Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Hadron beam cooling status and challenges

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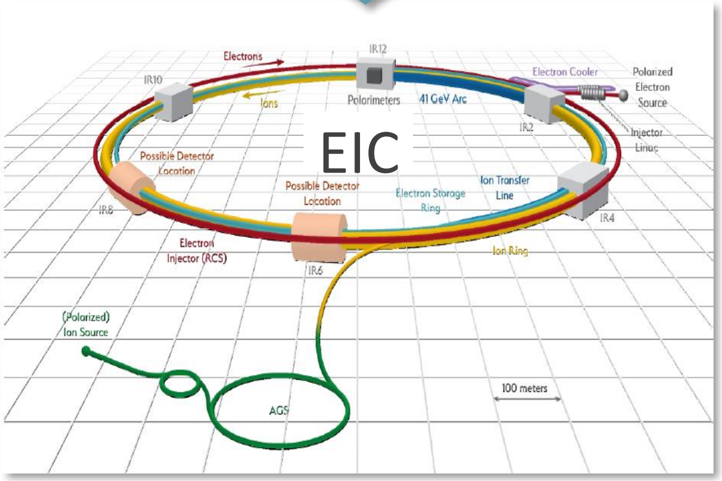
EIC Collider Concept

Design is based on **existing** RHIC,
RHIC is well maintained, operating at its peak

- **Hadron storage ring 40-275 GeV** (existing)
  - Many bunches
  - Bright beam emittance
  - Needs strong cooling **or** frequent injections
- **Electron storage ring (2.5–18 GeV** (new))
  - Many bunches,
  - Large beam current (2.5 A) ➔ 10 MW S.R. power
- **Electron rapid cycling synchrotron** (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (new)
  - $L = 10^{34} cm^{-2}s^{-1}$
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation



Design Parameters for e-p 10GeV * 275 GeV collision

Parameter	proton	electron
Ring circumference [m]	3833.8451	
Particle energy [GeV]	275	10
Lorentz energy factor γ	293.1	19569.5
Bunch population [10^{11}]	0.688	1.72
RMS emittance (H,V) [nm]	(11.3, 1.0)	(20.0, 1.3)
β^* at IP (H, V) [cm]	(80, 7.2)	(45, 5.6)
RMS bunch size σ^* at IP (H, V) [μm]	(95, 8.5)	
RMS bunch length σ_l at IP [cm]	6	2.0
Beam-beam parameters (H, V)	(0.012, 0.012)	(0.072, 0.1)
RMS energy spread [10^{-4}]	6.6	5.5
Transverse tunes (H,V)	(29.228, 30.210)	(51.08, 48.06)
Synchrotron tune	0.01	0.069
Longitudinal radiation damping time [turn]	-	2000
Transverse radiation damping time [turn]	-	4000
Luminosity [10^{34}cm^{-2}s^{-1}]	1.0	

Unequal proton emittances (n, rms): 3.3 µm and 0.3 µm

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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)

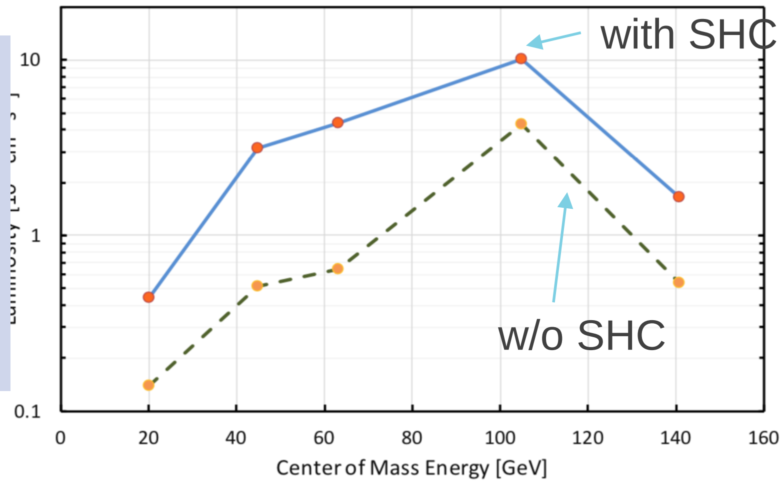
High Luminosity and Strong Hadron Cooling

- Luminosity of lepton-hadron colliders in the energy range of the EIC benefits strongly (factor ≈ 3-10) from cooling the hadron’s transverse and longitudinal beam emittance (at collisions)
- Reducing hadron beam emittance with strong hadron cooling enables reaching maximum strength of the beam-beam interaction and therefore achieving a maximum luminosity
- Intra-beam scattering (IBS), a fundamental process, which prevents small emittance & causes emittance growth.

Strong hadron cooling with cooling rate of **1h^{-1}**, counteracts IBS

➔EIC design luminosity **L = 1·10^{34}cm^{-2}s^{-1} at Ecm=105 GeV** is achieved & full range of EIC physics can be exploited.

➔ EIC design includes strong hadron cooling



The EIC cooling system has to provide cooling times of 1-2 hours

What is beam cooling?

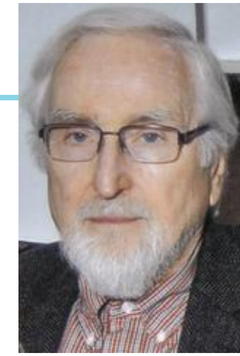
- Cooling is a reduction in the phase space occupied by the beam (for the same number of particles).
  - It's not about the beam temperature
- Equivalently, cooling is a reduction in the random motion of the beam.

- 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

JAMES D. BJORKEN
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and

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and
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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.

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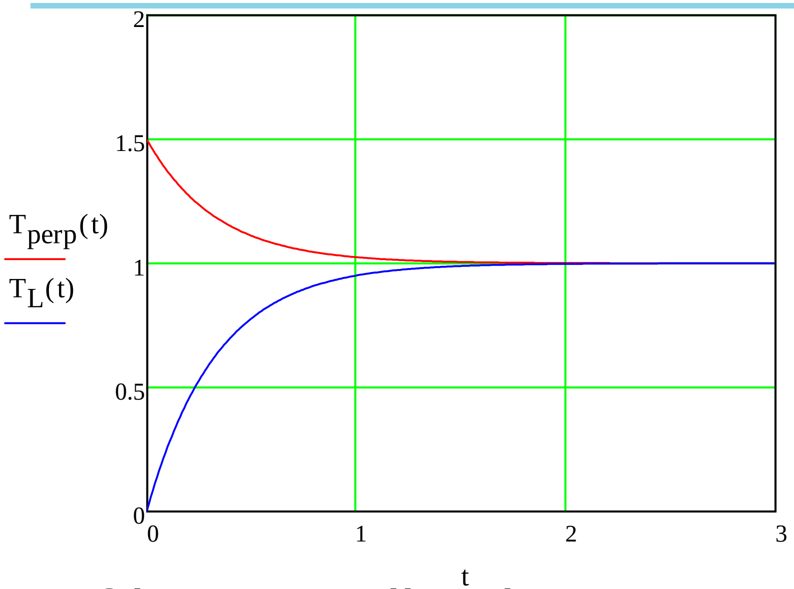
Example of IBS: the Boersch effect



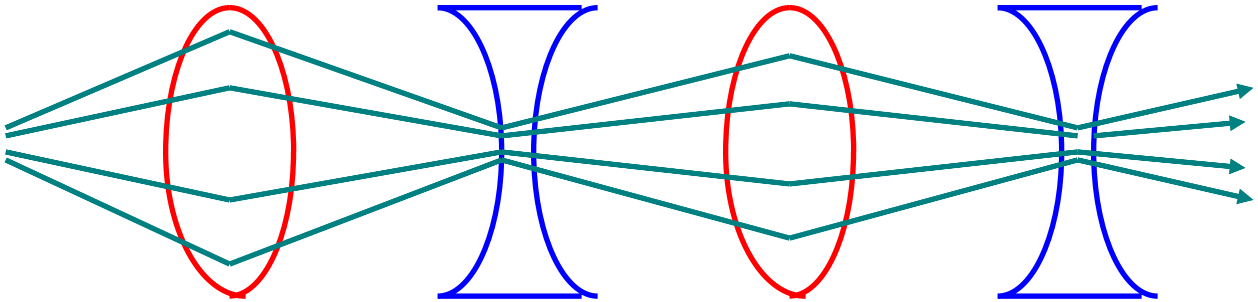
$$\frac{dT_\perp}{dt} = -\frac{1}{2}\frac{dT_L}{dt} = -\frac{T_\perp - T_L}{\tau}$$

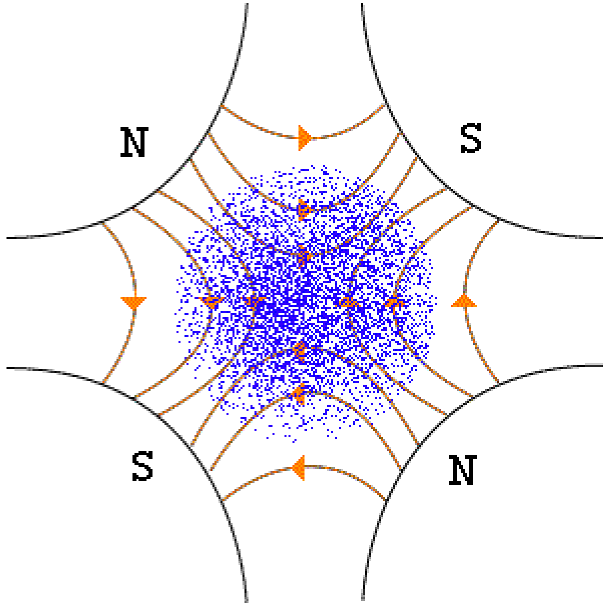
$$\frac{1}{\tau} = \frac{8\sqrt{\pi} n r_c^2 c}{15\left(kT_{eff} / mc^2\right)^{3/2}} \ln \Lambda$$

- 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). :



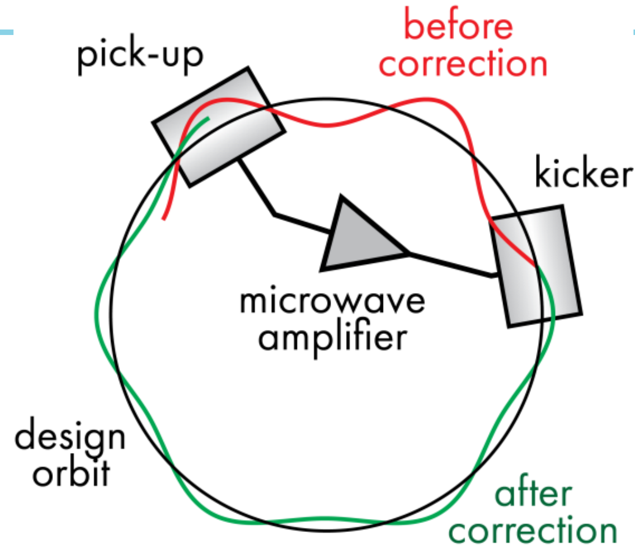


Hadron beam cooling methods

- 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: an enabling technology for colliders



(simplified stochastic cooling system)

$$\mathcal{L} \sim \frac{f N_b N^2}{4\pi\sigma_x^* \sigma_y^*}$$

1984 Nobel: van der Meer/Rubbia

Simon van der Meer (COOL 1993 workshop, Montreux):

"How then can cooling work? It must necessarily be through deformation of phase space, such that particles move to the center of the distribution and (to satisfy Liouville) the empty phase space between the particles moves outwards. Clearly, the fields that do this must have a very particular shape, strongly correlated with particle position. In fact, at least two conditions must be satisfied:

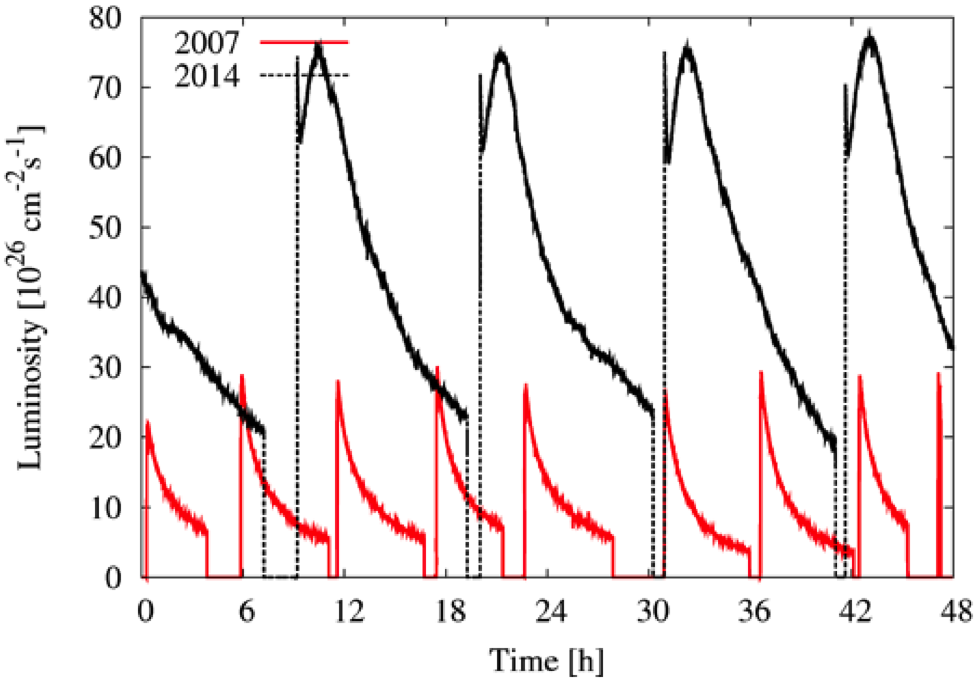
1. The field that cools a particular particle must be correlated with the particle's phase-space position. **In short, the field must know where each particle is.**
2. The field that pushes a particular particle towards the centre should preferably push the empty phase-space around it outwards. **It should therefore treat each particle separately.**

With stochastic cooling, these two conditions are clearly corresponding to the function of the pickup and kicker. **Both must be wide-band in order to see individual particles as much as possible**."

