Ring-based high-energy electron cooler

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Ring-based high-energy electron cooler

DOE NP-funded R&D project (2018 – 2020)

PI: S. Nagaitsev

- The project goals (as proposed) are now achieved, but some R&D remains. We are looking for means to complete the R&D.

Conceptual design report posted:

Ring-Based Electron Cooling System for the EIC

arXiv:2010.00689

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

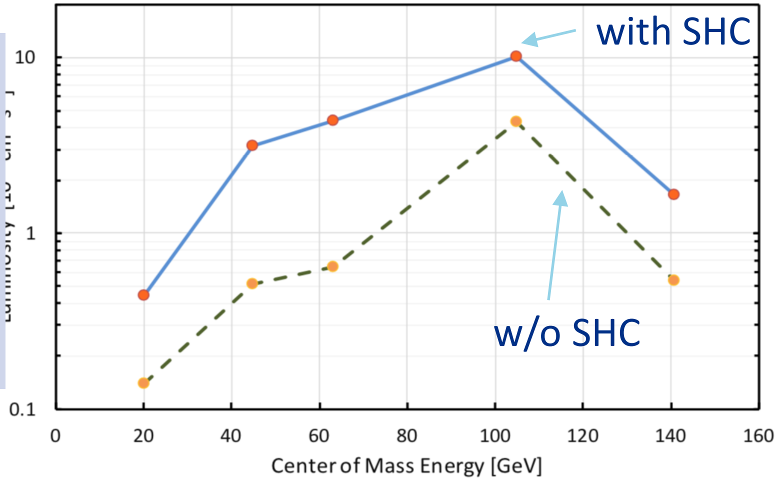
High Luminosity and Strong Hadron Cooling

- 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 **$L = 1\cdot10^{34} cm^{-2}s^{-1}$ 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

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

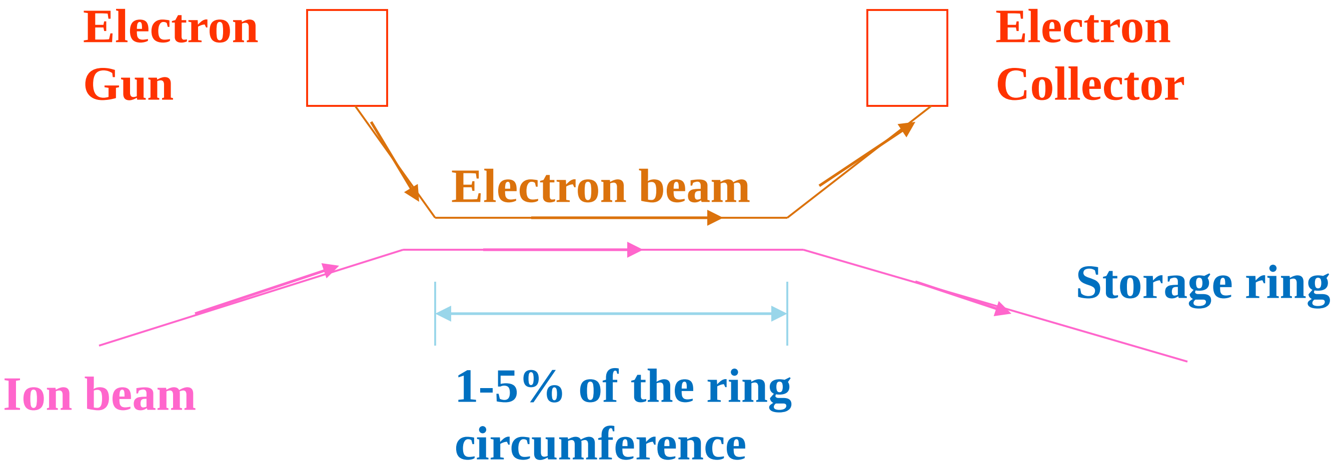
Hadron beam cooling

- <u>Electron cooling </u>– 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.

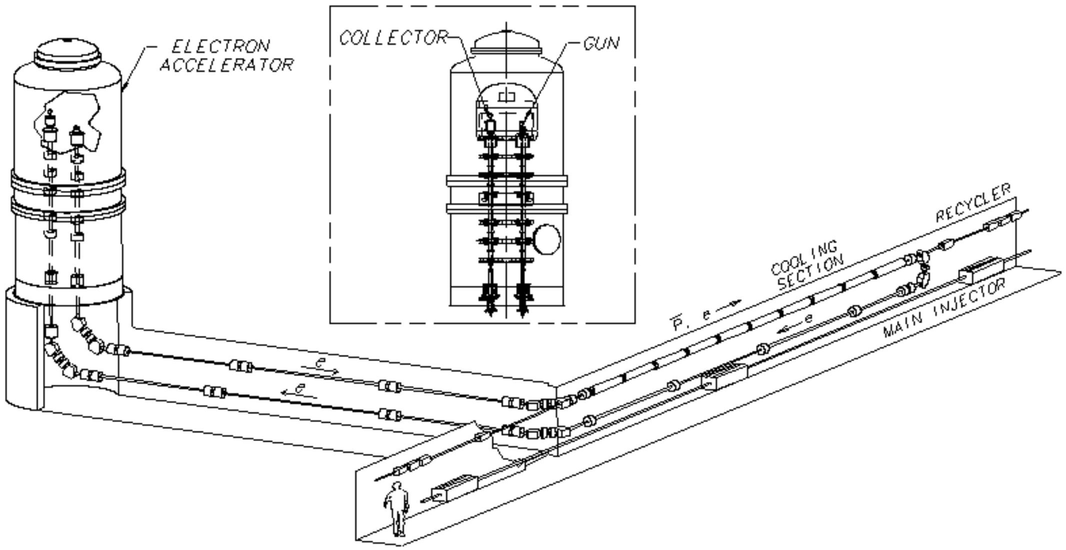
The ions undergo Coulomb scattering in the electron “gas” and lose (or gain) energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.



