CeC Electron Linac Simulation

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CeC Simulation Meeting
21st January 2016

Outline

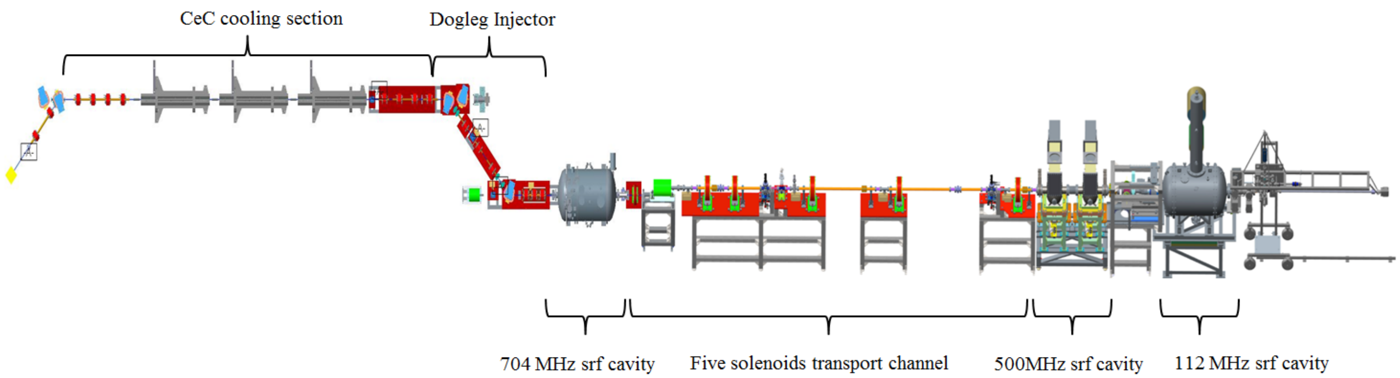
- Coherent Electron Cooling PoP
  - Overviews of CeC
  - Electron Beam Optimization

- Electron Beam Optimization
  - Space charge effect
  - Optimization Algorithms
  - Main Parameters and Optimization strategy
  - Simulation Results

- Lattice Matching for Dogleg Injector
  - Achromatic effect
  - CSR effect
  - Simulation Results

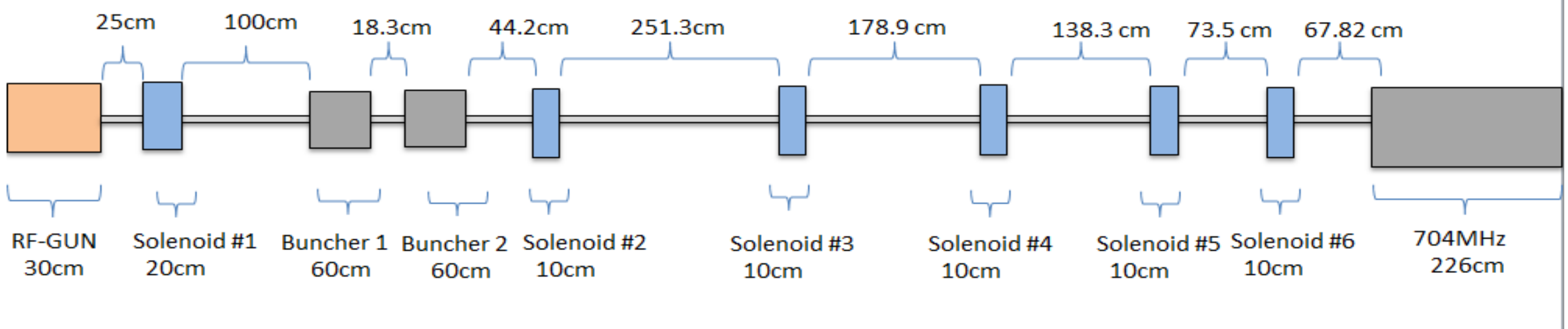
Overview of CeC

CeC PoP Electron Linac + FEL cooling section

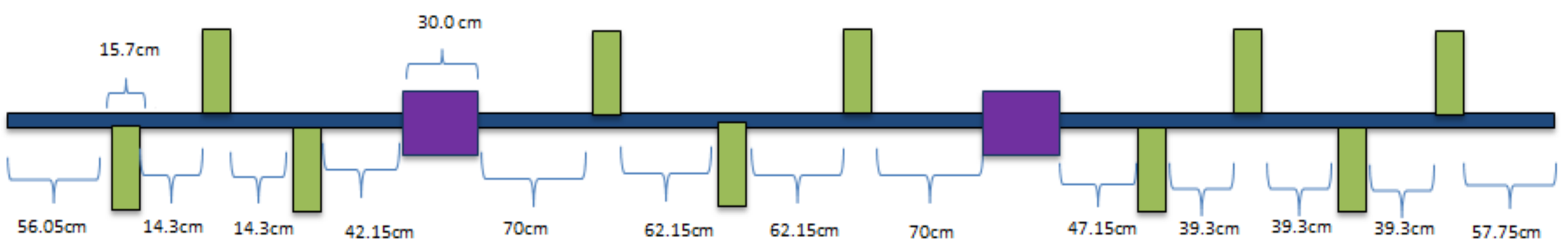


- 112MHz srf cavity gun
  - Provide initial beam acceleration from photocathode (~2MeV)
  - Always accelerate the electron on crest, sometimes can combine with two 500MHz to provide energy chirp for ballistic Bunching
- Two 500MHz buncher
  - Important to generate required peak current for maximum FEL gain
  - Adjust both phases to avoid over compression
- 704 MHz srf cavity
  - Provide velocity matching with ion beam, expected acceleration gain ~20MeV
  - Its phase should adjust to reduce the energy spread but not reduce its accelerating capacity too much,
- Solenoid focusing channel
  - Beam size control, reduce transverse emittance
  - Emittance compensation
- Dogleg Injector
  - Lattice matching
  - Chromatic effect
  - CSR effect

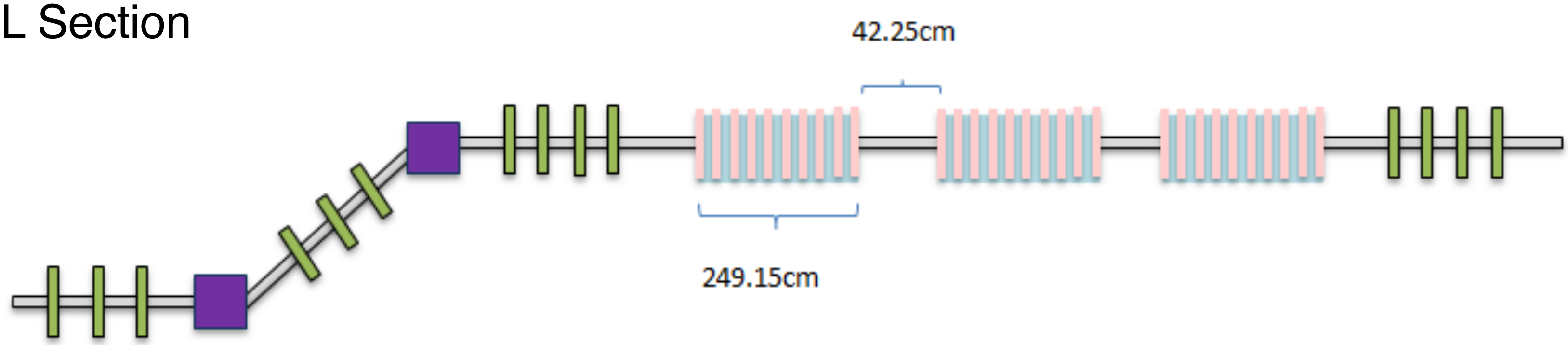
Electron Linac Section



Dogleg Injector Section

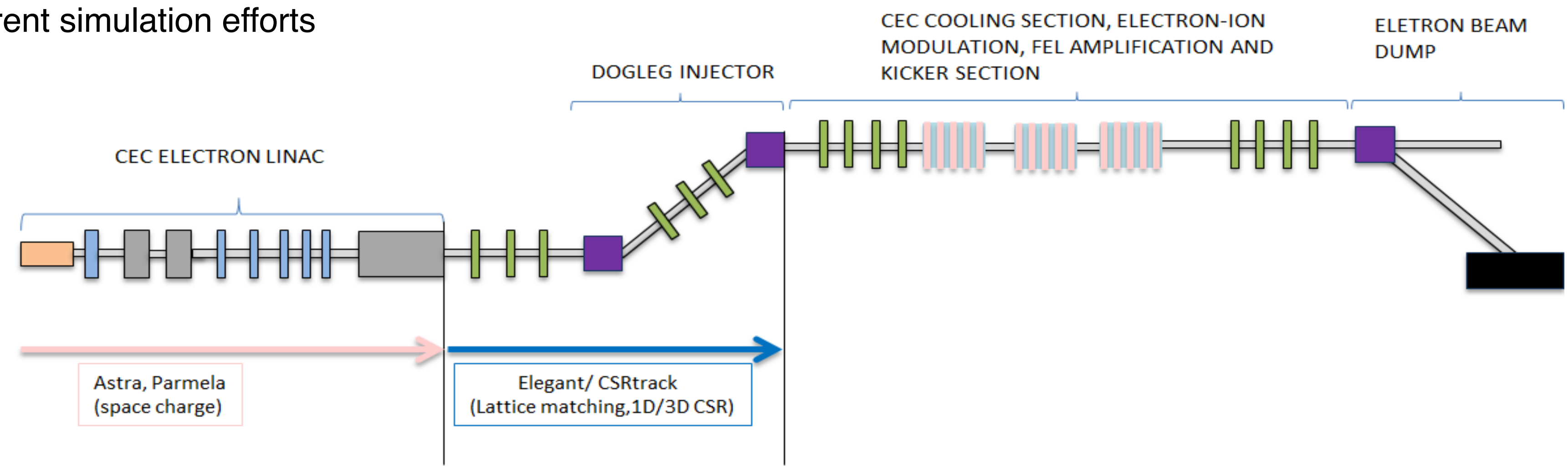


FEL Section



Overview of CeC Cont.

Current simulation efforts



- Parmela and Astra used for Space charge calculation
- Elegant and CSRtrack used to calculate 1D/3D CSR

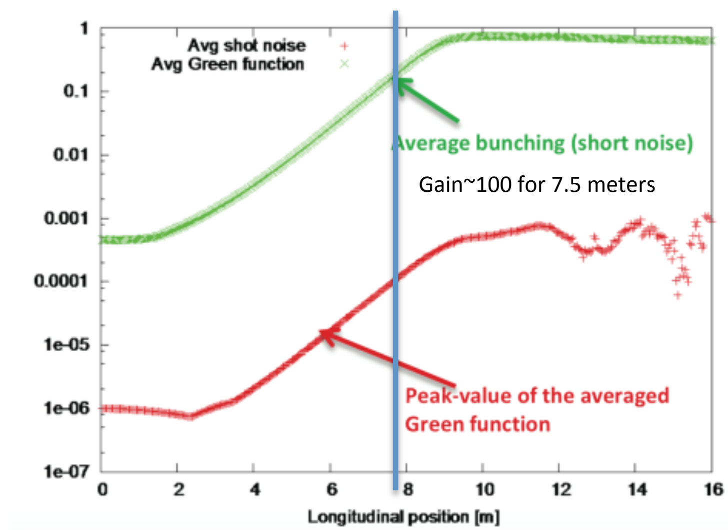
Why to optimize Electron Beam

The basic parameters used to describe the FEL process include, for the electron beam, electron energy E, normalized emittance ε_n , peak current I_{pk} , and relative rms energy spread $\sigma E/E$, and for the Undulator type, period λ_u , gap g, peak field B, and average beta-function $<\beta_{x/y}>$.

CeC PoP electron beam requirements, slice parameters used in simulation

TABLE I: Parameters for FEL simulation

Parameters / FEL type	Infrared PoP CeC	Visible eRHIC CeC	VUV LHC CeC	Hard X-rays LCLS
Beam energy (MeV)	21.8	136	3812.3	13643.7
Beam current (peak, A)	100	10	30	3400
Normalized emittance (μm rad)	5	1	1	1.2
Momentum spread (σ_p/p)	1×10^{-3}	1.5×10^{-5}	2.5×10^{-5}	1.05×10^{-4}
Undulator period (cm)	4	3	10	3
Undulator strength, a_w	0.4	1	10	2.4756
Radiation wavelength	12.7 μm	423.5 nm	90.7 nm	0.15 nm
N_c	35.8	102	70.6	14.5[a]



Radiation wave length $\lambda_r = \lambda_w / 2\gamma^2 \; (1+K_{rms}^2)$

Coherent length $L_c = 12.4\ \mu m * 200\ \text{periods}/c = 8.67\text{ps}$

@ Yichao

- Yichao Jing , Vladimir N. Litvinenko, Yue Hao , and Gang Wang, Model Independent Description of amplification and saturation using Green's Function

Why to optimize Electron Beam Cont.