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 were proposed for the EIC: coherent electron cooling, micro-bunching cooling, optical stochastic cooling.
    - Present baseline is based on the CEC-MB concept

Example: Au-Au stochastic cooling (~GHz BW) in RHIC

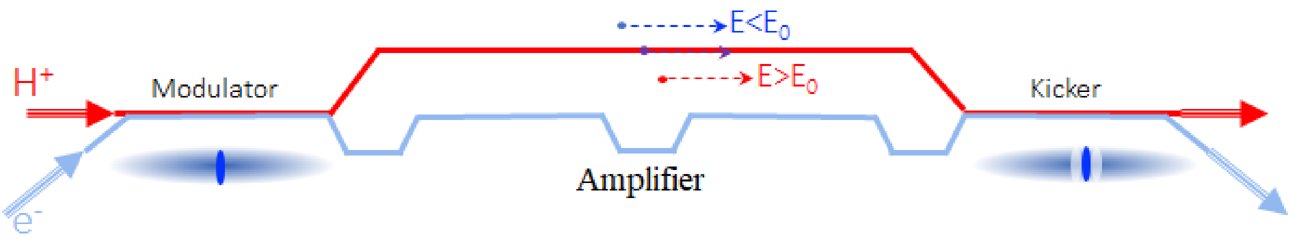


- 3-D stochastic cooling (5-9 GHz).
- ~5x U-U and ~ 4x Au-Au luminosity improvements.
- Cooling led to first increase of instantaneous luminosity and smallest emittance ever in a hadron collider.
- May be adequate for the EIC with e-ION collisions
- Is not adequate for protons

From GHz to THz

- Stochastic cooling
  - Microwave cooling (GHz-range bandwidth): past and present
    - Tested experimentally at CERN in ICE ring, 1977-78
    - Used for pbar accumulation at CERN & Fermilab (also at FAIR)
      - It’s the main foundation of p-pbar colliders (SppS, Tevatron)
  - Present R&D effort (THz and optical range)
    - Very challenging
    - EIC present baseline: coherent electron cooling (micro-bunching cooling)
    - Optical stochastic cooling R&D: Fermilab (IOTA) and Cornell (CBB)

CEC concepts

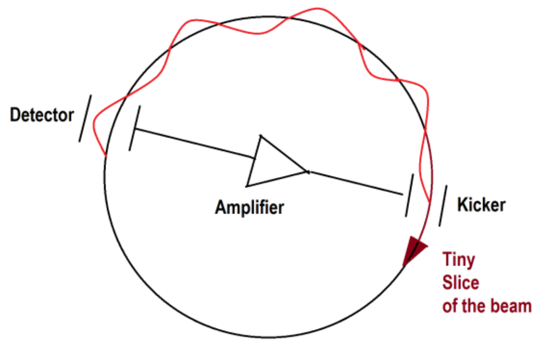


- Y. S. Derbenev, "On possibilities of fast cooling of heavy particle beams," *AIP Conference Proceedings*, vol. 253, no. 1, pp. 103–110, 1992, https://aip.scitation.org/doi/pdf/10.1063/1.42152
- V.N. Litvinenko and Y. S. Derbenev, "Coherent electron cooling," Phys. Rev. Lett., vol. 102, https://link.aps.org/doi/10.1103/PhysRevLett.102.114801
- D. Ratner, "Microbunched electron cooling for high-energy hadron beams," Phys. Rev. Lett., vol. 111, https://link.aps.org/doi/10.1103/PhysRevLett.111.084802

EIC Coherent Electron Cooling

Like stochastic cooling, tiny fluctuations in the hadron beam distribution (which are associated with larger emittance) are detected, amplified and fed back to the hadrons thereby reducing the emittance in tiny steps on each turn of the hadron beam

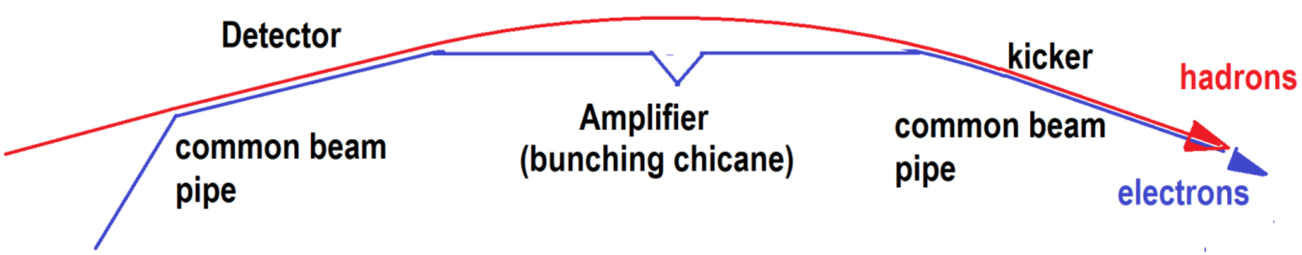
- High bandwidth (small slice size)
- Detector, amplifiers and kickers



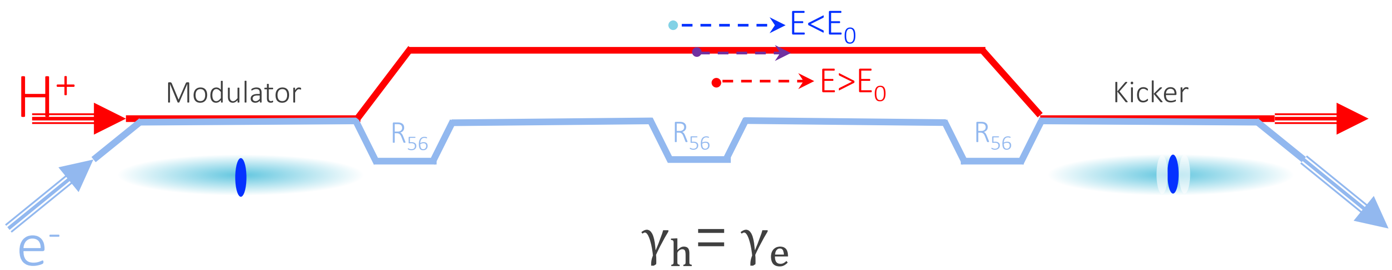
For high energy protons, the required bandwidth is much larger than possible with micro-wave cables, amplifiers and kickers

➔ Use an electron beam instead to detect fluctuations, to amplify and to kick

The use of electrons vastly increases the bandwidth.



Coherent Electron Cooling scheme



$$\gamma_h = \gamma_e$$

(Electrons and hadrons have exactly the same speed)

Imprinting: density fluctuation in hadron beam causes **energy modulation** of e-beam

Amplification: e-beam energy modulations are converted **to density fluctuation** by chicane

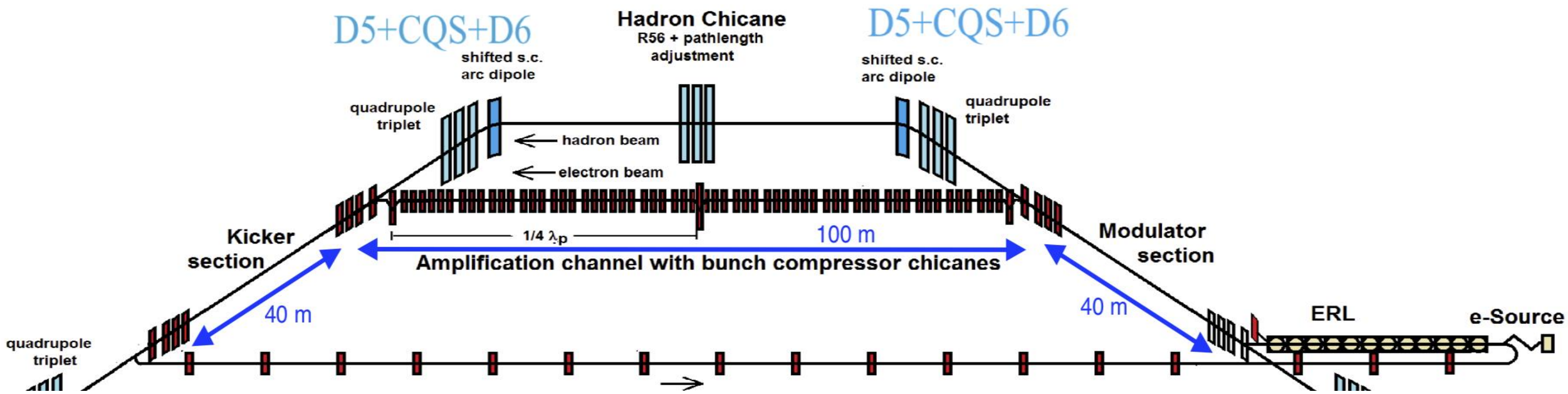
Hadron chicane: **Controls hadron travel time** with respect to electron path. Transfer to **correlated energy modulation**.

Kicker: longitudinal electric field of electrons **reduces the hadron beam correlated energy spread.**

The baseline design chooses Plasma enhanced micro-bunching

- Very broadband (~THz, slice size ~0.1 mm) amplifier
- Micro-bunching instability was well studied.
- Significant gain without saturation

EIC Strong Hadron Cooling System

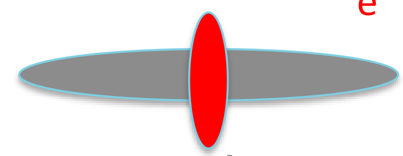


- 400 kV DC gun for 100 mA of beam and 4 MeV SRF injector
- Dogleg ERL merger
- 149 MeV Super conducting Energy Recovery LINAC (in existing tunnel)
- e Beam transport to merge hadron beam
- Amplification section with chicanes for electrons
- Hadron chicane (existing magnets) path length matching & R_{56} adjust
- Return transport of electron beam to ERL
- 2 K He sub cooler station, RF and power infrastructure
- Electron beam instrumentation and diagnostics

CeC concept: reasons for optimism

- Broad bandwidth: $BW \sim \dfrac{\gamma c}{a} \approx 100\ \text{THz}$ (a is the rms electron beam size, ~1 mm)
- Using a well-known formula (noiseless amplifier and optimal gain), the best longitudinal cooling time can be estimated as:

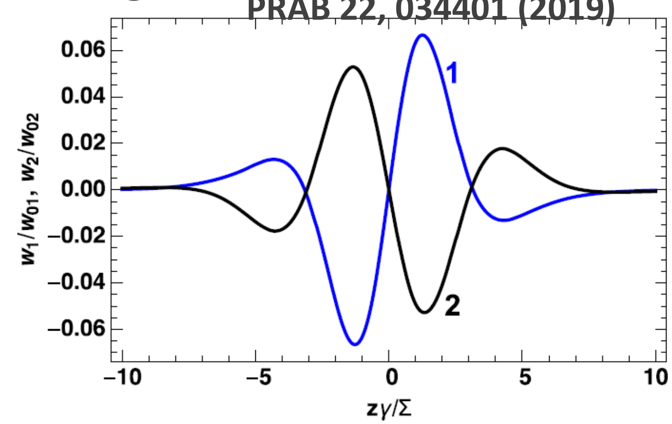
$$\tau_{\min} \sim \frac{N_p}{BW}\frac{C}{\sigma_p}\frac{\sigma_p}{\sigma_e}N_\sigma^2 \sim N_\sigma^2 \times 4.5\ \text{min}$$