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

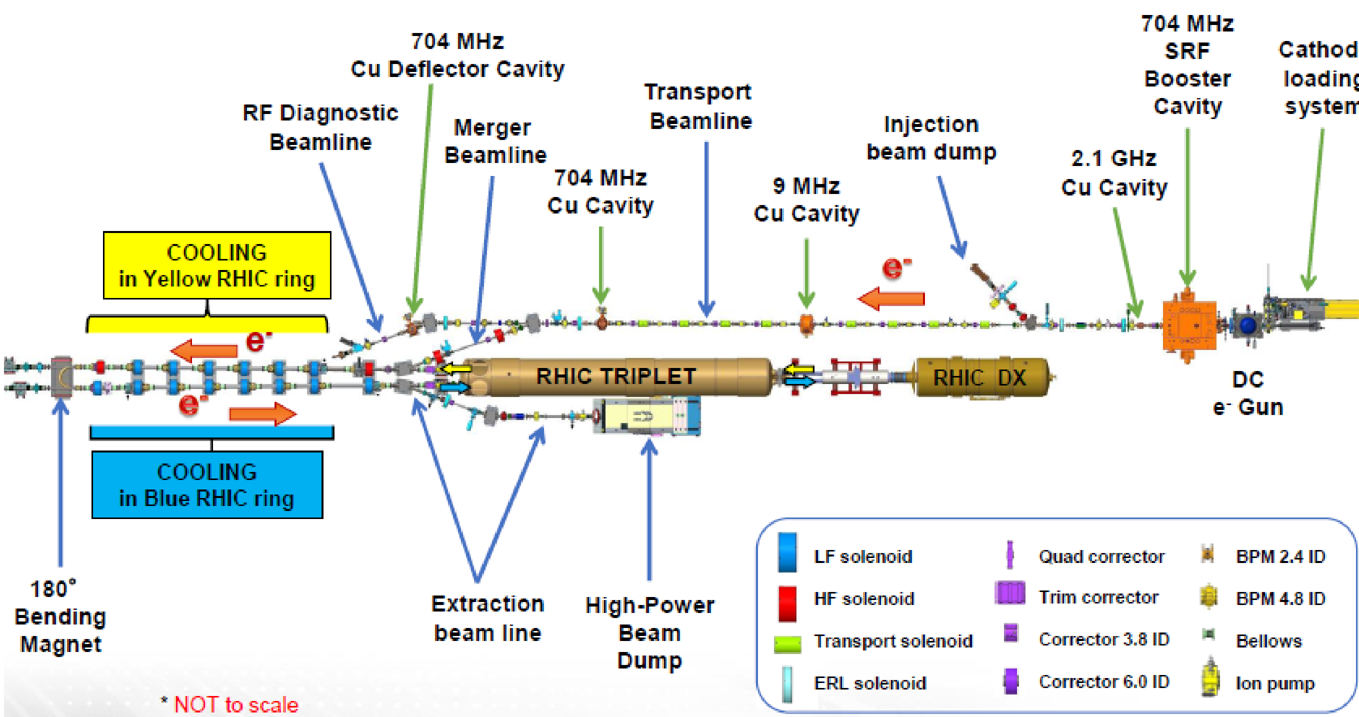
S. Nagaitsev, et al. "Experimental Demonstration of Relativistic Electron Cooling", Phys. Rev. Lett. 96, 044801 (2006)

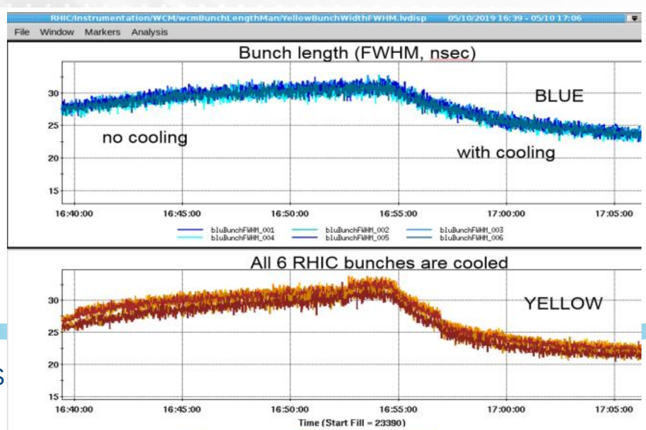
S. Nagaitsev, L. Prost and A. Shemyakin, "Fermilab 4.3-MeV electron cooler," 2015 JINST 10 T01001.

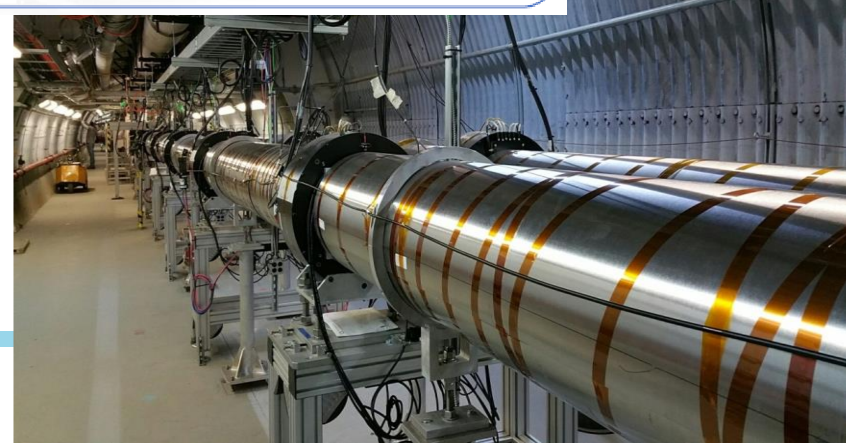
Low-Energy RHIC electron Cooler (LEReC) at BNL:

LEReC Accelerator

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



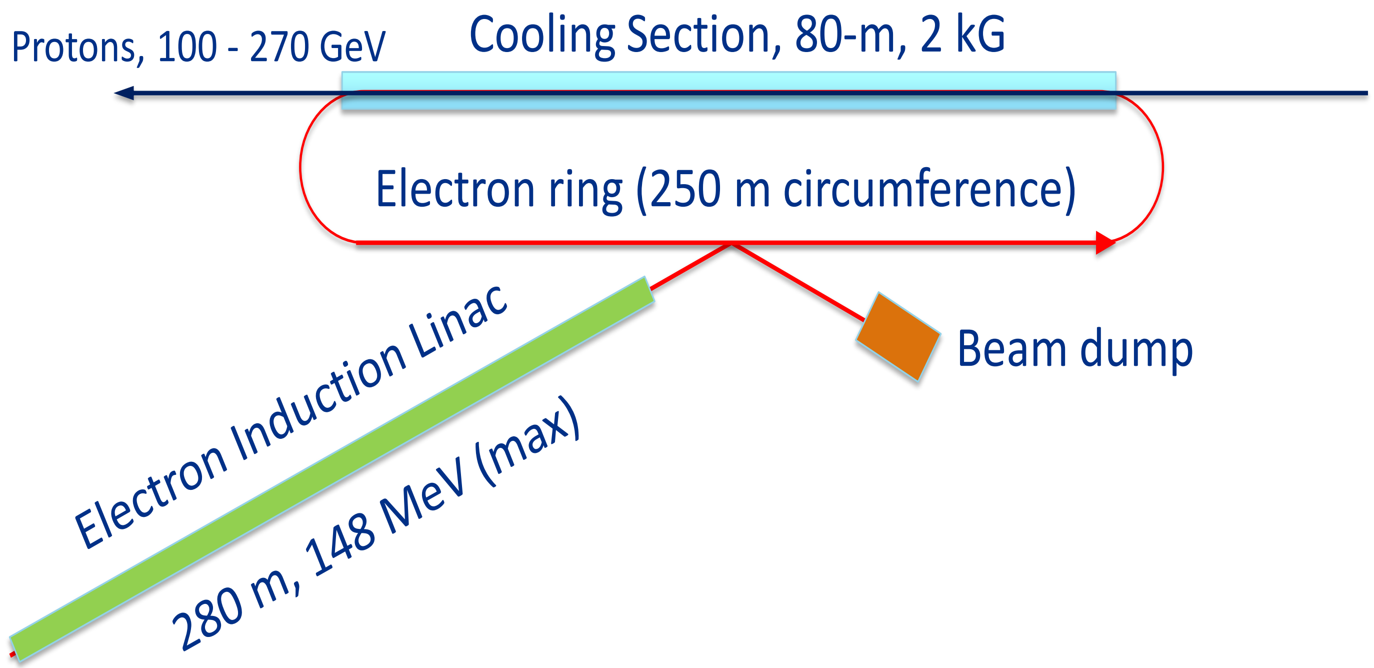




EIC electron cooling concept

- A well-known shortcoming of the electron cooling method is its unfavorable scaling of cooling time with energy (~γ^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 <u>1-2 hours</u>.

