

# Electron Cooler for High-Energy Hadrons Based on Energy Recovery Linac

Dmitry Kayran, Alexei Fedotov and Sergei Seletskiy

Brookhaven National Laboratory

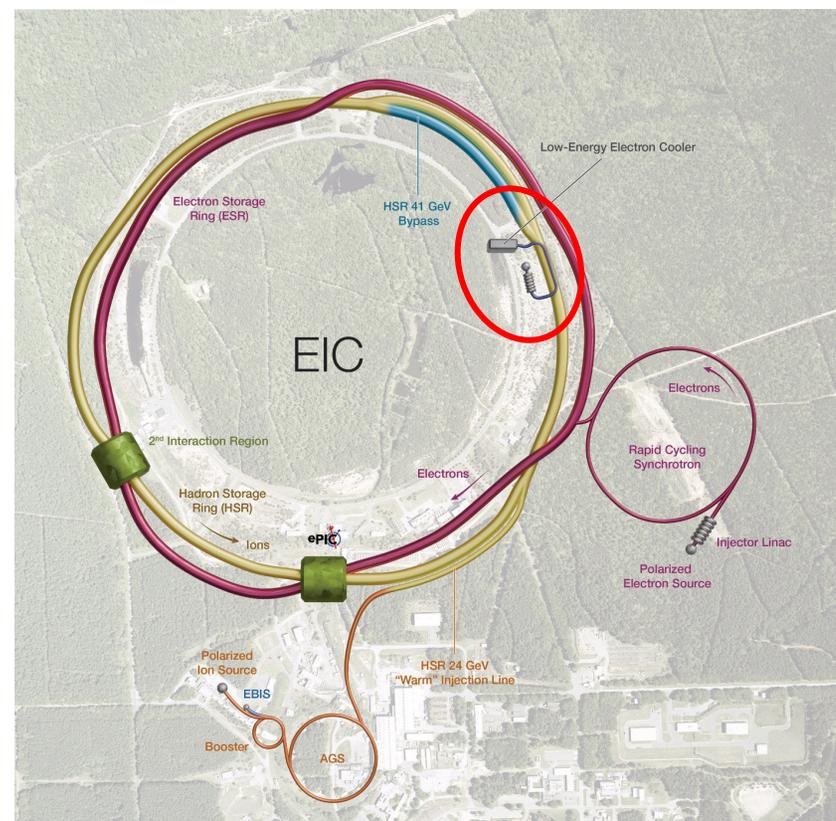
15th International Workshop on

**COOL25**

**Beam Cooling and  
Related Topics**

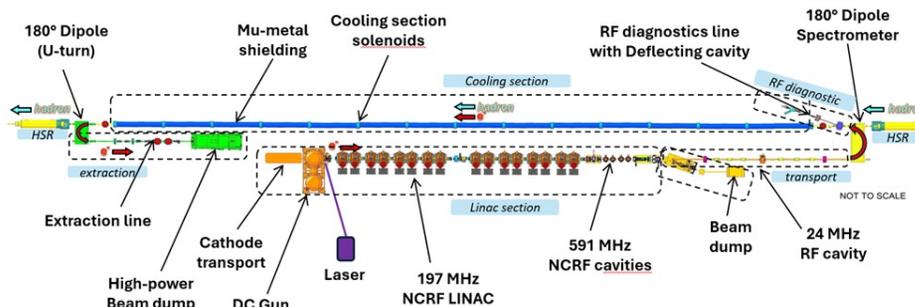
# Outline

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



# Hadron Cooling in the EIC

- Hadrons will be cooled at injection energy of 24 GeV by using **Low Energy Cooling (LEC)** to achieve required parameters



**LEC:** RF linac based single pass accelerator on 13 MeV upto 74 mA average current

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

- Currently, no hadron cooling is planning at collision energies
- However, it may be added in the future to increase the EIC average luminosity during store

If so , then cooler at **Store Energy** must be compatible with **LEC long cooling section**

# 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								
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 [ $\mu\text{m}$ ]	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
$\beta^*$ , 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 [ $\mu\text{m}$ ]	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 [ $\mu\text{rad}$ ]	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 [ $10^{33}\text{cm}^{-2}\text{s}^{-1}$ ]	1.54		10.00		4.48		3.68		0.44	

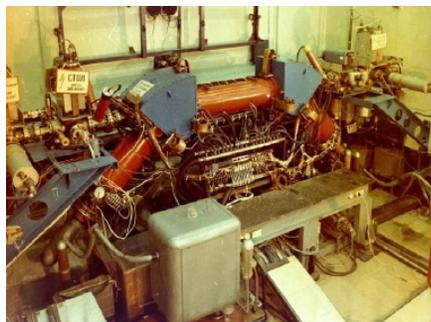
Strategy to get required luminosity

Use Low-Energy cooler to obtain initial proton beam parameters

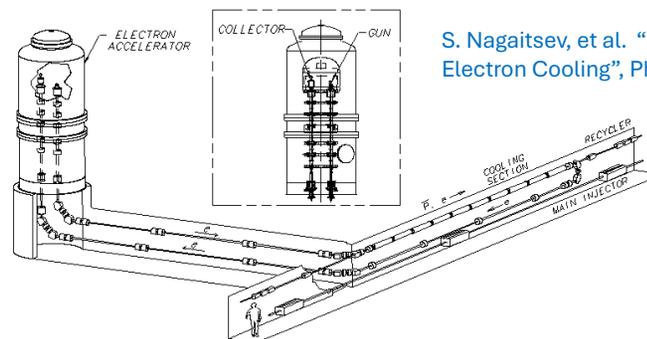
Ramp up to the store energy

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

# Why 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.

**LEC (13 MeV electrons): Under design right now** to cool hadrons at EIC injection energy of 24 GeV.

# How to design High Energy Electron Cooler

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- 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

