Beam dynamics studies for Low-energy Electron Cooler for Electron Ion Collider

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U.S. DEPARTMENT OF ENERGY

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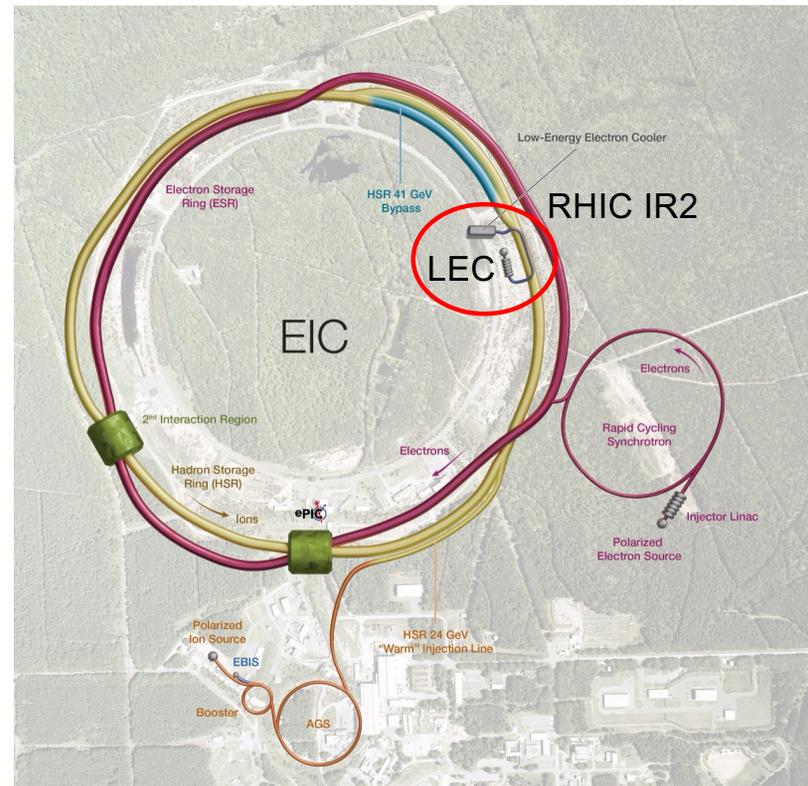**COOL25** | Beam Cooling and Related Topics

October 27–31, 2025

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Outline

- Required parameters
- General layout
- Beam Time structure
- Longitudinal gymnastics
- Transvers beam dynamics
- Gun at lower voltage
- Cathode off center operation
- Laser jitter
- Summary

Cooling Requirements for EIC

Low-Energy Cooling (LEC):

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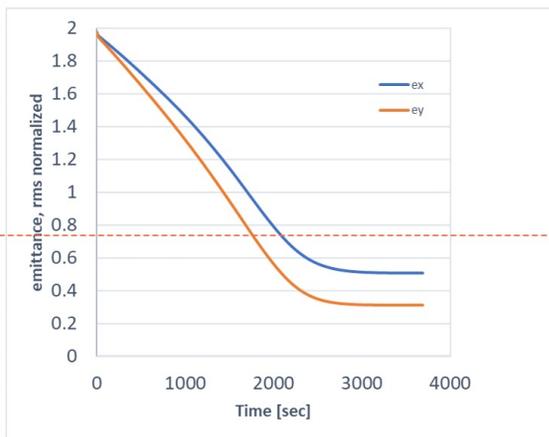
Cooling at injection energy of protons (24 GeV) requires a 13 MeV electron beam.

High-Energy Cooling (HEC) of protons:

High-Energy Cooling (HEC) system capable of fully counteracting emittance growth at collision energies (41, 100, and 275 GeV) would greatly improve luminosity in the EIC.

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EIC LEC Required Parameters *

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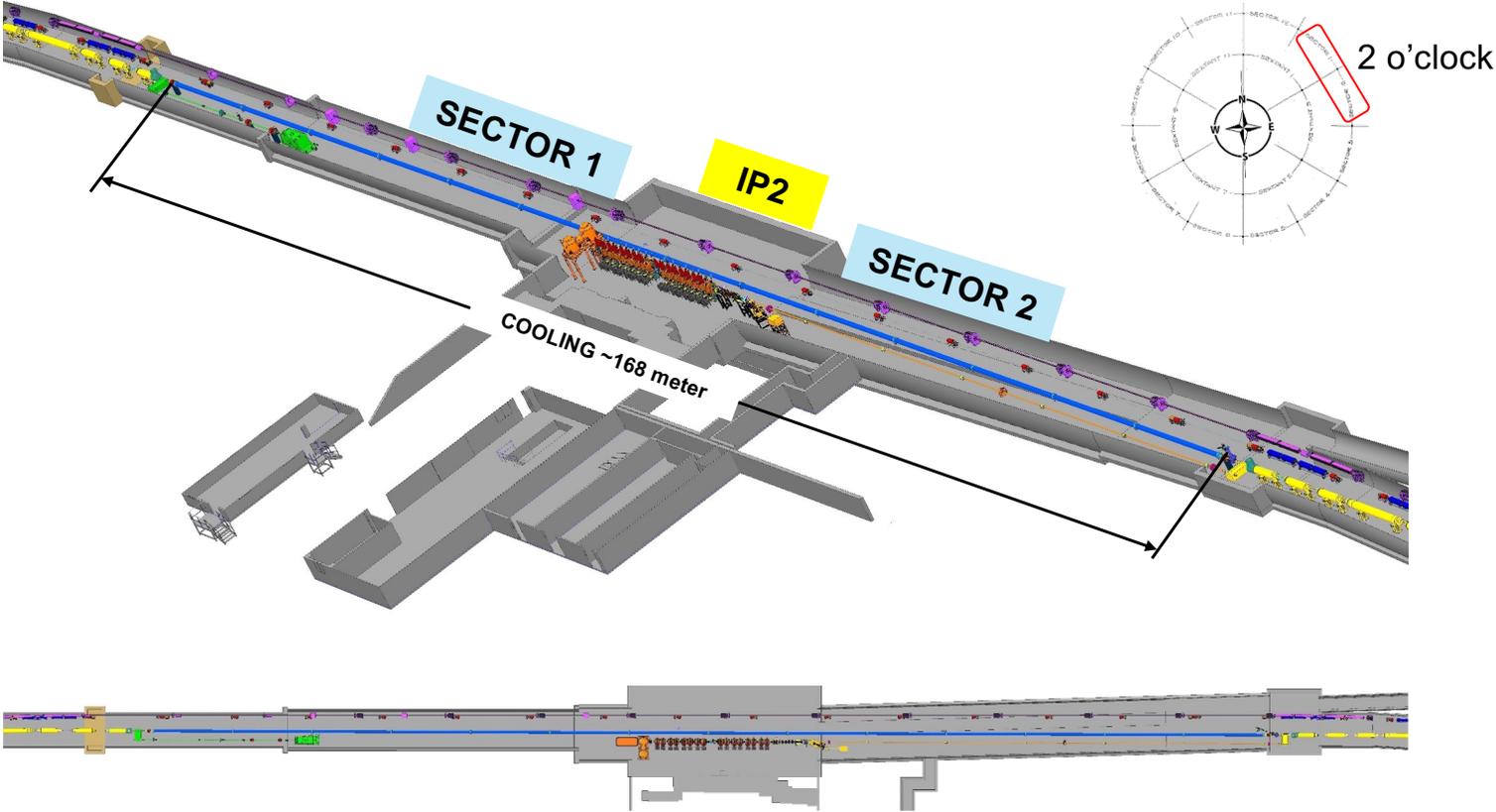Effective cooling section length: **168 meters**

