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# Electron Cooling for Future High-Energy Hadron Accelerators


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## Abstract

**The Electron-Ion Collider (EIC) at Brookhaven National Laboratory is approved at U.S.A. The hadron beam cooling at the top energy of 275 GeV is one of the key challenges in the EIC project. Based on the electron cooling method, we present a possible design of a ring-based electron cooler for the high energy hadron beam cooling. In this paper, we present the details of the cooler design as well as some calculation.**


## 1. Introduction

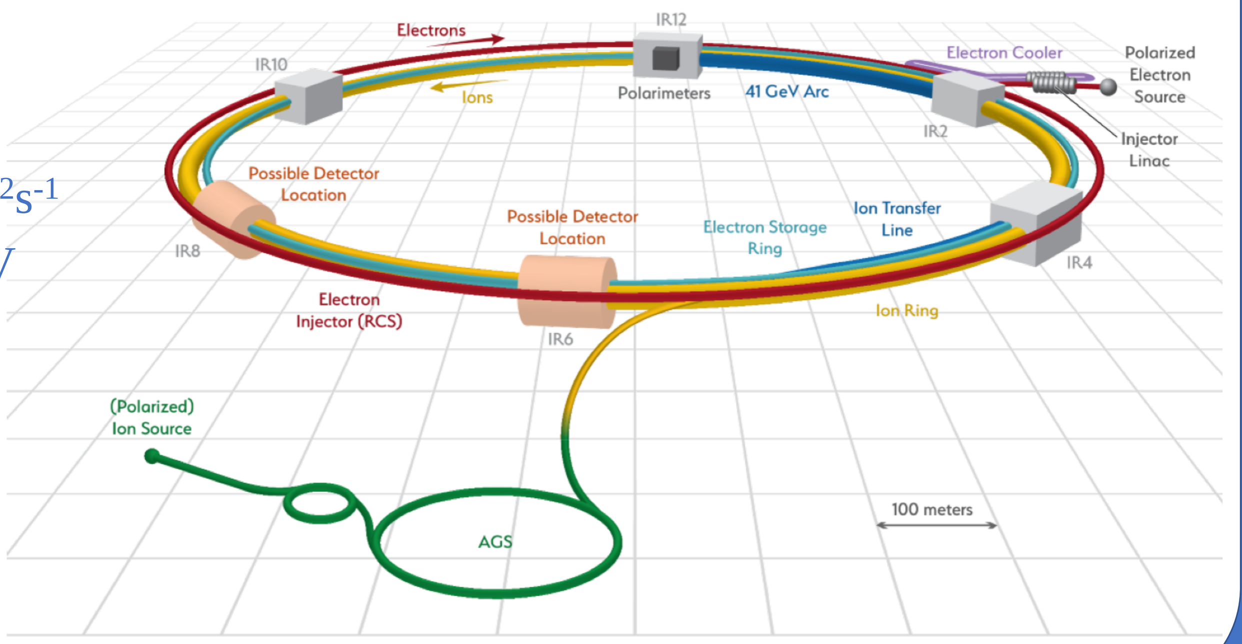
### BNL-EIC

**Parameters**

- Lumi.=$10^{33\text{-}34}$ $cm^{-2}s^{-1}$
- CoM=20-100 GeV
- Polarization>70%

