Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Proposal: ERL-based High Energy Cooler

Sergei Seletskiy

For CAD Cooling Studies group in collaboration with JLab

C-AD Machine Advisory Committee Meeting (MAC-22)

December 17-19, 2025

Proposal Team

- Sergei Seletskiy (Principal Investigator)
  Brookhaven National Laboratory

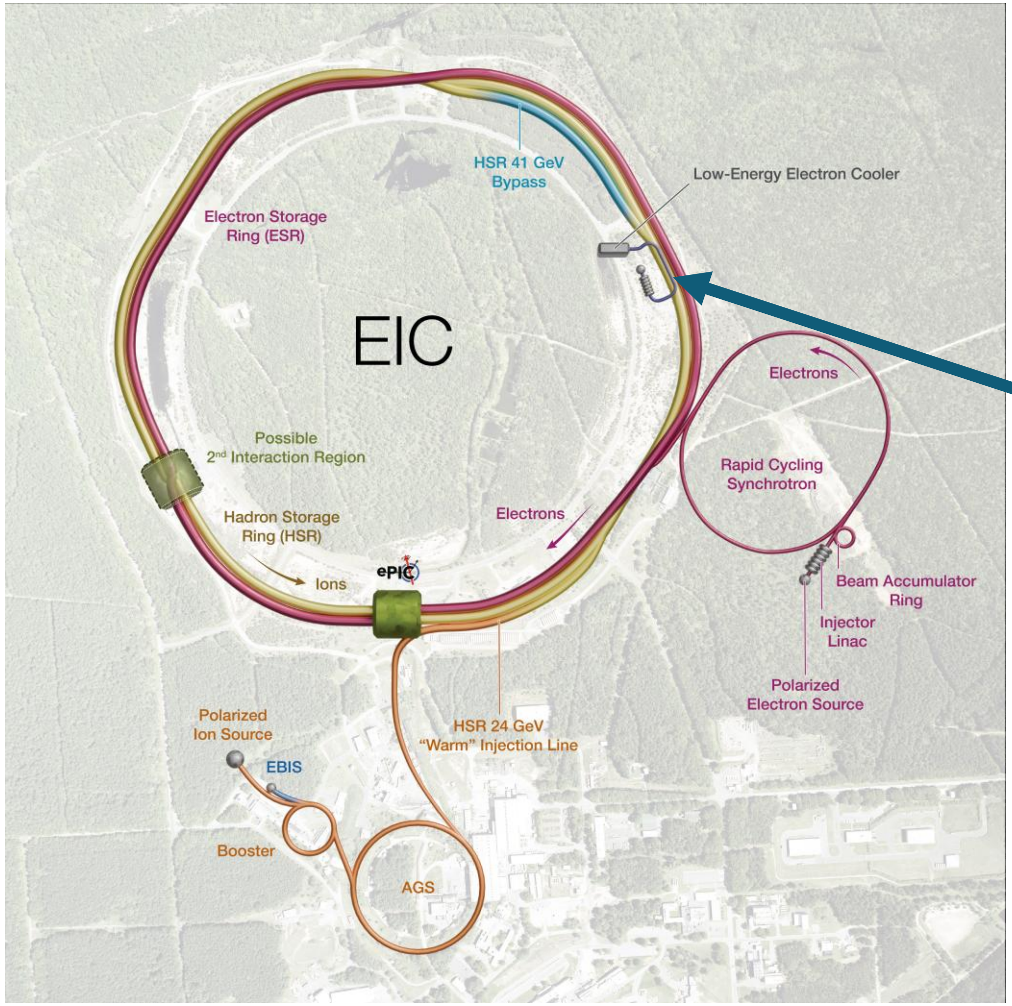
- Dmitry Kayran (Co-Investigator)
  Brookhaven National Laboratory

- Nick Sereno (Co-Investigator)
  Thomas Jefferson National Accelerator Facility

Proposal Objective

We propose to design a non-magnetized, RF-based electron cooler that employs an energy recovery linac to provide cooling of EIC protons at all collision energies.

Cooling requirements for Electron Ion Collider (I)

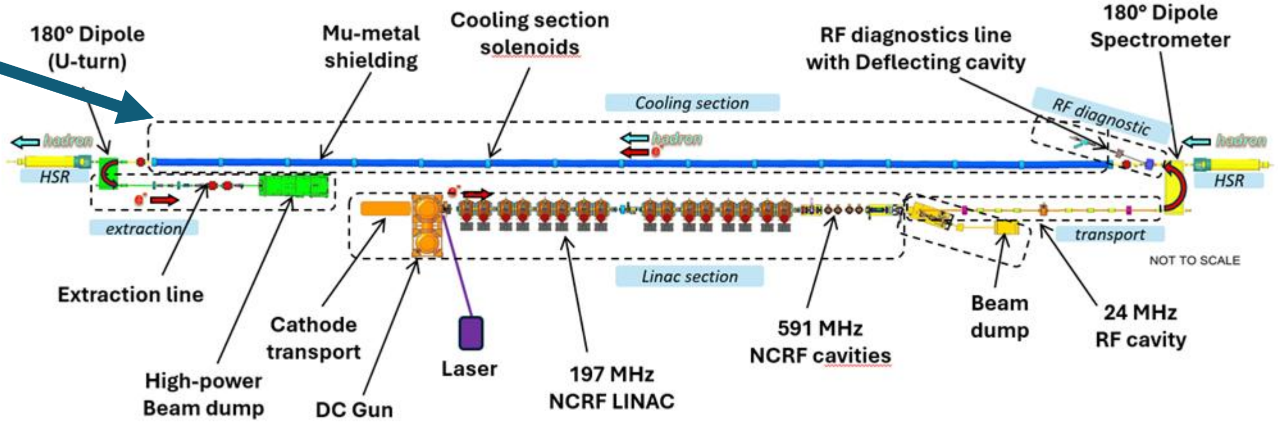


<u>Low-Energy Cooling (LEC):</u>

Cooling hadrons at injection energy (24 GeV):

The goal of cooling at injection energy is to obtain initial proton parameters by cooling the vertical emittance from ~2 um to 0.3-0.5 um (rms normalized). This requires a 13 MeV electron beam.