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.)

	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

See Alexei Fedotov's talk, TUA1 at this conference

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Low-Energy Cooler (LEC) Layout

SECTOR 1

IP2

SECTOR 2

COOLING ~168 meter

2 o'clock

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LEC schematic layout at IR2 @EIC

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

180°Dipole (U-turn)

Quad

Mu-metal shielding

LEReC Cooling Solenoids

RF diagnostics line with Deflecting cavity

180° Dipole Spectrometer

hadron

cooling

hadron

RF diagnostic

hadron

HSR

HSR

extraction

injection

Injector test

transport

NOT TO SCALE

SC Quad

Cathode transport

PM

PM

PM

Solenoids

Extraction line

930 kW Beam Dump

Laser 197 MHz

4x 591 MHz NCRF correction Cavities

130 kW Beam Dump

Not to scale

DC Gun 400kV

Injector/linac Test line

24MHz RF cavity

16x 197 MHz NCRF LINAC

Later we add one more 197 MHz cavity at the end of the transport line to allow fine energy and energy spread tuning

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Beam time structure

Use several electron bunches per hadron bunch to reduce bunch charge requirement per electron bunch

LEC beam structure in the cooling section
γ= 25.4 (E_{ke}=12.5 MeV)

Electrons: f=197 MHz, RMS length=4 cm,
Q_e=1 nC , I_peak=4 A,
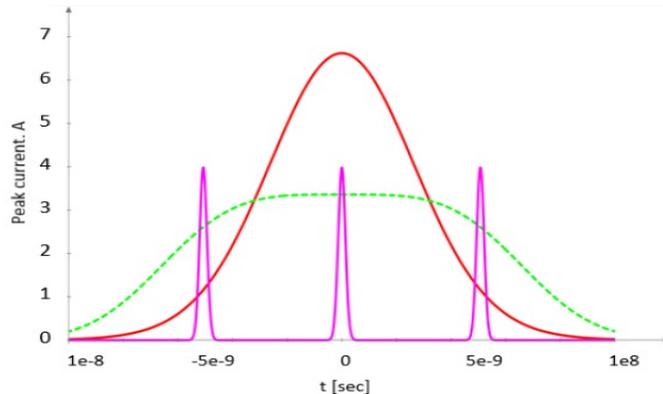**Protons:** rep.rate 24.6 MHz, RMS length 1 m,

Figure 3: Three electron bunches (magenta) spaced by 5.1ns placed on a single proton bunch (red: single RF harmonic; green: double RF harmonic).
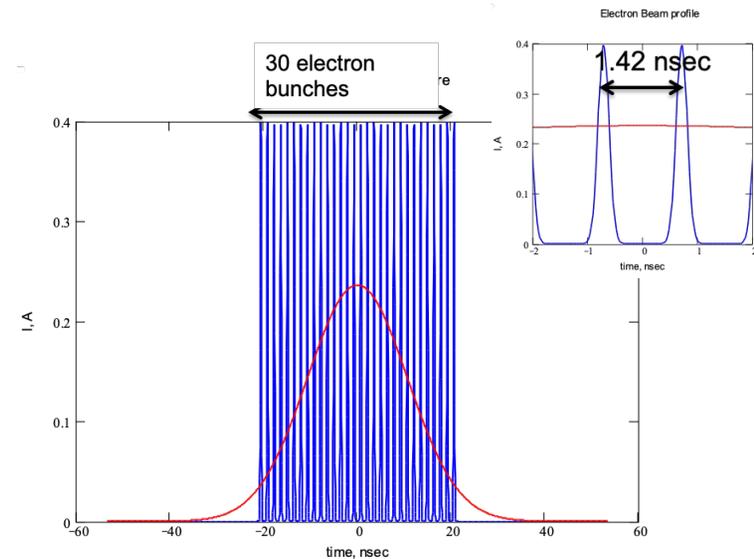
LEReC used similar multi bunches electron structure to cool hadrons at RHIC

LEReC beam structure in the cooling section
γ= 4.1 (E_{ke}=1.6 MeV)

Electrons: f=704 MHz, RMS length=3 cm,
Q_e=100 pC , I_peak=0.4 A,
Hadrons: rep.rate 9.3 MHz, RMS length 3 m,

30 electron bunches

1.42 nsec

Layout description (Accelerator)

- DC gun provides beams up to 0.4 MeV

- 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 (not shown) to compensate effect of beam loading from 1st to 3rd bunch in the macro bunch
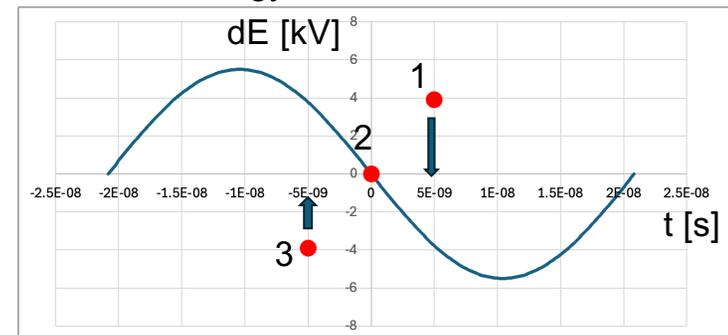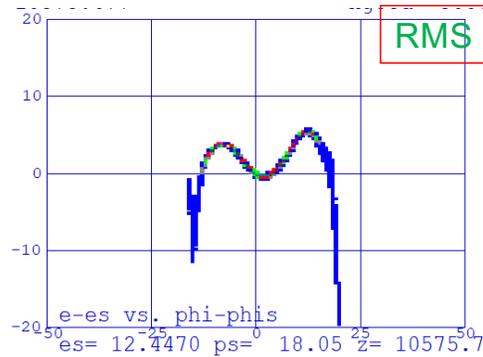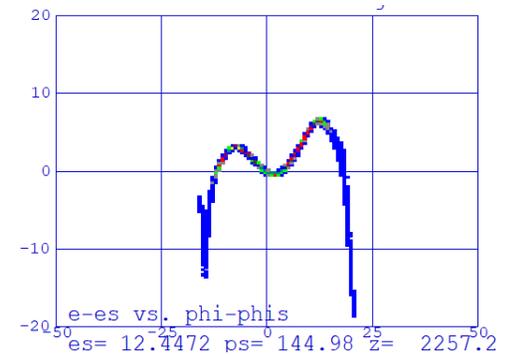