*Sergei Seletskiy "Advancing Electron Cooling to high energy"  
C-AD physics seminar, at BNL on July 26, 2024*

# Cooling rate scaling with beam parameters

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

- $\lambda \propto \frac{1}{\gamma^2}$  - 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
- $\lambda \propto \frac{1}{\left(\frac{\epsilon_{ne}}{\beta_e} + \frac{\epsilon_{ni}}{\beta_i}\right) (\epsilon_{ne}\beta_e + \epsilon_{ni}\beta_i) \sqrt{\sigma_{\delta e}^2 + \sigma_{\delta i}^2} \sqrt{\sigma_{ze}^2 + \sigma_{zi}^2}}$  - in an approximation of negligible

We need at ls 5 nC per bunch to cool hadrons at 275 GeV

|

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  $\epsilon_e \ll \epsilon_i$
  - $\epsilon_e \ll \epsilon_i \rightarrow$  core overcooling (bad for collider)

# Cooling rate scaling with beam parameters

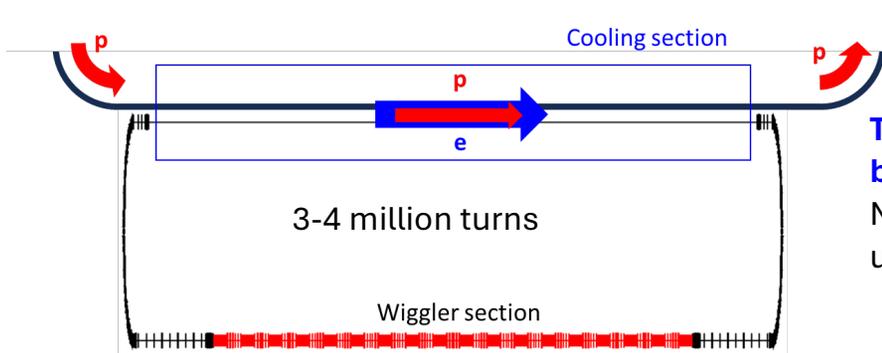
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$$\lambda \propto \frac{r_e^2 m_e c Z^2 \Lambda_c}{A_i m_p} \cdot \frac{1}{\gamma^2} \cdot N_e \cdot \frac{L_{CS}}{C_{ring}} \cdot \frac{1}{\left(\frac{\epsilon_{ne}}{\beta_e} + \frac{\epsilon_{ni}}{\beta_i}\right) (\epsilon_{ne} \beta_e + \epsilon_{ni}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

- Quick scaling from LEC parameters (Ee=13 MeV) to HEC (Ee=150 MeV) gives more than 2 order of magnitude reduction in the cooling rate
- Fortunately for HEC we only need to provide cooling rate ~2 hours to compensate IBS.
- With proper betafuction optimization we end up with a minimum **5 nC** per the hadron bunch or about **500 mA average current in the cooling section**

Reuse electron bunch several times significantly simplifies requirement for injector

# High-Energy Cooler based on reusing electron bunch MANY times



\* *Sergei Seletskiy, THB2, at this conference*

Ring based cooler use electron bunch a few million times

**The feasibility studies are going on right now in collaboration between BNL and Cornell University**

Many aspects have been considered already and some are still under consideration:

- Self-space charge

- Proton-electron focusing

- Beam-beam scattering in the cooling section

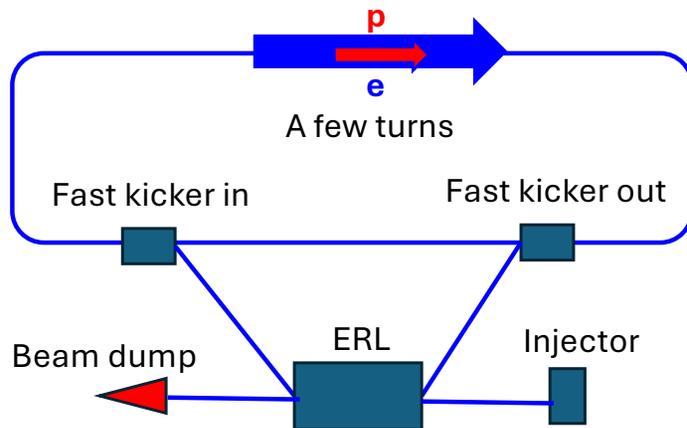
- To counteract IBS+BBS one needs strong damping wigglers

- Low Energy High Current Ring instability

**BUT ring based cooler is hard to scale to cool hadrons of 100 GeV and 41 GeV**

## High-Energy Cooler based on reusing electron bunch several times

Why not combine extremely good quality of electron bunches from the LINACs while use this bunch several times?