The LEC is an RF-based, single pass electron cooler.



<u>High-Energy Cooling of protons:</u>

At EIC proton collision energies ($\gamma = 294,\ \gamma = 108$ and $\gamma = 45$), cooling should counteract the longitudinal and transverse emittance growth.

A cooler must be compatible with the LEC.

Cooling requirements for Electron Ion Collider (II)

Table 1: Parameters of EIC protons at collision energies.

Proton energy, GeV	275	100	41
Number of protons per bunch	6.9×10^{10}	6.9×10^{10}	2.6×10^{10}
Geometric emittance (x, y), nm·rad	11.3, 1.0	30, 2.7	44, 10
Relative momentum spread (rms)	6×10^{-4}	6×10^{-4}	6×10^{-4}
Bunch length (rms), cm	6.8	9.7	10.3
Horizontal cooling time*, hours	2.0	2.0	3.4
Vertical cooling time*, hours	Not required**	4.0	2.1
Longitudinal cooling time*, hours	3.0	2.5	3.8

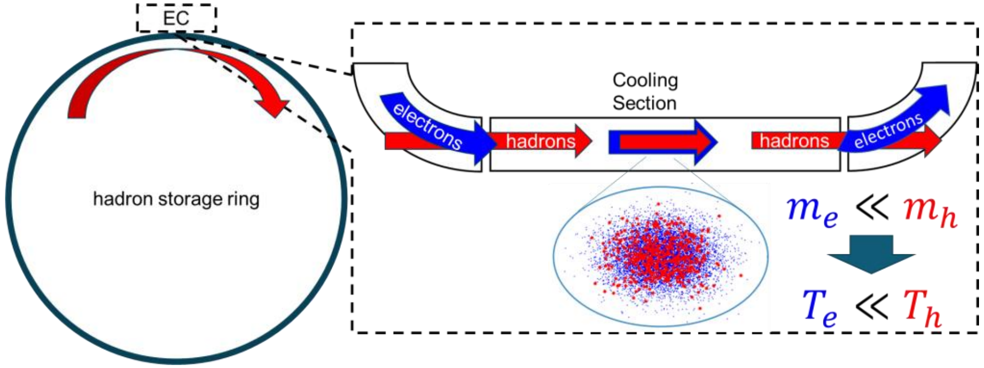
*During stores, emittance growth is dominated by IBS; the cooling times must be optimized to compensate for the IBS-driven heating of proton bunches

** Vertical IBS at these settings is so slow that no vertical cooling is required

A prospective cooler must counteract the IBS-driven longitudinal and transverse emittance growth and maintain close to initial beam emittances.

Brookhaven National Laboratory

Bringing Electron Cooling to high energies



- In electron cooling a bunch of hadrons co-travels with electrons (with matched γ) in a straight section of a hadron storage ring
- “Hot” hadron and “cold” electron gases exchange heat, which leads to reduction of the phase space volume occupied by hadrons

$$\lambda \propto \frac{r_e^2 m_e c Z^2 \Lambda_c}{A_i m_p} \cdot \frac{1}{\gamma^2} \cdot N_e \cdot \frac{L_{CS}}{C_{ring}} \cdot \frac{1}{\left(\frac{\varepsilon_{ne}}{\beta_e} + \frac{\varepsilon_{ni}}{\beta_i}\right)(\varepsilon_{ne}\beta_e + \varepsilon_{ni}\beta_i)\sqrt{\sigma_{\delta e}^2 + \sigma_{\delta i}^2}\sqrt{\sigma_{ze}^2 + \sigma_{zi}^2}}$$

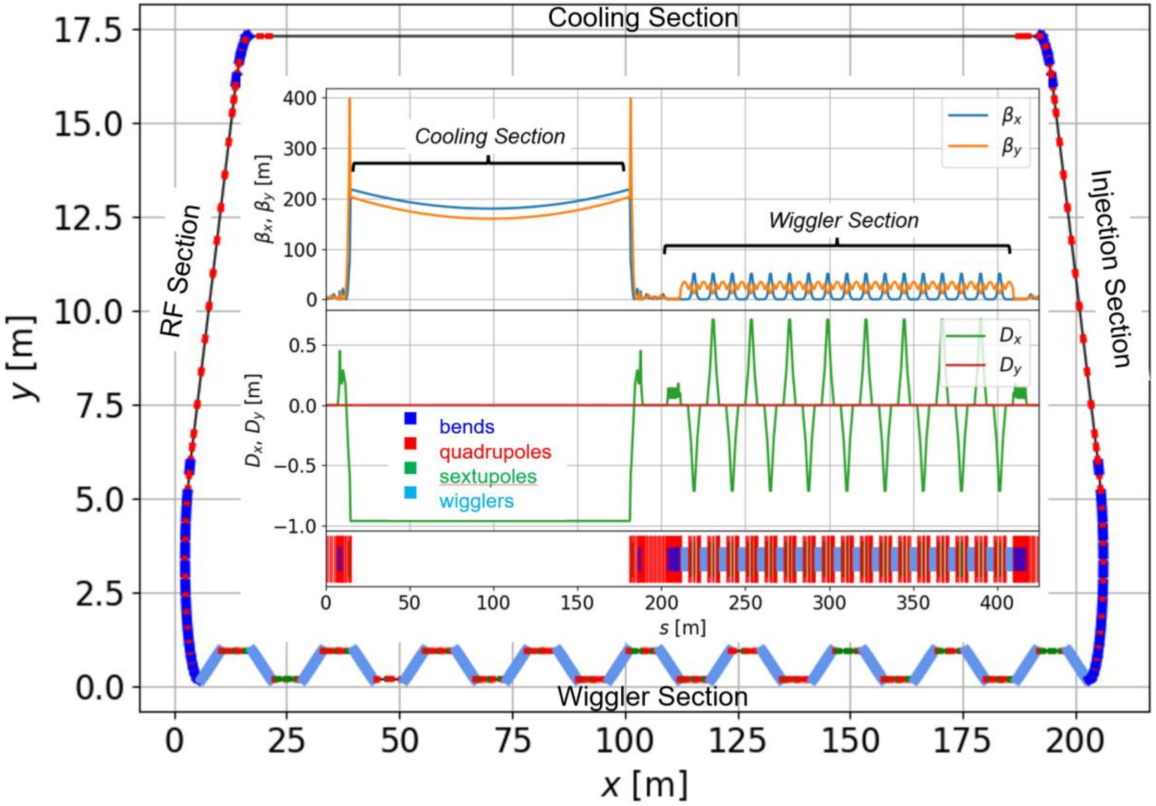
- Cooling rate drops quadratically with energy but grows linearly with number of electrons and length of the cooling section. Precooling helps (smaller ion emittances), so do small e-bunch emittances. Yet, we don’t want to make e-emittances much smaller than p-emittances:
  - gains in cooling rate become small when $\varepsilon_e \ll \varepsilon_i$
  - $\varepsilon_e \ll \varepsilon_i \quad \rightarrow \quad$ core overcooling (bad for collider)
- With available $L_{CS} = 170$ m and the required cooling times, we need to have hundreds of mA of average e-current in the cooling section.

