Design to Achieve Uniform Electron Beam in Coherent Electron Cooling

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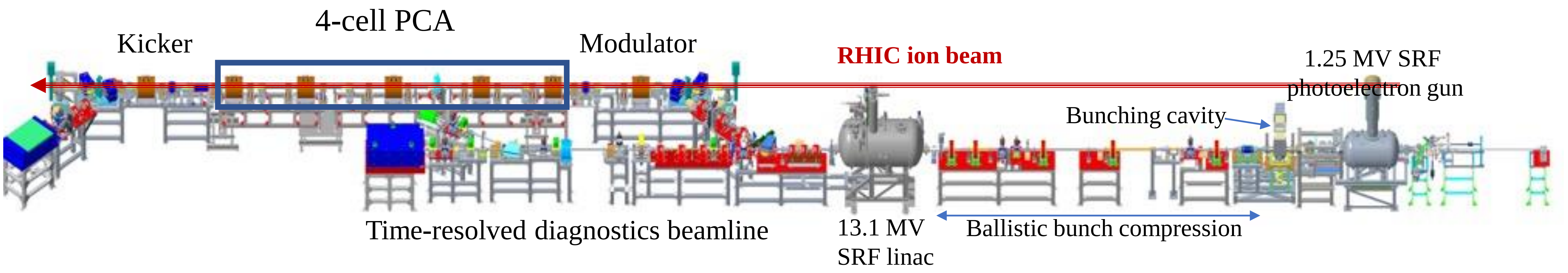
Outline

- ❑ Beam dynamics in CeC PoP
  - ➢Optimization with space charge and wakefield
  - ➢Chromatic aberration and Coherent Synchrotron Radiation effects
- ❑ Beamline diagnostics and comparison with simulation
- ❑ Path to achieve uniform beam distribution for compressed beam
- ❑ Summary

Beam dynamics/requirements in accelerator for CeC X



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

➢ Each element modeled with real geometry with measured fields
➢ Lattice matching design (Common section and/or doglegs)

- Collective effects

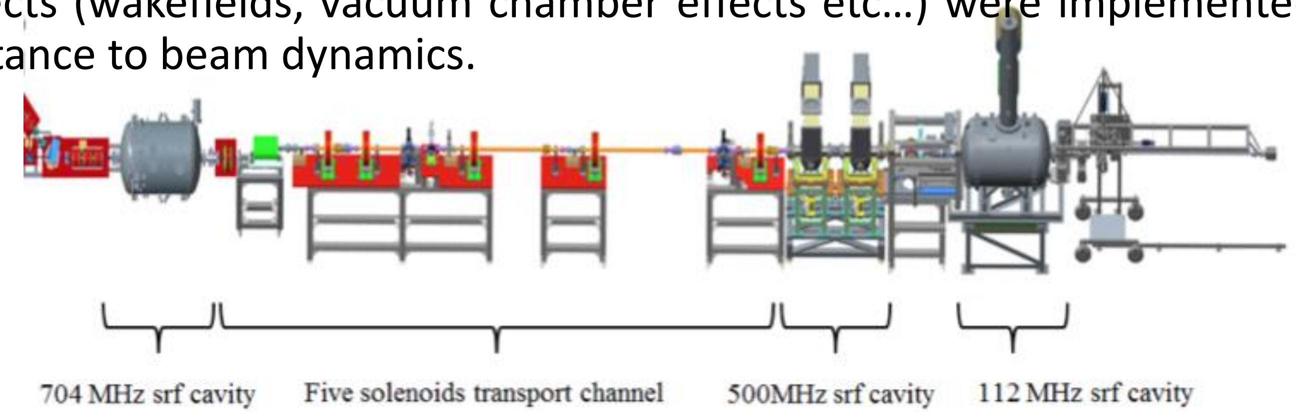
➢ Space Charge effect (ASTRA/GPT/IMPACT-T/PARMELA)
➢ Chromatic aberration and Coherent Synchrotron Radiation effect (ELEGANT/IMPACT-T/CSRTRACK)
➢ Wakefields (CST/ECHO/ABCI)

- High brightness electron beam required by CeC X

➢ peak electron current (> 50 A), slice Emittance < 1.5 micron, slice Energy spread < 0.02 %
➢ Core of the beam has uniform beam properties (e.g., flat top longitudinal distribution)

Coherent electron Cooler – Low energy beam transport (LEBT)

- For CeC proof of principle (PoP) experiment, space charge effect is dominated in the low energy region.
- 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

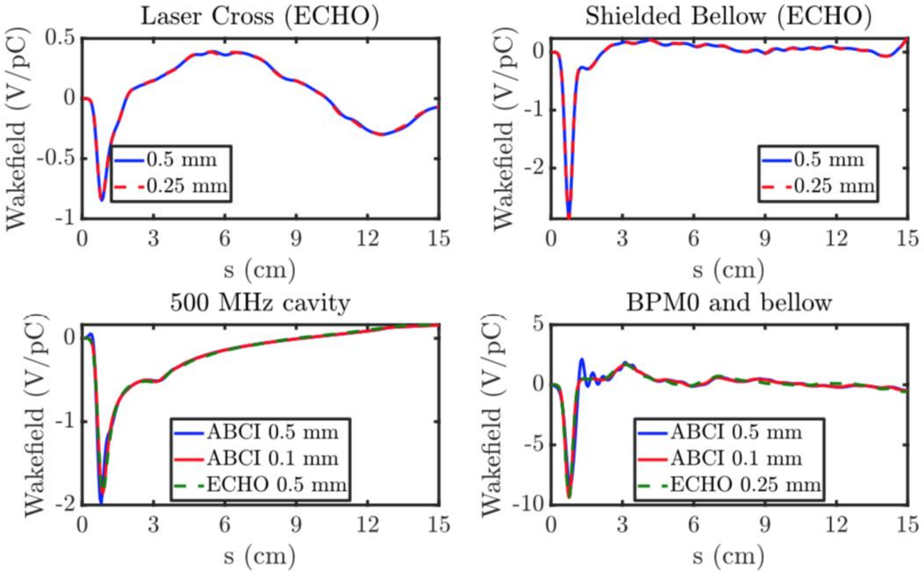
- Peak current > 50A by ballistic compression
- Slice Energy spread < 2e-4
- Slice Emittance < 1.5 mm-mrad

❖Optimization terms

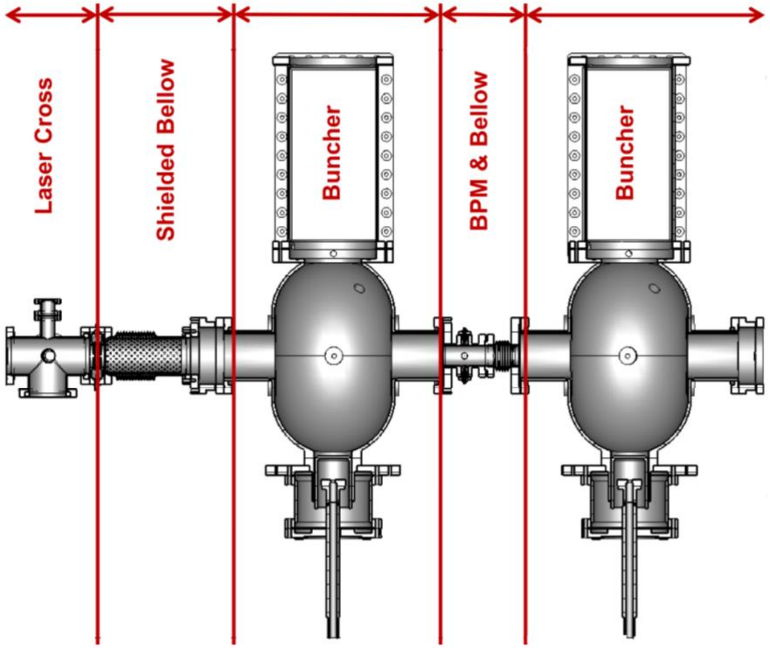
- 1+5 solenoids
- Cavities' phases (gun, buncher, linac)
- Bunching cavity voltages (#1 and #2)
- Adv., beam radius at cathode, laser pulse duration, etc…

Parameter	Value
Charge per bunch, nC	1.5
Peak current, A	50
Normalized emittance (slice), RMS, µm	1.5
Beam energy, Gamma	28.5
Beam energy, MeV	14.56
Energy spread (slice), RMS	$< 2 \times 10^{-4}$
Bunch rep-rate (CW), kHz	78

