Electron cooler for high-energy hadrons in the EIC based on ERL

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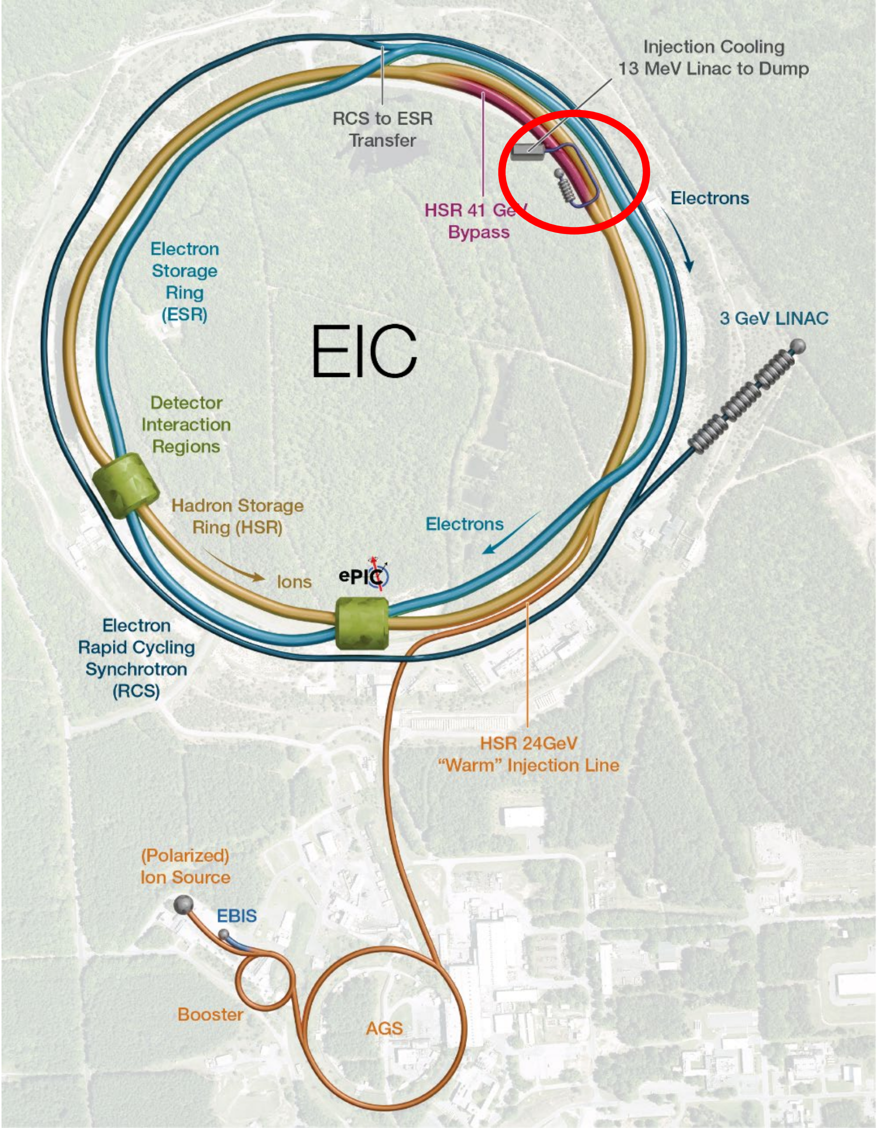
Brookhaven National Laboratory

Outline

- Motivation
- Why regular electron cooler
- Required beam parameters
- Challenges and our vision
- Conclusion



EIC parameters and cooling goals

Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

Strategy to get required luminosity

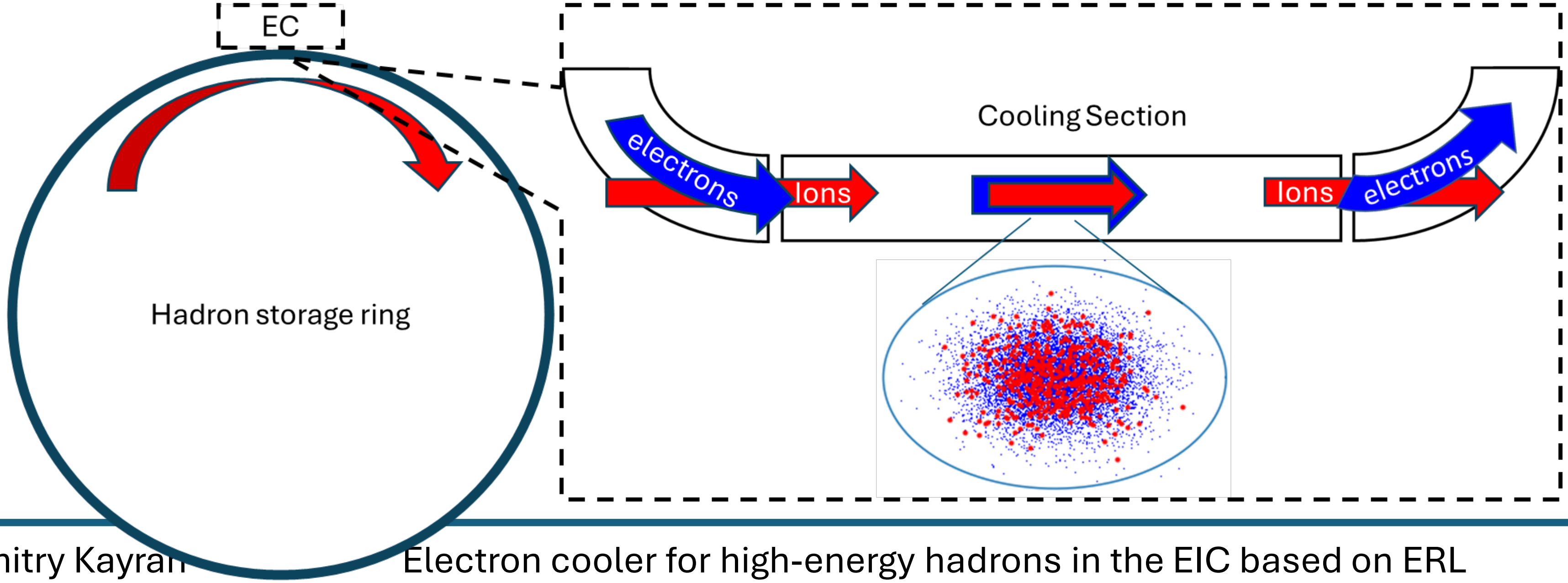
Use Low-Energy cooler to obtain initial proton beam parameters

Ramp up to the store energy

Provide cooling at store energy to compensate IBS (2-3 hours)) and other possible bunch degradation effects

What is Electron Cooling?

- Mix a hadron bunch with an electron bunch traveling with the same velocity and let the two bunches travel together over some length. ➡ The velocity spread of hadrons will get reduced. Why?
- In the co-moving frame, the mixture of an ion bunch and an electron bunch looks like a mixture of two gases – a gas of ions and a gas of electrons
- Electrons are much lighter; hence, the gas of electrons is much colder than the gas of ions. ➡ Heat transfer ≡ Electron Cooling