Brookhaven National Laboratory

One needs to reutilize the same e-beam on several passes

Possible approaches to high energy electron cooling

- Ring Electron Cooler (REC)
  - Electron storage ring with millions of turns
  - Relaxed requirements to an injector
  - Ring beam dynamics defines achievable emittances and energy spread → to get cooling one needs ≈ 2 A of average current in the ring (high current, low energy electron storage ring)
  - REC conceptual design was developed https://www.osti.gov/servlets/purl/2573763



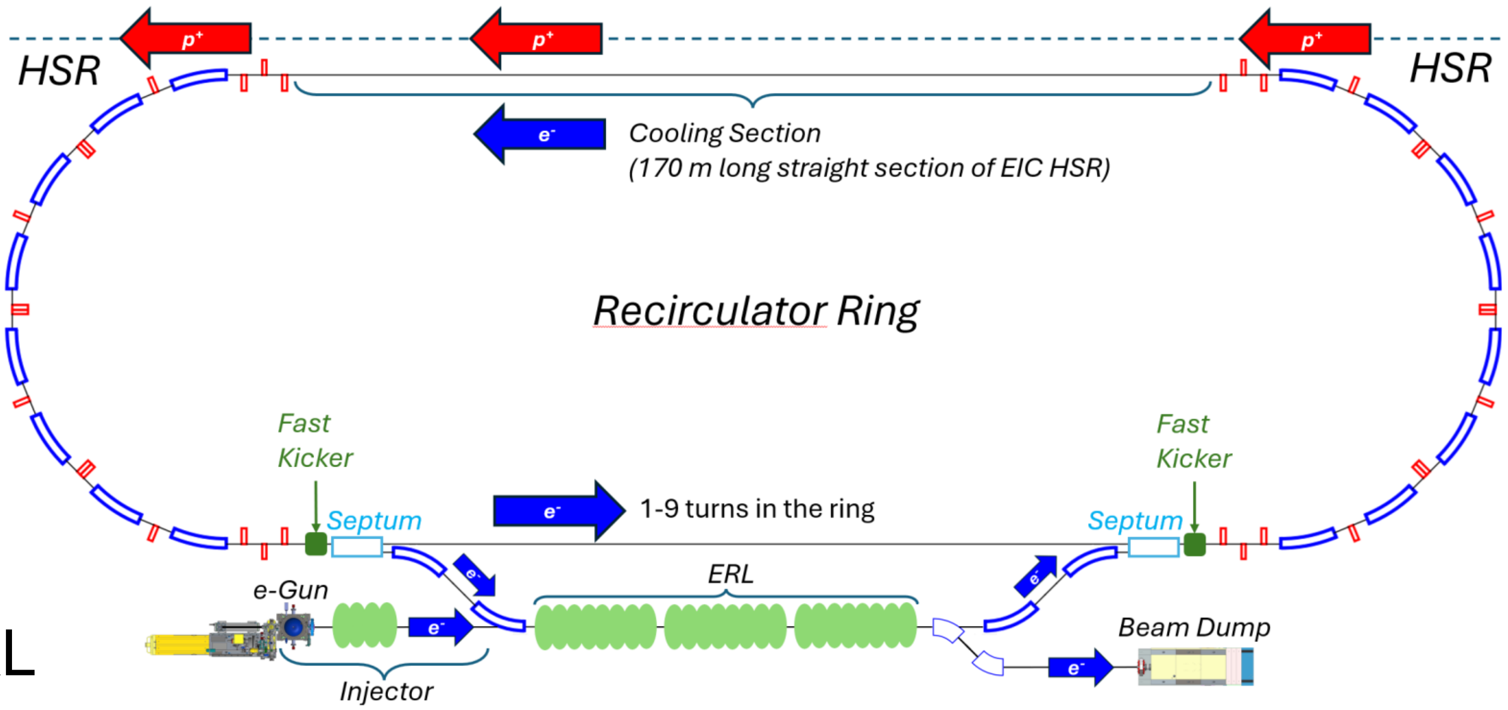
- ERL-based Electron Cooler (ERLEC)
  - There are just a few (1-9) revolutions of electrons in a “recirculator ring” (RR)
  - Achievable emittance and energy spread are defined by the gun/injector/ERL beam-dynamics → one needs ≤ 0.5 A of average current in the RR
  - High brightness, high current electron source & injector preserving high beam quality

