Electron Cooling Concept for the EIC

S. Nagaitsev (Fermilab/U.Chicago)

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A. Saini, and N. Solyak

Nov. 10, 2020

EIC electron cooling system concept

Conceptual design report:

Ring-Based Electron Cooling System for the EIC

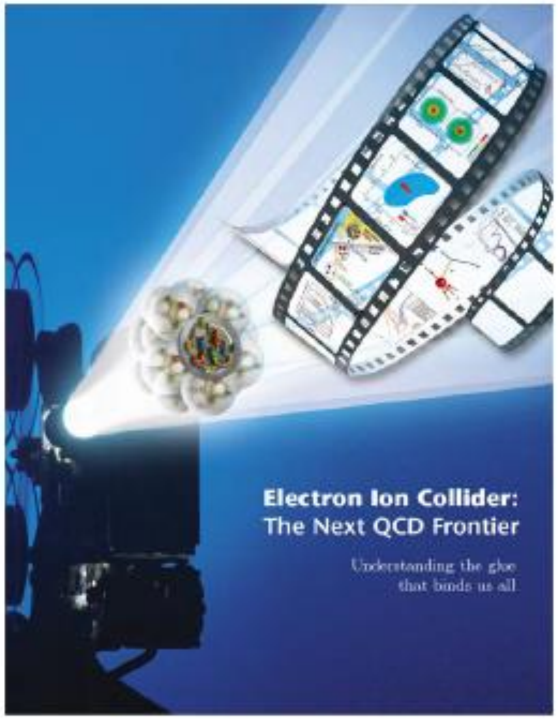
arXiv:2010.00689

- DOE NP-funded R&D project (2018 – 2020)
  - PI: S. Nagaitsev

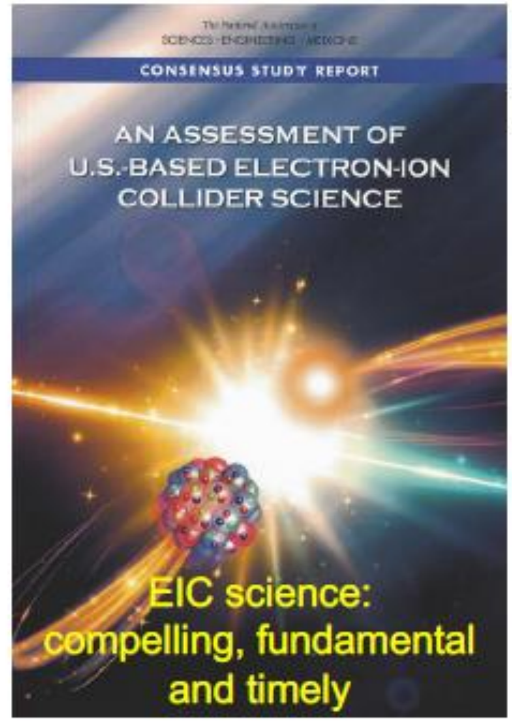
- More information about EIC cooling:
  - EIC Hadron Cooling Workshop, Oct 2019
  - https://indico.fnal.gov/event/20514/

- More information about EIC:
  - EIC Workshop – Promoting Collaboration, Oct 2020
  - https://indico.cern.ch/event/949203/

EIC Science Endorsed Unanimously by the NAS



Developed by US QCD community over two decades



Developed by NAS with broad science perspective

A consensus report July 26, 2018

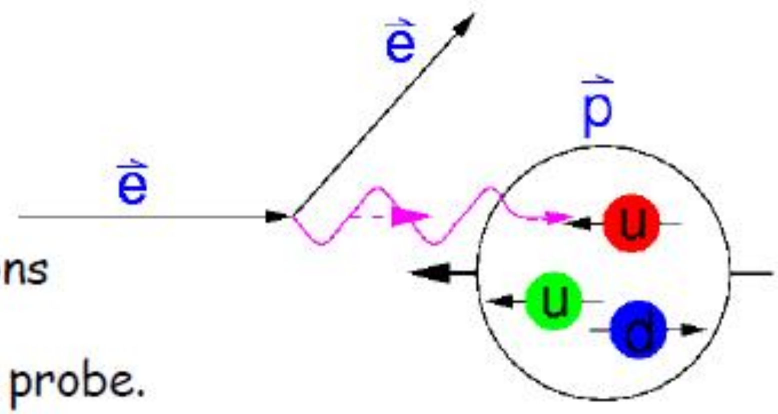
National Academy’s Findings

- **Finding 1**: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems of gluons?
- **Finding 2:** These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.
- **Finding 3**: An EIC would be a unique facility in the world and would maintain U.S. leadership in nuclear physics.
- **Finding 4:** An EIC would maintain U.S. leadership in the accelerator science and technology of colliders and help to maintain scientific leadership more broadly.
- **Finding 5:** Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

National Academy's Findings

- **Finding 6:** The current accelerator R&D program supported by DOE is crucial to addressing outstanding design challenges.
- **Finding 7**: To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD, and furthermore, to glean the fundamental insights into QCD that an EIC can reveal.
- **Finding 8**: The U.S. nuclear science community has been thorough and thoughtful in its planning for the future, taking into account both science priorities and budgetary realities. Its 2015 Long Range Plan identifies the construction of a high-luminosity polarized EIC as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.
- **Finding 9:** The broader impacts of building an EIC in the United States are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.

EIC: Probing the Femto-world



High energy collisions of electrons with nuclei, proceed via "virtual photon", which acts as a probe.

EIC physics goals

- The highest-level EIC physics goals (personal view)
  1. Origin of nucleon mass
  2. Origin of nucleon spin
  3. 3-d imaging of quarks and gluons

- There are more physics goals (see EIC reports)

EIC designed to meet NSAC and NAS Requirements

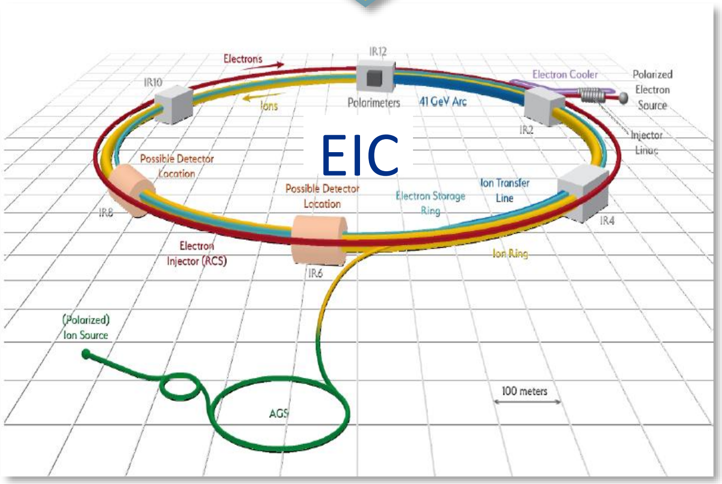
• Center of Mass Energies	20 GeV – 140 GeV
• Maximum Luminosity	10^{34} $cm^{-2}s^{-1}$
• Hadron Beam Polarization	>70%
• Electron Beam Polarization	>70%
• Ion Species Range	p to Uranium
• Number of interaction regions	up to two

NSAC - Department of Energy Nuclear Science Advisory Committee
NAS - National Academies of Sciences, Engineering, and Medicine

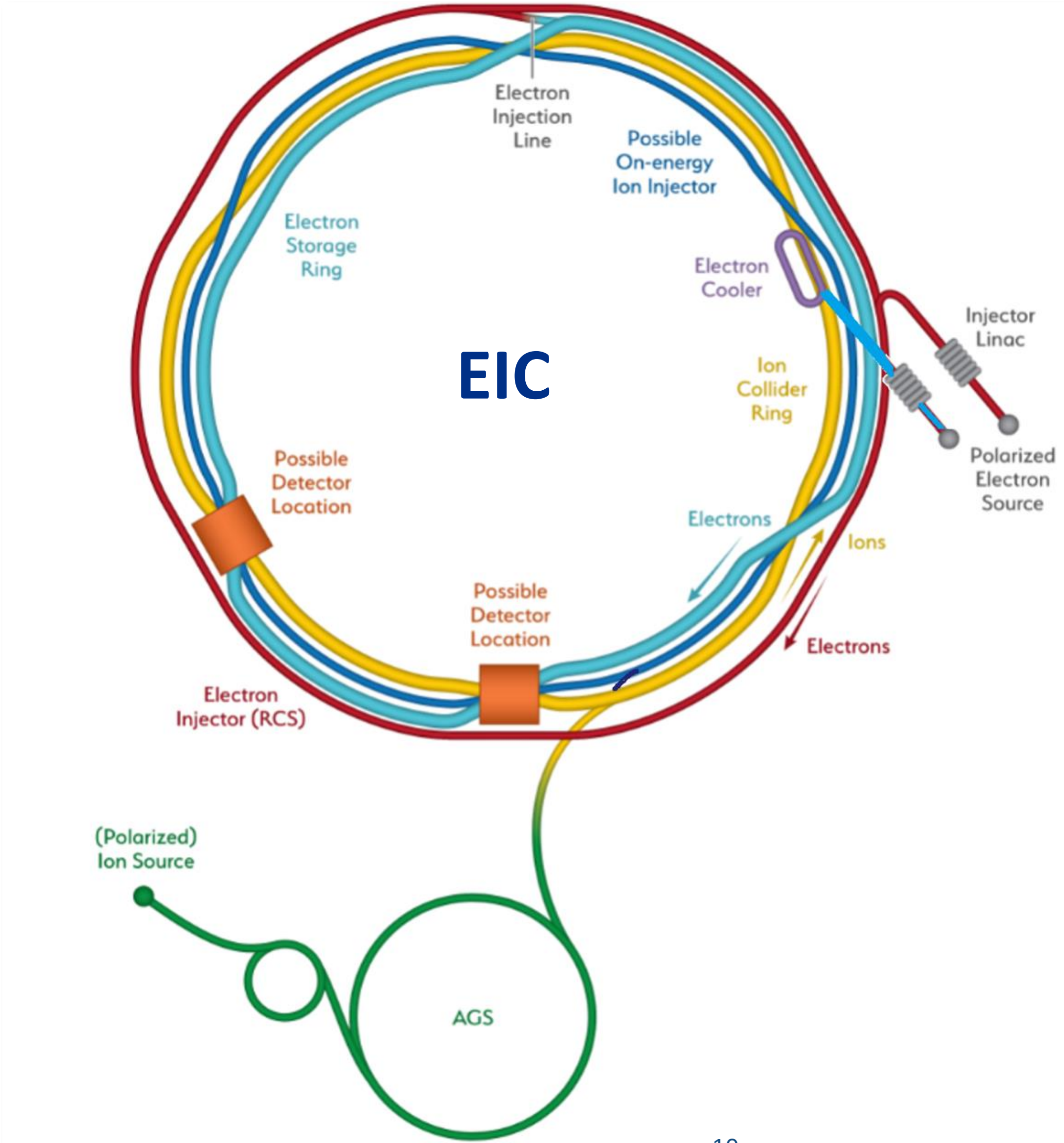
EIC Collider Concept

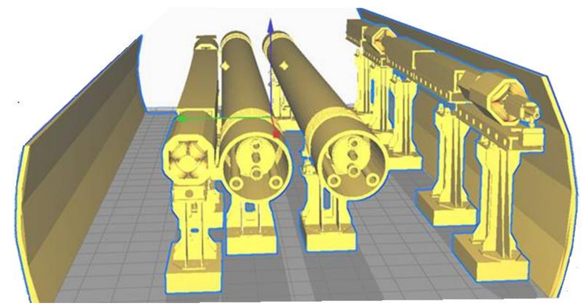
Design is based on **existing** RHIC,
RHIC is well maintained, operating at its peak

- **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



From RHIC to the EIC





The strong hadron cooling facility completes the facility

- Hadron Storage Ring
- Electron Storage Ring
- Electron Injector Synchrotron
- Possible on-energy Hadron injector ring
- Hadron injector complex

EIC covers full center of mass energy range of 20 GeV – 140 GeV

Protons up to 275 GeV:

- Existing RHIC with superconducting magnets allow up to **E_p = 275 GeV** and down to **E_p = 41 GeV**
- RHIC beam parameters are close to what is required for EIC

Electrons up to 18 GeV:

Electron storage ring with up to **18 GeV** installed RHIC tunnel,

readily achievable with

- large circumference of 3870 m and
- available superconducting RF technology ➔ U_{rf} = 62 MV

low electron energy of **2.5 GeV** is easily obtainable

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

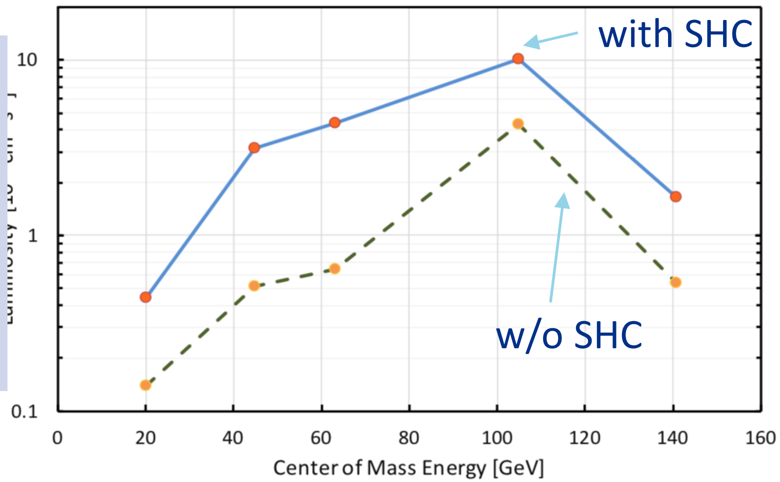
High Luminosity and Strong Hadron Cooling

- 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

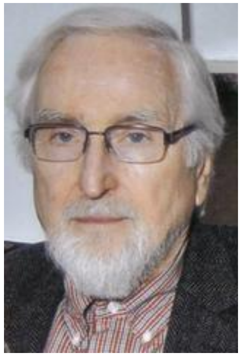
➔EIC design luminosity **$L = 1 \cdot 10^{34} cm^{-2}s^{-1}$ at Ecm=105 GeV** is achieved & full range of EIC physics can be exploited.

➔ EIC design includes strong hadron cooling



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

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.

What is beam cooling?

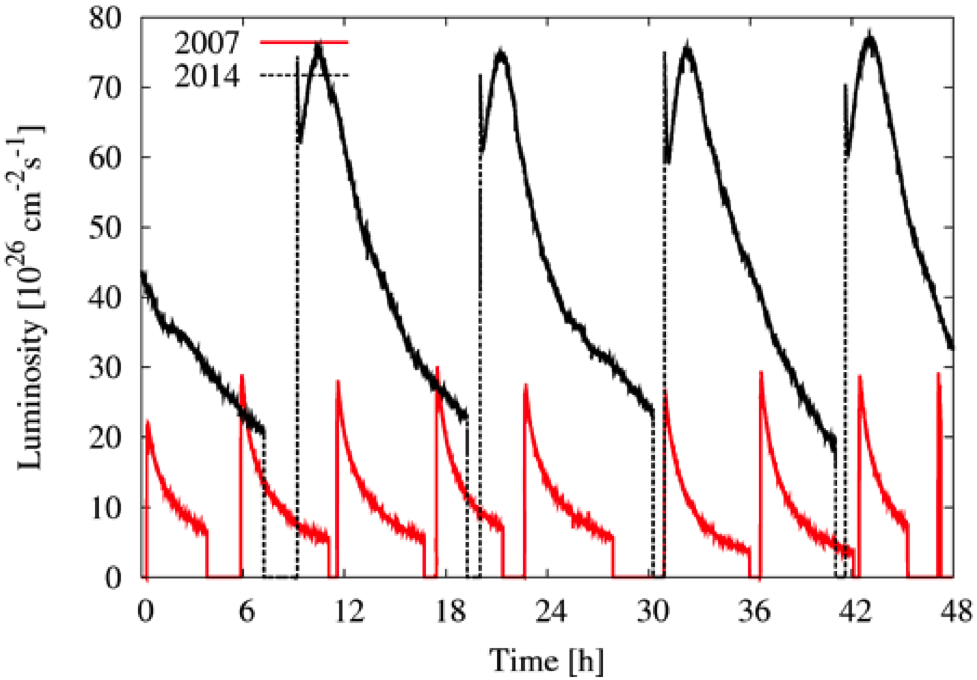
- Cooling is a reduction in the phase space occupied by the beam (for the same number of particles).
  - It's not the reduction of beam temperature, which varies around the ring. It's the reduction of beam emittance
- Equivalently, cooling is a reduction in the random motion of the beam.
- Examples of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

Hadron beam cooling (two basic methods)

First method:

- Stochastic cooling - Simon van der Meer, CERN, 1969
  - Microwave cooling (GHz-range bandwidth): well developed
    - 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)
    - Successfully employed for ion bunched-beam cooling at the top energy in RHIC;
  - 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)

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



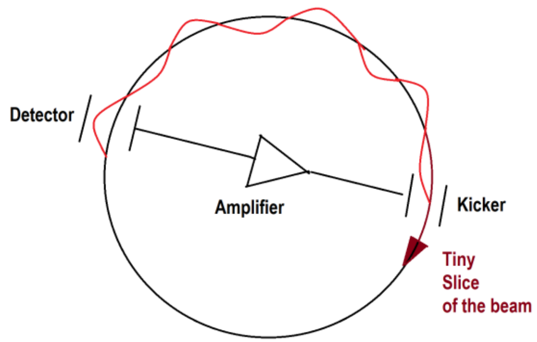
- 3-D stochastic cooling (5-9 GHz).
- ~5x U-U and ~ 4x Au-Au luminosity improvements.
- Cooling led to first increase of instantaneous luminosity and smallest emittance ever in a hadron collider.
- May be adequate for the EIC with e-ION collisions
- Is not adequate for protons

Fermilab

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

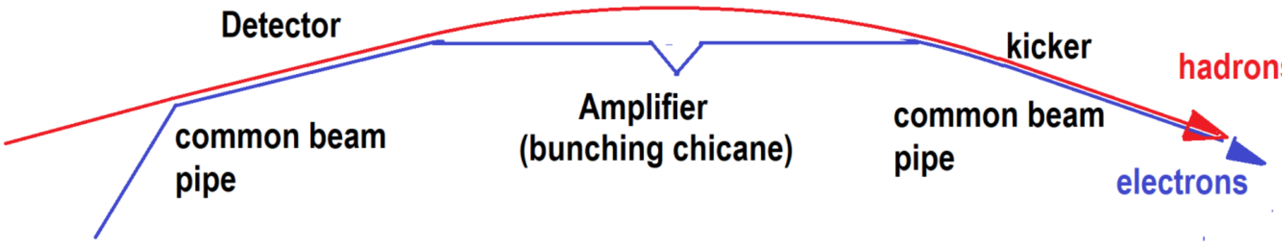
- High bandwidth (small slice size)
- Detector, amplifiers and kickers



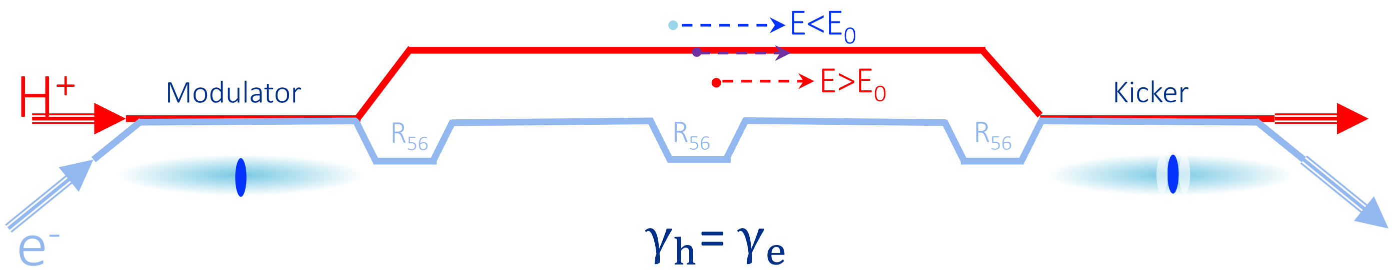
For high energy protons, the required bandwidth is much larger than possible with micro-wave cables, amplifiers and kickers

➔ 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

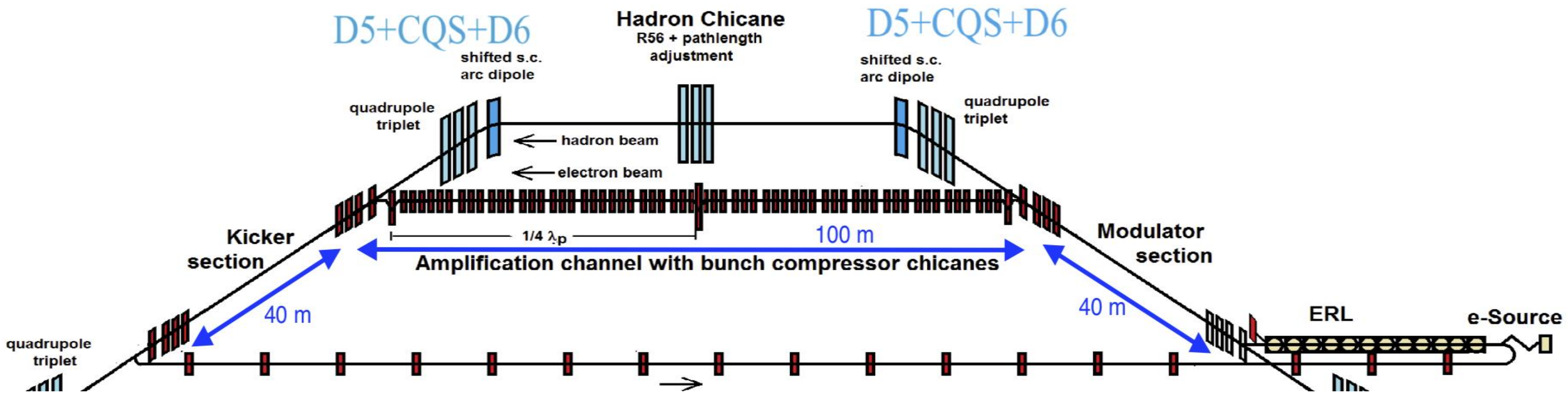
Hadron chicane: Controls hadron travel time with respect to electron path. Transfer to **correlated energy modulation**.

