Development of Storage Ring Electron Cooler for High Energy Applications

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COOL'25 - the 15th International Workshop on Beam Cooling and Related Topics
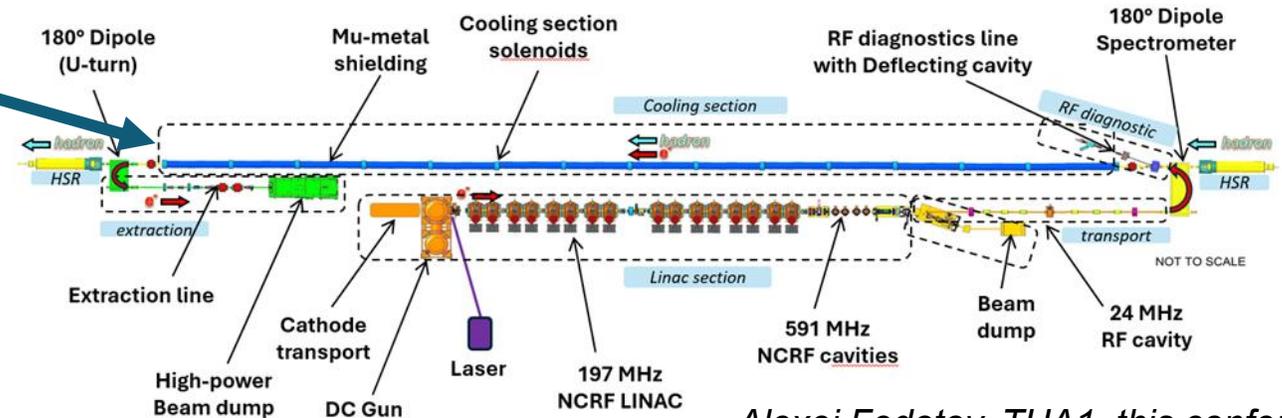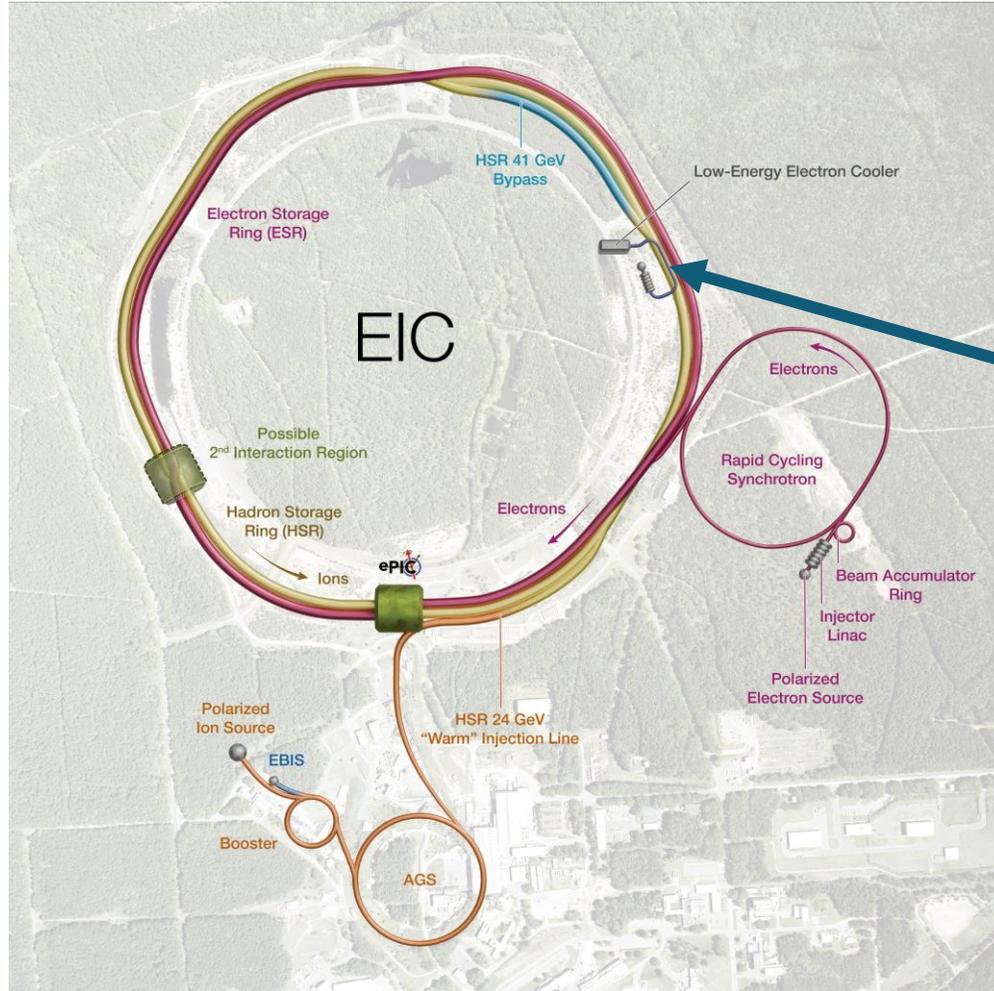
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Cooling requirements for Electron Ion Collider (I)

Low-Energy Cooling (LEC):

Cooling hadrons at injection energy (24 GeV):

The goal of cooling at injection energy is to obtain initial proton parameters by cooling the vertical emittance from ~2 um to 0.3-0.5 um (rms normalized). This requires a 13 MeV electron beam.

The LEC is an RF-based, single pass electron cooler.

Alexei Fedotov, TUA1, this conference
Dmitry Kayran, THB3, this conference

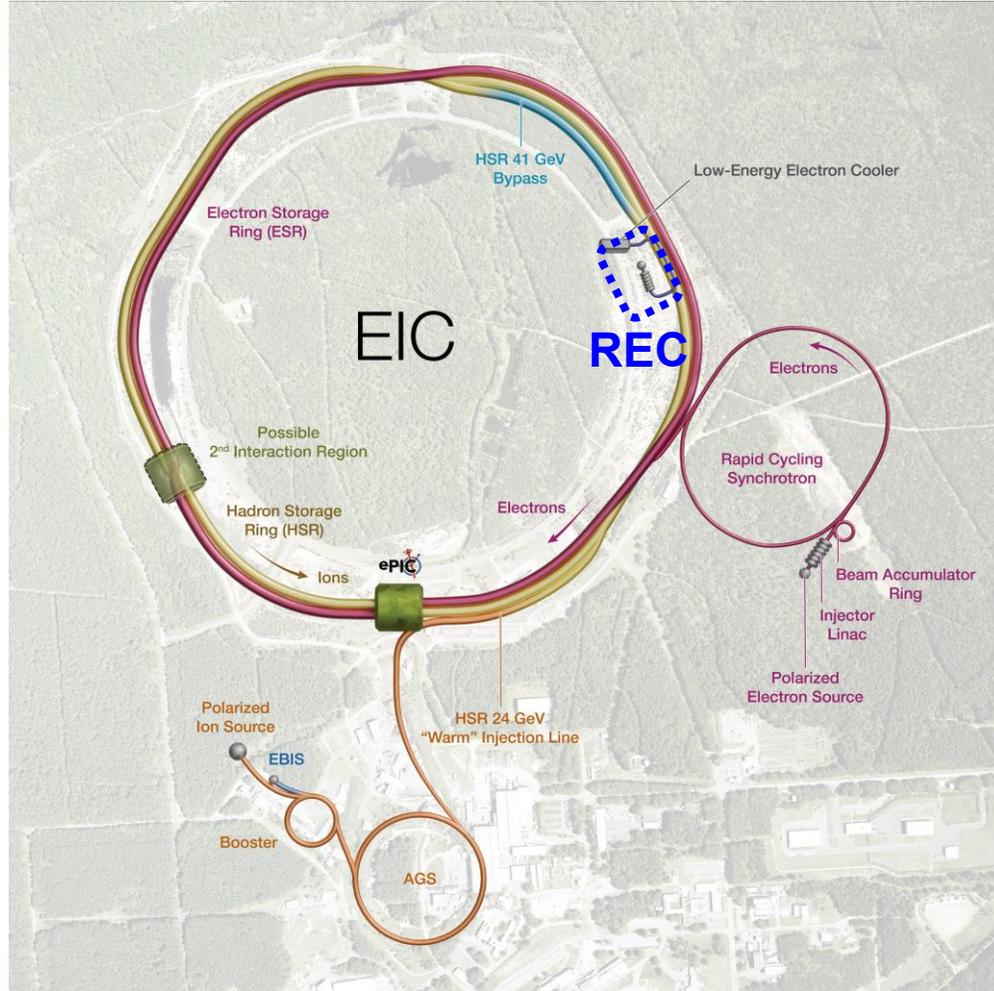*Sergei Nagaitsev, MOA1, this conference*

High-Energy Cooling of protons:

At EIC proton top collision energy ($\gamma = 293$), cooling should counteract the longitudinal and transverse emittance growth.

