

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



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COOL25

Beam Cooling and
Related Topics

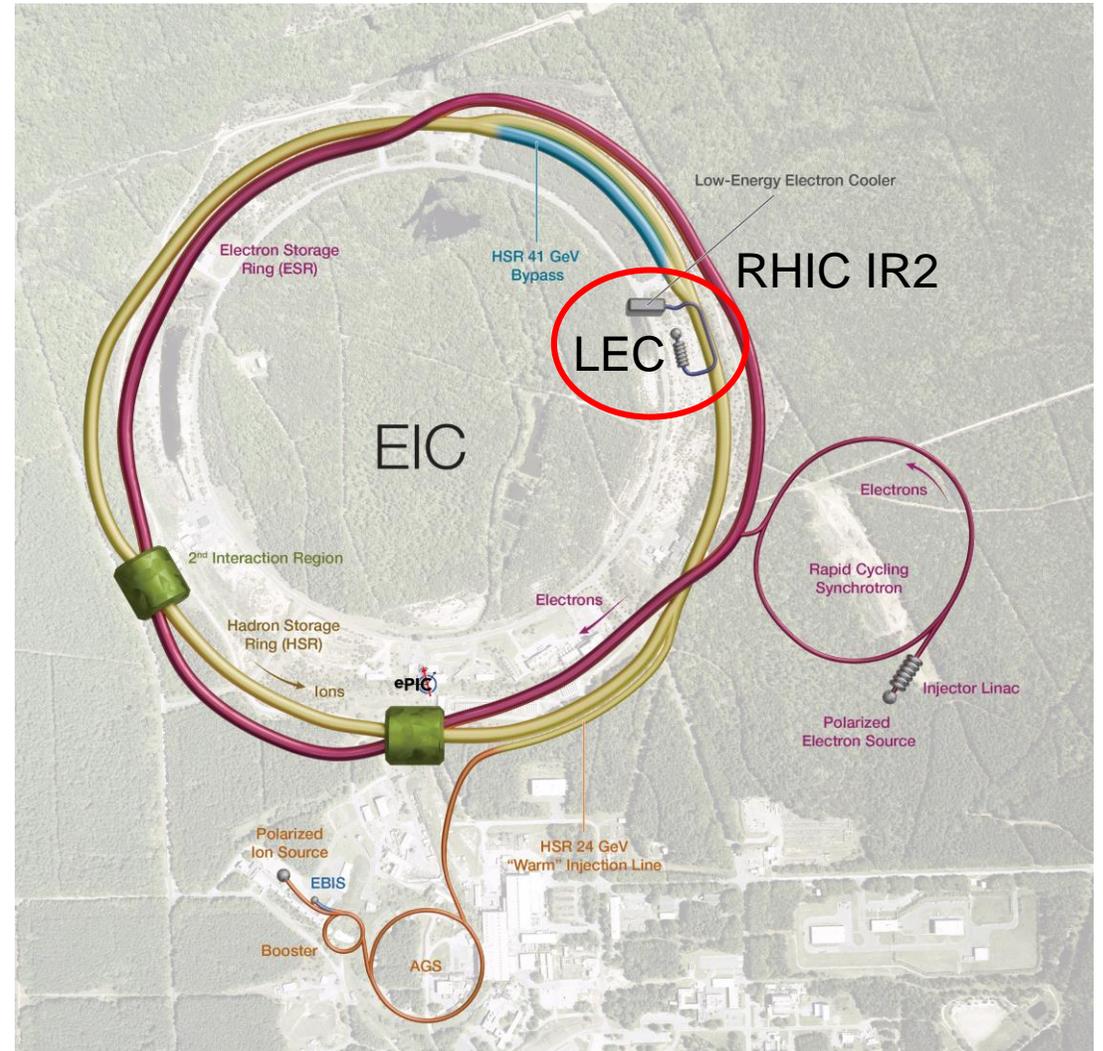
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@BrookhavenLab

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 $\sim 2 \text{ } \mu\text{m}$ to $0.3 \text{ } \mu\text{m}$** (rms normalized).

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

High-Energy Cooling (HEC) of protons:

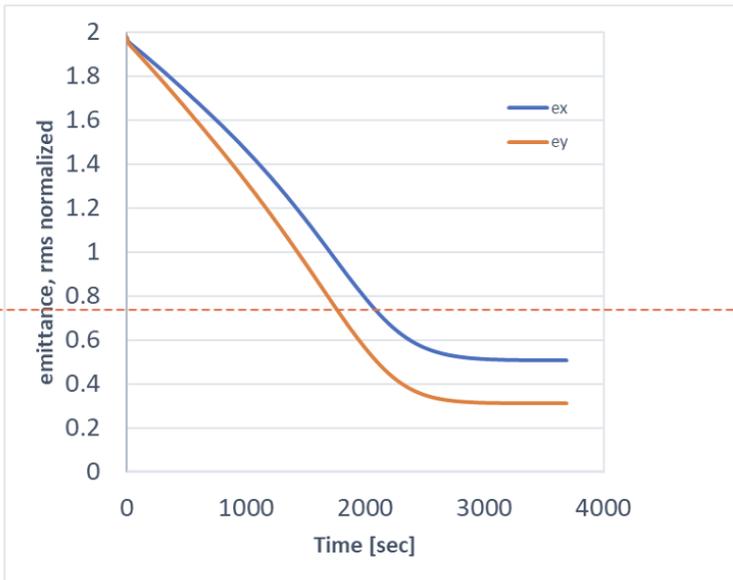
High-Energy Cooling (HEC) system capable of fully counteracting emittance growth at collision energies (41, 100, and 275 GeV) would greatly improve luminosity in the EIC.

EIC LEC Required Parameters *

Average current of electrons: $I_{av}=74\text{mA}$

Electrons rms angles in the cooling section: **25 urad**

Effective cooling section length: **168 meters**

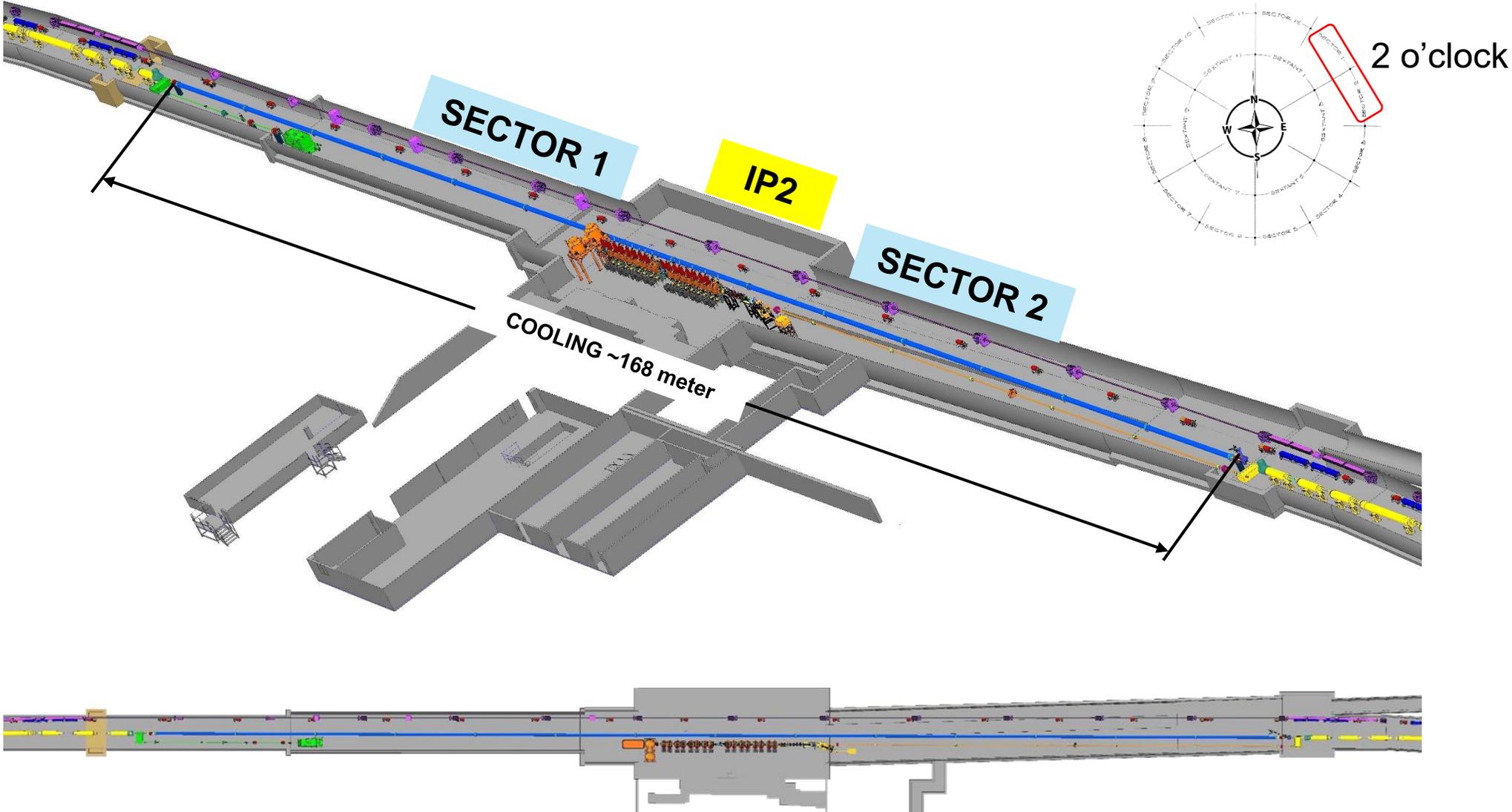


Cooling simulations of protons at $\gamma=25$, with decoupled transverse motion (**IBS+Cooling only**, using single harmonic RF). Longitudinal emittance is kept constant during cooling process. After cooling, **normalized rms emittances of protons $ex, ey=0.5, 0.3 \text{ um}$** (horizontal emittance 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 |

