A Dual Energy Electron Storage Ring Cooler *

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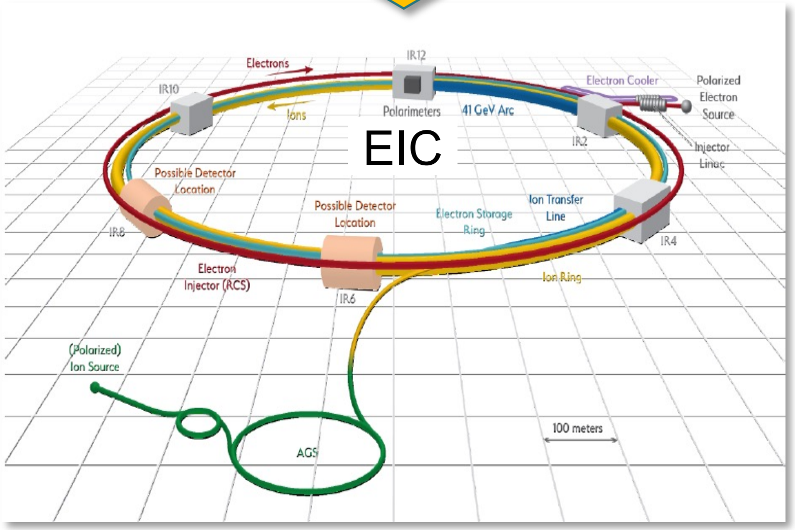
Outline

- Introduction
- A dual energy electron storage ring cooler
  - Motivation
  - Concept
  - Design
  - Study
  - Evaluation
- Summary

US EIC for QCD Frontier

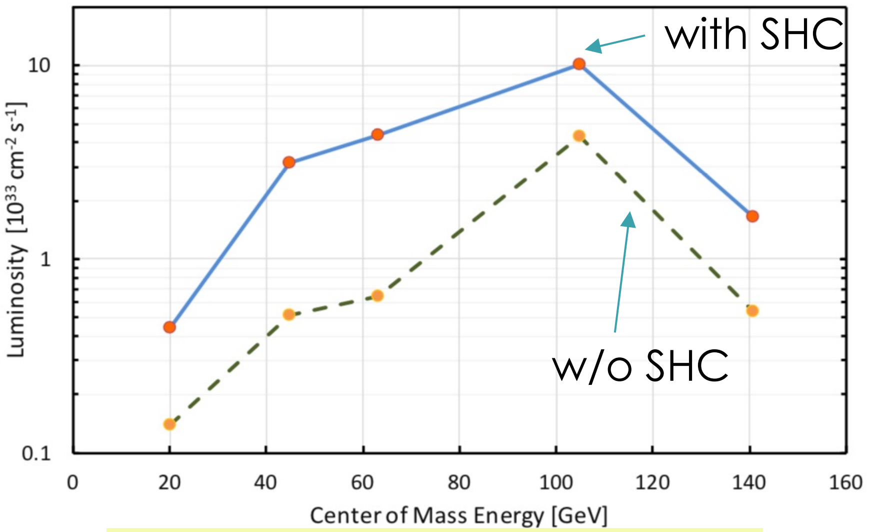
Electron Ion Collider (EIC) will be built at BNL, based on the existing RHIC

- **Goals**
  - High luminosity: L=(0.1-1)x10^{34} cm^{-2} s^{-1} $\rightarrow$ 10-100 fb^{-1}
  - 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, bright vertical beam emittance, **strong hadron cooling (coherent electron cooling)**
- **Electron storage ring (2.5–18 GeV** (new))
  - 1160 bunches, large beam current (2.5 A) $\rightarrow$ 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 with crab cavities
  - Spin Rotators (longitudinal electron spin)
  - Forward hadron instrumentation for tagging



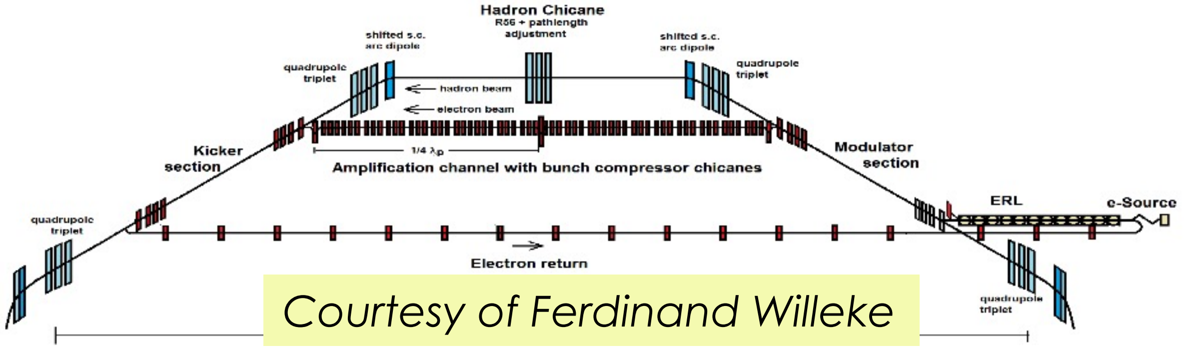
Courtesy of Ferdinand Willeke

High Luminosity EIC through Strong Hadron Cooling



Courtesy of Erdong Wang

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	$cm^{-2}sec^{-1}$	1×10^{34}	



