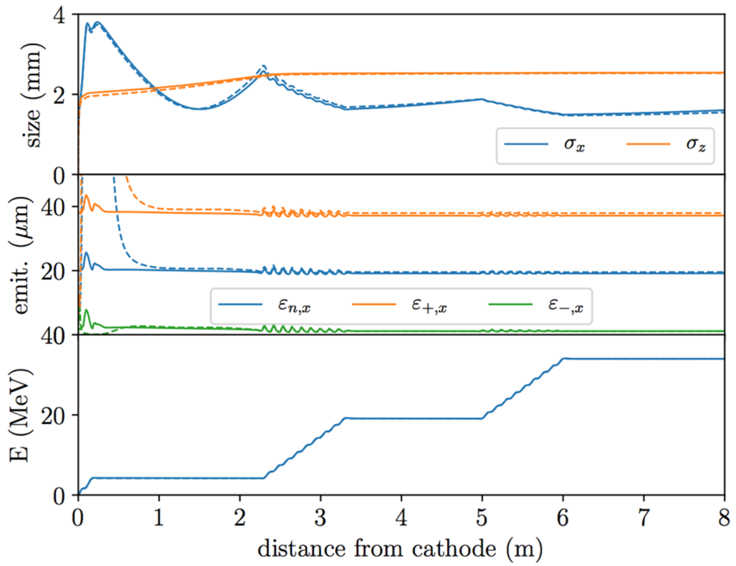
Item	Unit	Value	
Cooling Ring Energy	MeV	**55**[1]	**10.9**[2]
γ_L		107.8	21.3
Damping Ring Energy	MeV	**418**	**418**
γ_H		818	818
Total Gradient	MeV	363	407
Horizontal Damping Time	ms	**600**	**600**
Longitudinal Damping Time	ms	300	300

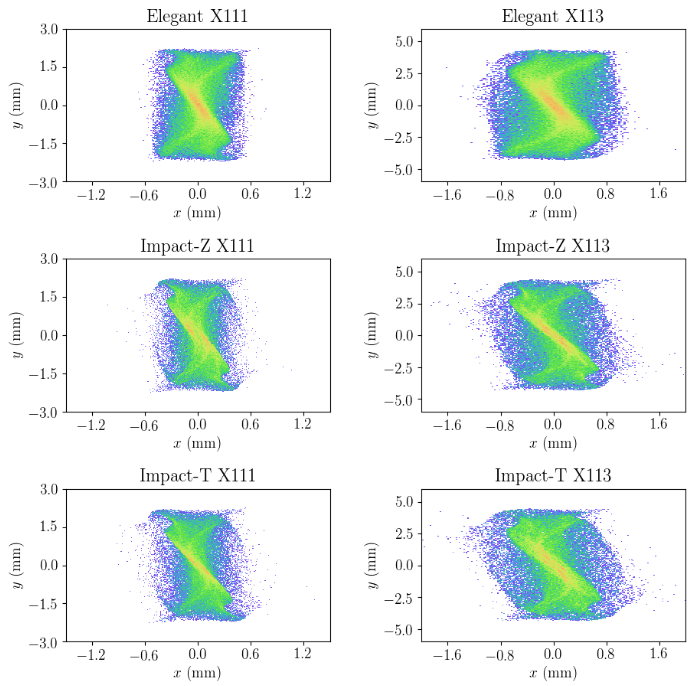
[1] to cool proton beam at 100 GeV
[2] to cool proton beam at 20 GeV