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

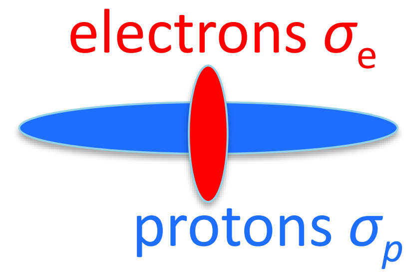


- 400 kV DC gun for 100 mA of beam and 4 MeV SRF injector
- Dogleg ERL merger
- 149 MeV Super conducting Energy Recovery LINAC (in existing tunnel)
- e Beam transport to merge hadron beam
- Amplification section with chicanes for electrons
- Hadron chicane (existing magnets) path length matching & R_{56} 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: $BW \sim \frac{\gamma c}{a} \approx 100\ \text{THz}$ (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:

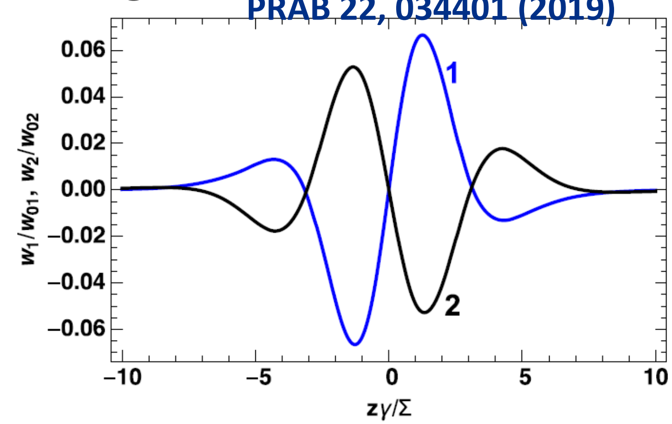
$$\tau_{\min} \sim \frac{N_p}{BW}\frac{C}{\sigma_p}\frac{\sigma_p}{\sigma_e}N_\sigma^2 \sim N_\sigma^2 \times 4.5\ \text{min}$$



- 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)

Ring-Based Electron Cooling System for the EIC

- Our concept offers an alternative 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

Hadron beam cooling (two basic methods)

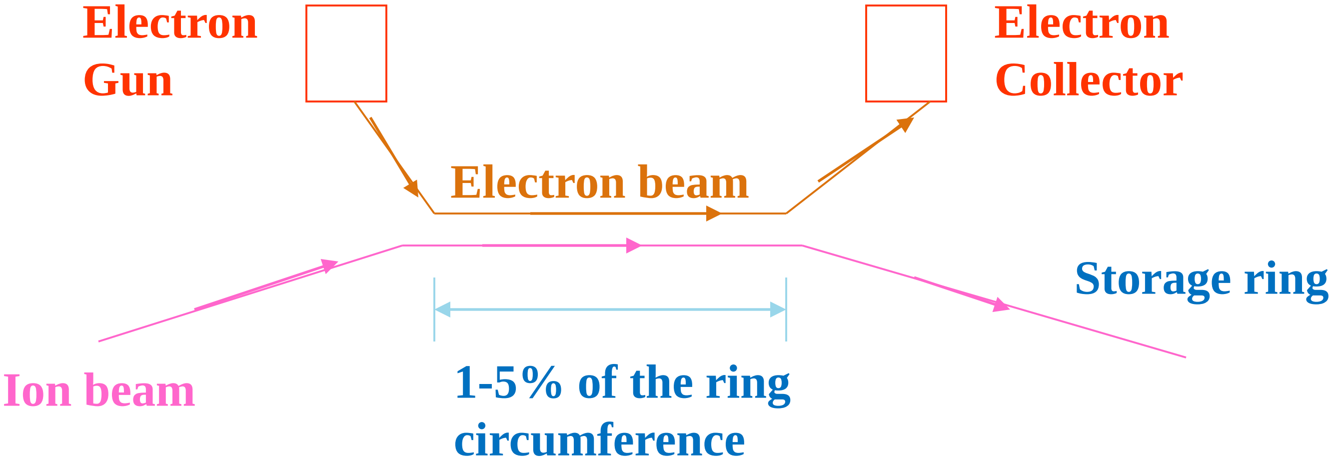
Second method

- 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)

How does electron cooling work?

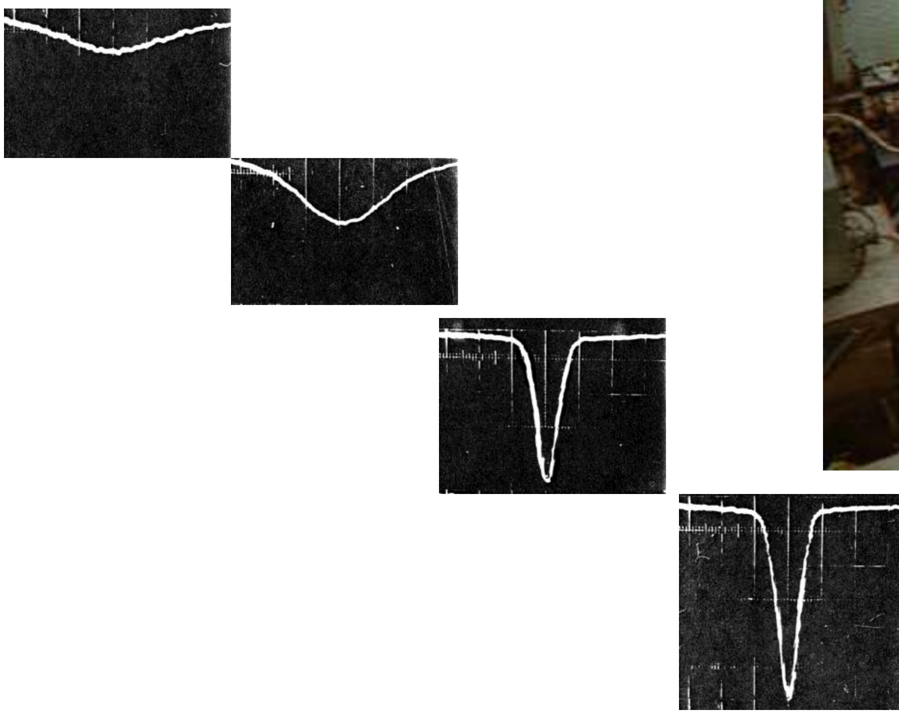
The velocity of the electrons is made equal to the average velocity of the ions.

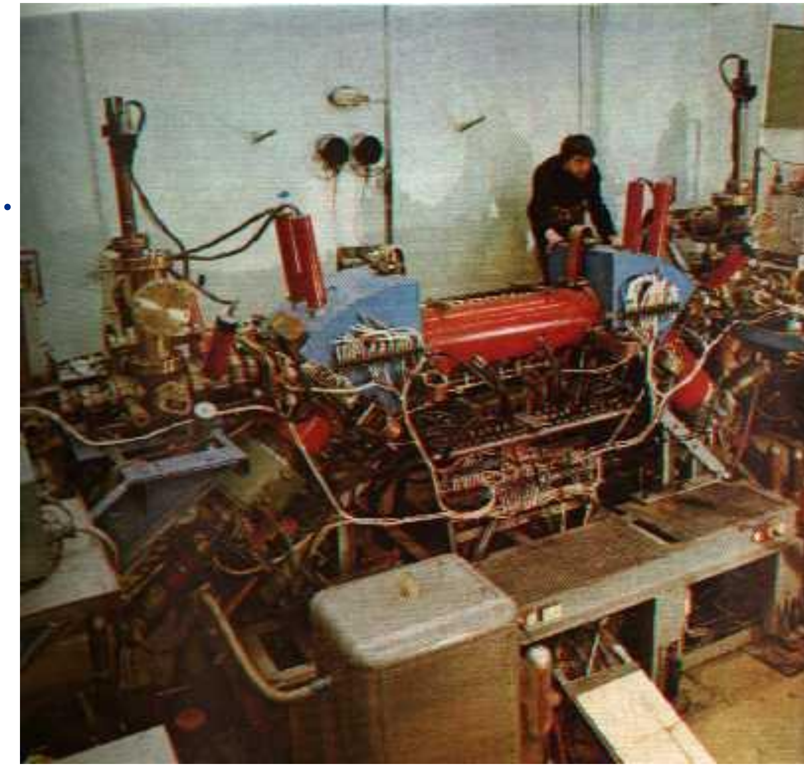
The ions undergo Coulomb scattering in the electron "gas" and lose (or gain) energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.