Courtesy of Ferdinand Willeke

- **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 baseline: ERL based Coherent Electron Cooling with micro-bunching amplification

- Design cooling rate R_{cool}= 1-2 h^{-1}
- Electron beam current I_e~100 mA (~1 nC/bunch)
- Electron beam emittance ϵ_{xyN}= 2.5/0.5 mm mrad

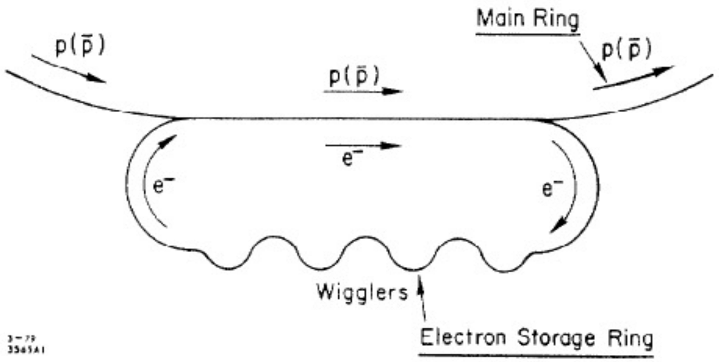
Any Other Alternative Solutions ?

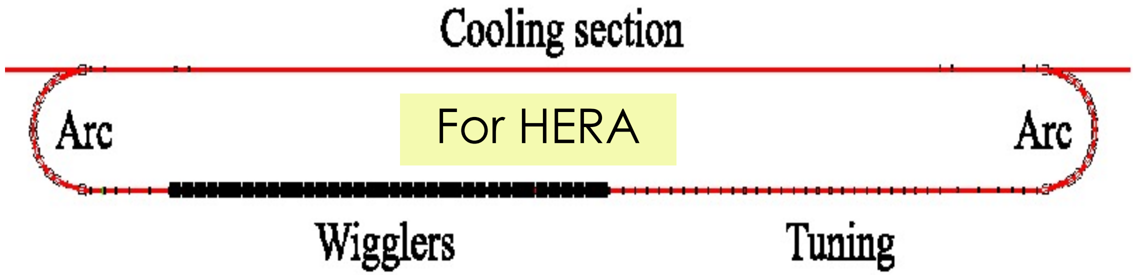
- Need to consider
  - If such an alternative solution works with a bunched proton beam demanding a large bunch charge in the EIC: 10 to 30 nC (6.9×10^{10} to 30×10^{10}), 1+ Amperes, hundreds of MW beam power
- This presentation describes one possible alternative cooling scheme: a storage-ring-based **dual energy electron storage ring cooler**
  - Focusing on the discussion of design, beam dynamics study and cooling performance evaluation

Electron Storage Ring Based Cooler

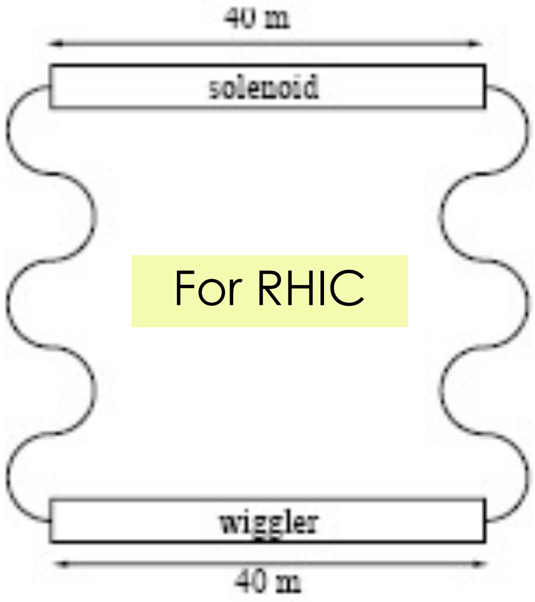
- Electron storage ring has been considered as a cooler since the late 1970s. However, no one has been built at present.

