Beam dynamics in CeC accelerator

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CeC mini workshop

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70 YEARS OF DISCOVERY

A CENTURY OF SERVICE

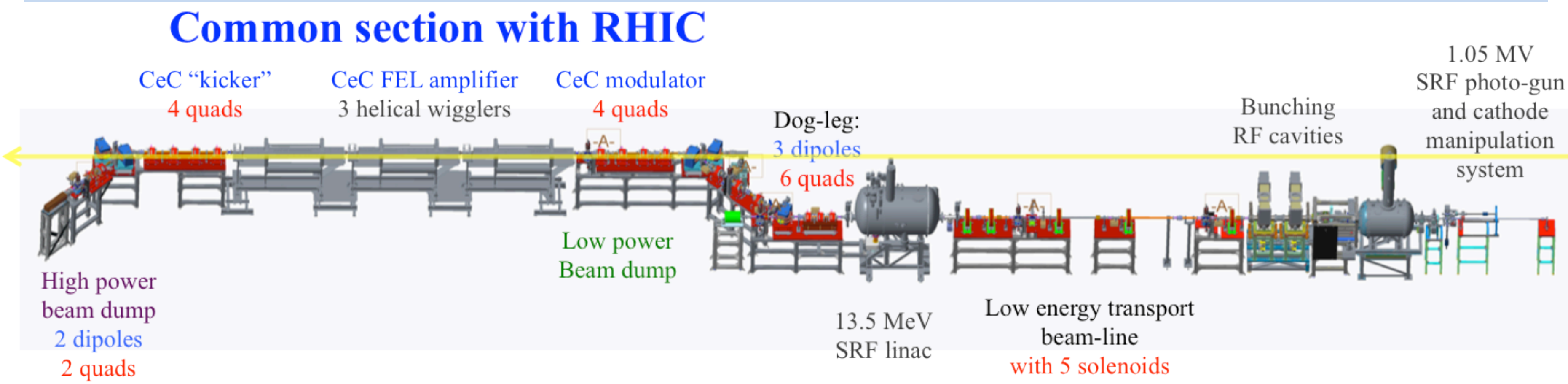
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

Outline

- Low energy beam transport
  - Electron Linac Simulation and Optimization
  - Multi-pacting and wakefields
  - Microbunching instability in LEBT
- Dogleg
  - Chromatic Effect
  - Coherent Synchrotron Radiation Effect
- Common section
  - Optics Matching
  - Space charge effect
  - FEL gain, evolution and saturation

Electron Linear Accelerator Simulation



- Start to end electron beam dynamics simulation from photocathode to the common section

- Each element is modeled with real geometry with measured fields
- Lattice matching design (Dogleg and Common section)

- Collective effects

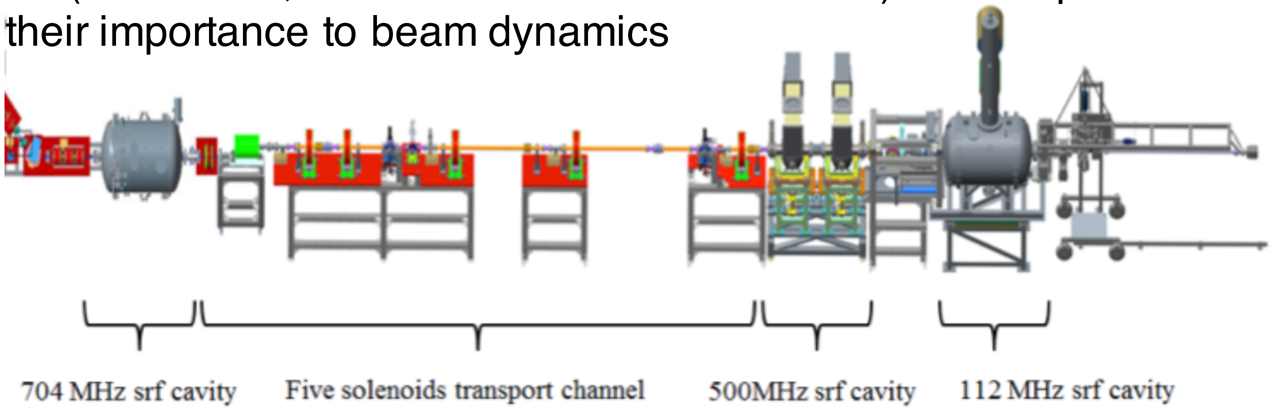
- Space Charge effect (ASTRA/GPT/IMPACT-T/PARMELA)
- Chromatic aberration and Coherent Synchrotron Radiation effect (ELEGANT)

- Demonstrate required electron beam can be generated using simulation

- peak electron current (50 - 100A), slice Emittance < 5 micro, Energy spread~0.1%
- Flat top longitudinal distribution

Low energy beam transport (LEBT)

- Space charge effect is dominated in the low energy region (before 704MHz srf cavity)
- Different simulation codes were benchmarked to have reasonable agreement in results (will focus on IMPACT-T simulation in this talk).
- Various effects (wakefields, vacuum chamber effects etc…) were implemented in codes to study/verify their importance to beam dynamics



❖Beam requirement

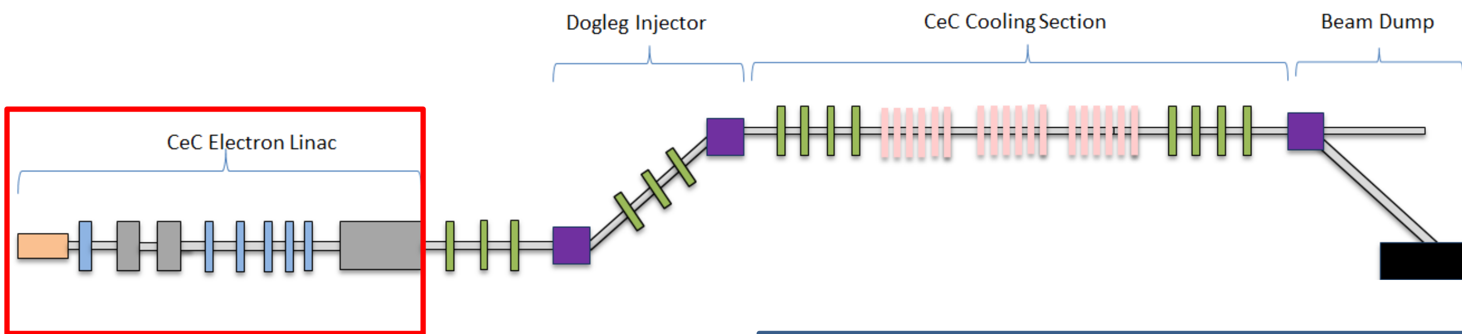
- Peak current 50A-100A
- Energy spread~0.1%
- sliced Emittance < 5 mm-mrad

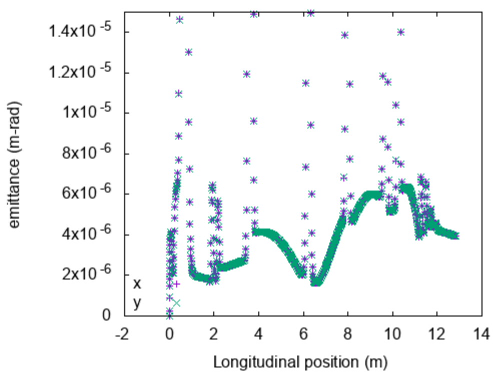
❖Optimization terms

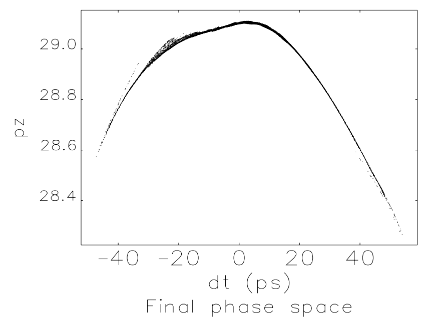
- 1+5 solenoids
- Cavities' phases (gun, buncher, linac)
- Bunching cavity voltages (#1 and #2)

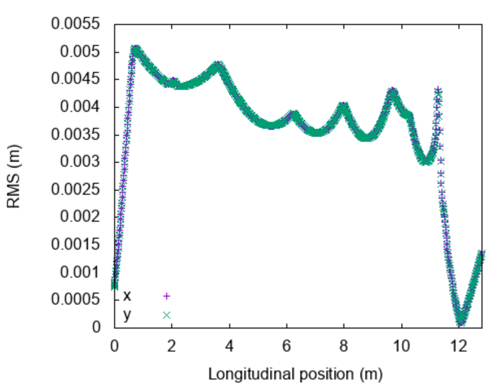
Parameter	Value
Bunch distribution	Beer can (tran.)/Flat w. gauss edge (long.)
Kinetic energy	~ 14.5 MeV
Charge per e-bunch	0.5-1.5 nC
Bunch length	100-400 ps
Radius	1-2 mm

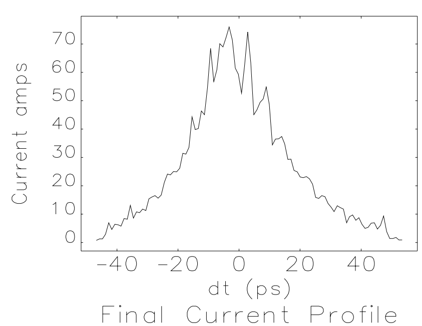
Low Energy Beam Transport Optimization

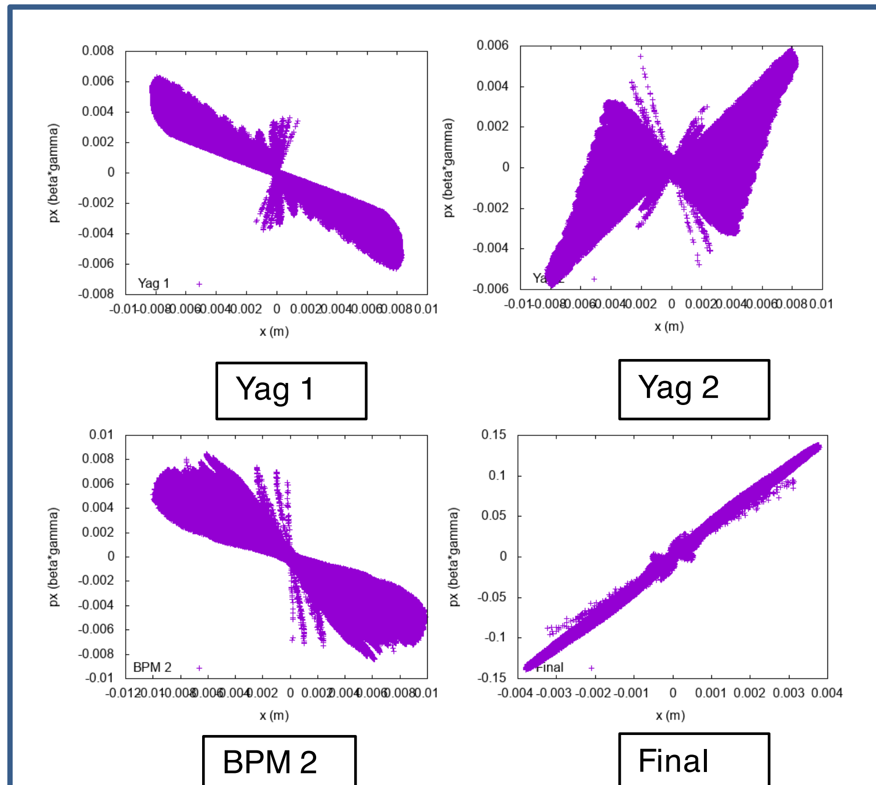




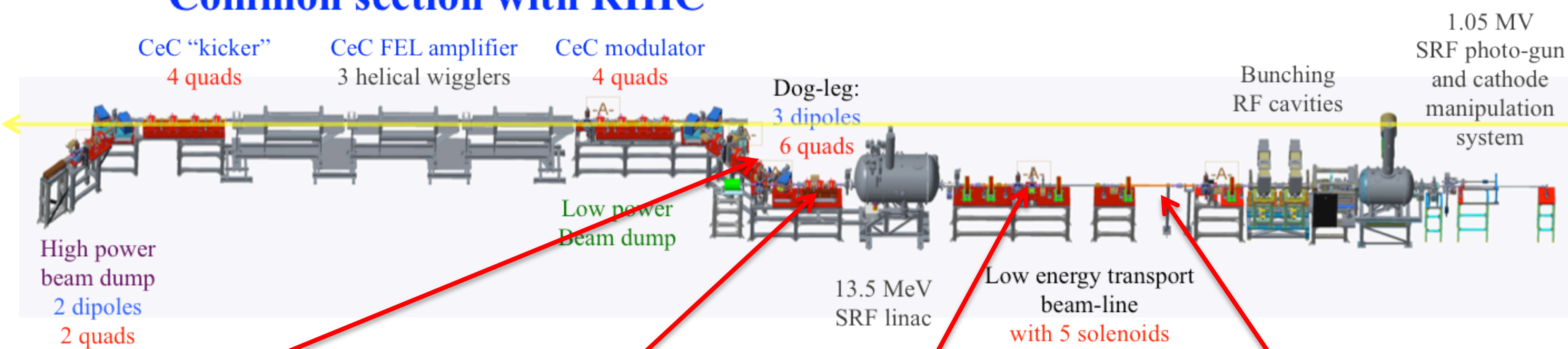


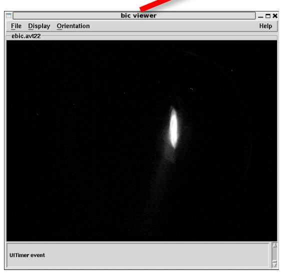




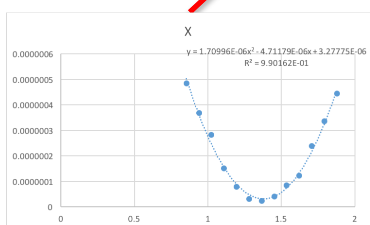


Beam property measured in CeC commissioning

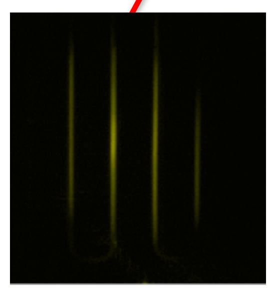




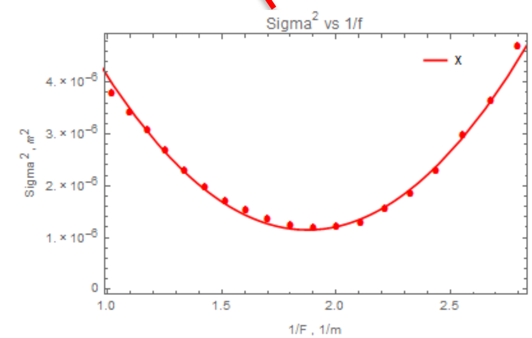
Beam compressed by ~ 20-40 folds after LEBT, energy spread ~ 0.1%



Quad scan, norm. emittance ~ 3.6 um



Slits, norm. emittance ~ 1-4 um



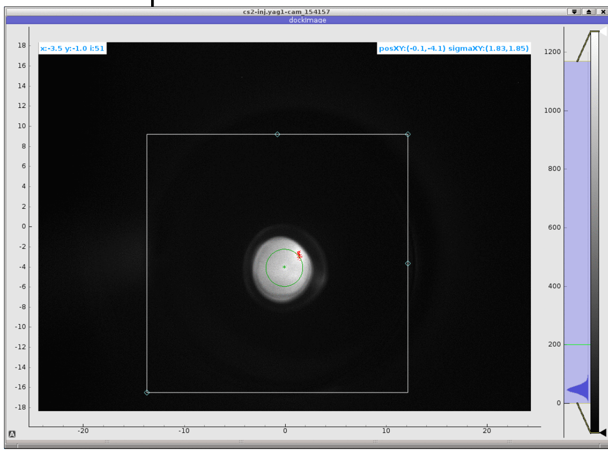
Sol scan, norm. emittance ~ 0.5-2 um

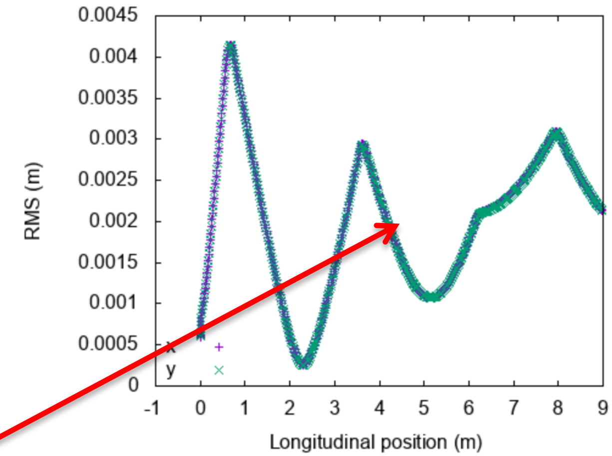
Properties measured by solenoids and slits in good agreements with simulation predicted: emittance ~ 3 - 4 mm- mrad, energy spread ~ 0.1%.

Beam quality sufficiently good for CeC demonstration

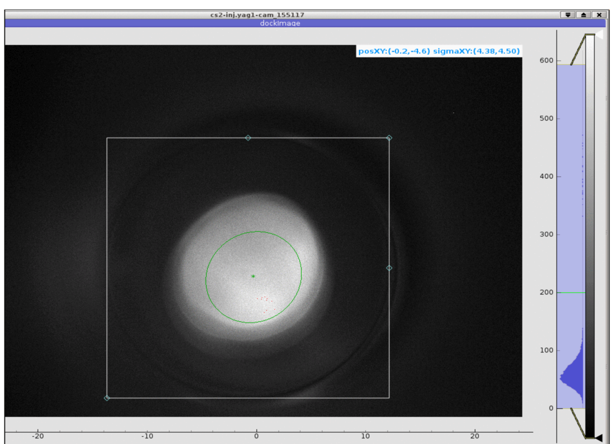
Comparison of measurements and simulations (trans.)

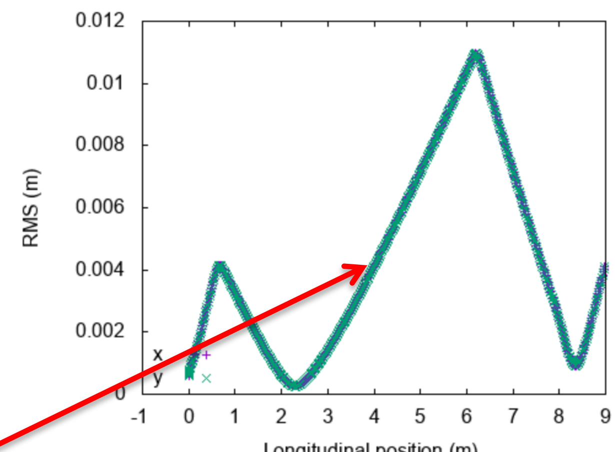
By varying solenoids strengths, we measured beam sizes on yag 1,2 and compare with simulated beam size





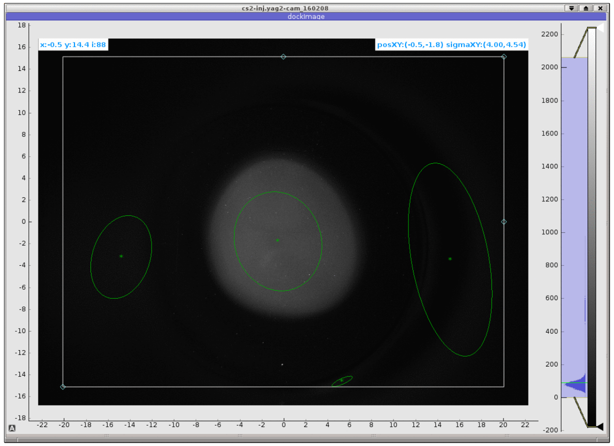
On yag 1, Measured (rms) 1.83 -1.85 mm vs simulated (rms) 1.84 mm

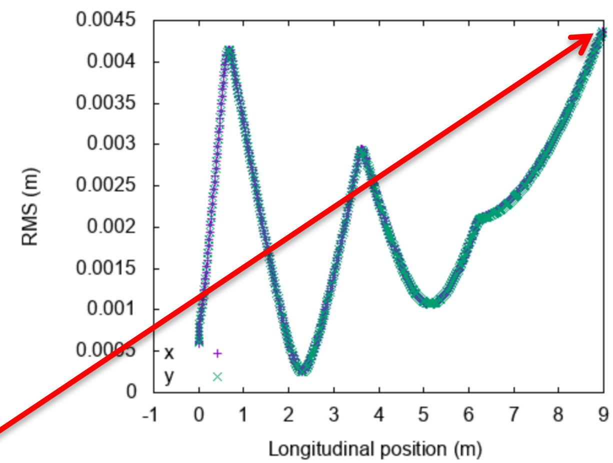




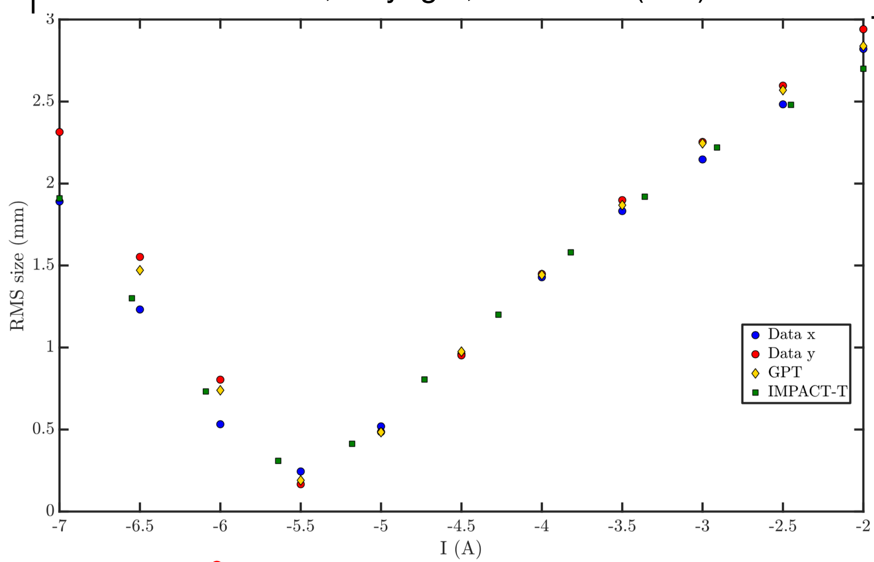
With LEBT sol 1 off, Measured (rms) 4.38 -4.5 mm vs simulated (rms) 4.7 mm

Comparison of measurements and simulations (trans., cont'd)





Turn off LEBT sol 3, on yag 2, Measured (rms) 4 -4.54 mm vs simulated (rms) 4.37 mmx



Another set of measurements were done by scanning LEBT sol 1 and measure beam size on yag 1. The comparisons of simulations in GPT and IMPACT-T with experiments are in good agreements.

