Perspective of a Dual Energy Storage Ring Cooler for Hadron Beam Cooling *

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Outline

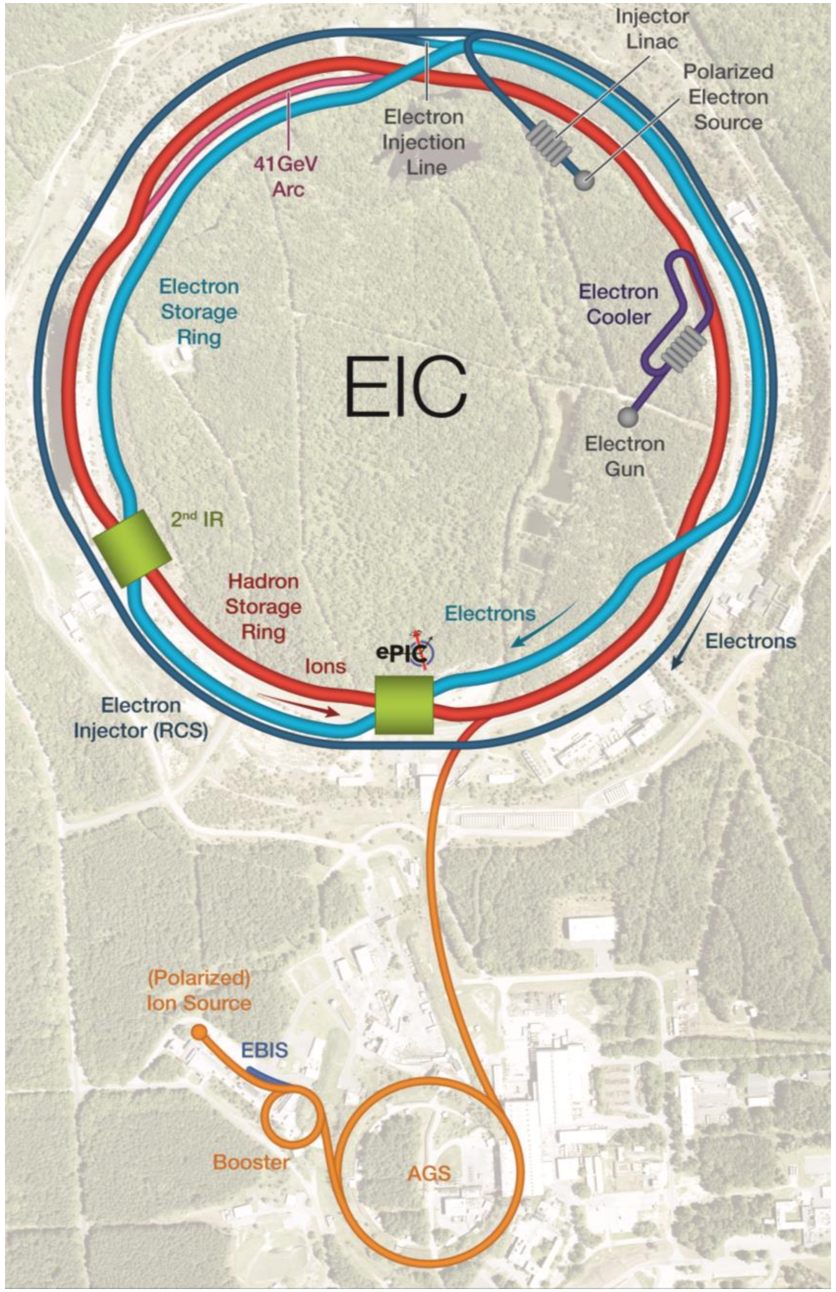
- Introduction and Motivation
- A dual energy electron storage ring cooler
  - Concept
  - Design
  - Beam dynamics
  - Cooling performance
- Summary

US EIC for QCD Frontier

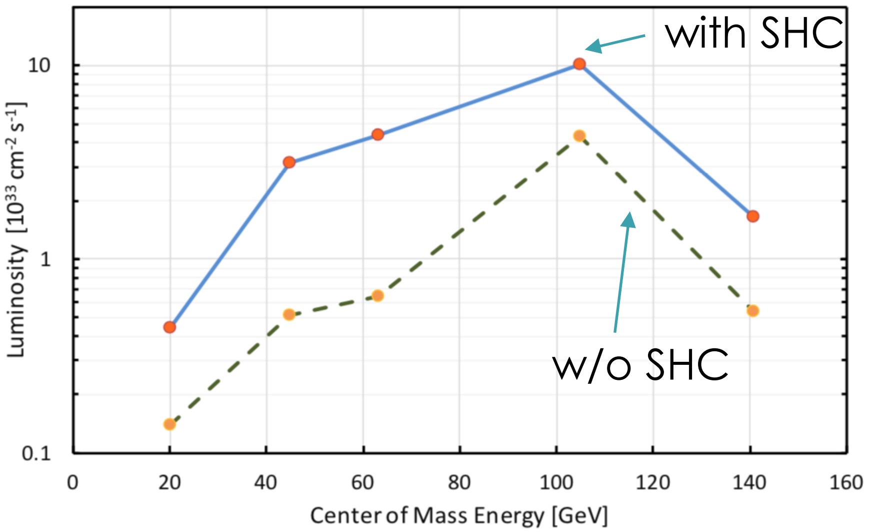
Electron Ion Collider (EIC) will be built at BNL, based on the existing RHIC, Jefferson Lab is a partner lab

- **Goals**
  - High luminosity: $L=(0.1\text{-}1)\times10^{34}\ cm^{-2}s^{-1}$ ➔ 10-100 fb^{-1} integrated luminosity
  - Collisions of highly polarized +/-70% e, p and light ion beams with flexible spin patterns
  - Large ranges of center of mass energies: E_{cm}=(20-140) GeV and ion species: protons–Uranium
  - Ensure accommodation of two IRs
  - Large detector acceptance and good background conditions
- **Hadron storage ring 40-275 GeV** (existing)
  - 1160 bunches, large beam current (up to 1 A) , **strong hadron cooling (coherent electron cooling)**
- **Electron storage ring (2.5–18 GeV** (new))
  - 1160 bunches, large beam current (up to 2.5 A) ➔ maximum 10 MW S.R. power, SRF cavities
- **Electron rapid cycling synchrotron** (new)
  - 2x28 nC bunches, 1 Hz cycle time, spin transparent for high polarization
- **High luminosity interaction region(s)** (new)
  - $L = 10^{34} cm^{-2}s^{-1}$ with superconducting magnets
  - 25 mrad crossing angle for the primary detector with crab cavities
  - Spin rotators (longitudinal electron spin)
  - Forward hadron instrumentation for tagging

EIC design report



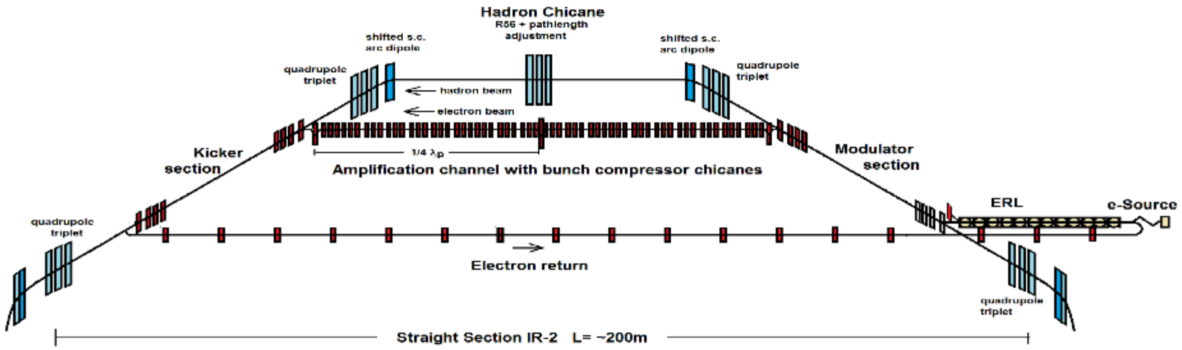
High Luminosity EIC through Strong Hadron Cooling



For 104.9 GeV CM energy		Proton	Electron
Energy	GeV	275	10
Bunch current / intensity	A / 10^{10}	1 / 6.9	2.5 / 17.2
RMS norm. emit. h / v	μm	3.3 / 0.3	391 / 26
RMS bunch length	cm	6	0.7
RMS long. emittance	eV.s	0.036	-
IBS growth time long. / h	h	**2.9 / 2**	-
Beta functions at IP	cm	80 / 7.2	45 / 5.6
Luminosity per IP	cm^{-2}sec^{-1}	1 x 10^{34}	

- **Unprecedented colliding proton/ion beams**: many bunches, large beam currents, small transverse emittance, flat beam, short bunches, and large beam-beam parameters
- **Particularly, short longitudinal and transverse IBS time ➔** unacceptable emittance growth over one typical beam store time (>8 hours) ➔ significant decay of instant luminosity
- **Strong cooling of hadron beam** is required to mitigate IBS and other effects to **reduce emittance (cooling before collision)** and to **preserve emittance (continuous cooling during collision)**

EIC design report



EIC baseline: bunched electron cooling after injection + ERL based Coherent Electron Cooling with micro-bunching amplification at collision energies

- Design cooling rate R_{cool}= 1-2 h^{-1}
- Electron beam current I_e~100 mA (~1 nC/bunch)
- Electron beam emittance $\epsilon_{x,y}^{N}$= 2.5/0.5 mm mrad

COOL'23, F. Lin

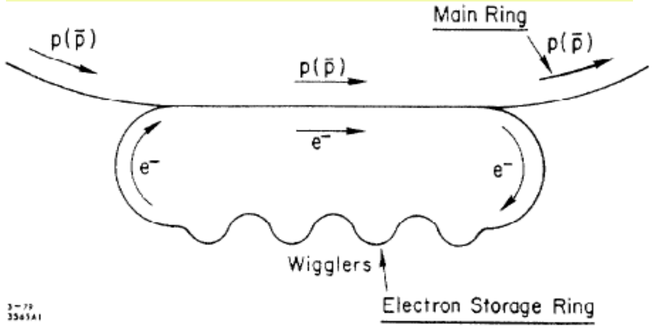
Other Alternatives ?

