Ring-based High Energy Electron Cooler

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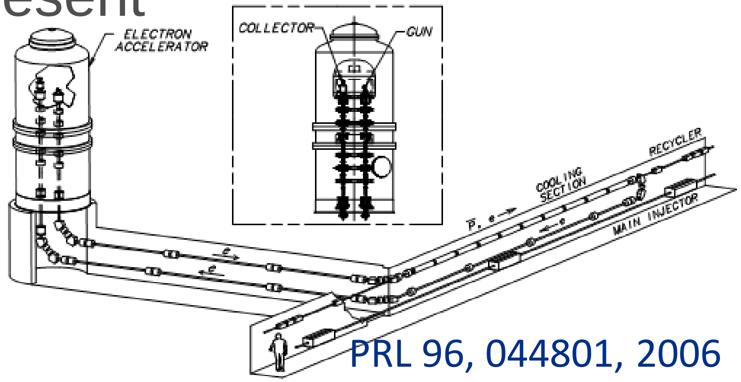
Introduction

- Fermilab is a world-recognized leader in beam cooling:
  - Both stochastic and electron cooling systems in the past
  - World's highest energy electron cooler in operation, 2005-2011
  - FAST/IOTA: beam cooling R&D at present
  - EIC hadron cooling workshop
    - Fermilab/UChicago/CBB: Oct 2019

http://indico.fnal.gov/e/EIC-HC2019



PRL 96, 044801, 2006

- Project funds allocated: FY18: $146k, FY19: $146k
- Project started: July 1, 2018
- Current balance (as of 10/31/19): $103k

Project Goals (from the FY18 proposal)

- The first goal of this proposal is to investigate conceptually the proposed multi-turn cooling system and the 3d cooling process of a 100-GeV proton beam.
- The second goal will be aimed at investigation of how cooling would change with the proton beam energy and will be aimed at a follow-on proposal of a conceptual design for the major subsystems (electron gun, induction linac, storage ring, cooling section).
- The output of this project would be a conceptual proposal for an electron cooling system, capable of operating in a broad energy range of ion/proton beams and supporting the EIC requirements.

Conceptual design report (draft):

http://home.fnal.gov/~nsergei/EIC/ElectronCoolingConcept_Nov_2019_v0.3.pdf

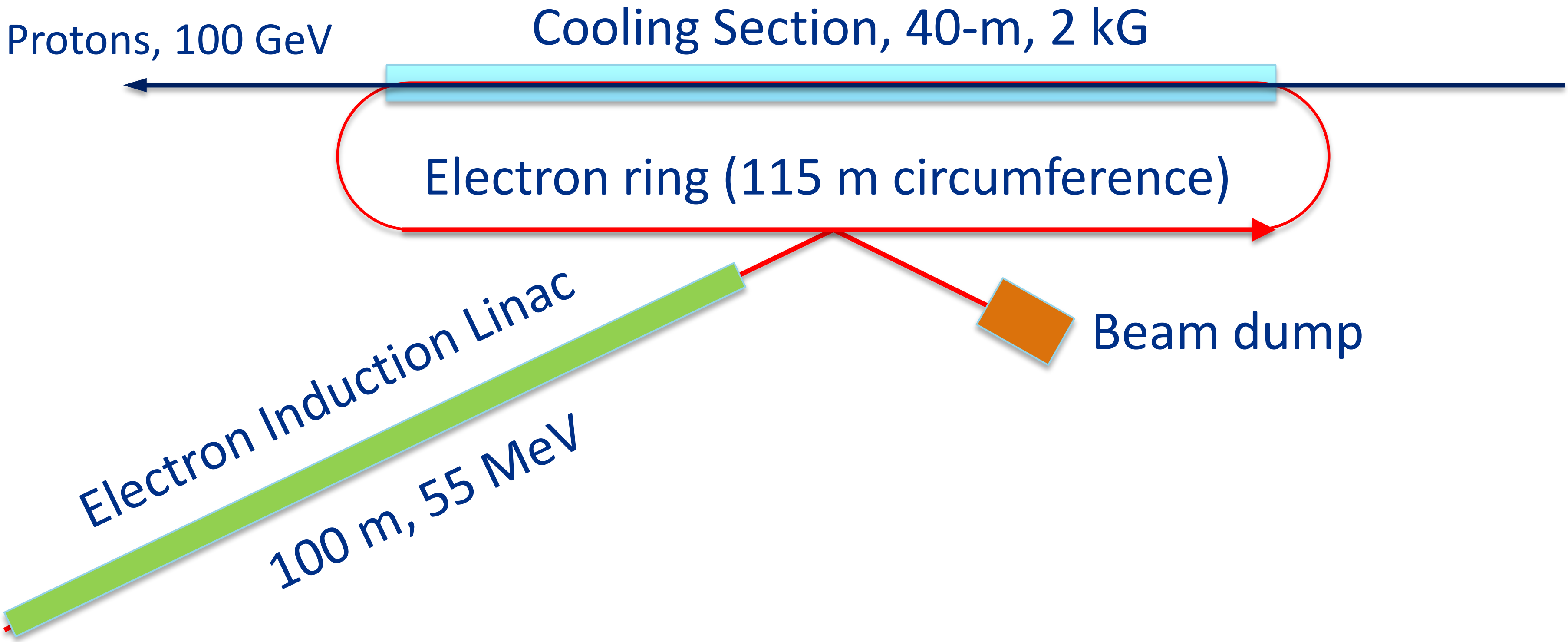
Potential Impact:

- A successful completion of the project would enable the design of the electron-proton and electron-ion colliders with required luminosities

Motivation

- At the initial project stage, we are focusing on cooling of ~100 GeV protons, aiming at ~1-hour cooling time.
  - Fermilab Recycler cooler (8-GeV antiprotons): cooling time was < 0.5 hour
- A well-known shortcoming of the electron cooling method: unfavorable scaling of cooling time with energy ($\sim\gamma^{2.5}$)
- One can compensate by increasing the electron beam current.
- We are aiming at a 100-A (DC) electron beam current at 55 MeV.
  - DC beams have many advantages as well as some challenges, compared to bunched beams.