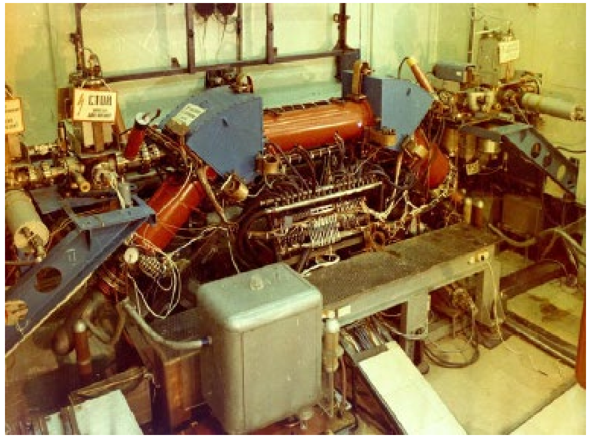


$$m_e \ll m_i$$

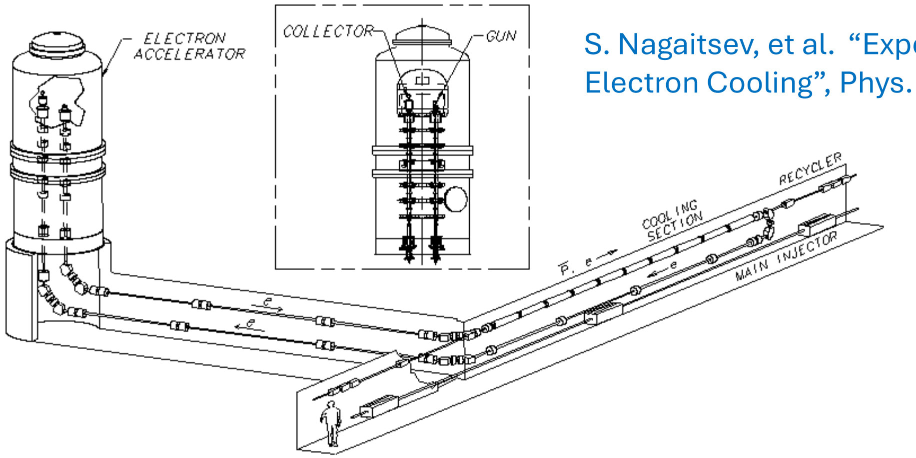
$$T = \frac{m\bar{v}^2}{3k_B}$$

$$T_e \ll T_i$$

Electron Cooling



Experimental demonstration of electron cooling at NAP-M (Novosibirsk, 1974).



S. Nagaitsev, et al. "Experimental Demonstration of Relativistic Electron Cooling", Phys. Rev. Lett. 96, 044801 (2006)

- **Electron Cooling is a well-established technique with 50 years of experimental experience**

High Voltage DC coolers: (1974-): all DC electrostatic accelerators; all use magnetic field to confine electron beam (magnetized cooling). **FNAL cooler (2005-11):** Extension to relativistic energies (4MeV electrons), transport of electron beam without continuous magnetic field.

RF acceleration (High Energy approach): BNL LEReC electron cooler (2019-21): First RF-linac based electron cooler (concept directly extendable to higher energies). LEReC does not use any magnetization of electrons. LEReC was successfully used for RHIC operations in 2020-21 to cool ion bunches directly at collision energy.

A. V. Fedotov et al. "Experimental Demonstration of Hadron Beam Cooling Using Radio-Frequency Accelerated Electron Bunches", Phys. Rev. Lett. 124, 084801 (2020)

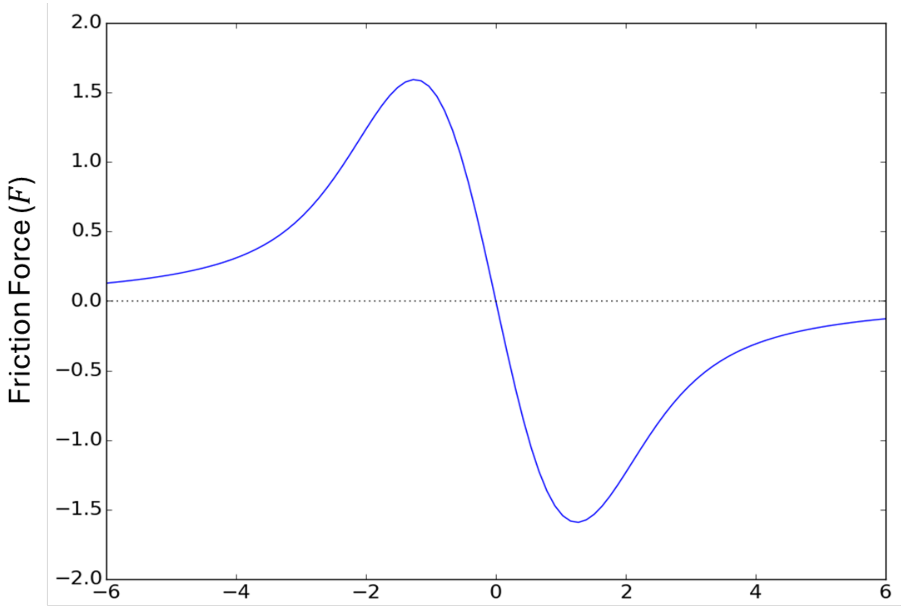
Friction force in Electron Cooling

$$\vec{F} = -\frac{4\pi n_e e^4 Z_i^2}{m_e}\int \Lambda_C \frac{\overrightarrow{v_i} - \overrightarrow{v_e}}{|\overrightarrow{v_i} - \overrightarrow{v_e}|^3} f_e(v_e) d^3 v_e$$

- density of electron bunch: n_e
- ion velocity: $\overrightarrow{v_i}$
- electron velocity: $\overrightarrow{v_e}$
- e-velocity distribution function: $f_e(v_e)$

Coulomb logarithm $\Lambda_C = \ln\left(\frac{\rho_{max}}{\rho_{min}}\right)$

$$\rho_{min} = \frac{Ze^2}{m_e}\frac{1}{|\overrightarrow{v_i} - \overrightarrow{v_e}|^2}; \quad \rho_{max} = \max\left(\frac{\langle v_i\rangle}{\sqrt{4\pi n_e r_e c^2}}, \frac{\langle v_i\rangle}{L_{CS}\gamma\beta c}\right)$$



ion velocity relative to electrons' velocity spread (v_i/σ_{v_e})

- 1943

DYNAMICAL FRICTION

I. GENERAL CONSIDERATIONS: THE COEFFICIENT OF DYNAMICAL FRICTION

S. CHANDRASEKHAR
Yerkes Observatory
Received January 7, 1943

ABSTRACT

In this paper it is shown that a star must experience *dynamical friction*, i.e., it must suffer from a systematic tendency to be decelerated in the direction of its motion. This dynamical friction which stars experience is one of the direct consequences of the fluctuating force acting on a star due to the varying complexion of the near neighbors. From considerations of a very general nature it is concluded that the *coefficient of dynamical friction*, η, must be of the order of the reciprocal of the time of relaxation of the system. Further, an independent discussion based on the two-body approximation for stellar encounters leads to the following explicit formula for the coefficient of dynamical friction:

$$\eta = 4\pi m_1 (m_1 + m_2)\frac{G^2}{v^3}\log_e\left[\frac{D_0 \overline{|u|^2}}{G(m_1+m_2)}\right]\int_0^v N(v_1)dv_1 ,$$

- 1956; 1966

AN EFFECTIVE METHOD OF DAMPING PARTICLE OSCILLATIONS IN PROTON AND ANTIPROTON STORAGE RINGS

G. I. Budker

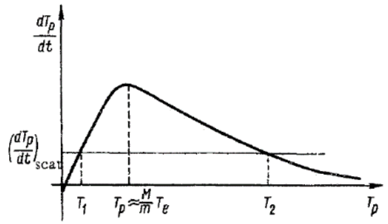


Fig. 1. Rate of change of the proton temperature during interaction with electrons.

S.T. Belyaev and G.I. Budker, Doklady Akad. Nauk SSSR, 107, 807 (1956).

- 1977

Particle Accelerators
1977, Vol. 8, pp. 1–20

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THE KINETICS OF ELECTRON COOLING OF BEAMS IN HEAVY PARTICLE STORAGE RINGS†

YA. S. DERBENEV and A. N. SKRINSKY
Institute of Nuclear Physics, Siberian Division, USSR Academy of Sciences, Novosibirsk 90, USSR

(*Received September 16, 1976*)

$$\mathbf{F}^0 = -\frac{4\pi n Z^2 e^4}{m}\int L^0(u)\frac{\mathbf{u}}{u^3} f(\mathbf{v}_e)d^3 v_e \quad (2.2)$$

Cooling rate scaling with beam parameters

- $\lambda \propto \frac{1}{\gamma^2}$ - cooling rate drops quadratically with energy
- $\lambda \propto N_e$ - cooling rate grows linearly with number of electrons
- $\lambda \propto L_{CS}$ - cooling rate grows linearly with the length of the cooling section
- $\lambda \propto \frac{1}{\left(\frac{\varepsilon_{ne}}{\beta_e}+\frac{\varepsilon_{ni}}{\beta_i}\right)(\varepsilon_{ne}\beta_e+\varepsilon_{ni}\beta_i)\sqrt{\sigma_{\delta e}^2+\sigma_{\delta i}^2}\sqrt{\sigma_{ze}^2+\sigma_{zi}^2}}$ - in an approximation of negligible ions' 6D emittance the cooling rate is inversely proportional to the normalized electrons' emittance.