Proposed solution

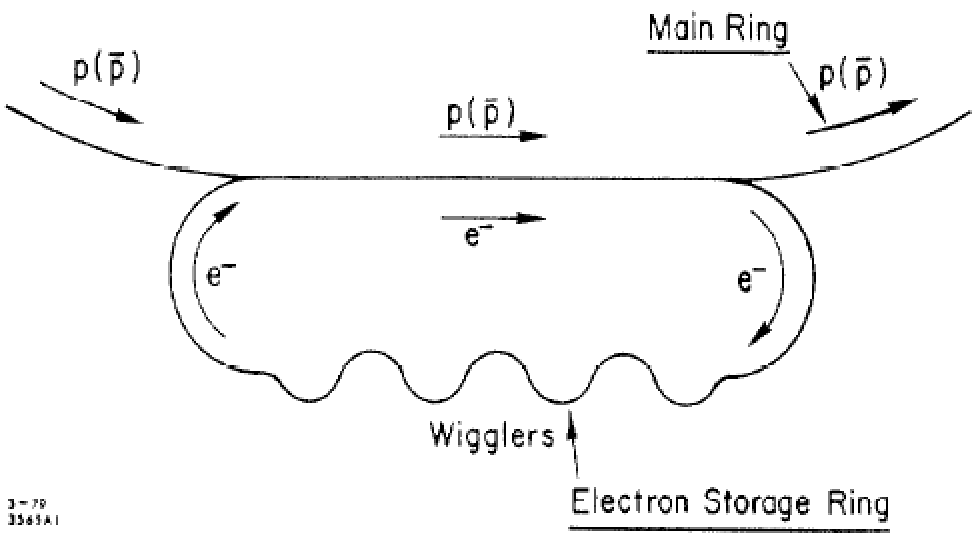


- We are considering a range of electron beam and linac parameters:
  - beam current 50-100 A
  - Rep rate: 100 – 200 Hz (~10,000 turns storage time)
- Pulse length: ~700 ns (to fill the ring)
- Beam power to dump: < 400 kW
- Beam power, lost in the ring < 2 kW (Touschek & extraction)

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]



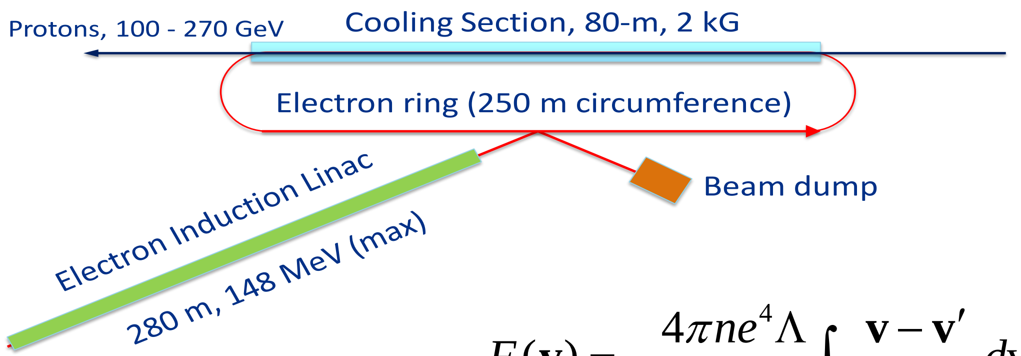
In this scheme, the electron beam is “cooled” via synchrotron radiation damping, while cooling colliding proton beams.

- 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)



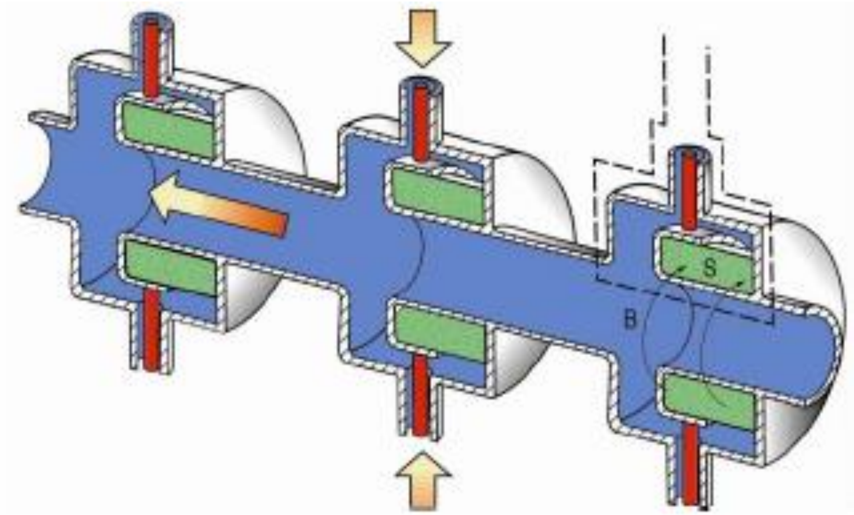
$$F(\mathbf{v}) = -\frac{4\pi n e^4 \Lambda}{n} \int \frac{\mathbf{v}-\mathbf{v}'}{\left|\mathbf{v}-\mathbf{v}'\right|^3} d\mathrm{v}^3 \Rightarrow F_{\max} \propto \frac{1}{\sigma_p^{\;2} + \sigma_e^{\;2}}$$