First Cooling Demonstration

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



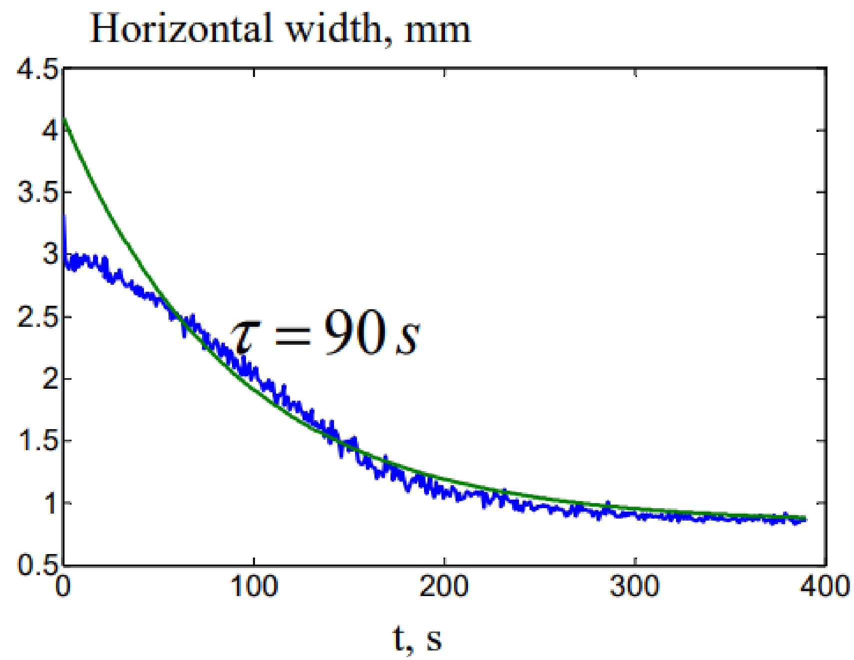


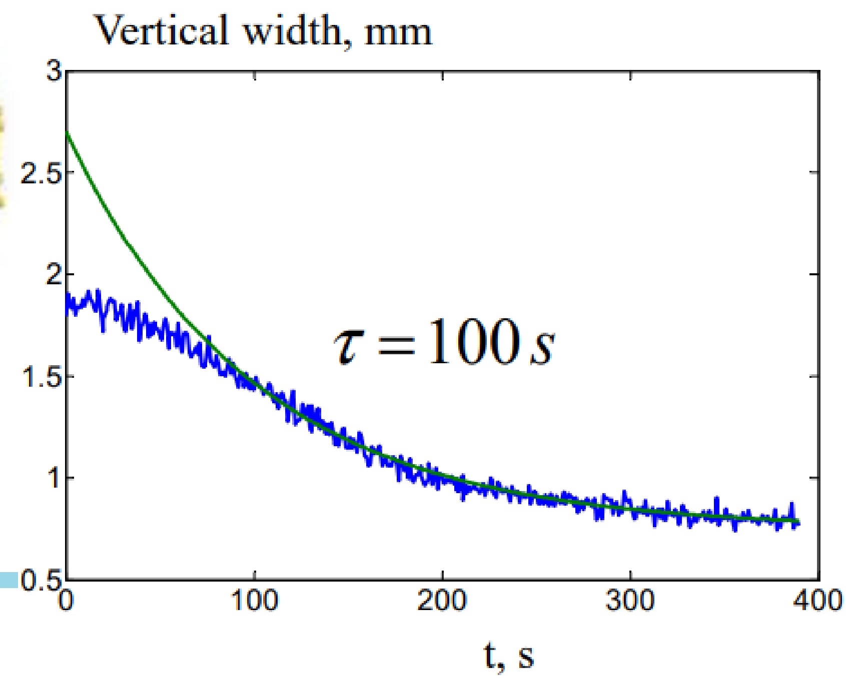
Fermilab

2 MeV electron cooler

COSY 2013

JÜLICH
FORSCHUNGSZENTRUM



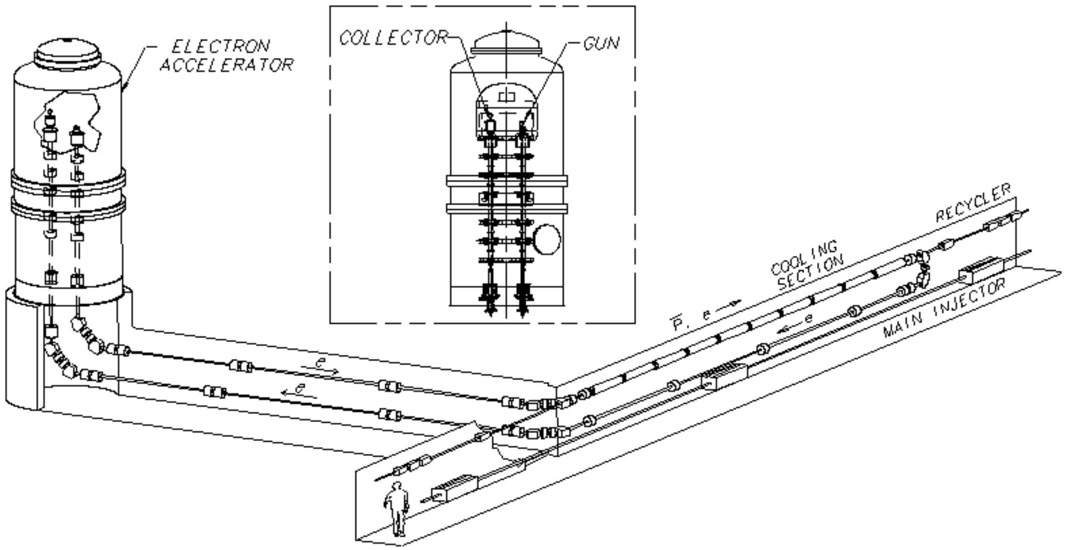


Cooling of 4 GeV protons

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

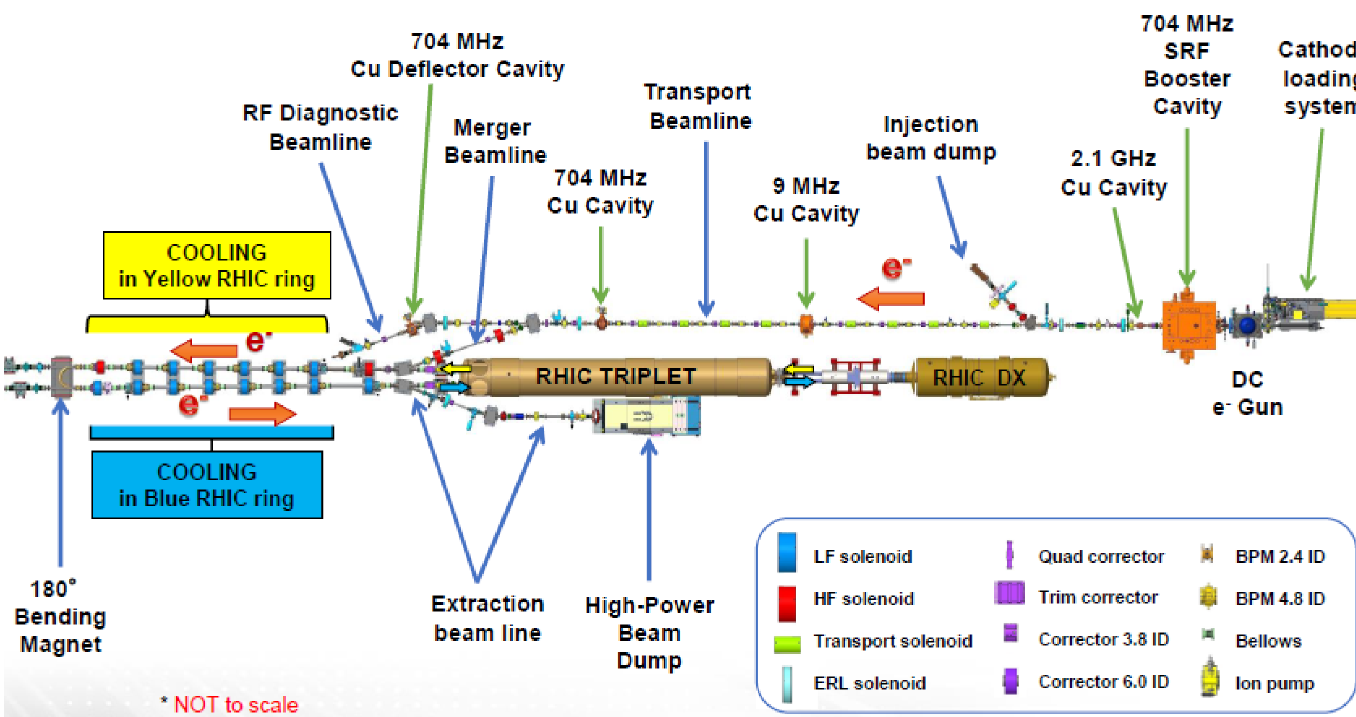
S. Nagaitsev, et al. "Experimental Demonstration of Relativistic Electron Cooling", Phys. Rev. Lett. 96, 044801 (2006)

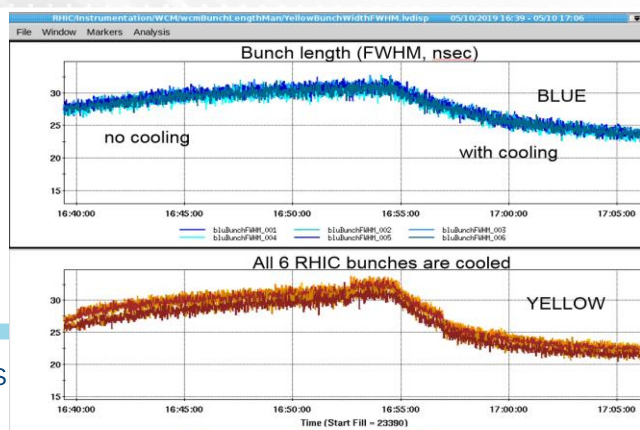
S. Nagaitsev, L. Prost and A. Shemyakin, "Fermilab 4.3-MeV electron cooler," 2015 JINST 10 T01001.

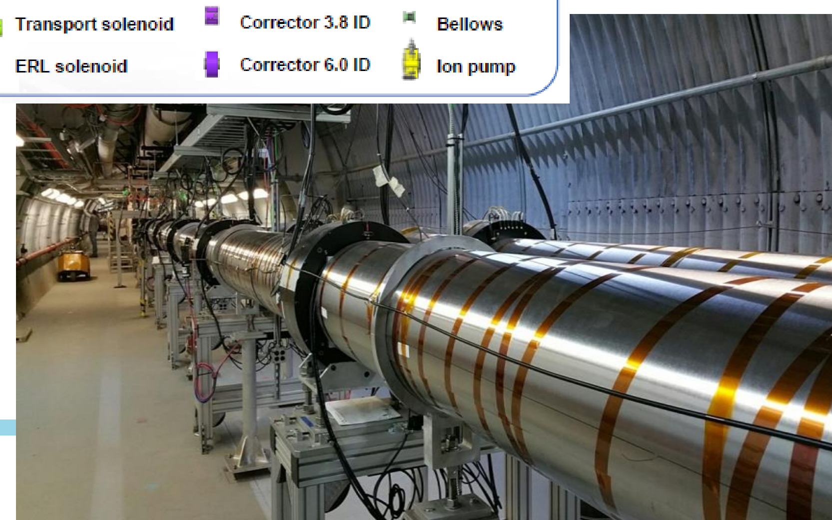
Low-Energy RHIC electron Cooler (LEReC) at BNL:

LEReC Accelerator

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



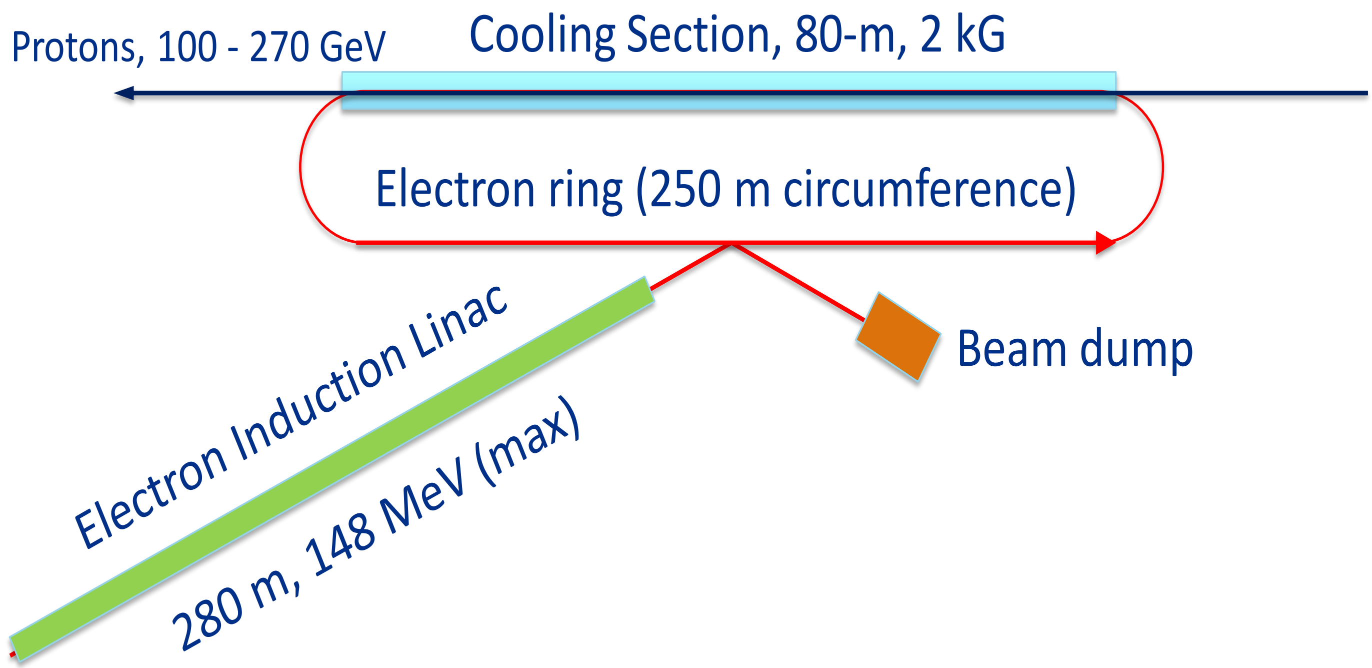




EIC electron cooling concept

- 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

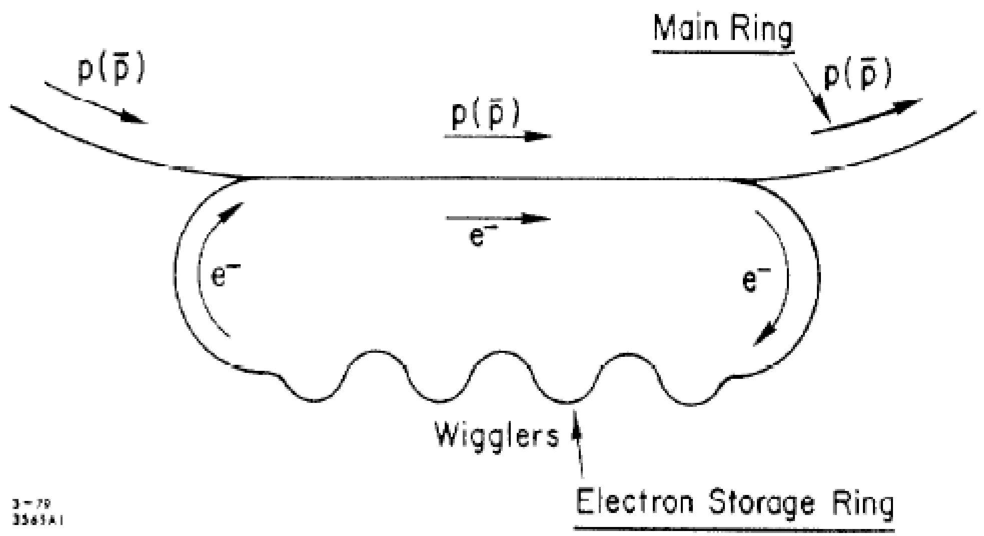


- We are considering a range of electron beam and linac parameters:
  - beam current 50-100 A
  - Rep rate: 100 – 200 Hz (~10,000 turns storage time)
- Pulse length: ~700 ns (to fill the ring)
- Beam power to dump: < 400 kW
- Beam power, lost in the ring < 2 kW (Touschek & extraction)

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]

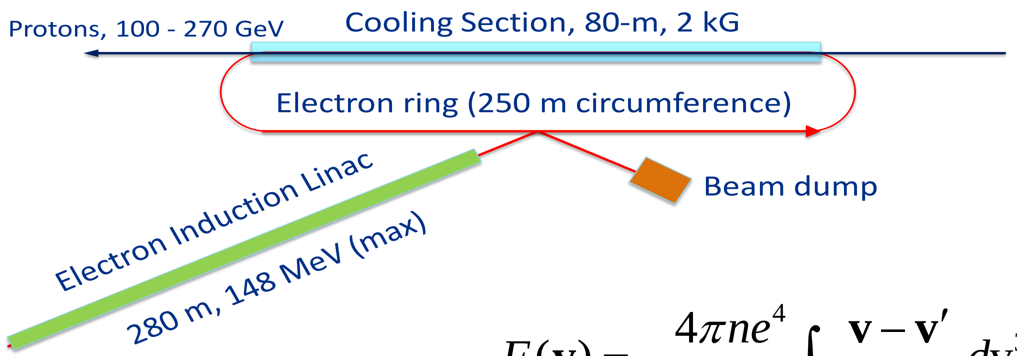


In this scheme, the electron beam is “cooled” via synchrotron radiation damping, while cooling colliding proton beams.