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





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



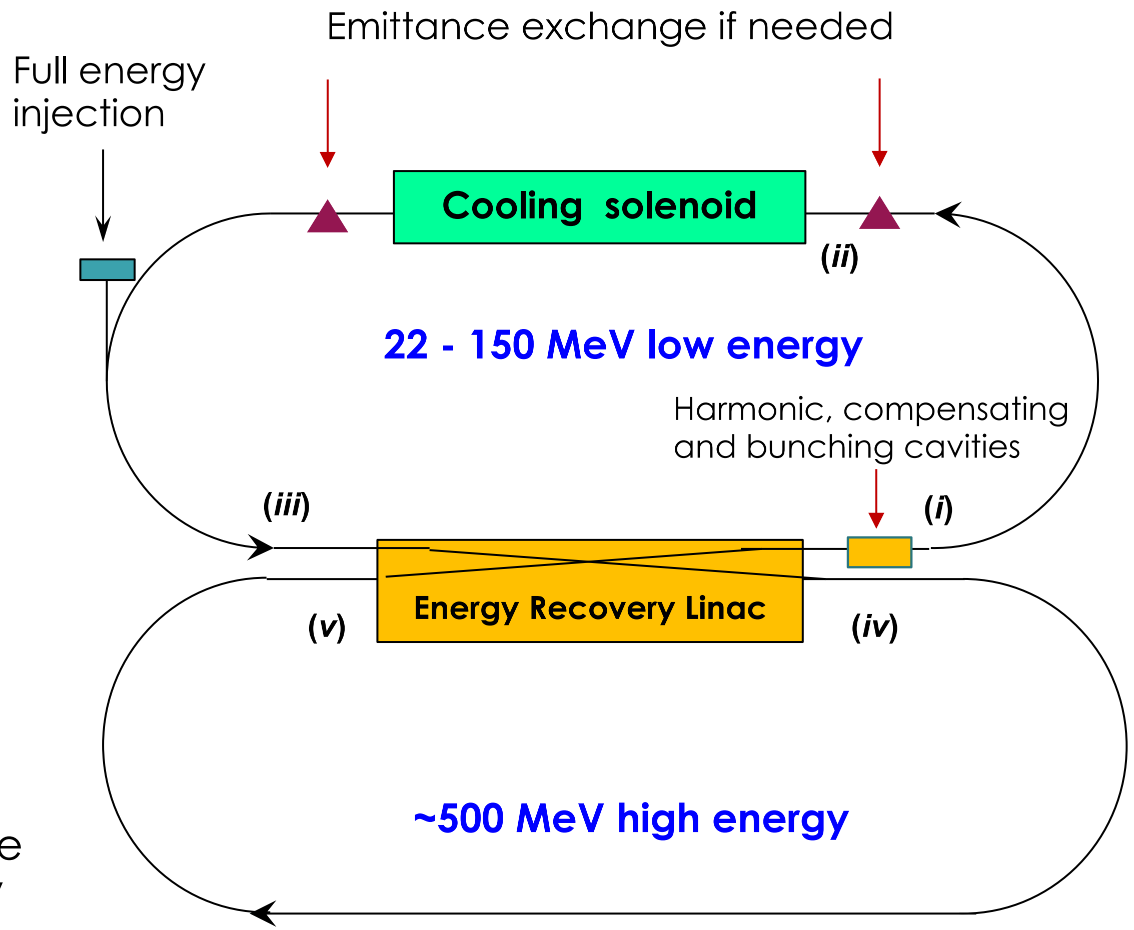
A. Burov, S. Derbenev, et. al., FERMILAB-TM-2058, 1998

Motivation

- 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-second
  - Typical synchrotron radiation damping is very weak -> long damping time, second up to minutes
  - Unbalanced IBS and radiation damping can be mitigated through higher electron energies and/or damping wigglers

Concept of a Dual Energy Storage Ring Cooler

- Idea
  - divide and conquer separately the ion cooling problem and the heat removal (radiation) problem using a dual energy storage ring
    - Ion beam to be cooled sets lower electron energy: **22 – 150 MeV** (goal)
    - Heat removed by radiation sets higher electron energy: ~**500 MeV** (goal)
    - Energy recovery linac (ERL) connects the two different-energy rings
      - Large voltage results in a large longitudinal acceptance
    - 3rd harmonic cavity is used to extend the bunch length, compensating cavity is used to compensate the synchrotron radiation energy loss, bunch cavity is used to create the longitudinal focusing



