EIC hadron beam cooling

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July 23, 2019

Beam Cooling: introduction

- Beam cooling at collision energies is required for future hadron colliders with energies below a few TeV
  - Already part of RHIC ion-ion operations
  - The LHC & FCC are exceptions due to sufficiently fast radiation damping at very high energies
  - Next-generation hadron colliders:
    - Electron Ion Collider (EIC)
      - CM energies 20-150 GeV/u
      - Broad range of ion species: p to heavy ions
      - Fast hadron bunched-beam cooling is required
    - NICA @ Dubna: an ion-ion collider at 1-5 GeV/u/beam
      - Construction started
      - Both electron and stochastic cooling are part of the project

EIC proposed parameters

design parameter	eRHIC proton	eRHIC electron	JLEIC proton	JLEIC electron
center-of-mass energy [GeV]	105		44.7	
energy [GeV]	275	10	100	5
number of bunches	1320		3228	
particles per bunch [10^{10}]	6.0	15.1	0.98	3.7
beam current [A]	1.0	2.5	0.75	2.8
horizontal emittance [nm]	9.2	20.0	4.7	5.5
vertical emittance [nm]	1.3	1.0	0.94	1.1
β_x^* [cm]	90	42	6	5.1
β_y^* [cm]	4.0	5.0	1.2	1
tunes (Q_x, Q_y)	.315/.305	.08/.06	.081/.132	.53/.567
hor. beam-beam parameter	0.013	0.064	0.015	0.068
vert. beam-beam parameter	0.007	0.1	0.015	0.068
IBS growth time hor./long. [min]	126/120	n/a	0.7/2.3	n/a
synchrotron radiation power [MW]	n/a	9.2	n/a	2.7
bunch length [cm]	5	1.9	1	1
hourglass and crab reduction factor	0.87		0.87	
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.05		2.1	
integrated luminosity/week [fb^{-1}]	4.51		9.0	

From F. Willeke (BNL) and A. Seryi (JLab)

The beam cooling challenge

- The EIC accelerator systems are very interesting and challenging to accelerator scientists.
  - Perhaps one of the most interesting colliders considered.
  - Beam cooling at collision energies is one of such interesting challenges
- There are several concepts (~6) being considered in various stages of readiness.
  - Several groups are working in parallel (nat. labs and universities)
  - We are aiming at <1 hour cooling time
- I am confident that we will be able to solve this challenge

- EIC Hadron Cooling workshop: Oct 7-8, 2019, Univ of Chicago https://indico.fnal.gov/event/20514/

What is beam cooling?

- Cooling is a reduction in the phase space occupied by the beam (for the same number of particles).
  - It's not about the beam temperature
- Equivalently, cooling is a reduction in the random motion of the beam.

- Examples of non-cooling:
  - Beam scraping (removing particles with higher amplitudes) is NOT cooling;
  - "Cooling" due to beam acceleration;
  - Expanding the beam transversely lowers its transverse temperature. This is NOT cooling;
  - Coupling between degrees of freedom may lead to a reduction in the phase-space projection area. This is NOT cooling.

Why cool beams?

- Particle accelerators create a beam with a virtually limitless reservoir of energy in one (longitudinal) degree of freedom. This energy can couple (randomly and coherently) to other degrees of freedom by various processes, such as:
  - Scattering (intra-beam, beam-beam, residual gas, internal target, foil @ injection);
  - Improper bending and focusing;
  - Interaction with beam's environment (e.g. wake fields);
  - Space-charge effects;
  - Secondary and tertiary beams;
- Normally, it is necessary to keep momentum spreads in the transverse degrees of freedom at ~10^{-4} of the average longitudinal momentum.

Particle Accelerators
1983 Vol. 13 pp. 115–143
0031-2460/83/1303/0115$06.50/0

INTRABEAM SCATTERING

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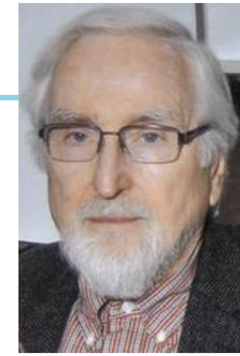
(*Received October 1, 1982*)

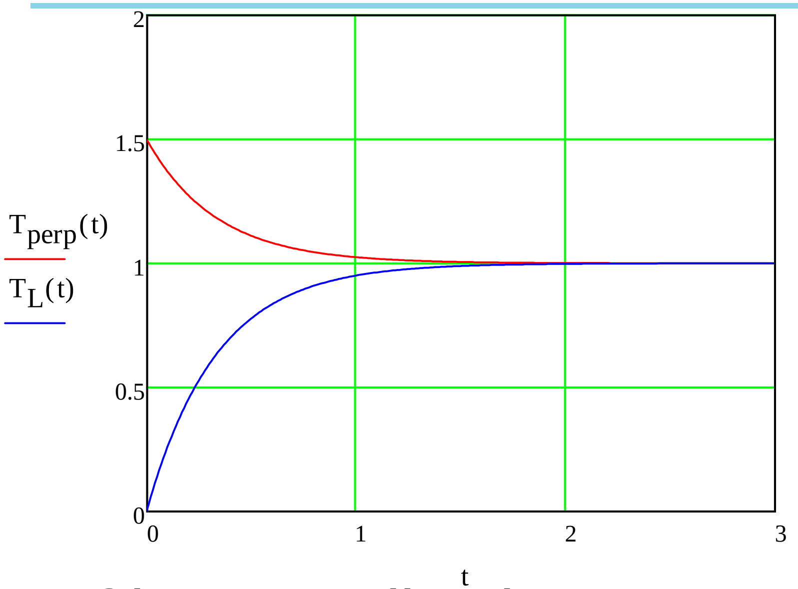


2017 Robert R. Wilson Prize for Achievement in the Physics of Particle Accelerators

A. Piwinski, J. Bjorken and S. Mtingwa

For the detailed, theoretical description of intrabeam scattering, which has empowered major discoveries in a broad range of disciplines by a wide variety of accelerators, including hadron colliders, damping rings/linear colliders, and low emittance synchrotron light sources.

Example of IBS: the Boersch effect



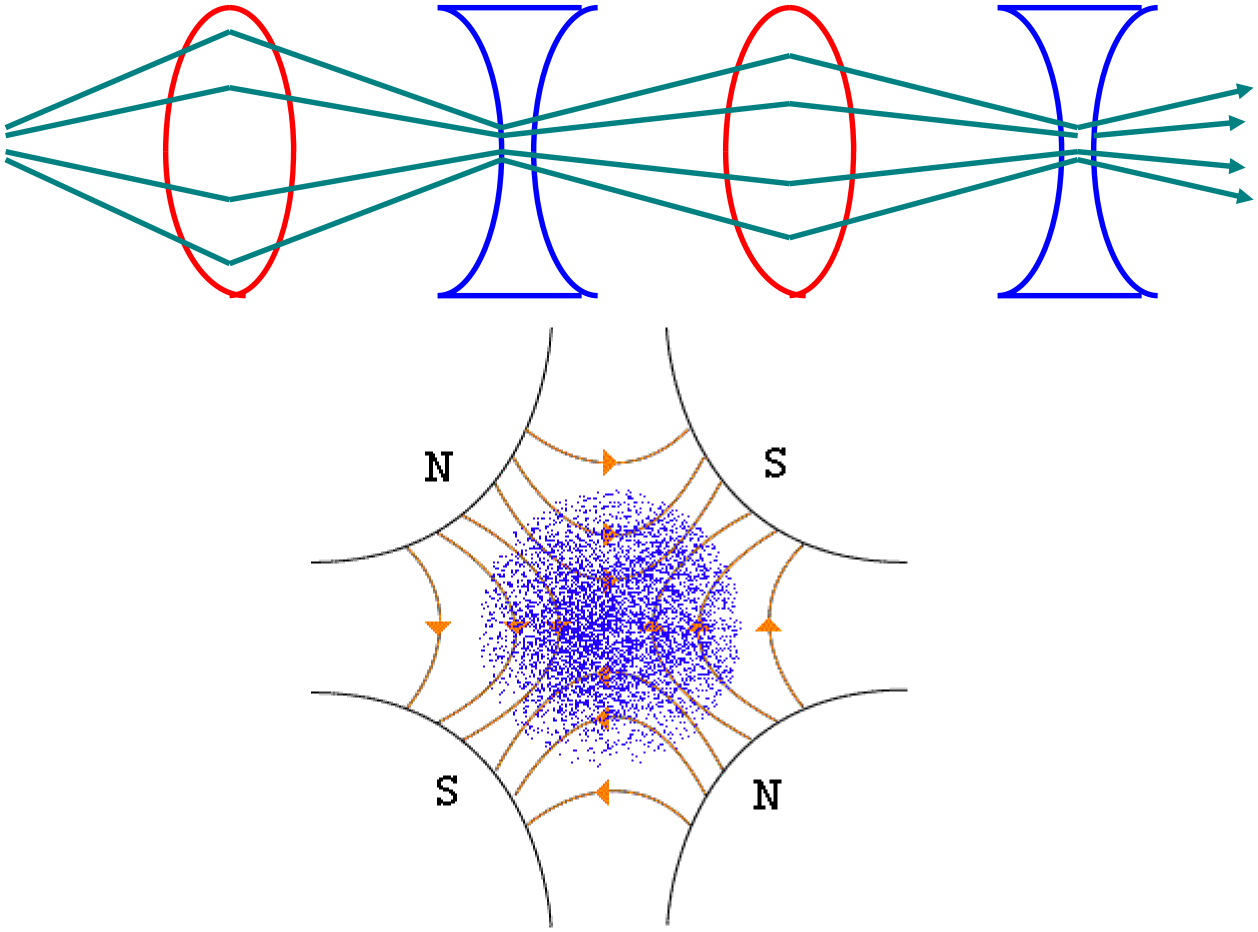
$$\frac{dT_\perp}{dt} = -\frac{1}{2}\frac{dT_L}{dt} = -\frac{T_\perp - T_L}{\tau}$$

$$\frac{1}{\tau} = \frac{8\sqrt{\pi} n r_c^2 c}{15\left(kT_{eff} / mc^2\right)^{3/2}} \ln \Lambda$$

- If beam radius is constant, the beam temperatures eventually come to a thermal equilibrium due to Coulomb (intra-beam) scattering
  - H. Boersch, Z. Phys 139, 115 (1954), S. Ichimaru and M.N. Rosenbluth, Phys. Fluids 13, 2778 (1970).
- If beam radius is modulated (quadrupole focusing), beam temperatures never come to a thermal equilibrium
  - Energy is continuously supplied from the longitudinal motion

Continuous temperature modulation in a FODO channel

FODO focusing channel (Focus-Drift-Defocus-Drift). :



Hadron beam cooling methods

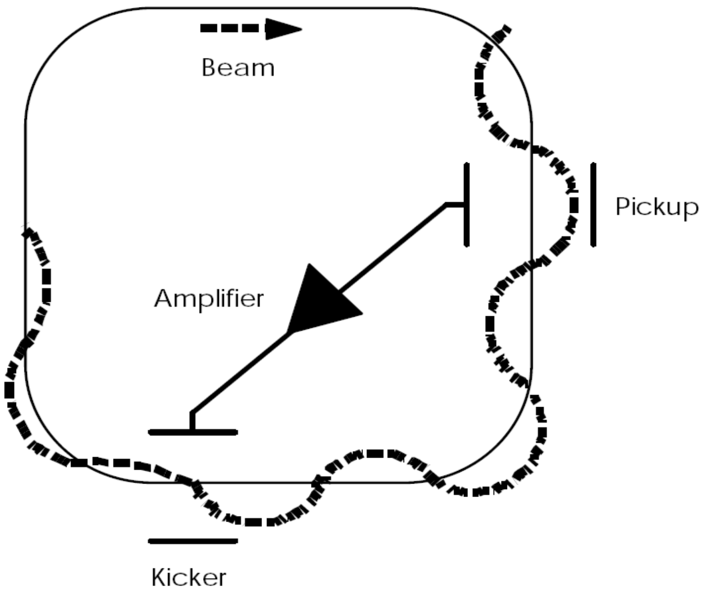
- Two basic methods employed for hadron cooling today:
  – Stochastic cooling (1984 Nobel Prize in Physics)
  – Electron cooling