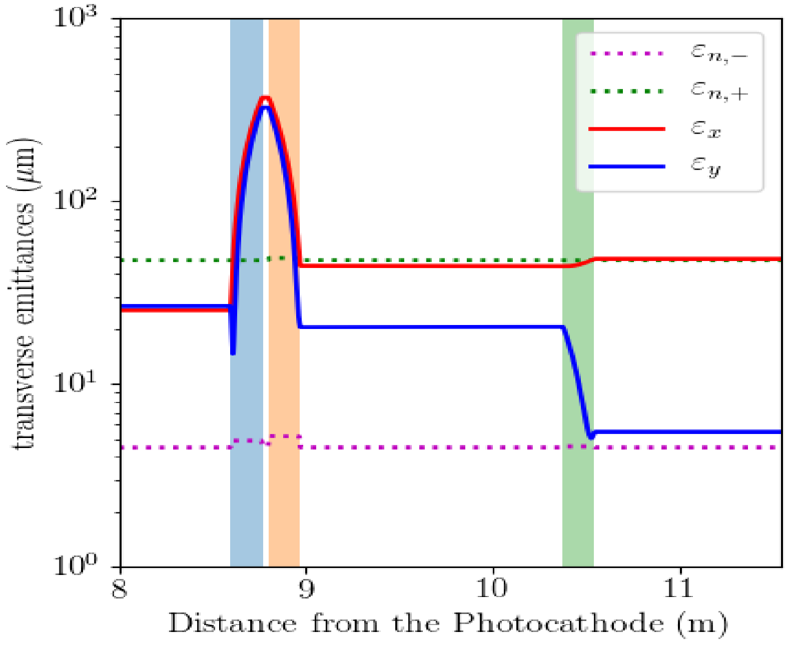
Magnetized Beam Transport

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





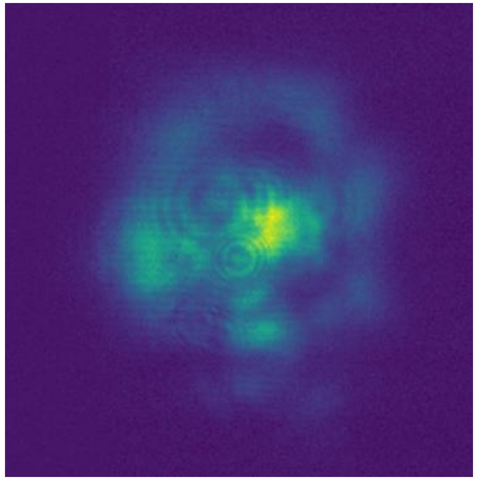


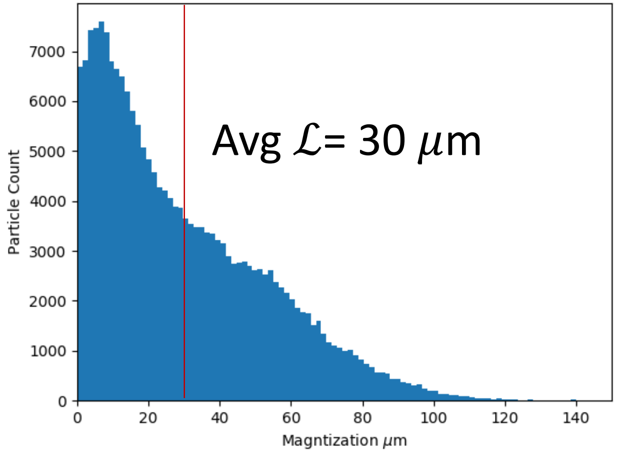
Transport Experiment

Parameters	Measurements
Magnetic field (Tesla)	0.0665±.0005
Beam Spot Size (mm)	1.448±.004
Energy (MeV/c)	32.436±.001
Emittance	**Calculations**
Magnetization $\mathcal{L}$ (μm)	30
Drift emit., $\epsilon_{n,+}$ (μm)	60
Cyclotron emit., $\epsilon_{n,-}$ (μm)	3
Emittance	**Measurements**
Magnetization $\mathcal{L}$ (μm)	31.2±1.1
$\epsilon_{n,+}$ (μm)	62.4±2.2
$\epsilon_{n,-}$ (μm)	3±0.8

$$\gamma\mathcal{L} = \frac{eB_c}{2mc}\sigma_c^2$$

$$\langle L\rangle = 2p_z\frac{\sigma_1\sigma_2 \sin\theta}{D}.$$



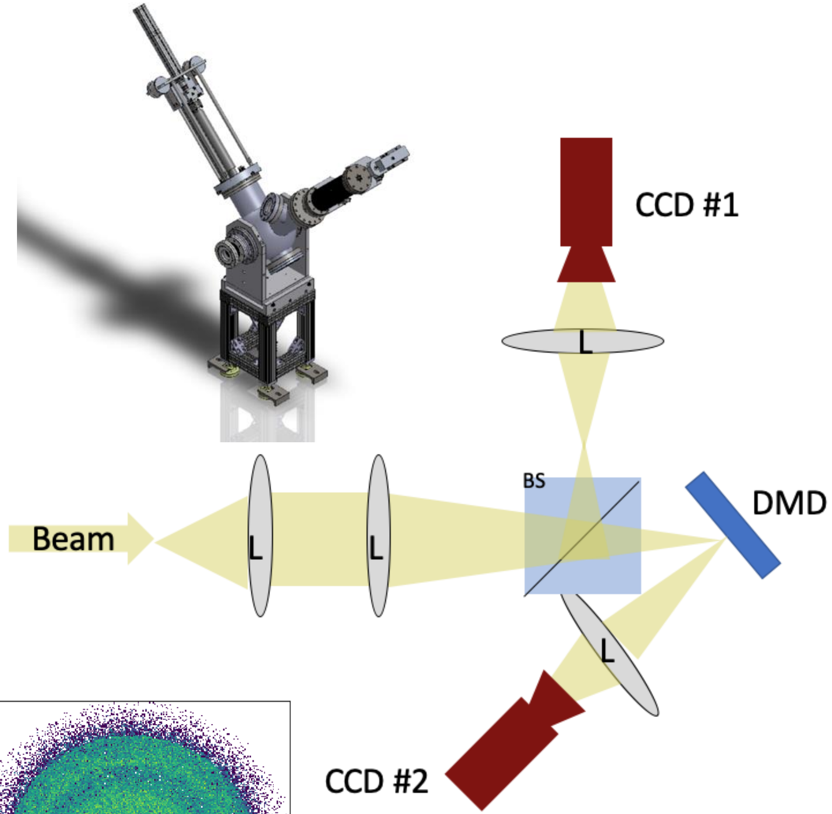


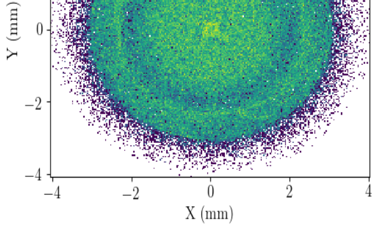
- Use the laser distribution to measure the average angular momentum from the cathode as a function of r.