Wakefields in LEBT



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



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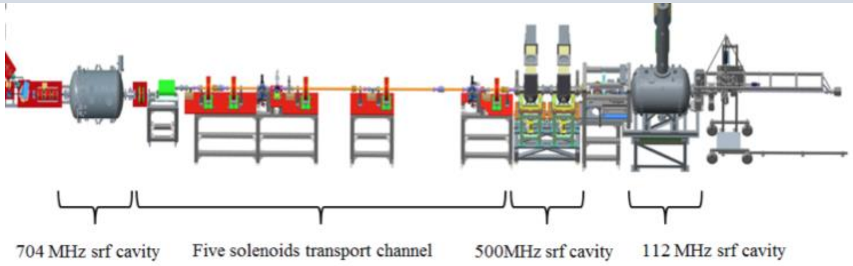
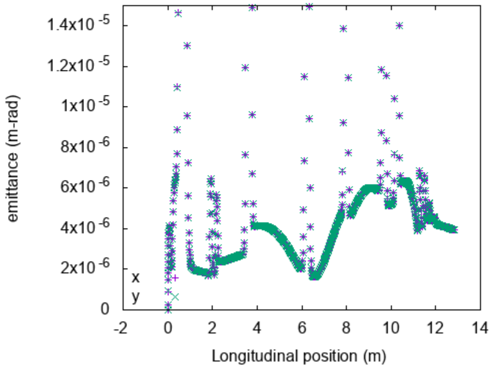
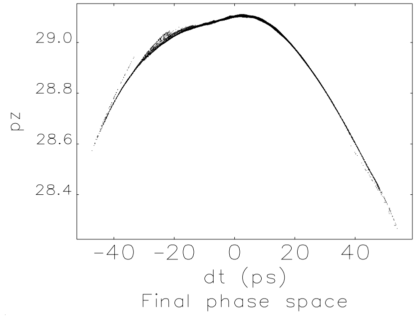
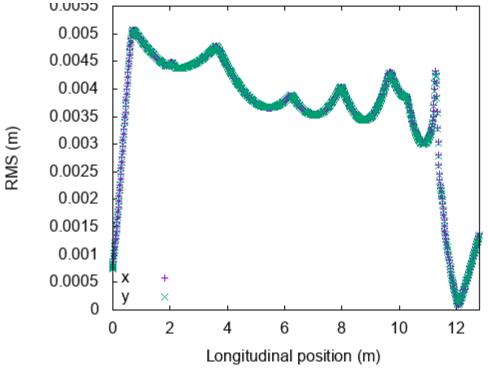
- 10 different types of wakes (cavities, bellows, BPMs, PMs, etc…) from after gun to after linac were simulated in ABCI/ECHO. Cross-checking was performed and calculated wakes were imported into IMPACT-T.
- Total longitudinal wakefield < 20 V/pC. For our operation regime (charge 0.6 – 1.5 nC), the resulted effect in beam distribution is small.

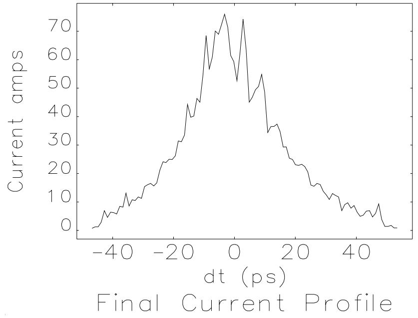
Low Energy Beam Transport Optimization

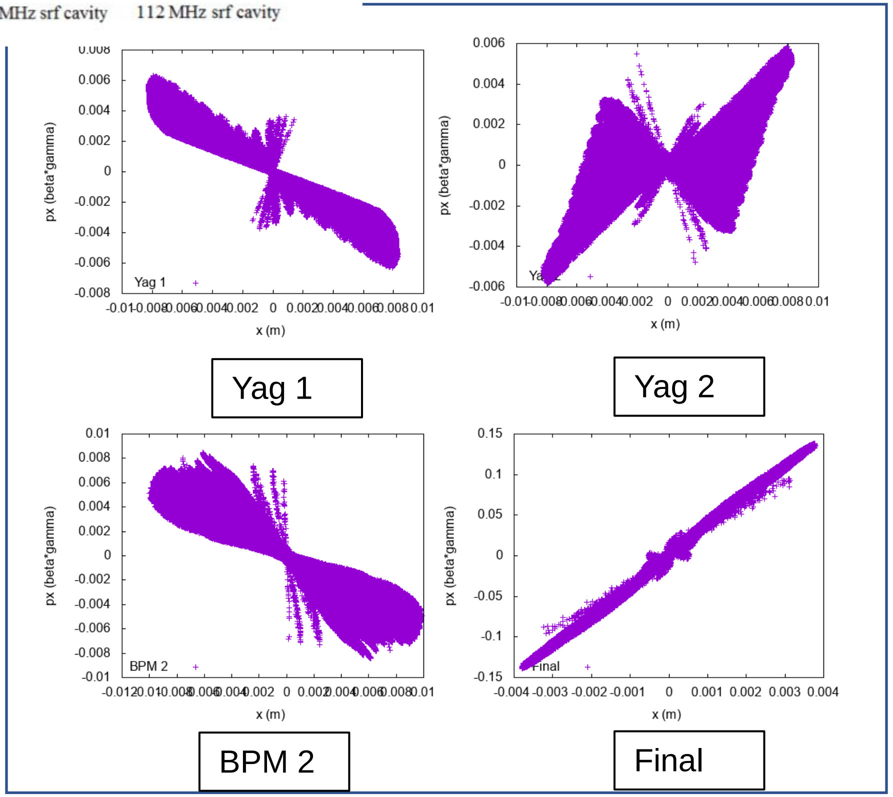






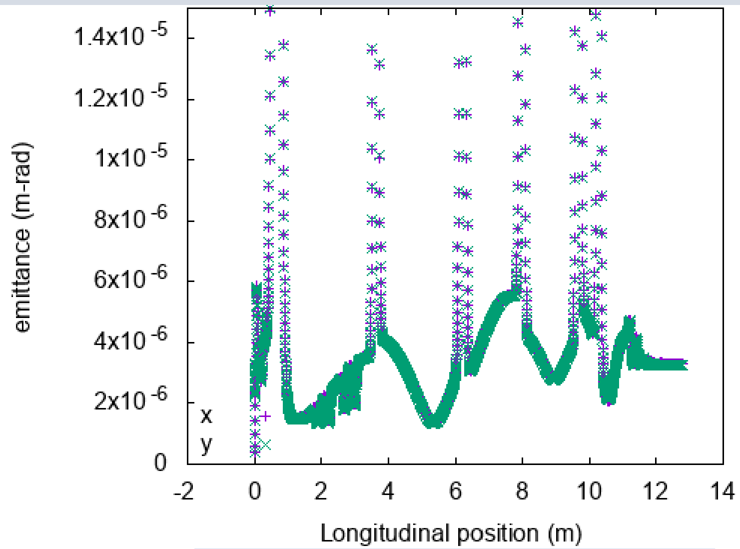


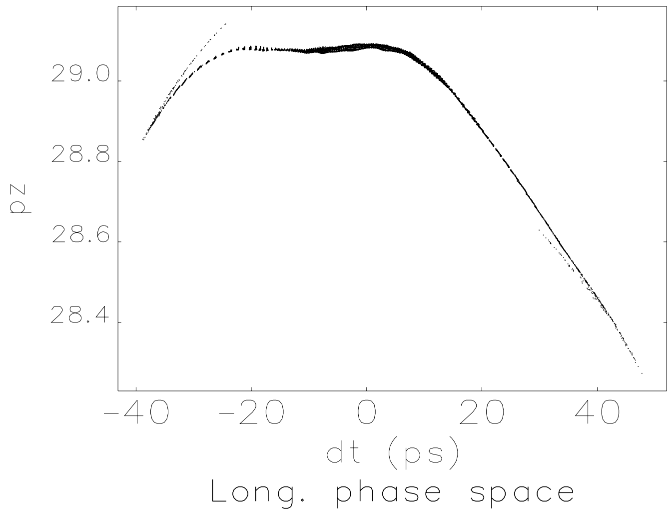




Emittance compensation by aligning all slices are not only important for reducing projected emittances but also key to make core part of the beam having same/similar TWISS parameters.