Proposed solution



Protons, 100 GeV

Cooling Section, 40-m, 2 kG

Electron ring (115 m circumference)

Electron Induction Linac

100 m, 55 MeV

Beam dump

- We are considering a range of electron beam and linac parameters: < 100 A beam current, 100 – 200 Hz rep. rate (10,000 turns storage time)
- Pulse length: 380 ns (to fill the ring)
- Beam power to dump: < 400 kW
- Beam power, lost in the ring < 2 kW (Touschek & extraction)

Advantages compared to ERLs:

- Conventional induction linac technology
- Conventional electron gun with a thermionic cathode:
  - Well-understood technology
  - Expect long cathode lifetime
- Longer beam storage time in a ring (limited by IBS only)
  - Cooling process is not limited by beam-beam temperature transfer but by IBS heating of e-beam itself
- No issues with wake fields for a dc beam
- No issues with variable bunch patterns/frequencies for a proton beam

Main project elements

1. Cooling dynamics; overall optimization and integration
2. Ring optics, layout and design
   - Space-charge modeling, instabilities, CSR
3. Injector
   - E-gun
   - Linac
   - Emittance preservation
   - Beam transport
4. Extraction and beam dump

- Conceptual design report (draft): http://home.fnal.gov/~nsergei/EIC/ElectronCoolingConcept_Nov_2019_v0.3.pdf
- Work on element 4 not started yet.

Cooling dynamics

- Weakly-magnetized cooling is preferred due to large temperature in proton beam
  - Electron temp. with the same rms velocity: $T_{eff} = m_e c^2 \beta\gamma\varepsilon_n / \beta_x \approx 1.4\,\mathrm{eV}$

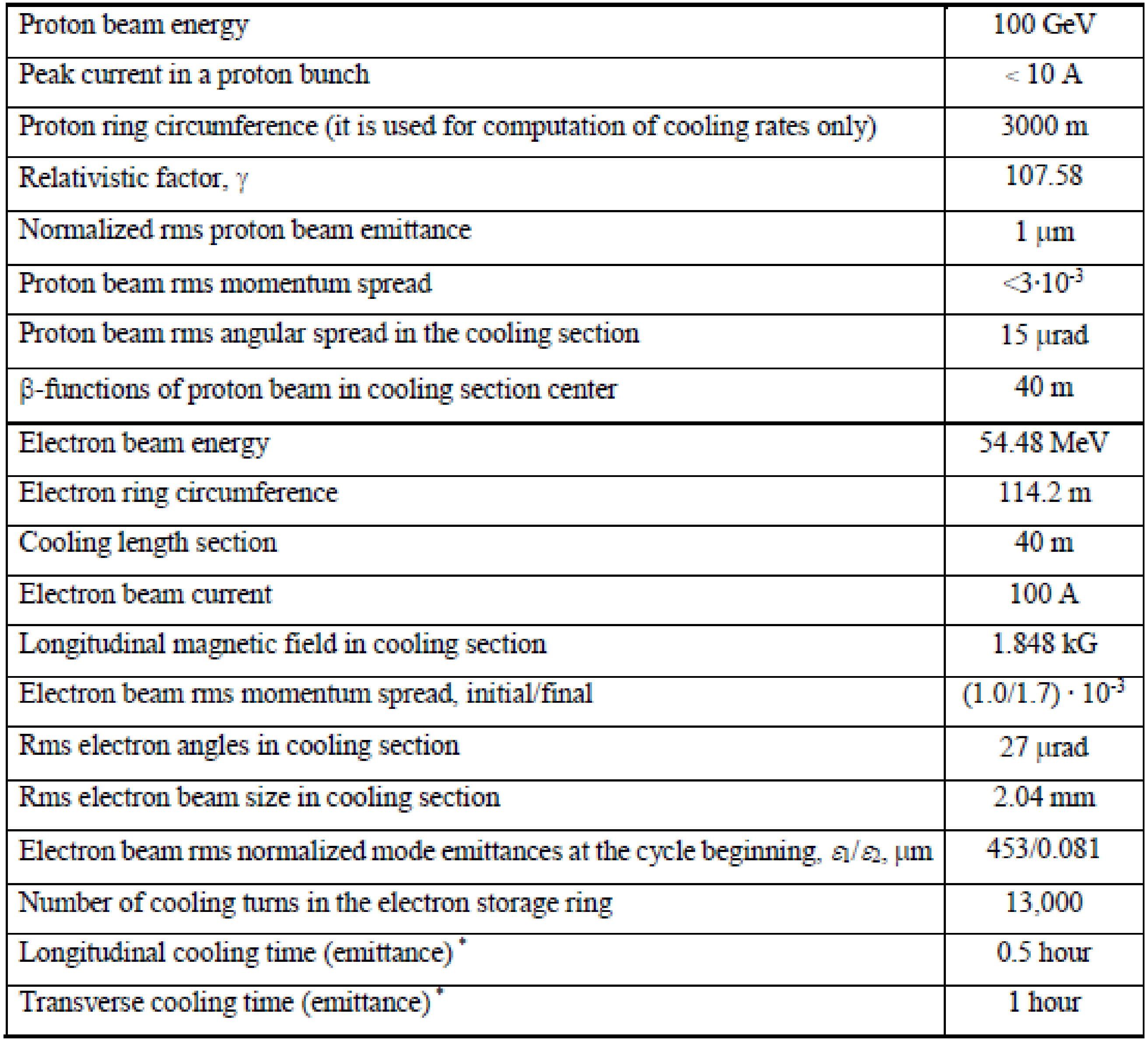
    for pc = 100 GeV, ε_n = 1 mm, β_x = 40 m
  - Magnetization helps only for small amplitude particles – therefore not optimal!!!