Brookhaven National Laboratory

Our goal is to develop a conceptual design of ERLEC

Stages of ERLEC design

The goal of providing a feasible conceptual design of ERLEC can be split in several tasks:



- Finding electron beam parameters for optimal cooling
- Optimizing settings of electron source
- Designing and optimizing beam injector
- Designing and optimizing ERL
- Designing and optimizing recirculator ring
- Evaluating design options for fast kickers

Tentative ERLEC parameters

We performed the first round of cooling optimization, taking into account beam dynamics in the recirculator while keeping the average current from the injector at ≈40-60 mA

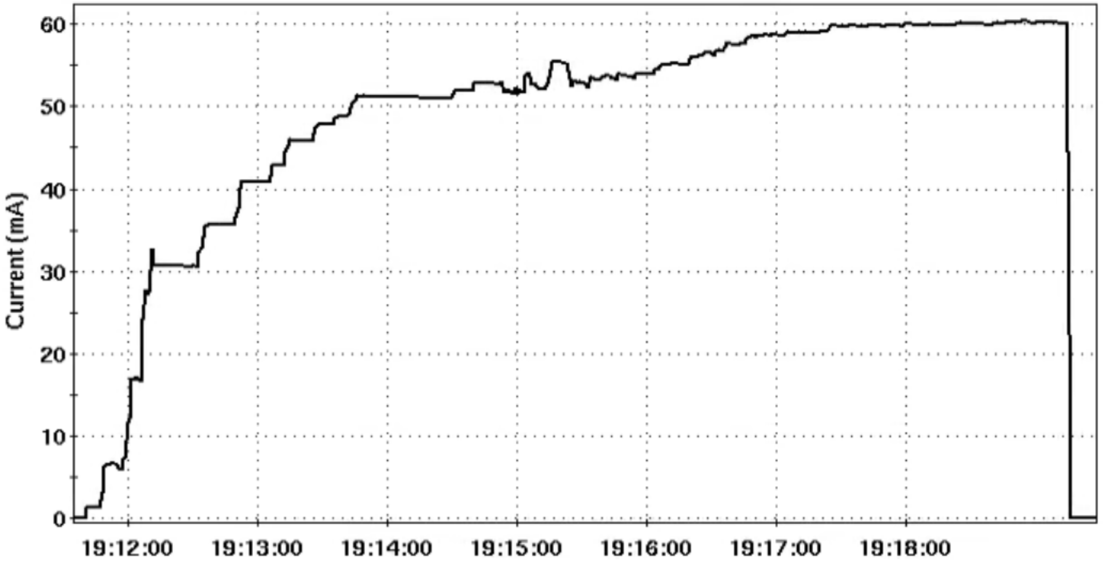
Proton energy, GeV	275	100	41
Electron energy, MeV	150	55	22
Number of electrons per bunch	3×10^{10}	1.25×10^{10}	4×10^{9}
Charge of electron macro-bunch, nC	4.8	2	0.64
Repetition rate in cooling section, MHz	98.5	98.5	98.5
Average repetition rate in injector and ERL, MHz	10.9	19.7	98.5
Number of turns in storage ring	9	5	1
Average current in injector and ERL, mA	53	40	63
Normalized emittance (x, y), μm·rad	2.0, 2.0	1.5, 1.5	1.5, 1.5
Relative momentum spread (rms)	3×10^{-4}	3×10^{-4}	3×10^{-4}
Bunch length (rms), cm	2.5	2.5	2.5
Horizontal cooling time, hours	1.8	1.9	2.0
Vertical cooling time, hours	3.6	3.9	1.8
Longitudinal cooling time, hours	2.9	1.6	1.0

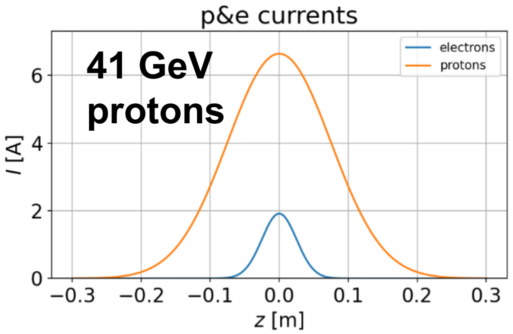
Brookhaven National Laboratory

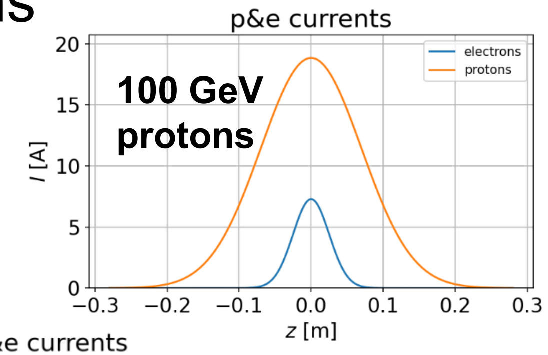
Electron Source

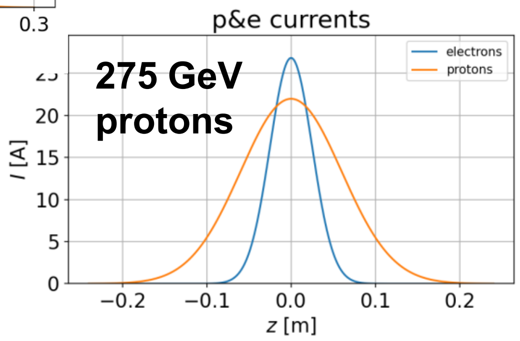
LEReC Gun – DC electron gun driven by a laser