A cooler must be compatible with the LEC.

Cooling requirements for Electron Ion Collider (II)

Cooling protons at top energy:

Protons	
relativistic γ	293
number of particles per bunch	$6.9 \cdot 10^{10}$
geometric emittance (x, y) [nm]	11.3, 1
rms relative momentum spread	$6 \cdot 10^{-4}$
rms bunch length [cm]	6
required cooling times (x,z) [hrs]	**2, 3**

A prospective cooler must counteract the IBS-driven longitudinal and transverse emittance growth and maintain close to initial beam emittances.

Electron cooling is a well-established technique at low energy. To bring it to high energies one can employ a RF-based electron cooling.

The two options for high energy RF-based electron coolers for the EIC are:

Ring Electron Cooler

ERL with several-turns' storage ring

(*Dmitry Kayran, TUB2, this conference*)

Bringing Electron Cooling to high energies

$$\lambda \propto \frac{r_e^2 m_e c Z^2 \Lambda_c}{A_i m_p} \cdot \frac{1}{\gamma^2} \cdot N_e \cdot \frac{L_{CS}}{C_{ring}} \cdot \frac{1}{\left(\frac{\varepsilon_{ne}}{\beta_e} + \frac{\varepsilon_{ni}}{\beta_i}\right)(\varepsilon_{ne}\beta_e + \varepsilon_{ni}\beta_i)\sqrt{\sigma_{\delta e}^2 + \sigma_{\delta i}^2}\sqrt{\sigma_{ze}^2 + \sigma_{zi}^2}}$$

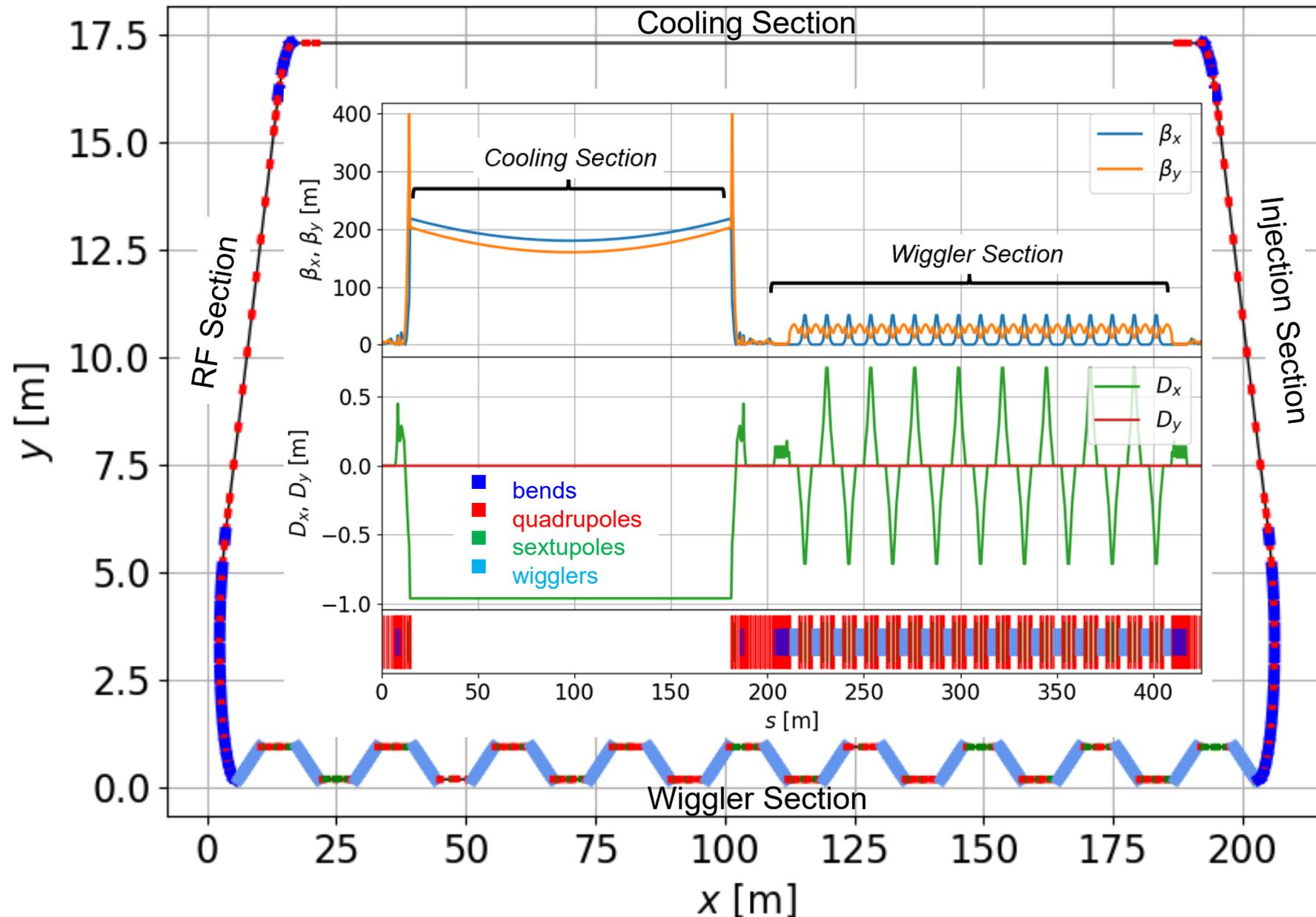- Cooling rate drops quadratically with energy but grows linearly with number of electrons and length of the cooling section. Precooling helps (smaller ion emittances), so do small e-bunch emittances. Yet, we don't want to make e-emittances much smaller than p-emittances:
  - The gains in cooling rate become small when $\varepsilon_e \ll \varepsilon_i$
  - $\varepsilon_e \ll \varepsilon_i$ → core overcooling (bad for collider)

- With available $L_{CS} = 170$ m and the required cooling time of $\tau_{cool(x,y)} = 2,3$ h, we need to have from hundreds of mA to a few A average e-current in the cooling section.
- **One needs to reutilize the same e-beam on several passes through the CS**

Ring Electron Cooler idea

- Keeping electrons in the electron storage ring for many turns helps to relax requirements to an average current from an injector

- As stored electrons are cooling hadrons, the hadrons are heating-up the electron bunches. The electrons' emittance will also be increased due to the IBS and other collective effects

- Electrons' emittance is kept constant with a help from damping wigglers

- Our approach to the Ring Electron Cooler is the RF-based, non-magnetized cooling.

- Non-magnetized, RF-based electron cooling was successfully employed in Low Energy RHIC Electron Cooler (LEReC), which provided cooling of gold ions (and substantially increased luminosity) during 2020-2021 RHIC run.

REC layout and lattice

Jorg Kewisch, THB2, this conference

- 170 m long cooling section (layout is compatible with EIC LEC)
- Ring circumference 426 m
- 140 e-bunches in the ring, each e-bunch makes 9 turns per 1 turn of hadrons in HSR
- Electrons are cooled by radiation damping in a wiggler section (18 damping wigglers, each wiggler 4.2 m long)
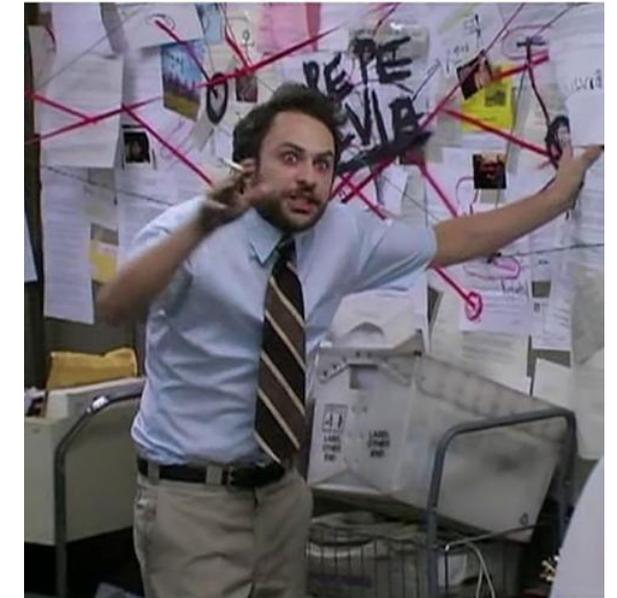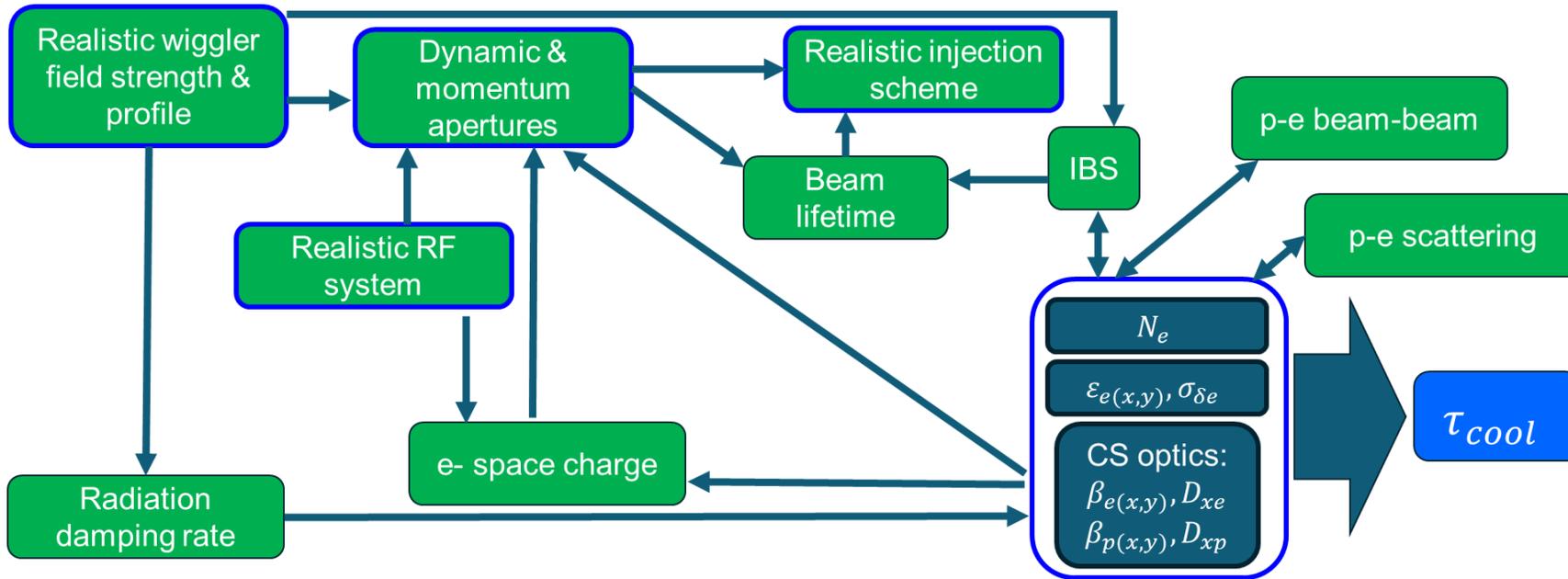
Factors driving REC design