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

Basic system parameters

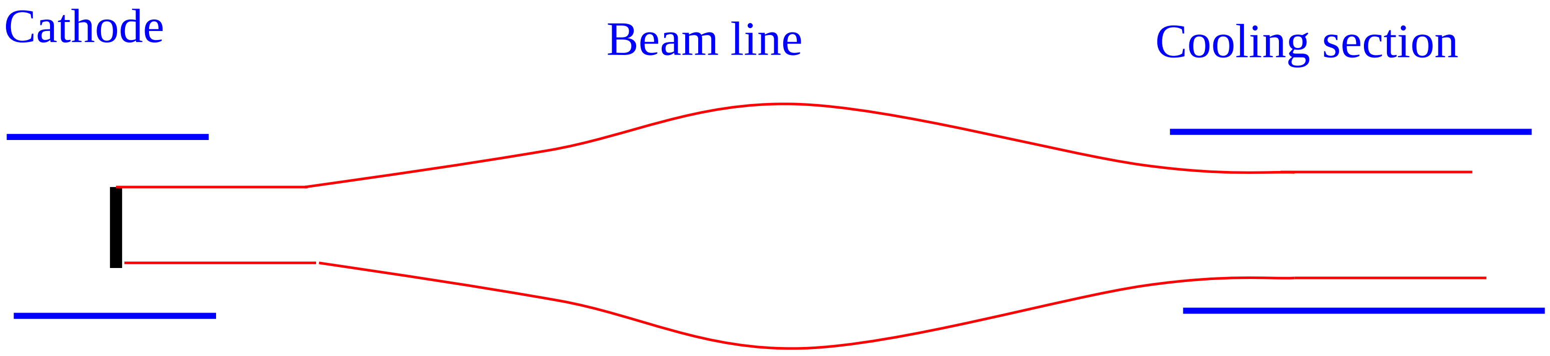
- Small ⊥ temperature of e-beam is not required
  - Thermionic cathode with moderate current density + large compression in the gun to create small e-beam size in the cooling section
  - Longitudinal magnetic field to keep constant e-beam size in the cooler (beam focusing => ⊥ beam stability)
    - Magnetic field at the cathode to compensate rotation appearing at the solenoid entrance
- Use DC beam to avoid problems with wakes. Beam current in the ring is limited to ~100 A by IBS and instabilities.
- For 100 A beam the instabilities are a serious issue
  - Beam is stabilized by dampers (BW~200 MHz) in each of 3 planes
  - No RF is foreseen to minimize ring impedances
  - No abort gap: beam loss at extraction (however at an acceptable level)
  - May need additional Landau damping for transverse stability
  - CSR may be challenging

Preliminary cooling system parameters



Proton beam energy	100 GeV
Peak current in a proton bunch	< 10 A
Proton ring circumference (it is used for computation of cooling rates only)	3000 m
Relativistic factor, γ	107.58
Normalized rms proton beam emittance	1 μm
Proton beam rms momentum spread	$<3\cdot10^{-3}$
Proton beam rms angular spread in the cooling section	15 μrad
β-functions of proton beam in cooling section center	40 m
Electron beam energy	54.48 MeV
Electron ring circumference	114.2 m
Cooling length section	40 m
Electron beam current	100 A
Longitudinal magnetic field in cooling section	1.848 kG
Electron beam rms momentum spread, initial/final	$(1.0/1.7)\cdot10^{-3}$
Rms electron angles in cooling section	27 μrad
Rms electron beam size in cooling section	2.04 mm
Electron beam rms normalized mode emittances at the cycle beginning, $\varepsilon_1/\varepsilon_2$, μm	453/0.081
Number of cooling turns in the electron storage ring	13,000
Longitudinal cooling time (emittance) *	0.5 hour
Transverse cooling time (emittance) *	1 hour

Effective beam emittance



Cathode

Beam line

Cooling section

$B_c = 12$ G
$R_{cath} = 25$ mm

$$\varepsilon_t = \frac{1}{2} R_{cath} \sqrt{\frac{T}{mc^2}}$$

$\approx 6\ \mu m$ (rms, normalized)

$B_z = 0$

$$\varepsilon_{eff} = B_c R_{cath}{}^2 \frac{e}{8mc^2}$$

$= 180\ \mu m$ (rms, normalized)