**Challenges**

- Hadron cooling
- Polaried beam
- IR design




## 2. Electron Cooling Method

### Theory (Gas model)

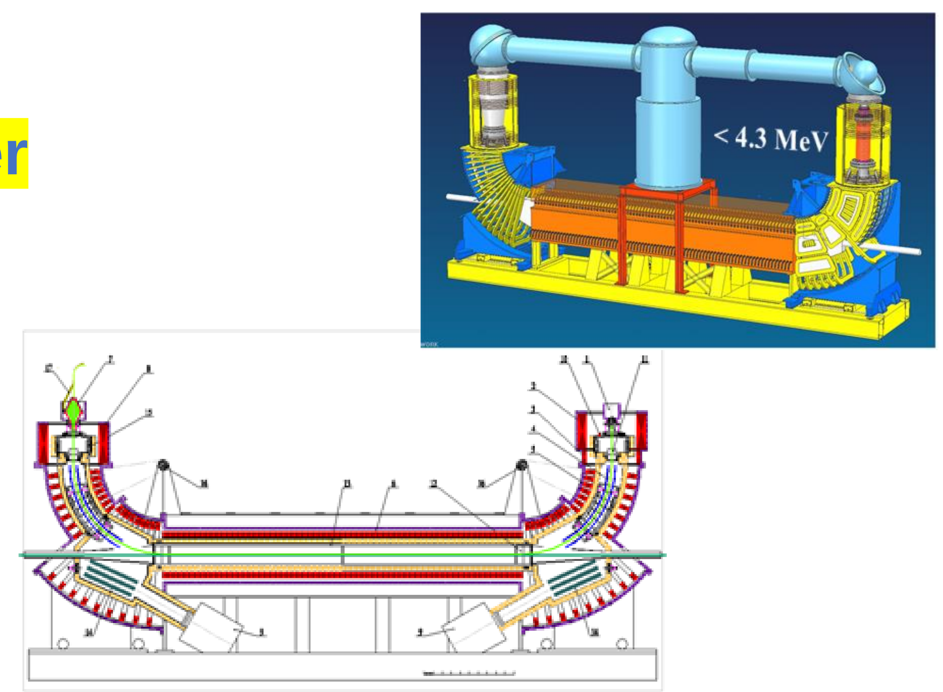
Both electron and ion beam have Boltzmann velocity distribution but with difference temperature *Ti* and *Te*. This formula gives the average temperature changes in one-dimension.

$$\frac{dT_e}{dt} = \frac{T_i - T_e}{\tau_{eq}} \qquad \tau_{eq} = \frac{3\mathrm{m_i m_e}(4\pi\varepsilon)^2}{8\sqrt{2\pi}\mathrm{n_i Z^2 e^4 \ln\Lambda}}\left(\frac{\mathrm{kT_e}}{\mathrm{m_e}} + \frac{\mathrm{kT_i}}{\mathrm{m_i}}\right)^{3/2}$$

### Electron cooler

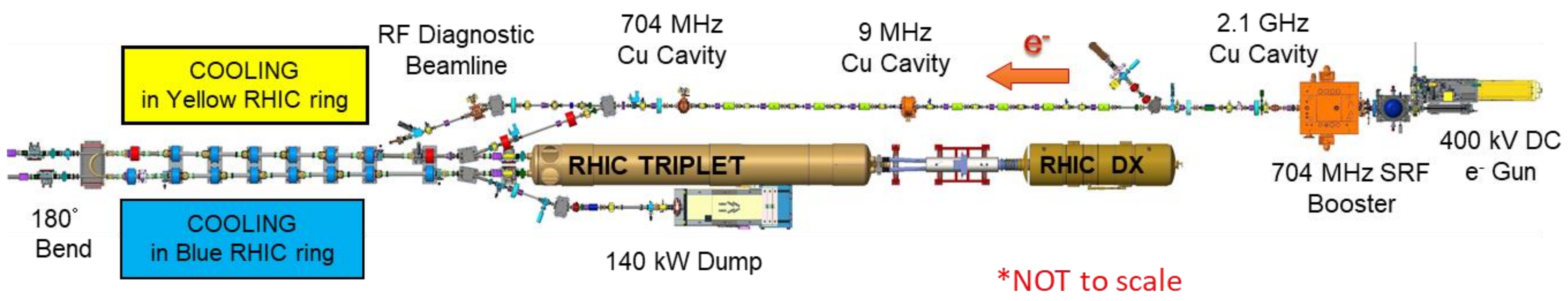
#### I- Conventional E-Cooler

- Using electrostatics field for accelerating
- DC e-beam
- Magnetized cooling
- WR: 4.3 MeV @ FNAL