Protons

relativistic γ	293
number of particles per bunch	$6.9 \cdot 10^{10}$
geometric emittance (x, y) [nm]	11.3, 1
rms relative momentum spread	$6 \cdot 10^{-4}$
rms bunch length [cm]	6
required cooling times (x,z) [hrs]	**2, 3**

- **Our goal is to achieve $\tau_{cool(x)} = $ 2h, $\tau_{cool(z)} = $ 3h with as small e-bunch charge as possible**
- Equilibrium e-bunch emittances are determined by a balance of the IBS rate, beam-beam scattering (BBS) rate, quantum excitations, and a rate of radiation damping. The equilibrium emittance is found by iterating:

$$\varepsilon_{new} = \frac{\lambda_{rad} + \lambda_{IBS}(\varepsilon_{old}) + \lambda_{BBS}(\varepsilon_{old})}{\lambda_{damping}}$$

- Considerations of electron beam dynamics in the REC must include
  - optimization of momentum and dynamic apertures (strongly affected by the choice of a wiggler field profile)
  - proton-electron beam-beam effect
  - self space charge
  - optimization of electron and proton beams optical functions in the cooling section to both maximize the cooling and to minimize BBS rate and beam-beam parameter

REC design is a multistep iterative process

- Choosing field profile of damping wigglers (strongly affects dynamic and momentum apertures)
- Finding equilibrium e-bunch parameters
- Choosing e- and p-bunches parameters in the cooling section (affect cooling rate, proton-electron beam-beam focusing, p-e beam-beam scattering)
- Checking resulting cooling rates, collective effects and beam lifetime.
- Optimizing the REC dynamic and momentum apertures, adjusting the REC lattice.

Electron Cooling with $z - x$ redistribution

- For any realistically achievable e-bunch parameters the longitudinal cooling is faster than the transverse one.
- Therefore, we employ $z \rightarrow x$ redistribution by introducing electron and ion horizontal dispersions into the cooling section.
- Respective analytic expressions in "Binney's form" (facilitating fast optimization algorithms) were derived

$$\lambda_x = -\frac{A_0}{\sigma_x \sigma_y \sigma_z}\left(\Psi_x + \kappa \Psi_z\right)$$

$$\lambda_y = -\frac{A_0}{\sigma_x \sigma_y \sigma_z}\Psi_y$$

$$\lambda_z = -\frac{A_0}{\sigma_x \sigma_y \sigma_z}\left(\Psi_z - \kappa \Psi_z\right)$$

$$\Psi_x = \int_0^\infty \frac{q^2 dq}{\left(1+2q^2\gamma^2\sigma_{\theta x}^2\right)^{3/2}\sqrt{1+2q^2\gamma^2\sigma_{\theta y}^2}\sqrt{1+2q^2\sigma_\delta^2}}$$

$$\Psi_y = \int_0^\infty \frac{q^2 dq}{\sqrt{1+2q^2\gamma^2\sigma_{\theta x}^2}\left(1+2q^2\gamma^2\sigma_{\theta y}^2\right)^{3/2}\sqrt{1+2q^2\sigma_\delta^2}}$$

$$\Psi_z = \int_0^\infty \frac{q^2 dq}{\sqrt{1+2q^2\gamma^2\sigma_{\theta x}^2}\sqrt{1+2q^2\gamma^2\sigma_{\theta y}^2}\left(1+2q^2\sigma_\delta^2\right)^{3/2}}$$

$$A_0 = \frac{4\sqrt{2}}{\pi}cr_e r_i \frac{\eta N_e \Lambda_C}{\gamma^2 \beta^3}$$

$$\kappa = \frac{D_{ex}D_{ix}\sigma_{\delta e}^2 + D_{ix}^2\sigma_{\delta i}^2}{\sigma_{xe}^2 + D_{ex}^2\sigma_{\delta e}^2 + \sigma_{xi}^2 + D_{ix}^2\sigma_{\delta i}^2}$$

$$\sigma_x = \sqrt{\sigma_{xe}^2 + D_{ex}^2\sigma_{\delta e}^2 + \sigma_{xi}^2 + D_{ix}^2\sigma_{\delta i}^2}$$

$$\sigma_y = \sqrt{\sigma_{ye}^2 + \sigma_{yi}^2}$$

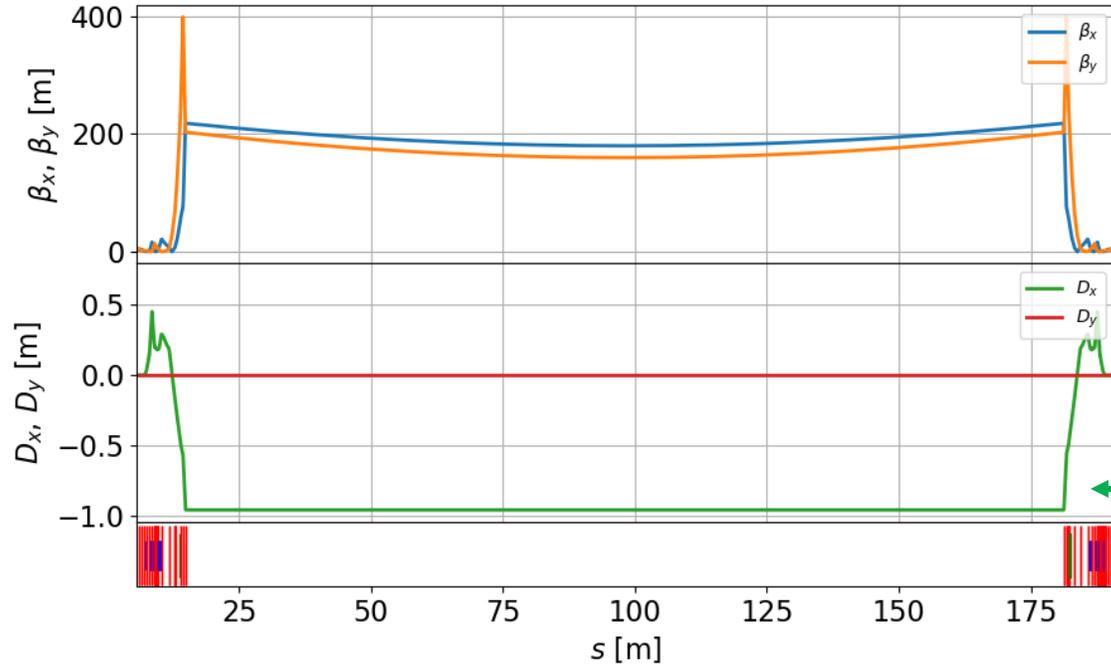$$\sigma_z = \sqrt{\sigma_{ze}^2 + \sigma_{zi}^2}$$

$$\sigma_{\theta x} = \sqrt{\sigma_{\theta xe}^2 + \sigma_{\theta xi}^2}$$

$$\sigma_{\theta y} = \sqrt{\sigma_{\theta ye}^2 + \sigma_{\theta yi}^2}$$

$$\sigma_\delta = \sqrt{\sigma_{\delta e}^2 + \sigma_{\delta i}^2 - \frac{\left(D_{ex}\sigma_{\delta e}^2 + D_{ix}\sigma_{\delta i}^2\right)^2}{\sigma_{xe}^2 + D_{ex}^2\sigma_{\delta e}^2 + \sigma_{xi}^2 + D_{ix}^2\sigma_{\delta i}^2}}$$