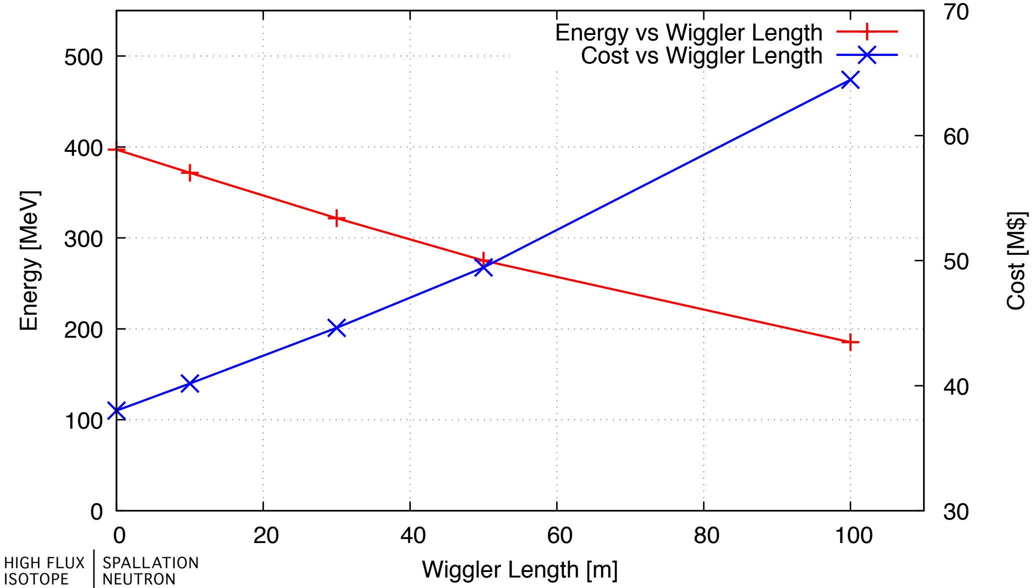
Why High Damping Energy **NOT** Wigglers

- Damping time in a dual 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: $C(\gamma_H, L) = \frac{511kV}{0.9}\left(\frac{10\$}{100V}\right)\left(\gamma_H + \frac{CL_w}{\lambda_{ID}}\right) - \frac{511kV}{0.9}\left(\frac{10\$}{100V}\right)\gamma_L$

*Assumed
- cost of acceleration = 10$/100V
- cost of wiggler = 500,000$/m



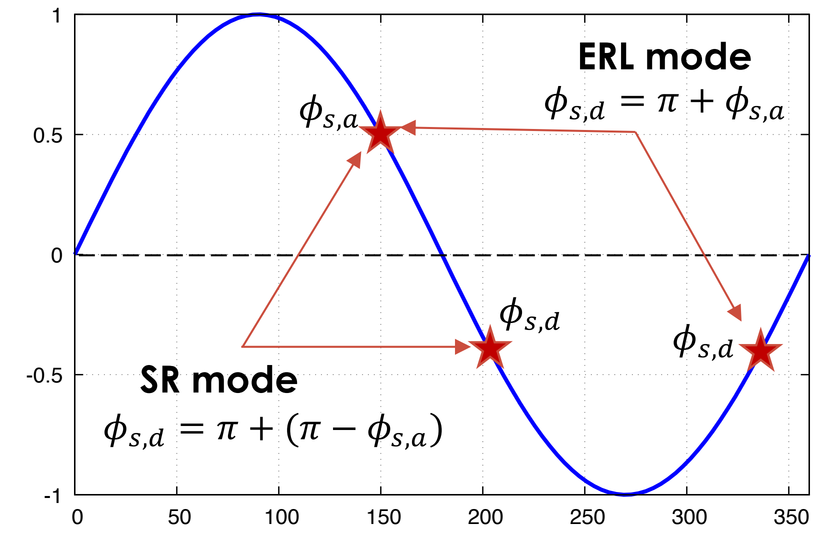
Parameters used for this evaluation

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

[1] for cooling 20 GeV protons

Longitudinal Stable Modes

- Storage Ring (SR) mode: longitudinal focusing in 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 $(\Delta\phi, \Delta E)$:



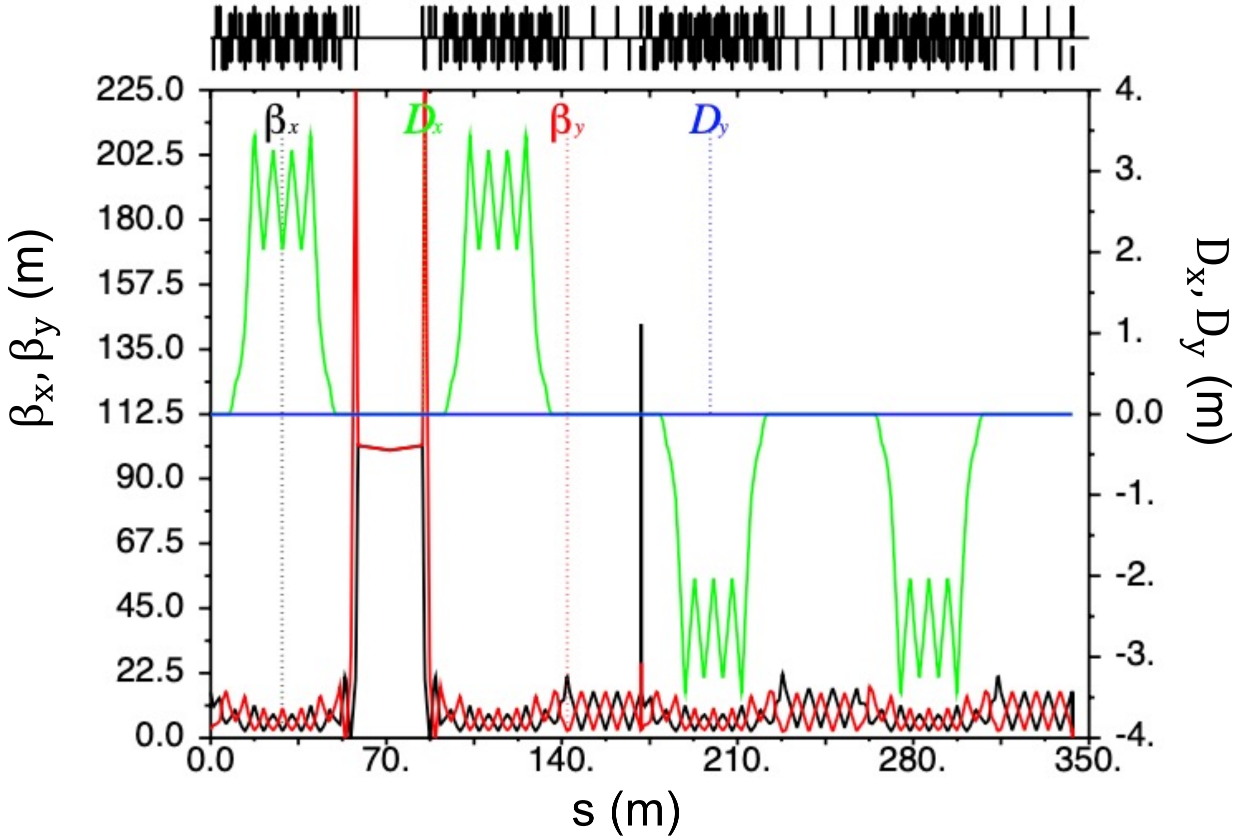
$$M = \begin{pmatrix} 1 & h_L/E_L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ V\cos\phi_{s,d} & 1 \end{pmatrix} \begin{pmatrix} 1 & h_H/E_H \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ V\cos\phi_{s,a} & 1 \end{pmatrix}$$

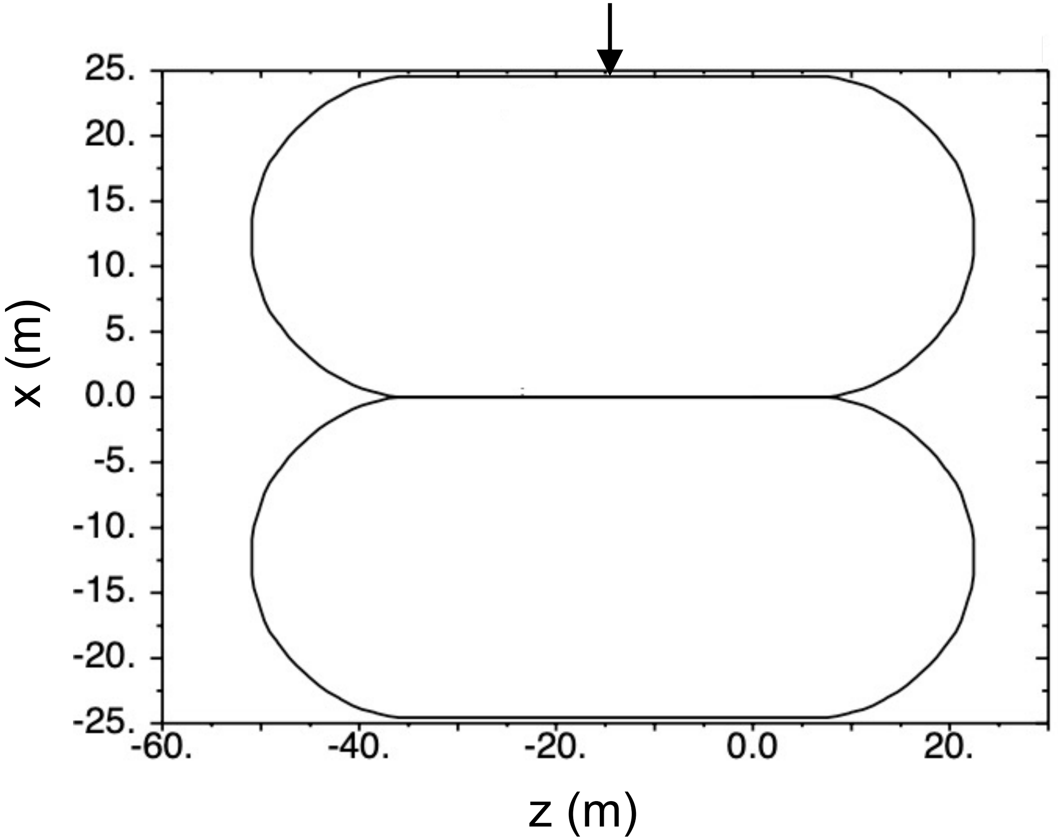
$$\Rightarrow \begin{cases} Q_{SR} = \dfrac{1}{2\pi}\sqrt{2\left(h_L V \dfrac{-\cos\phi_{s,a}}{E_L} + h_H V \dfrac{-\cos\phi_{s,a}}{E_H}\right)} \\ Q_{ERL} = \sqrt{h_L h_H \dfrac{V^2 \cos^2 \Phi_{s,a}}{E_L E_H}} \end{cases}$$