- C = 3.8 km (EIC circumference)
- N_σ is the number of “beam rms sigmas” to cool.
  – At some “sigma”, cooling becomes “heating”…
- For N_σ = 3, the best cooling

time achievable at 275 GeV is ~40 min

G. Stupakov and P. Baxevanis PRAB 22, 034401 (2019)

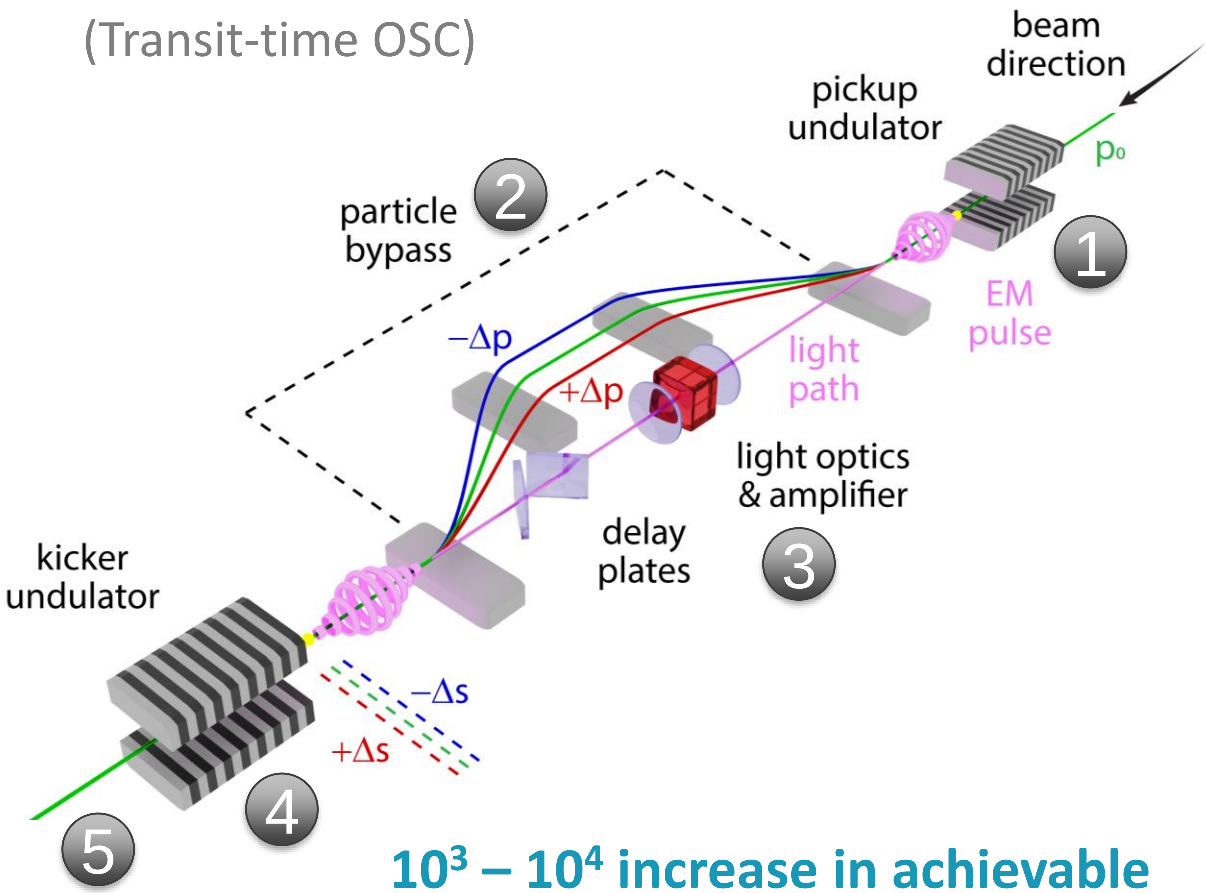


CeC concepts: challenges and concerns

- The present EIC project base-line concept (CEC or micro-bunch stochastic cooling) relies on untested technologies:
  - High-current ERL (100 mA at 150 MeV)
  - Electron beam serves as both a “pickup” and a “kicker”
  - Needs a quiet electron bunch (no “density clumps”!)
  - Relies on a micrometer-scale path-length control for both beams
- Need to redistribute 1D longitudinal cooling in 3D (x, y, z)
  - Change proton optics without affecting the vertical IBS rates
  - Achieve flat proton beams: emittances (n, rms): 3.3 μm and 0.3 μm)

Optical stochastic cooling

(Transit-time OSC)



1. Each particle generates EM wavepacket in pickup undulator
2. Particle's properties are "encoded" by transit through a bypass
3. EM wavepacket is amplified (or not) and focused into kicker und.
4. Induced delay relative to wavepacket results in corrective kick
5. Coherent contribution (cooling) accumulates over many turns

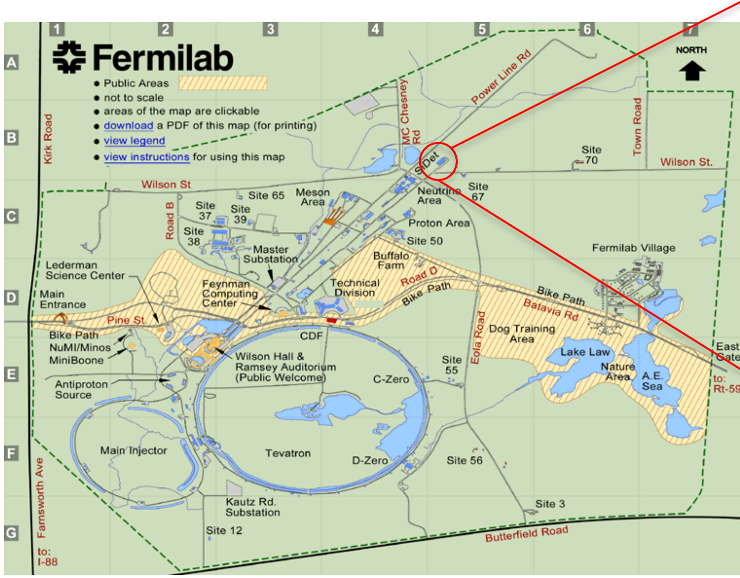
10^3 – 10^4 increase in achievable stochastic cooling rate (~10s of THz BW vs few GHz)

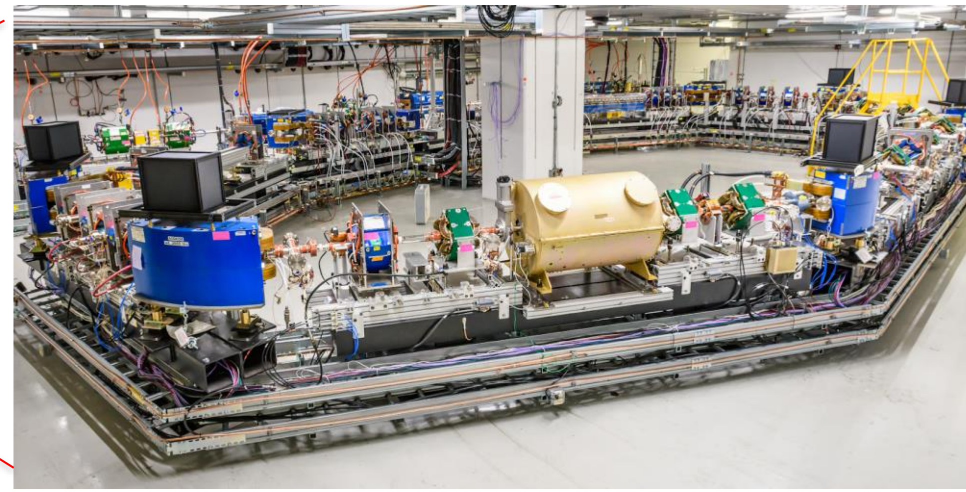
A.A.Mikhailichkenko, M.S. Zolotorev, "*Optical stochastic cooling*," Phys. Rev. Lett. 71 (25), p. 4146 (1993)
M. S. Zolotorev, A. A. Zholents, "*Transit-time method of optical stochastic cooling*," Phys. Rev. E 50 (4), p. 3087 (1994)

Optical Stochastic Cooling demonstration at Fermilab

Fermilab's Integrable Optics Test Accelerator (IOTA)

First beam Aug 21, 2018





Circumference: 40 m (133 ns)

Electron energy: 100-150 MeV

Primary purpose of IOTA: accelerator science and technology research

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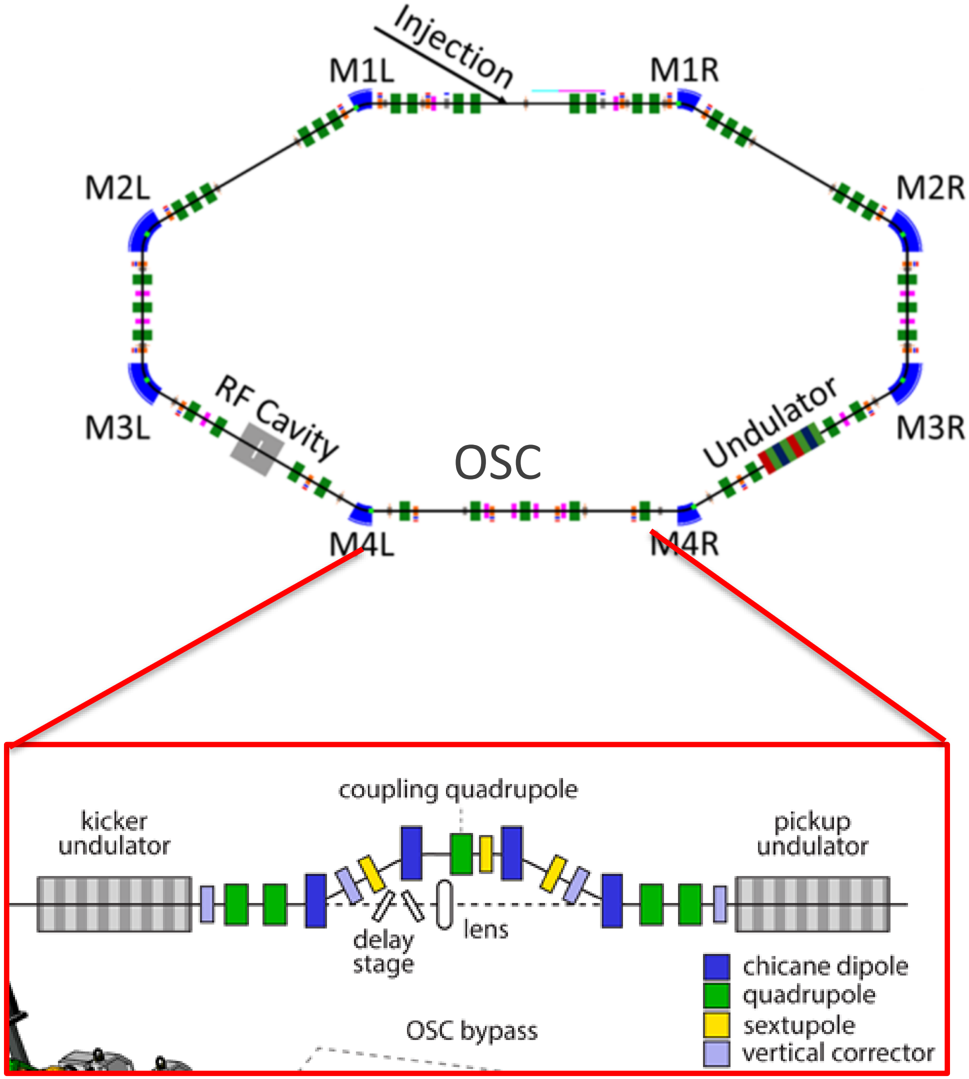
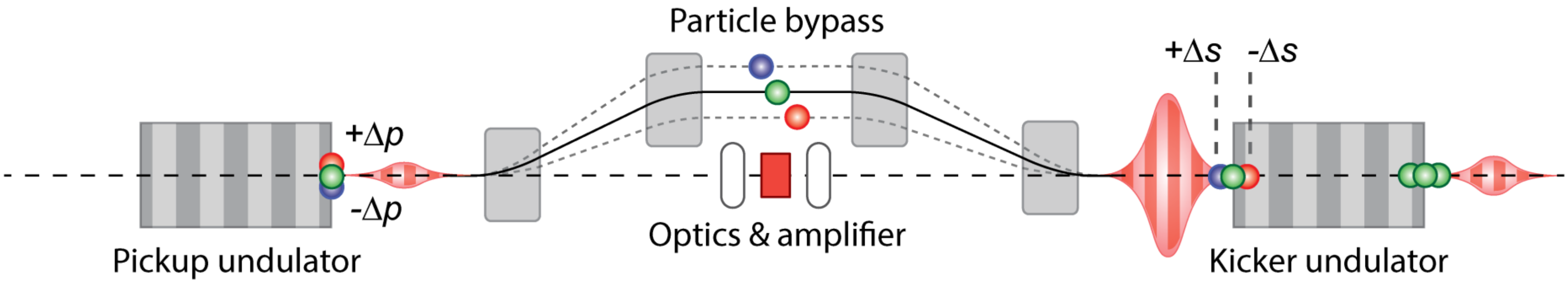
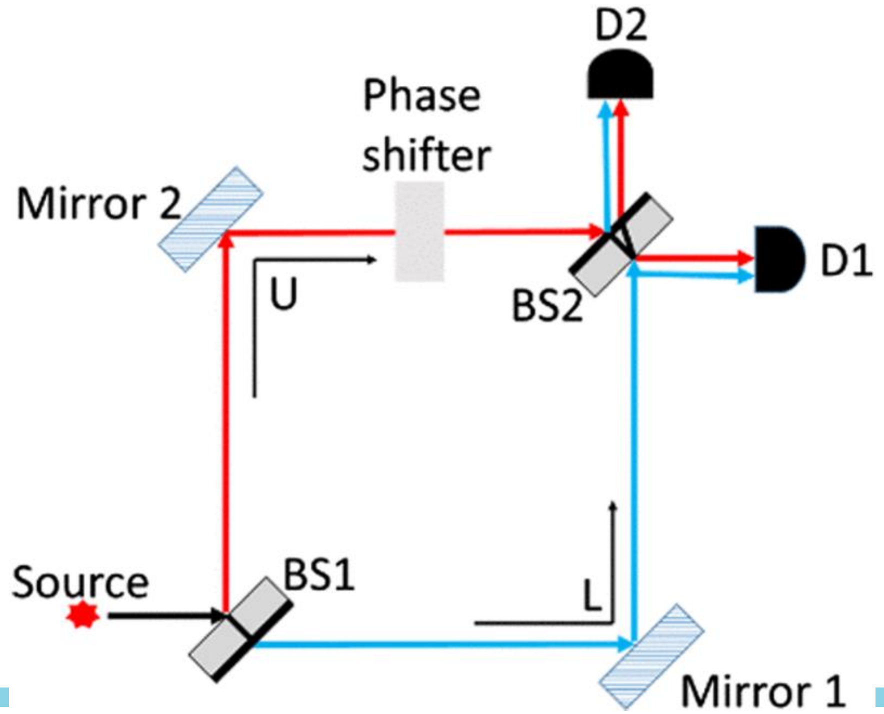
Layout of the OSC section in IOTA