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

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)



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

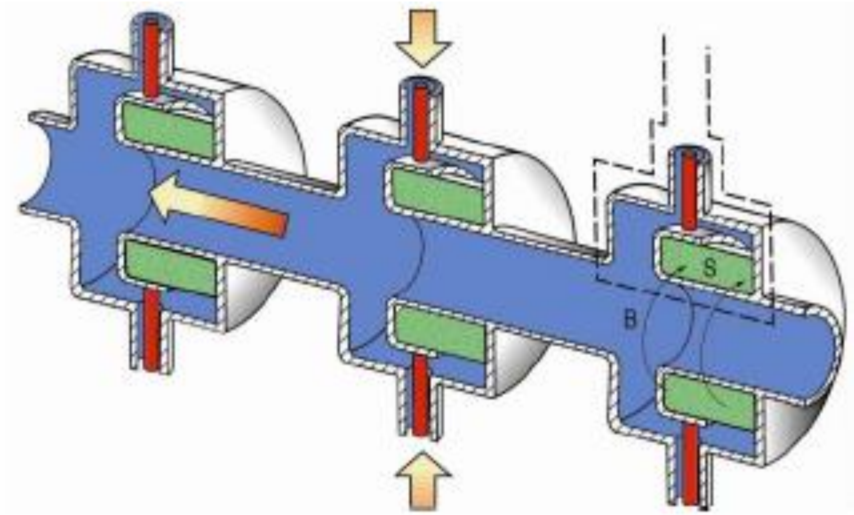
  - Weakly-magnetized cooling

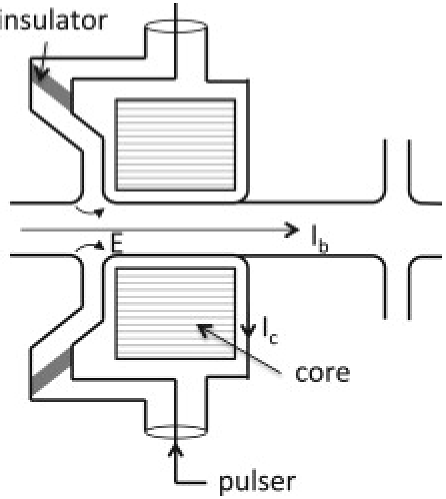
    is preferred due to large temperature in proton beam
    - Magnetization helps only for small amplitude particles – not good!!!

Fermilab

Induction linac

DARHT at LANL

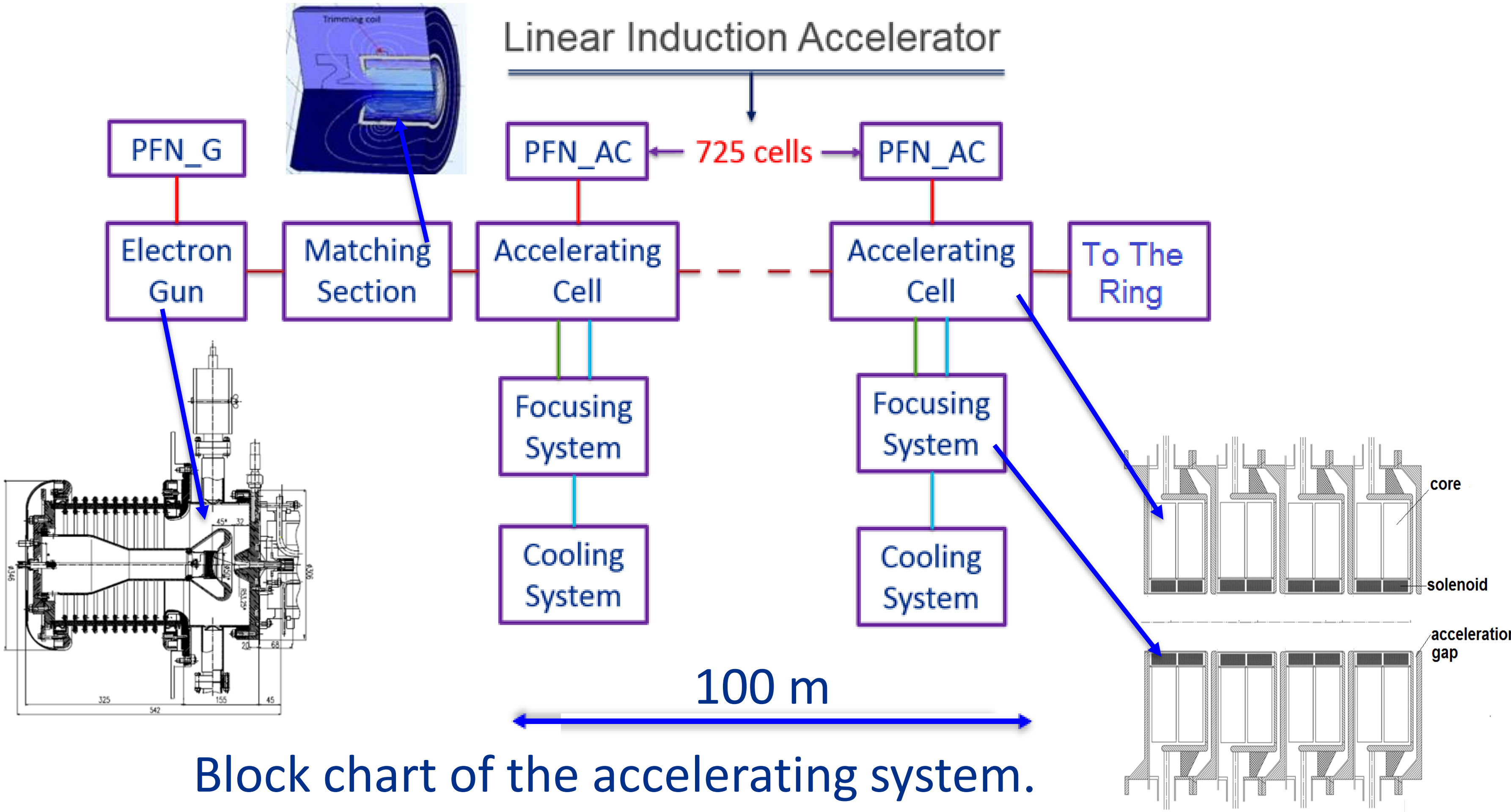




Injector Voltage	2.5 MV
Injector Current	2.0 kilo-Amperes
Injector Pulse Length	1.6 micro-seconds
Number of Injector Cells	6 @ 175 kV/cell
Number of Accelerator Cells	68 @ 200-235 kV/cell
Total Beam Energy	17.1 MeV (goal 18.1 MeV)

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

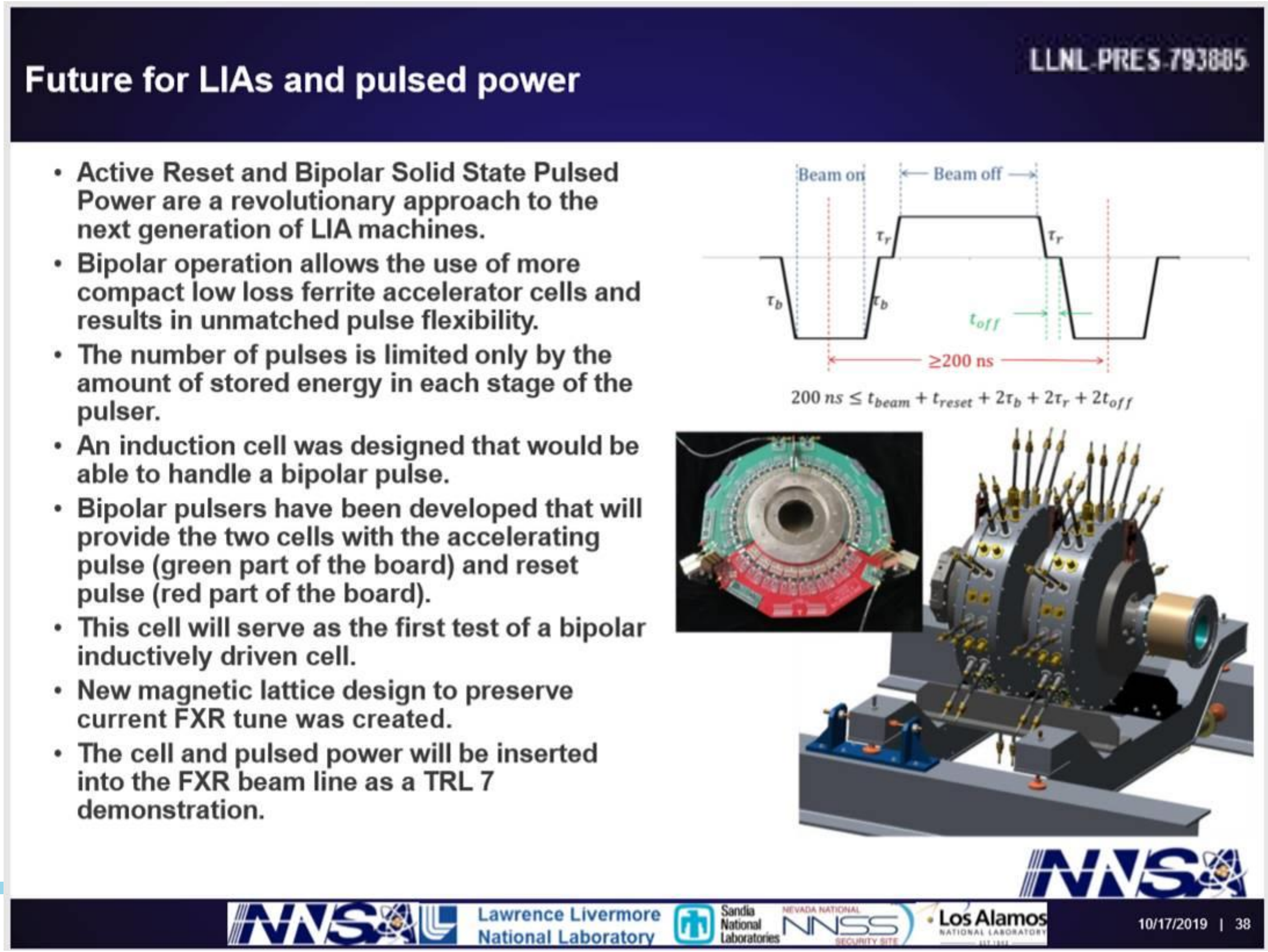
Induction Linac for Electron Cooling (55 MeV concept)



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



Parameter choices

- Small ⊥ temperature of e-beam is not required
  - thermionic cathode with moderate current density + large compression in the gun to create small e-beam size in the cooling section
  - Longitudinal magnetic field to keep constant e-beam size in the cooler (beam focusing => ⊥ beam stability)
    - Magnetic field at the cathode to compensate rotation appearing at the solenoid entrance
- DC beam to avoid problems with wakes and CSR in the ring
  - Pulses electron gun (< 1 μs) and induction linac
  - Beam current in the ring is limited to ~100 A by IBS and instabilities
- For 100 A beam the instabilities are a serious issue
  - The beam is stabilized by wide band dampers (~200 MHz) in each of 3 planes
  - No RF to minimize the ring impedances
  - No abort gap; Beam loss at extraction (however at acceptable level)

