Review of Recent Advances in Cooling Techniques

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Sep 6, 2019

Beam Cooling: introduction

- Beam cooling at collision energies is desired/required for future hadron colliders with energies below a few TeV
  – Already part of RHIC ion-ion operations (first ever in colliders)
  – 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 50-150 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

The beam cooling challenge

- The 2017 EIC R&D report has identified cooling of hadrons in collider rings as on the highest-risk elements
  - The highest risk is associated with cooling of protons at collisions

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

February 13, 2017

2017

- Today, 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, Fermilab https://indico.fnal.gov/e/EIC-HC2019/

In coordination with the EIC Accelerator Collaboration meeting (www.anl.gov/EIC2019)

What is beam cooling?

- Cooling is a reduction of the 6D phase space volume, occupied by the beam (for the same number of particles).

$$\varepsilon_{6D} = \int f(\vec{p},\vec{q})\, d^3p\, d^3q$$

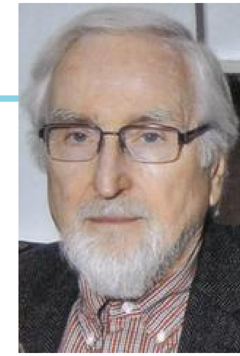
- Equivalently, cooling is a reduction in the random motion of the beam.

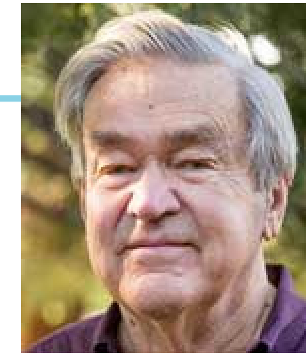
- Examples of non-cooling:
  - Beam scraping (removing particles with higher amplitudes) is NOT cooling;
  - "Cooling" due to beam acceleration;
  - Expanding the beam transversely lowers its transverse temperature. This is NOT cooling;
  - Coupling between degrees of freedom may lead to a reduction 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);
  - Mismatch in focusing;
  - Interaction with beam's environment (e.g. wake fields);
  - Space-charge effects;
  - Production and accumulation of secondary and tertiary beams;
- Normally, it is necessary to keep momentum spreads in the transverse degrees of freedom at $\sim 10^{-4}$ of the average longitudinal momentum.

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





INTRABEAM SCATTERING

JAMES D. BJORKEN
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510 U.S.A.

and

SEKAZI K. MTINGWA
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510 U.S.A.
and
Department of Physics, University of Illinois, Chicago, Illinois 60680 U.S.A.

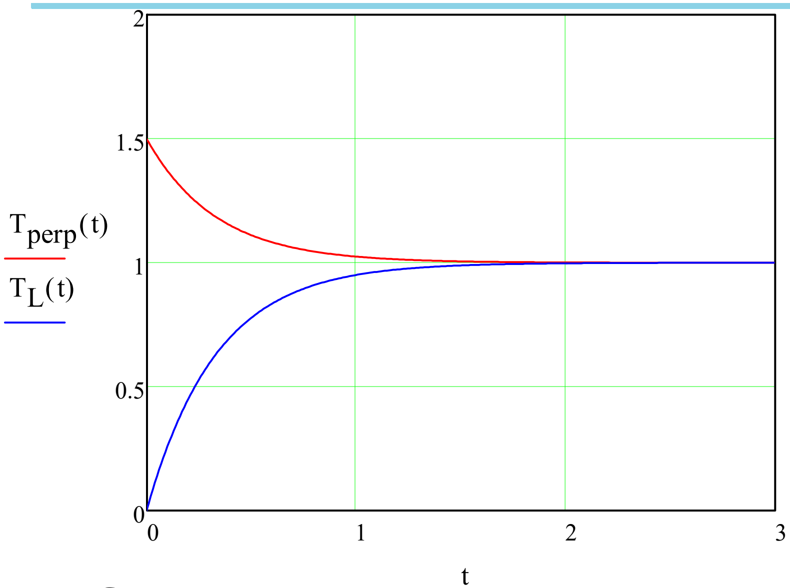
(Received October 1, 1982)

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



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

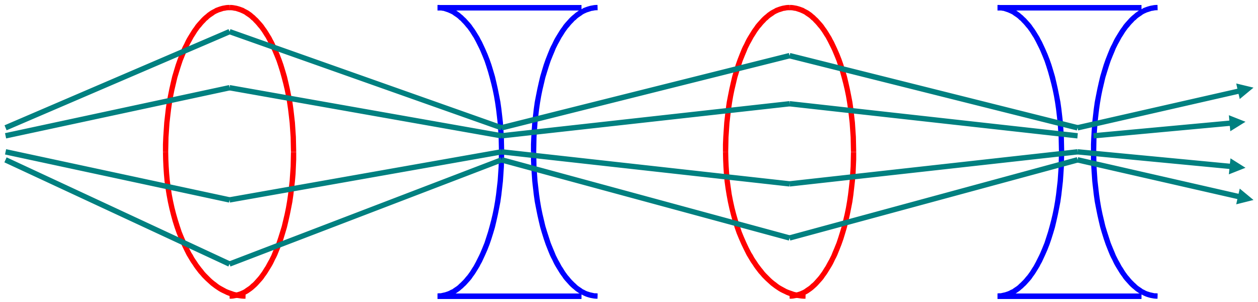
$$\frac{1}{\tau} = \frac{8\sqrt{\pi} n r_c^2 c}{15\left(kT_{eff} / mc^2\right)^{3/2}} \ln \Lambda$$

$$\tau \propto \frac{T_{eff}^{\;3/2}}{n} \propto \frac{\varepsilon^{3/2}}{\beta(s)^{3/2}} \varepsilon\beta(s) \propto \frac{\varepsilon^{5/2}}{\beta(s)^{1/2}}$$

- 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 FODO 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). :



Beam cooling methods

- Two methods widely employed for beam cooling today:
  - Stochastic cooling (1984 Nobel Prize in Physics)
  - Electron cooling

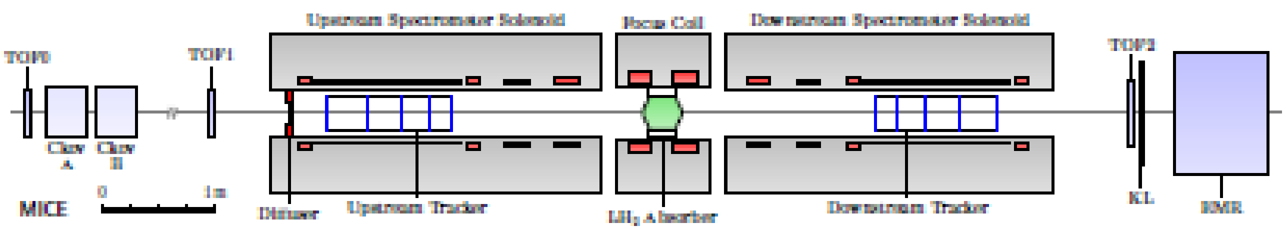
- Two other methods had recent interesting developments:
  - Muon (ionization) cooling
  - Laser (Doppler) cooling

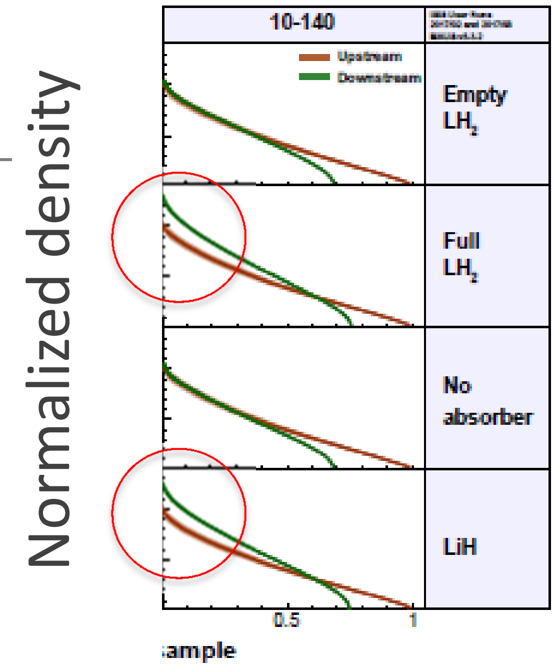
- I will not discuss:
  - Radiation damping

Muon (Ionization) Cooling

- MICE collaboration has just reported (arXiv:1907.08562):

“First demonstration of ionization cooling by the Muon Ionization Cooling Experiment”





Absorbers:

65 mm LiH disk

350 mm LH2

Ionization cooling:

Due to energy loss in absorber

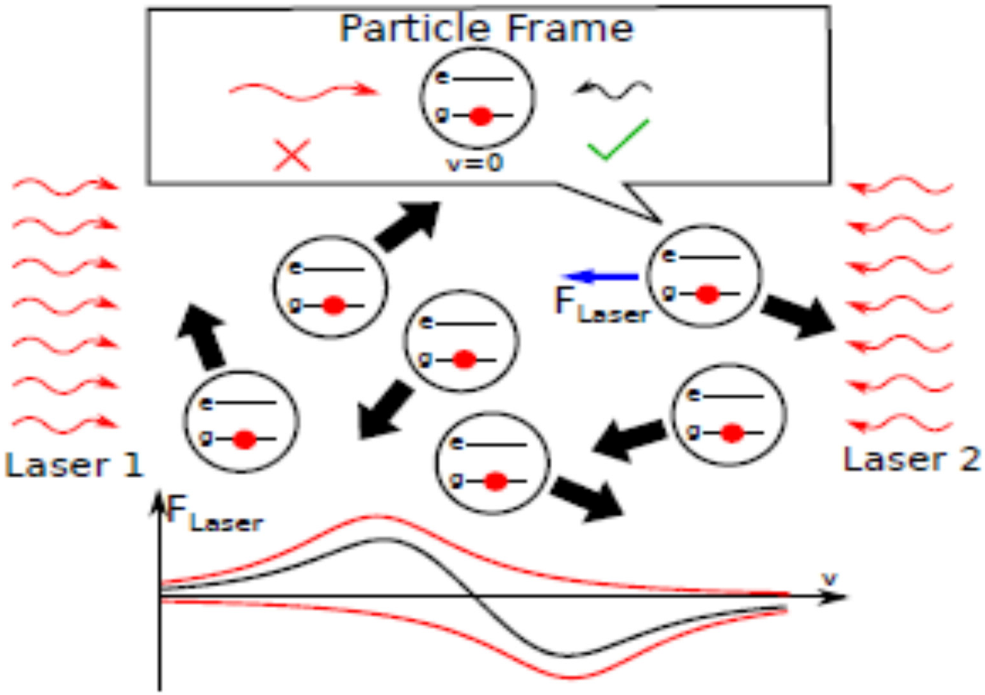
Observe by comparing:

Beam d/s of absorber to that u/s

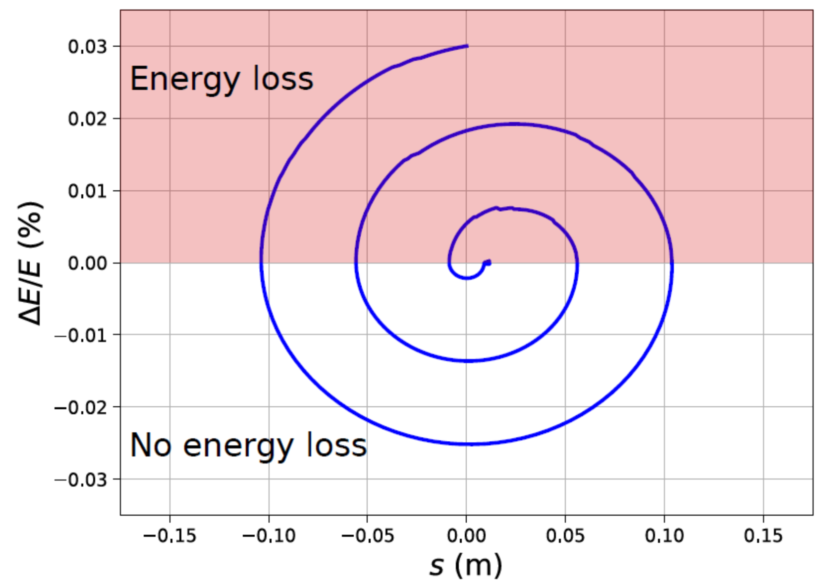
ure 4). The ground-breaking demonstration of ionization cooling presented here is a significant advance in the development of high-brightness muon beams. The

Laser (Doppler) longitudinal cooling

Coasting beam



Bunched beam (e.g. LHC)



An on-going study of laser cooling in the LHC:

Hydrogen-like lead ion in the LHC (top **Gamma Factory** parameters): $Z = 81$, A = 208, $\boldsymbol{\gamma = 2928}$, $p_z =$ 567 TeV/c, $\boldsymbol{\hbar\omega' = 69}$ **keV** (Lyman-alpha line), laser $\boldsymbol{\hbar\omega = 12}$ **eV** (FEL), max. emitted gamma $\boldsymbol{\hbar\omega_{1,max}} =$ **402 MeV**, typical angle of emission $\theta_1 \sim 1/\gamma \sim 0.3$ mrad.