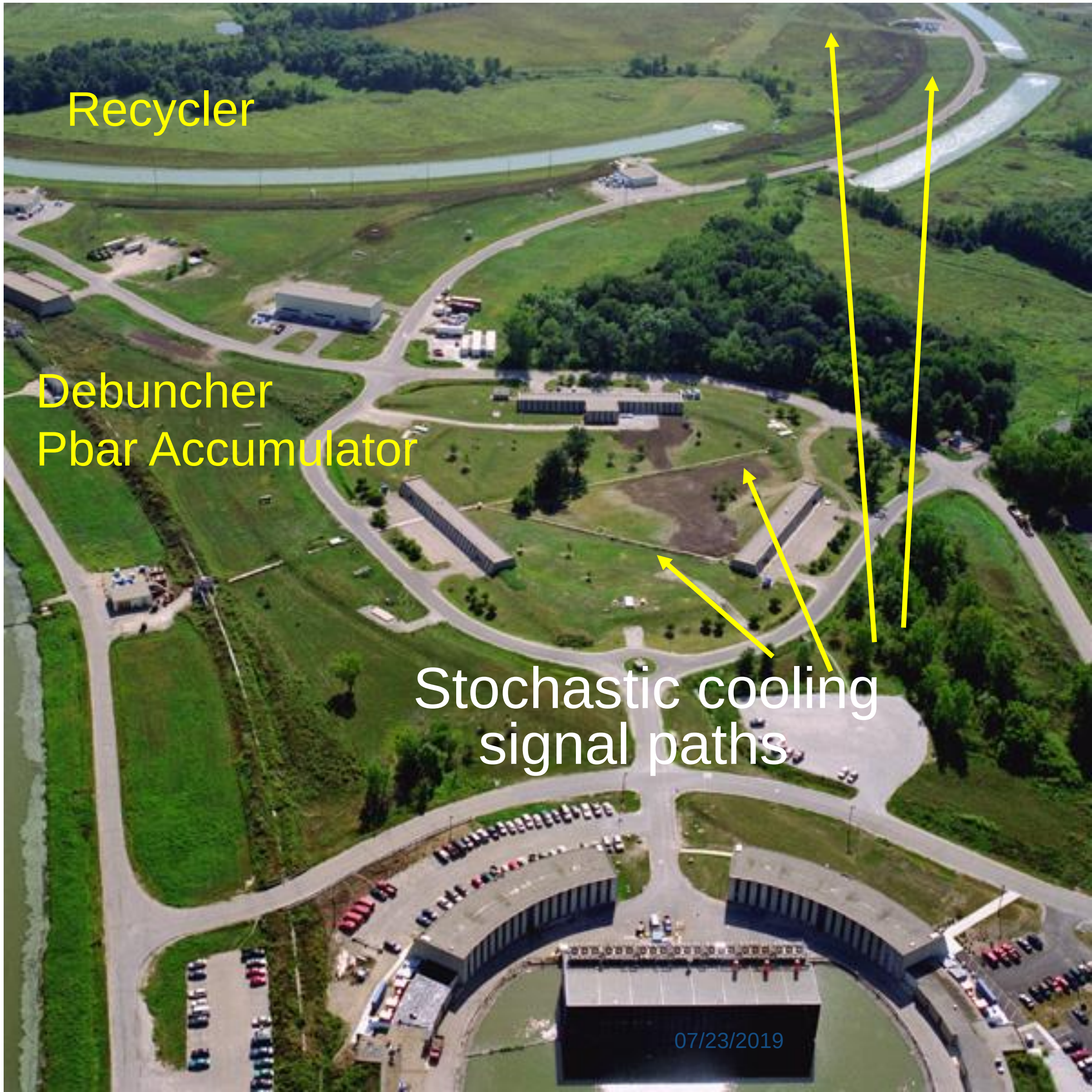
- I will not discuss:
  – Radiation damping
  – Muon cooling
  – Laser cooling

Stochastic Cooling

- Simon van der Meer, CERN, 1969
  - Tested experimentally at CERN in ICE ring, 1977-78
  - Employed in the past for pbar accumulation at CERN & Fermilab (also planned at FAIR)
    - It was the main basis for p-pbar colliders (SppS, Tevatron)
  - Successfully employed for ion bunched-beam cooling at the top energy in RHIC;
  - Bunched beam stochastic cooling of protons in both Tevatron and RHIC was not successful;
  - Various variations of stochastic cooling are proposed for the EIC: coherent electron cooling, micro-bunching cooling, optical stochastic cooling.

Stochastic Cooling



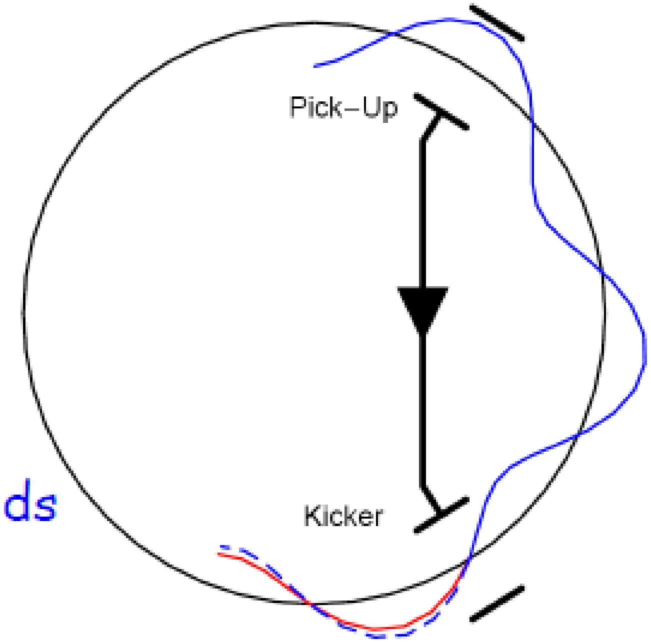


Stochastic Cooling

Transverse stochastic cooling

- Naïve model for transverse cooling
  - 90 deg. between pickup and kicker

$$\delta\theta = -g\theta$$



  - Averaging over betatron oscillations yields

$$\delta\overline{\theta^2} = -\frac{1}{2}2g\overline{\theta^2} \equiv -g\overline{\theta^2}$$

  - Adding noise of other particles yields

$$\delta\overline{\theta^2} = -g\overline{\theta^2} + N_{sample}g^2\overline{\theta^2} \equiv -\left(g - N_{sample}g^2\right)\overline{\theta^2}$$

That yields optimal gain

$$\delta\overline{\theta^2} = -\frac{1}{2}g_{opt}\overline{\theta^2} \quad , \quad g_{opt} = \frac{1}{2N_{sample}} \quad , \quad N_{sample} \approx N\frac{f_0}{W}$$

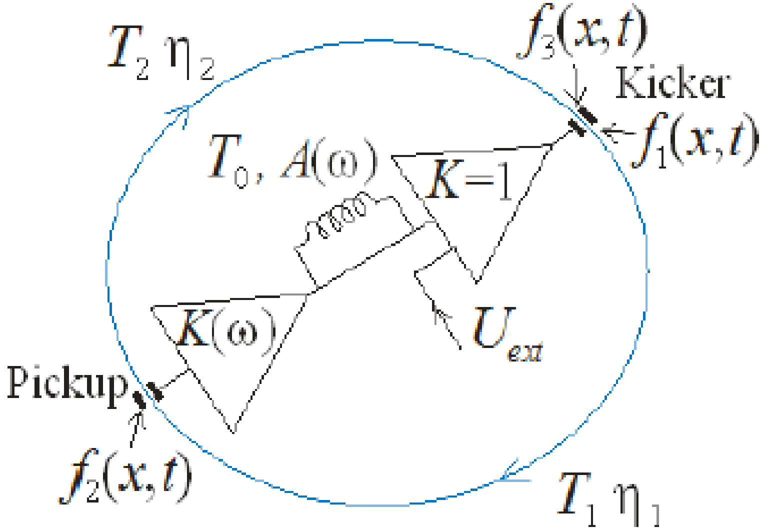
⇨ Cooling rate: $$\lambda_{opt} = \frac{1}{2}g_{opt}f_0 = \frac{W}{4N}$$

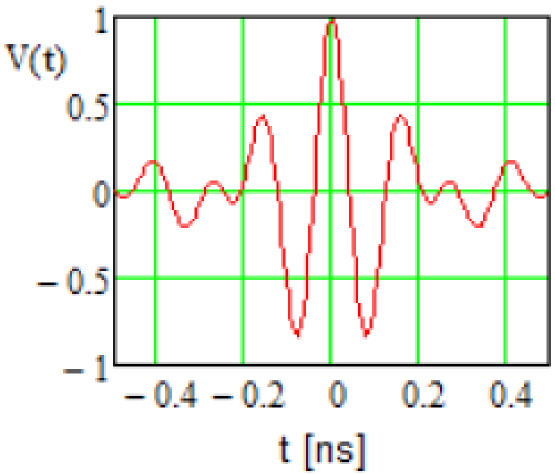
Longitudinal Stochastic Cooling

- Palmer cooling
  - Signal is proportional to particle momentum. It is measured by a pickup at high dispersion location
  - Example: FNAL Accumulator
- Filter cooling
  - Signal proportional to particle momentum is obtained as difference of particle signals for two successive turns (notch filter)

$$U(t) = u(t) - u\left(t - T_0\left(1 + \eta\frac{\Delta p}{p}\right) + T_0\right) \approx \frac{du}{dt}T_0\eta\frac{\Delta p}{p}$$

  - Examples: FNAL Debuncher and Recycler
- Transit time cooling
  - No signal treatment
  - The same expression for kick as for FC
  - Larger diffusion => less effective than FC
  - Examples: OSC, CEC





Kicker voltage excited by single particle in a system with constant gain in 4-8 GHz band

Fermilab

Bunched-beam Cooling

- The optimal gain is determined by the longitudinal density

$$\frac{N}{C} \xrightarrow[\text{beam}]{\text{Bunched}} \frac{N}{\sqrt{2\pi}\sigma_s}$$

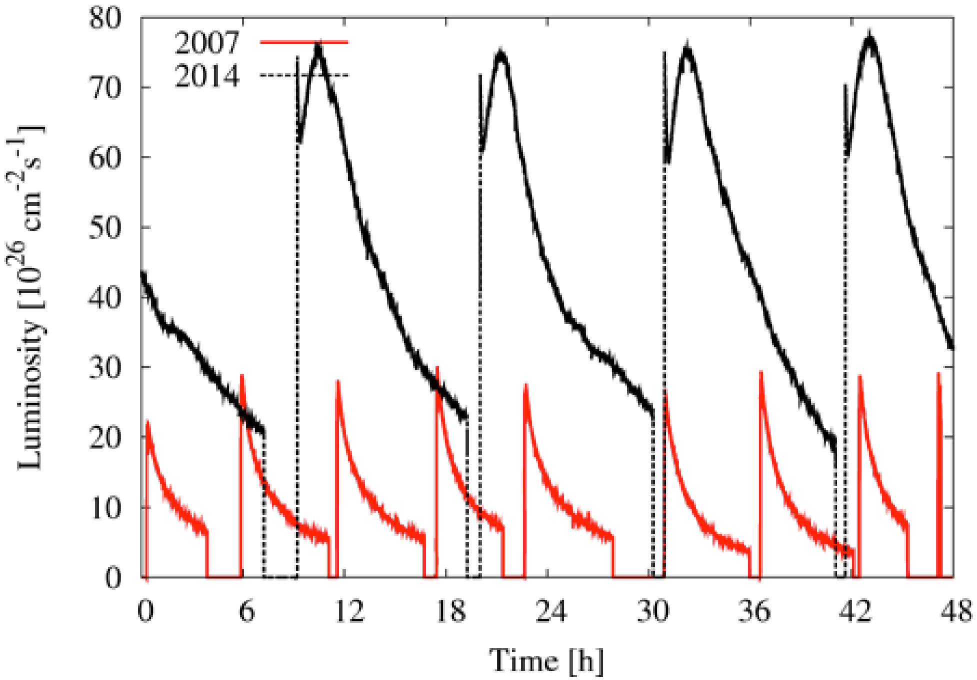
⇨ An estimate of maximum cooling rate: $$\lambda_{opt} \cong \frac{W}{4N}\frac{\sqrt{2\pi}\sigma_s}{C}$$

- An accurate result for the transit-time cooling with rectangular band

$$\lambda_{opt} \approx \frac{2\pi^2 W}{N n_\sigma^{\ 2}}\frac{\sqrt{\pi}\sigma_s}{C} \qquad W = \frac{n_{\max} - n_{\min}}{T_0}, \quad n_\sigma = \frac{(\Delta p / p)_{\max}}{\sigma_p}.$$

- The cooling rate is decreasing with an increase of cooling range (n_σ) expressed in cooling acceptance $(\Delta p/p)_{max}$

