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U.S. DEPARTMENT OF ENERGY

Beam Dynamics Challenges and Solutions for a High-Current Electron Cooler Linac at the Electron Ion Collider

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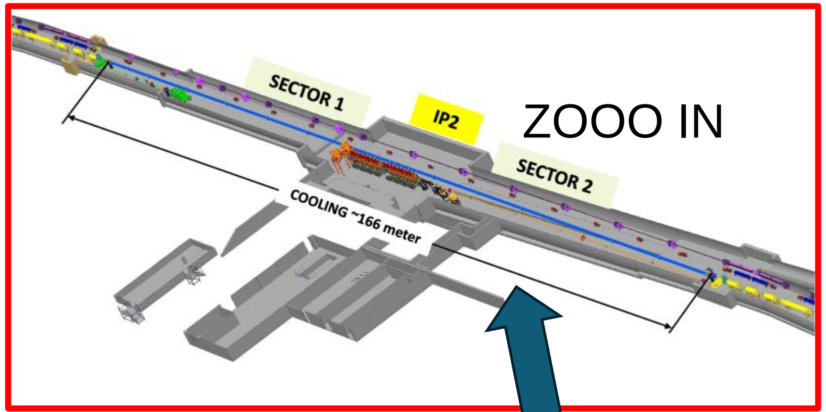
Low Energy Cooler at EIC: motivating

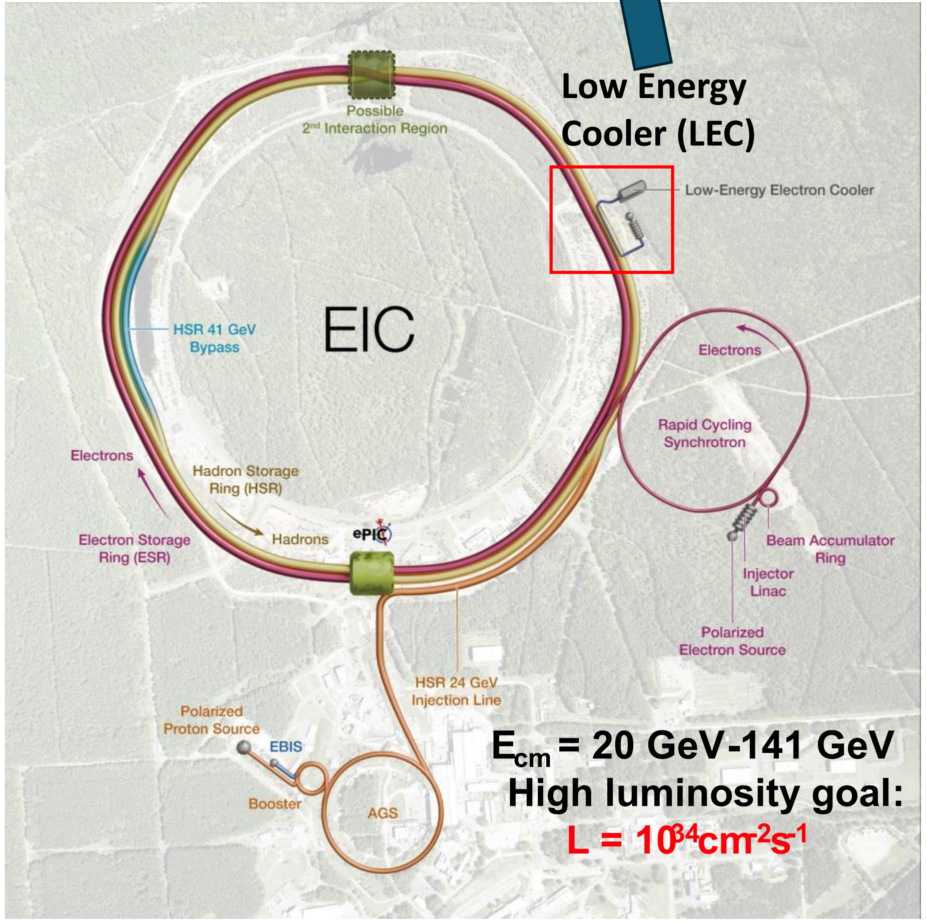
- Electron Ion collider at BNL is aiming to achieve luminosity