OSC as interference

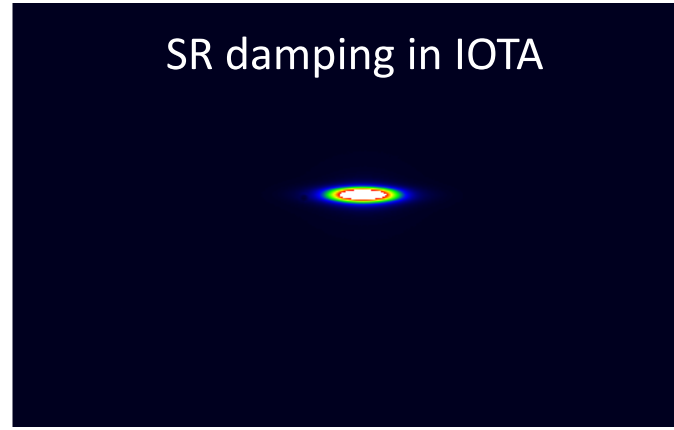


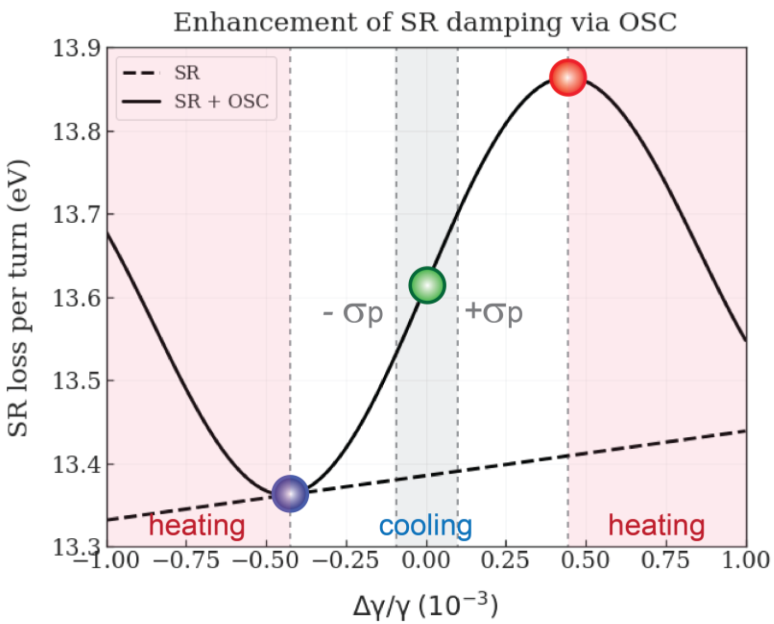
Mach-Zehnder Interferometer

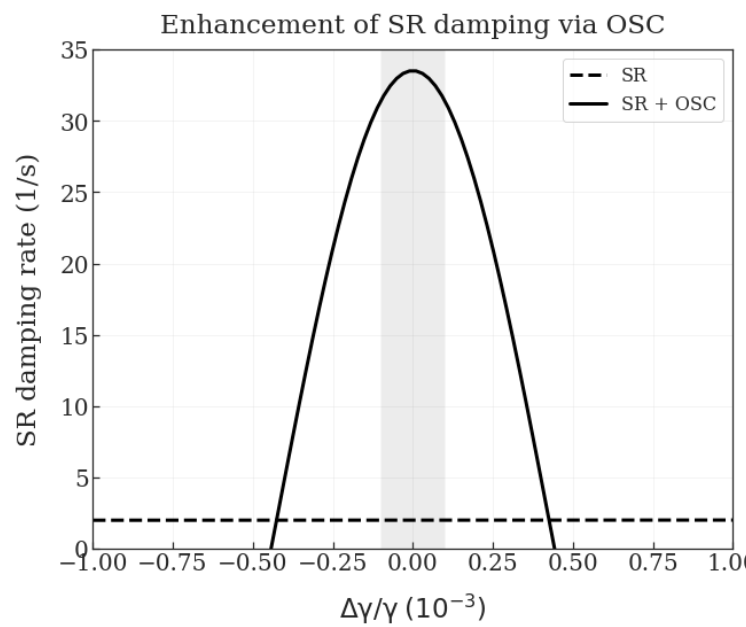


“Interference” of UR greatly amplifies SR damping

- SR-damping rate goes as ***dU/dE***
- UR interference produces large ***dU/dE*** for small deviations in ***E***
- IOTA’s OSC was designed to dominate SR damping by ~10x without any optical amplification ($\tau_{\varepsilon s}$~50 ms, $\tau_{\varepsilon x/y}$~100 ms)







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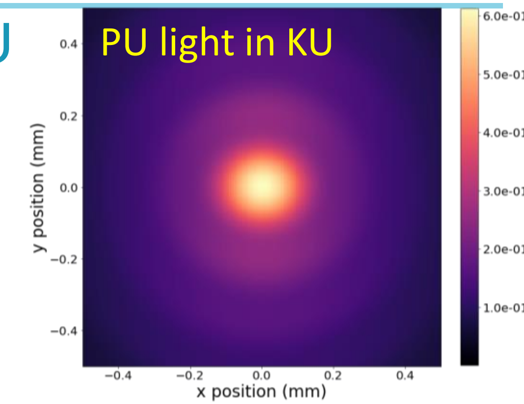
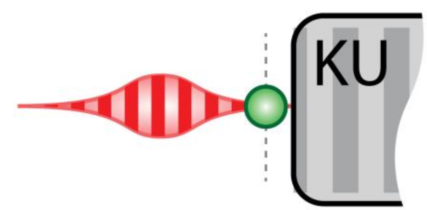
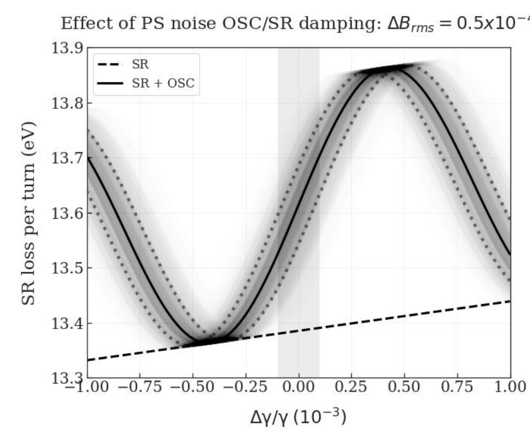
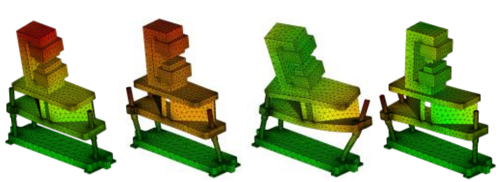
What makes ("simple") OSC challenging?

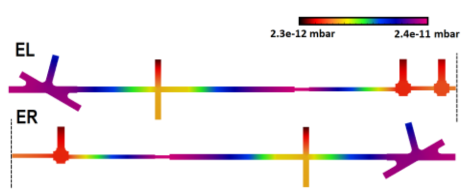
1. Beam and PU light must overlap through the KU
   - The undulator light is **~200 μm** wide
   - Want angle between light and beam at < **~0.1 mrad**
2. Beam and PU light must arrive ~simultaneously for maximum effect
   - Absolute timing should be better than **~0.3 fs**
   - The entire delay system corresponds to ~2000 fs
3. The electron bypass and the light path must be stable to much smaller than the wavelength
   - Arrival jitter at the KU should be better than **~0.3 fs**
   - This means total ripple+noise in chicane field must be at the **~mid 10^{-5}** level
4. Practical considerations of design and integration!