**ERL** with passing through the cooling section a **few times**

Reduce requirement for injector

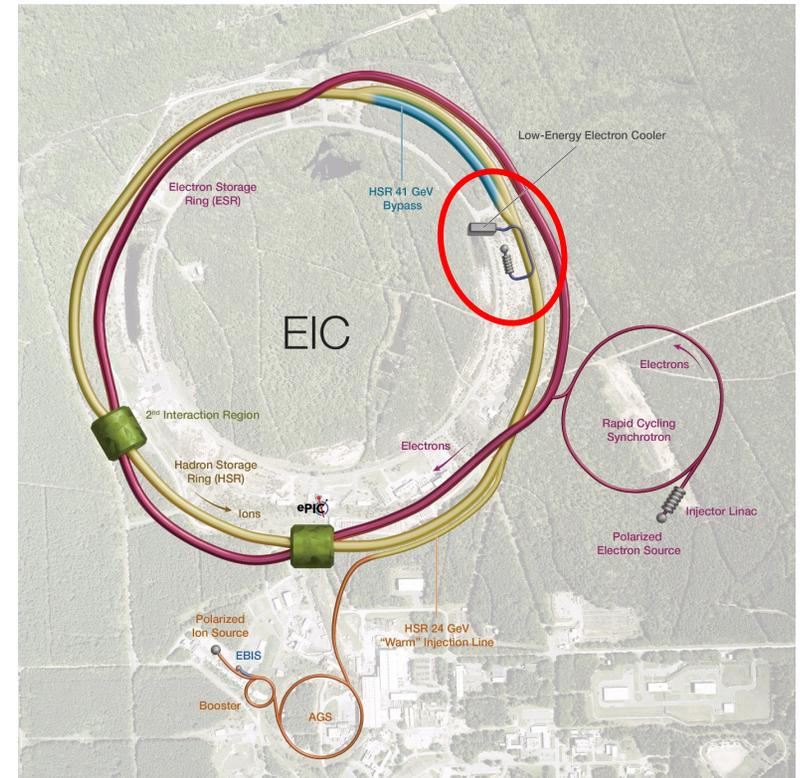
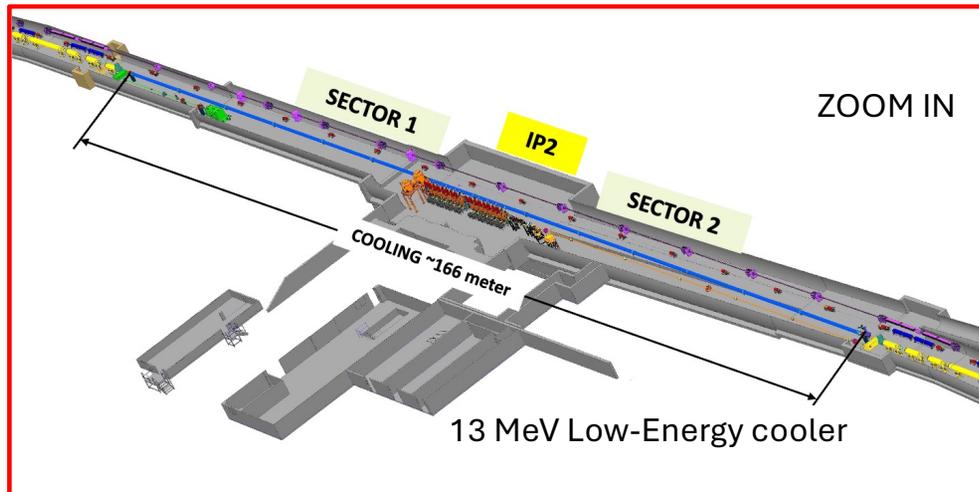
Less interaction with protons per e-bunch,