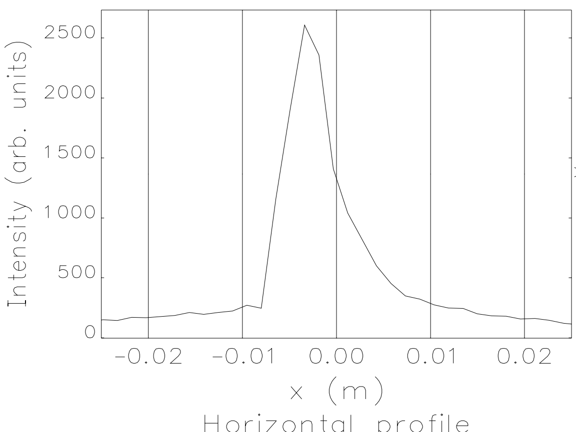
Stronger solenoid focusing

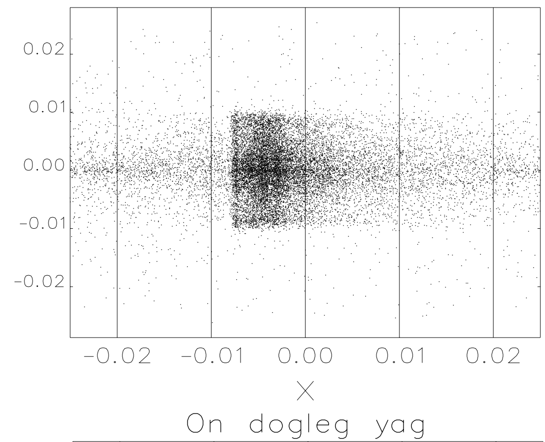
Comparison of measurements and simulations (long.)

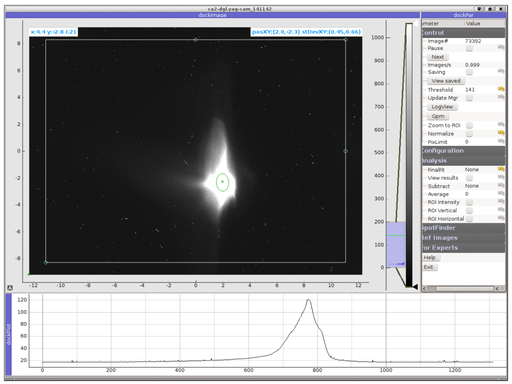
To check beam's longitudinal distribution, we need to propagate beam to yag in dogleg where dispersion function will couple energy variation to horizontal displacement. In addition, we vary the linac's phase to compare the bunch pattern on dogleg yag with simulation.

Linac phase

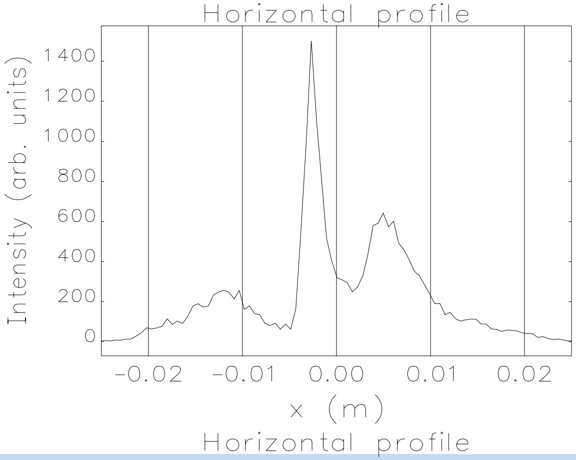
0 deg

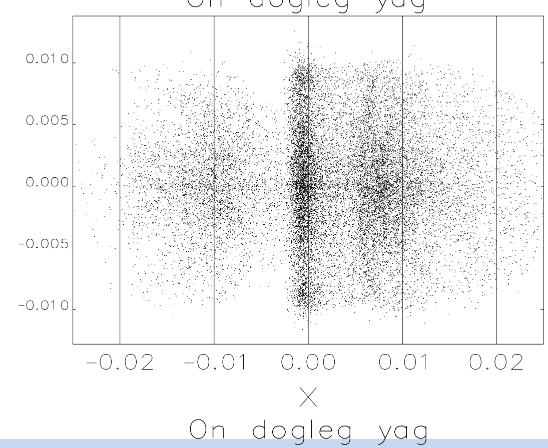


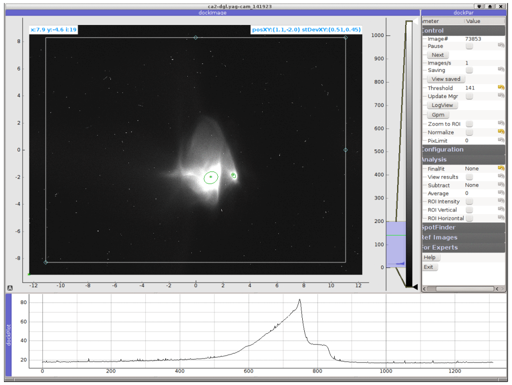




-5 deg

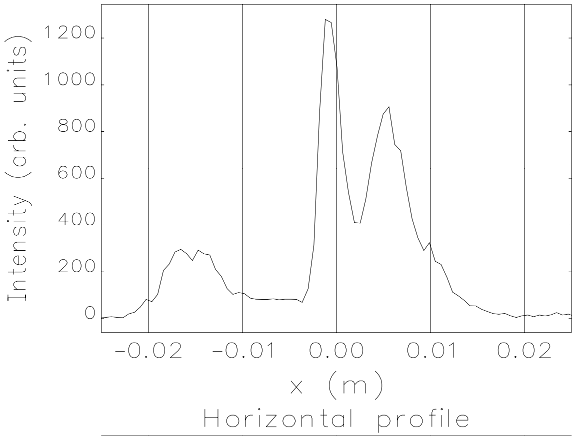


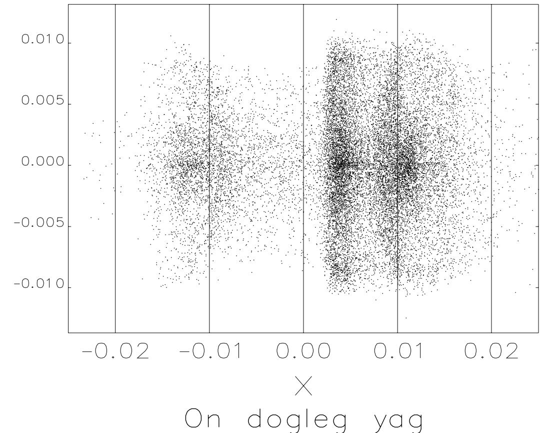


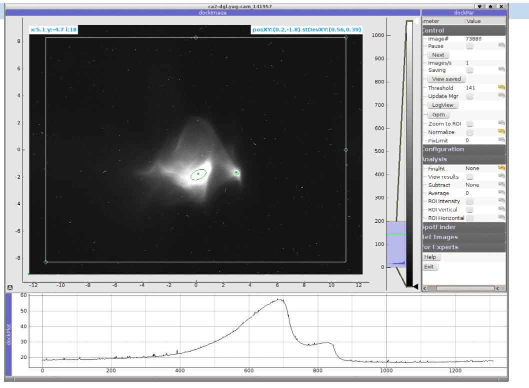


Comparison of measurements and simulations (long., cont'd)

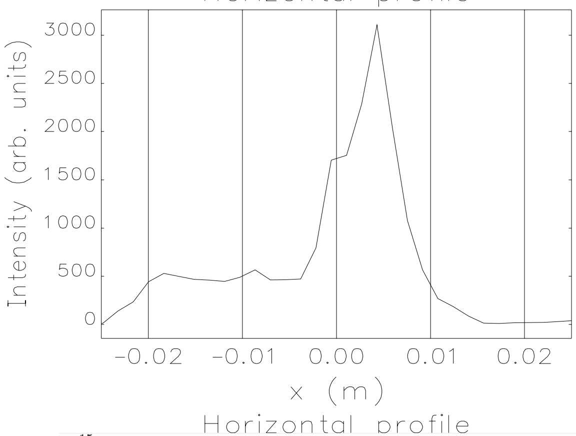
-10 deg

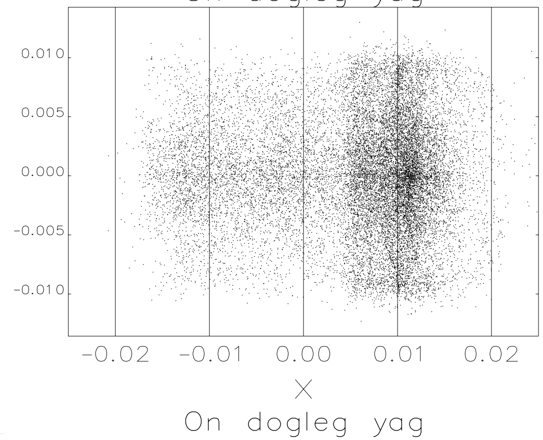


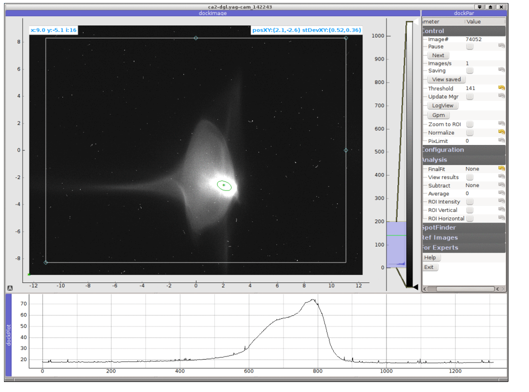


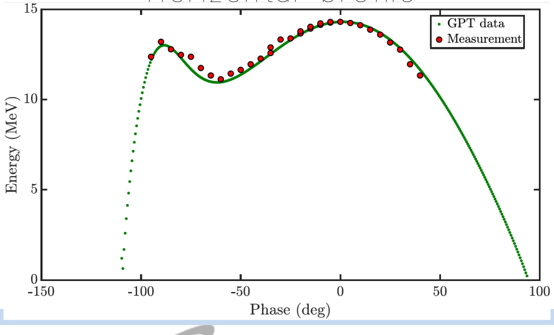


+10 deg





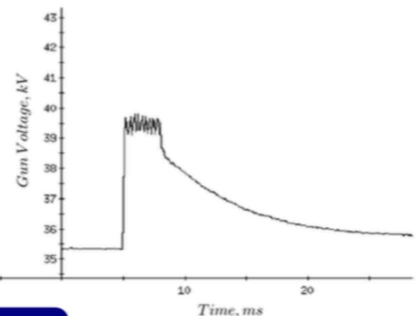


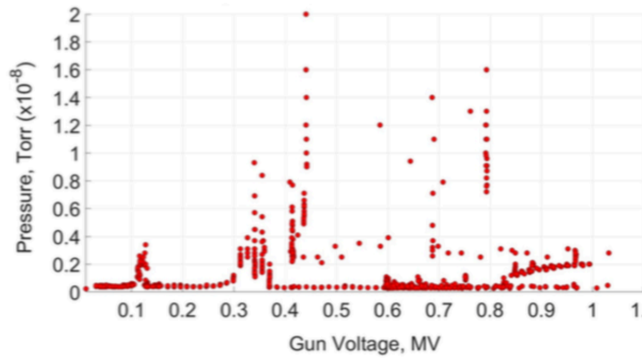


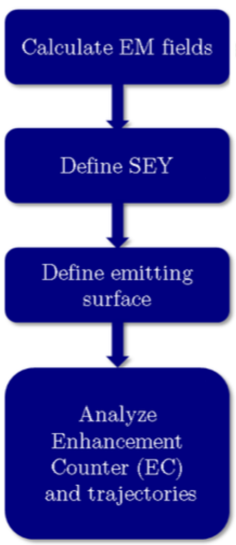
The asymmetry in RF phases, i.e., +10 deg and -10 deg has difference pattern can be visualized from energy gain RF phase dependency.

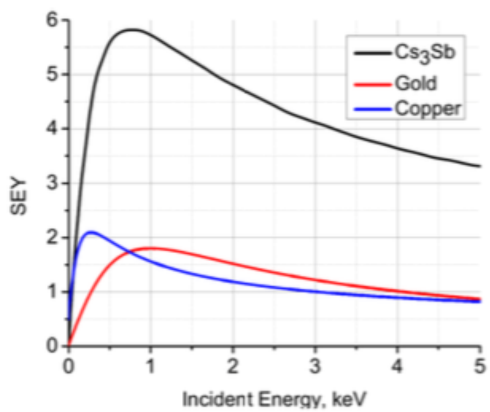
Multi-pacting in CeC SRF Photo-injector

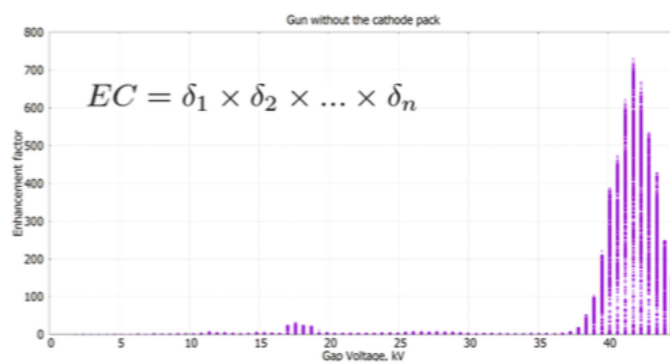
In commissioning, we encountered multi-pacting zones and observed vacuum activities at different gun voltage level. By assigning the emitting surface and SEY (materials), we can reconstruct the multi-pacting zones from experiment.











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Multi-pacting (cont'd)

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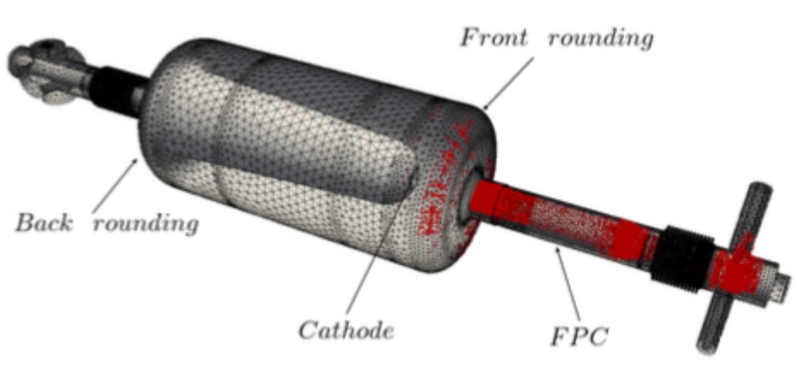

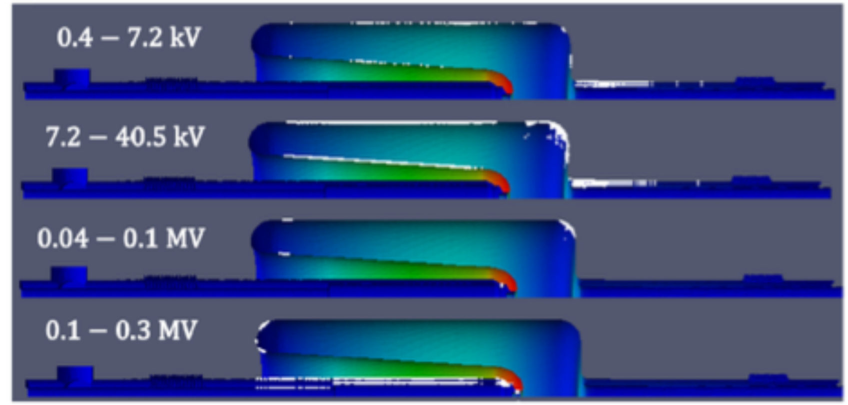

In simulation, we found different levels of multi-pacting are correspondent to SEY electrons trapped at different locations. When the cavity voltage increases, the multipacting zone is moving from corner of the cavity to the end of the cavity, causing less trouble in raising the voltage further.

By applying an abrupt strong RF power (max FPC insertion) to the cavity (pulsed thus not affecting vacuum), the multipacting is not fast enough to catch up with the RF power. Thus we were able to "jump" over MP zones. As soon as the RF voltage reaches to a level where we believe is safe, a tool developed by LLRF group will switch the RF pulse to CW for continuing operation.

Wakefields

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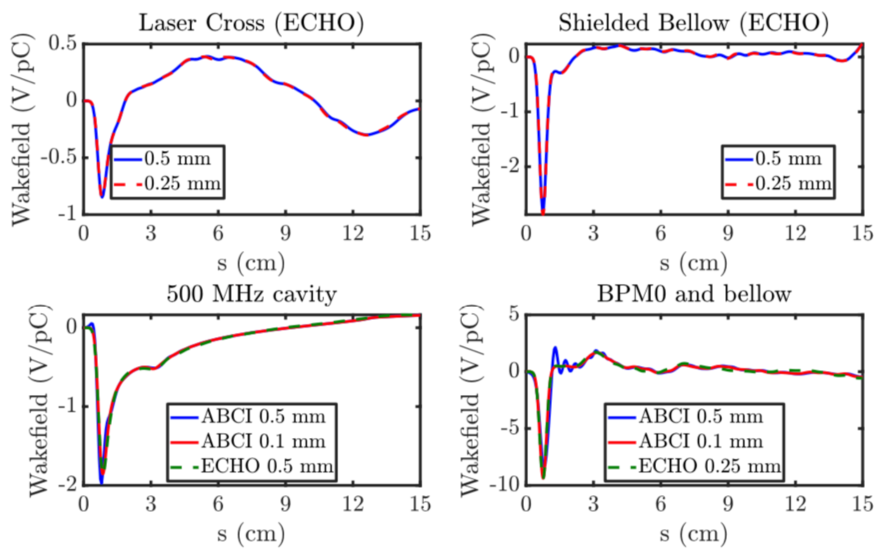
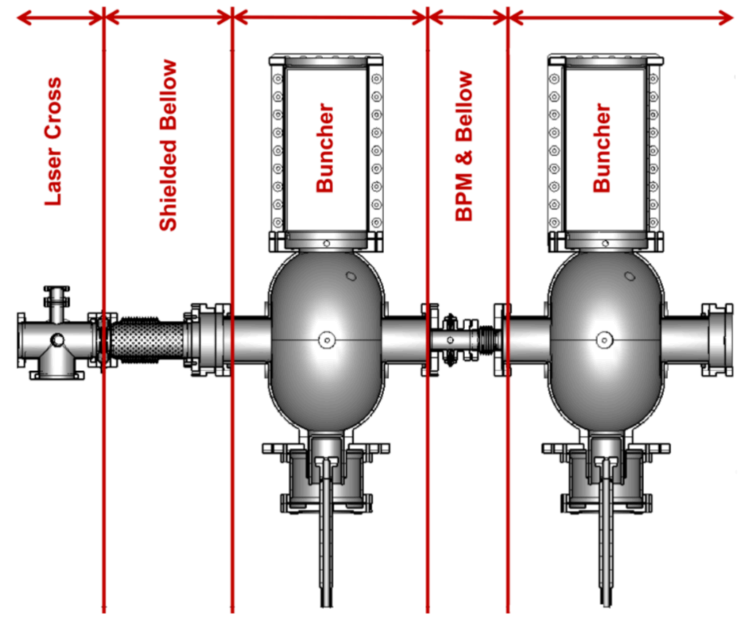


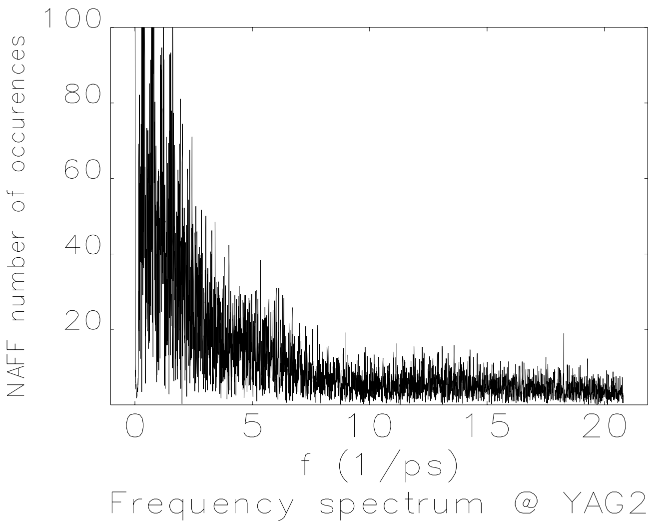
Wake potential in the elements of the laser cross and buncher assembly.