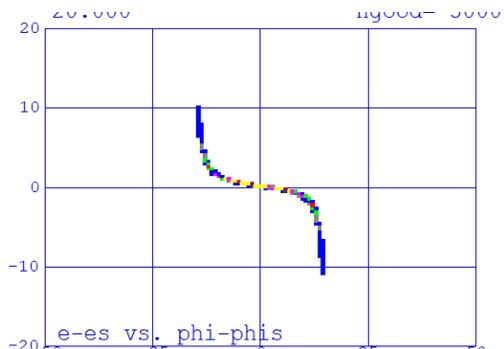DC gun

16x 197 MHz RF cavities

4x 591 MHz RF cavities

Beam loading effect on final beam energy

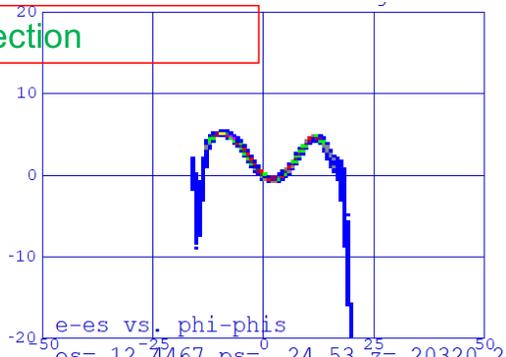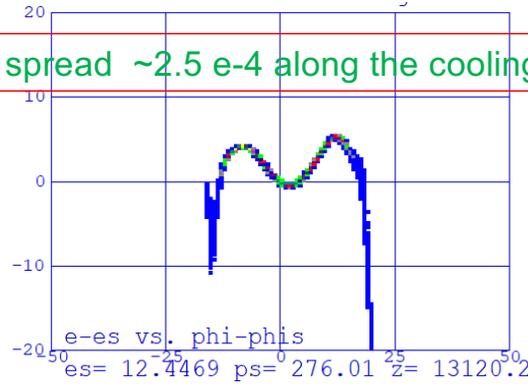|	197 MHz	591 MHz
Frequency [MHz]	197.0508	591.1524
Tuning range [MHz]	±0.12	-0.5~+1.0
Total Voltage [MV]	13.6	1.5
# of Cavities	17	4
Voltage per cavity [kV]	800	400
R/Q cir. [Ω]	170	96
Q0	48000	34000
FPC Qext	24000	34000
Pcav [kW]	60	25
Pbeam [kW]	60	-
RF power [kW]	70+70	35
Wake Loss Factor [V/pC]	0.167	0.275*
Voltage droop from 1 to 3 bunches [keV]	0.32	0.55

For operation using 3x1nC bunches :

- Energy difference between 1st and 3rd bunches could reach

- 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=6x10^{-4}

- Will use low frequency (24 MHz) cavity 5 kV to minimize energy difference between e-bunches

Longitudinal dynamics (phase space)

At the entrance to the 1st cavity

At the end to the 16th cavity

At the end of the LINAC

RMS energy spread ~2.5 e-4 along the cooling section

At the beginning of the cooling section

At the center of the cooling section
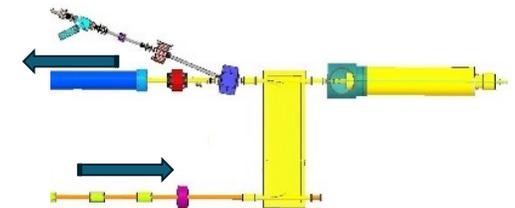
At the end of the cooling section

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Layout description (transport and cooling section)

- In transport line we use solenoids every ~10 m to control and match transvers bunch size from the accelerator to the cooling section
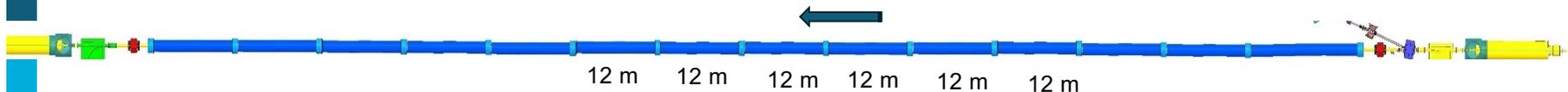

- A single 180-degree (non achromatic) turn-around dipole

merges electron bunches with hadron bunches into
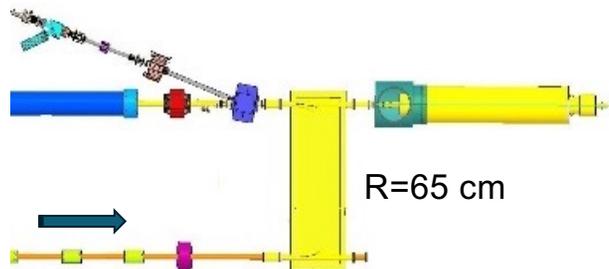
the cooling section

- 2 quadrupoles at each ends of the 180d dipole are

 installed for fine matching electron bunches into the cooling section

- In the cooling section, we placed solenoids every 12 m to keep angular spread under control and use u-metal shielding to cover rest of the colling section

12 m   12 m   12 m   12 m   12 m   12 m

180 degree single magnet turn around

R=65 cm

Same idea works well at LEReC:
merging cooling sections in
YELLOW and BLUE rings is single
180 degree magnet with 35 cm radius