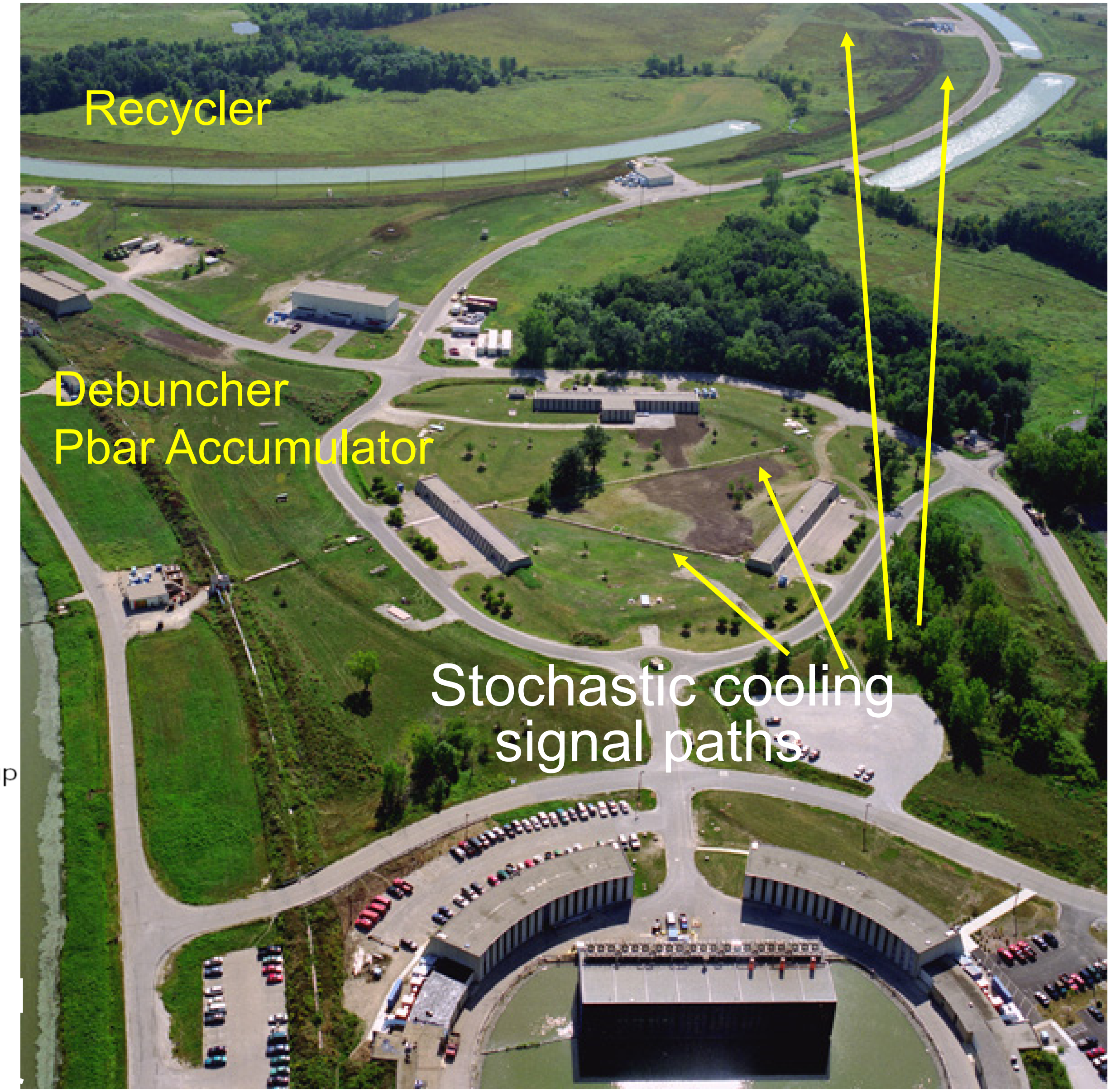
The enhanced version of longitudinal cooling can be demonstrated in the proposed SPS-based experiment: R. Alemany-Fernandez et al. Gamma Factory at CERN: Design of a Proof-of-Principle Experiment. IPAC'2019.

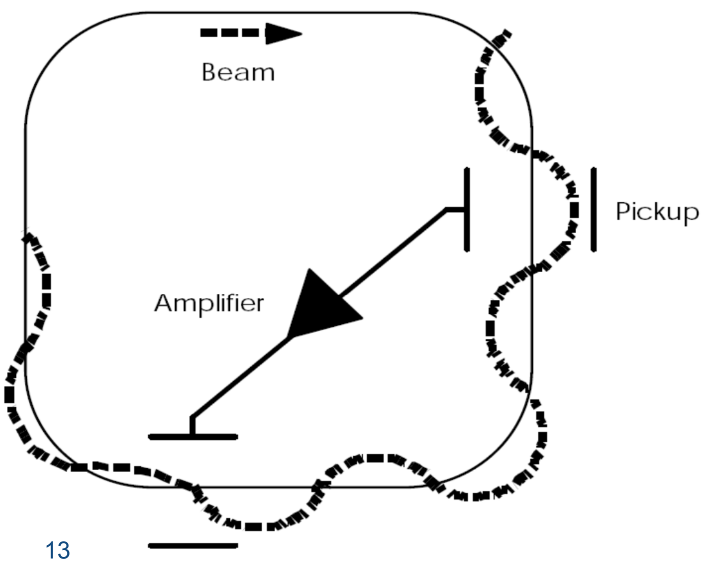
Stochastic Cooling

- 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

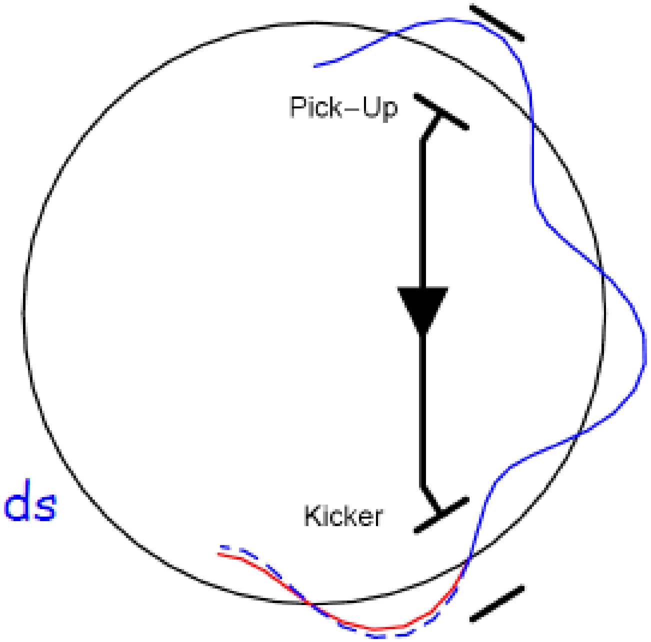
<u>At present</u>:
COSY (Juelich)
Nuclotron (JINR)
ESR (GSI)
RHIC (for heavy ions)
AD (CERN)





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

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

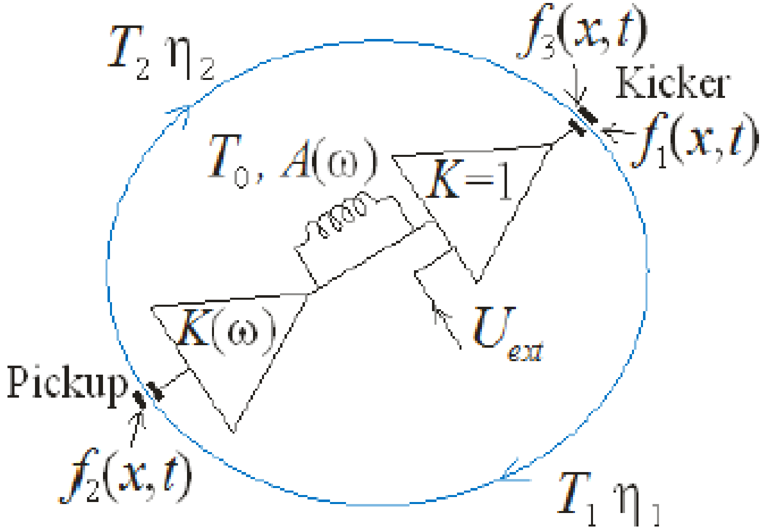
⇨ Cooling rate: $$\lambda_{opt} = \frac{1}{2}g_{opt}f_0 = \frac{W}{4N}$$

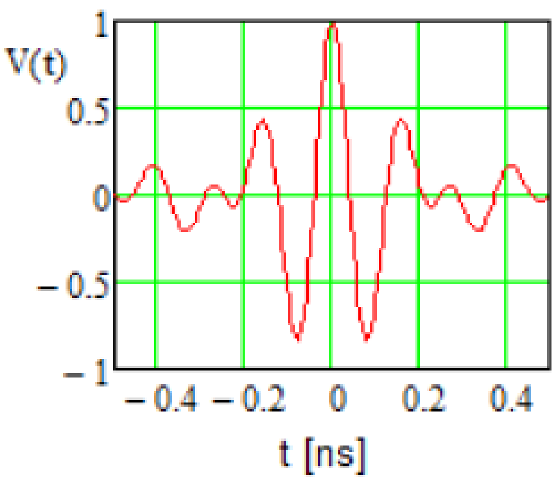
Longitudinal Stochastic Cooling

- 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

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: $$\lambda_{opt} \cong \frac{W}{4N}\frac{\sqrt{2\pi}\sigma_s}{C}$$

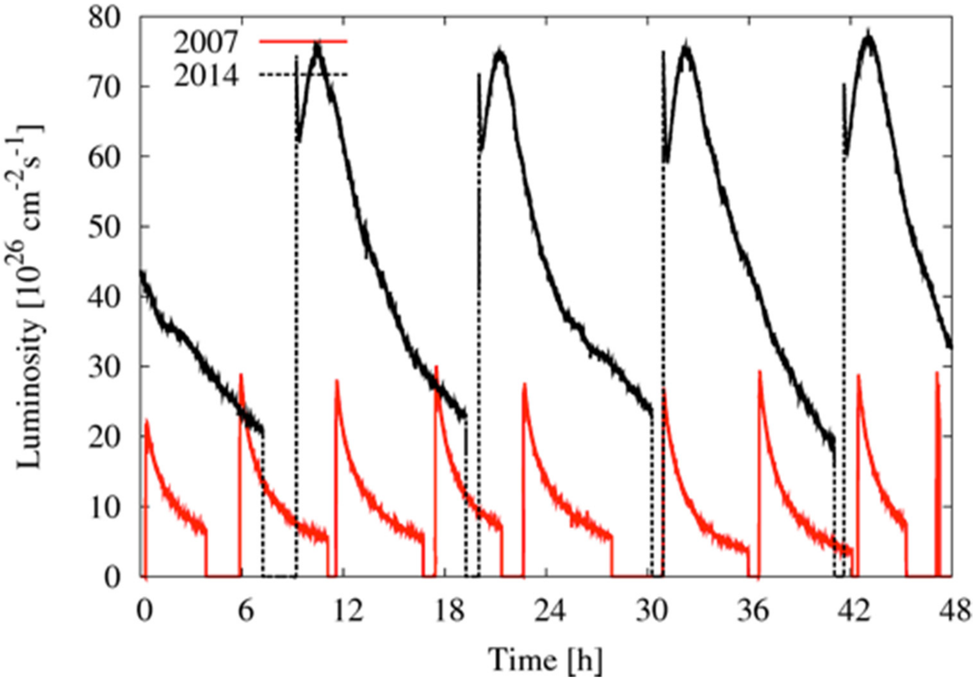
- An accurate result for the transit-time cooling with rectangular band

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

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

“Bunched beam stochastic cooling in a collider”
M. Blaskiewicz and J. M. Brennan
Phys. Rev. ST Accel. Beams 10, 061001 (2007)

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 ever increase of instantaneous luminosity and smallest emittance in a hadron collider.