Many papers have published from CeC group to analyze the impact of non-flattop electron distribution to CeC cooling

❖ G. Wang and V. N. Litvinenko, Influence of e-beam Parameters on Coherent Electron Cooling, these proceedings.
❖ Y. Hao , and V.N. Litvinenko, Simulation Study of Electron Response Amplification in Coherent Electron Cooling

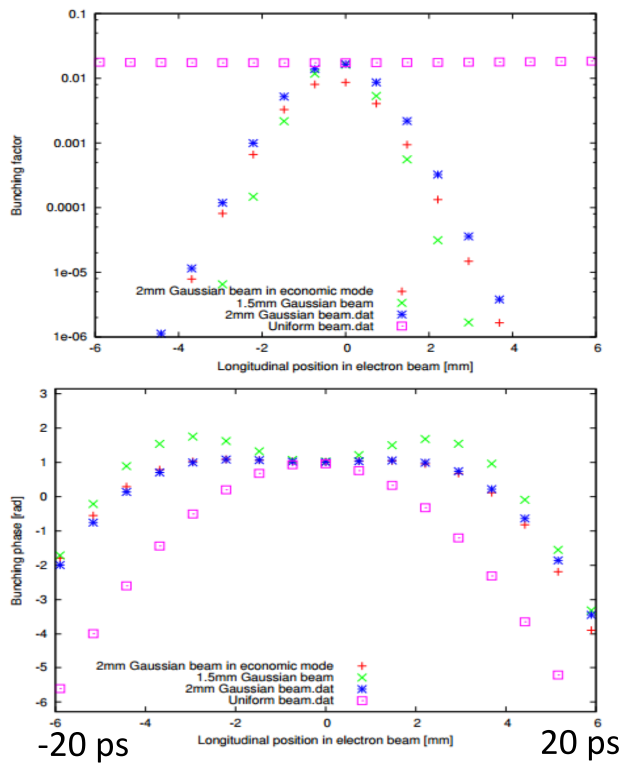
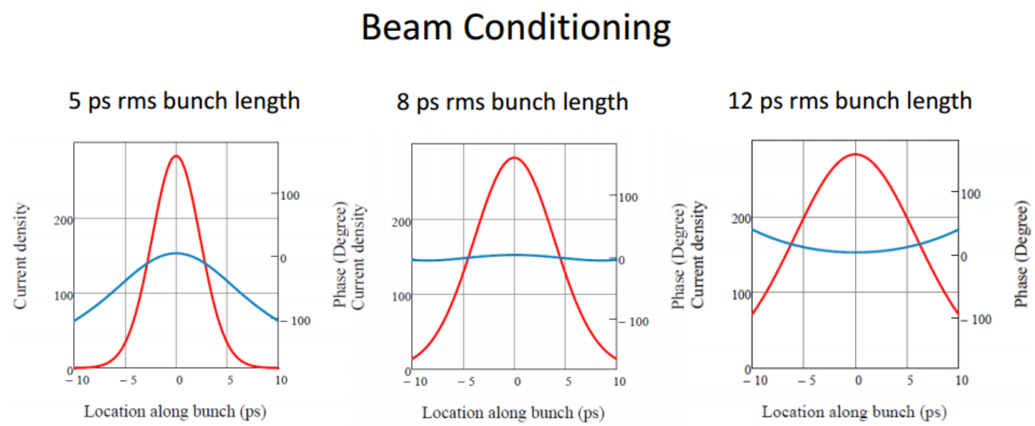


Figure 4: The output bunch factor (top) and phase (bottom) that the ion encounters at the exit. The bunch length is rms value.

@Yue

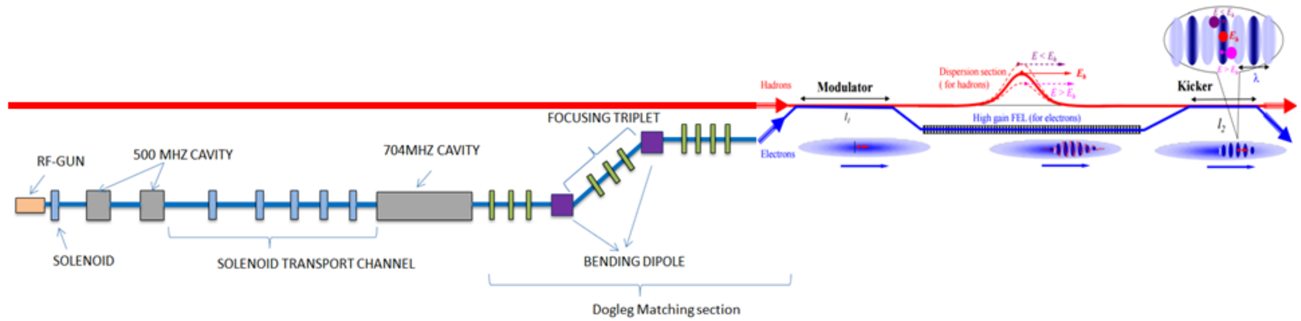


- With the same peak current density, there is an optimum bunch length to minimize phase variation of the wave packet with respect to ions located at different portion of the electron bunch.
- For the specific parameters that we consider, the optimum bunch length is around 8 ps, which reduce the phase variation to the level of 5 degree .

Optimum electron beam: both cosine energy variation and Gaussian current density distribution

@Gang

Electron Linear Accelerator Simulation



- Start to end electron beam dynamics simulation from photocathode to beam dump

1. Each EM device is modeled with real geometry with measured electric and magnetic field
2. Developed optimization techniques to estimate the performances and limit of the LINAC
3. Lattice matching design (Dogleg and FEL section)

- Collective effects that can leads to emittance growth

1. Space Charge effect (PARMELA code)
2. Synchrotron Radiation effect (ELEGANT and CSRtrack code)

- Demonstrate required electron beam can be generated using simulation

1. peak electron current (60A-100A), Emittance < 5 micro, Energy spread~0.2% [4]
2. Flat top longitudinal distribution [2][3]

Space Charge Calculation (PARMELA)

Phase and Radial Motion in Electron Linear Accelerators (PARMELA)

- It is a versatile multi-particle code that transforms the beam, represented by a collection of particles, through a user-specified linac and/or transport system. It includes options for 2-D and 3-D space-charge calculations.
- Developed in 1980s at LANL for FEL and accelerator design, have used in accelerator physics community and have benchmarked with experimental results
- Other codes: PARMELA, ASTRA, GPT, Impact-T

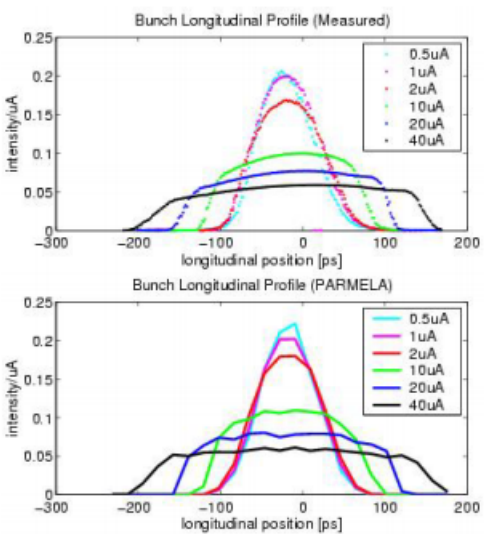


Figure 2. Longitudinal density profiles for a beam with 31 MHz repetition rate at the chopper slit. Wien filter is off. Top panel, measured. Bottom panel, simulations.

Jefferson Lab CEBAF photoinjector

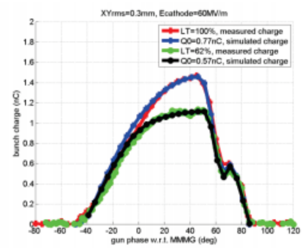


Figure 5: Measured and PARMELA phase scans (2011).

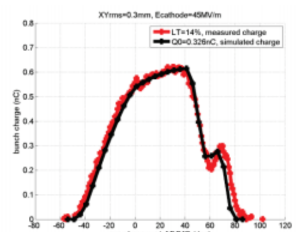


Figure 6: Measured and PARMELA phase scans (2012).

The Photoinjector Test facility at DESY

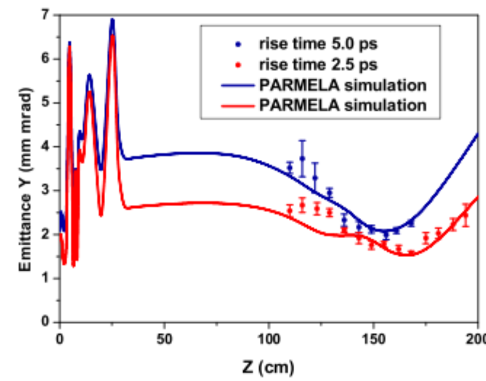


FIG. 15. (Color) Vertical emittance evolution for the beams with the longitudinal profiles of Fig. 14 and parameters of Table III.

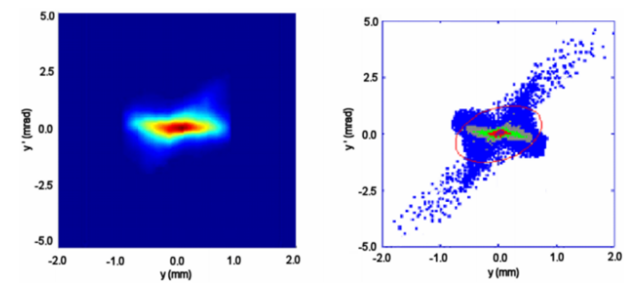


FIG. 21. (Color) On the left: measured transverse phase space in the vertical plane at $z = 1500$ mm from the cathode. On the right: PARMELA simulation obtained with the parameters of the measurement.

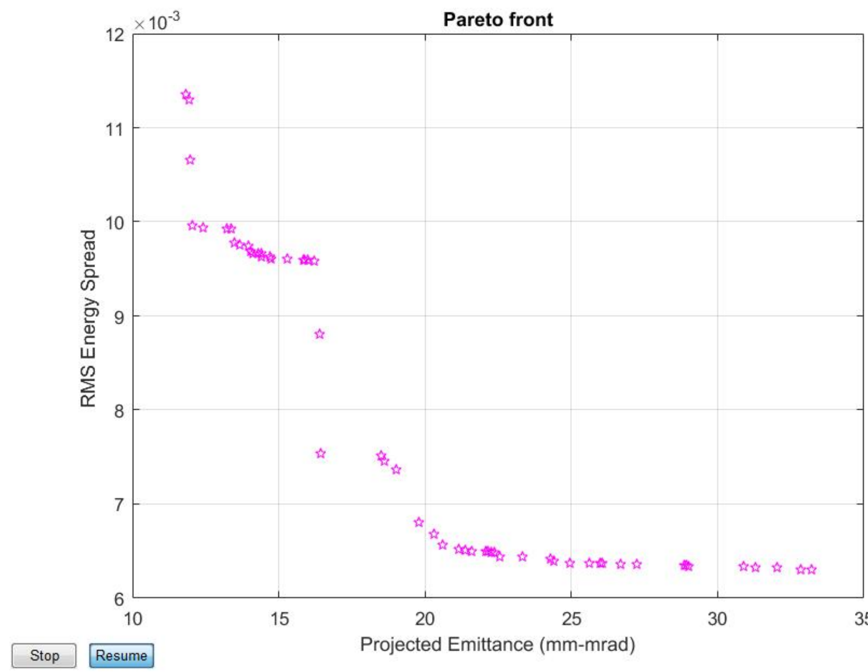
Phys. Rev. ST Accel. Beams 11, 032801 (2008)

Multiobjectives Genetic Algorithm (GA)

- Global optimization technique
- Algorithm can look for the solutions that offer the best trades-off which form a Pareto front.
- MOGA toolbox from MATLAB was used for this optimization, also available in inspyred Python package
- Start with small number of Macro-particle, much CPU times is spent on evaluate the objective function from PARMELA output
- Trade-off: not as efficient as traditional methods

Algorithm 2 Genetic Algorithm

1: Initialize population (first generation, random)
2: Evaluate objectives / constraints
3: Apply selection to create mating pool (subset)
4: Apply crossing operators to generate offspring
5: Mutate offspring
6: Evaluate objectives / constraints for the offspring
7: 'Good' solutions make it to the next generation
8: Repeat from step 3



Condor Algorithm

COnstrained, Non-linear, Direct, parallel Optimization algorithm using a trust Region method

❖ The algorithm will only find a local (maybe global) minimum of F(x).

❖ CONDOR algorithm is an extension of Michael Powell's unconstrained optimization by quadratic approximation method to a constrained problem.

❖ Parallel computing, much faster converge speed compare with GA and existing state of art optimizer

$$\mathcal{F}(x^*) = \min_x \mathcal{F}(x) \quad \text{Subject to: } \begin{cases} b_l \le x \le b_u, & b_l, b_u \in \Re^n \\ Ax \ge b, & A \in \Re^{m \times n}, b \in \Re^m \\ c_i(x) \ge 0, & i = 1, \ldots, l \end{cases}$$

1. Build an approximation (also called local model) of the objective function around the current point.

2. Find the minimum of this model and move the current point to this minimum. This is called an optimization step

3. Evaluate the objective function at this new point. Reconstruct the local model" of the objective function around the new point using the new evaluation. Go back to step 2.