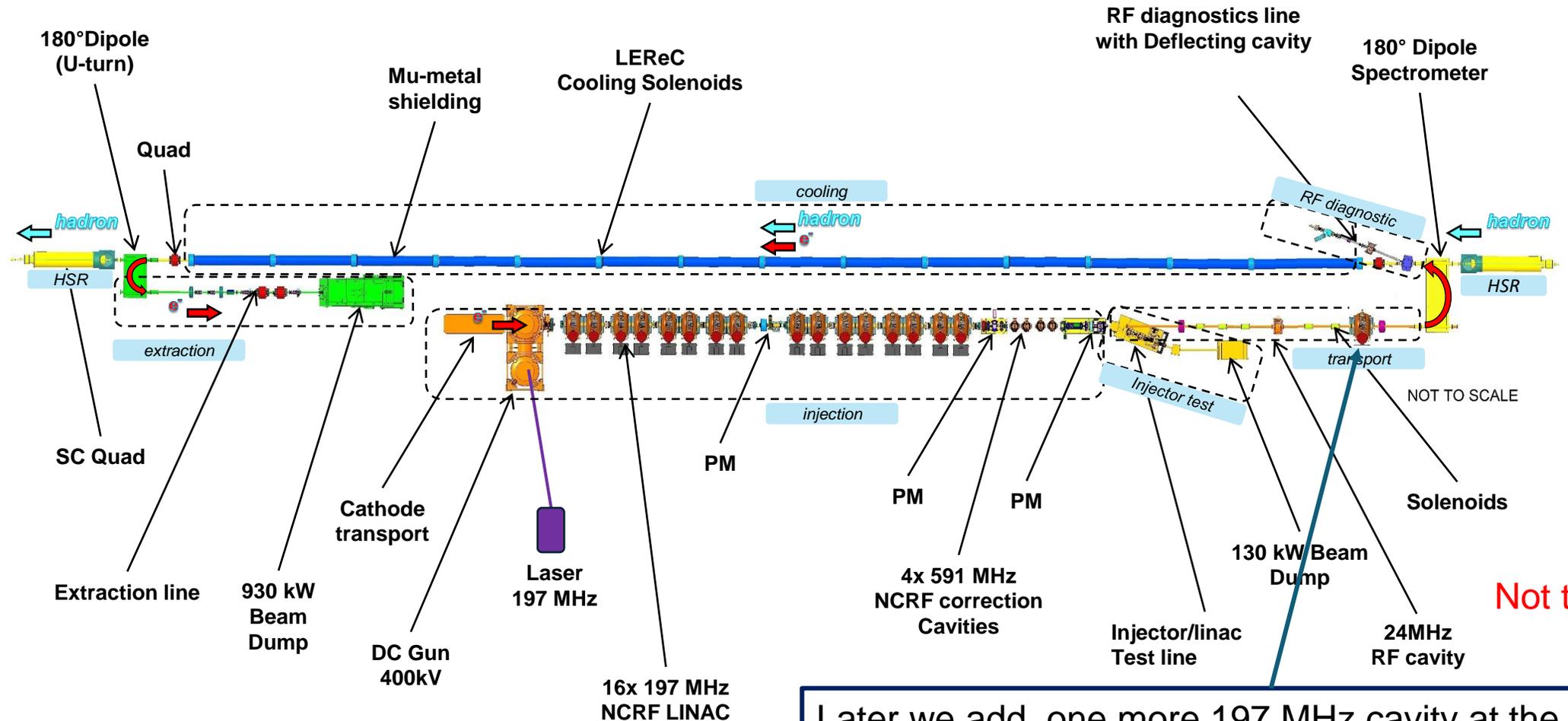
* See Alexei Fedotov's talk, TUA1 at this conference

Low-Energy Cooler (LEC) Layout



LEC schematic layout at IR2 @EIC

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



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

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
 $\gamma = 25.4$ ($E_{ke} = 12.5$ 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,

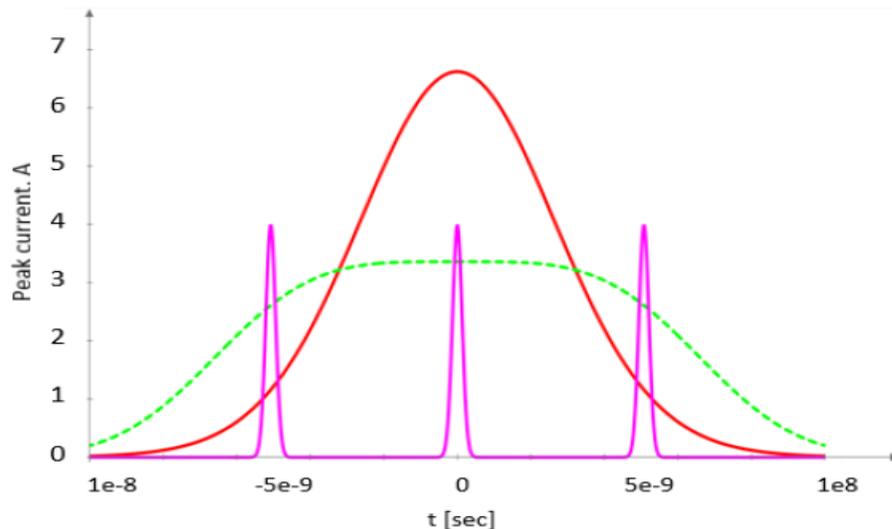
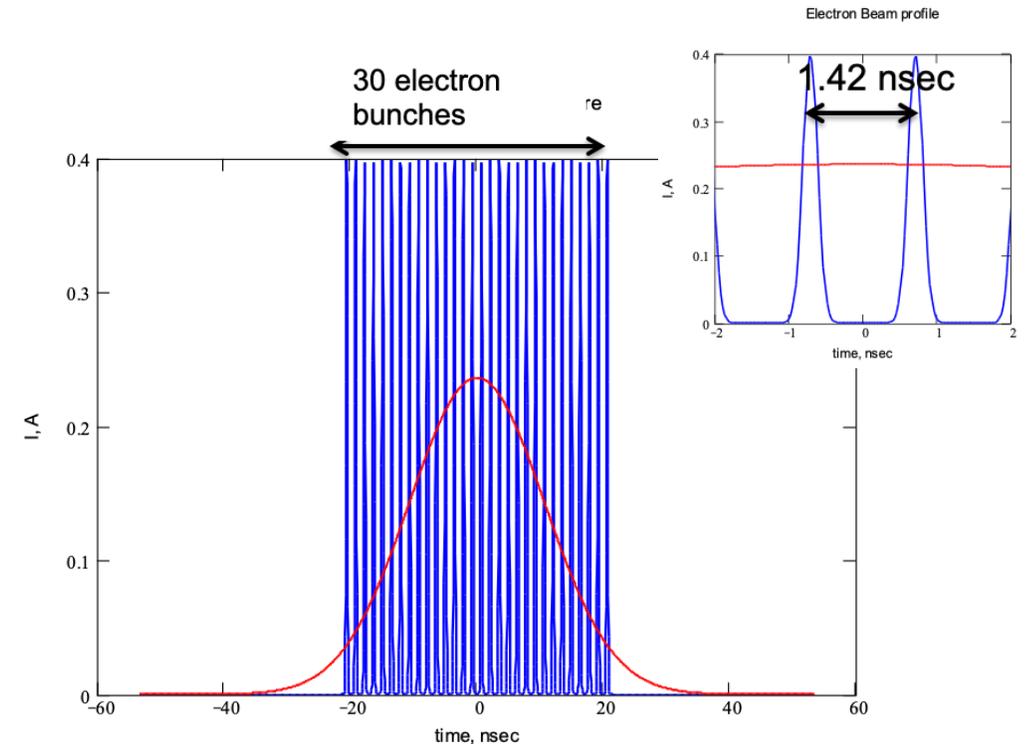


Figure 3: Three electron bunches (magenta) spaced by 5.1 ns placed on a single proton bunch (red: single RF harmonic; green: double RF harmonic).

LEReC used similar multi bunches electron structure to cool hadrons at RHIC

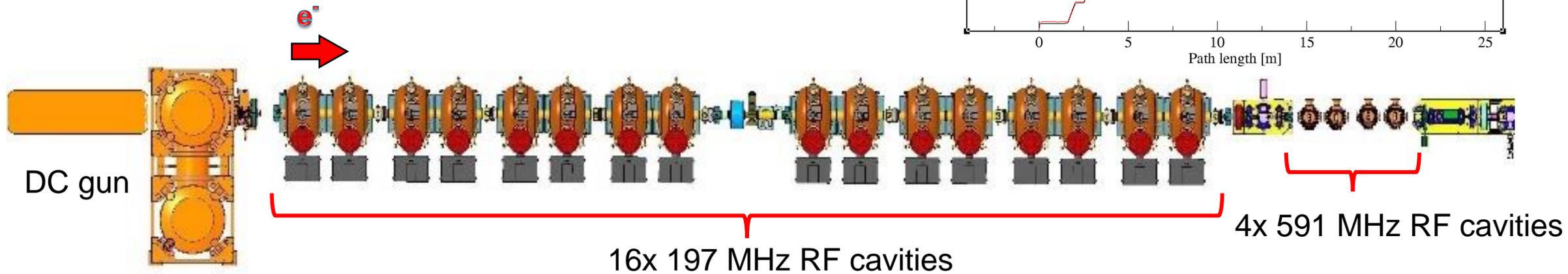
LEReC beam structure in the cooling section
 $\gamma = 4.1$ ($E_{ke} = 1.6$ MeV)

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,



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

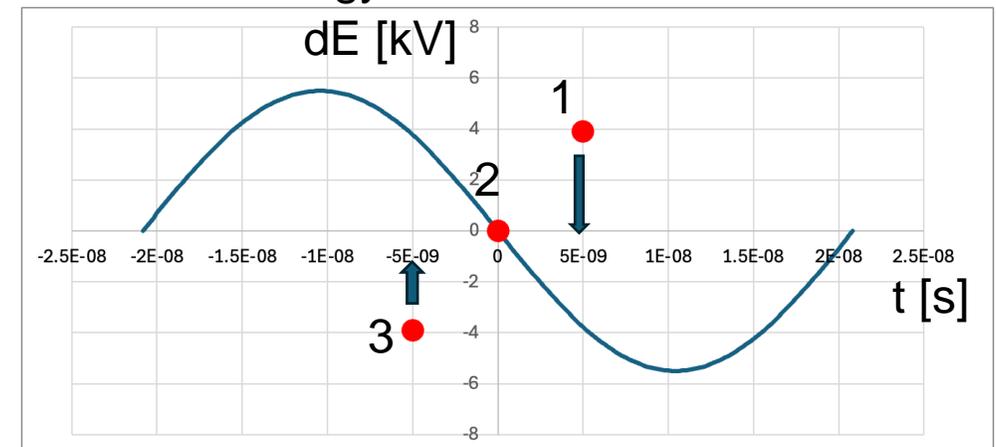


Beam loading effect on final beam energy

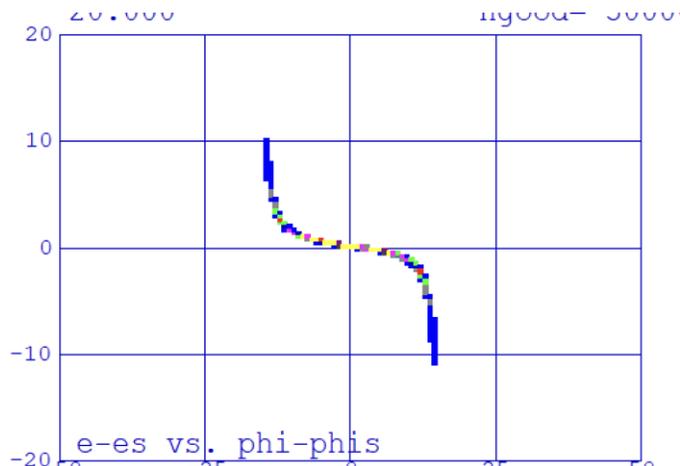
| | 197 MHz | 591 MHz |
|---|----------|-----------|
| Frequency [MHz] | 197.0508 | 591.1524 |
| Tuning range [MHz] | ±0.12 | -0.5~+1.0 |
| Total Voltage [MV] | 13.6 | 1.5 |
| # of Cavities | 17 | 4 |
| Voltage per cavity [kV] | 800 | 400 |
| R/Q cir. [Ω] | 170 | 96 |
| Q0 | 48000 | 34000 |
| FPC Qext | 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 :