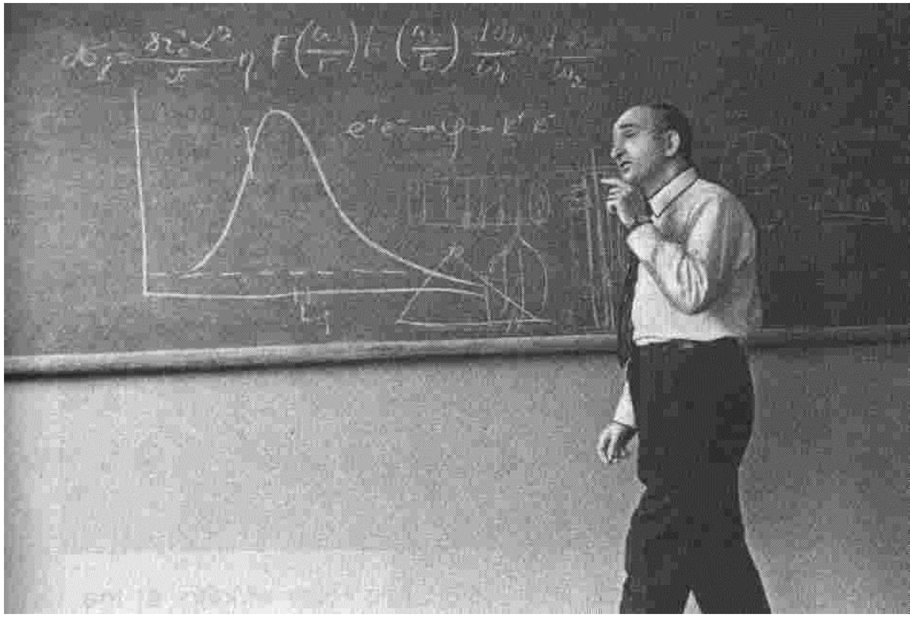
Au-Au stochastic cooling in RHIC



- 3-D stochastic cooling (5-9 GHz).
- ~5x U-U and ~ 4x Au-Au luminosity improvements.
- Cooling led to first increase of instantaneous luminosity and smallest emittance ever in a hadron collider.
- Adequate for eRHIC e-ION collisions
- Doesn't work with protons

Electron cooling

- Was invented by G.I. Budker (INP, Novosibirsk) as a way to increase luminosity of p-p and p-pbar colliders.
- First mentioned at Symp. Intern. sur les anneaux de collisions á electrons et positrons, Saclay, 1966: "Status report of works on storage rings at Novosibirsk"
- First publication: Soviet Atomic Energy, Vol. 22, May 1967 "An effective method of damping particle oscillations in proton and antiproton storage rings"



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Laboratoire de
l'Accélérateur Linéaire
ORSAY

Institut National des
Sciences et Techniques Nucléaires
SACLAY

SYMPOSIUM INTERNATIONAL SUR LES ANNEAUX DE COLLISIONS

A ELECTRONS ET POSITRONS

Sous la présidence de

Monsieur Alain Peyrefitte

Ministre délégué chargé de la recherche scientifique
et des questions atomiques et spatiales

tenu à

l'Institut National des Sciences et Techniques Nucléaires, Saclay
26-30 Septembre 1966

Edité par

H. ZYNGIER
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Fermilab

Electron Cooling

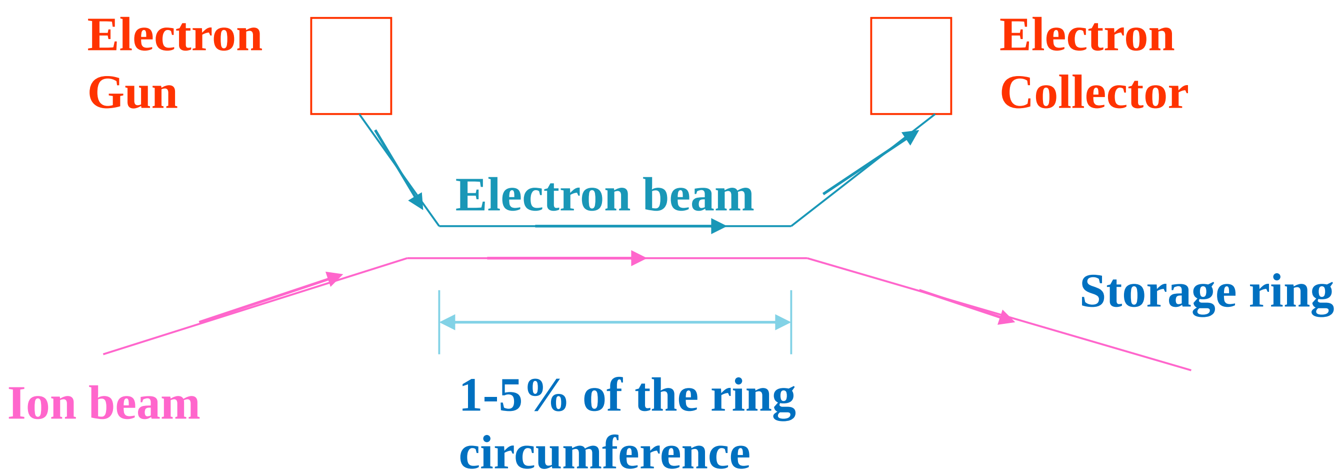
- Tested experimentally at BINP in NAP-M ring, Novosibirsk, 1974-79
- Many projects are based on the same technology: most recent a 2-MeV cooler at COSY, Juelich (~4 GeV protons)
- Highest energy electron cooling: at the Fermilab Recycler: E=4.3 MeV electrons (8 GeV – pbars) – the only e-cooler used for HEP colliders
- Never used for cooling at collider top energy so far. First attempt was at RHIC (LEReC project) in 2019 (Electron energy = 1.6 – 2.6 MeV) in a test mode.

Electron cooling

- Does not directly depend on the number of cooled particles
- Cools until the equilibrium of temperatures in the rest frame

$$\overline{v_p^{\,2}} \approx \frac{m_e}{m_p}\overline{v_e^{\,2}}$$

- $T_{||} << T_{tr}$ for electrostatic acceleration
- T_{tr} can be “frozen out” by strong continuous longitudinal magnetic field



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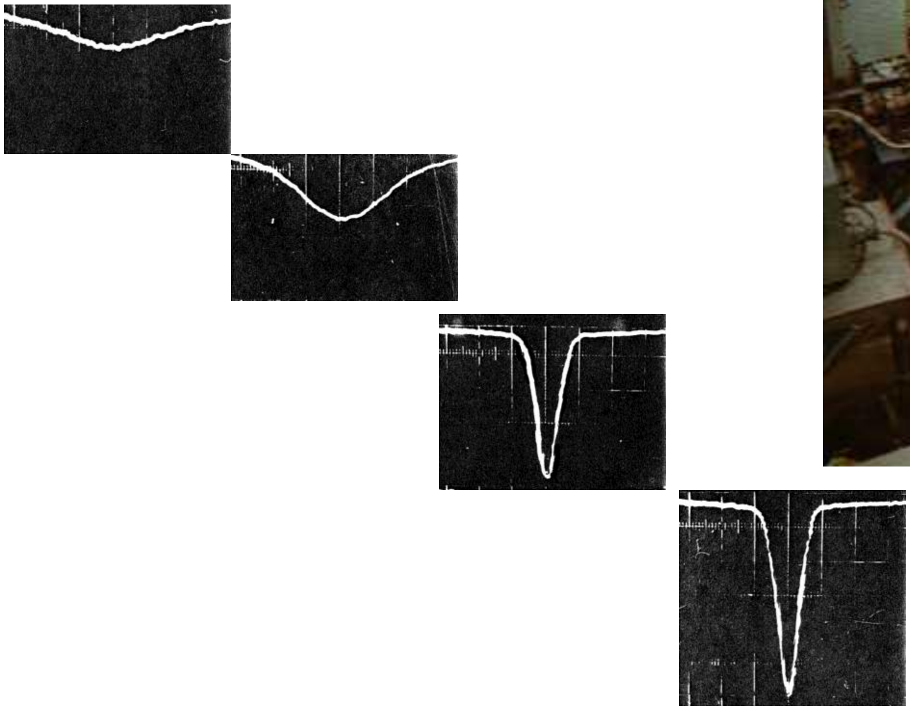
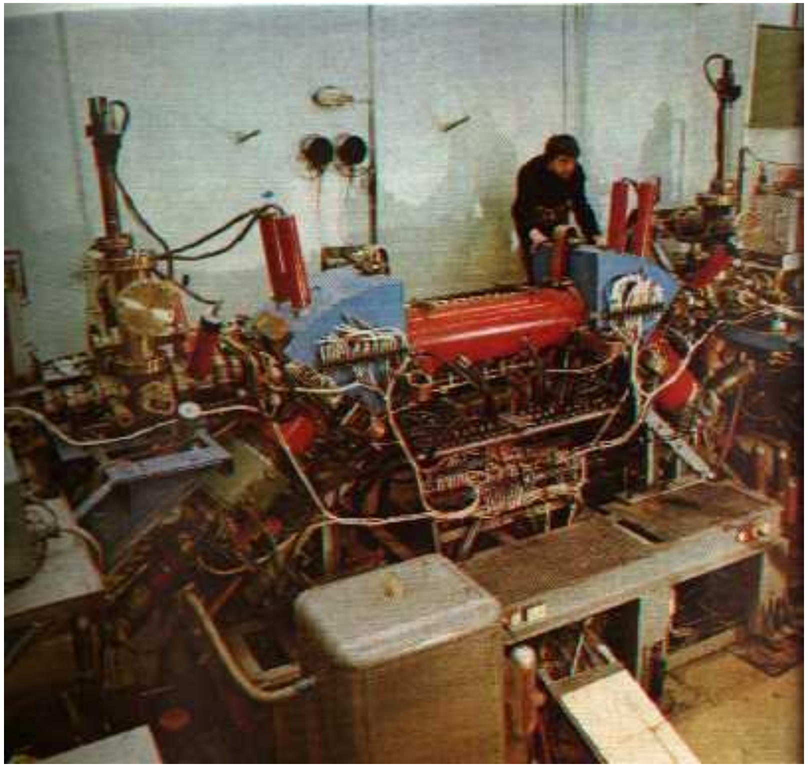
First Cooling Demonstration

- Electron cooling was first tested in 1974 with 68 MeV protons in NAP-M storage ring at INP(Novosibirsk).





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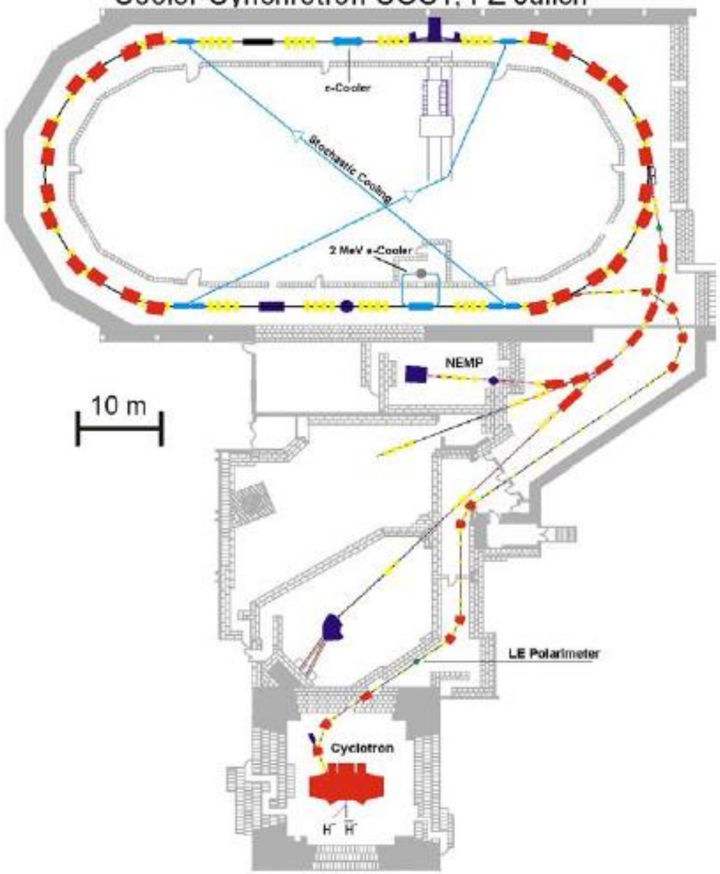
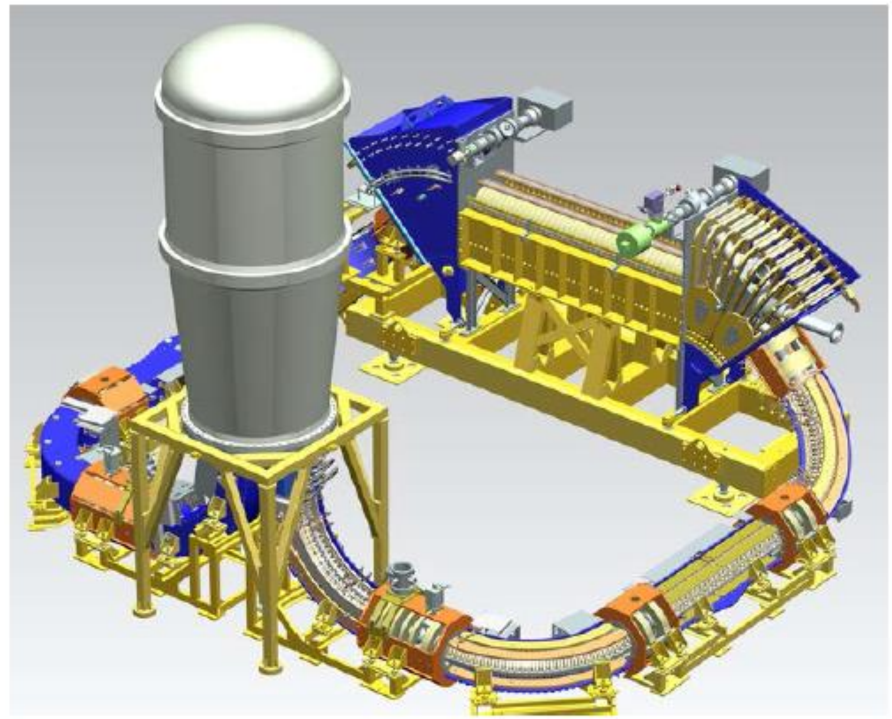
The 2 MeV electron cooler at COSY