$L = 10^{34}\ cm^{-2}s^{-1}$

- High luminosity requires high intensity and low emittances beams

$$L = f_c \frac{N_1 N_2}{A} \simeq f_c \frac{N_1 N_2}{2\pi\sqrt{\beta_{x1}\varepsilon_{x1}+\beta_{x2}\varepsilon_{x2}}\sqrt{\beta_{y1}\varepsilon_{y1}+\beta_{y2}\varepsilon_{y2}}}$$





<u>Low-Energy Cooling (LEC):</u>
The goal of cooling at proton injection energy is to obtain initial proton parameters by cooling the vertical emittance from ~2 um to 0.3 um (rms normalized).

Cooling at injection energy of protons (24 GeV) requires a 13 MeV electron beam.

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What is Electron Cooling? The simple principal

Mix a hadron bunch with an electron bunch traveling with the same velocity and let the two bunches travel together over some length. ➡ The velocity spread of hadrons will get reduced.   Why?

In the co-moving frame, the mixture of an ion bunch and an electron bunch looks like a mixture of two gases – a gas of ions and a gas of electrons

Electrons are much lighter; hence, the gas of electrons is much colder than the gas of ions.

Heat transfer ≡ Electron Cooling

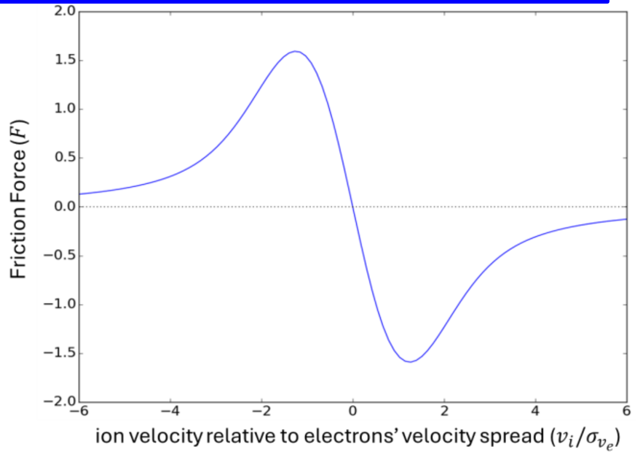
$$m_e \ll m_i$$

$$T = \frac{m\bar{v}^2}{3k_B}$$

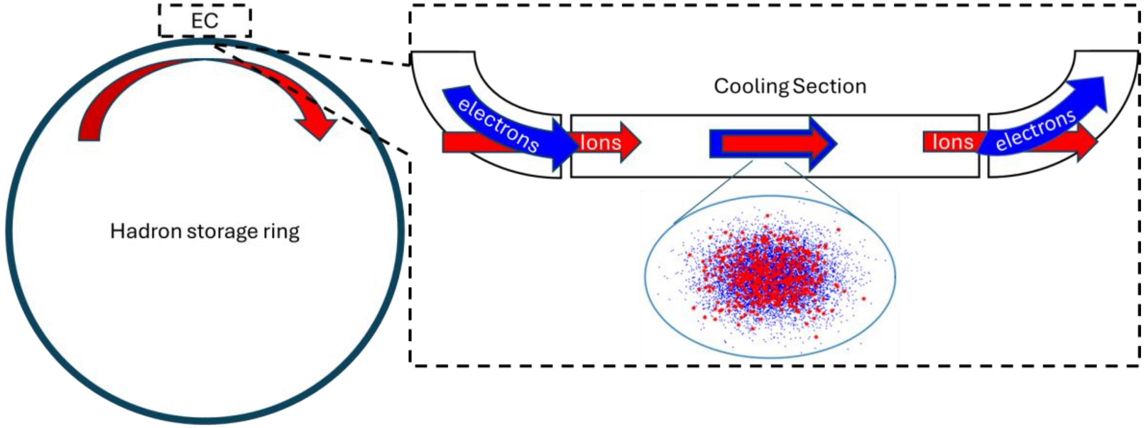
$$T_e \ll T_i$$

Friction force in Electron Cooling

$$\vec{F} = -\frac{4\pi n_e e^4 Z_i^2}{m_e}\int \Lambda_C \frac{\vec{v_i}-\vec{v_e}}{|\vec{v_i}-\vec{v_e}|^3} f_e(v_e)d^3v_e$$