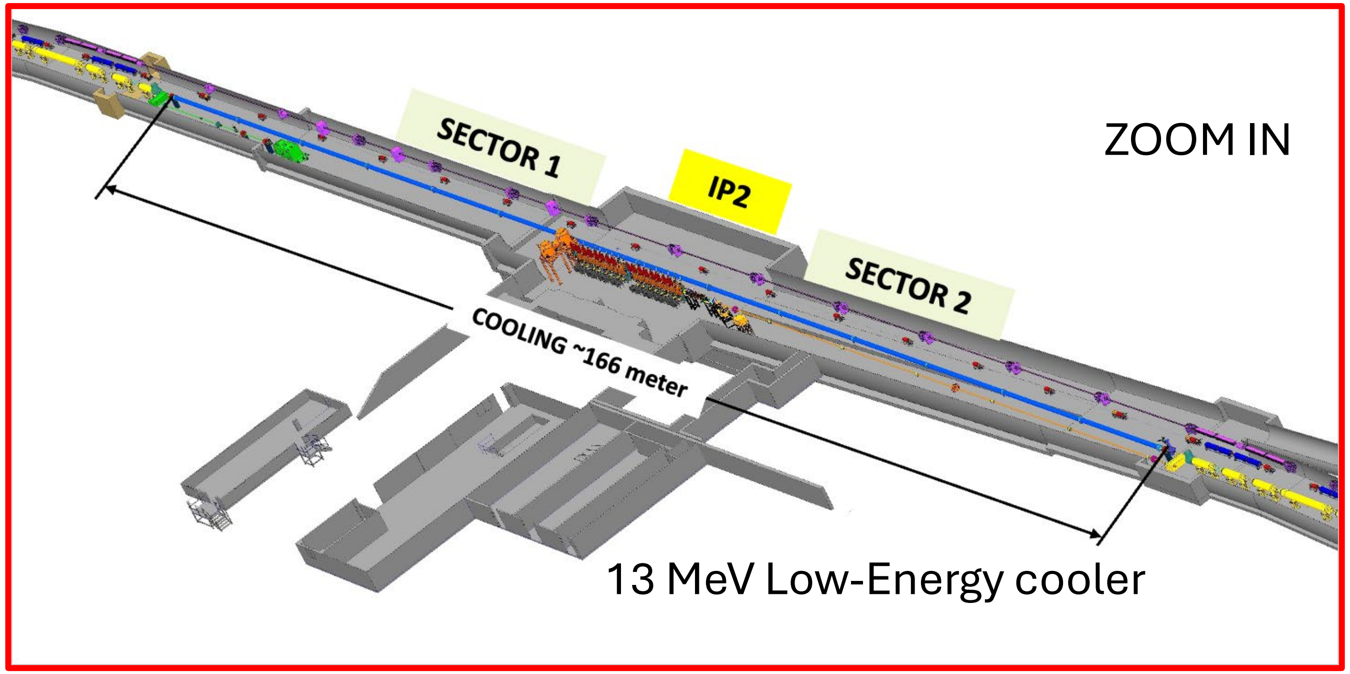
- Yet, we don't want to make e-emittances much smaller than i-emittances:
  - The gains in cooling rate become small when $\varepsilon_e \ll \varepsilon_i$
  - $\varepsilon_e \ll \varepsilon_i \quad \rightarrow$ core overcooling (bad for collider)

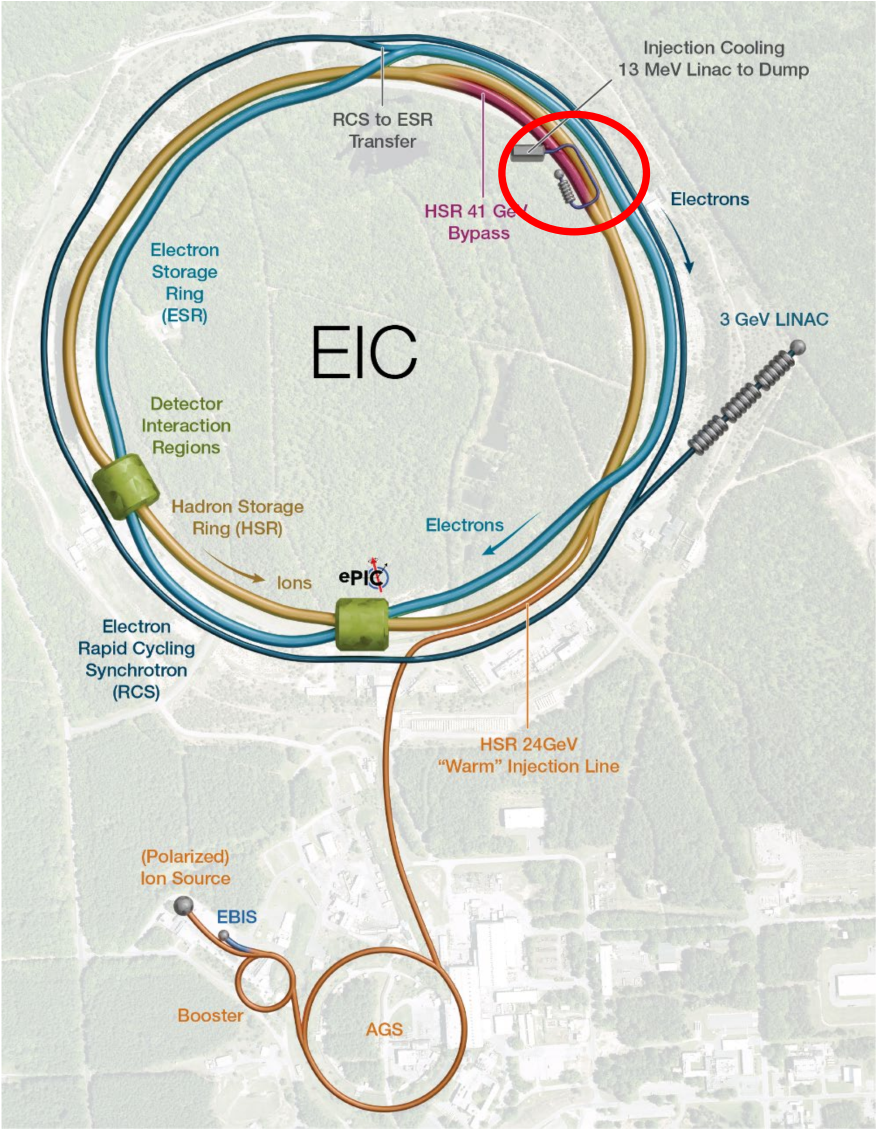
How to design High Energy Electron Cooler

- Start with the Electron Cooling theory:
  - Figure out what length of the cooling section is available in the hadron storage ring (the longer the better)
  - Assume transversely symmetric velocity distribution for the hadron bunch, completely match e-bunch to your hadrons
  - Use simple analytic formulas to estimate requirements to electrons' charge per hadron bunch (Q_e)
  - If you see that $\lambda_{\parallel} \leftrightarrow \lambda_{\perp}$ redistribution is beneficial then use a little bit bulkier redistribution formulas to reduce Q_e (calculations with redistribution formulas still can be done with pen and paper)
- Now, that you know both the required Q_e and $f_e = f_h$, estimate the requirements to average electron current $\langle I_e \rangle$
  - Most probably you will decide that you need a bunched electron cooling
  - Decide whether you need several (maybe many) recirculations of electrons or you can get away with a single pass machine
- It is time to decide whether you want to build a high energy high current ERL with just a few recirculations or an electron storage ring

Cooler’s location

- Both the pre-cooler and the top energy cooler are located at a 2 o’clock hall.
- They must share the same section of the Hadron Storage Ring (HSR)
- About 170 m of the HSR are available for the cooling section