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

Electron gun: 300 kV, 50-100 A, pulsed 200 Hz, 1 us

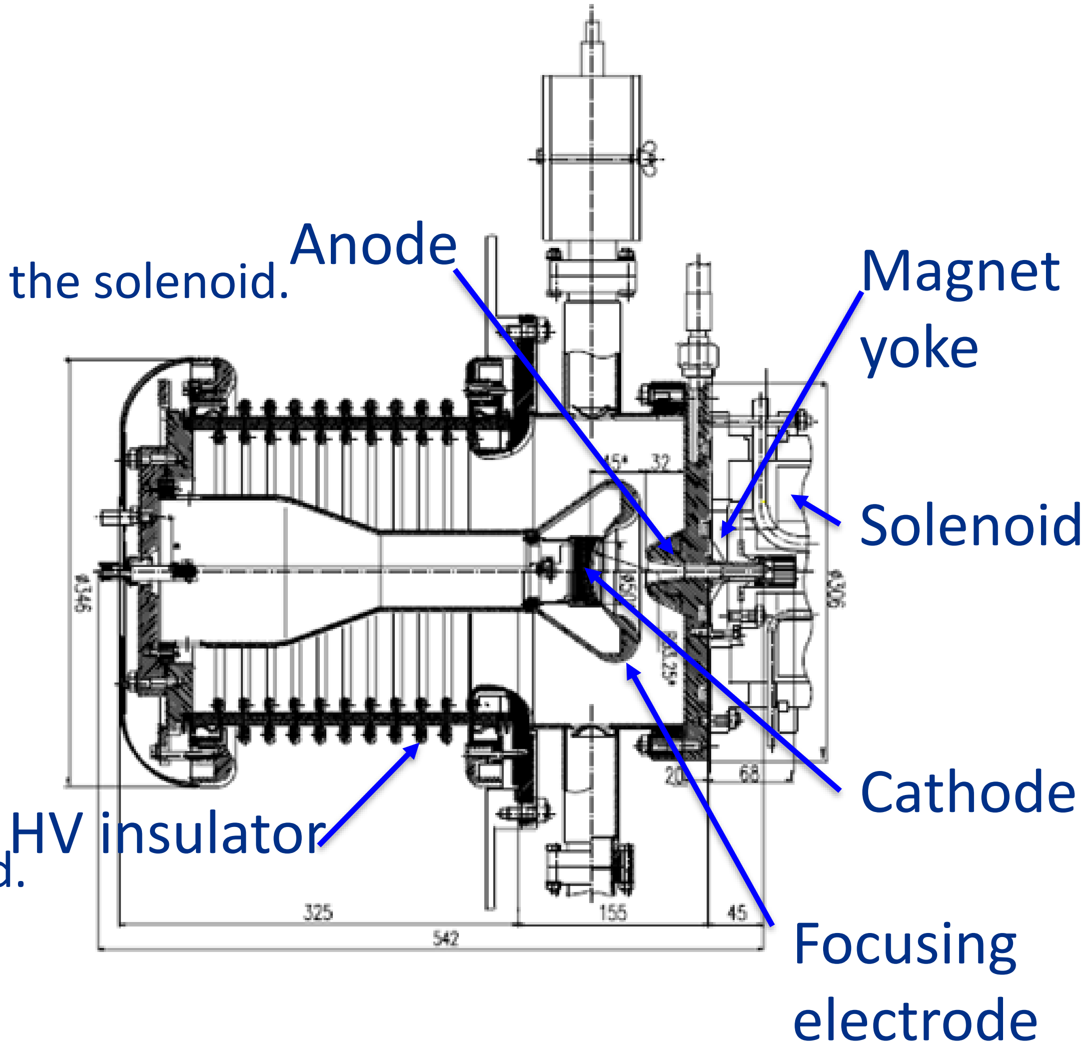
❑ Gun concept:

- Low – aberration electron gun;
- Magnetic yoke for matching with the solenoid.

❑ Example:

Electron gun for 34 GHz magnicon*

- Beam voltage: 500 kV;
- Beam current: 200 A;
- Beam transverse area compression: 3000:1 (low emittance is essential)
- Constructed, tested and operated.



* V.P. Yakovlev, O.N. Nezhevenko, *et al*, PAC2001

Electron gun: main ideas

- Large beam compression in electron gun
- Rms normalized emittance is set by the cathode temperature (0.11 eV) and its radius (1.25 cm)

$$\varepsilon_n = \frac{r_c}{2}\sqrt{\frac{T_c}{m_e c^2}} \approx 3\,\mu\text{m}$$

- Magnetic field at the cathode (~ 12 G) is chosen to match magnetic flux coming through beam cross-section

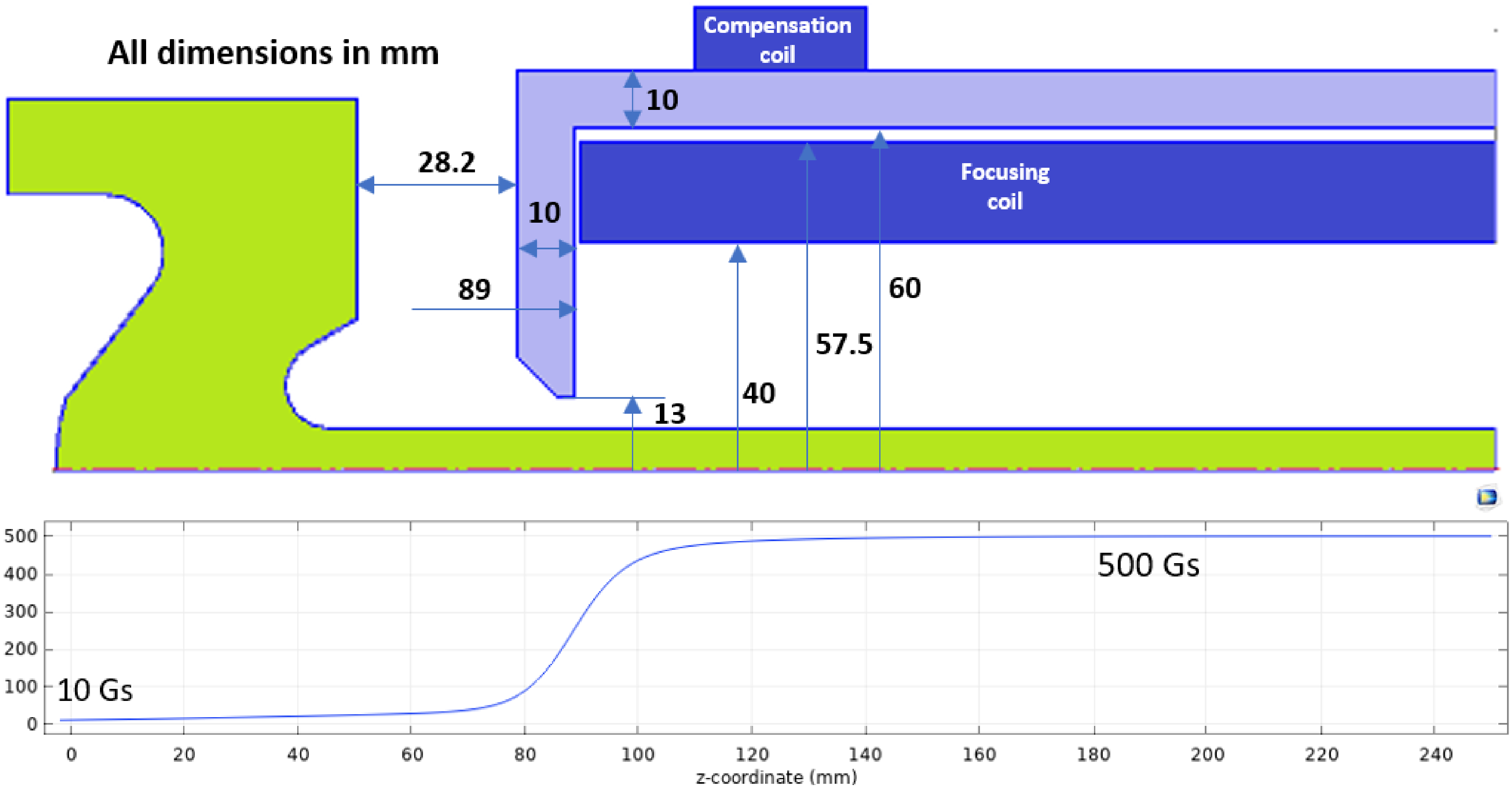
$$r_{cath}{}^2 B_{cath} = r_{cs}{}^2 B_{cs}$$

- Magnetic field makes 2 emittances of normal modes different

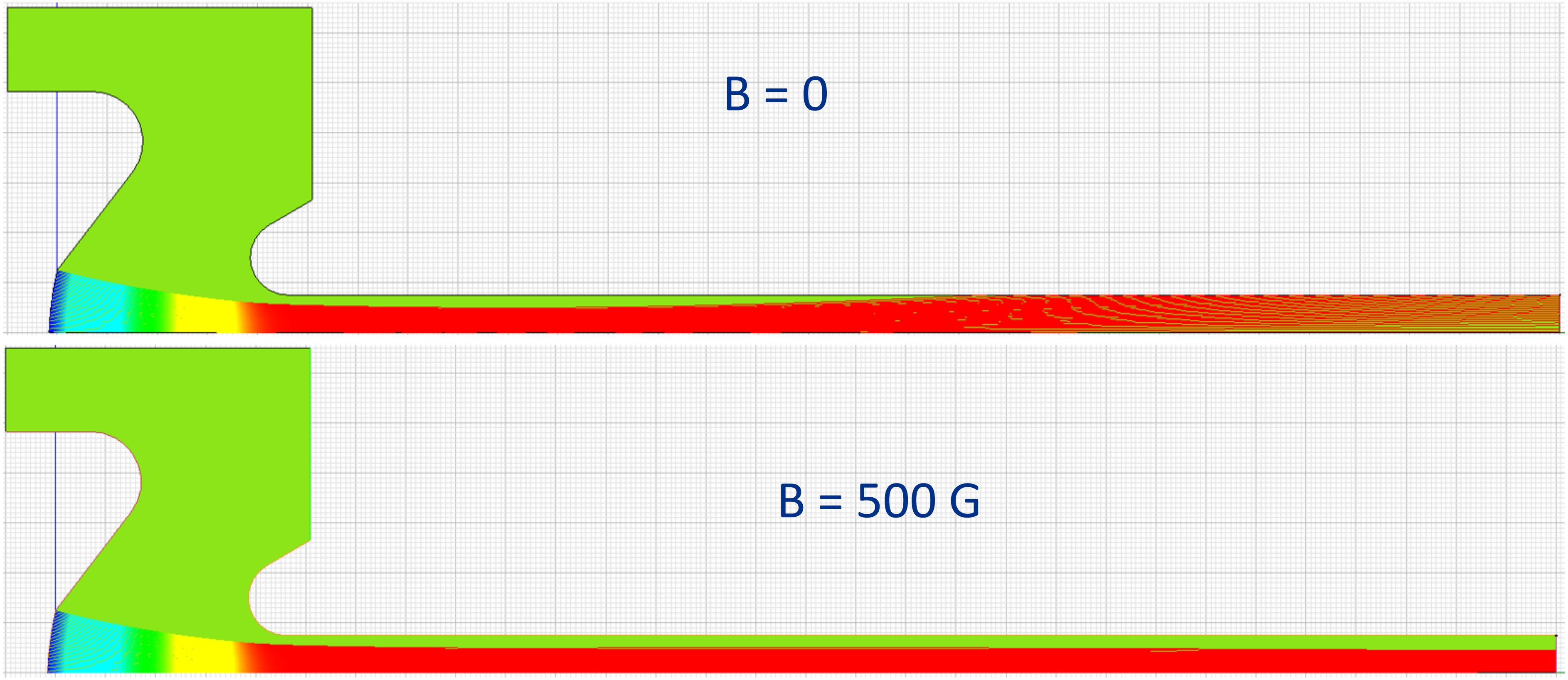
$$\varepsilon_{1n,2n} = \frac{\varepsilon_n}{\sqrt{1+\Phi^2\beta_0{}^2} \pm \Phi\beta_0}, \quad \Phi = \frac{eB_{cs}}{2\gamma\beta m_e c^2}, \quad \beta_0 = \frac{r_{cs}{}^2}{\varepsilon_n / \beta\gamma}$$