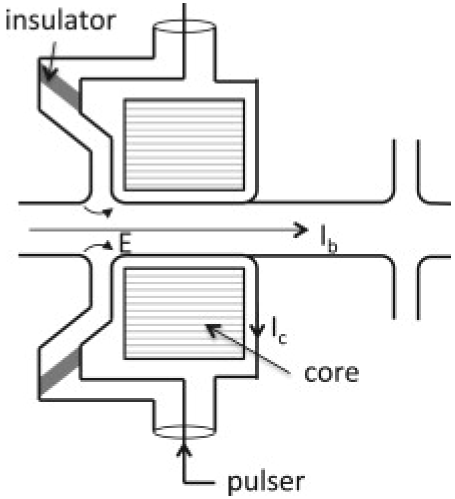
  - Weakly-magnetized cooling

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

Induction linac

DARHT at LANL

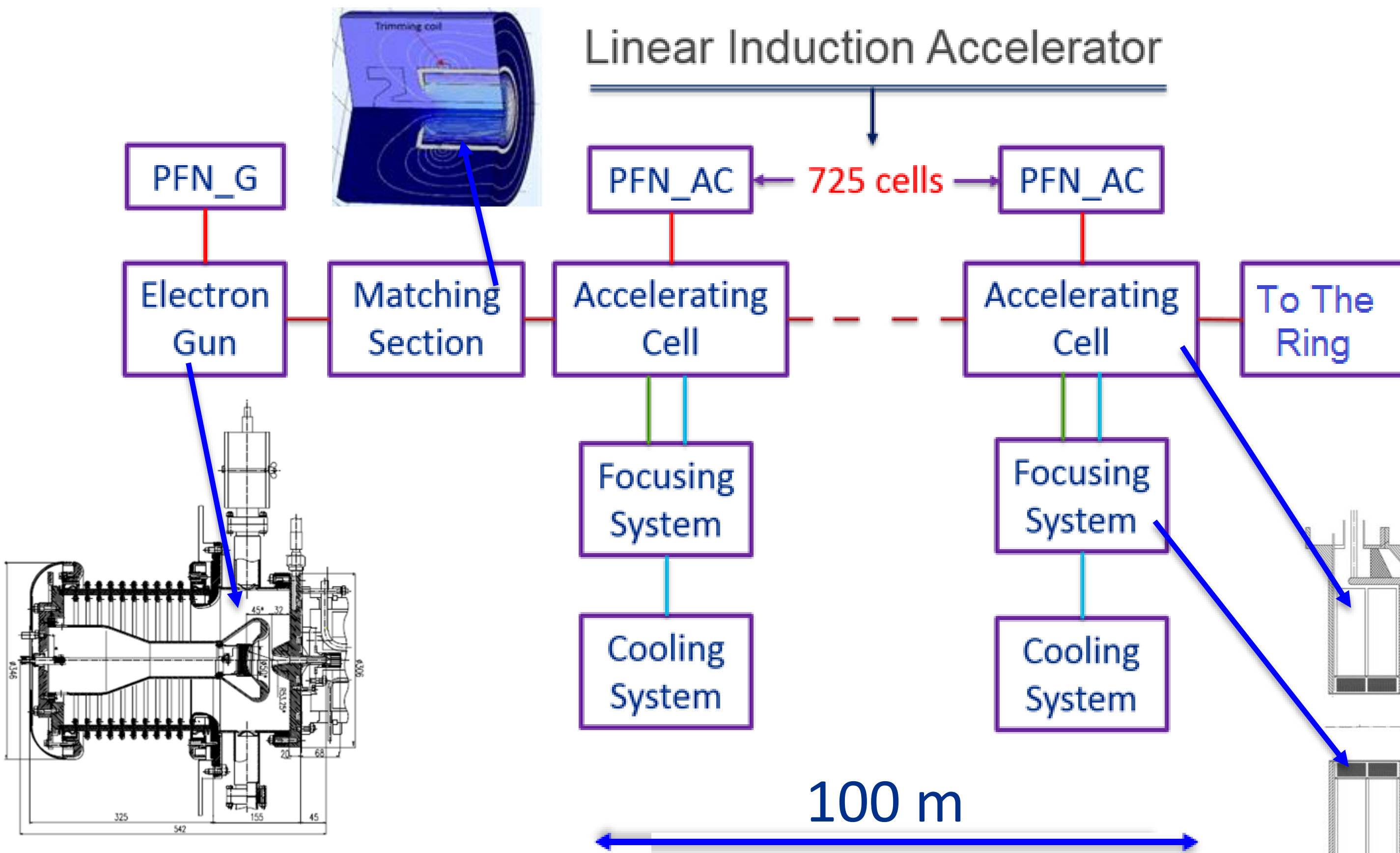


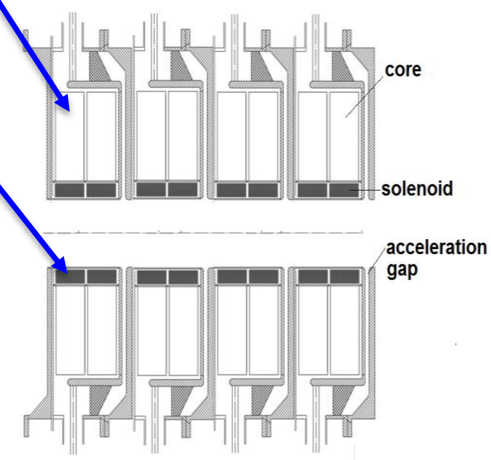


Injector Voltage	2.5 MV
Injector Current	2.0 kilo-Amperes
Injector Pulse Length	1.6 micro-seconds
Number of Injector Cells	6 @ 175 kV/cell
Number of Accelerator Cells	68 @ 200-235 kV/cell
Total Beam Energy	17.1 MeV (goal 18.1 MeV)

- 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.

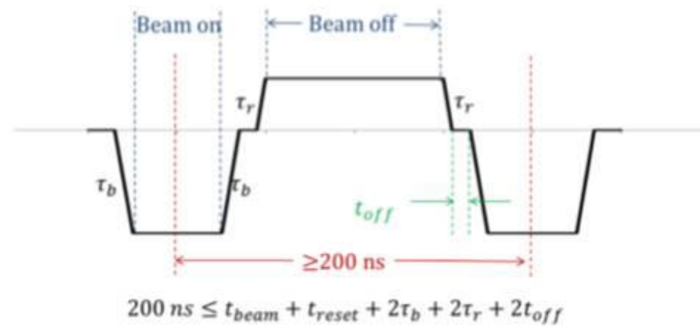
Strict requirement for the emittance of the electron beam constitutes the most challenging part of the injector and the transport line design.

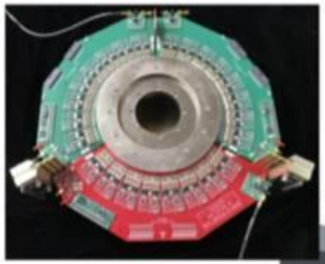
Our proposed induction cell concept is similar to an existing prototype at LLNL

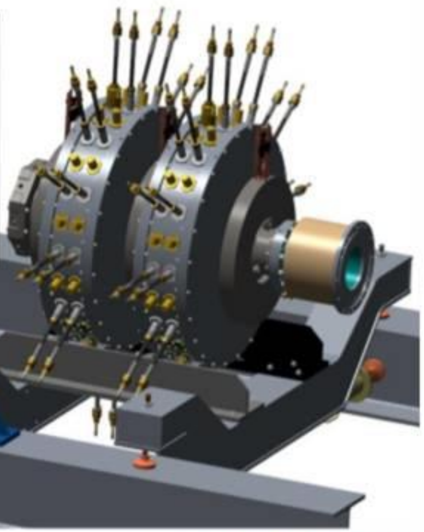
Future for LIAs and pulsed power

LLNL-PRES-793805

- 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.