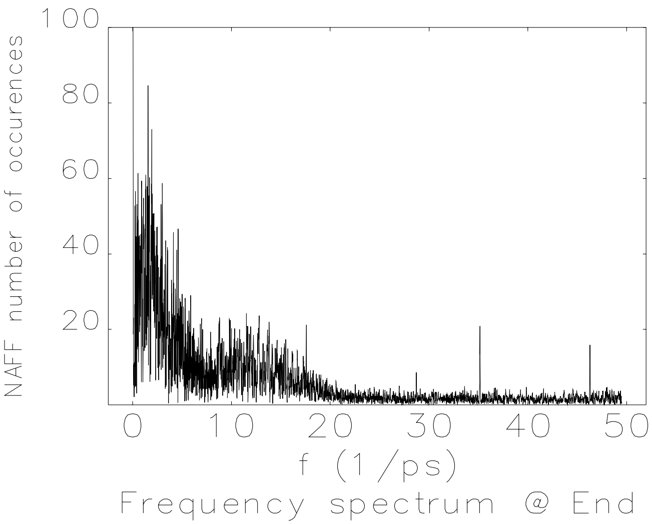


10 different types of wakes (cavities, bellows, BPMs, PMs, etc…) from after gun to after linac were simulated in ABCI/ECHO. Cross-checking was performed and calculated wakes were imported into IMPACT-T.

Microbunching instability in LEBT

In operation, we observed significant higher level of radiation from FEL. We suspect that there were microbunching instabilities in our LEBT, i.e., the bunch has pre-bunched slices which dominated signals.
With large number of particles (20 mil macro particles) and fine simulation step/meshes, we were able to simulate and reconstruct this microbunching structure.

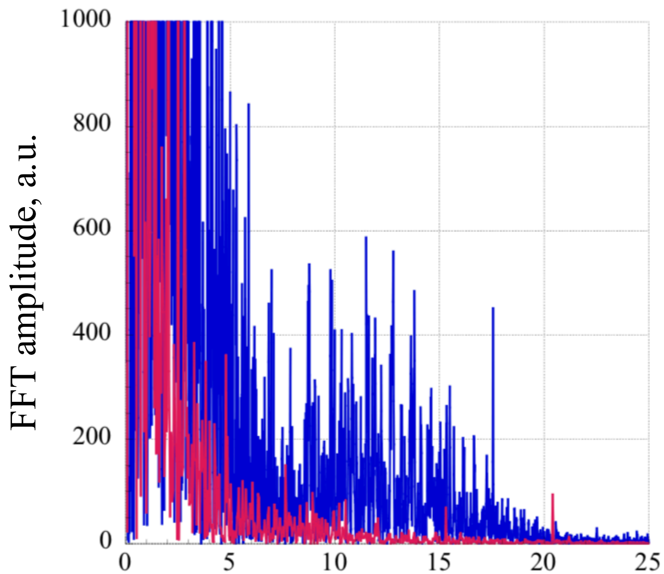


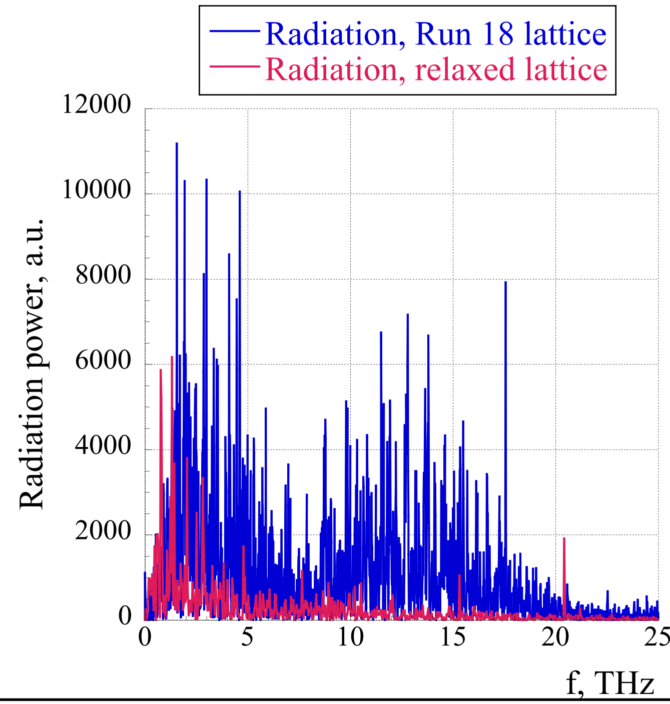


As bunch propagates through LEBT, it gets ballistically compressed. The spectrum extends to higher frequencies. The signal around 10 THz is suspected to be induced by PCI.

Microbunching instability in LEBT(cont'd)

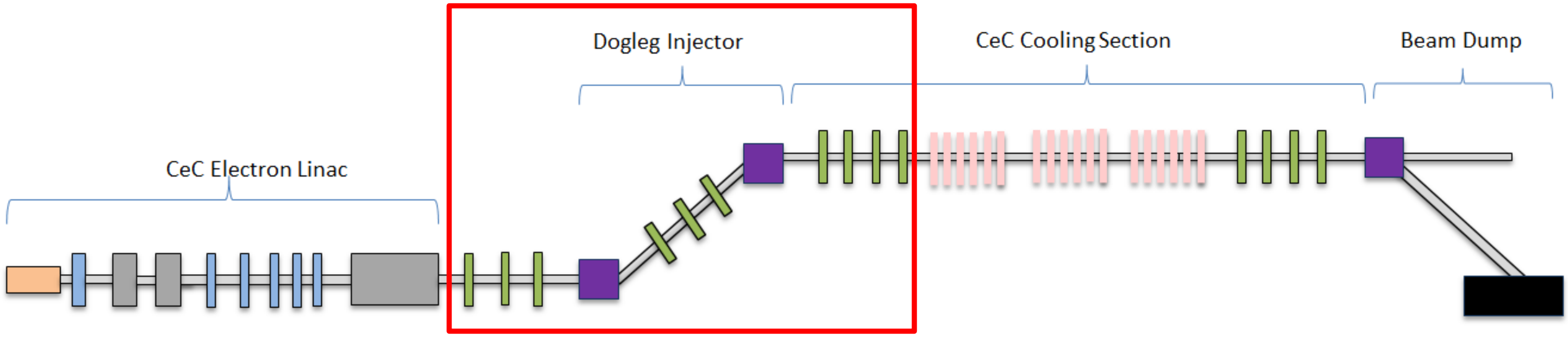
By reducing solenoid strengths, we were able to generate a smooth transition in beam envelope in LEBT and the microbunching structure (in the frequency region of interest ~ 10 THz is greatly reduced.

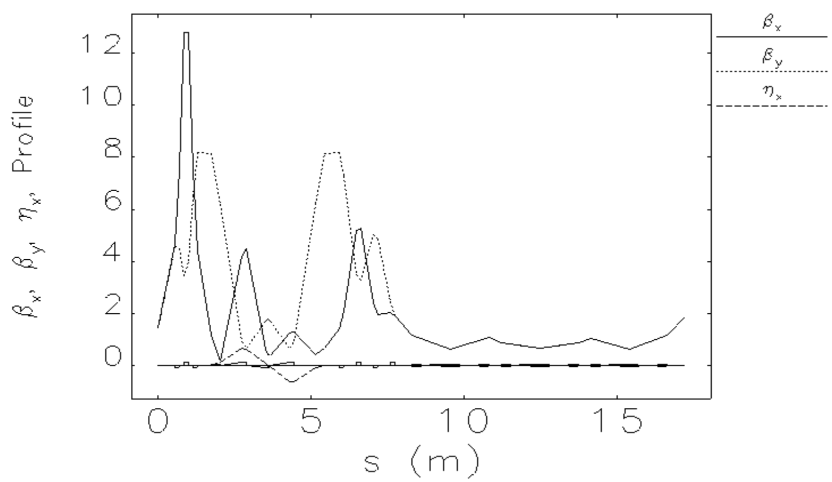




Red curves show the frequency spectrum at the end of 704 MHz cavity for relaxed lattice. The low frequency structures represent the compressed electron bunch. Sharp spikes are numerical structures which are related to mesh size and integration time steps.

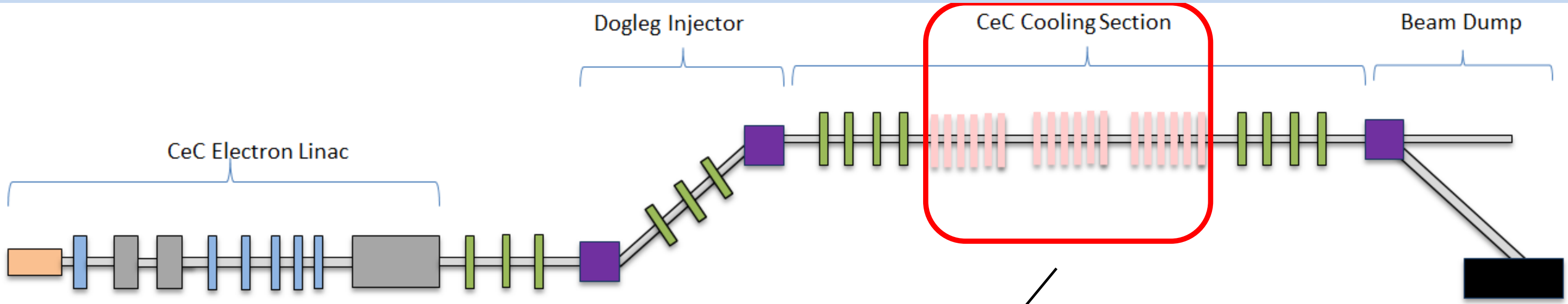
Dogleg – lattice matching

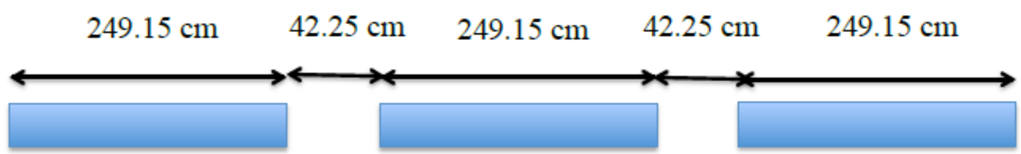




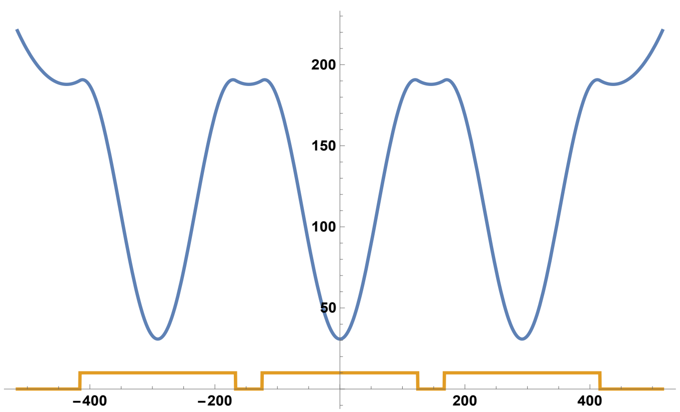
We used 8 quadrupoles to match the beam optics from the exit of LEBT to the entrance of FEL (2 quads in dogleg are fixed for dispersion matching). We used alternating quadrupole settings to minimize the beam size along the beam line and make β_x/β_y small.

Lattice Matching Cont.

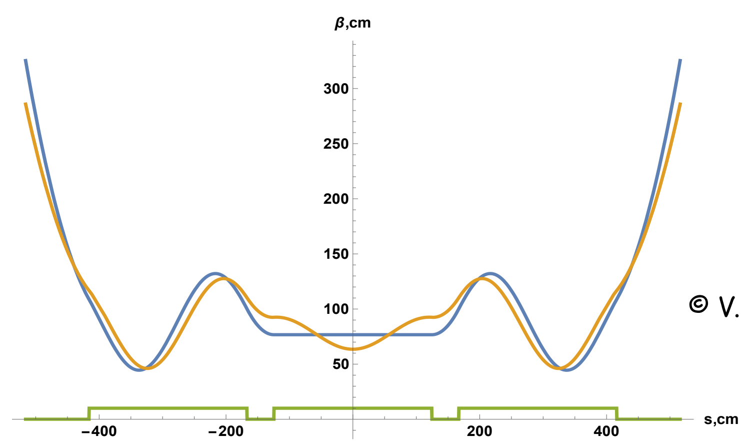




Periodic solution (Betatron function) :



bilateral symmetry solution (Betatron function) :



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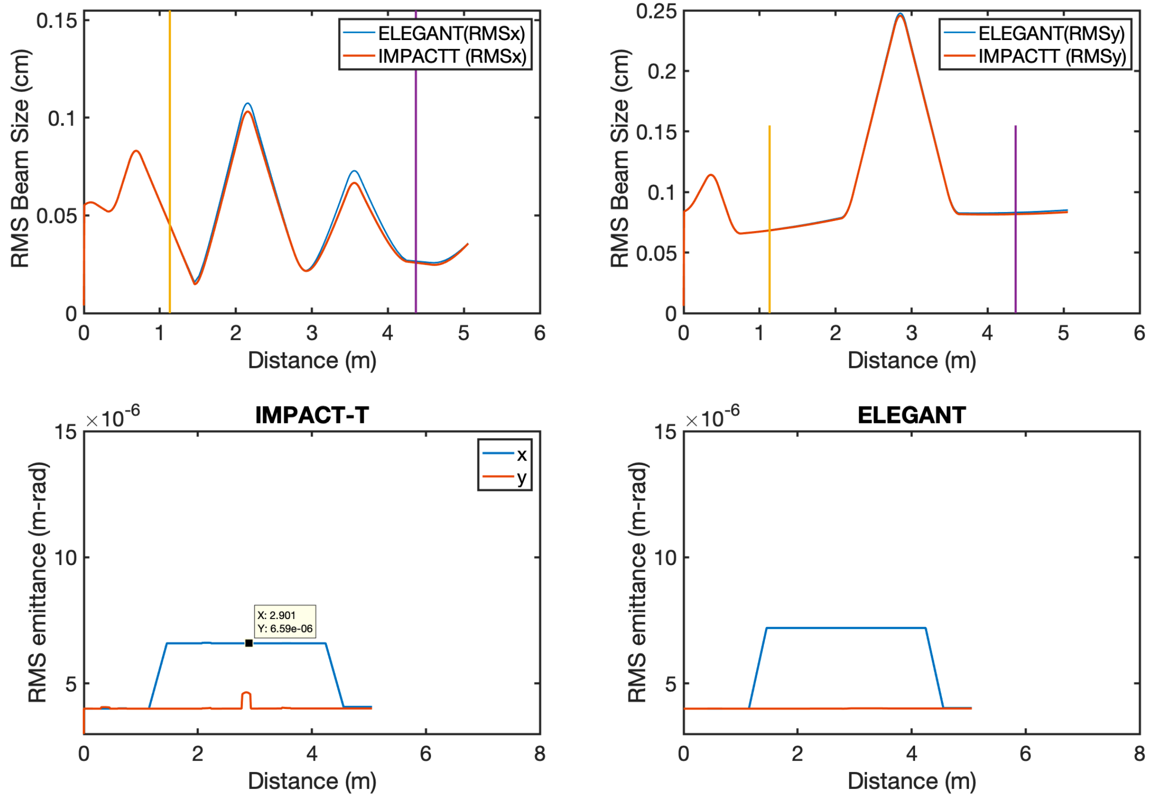
βmin =30.82 cm. and βmax = 191 cm – 6-fold beta-beat

non-periodic solution is a better choice for low beta beat

Blue: βx,y=1.08741 m and αx,y= 0.50569.

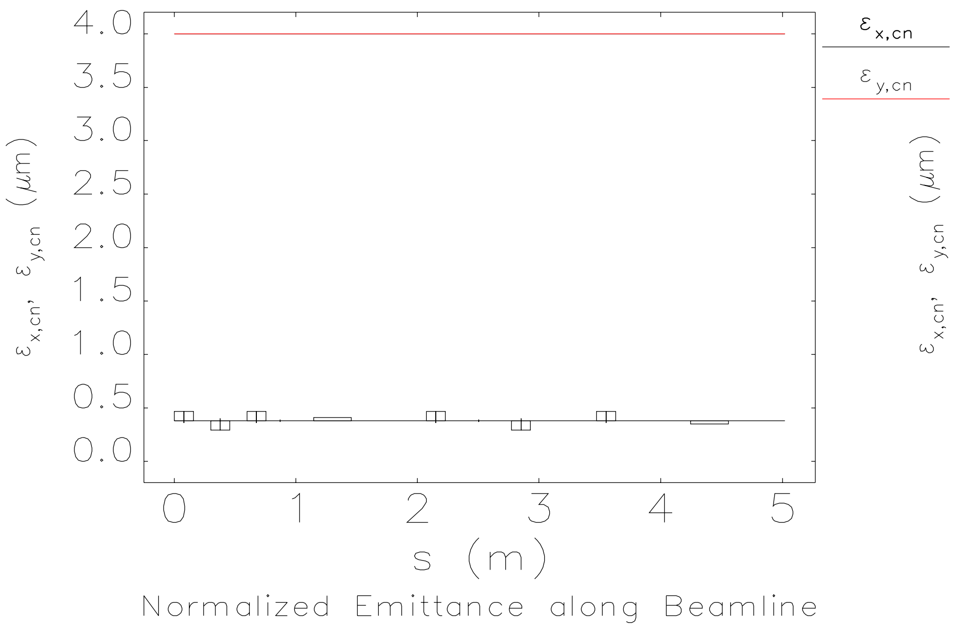
Yellow_grey: βx,y= 1.16704 m and αx,y= 0.361416.

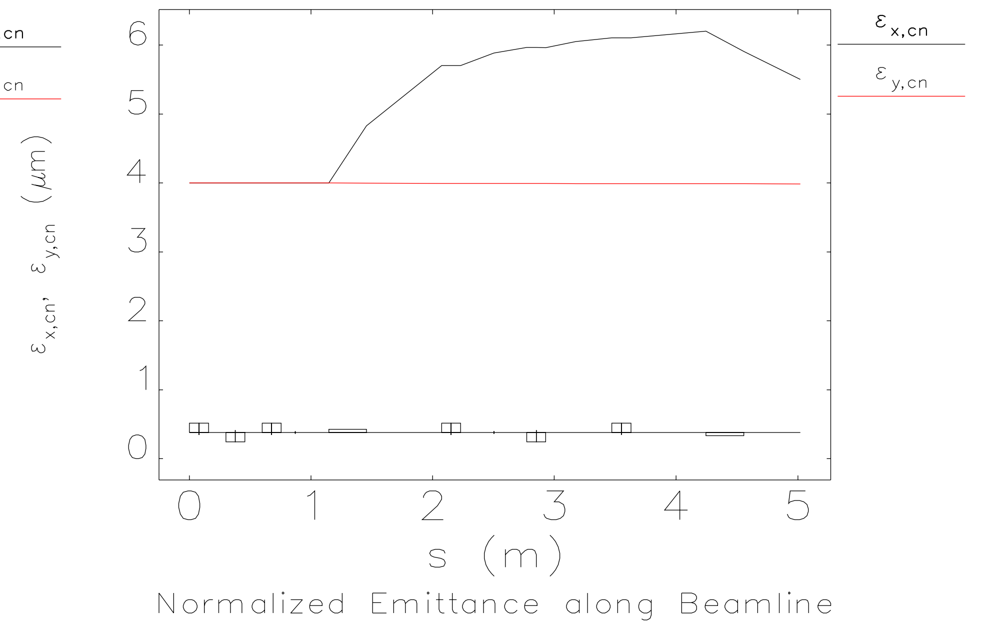
Dogleg – IMPACT-T vs ELEGANT



Impact-T has very close results in simulated beam size and emittance in the dogleg with ELEGANT, which is a more convenient code for beamline matching and optimization. We simulated the dogleg using ELEGANT for both chromatic aberration and coherent synchrotron radiation (CSR) effects.