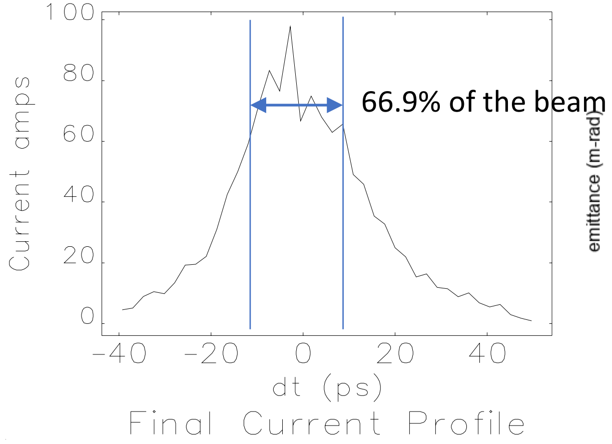
Optimized beam setup for low noise and high gain demonstration

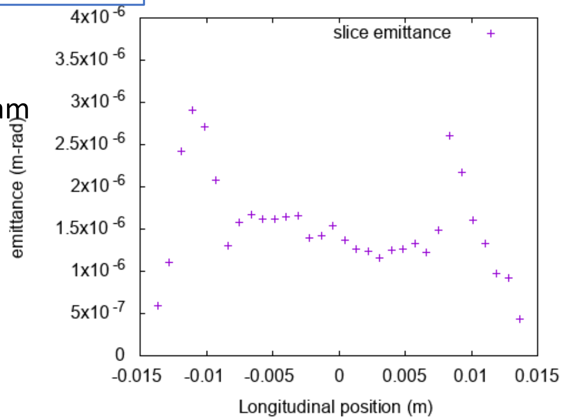


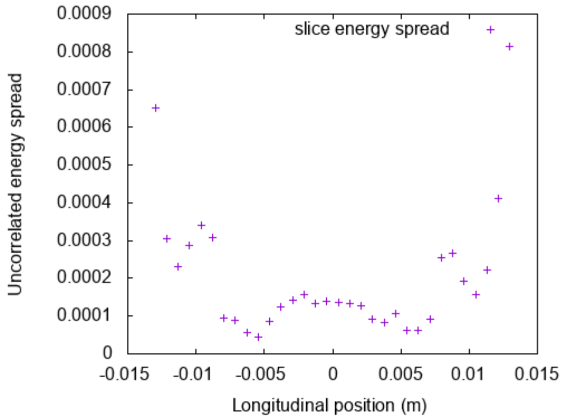


Charge per bunch	1.5 nC
σ_s, FWHM	380 ps
Beam radius	1.88 mm

Projected norm. emittance ~ 3.3 um



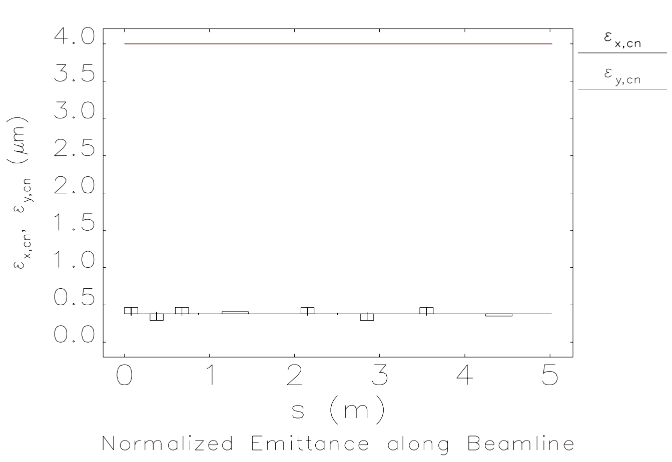


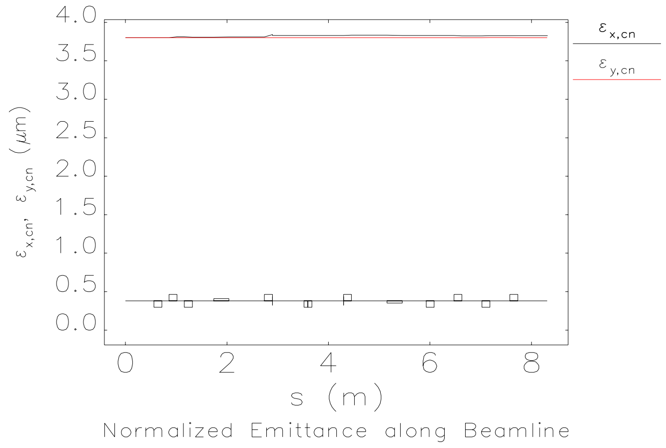


Core part of the beam's norm. emittance < 1.5 um, slice energy spread ~ 1e-4, peak current ~ 70 A, this type of beam setup has been used in run 20-21 and in PCA gain demonstration.

Other effects (CSR, chromatic) are not dominating

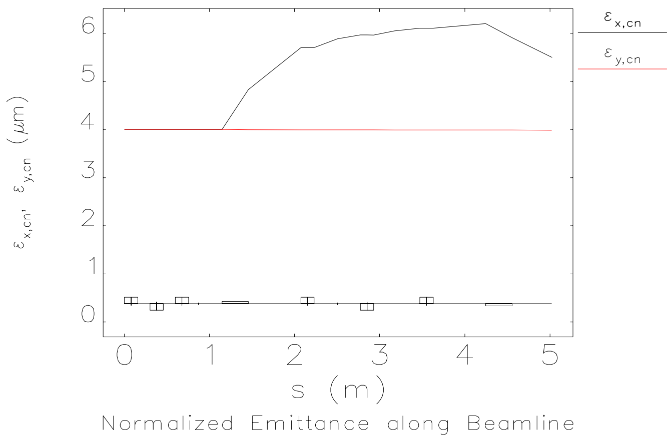
Nominal, C = 1.5 nC

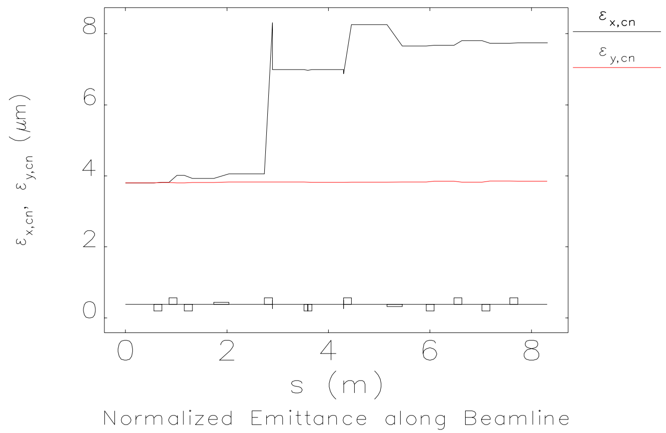




Nominal, rms δ = 0.1 %

C = 10 nC

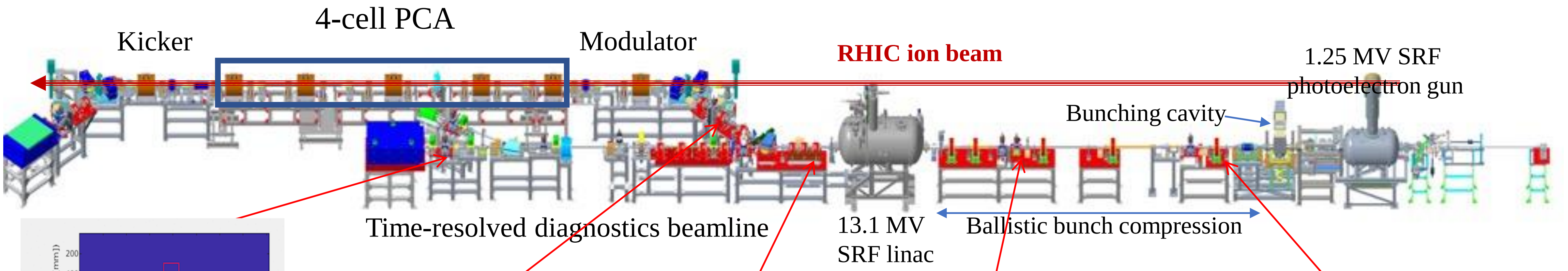


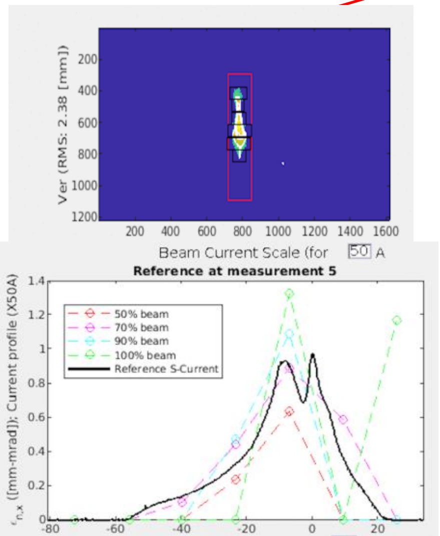


rms δ = 1 %

CSR and chromatic aberration do not play an important role for our chosen beam parameters thus are not incorporated in routine simulation.