$B_c = 1.8$ kG
$R_{beam} = 2$ mm

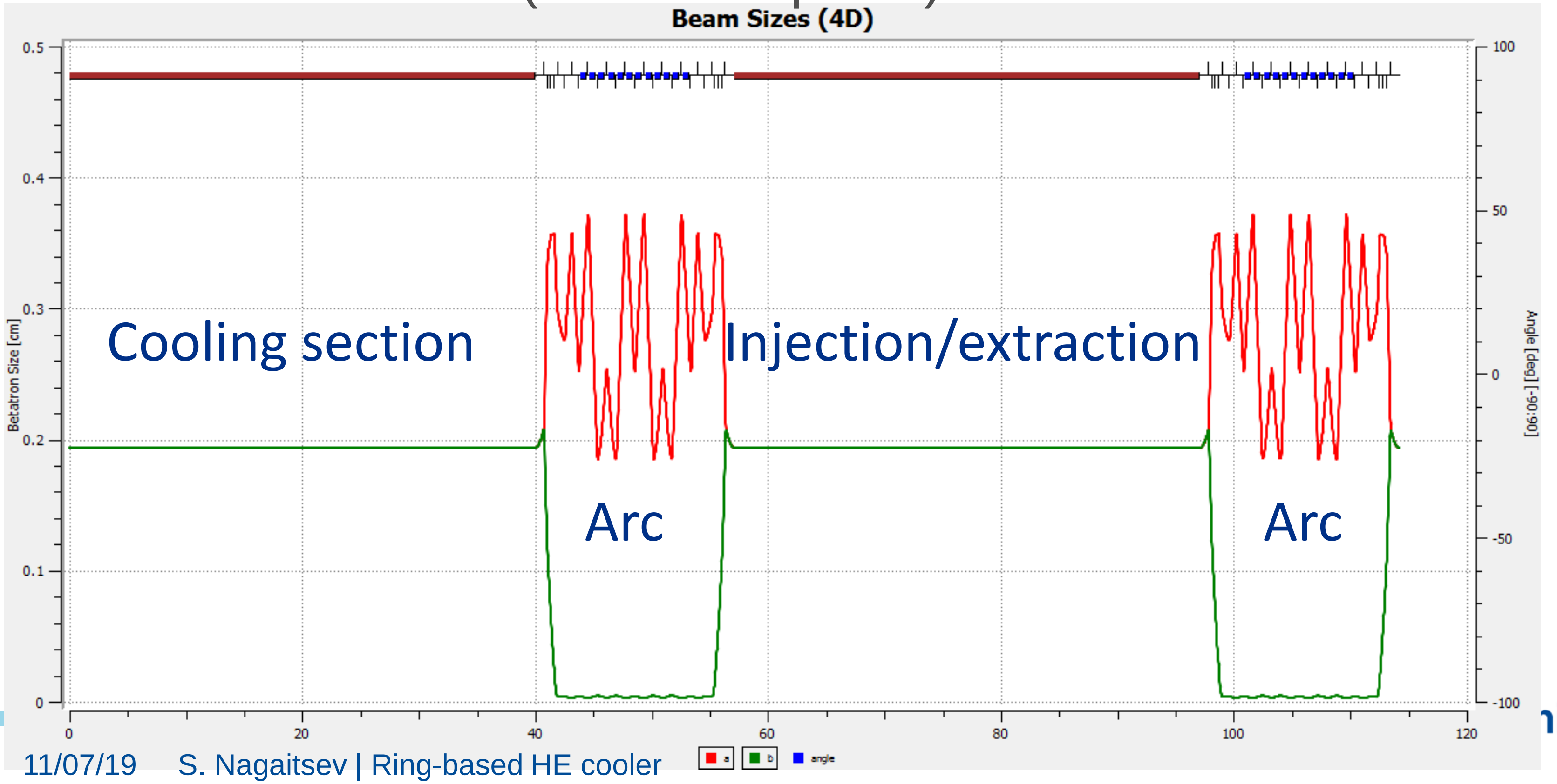
$$\varepsilon_{cs} < 7\,\mu m$$

(rms, normalized)
Increase with time
because of IBS

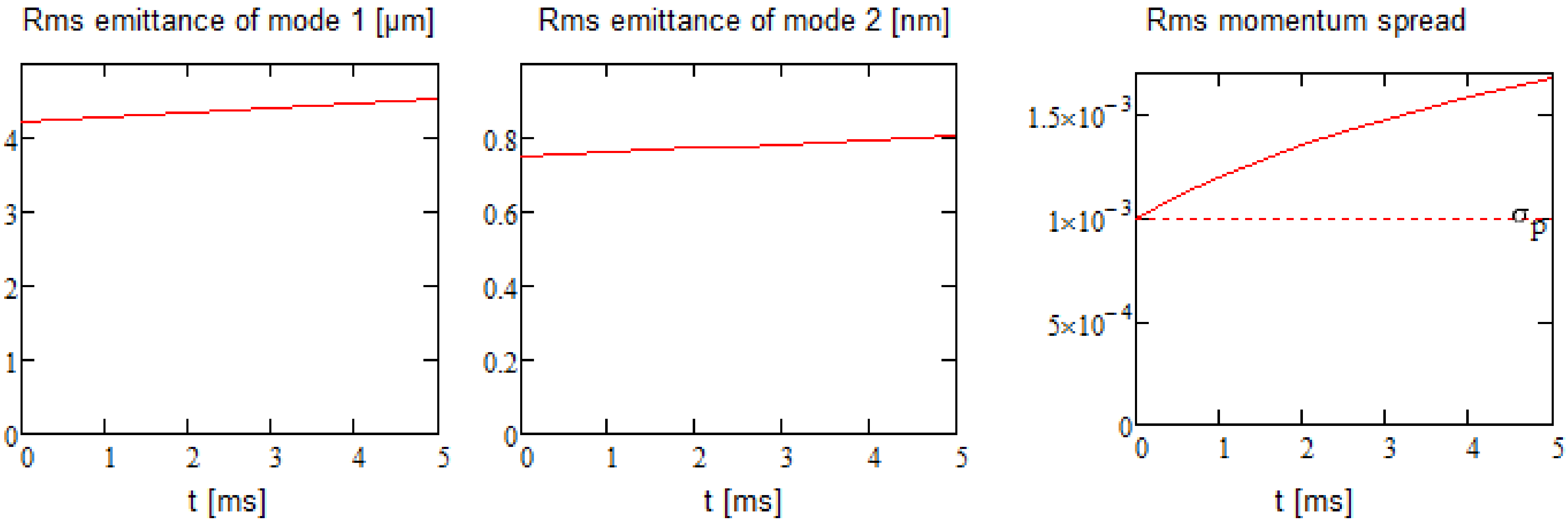
- The concept of a magnetized beam transport was employed in the Fermilab cooler
- We also propose to use a “round-flat-round” optics in arcs
  - Mode emittances (rms, norm): 450/0.08 μm
  - Emittance ratio: ~5,300 (a bit challenging)