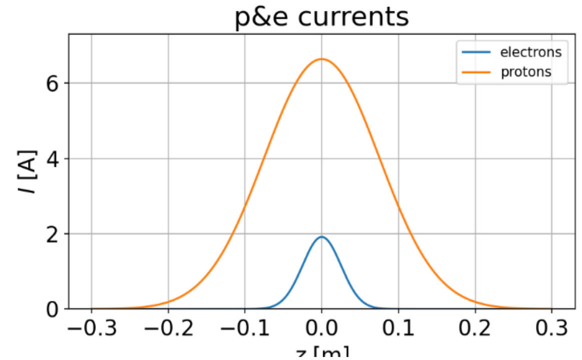


Basic required parameters for different EIC protons energies

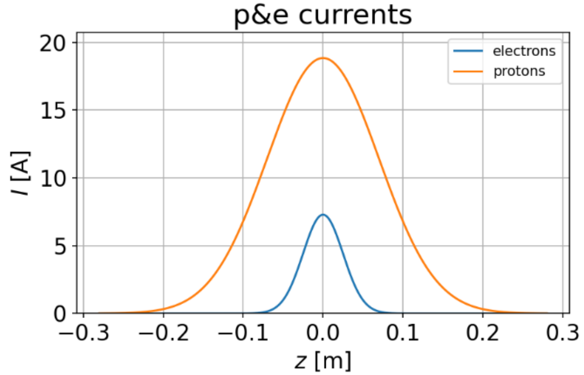
Proton Energy , GeV	275	100	41
Ne	3.00E+10	1.25E+10	4.00E+09
Qe, nC	5	2	0.64
Rms bunch length, cm	2.5	2.5	2.5
Peak Current, A	24	10	3
Rep rate, MHz	98	98	98
I ave in CS, mA	490	196	63
N _rec	7-9	3-4	1
Iav Gun, mA	70-54	65-49	63
Rms energy Spread in CS	3.00E-04	3.00E-04	3.00E-04
RMS Angular spread in CS, rad	5.20E-06	1.70E-05	2.60E-05
RMS Normilized Emittance, m	2.00E-06	1.50E-06	1.50E-06
Cooling Time_x, hrs *	1.8	1.9	2
Cooling Time_y, hrs *	3.6	3.9	1.8
Cooling Time_z, hrs *	2.9	1.6	1

*) The cooling rates assumed 177 m cooling cooling section and averaging by beta- and synchrotron oscillations of protons

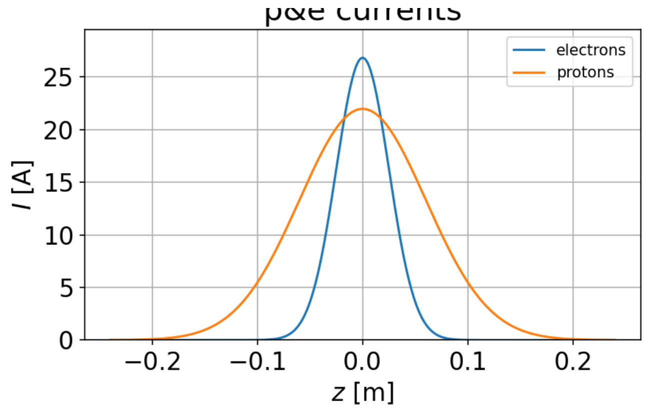
41 GeV protons



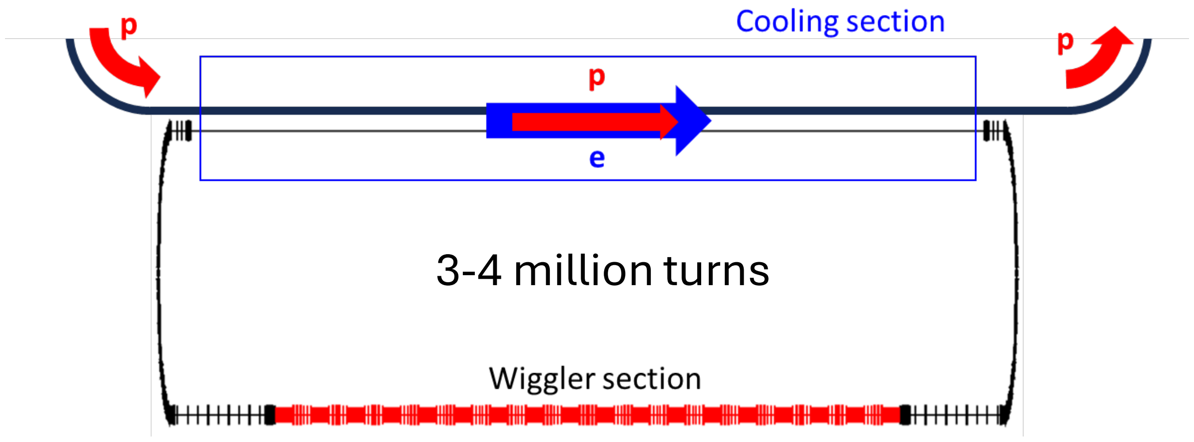
100 GeV protons



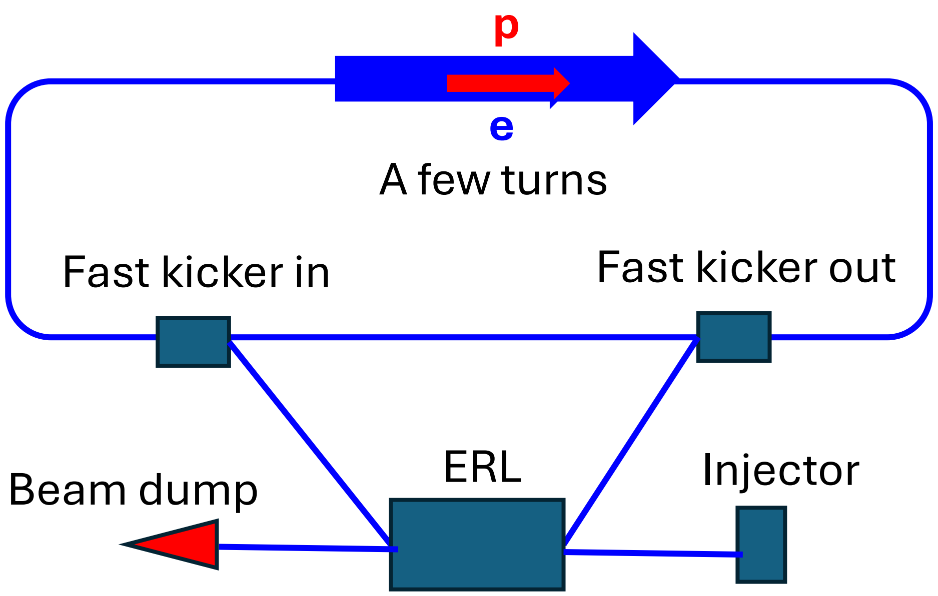
275 GeV protons



High-Energy Cooler based on reusing electron bunch several times



Ring based cooler use electron bunch a few million times



The feasibility studies are going on right now at BNL/Cornell

The present approach to Ring Electron Cooler (non-magnetized cooling) has some constraints :

- Self-space charge
- Proton-electron focusing
- Beam-beam scattering in the cooling section
- To counteract IBS+BBS one needs strong damping wigglers
- Low Energy High Current Ring instability
- Also ring cannio be scaled to cool 100GeV or 41 GeV

ERL with passing through the cooling section a few times

Less interaction with protons per e-bunch,
Better bunch quality for the same bunch charge
More flexibility to choose operational energy

Challenges & Mitigation

Challenges

- High average current operation of injector
- High bunch charge operation
- High peak current operation
- Produce and preserve small energy spread and emittances for the high intensity

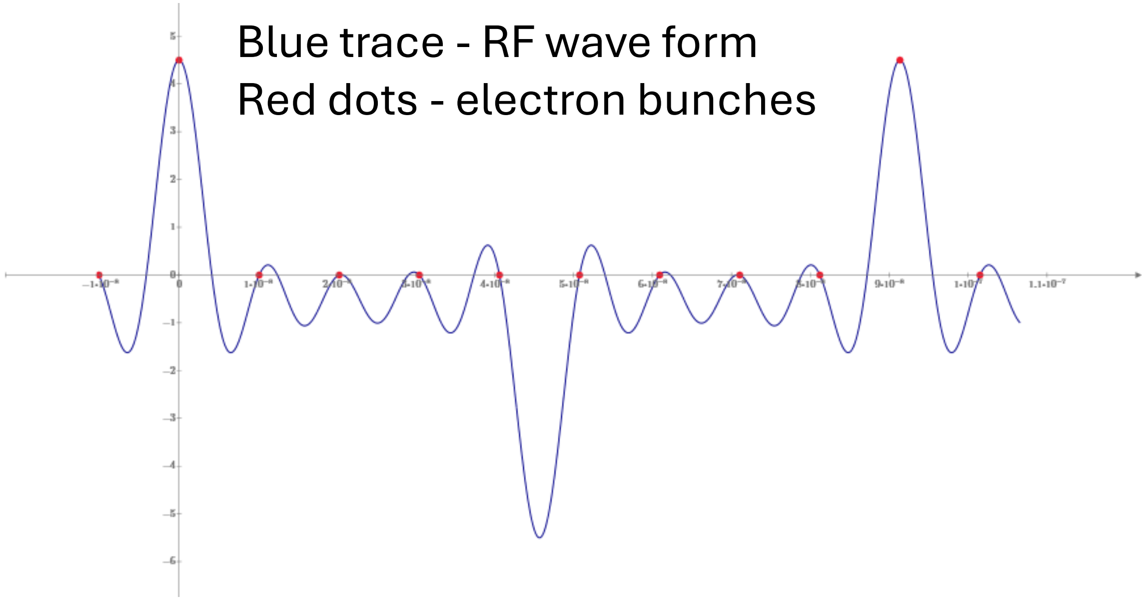
Mitigation

- Reuse the same bunch several times (fast kickers)
- Use low frequency RF at least at low energy injection ~10 MeV
- Do Not over compress bunch instead use bunch length comparable with hadrons bunch length 3-5 cm

What about kickers?