Cooling Rate



$$\lambda \propto \frac{r_e^2 m_e c Z^2 \Lambda_c}{A_i m_p} \cdot \frac{1}{\gamma^2} \cdot \frac{N_e}{\varepsilon_{xn}\varepsilon_{yn}\sigma_z\sigma_\delta} \cdot \frac{L_{CS}}{C_{ring}}$$

$\lambda \propto \frac{1}{\gamma^2}$ - drops quadratically with energy

$\lambda \propto N_e$ - grows linearly with number of electrons

$\lambda \propto L_{CS}$ - grows linearly with the length of the cooling section

$\lambda \propto \frac{1}{\varepsilon_{xn}\varepsilon_{yn}}$ is inversely proportional to the normalized emittances

- **Electron Cooling is a well-established technique with 50 years of experimental experience to cool hadrons using DC sources for electron beam. Limited to few MeV . For higher energy RF acceleration is more useful.**

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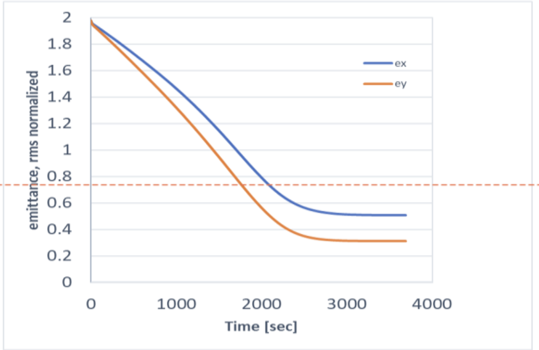
EIC LEC Required Parameters

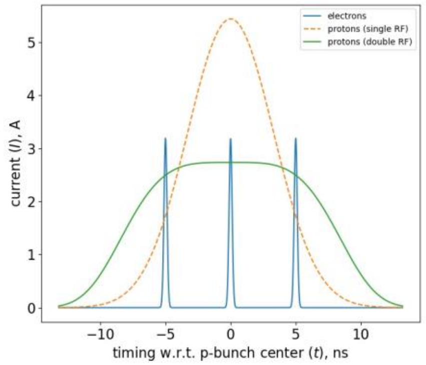
Cooling simulation

Average current of electrons: **I_{av}=74mA**
Electrons rms angles in the cooling section: **25 urad**
Effective cooling section length: **168 meters**



Cooling simulations of protons at γ=25, with decoupled transverse motion (**IBS+Cooling only,** using single harmonic RF).
Longitudinal emittance is kept constant during cooling process.
After cooling, normalized rms emittances of protons **ex, ey=0.5,0.3 um**
(horizontal emittance can be increased further as needed.**)**

Beam Structure in the Cooling Section



Protons bunch structure:
f_rep=24.6 MHz
N_p=2.8e11, I_peak=2.7 A (with 2nd harmonic RF)
Rms length=1m

Electrons bunch structure:
f_RF=197 MHz
Single bunch: Q_e=1 nC
Number of bunches in macro-bunch: 3
Rms length=0.04m

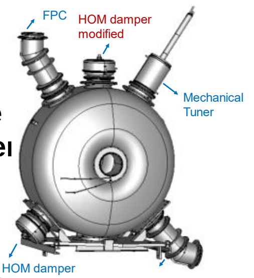
2nd harmonic RF alleviates space-charge effects reducing peak current of protons to about 3A (space charge tune shifts after cooling $\Delta Q_{sc,x,y}$=0.06, 0.1), allowing vertical emittance to be cooled without introducing additional heating of horizontal emittance