- Must work with an intense bunched proton beam in the EIC: 10 to 30 nC per bunch up to1 Ampere average current
- This presentation describes one possible alternative cooling scheme: a **dual energy electron storage ring cooler**
  - Focusing on discussion of design, beam dynamics and cooling performance

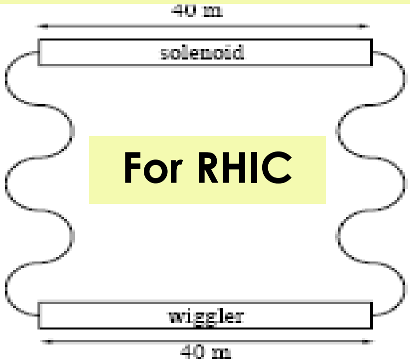
Electron Storage Ring Based Cooler

- Electron storage ring has been considered as a cooler since the late 1970s. However, none has been built up to now.

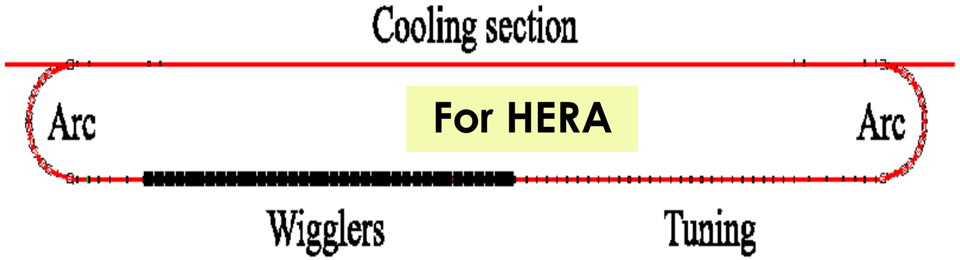
D. Cline, et. al., SLAC-PUB-2278, Mar 1979

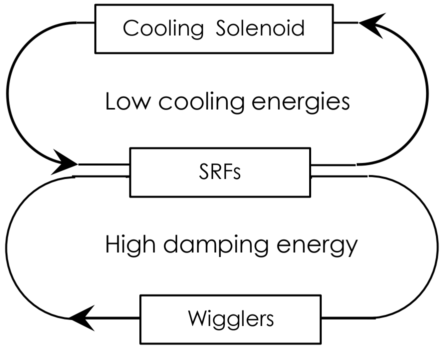


A. Burov, S. Derbenev, et. al., FERMILAB-TM-2058, 1998

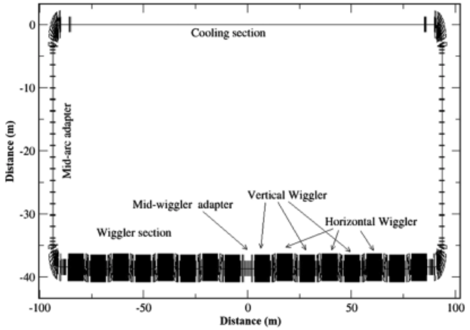


M. Gentner, S. Derbenev, et. al., Nuc. Inst. Meth. Res. A, 424, 277-295, 1999





F. Lin, et. al, IPAC2016, Busan, Korea (2016)



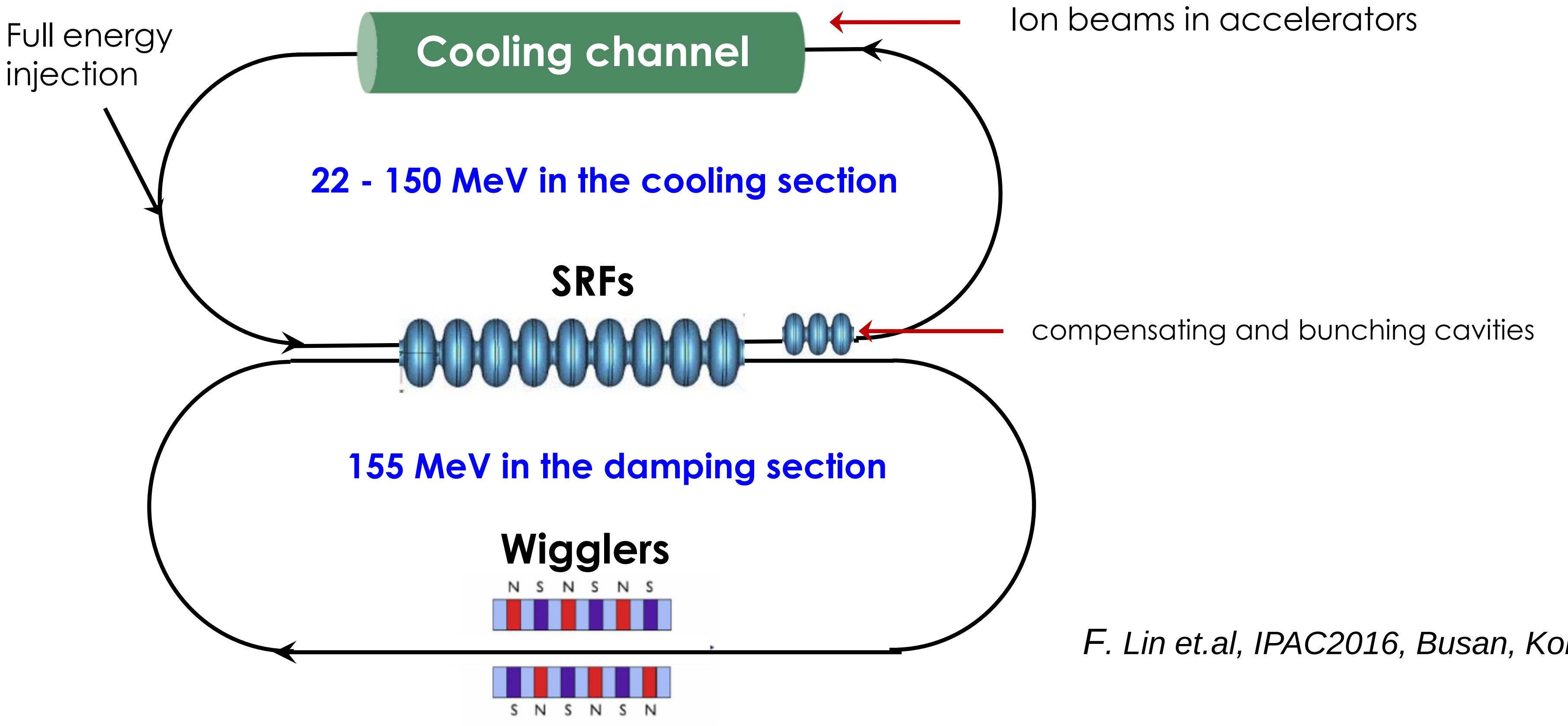
H. Zhao, et. al, PRAB 24, 043501 (2021)

Requirements

- EIC proton beam energy: 41 – 275 GeV
- Required cooling electron beam energy: 22 – 150 MeV
  - Typical electron IBS effect is very strong -> very short IBS times ~ tens of milli-seconds
  - Typical synchrotron radiation damping is very weak -> long damping time, seconds up to minutes
  - Unbalanced IBS and radiation damping can be mitigated through higher electron energies and/or damping wigglers
  - Beam-beam scattering effect from ion beams can be problematic with certain beam parameters