Cooler-Synchrotron COSY, FZ Jülich

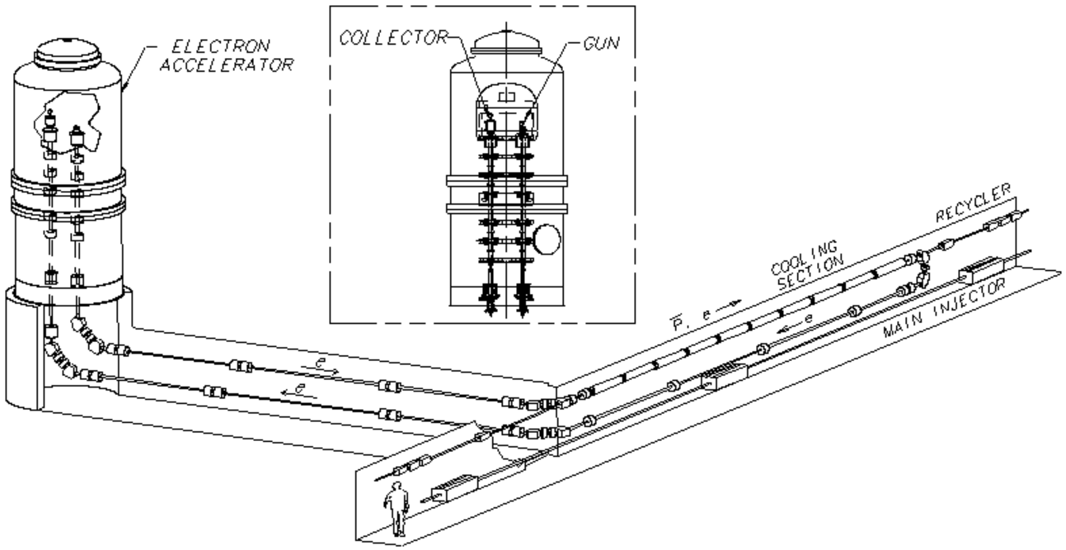




The Fermilab Electron Cooling System

Design parameters

Energy	4.3 MeV
Beam current (DC)	0.5 Amps
Angular spread	0.2 mrad
Effective energy spread	300 eV



Electron beam:

- 4 MeV × 0.5 A = 2 MW DC
  - Energy recovery scheme
  - Very low beam losses are required
  - High voltage discharges need to be avoided
  - Interaction length – 20 m (of 3320 m Recycler circumference)

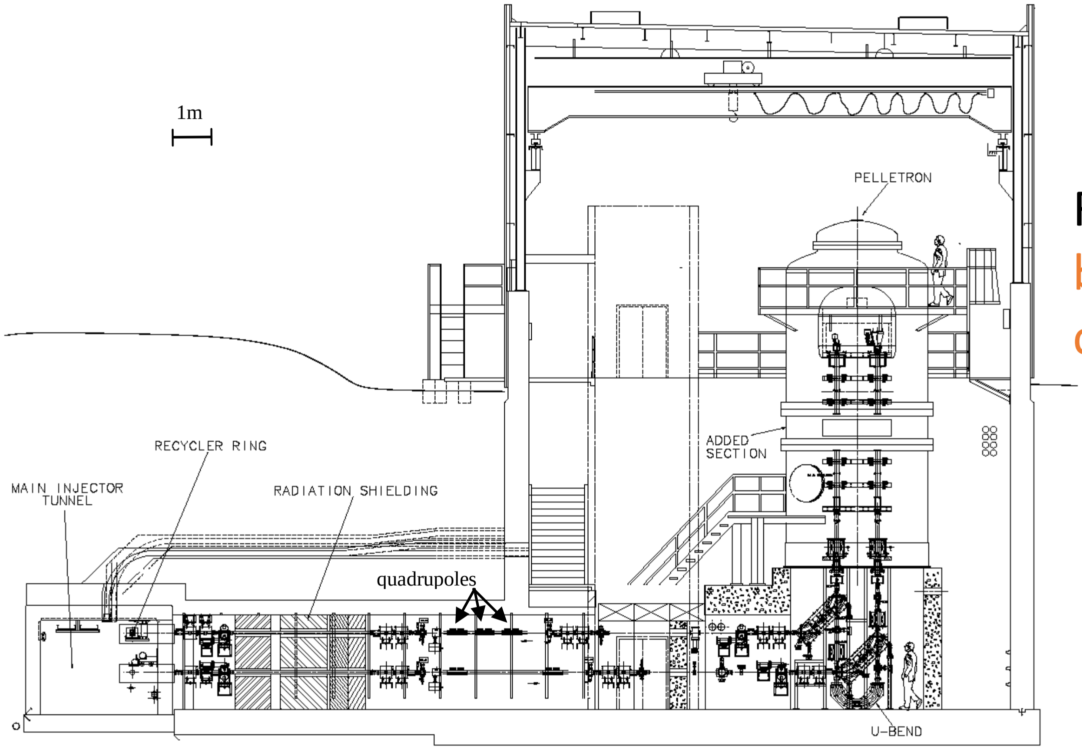
Beam quality:

- Transverse electron beam temperature (in the rest frame) should be comparable to the cathode temperature ~1400K

Development: 1996-2004

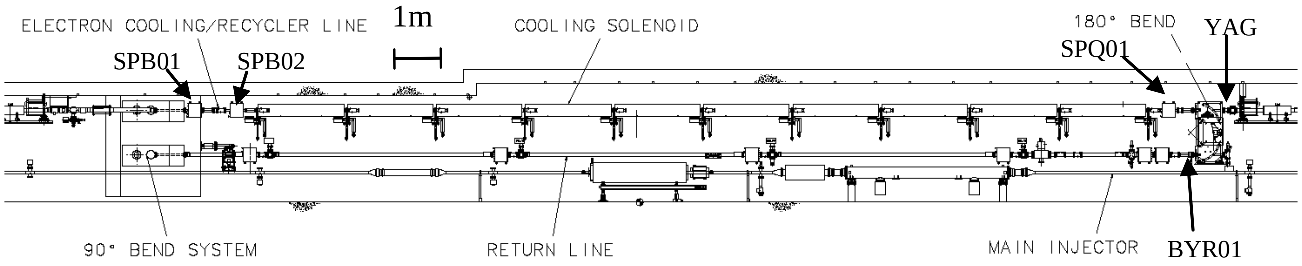
- Operations: 2005 – 2011

S. Nagaitsev, et al. "Experimental Demonstration of Relativistic Electron Cooling", Phys. Rev. Lett. 96, 044801 (2006)
S. Nagaitsev, L. Prost and A. Shemyakin, "Fermilab 4.3-MeV electron cooler," 2015 JINST 10 T01001.



February, 2005- beginning of commissioning

The Pelletron and beam "supply" and "transfer" lines



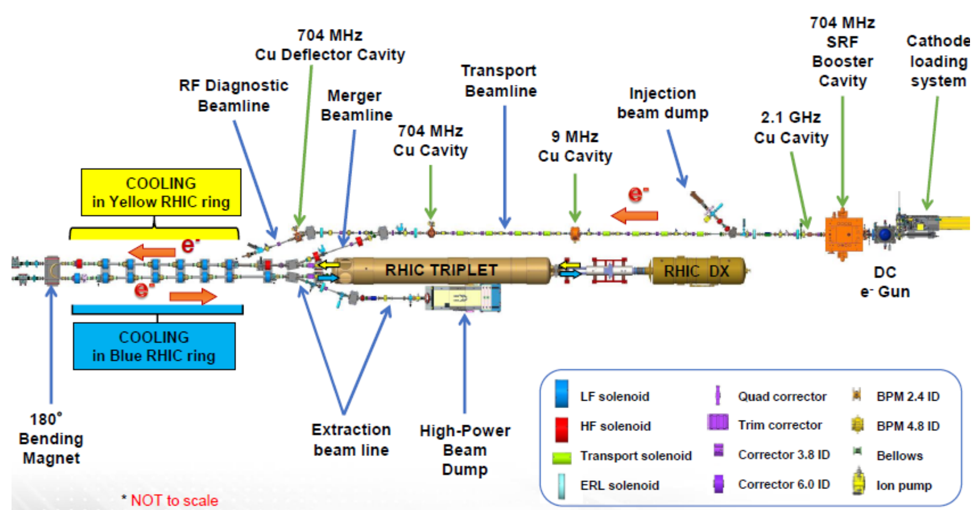
The Main Injector/Recycler tunnel containing the cooling section and the "return" line.

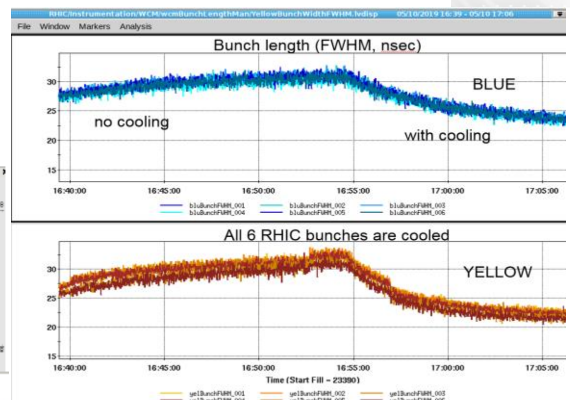
Low-Energy RHIC electron Cooler (LEReC) at BNL:

- LEReC is first electron cooler based on the RF acceleration of electron beam (technology allowing to extend electron cooling to high energies).
- State of the art electron accelerator which uses photocathode high-current gun, high-power laser and several RF cavities was successfully built and commissioned.
- Electron beam parameters suitable for cooling were successfully generated and transported to the cooling sections in RHIC.
- First electron cooling of hadron beams using such bunched electron beam was demonstrated on April 5, 2019.
- Both longitudinal and transverse cooling was achieved.
- Cooling of ion bunches in two separate RHIC rings (Yellow and Blue) simultaneously using single electron beam was demonstrated.
- Present focus is on operational aspects of e-cooling in RHIC.

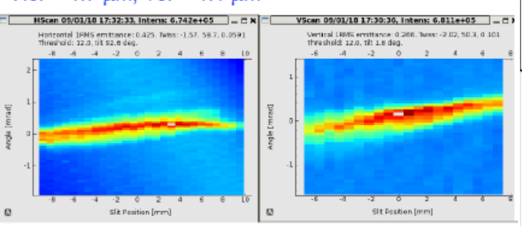
LEReC Accelerator

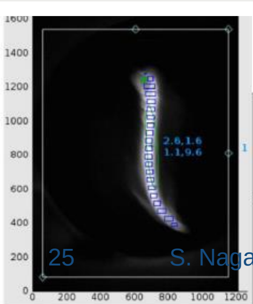
(100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF systems, including one SRF, many magnets and instrumentation)



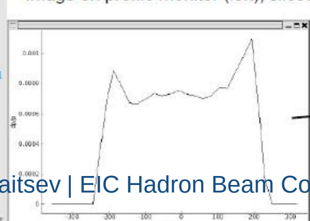


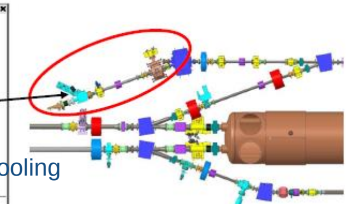
RMS normalized emittance in Yellow cooling section
Hor = 1.7 µm; Ver = 1.1 µm

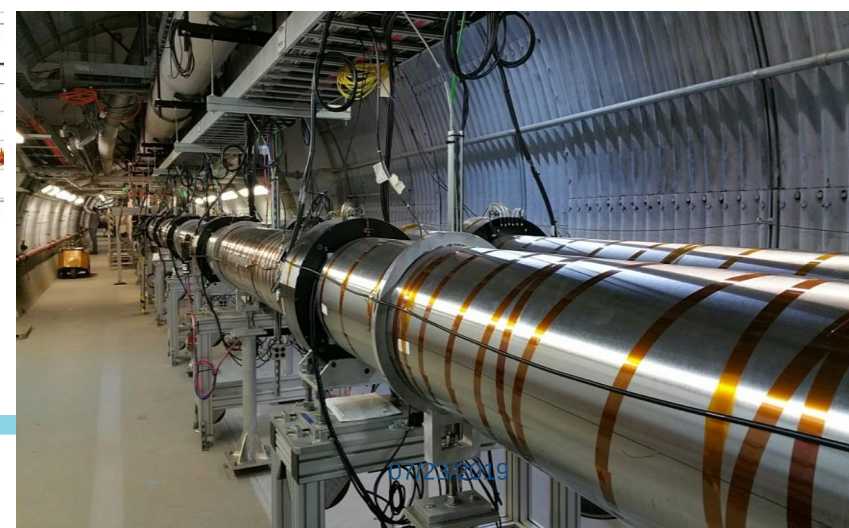




RMS momentum spread in RF diagnostics beam line: rms dp/p < 1×10^{-3}
Image on profile monitor (left), sliced energy spread along the bunch (right).