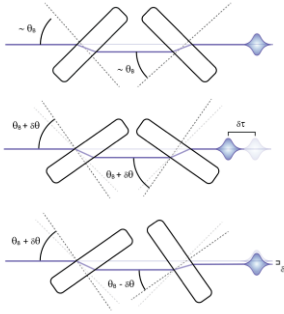




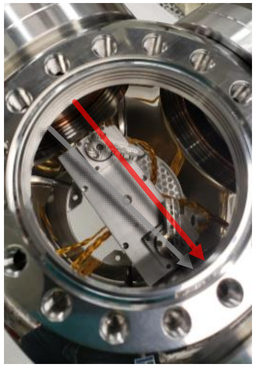


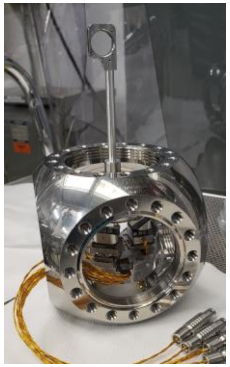
OSC apparatus successfully integrated in IOTA

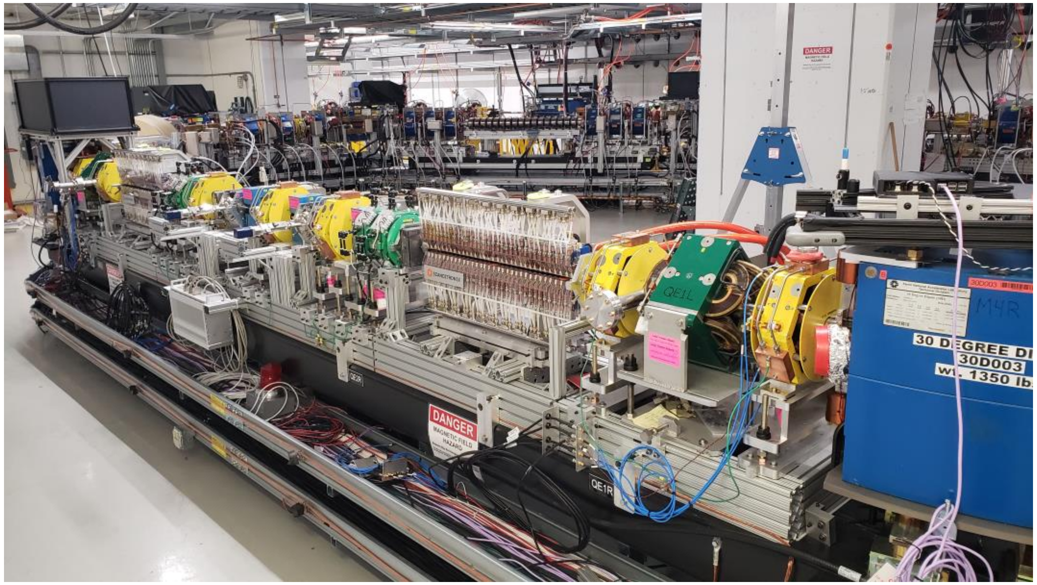
- Established and corrected OSC lattice to desired precision
- Achieved ~80% of theoretical max aperture and ~20-min lifetime; sufficient for detailed OSC studies
- OSC chicane and the optical-delay stage were demonstrated to have the required control and stability for OSC
- Successfully validated all diagnostic and control systems

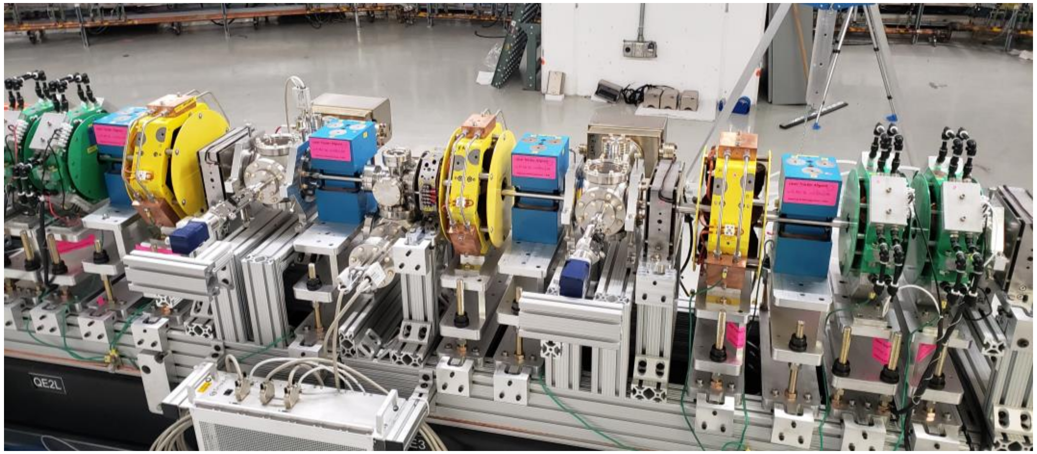


Delay stage



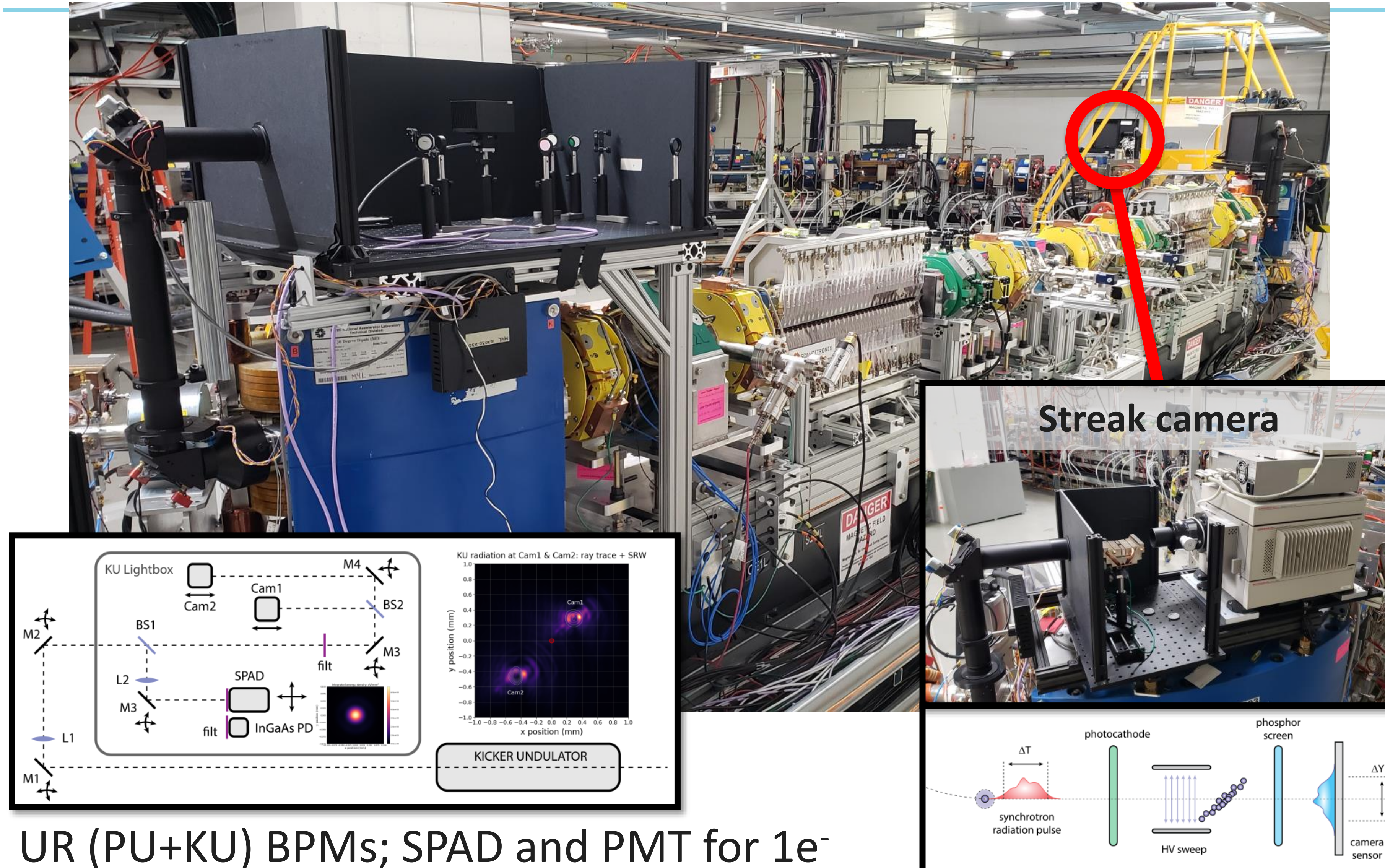






Fermilab

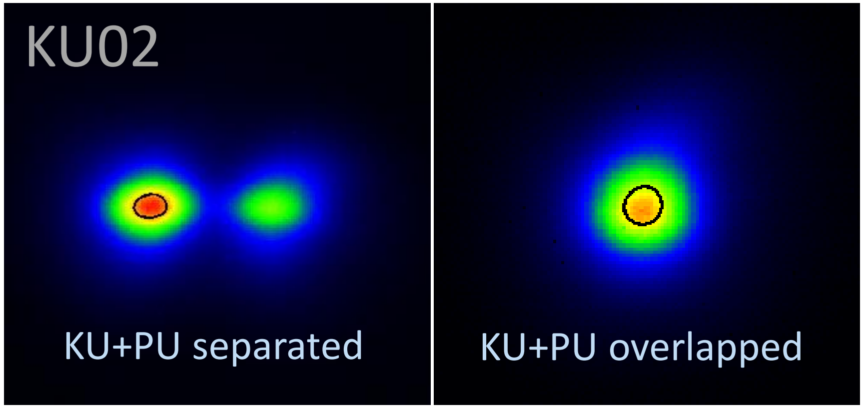
OSC is monitored via synchrotron-rad. stations

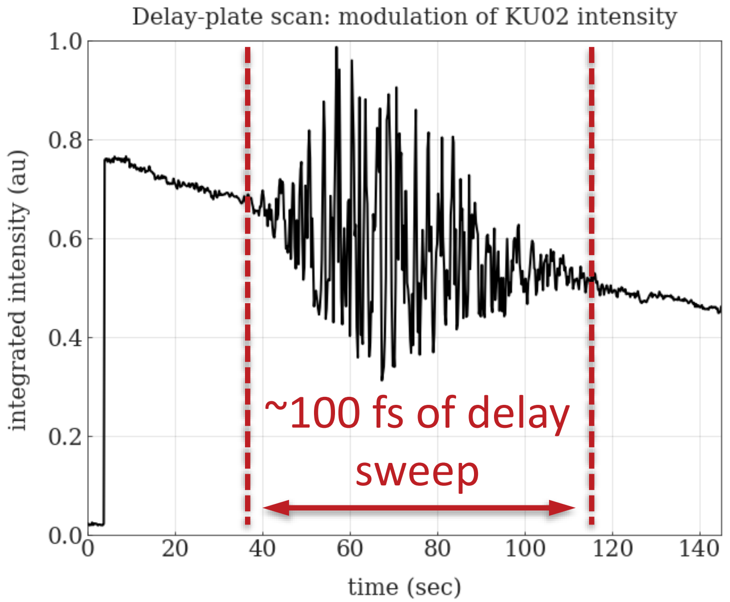


UR (PU+KU) BPMs; SPAD and PMT for $1e^-$

On 04/20/21, interference was observed at full undulator power

- The undulators were brought to their nominal, high-power setting ($\lambda = 950$ nm)
- In-vacuum light optics and closed-orbit bumps were used to maximally overlap the coherent modes of the undulators, first on the detectors and then inside the kicker undulator
- This coherent-mode overlap, in both space and time, is the fundamental requirement for producing OSC
- When this condition was met, synchrotron-radiation cameras throughout IOTA were monitored for a definite effect on the beam….