Concept of a **Dual Energy** Storage Ring Cooler

Solve the ion cooling and the heat removal (radiation) problems separately

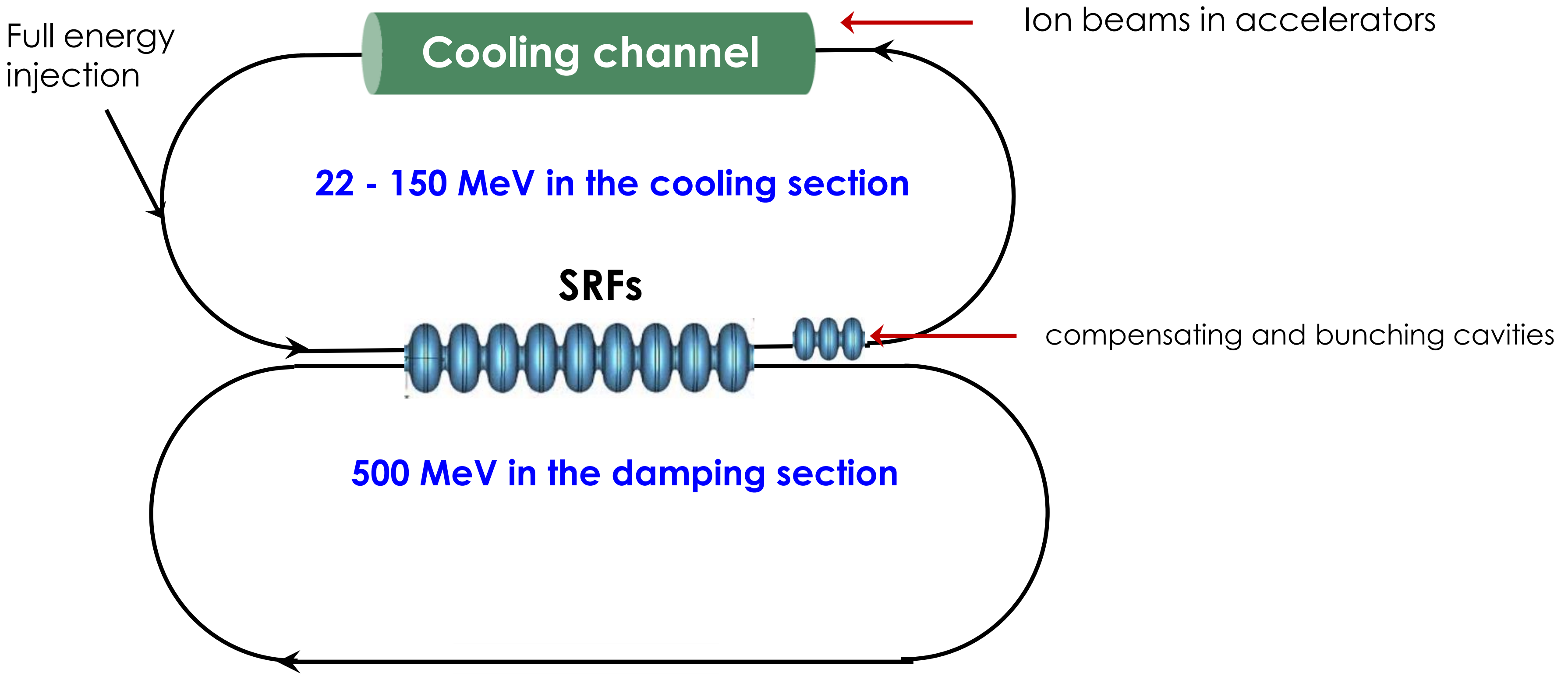


F. Lin et.al, IPAC2016, Busan, Korea

Original Idea: use wigglers in the damping ring to enhance the damping

Concept of a **Dual Energy** Storage Ring Cooler

Solve the ion cooling and the heat removal (radiation) problems separately



Explored Idea: increase the beam energy in the damping ring to enhance the damping

Comments on this Concept

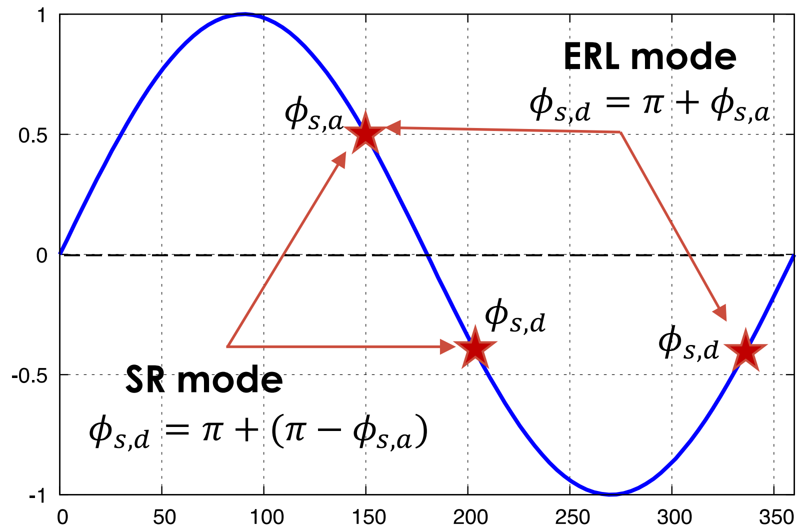
- The essential of this concept is "**dual energy**": lower energy cooling section and higher energy damping section
- The technical approaches can be different in details. For example:
  - Cooling section
    - Magnetized cooling
    - Non-magnetized cooling
  - Energy exchange between the two sections with SRF cavities
    - Conventional single axis ERL SRF cavities
    - Twin axes cavities
  - Damping mechanisms
    - Wigglers
    - High energy
    - Combination of wigglers and high energy

Study of the Dual Energy Storage Ring Cooler

- With the following assumptions in the design
  - Magnetized cooling
  - High energy in the damping section, without wigglers
- These assumptions were optimal for the proton beam parameters we were considering. They were chosen after carefully considering various potential cooling scenarios.

Longitudinal Stable Modes

- Storage Ring (SR) mode: longitudinal focusing on both accelerating and decelerating passes
- ERL mode: net focusing (like alternate phase focusing(APF)), i.e., longitudinal focusing occurs in one of accelerating and decelerating passes, while the other is defocusing
- Linear transfer matrix for $(\Delta\phi, \Delta E)$:



$$M = \begin{pmatrix} 1 & h_L/E_L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ V\cos\phi_{s,d} & 1 \end{pmatrix} \begin{pmatrix} 1 & h_H/E_H \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ V\cos\phi_{s,a} & 1 \end{pmatrix}$$

$$\Rightarrow \begin{cases} Q_{SR} = \frac{1}{2\pi}\sqrt{2\left(h_L V \frac{-\cos\phi_{s,a}}{E_L} + h_H V \frac{-\cos\phi_{s,a}}{E_H}\right)} \\ Q_{ERL} = \sqrt{h_L h_H \frac{V^2 \cos^2 \Phi_{s,a}}{E_L E_H}} \end{cases}$$

Here $h_{L,H} = \frac{2\pi f_0 L_{L,H} \eta_{L,H}}{\beta_H^3 c}$

	SR mode	ERL mode
Qs from formula	0.03448	0.001627
Qs from simulation	0.03415	0.001631
Difference in %	0.9	0.2

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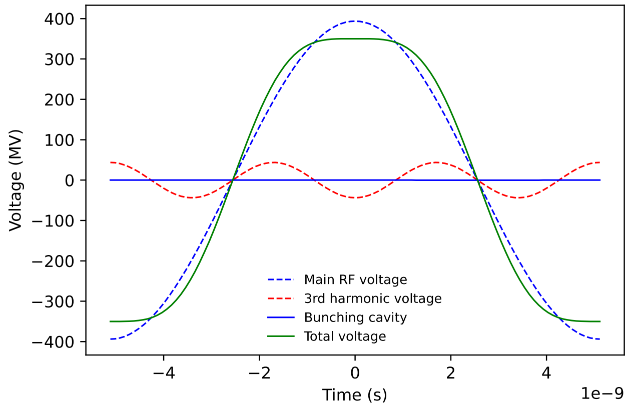
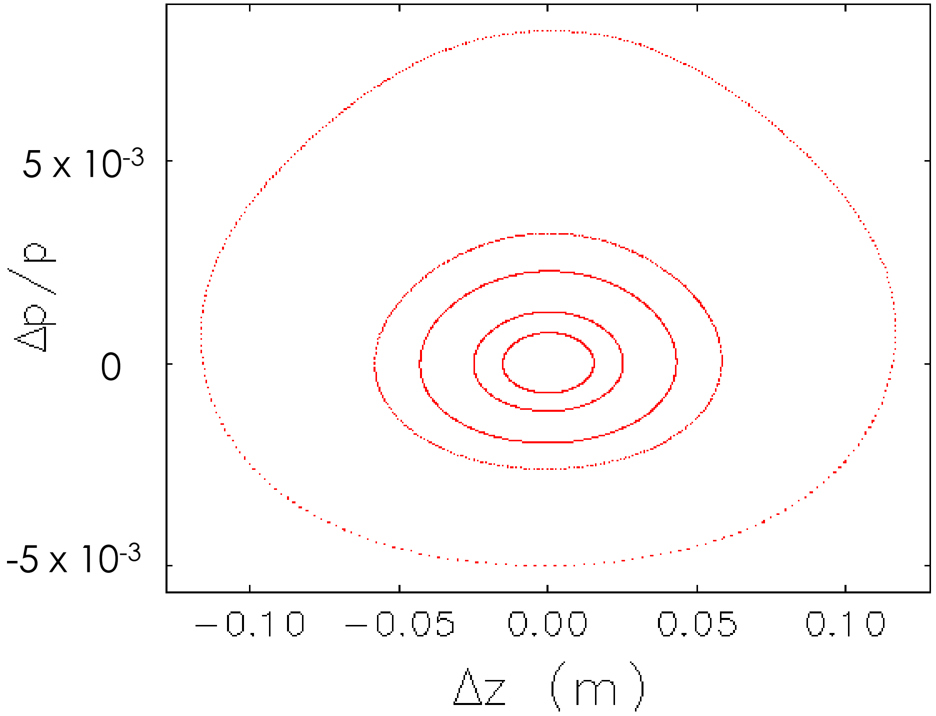
Longitudinal Phase Space w/ Main Cavity $f = 97.7$ MHz