BNL LEReC is a testbed of high-energy cooling

- **Production of high-brightness electron beams in 3-D**
- **RF-based (bunched beam) electron cooler**
- **Transport of such electron bunches maintaining "cold" beam**
- **Control of electron angles in the cooling section to a very low level required for cooling**
- **Various aspects of bunched beam electron cooling**
- **Electron cooling in a collider:**

  - Effects on hadron beam.

  - Interplay of space-charge and beam-beam in hadrons.

  - Cooling and beam lifetime (as a result of many effects).

All of these are essential elements of high-energy cooling.

High-energy electron cooling

- Cooling rates at relativistic energies
  - Consider the optimistic case when everything is optimized: thermionic cathode, non-magnetized cooling, $\overline{v_{p\perp}^{\,2}} \approx \overline{v_{e\perp}^{\,2}}$:

$$\lambda_{\perp} \approx 5 \frac{r_p r_e \Lambda_c}{\gamma^{2.5}} \frac{L_{cool}}{C} \sqrt{\frac{\beta_x}{\varepsilon_{np}}} \frac{j_{catode}}{e} \frac{m_e c^2}{T_{cathode}}$$

where: $\Lambda_c = \ln \frac{\rho_{\max}}{\rho_{\min}}$, $\beta_x \cong L_{cool}$

The electron beam current is set by $j_{cathode}$ and the rms norm. emit. of p beam:

$$I_e \approx 8\pi \varepsilon_{np}^{\,2} \left(1 + \frac{L_{cool}^{\,2}}{4\beta_x^{\,2}}\right) \frac{m_e c^2}{T_{cathode}} j_{cathode}$$

- The reduction of IBS rates with energy enables the attainment of required cooling rates with increased energy:

$$\lambda_{IBS\perp} \approx 0.3 \frac{r_p N_p c \Lambda_c \sqrt{C}}{\gamma^{1.5} \sigma_s \varepsilon_{np}^{\;1.5} \nu_x^{\;2.5}}$$

- To achieve such cooling rates one needs the longitudinal magnetic field with very high accuracy: $\Delta B / B \ll \sqrt{\varepsilon_{np} / (\gamma \beta_x)}$,

  i.e. $\Delta B/B \lesssim 10^{-5}$ for E_p=100 GeV

Technology gap

- The proton beam cooling challenge
- The present electron cooling technology is not scalable to ion energies above ~10 GeV/u
- Conventional bunched-beam stochastic cooling does not work with bunched protons (RHIC and Tevatron experience)
- The EIC R&D report has identified Bunched-Beam cooling of hadrons in the collider rings as on the highest-risk elements

Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

February 13, 2017

2017

Present EIC cooling concepts

- Electron cooling (50 – 150 MeV electron beam):
  - The key idea here is to compensate for $\gamma^{2.5}$ dependence by a higher electron beam current density
  - ERL- based (JLab/ODU): bunched beam ERL and a muti-turn cooling ring
  - Induction Linac – based (Fermilab): DC beam (100 A) and a storage ring
- Stochastic cooling
  - All concepts are based on a transit time method
  - The key idea here is to increase the bandwidth from ~10xGHz to ~many THz's
  - Coherent Electron Cooling (BNL/SBU)
  - Micro-bunched Electron Cooling (SLAC)
  - Optical Stochastic Cooling (Fermilab)

Multi-Phase Electron Cooling for High Luminosity

JLab/ODU

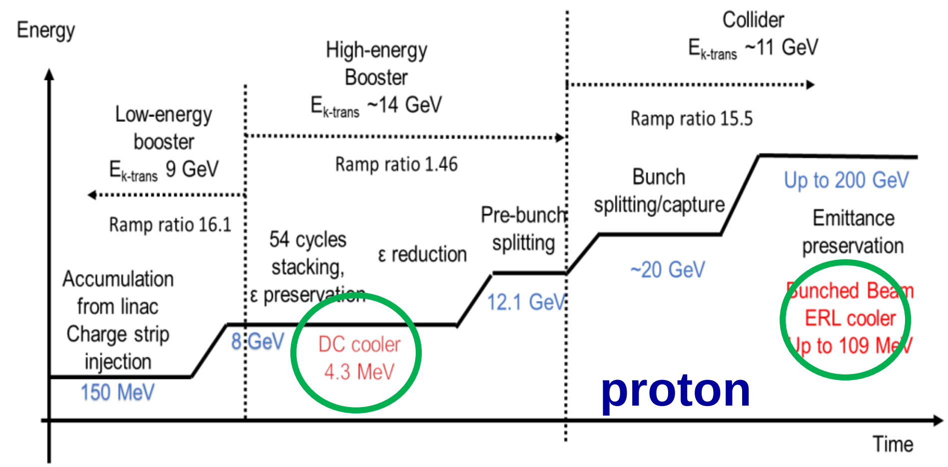
- JLEIC choice: conventional electron cooling and multi-phase
- Achieving small emittance (up to **~10 times** reduction) and very short bunch length (**~2 cm**)
- Assisting injection/accumulation of heavy ions
- Suppressing IBS induced emittance growth during beam store
- Multi-phase cooling could reduce total cooling time by orders of magnitude: high cooling efficiency at low energy/small emittance

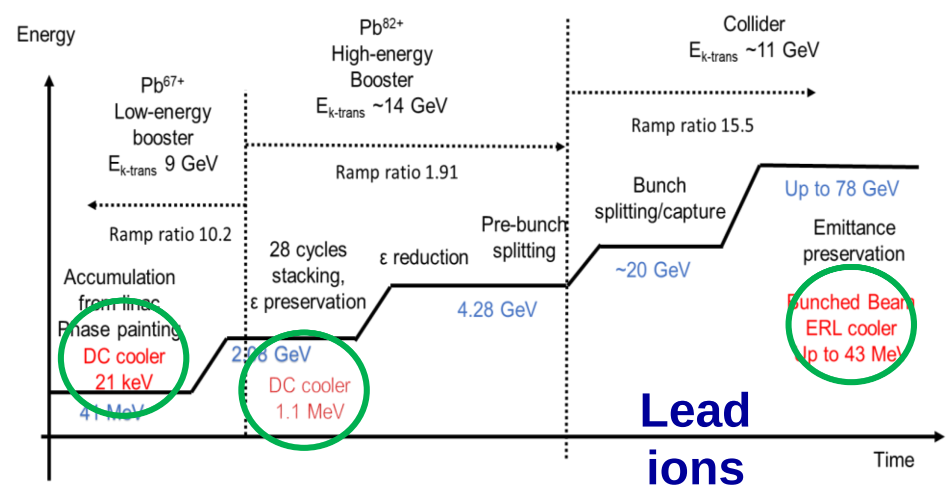
Pre-cool when energy is low

$$\tau_{cool} \sim \gamma^2 \frac{\Delta\gamma}{\gamma} \sigma_z \varepsilon_{4d}$$

Cool after emittance is reduced (after pre-cool at low energy)

Ring	Functions	Kinetic energy (GeV / MeV)			Cooler type
		Proton	Lead ion	Electron	
Low Energy Booster	Accumulation of positive ions		0.1 (injection)	0.054	DC
High Energy booster	Maintain emitt. during stacking	7.9 (injection)	2 (injection)	4.3 (proton) 1.1 (lead)	DC
	Pre-cooling for emitt. reduction	7.9 (injection)	7.9 (ramp to)	4.3	
collider ring	Maintain emitt. during collision	Up to 150	Up to 78	Up to 81.8	ERL