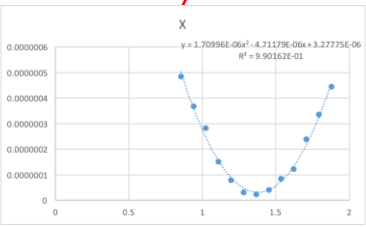
Beam measurements along the CeC beamline



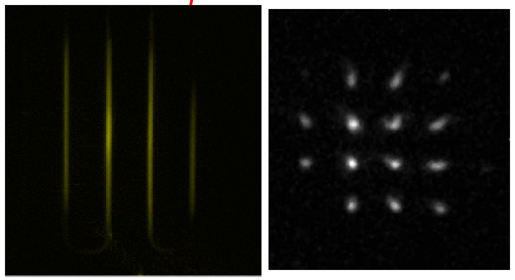


With T-Cav, slice emit. ~ 1-1.4 um, slice energy spread ~ 2e-4

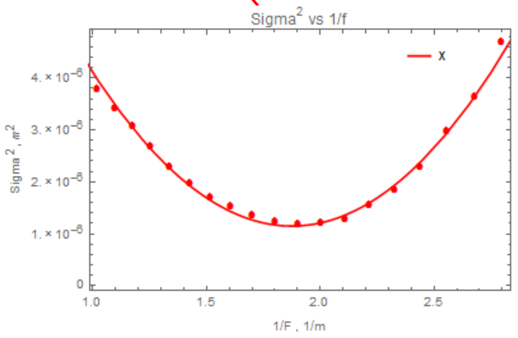
Beam compressed by ~ 20-40 folds after LEBT, energy spread ~ 0.1%



Quad scan, norm. emittance ~ 3.6 um



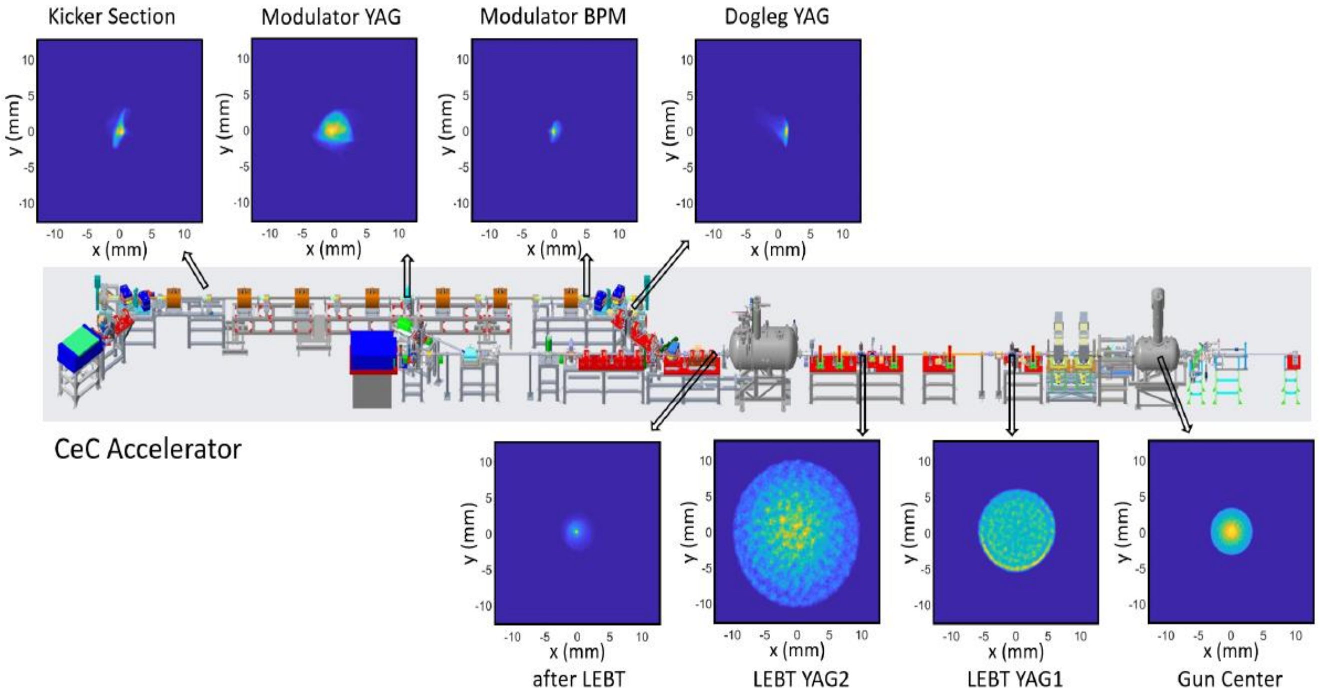
Slits/pep-pot, norm. emittance ~ 1-4 um

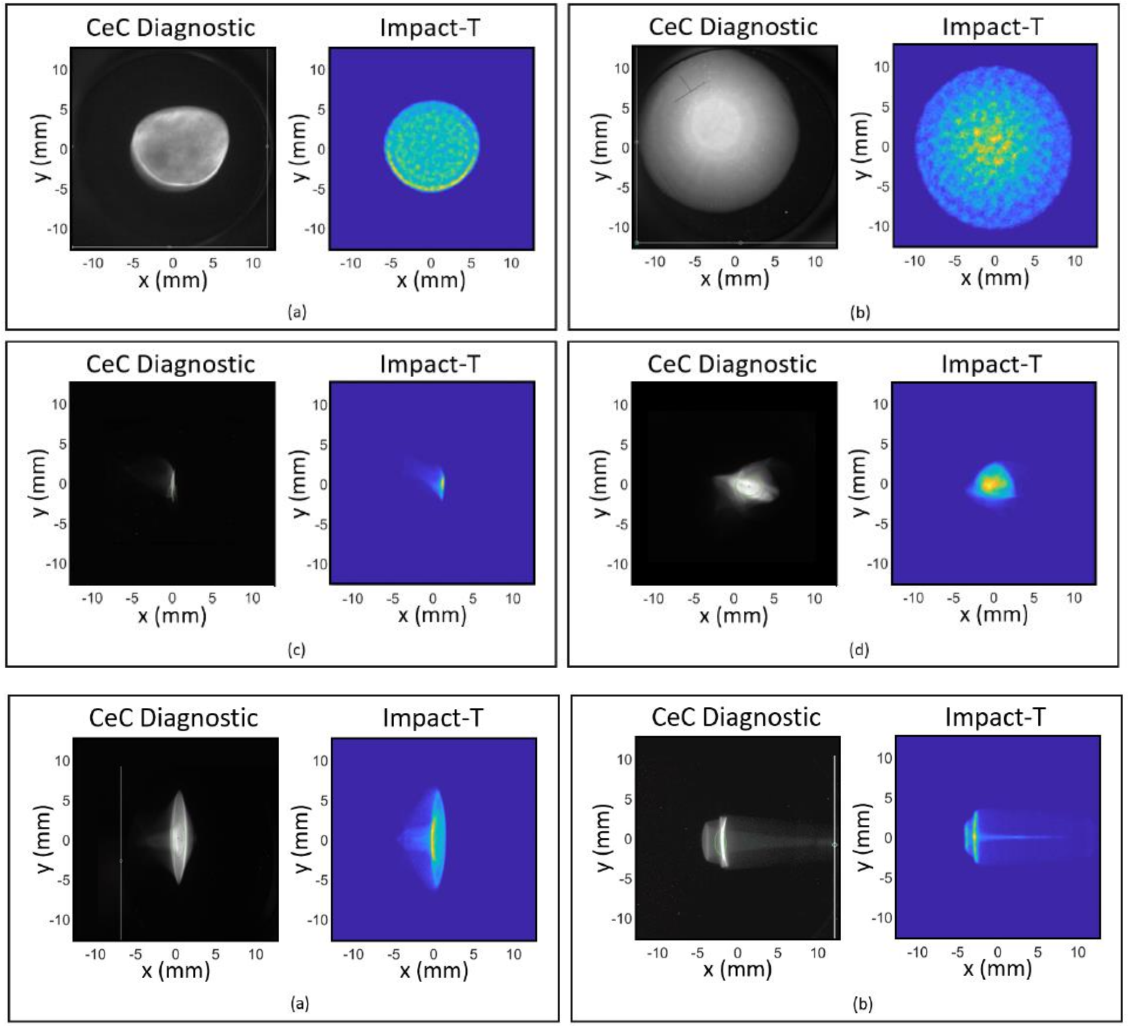


Sol scan, norm. emittance ~ 0.5 - 1 um

Properties measured by solenoids and slits in good agreements with simulation predicted: proj. emittance ~ 3 - 4 mm- mrad, energy spread ~ 0.1%; slice emit ~ 1– 1.5 um, slice rel. energy spread < 2e-4

