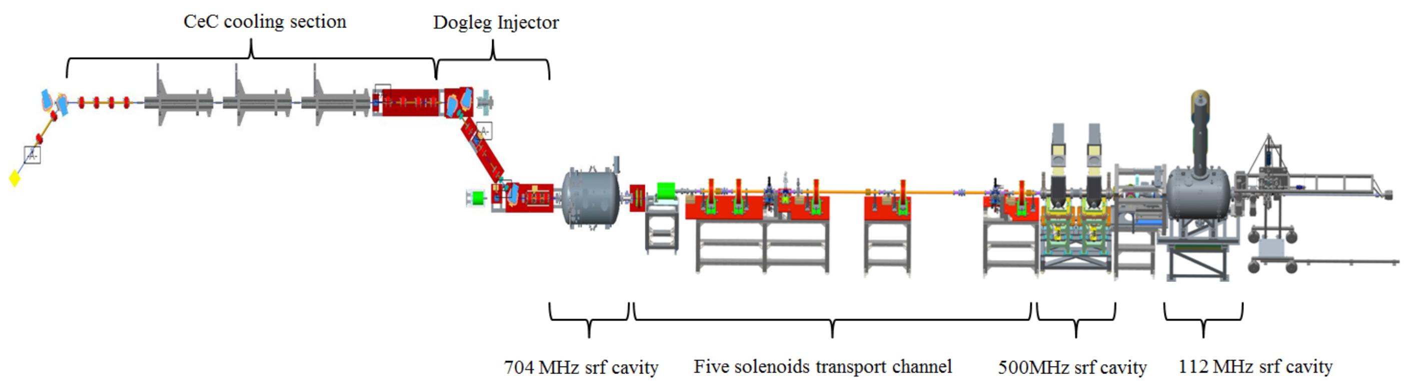
CeC simulation status and forward

Many physics issues in CeC



- LEBT (up to 5 cell cav): design injector and transport lattice for beam quality optimization (under SC). Provide model for beam-based measurements and corrections.
- Dogleg + quad triplet: beam quality preservation under CSR, chromatic aberration etc. Beam quality control.
- Cooling section (modulator + wiggler + radiator): simulation of ion-electron interaction and amplification of signal.

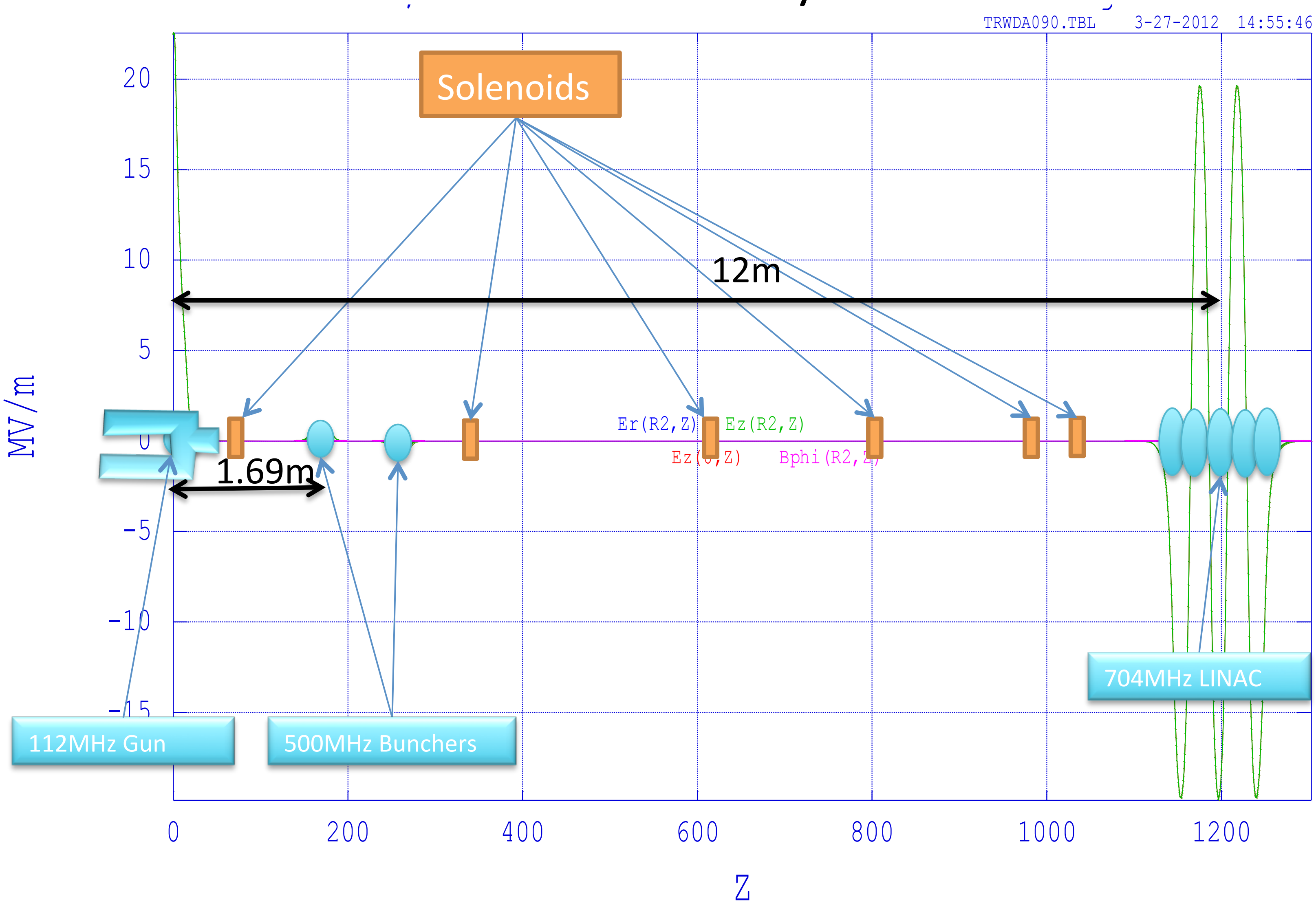
Many codes, many results

- We used different codes (PARMELA, ASTRA, MADX, ELEGANT) to simulate different beam dynamics in sections in CeC:
- Injector: PARMELA (DK/YW), ASTRA (IP)
- Dogleg: MADX (IP/GW), ELEGANT (YJ)
- Modulator/wiggler: SPACE + GENESIS (JM/GW)
- FEL: GENESIS (YJ/YH)
- Preliminary line-up of the system (without e-ion interaction): dump-import (YW)

Selected results (best?)

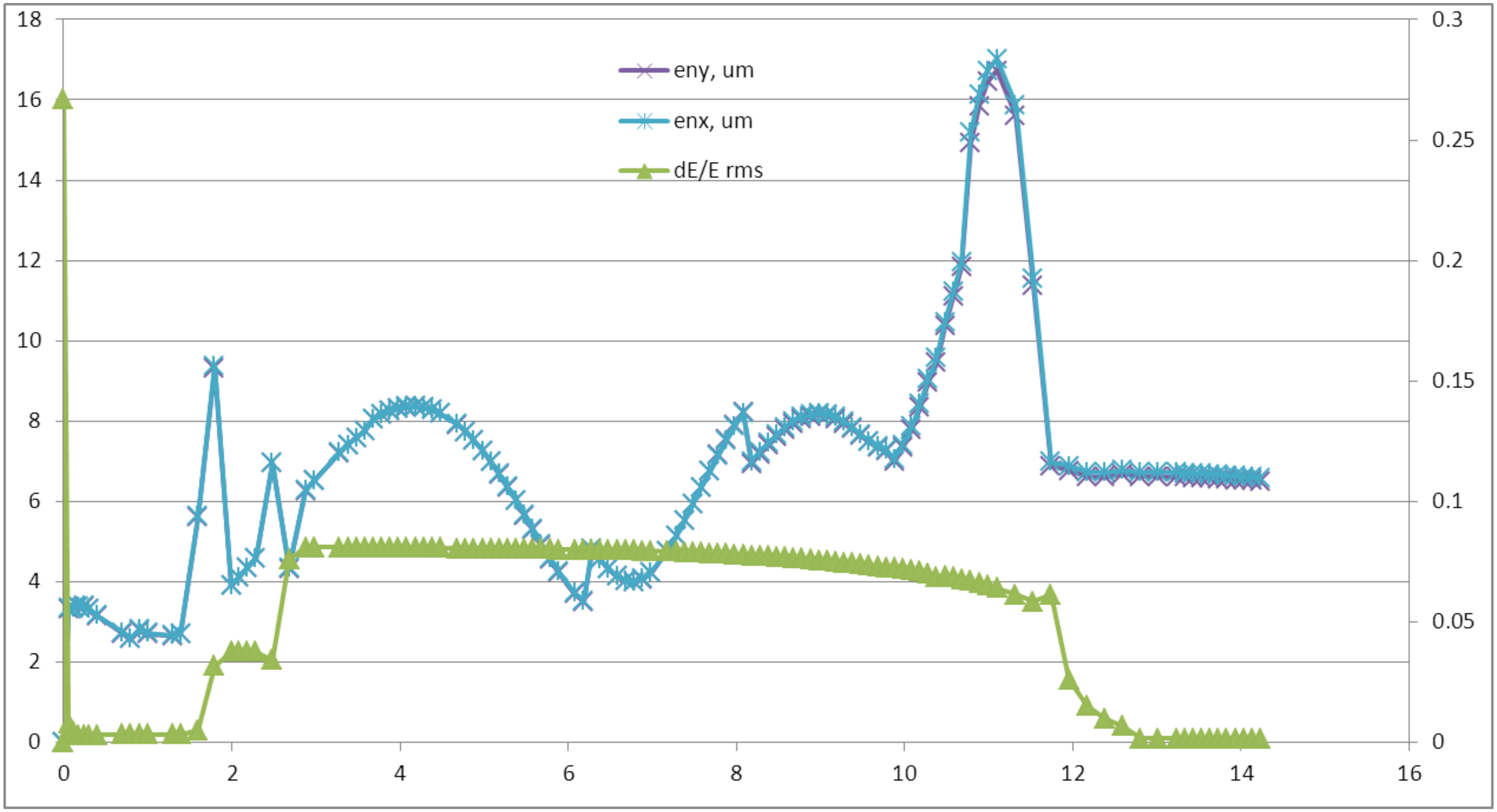
Dmitry Kayran (PARMELA)

Schematic layout

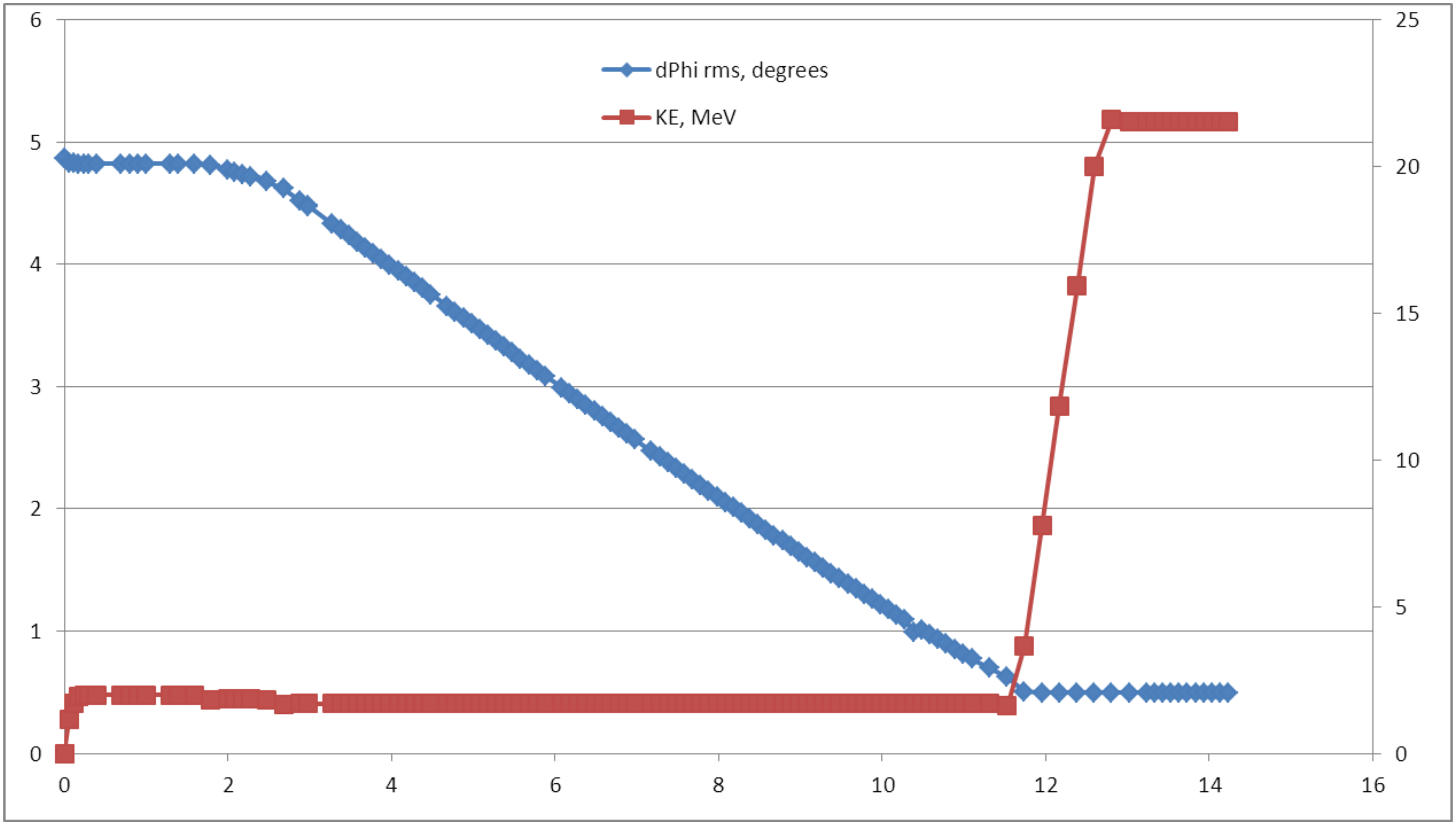


Start from long bunch, then using 2x500MHz cavies and ballistic compression to reach required peak current