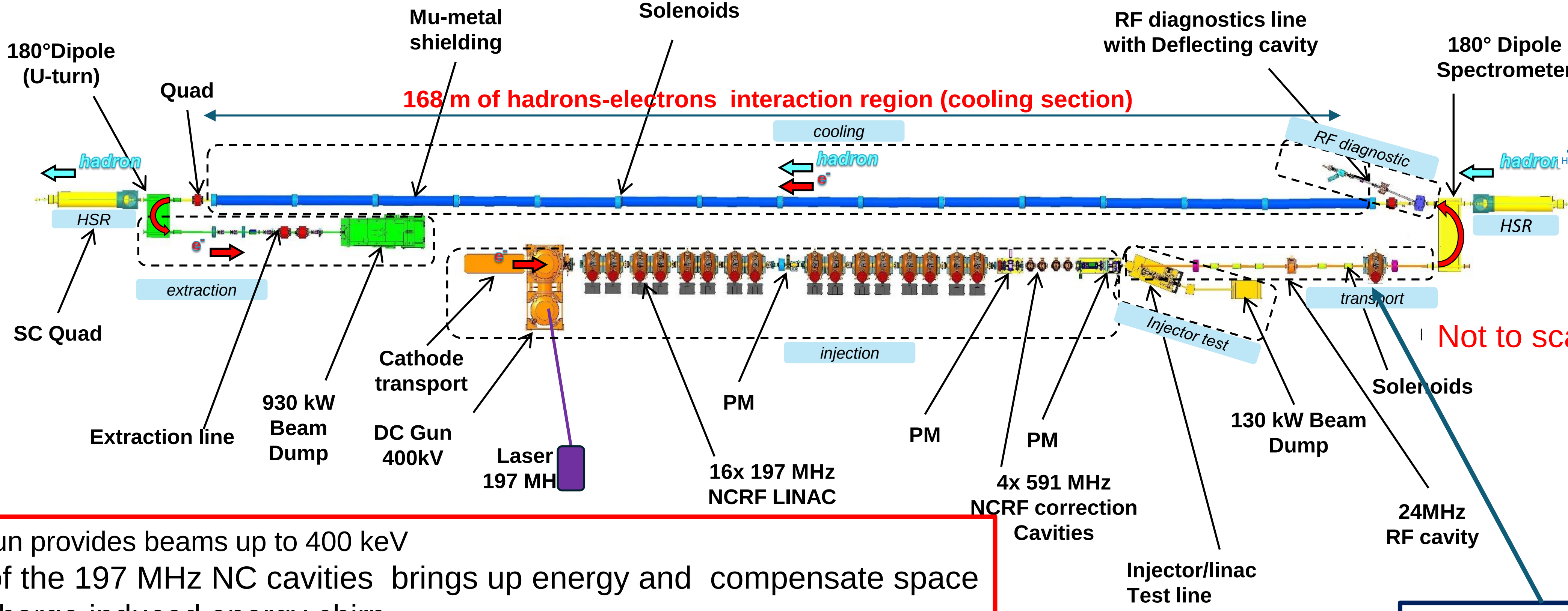
	electrons	protons
Relativistic factor gamma	25.4	25.4
RF frequency, MHz	197	24.6
Cooling section length, m	168	168
Cooling sections beta function, m	150	100-200
Hadrons Dy, Dy', m, rad		<1, <0.02
Total charge per proton bunch, nC	3	45
Electrons kinetic energy, MeV	12.5	
Electron average current, mA	74	
Normalized emittance, rms, um	<1.5	2
rms bunch length, cm	4	100
rms dp/p	<5e-4	6e-4
Angles in cooling section, urad	20-30	20

Absolute RMS energy spread: < **6 keV!!!**

LEC schematic layout at IR2 @EIC

197MHz Cavity – CERN SPS/RHIC





DC gun provides beams up to 400 keV

Set of the 197 MHz NC cavities brings up energy and compensate space charge induced energy chirp

Set of 3rd harmonic NC cavities (4x591 MHz) corrects correlated energy spread and brings beam energy to the required energy

Low frequency 24 MHz cavity installed downstream in the transport line to compensate effect of beam loading from 1st to 3rd bunch in the macro bunch

197 MHz cavity at the end of the transport line for final longitudinal phase space correction and energy adjustment

The LEC is scaled up version of LEReC*: more RF cavities, longer cooling section, higher beam current.