Better bunch quality for the same bunch charge

**More flexibility to choose operational energy**

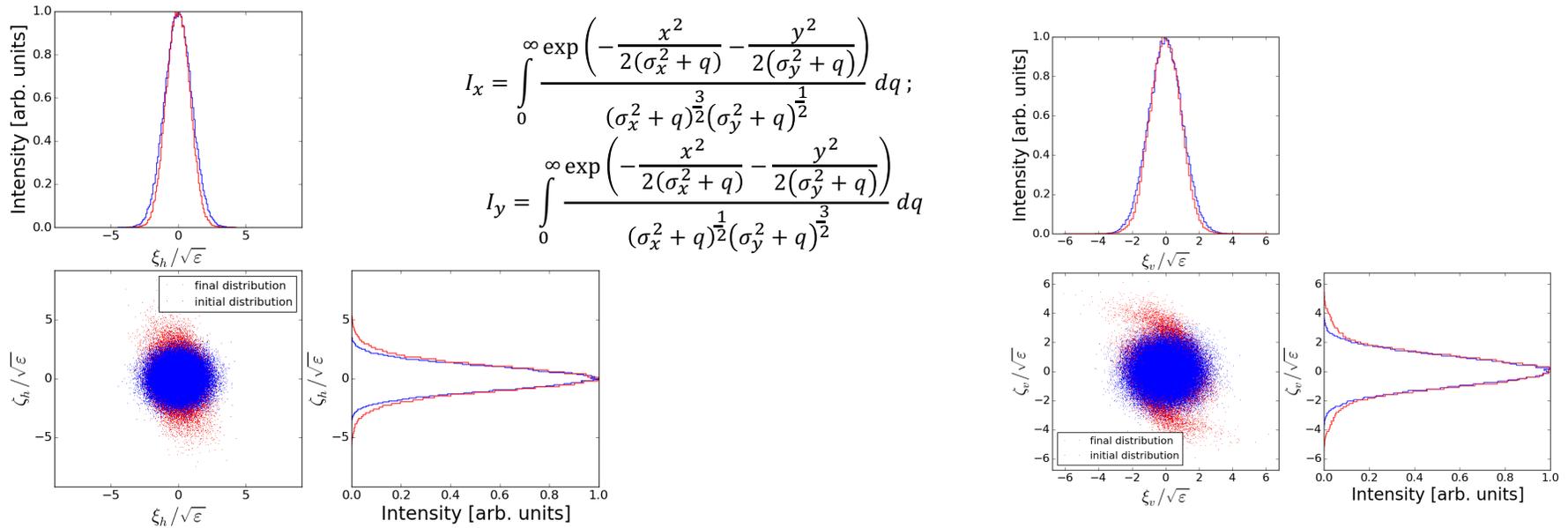
# Cooler's location

- 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



# Numbers of turns consideration

How many times we can reuse electron bunch before its emittance degrades  
is nonlinear space charge effect from protons to electron in the cooling section



Results of 6 turns tracking with 100k particles for cooling parameters at the 275 GeV storage energy shows :

**the final distribution is well contained within  $\pm 6\sigma$**

# Basic required parameters for different protons energies at EIC\*

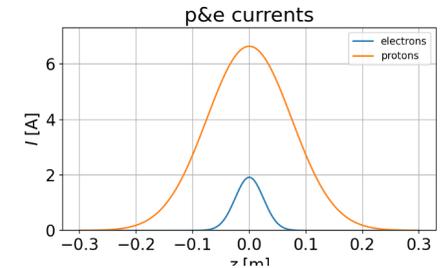
Proton Energy , GeV	275	100	41
Ne	3.00E+10	1.25E+10	4.00E+09
Qe, nC	5	2	0.64
Rms bunch length, cm	2.5	2.5	2.5
Peak Current, A	24	10	3
Rep rate, MHz	98	98	98
I ave in CS, mA	490	196	63
N_rec	7-9	3-4	1
Iav Gun, mA	70-54	65-49	63
Rms energy Spread in CS	3.00E-04	3.00E-04	3.00E-04
RMS Angular spread in CS, 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 section and averaging by beta- and synchrotron oscillations of protons

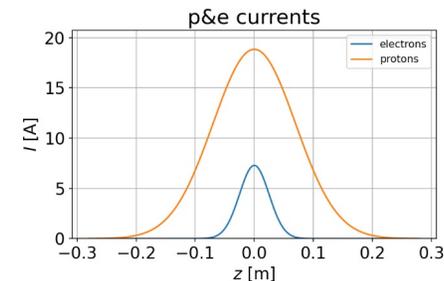
\*) After several rounds of optimization and cooling rates redistribution.

For details how to effectively use redistribution see Sergei Seletskiy's talk TUB1 at this workshop

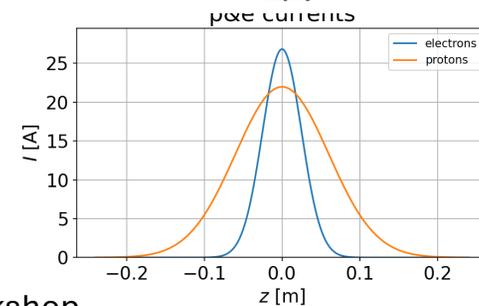
41 GeV  
protons



100 GeV  
protons



275 GeV  
protons



# 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
- And how to provide a fast kick

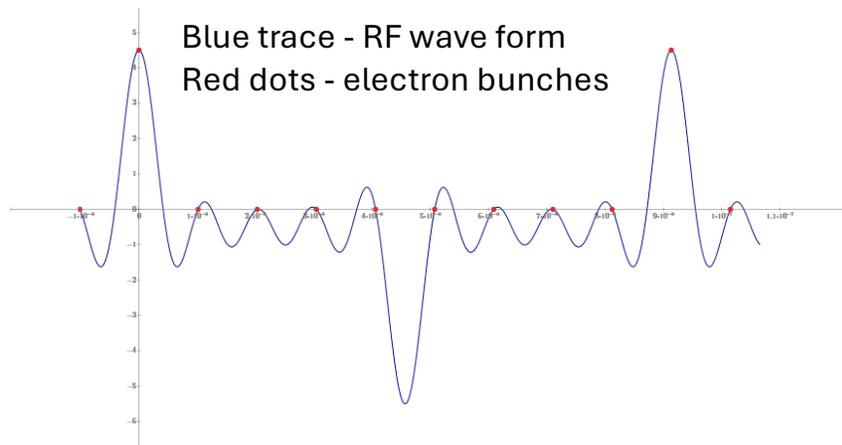
# & Mitigation

- Reuse the same bunch several times (fast kickers)
- Use low frequency RF at least at low energy injection  $\sim 15$  MeV
- Do Not over compress bunch instead use bunch length comparable with hadrons bunch length 3-5 cm
- Next slide

# What about kickers?

The overall length of e-bunches is  $12\sigma_z = 1$  ns  
 Repetition frequency in the recirculating ring is 98 MHz