Electron beam main heating mechanism: IBS

- E-beam IBS determines the rep rate of the induction linac
- The effect of IBS – increases of momentum spread and horizontal emittance
  - We propose to use two methods: keep beam density low, keep beam “flat” in arcs (horizontal plane)



IBS growth in electron ring vs time (in msec)



Rms emittance of mode 1 [μm]

Rms emittance of mode 2 [nm]

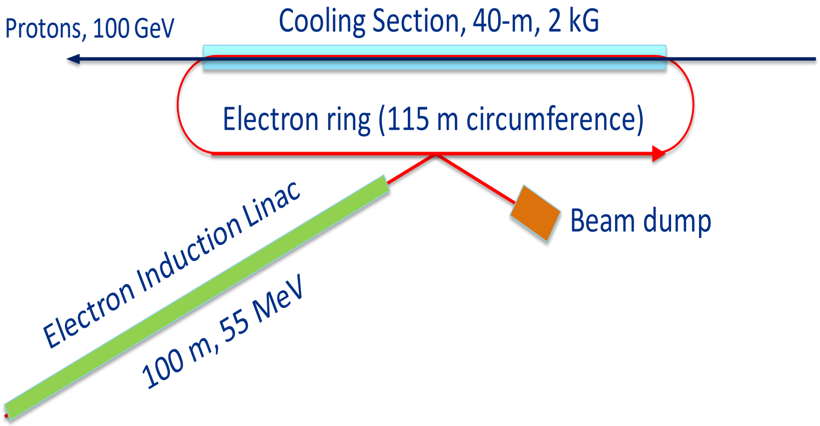
Rms momentum spread

- IBS longit. heating time (~5 ms) sets the re-injection rate, 200 Hz
- The electron beam transverse “temperature” (mode 2) in the cooling section doesn’t grow.
- x-y coupling is fully accounted for.
  - As part of this project, we have developed a complete IBS model in fully coupled optics. (arXiv:1812.09275)

Induction Linac for Electron Cooling

- Induction Linac Parameters:

- Energy	54.5 MeV
- Current	100 A
- Pulse duration	380 ns
- Repetition rate	200 s^{-1}
- Beam transverse emittance at the injection:	$\lesssim$ 6 µm

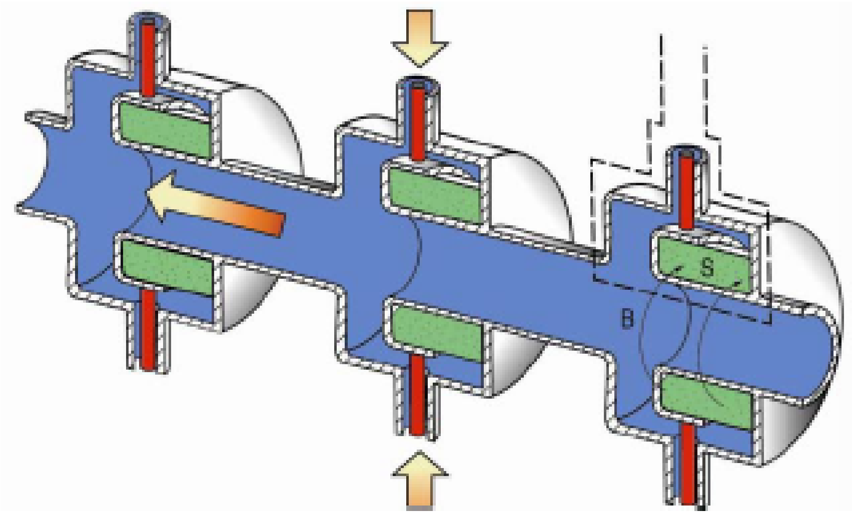


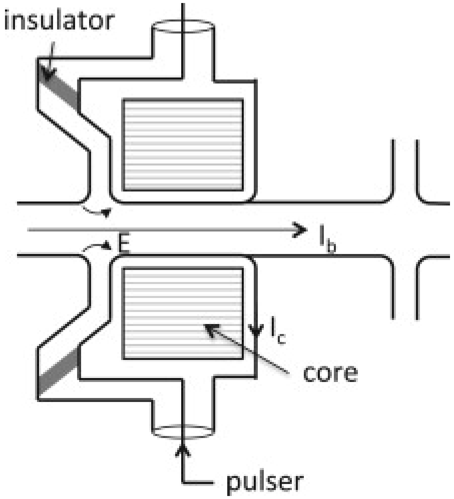
- The beam transverse emittance at injection into the ring should be determined by the beam emittance at the cathode.
- The corresponding rms normalized emittance is:

$$\varepsilon_n = \frac{r_c}{2}\sqrt{\frac{T_c}{m_e c^2}}$$

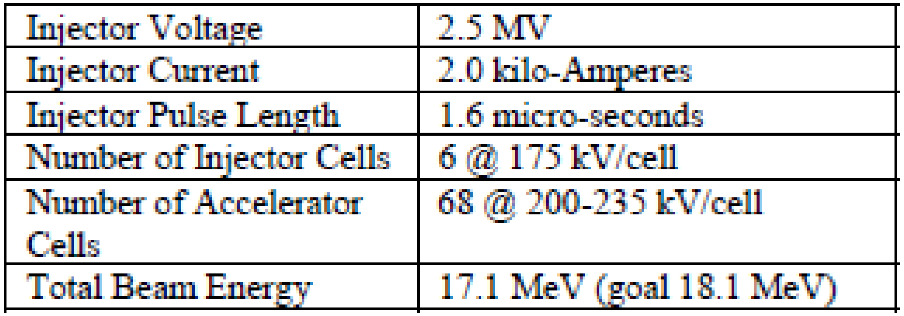
where m_e is the electron mass, c is the light speed, r_c is the cathode radius, and T_c its temperature.