Stochastic cooling challenges

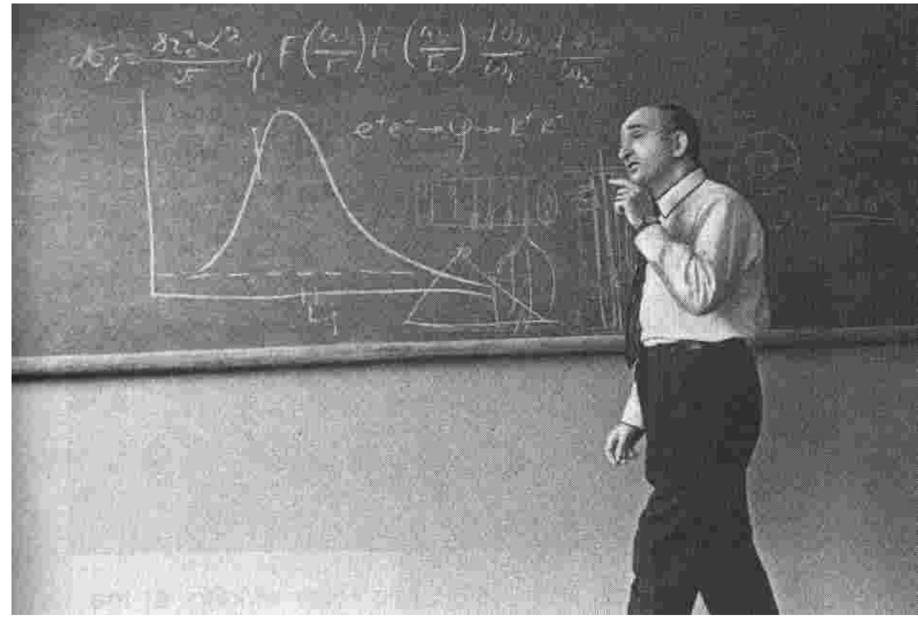
- Traditional microwave stochastic cooling (W ~ 1 GHz) may be adequate for EIC e-ION collisions

- However, it is TOO SLOW for protons (10^{11} ppb vs 10^{9} ions per bunch)

Fermilab

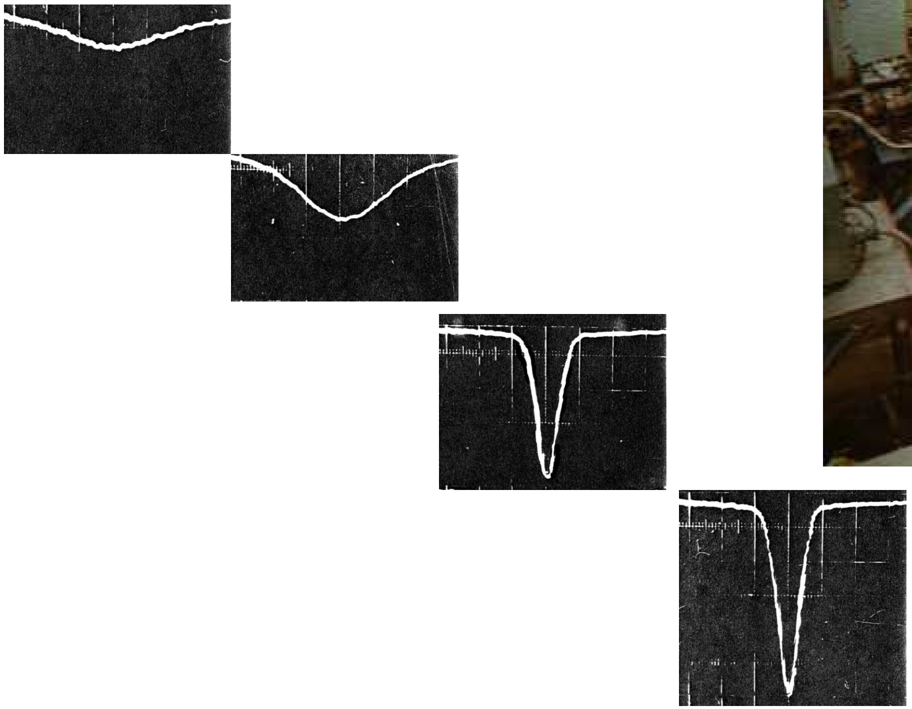
Electron cooling

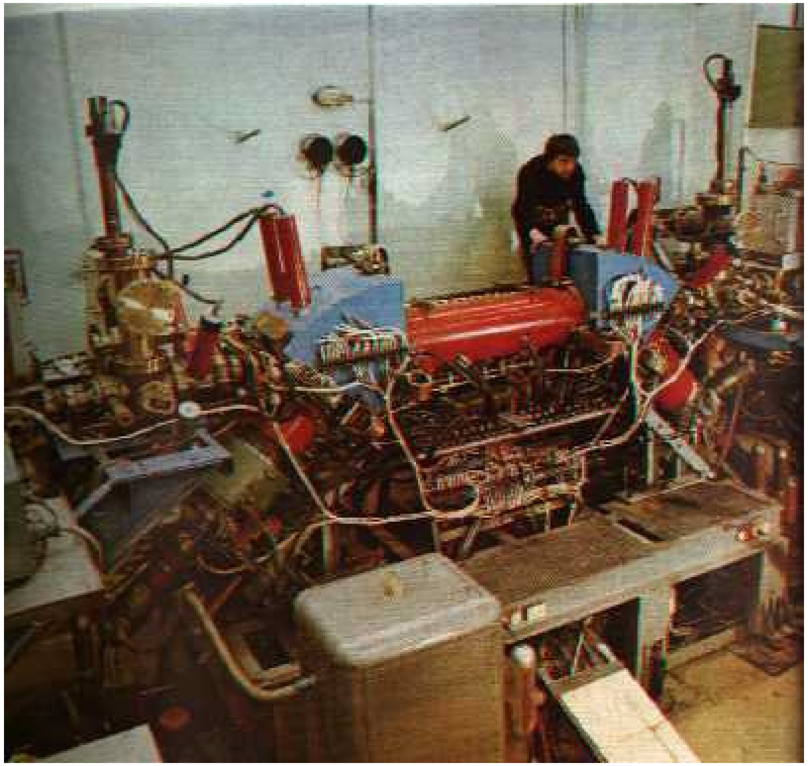
- Was invented by G.I. Budker (INP, Novosibirsk) as a way to increase luminosity of p-p and p-pbar colliders.
- First mentioned at Symp. Intern. sur les anneaux de collisions á electrons et positrons, Saclay, 1966: "Status report of works on storage rings at Novosibirsk"
- First publication: Soviet Atomic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



First Cooling Demonstration

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



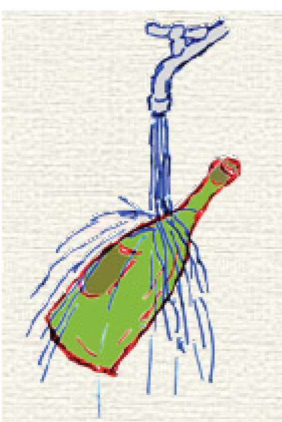


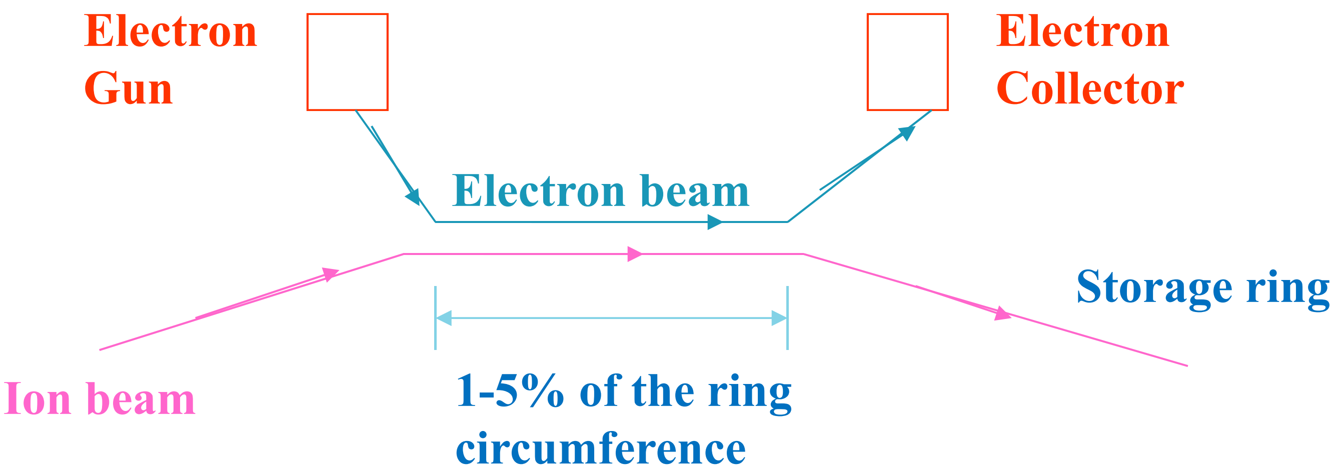
Electron cooling

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

$$\overline{\mathrm{v}_p{}^2} \approx \frac{m_e}{m_p}\overline{\mathrm{v}_e{}^2}$$