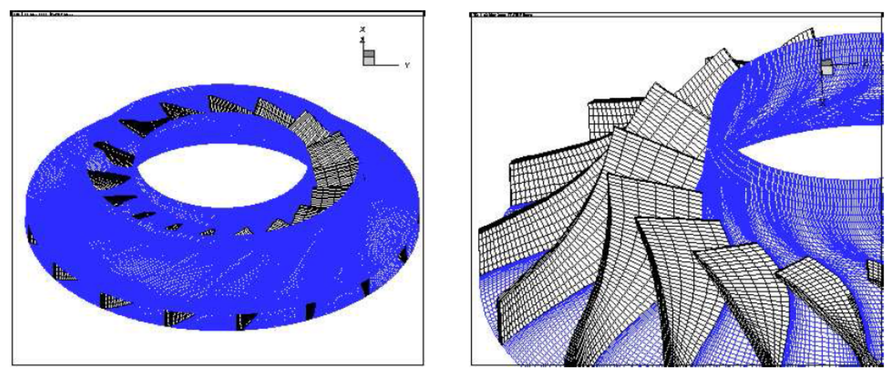


Figure 1.1: Illustration of the blades of the compressor

Courtesy of Jorg Kiwesch

Electron Beam Optimization

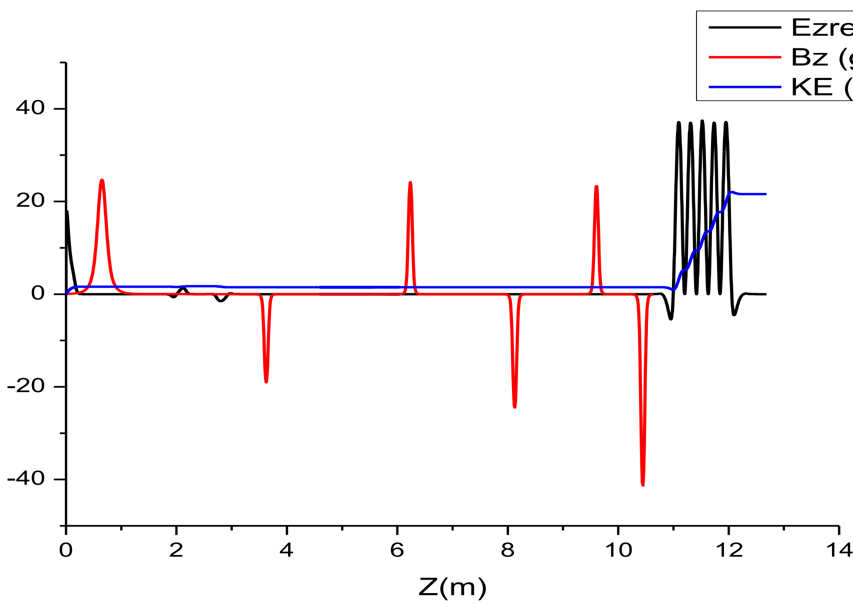
Main Parameters

Decision Variables

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

Fixed Variables

$(\gamma_{electron} \sim \gamma_{ion})$

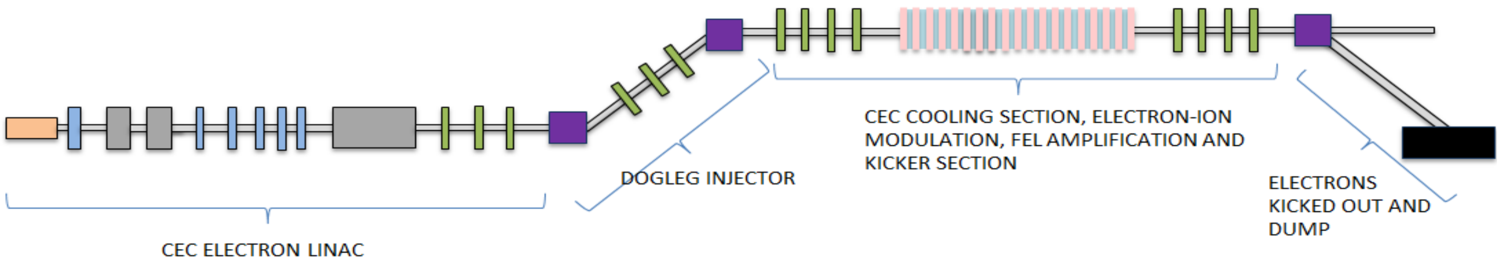


- Optimization algorithms: GA (global) and Condor (local)

- With initial 400ps and 2nC, to
Achieve 100 Ampere peak current,
The bunch length need to compress
To about 20 ps, this correspond to
Five degree difference of 704Mhz cavity phase, and the lowest energy spread can be generated without consider nonlinearity from space charge effect is 0.1%

Decision Variables: 6 solenoid strength (used to optimize transverse emittance)
Decision Variables: Phase of 112MHz, 500MHz , 704 MHz cavity (used to optimize longitudinal emittance)
Total of 13 variables

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

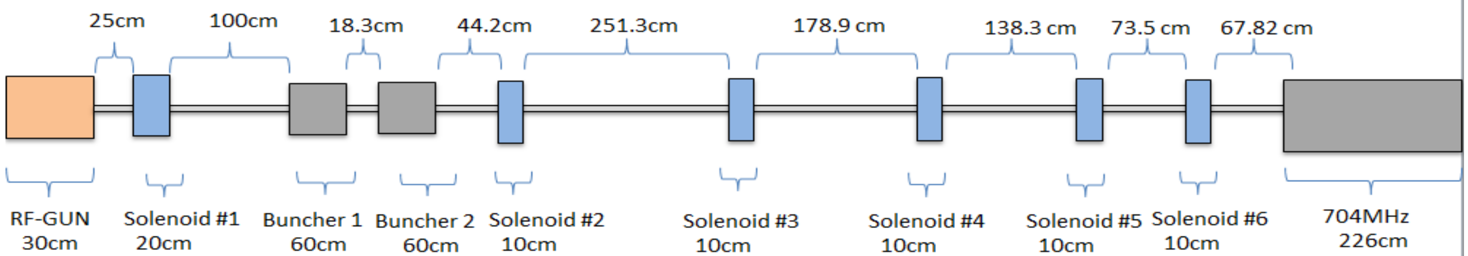
➢ **Six decision variables**: 6 magnets strength

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

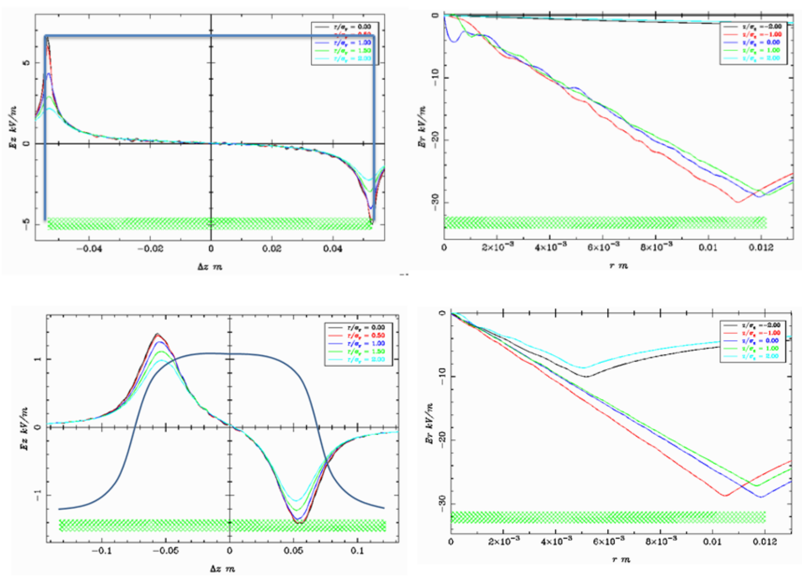
Parameter	Value
Species in RHIC	Au^{+79} ions, 40 GeV/u
Relativistic factor	42.96
Electron energy	~22 MeV
Charge per e-bunch	0.5-5 nC
Bunch length	100-400ps
Radius	2-5 mm

Electron and Ion beam parameters

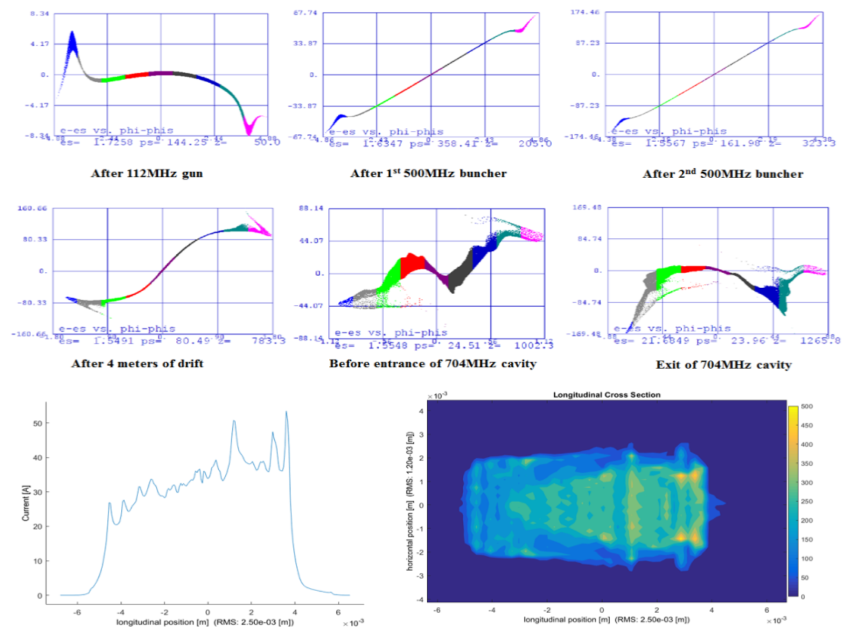
Space Charge Effect



- Space charge effect is dominated in the low energy region (before 704MHz cavity)
- Longitudinal space charge distorted the longitudinal phase space of electron beam. The longitudinal phase space generated after ballistic bunching is far from ideal, this limits us from generating flat-top longitudinal distribution