- Using the positional angular dependence for angular momentum the avg magnetization can be calculated by $\mathcal{L} = 147\, B_c\, r^2$

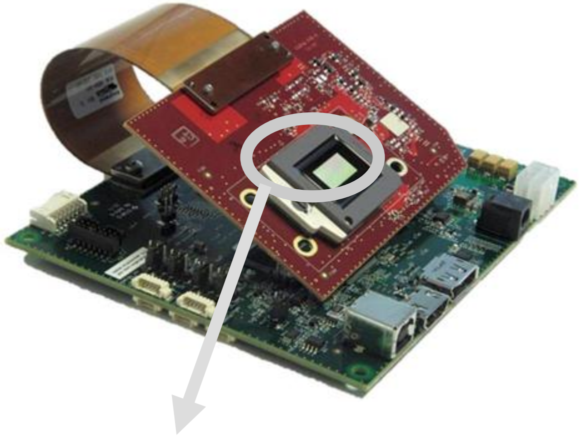
- Using the numbers above to calculate the estimated e-emittances we will get ε_+=78 and ε_-=3.5 microns.

Beam Halo Measurements

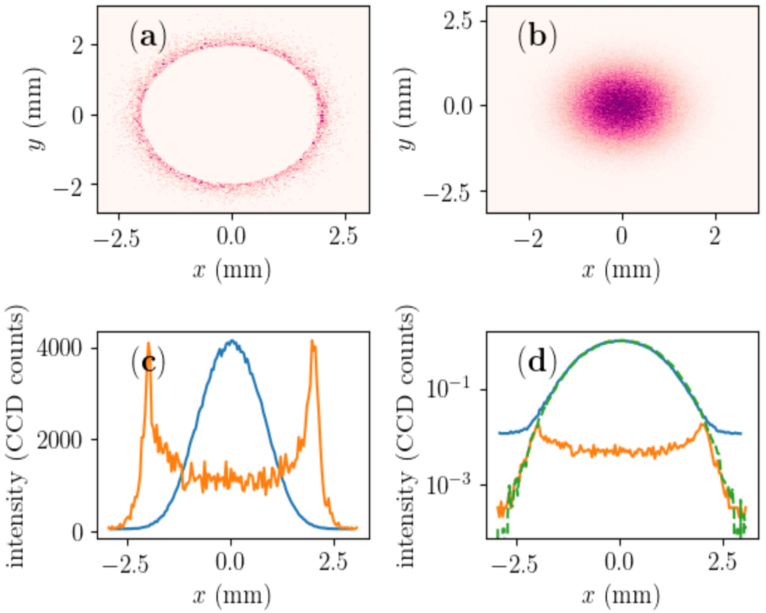




- Using a Digital Micromirror Device (DMD) the beam core can be blocked to show just a halo.
- Combining the two pictures reconstruct