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

Preliminary Lattice Design





- The preliminary lattice design is composed of FODO cells in arcs
- We realize an isochronous-like arcs is required with small M_{56}~71cm
- Optics optimization is in progress
- Two rings can be **vertically stacked** to reduce the size of the footprint

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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	um	652	652
Normalized vertical emittance	um	31.05	31.05
Un-normalized horizontal emittance	um	0.667	2.225
Un-normalized vertical emittance	um	0.032	0.106
Energy Spread	10^{-4}	2.2	7.5
Bunch Length (rms)	cm	2.5	2.5

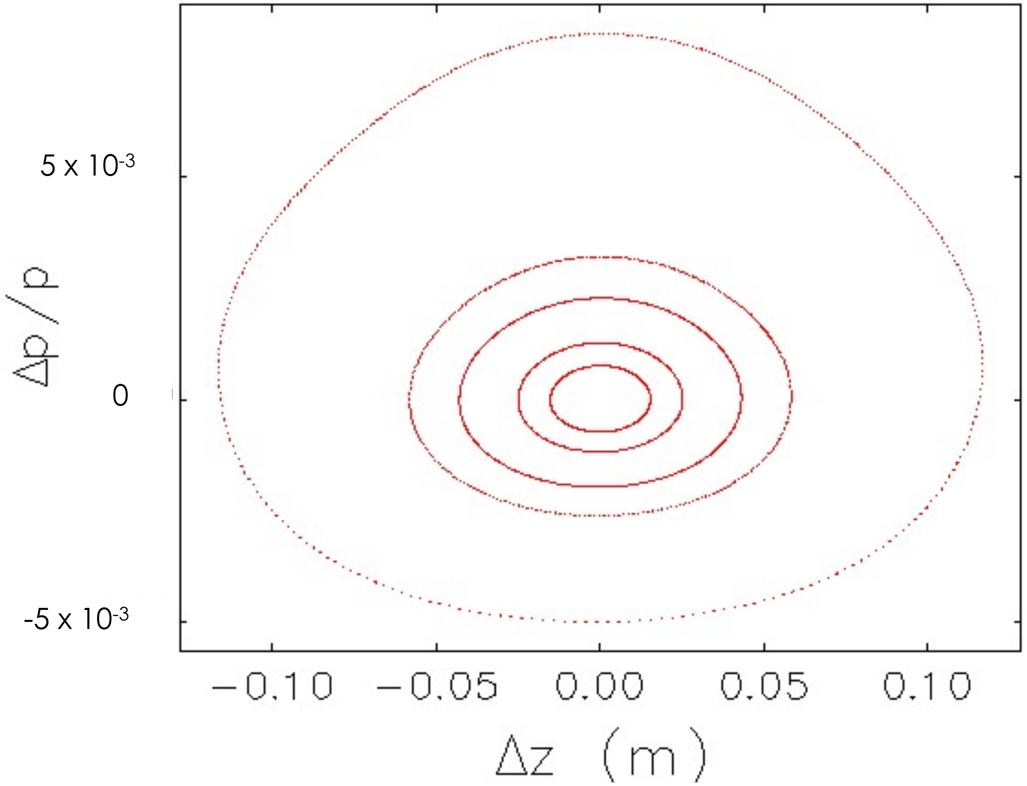
Analytical Calculation and Tracking Simulation

Parameter	Low Energy Section		High Energy Section	
	Analytical calculation	Tracking simulation	Analytical calculation	Tracking simulation
ε_x (μm)	18.20	19.99	2.73	2.55
Difference (%)	9.83		6.59	
$\frac{\sigma_E}{E}$ $(\times 10^{-3})$	3.03	3.28	0.454	0.509
Difference (%)	8.25		12.11	

- Note that:
  - Electron energy of 1GeV in the high energy section is used to save the simulation time (fast damping effects).
  - Only 100 particles are used to extract the damped parameters. The discrepancy between the analytical calculation and tracking simulation is expected to be further reduced with more particles.