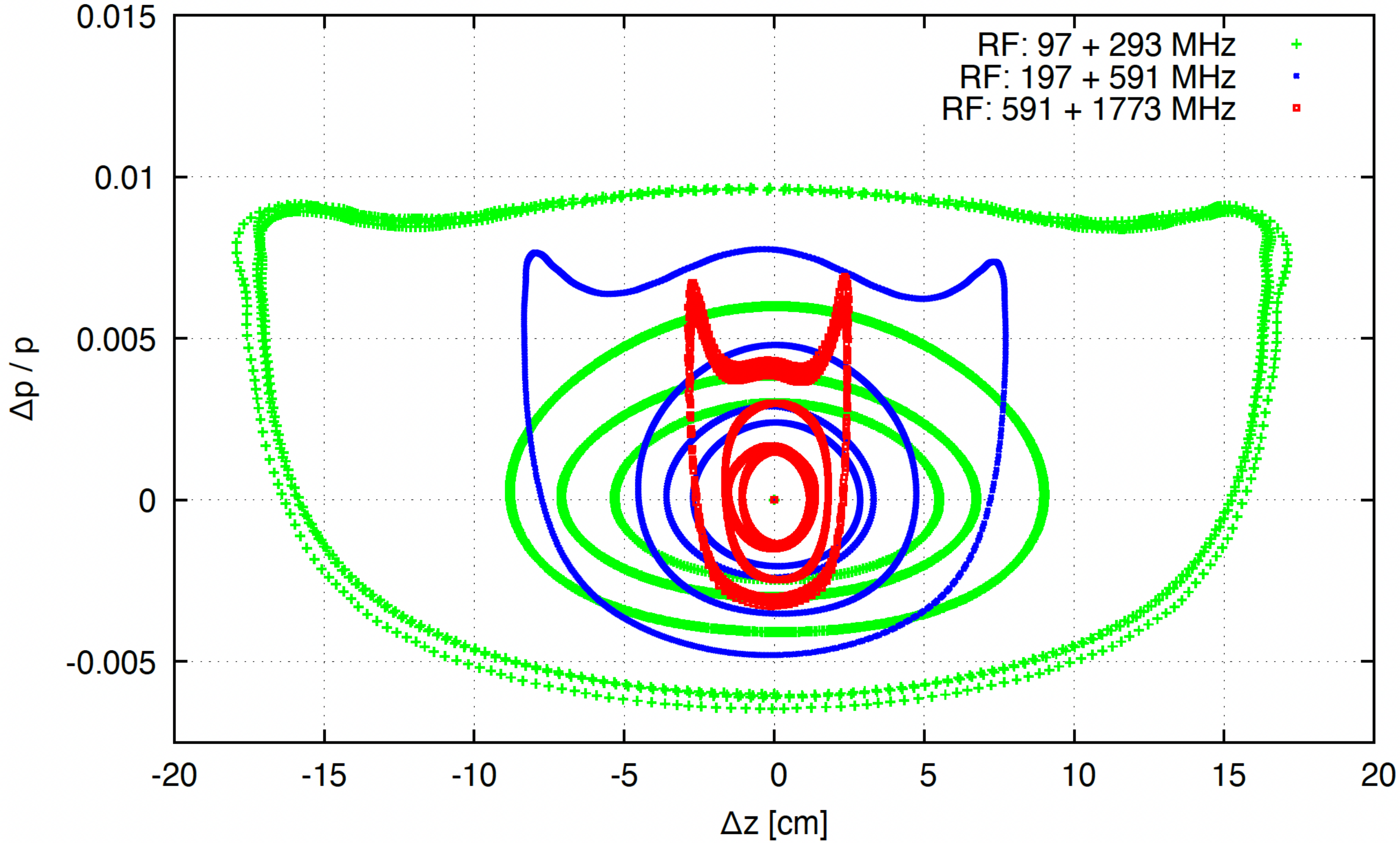
	f (MHz)	V (MV)	ϕ (degree)
Main cavity	97.7	393.75	90/270
Harmonic cavity	293.1	43.75	270/90
Compensating cavity	97.7	1.64×10^{-3}	90
Bunching cavity	97.7	80×10^{-6}	180





- Watching point is in the cooling session
- $\left(\frac{\Delta p}{p}\right)_{max} \sim 8\times10^{-3}$ and $z_{max} \sim 24\ cm$

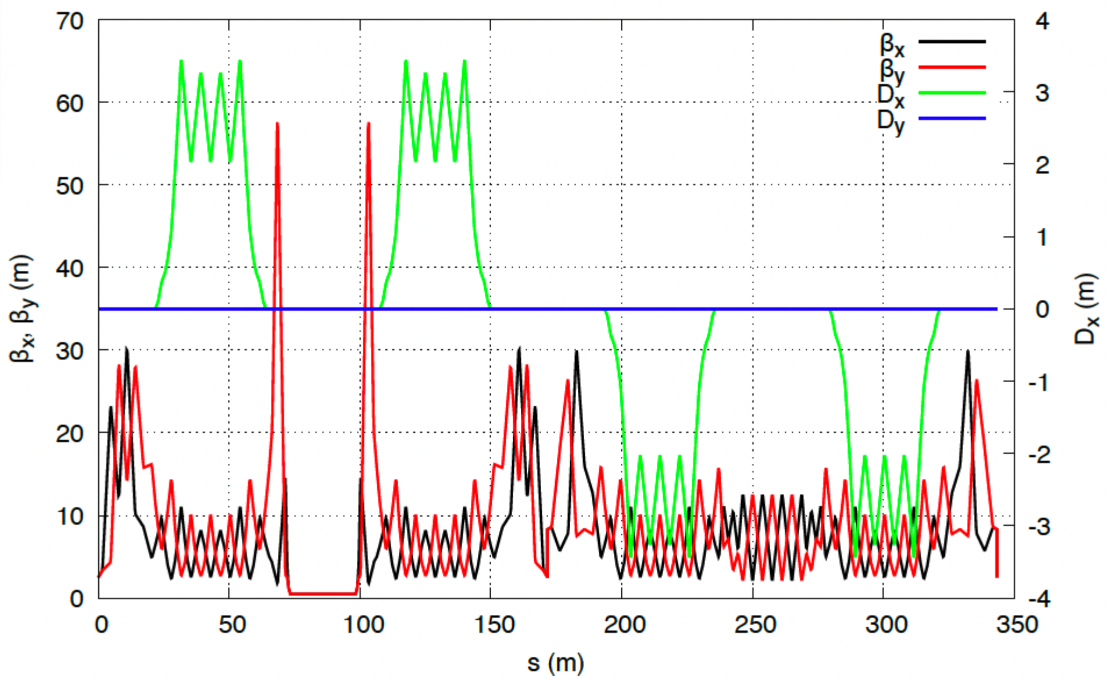
Longitudinal Phase Space w/ Various Main Cavity Frequencies



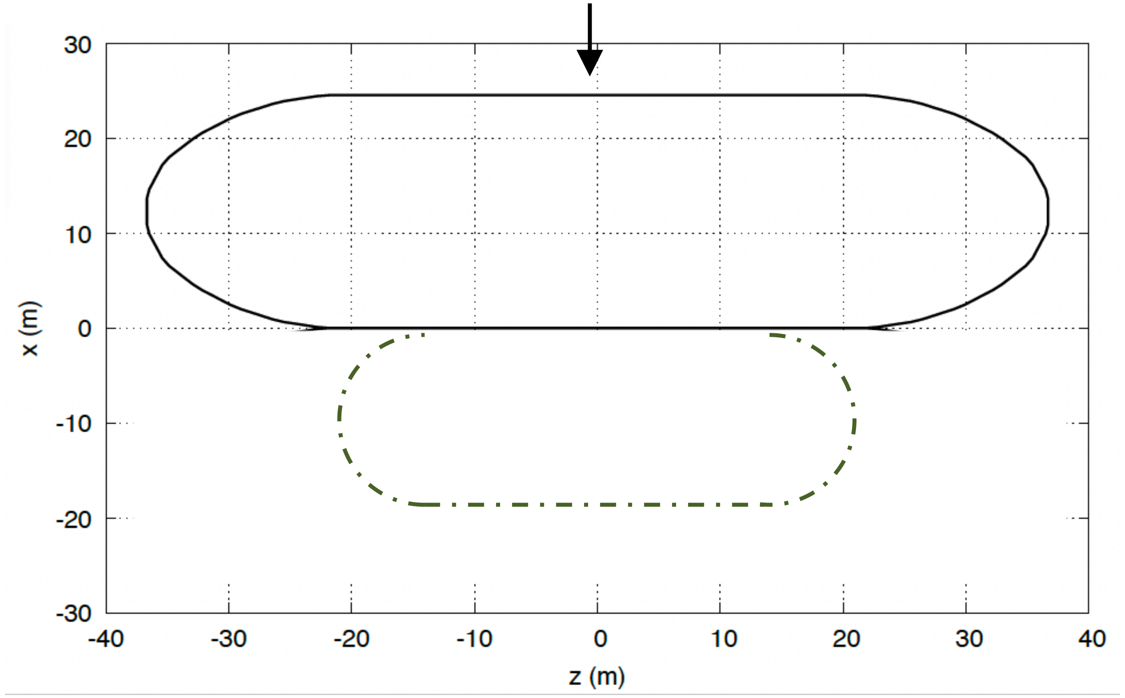
The lower RF frequency, the larger longitudinal phase space volume => longer bunch length

* We note that the low frequency cavities will be costly to build, especially for cavities with frequency < 300 MHz.