* A. V. Fedotov et al. “Experimental Demonstration of Hadron Beam Cooling Using Radio-Frequency Accelerated Electron Bunches”, Phys. Rev. Lett. 124, 084801 (2020)

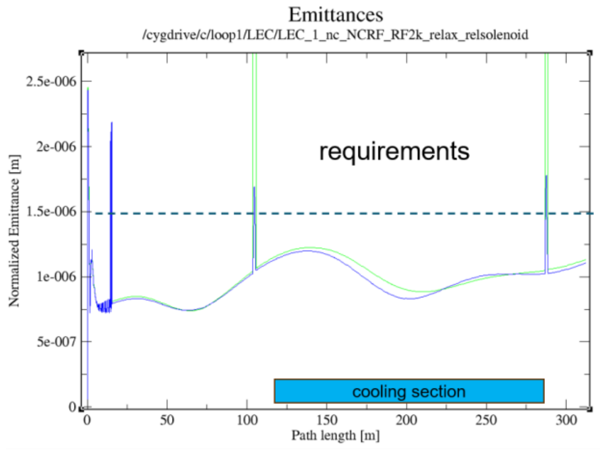
Simulation approach and results

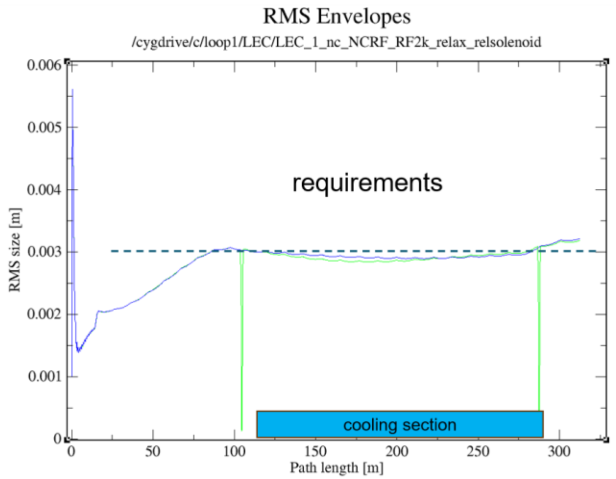
- Space charge effect dominated beam dynamic from start to end

$$\frac{\varepsilon^2}{a^3} << \frac{2Q}{a+b},$$

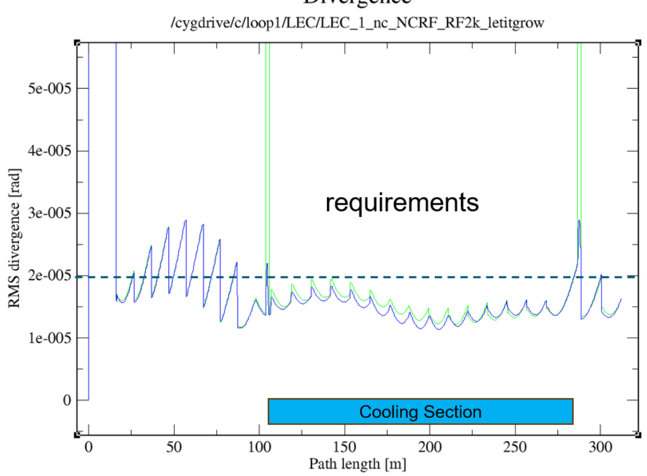
- Beam dynamics simulation/optimization were conducted using code PARMELA
- PARMELA is a well recognized code when space charge plays important role
- The benchmark PARMELA simulation results with other codes (GPT, IMPACT-T) The first prelaminar results shows a good agreement between PARMELA and IMPACT-T
- For all simulation we are using initial bunch distribution: beer-can, with pulse length of 400 ps and radius at the cathode of 2 mm

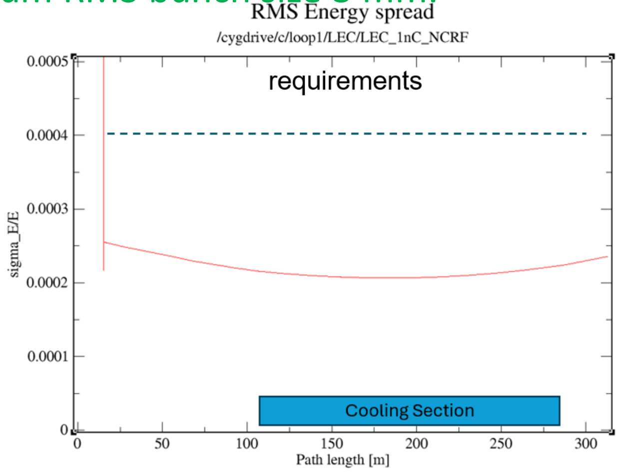
Gun-to-dump simulations results: single bunch charge of 1 nC





Normalized rms emittances <1.5um RMS bunch size 3 mm.