Induction linacs





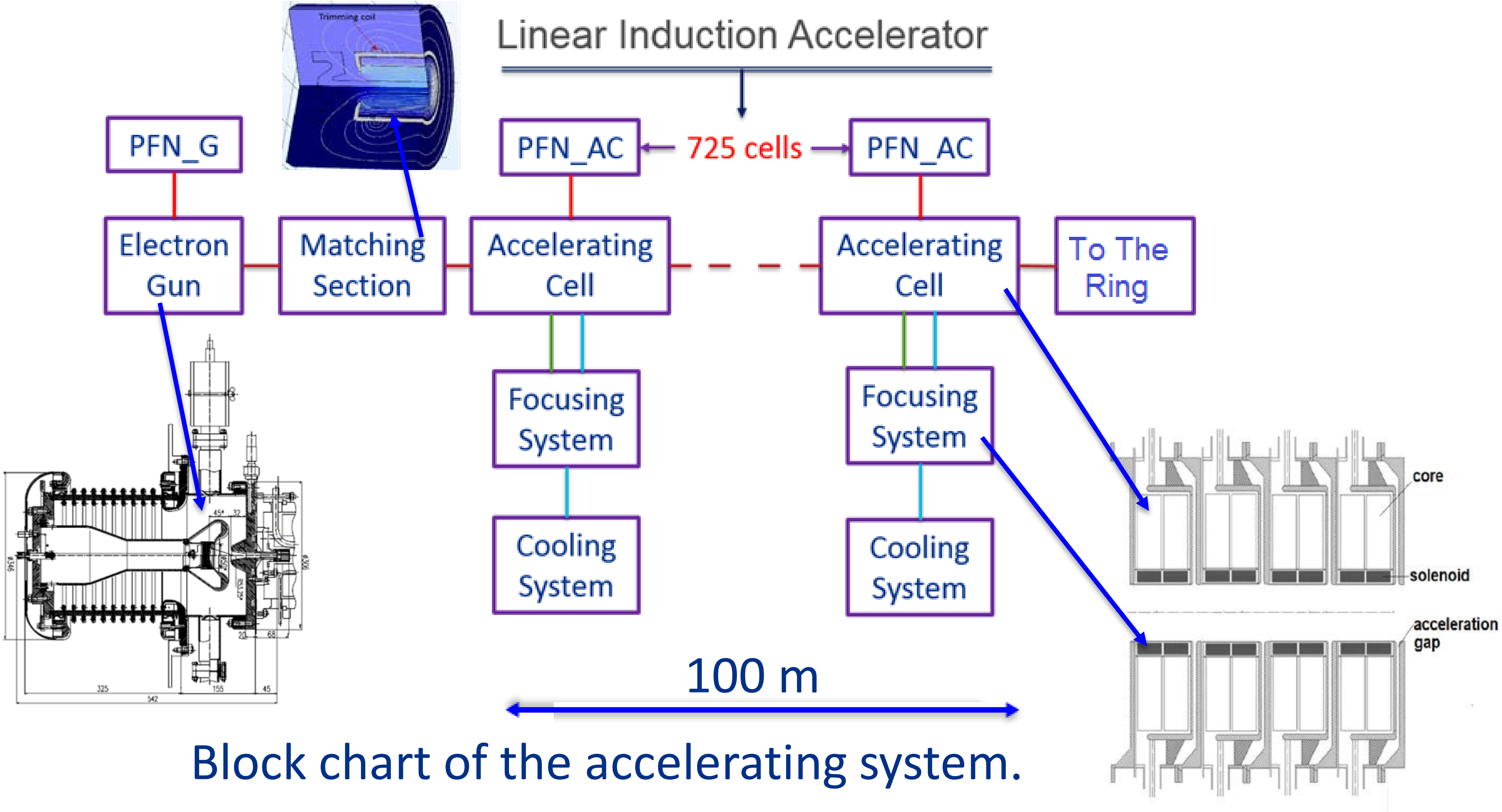
DARHT at LANL



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



Linear Induction Accelerator

PFN_G

PFN_AC ← 725 cells → PFN_AC

Electron Gun

Matching Section

Accelerating Cell

Accelerating Cell

To The Ring

Focusing System

Focusing System

Cooling System

Cooling System

100 m

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.