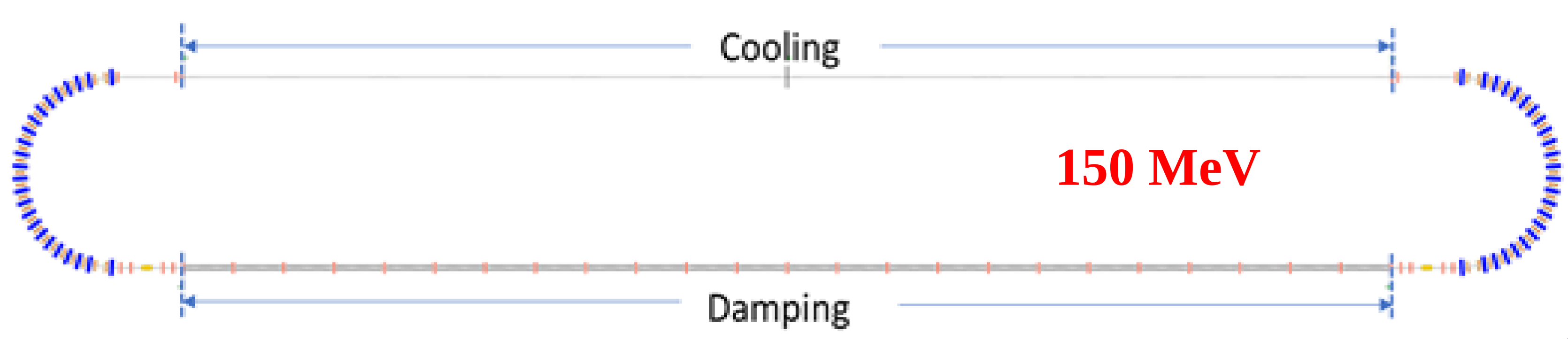

#### II- RF-based E-Cooler

- World first e-cooler @ BNL using SRF cavity (2019)
- 1.6-2.6 MeV e-beam, <100 pC/bunch
- cooling both yellow and blue ring of RHIC to improve the collision luminosity.




#### III- Ring-based E-Cooler

- Continuous cooling with electron and ion beam
- Synchrotron radiation damping for cooling electron beam itself