Preliminary Lattice Design



The length of cooling section can be adjusted to meet the requirement.



- We realize that arcs with small M_{56}~71cm are preferred
- Two sections can be **vertically stacked** to reduce the footprint and don't have to be the same sizes

Electron Equilibrium Emittance and Energy Spread

$$\epsilon_x = \frac{C_q}{\hat{\gamma}} \frac{\left(\gamma_H^6 \left\langle \frac{\mathcal{H}_x^H}{\rho_H^3} \right\rangle + \gamma_L^6 \left\langle \frac{\mathcal{H}_x^L}{\rho_L^3} \right\rangle\right)}{\left[\left((1-\xi_x^H)\gamma_H^3 \left\langle \frac{1}{\rho_H^2} \right\rangle + (1-\xi_x^L)\gamma_L^3 \left\langle \frac{1}{\rho_L^2} \right\rangle\right)\right]}$$

$$\frac{\sigma_E^2}{E^2} = \frac{C_q}{\hat{\gamma}^2} \frac{\left(\gamma_H^7 \left\langle \frac{1}{\rho_H^3} \right\rangle + \gamma_L^7 \left\langle \frac{1}{\rho_L^3} \right\rangle\right)}{\left[\left((2+\xi_H)\gamma_H^3 \left\langle \frac{1}{\rho_H^2} \right\rangle + (2+\xi_L)\gamma_L^3 \left\langle \frac{1}{\rho_L^2} \right\rangle\right)\right]}$$

Parameters	**Unit**	**High Energy Section**	**Low Energy Section**
Energy	MeV	**500**	**150**
Normalized horizontal emittance	μm	653	
Normalized vertical emittance	μm	31	
Un-normalized horizontal emittance	μm	0.64	2.12
Un-normalized vertical emittance	μm	0.032	0.106
Energy Spread	10^{-4}	2.2	7.4

Electron Damping Times and Inter Beam Scattering Times

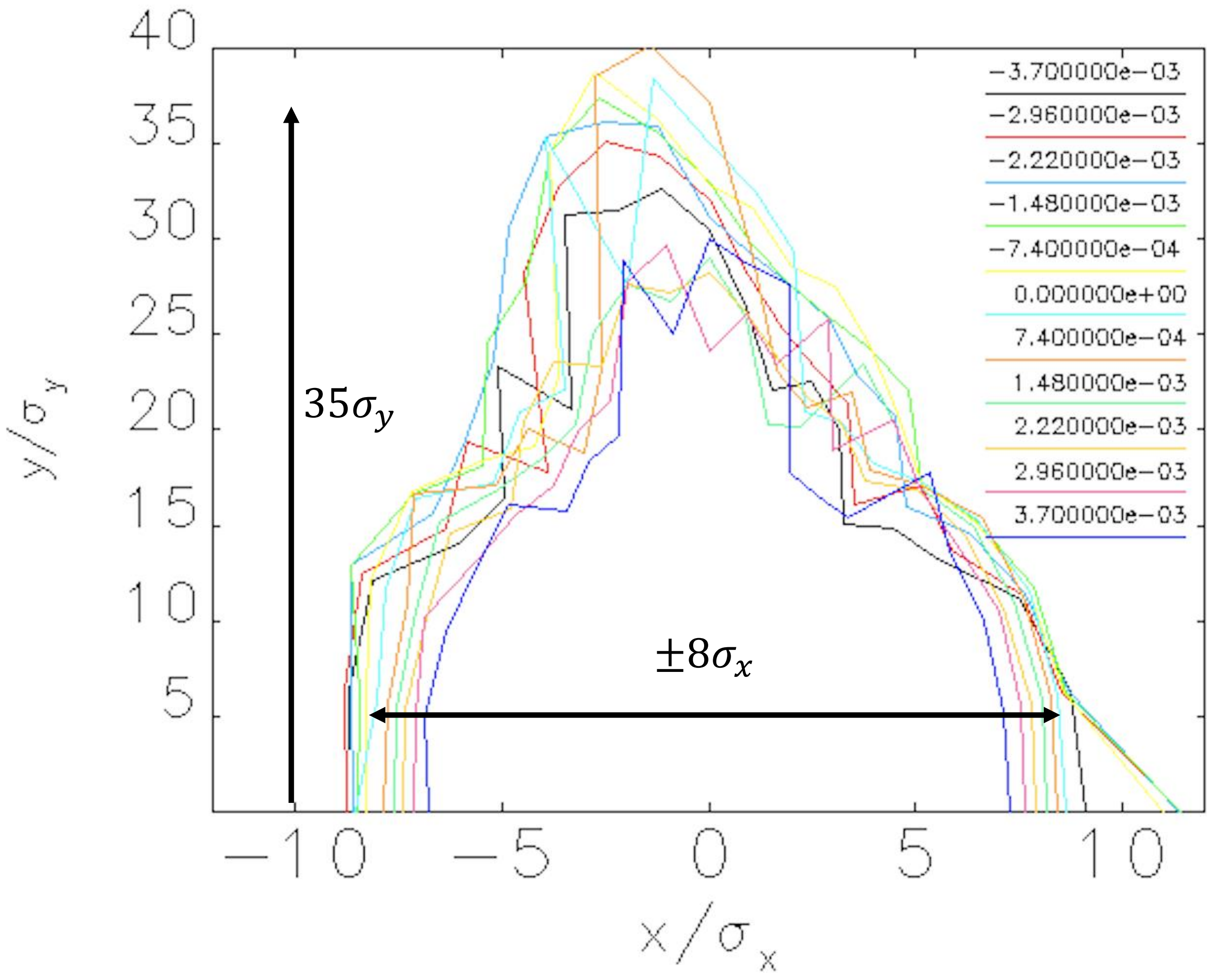
- Damping time(s): $$\frac{t_{rev,tot}}{\tau_{rad,tot}} = \frac{t_{rev,L}}{\tau_{rad,L}} + \frac{t_{rev,H}}{\tau_{rad,H}}$$
- IBS time(s)*: $$\frac{t_{rev,tot}}{\tau_{IBS,tot}} = \frac{t_{rev,L}}{\tau_{IBS,L}} + \frac{t_{rev,H}}{\tau_{IBS,H}}$$

* Used the code elegant, based on the Bjorken-Mtingwa formula

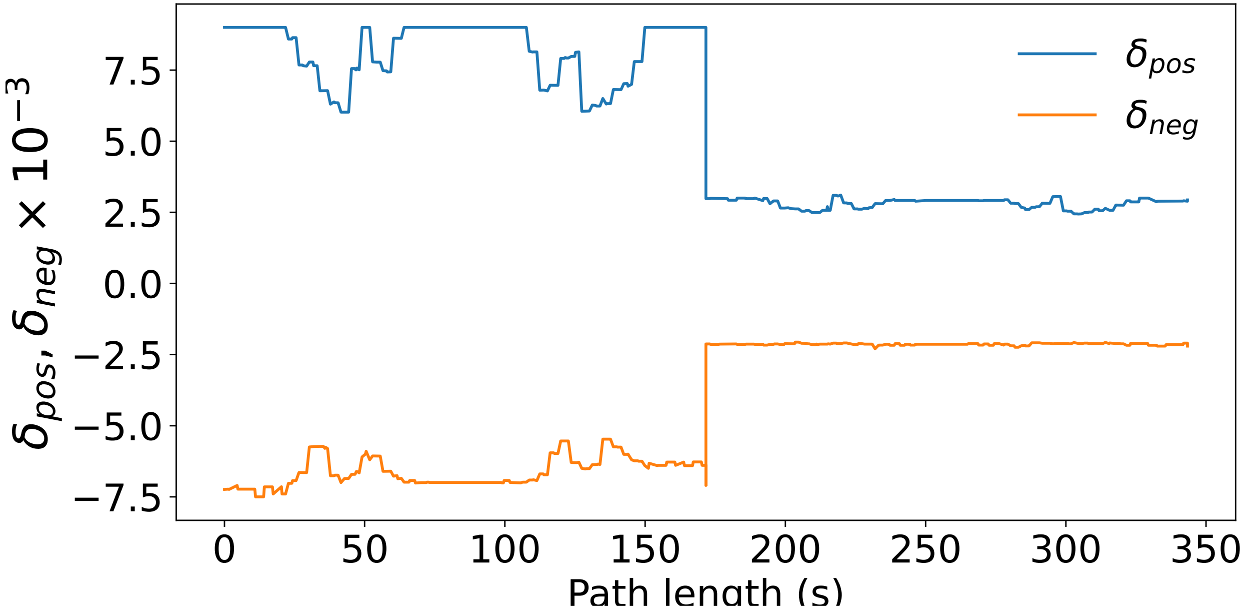
Parameters	**unit**	**Dual Energy Storage Ring Cooler (E_{high}=500 MeV, E_{low}=150MeV)**
Horizontal damping time vs. IBS time	s	3.20 vs. 5
Vertical damping time vs. IBS time	s	0.69 vs. 12328.33
Longitudinal damping time vs. IBS time	s	0.25 vs. 0.44