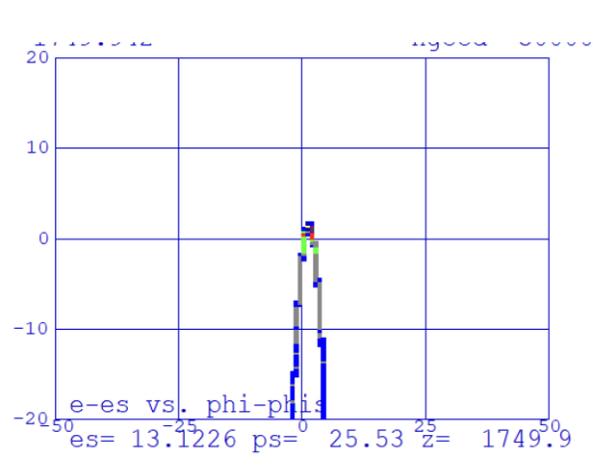
- Energy difference between 1st and 3rd bunches could reach
- Results of 17 (197 MHz) cavities
 $dE_{197\text{MHz}} = 5.6 \text{ keV}$
- Results of 4 (591 MHz) cavities
 $dE_{591\text{MHz}} = 2.2 \text{ keV}$
- **Maximum accumulated effect:**
 $dE_{\text{max}}/E = 7.8 \text{ keV}/13 \text{ MeV} = 6 \times 10^{-4}$
- Will use low frequency (24 MHz) cavity 5 kV to minimize energy difference between e-bunches



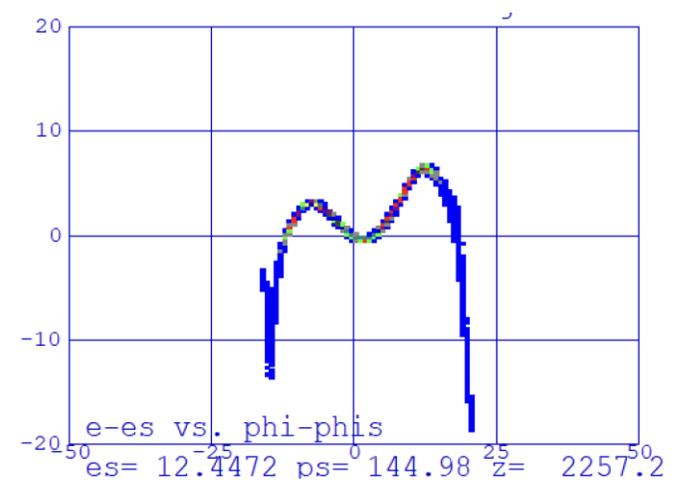
Longitudinal dynamics (phase space)



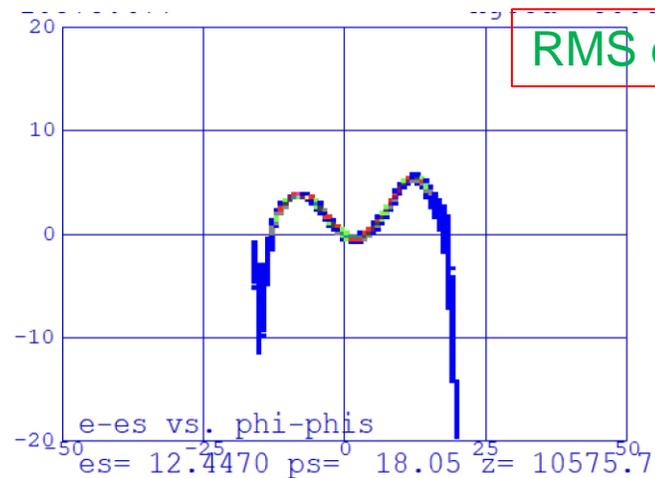
At the entrance to the 1st cavity



At the end to the 16th cavity

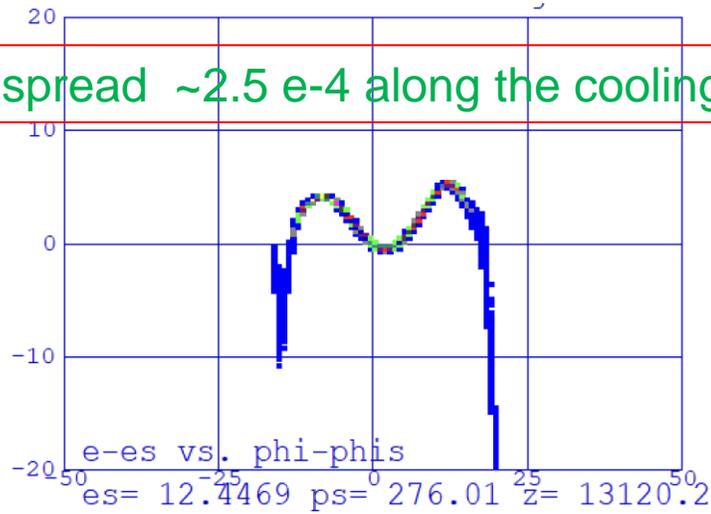


At the end of the LINAC

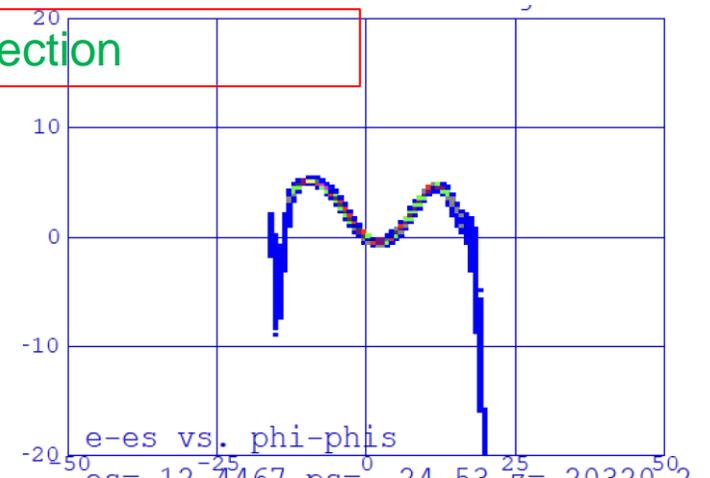


At the beginning of the cooling section

RMS energy spread $\sim 2.5 \times 10^{-4}$ along the cooling section



At the center of the cooling section



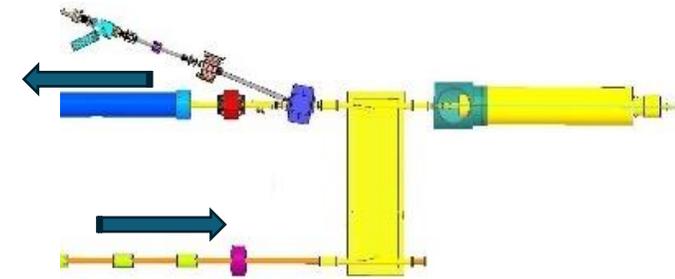
At the end of the cooling section

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

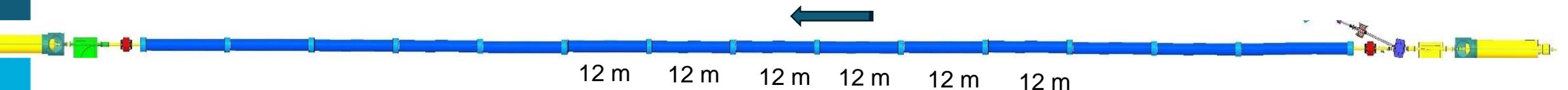


- A single 180-degree (non achromatic) turn-around dipole merges electron bunches with hadron bunches into the cooling section

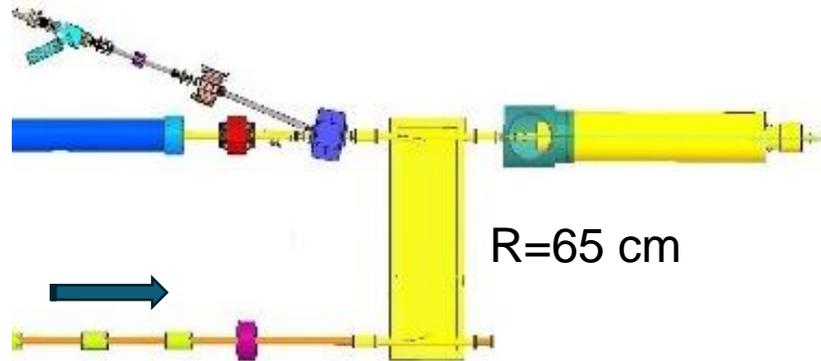


- 2 quadrupoles at each ends of the 180d dipole are installed for fine matching electron bunches into the cooling section

- 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



180 degree single magnet turn around



Energy spread: $5E-04$

Bunch size /Angular spread in the cooling section : 3 mm /20 urad

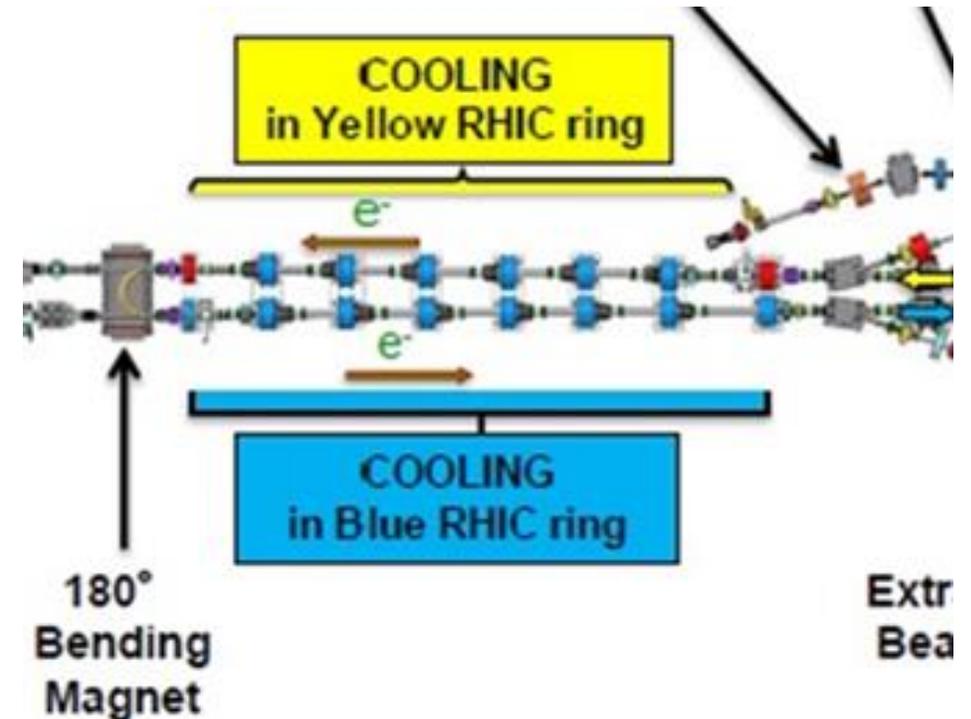
Then requirement for the dispersion

$D \ll 6$ m and $D' \ll 0.04$

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

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



LEC: Space charge dominated beam dynamic

Envelope equation*

where:

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

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

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

Space Charge effect term

Emittance effect term

Space charge dominated regime

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

Space Charge effect domination parameters

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

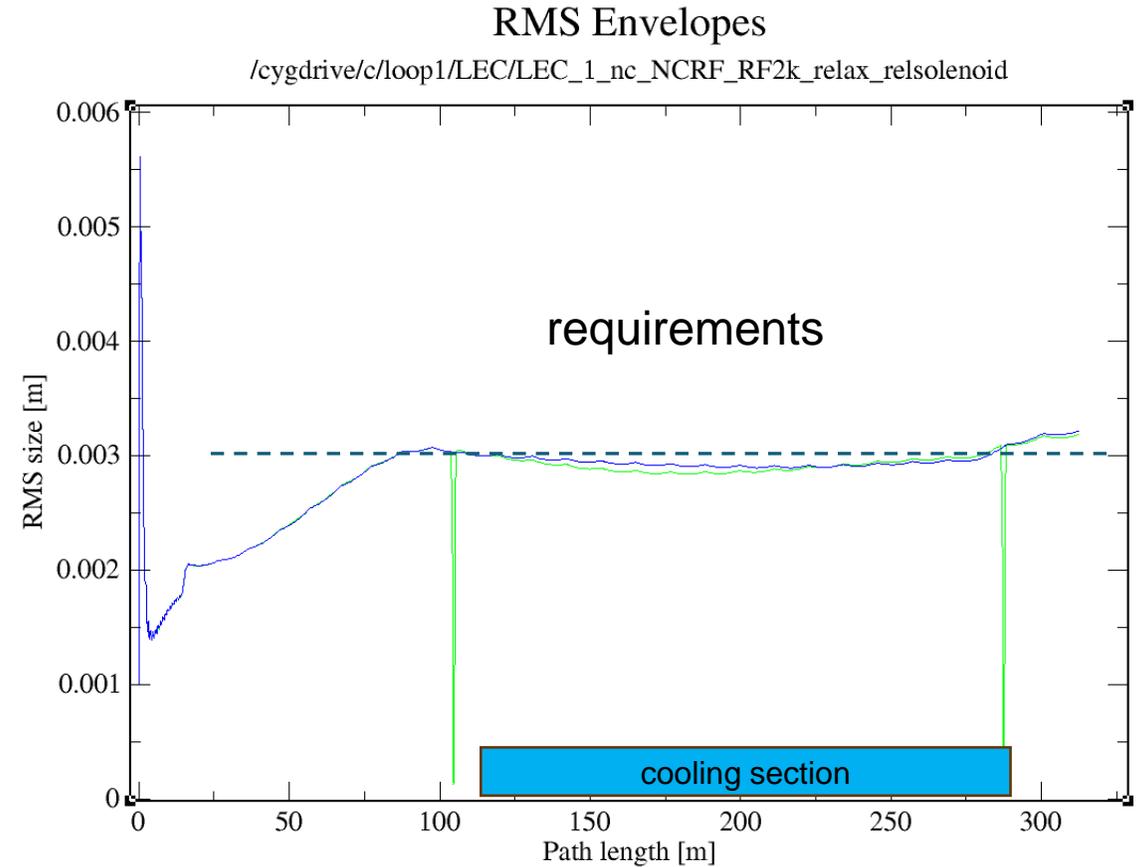
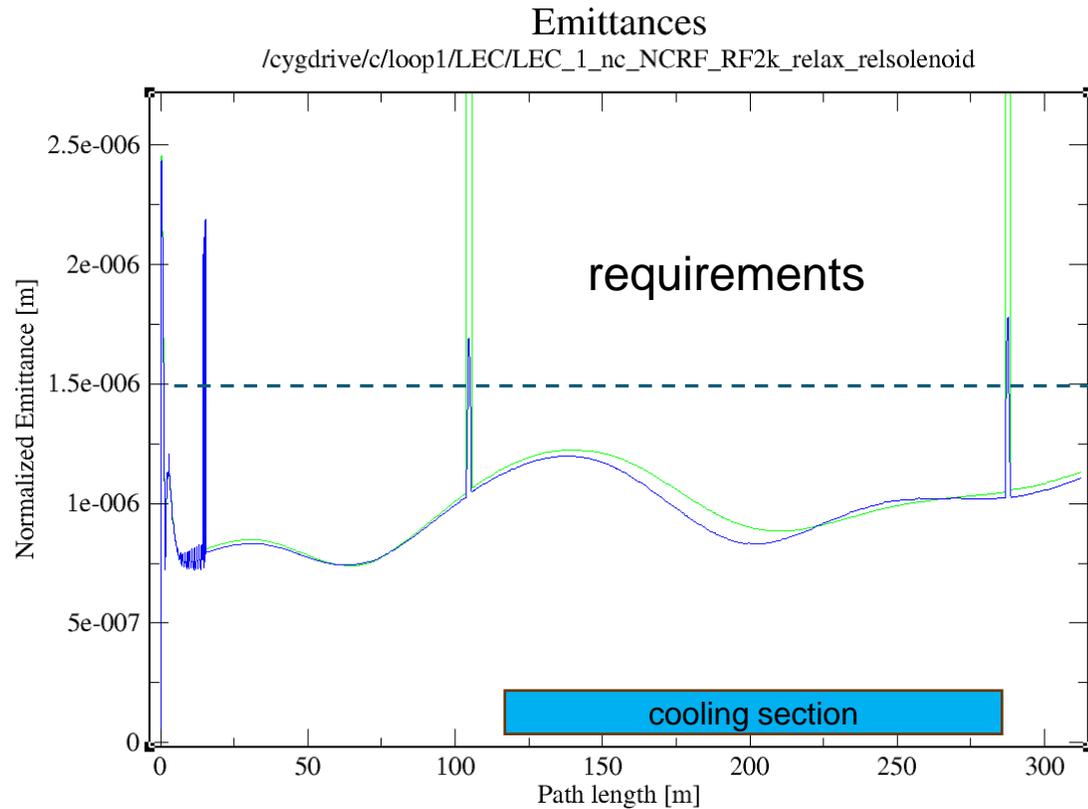
$$P_{LEC}/P_{LeRHIC} = 1.6$$

| | 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 |

Simulations approach

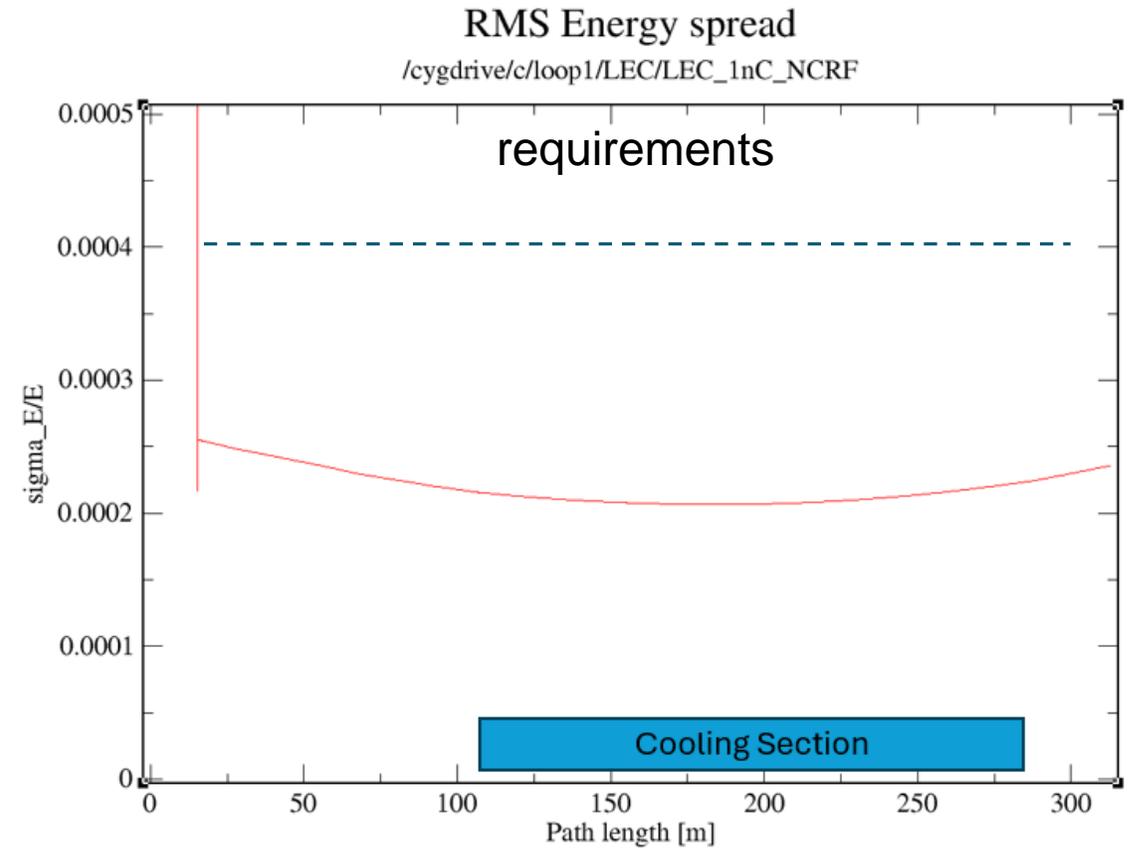
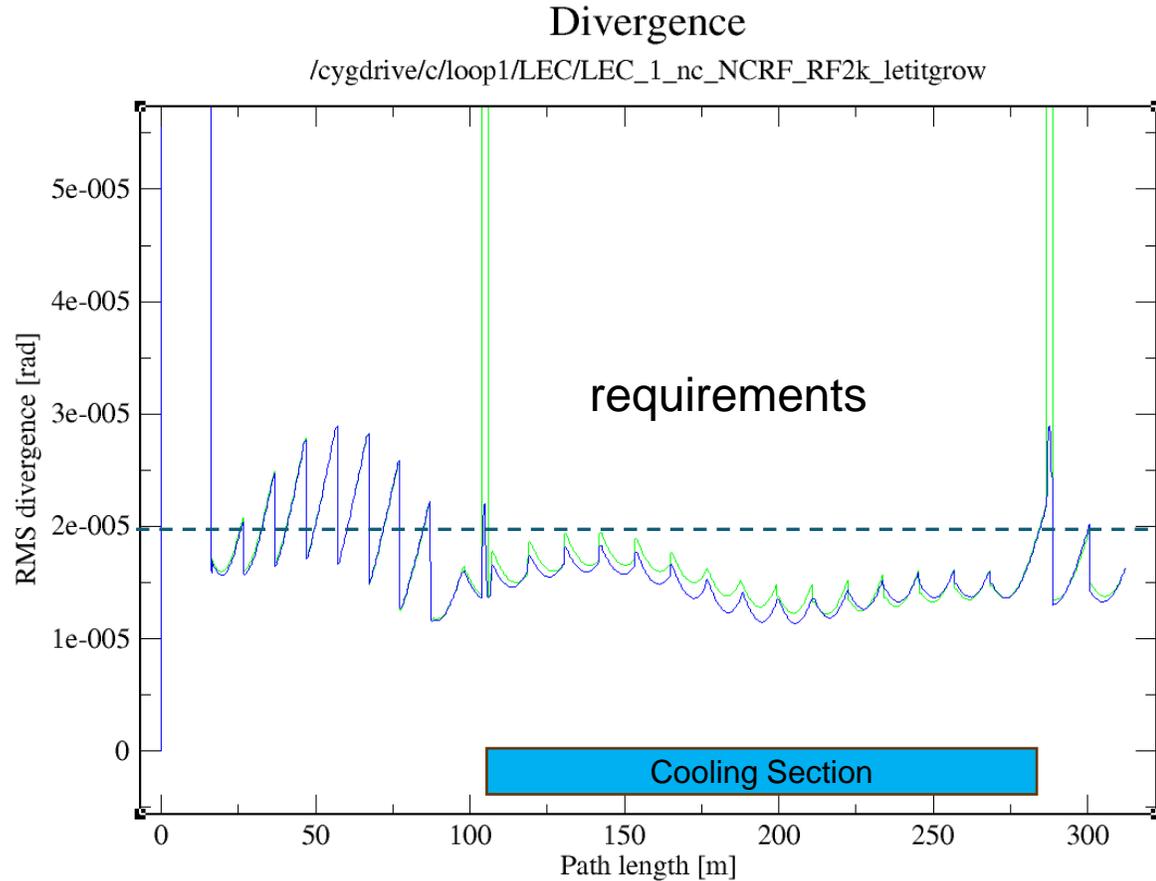
- Space charge effect dominated beam dynamic from start to end
- Beam dynamics simulation/optimization were conducted using code PARMELA
- PARMELA is a well recognized code when space charge plays important role
- The benchmark PARMELA simulation results with other codes (GPT, IMPACT-T) just started
- The first preliminary 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



Results:
Normalized rms emittances $< 1.5 \mu\text{m}$
RMS bunch size 3 mm.