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



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

## Operation of harmonic kicker with beam was demonstrated at Jlab

12<sup>th</sup> Int. Beam Instrum. Conf.  
 ISBN: 978-3-95450-236-3

IBIC2023, Saskatoon, Canada  
 ISSN: 2673-5350

JACoW Publishing  
 doi:10.18429/JACoW-IBIC2023-TUP031

### BEAM TEST OF A HARMONIC KICKER CAVITY\*

M. W. Bruker<sup>1</sup>, 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

\*work must maintain attribution to the author(s), title of the work, publisher, and DOI

#### 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

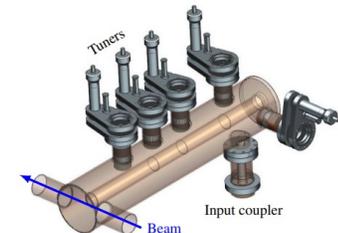


Figure 1: CAD model of a 5-mode harmonic kicker cavity. Five stub tuners are needed to tune all modes. The RF signal is coupled in through a single port; another port serves as the field probe (not shown here).

12<sup>th</sup> Int. Beam Instrum. Conf.  
 ISBN: 978-3-95450-236-3

IBIC2023,  
 ISSN: 2673-5350



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

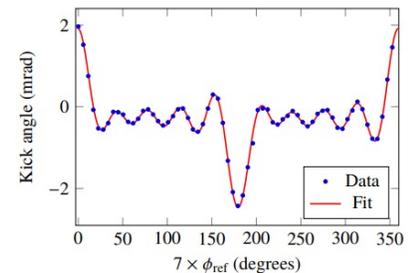
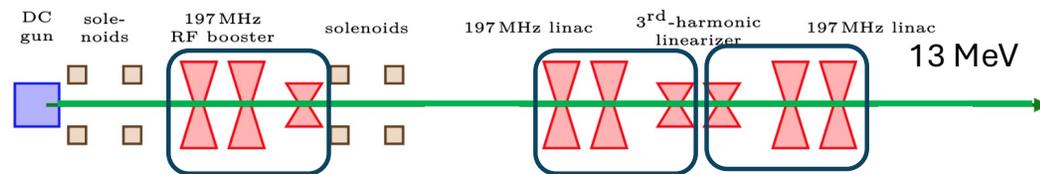
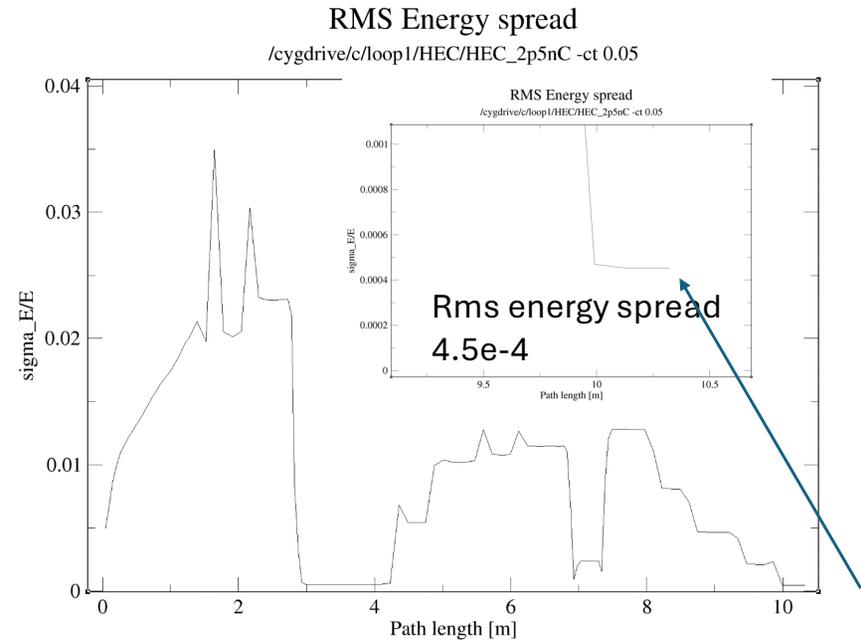
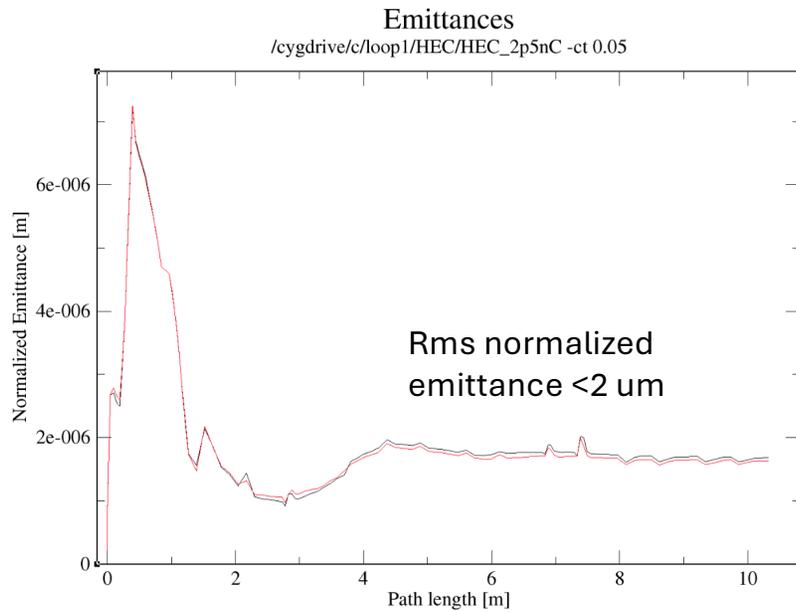


Figure 7: Deflection waveform with all five modes powered and optimized.