- Typically operated in 350 -380 kV range
- Cathode has 4-6% QE and ≈month long lifetime
- 60 mA current was achieved in LEReC (with a reduced voltage)
- This gun is a baseline for the EIC LEC
- We tentatively assume one e-bunch per one p-bunch for ERLEC but LEReC gun supports various timing patterns

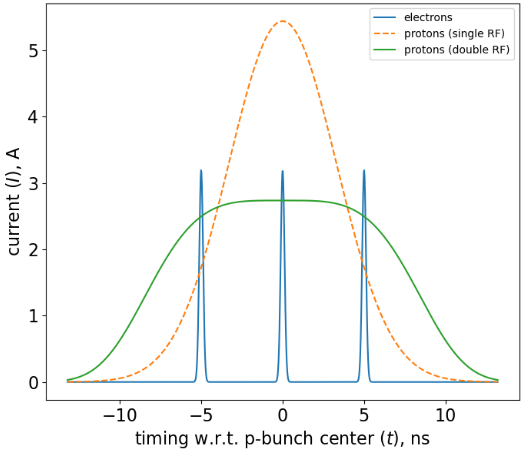




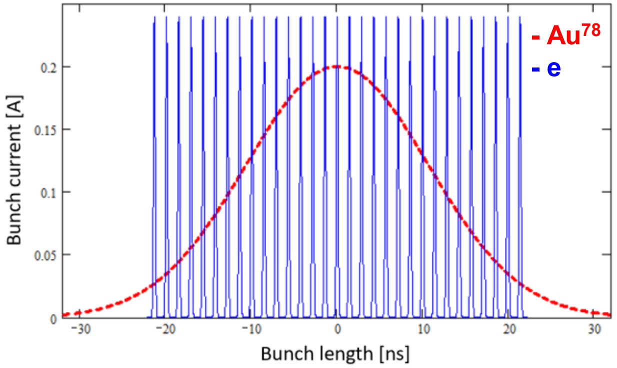




EIC LEC



LEReC



Injector optimization and beam parameters

- The toughest requirement is obtaining 4.8 nC bunch (or a macro-bunch containing multiple bunches with overall charge of 4.8 nC) with normalized emittance $\varepsilon_{n(x,y)} = 2\ \mu\text{m}$.
- A feasible way of obtaining low emittance and low energy spread bunches with high charge is to start with longer bunches and accelerate them with low RF frequency (98 MHz) first. Then the bunches can be compressed and brought to required energy with 591 MHz RF.

Proceedings of PAC07, Albuquerque, New Mexico, USA THPMS087

LOW EMITTANCE ELECTRON BEAMS FOR THE RHIC ELECTRON COOLER

Jörg Kewisch, Xiangyun Chang, Brookhaven National Laboratory*
Upton, NY 11973, U.S.A.

Table 1: Optimization Results

Bunch shape	Transverse Temperature	Bunch charge [nC]	Parmela optimized Emittance in the middle of the linac	Parmela optimized Emittance at the exit of the linac	Energy spread
Beer Can	0.1 eV	5 nC	2.300	2.992	1.20e-3
		7 nC	2.779	3.626	5.22e-4
		10 nC	5.220	5.364	1.58e-3
	0.3 eV	5 nC	2.908	2.941	2.11e-4
		7 nC	3.508	4.047	2.64e-4
		10 nC	7.031	7.773	5.39e-4
Tear Drop	0.1 eV	5 nC	0.915	0.917	2.84e-4
		7 nC	1.247	1.448	2.80e-4
		10 nC	2.235	3.282	3.44e-4
	0.3 eV	5 nC	2.066	2.166	3.00e-4
		7 nC	2.464	2.711	8.16e-4
		10 nC	2.586	2.643	3.44e-4