1080p Resolution

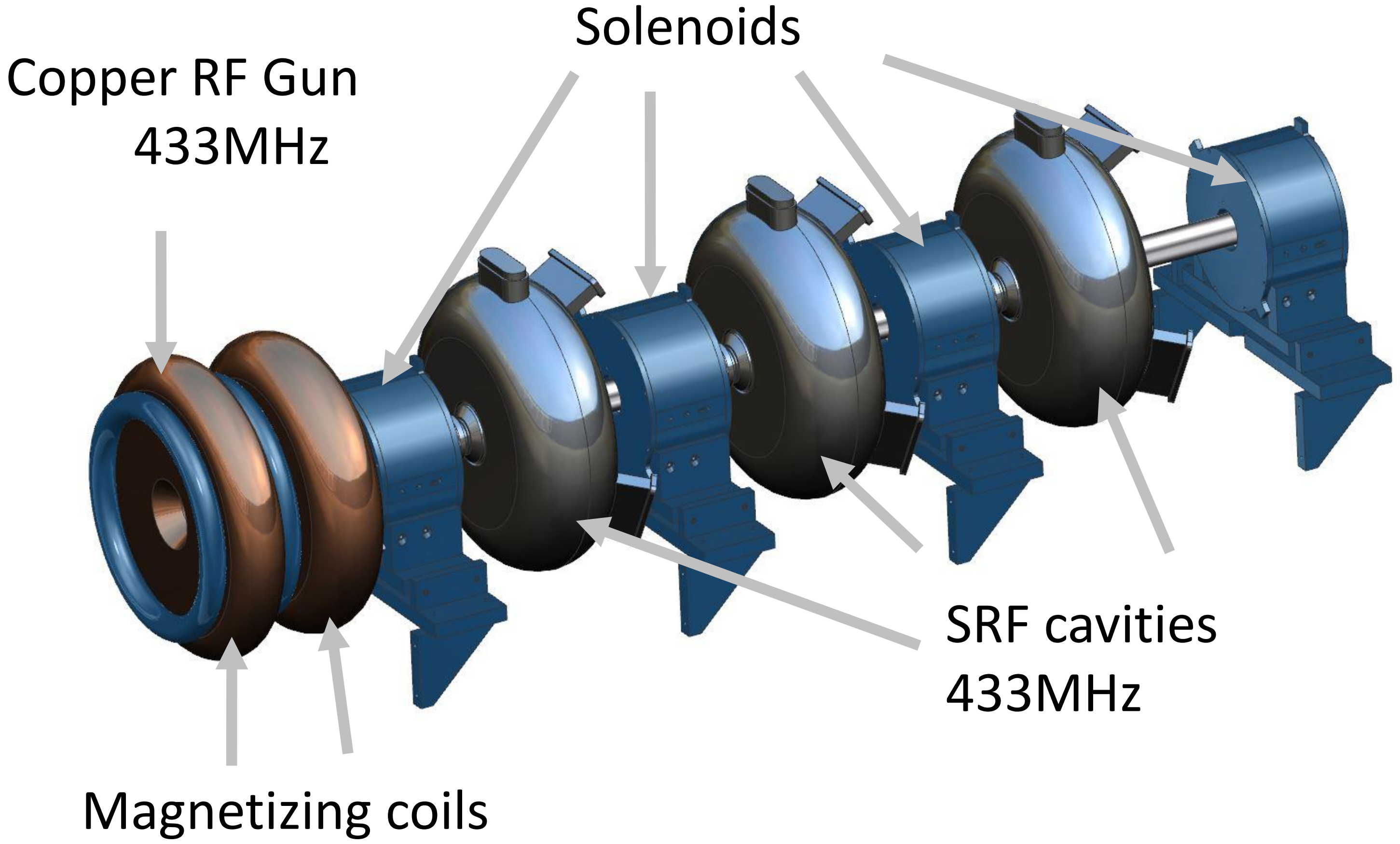


C. Marshall, *Design and Analysis of a Halo-Measurement Diagnostics,* NAPAC2019

Cooler Hardware

Injector and Linac Development

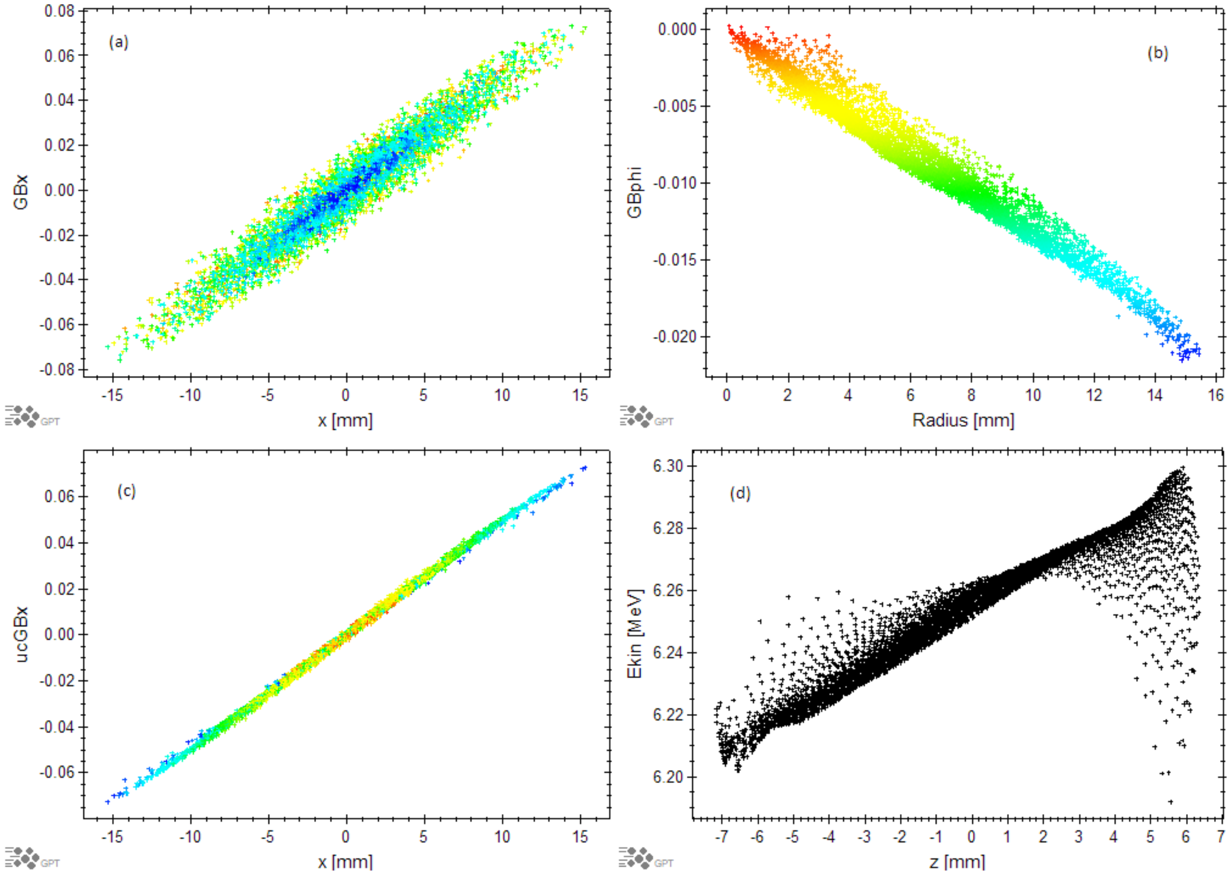
- Currently uses NCRF photocathode gun based on the Boeing injector.
- The SRF booster will have three single cell cavities followed by a 3rd harmonic linearizer.
- Optimization in progress