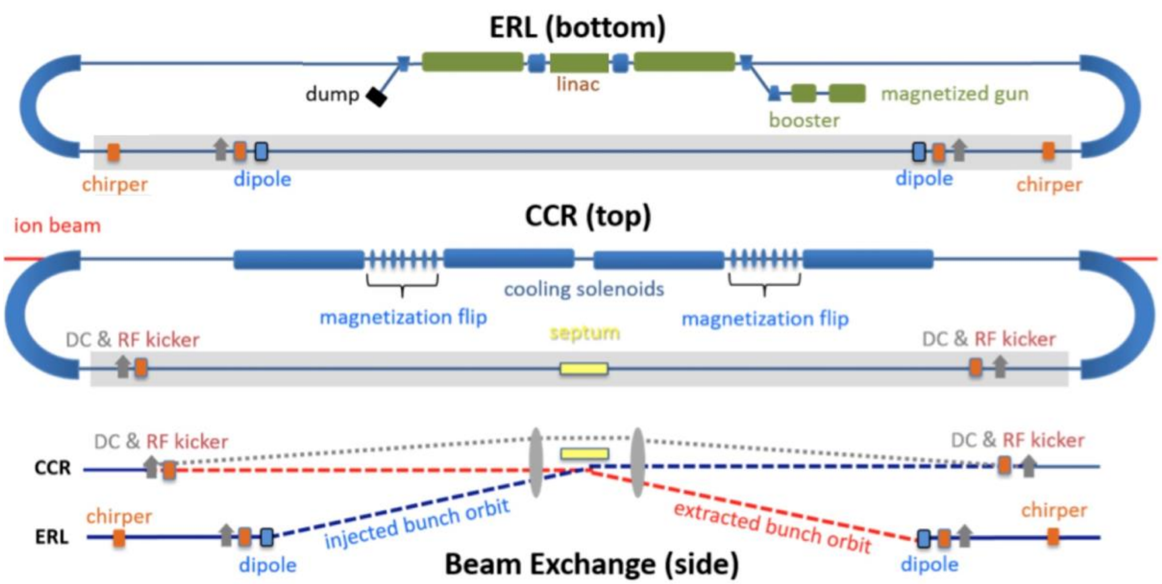




High Energy Cooler Design is Cooling Ring Fed by ERL

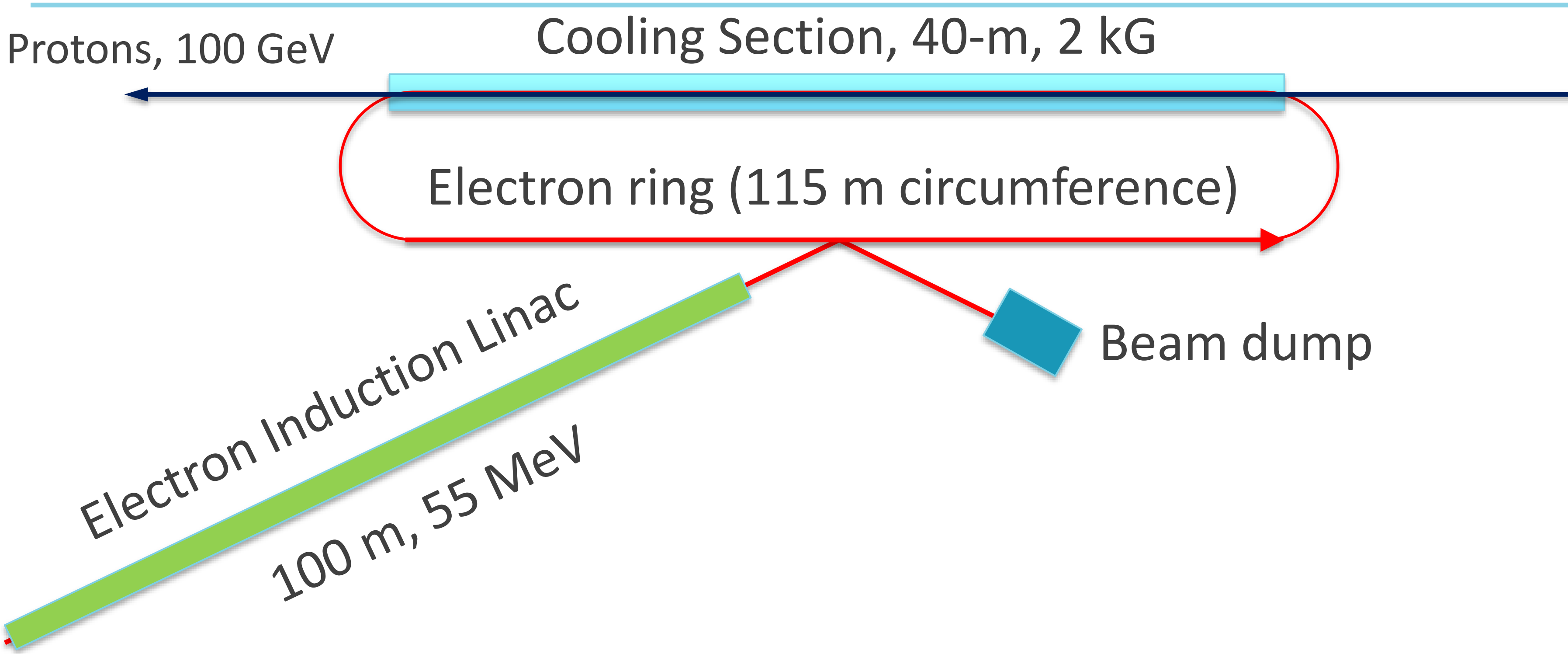
JLab/ODU

- Same-cell energy recovery in 476.3 MHz SRF cavities with Harmonic linearizer
- Uses harmonic kicker to inject and extract from CCR (divide by 11)
- Assumes high charge, low rep-rate injector (w/ harmonic linearizer acceleration)
- Use magnetization flips to compensate ion spin effects



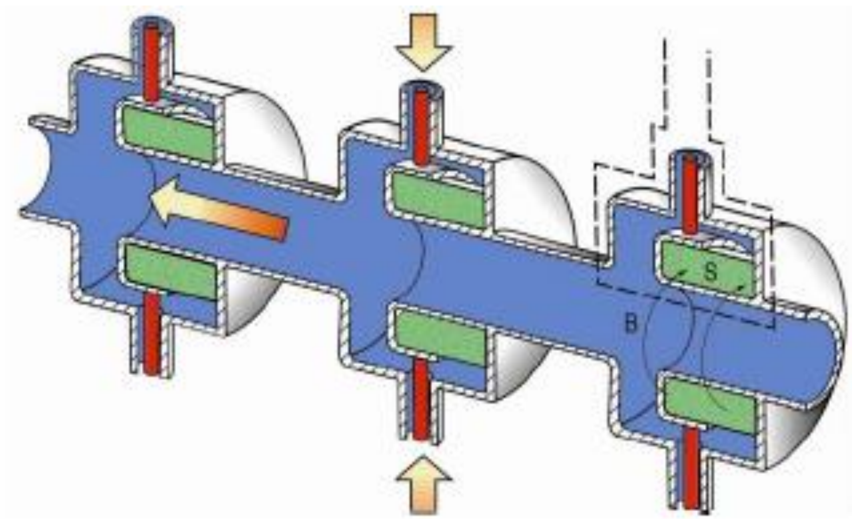
•	Energy	20–110 MeV
•	Charge	1.6 (3.2) nC
•	CCR pulse frequency	476.3 MHz
•	Gun frequency	43.3 MHz
•	Bunch length (tophat)	3 cm (17°)
•	Thermal (Larmor) emittance	<19 mm-mrad
•	*rms* Energy spread (uncorr.)*	3×10^{-4}
•	Energy spread (p-p corr.)*	$<6\times10^{-4}$
•	Solenoid field	1 T
•	Solenoid length	4x15 m
•	Bunch shape	beer can

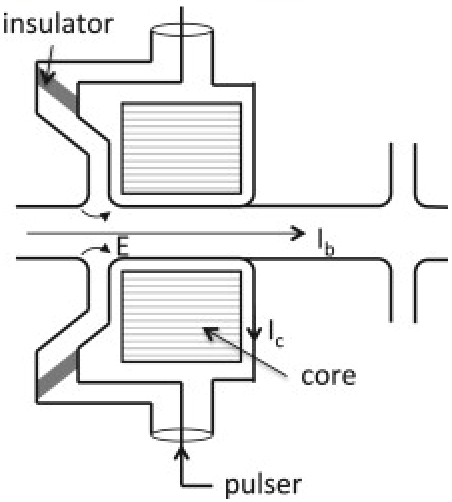
Induction Linac Concept (Fermilab)



- We are considering a range of electron beam and linac parameters: 100-200 A beam current, 100 – 200 Hz rep. rate
- Pulse length: 380 ns (to fill the ring)
- Beam power to dump: 0.8 MW (worst case), 200 kW (best case)

Induction linac (Fermilab)





DARHT at LANL

Injector Voltage	2.5 MV
Injector Current	2.0 kilo-Amperes
Injector Pulse Length	1.6 micro-seconds
Number of Injector Cells	6 @ 175 kV/cell
Number of Accelerator Cells	68 @ 200-235 kV/cell
Total Beam Energy	17.1 MeV (goal 18.1 MeV)

- H. Davis and R. Scarpetti, “Modern Electron Induction LINACs”, LINAC 2006,

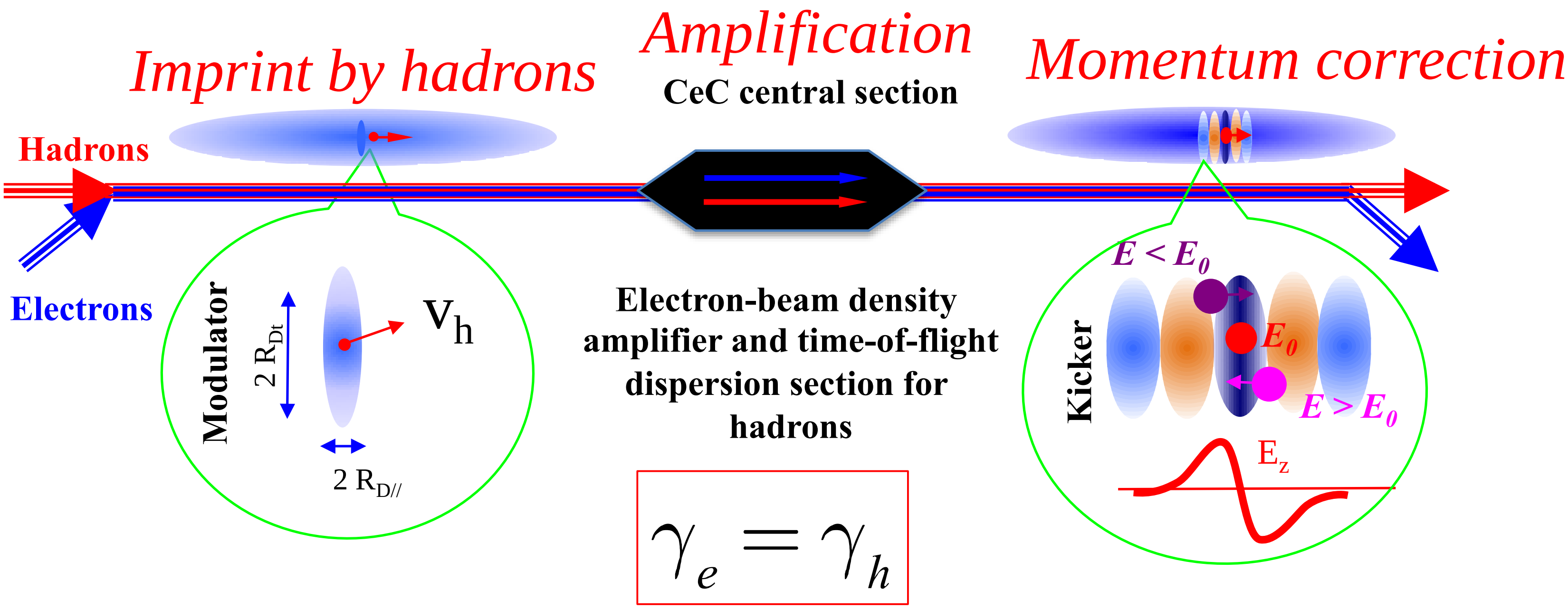
Preliminary ring-based cooling system parameters

Proton beam energy	**100 GeV**
Proton ring circumference	3000 m
Relativistic factor, γ	107.58
Normalized rms proton beam emittance	1 µm
Proton beam rms momentum spread	$<3\cdot10^{-3}$
Proton beam rms angular spread	15 µrad
β-functions of proton beam in cooling section center	40 m
Electron beam energy	54.48 MeV
Electron ring circumference	114.2 m
Cooling length section	40 m
Electron beam current	100 A
Longitudinal magnetic field in cooling section	1.85 kG
Electron beam rms momentum spread, initial/final	$(1.0/1.7) \cdot 10^{-3}$
Rms electron angles in cooling section	27 µrad
Rms electron beam size in cooling section	2.04 mm
Electron beam rms normalized mode emittances (initial), µm	453/0.081
Number of cooling turns in the electron storage ring	13,000
Longitudinal cooling time (emittance)	1 hour
Transverse cooling time (emittance)	2 hour

Coherent electron Cooling

BNL/Stonybrook U

- Transient stochastic cooling of hadron beams with bandwidth at optical wave frequencies: 1 – 1000 THz



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Coherent Electron Cooling

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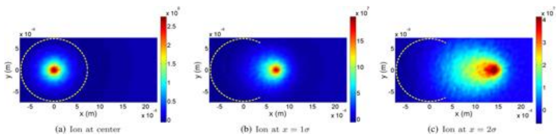
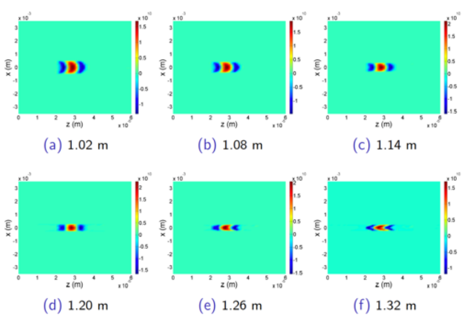
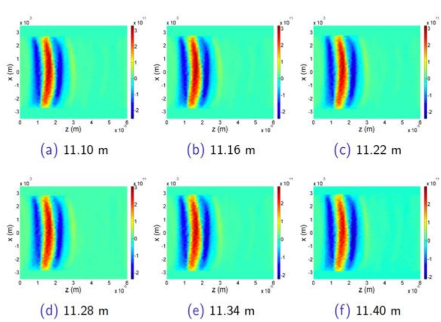
Simulated performance: 26.5 GeV Au ion bunch in RHIC

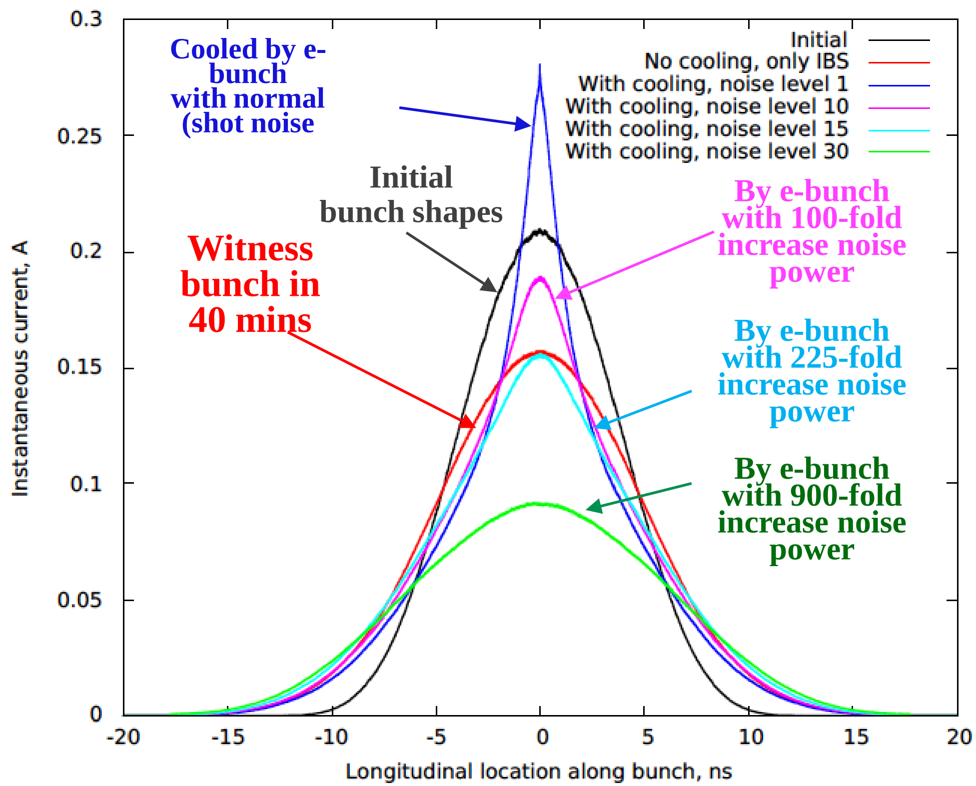
We had developed a suite of codes to simulate the complete beam dynamics in the CeC accelerator, the interaction with ion beam and the cooling of the ion beam with CeC using any type of amplifier. It is done without relying on any model: standard codes use 3D PIC simulations and super-computers.