5 MeV injector
2.4 cm FWHM e-bunches

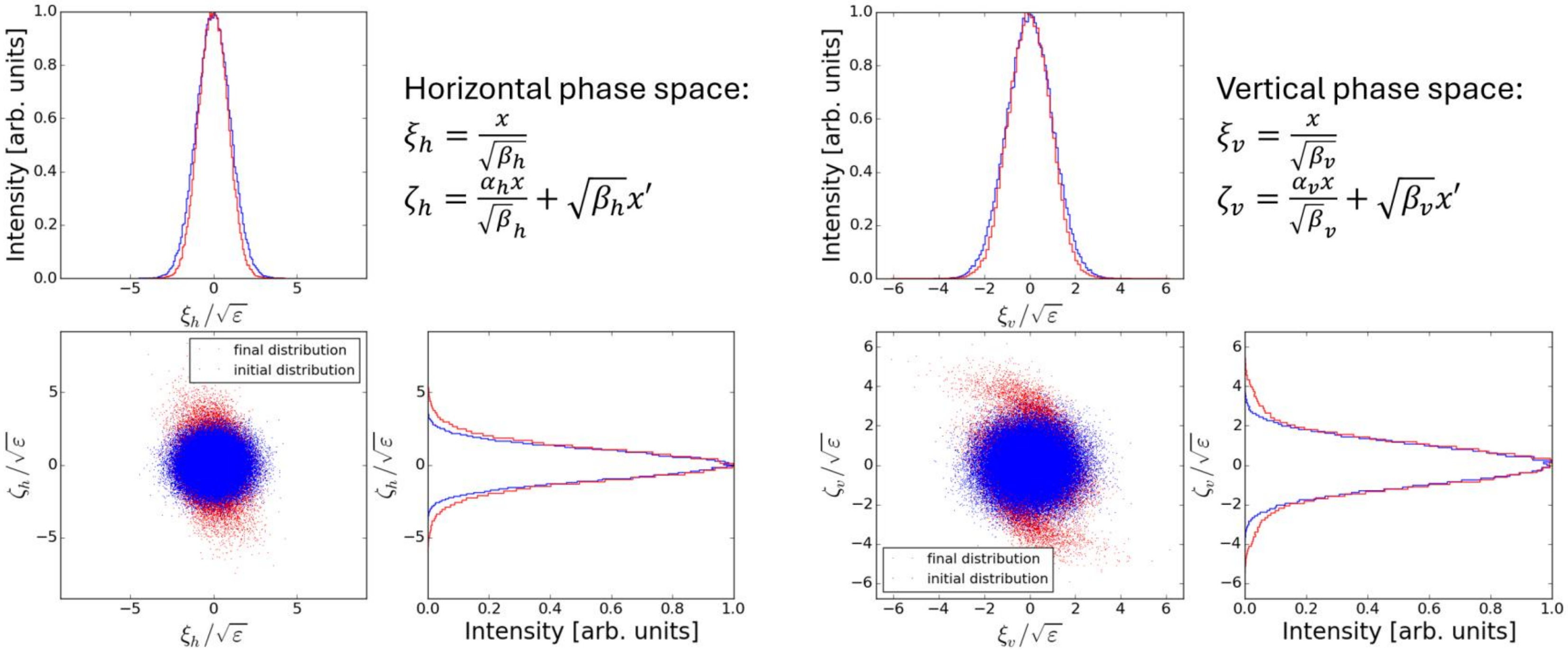
Brookhaven National Laboratory

ERL design

- The project requires an ERL capable of operating in a wide range of parameters: from 22 MeV with 63 mA electron current to 150 MeV with 53 mA electrons
- Designing ERL will be based on the recent experience with designing the 150 MeV, 100 mA energy recovery linac:
  - Evaluating of the beam breakup instability for realistic set of RF cavity HOM parameters
  - Development of an impedance budget
  - Evaluating e-source, injector and ERL for potential development of CSR/LSC - driven microbunching instability
  - Studies of beam halo and mitigation strategies
  - Exploring tolerances to lattice errors

Recirculator Ring

- While electrons make just up to 9 turns in the RR, the ring still must be designed taking into consideration various collective effects which influence e-bunches quality in the cooling section (and on return path through ERL)
  - Space charge effect
  - Proton-electron space charge focusing (beam-beam effect)
  - CSR-driven instability
  - Beam-beam scattering of electrons on protons

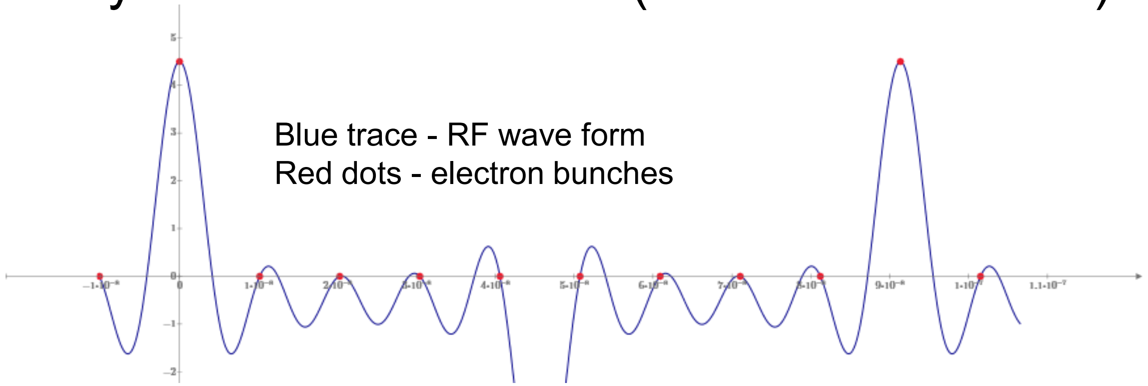


Initial and final (after 9 turns) transverse distribution of e-bunch in the RR for parameters corresponding to 150 MeV electrons

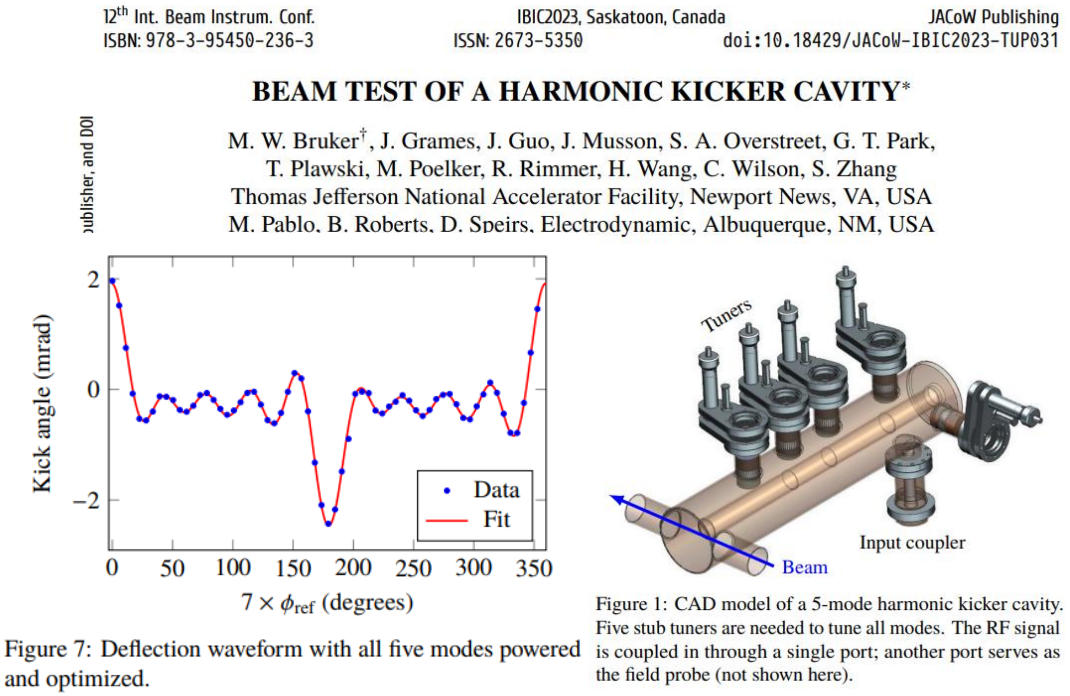
Fast Kickers

Operation of harmonic kicker with beam was demonstrated at Jlab

- One option is to use a "harmonic kicker" to kick every 9th bunch in and out (150 MeV electrons)