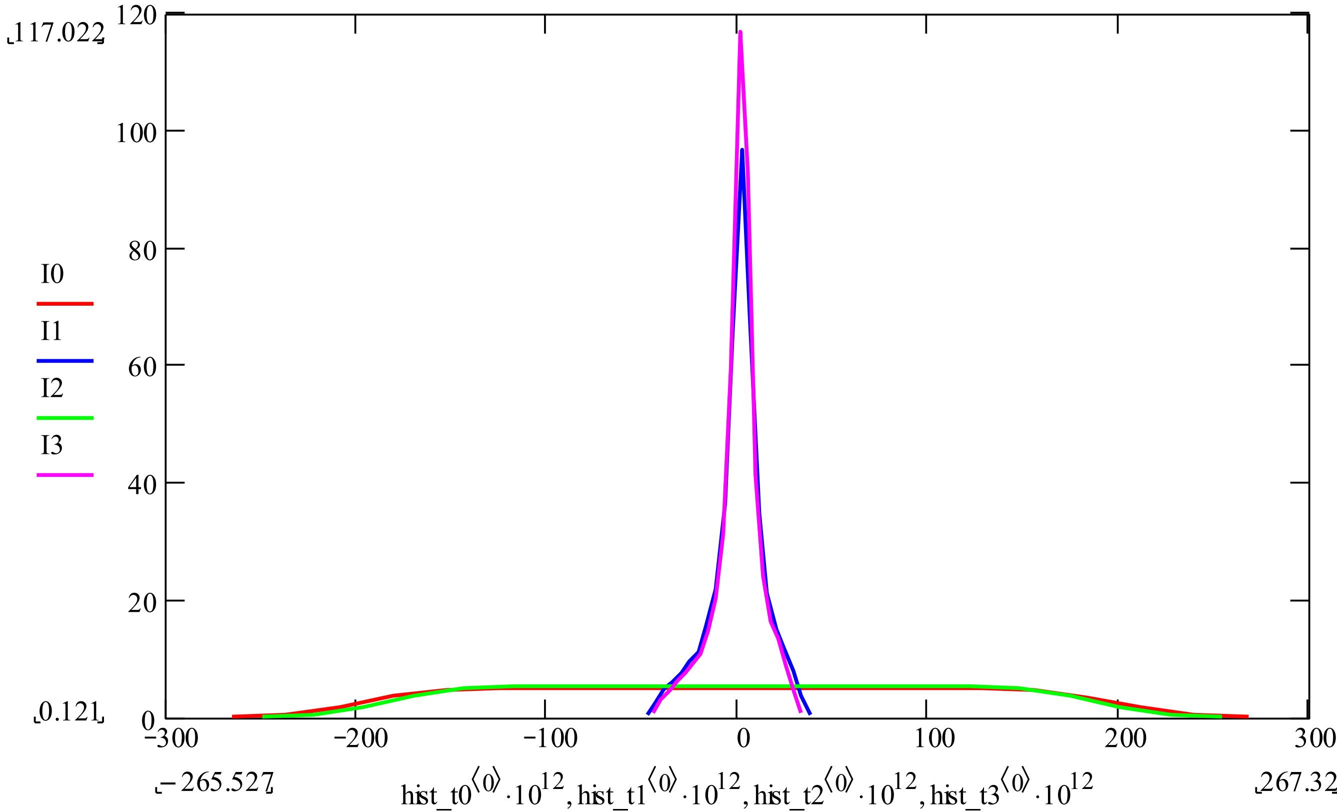
Normalized emittances and energy spread along the CEC POP injector line (full distribution)



Energy and rms bunch length along the CEC POP injector line (full distribution)

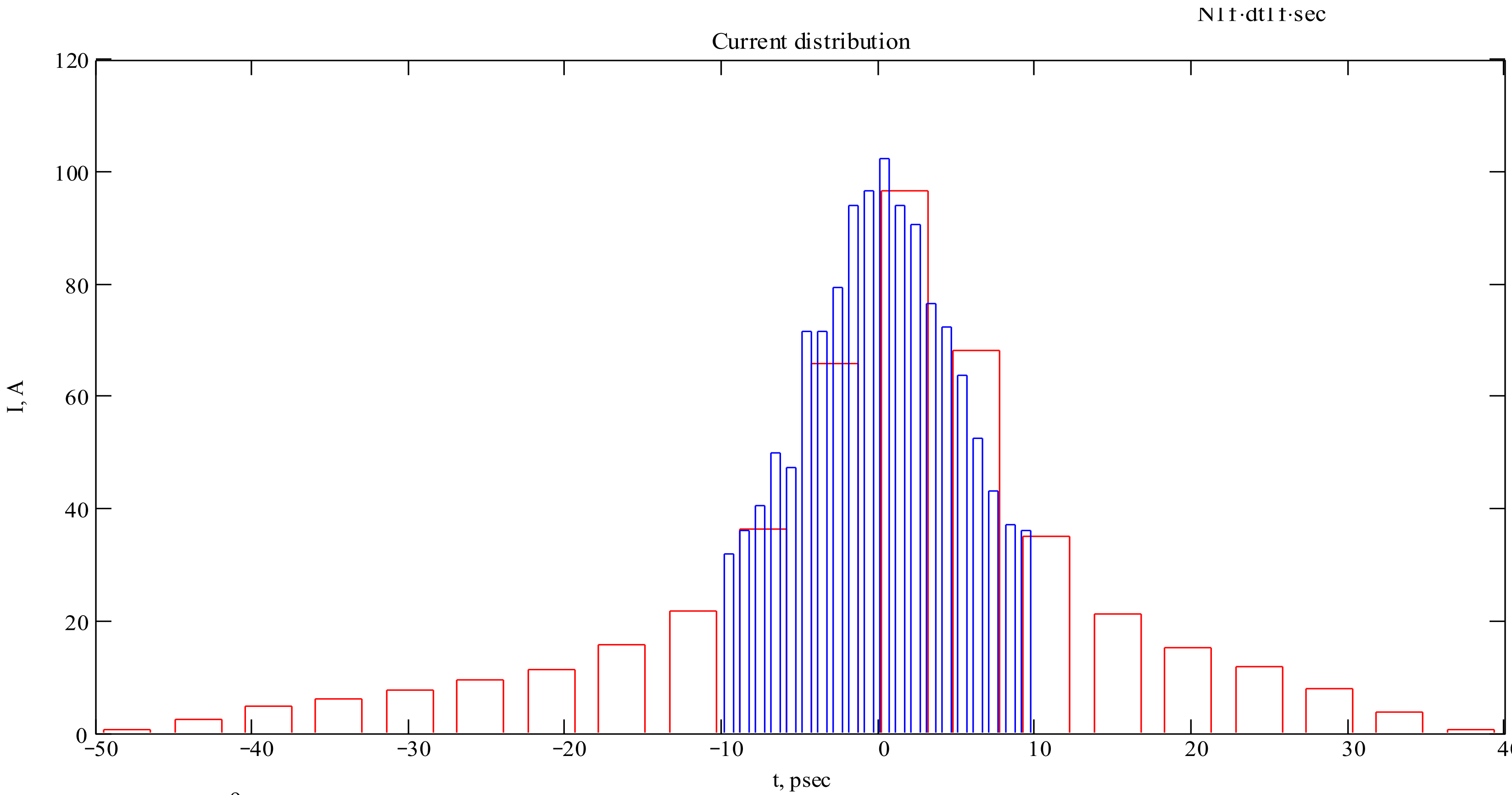


Initial and final current distributions



Q=2nC,
Ugun=2 MV
UBuncher=2x250 MV

Full and core final current distributions



$Q1 = 2\times 10^{-9}\,C$

$\max(I1) = 96.671A$

$\mathrm{mean}(I1) = 22.14A$

$$\frac{1}{e^{\alpha}}\cdot\sum_{i=0}^{NN-1}\left[\left[I1_i\cdot e^{\alpha\cdot\left(\frac{I1_i}{\max(I1)}\right)}\right]\cdot dt1\cdot sec\right] = 6.144\times 10^{-10}\,C$$

$enx1 = 8.626\times 10^{-6}$

$\mathrm{stdev}(de1) = 2.055\times 10^{-3}$

$Q1f = 1.287\times 10^{-9}\,C$

$\max(I1f) = 102.324A$

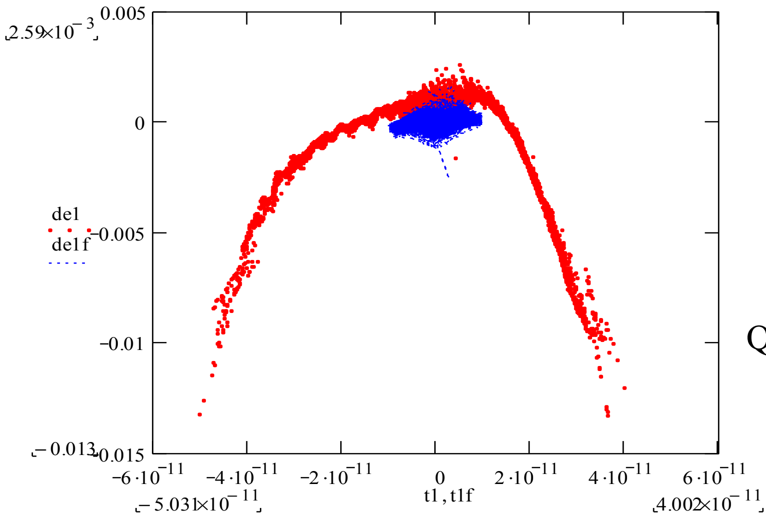
$\mathrm{mean}(I1f) = 64.398A$

$$\frac{1}{e^{\alpha}}\cdot\sum_{i=0}^{NN-1}\left[\left[I1f_i\cdot e^{\alpha\cdot\left(\frac{I1f_i}{\max(I1f)}\right)}\right]\cdot dt1f\cdot sec\right] = 5.046\times 10^{-10}\,C$$

$enx1f = 3.327\times 10^{-6}$

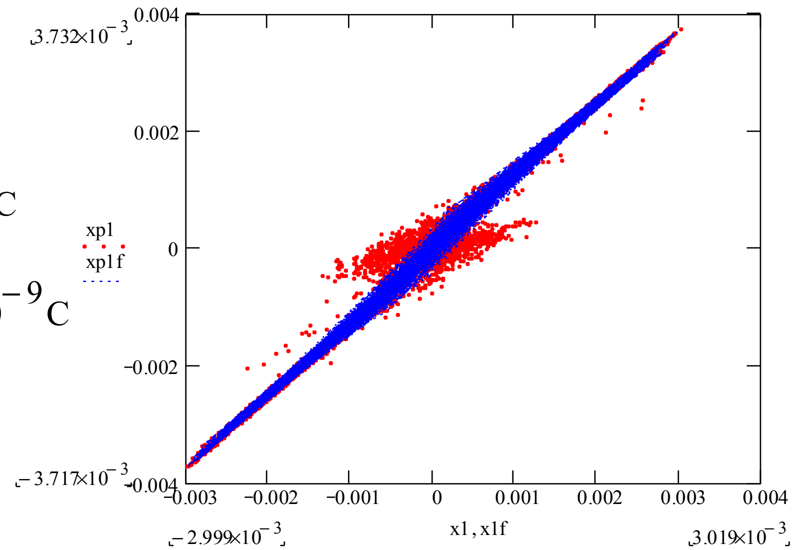
$\mathrm{stdev}(de1f) = 3.012\times 10^{-4}$