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



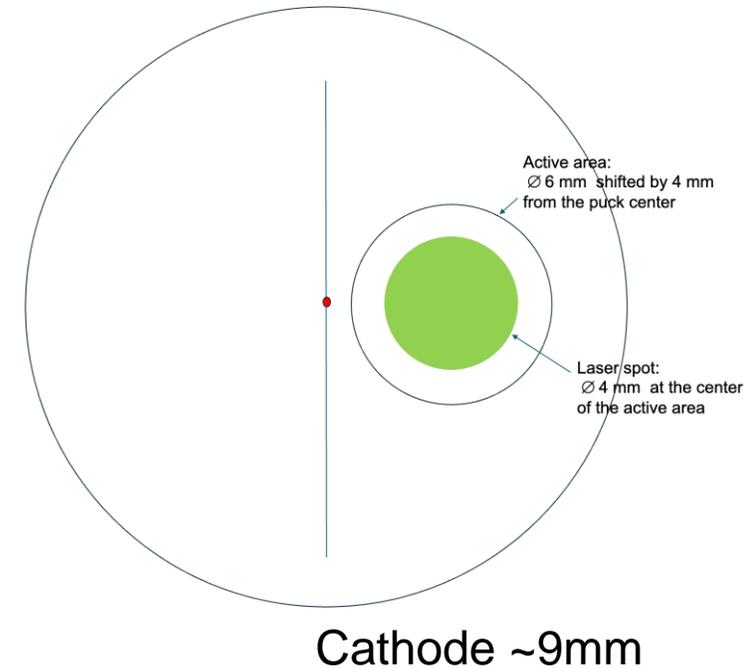
Results:

RMS energy spread $<4e-4$

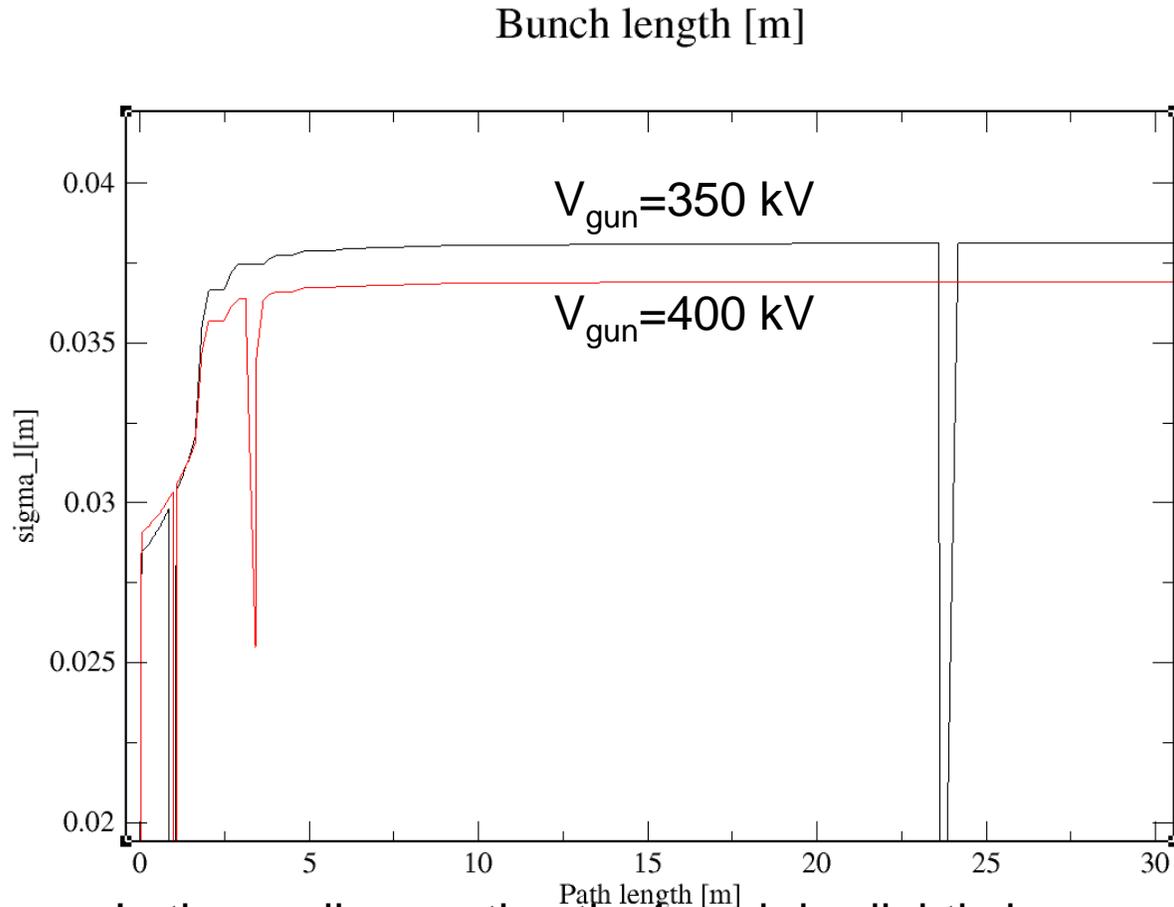
Electron beam divergence in the cooling <20 urad.

High current operation challenges and mitigations

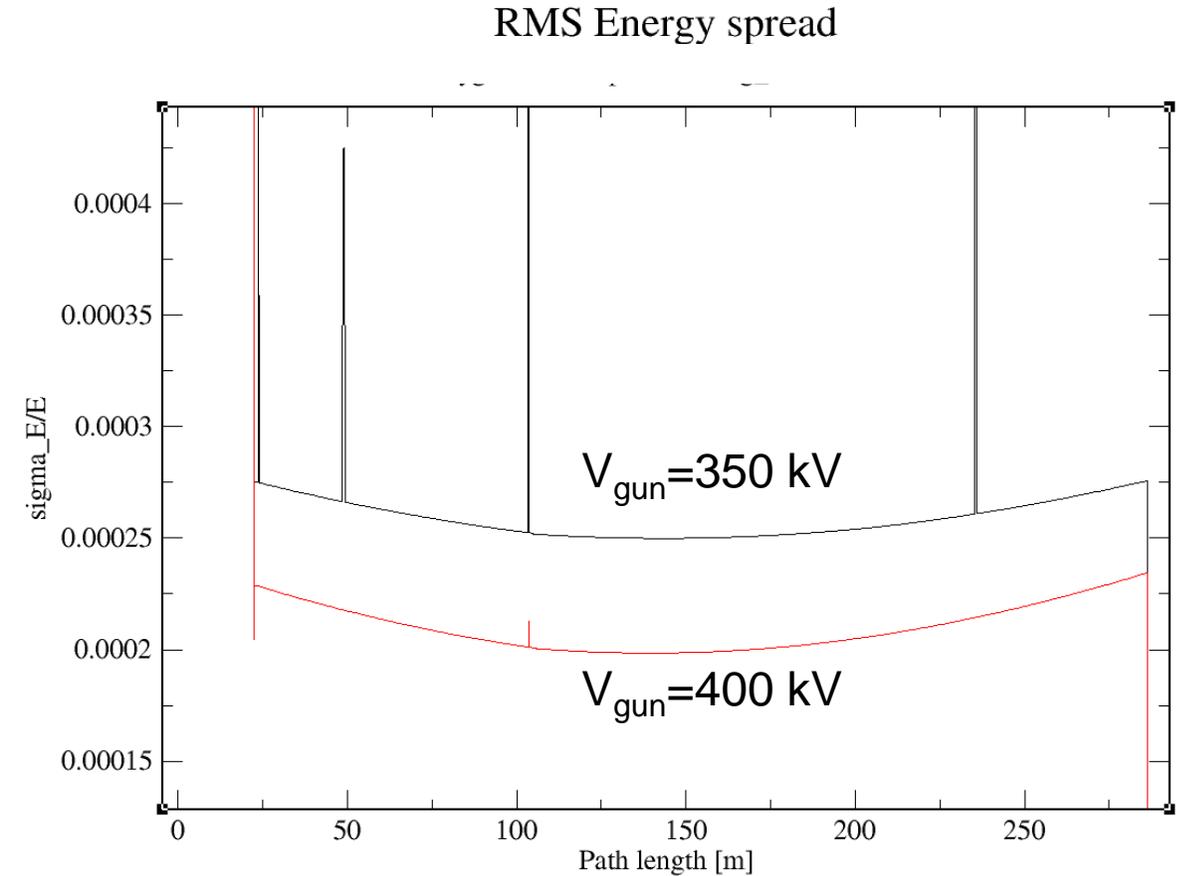
- LEReC experience (as well as other labs) DC gun high current operates more stable at lower voltage and with laser spot shifted from the center at the cathode
- For example:
 - LEReC DC gun 20 mA - 30 mA routinely (hours) operates at 375 kV and demonstrated operation up to 60 mA at 350 kV
 - Laser spot 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