Energy spread: 5E-04
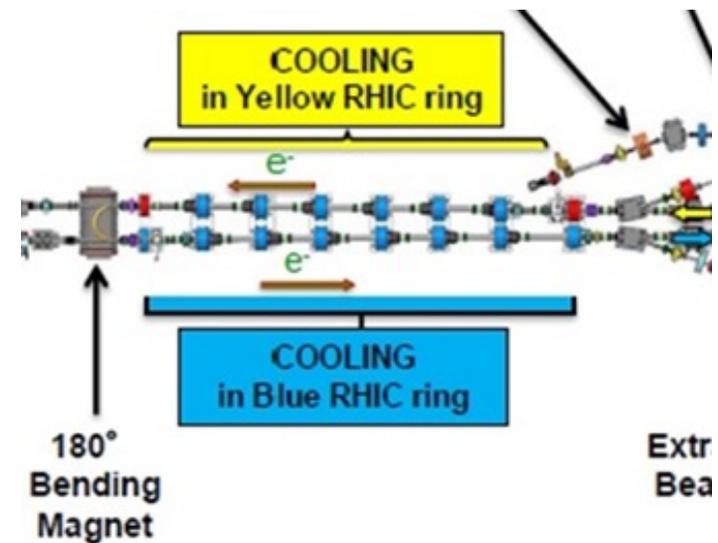Bunch size /Angular spread in the cooling
section : 3 mm /20 urad
Then requirement for the dispersion
D << 6 m and   D' << 0.04
By design after the magnet: D=1.3 m and D'=0

Beam dynamics simulations confirms there is no
emittance degradation as a result of this dipole

COOLING
in Yellow RHIC ring

e⁻

e⁻

COOLING
in Blue RHIC ring

180°
Bending
Magnet

Extr
Bea

LEC: Space charge dominated beam dynamic

Envelope equation*

$$\frac{d^2a}{dz^2} = -K(z)a + \frac{\varepsilon^2}{a^3} + \frac{2Q}{a+b},$$

$$\frac{d^2b}{dz^2} = +K(z)b + \frac{\varepsilon^2}{b^3} + \frac{2Q}{a+b}.$$

Space Charge effect term

Emittance effect term

where:

$$Q = \frac{2qI}{(\beta\gamma)^3 mc^3 4\pi\varepsilon_0},$$

Space charge dominated regime

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

Space Charge effect domination parameters

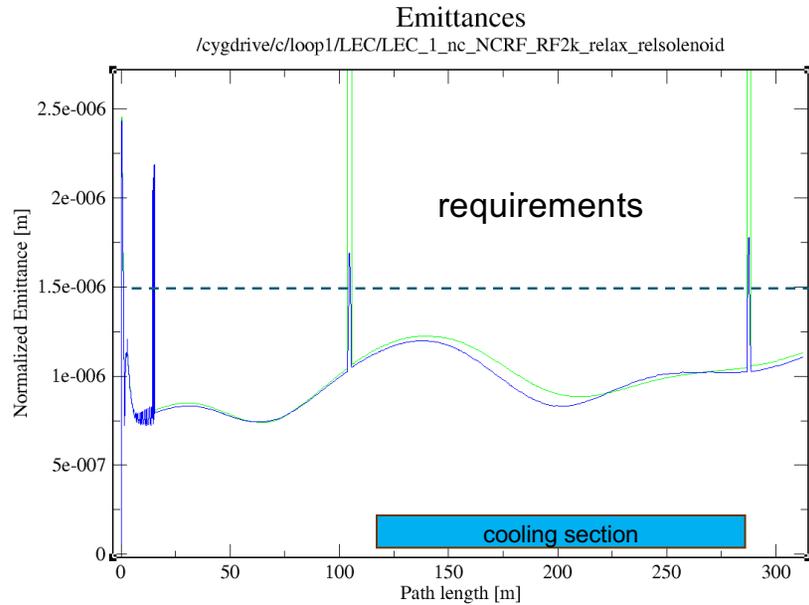$$P = \frac{2Q}{a+b} / \frac{\varepsilon^2}{a^3}$$

$P_{LEC}/P_{LeRHIC} = 1.6$

	LEC	LEReC
gamma	25.4	4.1
Single bunch charge, nC	1	0.1
Electron peak current, A	4	0.4
Emittance, rms, nm	60	500
Bunch size, rms, mm	3	4
P (space charge/ emittance)	37	24

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*) https://cds.cern.ch/record/1120227/files/p115.pdf
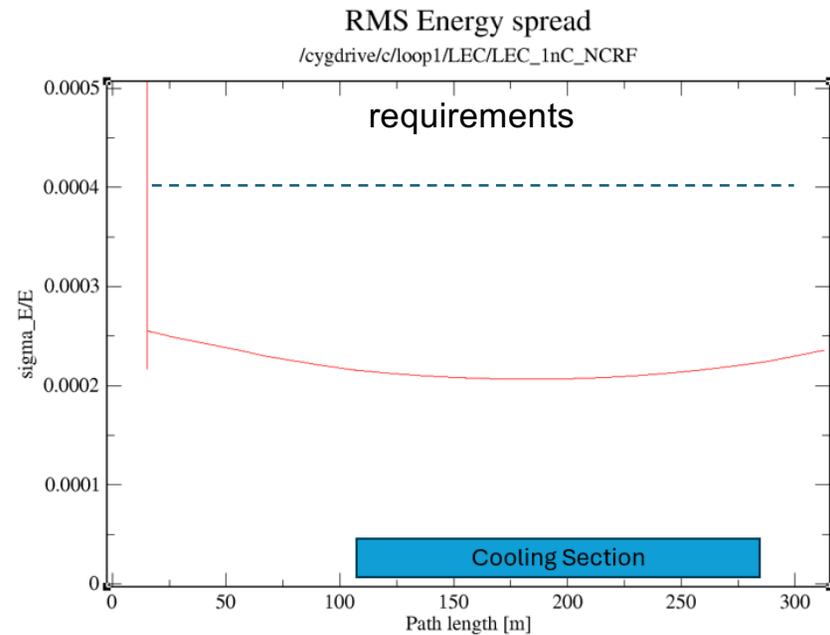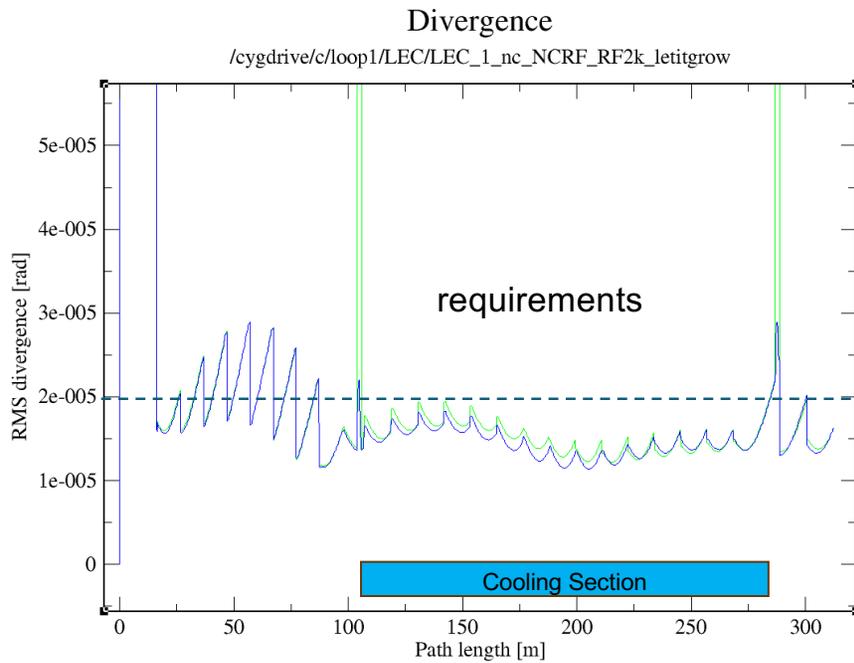
Simulations approach