Dogleg – CSR



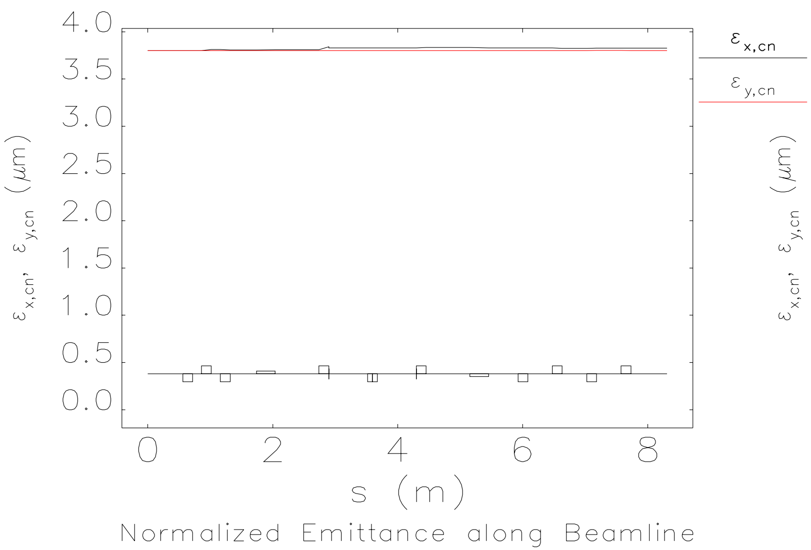


CSR is negligible for our norminal machine parameters. Beam current increased by 10 fold to show effect.

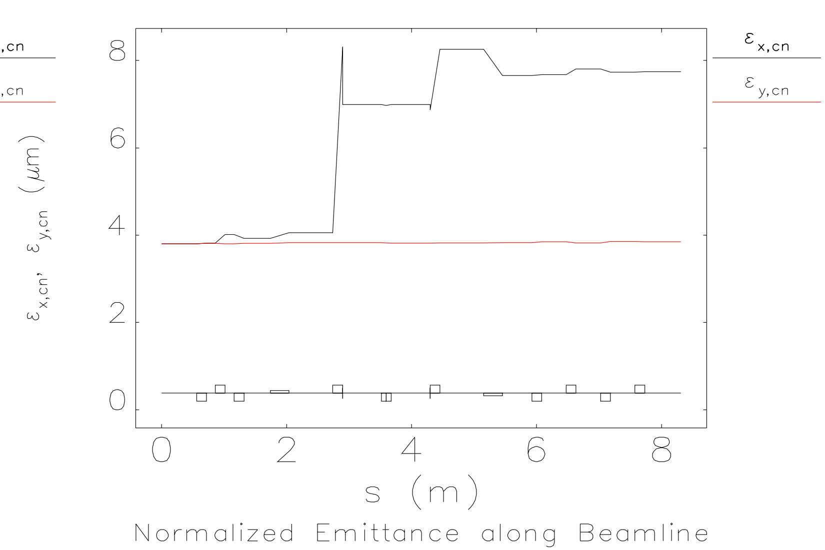
Chromatic effect

We checked the chromatic aberration in dogleg. For our operational regime (energy spread ~ 0.1%), chromatic aberration has no significant effects on the emittance.

Energy spread= 0.25 %



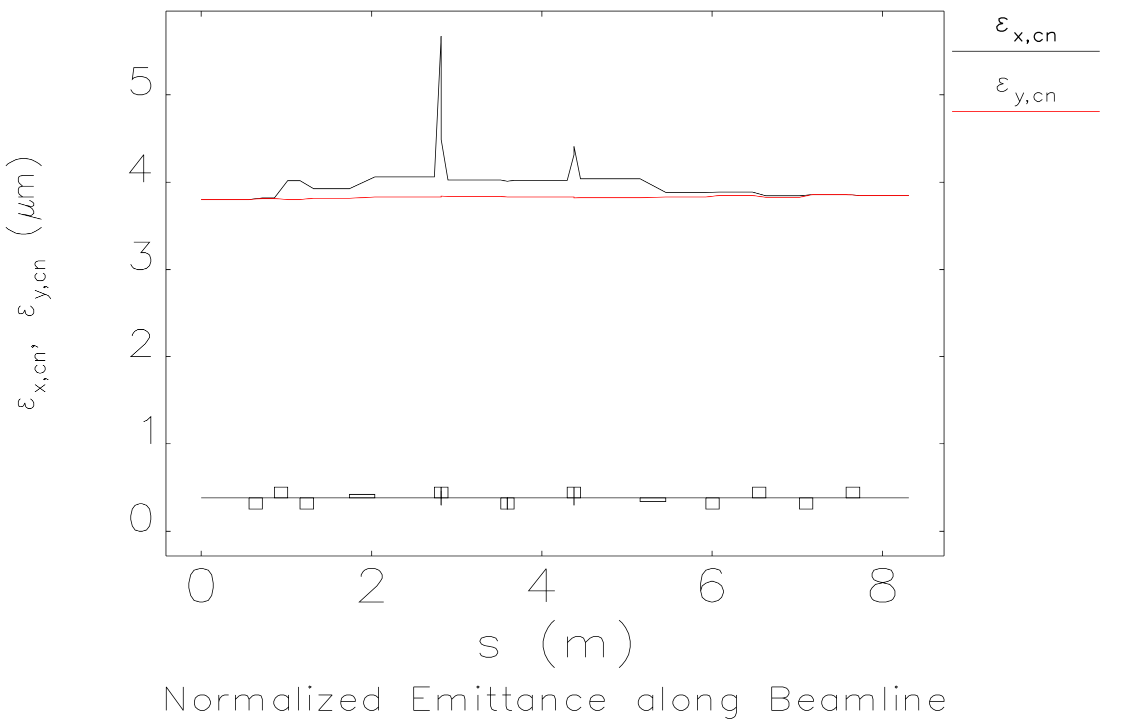
Energy spread= 1.0 %



Emittance could be blown up by factor of 2 in CeC lattice by chromatic effect (large energy spread was intentionally used to show effect).

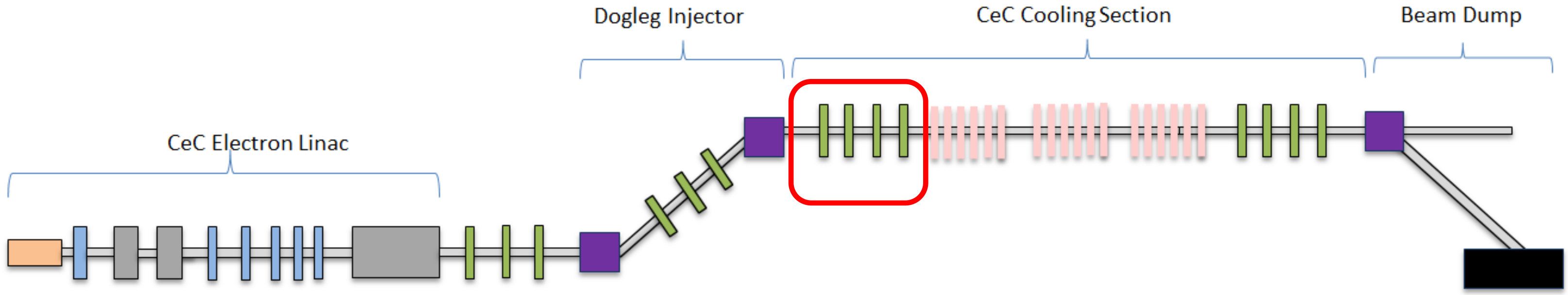
Nonlinear correction on chromatic effect

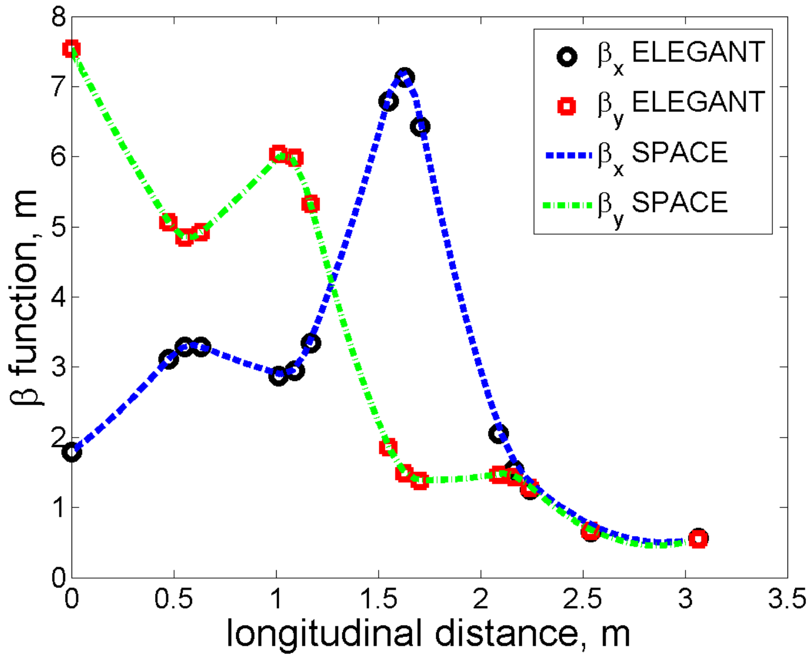
Energy spread= 1.0 %



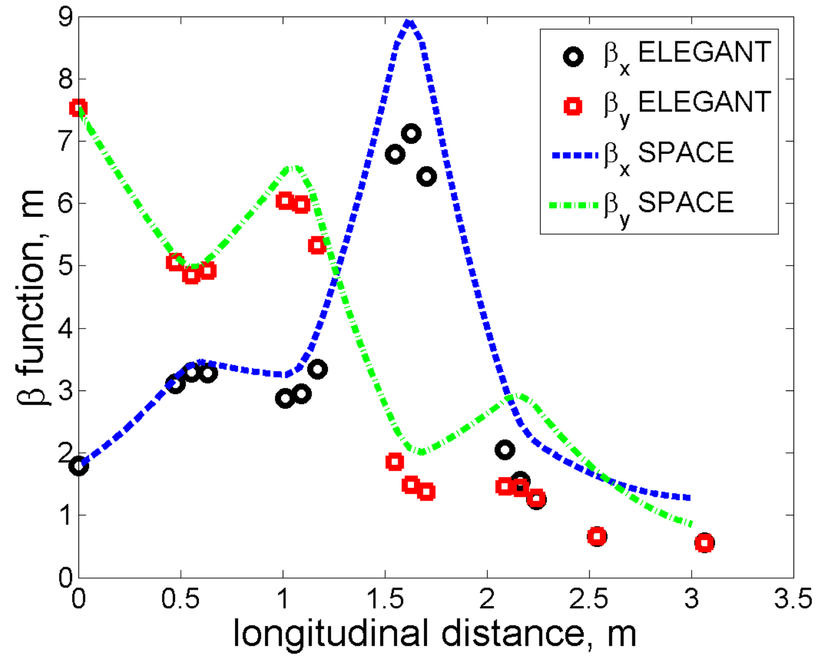
In case of large errors, we could use pair of sextupole located at Q1 and Q3 in dogleg to correct the chromatic aberration.

Space charge effect on optics matching into FEL





No space charge

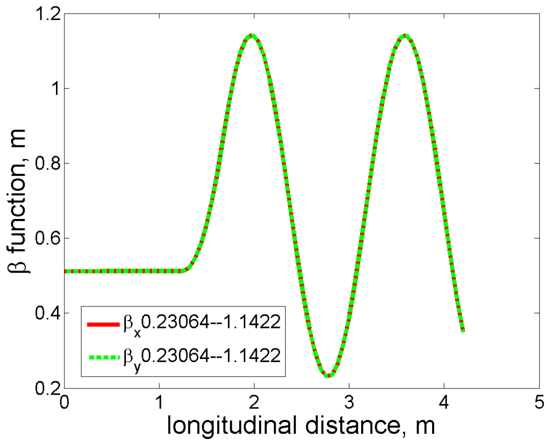


With space charge

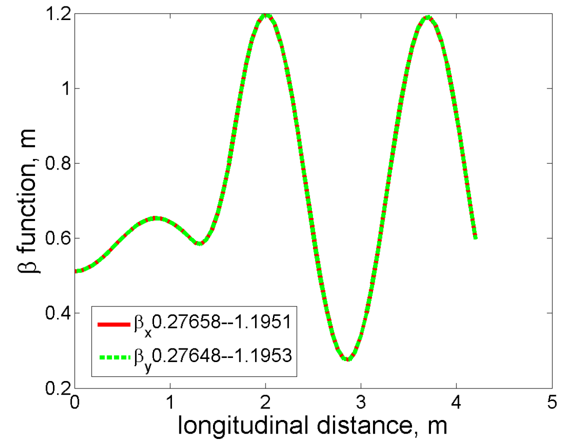
© J. Ma

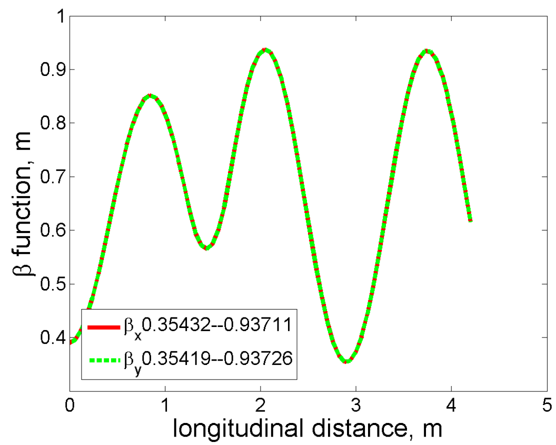
Space charge effect on envelope function in FEL

No space charge



With space charge





We studied different envelope function for different beta function and find the minimum ratio of beta beat for best matching with space charge.

FEL simulation setup and amplification

GENSIS

Signal (δ like)+ shot noise — Shot noise

=

response

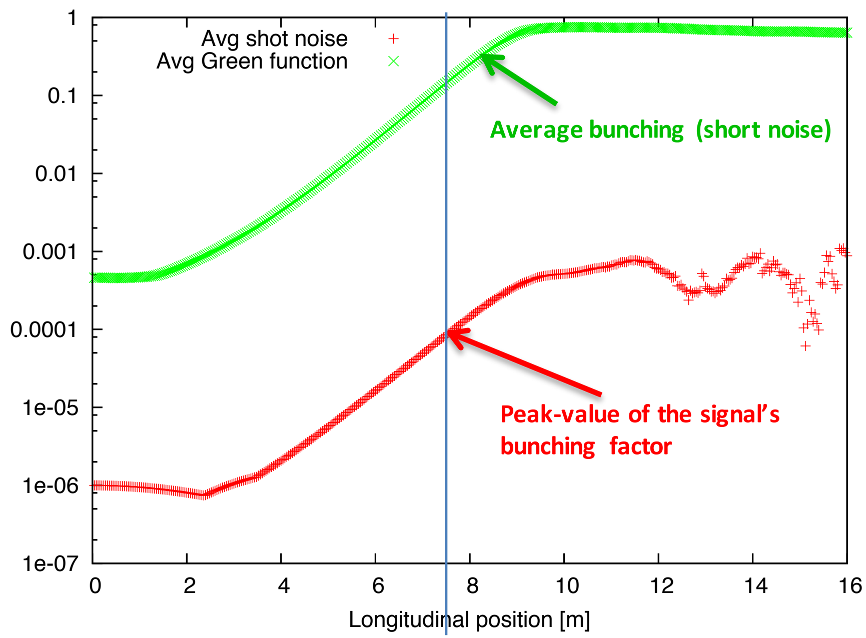
Being the difference between two complex numbers, such a FEL response is a complex function, i.e., it is described both by the amplitude, and the phase.

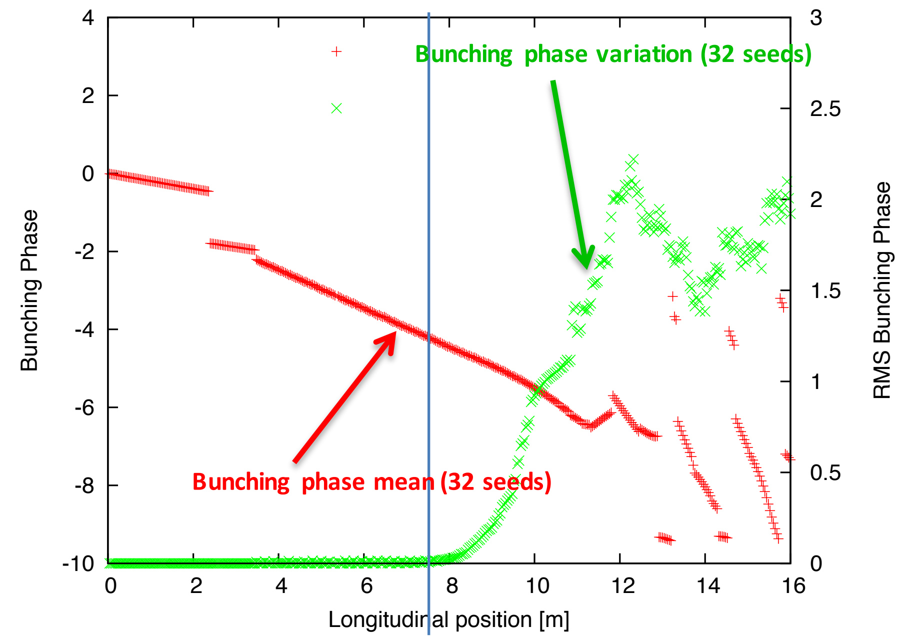
$$b_1(z) = |b_1(z)| e^{i\theta_1(z)}, b_2(z) = |b_2(z)| e^{i\theta_2(z)} \quad b_s(z) = |b_s(z)| e^{i\theta_s(z)} \equiv b_2(z) - b_1(z)$$

In GENESIS, we generate shot noise with different random number seeds (32 seeds), thus we can study the statistics of the amplification of FEL and its variation.

FEL gain and saturation

Electron slice with highest bunching factor is selected and its amplitude and phase are recorded along the FEL.





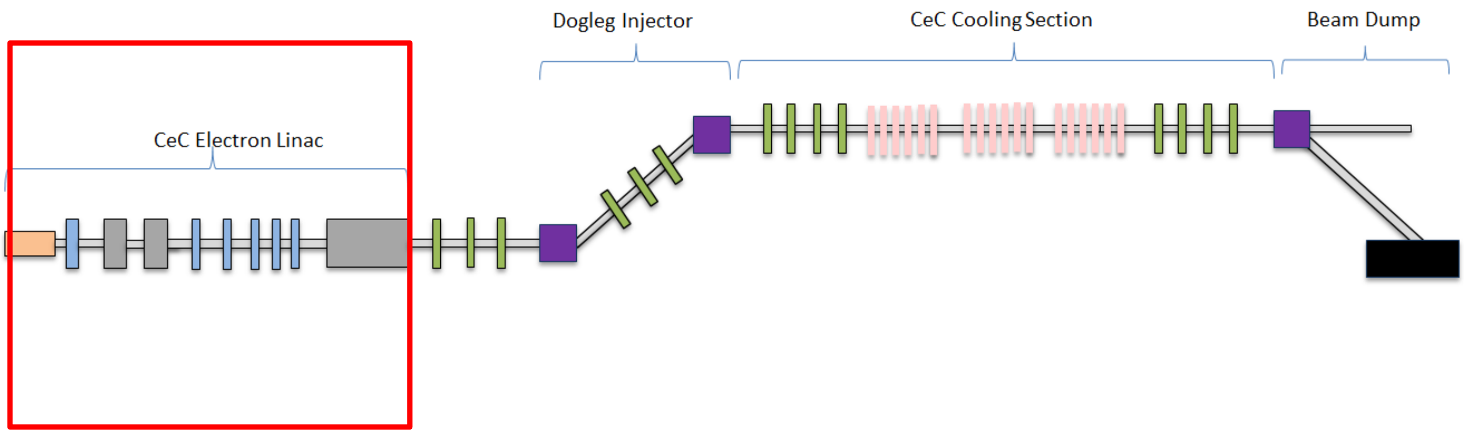
The FEL ends at about 7.5 m, we want to operate the FEL in linear regime where it has predictable phase information, i.e., the variation of phase of the signal over different random noise is low. The bunching amplitude non-linear regime when SASE noise is close to saturation.