Side by side comparison: gun at 350 kV and gun at 400 kV



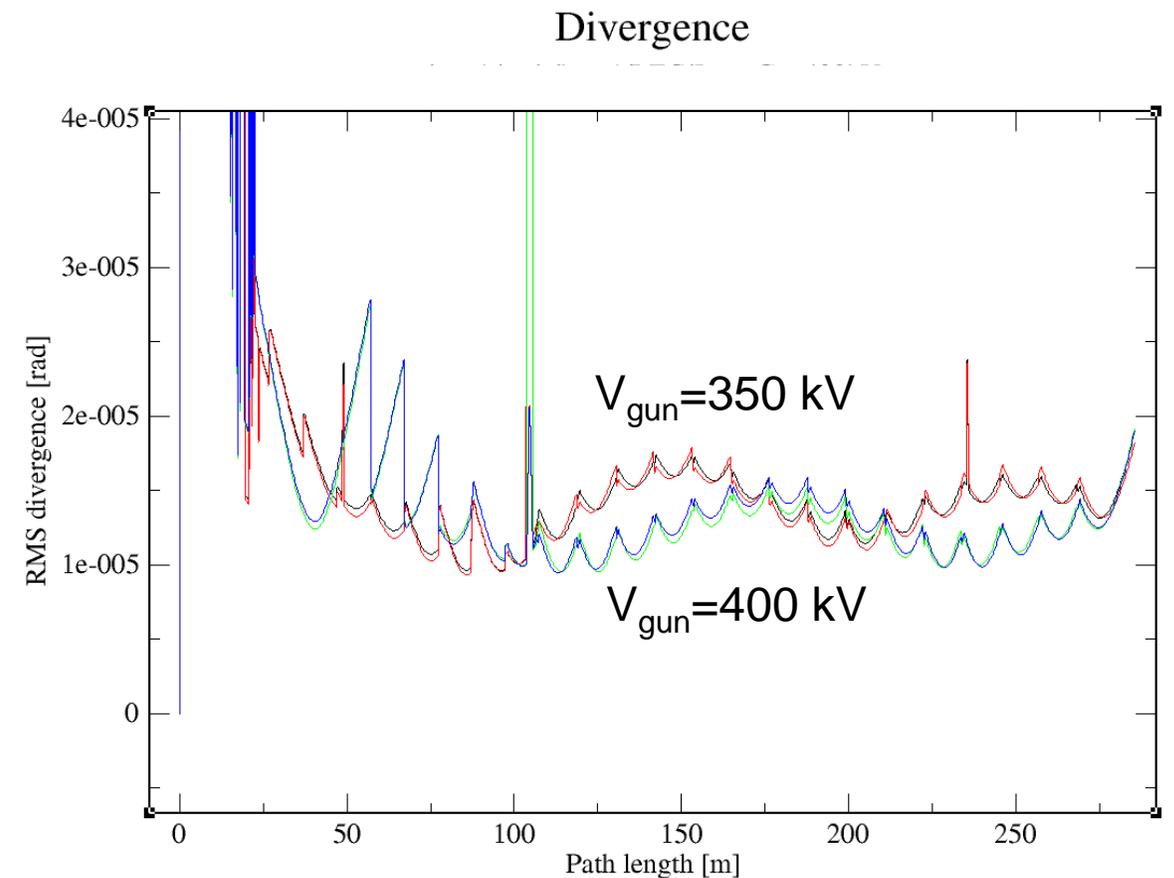
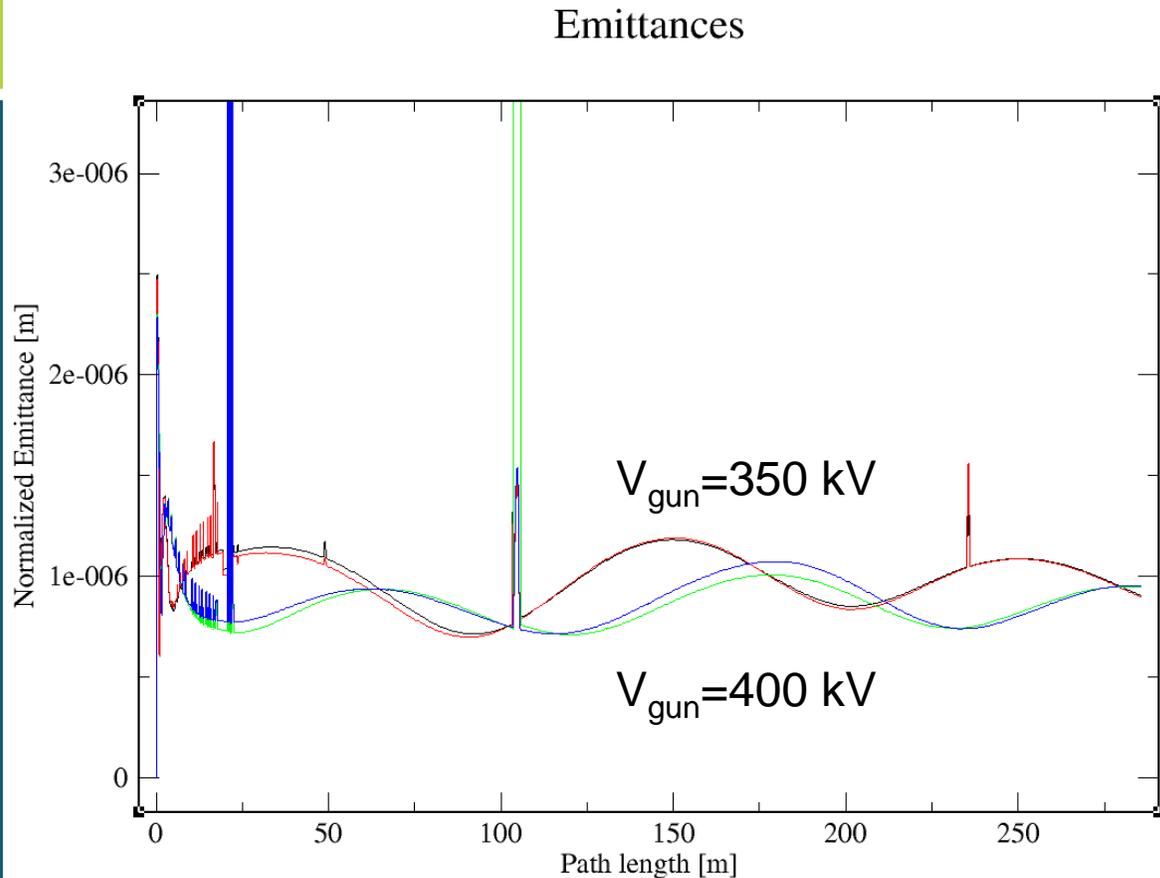
In the cooling section the bunch is slightly longer for the case with gun voltage of 350 kV vs 400 kV: 3.8 cm vs 3.65 cm



For longer bunches (gun voltage of 350kV), the energy spread is slightly 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)



Results:

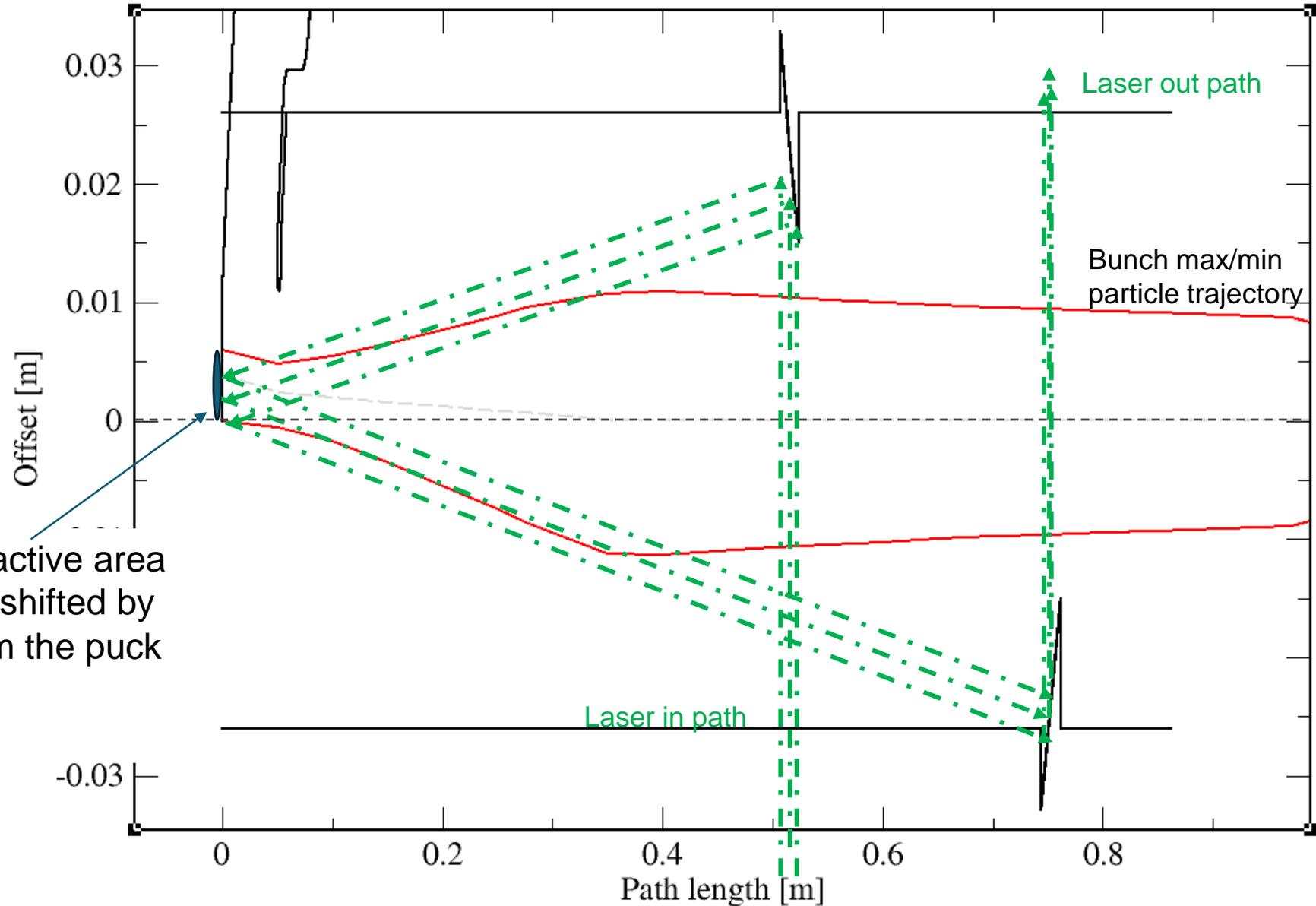
Normalized rms emittances $< 1.5 \mu\text{m}$

Electron beam divergence in the cooling $< 20 \text{ urad}$.