Simulation’s prediction with real beam (with misalignments/field errors)



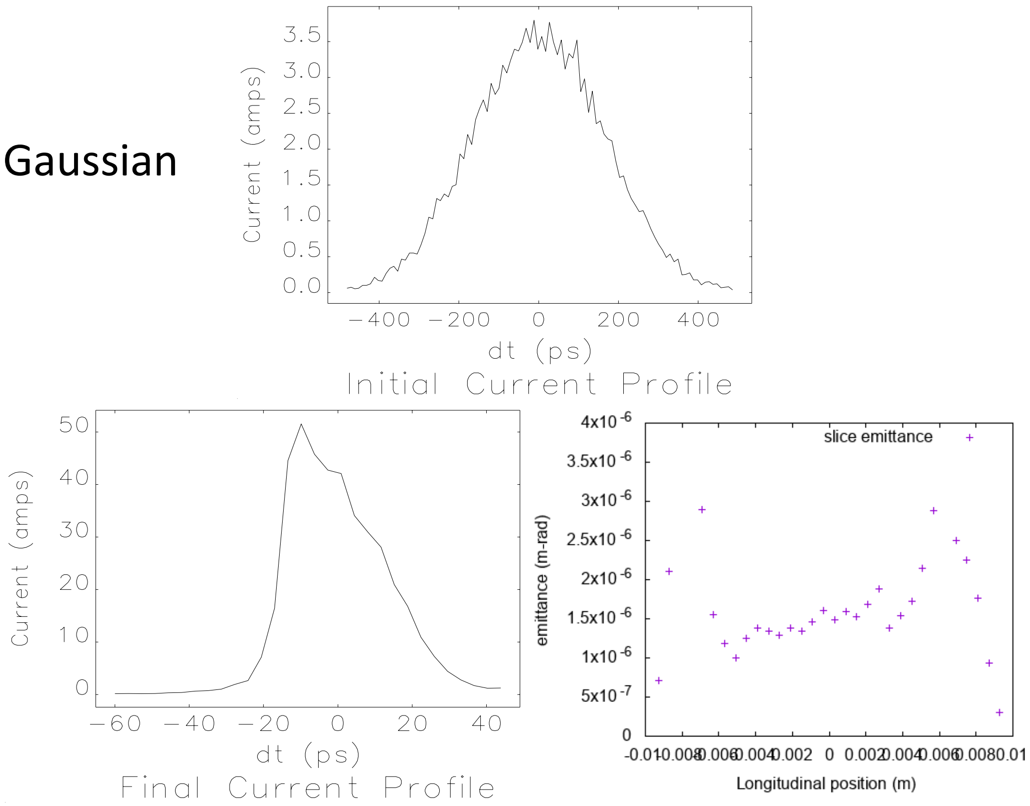


Our simulation has qualitatively good agreement in predicting the unusual behaviors in the real beam when misalignment/field errors in the beamline are included.

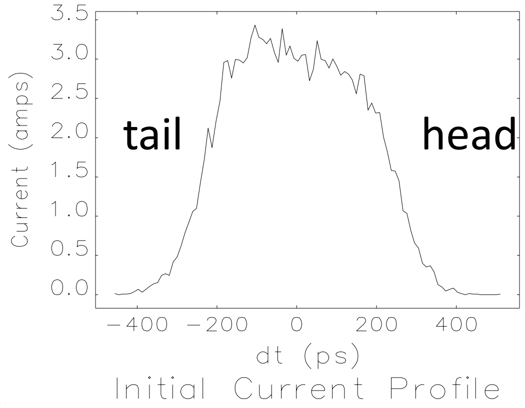
Road to beam with uniform temporal distribution – flat top initial dist. no good

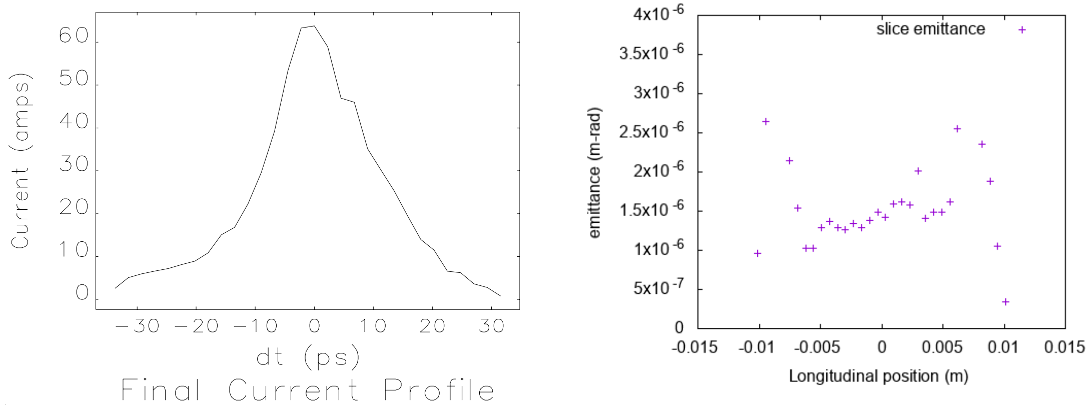
Due to the strong compression and space charge dominated nature, for an initial flat top distribution, final distribution is close to triangular shape.

Gaussian



Flat-top with linear chirp (real)

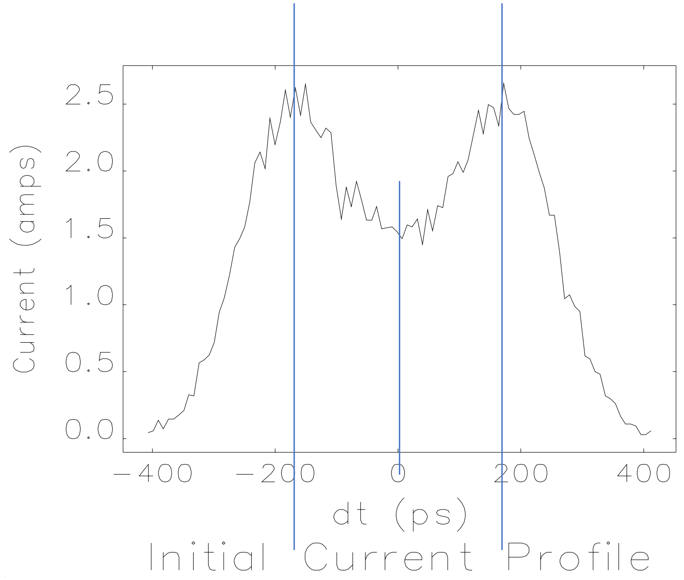




Both Gaussian and semi-flat top distributions cannot produce uniform temporal distribution for compressed beam. Need some innovative laser pattern!