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

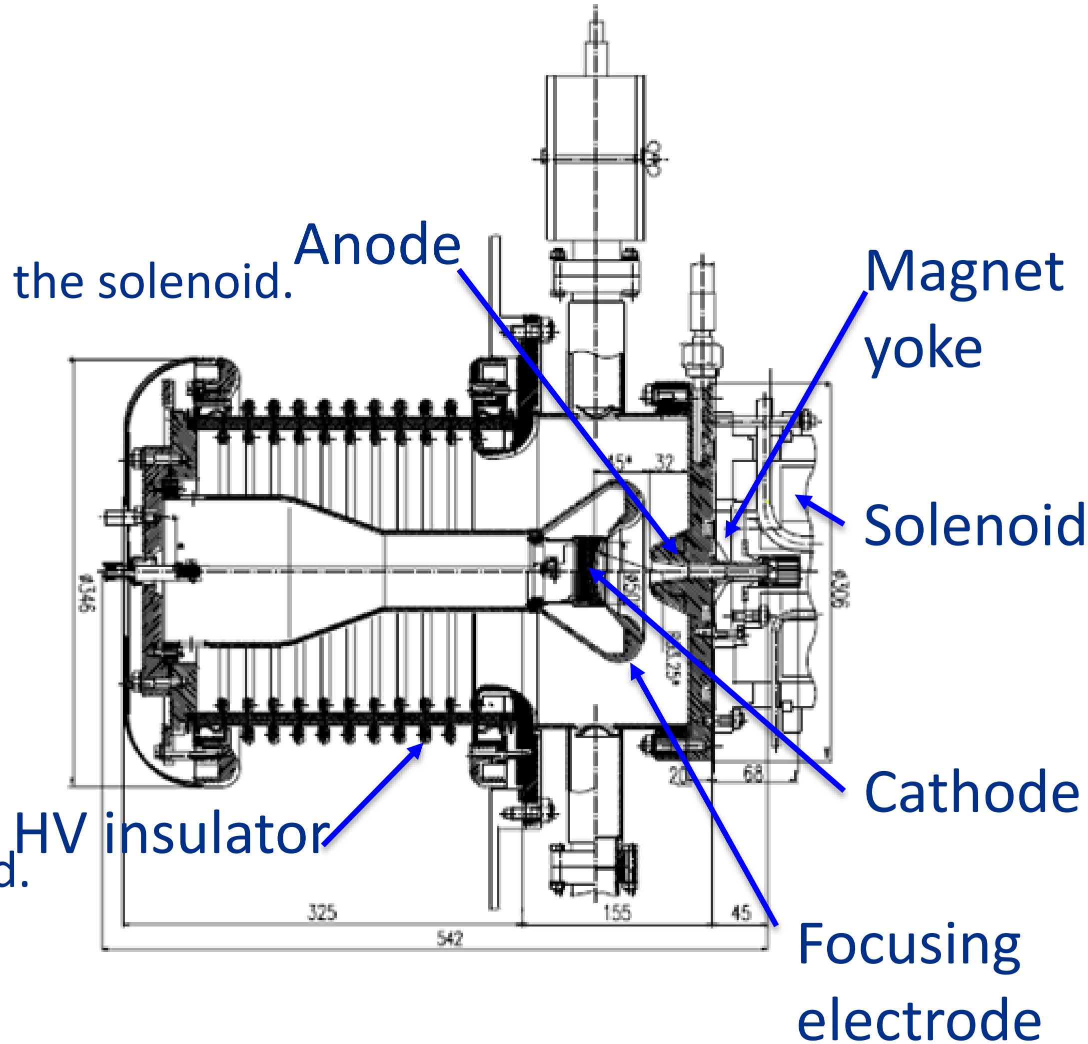
❑ Gun concept:

- 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)

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

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

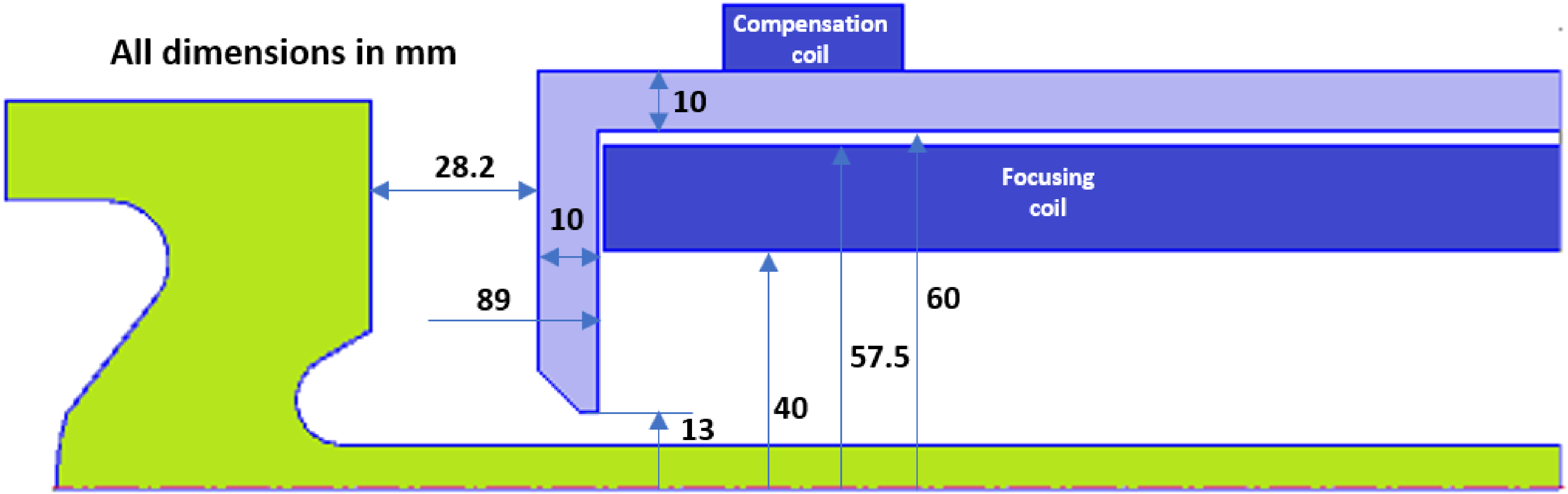
$$r_{cath}{}^2 B_{cath} = r_{cs}{}^2 B_{cs}$$

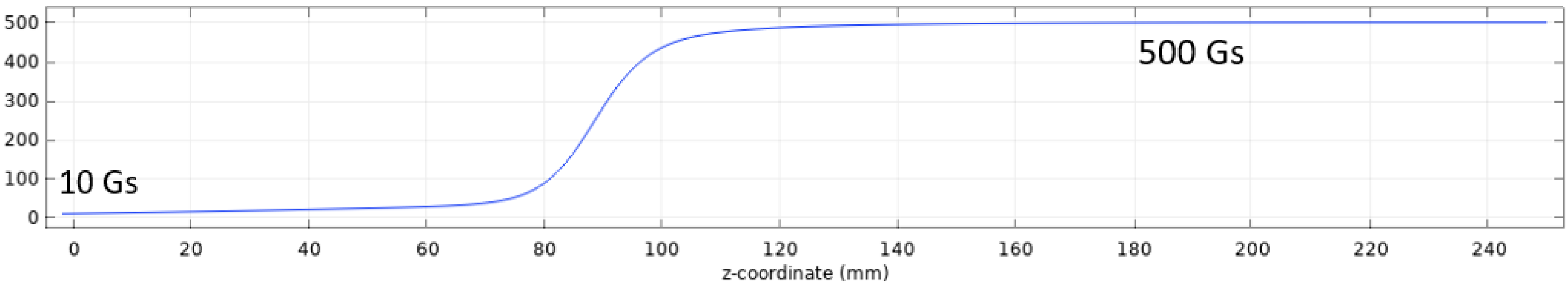
- Magnetic field makes 2 emittances of normal modes different