The paper is being prepared for publication

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Cooling section optimization (I)

- The REC shares the cooling section with the LEC
- 170 m long drift, shielding gives > 1000 attenuation
- LEC uses short solenoids every 12 m (they can be employed for REC e-beam, if needed)
- REC requires horizontal dispersion (D_{ex}) in the CS. Optics in the arcs is set to produce needed D_{ex}.
- A combination of cooling optimization and optimization of dynamic aperture resulted in the lattice with $D_{ex} = 1$ m in the CS

- Larger N_e improves the cooling rate, but it also increases IBS, thus increasing e-bunch emittances and making cooling worse. We use a dedicated code, which allows us to find an optimal combination of bunch charge and 6-D phase space volume
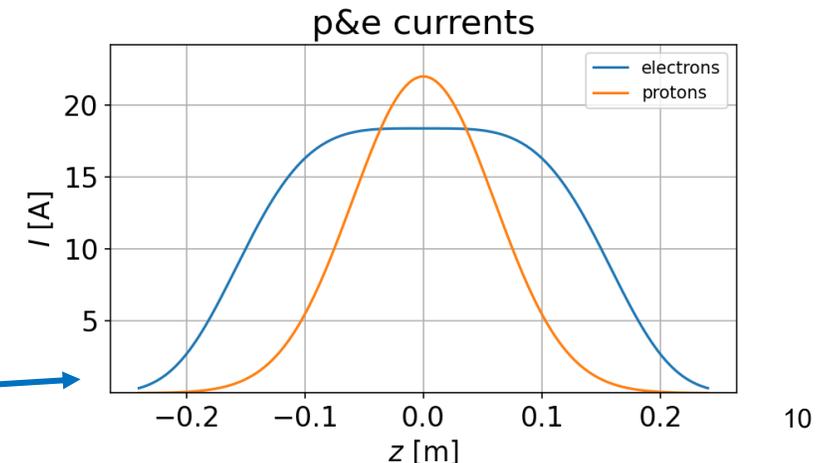
- **For optimized lattice we achieved:**
  $N_e = 1.3 \cdot 10^{11} \ (Q_e = 21 \ nC)$
  $\varepsilon_{xe} = \varepsilon_{ye} = 7.8 \ nm$
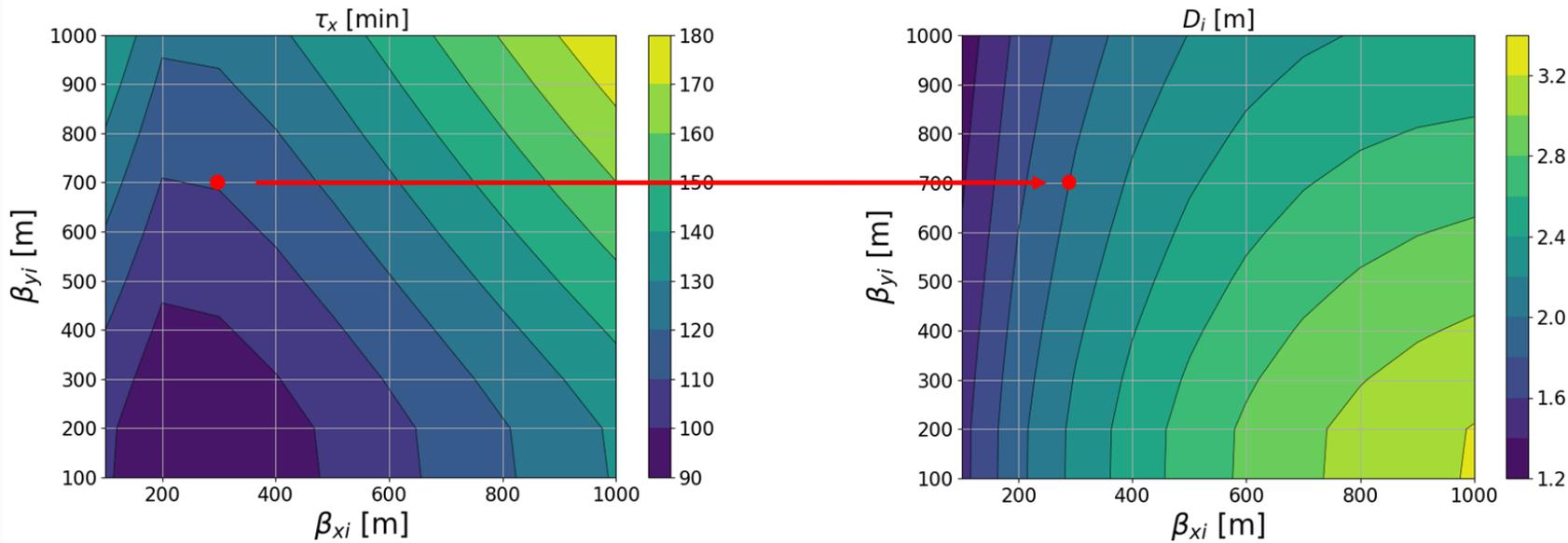 $\sigma_{pe} = 9.8 \cdot 10^{-4}$
  $L_{FWHM} = 34 \ cm$ (double-RF $\Leftrightarrow$ flat-top e-bunch, which helps to limit the space charge)

p&e currents

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Cooling section optimization (II)

- Finalized choice of e- and p- dispersions and β-functions in the CS, as well as the fine-tuning of the e-bunch charge is driven by cooling optimization.
- We use a set of codes to explore the space of beams' parameters in the CS and to optimize the CS Twiss functions for both beams.
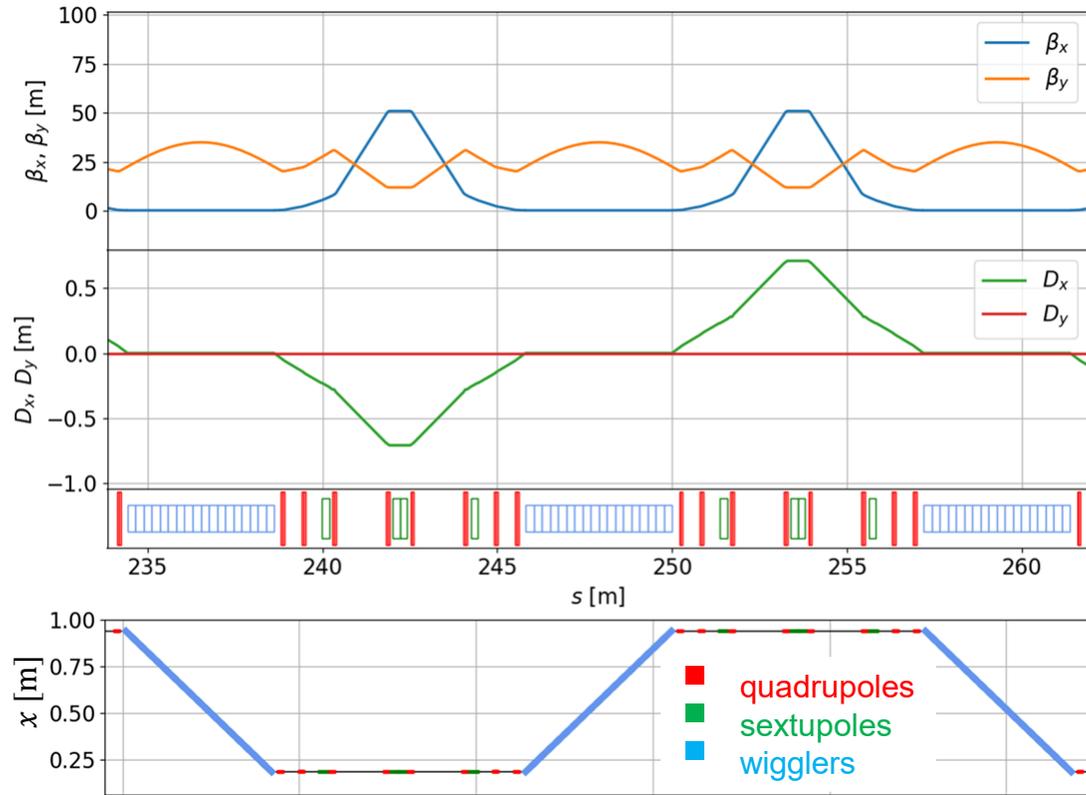
In this example the e-bunch parameters were fixed and the optimizer kept $\tau_z = 3$ h while minimizing τ_x by varying D_i for each combination of (β_{xi}, β_{yi}).