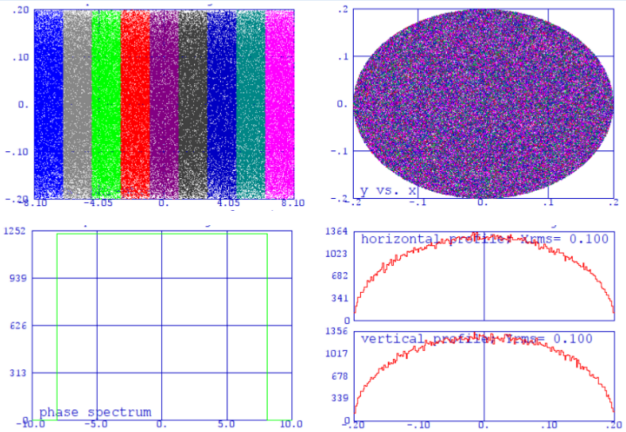


Longitudinal and transverse space charge calculated by Astra



Examples of longitudinal phase space evolution for 200ps with 1nC

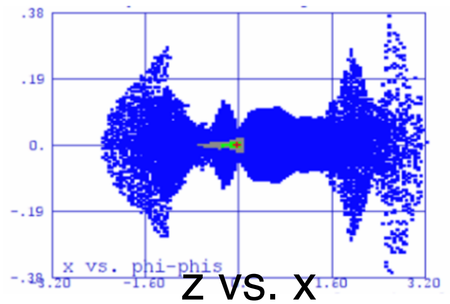
Optimized Electron Beam



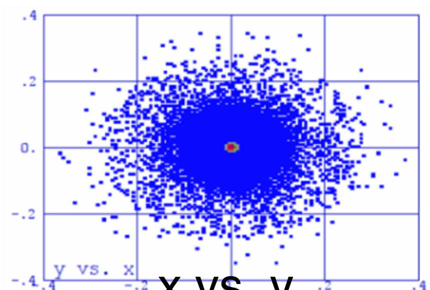
Initial electron beam distribution

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

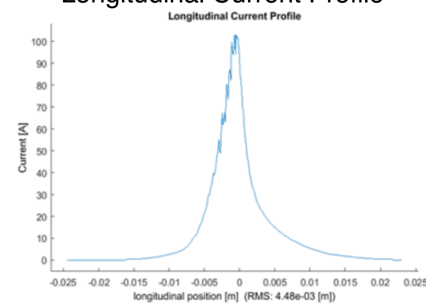


z vs. x

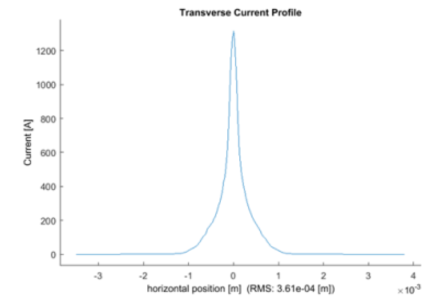


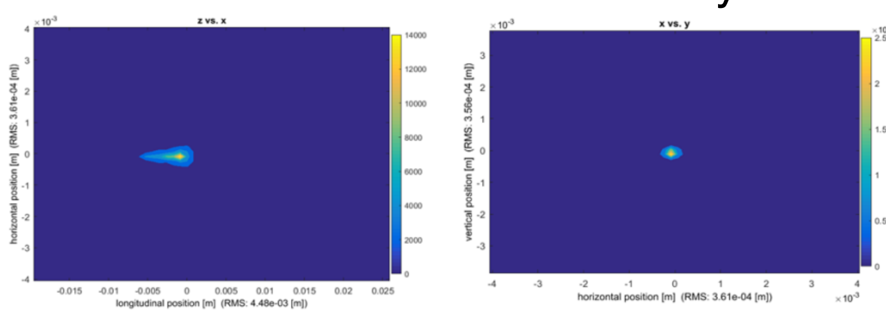
x vs. y

Longitudinal Current Profile

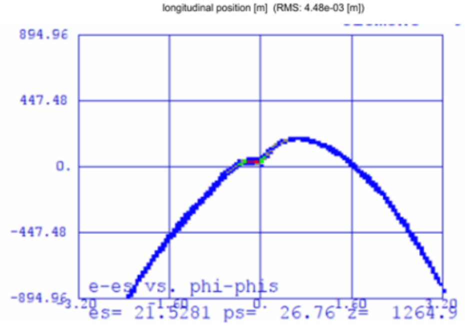


Transverse Current Profile

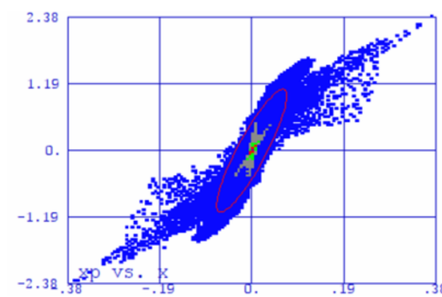




Final optimized electron beam

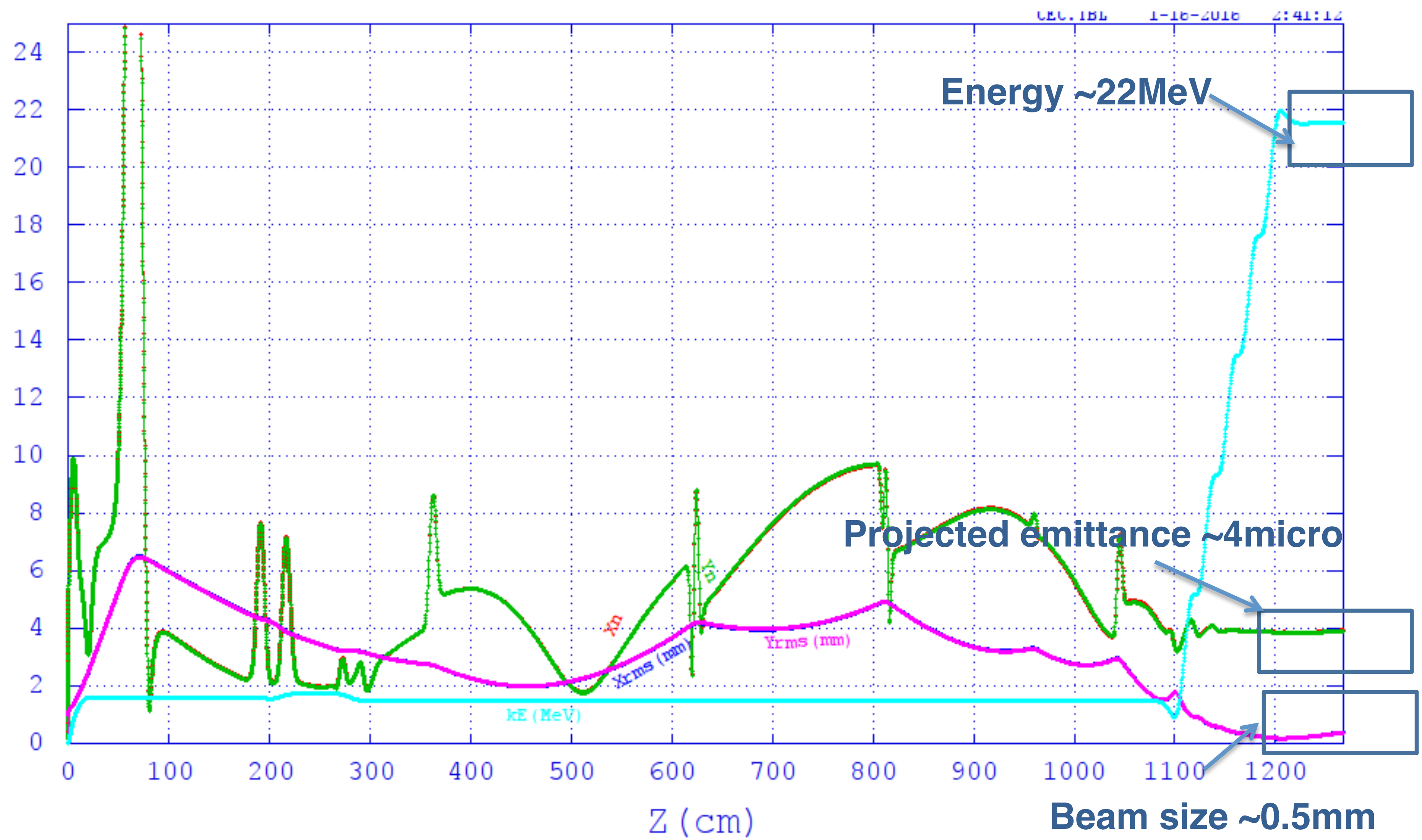


z vs. pz

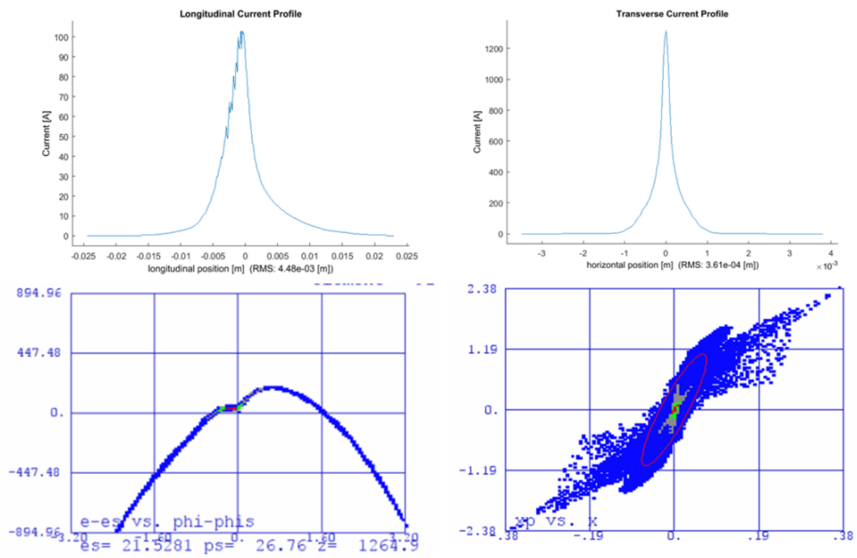


x vs. px

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

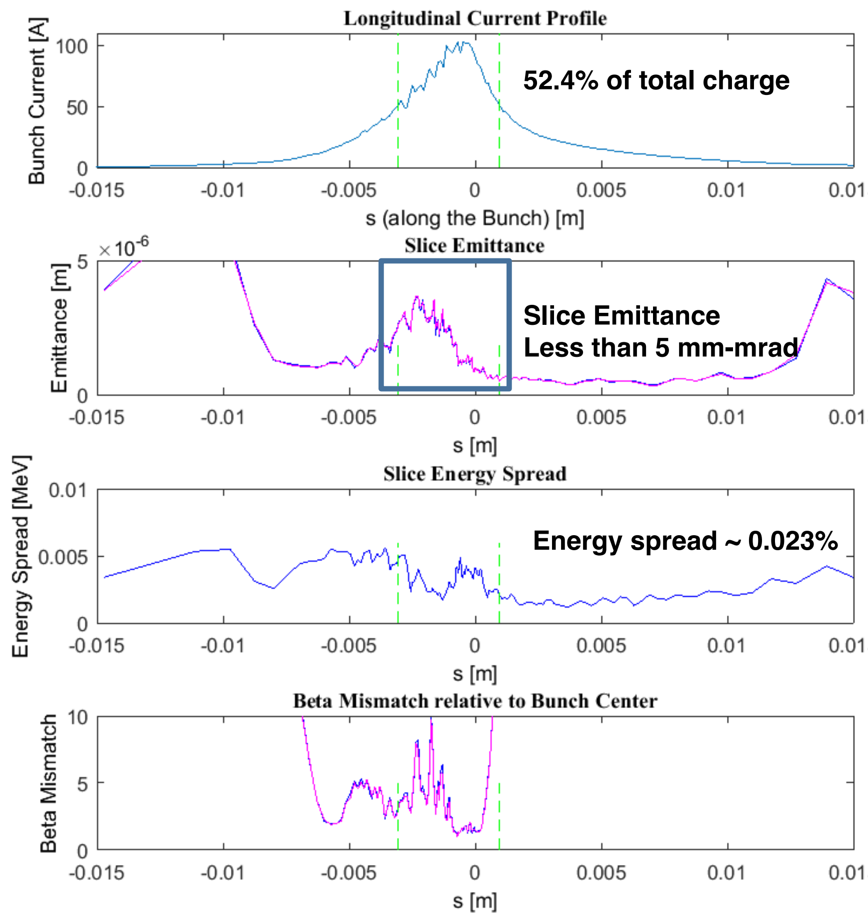
RMS Values for all Particles:

```
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
```

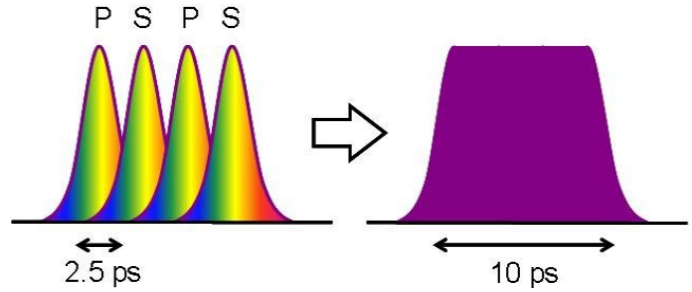
α_x	β_x	α_y	β_y
-1.94	1.44	-1.91	1.41



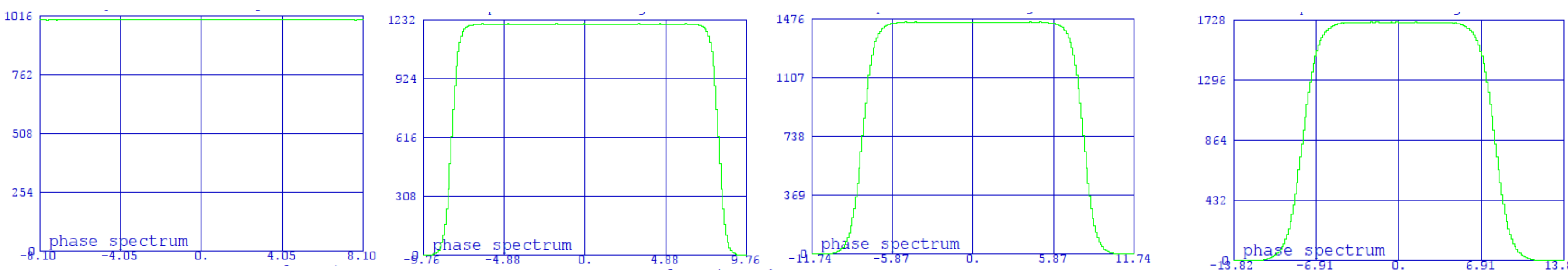
Projected emittance within FWHM $=x_{rms}^2/\beta\ \gamma=3.56$

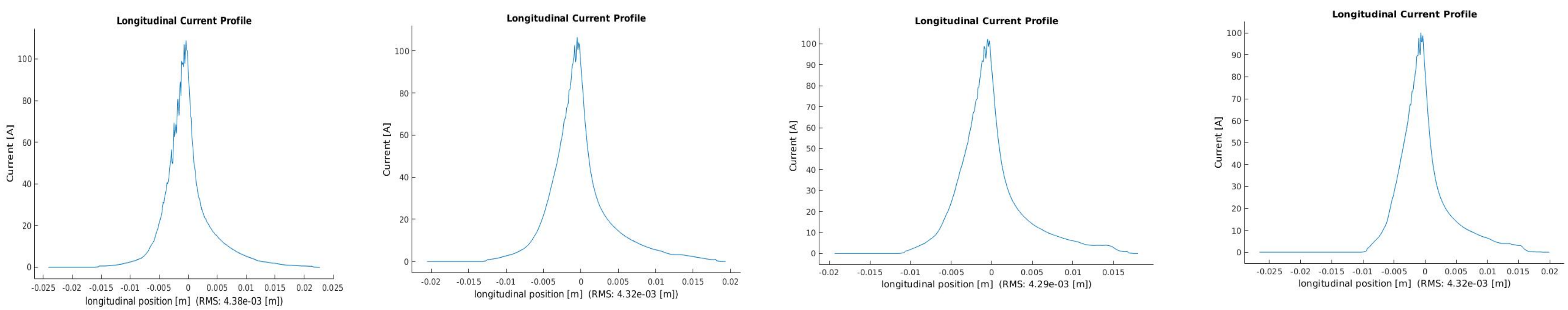
Electron Beam with Different Rise Time

- 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.



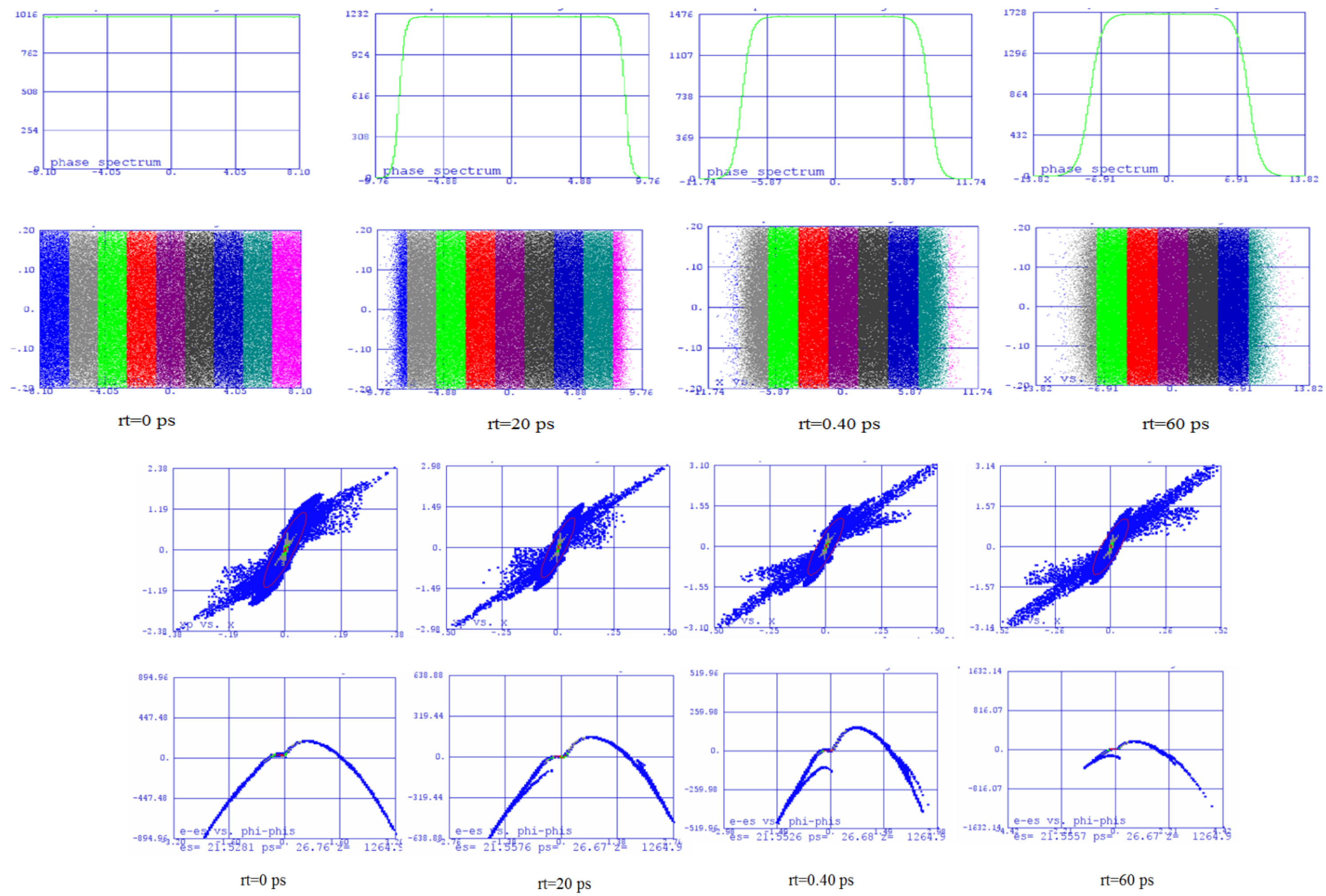
Principle of pulse stacking





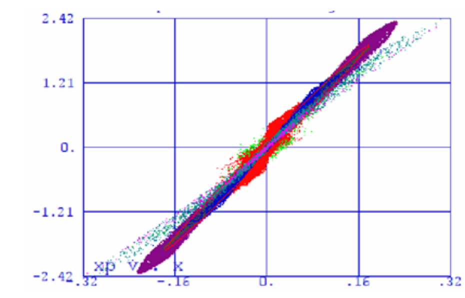
For the same optimized setting, initial electron beam with different rise time has similar final current profile

Electron Beam with Different Rise Time Cont.