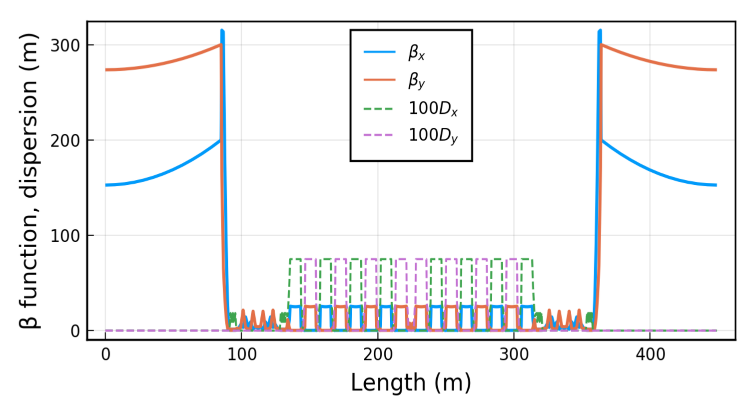

## 3. Ring Cooler Design

### Parameters

| | |
|---|---|
| Beam energy [MeV] | 149.8 |
| Relativistic factor $\gamma$ | 293.1 |
| Number of electrons per bunch | $3\times10^{11}$ |
| Peak current [A] | 48.3 |
| Number of bunches | 135 |
| Average current [A] | 4.4 |
| rms emittance (x/y) [nm] | 21/18 |
| rms momentum spread | $8.9\times10^{-4}$ |
| rms bunch length [cm] | 12 |
| Required rf voltage [kV] | 6.1 |
| Synchrotron tune $Q_s$ | $1.63\times10^{-3}$ |
| Maximum space charge (x/y) | 0.19/0.21 |
| Damping rates (x/y/s) [$s^{-1}$] | 32/32/64 |
| IBS rates (x/y/s) [$s^{-1}$] | 54/53/68 |
| BBS rates (x/y/s) [$s^{-1}$] | −0.4/1.0/49 |
| Dynamic aperture (x/y/s) | $6\,\sigma/6\,\sigma/13\,\sigma$ |
| Momentum aperture | 0.79% |
| Quantum lifetime [hour] | 2.8 |
| Touschek lifetime [s] | < 55 |

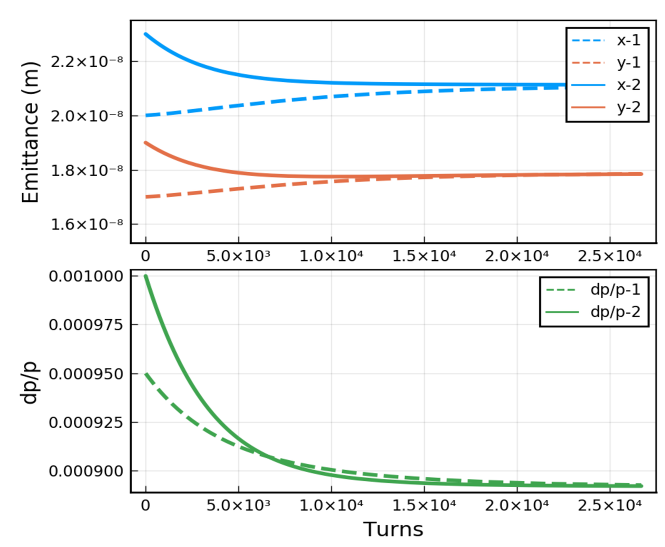
| | |
|---|---|
| Circumference [m] | 449.079 |
| Length of cooling section [m] | 170 |
| Average $\beta$ function in cooling section [m] | 170/280 |
| Dispersion in arc [cm] | 18.5 |
| Wiggler field [T] | 1.88 |
| Length of wiggler [m] | 7.44 |
| Bend radius of wiggler [m] | 0.246 |
| Poles in wiggler | 158 |
| Wiggler period [cm] | 4.8 |
| $\beta$ function in wiggler [m] | 25 |
| Max. Dispersion in wiggler [cm] | 75 |
| Number of wiggler magnets | 16 |
| Tune ($Q_x/Q_y$) | 59.92/59.85 |
| Chromaticity before correction (x/y) | -117.8/-114.4 |
| Momentum compaction factor $\alpha$ | $-3.21\times10^{-3}$ |
| Natural emittance (x/y) [nm] | 3.1/3.1 |
| Natural momentum spread | $2.6\times10^{-4}$ |