- Space charge effect dominated beam dynamic from start to end
- 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) just started
- 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

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

Emittances
/cygdrive/c/loop1/LEC/LEC_1_nc_NCRF_RF2k_relax_relsolenoid

requirements

cooling section

RMS Envelopes
/cygdrive/c/loop1/LEC/LEC_1_nc_NCRF_RF2k_relax_relsolenoid

requirements

cooling section

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

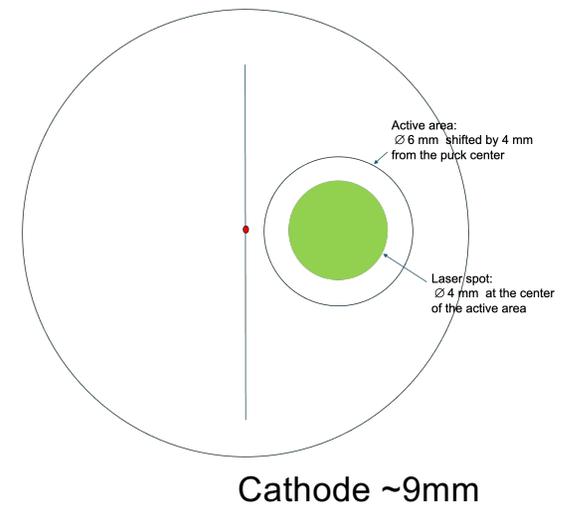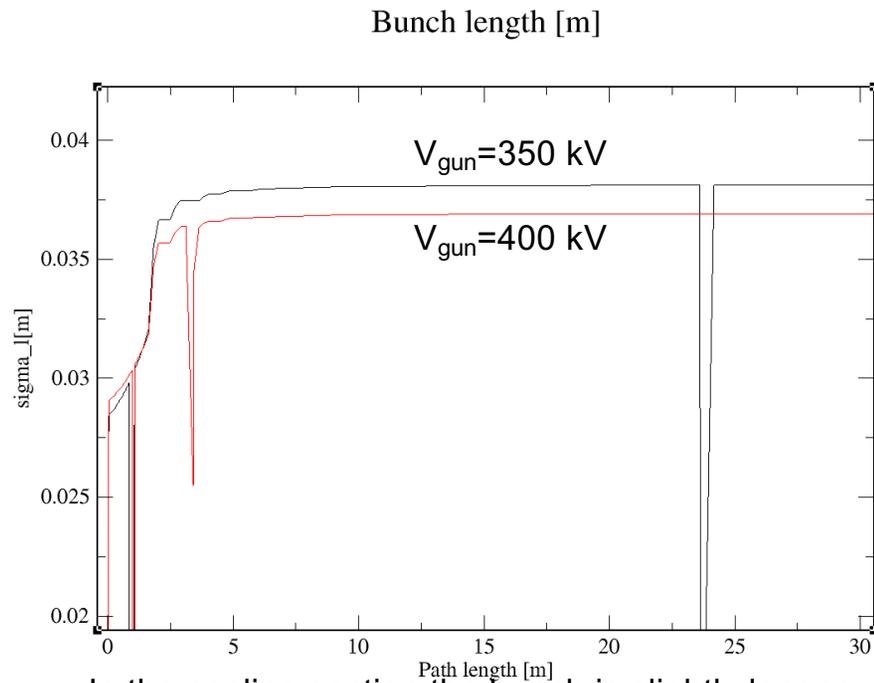# Gun-to-dump simulations results: single bunch charge of 1 nC (continue)

Divergence

/cygdrive/c/loop1/LEC/LEC_1_nc_NCRF_RF2k_letitgrow

requirements

Cooling Section

RMS divergence [rad]

Path length [m]

RMS Energy spread

/cygdrive/c/loop1/LEC/LEC_1nC_NCRF

requirements

Cooling Section

sigma_E/E

Path length [m]

Results:
RMS energy spread <4e-4
Electron beam divergence in the cooling <20 urad.
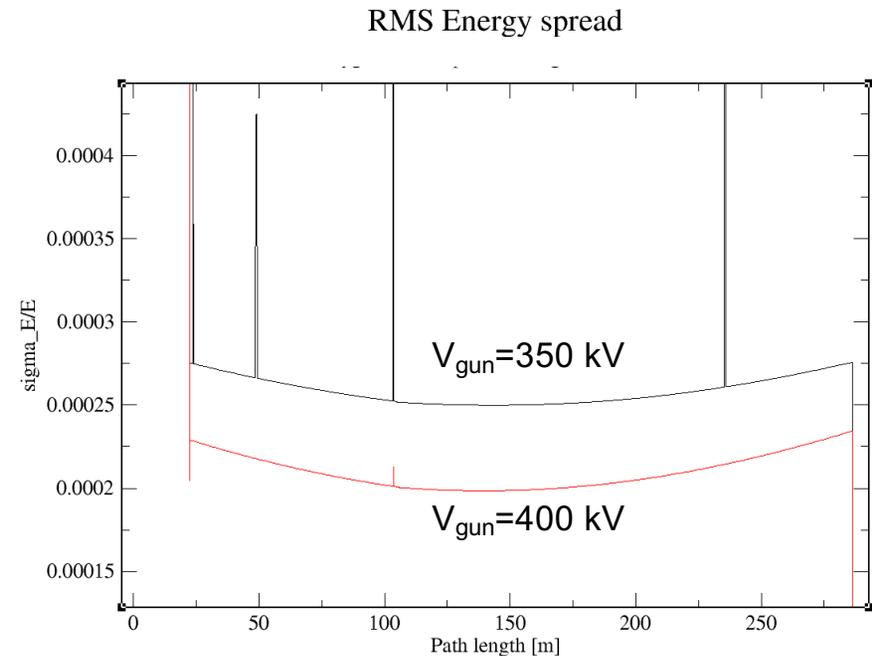
High current operation challenges and mitigations