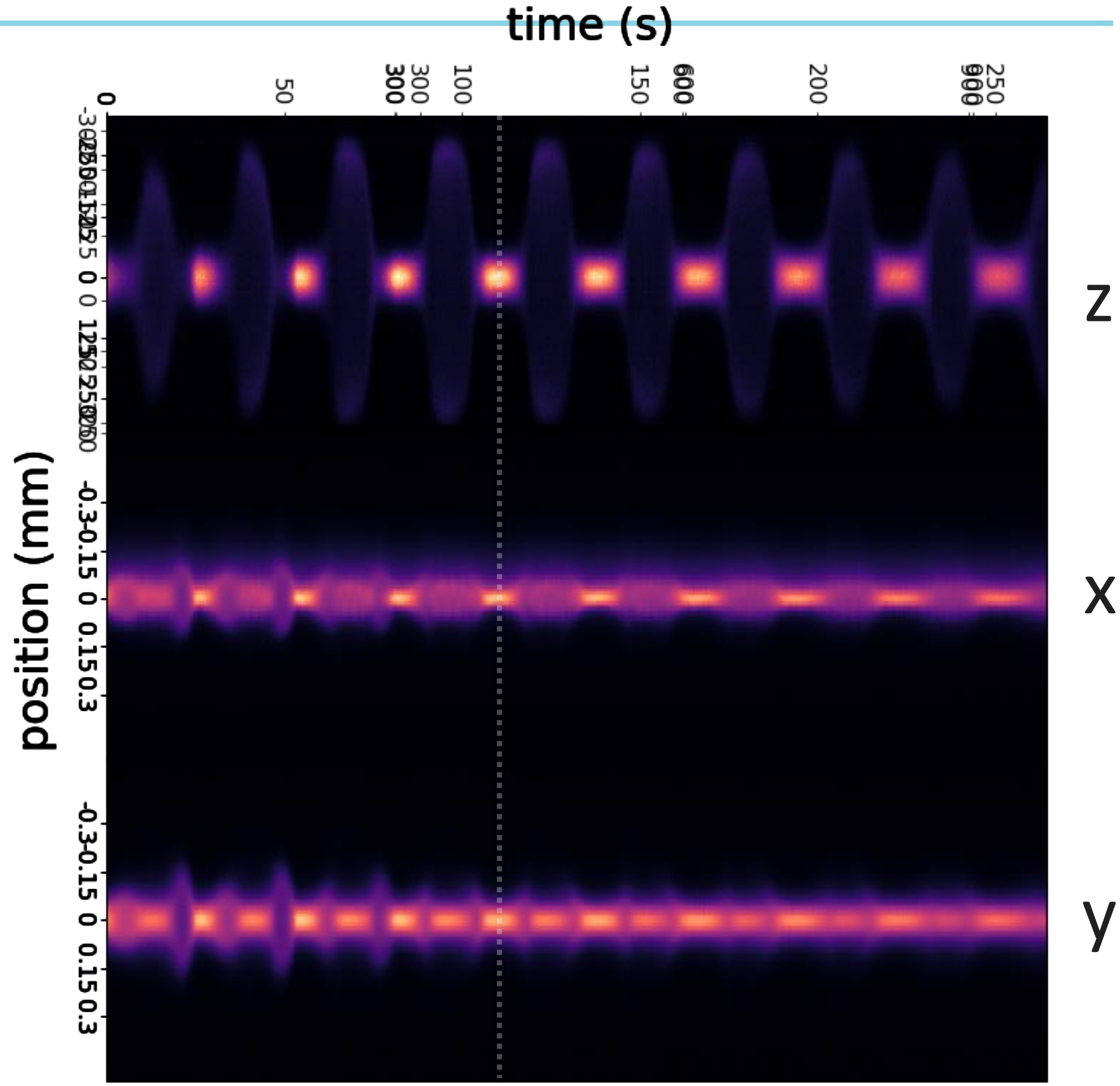




Delay scan through entire wavepacket-overlap region

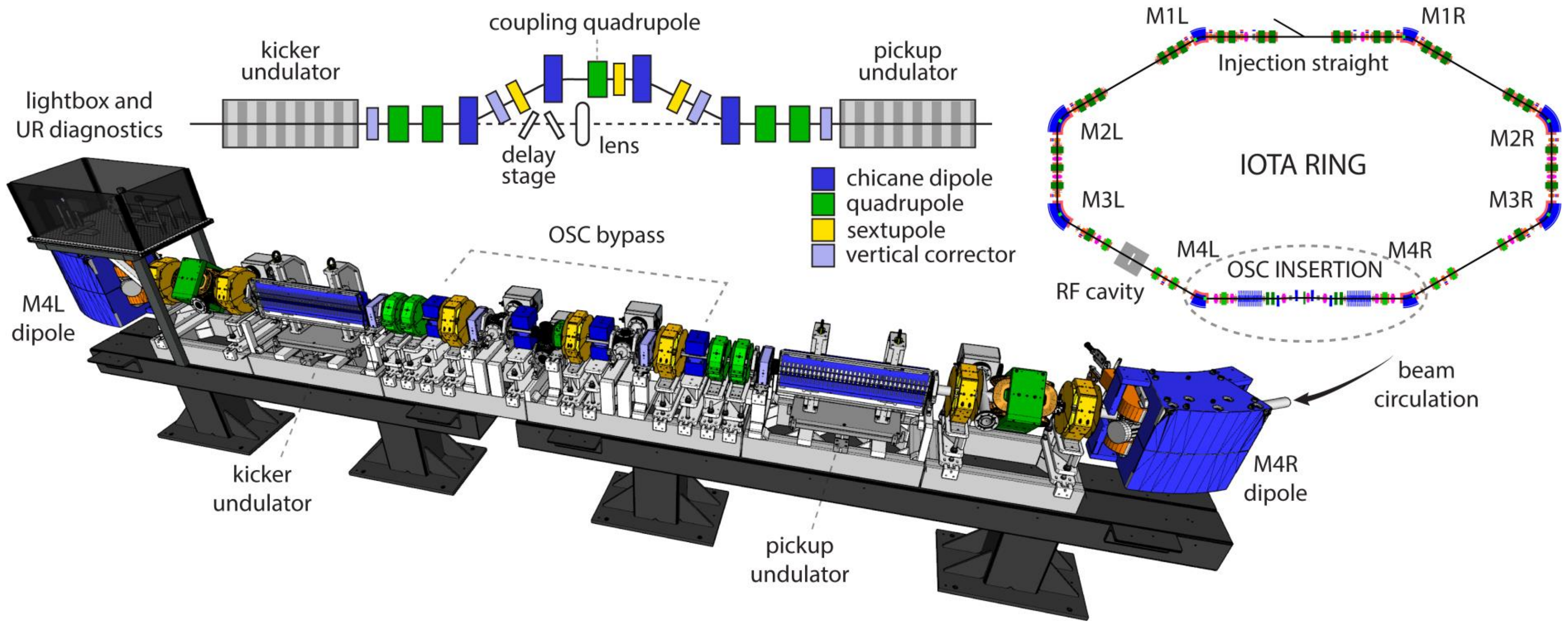
After much work… OSC was strong and stable

- 1D: lattice decoupled and bypass quad set to null transverse response to OSC; some residual due to dispersion @ SR BPM
- 2D: lattice decoupled and bypass coupling to nominal
- 3D: lattice coupled and bypass to nominal
- OSC system is reoptimized for each configuration
- Delay system is scanned at a constant rate of 0.01deg/sec
- Corresponds to ~one wavelength every 30 sec



https://arxiv.org/abs/2203.08899 -- Accepted for publication in *Nature*

A staged approach for OSC at IOTA



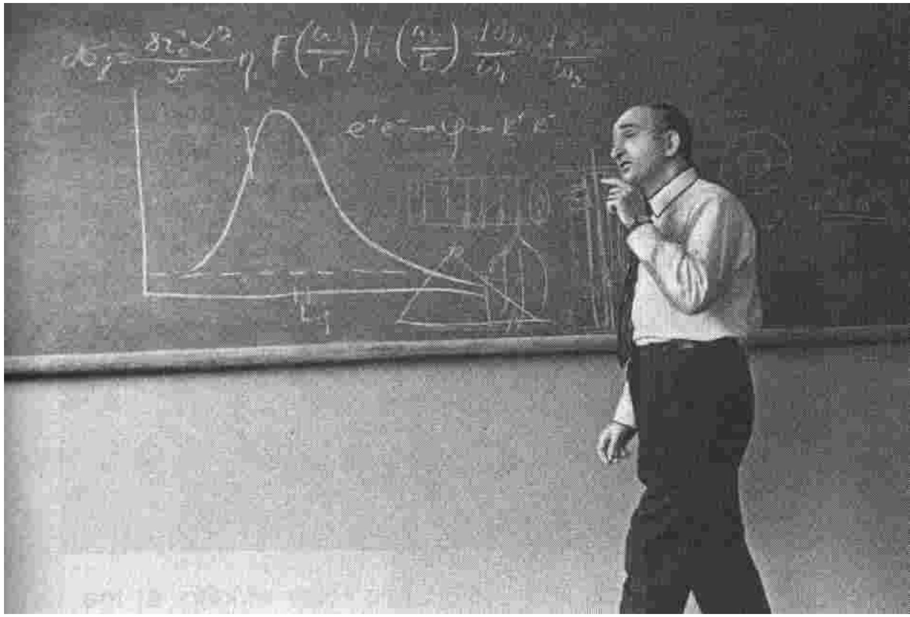
- **Non-amplified OSC (~1-μm)**: simplified optics with strong cooling to enable early exploration of fundamental physics; cooling rates, ranges, phase-space structure of cooling force, single and few-particle OSC
- **Amplified OSC (~2-μm)**: OSC amplifier dev., amplified cooling force, QM noise in amplification + effect on cooling, active phase-space control for improved cooling

Conclusions from our OSC experiments

- Our first ever demonstration of stochastic beam cooling at optical frequencies serves as a foundation for more advanced experiments with high-gain optical amplification and advances opportunities for future operational OSC systems with potential benefit to a broad user community in the accelerator-based sciences.
- Many of the OSC (technical) features are common to the CEC method
- May offer a feasible method for cooling hadrons at energies below ~4 TeV (e.g. at the EIC). May also enhance the existing synch radiation facilities.

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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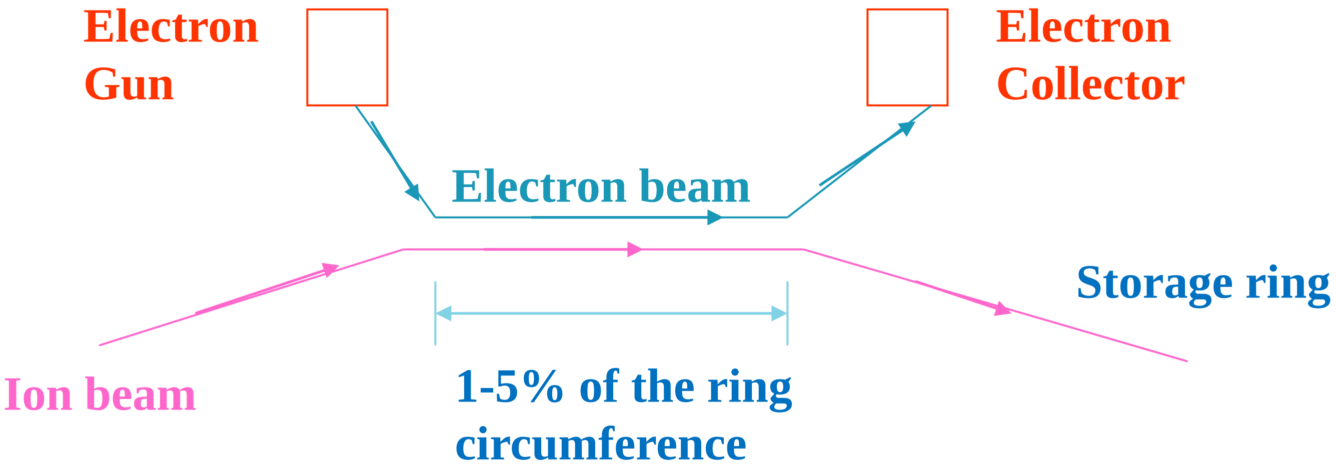
Electron cooling

- 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



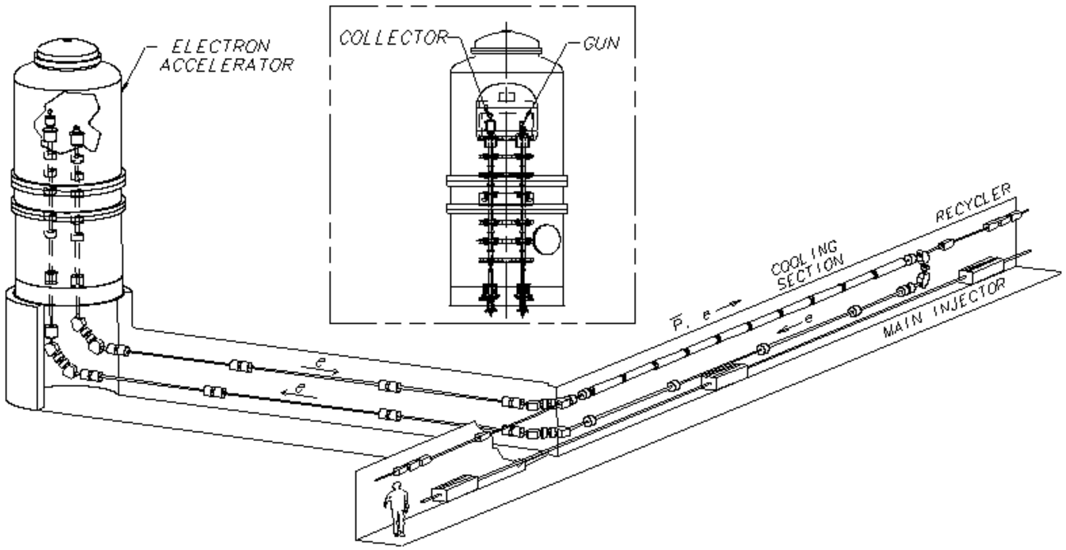
Electron cooling

- Electron cooling – Gersh Budker, Novosibirsk, 1966
  - Tested experimentally at BINP in NAP-M ring, 1974-79
  - Many projects are based on the same technology since then, up to 2-MeV electron beam (COSY, Juelich) (~4 GeV protons)
  - Highest-energy cooling: at Fermilab Recycler: E=4.3 MeV electrons (8 GeV pbars) – the only e-cooler used for HEP colliders
    - First deviation from the NAP-M cooler (no continuous magnetic field)
  - Successfully used for hadron cooling at collider top energy in RHIC (LEReC project) in 2019.
    - Second deviation from NAP-M and Fermilab coolers (rf acceleration)