The ultimate choice of Twiss functions in the CS incorporates DA/MA optimization and consideration of beam-beam effect

CS parameter	electrons	protons
β_x [m]	180	300
β_y [m]	160	700
D_x [m]	1	2.1

REC wigglers

S. Seletskiy et al., *BNL-225896-2024-TECH, 2024*
https://technotes.bnl.gov/PDF?publicationId=225896

S. Seletskiy et al., *TUP073, NAPAC25*

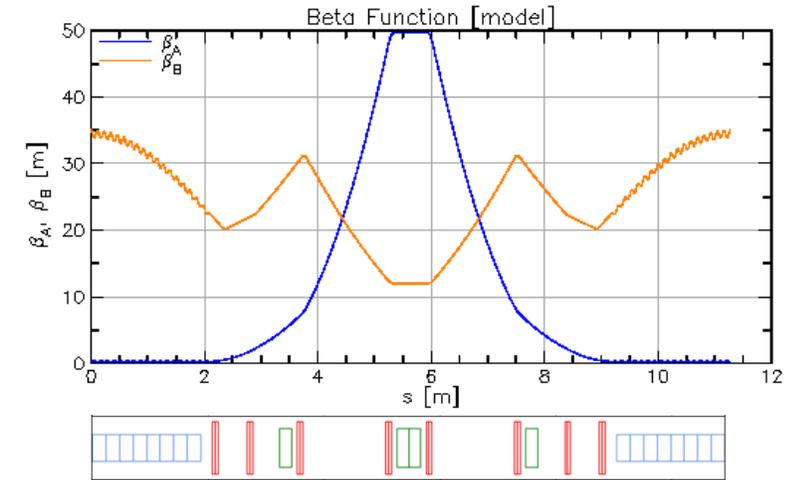https://prebys.physics.ucdavis.edu/NAPAC-25/proceedings/pdf/TUP073.pdf

- 18 wigglers, 4.2-m long each, with peak field of 2.4 T.
- We enter and exit wigglers with a non-zero angle. The regions with large dispersion between wigglers are used for chromaticity correction.
- To minimize the IBS-driven emittance growth in wigglers we need a tight focusing in horizontal direction (it minimizes H-function for small D_x, large D_x' case)
- Because we work with high field / low energy wigglers, a specific field profile is needed to minimize chromaticity

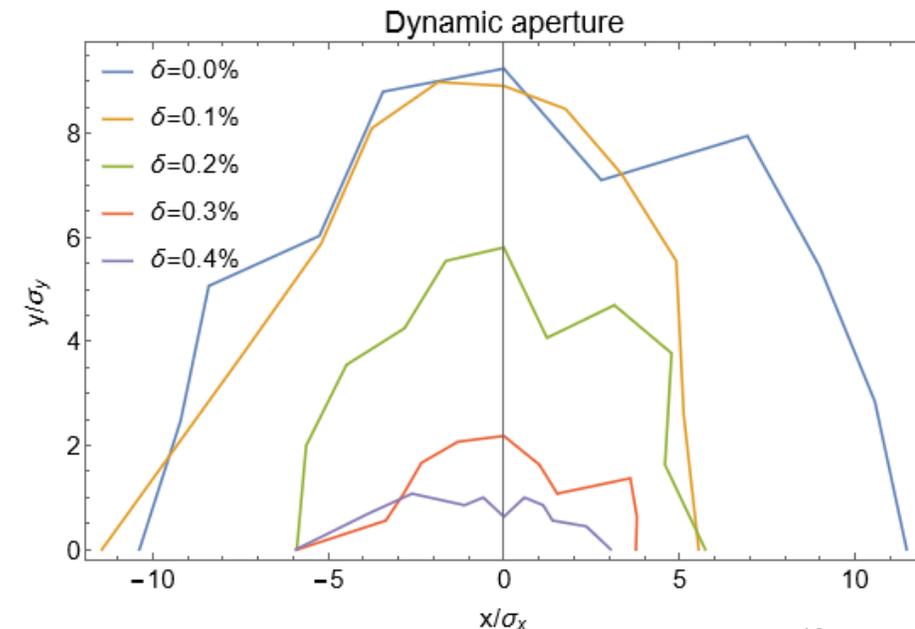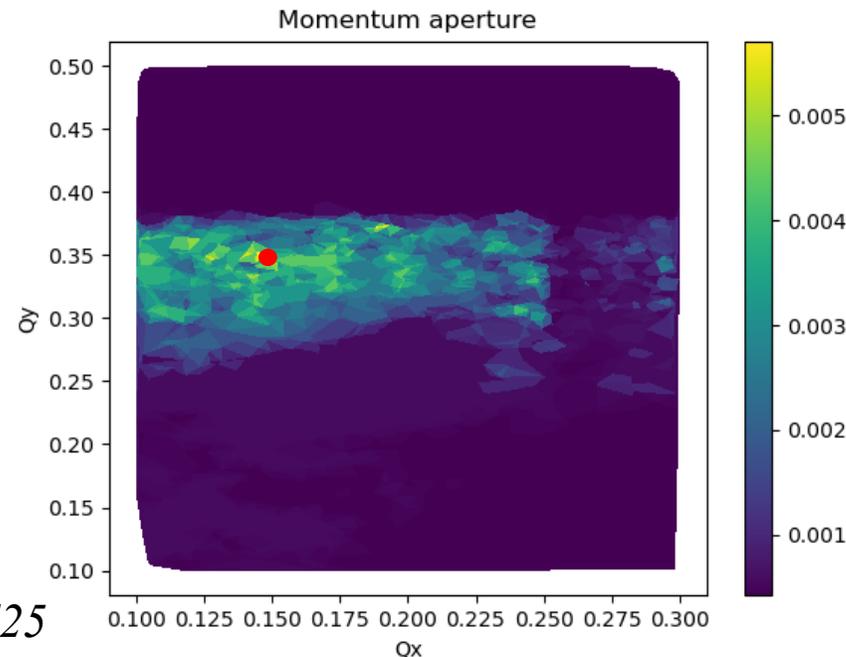- **It was confirmed that required wigglers parameters are achievable, and a preliminary design was created.**

Wiggler parameter	value
Number of wigglers	18
Length [m]	4.2
Peak field [T]	2.38
Period [m]	0.2
Gap [cm]	2
Radiated power (per wiggler) [W]	674

Dynamic and momentum aperture optimization

- Optimization of wigglers' field profile allowed to substantially reduce chromaticity and utilize weaker sextupoles

- Phase advance over wiggler and sextupole blocks is an important parameter for dynamic aperture

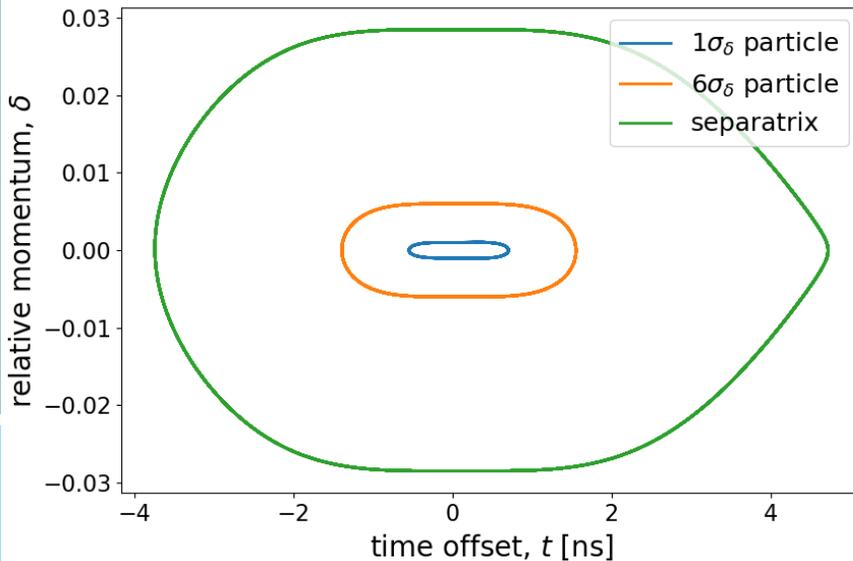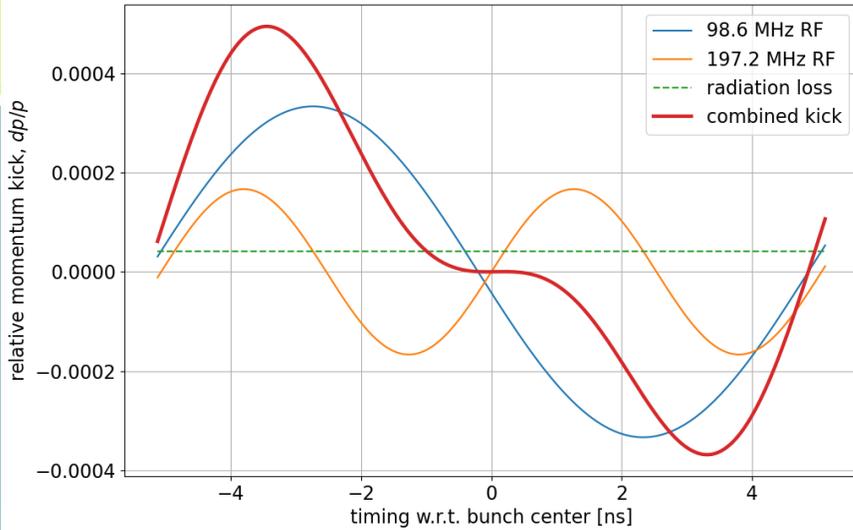- Two families of octupoles were optimized to reduce non-linear motion