- The cooling electron beam has shorter damping times than IBS times

Dynamic Aperture (DA) in the Bare Lattice



Momentum Aperture (MA) and Touschek Lifetime



- High energy ring momentum acceptance is reduced by a factor of the energy ratio of low to high energy rings

	Touschek lifetime (h)		
	$\tau_{tous,L}$ @ 150MeV	$\tau_{tous,H}$ @ 500MeV	τ_{tous}
Elegant	0.67	0.31	0.42
Formula	0.68	0.23	0.34

$$\frac{1}{\tau} = \frac{r_e^2 cq}{8\pi e \gamma^3 \sigma_s} \cdot \frac{1}{C} \cdot \oint_C \frac{F\left(\left(\delta_{acc}(s) / \gamma\sigma_{x'}(s)\right)^2\right)}{\sigma_x(s)\sigma_z(s)\sigma_{x'}(s)\delta_{acc}^2(s)} ds$$

$$F(x) = \int_0^1 \left(\tfrac{1}{u} - \tfrac{1}{2}\ln\tfrac{1}{u} - 1\right) \cdot e^{-x/u} du$$

Space Charge Effect

$$\Delta\nu_{u,sc,coh} \approx -\frac{r_e}{2\pi\beta_L\gamma_L^2}\cdot\frac{N_b}{\sqrt{2\pi}\sigma_{Lz}}\cdot\frac{C/2}{\varepsilon_y^N(1+\sqrt{\varepsilon_x/\varepsilon_y})} - \frac{r_e}{2\pi\beta_H\gamma_H^2}\cdot\frac{N_b}{\sqrt{2\pi}\sigma_{Hz}}\cdot\frac{C/2}{\varepsilon_y^N(1+\sqrt{\varepsilon_x/\varepsilon_y})}$$

For cooling 275 GeV protons (Low energy / High energy columns 1–2); For cooling 100 GeV protons (Low energy / High energy columns 3–4)

	Low energy	High energy	Low energy	High energy
energy (MeV)	150	500	55	500
beta	0.999994179	0.999999478	0.999956839	0.999999478
gamma	293	978	108	978
circumference (m)	171.7			
r_e (m)	2.82e-15			
N_b	6.90E+10			
rms bunch length (cm)	2.5			
normalized horizontal emittance (um)	653			
normalized vertical emittance (um)	31			
epsilon_x/epsilon_y	18			
Laslett tune shift (separate rings)	0.00562	0.000504	0.0417	0.000504
Laslett tune shift (whole ring)		0.00612		0.0422

Space-charge induced Laslett tune shift of the electron beam is acceptable for cooling the ion beam with energies of 100 and 275 GeV

Electron Parameters for Cooling

Cooling Electron Energy	MeV	150	55
Bunch intensity	10^{10}	6.9	
Bunch charge	nC	11.1	
Peak bunch current	A	52.9	
Average bunch current	A	1.08	
RMS bunch length	cm	2.5	
Natural chromaticity h/v		-16.17 / -24.70	-16.21 / -24.82
Corrected chromaticity h/v		1.0 / 0.87	
Normalized emittance h/v	μm	653 / 31	
RMS beam size h/v @ cooler	mm	0.74 / 0.16	1.22 / 0.26
RMS angle spread @ cooler	μrad	608	1655
Energy spread @ cooler	10^{-4}	7.4	20.2
Space Charge tune shift		0.00612	0.0422
Electron IBS time (h/v/l)	s	**5 / 12328 / 0.44**	**4.4 / 703 / 0.44**
Electron BBS time* (h/v/l)	s	**- 3.56e6 / 6.44e6 / 2.59**	**- 1.14e6 / 1.91e6 / 6.08**
SR damping time (h/v/l)	s	**3.2 / 0.69 / 0.25**	

* BBS: Beam-beam scattering from ion beams, calculated using the code *getrad7* developed by H. Zhao

Cooling Performance

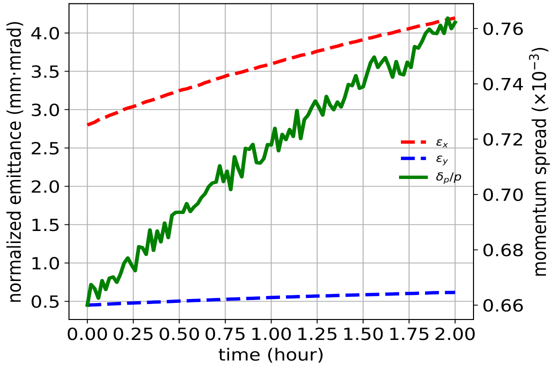
Calculated using the code JSPEC, H. Zhang

	Unit	Protons	
Ion Energy	GeV	275	100
Bunch intensity	10^{10}	6.9	
Bunch charge	nC	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**
Horizontal dispersion	m	**2**	**1.6**
Transverse coupling	%	**20**	**10**
Cooling channel	m	**120***	
Force Formula		Parkhomchuk	
Cooling solenoid	kG	**40**	
		When electron intensity 6.9x10^{10}	
Proton IBS time (h/v/l)	h	2.67/3.82/4.42	**3.09/1.59/3.03**
Cooling time (h/v/l)	h	8.16/13.97/15.76	**2.26/1.43/2.48**
		When electron intensity 6.9**x6**x10^{10}	
Proton IBS time (h/v/l)	h	**2.67/3.82/4.42**	3.09/1.59/3.03
Cooling time (h/v/l)	h	**2.27/3.38/4.22**	0.60/0.37/0.64

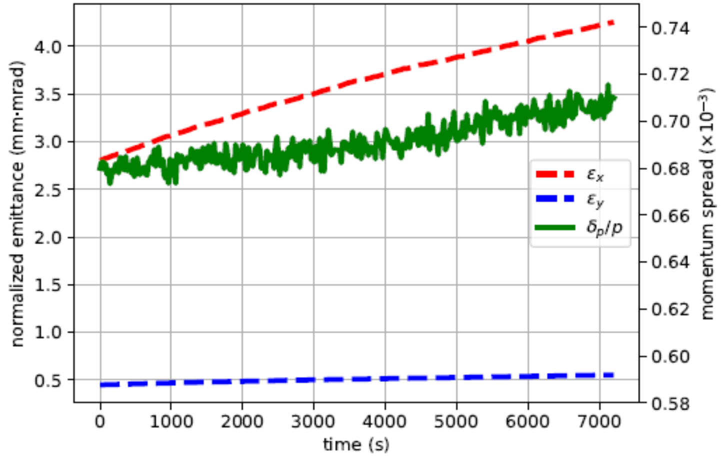
* Notice that the length of cooling channel 120 m available in the EIC

Cooling Performances for Protons @ 275 GeV

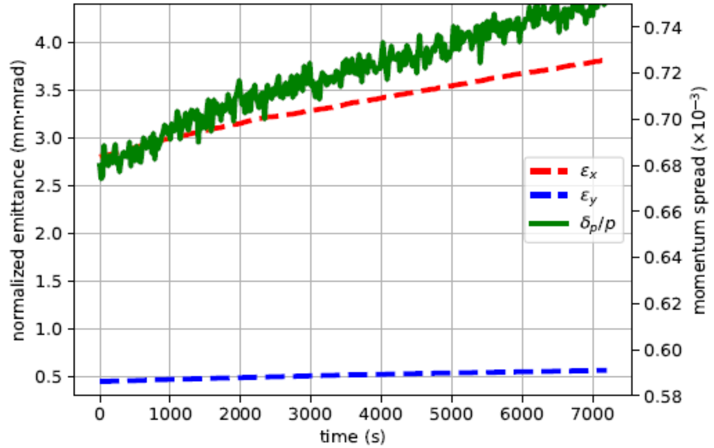
No cooling



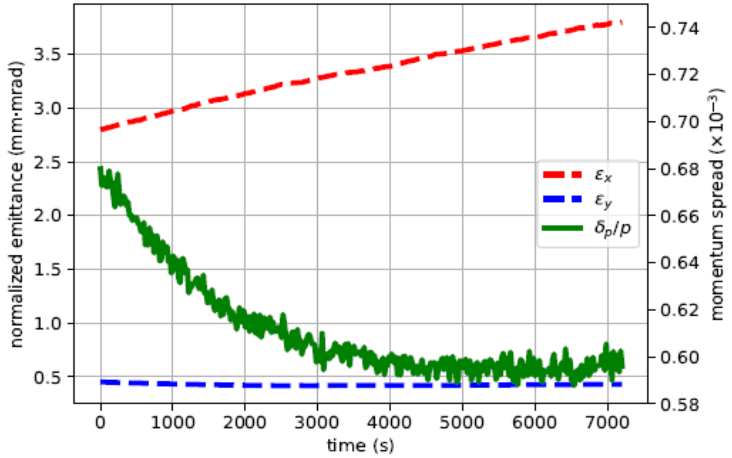
Electron intensity 6.9E10, Proton $D_{x,y}$ =0