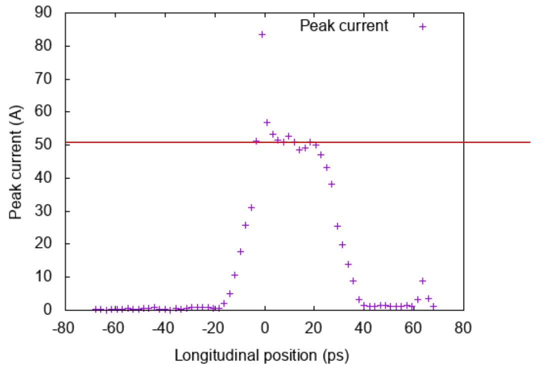
New laser pattern with combinations of Gaussian beamlets

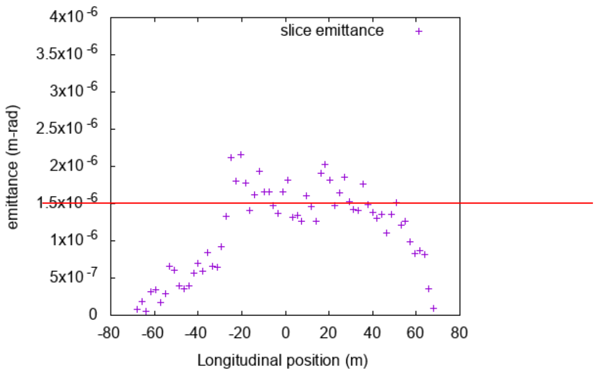
We first start with 3 Gaussian beamlets for uniform final distribution

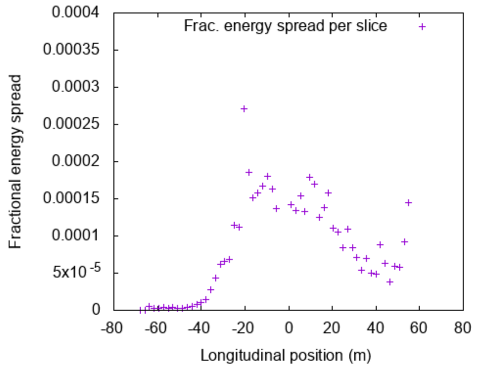


Laser profile: 3 degrees of freedom

Item	Unit
Side beam center	180 ps
Beamlets' r.m.s	80 ps
Relative intensity center/sides	0.5



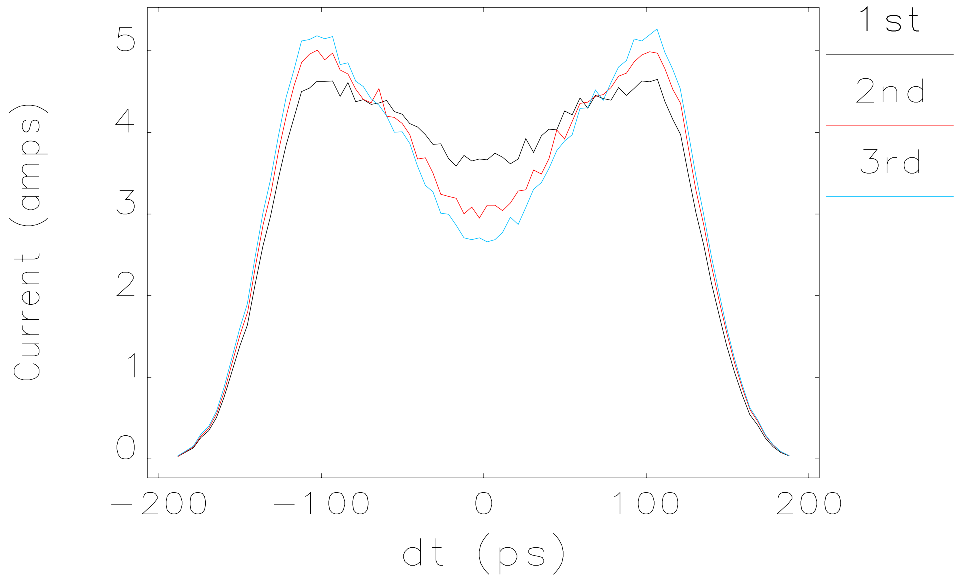




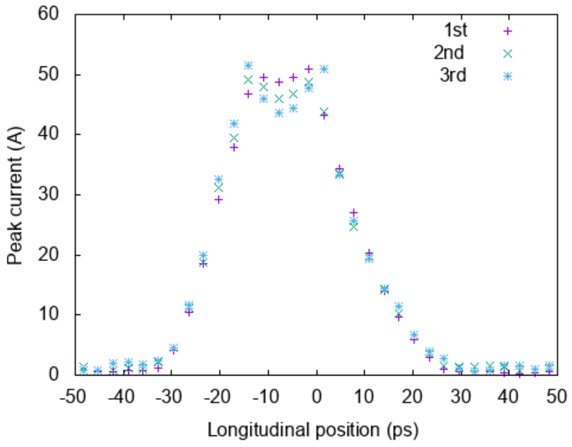
Slice emittances (~1.5 um) and peak current (~ 50 A) are satisfactory. Slice energy spread (for core, > 1.5e-4) is too large due to long initial bunch length and strong compression.

Laser pattern more Gaussian beamlets

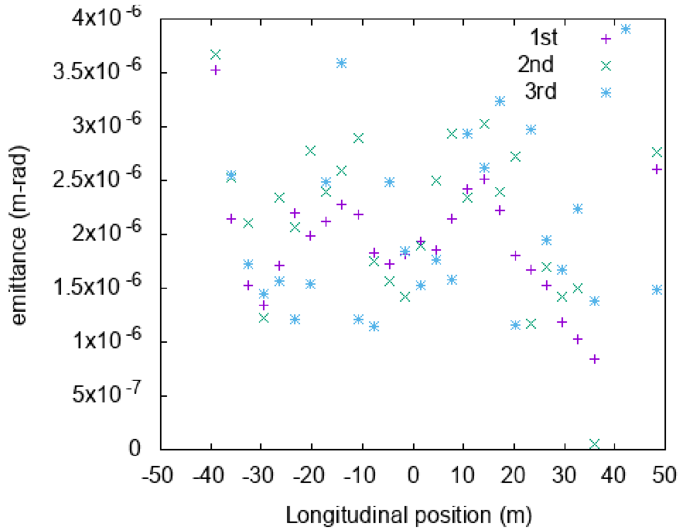
We then used 5 Gaussian beamlets and optimized the relative strengths between beamlets



Initial Current Profile

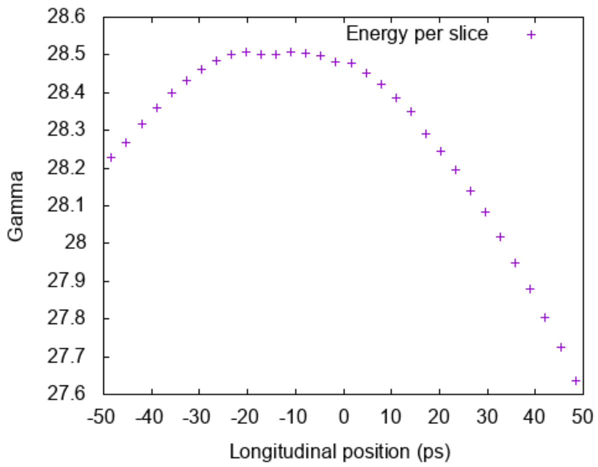


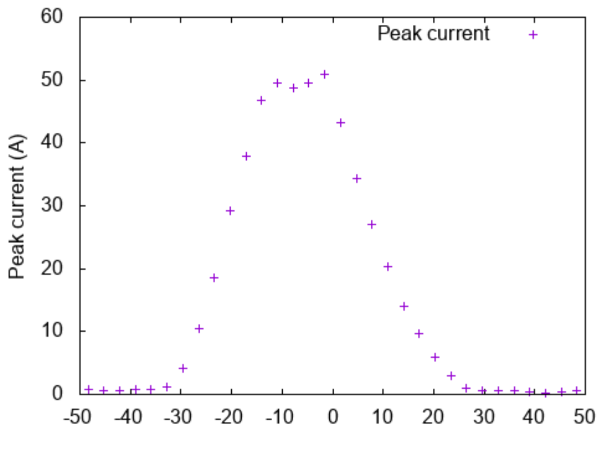
1st: (1;0.85;0.7;0.85;1)
2nd: (1;0.75;0.5;0.75;1)
3rd: (1;0.7;0.4;0.7;1)