- Tune was adjusted to maximize MA

- **Resulting DA/MA are:**

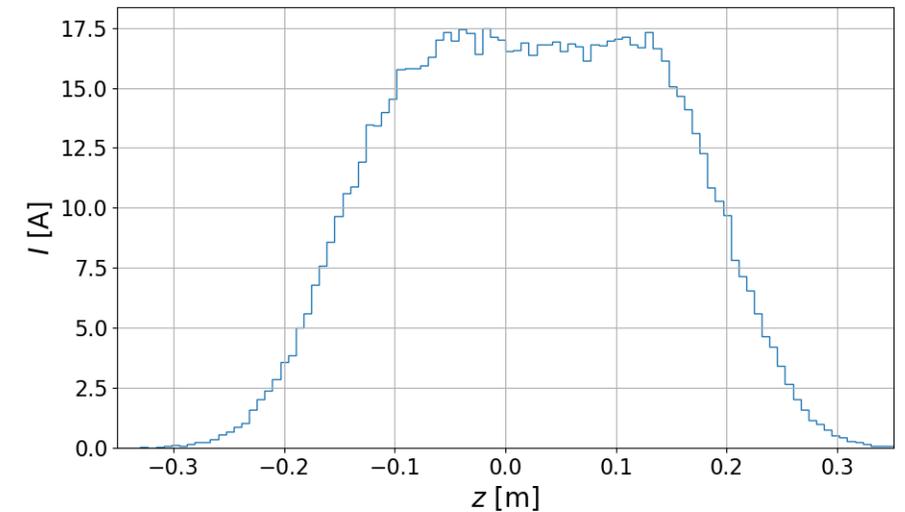 - $A_x = 10\sigma_x$
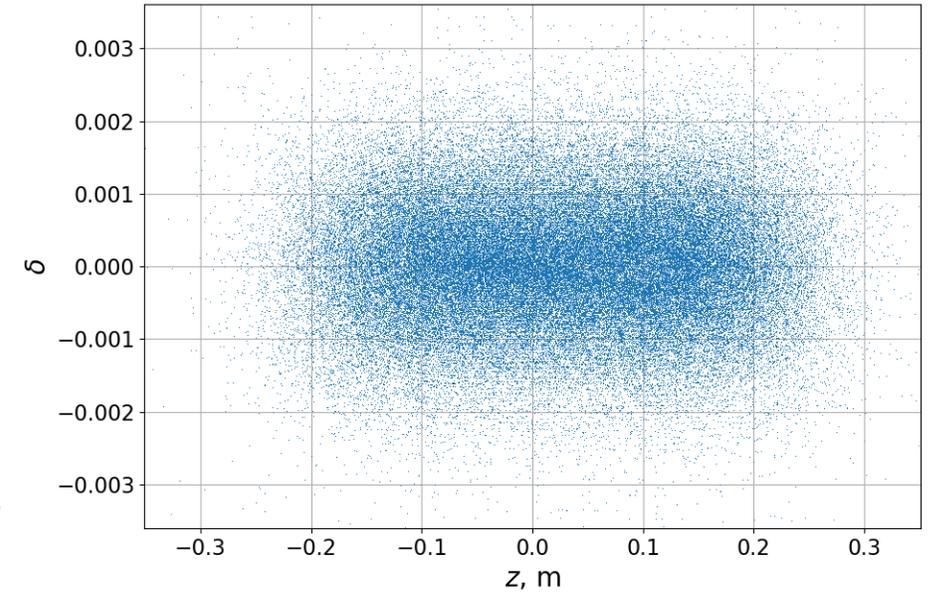
  - $A_y = 9\sigma_y$

  - $A_\delta = 0.5\,\%$

J. Unger et al., TUP031, NAPAC25

https://prebys.physics.ucdavis.edu/NAPAC-25/proceedings/pdf/TUP031.pdf

Beta Function [model]

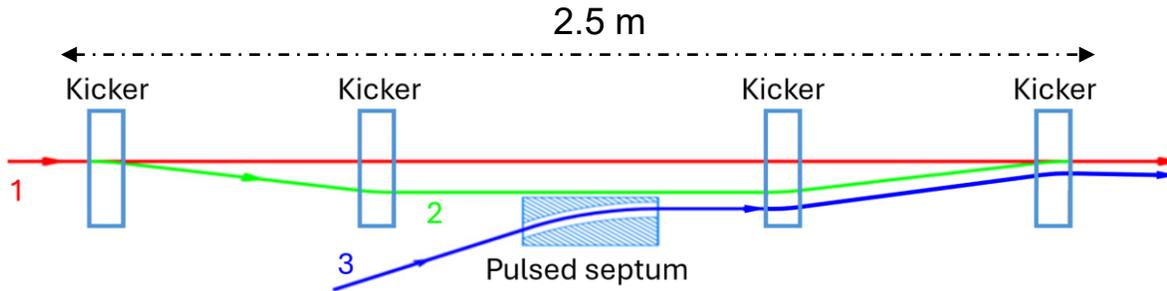Momentum aperture

Dynamic aperture

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REC RF system

- The ring utilizes a dual RF system with fundamental frequency of 98.6 MHz and voltage of 50 kV and the 2nd harmonic (25 kV).

- To compensate for the radiation loss of 6 kV/turn, the fundamental phase is shifted by 7.24 degrees.

- The resulting RF bucket corresponds to the flat-top e-bunch with FWHM length L_{FWHM}=34 cm and $\sigma_\delta = 9.8 \cdot 10^{-4}$.

- For $1.3 \cdot 10^{11}$ electrons per bunch, the peak current is $I_p = 17.5 \, A$

Injection scheme

Beam parameter	Stored	Injected
β_x [m]	60	20
ε_x [nm]	8	5
ε_{nx} [μm] (out of the gun)		1.5
Q_b [nC]	21	1.75

- We are planning to have a top-off injection replenishing 10% of each bunch every 1.6 s.

- Four kickers will create a closed bump bringing the stored beam closer to the injection septum. At the exit of the bump the injected beam will be displaced by 6 mm from the stored beam trajectory.
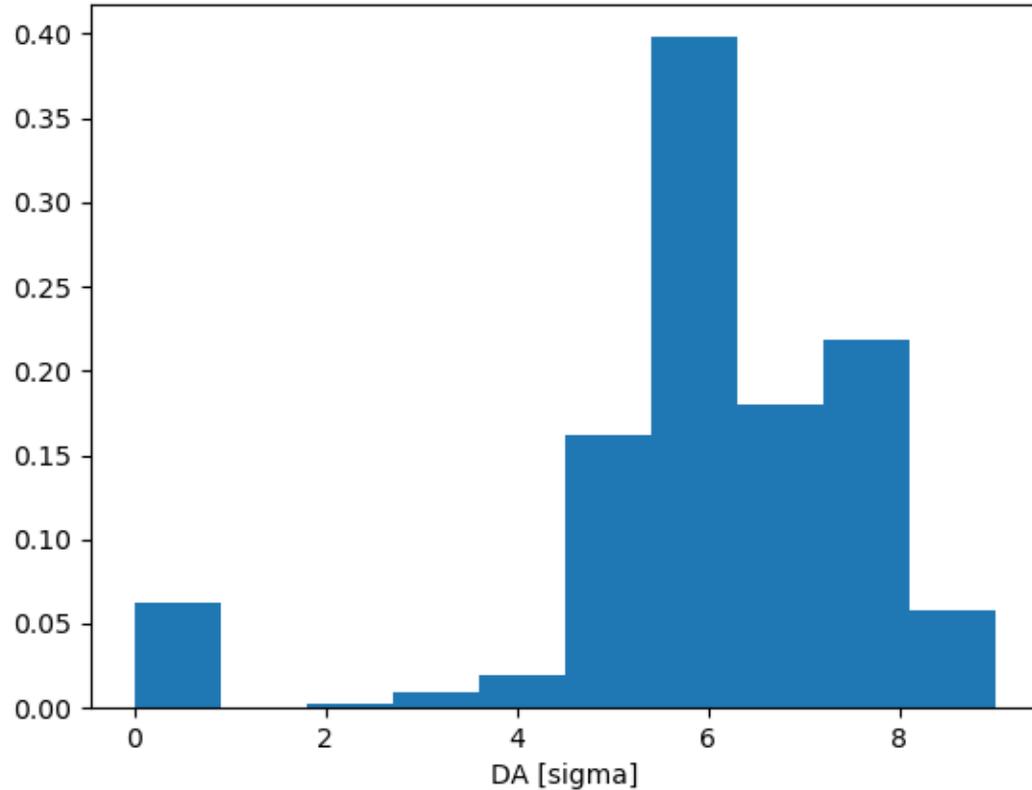
Parameter	Kicker	Septum
Maximum Field (B_k) [G]	760	7000
Magnetic Length (L_k) [m]	0.2	≥ 0.38
Pulse Shape	trapezoid	full $\sin$ - wave
Rise/Fall time [ns]	200	N/A
Flat-top duration [ns]	284	N/A
Wavelength (λ) [μs]	N/A	200
Repetition rate (f_k) [Hz]	3	3

- The injector will be running with $f_{inj} = 3$ Hz injecting into 1/5 of the ring (28 bunches) each time.