Induction Linac (project elements)

Beam emittance preservation:

- E-gun:
  - Thermal emittance;
  - The cathode roughness;
  - Aberrations (cathode, anode, cathode edge) ;
  - Misalignments;
  - Pulse flatness;
  - …
- Gun matching to the acceleration system:
  - Aberrations;
  - Space charge transverse force non-linearities;
  - Longitudinal space charge effects;
  - Misalignments;
  - …
- Linac (emittance preservation):
  - Aberrations;
  - Misalignments;
  - Space charge effects;
  - …

Induction Linac for Electron Cooling

E-gun

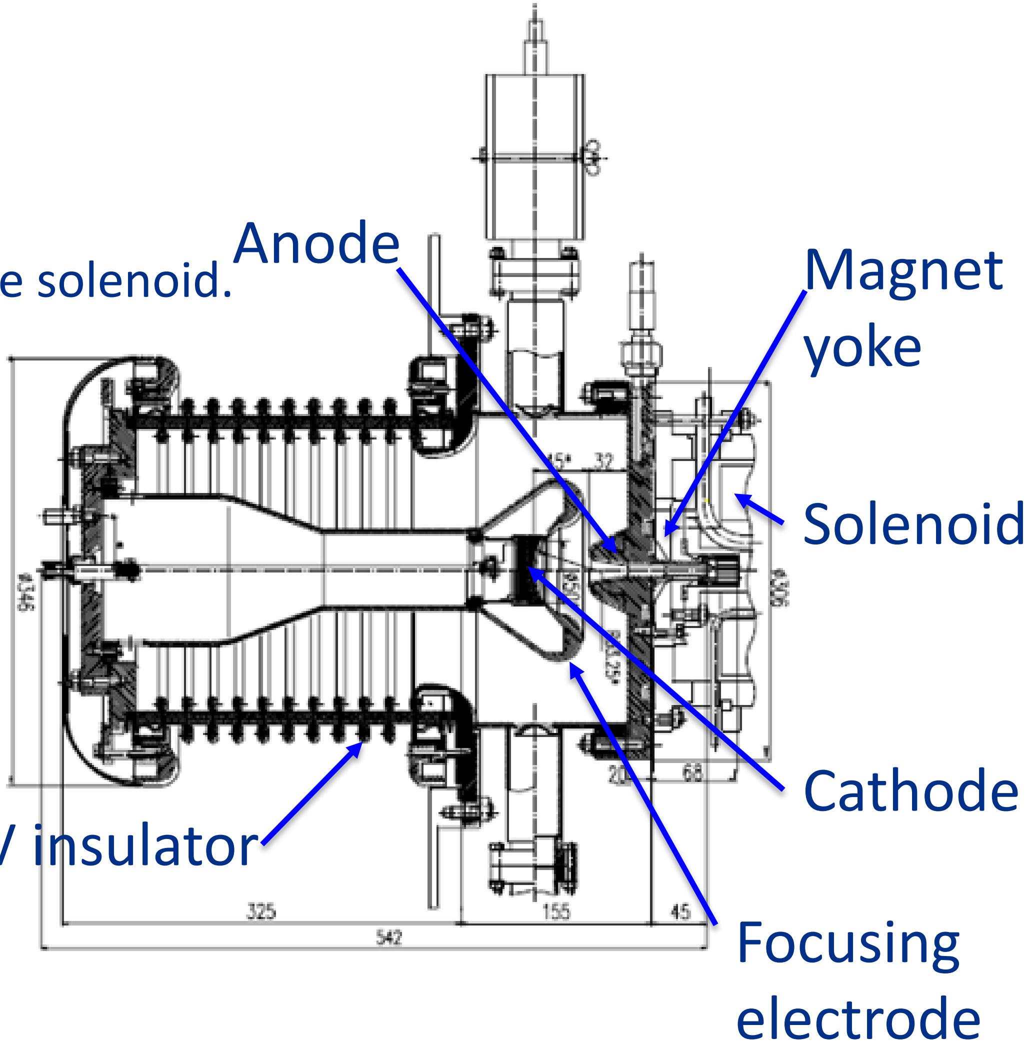
❑ The gun concept:

- 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)
- 3 such guns were built, tested and operated.



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

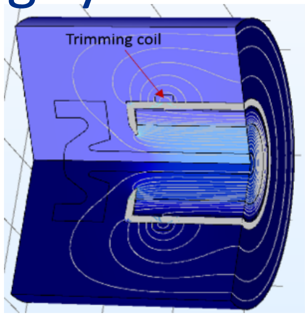
Initial gun concept (200 A)

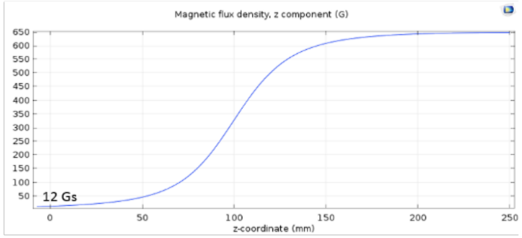
- Current density at the output close to homogeneous;
- Aberrations are still not compensated completely, $\varepsilon_{\text{eff}} \sim 20\mu$

Matching to Induction Linac

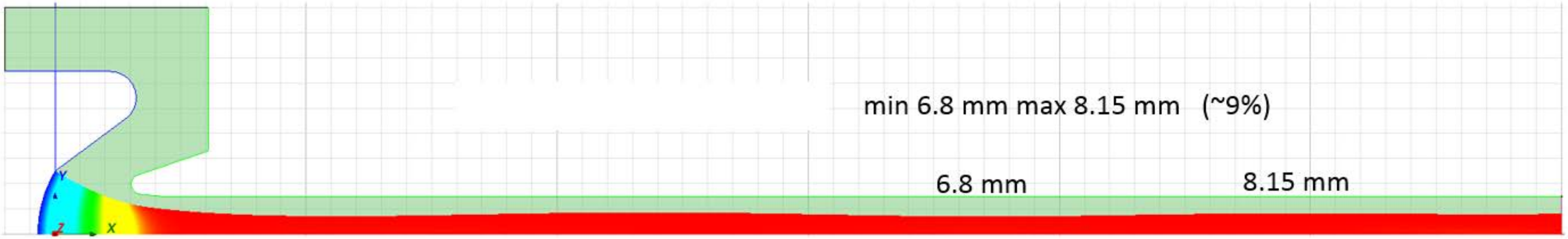
- Matching system:
  - Solenoid;
  - Magnet yoke;
  - Trimming coil.