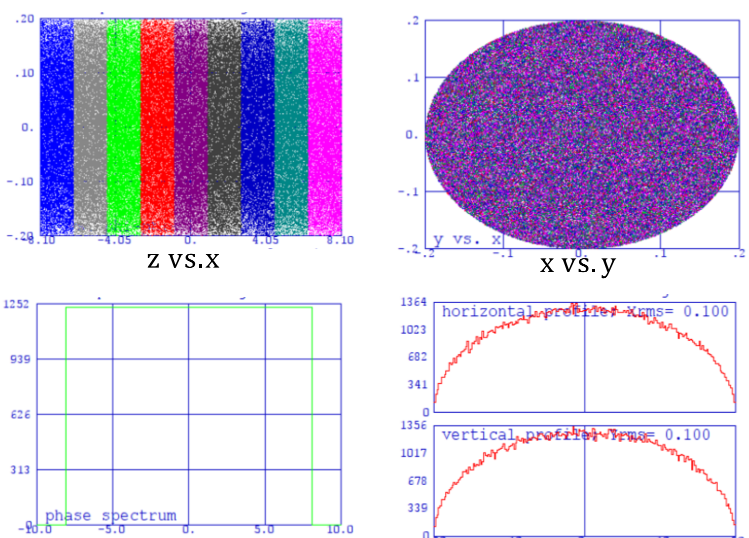
Summary

- ✓ The low energy beam transport line was designed and optimized to fulfill cooling requirement. The simulation results for low energy beam transport was demonstrated in CeC PoP commissioning.
- ✓ We start a self-consistent simulation of the photo-injector cavity including wakefields and the beam distribution was used to setup a S2E simulation of CeC accelerator.
- ✓ We studied various collective effects, especially in dogleg and proposed possible fix for these issues in case that they are significant.
- ✓ We studied FEL section and demonstrate its performance is sufficient for cooling purpose.

additional slides

Low Energy Beam Transport Optimization (cont'd)





Longitudinal Profile

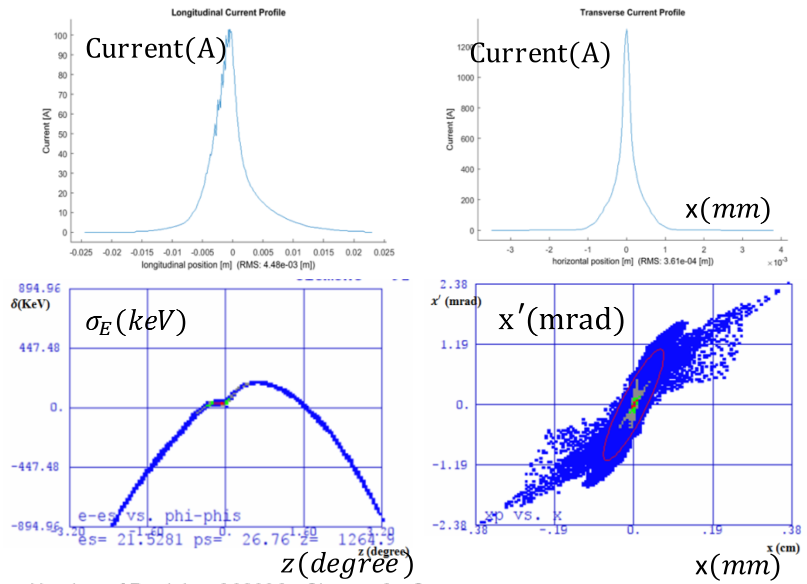
Transverse Profile (x/y)

Initial electron beam distribution

Bunch charge	2 nC
Initial Bunch radius at the cathode	2mm
RMS laser pulse length	400 ps
Maximum accelerating gradient of 112 MHz Gun	19 MV/m
Maximum accelerating gradient of the 500 MHz buncher	1.5 MV/m
Maximum accelerating gradient of the 704 MHz Cavity	37 MV/m

Main parameters used for beam and srf cavities

Optimized Electron Beam



Number of Particles: 200002 Charge: 2 nC
Position: 0 m Beam Energy: 21.528 MeV

FWHM (distance between green bars): 4.03e+03 μ m (13.4 ps)
Charge within FWHM: 52.4 %
Projected Emittance: $\gamma\epsilon_x$ = 3.83e-06 m $\gamma\epsilon_y$ = 3.82e-06 m
Optics @ I_{peak}: α_x = -2.77 β_x = 0.986m α_y = -2.7 β_y = 0.955m

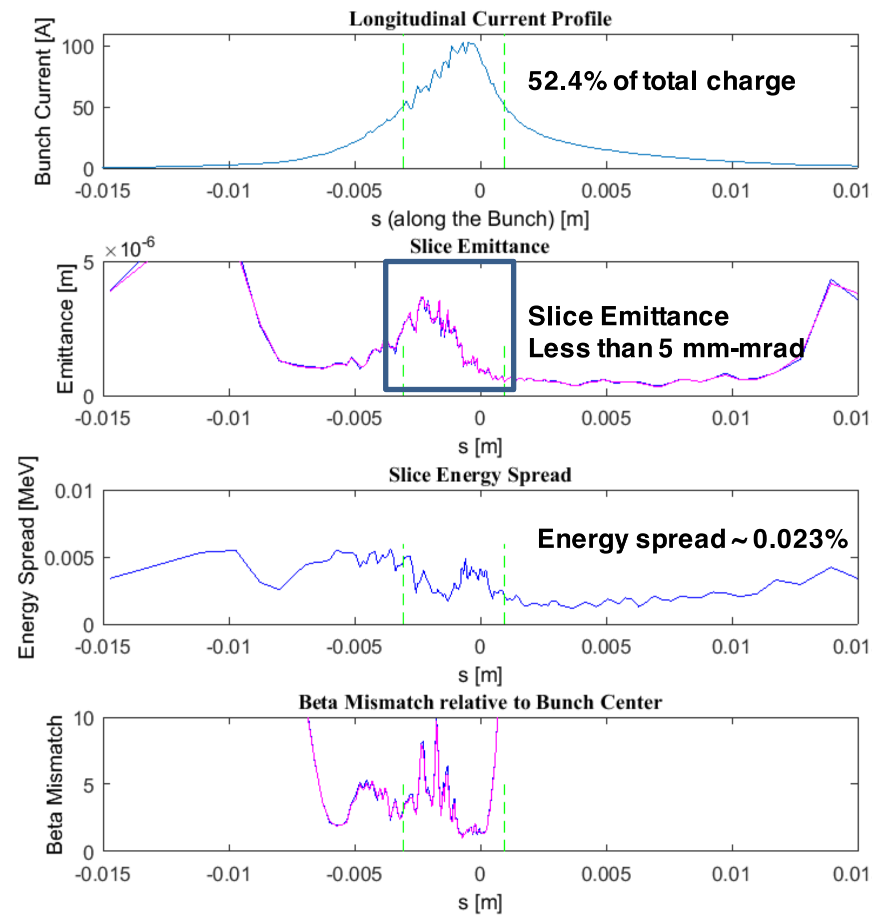
RMS Values for all Particles:

```
x = 3.61e-04 m   x' = 5.49e-04
y = 3.56e-04 m   y' = 5.47e-04
s = 4.48e-03 m   δ  = 5.10e-03
```

RMS Values within FWHM:

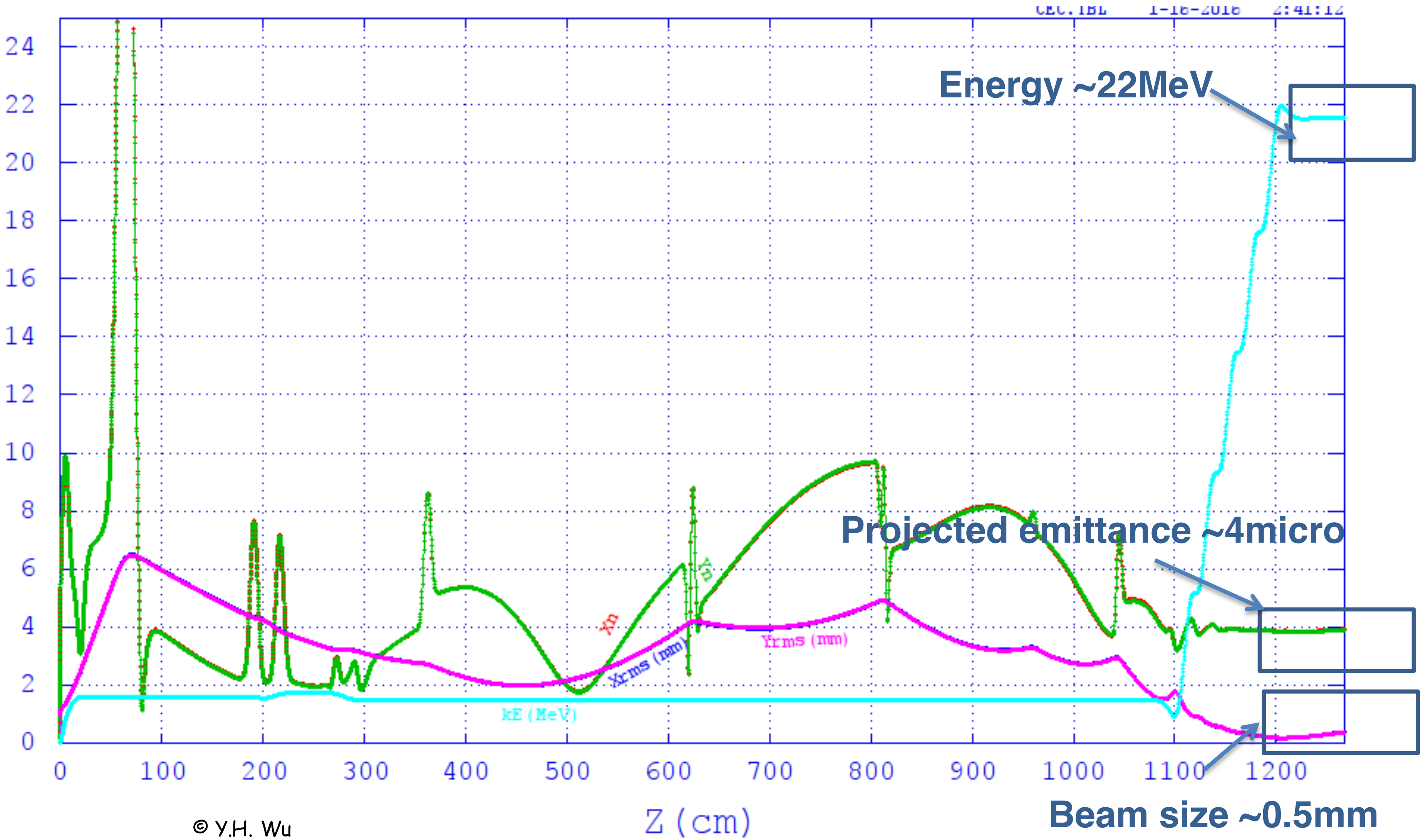
```
x = 2.89e-04 m   x' = 5.87e-04
y = 2.84e-04 m   y' = 5.85e-04
s = 1.05e-03 m   δ  = 7.85e-04
```

α_x	β_x	α_y	β_y
-1.94	1.44m	-1.91	1.41m

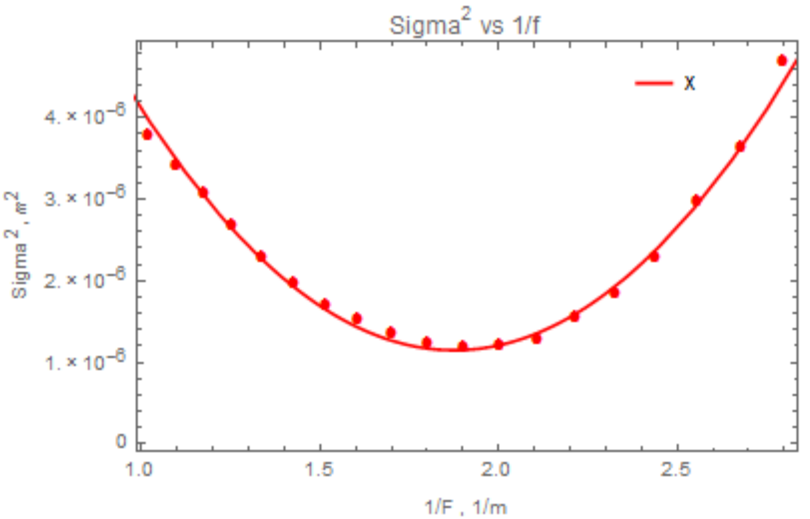


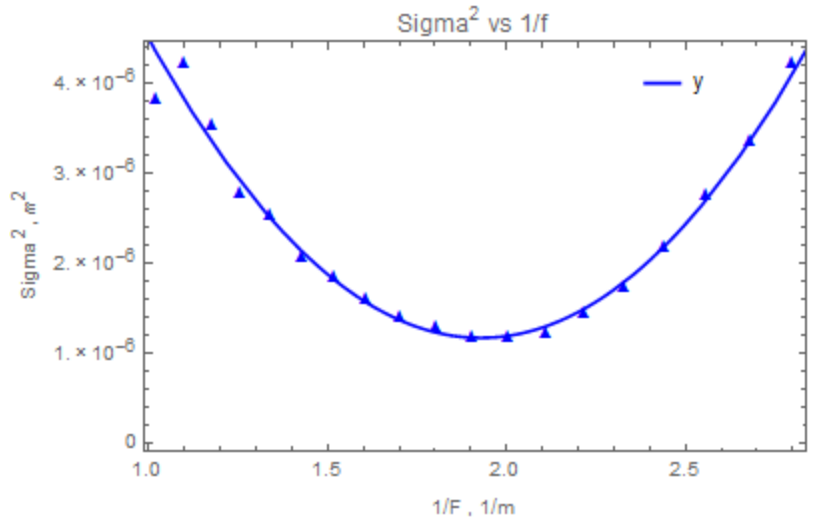
- Projected emittance within FWHM is 3.56 mm-mrad
- Energy spread ~ 0.023%
- Peak current is 100 Ampere

Optimized Electron Beam cont.



Low charge 5pC, 1.08MeV with Gun Solenoid





fit	ax^2+bx+c
a	3.857×10^{-6}
b	-0.0000144656
c	0.0000147114

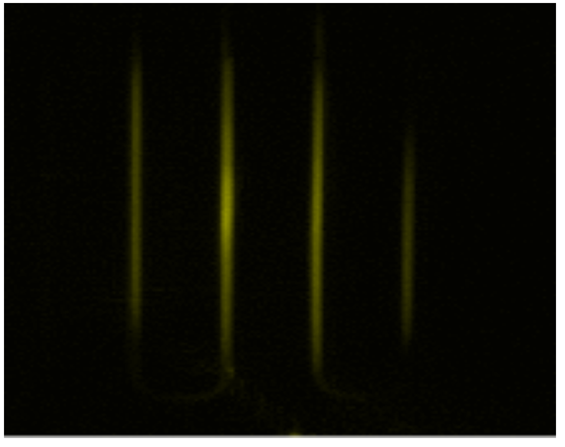
β_x [m]	1.83285
α_x [rad]	-2.93157
ϵ_x [m rad]	1.60054×10^{-7}
ϵ_{xn} [m rad]	4.98329×10^{-7}

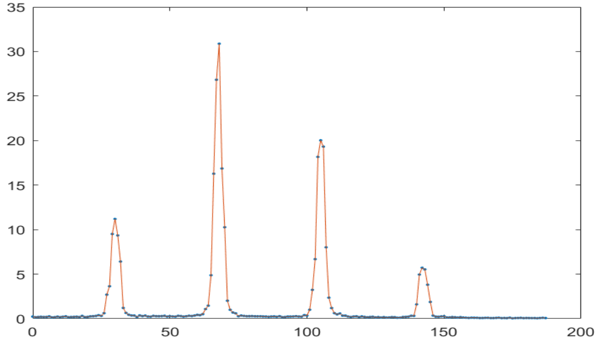
fit	ax^2+bx+c
a	3.848×10^{-6}
b	-0.0000148339
c	0.0000154706

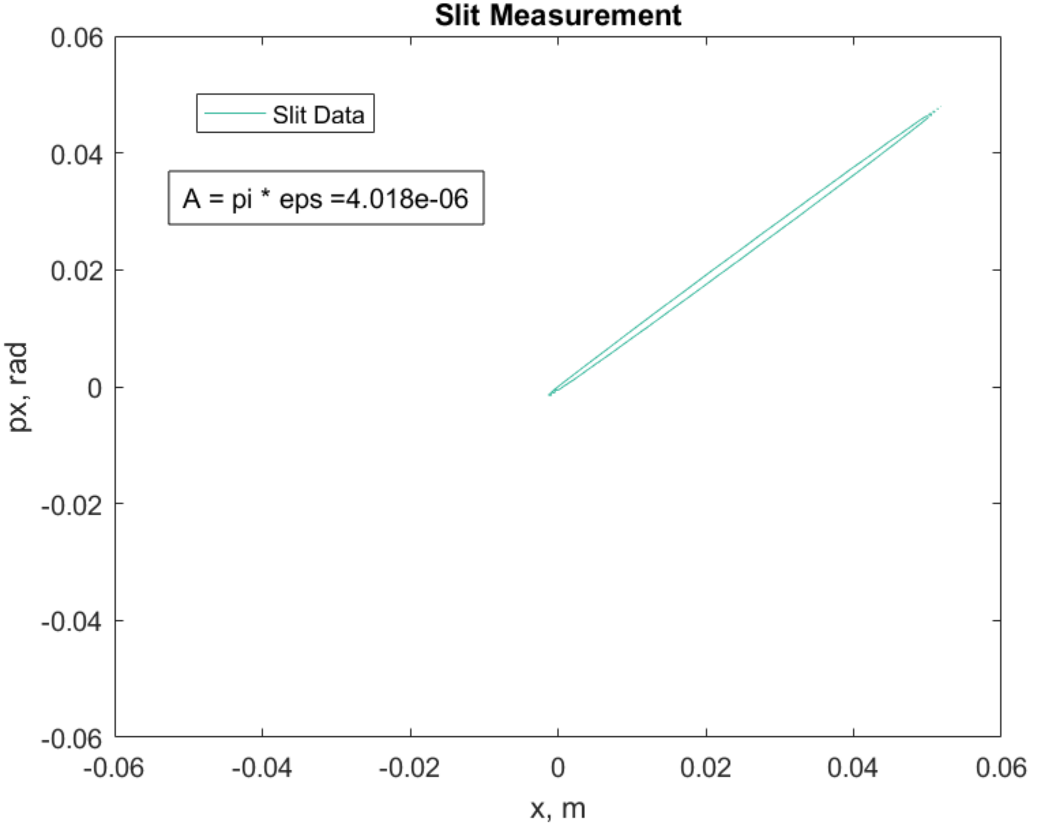
β_y [m]	1.81002
α_y [rad]	-2.9896
ϵ_y [m rad]	1.61695×10^{-7}
ϵ_{yn} [m rad]	5.03437×10^{-7}

Measured emittance (cont'd)

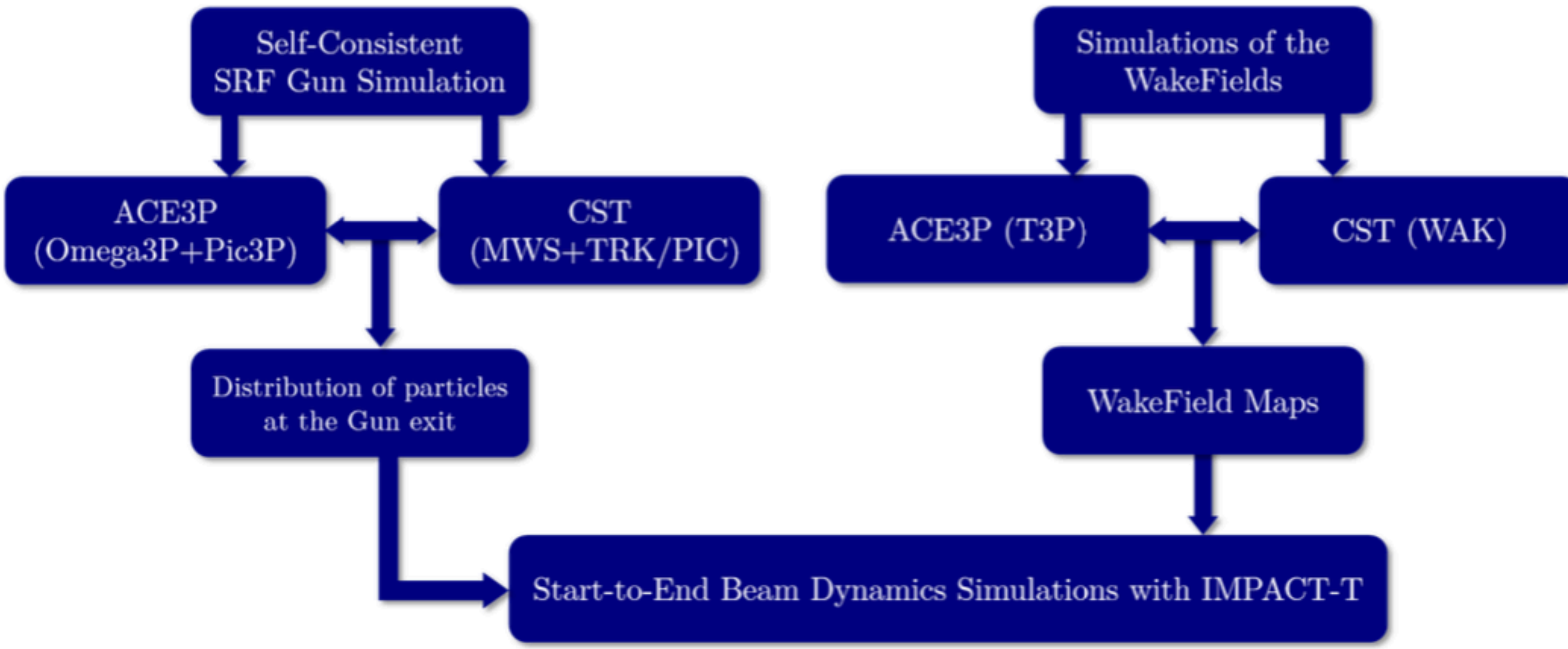
Slit Measurement



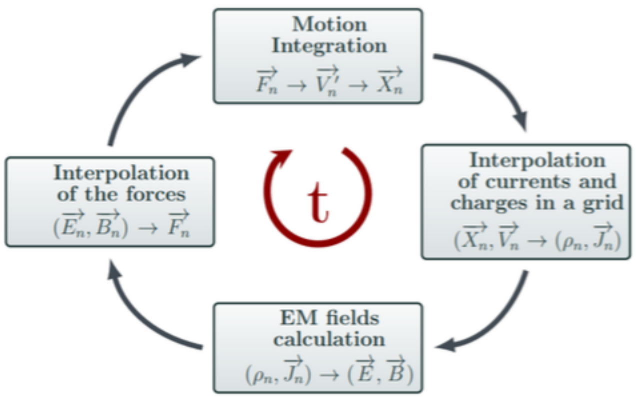


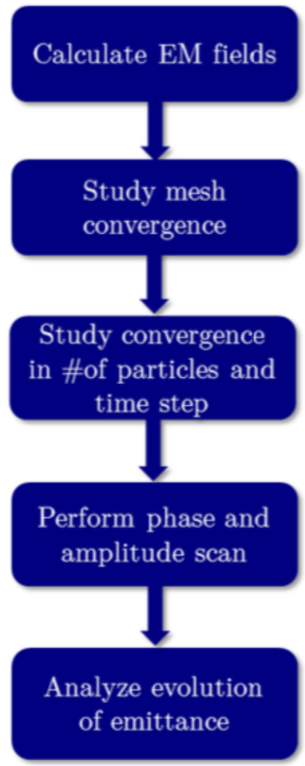


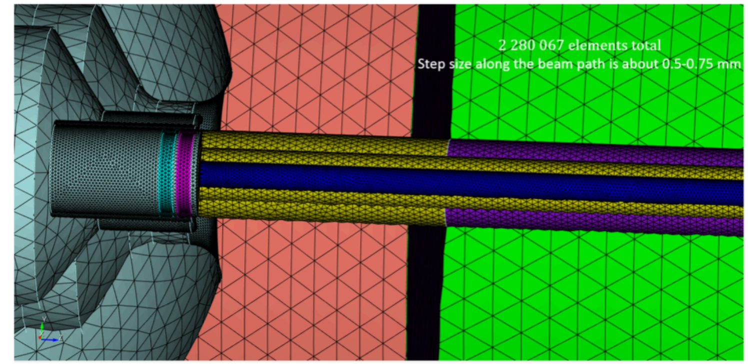
Full S2E simulation



Self-consistent Gun simulation

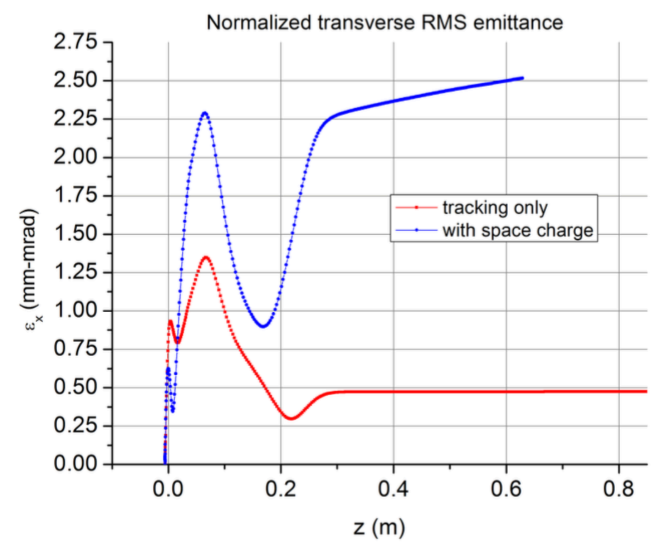






Parameters of the beam.