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

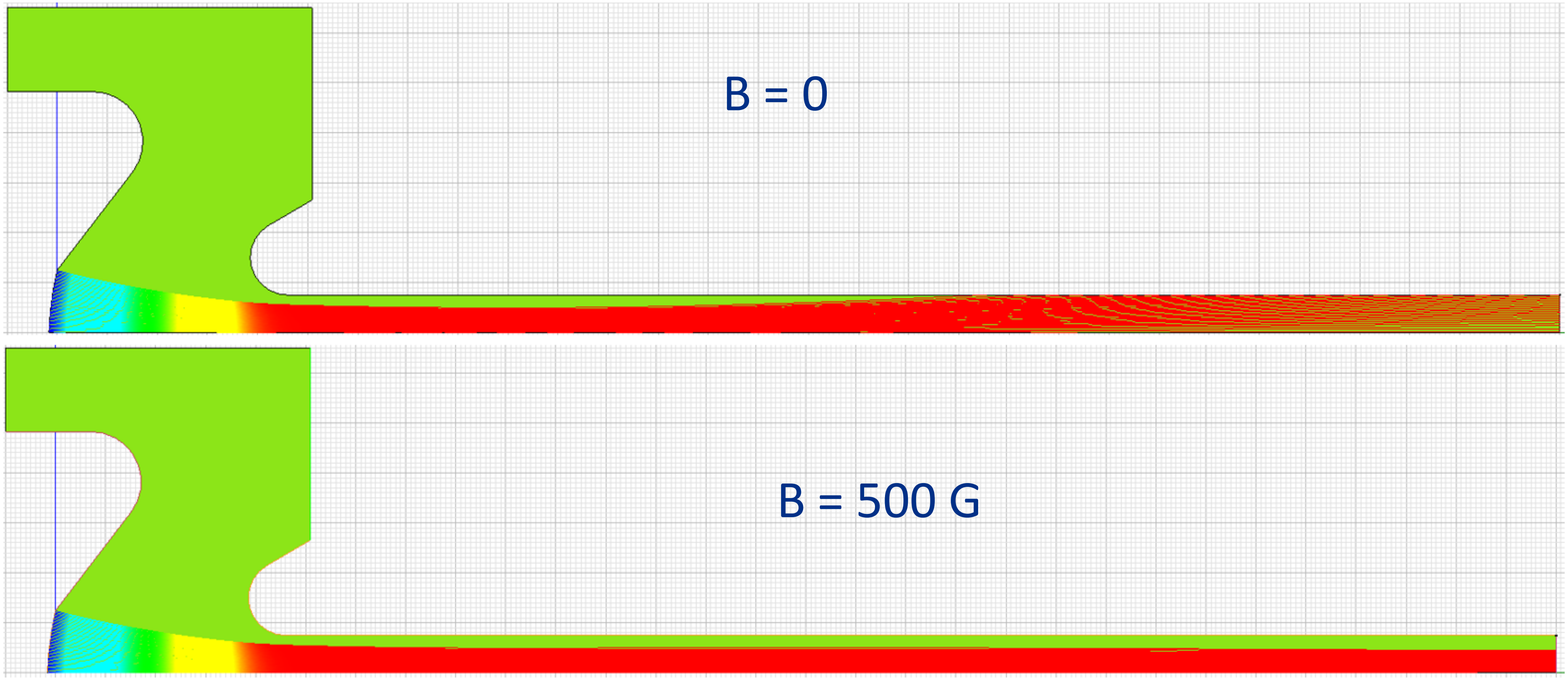
  – Mode 1 with larger emittance determines the rms beam size
  – Mode 2 with smaller emittance determines the angular spread

Gun and solenoid matching schematic





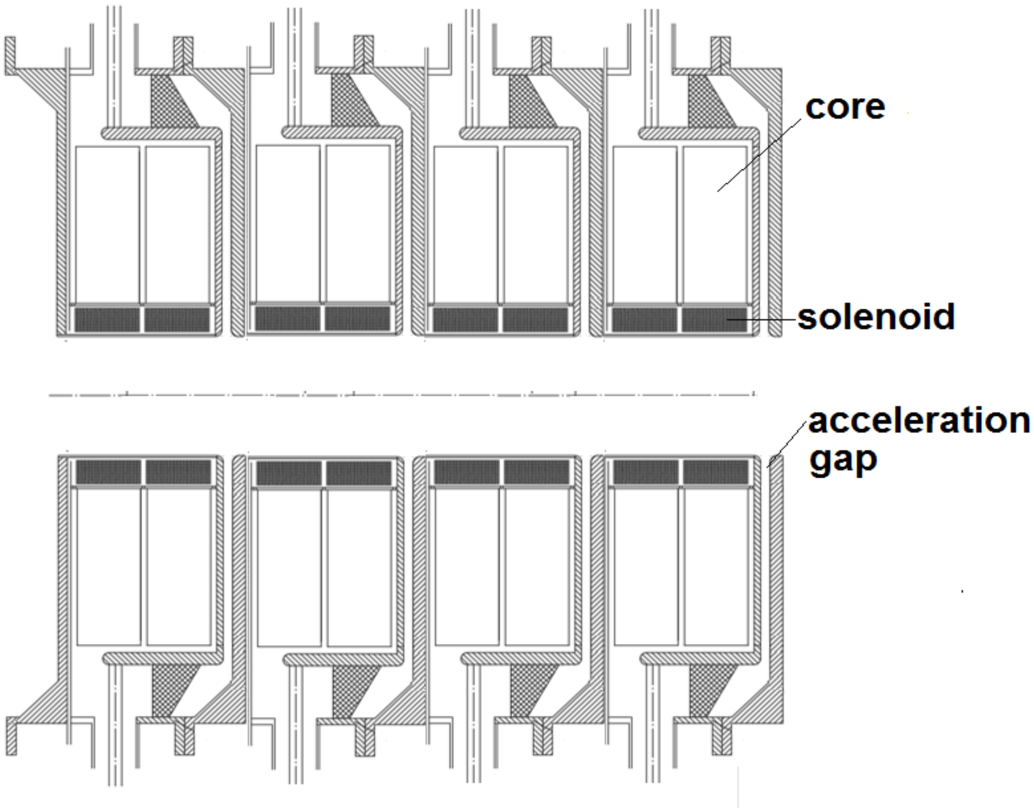
Beam propagation without (top) and with (bottom) magnetic field

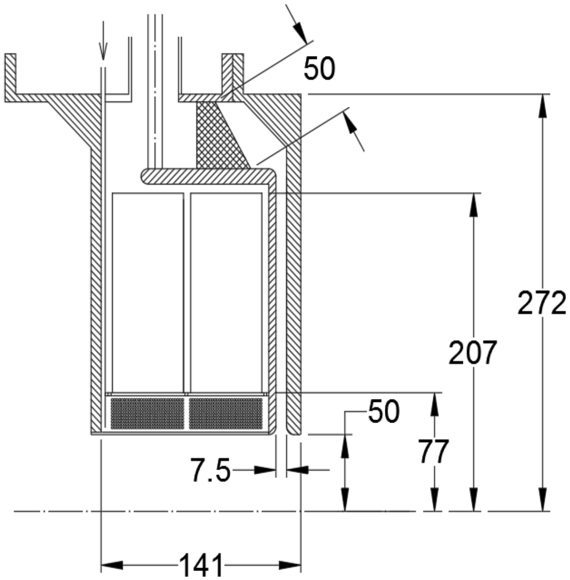


No emittance growth observed at 300 keV (no induction linac)

Induction Linac for Electron Cooling

❑ Linac concept:

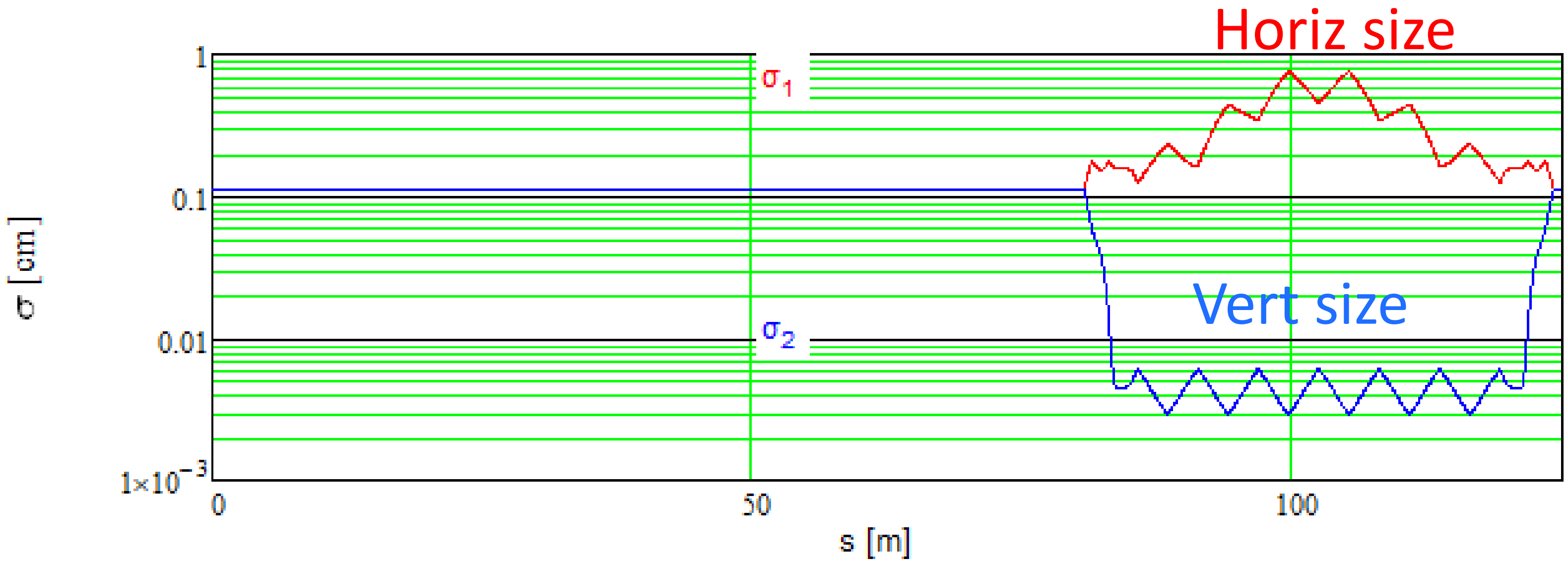




- 75 keV energy gain per cell
- Each cell contains two cores, two focusing solenoids and an acceleration gap.

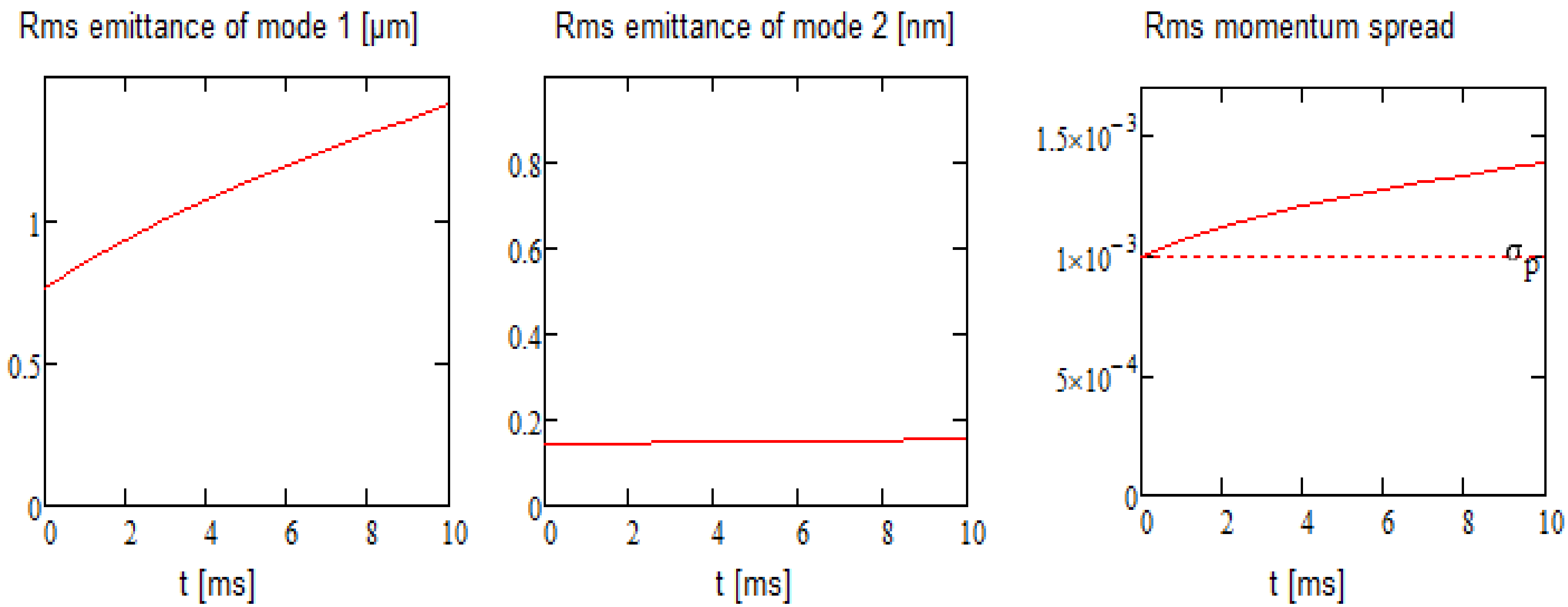
Cooler ring: main ideas

- 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



Fermilab

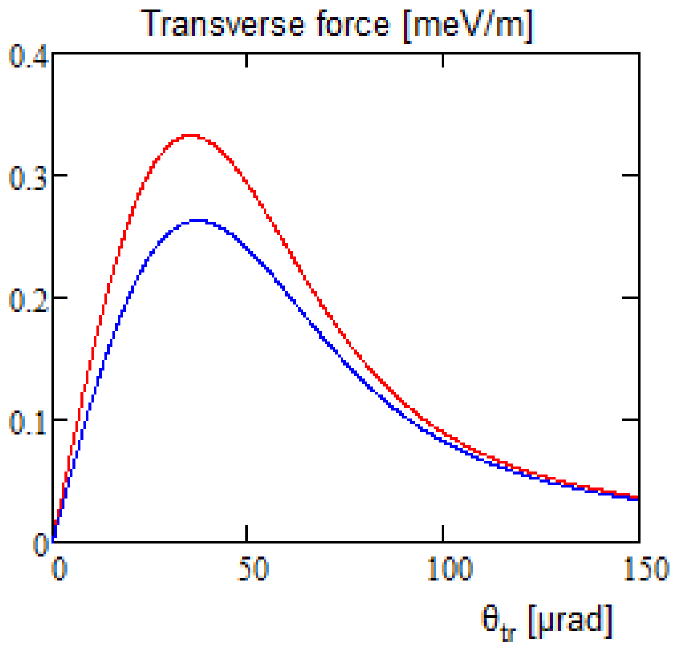
Electron beam heating is due to its own IBS