Kicker fundamental is 10.95 MHz (1/9th of the proton bunches repetition rate of 98 MHz)



12th Int. Beam Instrum. Conf. IBIC2023, Saskatoon, Canada JACoW Publishing
ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-TUP031

BEAM TEST OF A HARMONIC KICKER CAVITY*

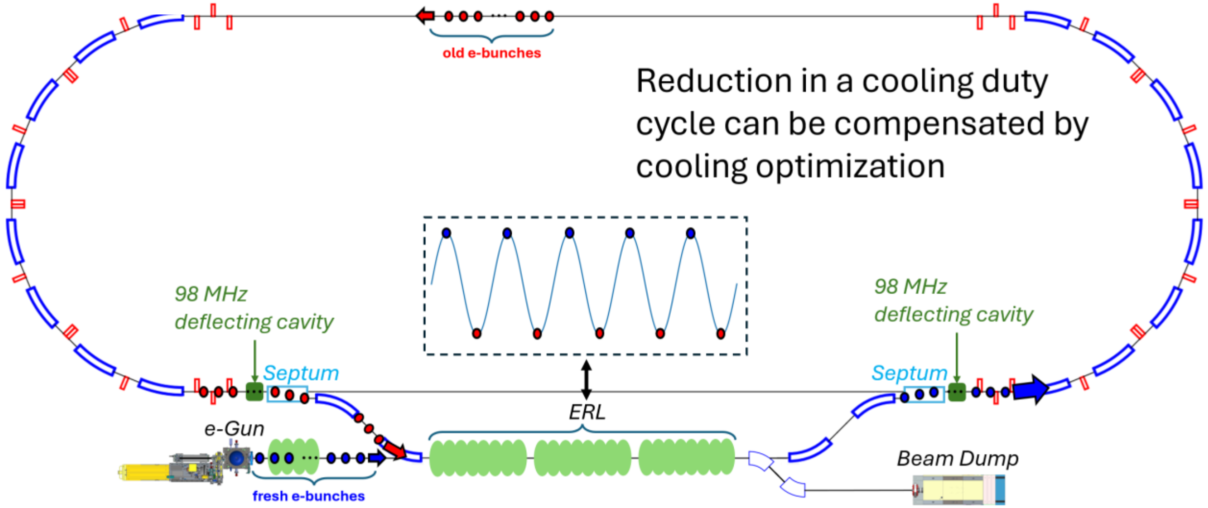
M. W. Bruker†, J. Grames, J. Guo, J. Musson, S. A. Overstreet, G. T. Park, T. Plawski, M. Poelker, R. Rimmer, H. Wang, C. Wilson, S. Zhang
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
M. Pablo, B. Roberts, D. Speirs, Electrodynamic, Albuquerque, NM, USA

Figure 7: Deflection waveform with all five modes powered and optimized.

Figure 1: CAD model of a 5-mode harmonic kicker cavity. Five stub tuners are needed to tune all modes. The RF signal is coupled in through a single port; another port serves as the field probe (not shown here).

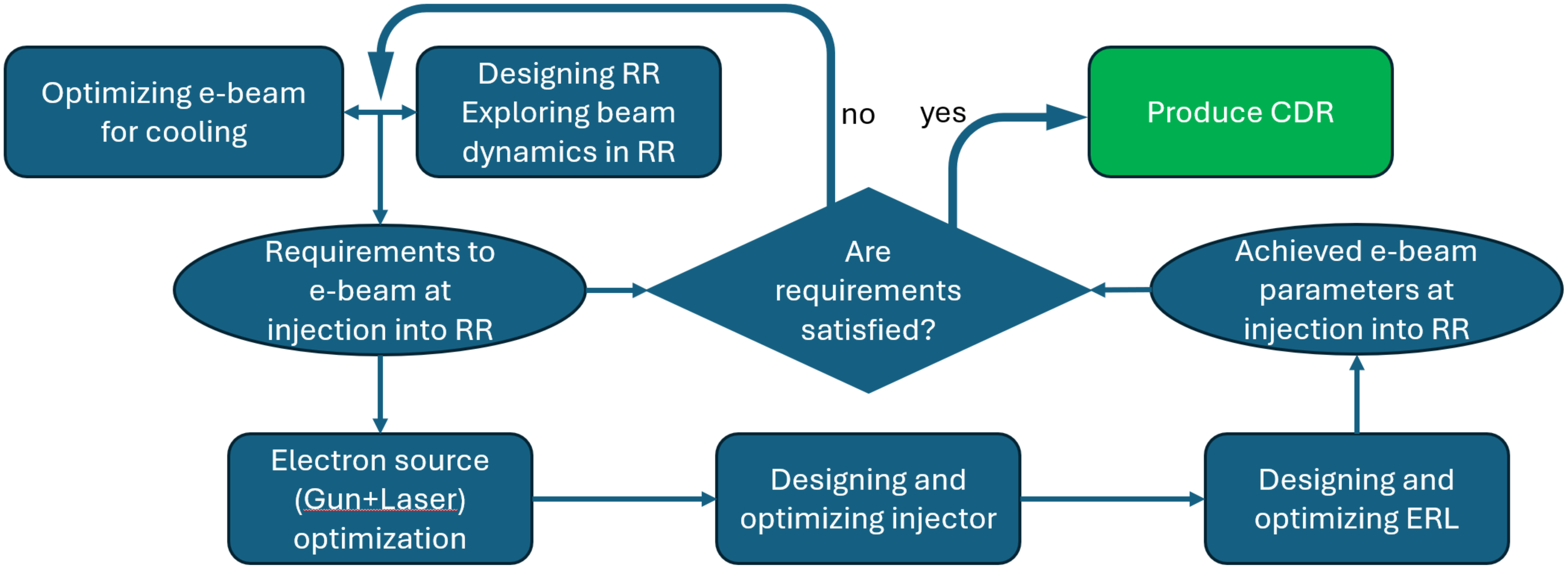
- Another possibility is to extract/inject the train of 140 bunches after 9 turns