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



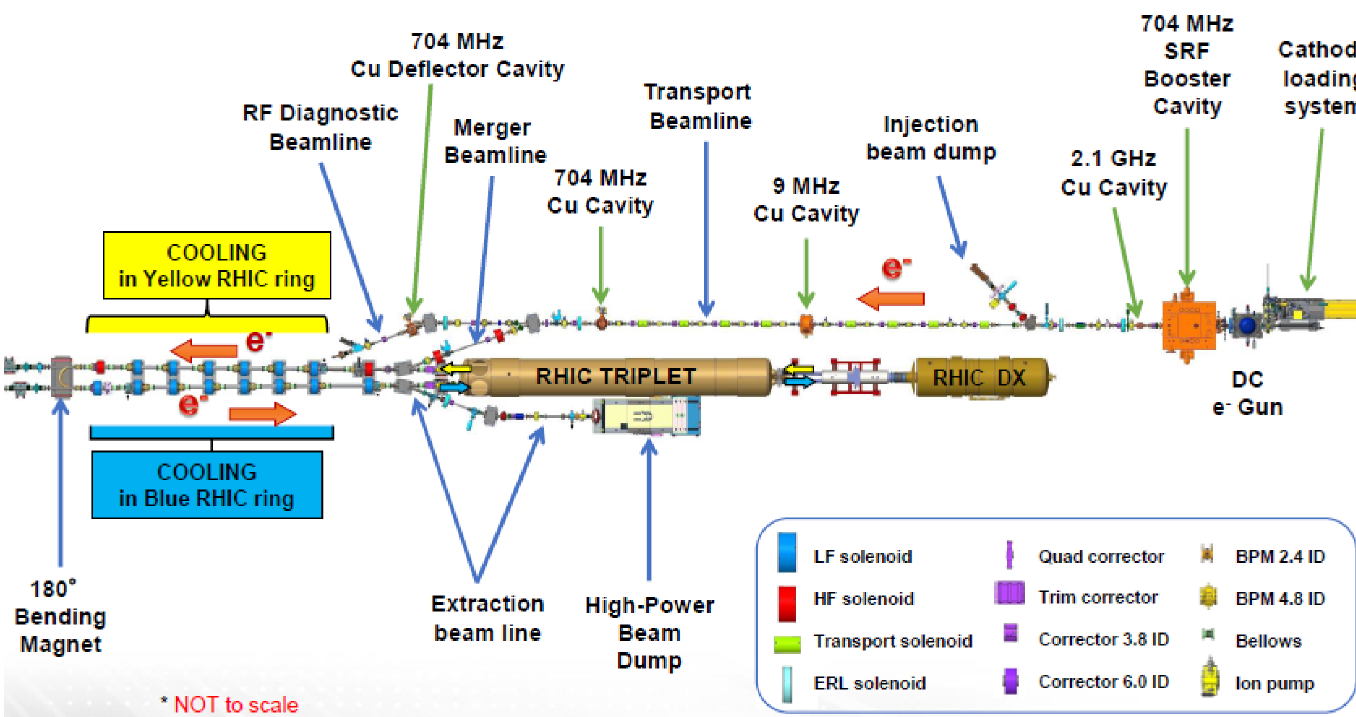
- Electron beam:
  - 4 MeV × 0.5 A = 2 MW DC
    - Energy recovery scheme
    - Very low beam losses are required
    - High voltage discharges need to be avoided
    - Interaction length – 20 m (of 3320 m Recycler circumference)
- Beam quality:
  - Transverse electron beam temperature (in the rest frame) should be comparable to the cathode temperature ~1400K
- Development: 1996-2004
  - Operations: 2005 – 2011

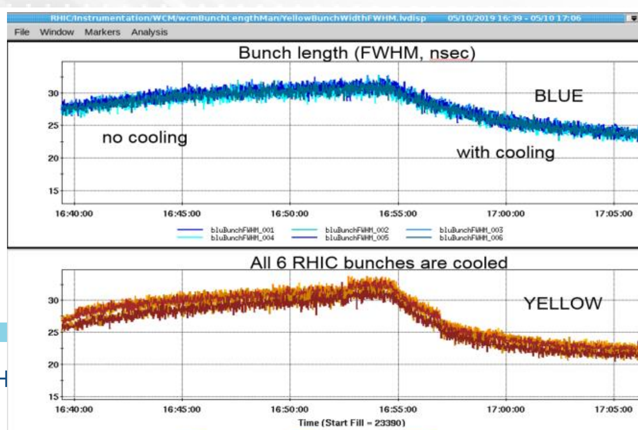
S. Nagaitsev, et al. "Experimental Demonstration of Relativistic Electron Cooling", Phys. Rev. Lett. 96, 044801 (2006)
S. Nagaitsev, L. Prost and A. Shemyakin, "Fermilab 4.3-MeV electron cooler," 2015 JINST 10 T01001.

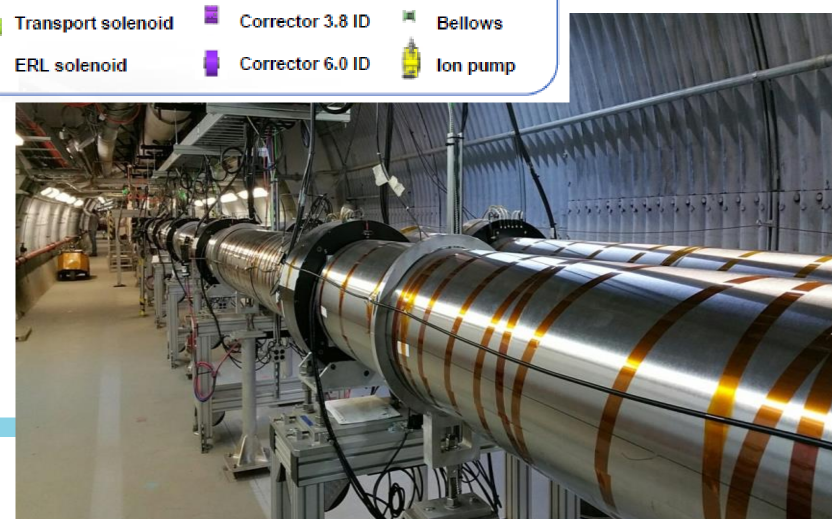
Low-Energy RHIC electron Cooler (LEReC) at BNL:

LEReC Accelerator

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







Ring-Based Electron Cooling System for the EIC

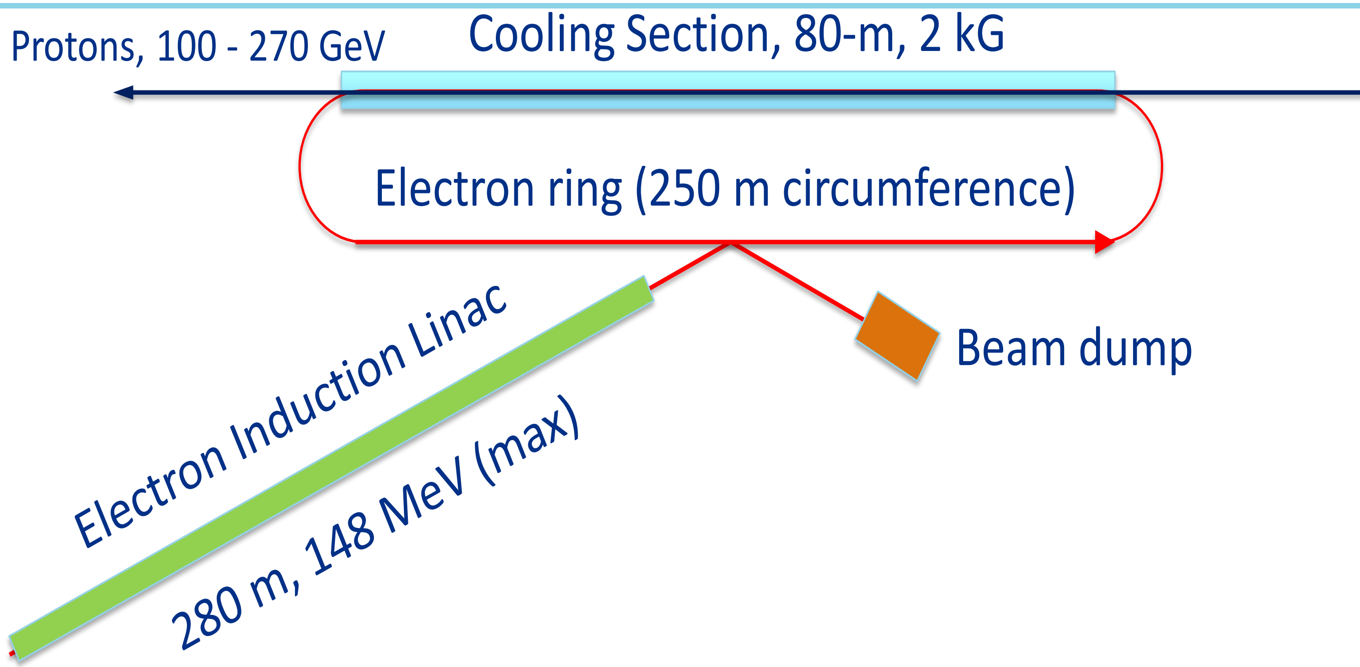
- Offers an alternative cooling approach, based on mostly well-tested technologies
  - But not without challenges!

- The proposed system is capable of delivering the required performance in the entire EIC energy range with emittance cooling times of less than 1-2 hours.
  - See: https://arxiv.org/abs/2010.00689

EIC electron cooling concept

- A well-known shortcoming of the electron cooling method is its unfavorable scaling of cooling time with energy ($\sim\gamma^2$)
  - Fermilab cooler ($\gamma \approx 10$): cooling time was < 0.5 hour
- One can compensate by
  - Increasing the electron beam current
  - Increasing the cooling section length
- We are aiming at a >50 - 100-A (DC) electron beam current at 50 - 150 MeV.
  - DC beams have many advantages as well as some challenges, compared to bunched beams.
- The system is capable of delivering the required performance in the entire EIC energy range with emittance cooling times of less than 1-2 hours.

Proposed solution

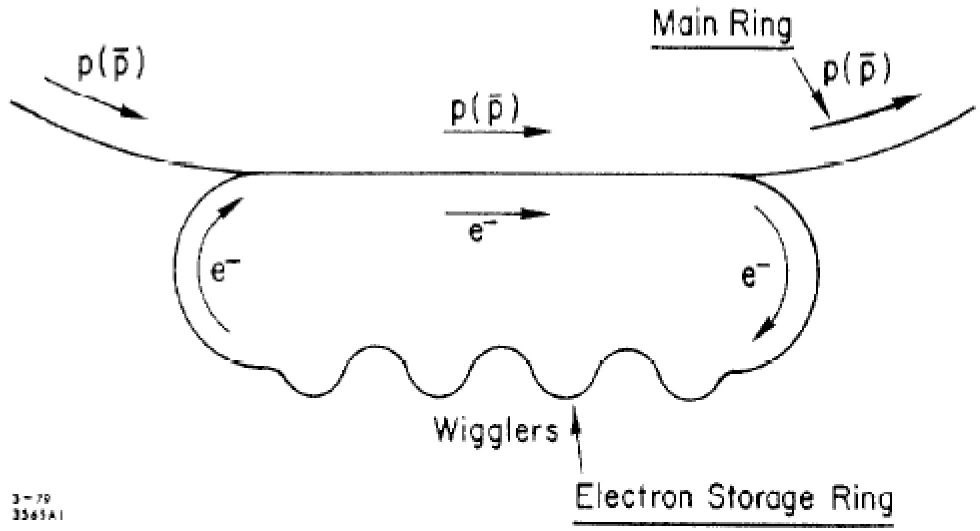


- We are considering a range of electron beam and linac parameters:
  - beam current 50-100 A
  - Rep rate: 100 – 200 Hz (~10,000 turns storage time)
- Pulse length: ~700 ns (to fill the ring)
- Beam power to dump: < 400 kW
- Beam power, lost in the ring < 2 kW (Touschek & extraction)

IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

HIGH ENERGY ELECTRON COOLING TO IMPROVE THE LUMINOSITY AND LIFETIME IN COLLIDING BEAM MACHINES*

D. Cline,[a,b,†] A. Garren,[c] H. Herr,[d] F. E. Mills,[a] C. Rubbia,[d,‡] A. Ruggiero[a] and D. Young[a]



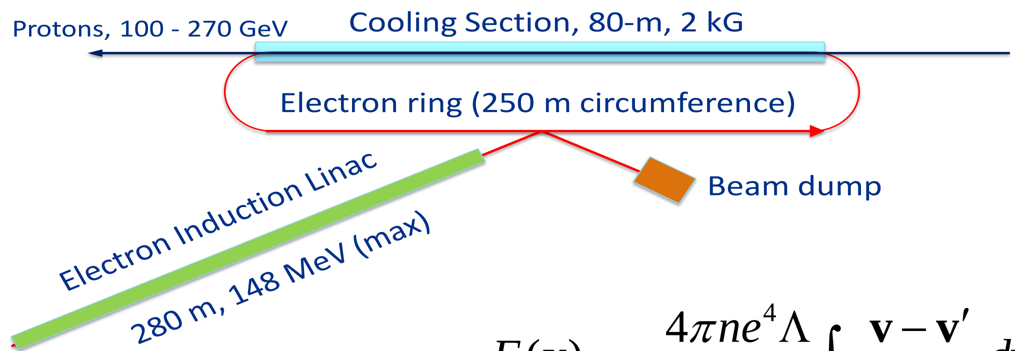
In this scheme, the electron beam is "cooled" via synchrotron radiation damping, while cooling colliding proton beams.