Injector Optimization

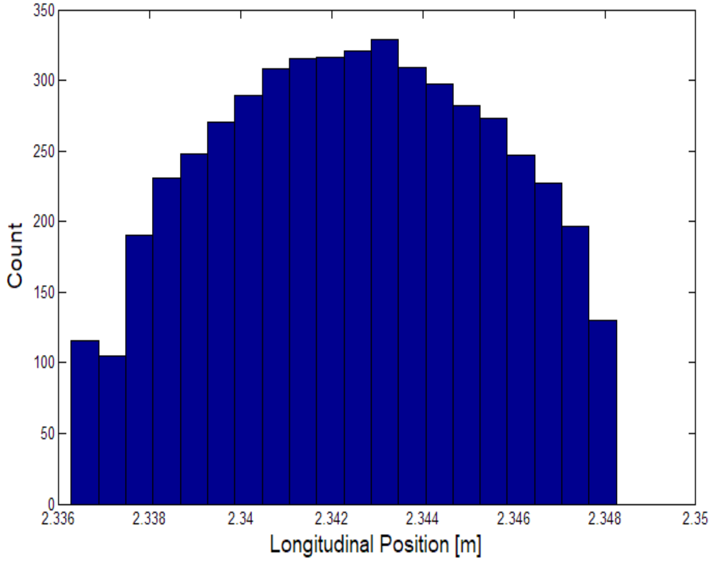
Effective emittance (mag + thermal)

Radius vs. p_phi indicated how good magnetization is – need straight line

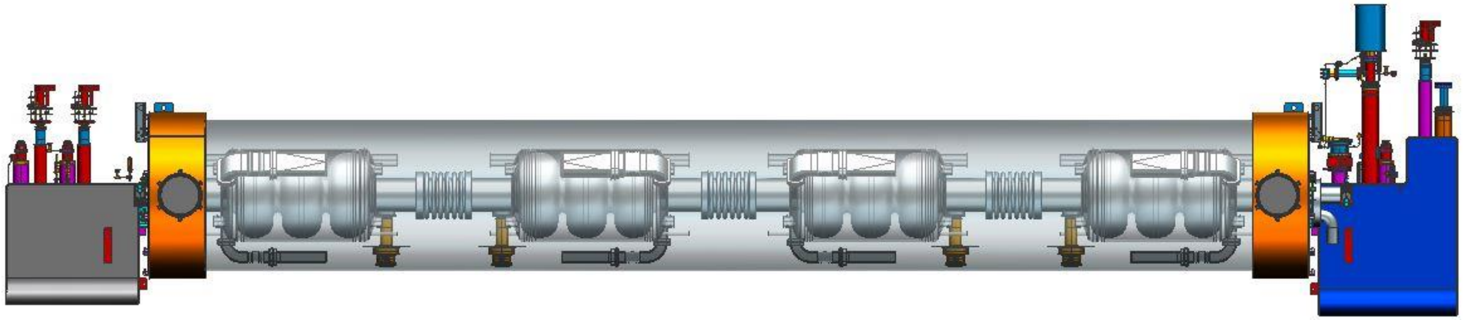


Longitudinal profile – not uniform.

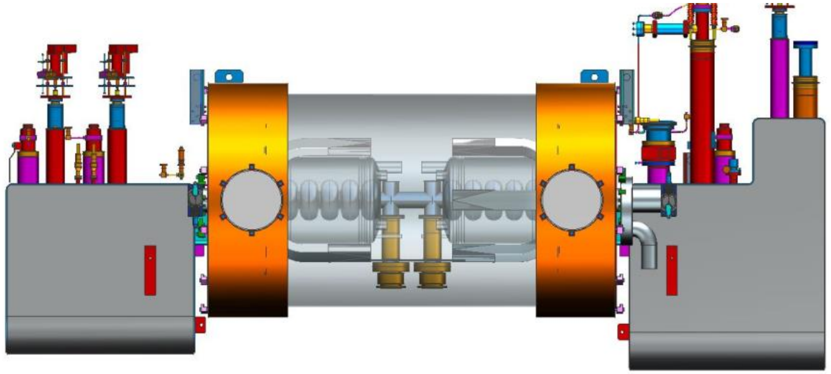
There is a trade off with magnetization and uniformity