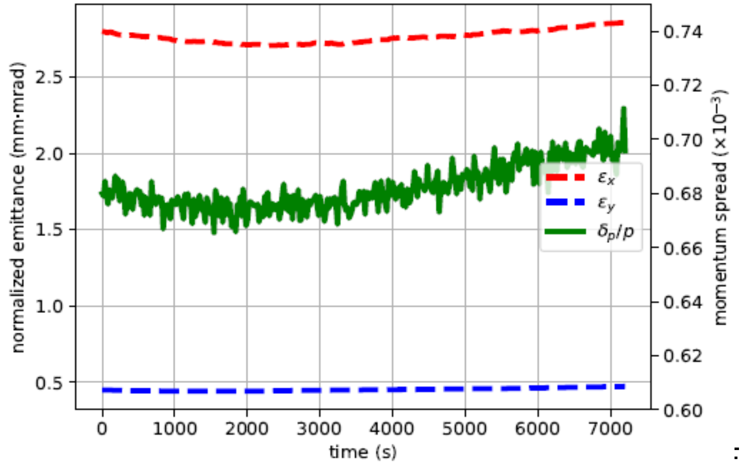
Electron intensity 6.9E10, Proton D_x =2.0 m and D_y=0



Electron intensity 6.9*6E10, Proton $D_{x,y}$ =0



Electron intensity 6.9*6E10, Proton D_x =2.0 m, D_y=0



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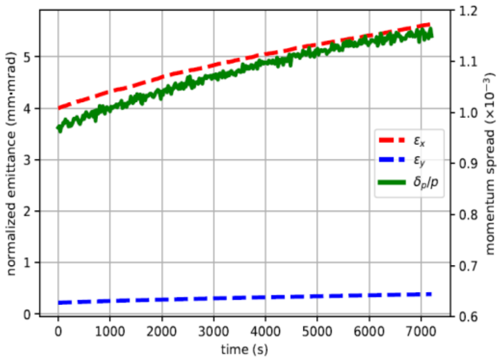
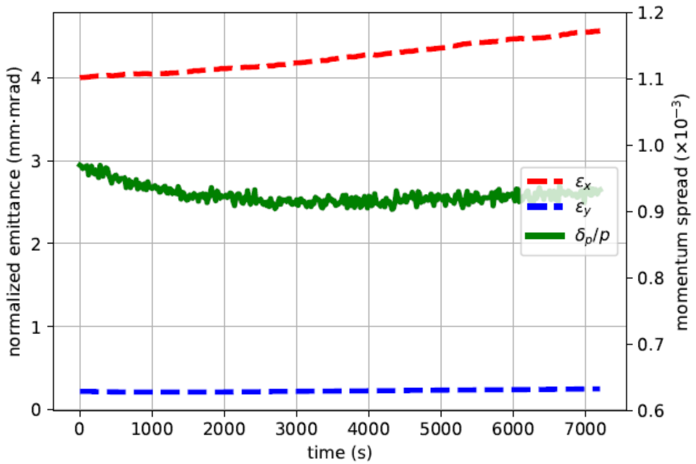
Cooling Performances for Protons @ 100 GeV

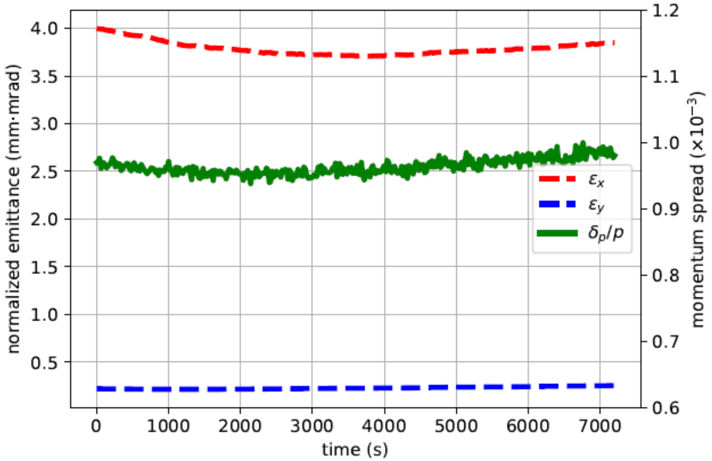
No cooling



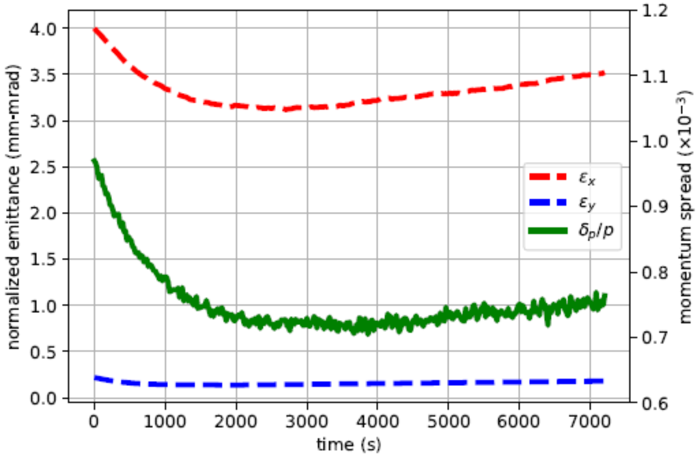
Electron intensity 6.9E10, Proton $D_{x,y}$ =0



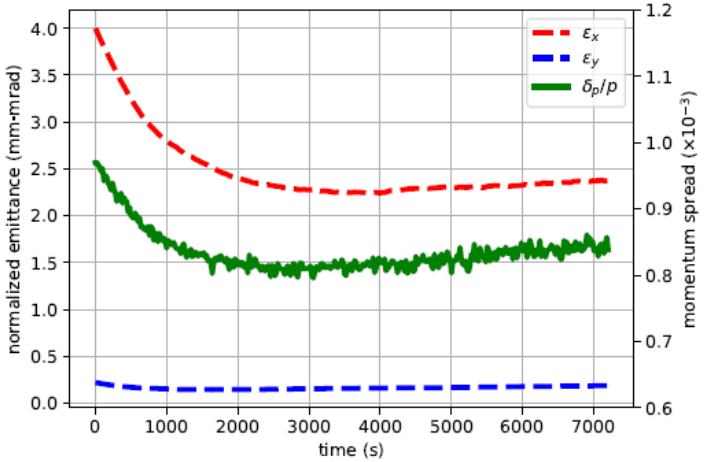
Electron intensity 6.9E10, Proton D_x =2.0 m and D_y=0



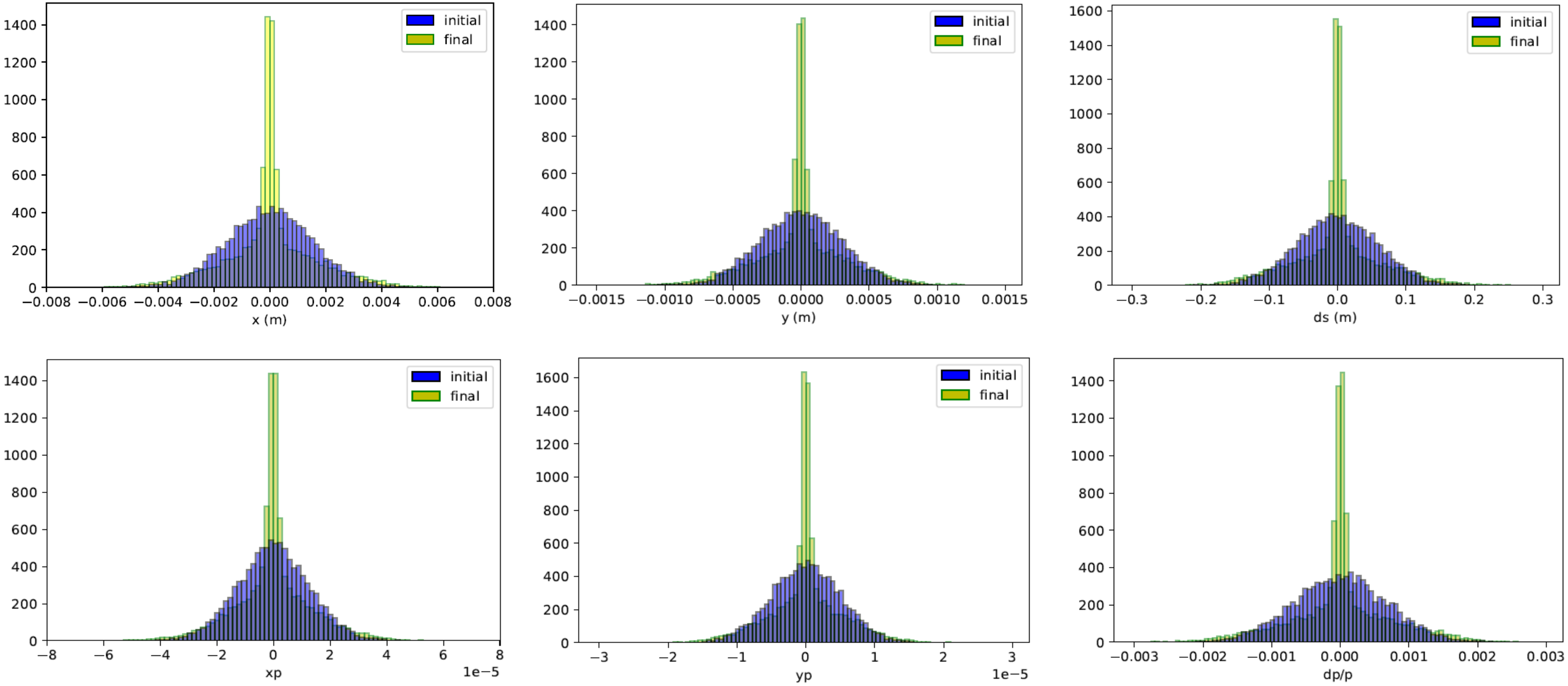
Electron intensity 6.9*6E10, Proton $D_{x,y}$ =0