# LEC 197MHz SRF Injector 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

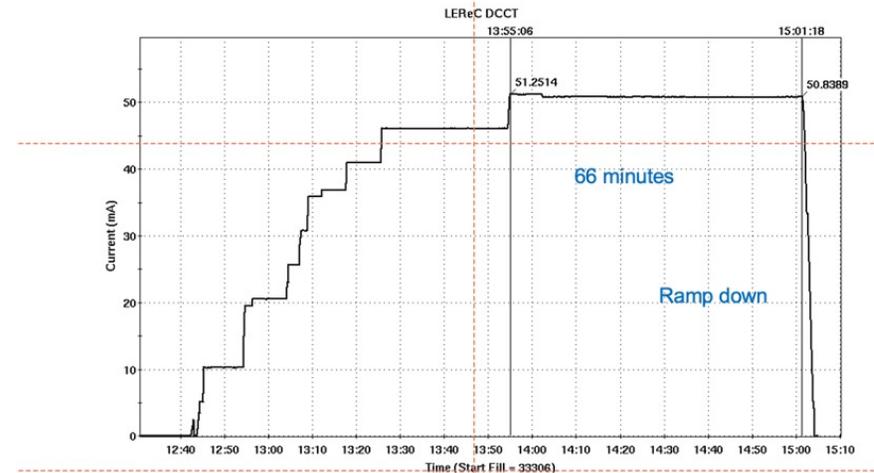
# Why we are optimistic about regular cooling option based on ERL ( p1)

## Injector with high current operation

- **DC Gun high current test: 50 mA stable** operation for has been demonstrated in 2022
- Short term 60 mA average current was achieved at lower Gun voltage in 2024
- Until the last week we were limited by 25 kW beam dump power
- After additional studies and test run just recently the LEReC injection beam dump power limit was increased to 32 kW

We plan to demonstrate 80 mA from the gun this year

- **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 RH which typically results in high losses in the location of the Gun.
- **50 mA**: limited by the injection dump power (25kW);



Xiaofeng Gu at all “DC gun for Low Energy RHIC Cooler Project” presented at at ERL’2022

# Why we are optimistic about regular cooling option based on ERL (p.2)

- High Charge Bunch quality

- Beam dynamics simulations for 1 nC and 2.5 nC bunches for the injector using low frequency RF (197 MHz) shows good results
- Then we compress and accelerate these bunches using 591MHz cavity
- Operation with higher bunch charge of 5 nC per bunch might require use of lower RF frequency in injector (98 MHz)
- Or consider using SRF gun
- Long time ago similar studies were performed to use electron cooler for RHIC-II luminosity upgrade
- Bunch quality was satisfied to (<https://epaper.kek.jp/p07/PAPERS/THPMS087.PDF>)

Proceedings of PAC07, Albuquerque, New Mexico, USA THPMS087

**LOW EMITTANCE ELECTRON BEAMS FOR THE RHIC ELECTRON COOLER**

Jörg Kewish, 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
		5 nC	2.908	2.941	2.11e-4
Tear Drop	0.1 eV	7 nC	3.508	4.047	2.64e-4
		10 nC	7.031	7.773	5.39e-4
		5 nC	0.915	0.917	2.84e-4
		7 nC	1.247	1.448	2.80e-4
	0.3 eV	10 nC	2.235	3.282	3.44e-4
		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

**Jorg Kewish at all “Low Emittance Electron Beams For the RHIC electron cooler gun for RHIC Cooler Project” presented at at PAC’ 07**

## What if?

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- Q: What if ERL can only achieve required bunch quality for the less charge/current?
- 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

# Conclusion

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- 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 times
- 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,
  - instabilities,
  - the list could go on and on...
- Our work just started
- Any cooperation are welcome

Thank you for your attention!

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# 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<sup>1</sup>

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

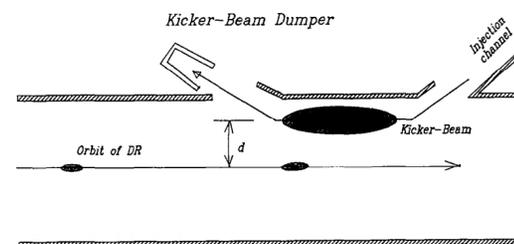


Fig. 1. General scheme of the "head-on" beam-beam kicker.