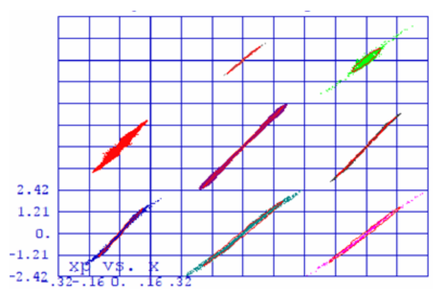


Projected emittance due to different rise time are 3.83, 4.26, 4.77 and 5.32micro respectively.

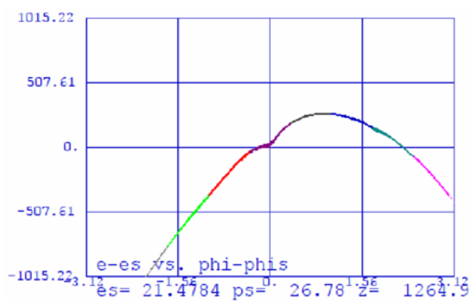
Electron Beam with Lowest Emittance



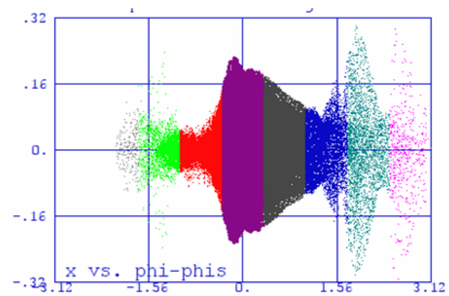
Transverse Phase Space (x vs. px)



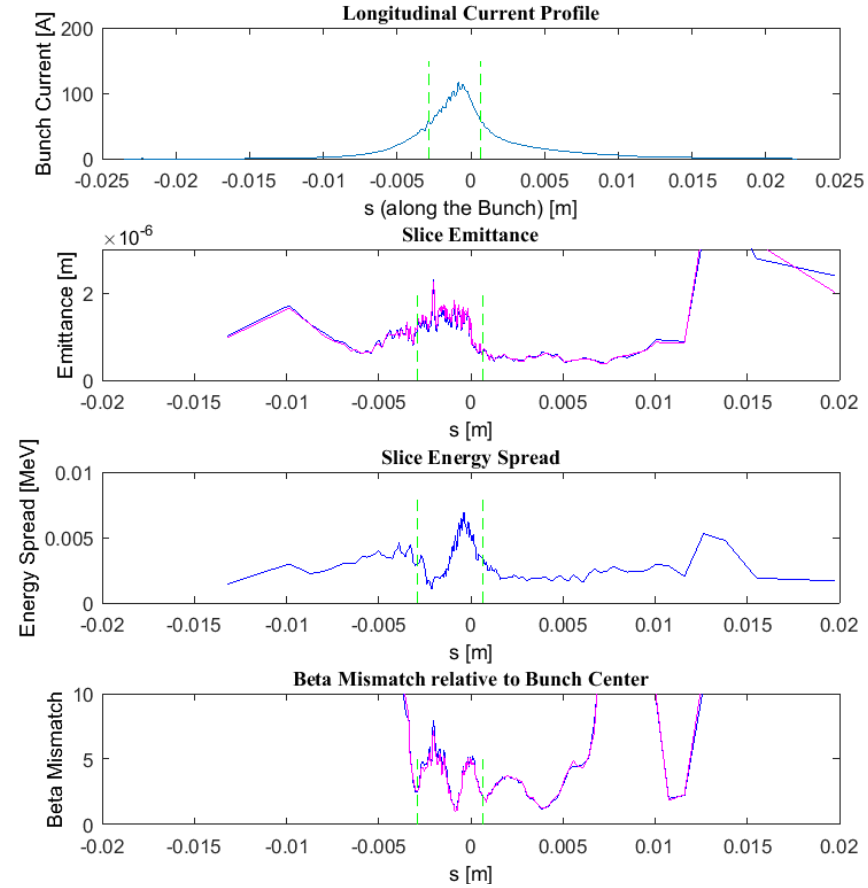
Transverse Phase Space for different Slices



Longitudinal Phase Space (z vs. pz)



z vs. x



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
```

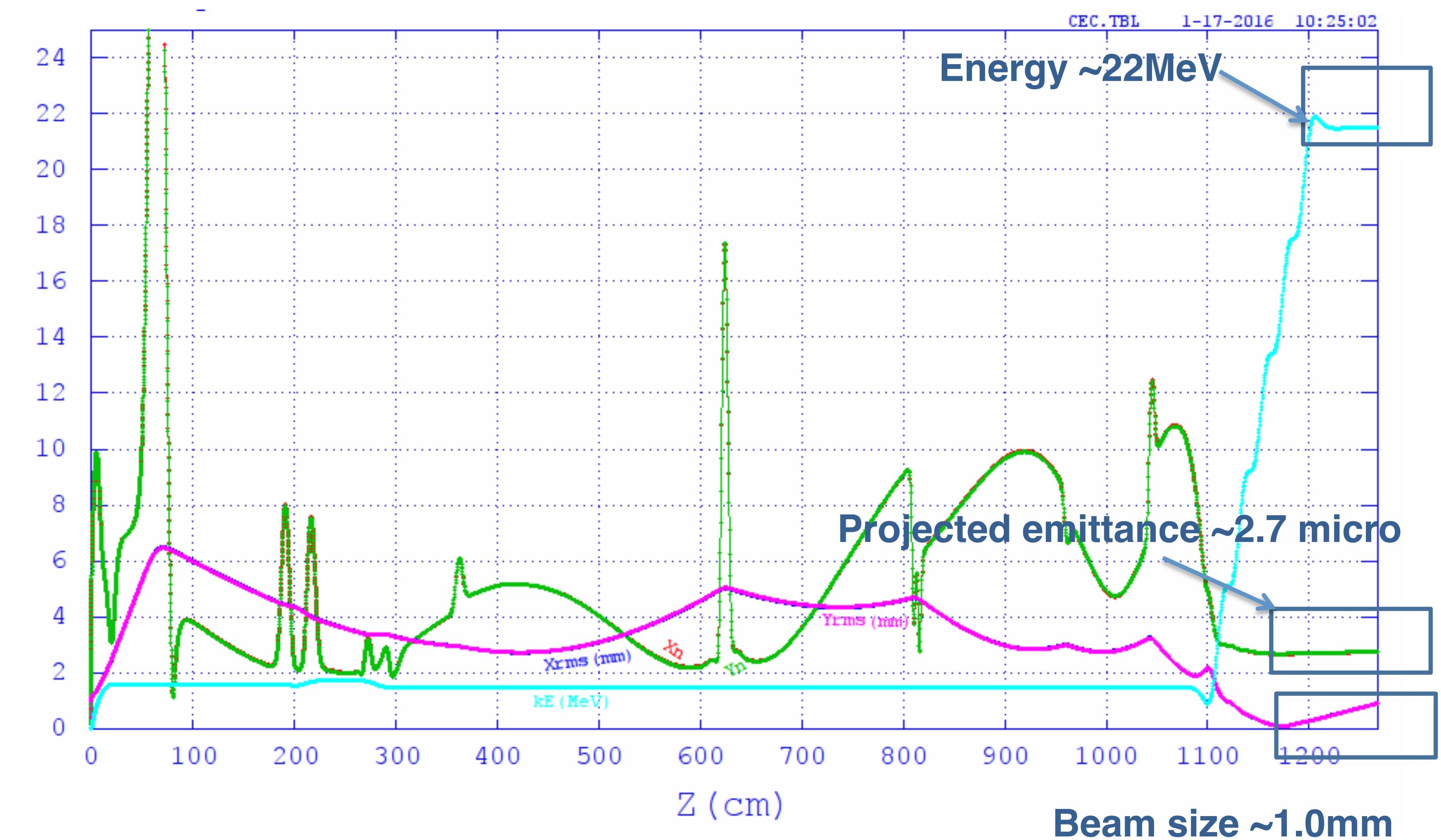
RMS Values within FWHM:

```
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

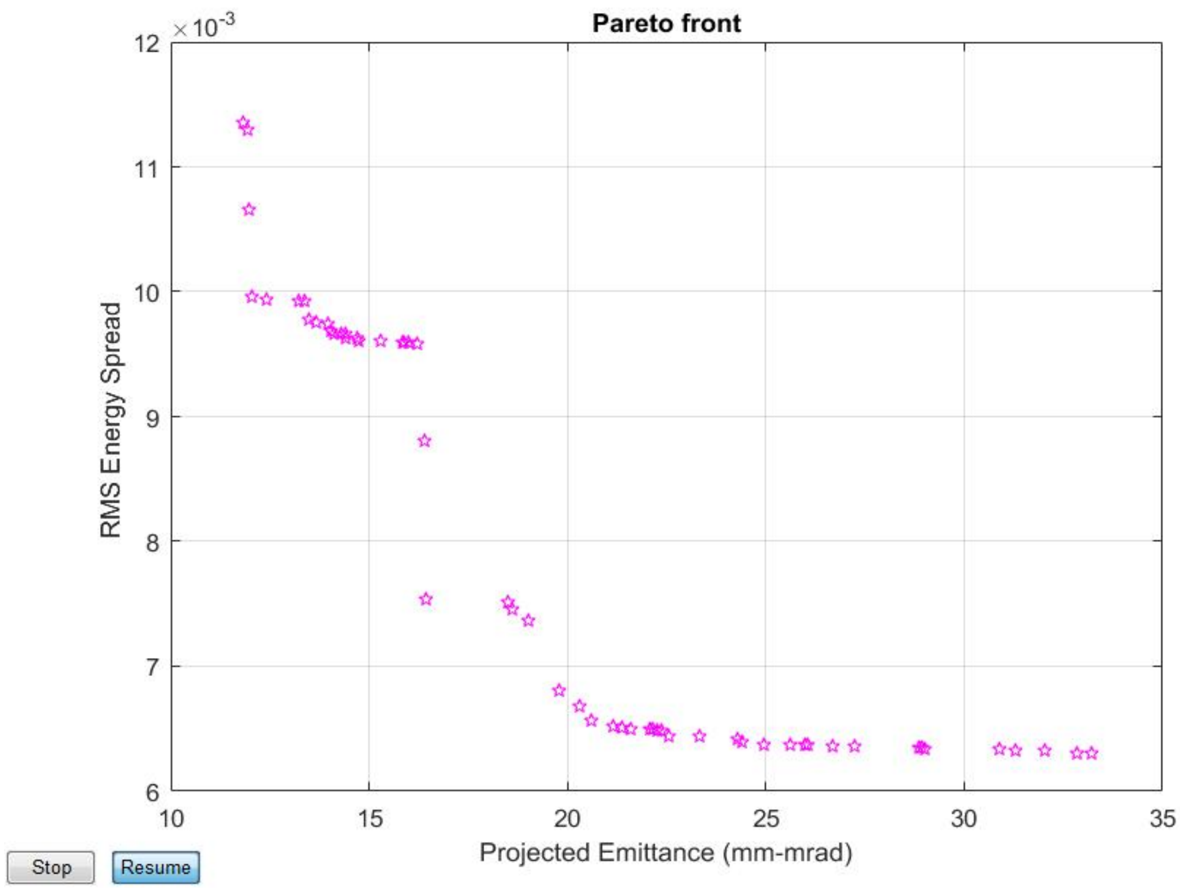
α_x	β_x	α_y	β_y
-13.3	12.3	-13.3	12.3

Electron Beam with Lowest Emittance Cont.