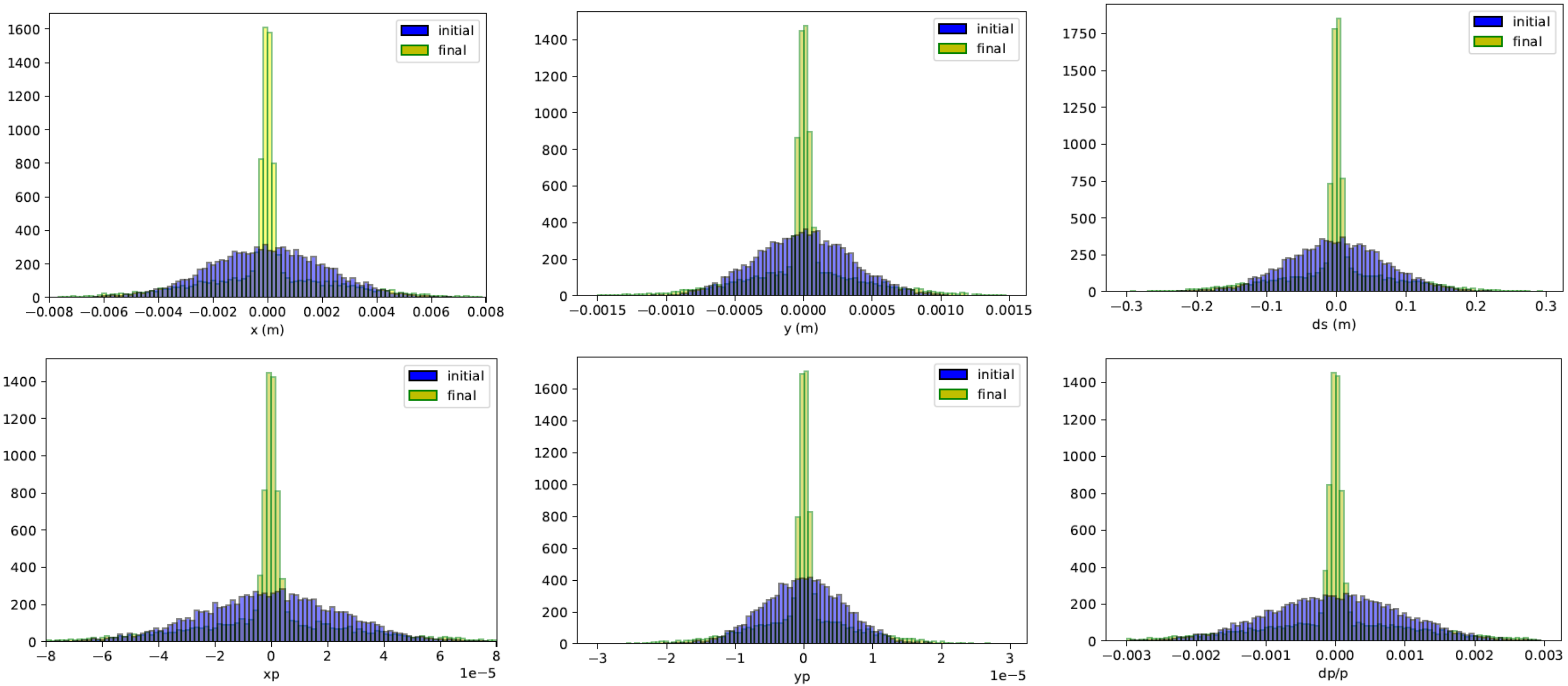
Electron intensity 6.9*6E10, Proton D_x =2.0 m, D_y=0



Proton Beam Distributions *before* and *after* Cooling @ 275 GeV with Electron Intensity 6*6.9e10



Proton Beam Distributions *before* and *after* Cooling @ 100 GeV with Electron Intensity 6.9e10



Summary

- Design and study of beam dynamics are carried out for a proposed dual energy electron storage ring cooler.
- Cooling performance using the EIC ion beam parameters is evaluated and results are promising.
- Optimization of the design can be further pursued to improve the cooling performance.

Publications

- F. Lin, et.al., “Storage-Ring Electron Cooler for Relativistic Ion Beams”, IPAC’16.
- B. Dhital, et al., “Two-Energy Storage-Ring Electron Cooler for Relativistic Ion Beams”, NAPAC19, TUPLM13.
- B. Dhital, et al., “Equilibria and Synchrotron Stability in Two Energy Storage Rings”, IPAC19, MOPGW104.
- B. Dhital, et al., “Estimates of Damped Equilibrium Energy Spread and Emittance in a Dual Energy Storage Ring”, IPAC21, MOPAB240.
- B. Dhital, et al., “Beam Dynamics Study in a Dual Energy Storage Ring for Ion Beam Cooling”, IPAC21, TUXA07.
- B. Dhital, et al., "Dual Energy Storage Ring and Possible Applications", AccApp’21.
- B. Dhital, et al., “Cooling Performance in a Dual Energy Storage Ring Cooler”, IPAC22, MOPOTK047.
- B. Dhital, et al., “Dual Energy Storage Ring Electron Cooler for Ion Beam Cooling,” *PRAB under revision.*
- H. Zhang, et al., “Latest Updates on JESPEC – an IBS and Electron Cooling Simulation Program”, IPAC’23
- H. Zhang, et al., “JSPEC: a Program for IBS and Electron Cooling Simulation”, COOL23

Thank you for your attention !

Danke!

Merci!

Grazie!

Back Up

Electron Parameters for Cooling

Cooling Electron Energy	MeV	150	55
Bunch intensity	10^{10}	6.9	
Bunch charge	nC	11.1	
Peak bunch current	A	52.9	
Average bunch current	A	1.08	
RMS bunch length	cm	2.5	
FWHM bunch length	cm	6.3	
Bunch spacing	m	3.07	
Beam energy to dump	J	1078	923
Ring circumference	m	532.8	
Natural chromaticity h/v		-16.17 / -24.70	-16.21 / -24.82
Corrected chromaticity h/v		1.0 / 0.87	
Normalized emittance h/v	µm	653 / 31	
RMS beam size h/v @ cooler	mm	0.74 / 0.16	1.22 / 0.26
RMS angle spread @ cooler	µrad	608	1655
Energy spread @ cooler	10^{-4}	7.4	20.2
Space Charge tune shift		0.00612	0.0422
Electron IBS time (h/v/l)	s	**5 / 12328 / 0.44**	**4.4 / 703 / 0.44**
SR damping time (h/v/l)	s	**3.2 / 0.69 / 0.25**	

Heating from ion beam*

Energy (MeV)	Beta function (m)	Ion beta func. (m)	Ion dispersion (m)	Heating h/v/l (s)
150	0.25	100	0	- 2.61e6 / 5.32e6/ 2.15
150	0.25	100	2	- 5.32e6 / 9.64e6 / 3.88
150	0.25	60	0	- 1.98e6 / 3.6e6 / 1.45
150	0.25	60	2	- 3.56e6 / 6.44e6 / 2.59
55	0.09	100	0	-1.13e6 / 1.87e6 / 6.02
55	0.09	100	2	-1.56e6 / 2.62e6 / 8.35
55	0.09	60	0	- 6.67e6 / 1.11e6 / 3.58
55	0.09	60	2	- 1.14e6 / 1.91e6 / 6.08

- cooling in horizontal direction

* Calculated using the code getrad7, H. Zhao

Non-magnetized cooling

	Electron beam	Proton beam
Lorentz factor γ	293.1	293.1
Particle number	2.8×10^{11}	6.9×10^{10}
Norm. emit. (μm)	7.6/3.0	2.8/0.45
Bunch length (cm)	6.0	6.0
Momentum spread	7.4×10^{-4}	6.8×10^{-4}
β cooler center (m)	66/26	180/180

	R_x ($10^{-5}s^{-1}$)	R_y ($10^{-5}s^{-1}$)	R_z ($10^{-5}s^{-1}$)
IBS	11.81	0.097	6.810
Cooling	-12.15	-2.191	-7.843
Total	-0.034	-2.094	-1.033

- Introduce electron beam and ion beam dispersion