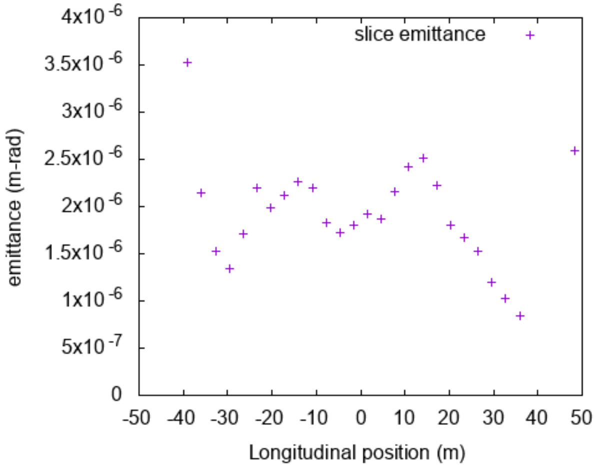


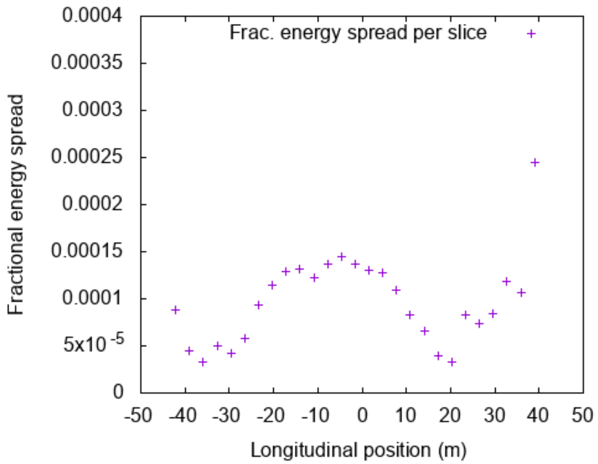
Initial dip's height seems to have strong effect on the final current distribution's uniformity.
Slice emittances in the core part are 1.3 – 1.8 um (has relationship with local compression).

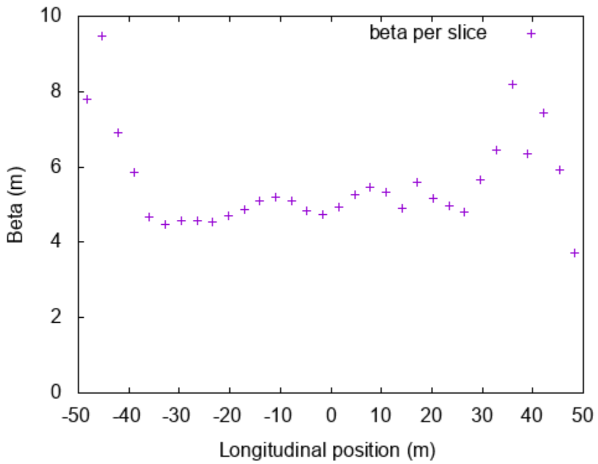
Slice performance for optimized setup (1st)

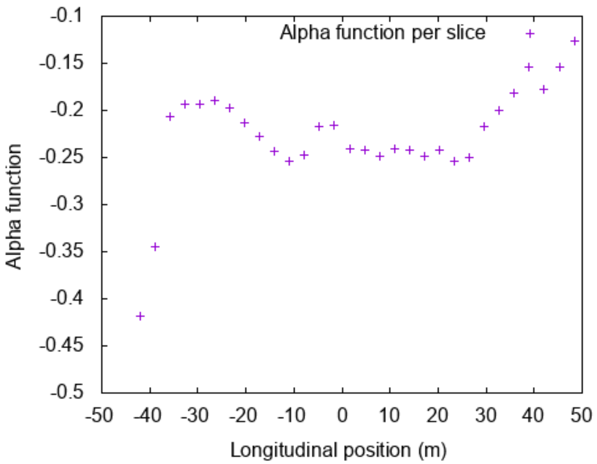






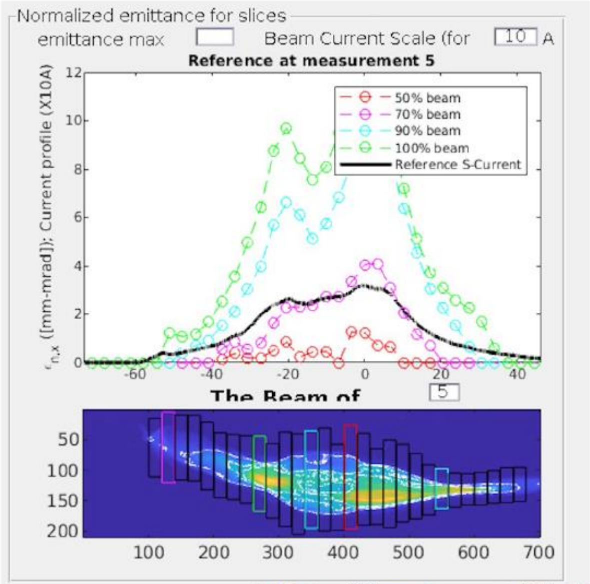


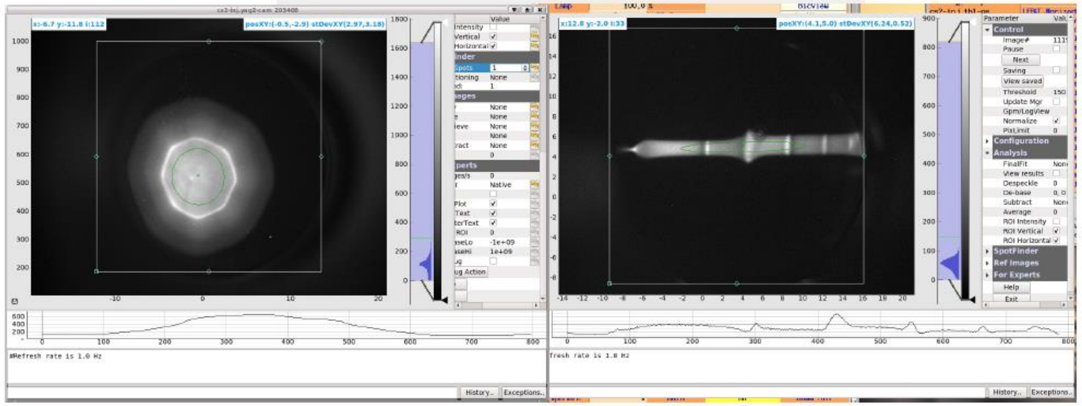




Beam measurements Run 23

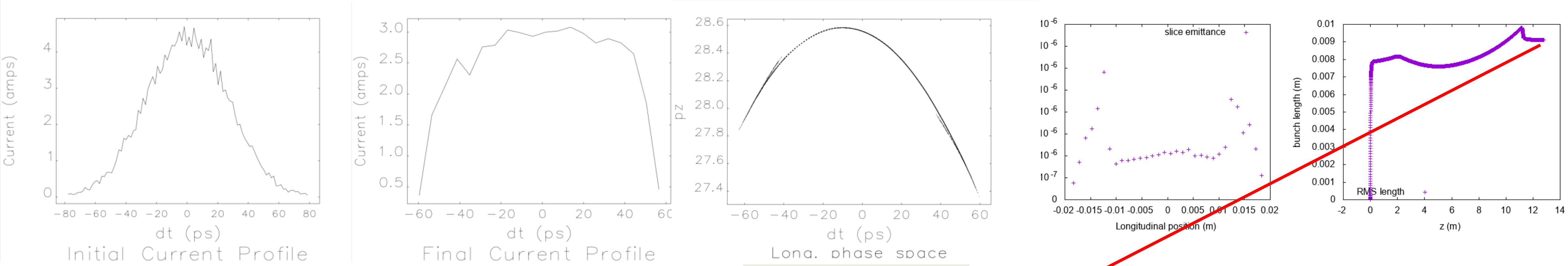
- Whole beam (with all 5 beamlets) has worse performance than expected.
- Measured beam emittances (slice and projected) are significantly larger (2 – 2.5 times) than what we achieved earlier.
- Different beamlets seem to have huge uncompensated chromatic effects when time dependent energy variation is introduced (buncher cavity on).
- Density/energy modulation along the beam becomes obvious in dispersive region (dogleg) as supposed to be smooth distribution.