For the highest energy we would need to kick every 9th bunch in and out

Blue trace - RF wave form
Red dots - electron bunches



Kicker fundamental 10.95 MHz (1/9th of the proton bunches rep. rate 98 MHz)

Operation of harmonic kicker with beam was recently demonstrated at Jlab

12th Int. Beam Instrum. Conf. IBIC2023, Saskatoon, Canada JACoW Publishing
ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-TUP031

BEAM TEST OF A HARMONIC KICKER CAVITY*

M. W. Bruker†, J. Grames, J. Guo, J. Musson, S. A. Overstreet, G. T. Park, T. Plawski, M. Poelker, R. Rimmer, H. Wang, C. Wilson, S. Zhang
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
M. Pablo, B. Roberts, D. Speirs, Electrodynamic, Albuquerque, NM, USA

Abstract

A harmonically resonant kicker cavity designed for beam exchange in a circulator cooler was built and successfully tested at the Upgraded Injector Test Facility (UITF) at Jefferson Lab. This type of cavity is being considered for the injection scheme of the Rapid Cycling Synchrotron at the Electron-Ion Collider, where the spacing of neighboring bunches demands very short kicks. Operating with five transversely deflecting modes simultaneously that resonate at 86.6 MHz and consecutive odd harmonics thereof, the prototype cavity selectively deflects 1 of 11 electron bunches while leaving the others unperturbed. An RF driver was developed to synthesize phase- and amplitude-controlled harmonic signals and combine them to drive the cavity while also separating the modes from a field-probe antenna for RF feedback and dynamic tuning. Beam deflection was measured by sweeping the cavity phase; the deflection waveform agrees with expectations, having sub-nanosecond rise and

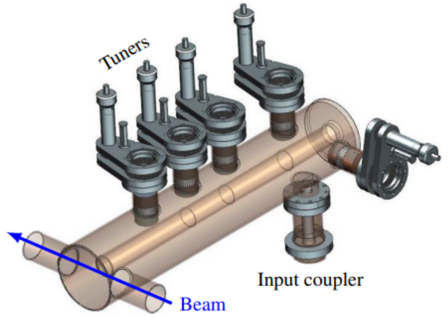


Figure 1: CAD model of a 5-mode harmonic kicker cavity. Five stub tuners are needed to tune all modes. The RF signal is coupled in through a single port; another port serves as the field probe (not shown here).

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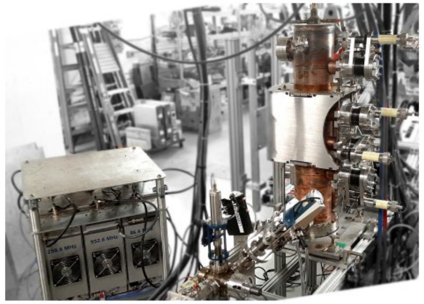


Figure 5: Harmonic kicker installed in the UITF beam line with the HAWG next to it.

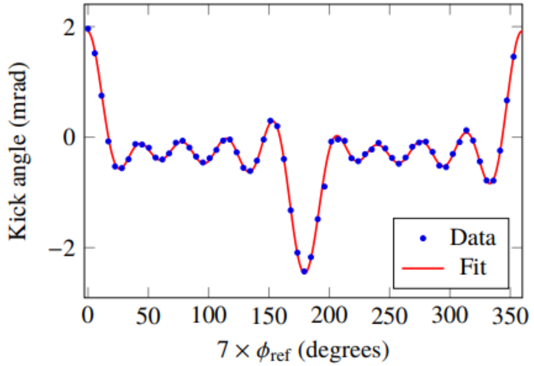
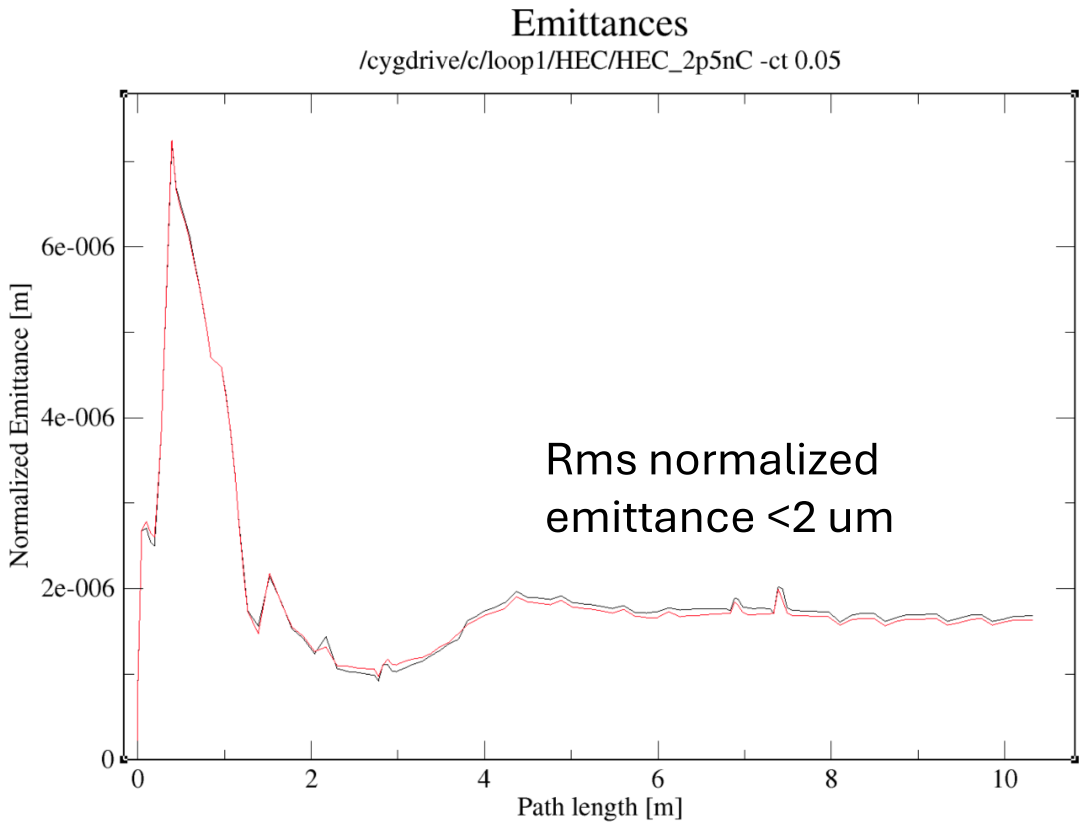
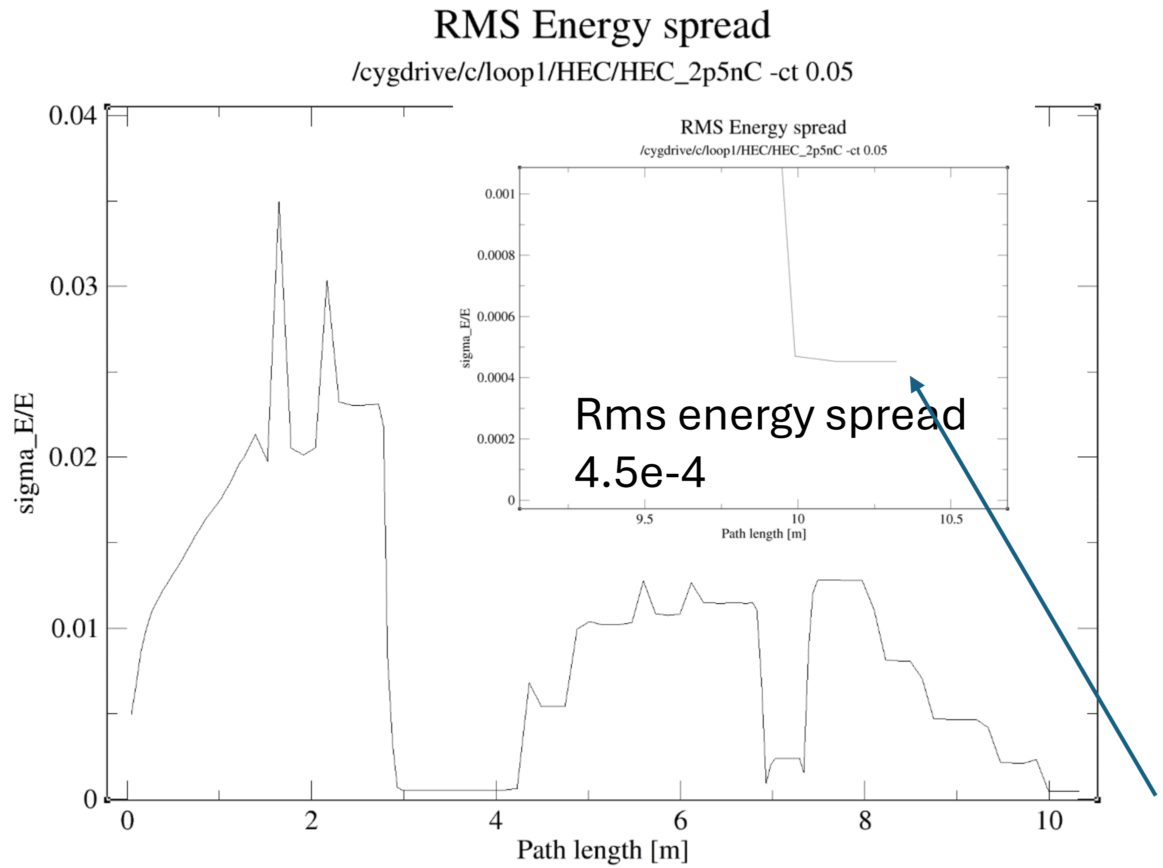
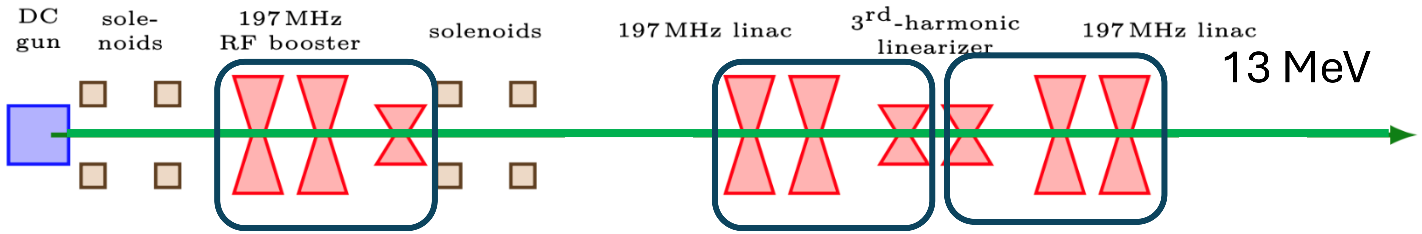