This scheme can employ a 98 MHz deflecting cavity as a kicker, with the cavity being on for 140 cycles and off for 1260 cycles.



Brookhaven National Laboratory

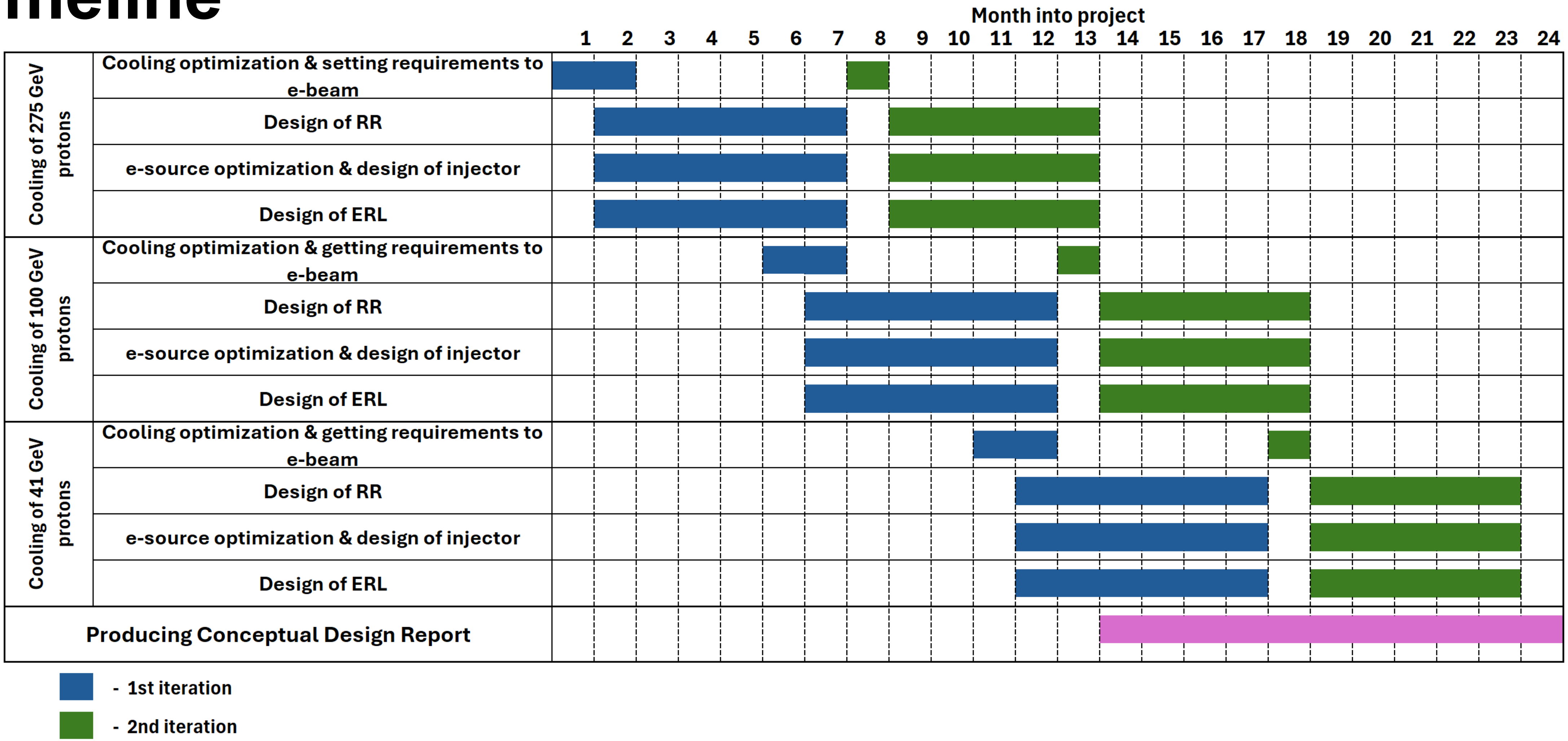
Workflow



We plan to start with the ERLEC design for 275 GeV proton cooling, which is the most demanding case. The designs for 100 GeV and 41 GeV protons cooling will be compatible with optimized cooling at 275 GeV.

Brookhaven National Laboratory

Timeline



- We expect that development of the ERLEC to the conceptual level for each cooling energy will take two iterations. For each iteration the work on the described modules will progress in parallel.
- We plan to have weekly meetings where team members will be coordinating their efforts.

Summary

- We plan to develop a conceptual design of an ERL-based non-magnetized electron cooler for the EIC. This cooler will provide the required cooling at all EIC collision energies and will offer a viable high-energy cooling option for the EIC luminosity upgrade.
- Design efforts will be split in several modules (with work on the modules progressing in parallel):
  - Optimizing electron beam parameters for cooling protons at all three EIC collision energies
  - Designing recirculator ring
  - Electron source optimization and design of injector
  - Designing and optimizing ERL
- Our team has extensive expertise in all the areas necessary for this project, and a consistent track record of success.