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





Electron coolers

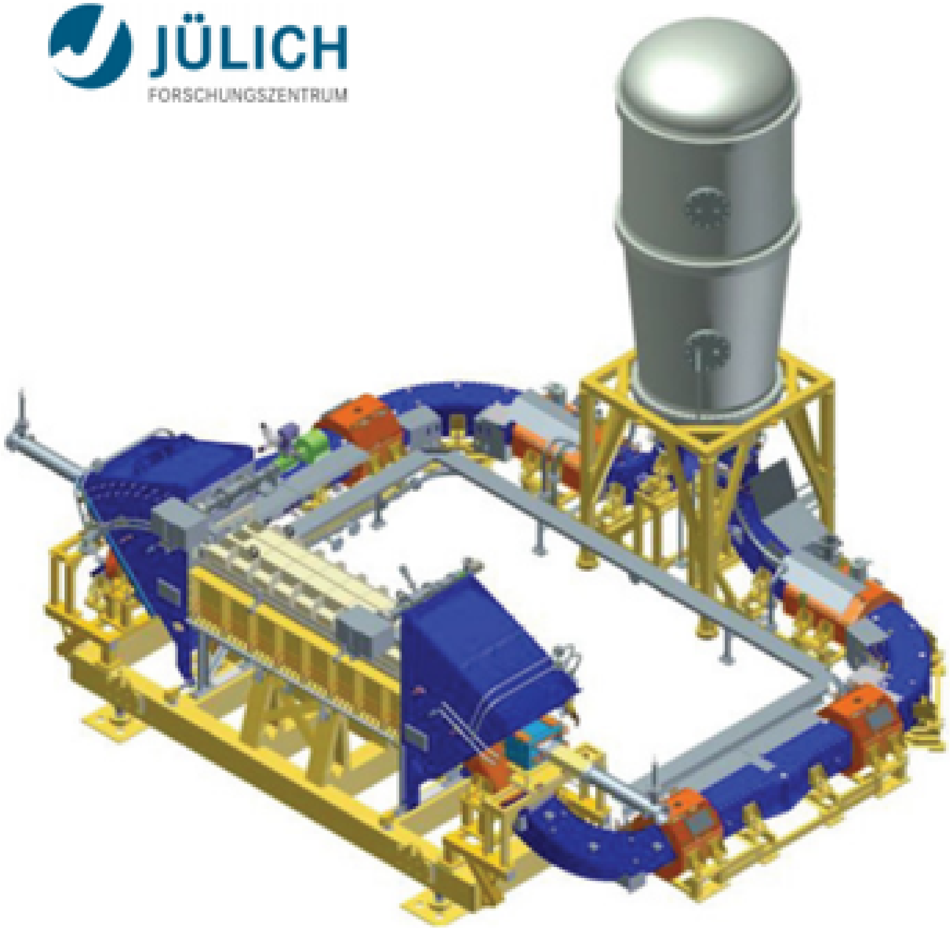
- About 20 operated (1974 to present)
- At present:
  - 3 at CERN (LEIR, AD, ELENA 2018)
  - 3 at GSI (SIS, ESR, CRYRING)
  - 2 at COSY (Juelich)
  - 2 in Japan (HIMAC and S-LSR)
  - 2 + 1 (under construction) at IMP (Lanzhou)
  - 1 at MPI (Heidelberg), 2017
  - 1 in RHIC (Brookhaven), 2019
  - 2 under construction at JINR (NICA and Booster)

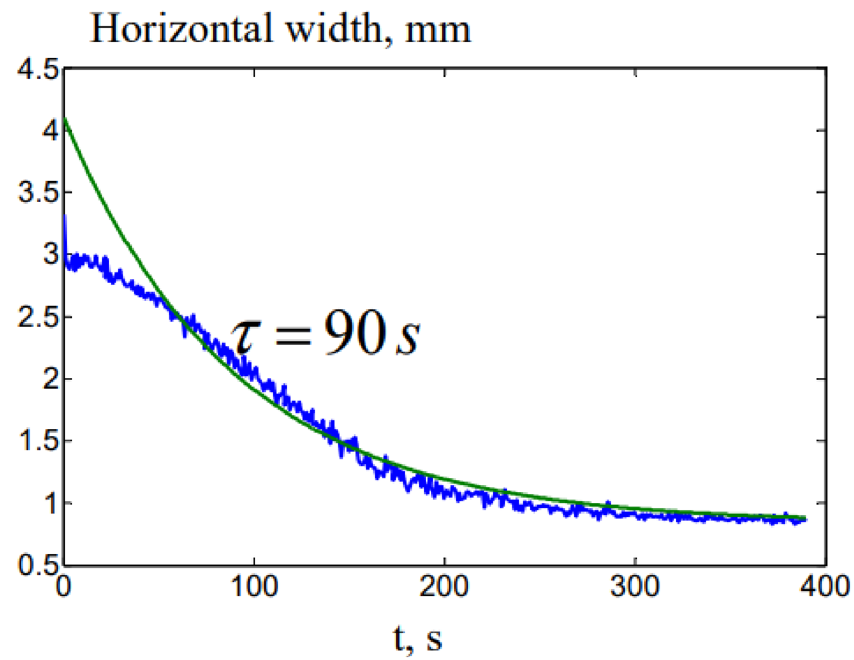
Electron Cooling

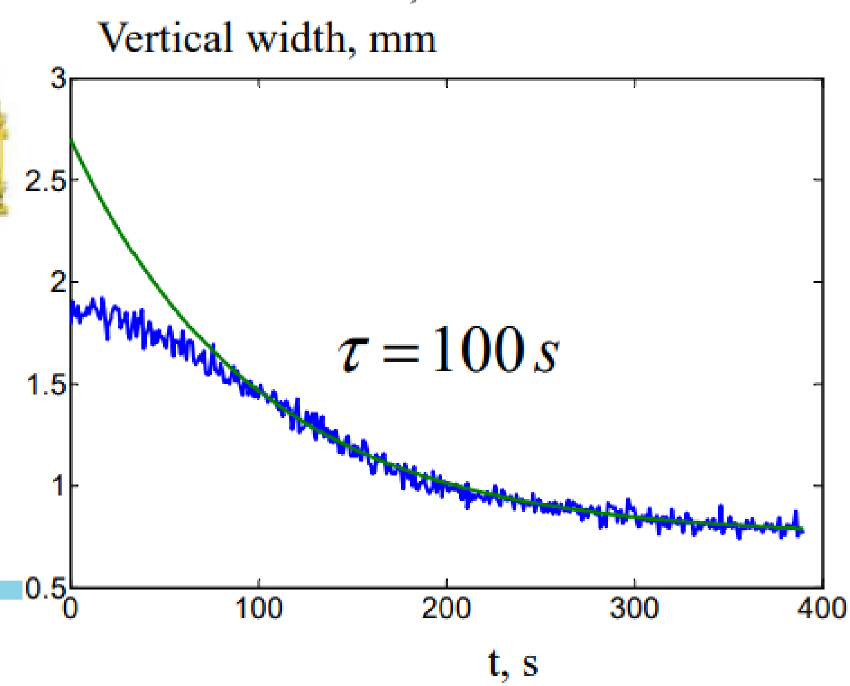
- Many systems are based on the same technology, developed at BINP: most recent, a 2-MeV cooler at COSY, Juelich (~4 GeV protons)
- Highest energy electron cooling (different technology): at the Fermilab Recycler, 4.3 MeV electrons (8 GeV – pbars) – the only e-cooler used for HEP colliders (2005 – 2011)
- First attempt to cool two beams at collision energy: RHIC (LEReC project) in 2019 (Electron energy = 1.6 – 2.6 MeV) in a test mode. Based on rf-bunched beams – new technology.

2 MeV electron cooler

COSY 2013

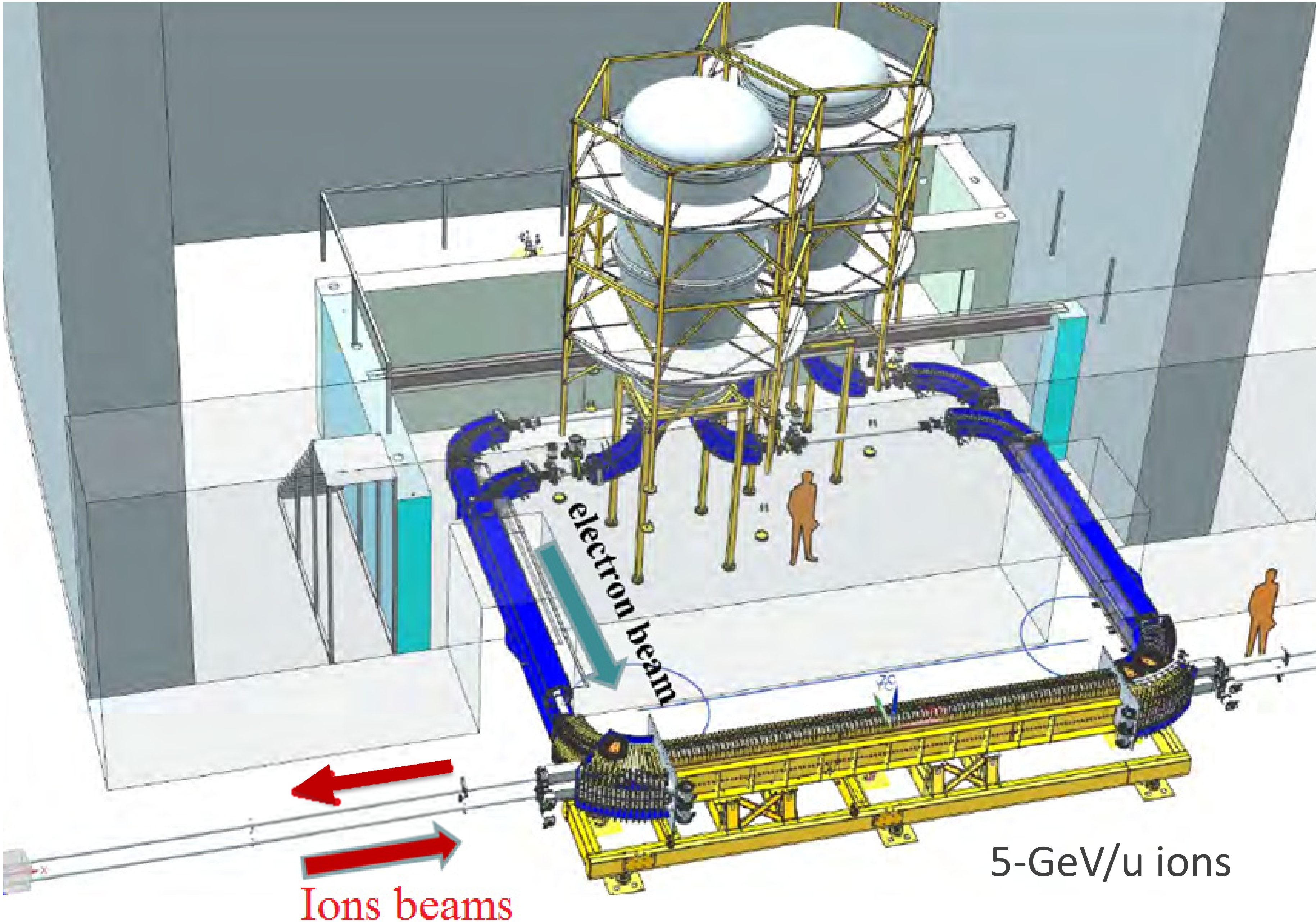






Cooling of 4 GeV protons

Concept of NICA cooler, 2.5-MeV electron beam



Cryogenic electrostatic storage ring CSR

Max Planck Institute for Nuclear Physics, Heidelberg

Ion sources 20 … 300 keV

Atomic, molecular and cluster ions (cations, anions)