Figure 7: Deflection waveform with all five modes powered and optimized.

LEC 197MHz SRF Injection simulation for 2.5 nC bunch charge (example)







For High-Energy cooler and 5 nC bunches we can use the same concept buy reduce RF frequency to 98 MHz

Why we are optimistic about regular cooling option based on ERL

Injector with high current operation

- DC Gun high current test: 50 mA stable operation for an hour has been demonstrated in 2022.
- In current configuration we limited by 25 kW beam dump. For this year we will operate with reduce energy. For future test then RHIC finish its operation we move a high-power beam dump closereto the injection line

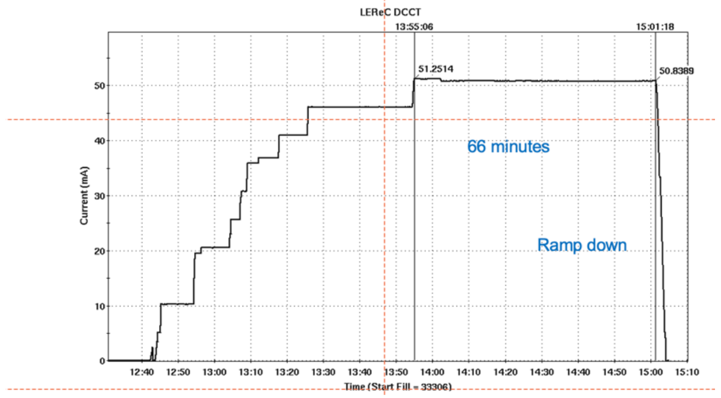
High Charge Bunch quality

- Beam dynamics simulations for 1 nC and 2.5 nC bunches for LEC using low RF frequency of 197 MHz RF shows good results.
- Then we compress and accelerate these bunches using 591MHz cavity
- Previously similar bunch quality was planned for RHIC-II cooling using 704 MHz main frequency cavities (https://epaper.kek.jp/p07/PAPERS/THPMS087.PDF)

- Q: What if ERL can only achieve required bunch quality for the less charge?
- A: We know that the cooling rate is scaled linearly with a bunch charge then cooling will still compensate a portion of the IBS resulted heating.
- The regular cooling still capable to provide a boost to integrated luminosity

Xiaofeng Gu at all "DC gun for Low Energy RHIC Cooler Project" presented at at ERL'2022

- 320kV: if the HVPS Faults are not caused by the voltage, could try 350kV later.
- 66 minutes: The current was ramped down prior to next polarization measurements in RHIC which typically results in high losses in the location of the Gun.
- 50 mA: limited by the injection dump power (25kW);



Proceedings of PAC07, Albuquerque, New Mexico, USA THPMS087

LOW EMITTANCE ELECTRON BEAMS FOR THE RHIC ELECTRON COOLER

Jörg Kewisch, Xiangyun Chang, Brookhaven National Laboratory*
Upton, NY 11973, U.S.A.

Table 1: Optimization Results

Bunch shape	Transverse Temperature	Bunch charge [nC]	Parmela optimized Emittance in the middle of the linac	Parmela optimized Emittance at the exit of the linac	Energy spread
Beer Can	0.1 eV	5 nC	2.300	2.992	1.20e-3
		7 nC	2.779	3.626	5.22e-4
		10 nC	5.220	5.364	1.58e-3
	0.3 eV	5 nC	2.908	2.941	2.11e-4
		7 nC	3.508	4.047	2.64e-4
		10 nC	7.031	7.773	5.39e-4
Tear Drop	0.1 eV	5 nC	0.915	0.917	2.84e-4
		7 nC	1.247	1.448	2.80e-4
		10 nC	2.235	3.282	3.44e-4
	0.3 eV	5 nC	2.066	2.166	3.00e-4
		7 nC	2.464	2.711	8.16e-4
		10 nC	2.586	2.643	3.44e-4

704 MHz main RF frequency + 3rd harmonic

Conclusion

- Regular electron cooling of hadrons at high energy required 100s of mA average electron beam current which is in order of magnitude what is currently demonstrated in ERLs
- In order to, reduce injector operation current we proposed to use the same electron bunch several time
- Bunch intensity and bunch quality requirement for 3 different energies has been discussed
- At very first look we think that with proper design of RF, longitudinal gymnastics and transport system such bunch quality could be achieve at least for two EIC operation energies
- We understand that detailed studies of many different effects are needed

  effect of wakes,

  kicker impact to the bunch

  quality, beam break up,

  instability and list could go on and on…
- Our work just started

Thank you for your attention!