Different projections of full and core particles distribution



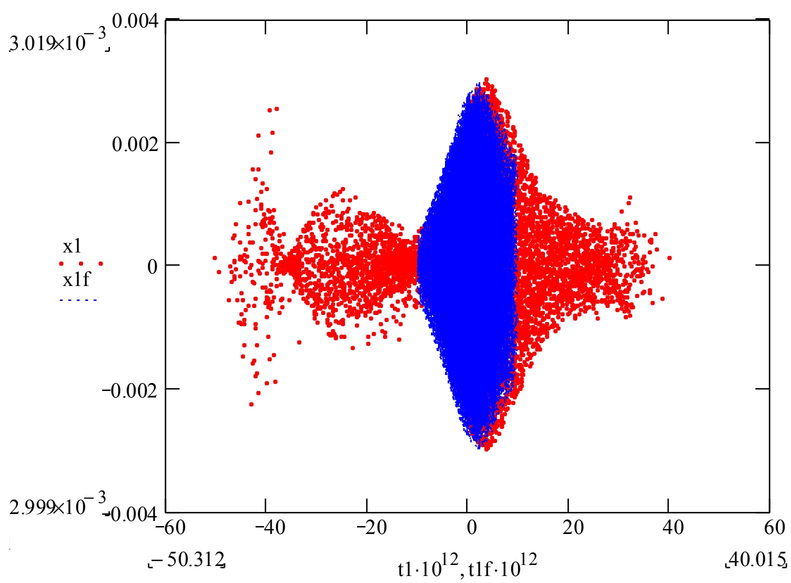
$$Q1 = 2\times 10^{-9}\,C$$

$$Q1f = 1.287\times 10^{-9}\,C$$



$$\mathrm{stdev}(de1) = 2.055\times 10^{-3}$$

$$\mathrm{stdev}(de1f) = 3.012\times 10^{-4}$$



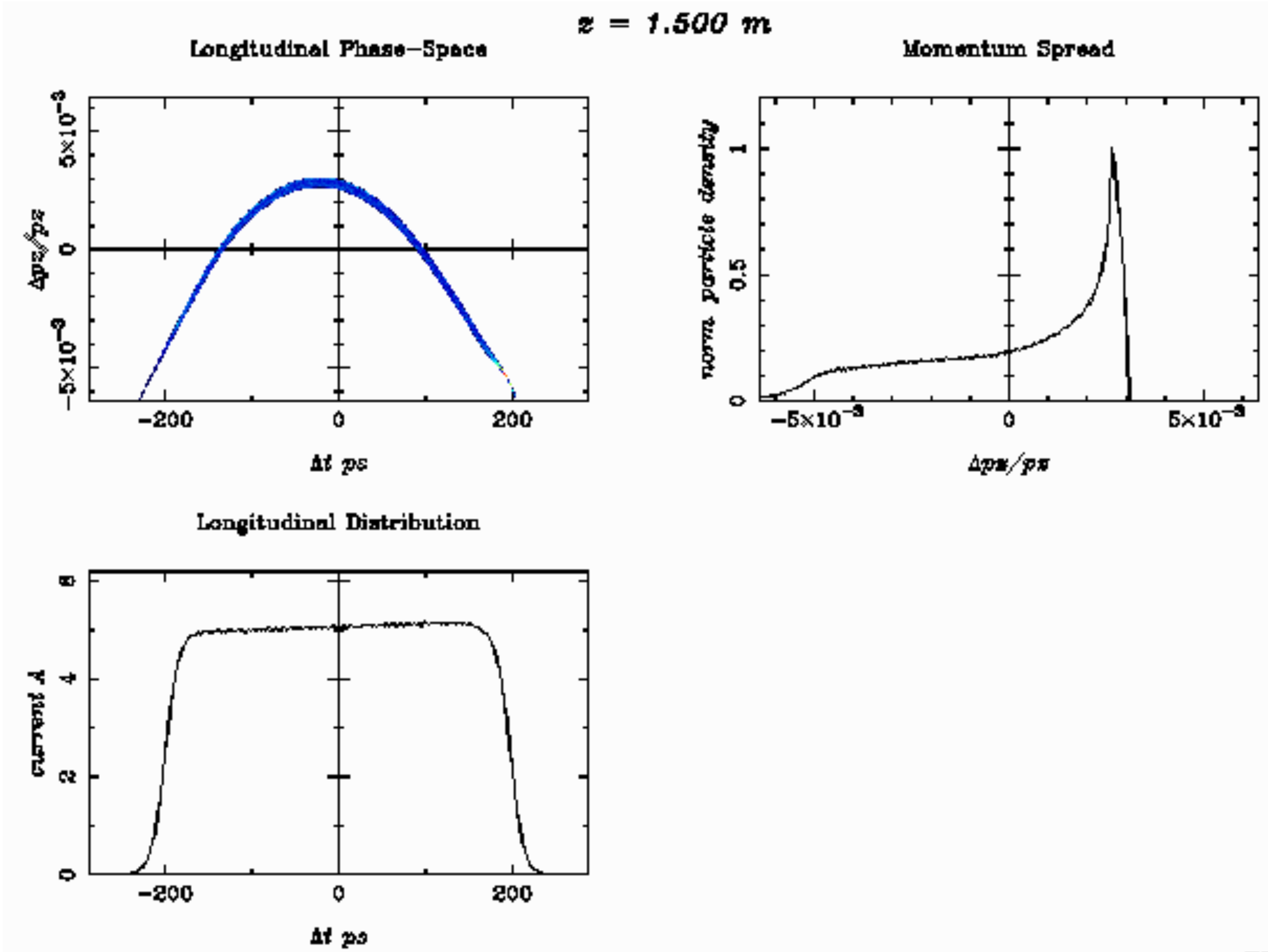
$$enx1 = 8.626\times 10^{-6}$$

$$enx1f = 3.327\times 10^{-6}$$

Igor Pinayev (ASTRA)

Gun Parameter Scan

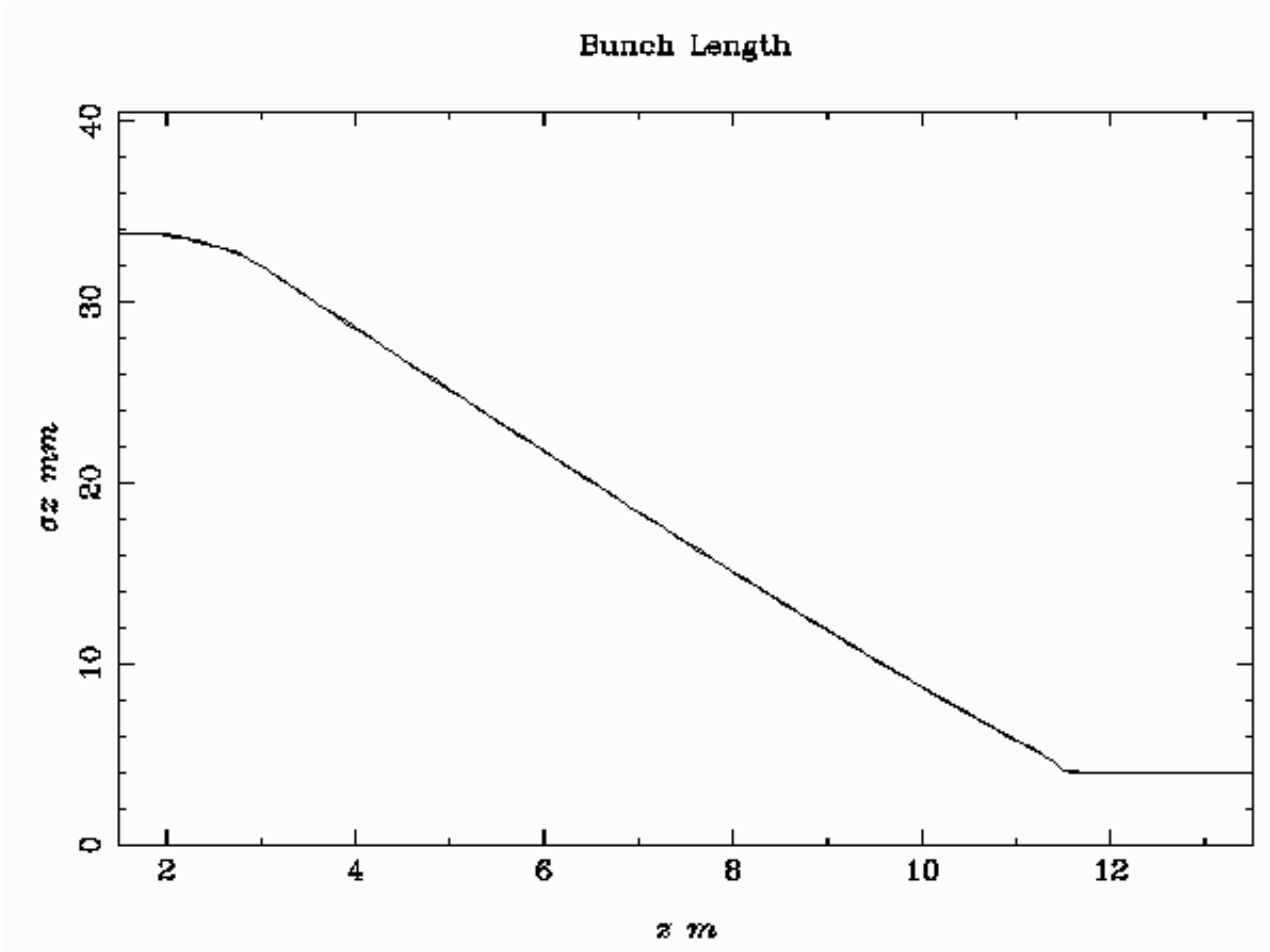
- Initial beam size (Bsol = 0.06, Q=2 nC, beer can beam with 400 ps duration, 0^{o} injection) for minimal emittance at 1.5 m – radius 1.5 mm gives minimal emittance of 2.4 mm mrad
- Cavity phase scan – no losses from -60 ^{o} to 70^{o}
- There was small cavity phase scan for emittance growth due energy modulation (Bsol=0.063 T) – minimal emittance at 1.5^{o}, at -8^{o} emittance 4.8 mm mrad



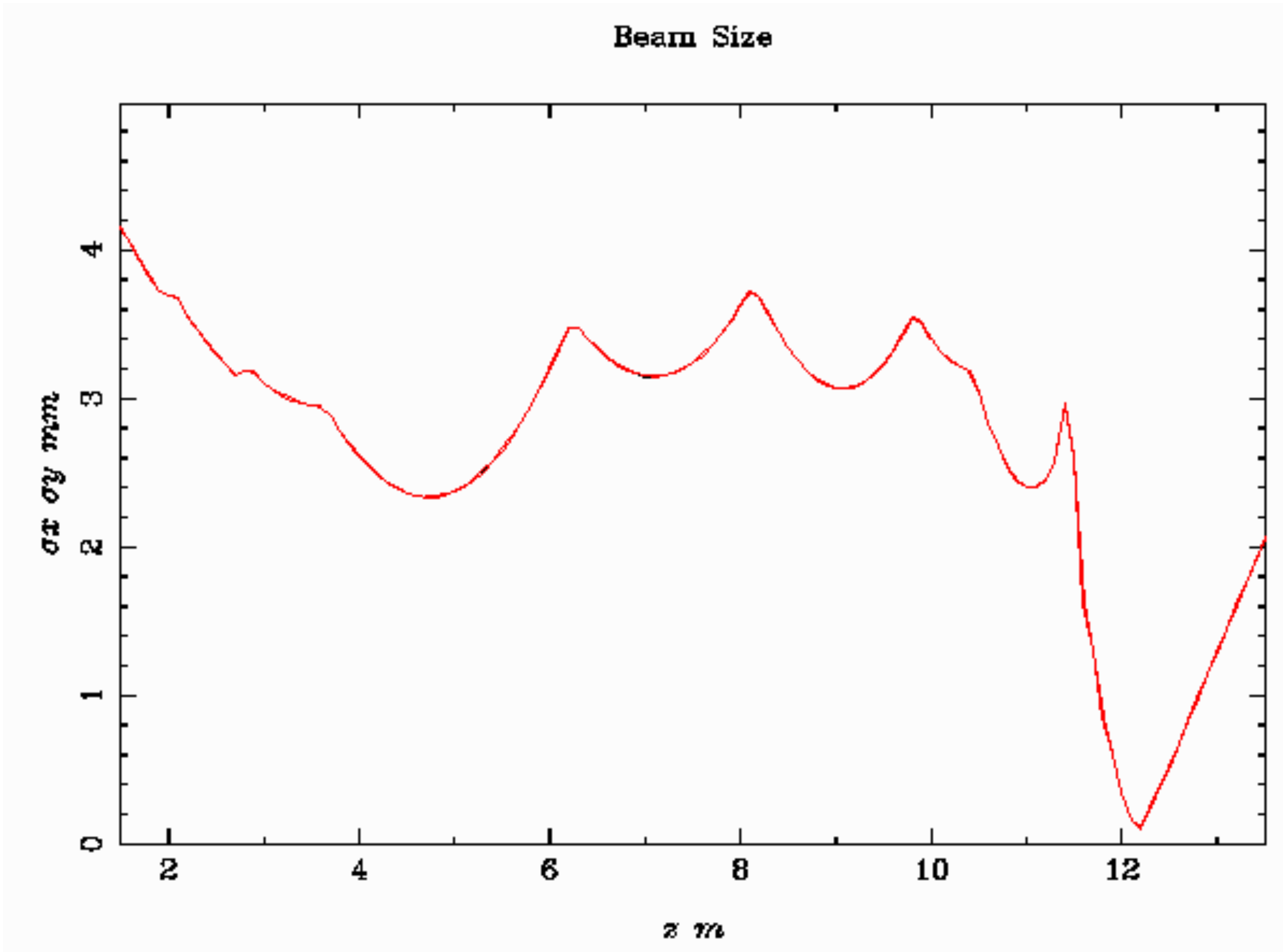
z = 1.500 m
Longitudinal Phase-Space
Δpz/pz
5×10⁻³
0
−5×10⁻³
−200
0
200
Δt ps
Momentum Spread
norm. particle density
1
0.5
0
−5×10⁻³
0
5×10⁻³
Δpz/pz
Longitudinal Distribution
current A
6
4
2
0
−200
0
200
Δt ps