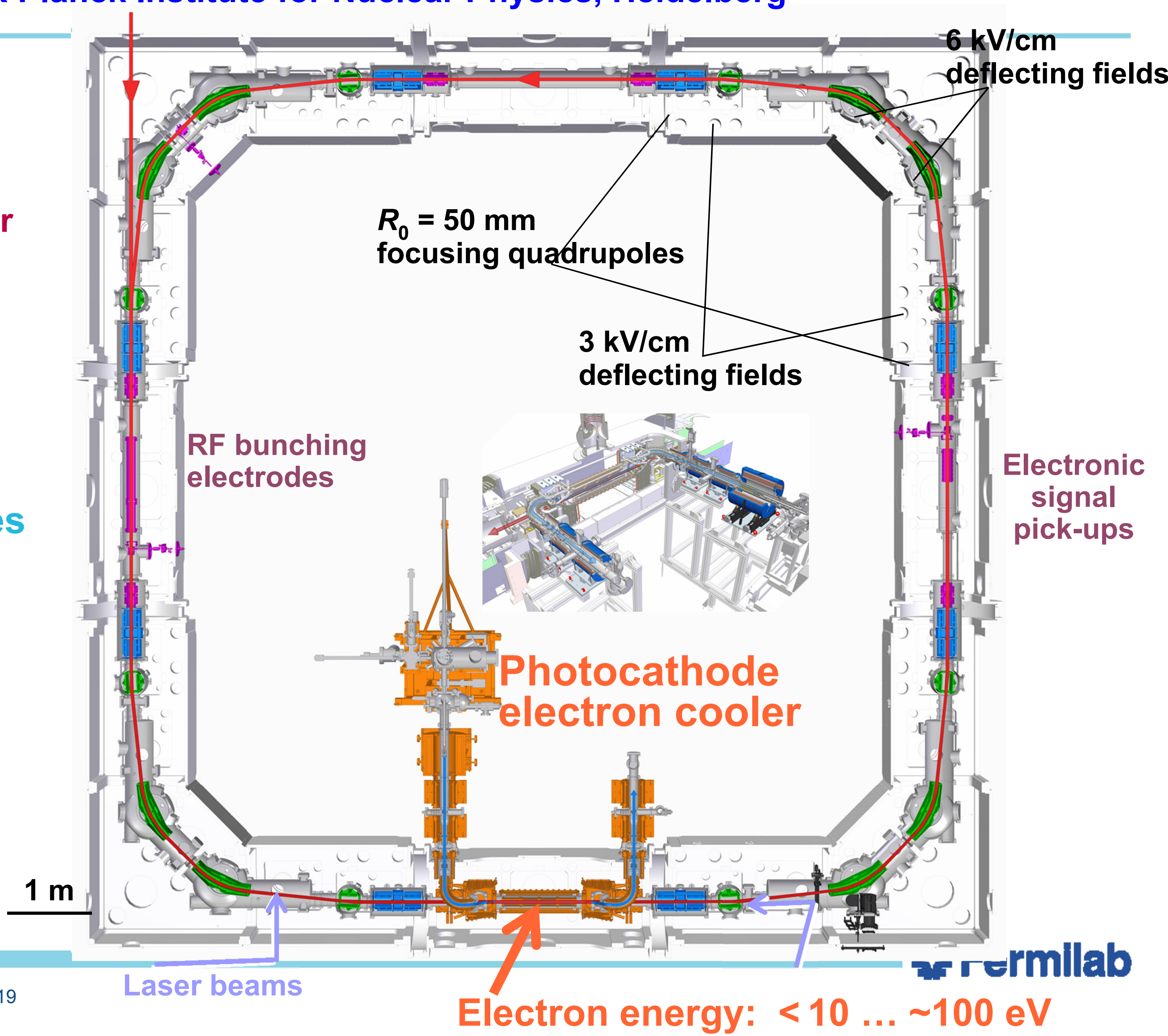
Vacuum chambers cooled to < 10 K

Beam storage times up to ~1 h

R. von Hahn et al., Rev. Sci. Instrum. 87, 063115 (2016)

C. Meyer et al., Phys. Rev. Lett. 119, 023202 (2017)

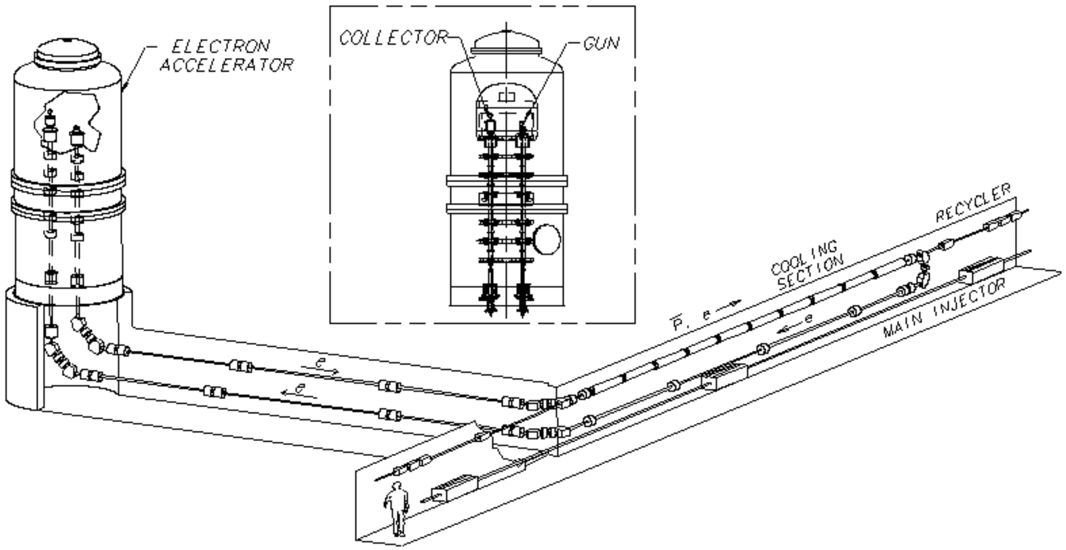
O. Novotný et al., Science 365, 676 (2019)



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)

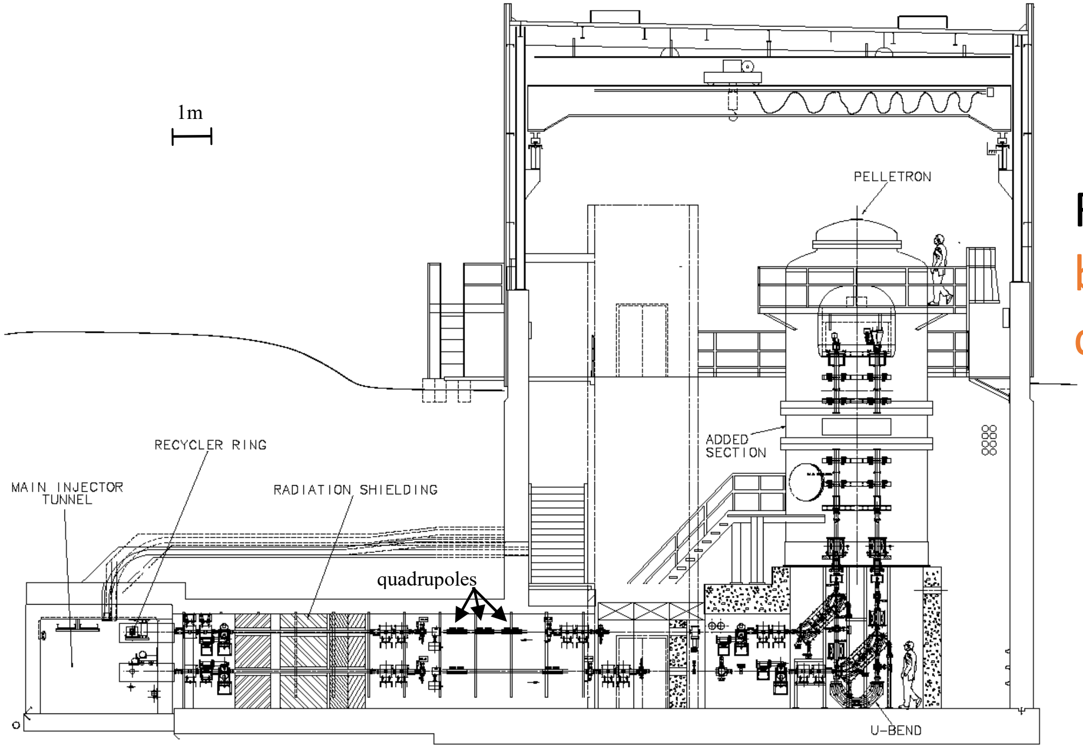
Beam quality:

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

Development: 1996-2004

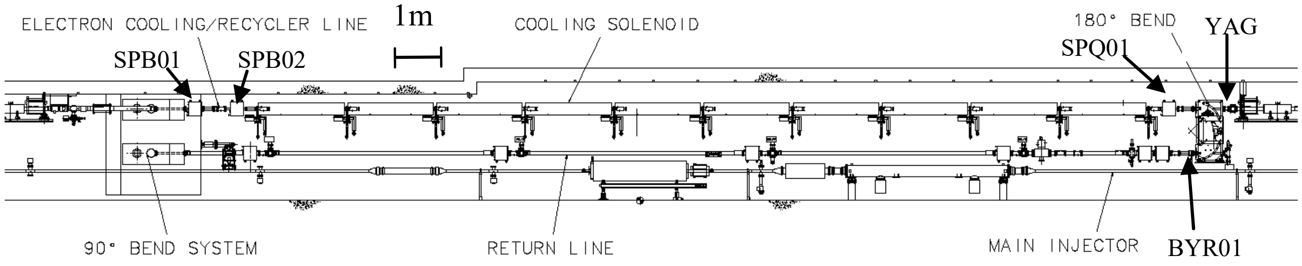
- Operations: 2005 – 2011

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

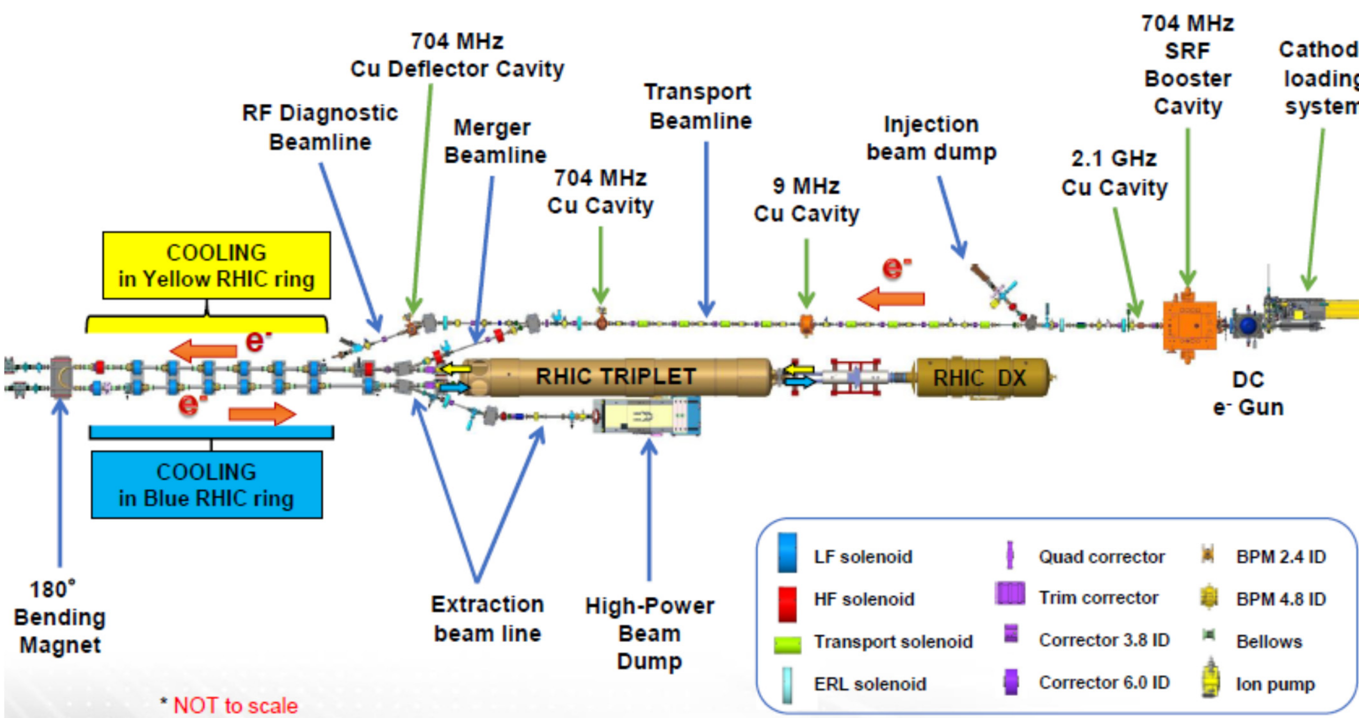


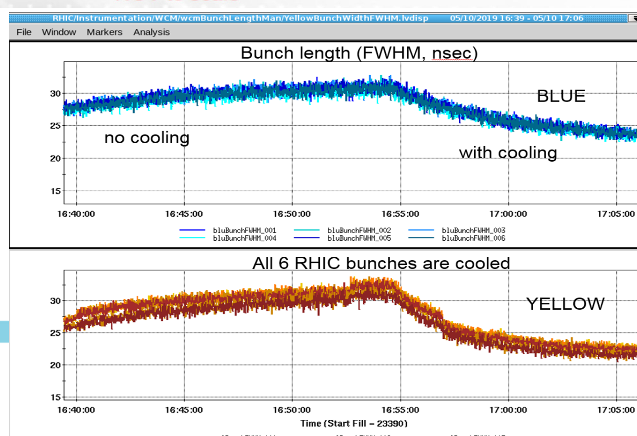
The Main Injector/Recycler tunnel containing the cooling section and the “return” line.