Parameter	Value
Total Charge, nC	0.5
Initial Velocity, β_z	0.003
Type of radial Distribution	Uniform
Radius, mm	1.5
Type of Longitudinal Distribution	Flat Top
Duration of the flat top, ns	0.5
Rise/Drop time, ns	0.005



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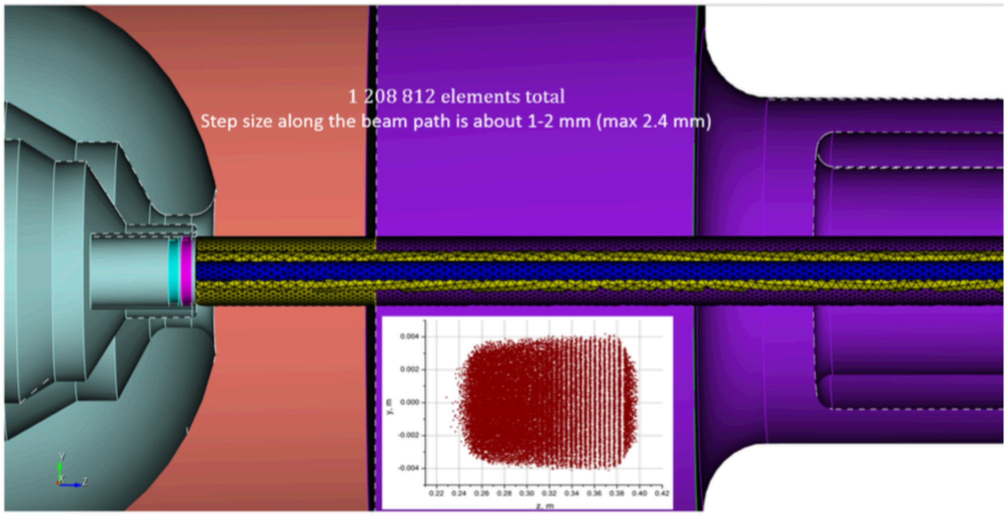
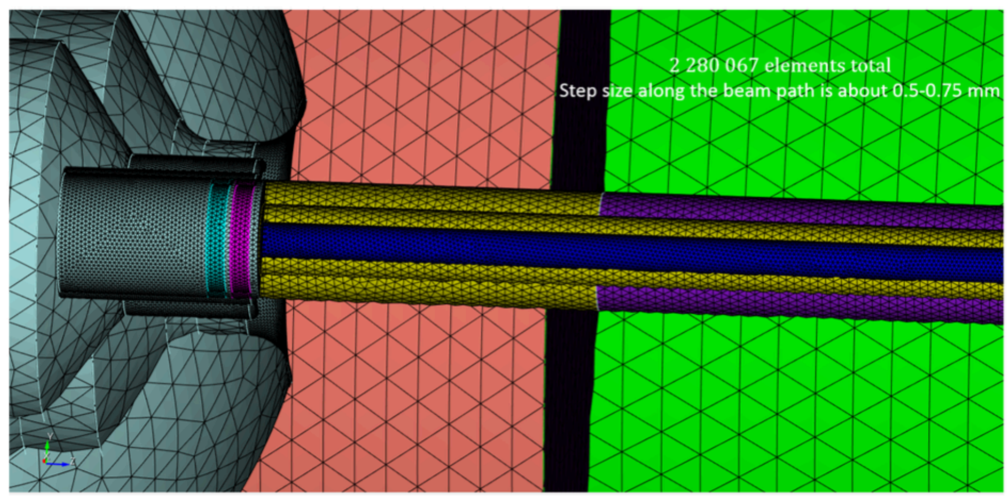
Simulation mainly done in ACE3P and cross-checked with CST.

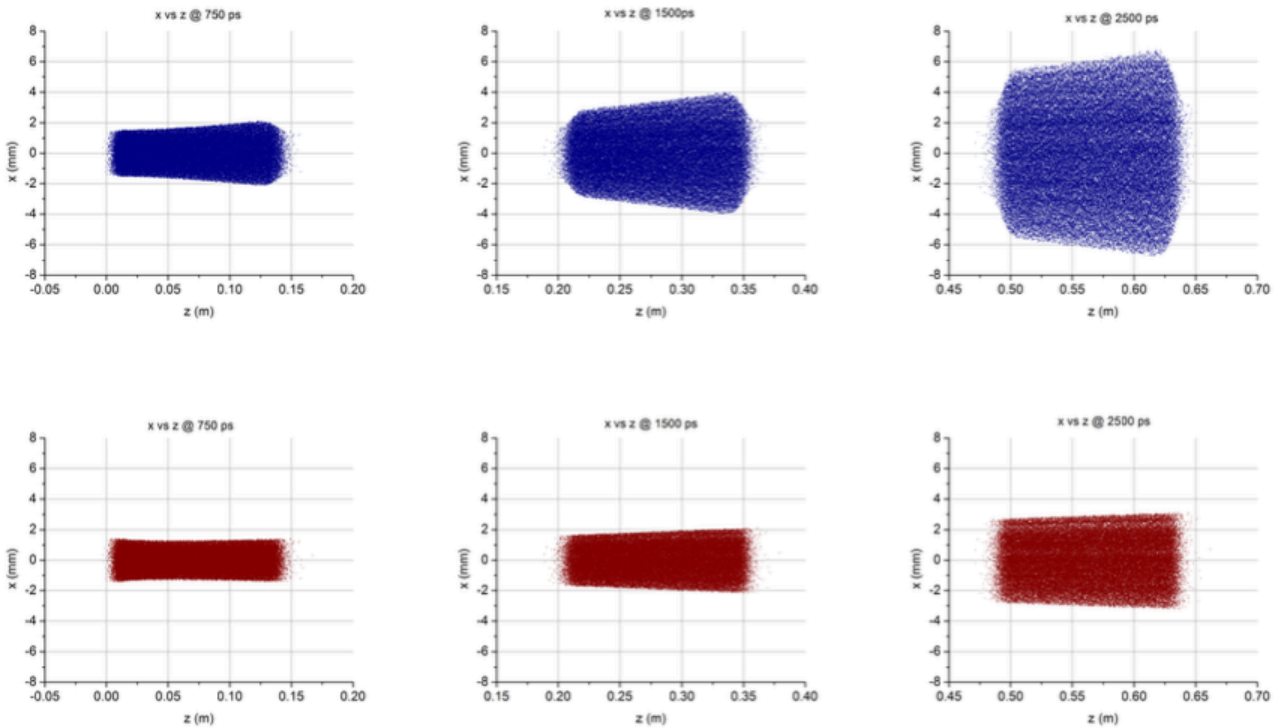
Fine mesh of gun cavity





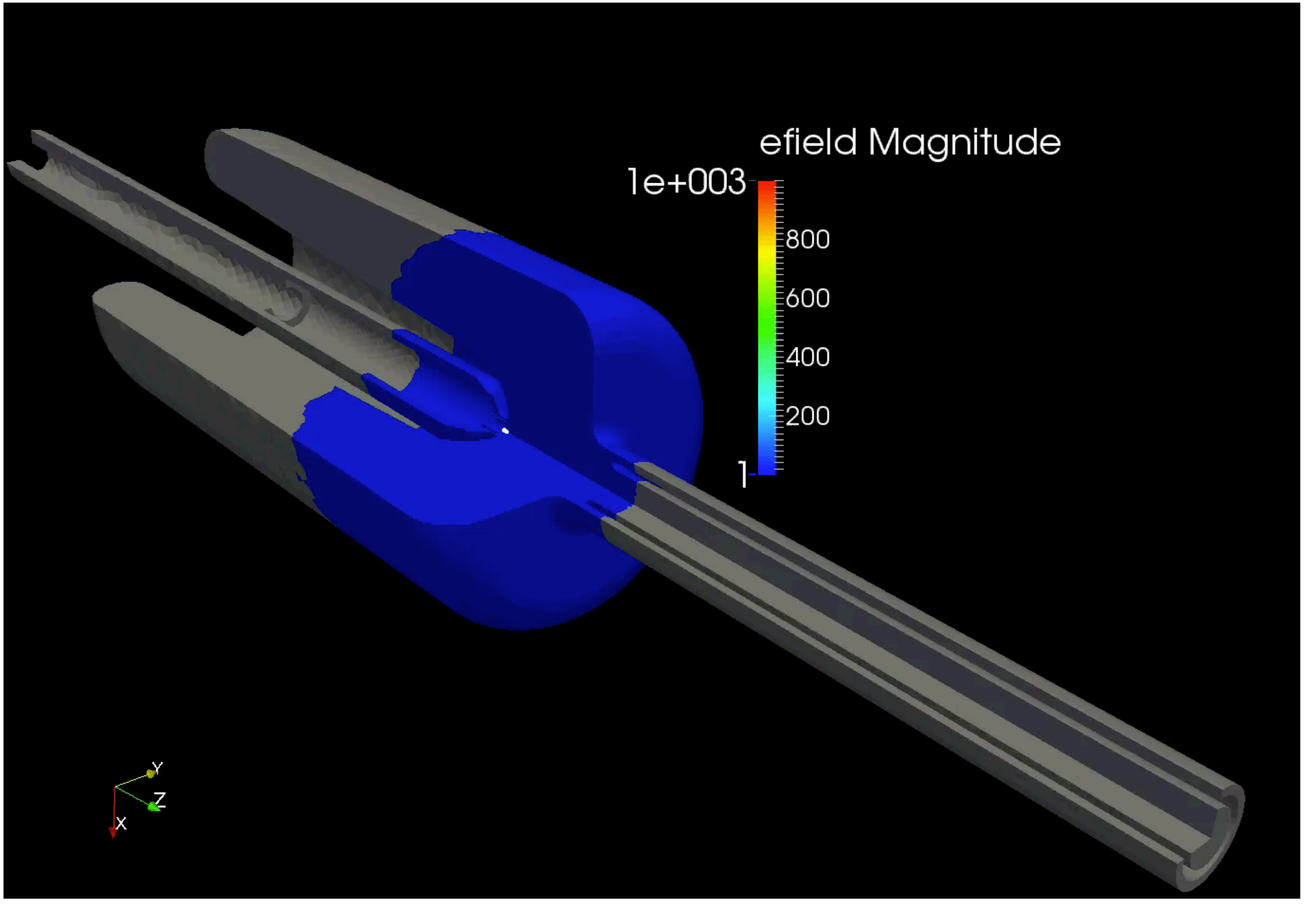
Selected phase space plots after gun cavity (x-z)

With Space Charge

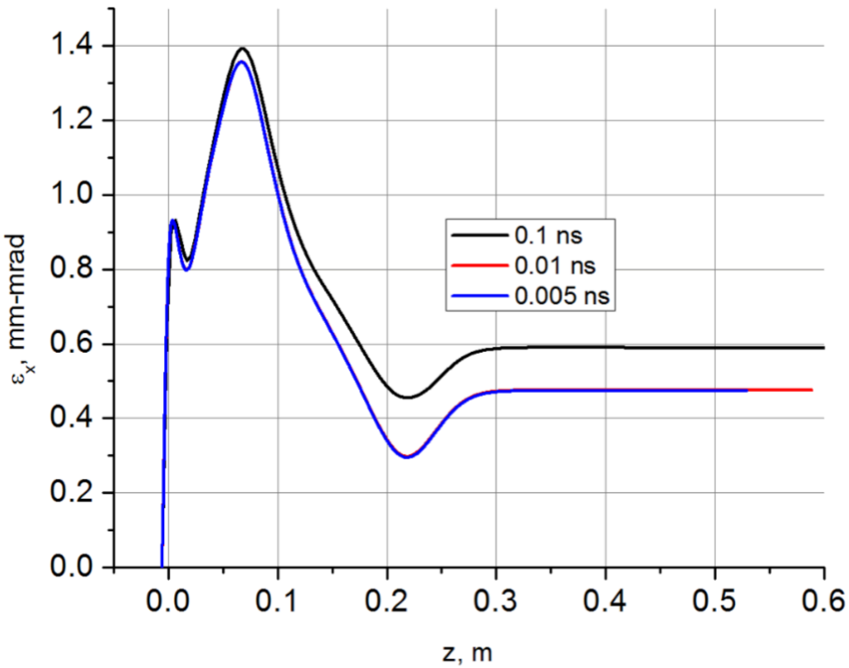


Without Space Charge

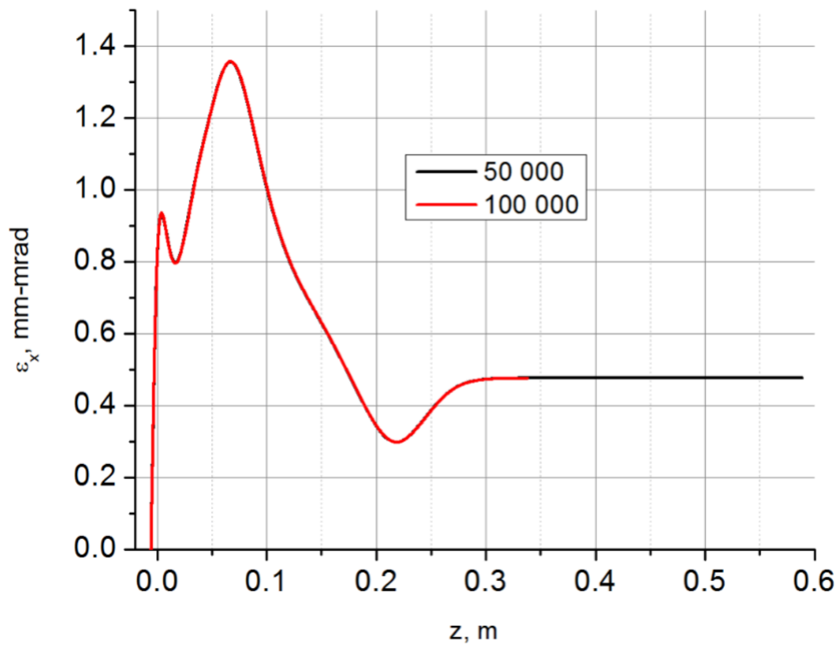
Beam tracking (including wakefield) thru the gun cavity



Choice of right simulation setups for convergence

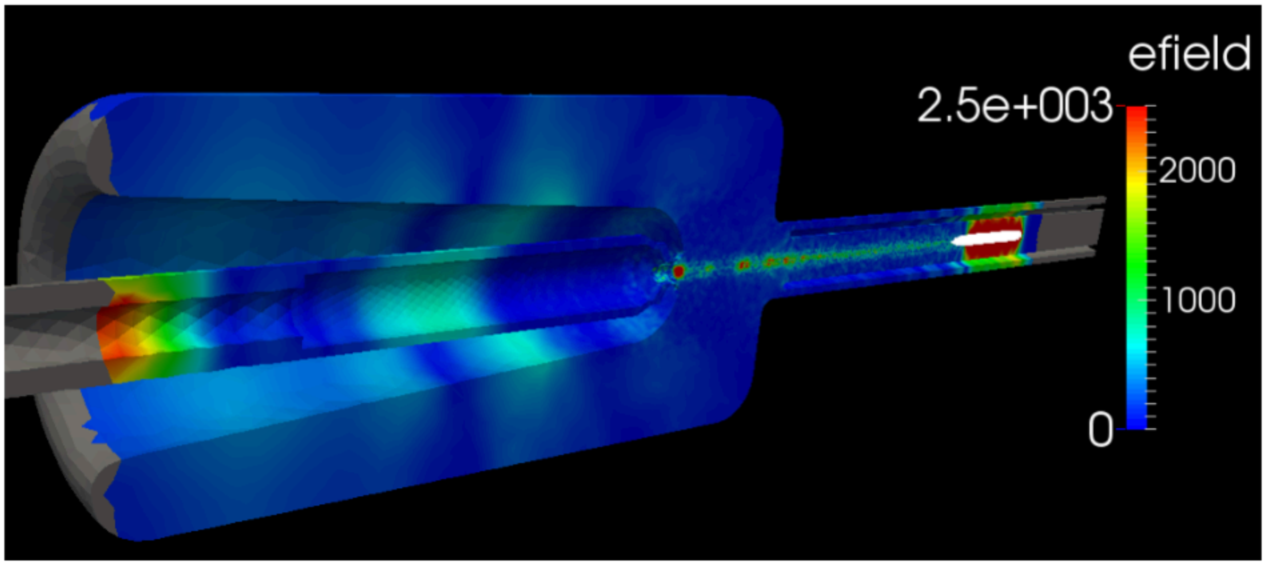


Time step



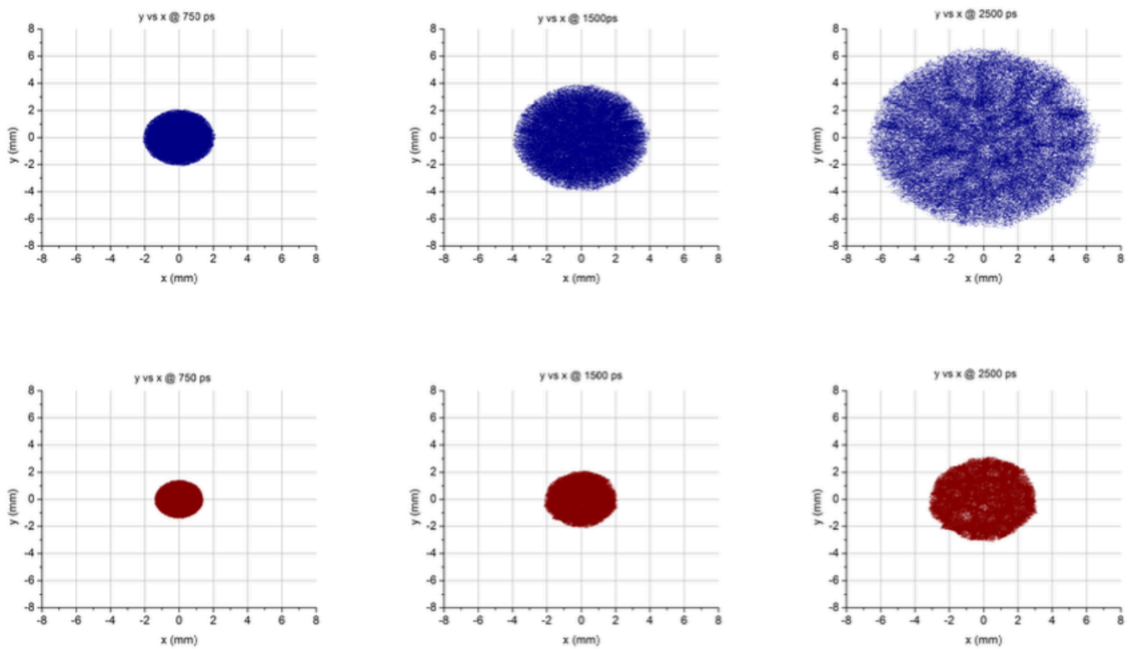
Number of particles

Scattered fields (a wakefield)