Back up slides

Use of a beam-beam kicker

Instead of RF harmonics-based transvers kicker we might consider to use beam-beam based kicker originally proposed by V. Shiltsev in 1996

ELSEVIER

Section A

Beam–beam kicker for superfast bunch handling

V.D. Shiltsev [1]

DESY-MPY, Notkestrasse 85, 22603 Hamburg, Germany

Received 6 October 1996; revised form received 3 January 1996

Abstract

A novel method of a very fast kicker based on beam–beam forces is suggested. The method assumes impact of a high pulse current, low energy beam on the bunches which circulate in a storage ring. The kicker allows to handle separately the bunches spaced by only a few tens of centimeters. The article is devoted to the technical consideration of the kicker construction, its ultimate possibilities and the choice of its' parameters. Two schemes with head-on and perpendicular crossing are considered. The possible applications of the beam–beam kicker as an injector/extractor for the TESLA damping ring and as a diagnostic tool at multibunch storage rings are discussed.

V.D. Shiltsev/Nucl. Instr. and Meth. in Phys. Res. A 374 (1996) 137–143

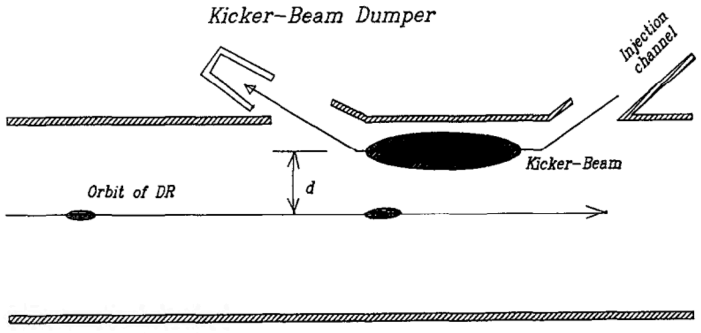


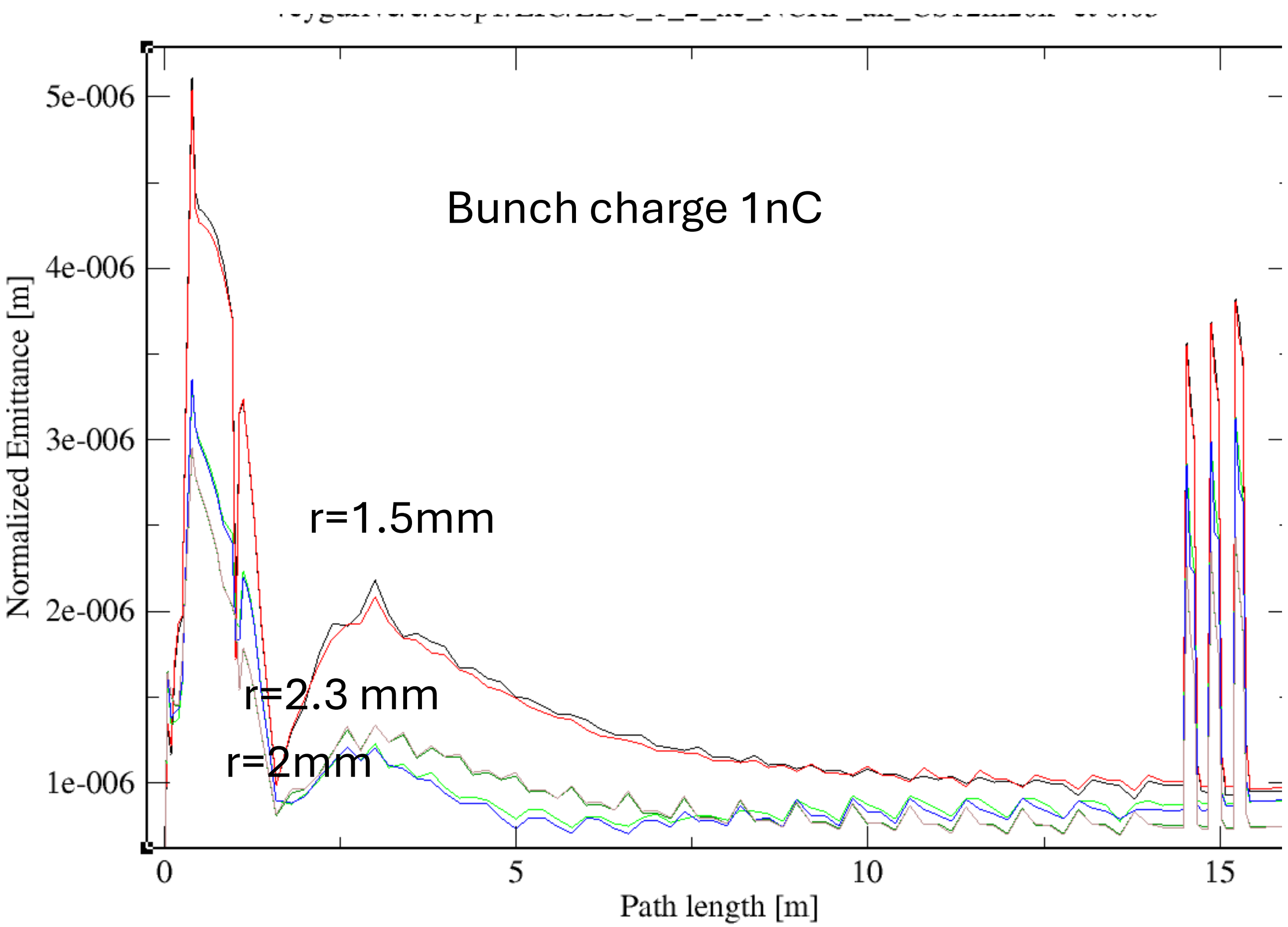
Fig. 1. General scheme of the "head-on" beam–beam kicker.

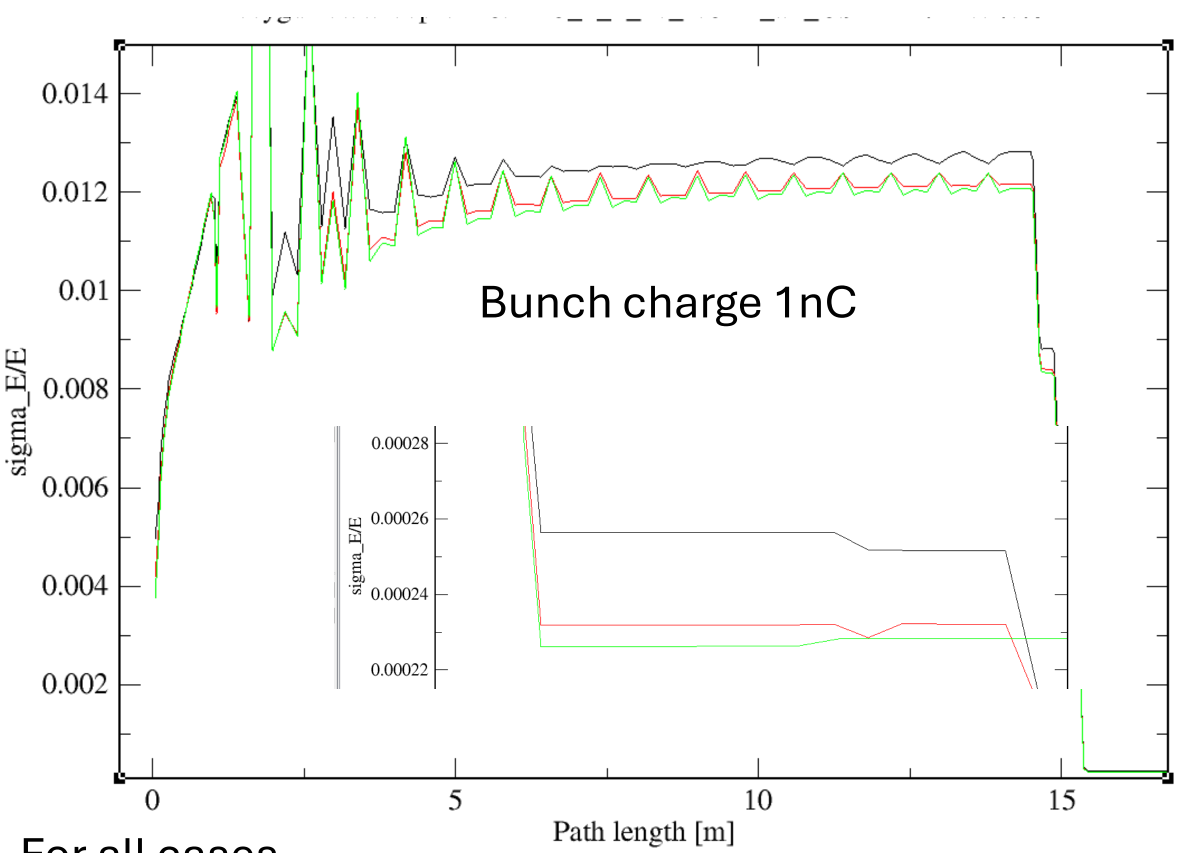
Using the last equation, useful formulas can be derived for the kick angle θ_0 and for the kicker strength P_{BBK}:

$$\theta_0[\mu\mathrm{rad}] = 250\frac{N[10^{11}]}{\sigma_r[\mathrm{mm}]E[\mathrm{GeV}]},$$

$$P_{\mathrm{BBK}}[\mathrm{Gs\,m}] = 8.4\frac{N[10^{11}]}{\sigma_r[\mathrm{mm}]}. \qquad (8)$$