  - Mode 1 with larger emittance determines the rms beam size
  - Mode 2 with smaller emittance determines the angular spread

Gun and solenoid matching schematic



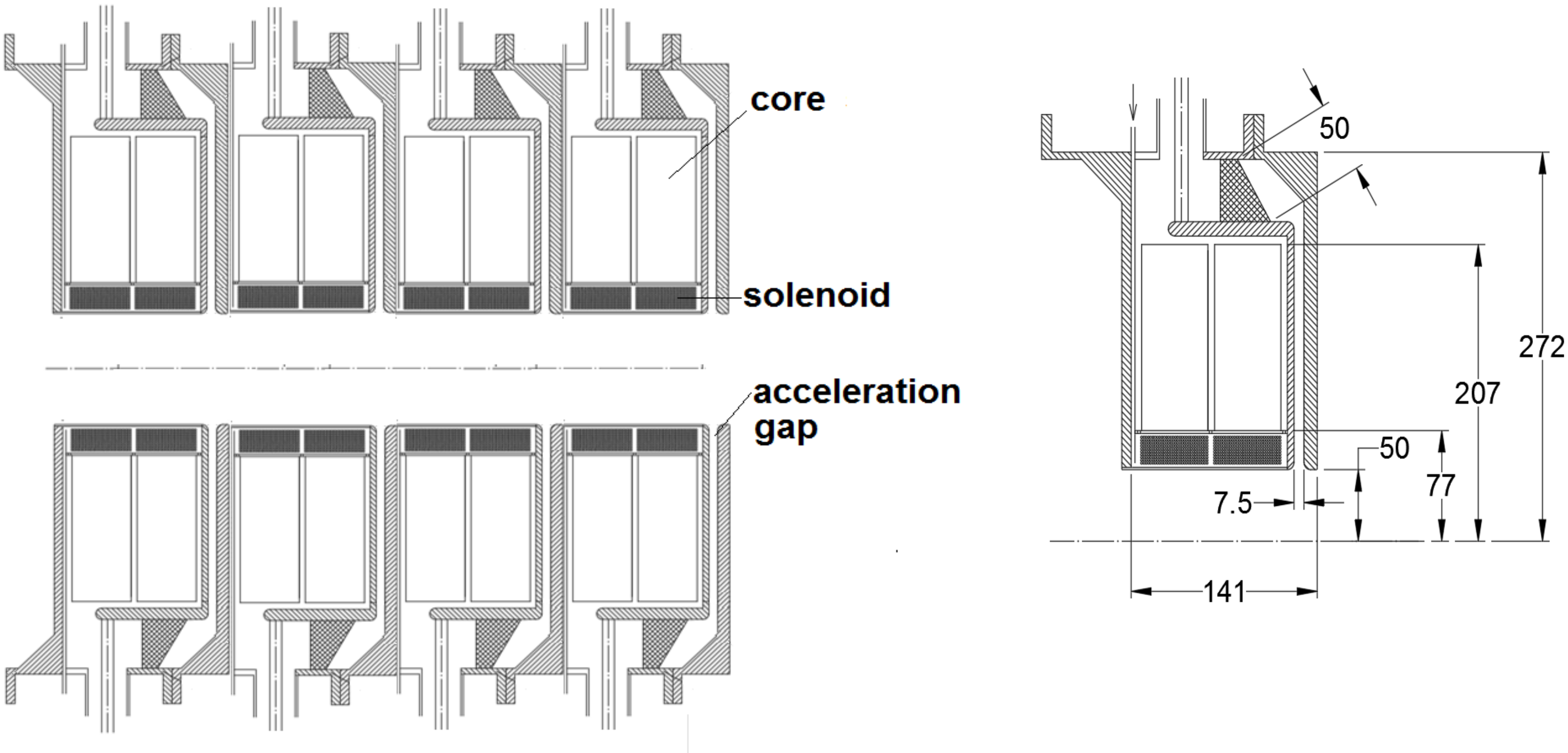
Beam propagation without (top) and with (bottom) magnetic field



No emittance growth observed at 300 keV (no induction linac)

Induction Linac for Electron Cooling

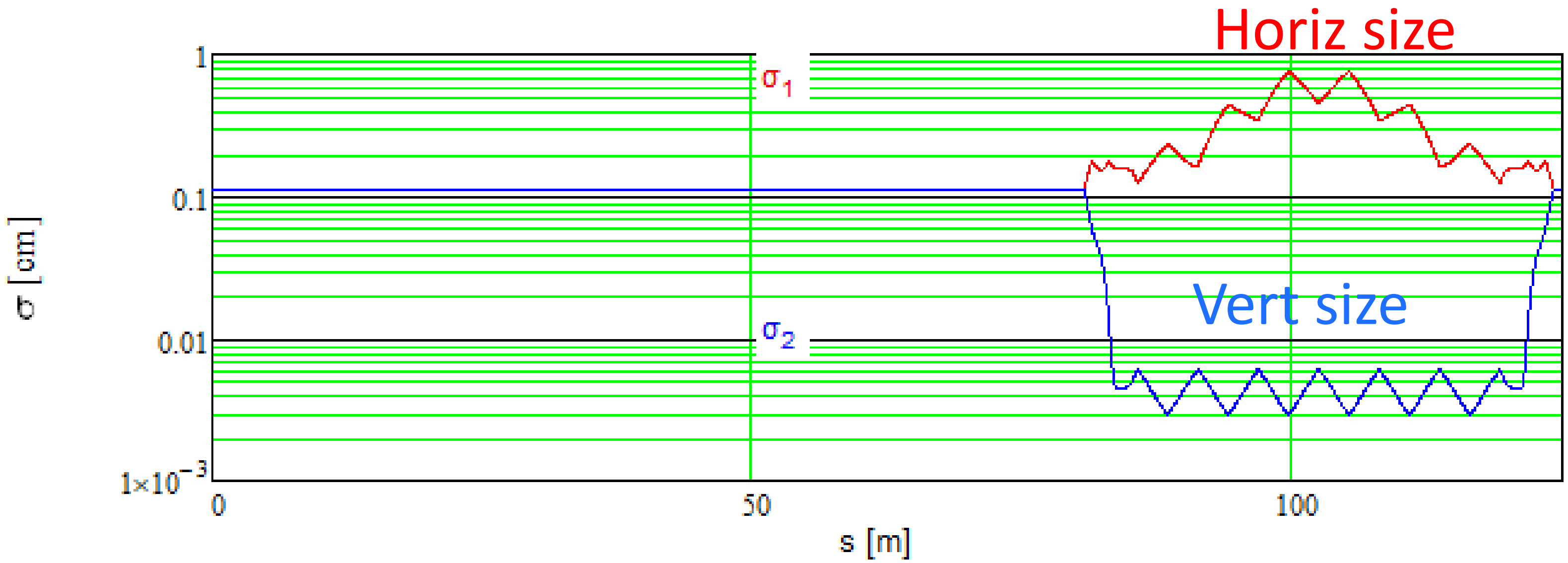
- Linac concept:



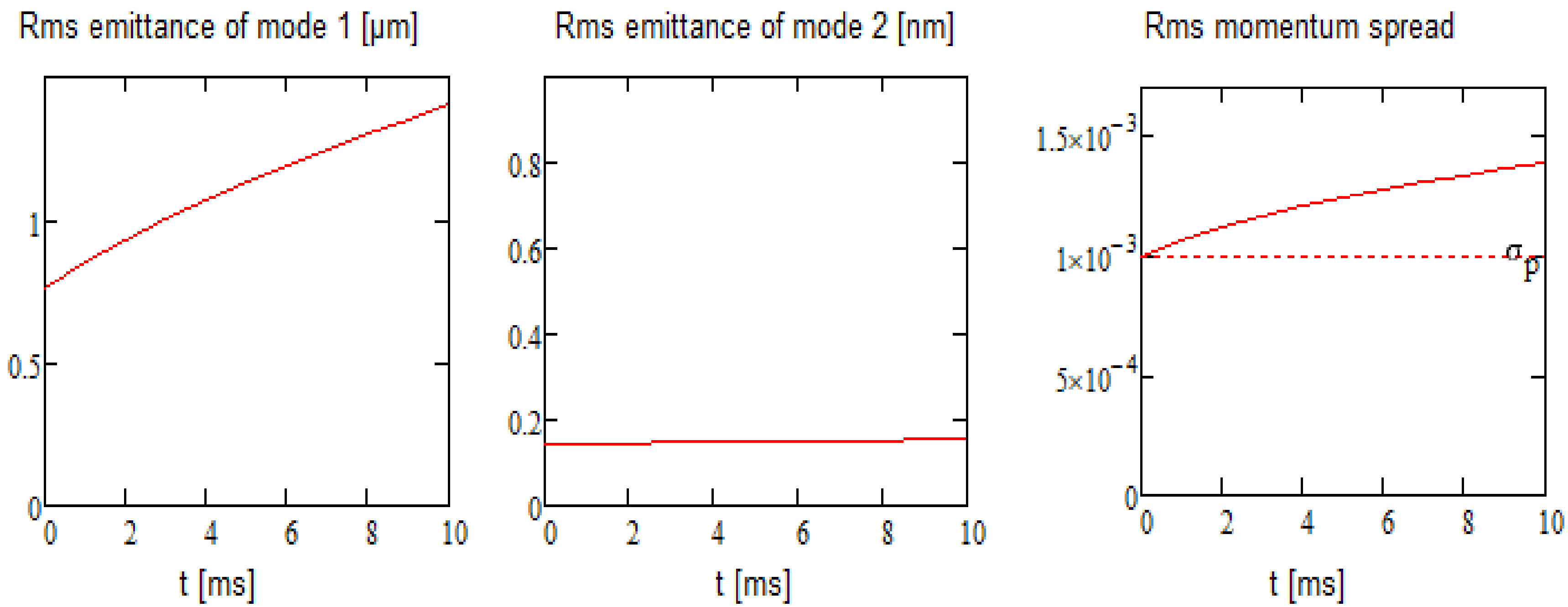
- 75 keV energy gain per cell
- Each cell contains two cores, two focusing solenoids and an acceleration gap.

Cooler ring: main ideas

- Use of Derbenev's round-to-flat adaptors in arks to reduce IBS heating
  - Large horizontal beam size in arks
  - Ya. Derbenev, "Adapting Optics for High Energy Electron Cooling", Univ. of Michigan, UM-HE-98-04, Feb. 1998
  - Tested at Fermilab A0 photoinjector (emit ratio ~ 100)
- Use a ~ 1 kG solenoidal field in the cooling section
  - Round electron beam matches ~3 sigma proton beam size



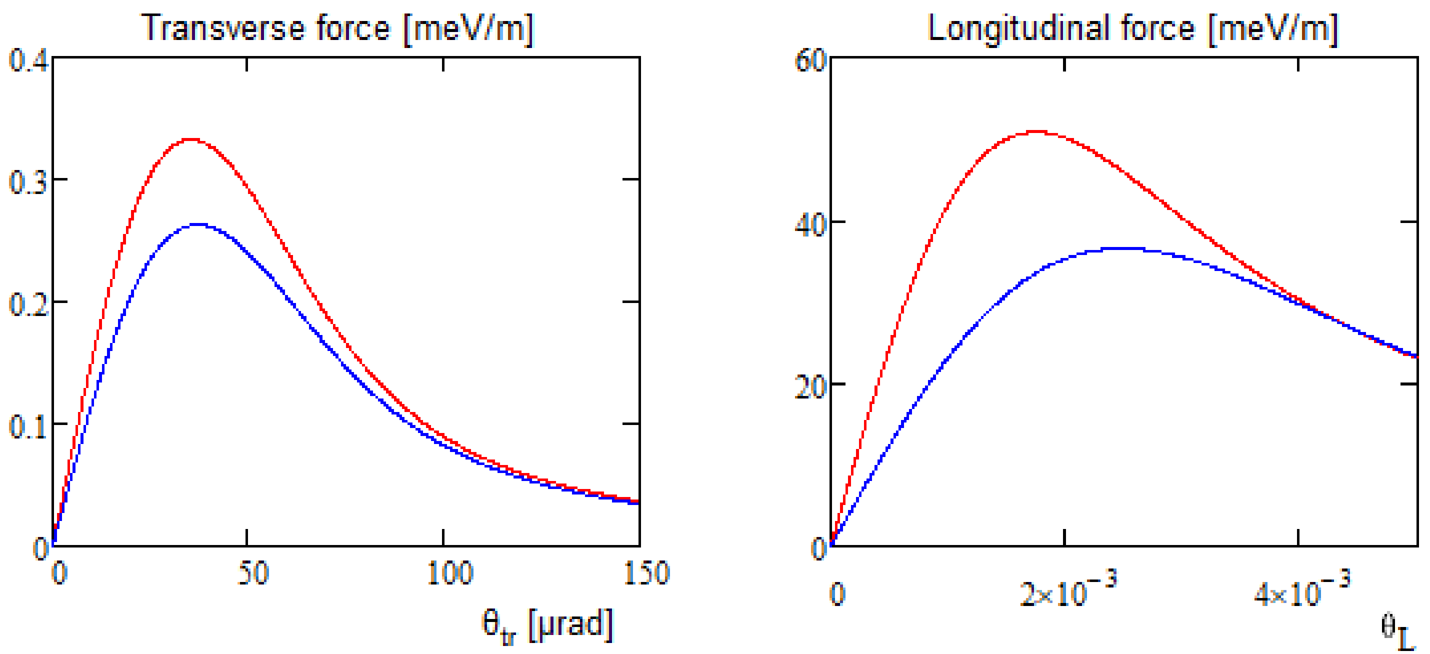
Electron beam heating is due to its own IBS



Dependencies of rms non-normalized mode emittances and the momentum spread on time for a 100-A, 147 MeV electron beam due to intra-beam scattering.