RMS energy spread <4e -4, Electron beam divergence <20 urad.

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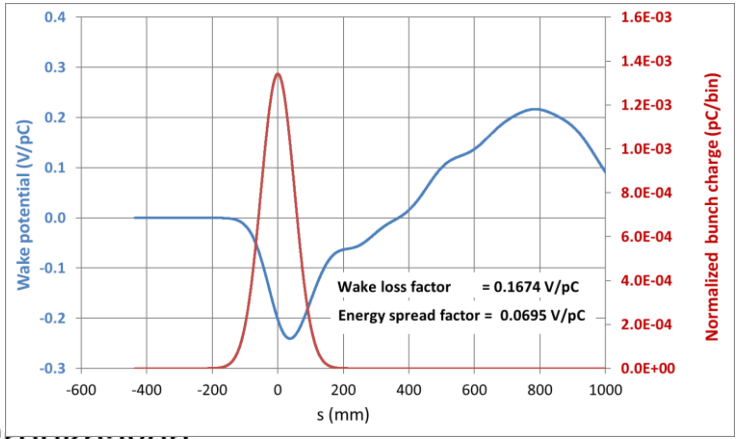
Beam loading effects on final bunch-by-bunch energy distribution

	197 MHz	591 MHz
Frequency [MHz]	197.0508	591.1524
Tuning range [MHz]	±0.12	-0.5~+1.0
Total Voltage [MV]	13.6	1.5
# of Cavities	17	4
Voltage per cavity [kV]	800	400
R/Q cir. [Ω]	170	96
Wake Loss Factor [V/pC]	0.167	0.275*
Voltage droop from 1 to 3 bunches [keV]	0.32	0.55

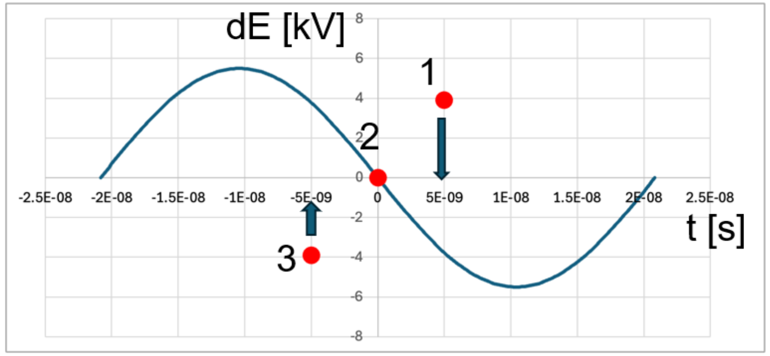
Example: Warm 197MHz cavity wake field



For operation using 3x1nC bunches :

- Energy difference between 1st and 3rd Results of 17 (197 MHz) cavities
  dE_{197MHz}= 5.6 keV
- Results of 4 (591 MHz) cavities
  dE_{591MHz}=2.2 keV
- **Maximum accumulated effect:**
  dE_{max}/E=7.8 keV/13 MeV=6×10^{-4} is too large

- Will use low frequency (24 MHz) cavity with V of 10kV to minimize energy difference between e-bunches



Summary and outlook

- RF-based electron cooler is being developed to provide cooling of protons at injection energy of 24GeV. Such a Precooler requires 13MeV electron accelerator.
- Current design of LEC accelerator and transport fulfills the bunch quality requirement in the cooling section
- We start addressing other beam dynamics effects: such as beam loading, laser jitter, interaction with protons and more
- Preservation of the beam quality through the entire accelerator and long cooling section remains a primary design objective
- The low energy spread depends on careful RF phase control, wakefield management, and a tight impedance budget.

Thank you for your attention!

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