- Initial injection can be performed with $f_0 = 5$ Hz frequency, filling up the ring in 20 s.

Misalignment tolerances

DA spread for misalignments after correction with 10um BPM errors
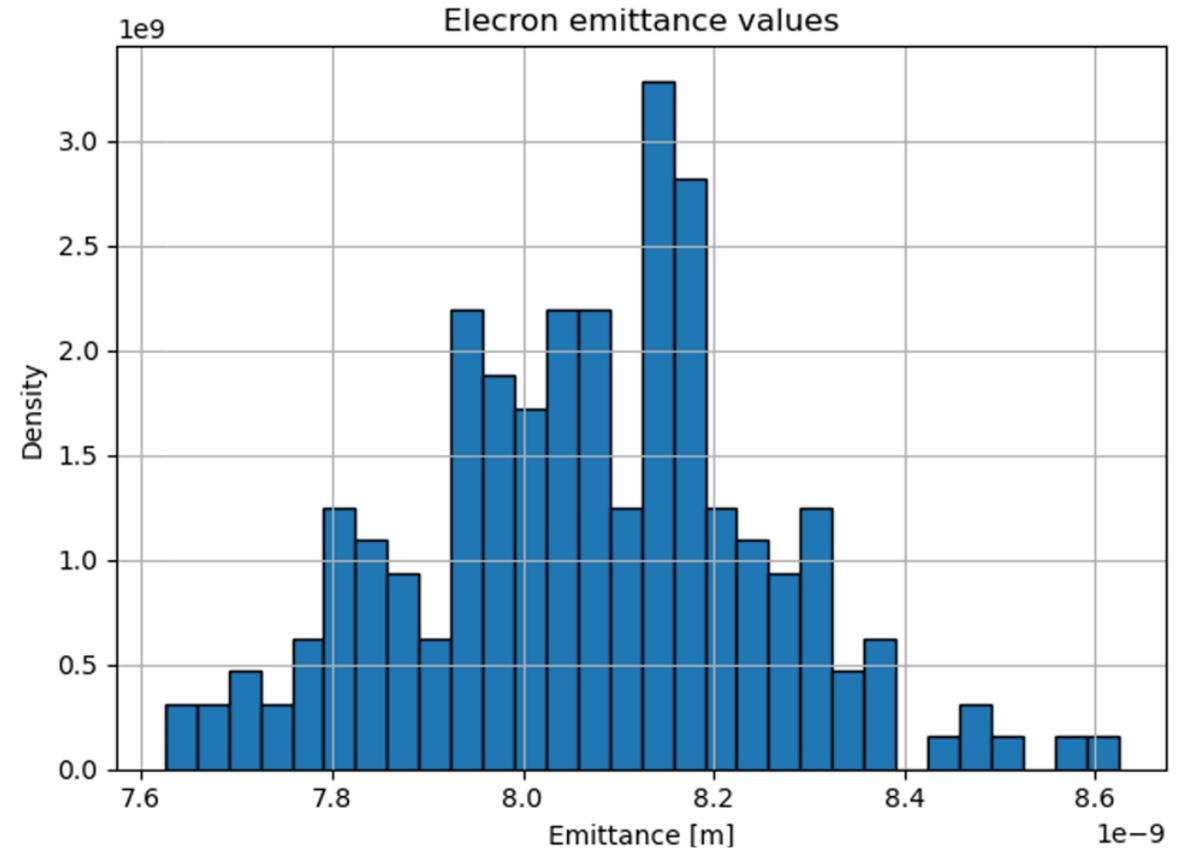

Elecron emittance values

Error RMS values:

Wigg: 50μm   Sextupole: 100μm

Quad: 50μm   BPM: 10μm

Dipole: 100μm

BPM and kicker at every quadrupole

Sextupoles set for linear chromaticity

Courtesy of J. Unger

Parameters

Table 1: The REC parameters (electron storage ring)

relativistic γ	293
ring circumference [m]	426
cooling section length [m]	170
horizontal dispersion in the CS [m]	1
number of damping wigglers	18
damping wiggler length [m]	4.2
damping wiggler field [T]	2.4
wiggler gap [cm]	2
wiggler period [cm]	20
momentum compaction	$-1.5 \cdot 10^{-3}$
main RF frequency [MHz]	98.6
main RF voltage [kV]	50
2nd harmonic RF voltage [kV]	25
number of bunches	140
number of particles per bunch	$1.3 \cdot 10^{11}$
charge per bunch [nC]	21
peak current [A] (flat top e-bunch)	17.5
average current [A]	2
geometric emittance (x, y) [nm]	7.8, 7.8
CS β-function (x, y) [m]	180, 160
rms relative momentum spread	$9.8 \cdot 10^{-4}$
FWHM bunch length (flat top e-bunch) [cm]	34
space charge tune shift (x,y)	0.14, 0.14
p-e focusing tune shift (x,y)	0.04, 0.09
radiation damping rate (x,y,z) [s^{-1}]	31, 31, 62
BBS rate (x,y,z) [s^{-1}]	0.8, -0.3, 12
IBS rate (x,y,z) [s^{-1}]	31, 31, 48

Table 2: The REC parameters (protons)

relativistic γ	293
number of particles per bunch	$6.9 \cdot 10^{10}$
geometric emittance (x, y) [nm]	11.3, 1
CS β-function (x, y) [m]	300, 700
rms relative momentum spread	$6 \cdot 10^{-4}$
rms bunch length (Gaussian p-bunch) [cm]	6
horizontal dispersion in the CS [m]	2.1
e-p focusing tune shift (x,y)	$1 \cdot 10^{-4}$, $1.7 \cdot 10^{-4}$
cooling time (x,y,z) [hrs]	**2, 4, 3**