Low-Energy cooler injector simulation with different spot size at the cathode

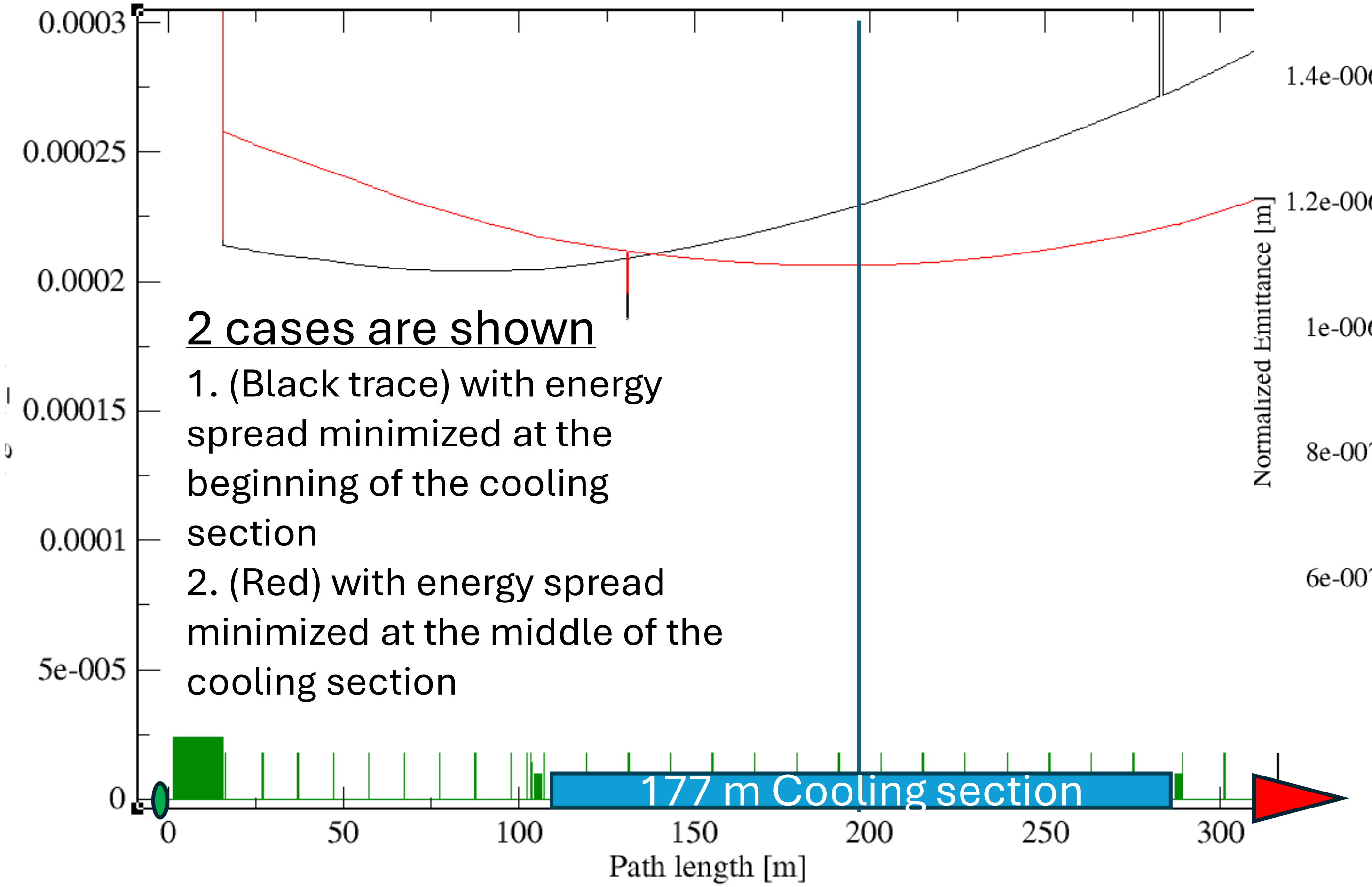




For all cases
Normalized emittances <1um
RMS energy spread <3e-4

Low-Energy Cooler beam quality optimization in the cooling section

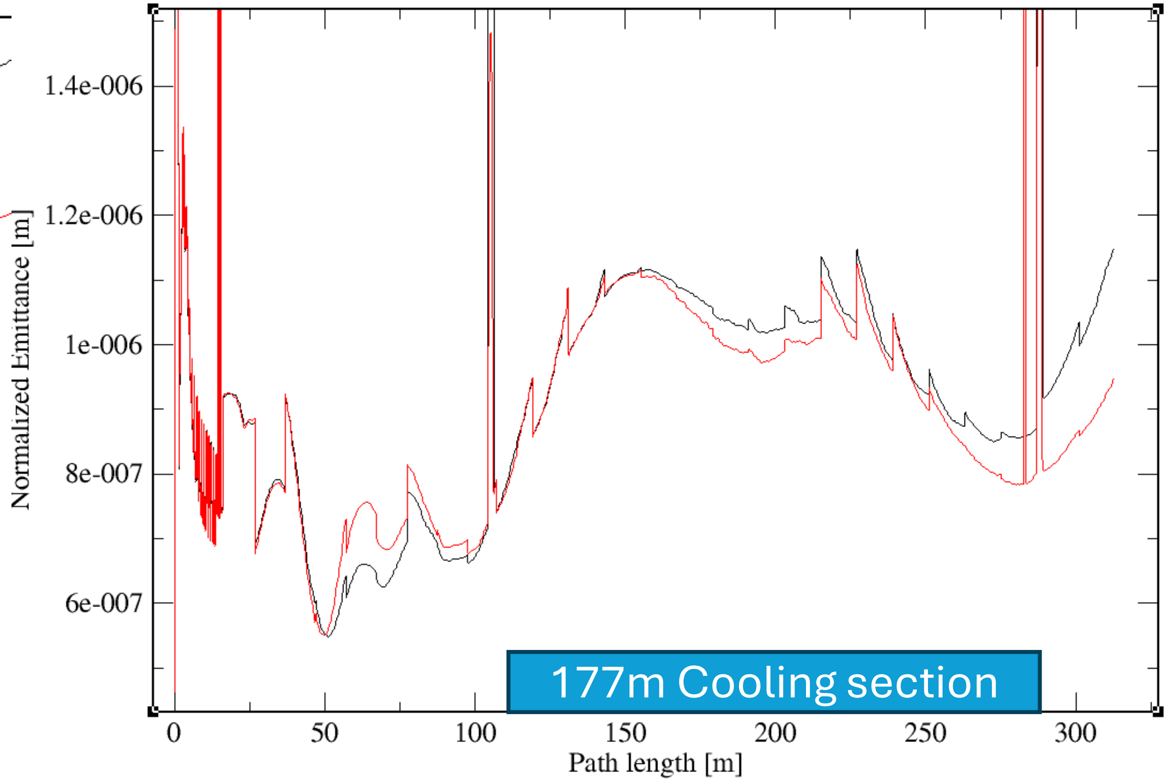
Energy spread optimization for 1 nC bunch



<u>2 cases are shown</u>

1. (Black trace) with energy spread minimized at the beginning of the cooling section
2. (Red) with energy spread minimized at the middle of the cooling section

Normalized emittance 1 nC bunch



Along cooling section
Projected normalized emittance~1um
energy spread 2e-4