40 mins of PCA CeC



Black – initial profile, red – witness (non-interacting) bunch after 40 minutes. Profiles of interacting bunches after 40-minutes in PCA-based CeC for various levels of white noise amplitude in the electron beam: dark blue – nominal statistical shot noise, magenta – 10 fold, light blue – 15 fold and green – 30 fold - higher than the statistical level.

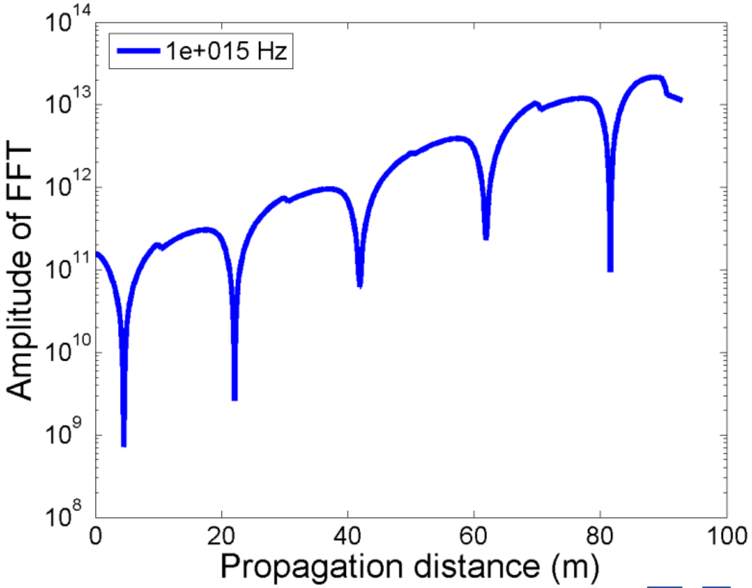
Cooling will occur when electron beam micro-bunching power (e.g. bending magnet radiation) does not exceed that of spontaneous (shot noise) radiation by more than 200-fold

eRHIC cooler simulations

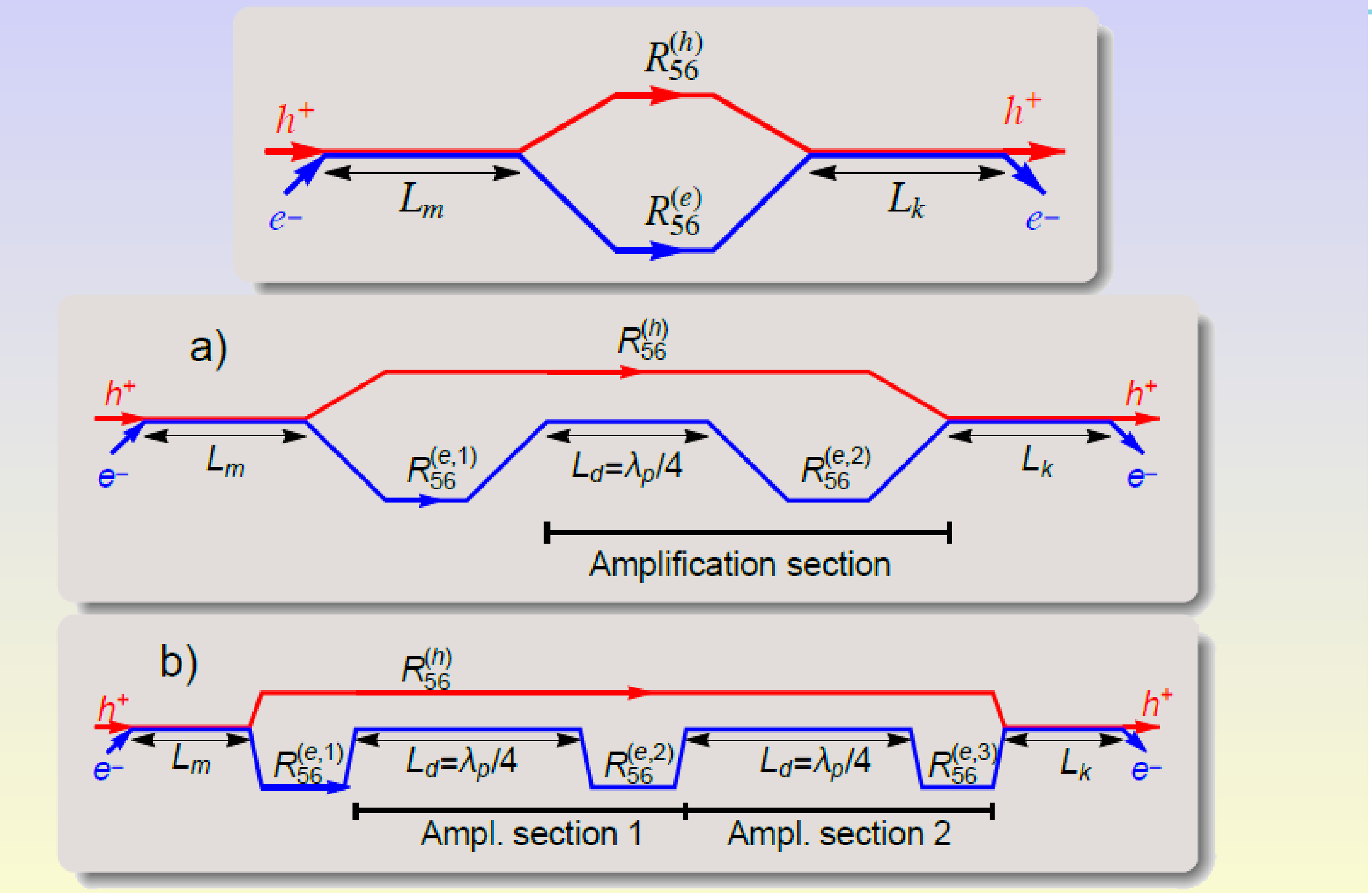
- We did full scale simulations for CeC with 4-cell PCA for our proposed test experiment as well as for eRHIC energy range – it proved that our expectations are correct and this system will have high gain (>100) and very large bandwidth: 25 THz for test experiment and 1,000 THz (1 PHz*) for CeC cooling 275 GeV protons
- This cost effective system – it does not need expensive separation system for hadrons - would be capable of 3D, e.g. longitudinal and transverse cooling of cooling hadron beams in RHIC and eRHIC independently of the design choice. Cooling time is ~ 10 minutes for protons. CeC will operate at all eRHIC hadron energies currently under consideration
- Still, it will be important to demonstrate untested micro-bunching cooling technique experimentally

- γ=275
- Cell length 20 m
- Solenoid length 1 m
- Beam waist 1e-4 m
- Peak current 250 A
- RMS energy spread 1e-4
- Normalized emittance 2e-6 m rad

Plasma-Cascade Amplifier gain
For 275 GeV protons in eRHIC



Micro-bunched cooling (SLAC)



- 1D theory of longitudinal cooling without amplification stages (G. Stupakov, PRAB, **21**, 114402 (2018))
- 1D theory of longitudinal cooling with one and two amplification cascades (G. Stupakov, P. Baxevanis, PRAB, **22**, 034401, 2019)
- Theory of transverse cooling (P. Baxevanis, G. Stupakov, in preparation)
- 3D theory, work in progress (G. Stupakov, P. Baxevanis, IPAC 2019)

Cooling rate for M-B Cooling (SLAC)

The electron beam overlaps only with a small fraction of the hadron beam. Over many revolutions, hadrons move longitudinally due to the synchrotron oscillations. One needs to average the cooling rate over the length of the electron bunch,

$$N_{\mathrm{c}}^{-1} = \frac{0.31}{\sigma_{\eta h}\sigma_{\eta e}} \frac{1}{\gamma^3} \frac{cQ_e}{\sqrt{2\pi}\sigma_{zh} I_A} \frac{r_h L_m L_k}{\Sigma_x^3}$$

the cooling time is

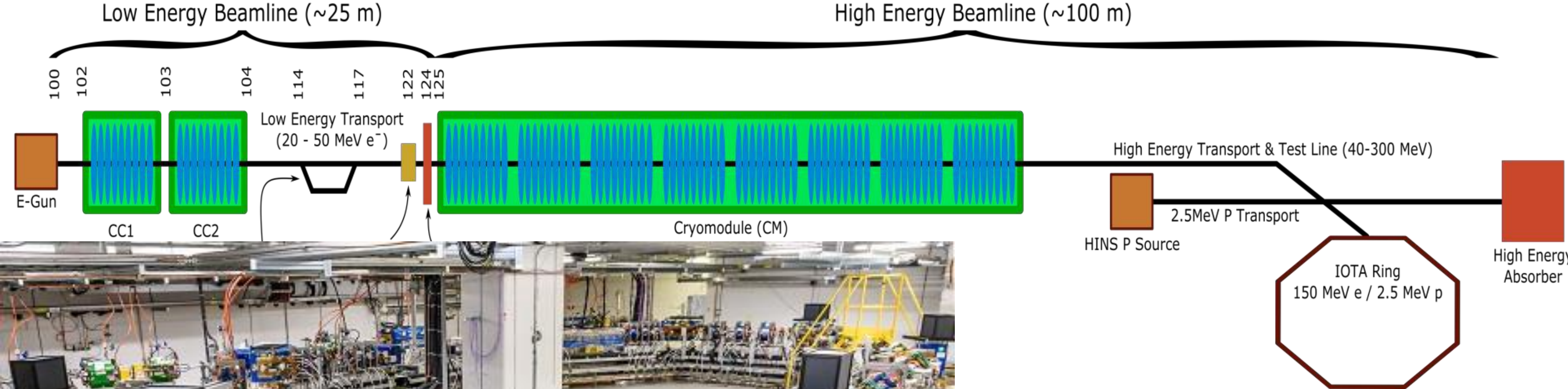
$$T_{\mathrm{c}} \approx 0.7 \text{ h} \quad \text{for JLEIC}$$

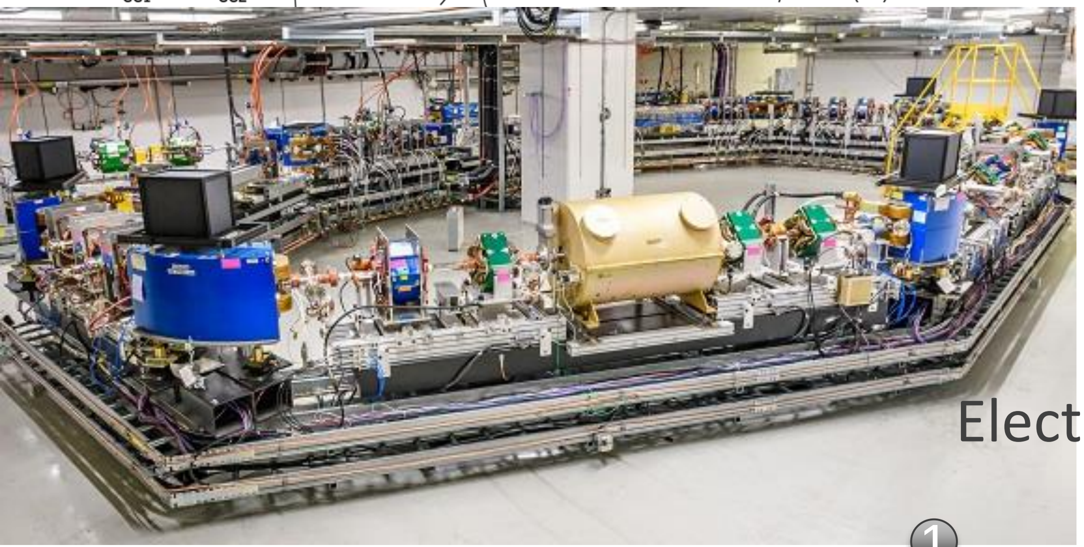
(for eRHIC this number was 41 h).