- Filed distribution in the matching system:
  - B_{sol} =650 Gs → r_b = 7.5 mm





- Beam envelope: scalloping amplitude 9%



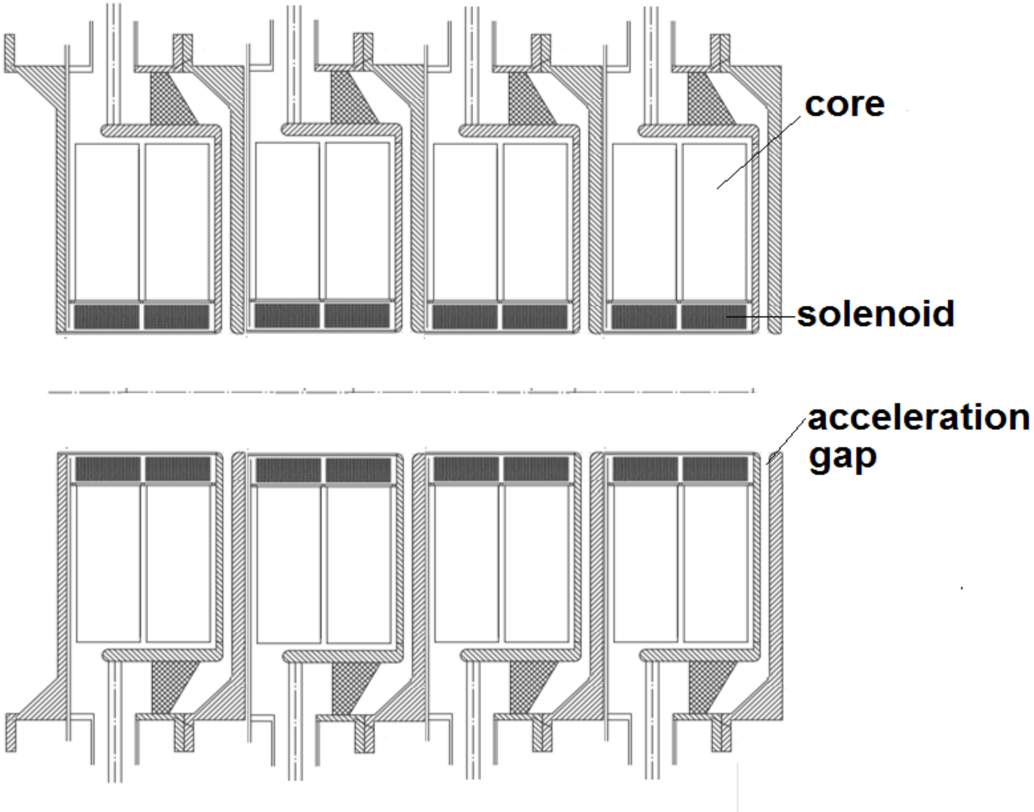
- First considerations give assurance that it is feasible to bulid the gun having parameters acceptable for Electron cooling.

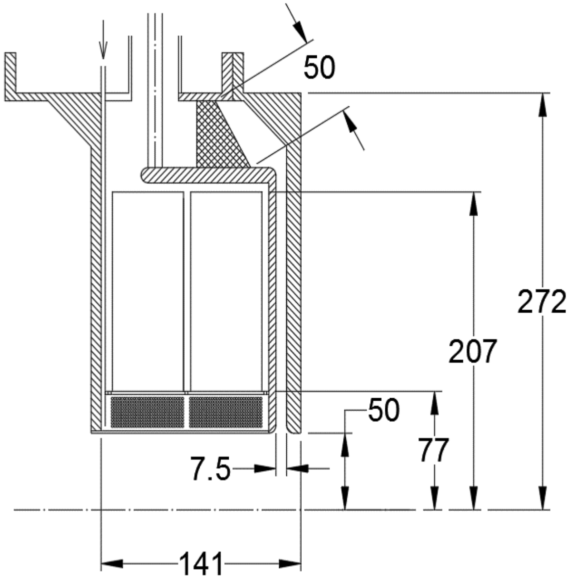
E-gun design

Next steps:

- Consider 100 A gun according to the latest requirement;
- Optimize the beam radius and the gun voltage to minimize emittance dilution in the magnetic system;
- Determine the gun geometry for the optimal voltage;
- Optimize the beam matching for the optimal voltage;
- Tolerance analysis.

Induction Linac concept





- Schematic of the induction accelerator showing accelerating cells.
- Each cell contains two cores, two focusing solenoids and an acceleration gap.

Induction Linac for Electron Cooling

- The linac contains 727 accelerating cells with lengths of 141 mm each. Each cell provides the energy gain of 75 keV.
- The total length of the linac is ~100 m (without injector).
- The power dissipation in the cores of each cell is ~6 kW. The total power dissipation in the LIA is ~4.3 MW.
- Concept scheme of a pulser to feed a cell of the LIA is suggested that meets the requirements of the voltage and pulse length.

Next steps

- Minimize emittance dilution in the linac.
- Tolerance analysis.

Summary

- Our project aims at developing an electron cooling system capable of providing cooling times of ~ 1 hour for 100-GeV protons.
- We have launched this R&D project in July 2018 and, so far, we identified no show-stoppers.
  - Developed a detailed IBS model with full coupling
    - Submitted to PRAB
  - Developed a ring optics concept and determined the required linac and e-gun parameters to meet the cooling requirements
  - Developed preliminary concepts of the electron gun and the induction linac with suitable beam parameters.

- Fermilab is very interested in being part of the EIC R&D
  - Looking for collaboration on cooling with all EIC partner labs