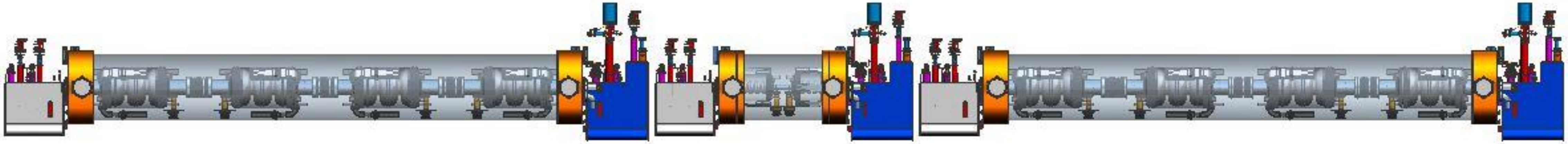


Linac Cryomodule Design



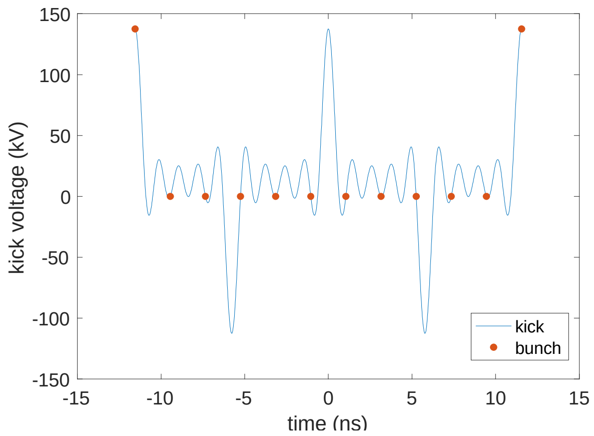
Two 5-cell 1428.9 MHz Cavities

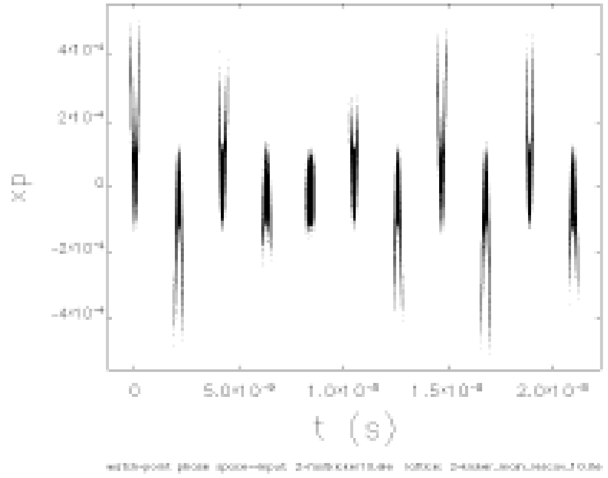




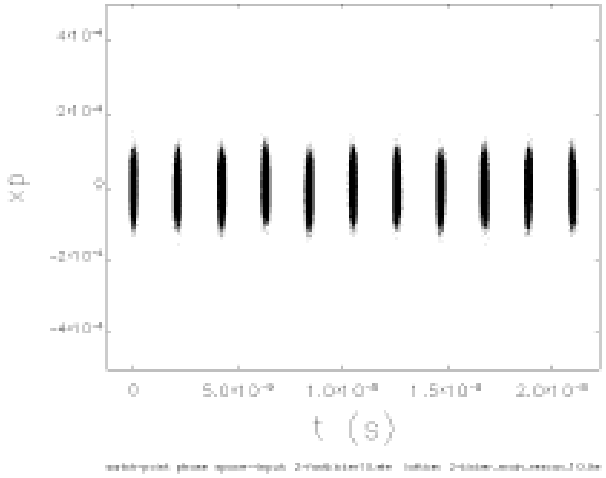
Harmonic Kicker Design

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.

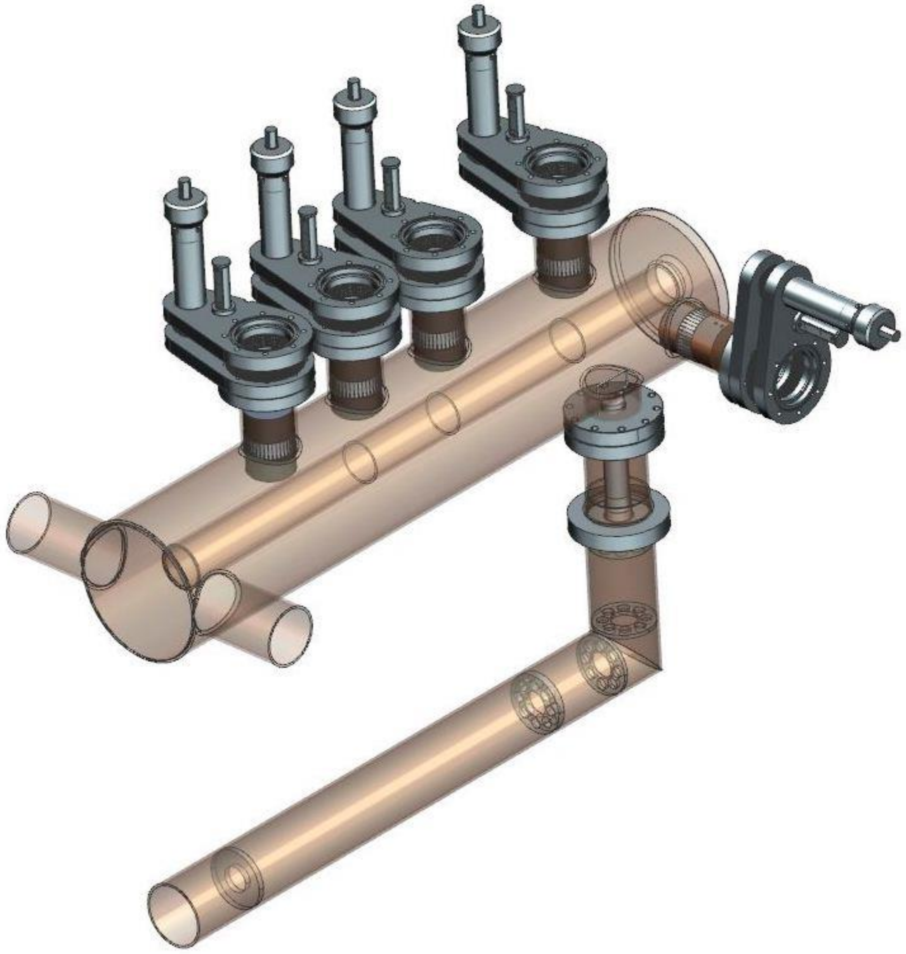




(a) Harmonic kicker only (without pre-kicker).