Using the last equation, useful formulas can be derived for the kick angle  $\theta_0$  and for the kicker strength  $P_{\text{BBK}}$ :

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

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

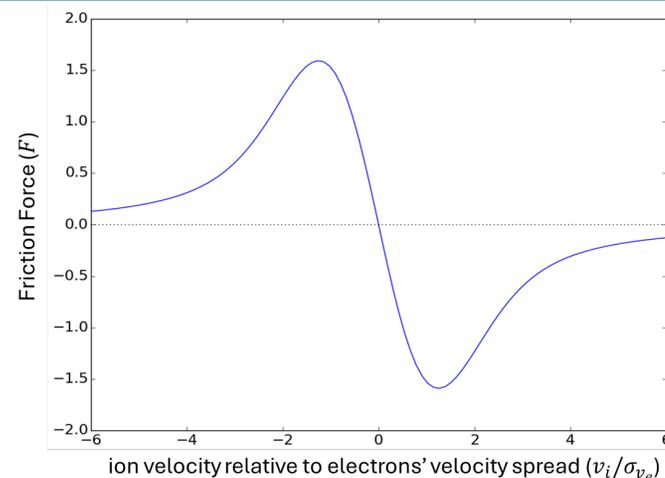
# Friction force in Electron Cooling

density of electron bunch
ion velocity
electron velocity

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

Coulomb logarithm  $\Lambda_C = \ln\left(\frac{\rho_{max}}{\rho_{min}}\right)$ 
e-velocity distribution function

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



• 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 completion of the near neighbors. From considerations of a very general nature it is concluded that the *coefficient of dynamical friction*,  $\eta$ , 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:

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

• 1956; 1966

### AN EFFECTIVE METHOD OF DAMPING PARTICLE OSCILLATIONS IN PROTON AND ANTI-PROTON STORAGE RINGS

G. I. Budker

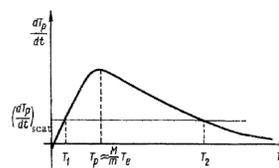


Fig.1. Rate of change of the proton temperature during interaction with electrons.

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

• 1977

Particle Accelerators  
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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)

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

# Parameters

$$N_e = 9.5 \cdot 10^9$$

$$\varepsilon_{e(x,y)\text{norm}} = 1.5 \text{ um}$$

$$\varepsilon_{e(x,y)} = 14 \text{ nm}$$

$$\sigma_\delta = 1 \cdot 10^{-4}$$

$$\sigma_z = 2.5 \text{ cm}$$

$$D_{e(x)} = 0. \text{ m}$$

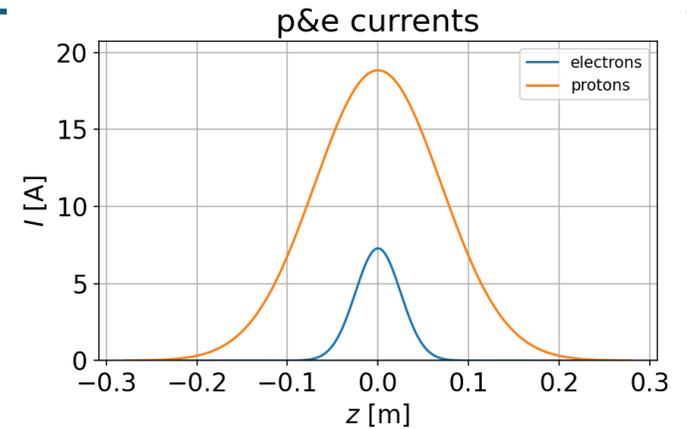
$$D_{i(x)} = 2.5 \text{ m}$$

$$\tau_{Cool,x} = 1.9 \text{ hrs}$$

$$\tau_{Cool,y} = 3.9 \text{ hrs}$$

$$\tau_{Cool,z} = 1.6 \text{ hrs}$$

i-mass number	1.0
i-charge number	1.0
CS length [m]	180.0
e-ring circumference [m]	426.0
i-ring circumference [m]	3834.0
e-kinetic energy [MeV]	54.0
ions per bunch	68800000000.0
electrons per bunch	9500000000.0
e-geometric emittance-x [m*rad]	1.4e-08
e-geometric emittance-y [m*rad]	1.4e-08
CS e-bunch beta-x [m]	50.0
CS e-bunch beta-y [m]	50.0
i-geometric emittance-x [m*rad]	3e-08
i-geometric emittance-y [m*rad]	2.7e-09
CS i-bunch beta-x [m]	150.0
CS i-bunch beta-y [m]	1500.0
i-bunch rms length [m]	0.07
e-bunch rms length [m]	0.025
e-bunch p-spread	0.0001
i-bunch p-spread	0.00068
CS e dispersion-x [m]	0.0
CS i dispersion-x [m]	2.5