Fermilab

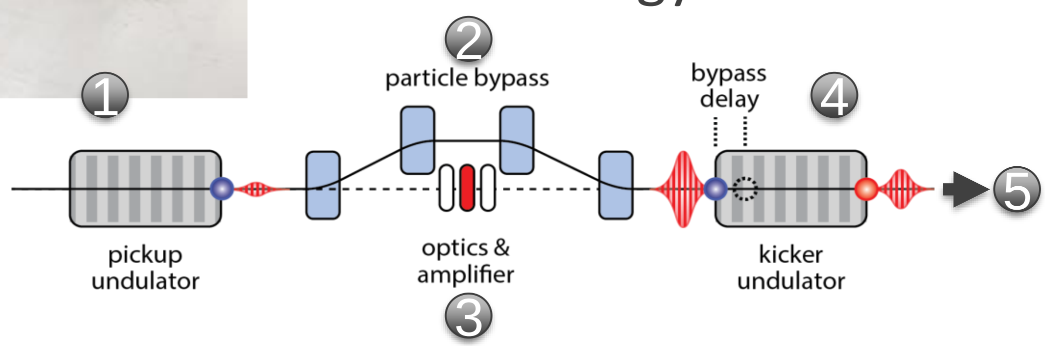
Optical Stochastic Cooling (Fermilab)

FAST/IOTA accelerator test facility at Fermilab



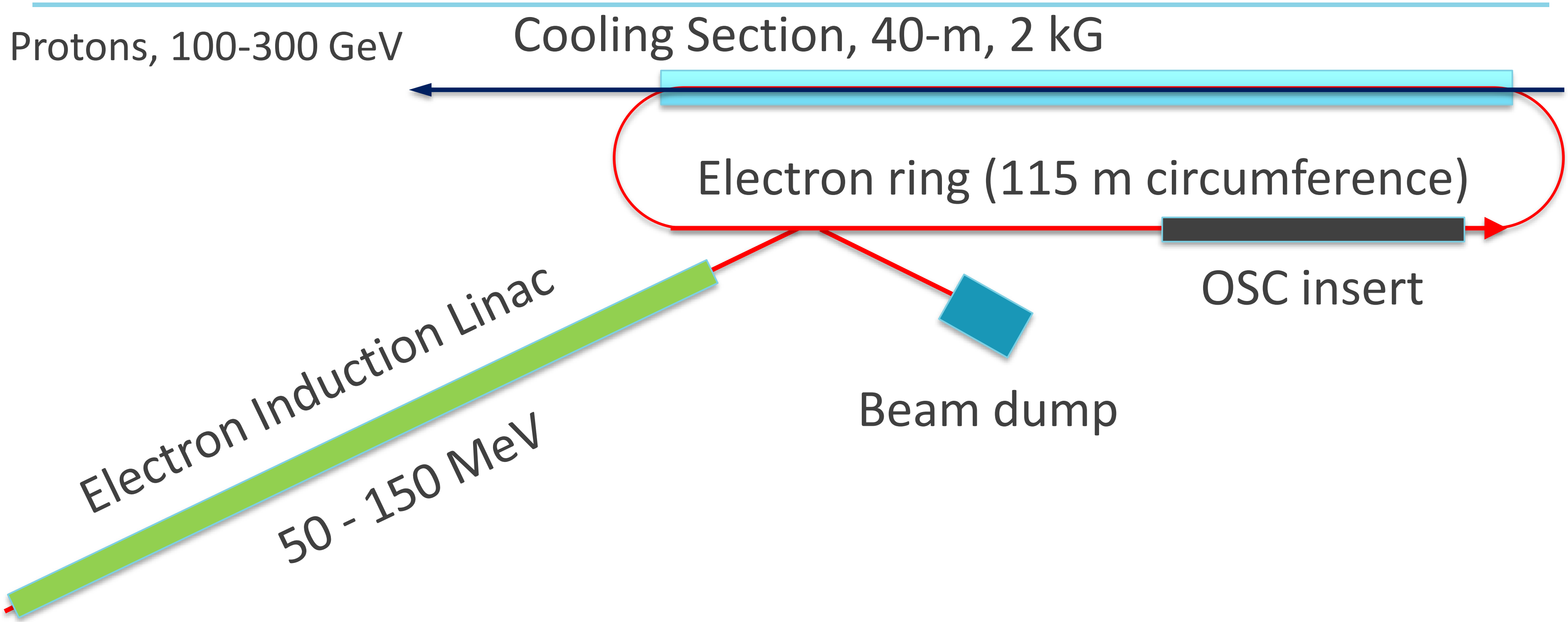


Electron beam energy: 70-150 MeV



Fermilab

Ring-based EIC electron cooler concept with OSC



- OSC would make the induction linac parameters much more relaxed: 100-200 A beam current, 10 – 20 Hz rep. rate
- Pulse length: 380 ns (to fill the ring)

Summary

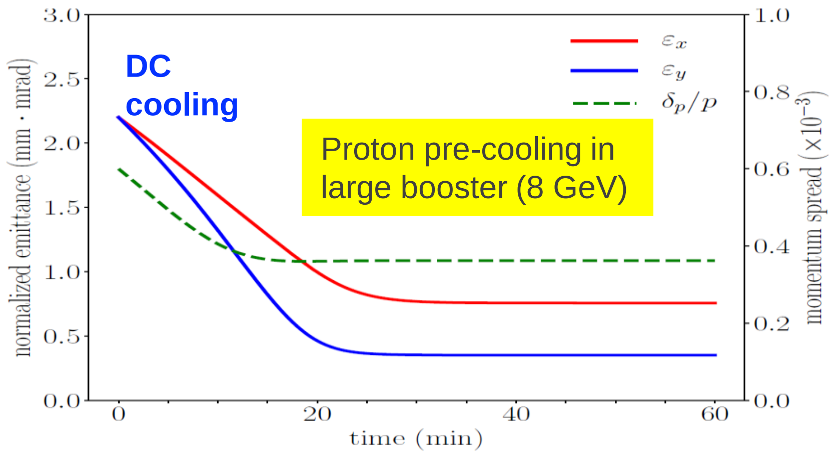
- Our main challenge is to develop a cooling system for protons (100-300 GeV) with cooling times of < 1 hour.
  - High-Z ions can be cooled by stochastic cooling (like in RHIC)
  - Traditional dc electron cooling schemes are not scalable to energies above >10 GeV
  - Conventional stochastic cooling is too slow for bunched protons

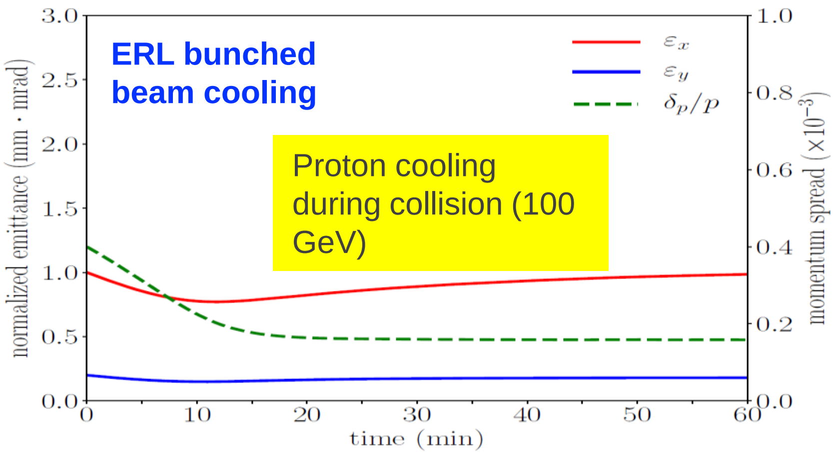
- We have a number of promising concepts to address the EIC hadron beam challenge. And we are confident that (with time and resources) we will develop an optimal hadron beam cooling system.

- EIC Hadron Cooling workshop: Oct 7-8, 2019, Univ of Chicago https://indico.fnal.gov/event/20514/

Extra slides

JLEIC Cooling Simulation and Software Development





JLEIC Proton beam cooling simulation

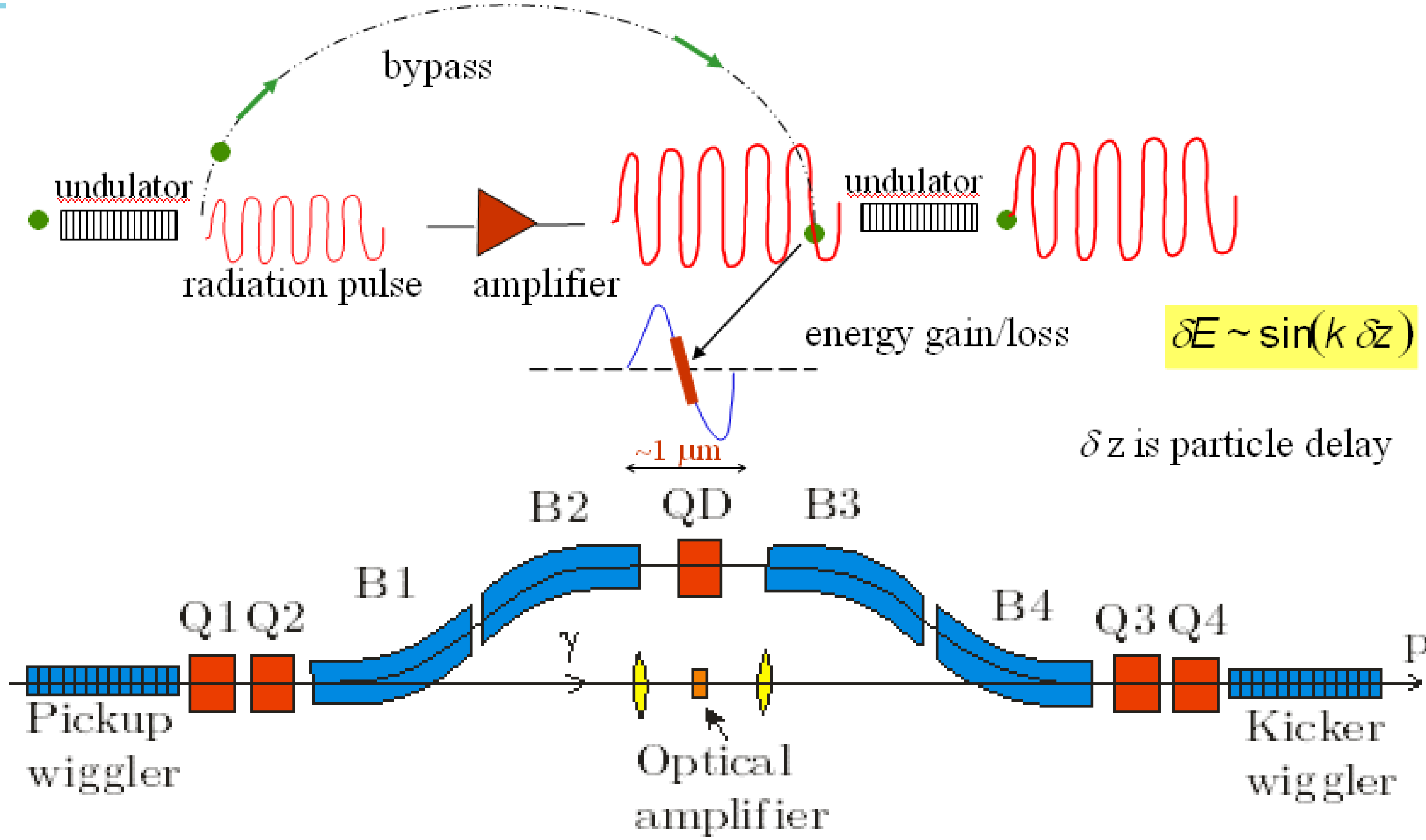
- Pre-cooling at lower energy to reduce the emittance. Cooling at the collision energy to maintain the emittance.
- Upper plot: DC cooling is sufficient for pre-cooling at 8 GeV
- Lower plot: high energy cooling is still a bit weak, proton current is reduce to 60% of the nominal value for lower IBS.
- High energy cooling challenge: imbalance between IBS and cooling (strong horizontal IBS vs. strong longitudinal cooling.)
- More study is needed to optimize cooling design

JSPEC: JLab Simulation Package for Electron Cooling

- Calculate the IBS rate and electron cooling rate
- Simulate the IBS and/or electron cooling process
- C++, open source https://github.com/zhanghe9704/electroncooling
- Benchmarked with BETACOOL
- Text-based user interface (UI)
- Online version by Radiasoft LLC https://beta.sirepo.com/#/jspec

Fermilab

Principles of Optical Stochastic Cooling



- Proposed by Zolotorev, Zholents and Mikhailichenko (1994)
- Obeys the same principles as microwave stochastic cooling, but exploits the superior bandwidth of optical amplifiers ~ 10^{14} Hz
- Pickups and kickers must work in the optical range