– Re-inject fresh electron beam every 5-10 ms.

Cooling force



Dependencies of transverse (left) and longitudinal (right) cooling forces at the cooling cycle beginning (red curve, 0 ms) and at the cooling cycle end (blue curve, 5 ms).

$$F_{\parallel}(\mathrm{v}_z) = \frac{4\pi n_e' e^4 L_c}{m_e}\left(\frac{4\mathrm{v}_z}{\sqrt{\pi}}\int_0^{\infty}\exp\left(-\frac{\mathrm{v}_z{}^2 t^2}{1+2\sigma_{\mathrm{vz}}{}^2 t^2}\right)\frac{t^2 dt}{\left(1+2\sigma_{\mathrm{v}\perp}{}^2 t^2\right)\left(1+2\sigma_{\mathrm{vz}}{}^2 t^2\right)^{3/2}}\right),$$

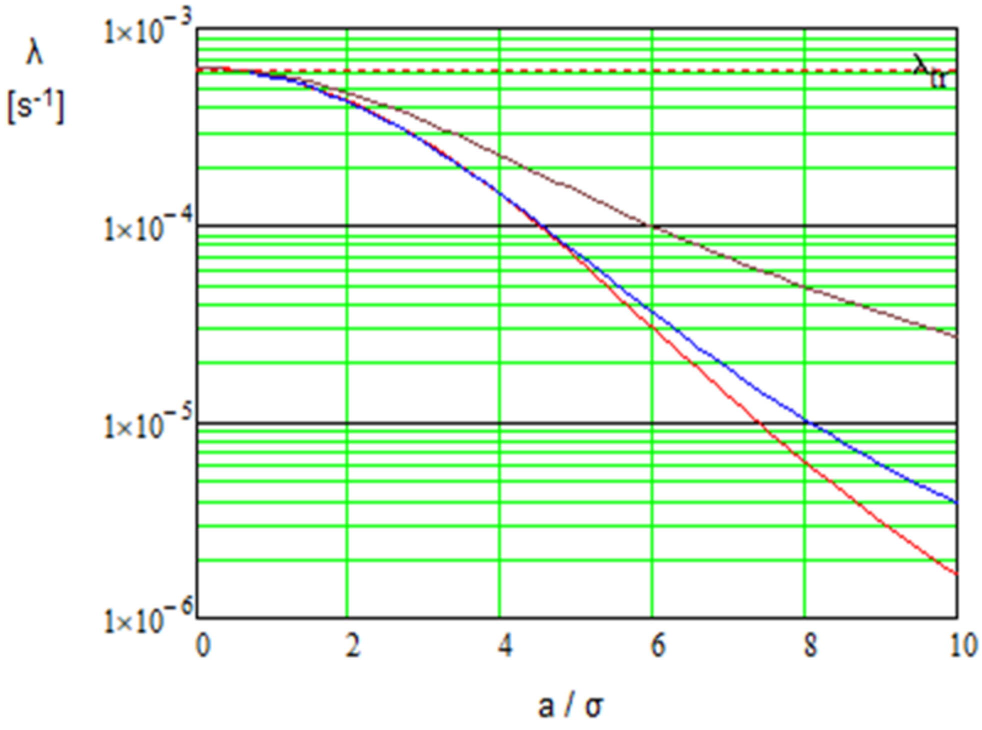
$$\mathbf{F}_{\perp}(\mathbf{v}_{\perp}) = \frac{4\pi n_e' e^4 L_c}{m_e}\left(\frac{4\mathbf{v}_{\perp}}{\sqrt{\pi}}\int_0^{\infty}\exp\left(-\frac{\mathrm{v}_{\perp}{}^2 t^2}{1+2\sigma_{\mathrm{v}\perp}{}^2 t^2}\right)\frac{t^2 dt}{\left(1+2\sigma_{\mathrm{v}\perp}{}^2 t^2\right)^2\sqrt{1+2\sigma_{\mathrm{vz}}{}^2 t^2}}\right),$$

Fermilab

Emittance cooling times for 270-GeV protons

Instantaneous rms emittance cooling time for 270-GeV protons as a function of cycle time.

Cooling range (how many sigmas?)



Example of cooling rates for various proton amplitudes

Summary

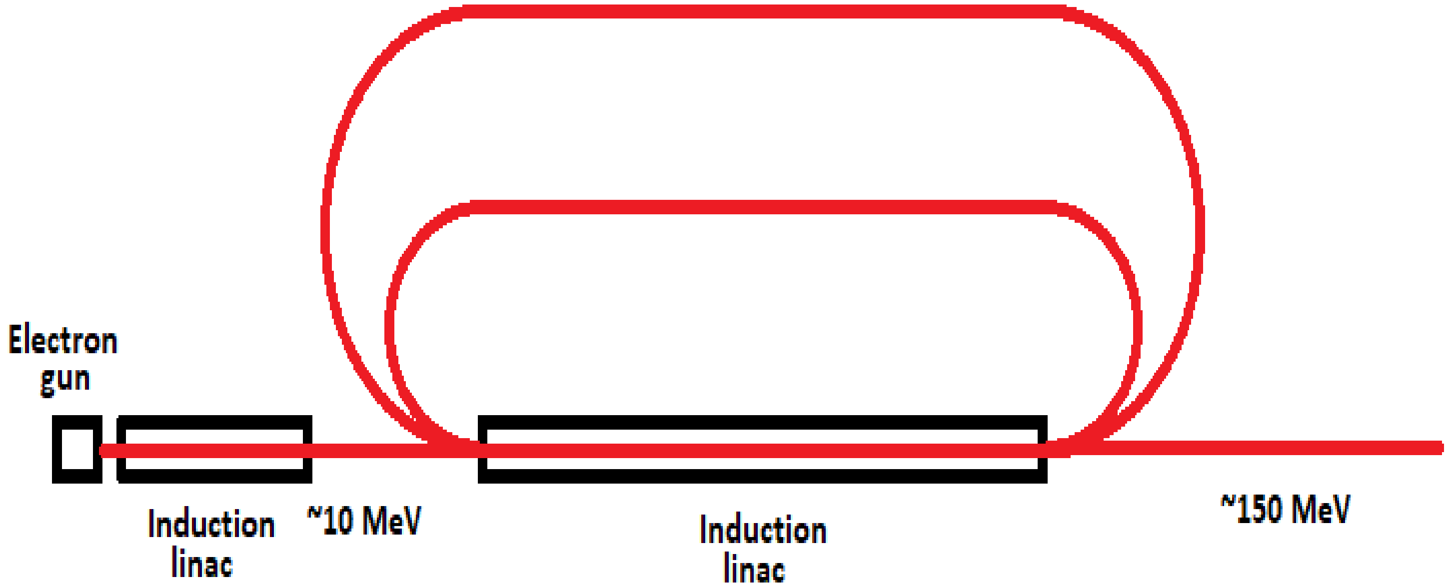
- The proposed concept meets the project requirements (1-2 hour cooling time for 100 – 270 GeV protons)
  - No show-stoppers so far
- Conventional induction linac and ring technology but with several new ideas:
  - Magnetized e-gun and linac transport, round-to-flat beam transformation in ring arks
- Several advantages, compared to ERL’s
  - No issues with wakes for a DC beam; no issues for variable proton bunch patterns/frequencies
- Conceptual design report published:
  - https://arxiv.org/abs/2010.00689
- Detailed IBS model with full coupling (4D)
    - arXiv:1812.09275

Remaining R&D topics

- Preservation of a large emittance ratio ($\varepsilon_1/\varepsilon_2$ ~ 5,000) for 10,000 turns
- Transverse electron beam heating due to electron beam space charge;
- Longitudinal electron beam instability driven by coherent synchrotron radiation;
- Multi-turn induction linac acceleration concept.

- We would like to finish these studies as part of the EIC collaboration effort.

A multi-turn linac concept



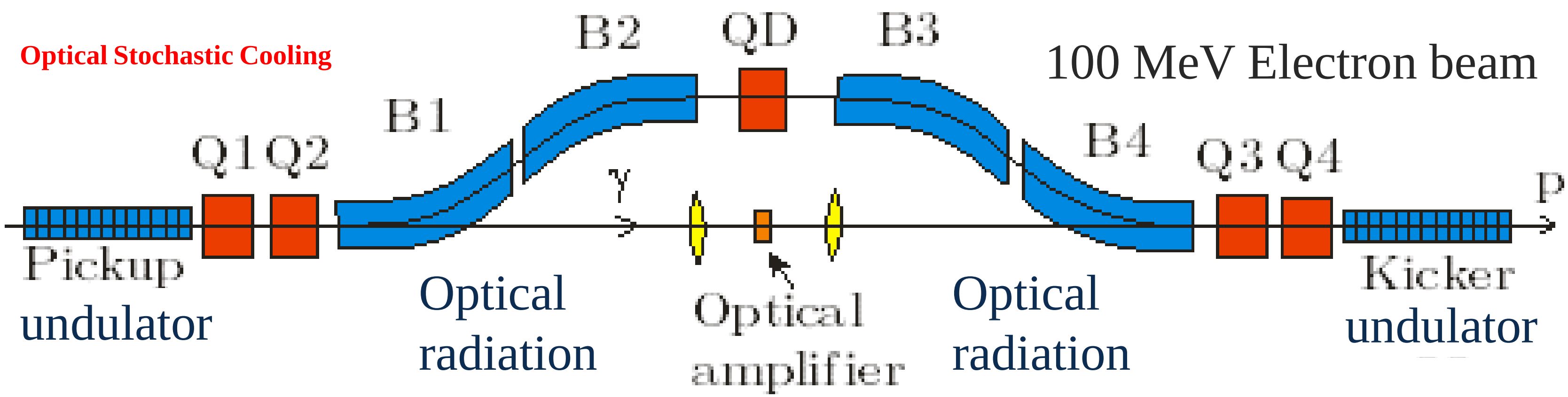
- Potentially, one can make the induction linac shorter by using a multi-turn scheme (requires R&D)

Thanks

- We are thankful to F. Willeke, A. Seryi for support and discussions.
- Several slides were copied from talks by E. Wang, A. Fedotov, W. Fischer, A. Seryi

- Fermilab is very interested in being part of the EIC project in many areas of accelerator science and technology!

Optical stochastic cooling at IOTA (2020-21)



Team: J. Jarvis (ECA), V. Lebedev, et al. + CBB (Cornell)

OSC will test many aspects, needed for the EIC CeC concept:

1. Sub-µm alignment
2. Re-distribution of longitudinal cooling to 3D cooling