Beam size ~1.0mm

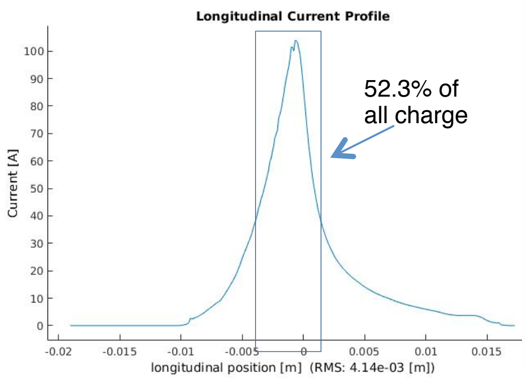
Genetic Algorithm



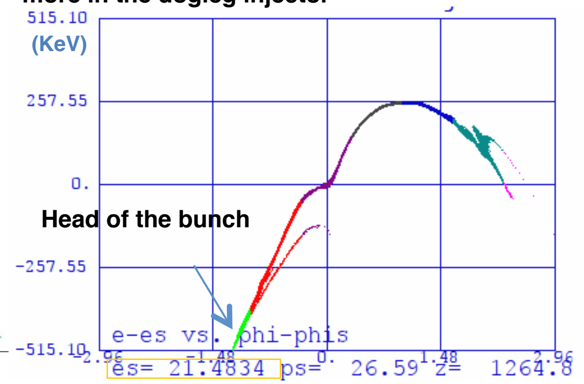
Pareto front for electron beam generated after 704MHz srf cavity. the two goals of minimizing the emittance and the energy spread are essentially competing.

Electron Beam with Low Energy Spread

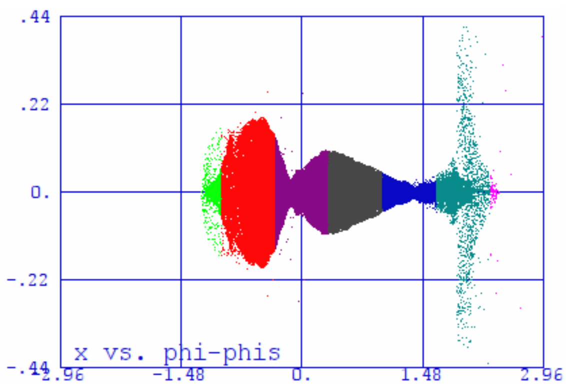
- Peak current :100 Ampere
- Projected Emittance: < 5 micro
- Energy deviation (2.4%), RMS energy spread (0.6%)

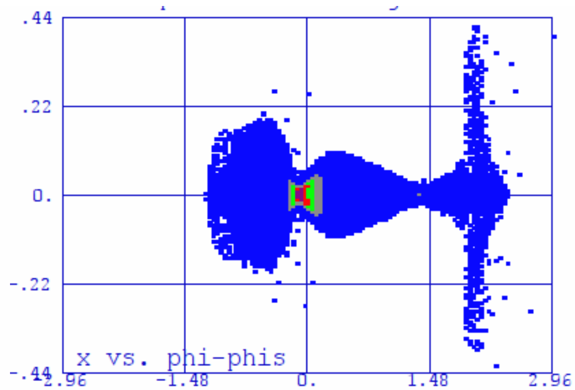


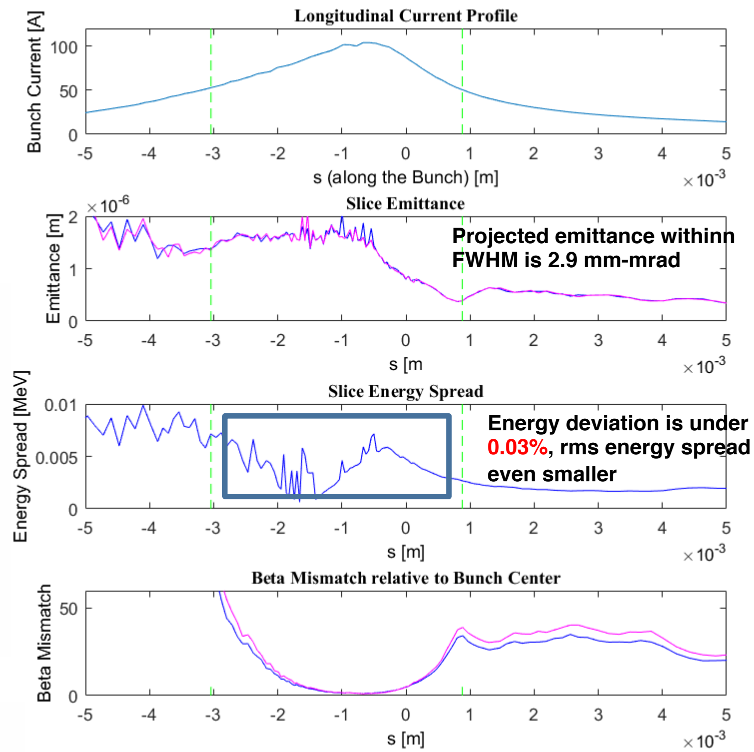
This negative chirp will compress electron beam more in the dogleg injector



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

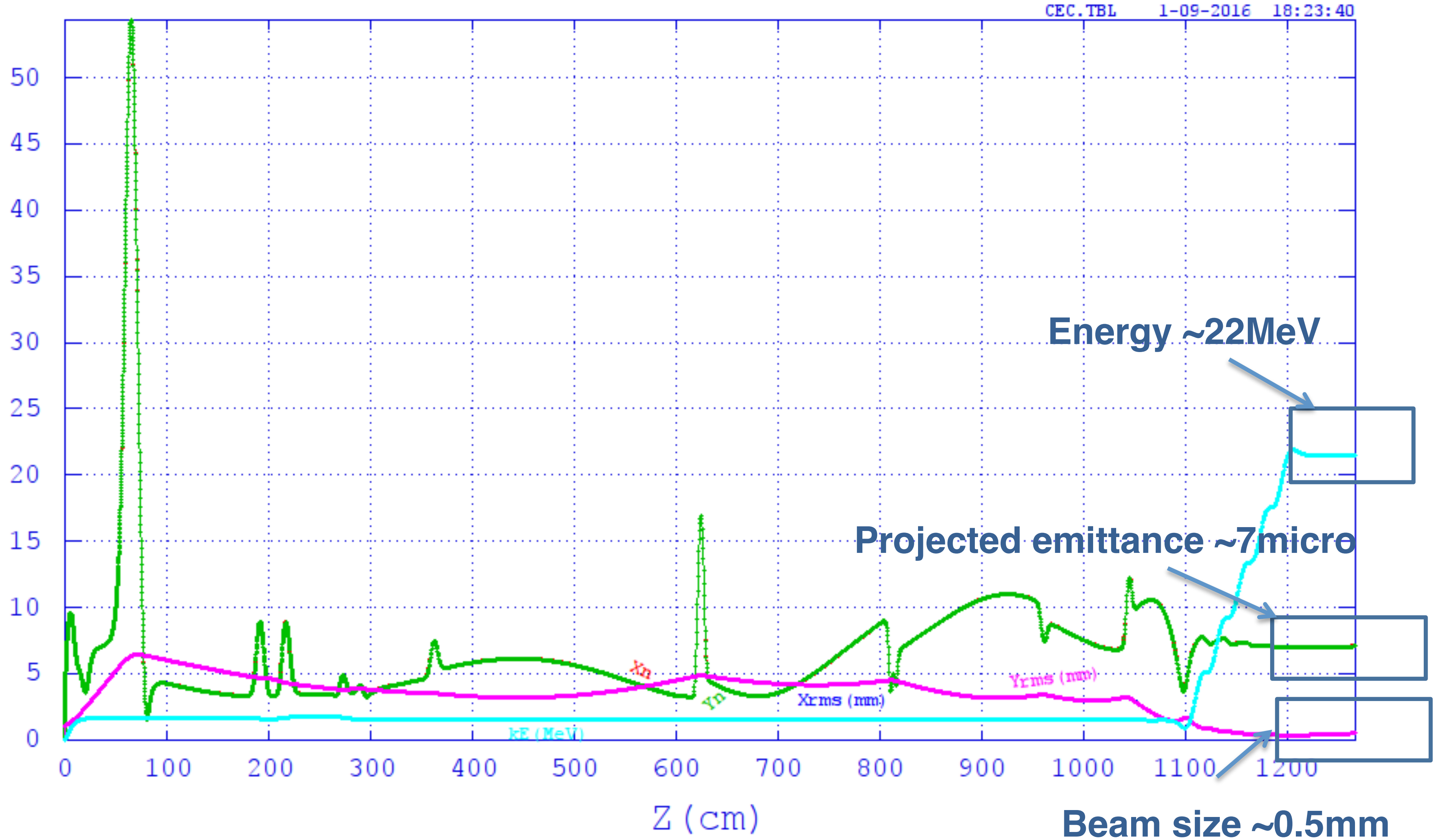
RMS Values for all Particles:

```
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
```