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

Orbit

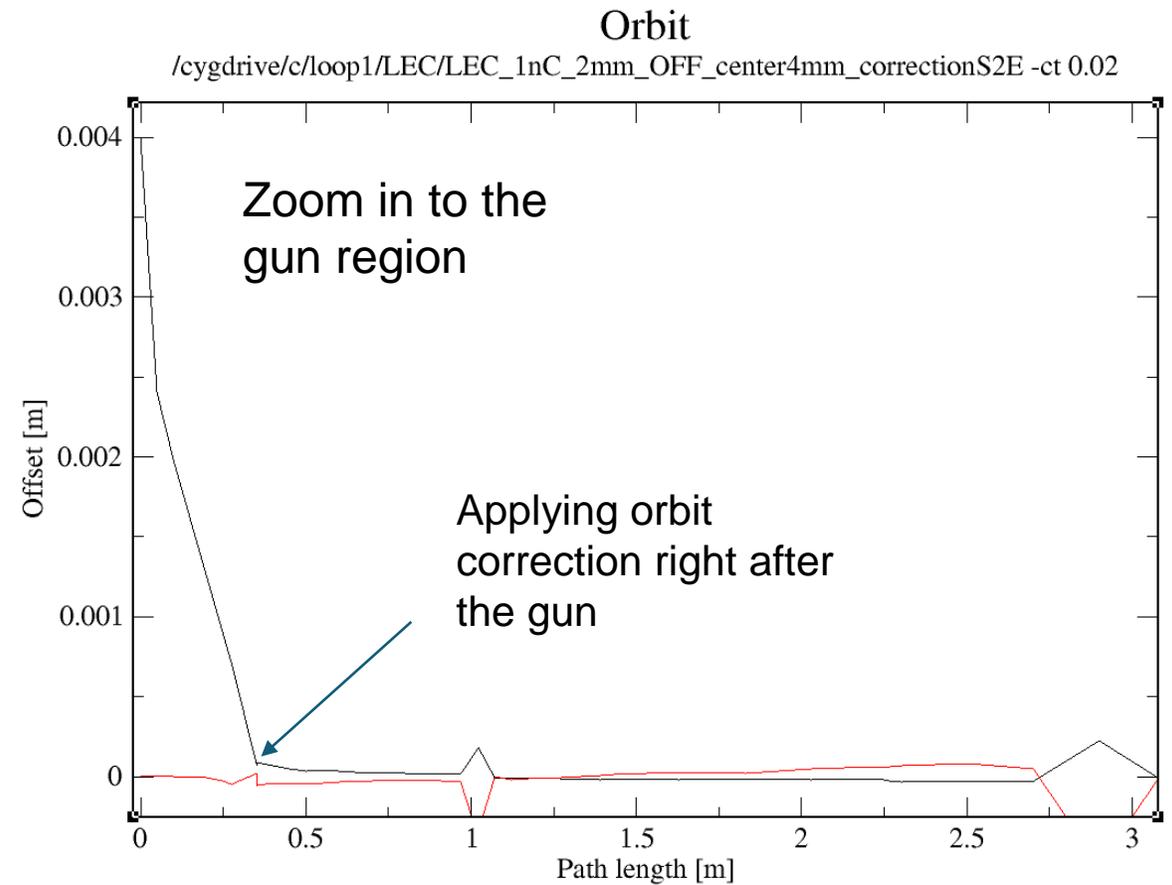
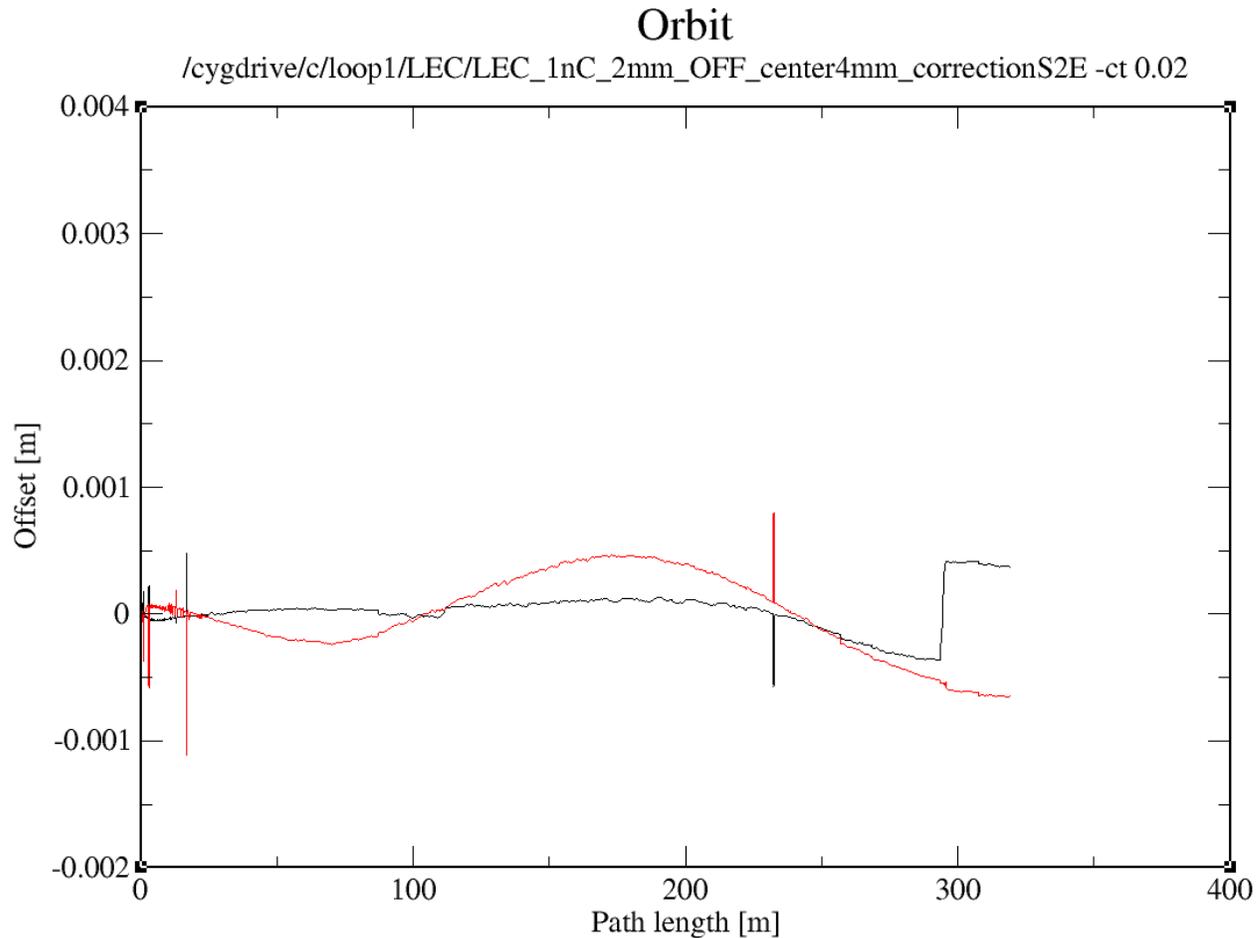
/cygdrive/c/loop1/LEC/LEC_1nC_2mm_OFF_center4mm_correction



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

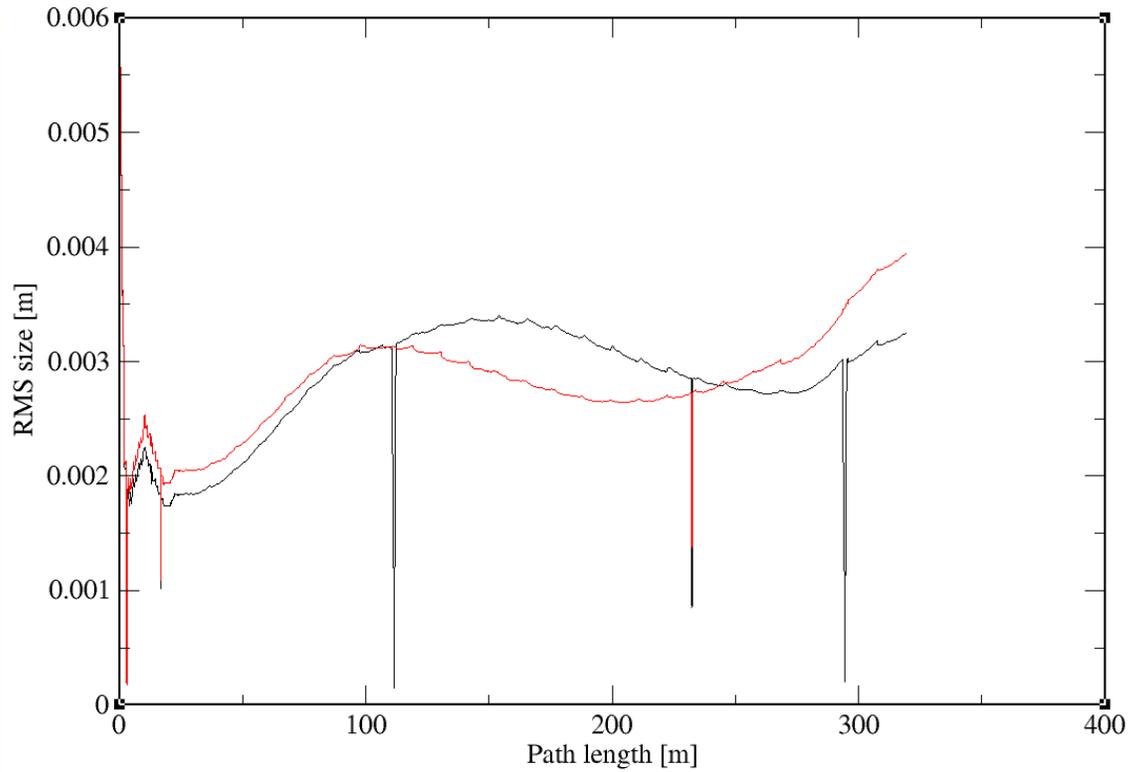
There is enough
stay clear
aperture with
current LEReC
laser box design

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

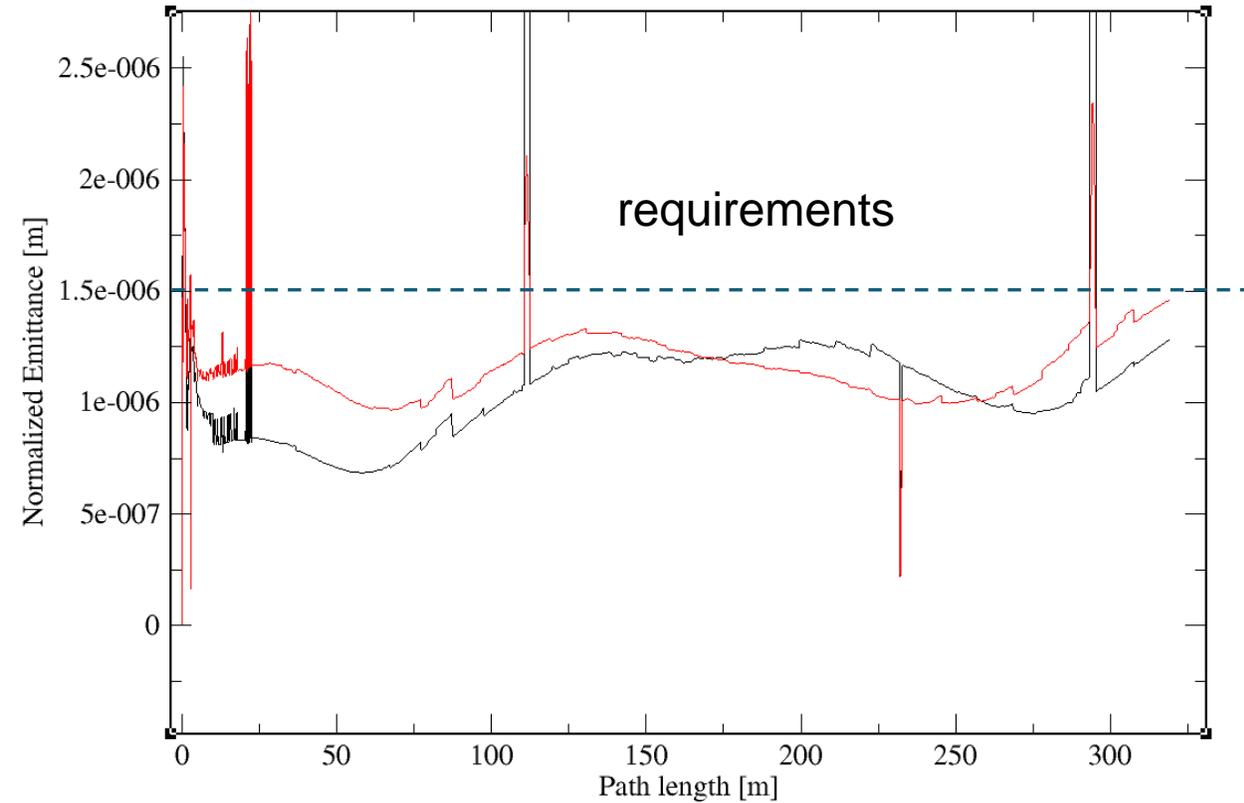


Gun-to-Dump simulations for bunch charge of 1 nC with 4 mm off center at the cathode (continue)