- LEReC experience (as well as other labs) DC gun high current operates more stable at lower voltage and with laser spot shifted from the center at the cathode

- For example:
  - LEReC DC gun 20 mA - 30 mA routinely (hours) operates at 375 kV and demonstrated operation up to 60 mA at 350 kV
  - Laser spot was shifted by 4 and 6 mm from the center

- LEC required operation at up to 74 mA

- More high current studies are planned for this RHIC run

- We studied beam dynamics at lower voltage and with laser spot shifted at the cathode

Active area:
∅ 6 mm shifted by 4 mm from the puck center

Laser spot:
∅ 4 mm at the center of the active area

Cathode ~9mm

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Side by side comparison: gun at 350 kV and gun at 400 kV
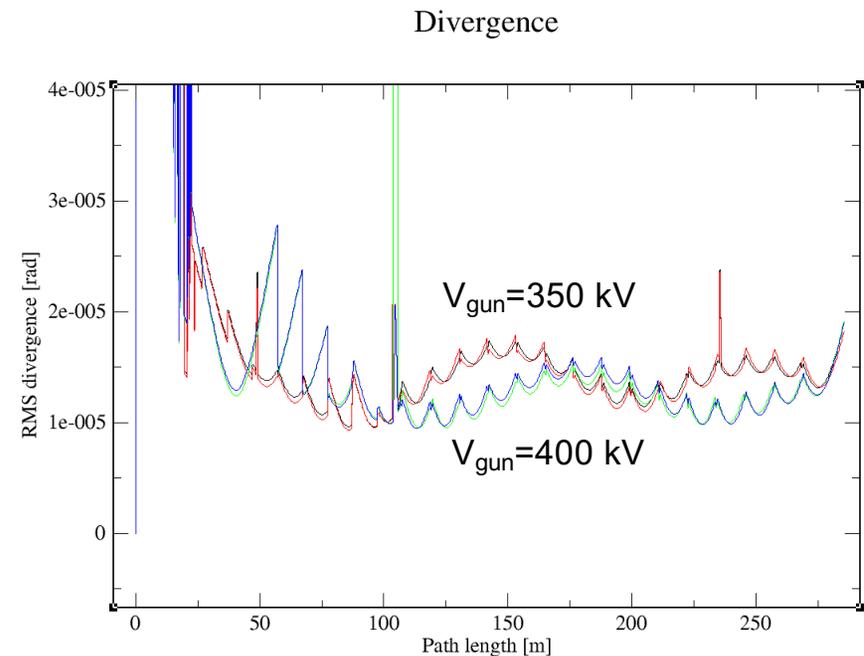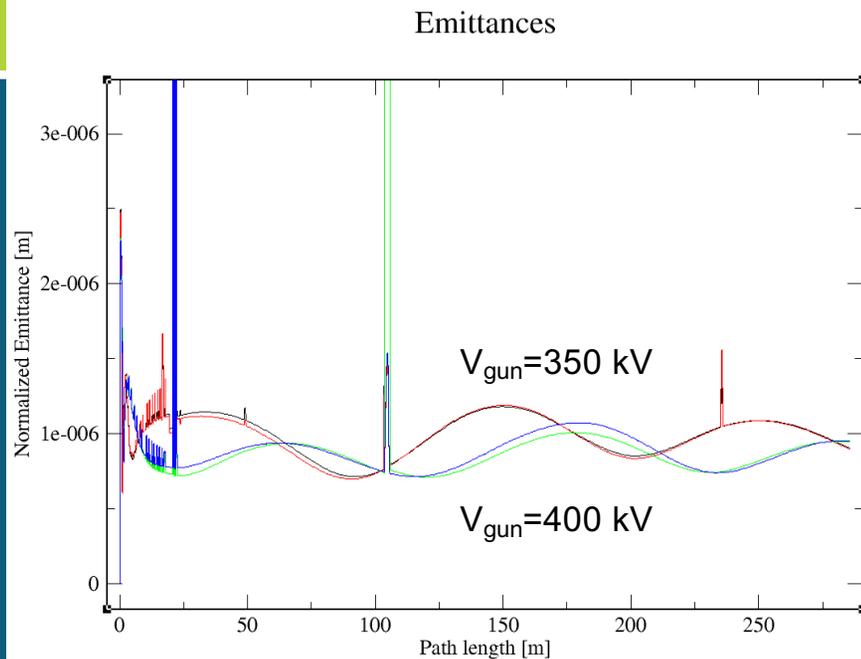
Bunch length [m]

RMS Energy spread

In the cooling section the bunch is slightly longer for the case with gun voltage of 350 kV vs 400 kV: 3.8 cm vs 3.65 cm

For longer bunches (gun voltage of 350kV), the energy spread is sightly higher: the minimum in the center of the cooling section: 2.5e-4 vs 2e-4

350 kV motivation to mitigate potential issue operate in CW modes

Side by side comparison gun at 350 kV and gun at 400kV (continue)

Emittances

Divergence

Results:
Normalized rms emittances <1.5um
Electron beam divergence in the cooling <20 urad.