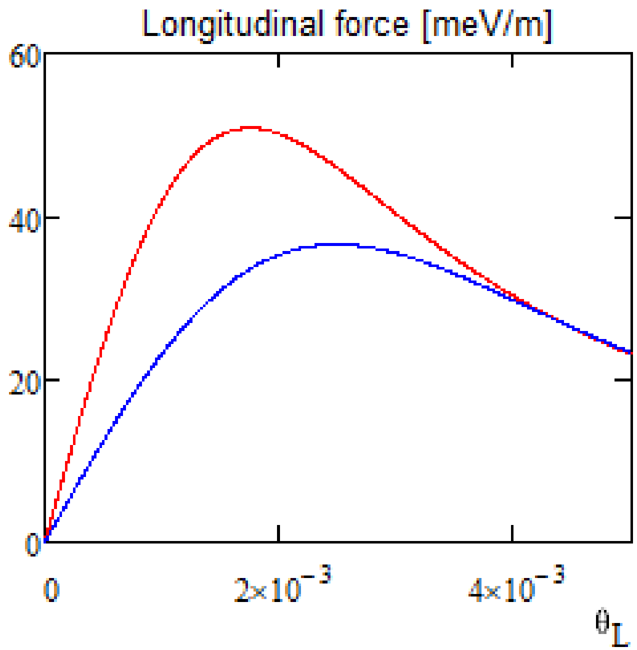


Dependencies of rms non-normalized mode emittances and the momentum spread on time for a 100-A, 147 MeV electron beam due to intra-beam scattering.

– 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).

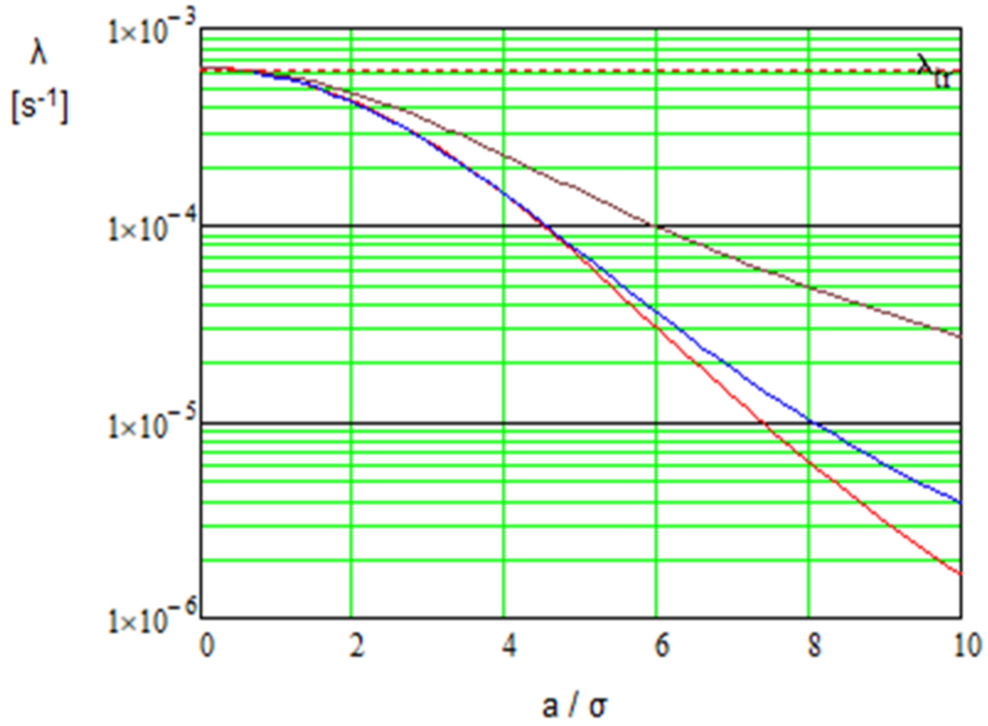
$$F_{\parallel}(\mathrm{v}_z) = \frac{4\pi n_e' e^4 L_c}{m_e}\left(\frac{4\mathrm{v}_z}{\sqrt{\pi}}\int_0^{\infty}\exp\left(-\frac{\mathrm{v}_z{}^2 t^2}{1+2\sigma_{\mathrm{v}z}{}^2 t^2}\right)\frac{t^2 dt}{\left(1+2\sigma_{\mathrm{v}\perp}{}^2 t^2\right)\left(1+2\sigma_{\mathrm{v}z}{}^2 t^2\right)^{3/2}}\right),$$

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

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

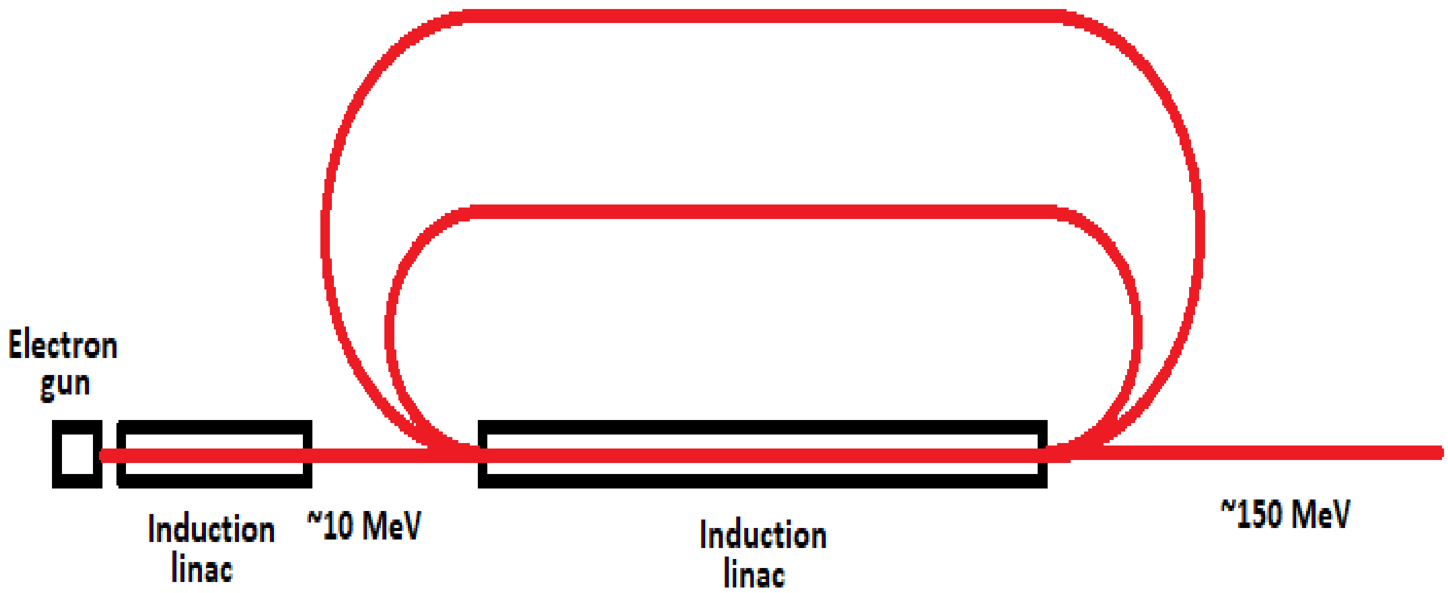
- The proposed concept meets the project requirements (1-2 hour cooling time for 100 – 270 GeV protons)
  - No show-stoppers so far
- Conventional induction linac and ring technology but with several new ideas:
  - Magnetized e-gun and linac transport, round-to-flat beam transformation in ring arks
- 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 ($\varepsilon_1/\varepsilon_2 \sim 5{,}000$) 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 and A. Seryi for support and discussions.