(b) With pre-kicker.



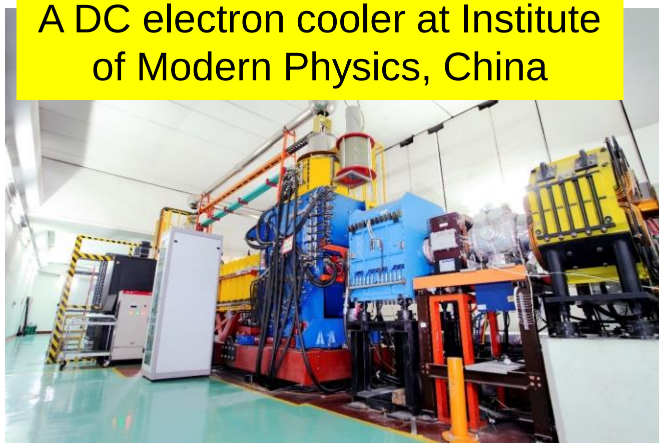
Bunched Beam Cooling Experiments

Bunched Beam Cooling Experiment

JLab-IMP Collaboration

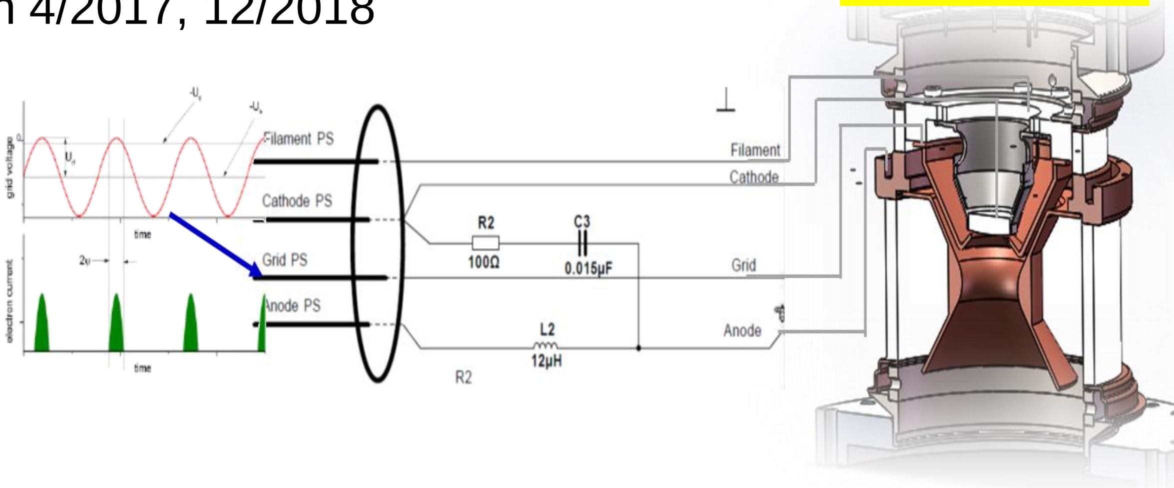
- Using a DC cooler to demonstrate cooling by a bunched electron beam
- Pulsed electron beam from a thermionic gun by switching on/off the grid electrode
- 1st Experiments performed on 4/2016, follow-up experiment on 4/2017, 12/2018

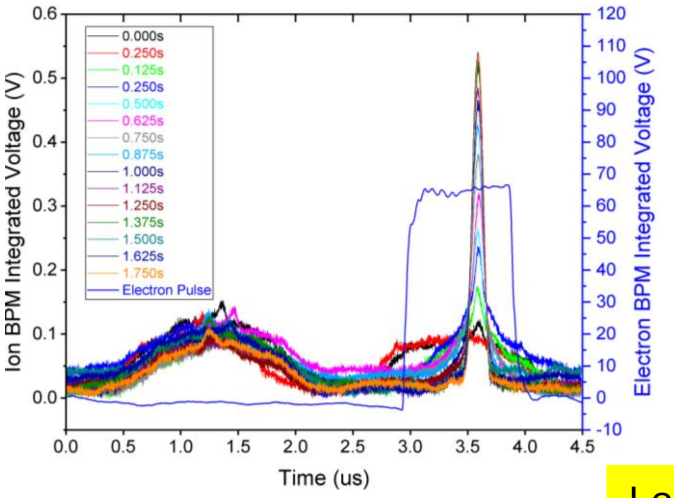
A DC electron cooler at Institute of Modern Physics, China