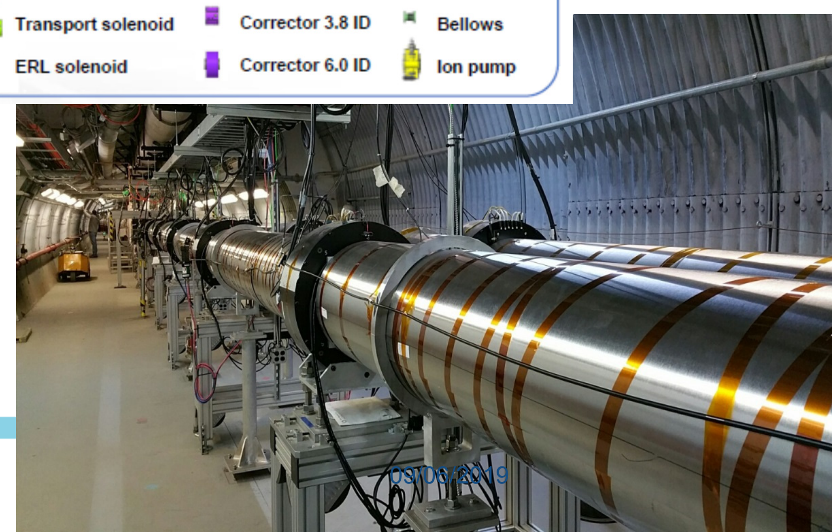
Low-Energy RHIC electron Cooler (LEReC) at BNL:

LEReC Accelerator

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







BNL LEReC is a testbed of high-energy cooling

- **Production of high-brightness electron beams**
- **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

The challenge of electron cooling is that it scales with beam energy as

$$\tau_{cool} \sim \gamma^2$$

The IBS time is also slower, scaling as $\sim \gamma^{1.5}$

Present EIC cooling concepts

- Electron cooling (50 – 150 MeV electron beam energy):
  - The key idea here is to compensate for the γ^2 dependence by a higher electron beam current density
  - ERL- based (JLab/ODU): bunched beam ERL and a multi-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 ~GHz 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

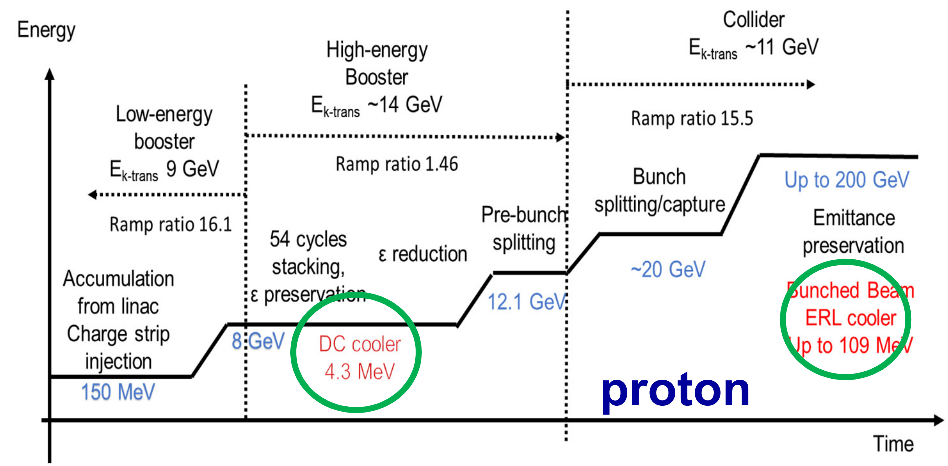
- JLEIC choice: conventional electron cooling and multi-phase
- Achieving small emittance (up to **~10 times** reduction) and very short bunch length (**~2 cm**)
- Assisting injection/accumulation of heavy ions
- Suppressing IBS induced emittance growth during beam store
- Multi-phase cooling could reduce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

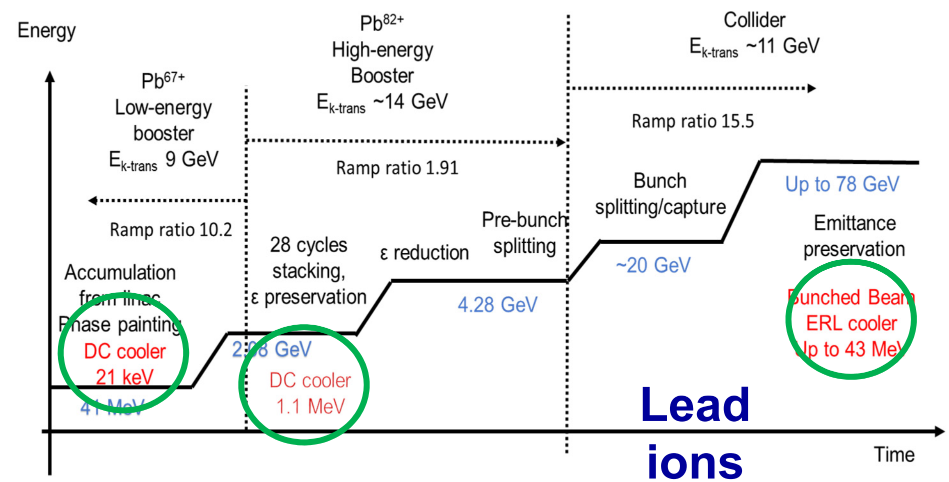
Pre-cool when energy is low

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

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



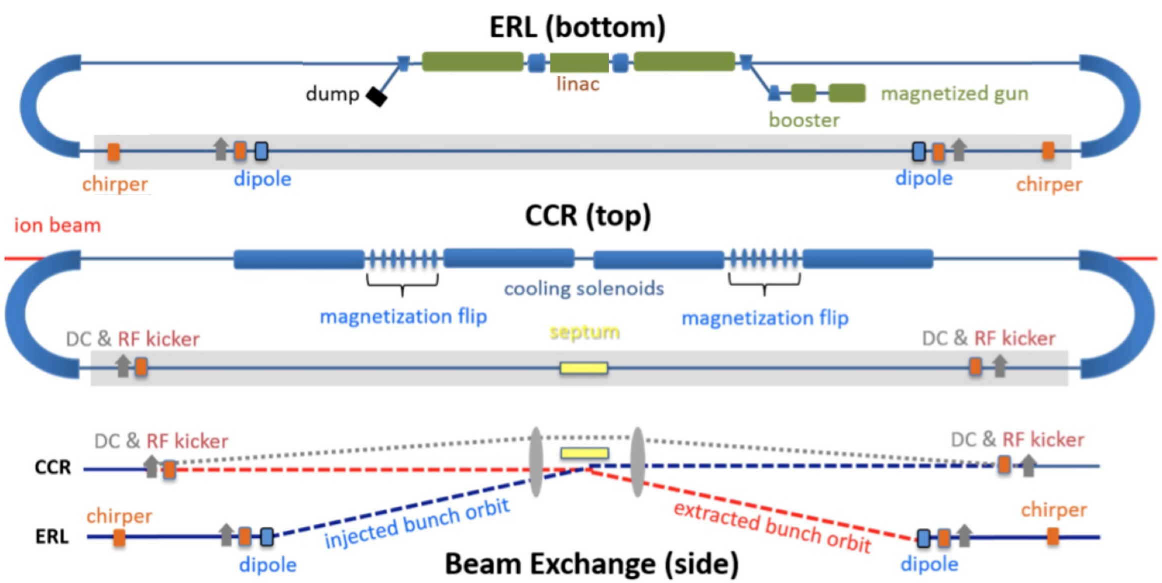


Fermilab

High Energy Cooler Design is Cooling Ring Fed by ERL

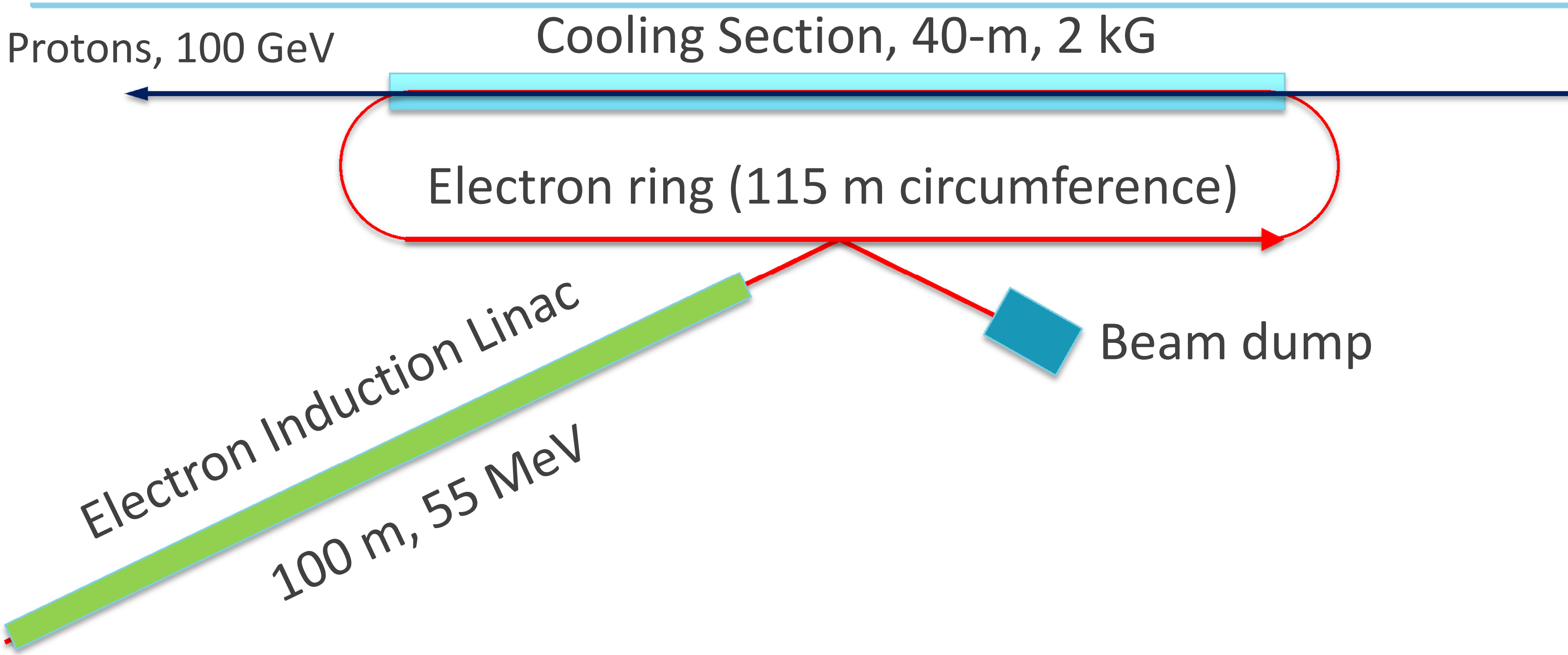
JLab/ODU

- 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)