### Ring Lattice

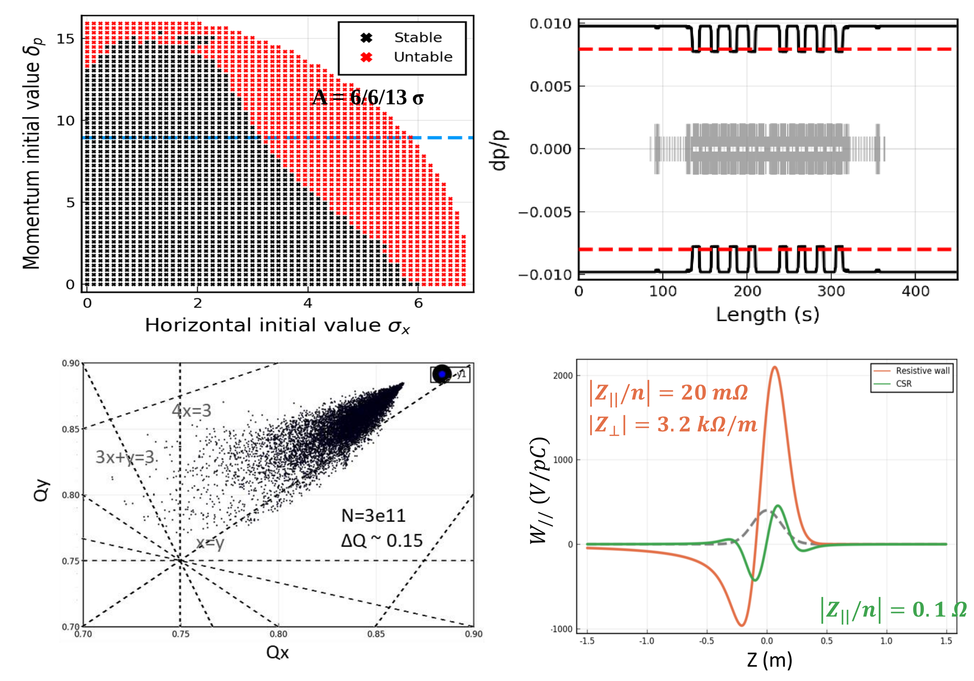



### Damping process

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

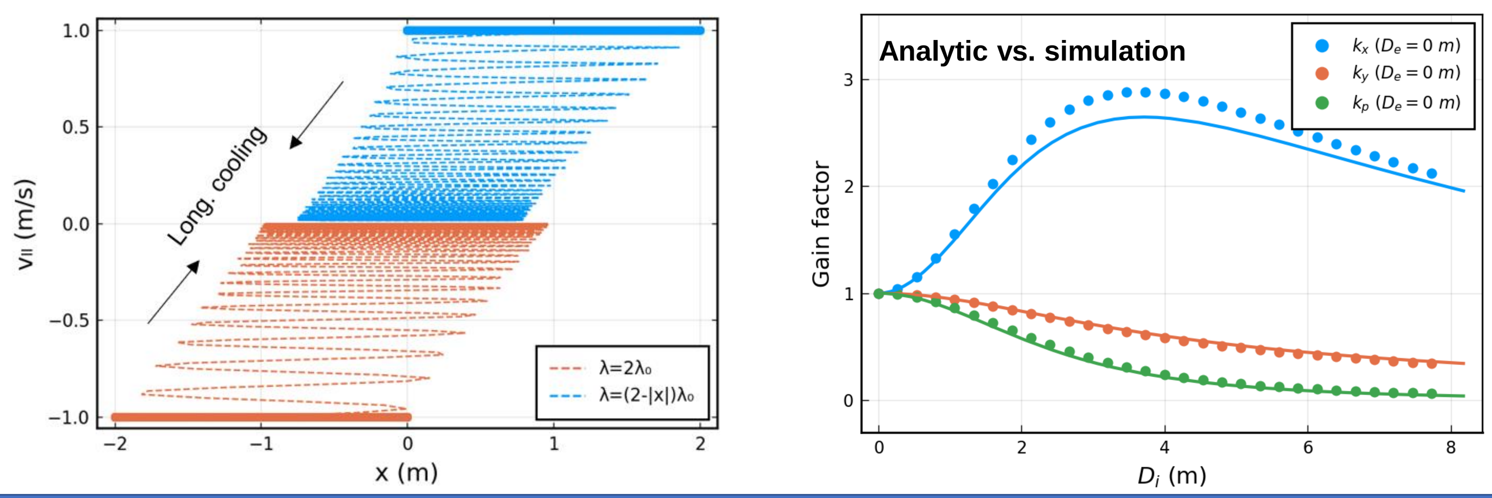



### DA and CSR effect



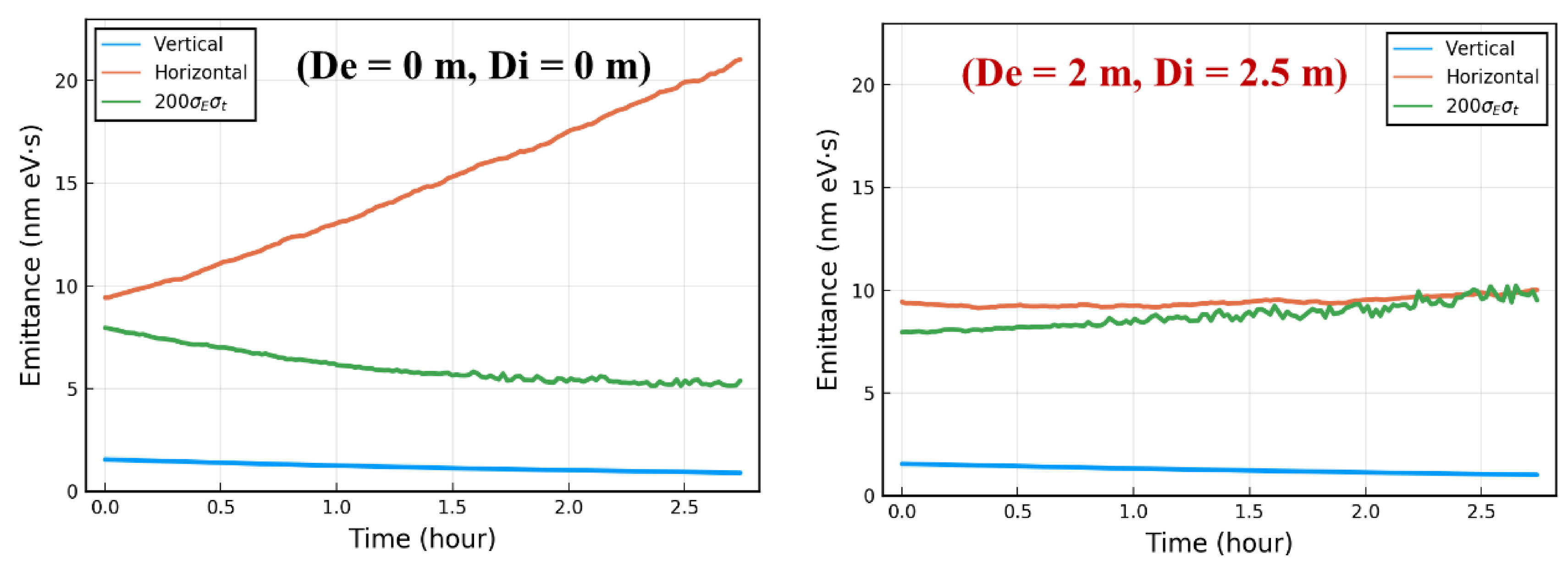

### Dispersive electron cooling

For high energy, the transverse cooling rate is much smaller than the longitudinal direction. We using dispersion to redistribution the cooling rates. ($p_\perp/mc = \gamma\theta_\perp \gg \sigma_\gamma/\gamma = p_\parallel/mc$)




## 4. Cooling Simulation

- 275GeV proton beam cooling simulation at BNL EIC
- Including all effects, such as IBS, space charge, dispersion, etc.




## Summary

- We present a possible design of high-energy ring-based electron cooler for high energy hadron beam cooling.
- The cooling performance on the hadron beam shows it is suitable for cooling of protons at the top energy in EIC, even though there are still some challenges.


H. Zhao, et al., Phys. Rev. Accel. Beams **24**, 043501 (2021)
H. Zhao and M. Blaskiewicz, Phys. Rev. Accel. Beams **24**, 083502 (2021)