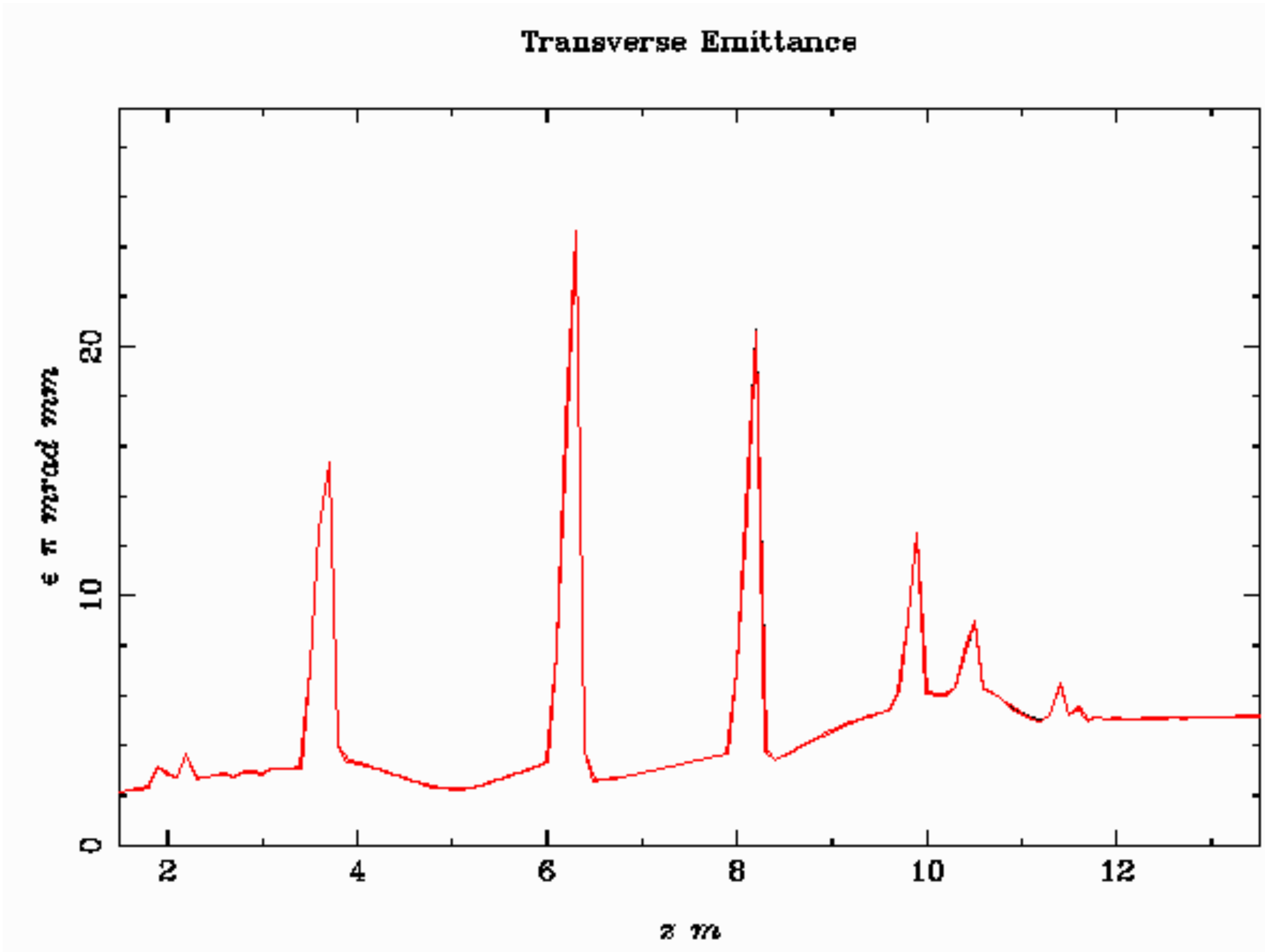
Compression study

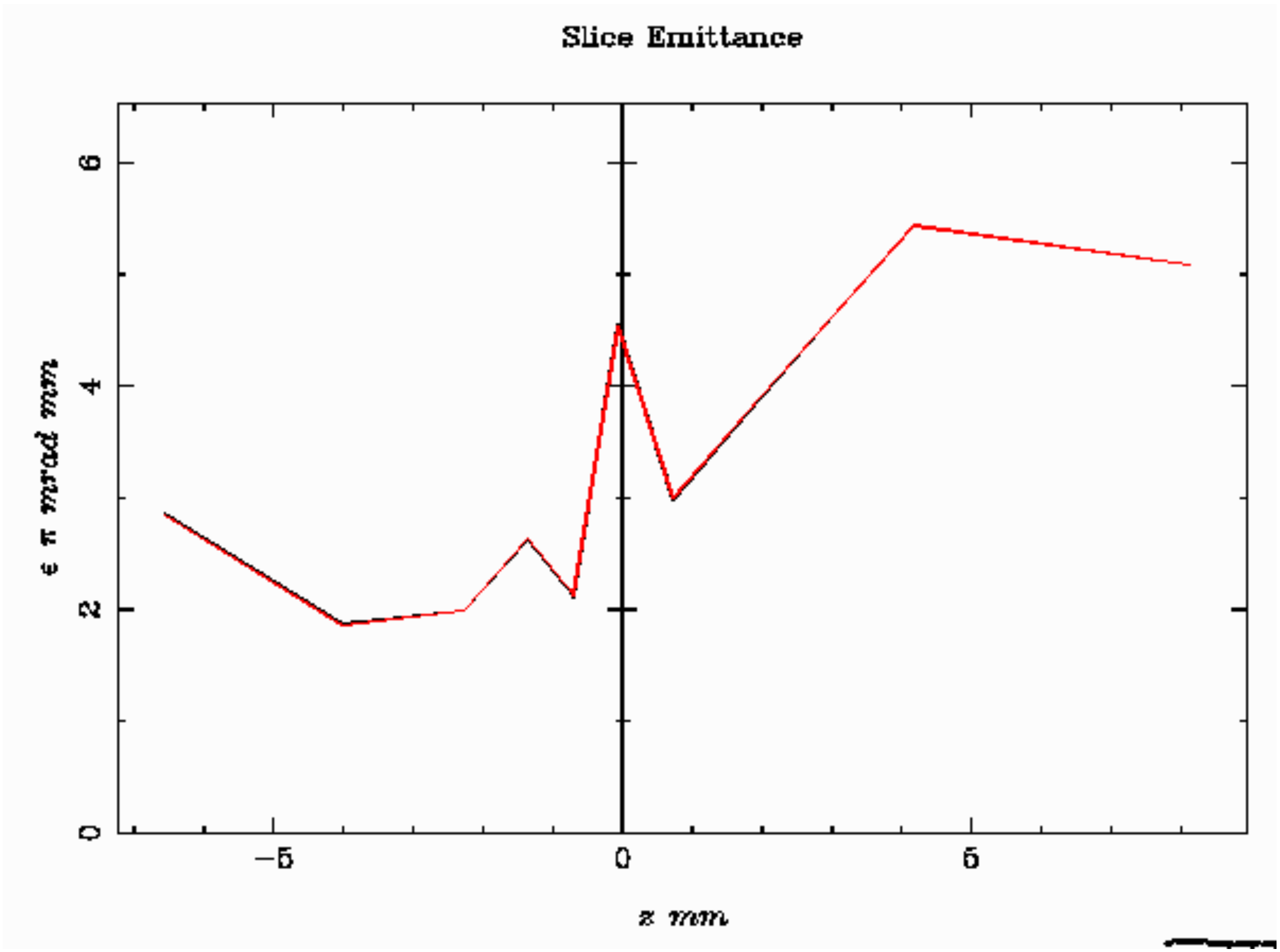
- Used beam from 1.5 m position generated during previous studies (E=22.5 MV/m, β=0.98, Bsol=0.06 T, beam radius 1.5 mm, 2 nC, 400 ps duration)
- Scanned solenoids for minimal emittance after linac at 13.5 m
- Adjusted linac phase and bunching cavity voltages to obtain proper peak current

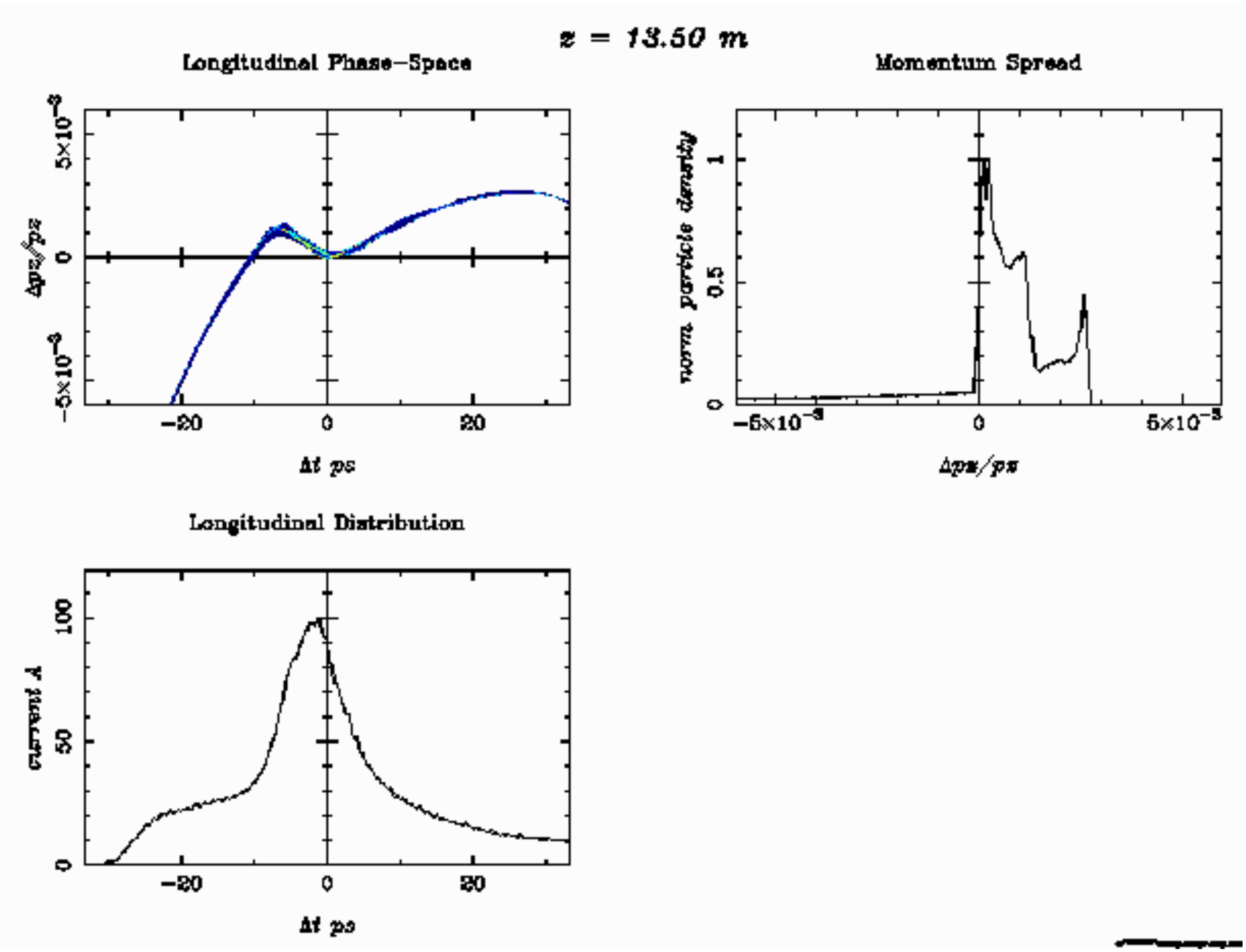


Bunch Length
σz mm
z m
0
10
20
30
40
2
4
6
8
10
12

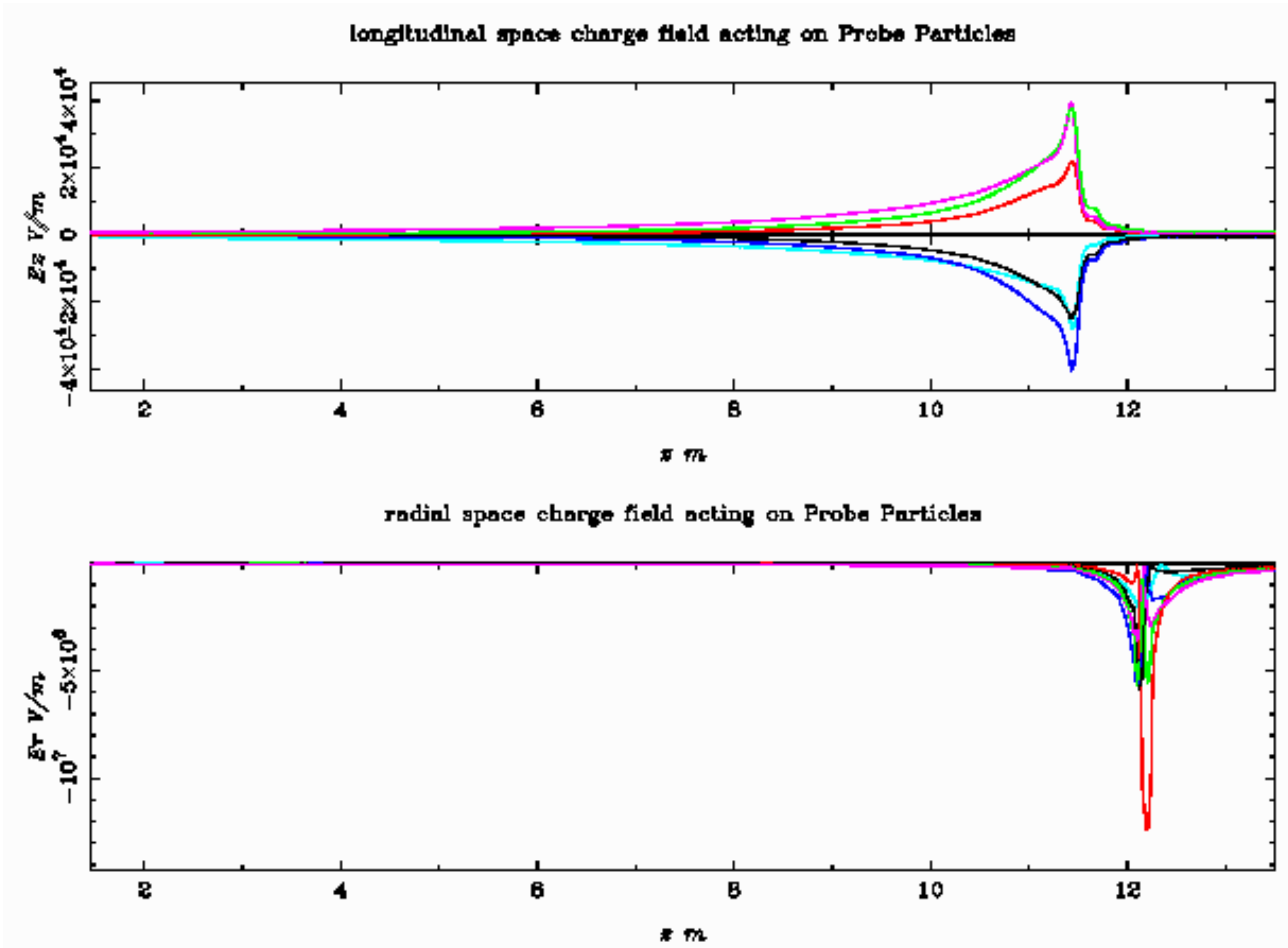

Beam Size
σx σy mm
z m
0
1
2
3
4
2
4
6
8
10
12


Transverse Emittance
ε π mrad mm
z m
0
10
20
2
4
6
8
10
12


Slice Emittance
ε π mrad mm
z mm
0
2
4
6
−5
0
5

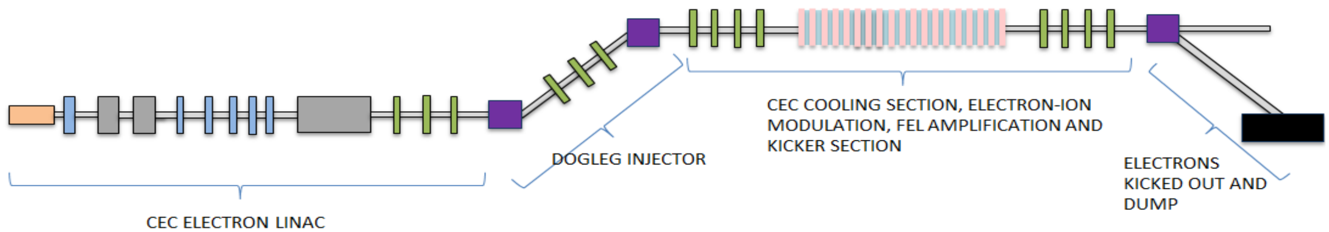


z = 13.50 m
Longitudinal Phase-Space
Δpz/pz
Δt ps
Momentum Spread
norm. particle density
Δpz/pz
Longitudinal Distribution
current A
Δt ps


longitudinal space charge field acting on Probe Particles
Ez V/m
z m
radial space charge field acting on Probe Particles
Er V/m
z m

YuanHui Wu (PARMELA + ELEGANT)

Electron Beam Optimization Cont.



❖ Beam requirement

Peak current 60A-100A , energy spread~0.2%, and emittance below 5 micro.