RMS Envelopes



Emittances



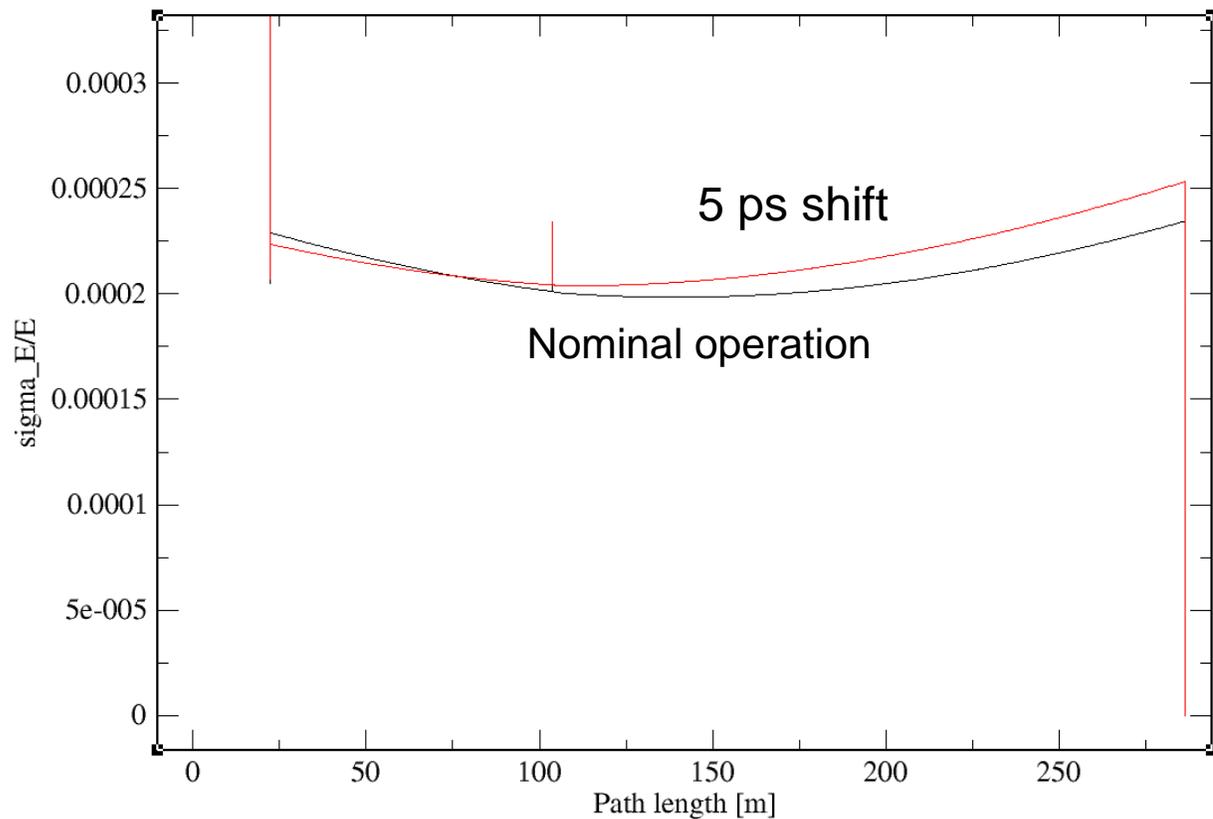
Bunch quality satisfied requirement emittance

The XY asymmetry is a result of initial DC gun focusing astigmatism due to off center operation.

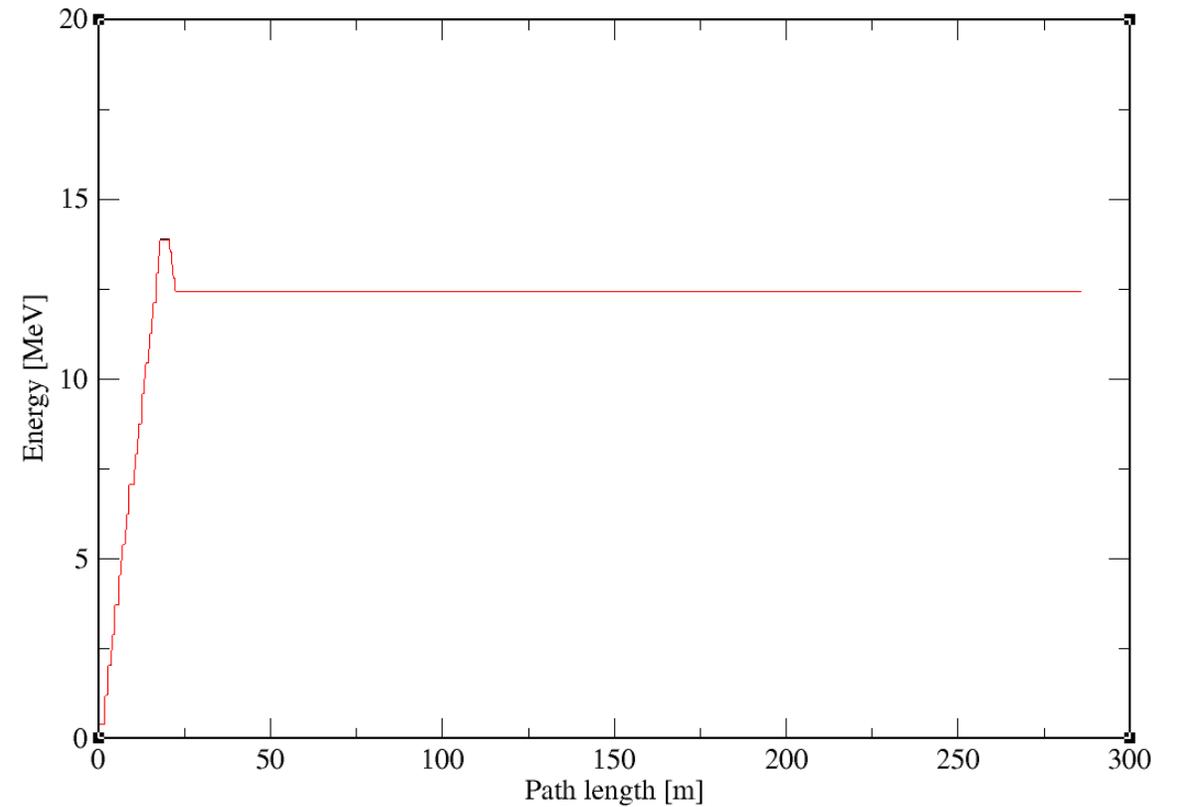
Laser arriving time shift effect on longitudinal beam dynamics

5 ps shift vs nominal operation

RMS Energy spread



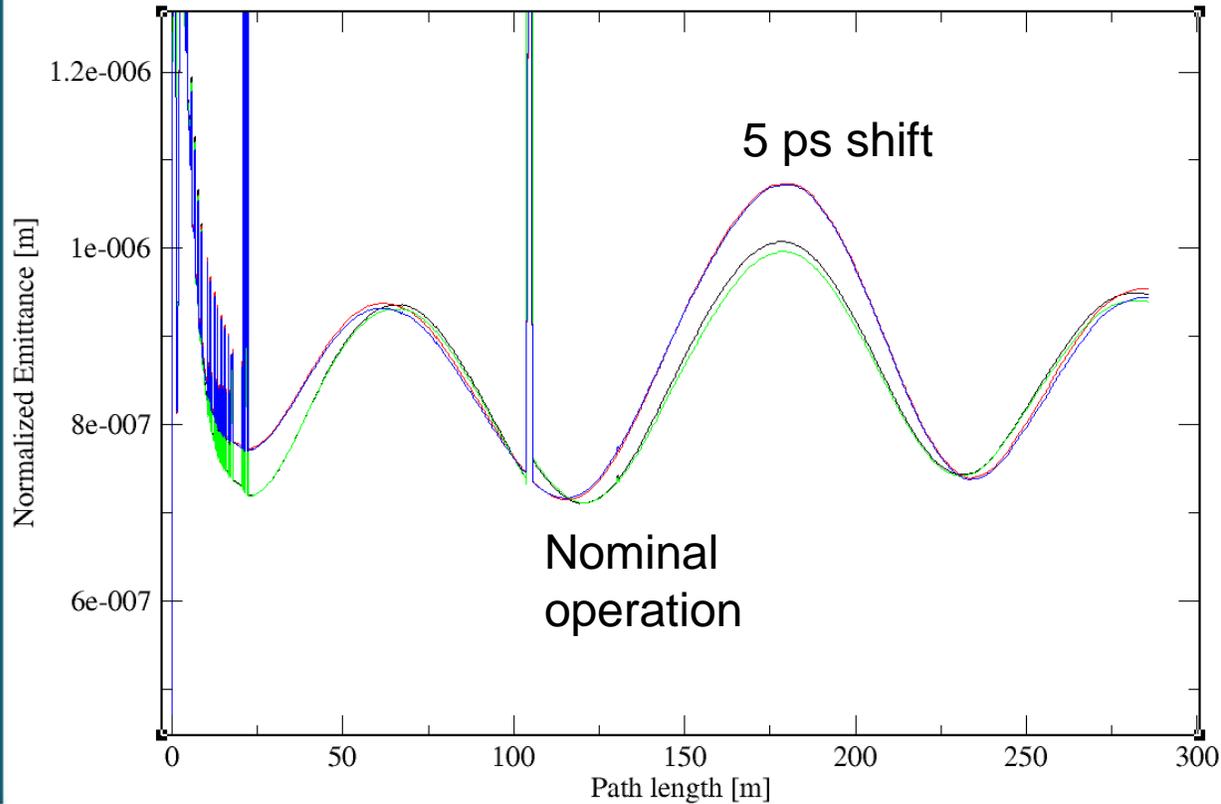
Average energy



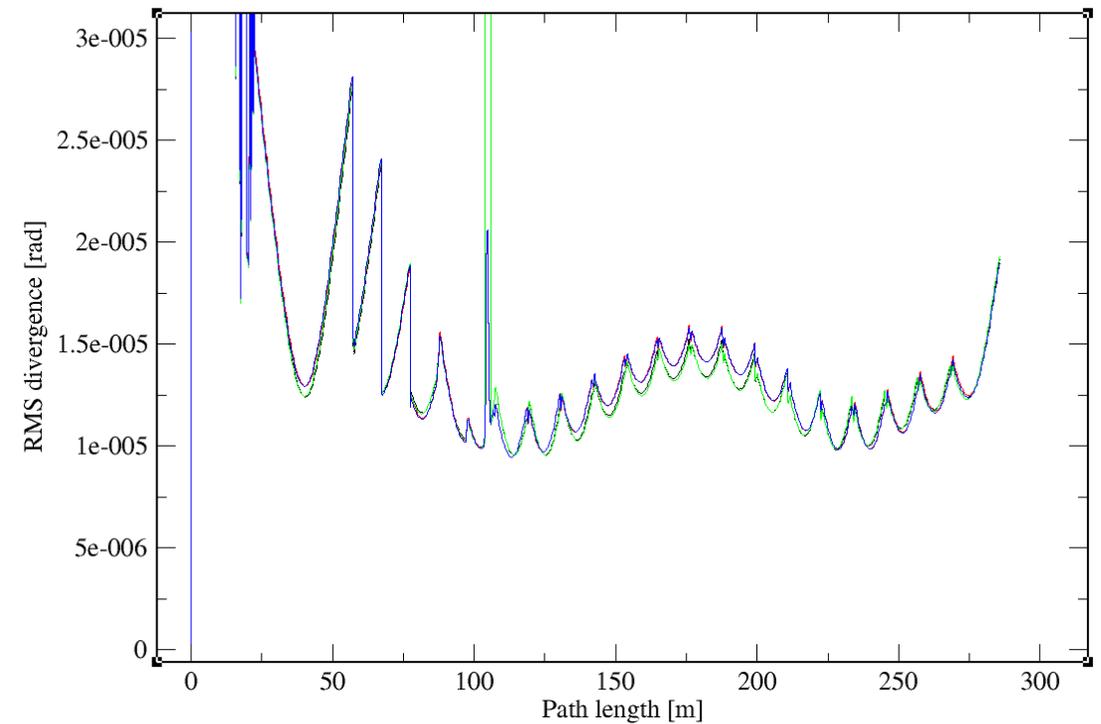
Laser arriving time shift effect on transvers beam dynamics (continue)

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!

Additional materials