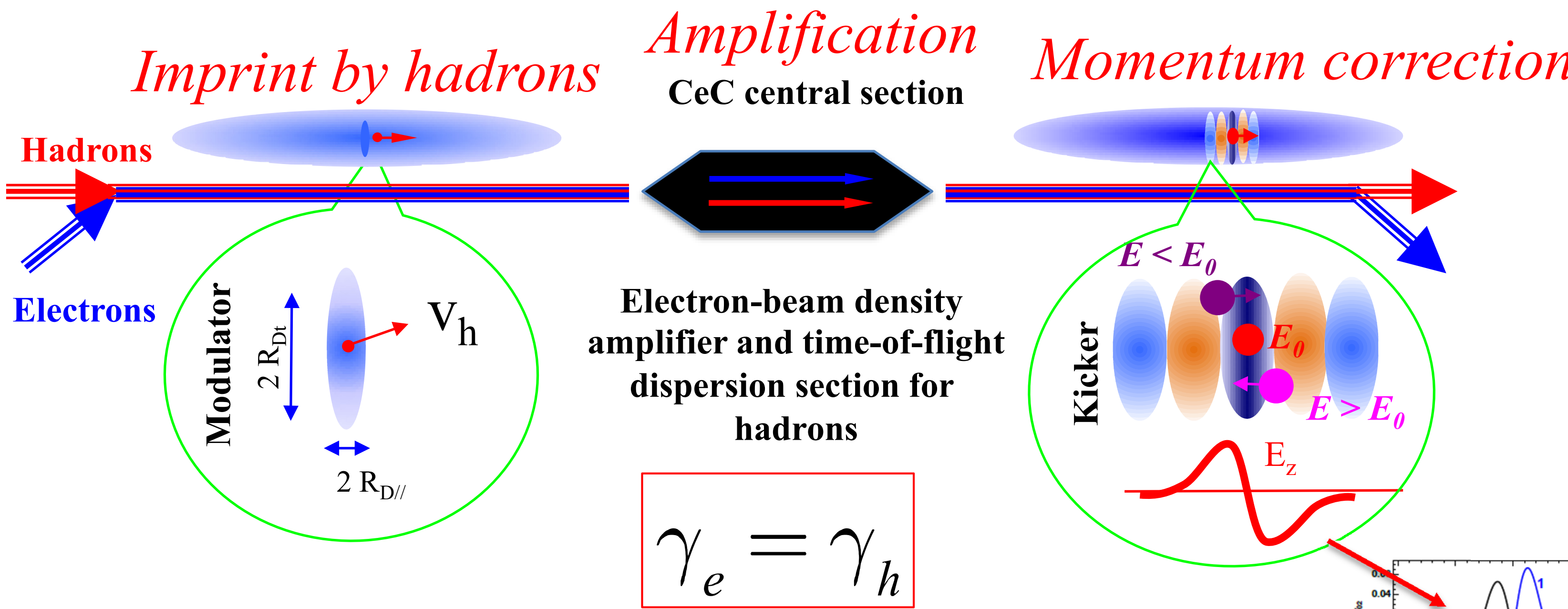


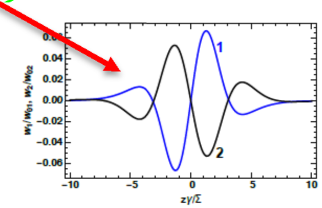
- We are considering a range of electron beam and linac parameters: 100-200 A beam current, 100 – 200 Hz rep. rate
- Pulse length: 380 ns (to fill the ring)
- Beam power to dump: 0.8 MW (worst case), 200 kW (best case)

Coherent electron Cooling

BNL/Stonybrook U

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





PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

Coherent Electron Cooling

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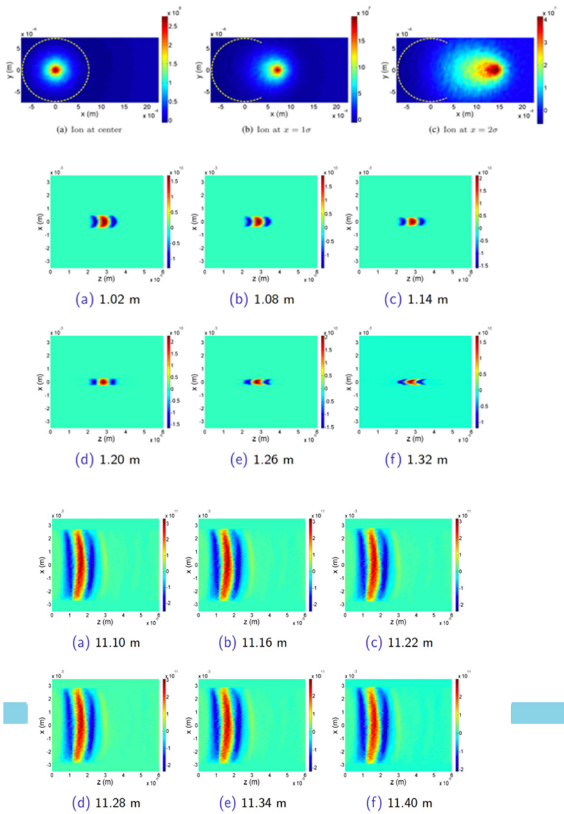
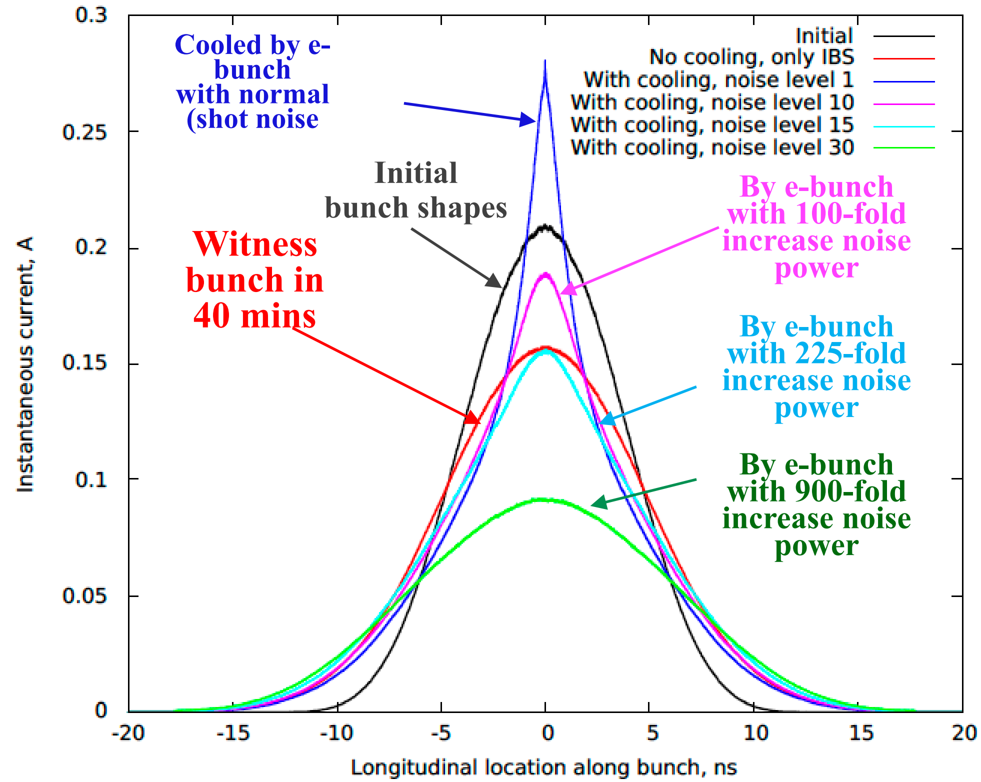
(Received 24 September 2008; published 16 March 2009)

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.

Simulated performance: 26.5 GeV Au ion bunch in RHIC

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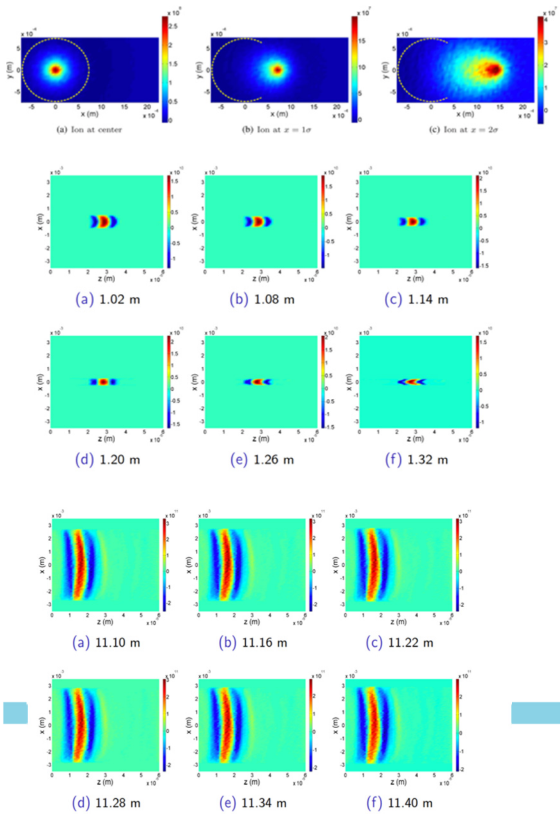
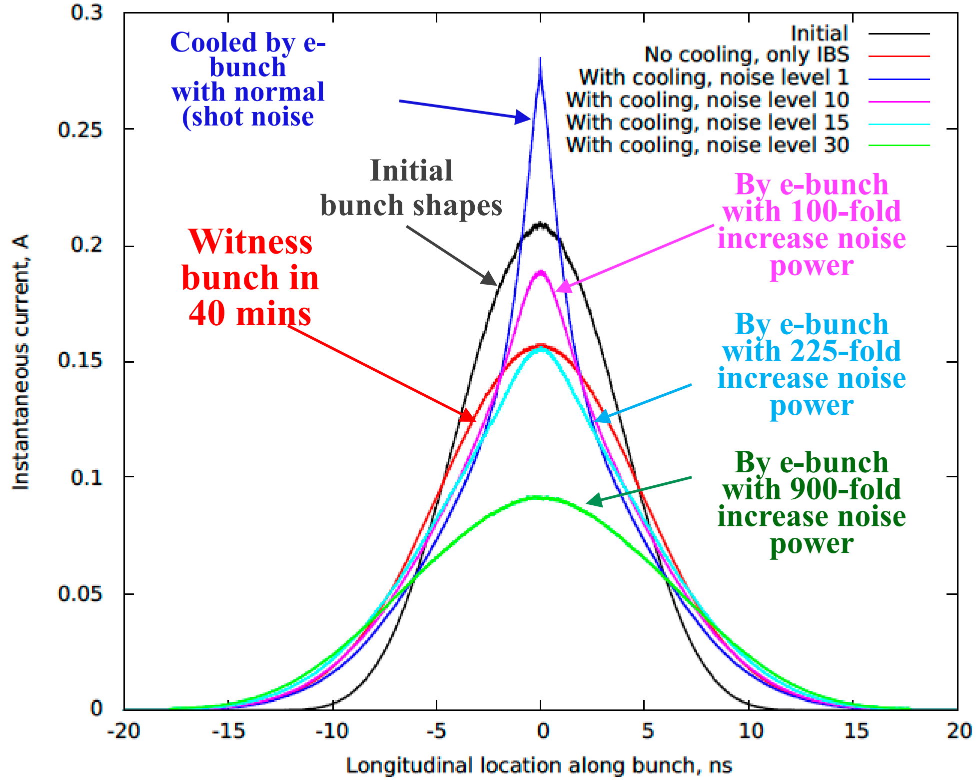