- Favors high electron energy
- High electron beam currents are not achievable (< 1 A), thus cooling is slow.

Fermilab

Parameter choices

- The required 100-A DC (pulsed) beam current can be provided by an induction linac.
  - Power efficiency is achieved by storage time (~10,000 turns)



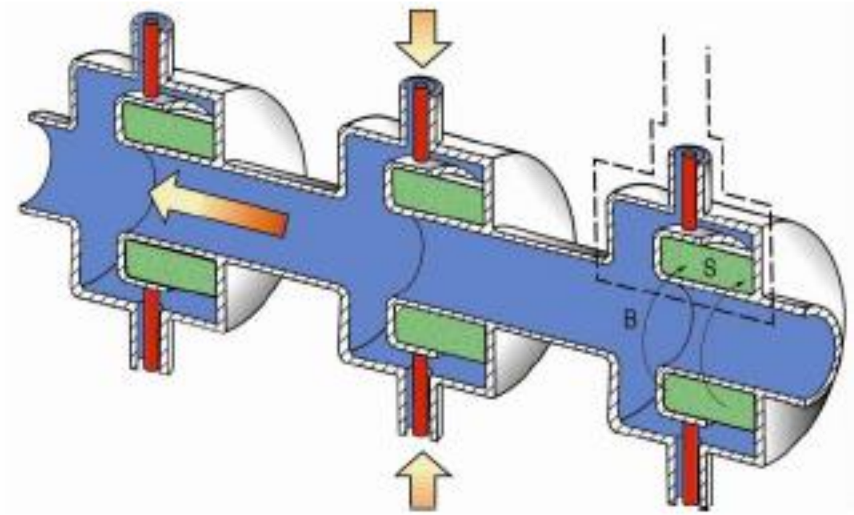
$$F(\mathbf{v}) = -\frac{4\pi n e^4 \Lambda}{n} \int \frac{\mathbf{v}-\mathbf{v}'}{\left|\mathbf{v}-\mathbf{v}'\right|^3} d\mathrm{v}^3 \Rightarrow F_{\max} \propto \frac{1}{\sigma_p{}^2 + \sigma_e{}^2}$$

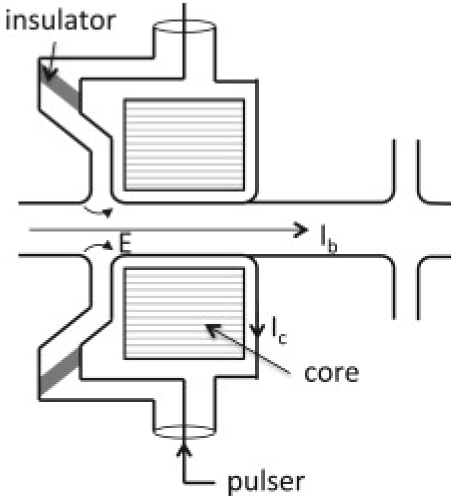
  - Weakly-magnetized cooling

    is preferred due to large temperature in proton beam
    - Magnetization helps only for small amplitude particles – not good!!!

Induction linac

DARHT at LANL

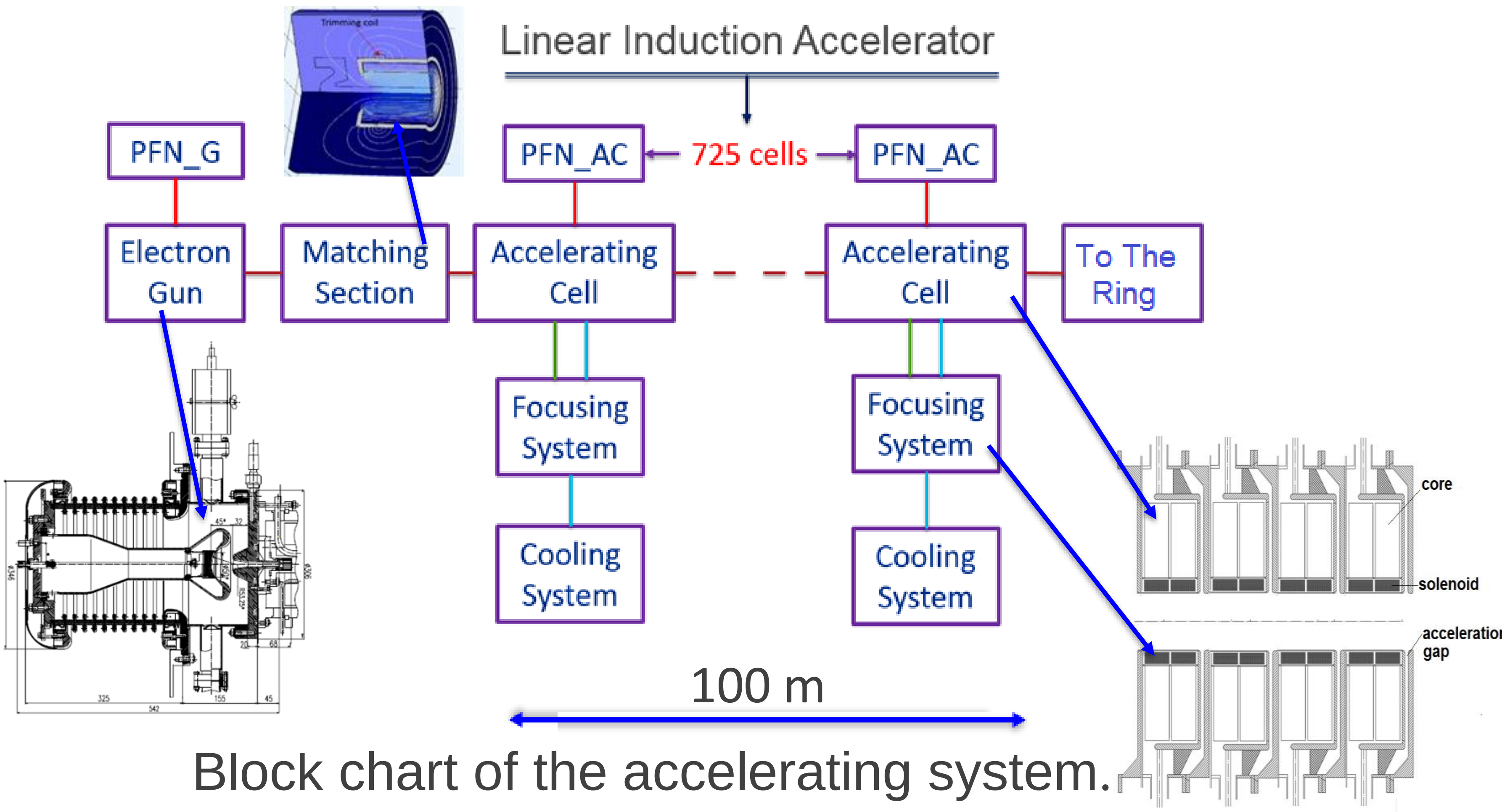




Injector Voltage	2.5 MV
Injector Current	2.0 kilo-Amperes
Injector Pulse Length	1.6 micro-seconds
Number of Injector Cells	6 @ 175 kV/cell
Number of Accelerator Cells	68 @ 200-235 kV/cell
Total Beam Energy	17.1 MeV (goal 18.1 MeV)

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

Induction Linac for Electron Cooling (55 MeV concept)



Block chart of the accelerating system.

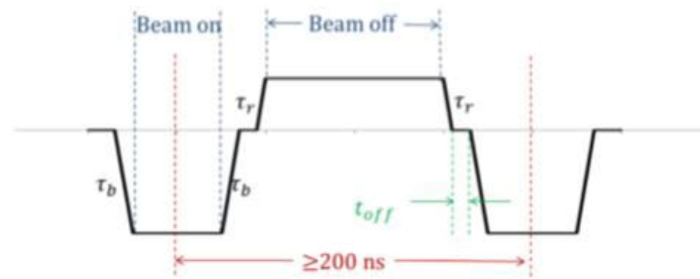
Strict requirement for the emittance of the electron beam constitutes the most challenging part of the injector and the transport line design.

Our proposed induction cell concept is similar to an existing prototype at LLNL

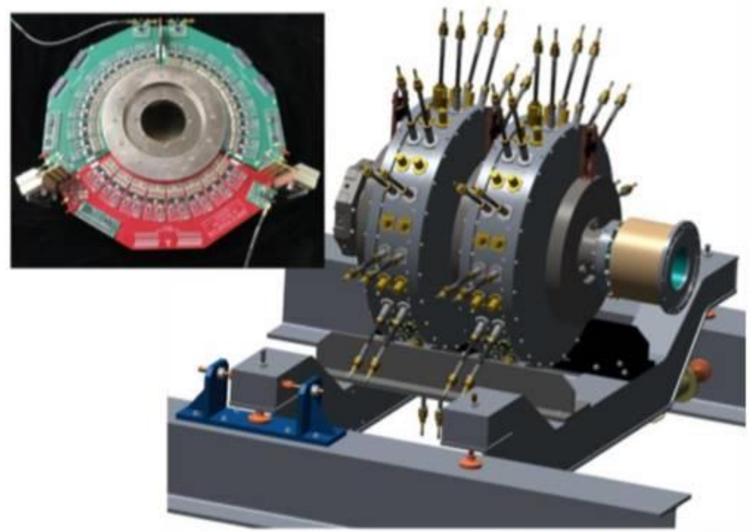
Future for LIAs and pulsed power

LLNL-PRES-793885

- Active Reset and Bipolar Solid State Pulsed Power are a revolutionary approach to the next generation of LIA machines.
- Bipolar operation allows the use of more compact low loss ferrite accelerator cells and results in unmatched pulse flexibility.
- The number of pulses is limited only by the amount of stored energy in each stage of the pulser.
- An induction cell was designed that would be able to handle a bipolar pulse.
- Bipolar pulsers have been developed that will provide the two cells with the accelerating pulse (green part of the board) and reset pulse (red part of the board).
- This cell will serve as the first test of a bipolar inductively driven cell.
- New magnetic lattice design to preserve current FXR tune was created.
- The cell and pulsed power will be inserted into the FXR beam line as a TRL 7 demonstration.



$$200\ ns \le t_{beam} + t_{reset} + 2\tau_b + 2\tau_r + 2t_{off}$$



Main parameters (for 270 GeV protons)

Proton beam energy	270 GeV
Relativistic factor, γ	289
Proton ring circumference (it is used to calculate cooling rates only)	3834 m
Cooling length section	80 m
Normalized rms proton beam emittances (x/y)	3/0.5 μm
Proton beam rms momentum spread	$<3\times10^{-3}$
β-functions of proton beam at the cooling midpoint	80 m
Proton beam rms size (hor/ver)	0.9/0.4 mm
Electron beam energy (50 – 150 MeV)	147 MeV
Electron beam current (50 – 100 A)	100 A
Cathode diameter	25 mm
Cathode temperature	1050ºC
Longitudinal magnetic field in cooling section, B_0	780 G
Electron beam rms momentum spread, initial/final	$(1.0/1.25)\cdot10^{-3}$
Rms electron angles in cooling section	4.8 μrad
Rms electron beam size in cooling section	2.2 mm
Electron beam rms norm. mode emittances at injection, $\varepsilon_{1n}/\varepsilon_{2n}$, μm	220/0.042
Number of cooling turns in the electron storage ring	6,000
Longitudinal cooling time (emittance) *	23 min
Transverse cooling time (emittance) *	30 min

Summary

- The EIC accelerator systems are very interesting and challenging to accelerator scientists.
- Our present 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 and in time, will be able to upgrade it for higher luminocites.