❖ Optimization Strategy

PART 1: Optimize for longitudinal emittance

➢ **Four decision variables**: gun phase, RF buncher #1 phase , RF buncher #2 phase and 704MHz cavity phase

PART 2: Optimize for transverse emittance

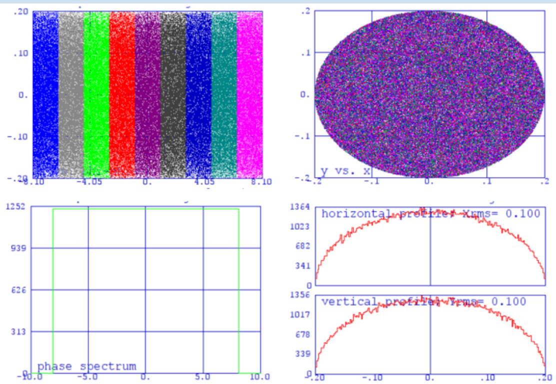
➢ **Six decision variables**: 6 magnets strength

➢ **Total of 13 decision variables** including beam size, bunch length and charge.

Parameter	Value
Species in RHIC	Au^{+79} ions, 40 GeV/u
Relativistic factor	42.96
Electron energy	~22 MeV
Charge per e-bunch	0.5-5 nC
Bunch length	100-400ps
Radius	2-5 mm

Electron and Ion beam parameters

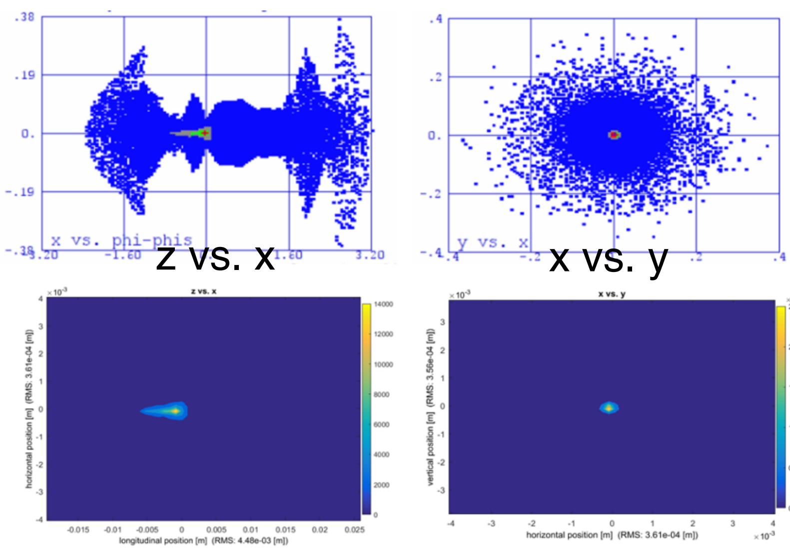
Optimized Electron Beam



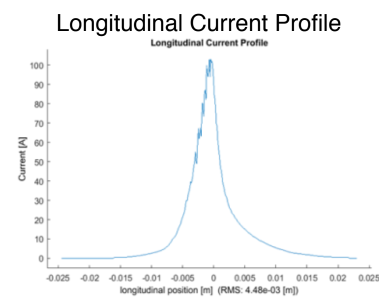
Initial electron beam distribution

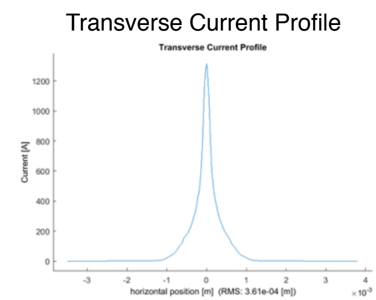
Bunch charge	2 nC
Initial Bunch radius at the cathode	2mm
RMS laser pulse length	400 ps
Maximum accelerating gradient of 112 MHz Gun	19 MV/m
Maximum accelerating gradient of the 500 MHz buncher	1.5 MV/m
Maximum accelerating gradient of the 704 MHz Cavity	37 MV/m

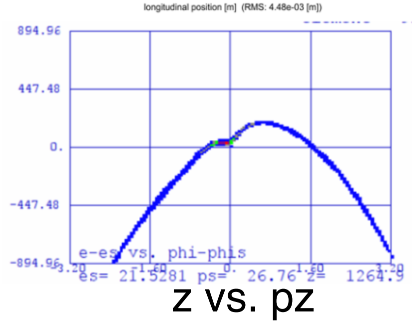
Main parameters used for beam and srf cavities

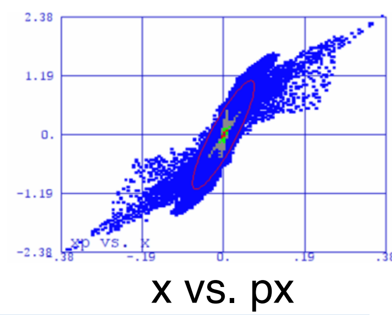


Final optimized electron beam

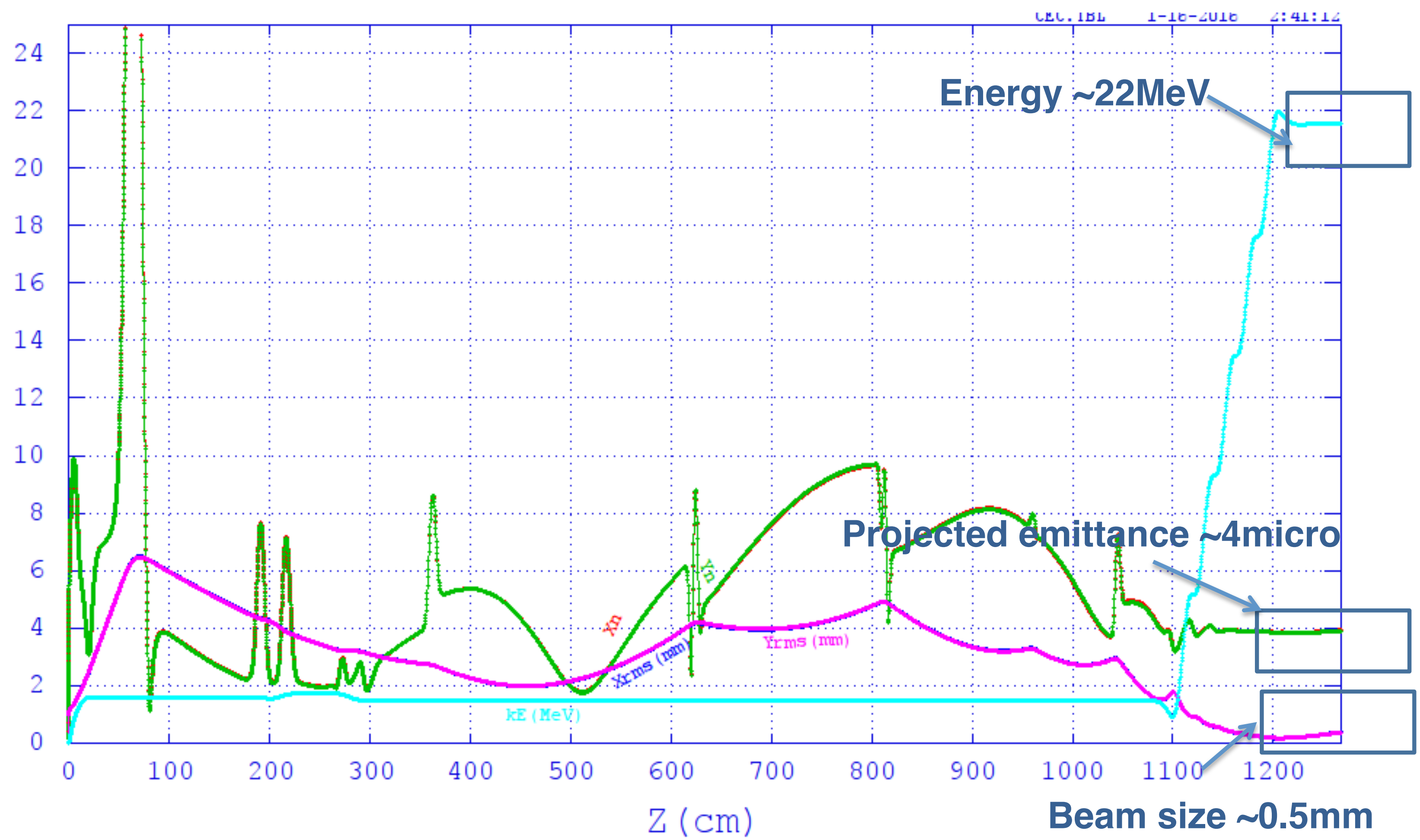




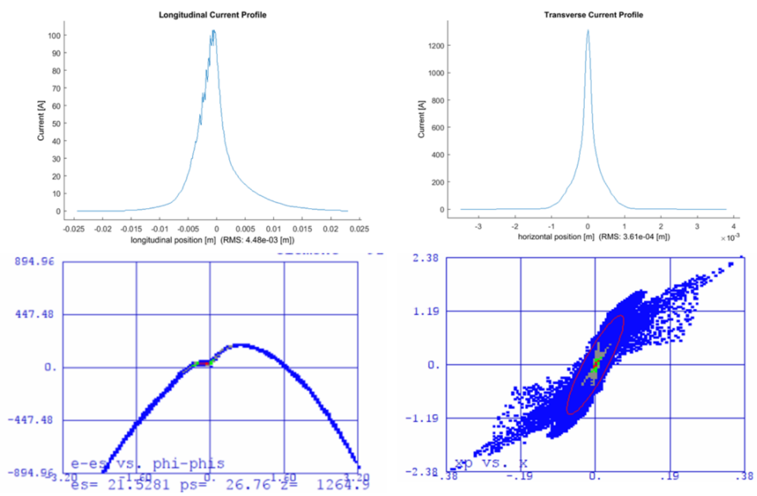




Optimized Electron Beam Cont.



Optimized Electron Beam Cont.



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

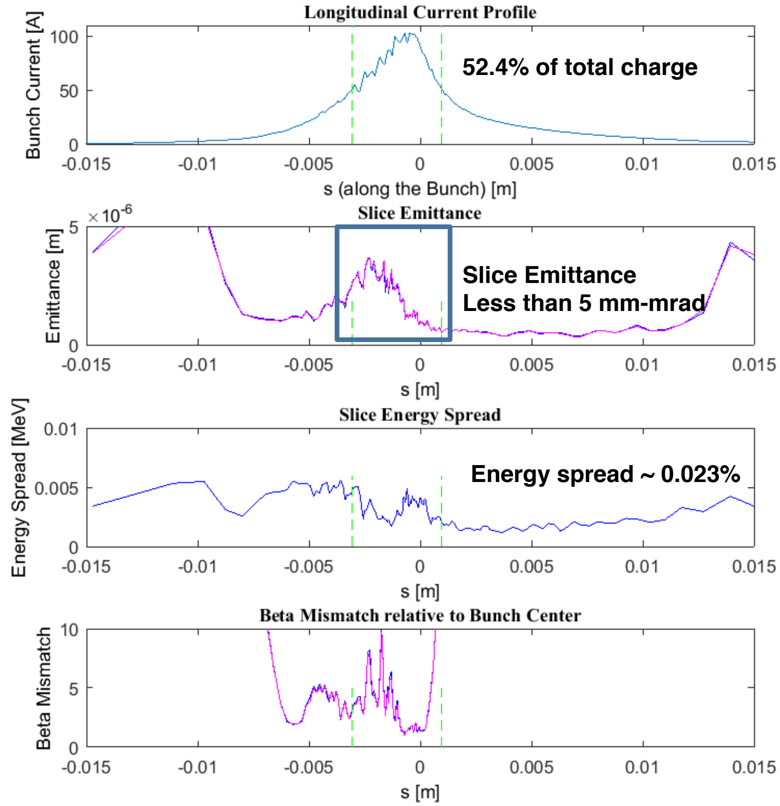
FWHM (distance between green bars): 4.03e+03 μ m (13.4 ps)
Charge within FWHM: 52.4 %
Projected Emittance: $\gamma\epsilon_x$ = 3.83e-06 m $\gamma\epsilon_y$ = 3.82e-06 m
Optics @ I_{peak}: α_x = -2.77 β_x = 0.986m α_y = -2.7 β_y = 0.955m