Selected phase space plots after gun cavity (x-y)

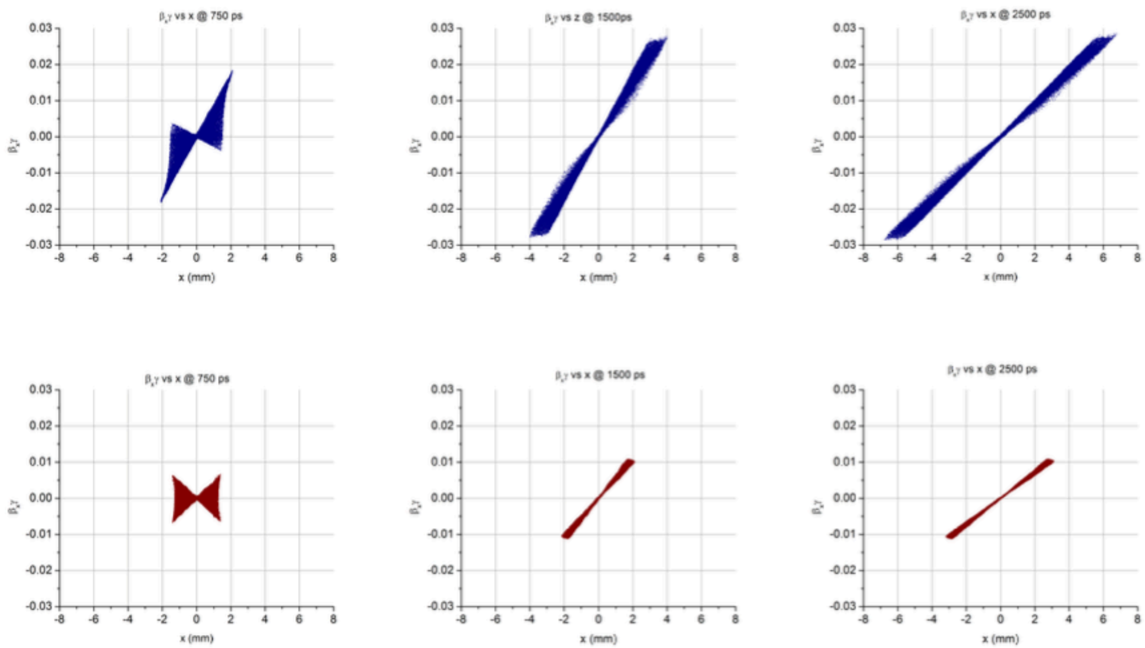
With Space Charge



Without Space Charge

Selected phase space plots after gun cavity (px-x)

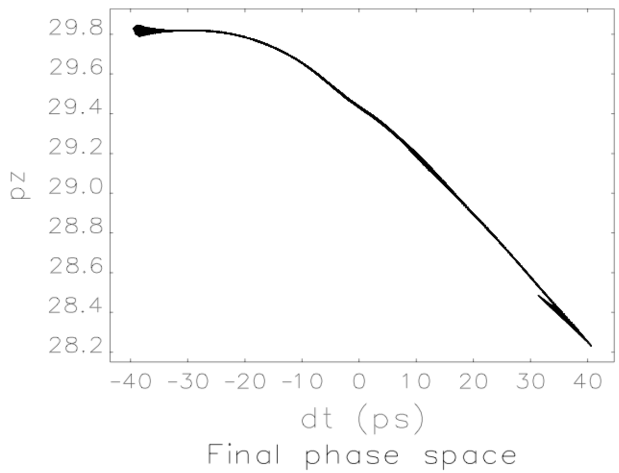
With Space Charge



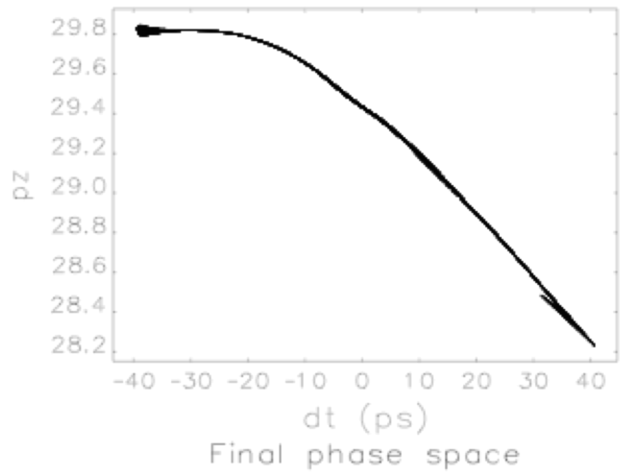
Without Space Charge

Phase space comparison (w and w/o wakes)

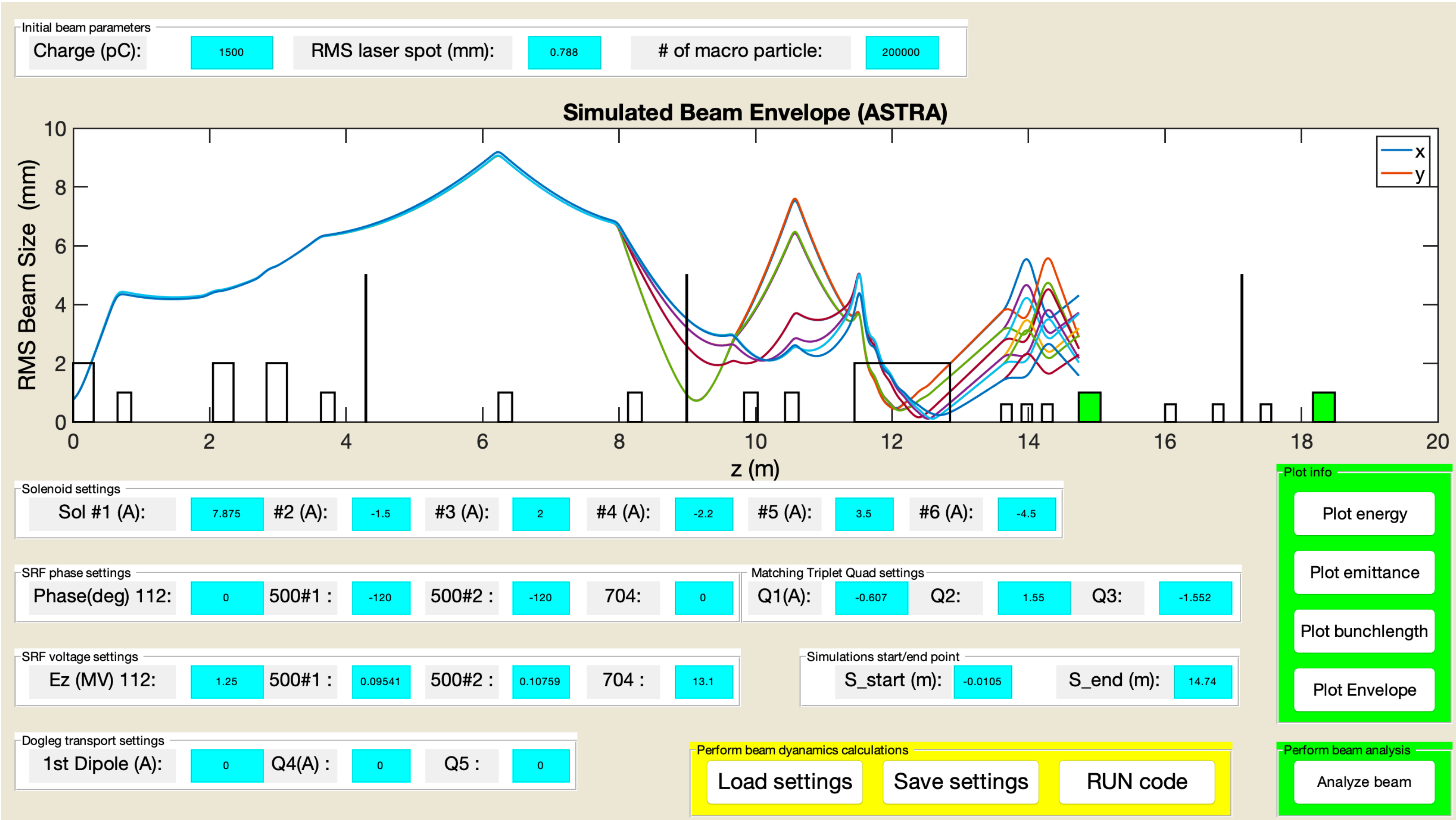
wake



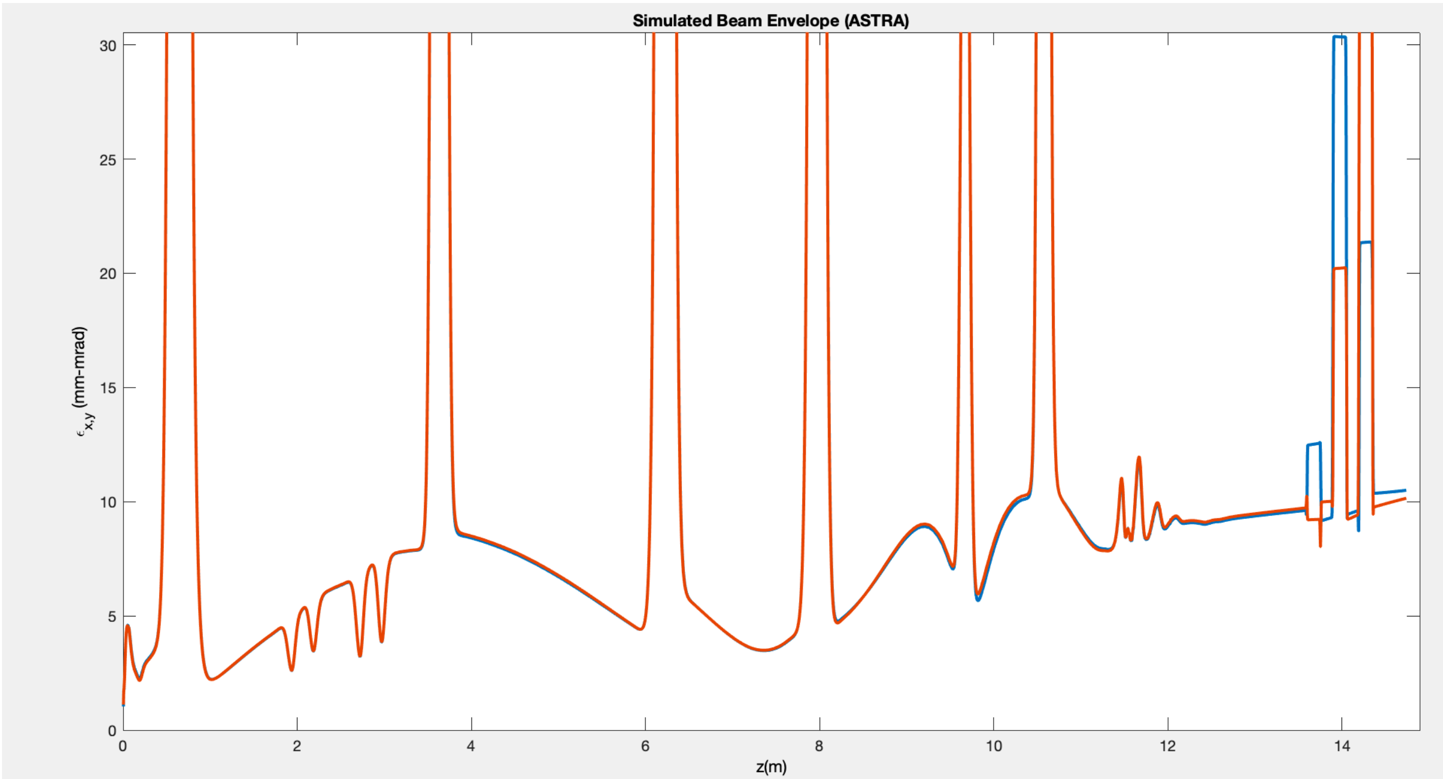
No wake



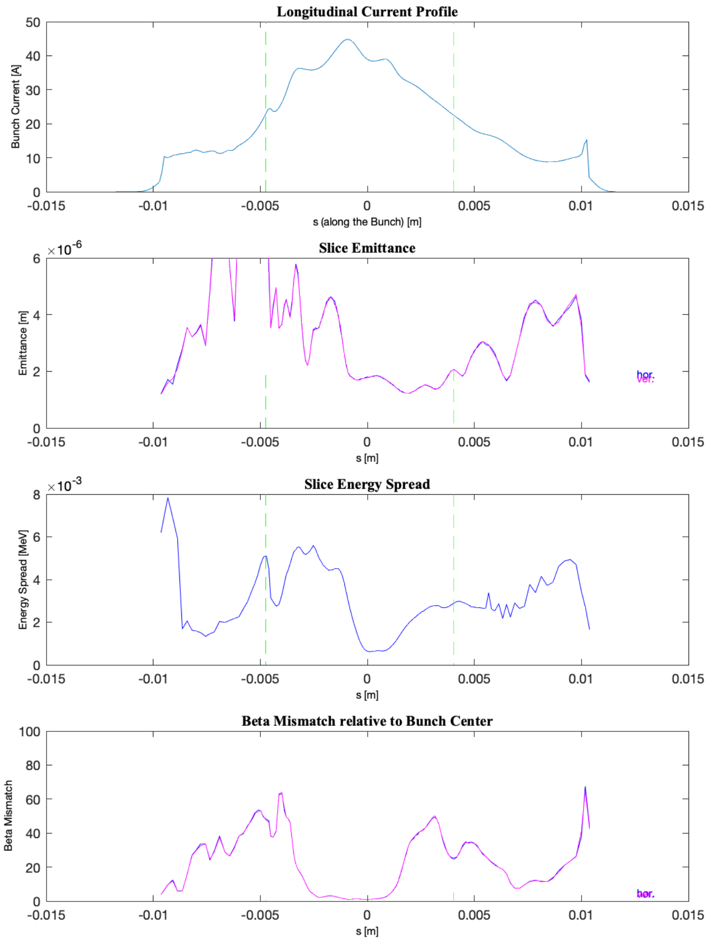
Barely see any noticeable difference for two cases

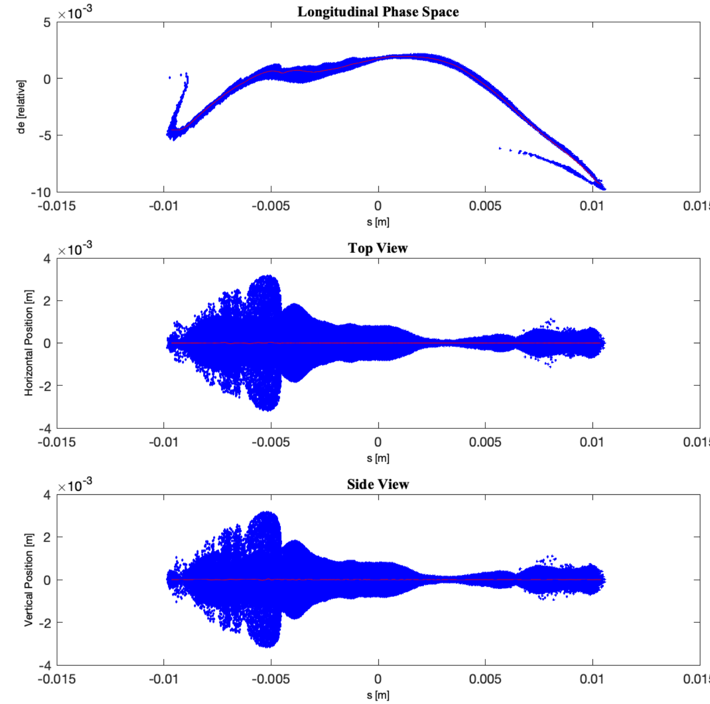


Optimized Machine settings. Blue line is the optimized envelope after manual optimization



Emittance envolution





Number of Particles: 199999 Charge: 1.5 nC

FWHM (distance between green bars): 8.8e+03 μ m (29.3 ps)

Charge within FWHM: 66.9 %

Projected Emittance: $\gamma\epsilon_x$ = 9.97e-06 m $\gamma\epsilon_y$ = 9.97e-06 m

Optics @ I_{peak}: α_x = -11.3 β_x = 2.75m α_y = -11.4 β_y = 2.77m

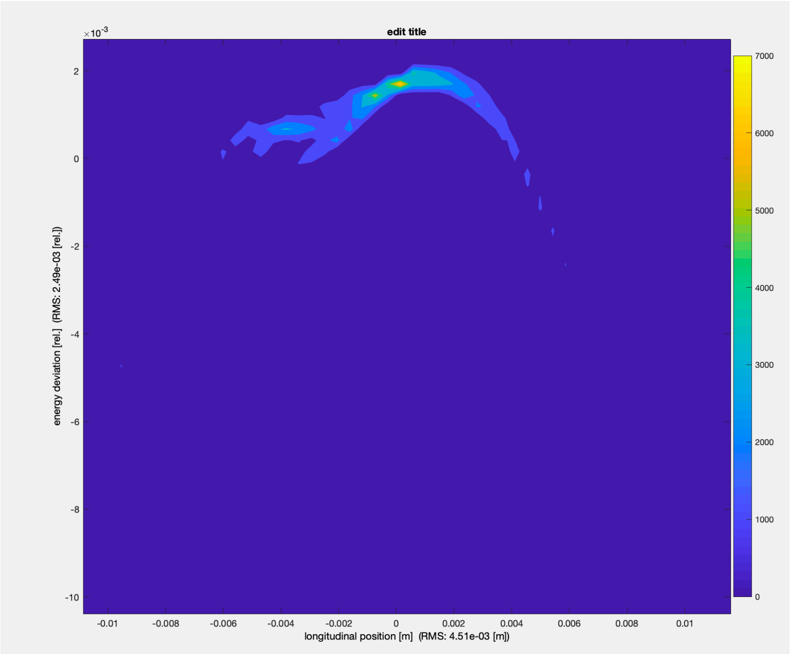
RMS Values for all Particles:

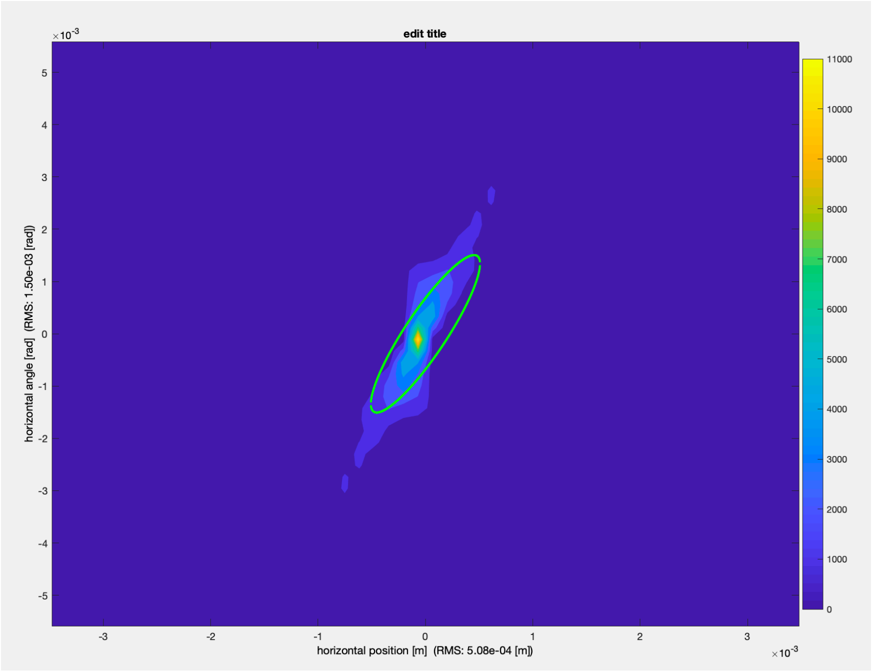
```
x = 5.08e-04 m  x' = 1.50e-03
y = 5.08e-04 m  y' = 1.51e-03
s = 4.51e-03 m  δ  = 2.49e-03
```

RMS Values within FWHM:

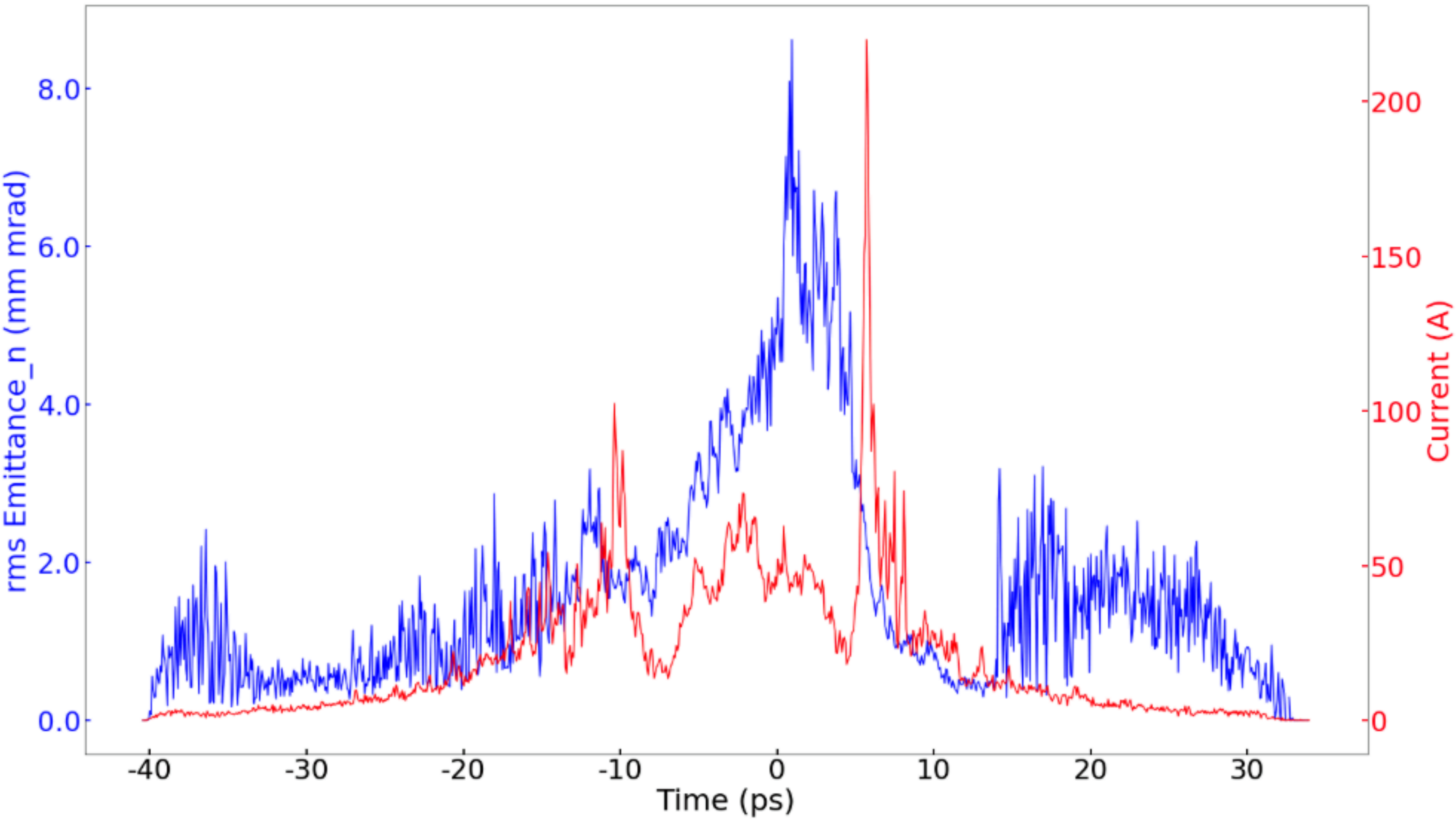
```
x = 4.64e-04 m  x' = 1.58e-03
y = 4.64e-04 m  y' = 1.58e-03
s = 2.33e-03 m  δ  = 5.58e-04
```

Summary of beam info at the linac exit



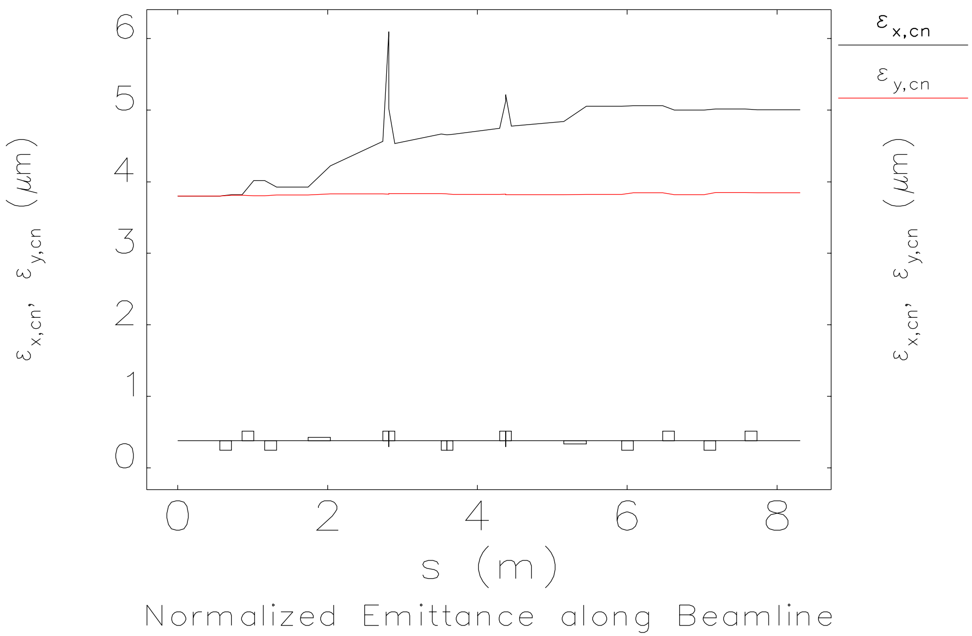


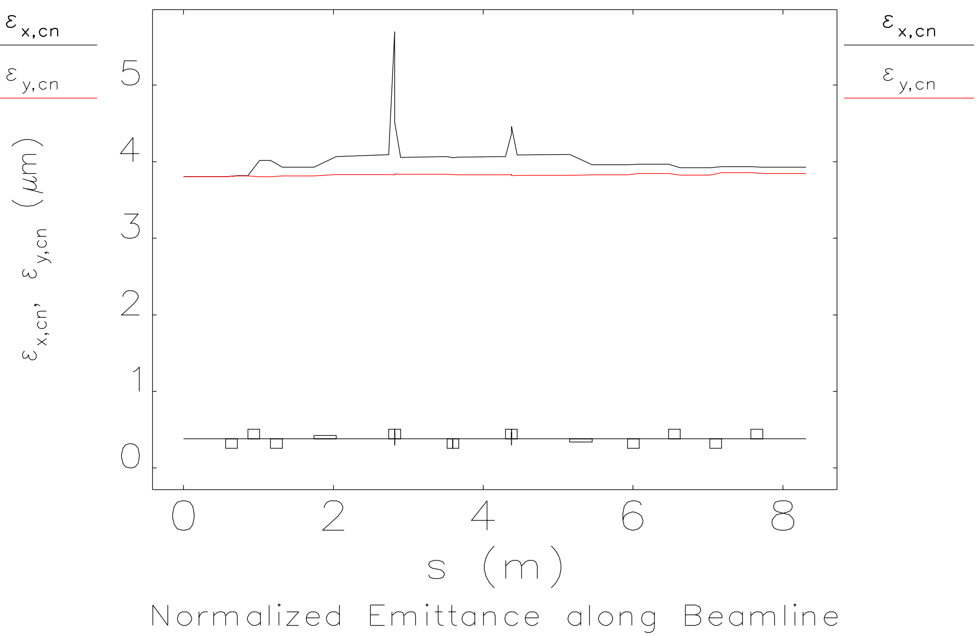
Longitudinal phase space and transerse phase space at linac exit


rms Emittance_n (mm mrad)
0.0
2.0
4.0
6.0
8.0
Current (A)
0
50
100
150
200
-40
-30
-20
-10
0
10
20
30
Time (ps)

CSR effect on chromatic aberration

With CSR, the correction is not perfect due to the fact that CSR introduce additional energy modulation along the bunch.

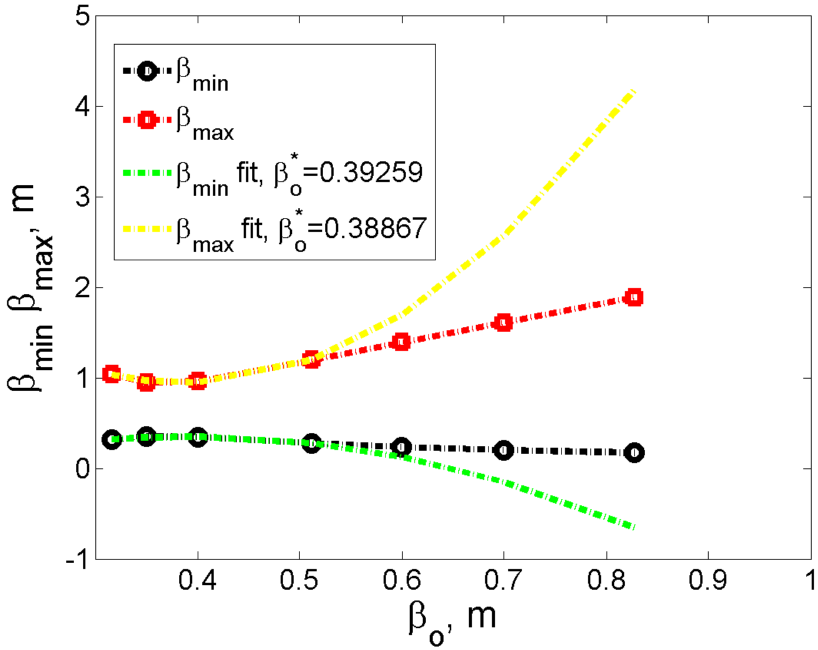


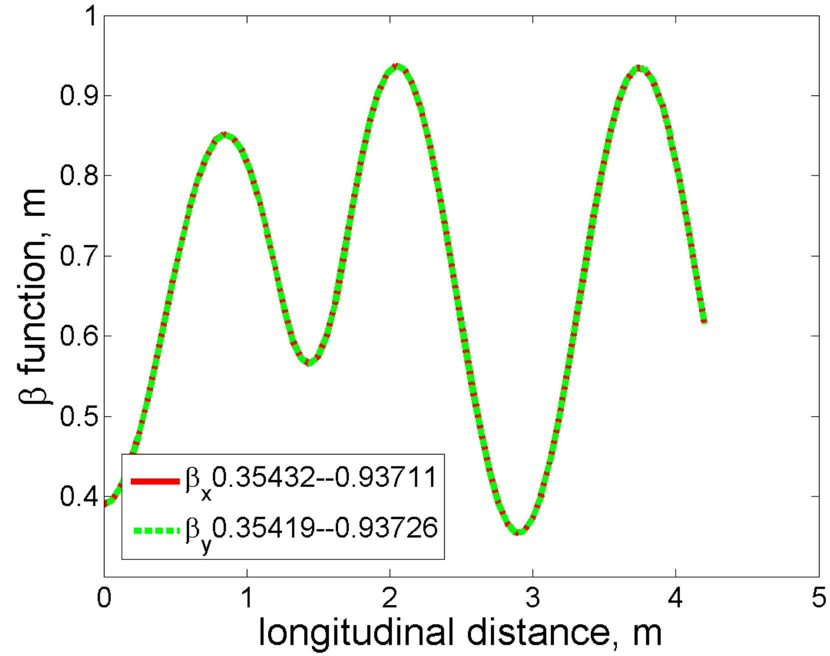


Norminal charge ~ 2 nC

Operational charge ~ 0.5 nC

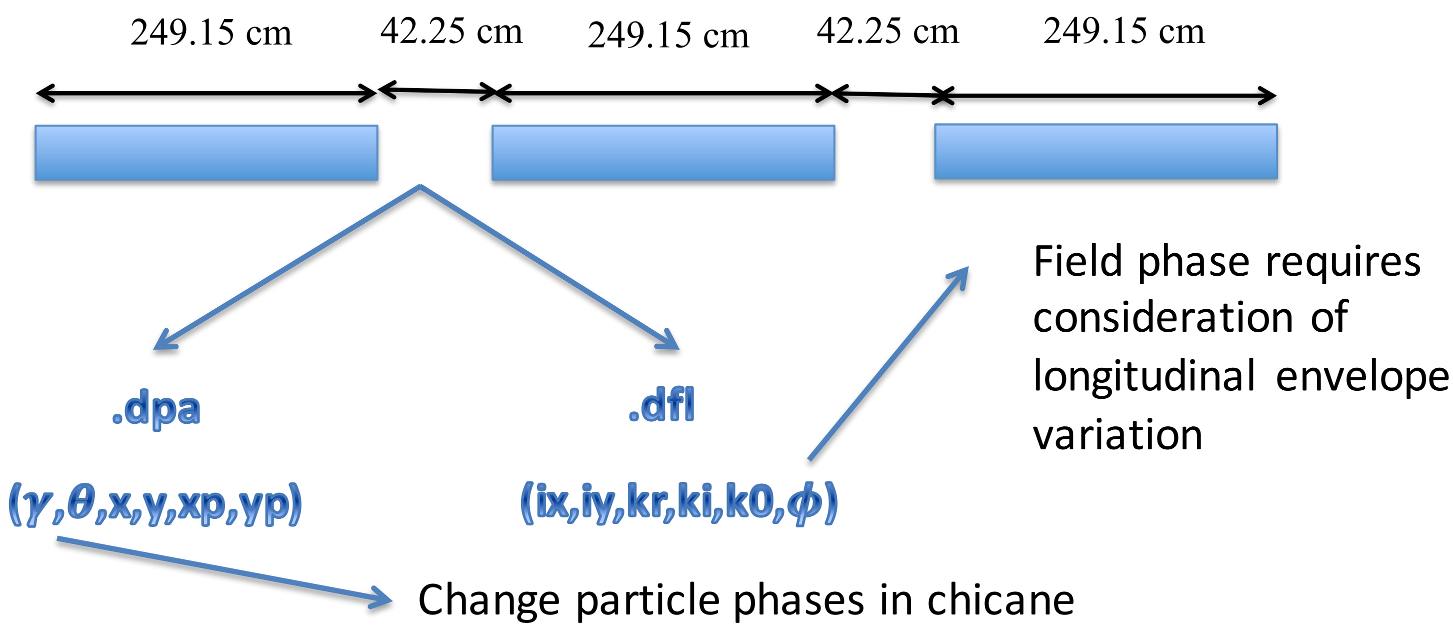
Effort to minimize beta-beat in FEL





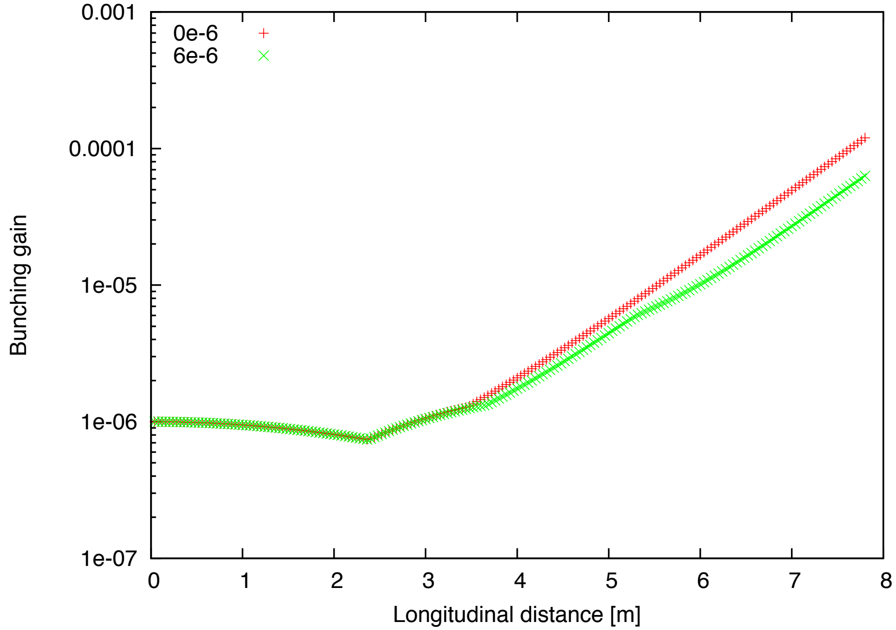
With polynomial fit, the optimal beta function at the middle of FEL is chosen to be 0.39 m, which results in the variation of beta function in FEL from 0.354 m to 0.934 m.

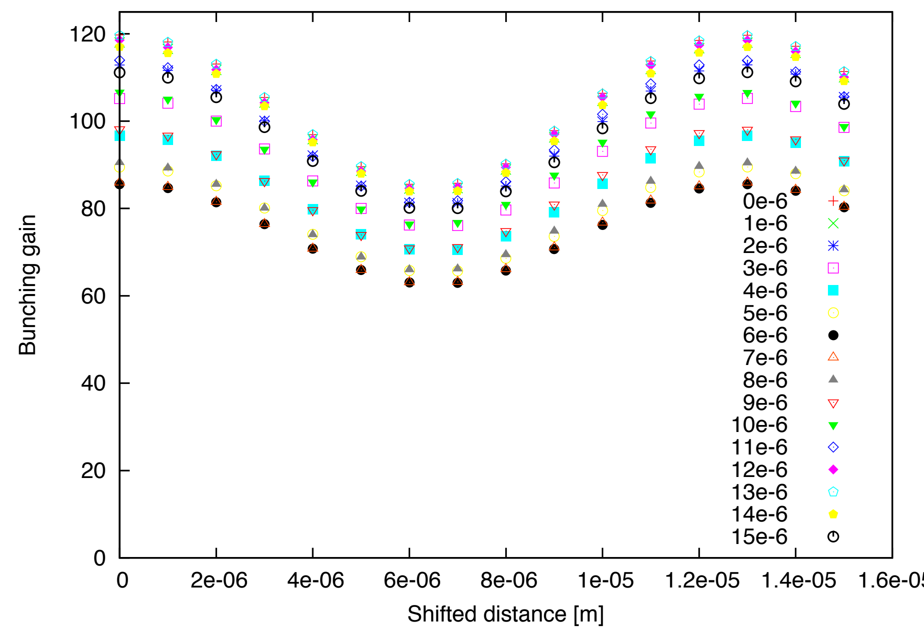
FEL phase shifters



Phase shifters in between two wigglers are used to adjust the relative phase (ponderomotive) between electrons and radiation thus can change the resulted amplification of FEL. In GENESIS simulation, the phase shifters was modeled with exporting the distributions and propagated with desired phase and envelope adjustment.

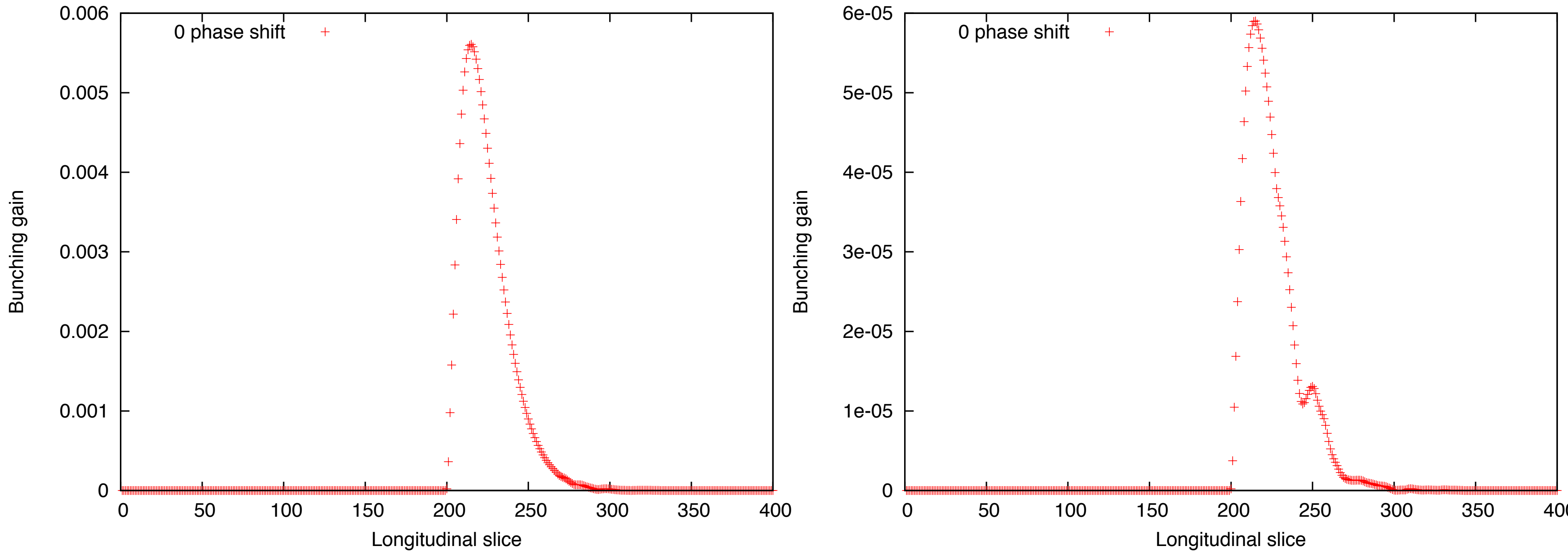
FEL gain for various phase shifters





Adjusting the phase shifter by 6 um, i.e., 20% of the radiation wavelength, results in dropping the gain from ~ 100 to ~ 80. Scanning of the two phase shifters shows that we will be able to control the signal's bunching gain in FEL in a range of ~ 60 – 120.

Bunch envelope: phase shifter vs cont. wiggler



Simulation of a continuous wiggler (left) shows rather smooth beam envelope in the FEL. For the case of three wigglers with phase shifters in between (right), the envelope develops some structure. This might be caused due to the Rayleigh length is comparable with the gap in between wigglers.

BROOKHAVEN NATIONAL LABORATORY

Collider-Accelerator Department