Operation with a laser spot shifted by 4 mm off the center

Orbit

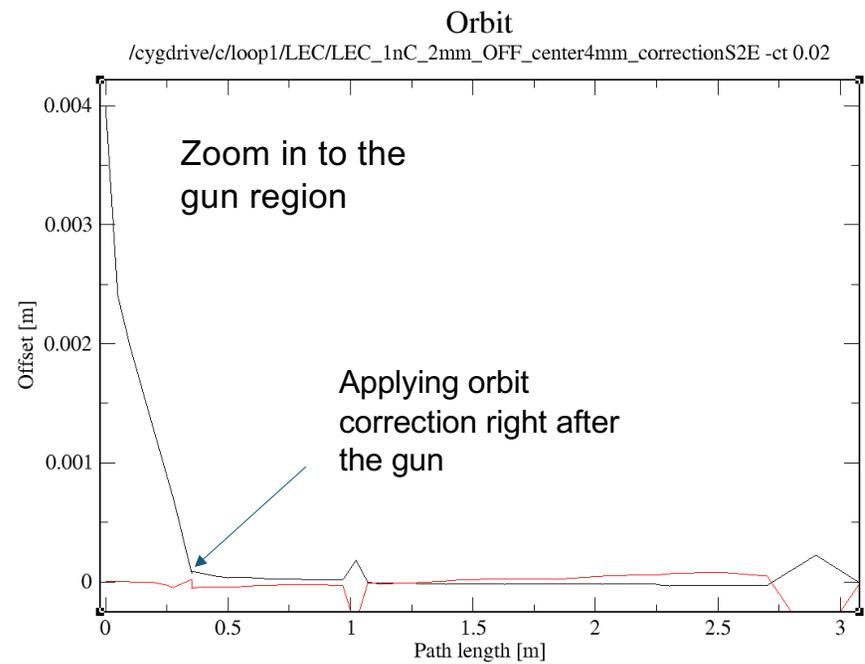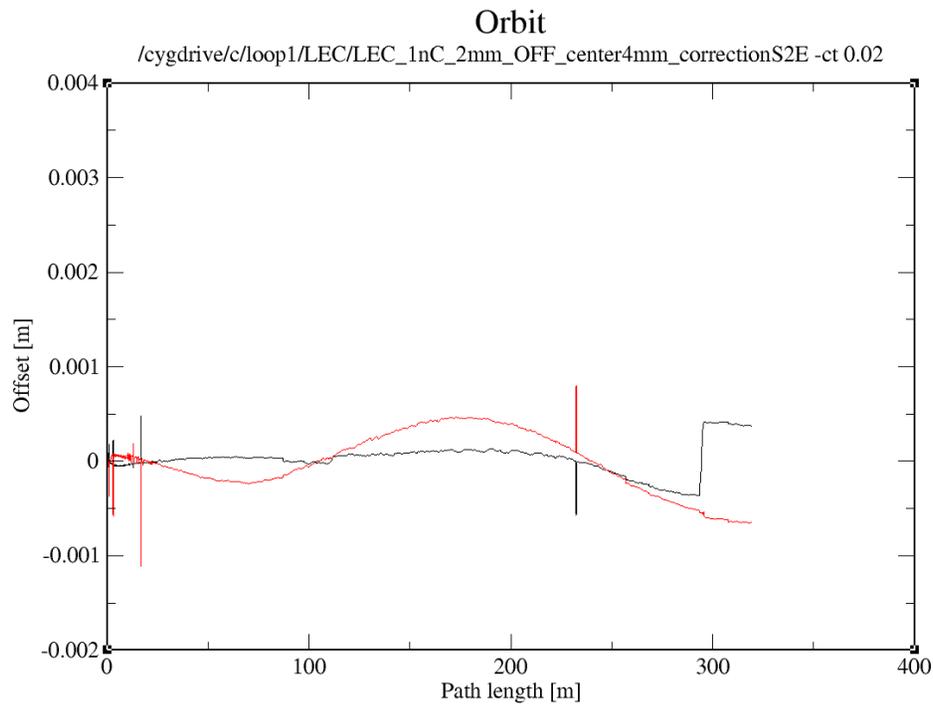/cygdrive/c/loop1/LEC/LEC_1nC_2mm_OFF_center4mm_correction

Laser out path

Bunch max/min particle trajectory

There is enough stay clear aperture with current LEReC laser box design

Gun axis

Cathode active area ∅ 6 mm shifted by 4 mm from the puck center

Laser in path

Gun-to-Dump simulations for bunch charge of 1 nC with 4 mm off center at the cathode

Orbit

/cygdrive/c/loop1/LEC/LEC_1nC_2mm_OFF_center4mm_correctionS2E -ct 0.02

Orbit

/cygdrive/c/loop1/LEC/LEC_1nC_2mm_OFF_center4mm_correctionS2E -ct 0.02

Zoom in to the gun region
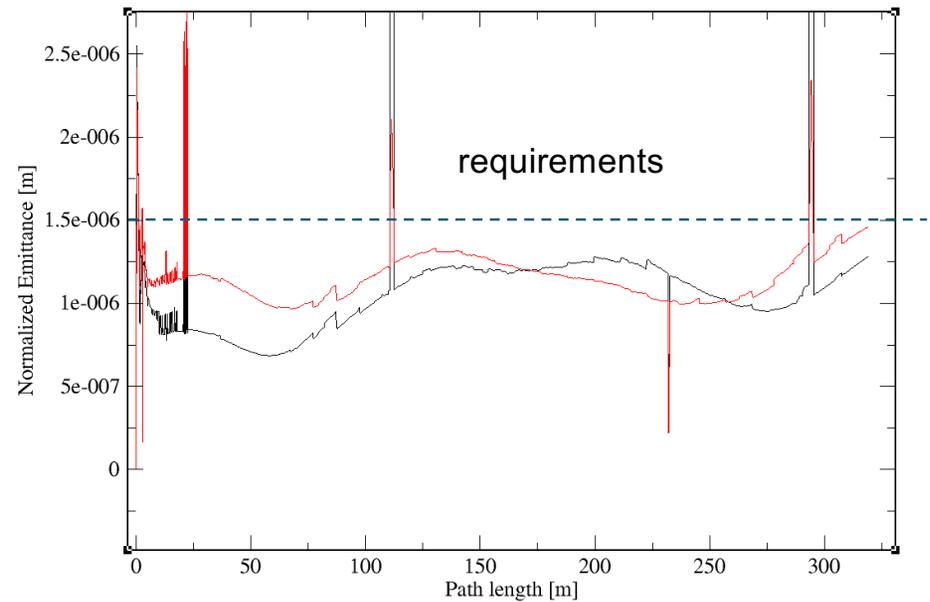
Applying orbit correction right after the gun

Gun-to-Dump simulations for bunch charge of 1 nC with 4 mm off center at the cathode (continue)
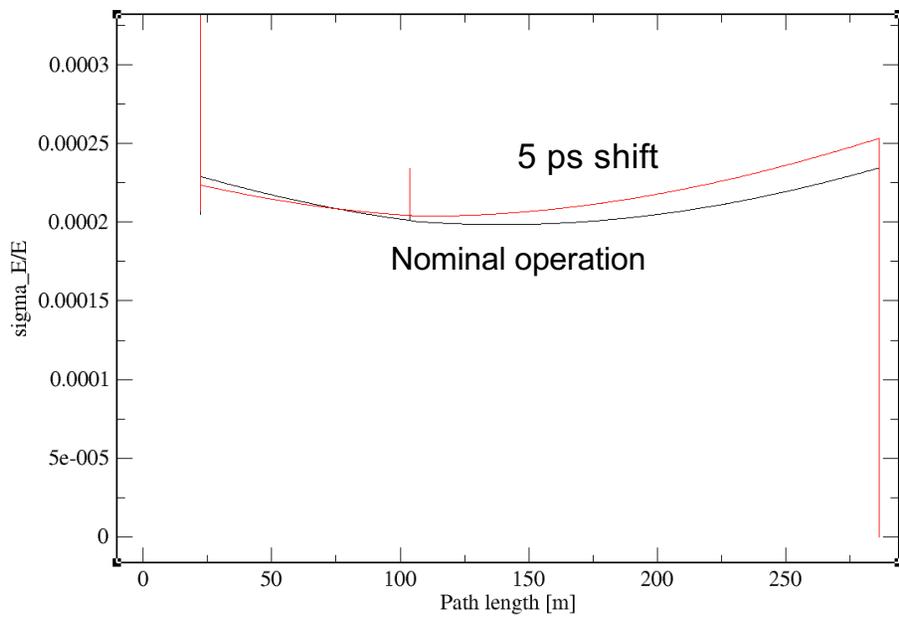
RMS Envelopes

Emittances

requirements

Bunch quality satisfied requirement emittance
The XY asymmetry is a result of initial DC gun focusing astigmatism due to off center operation.