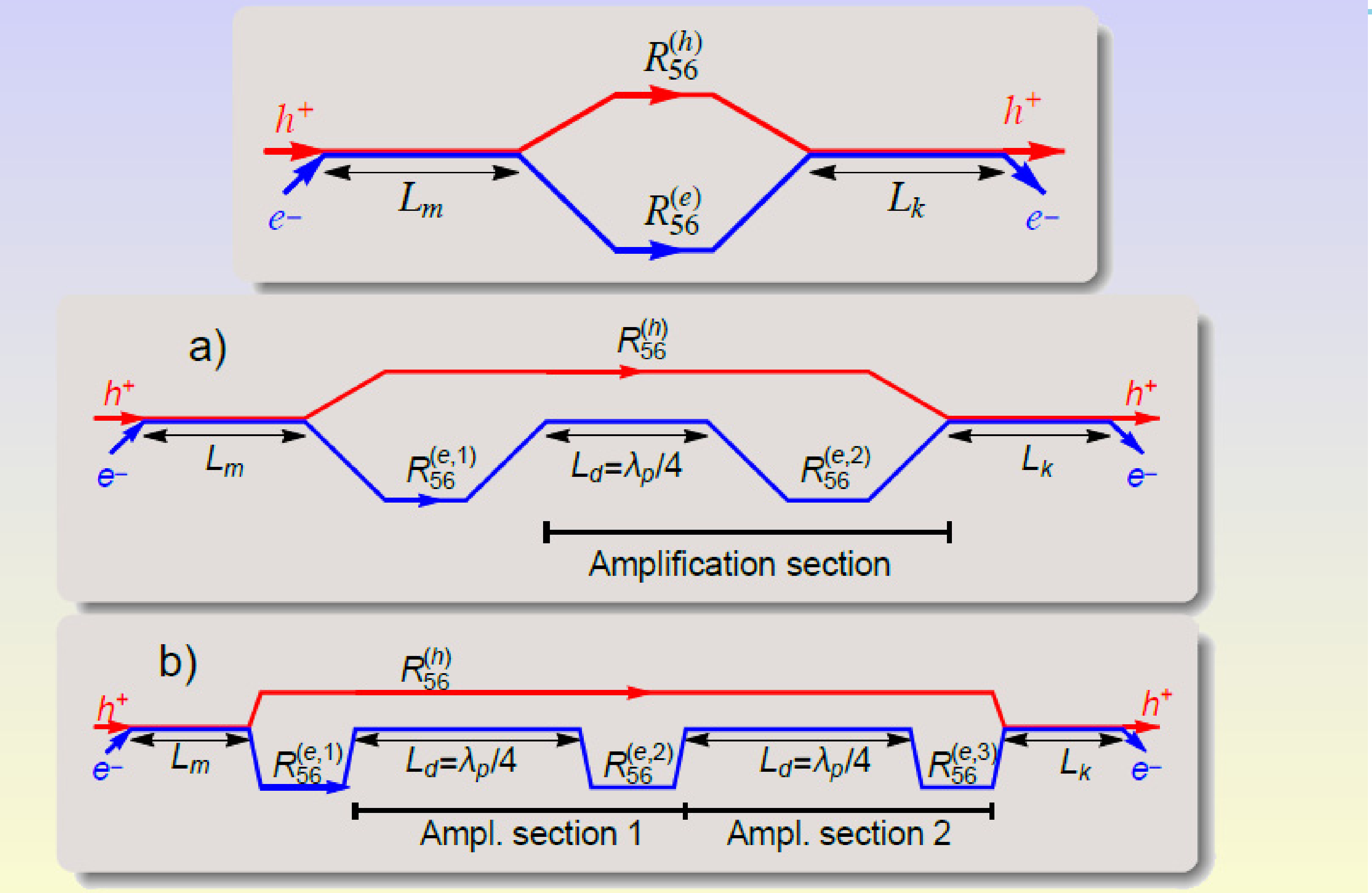
40 mins of PCA CeC



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

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,

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

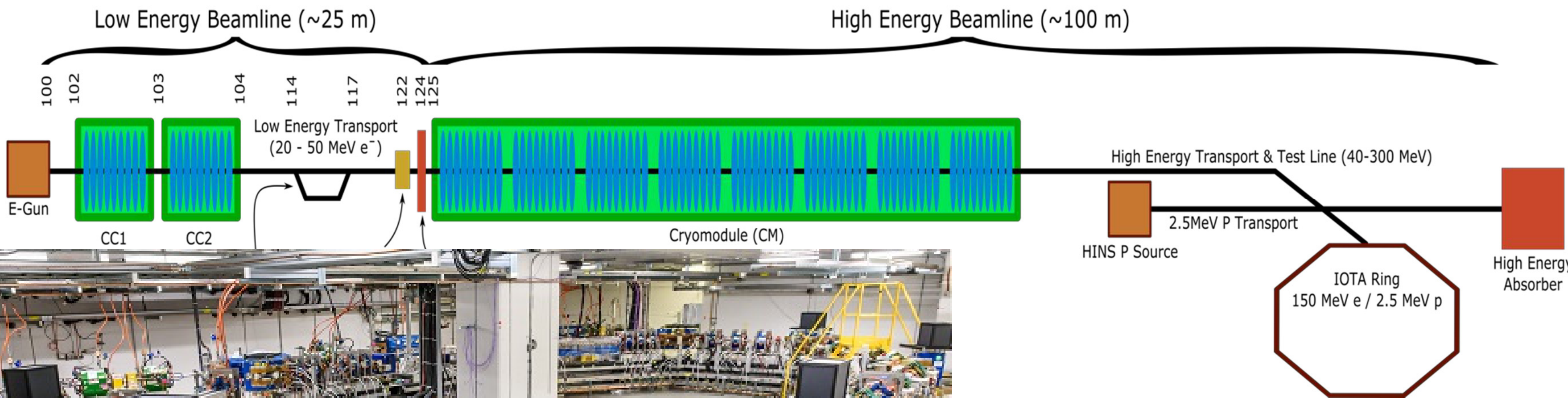
the cooling time is

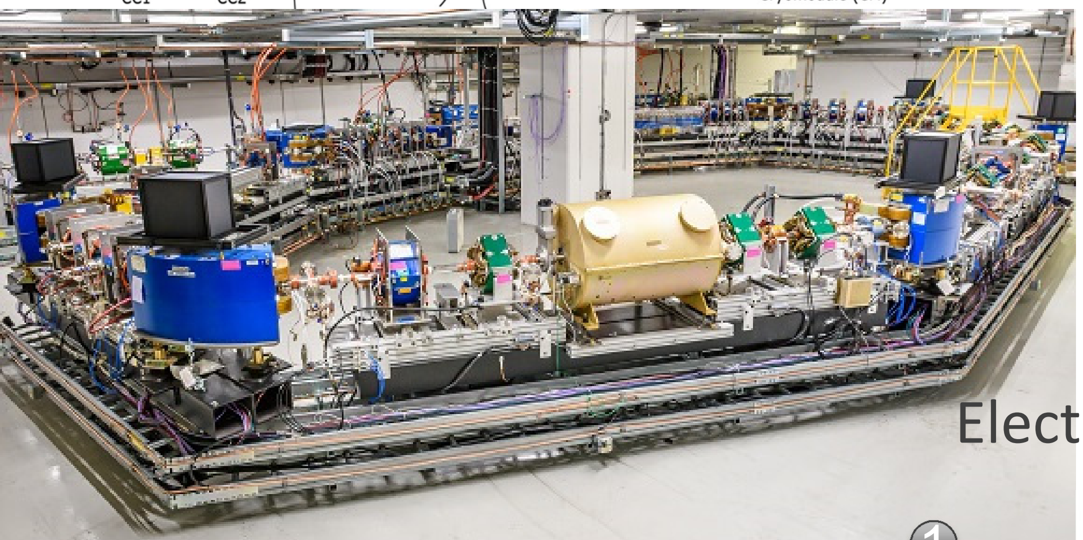
$T_{\mathrm{c}} \approx 0.7\ \mathrm{h}$ for JLEIC

(for eRHIC this number was 41 h).

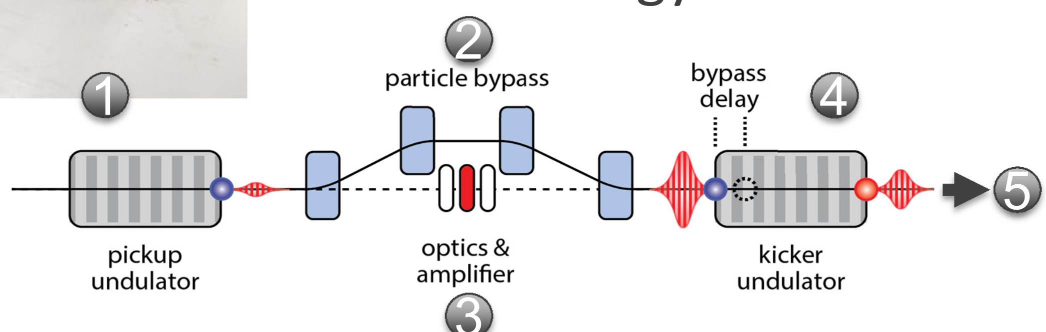
Optical Stochastic Cooling (Fermilab)

FAST/IOTA accelerator test facility at Fermilab



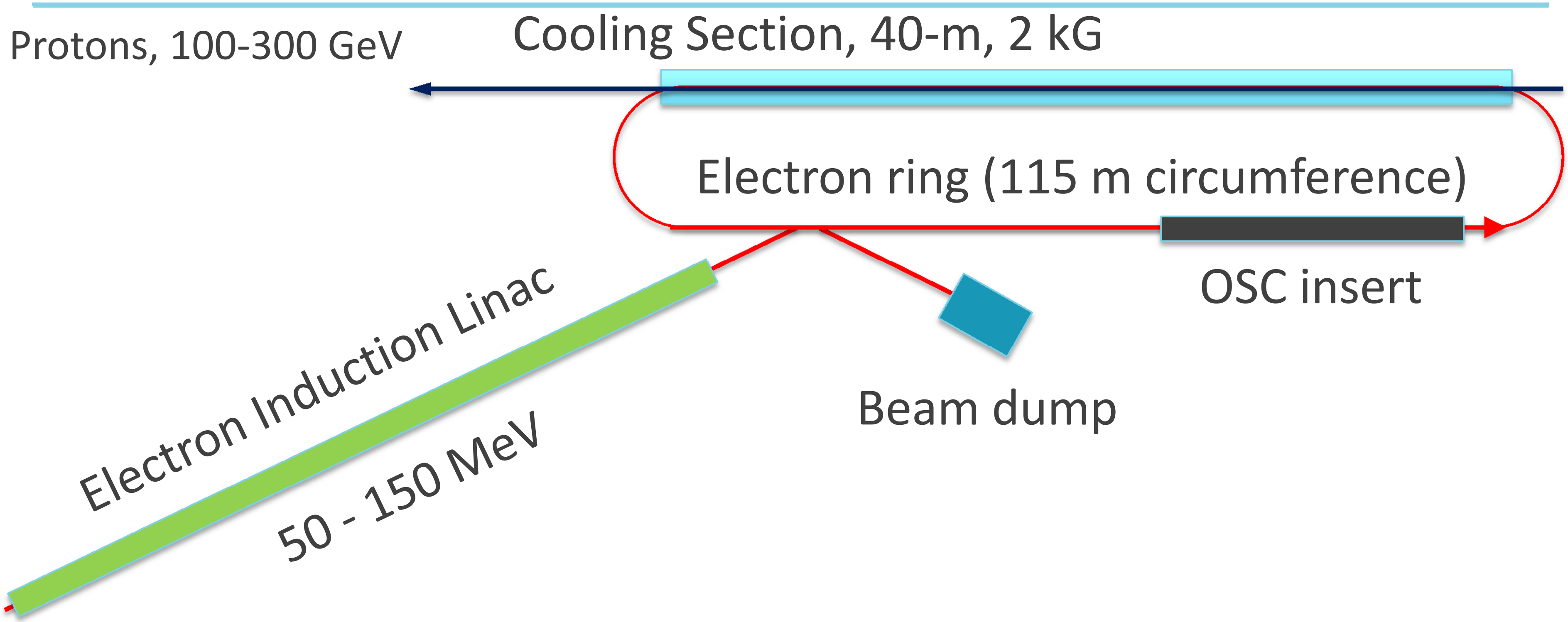


Electron beam energy: 70-150 MeV



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, Fermilab
  https://indico.fnal.gov/event/20514/

Acknowledgments

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