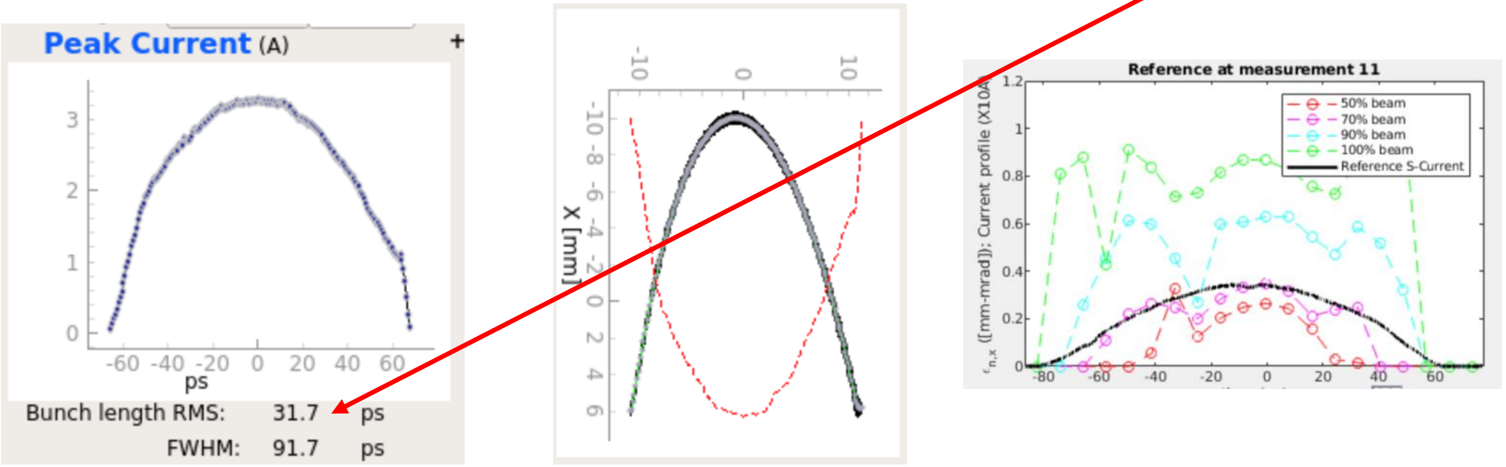


Measurements with individual beamlet

We then switch to single beamlet (by blocking others). Simulation predicts each individual beamlets' properties (slice emit., peak current, bunch length etc) reasonably well.



Simulated (top row) vs measured (bot row)



Problems found/to solve in the coming Runs

- The alignments of 5 beamlets need to be improved (smearing minimized) so that the emittance does not blow up (measured 10 um norm., slice).
- When combining 5 beamlets, the relative strength of laser power is not as desired, #1,3,5 have significantly weaker power than #2,4 (fixed).

- The beam test was not finished due to early RHIC operation termination (6 weeks earlier than planned) and many interruptions in operation due to high temperature and humidity.
- Will put all beamlets together and measure properties when laser tuning is done.

Parameter	Sim.	Exp.
Charge per bunch, nC	0.3	0.3
Bunch length, RMS, ps	30.8	31.7-32.4
Bunch length, FW, ps	119	120-123
Final peak current, A	3.0	3.2-3.4
Normalized emittance (slice), RMS, μm	1.0	0.9-1.0
Beamlets separation, ps	55	54-56

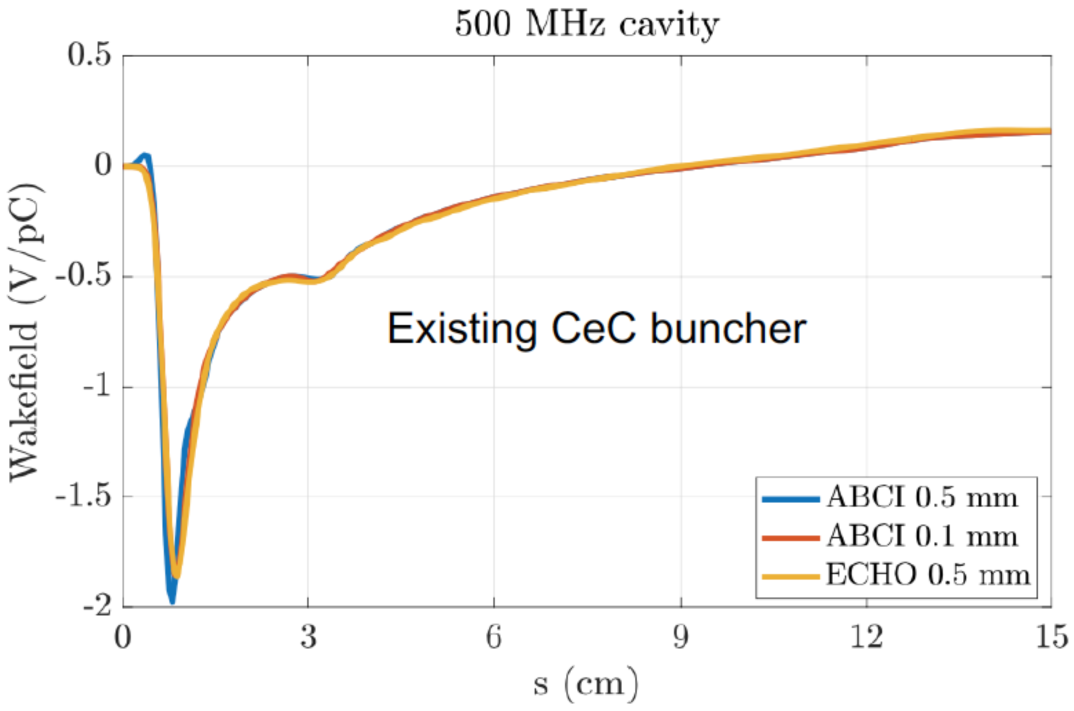
Summary

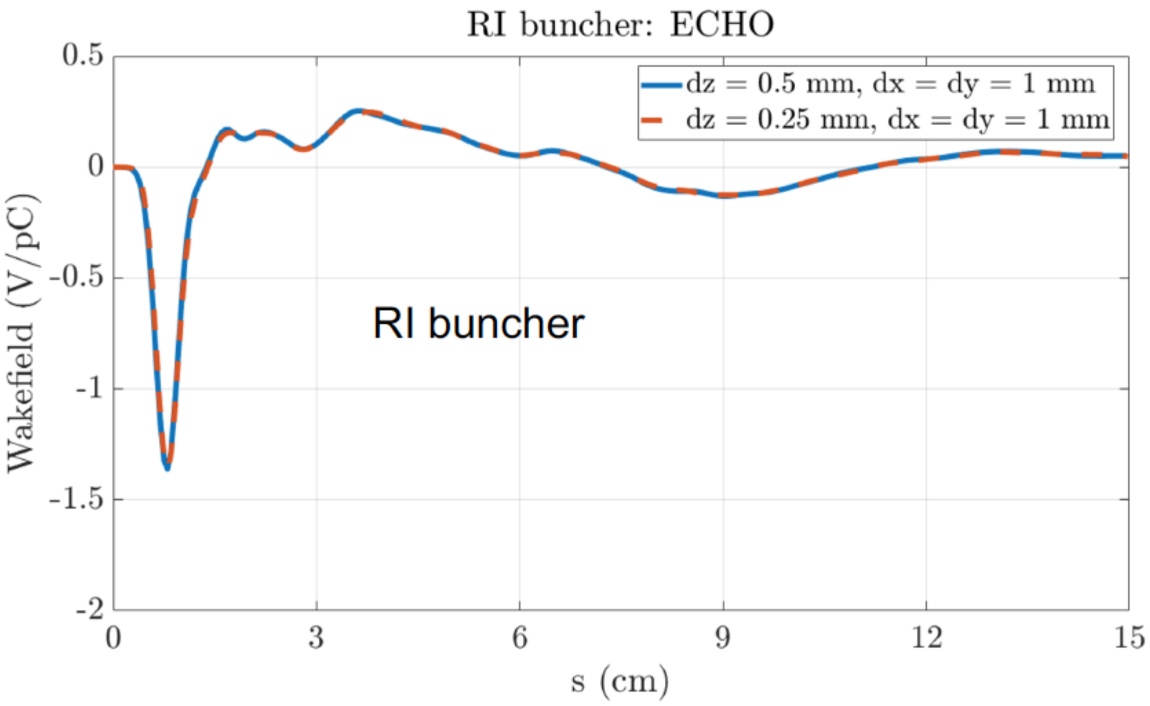
- Beam dynamics simulation for CeC PoP experiment provides good guidance in determining beam properties under various operation modes.
- New laser pattern was proposed to generate a compressed e- beam to provide uniform final beam distribution. Experiment will be performed to verify the e- beam's properties.
- Optimization in parametric space to achieve lower emittance and/or higher peak current is underway.

Back slides

Wakefield estimates using ECHO:

- The simulations were performed for bunch with $\sigma_z = 1.5$ mm.





- The mesh settings are listed in the legend for each simulation.
- For the RI buncher a simplified geometry with elongated beam pipes has been used.
- The transition between the cavity beam pipe and the CeC beam pipe is not included.