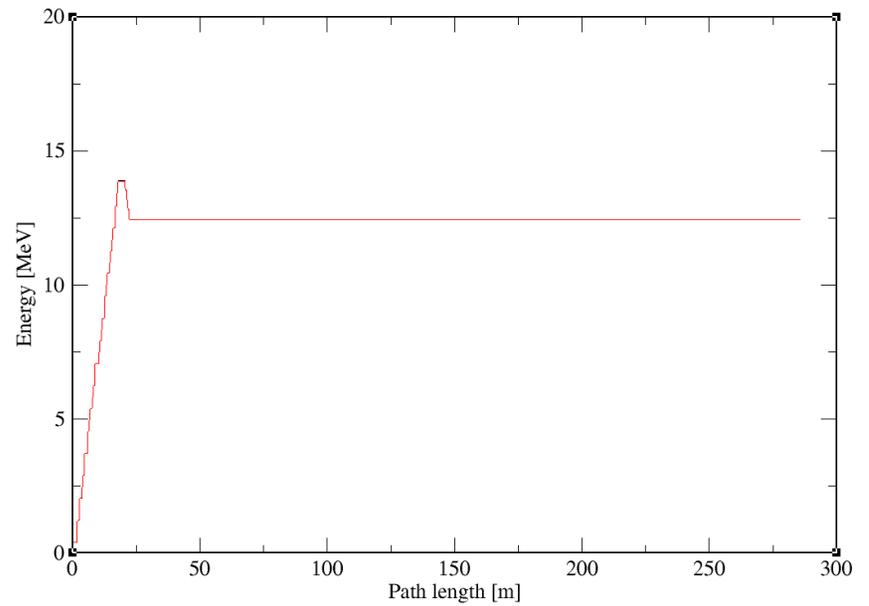# Laser arriving time shift effect on longitudinal beam dynamics

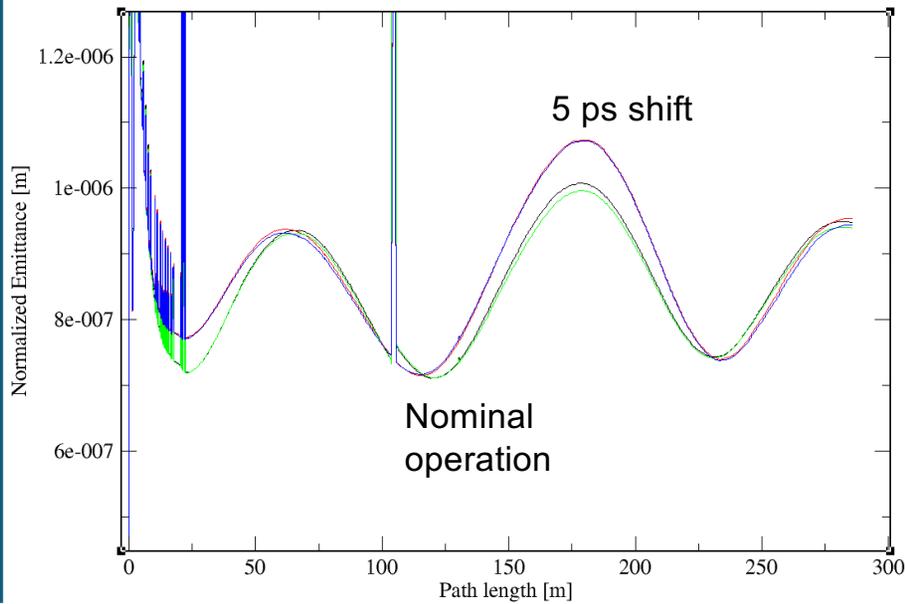## 5 ps shift vs nominal operation

RMS Energy spread

Avarage energy
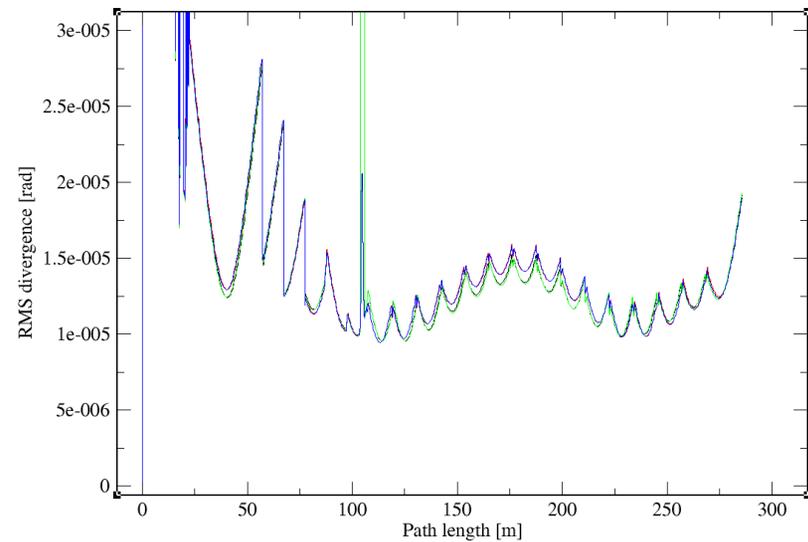

5 ps shift

Nominal operation

Laser arriving time shift effect on transvers beam dynamics (continue)

5 ps shift vs nominal operation

Emittances

Divergence

Summary

- Current design of LEC accelerator and transport fulfills the bunch quality requirement in the cooling section
- We checked that operation with 4 mm offset at the cathode satisfied LEC requirements
- We start addressing other beam dynamics effects: such as beam loading, laser jitter, interaction with protons and more

Thank you for your attention!

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Additional matirials