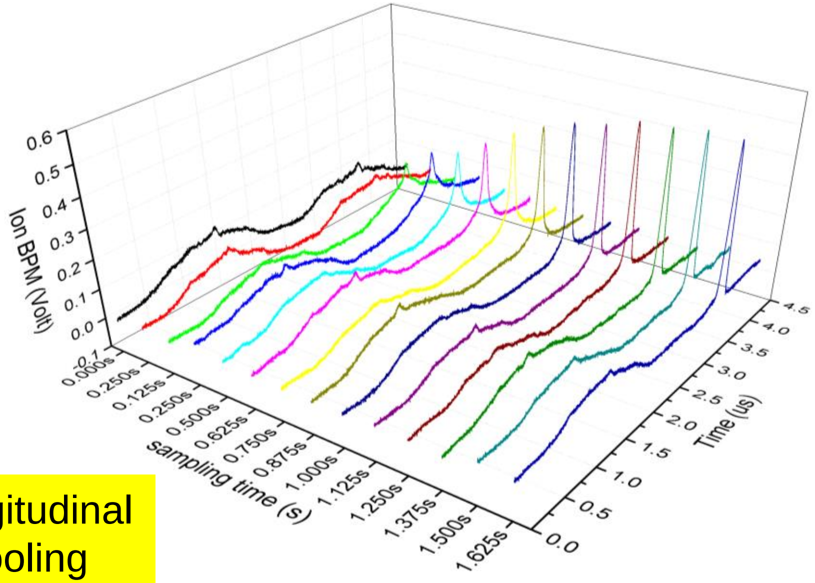


Ion	$^{86}Kr^{25+}$
Energy (i/e)	5 MeV/u & 2.7 KeV
Ion bunches	2
RF voltage	600 V
Stored ions	~10^8
Anode voltage	400 V, 600 V, 800 V
Pulse width	300 ns to 1200 ns

thermionic gun

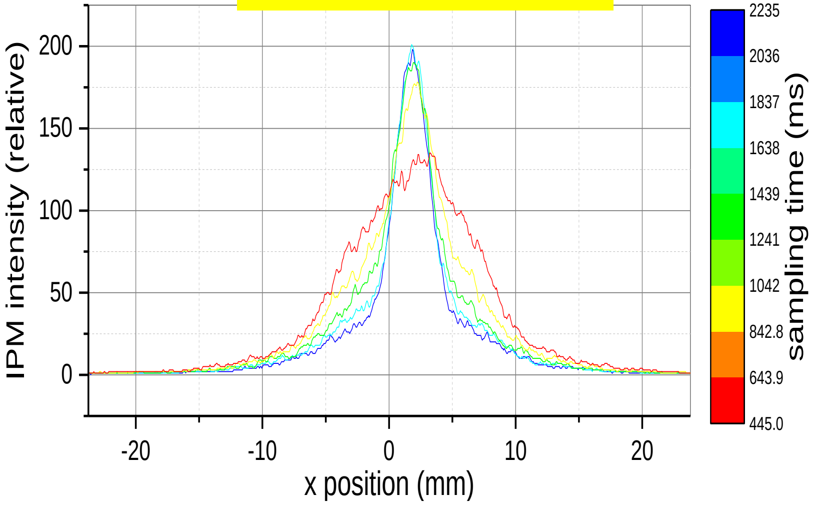






Longitudinal cooling

Transverse cooling



Possible 5.5 MeV DC Cooler Design

- Why 4.3 MeV? Already demonstrated by Fermilab, but can be increased
- New power conversion concept is needed anyway
- Try to design for 5.5 MeV (10 GeV protons). Numbers are preliminary estimates

	4.3 MeV	5.5 MeV
Length of acc. section (m)	5.0	6.5
Tank height (m)	7.5	9.0
Total height above toroid (m)	8.5	10.0
Tank diameter (m)	4.5	5.0
Coil power in tank (kW)	21	28
Collector power (kW)	10	10
Extra misc power (kW)	1	1
Net total power in tank (kW)	32	39

Summary

Many different threads to the research:

✓ **Cooling Simulations**
- ➢ Good advances in both capability and usability.
- ➢ Starting to get benchmark data from LEREC and IMP

✓ **Storage Ring Coolers**
- ➢ Still early in the design but making good progress
- ➢ Dynamic aperture is a big challenge due to wigglers.
- ➢ Two-energy solution may be able to avoid wiggler damping.

✓ **Magnetized beam transport**
- ➢ FAST gun can easily produce 3.2 nC of charge.
- ➢ Good agreement between simulations and experiment
- ➢ Halo work slow due to FAST schedule changes
- ➢ Might be able to do RF merge at AWA?

○ **Cooler Hardware**
- ➢ Low frequency design mostly done
- ➢ Harmonic kicker is being fabricated

○ **Bunch beam cooling experiment**
- ➢ Do see good evidence of transverse and longitudinal cooling.
- ➢ Travel difficulties have forced a change of the SOW.
- ➢ Exploring some new ideas for the low energy ring and DC cooler.

Thank You

Cooling Code Development

Features of Jlab Simulation Package for Electron Cooling (JSPEC)

- Developed at JLab for JLEIC cooling design.
- Models the ion beam w.r.t. the macro-parameters: emittances, momentum spread, bunch length. Various models available for different ion beam shapes and particle distributions.
- Calculates the IBS rate and electron cooling rate.
- Simulates the ion beam evolution under the IBS effect and/or electron cooling by RMS model, particle model.
- Written by C++ for high efficiency.
- Open source. Codes and documents available on github repository.
- Online version available through SIREPO by Radiasoft.