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
```

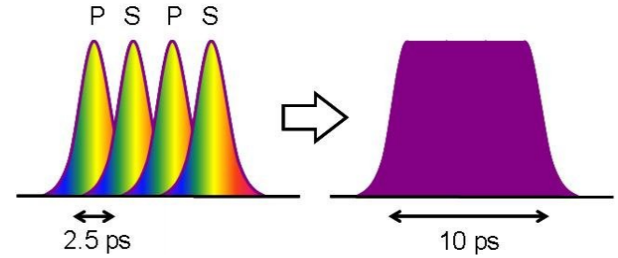


α_x	β_x	α_y	β_y
-1.94	1.44	-1.91	1.41

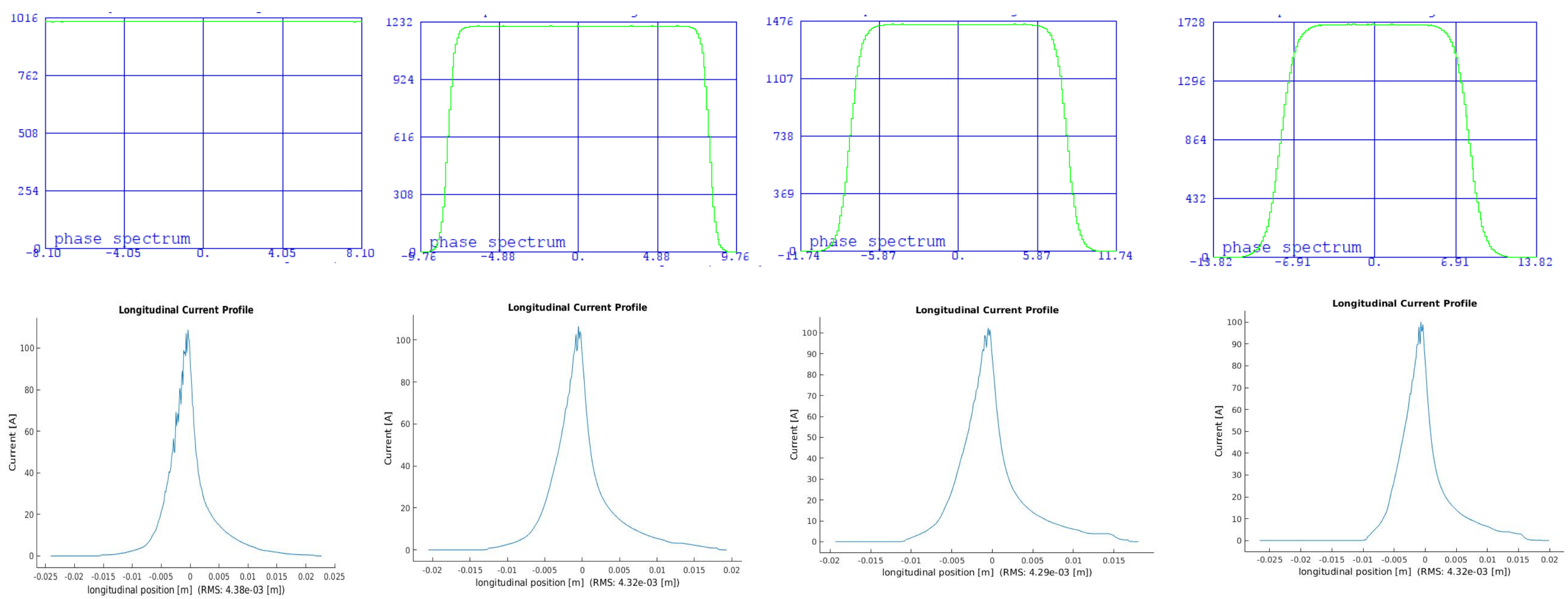
Projected emittance within FWHM $= x_{rms}^2 / \beta\gamma = 3.56$

Electron Beam with Different Rise Time

- Initial flat top electron beam is generated by pulse stacking technique
- Longitudinal rise time is determine by the laser pulse and caThode properties
- Gaussian laser pulse is about 100 to 200ps.

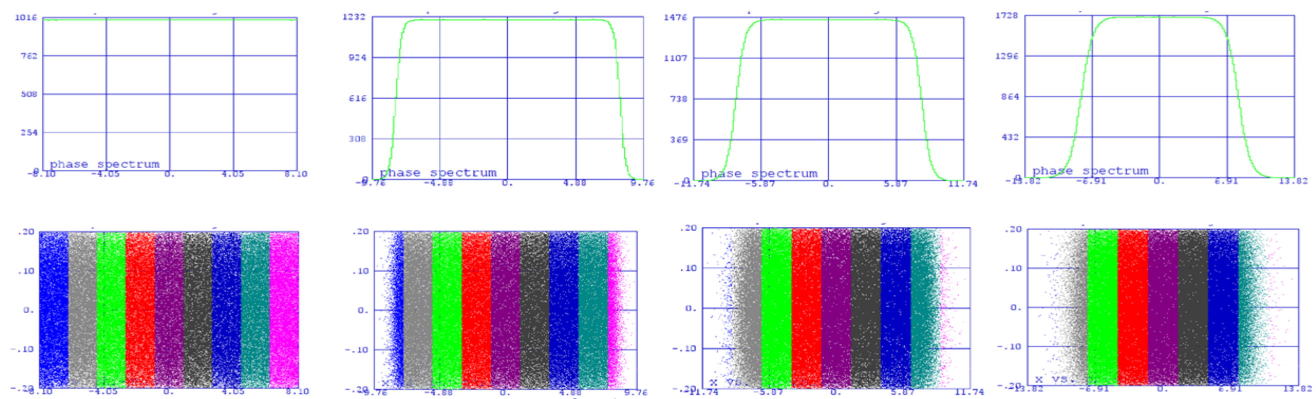


Principle of pulse stacking

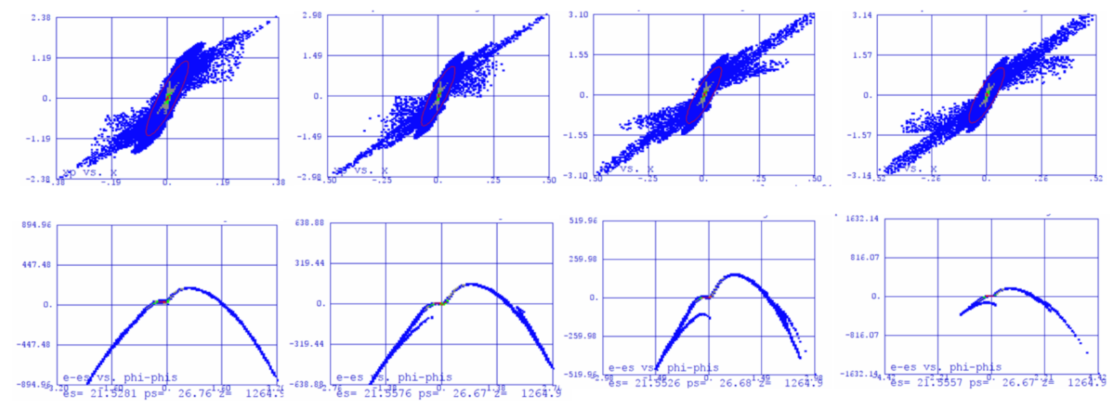


For the same optimized setting, initial electron beam with different rise time has similar final current profile

Electron Beam with Different Rise Time Cont.



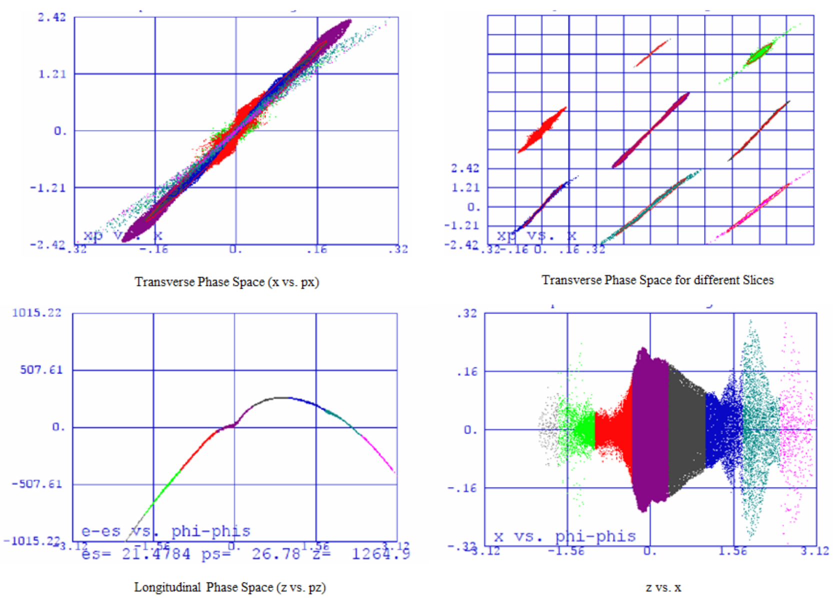
rt=0 ps rt=20 ps rt=0.40 ps rt=60 ps

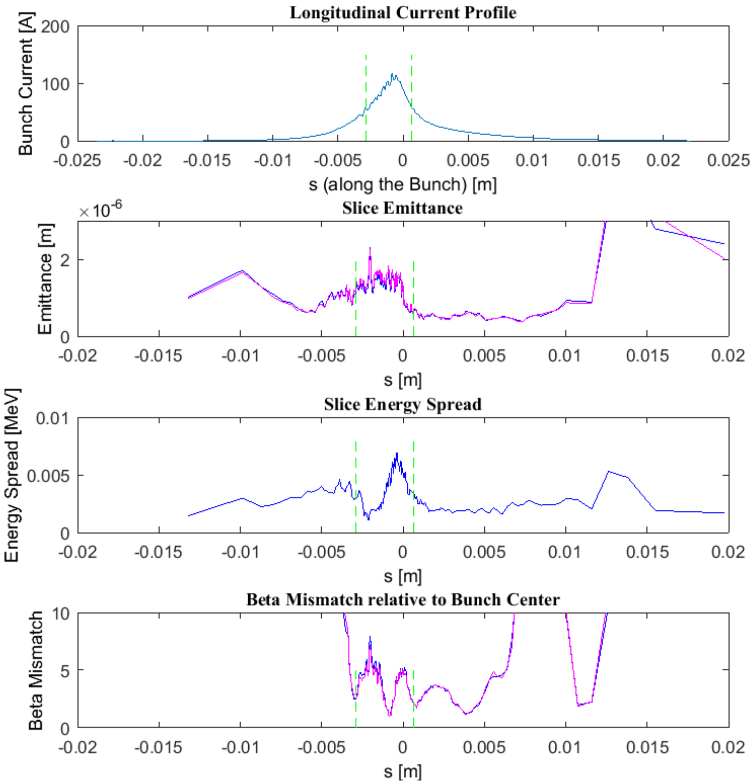


rt=0 ps rt=20 ps rt=0.40 ps rt=60 ps

Projected emittance due to different rise time are 3.83, 4.26, 4.77 and 5.32micro respectively.

Electron Beam with Lowest Emittance





Number of Particles: 200002 Charge: 2 nC
Position: 0 m Beam Energy: 21.478 MeV

FWHM (distance between green bars): 3.51e+03 μ m (11.7 ps)
Charge within FWHM: 49.8 %
Projected Emittance: $\gamma\epsilon_x$ = 2.68e-06 m $\gamma\epsilon_y$ = 2.68e-06 m
Optics @ I_{peak}: α_x = -38.8 β_x = 35.6m α_y = -38.1 β_y = 34.9m

RMS Values for all Particles:

```
x = 8.85e-04 m   x' = 9.62e-04
y = 8.86e-04 m   y' = 9.63e-04
s = 4.26e-03 m   δ  = 6.85e-03
```

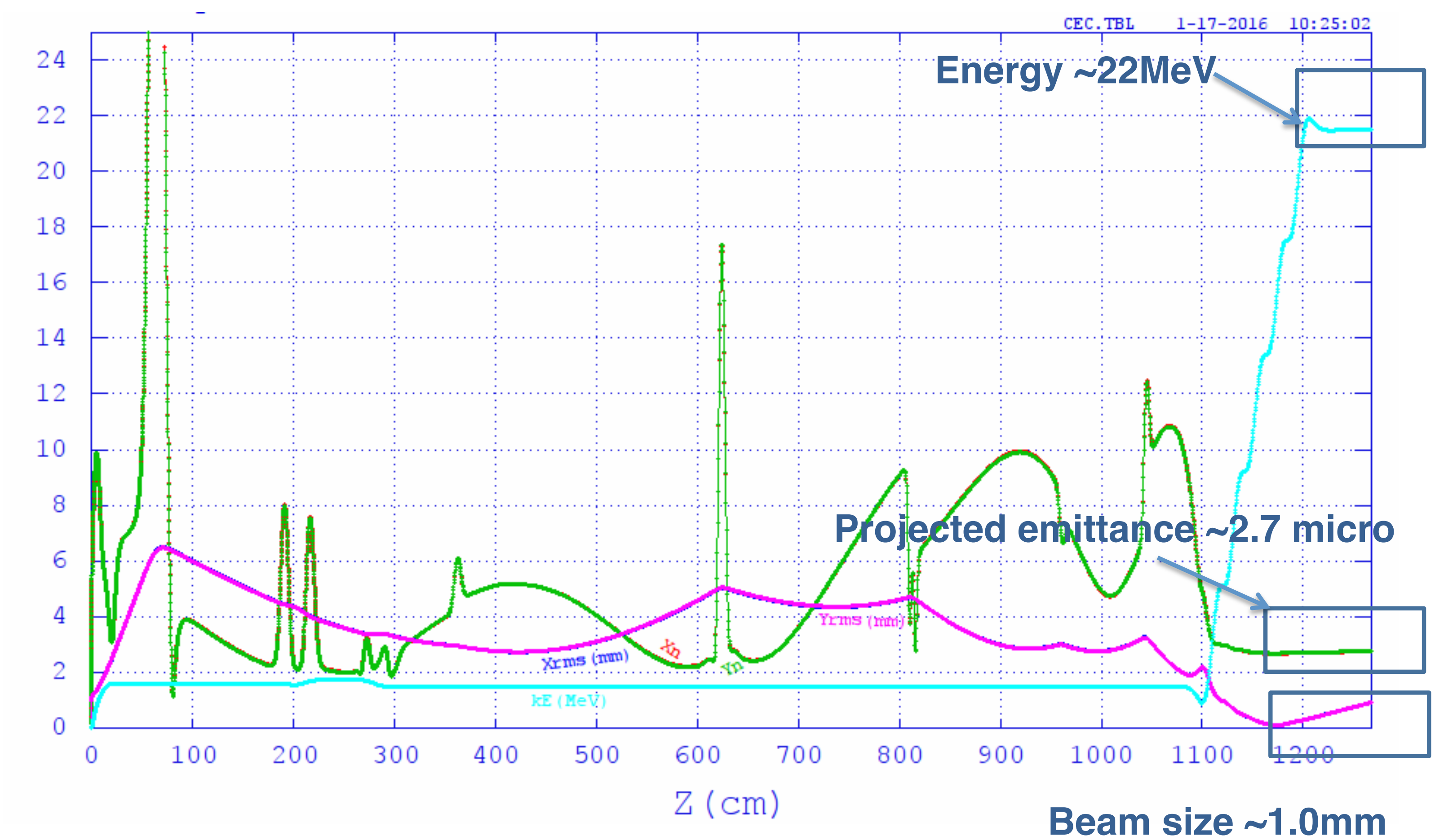
RMS Values within FWHM:

```
x = 1.04e-03 m   x' = 1.13e-03
y = 1.04e-03 m   y' = 1.13e-03
s = 9.17e-04 m   δ  = 1.31e-03
```

Projected emittance within FWHM $= x_{rms}^2/\beta\,\gamma = 1.3$ **mm−mrad**

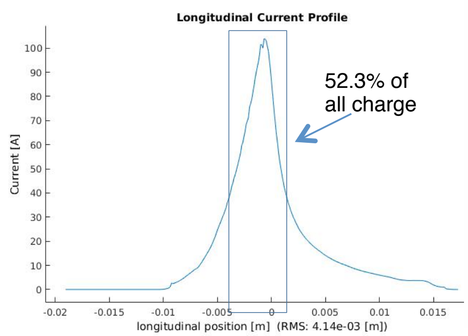
α_x	β_x	α_y	β_y
-13.3	12.3	-13.3	12.3

Electron Beam with Lowest Emittance Cont.

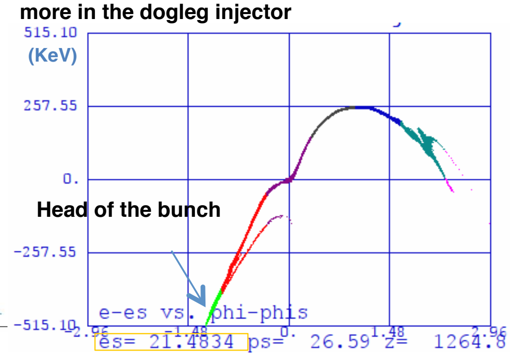


Electron Beam with Low Energy Spread

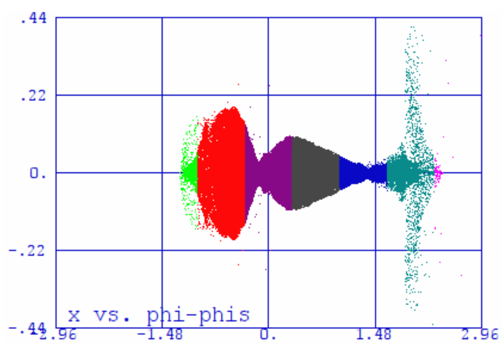
- Peak current :100 Ampere
- Projected Emittance: < 5 micro
- Energy deviation (2.4%), RMS energy spread (0.6%)

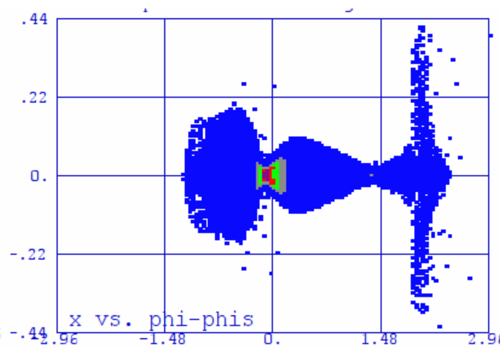


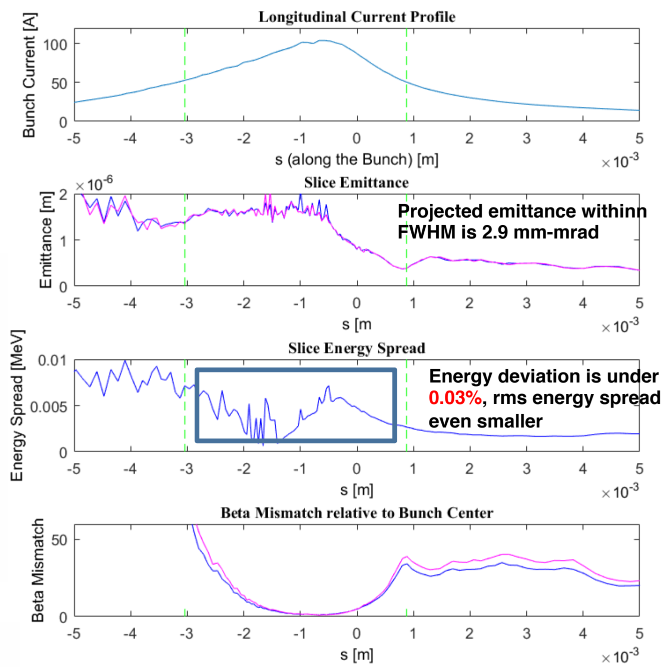
This negative chirp will compress electron beam more in the dogleg injector



Reference energy=21.5MeV







Number of Particles: 200002 Charge: 2 nC
Position: 0 m Beam Energy: 21.483 MeV

FWHM (distance between green bars): 3.92e+03 μ m (13.1 ps)
Charge within FWHM: 52.3 %
Projected Emittance: $\gamma\epsilon_x$ = 6.86e-06 m $\gamma\epsilon_y$ = 6.85e-06 m
Optics @ I_{peak}: α_x = -2.97 β_x = 1.33m α_y = -3.49 β_y = 1.51m

Twiss functions

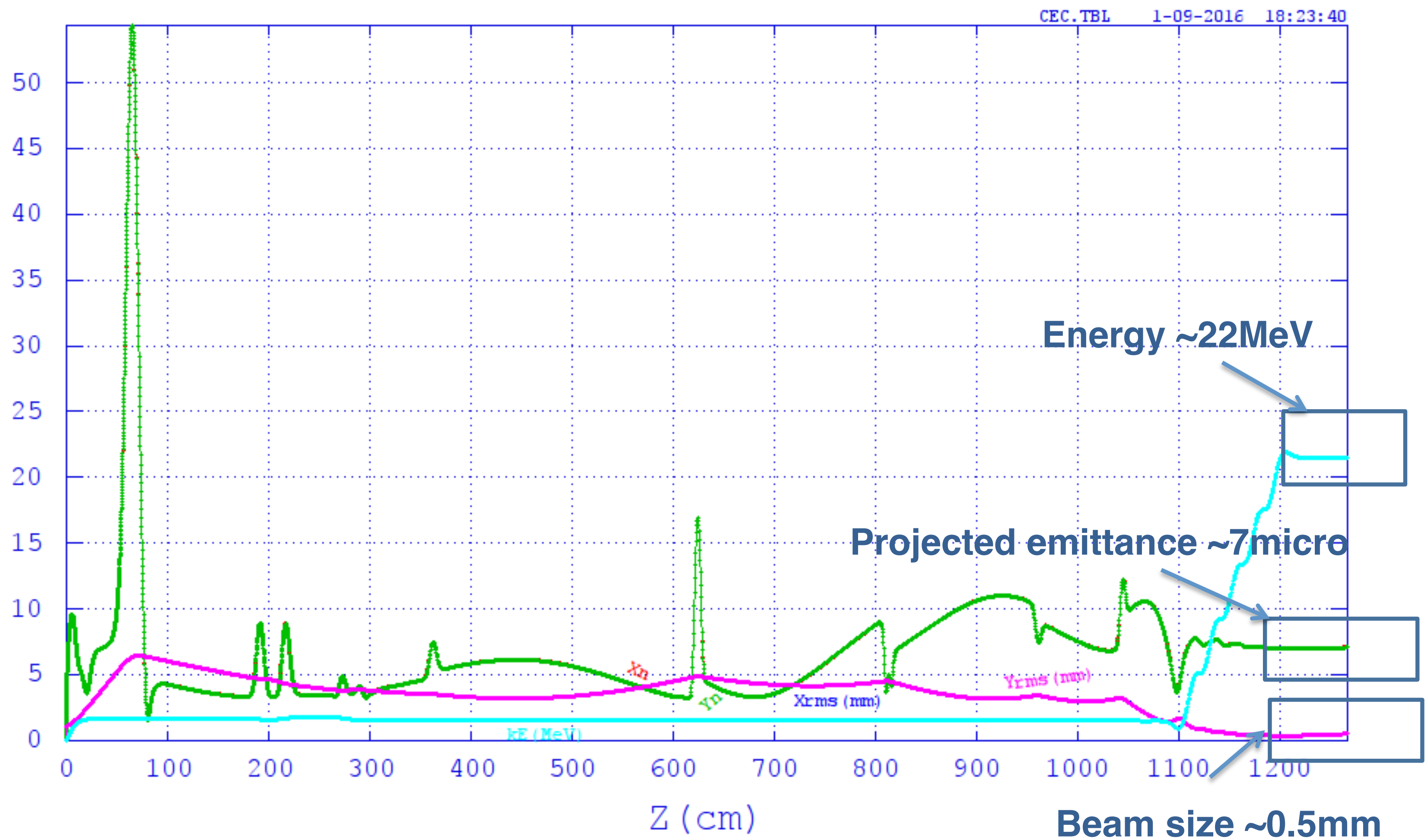
RMS Values for all Particles:

```
x = 4.84e-04 m   x' = 4.91e-04
y = 4.84e-04 m   y' = 4.90e-04
s = 4.14e-03 m   δ  = 6.24e-03
```

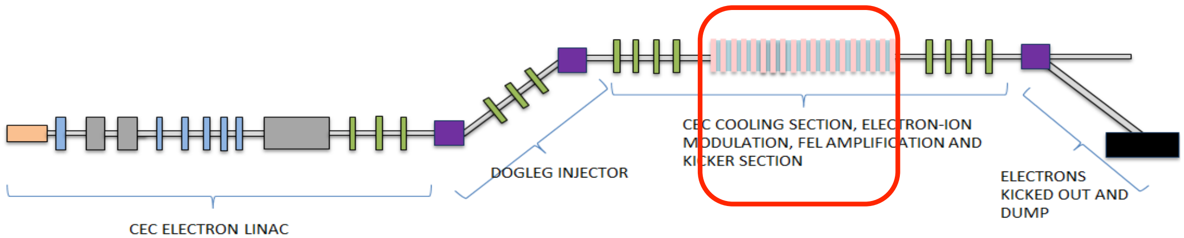
RMS Values within FWHM:

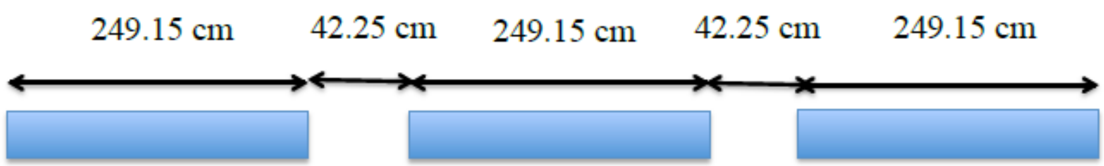
```
x = 3.03e-04 m   x' = 5.04e-04
y = 3.03e-04 m   y' = 5.03e-04
s = 1.02e-03 m   δ  = 1.49e-03
```

Electron Beam with Low Energy Spread Cont.



Lattice Matching Cont.





Periodic solution :

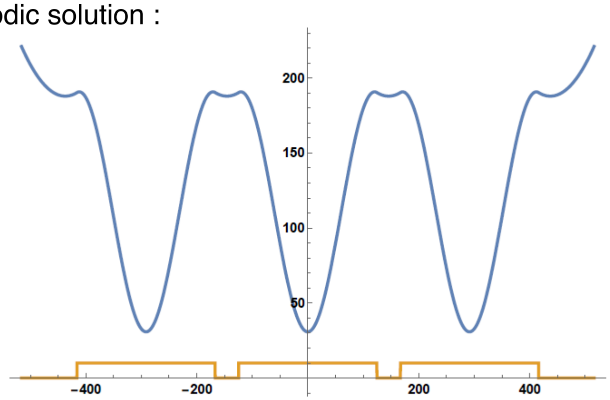


Fig. 1 Periodic solution for CeC FEL system

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

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

bilateral symmetry solution :

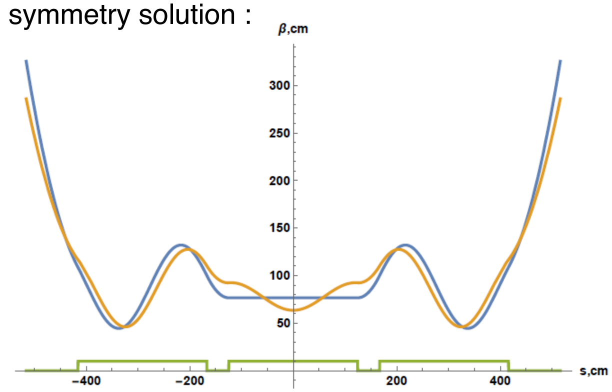
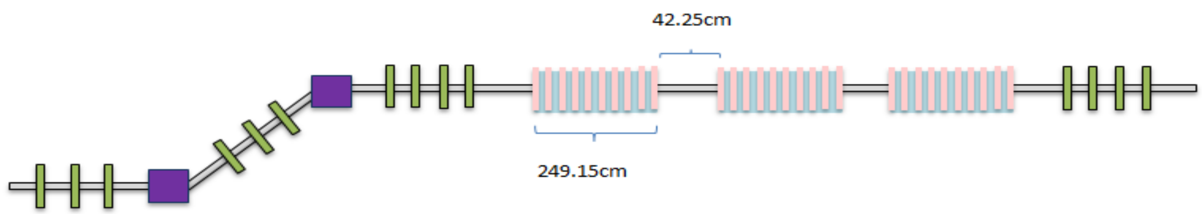


Fig. 2. Two solutions with bilateral symmetry: blue is for $\beta_c = \beta_o$ =76.7 cm – matched for the central wiggler; Yellow-grey for β_c =63.5 cm, which minimizes beta-beating in second wiggler.

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

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

Dogleg Injector Section (Lattice Matching)



The FEL section consists of 3 helical undulator segments that are separated from each other by about 40 cm long breaks, to provide space for phase shifters, diagnostics and vacuum components

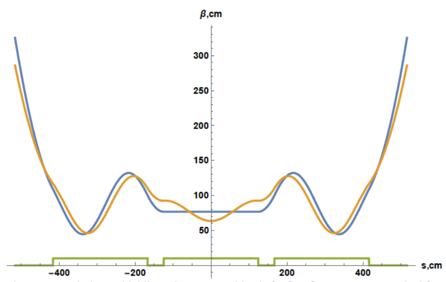
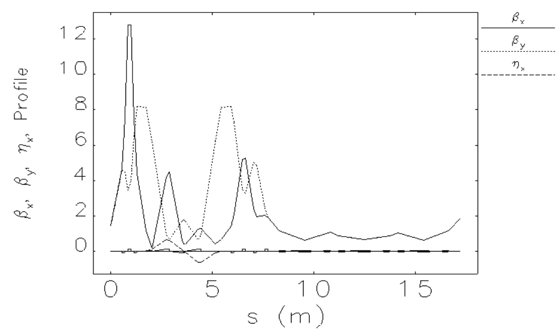
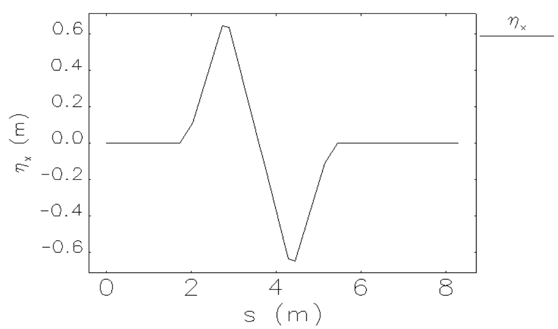
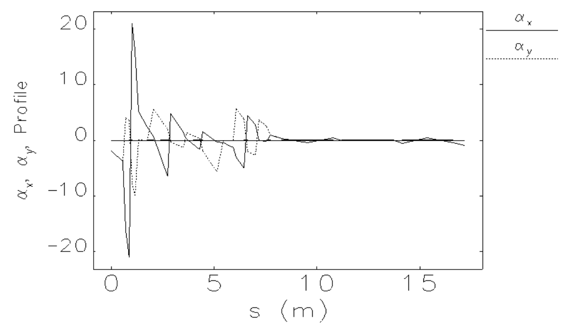


Fig. 2. Two solutions with bilateral symmetry: blue is for $\beta_c = \beta_o$ =76.7 cm – matched for the central wiggler; Yellow-grey for β_c =63.5 cm, which minimizes beta-beating in second wiggler.







Dogleg Injector Section (Achromatic Effect)

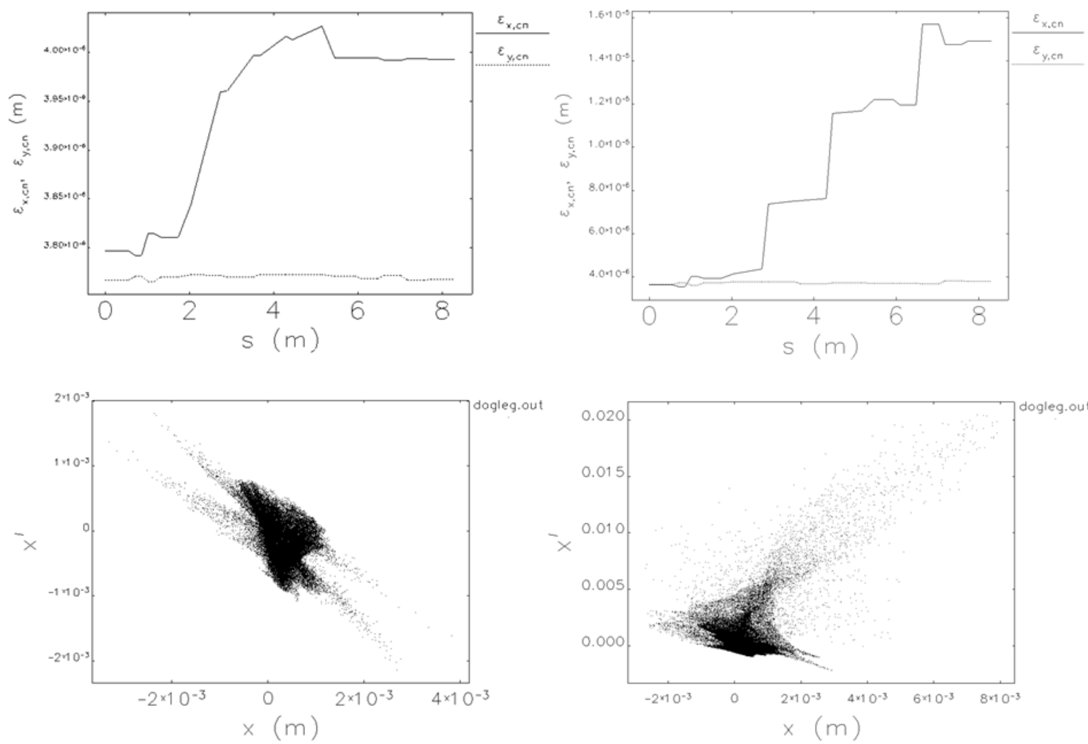
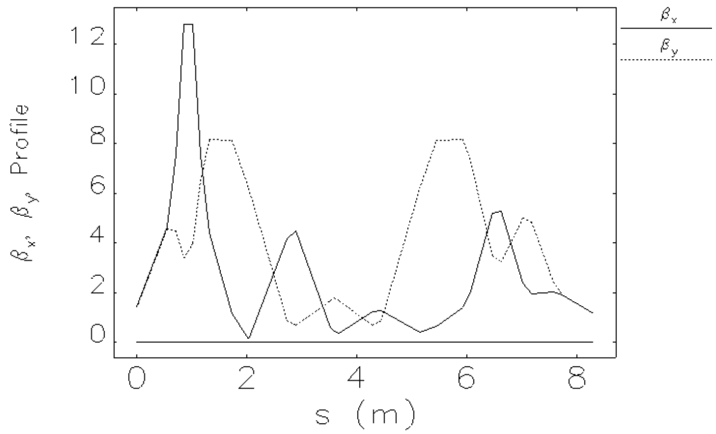
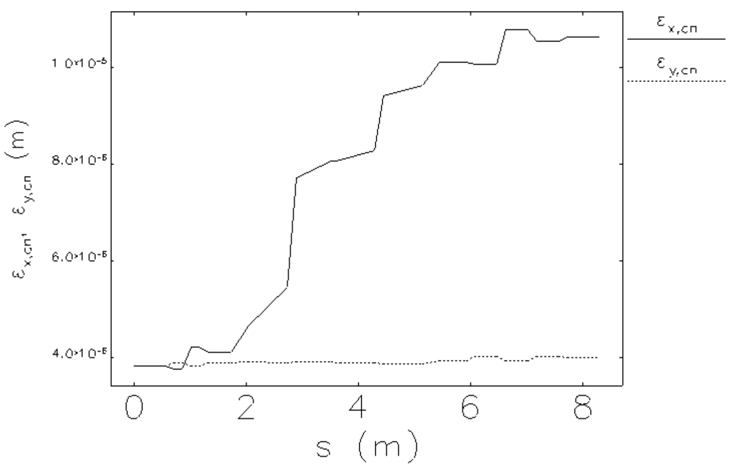


Figure 2.10 emittance evolutions (top) along horizontal bended dogleg achromatic for electron beam at initial average momentum error 0.25 % (left) and 5 % (right). The chromatic aberration effect distorts the initial matched beam phase space (bottom) and change the beam emittance.

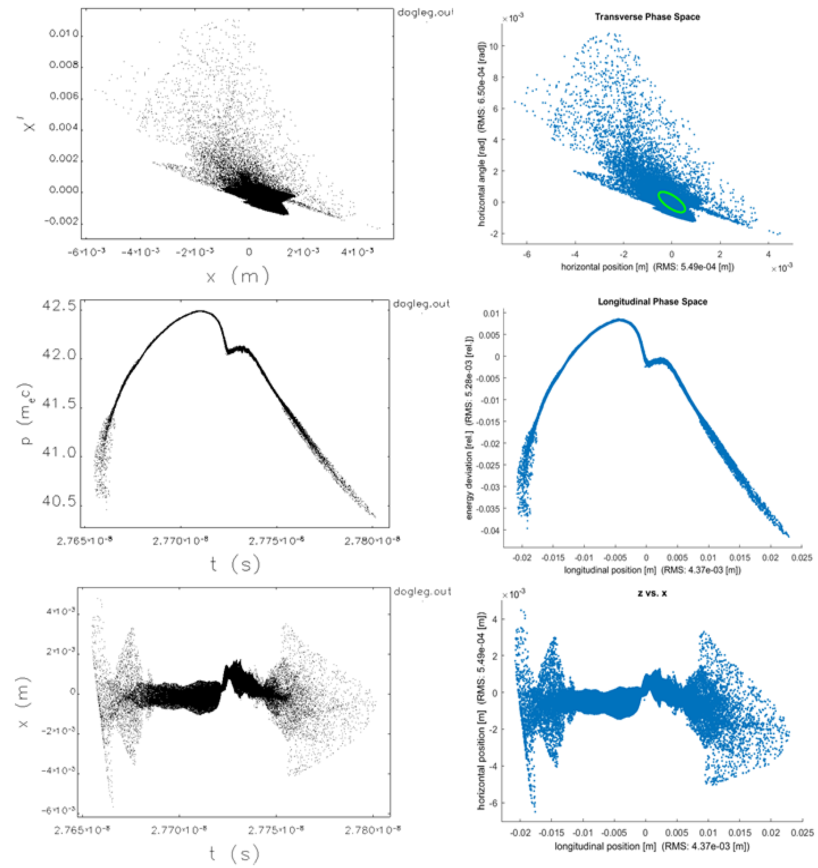
CSR Simulation for Optimized Electron Beam



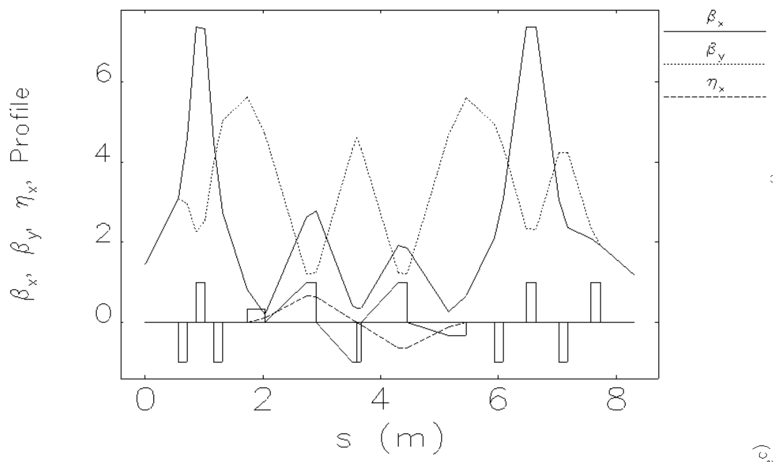


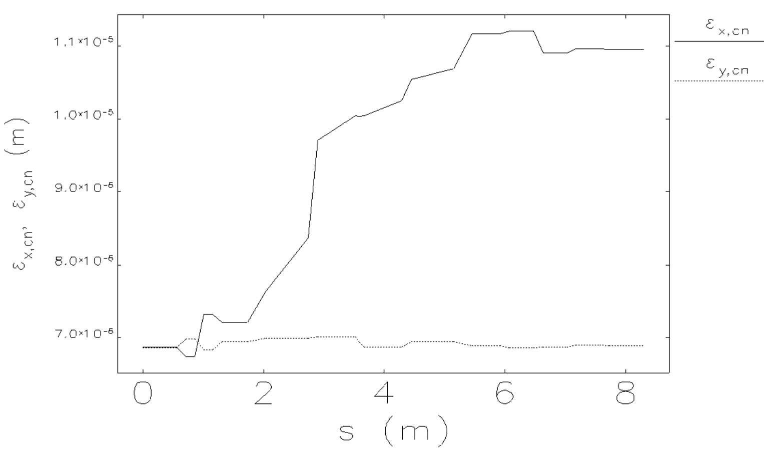
Elegant Results

CSRtrack Results

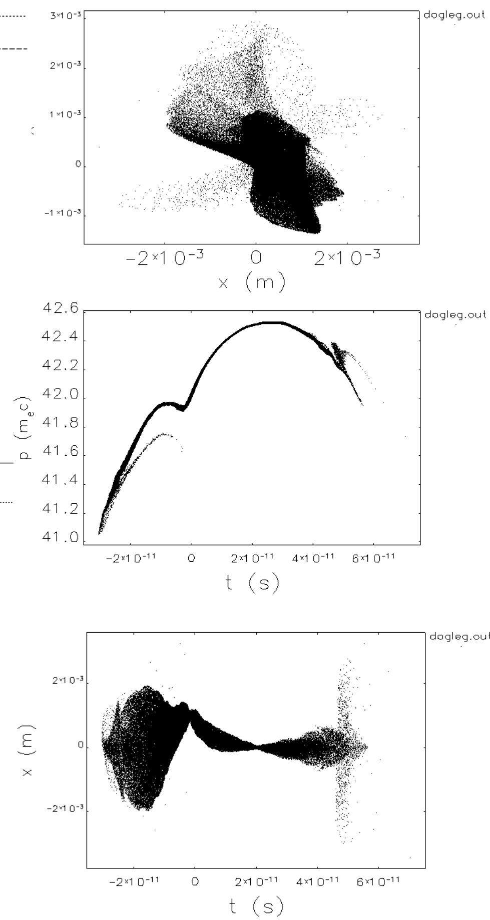


CSR Simulation for Electron Beam with Low Energy Spread

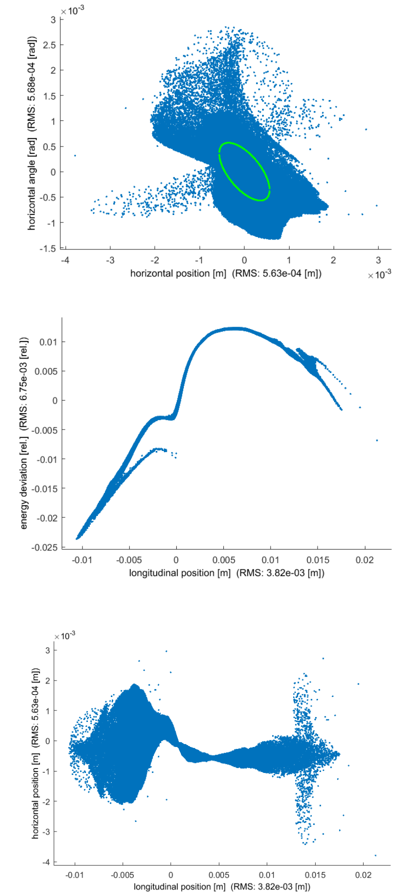




Elegant results



CSRtrack (1D) results



Many issues

- Multiple codes, they don't always agree (unless change some implicit initial conditions to make the results similar).
- Same effect in different code may use different model/formula thus some weird phenomena can't be 100% understood.
- I/O between codes might raise some more problems thus information might get lost.
- Different parameters were used thus resuls hard to compare

One code S2E => Good for potential on-line model development!

Impact? WARP?

- Both PIC, both can be parallelized, both have wakefields (T/L), CSR. Both were designed to deal with system with high SC (benchmarked with PARMELA/ASTRA).
- Impact: fortran code, not open source, can't do FEL simulation, input file purely composed of numbers (have strict formats), several people had experience with the code in our department.
- WARP: python code, open source, can (in principle) S2E, python input file while can recognize MAD-like lattice file, not much experience in our department.

Example: Impact input (chicane)

```
1 1
1.0e-12 200000 1
6 10000 1 0 2 0 1e-6
32 32 32 1 1 1 1.0e5
2 0 0 -1 6e-12
3.0e-5 2.24e-5 0.0  1.0 1.0 0.0 0.0
4.5e-5 1.5e-5 0.0  1.0 1.0 0.0 0.0
9.0e-4 7.43e-3 0.0  1.0 1.0 0.004 743.64
0.33333 3.8e8 0.511005e+06  -1.0 2856e6 0.0
0.0 1 1 -5 0 1 -0.1 /
1.14 1    1       4    0.0   0     0.5526  201 0.015 /
0.96    1    1       0    1.14   0.0  /
```