Longitudinal Phase Space from Tracking

- Bunching cavity voltage is 80kV
- Watching point is in the low energy ring with the maximum $\frac{\Delta p}{p} \sim 8\times10^{-3}$
- Full bunch length is ~24cm ($\pm$12)



Electron Damping Times and Inter Beam Scattering Times

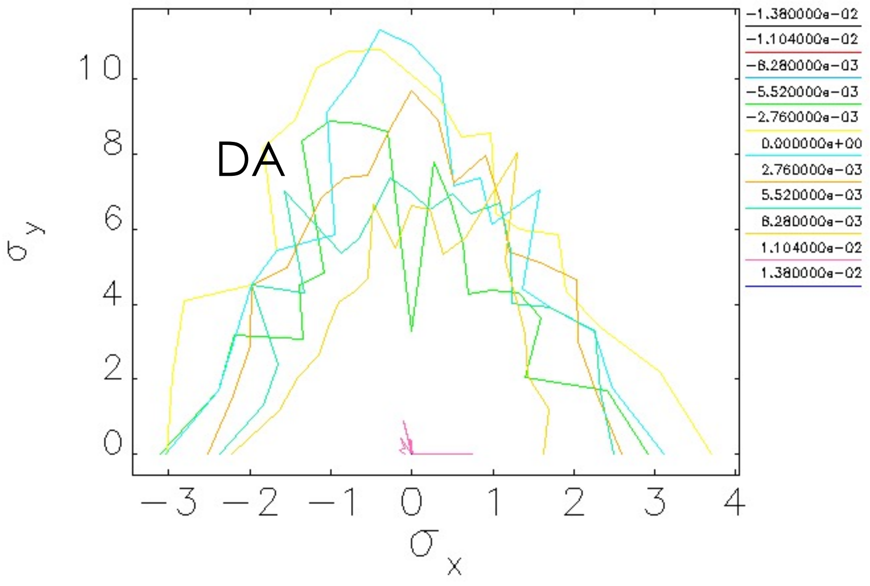
- Damping time(s): $$\frac{t_{rev,tot}}{\tau_{rad,tot}} = \frac{t_{rev,L}}{\tau_{rad,L}} + \frac{t_{rev,H}}{\tau_{rad,H}}$$
- IBS time(s)*: $$\frac{1}{\tau_{IBS,tot}} = \frac{1}{\tau_{IBS,L}} + \frac{1}{\tau_{IBS,H}}$$

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

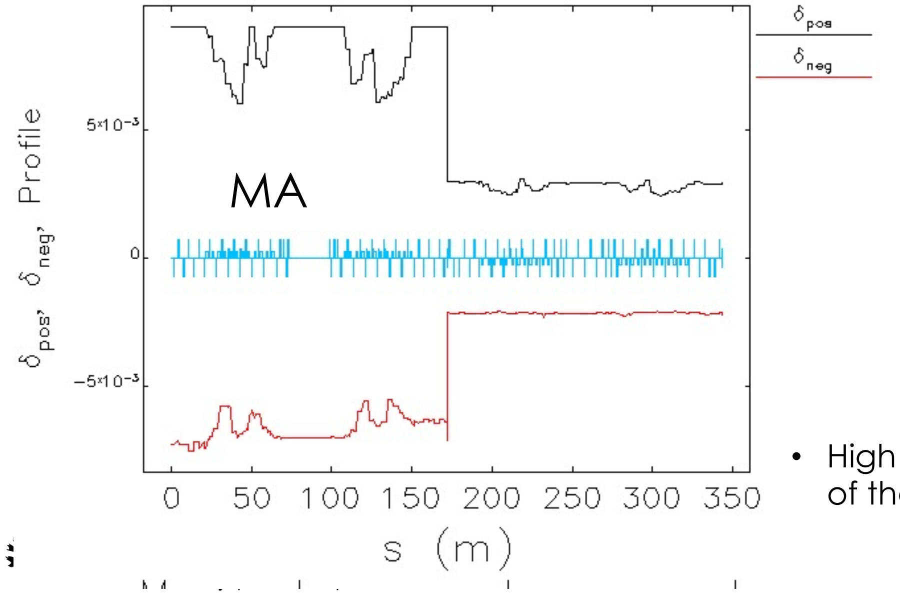
Parameters	**unit**	**Dual Energy Storage Ring Cooler (E_{high}=500 MeV, E_{low}=150MeV)**
Horizontal damping time vs. IBS time	s	3.20 vs. 5
Vertical damping time vs. IBS time	s	0.69 vs. 12328.33
Longitudinal damping time vs. IBS time	s	0.25 vs. 0.44

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

Dynamic Aperture, Momentum Aperture and Touschek Lifetime



	Touschek lifetime (h)					
	$\tau_{tous,L}$ @ 150MeV	$\tau_{tous,H}$ @ 500MeV	τ_{tous}	$\tau_{tous,L}$ @ 150MeV	$\tau_{tous,H}$ @ 1000MeV	τ_{tous}
Elegant	0.67	0.31	0.42	14.79	3.70	5.92
Formula	0.68	0.23	0.34	13.27	2.88	4.73



$$\frac{1}{\tau} = \frac{r_e^2 cq}{8\pi e\gamma^3\sigma_s}\cdot\frac{1}{C}\cdot\oint_C \frac{F\left(\left(\delta_{acc}(s)\big/\gamma\sigma_{x'}(s)\right)^2\right)}{\sigma_x(s)\sigma_z(s)\sigma_{x'}(s)\delta_{acc}^2(s)}\,ds \qquad F(x) = \int_0^1 \left(\tfrac{1}{u} - \tfrac{1}{2}\ln\tfrac{1}{u} - 1\right)\cdot e^{-x/u}\,du$$