Due to cooling optimization and optimization of REC lattice we reduced bunch charge, average current and peak current by a factor of ~2.5, as compared to the initial REC design
(*H. Zhao, J. Kewisch, M. Blaskiewicz, A. Fedotov, Phys. Rev. Accel. Beams 24, 043501, (2021)*
https://link.aps.org/doi/10.1103/PhysRevAccelBeams.24.043501)
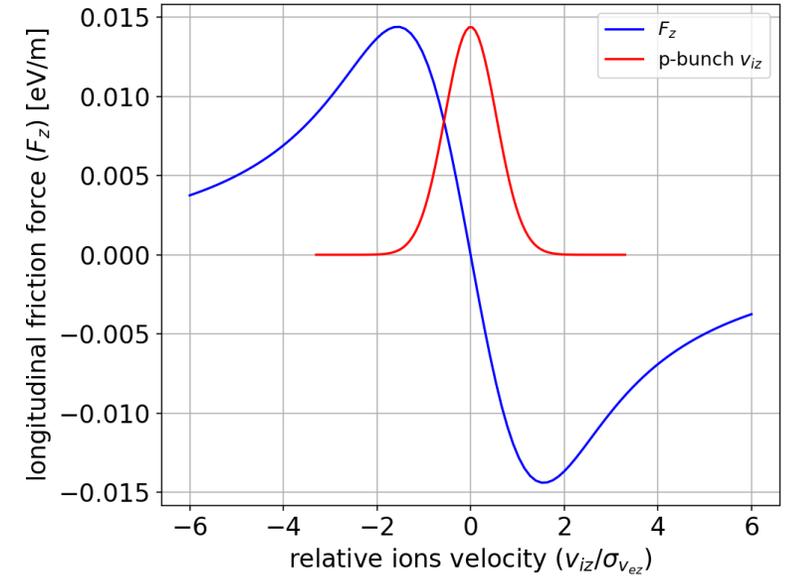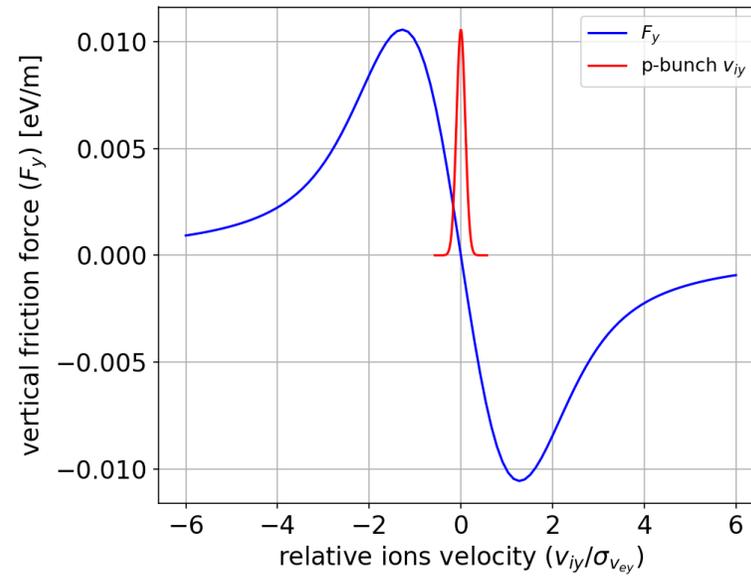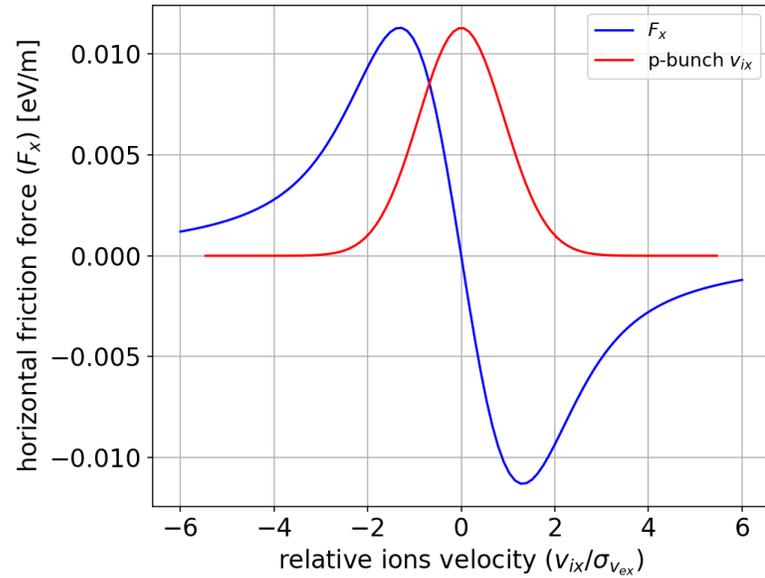
Summary

- The Ring Electron Cooler is designed to provide the cooling required for the EIC operation at the top energy.

- Optimization of the REC parameters allowed us to reduce the bunch charge and average current by a factor of ~2.5 as compared to preliminary REC design.

- The realistic lattice for the REC compatible with the EIC Low Energy Cooler was developed and optimized. The damping wigglers with realistic fields and optimized chromaticity contribution were developed. The conceptual design of the injection and RF systems was devised.

- A detailed study of various possible instabilities (CSR-driven microwave instability, transverse and longitudinal coupled-bunch instability, electron-ion instability etc.) in the REC is ongoing.
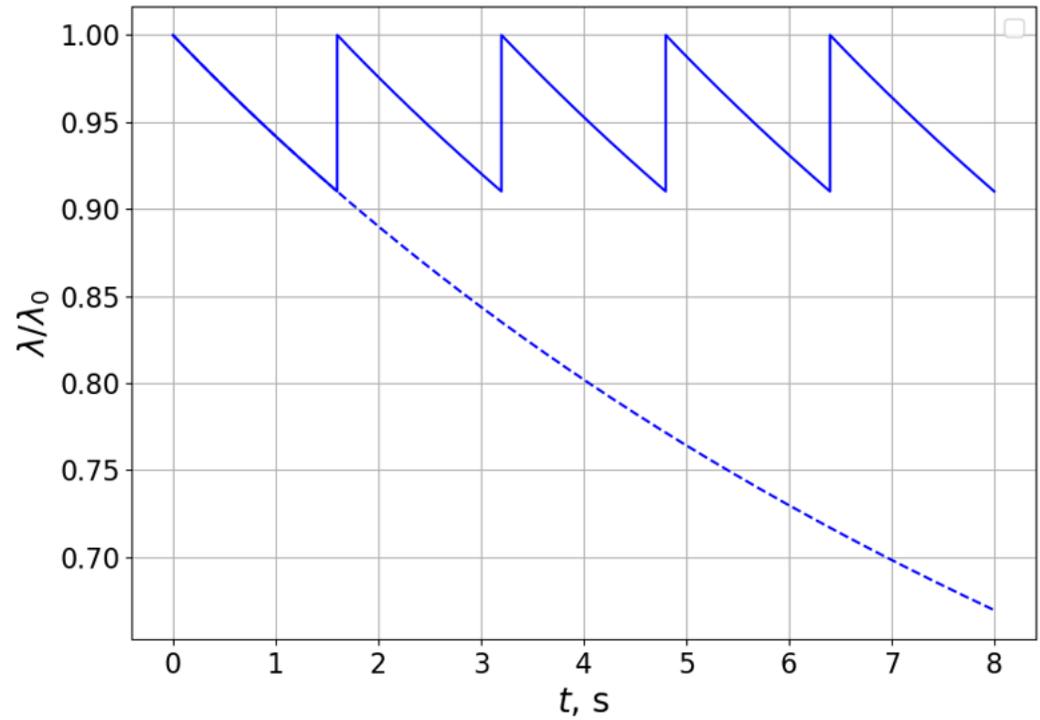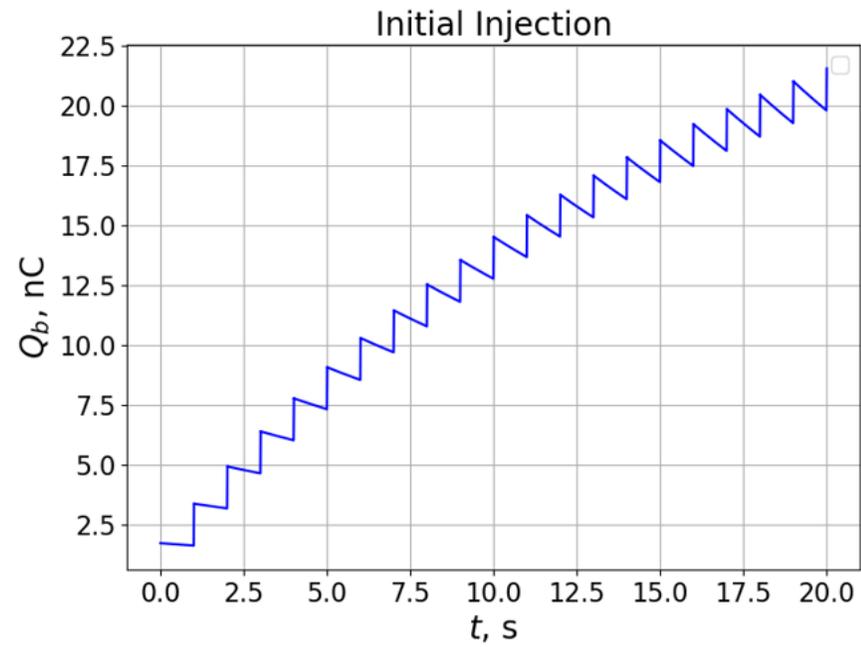
S. Seletskiy et al., "Ring Electron Cooler for Electron Ion Collider", BNL-228463-2025-TECH, 2025.
https://technotes.bnl.gov/PDF?publicationId=228463

Brookhaven National Laboratory

Additional slides

Cooling force

Injection

Longitudinal single bunch instability

The Keil-Schnell-Boussard criterion gives threshold of 78 mΩ:

$$\left|\frac{Z_\parallel}{n}\right| \lessapprox \sqrt{\frac{\pi}{2}} Z_0 \frac{\gamma \alpha_p \sigma_\delta^2 \sigma_z}{r_e N_e}$$

For REC parameters the resistive wall impedance is ≈25 mΩ:

$$\left|\frac{Z_\parallel}{n}\right|_{RW} = (1-i) \frac{\sigma_z}{r_{ch}\sigma_{con}\delta_{skin}}$$

From scaling the NSLS-II results it is expected that for the REC the reasonable resistive wall impedance is ≈47 mΩ
Blednykh et al., Phys. Rev. Accel. Beams 26, 051002 (2023)

The remedy for possible problems with CSR impedance from the wigglers is smoothly varying the wiggler's gap

Transverse mode-coupling instability

For REC parameters $Z_\perp^{thr} = 5 \text{ k}\Omega/\text{m}$

From the Panofsky-Wenzel theorem the transverse resistive wall impedance is 3.8 kΩ/m:

$$Z_\perp^{RW} = \frac{C_R}{\pi r_{ch}^2} \left| \frac{Z_\parallel}{n} \right|_{RW}$$

Lattice