$$Q_e = 1.5 \text{ nC}$$

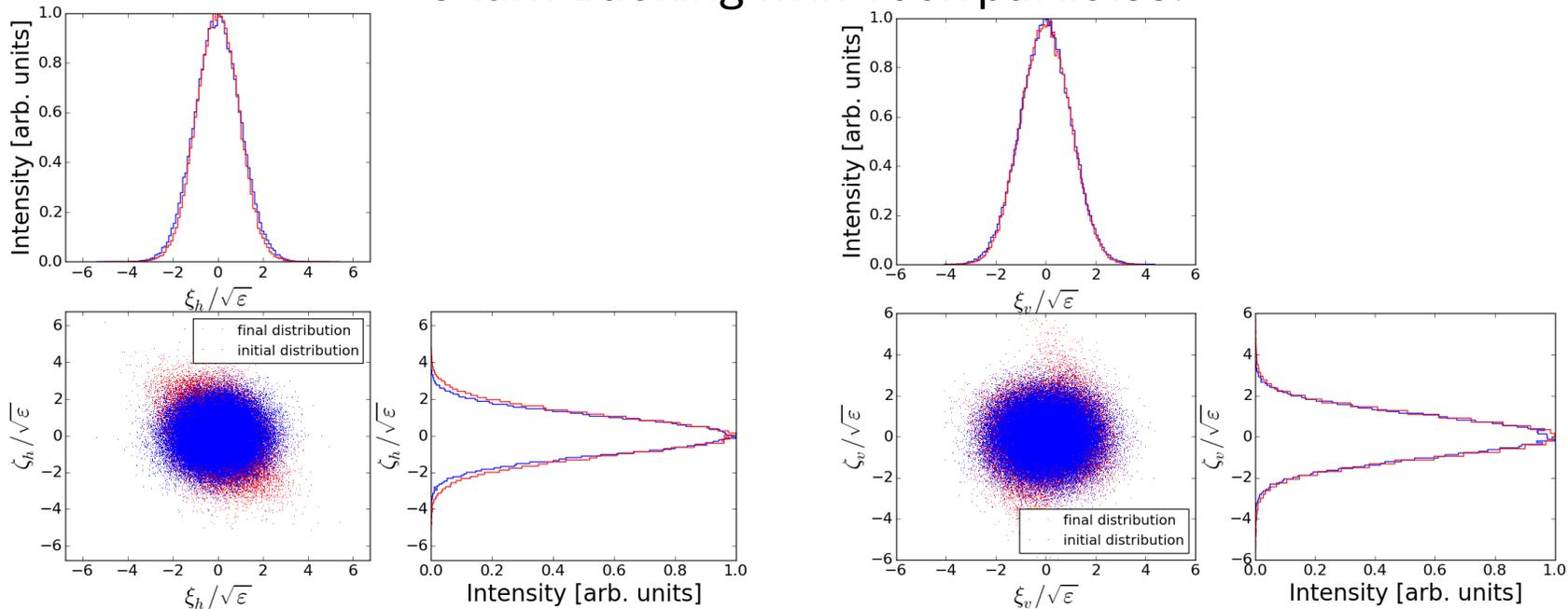
$$\langle I_{REC} \rangle = Q_e \cdot 98.5 \cdot 10^6 = 150 \text{ mA}$$

$$\langle I_{Gun\&ERL} \rangle = \frac{\langle I_{REC} \rangle}{3 \text{ turns}} = 50 \text{ mA}$$

# BBS & IBS: less than 0.2% emittance increase from BBS; IBS is negligible

p-e focusing:

3 turn tracking with 100k particles:



**the final distribution is well contained within  $\pm 6\sigma$**

# parameters

$$N_e = 2.5 \cdot 10^9$$

$$\varepsilon_{e(x,y)\text{norm}} = 1.5 \text{ } \mu\text{m}$$

$$\varepsilon_{e(x,y)} = 34 \text{ nm}$$

$$\sigma_\delta = 1 \cdot 10^{-4}$$

$$\sigma_z = 2.5 \text{ cm}$$

$$D_{e(x)} = 0. \text{ m}$$

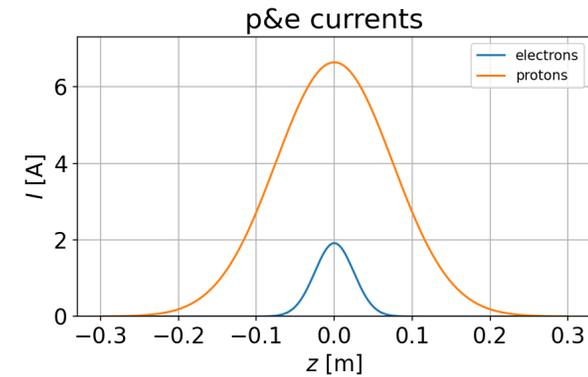
$$D_{i(x)} = 0. \text{ m}$$

$$\tau_{Cool,x} = 2 \text{ hrs}$$

$$\tau_{Cool,y} = 1.8 \text{ hrs}$$

$$\tau_{Cool,z} = 1.0 \text{ hrs}$$

i-mass number	1.0
i-charge number	1.0
CS length [m]	180.0
e-ring circumference [m]	426.0
i-ring circumference [m]	3834.0
e-kinetic energy [MeV]	22.3
ions per bunch	26000000000.0
electrons per bunch	2500000000.0
e-geometric emittance-x [m*rad]	3.4e-08
e-geometric emittance-y [m*rad]	3.4e-08
CS e-bunch beta-x [m]	50.0
CS e-bunch beta-y [m]	50.0
i-geometric emittance-x [m*rad]	4.4e-08
i-geometric emittance-y [m*rad]	1e-08
CS i-bunch beta-x [m]	250.0
CS i-bunch beta-y [m]	1000.0
i-bunch rms length [m]	0.075
e-bunch rms length [m]	0.025
e-bunch p-spread	0.0001
i-bunch p-spread	0.00068
CS e dispersion-x [m]	0.0
CS i dispersion-x [m]	0.0



$$Q_e = 0.4 \text{ nC}$$

$$\langle I_{REC} \rangle = Q_e \cdot 98.5 \cdot 10^6 = 40 \text{ mA}$$

A single pass is needed