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

Space Charge Effect

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

For cooling 275 GeV protons | For cooling 100 GeV protons

	Low energy	High energy	Low energy	High energy
energy (MeV)	150	500	55	500
circumference (m)	171.7	171.7	171.7	171.7
r_e (m)	2.82e-15	2.82E-15	2.82e-15	2.82E-15
N_b	6.9e+10	6.90E+10	6.9e+10	6.90E+10
beta	0.999994179	0.999999478	0.999956839	0.999999478
gamma	293	978	108	978
rms bunch length (cm)	2.5	2.5	2.5	2.5
normalized horizontal emittance (um)	636.7	636.7	636.7	636.7
normalized vertical emittance (um)	33.5	33.5	33.5	33.5
epsilon_x/epsilon_y	18	18	18	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

Parameters for Evaluation of Cooling Performance

Cooling Electron Energy	**MeV**	**150**	**55**
Bunch intensity	10^{10}	6.9	6.9
Bunch charge	nC	11.1	11.1
Bunch current	A	52.9	52.9
Average current	A	1.08	1.08
RMS bunch length	cm	2.5	2.5
FWHM bunch length	cm	6.3	6.3
Bunch spacing	m	3.07	3.07
Beam energy to dump	J	1078	923
Ring circumference	m	463.4	463.4
Natural chromaticity h/v		-16.17 / -24.70	-16.21 / -24.82
Corrected chromaticity h/v		1.0 / 0.87	1.0 / 0.87
Normalized emittance h/v	μm	670 / 108	670 / 108
RMS beam size h/v @ cooler	mm	0.756 / 0.303	0.756 / 0.303
RMS angle spread @ cooler	μrad	608	1655
Energy spread @ cooler	10^{-4}	6.9	18.9
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	

Cooling Performance*

	Unit		
Ion Energy	GeV	275	100
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
Force Formula		Meshkov	
Cooling solenoid	kG	20	20
Proton IBS time (h/v/l)	h	2.4/278/4.3	2.9/2.8/2.9
Cooling time (h/v/l)	h	2.2/26/0.4	2.8/5.7/0.8

* Calculated using the code JSPEC, H. Zhang

Summary

- Study of a dual energy electron storage ring cooler is performed in both design and beam dynamics.
- Cooling performance for the ion beam in the EIC is evaluated and the preliminary result is promising.
- Further optimization of the design is in progress to strengthen its cooling application in a collider.

Publications

1. F. Lin, et.al., "Storage-Ring Electron Cooler for Relativistic Ion Beams", IPAC'16.
2. G. A. Krafft, B. Dhital, F. Lin, V. Morozov, Y. Zhang "Comments on Equilibrium and Synchrotron Stability in Storage Ring Coolers", JLAB-TN-21-005.
3. B. Dhital, G. A. Krafft, F. Lin, V. Morozov, Y. Zhang "Comments on $M56$ and RF Accelerating Phase Angle ($\phi s,a$) in Dual Energy Storage Ring", JLAB-TN-21-006.
4. G. A. Krafft, B. Dhital, F. Lin, V. Morozov, Y. Zhang "Compressing and De-compressing Longitudinal Phase Space in a Dual Storage Ring", JLAB-TN-21-007.
5. B. Dhital, F. Lin, V. Morozov, G. A. Krafft, Y. Zhang "Two-Cavities Model to Accelerate and Decelerate the Electron Beam in Dual Energy Storage Ring", JLAB-TN-21-008.
6. G. A. Krafft, B. Dhital, F. Lin, V. Morozov, Y. Zhang "Damping Times in a Dual Energy Storage Ring", JLAB-TN-21-009.
7. B. Dhital, A. Hutton, G.A. Krafft, F. Lin, V. Morozov, Y. Zhang "Estimates of Damped Equilibrium Energy Spread and Emittance in a Dual Energy Storage Ring", JLAB-TN-21-010.
8. B. Dhital, et al., "Estimates of Damping Parameters in a Dual Energy Storage Ring", IPAC'21.
9. B. Dhital, et al., "Beam Dynamics Study in a Dual Energy Storage Ring for Beam Cooling", IPAC'21.
10. B. Dhital, et al., "Dual Energy Storage Ring and It's Applications", AccApp21.
11. M.W. Bruker, et.al., "Demonstration of Electron Cooling using a pulsed beam from an electrostatic electron cooler", PRAB2021.

Thank you for your attention !