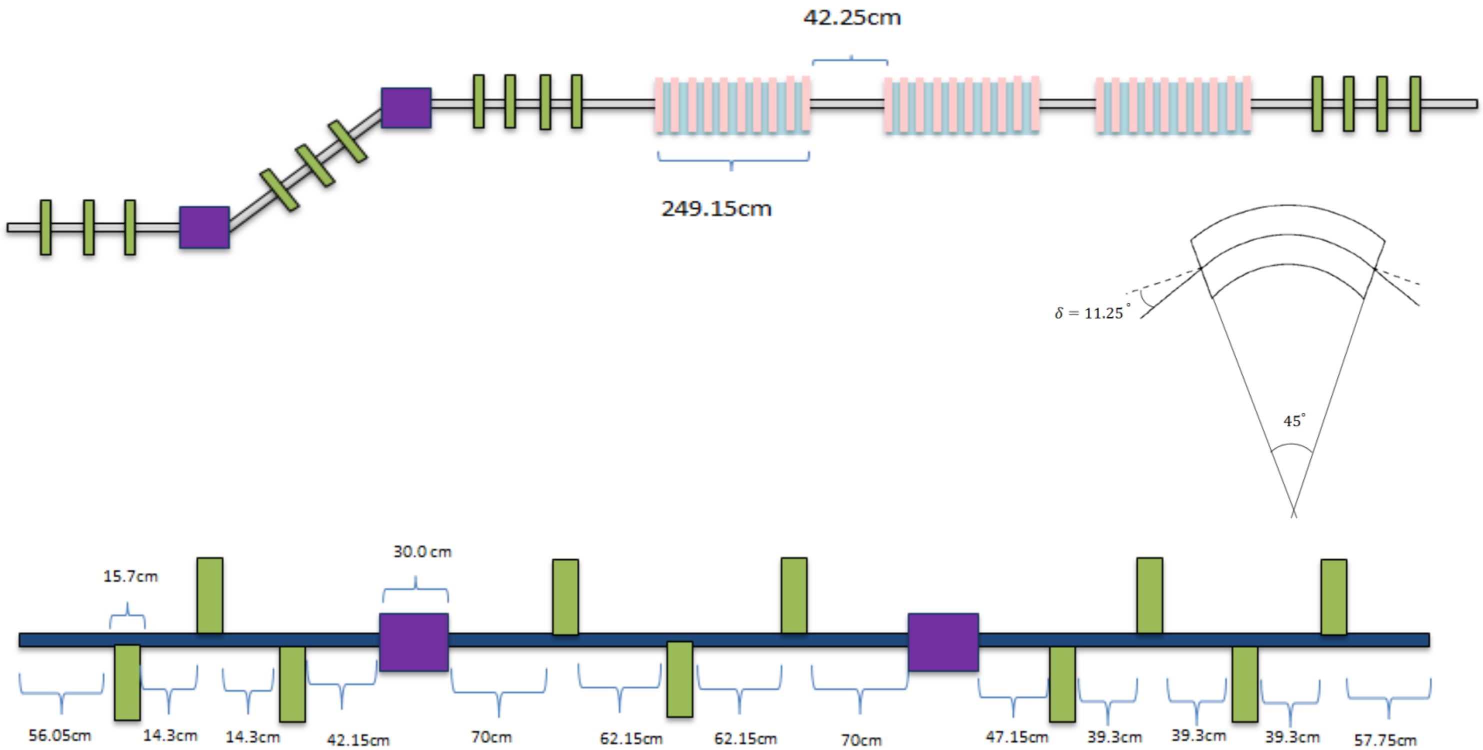
RMS Values within FWHM:

```
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 (Dogleg Injector)

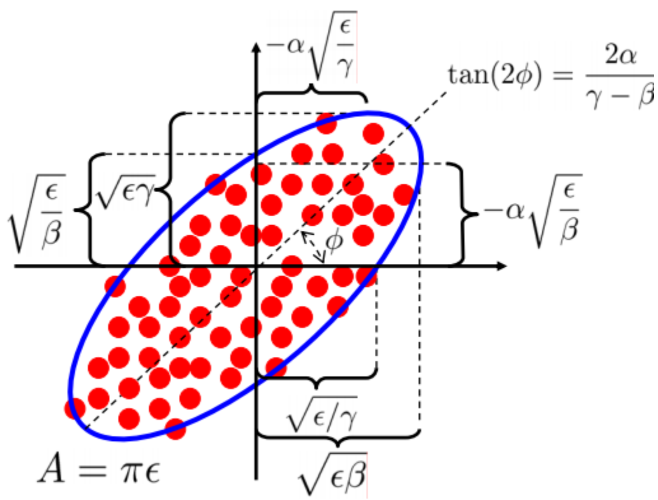


Lattice Matching Cont.

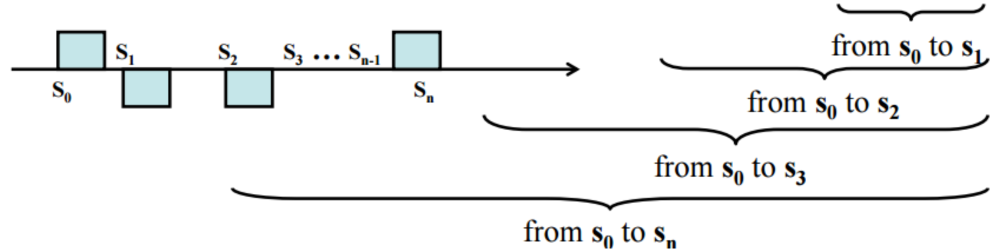
- The accelerator itself define ideal betatron functions for motion of individual particles on ellipses

- The beam Twiss functions should be equal to the betatron functions imposed by the machine structure

- For dogleg and Wiggler section, we have to design a lattice to propagate the electron beam generated after the 704MHz cavity and propagate it through the dogleg and wiggler section



$$\mathcal{M}(s_n|s_0) = \mathcal{M}(s_n|s_{n-1})\ldots\mathcal{M}(s_3|s_2)\cdot\mathcal{M}(s_2|s_1)\cdot\mathcal{M}(s_1|s0)$$



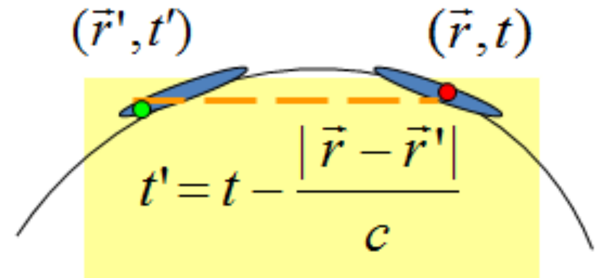
$$\begin{pmatrix}\beta\\ \alpha\\ \gamma\end{pmatrix}_2 = \begin{pmatrix} M_{11}^2 & -2M_{11}M_{12} & M_{12}^2 \\ -M_{11}M_{21} & M_{11}M_{22}+M_{12}M_{21} & -M_{12}M_{22} \\ M_{21}^2 & -2M_{21}M_{22} & M_{22}^2 \end{pmatrix} \begin{pmatrix}\beta\\ \alpha\\ \gamma\end{pmatrix}_1$$

Courant-Snyder parameters evolution can be calculated from trasfer matrix

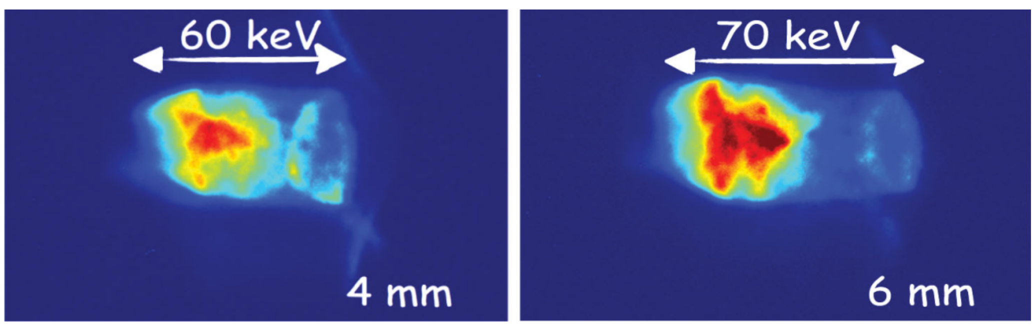
Twiss parameters ($\beta\gamma=1+\alpha^2$) used to represent beam phase space

Coherent Synchrotron Radiation Effect

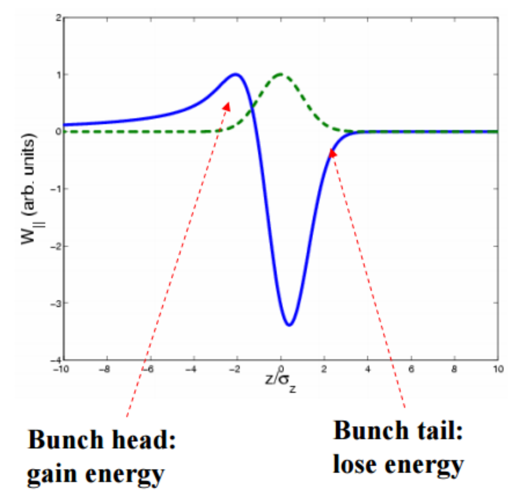
Coherent synchrotron radiation (CSR), the radiated power becomes quadratic with peak current. This effects is significant for bunch sufficiently short.



$$P_{\text{tot}} = \left| \sum_{i=1}^{N} E_i \right|^2 \approx |NE_0|^2 = \boxed{N^2} \; P_0$$

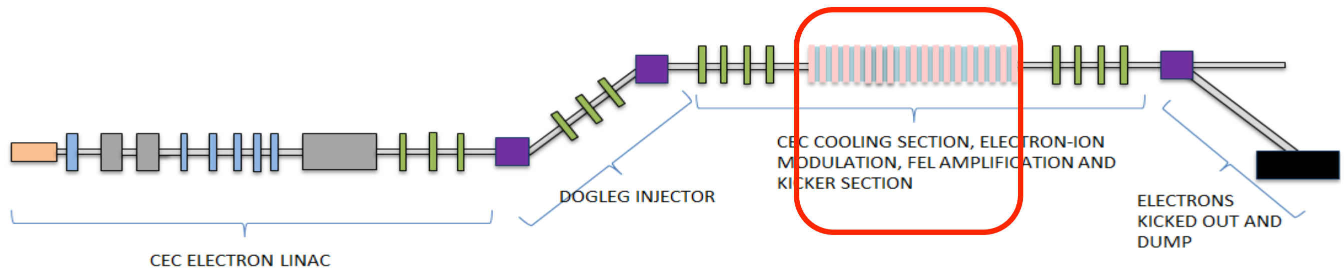


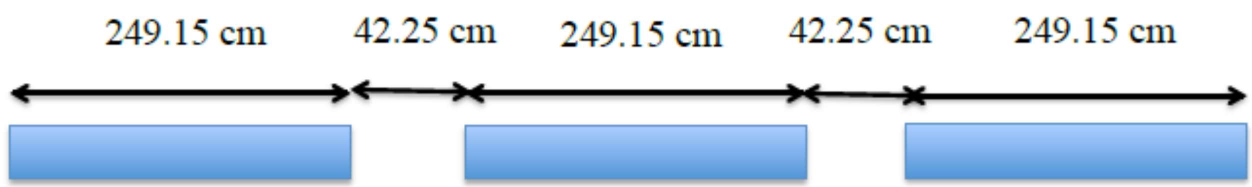
ATF experimental results: the effect of a CSR wake on a Gaussian beam for 4 and 6 mm gap. Beam-energy distribution is spread along the horizontal axis.



Radiation emitted from a tail particle at retarded time overtakes the bunch to interact with a head particle, this leads to CSR-Induced Emittance Growth

Lattice Matching Cont.





Periodic solution :

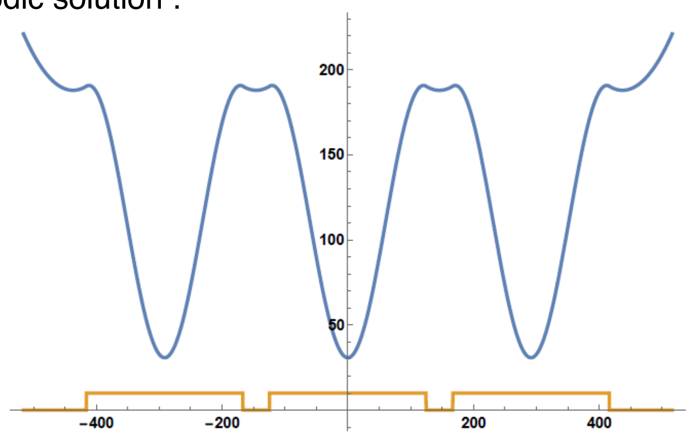


Fig. 1 Periodic solution for CeC FEL system

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 :

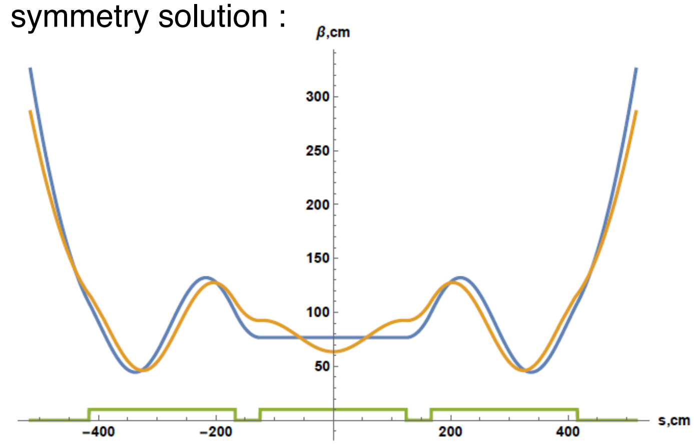
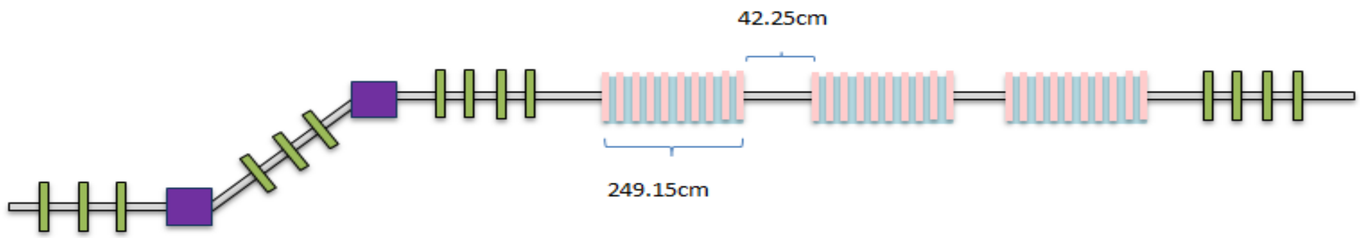


Fig. 2. Two solutions with bilateral symmetry: blue is for $\beta_c = \beta_o$ =76.7 cm – matched for the central wiggler; Yellow-grey for β_c =63.5 cm, which minimizes beta-beating in second wiggler.

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

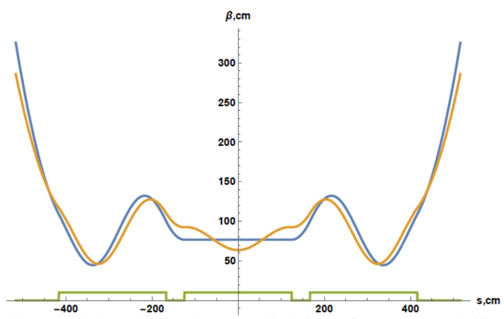
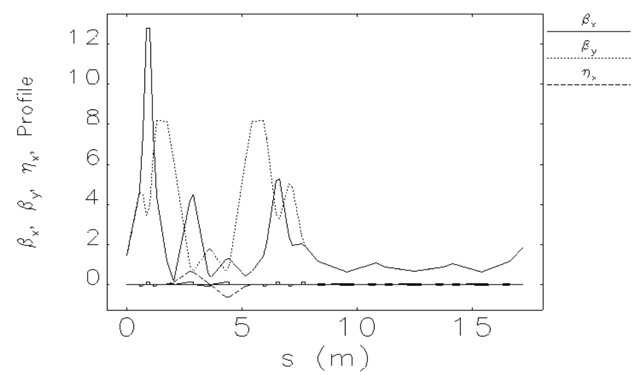
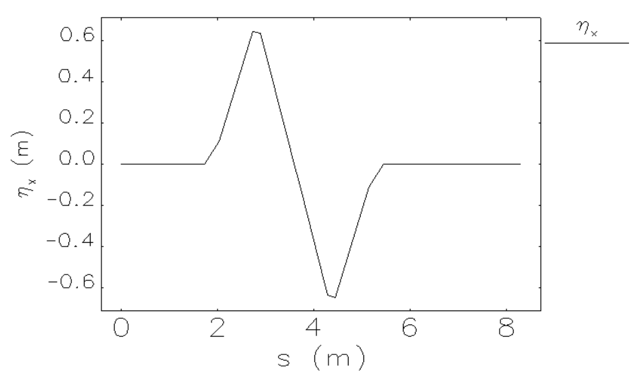
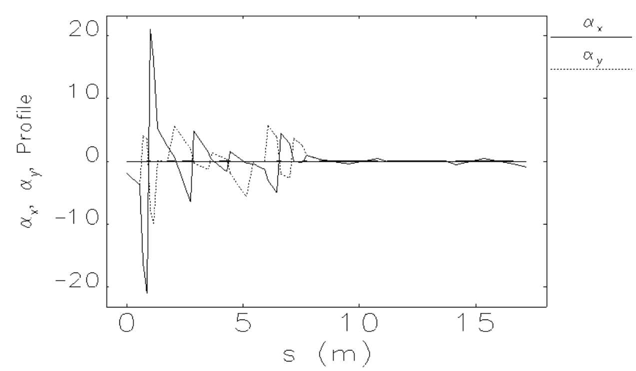


Fig. 2. Two solutions with bilateral symmetry: blue is for $\beta_c = \beta_0$ =76.7 cm – matched for the central wiggler; Yellow-grey for β_c =63.5 cm, which minimizes beta-beating in second wiggler.







Dogleg Injector Section (Achromatic Effect)

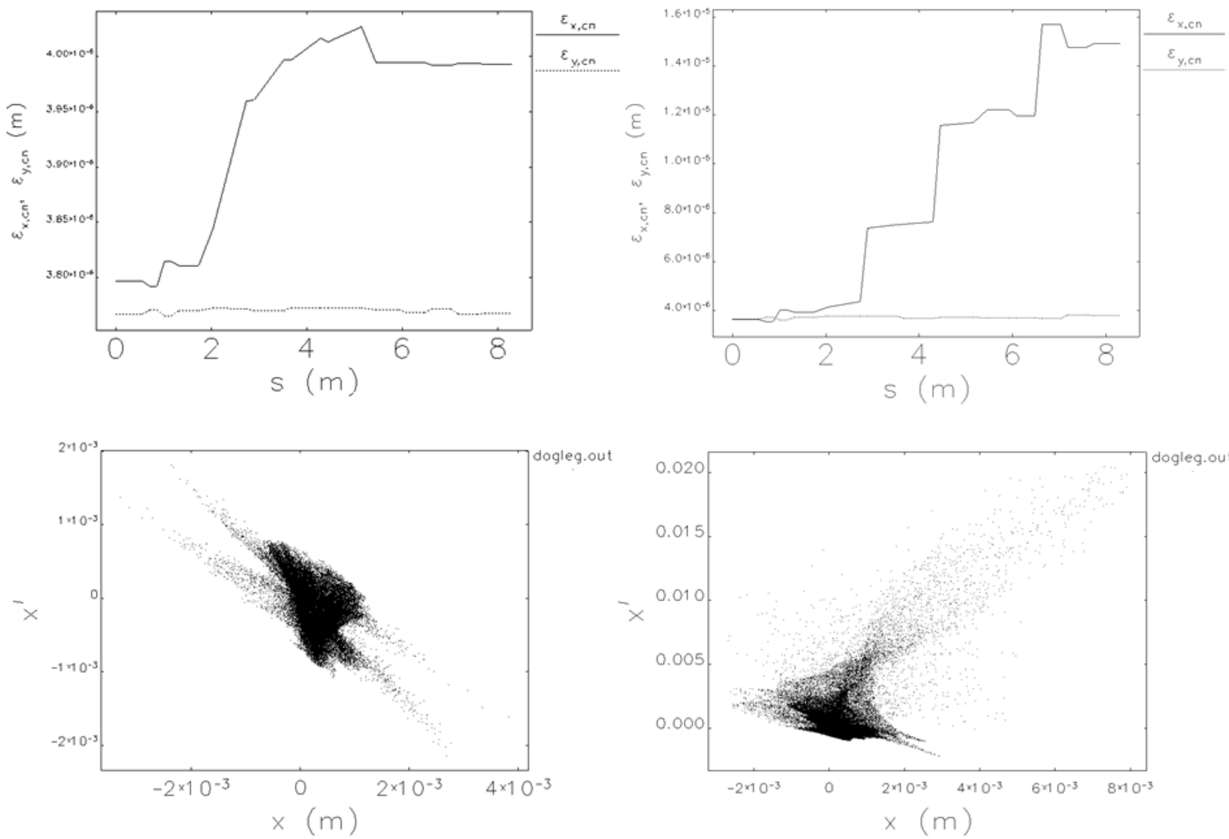
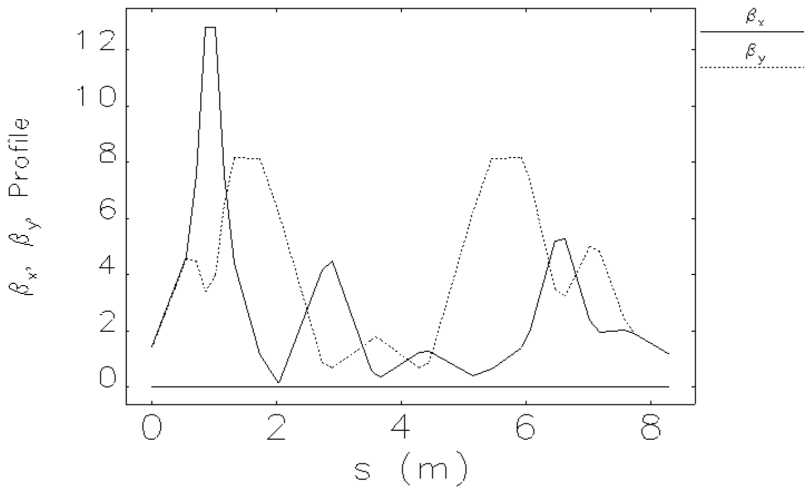
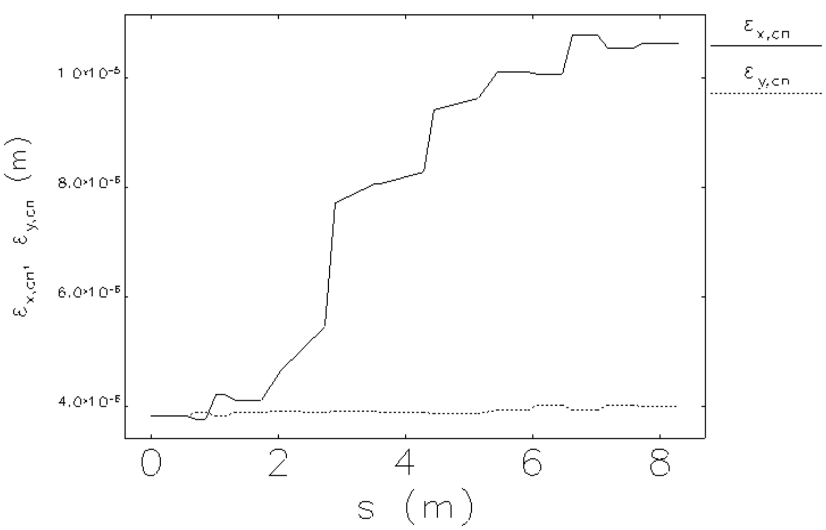


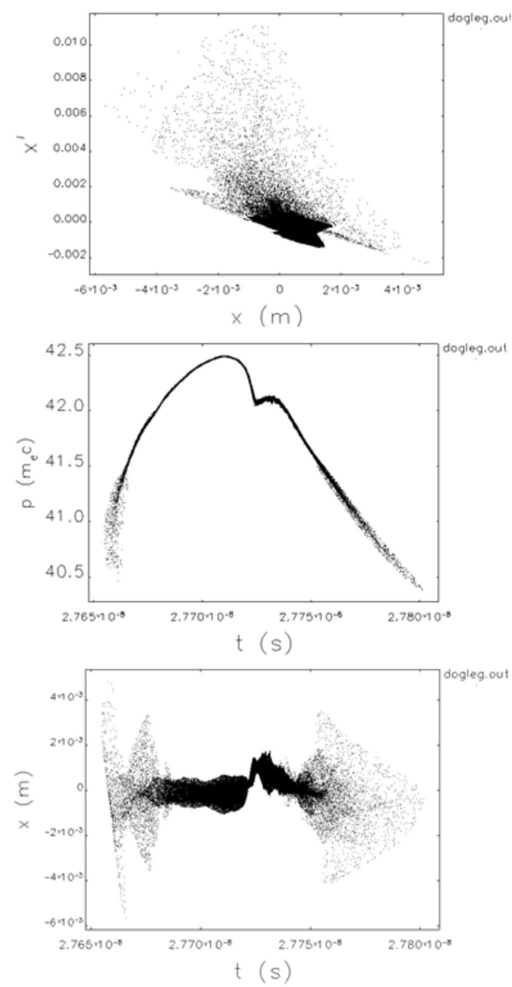
Figure 2.10 emittance evolutions (top) along horizontal bended dogleg achromatic for electron beam at initial average momentum error 0.25 % (left) and 5 % (right). The chromatic aberration effect distorts the initial matched beam phase space (bottom) and change the beam emittance.

CSR Simulation for Optimized Electron Beam

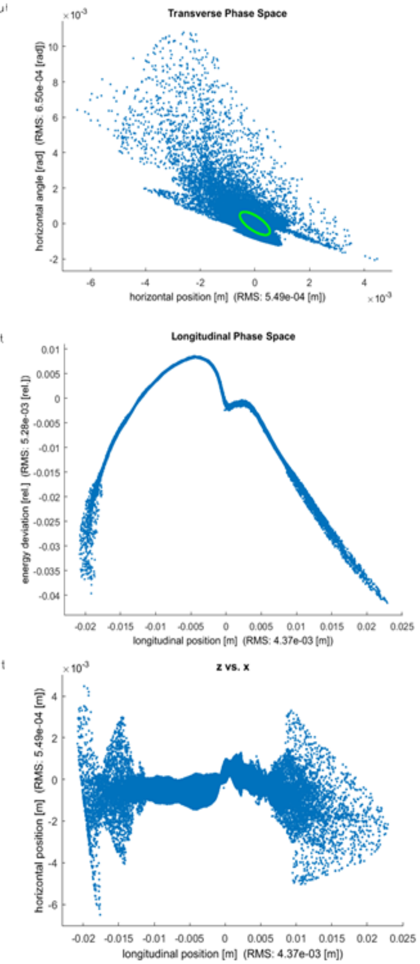




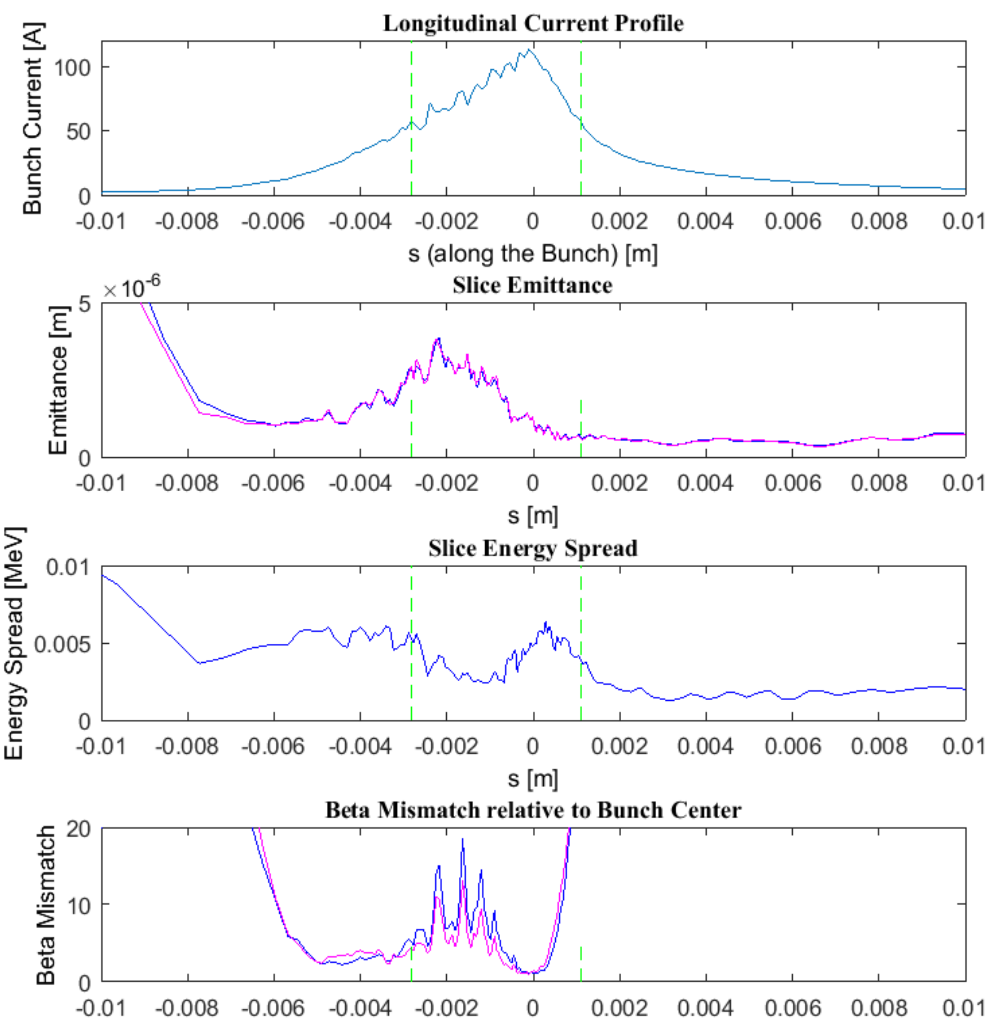
Elegant Results



CSRtrack Results



CSR Simulation for Optimized Electron Beam Cont.



Number of Particles: 200001 Charge: 2 nC
Position: 8.2138 m Beam Energy: 21.535 MeV

FWHM (distance between green bars): 3.92e+03 μ m (13.1 ps)
Charge within FWHM: 54.2 %
Projected Emittance: $\gamma\epsilon_x$ = 1.08e-05 m $\gamma\epsilon_y$ = 5.46e-06 m
Optics @ I_{peak}: α_x = 3.74 β_x = 2.27m α_y = -0.15 β_y = 0.363m

RMS Values for all Particles:

```
x = 5.49e-04 m   x' = 6.50e-04
y = 4.33e-04 m   y' = 7.48e-04
s = 4.37e-03 m   δ  = 5.28e-03
```

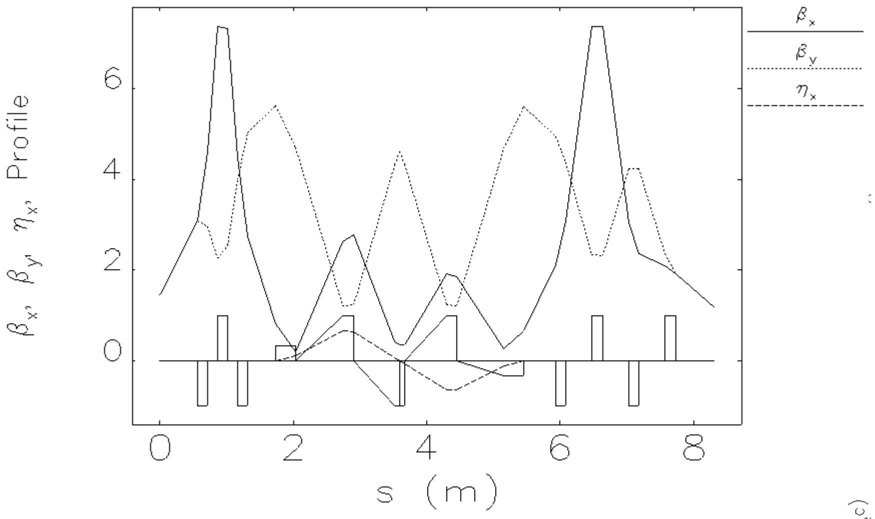
RMS Values within FWHM:

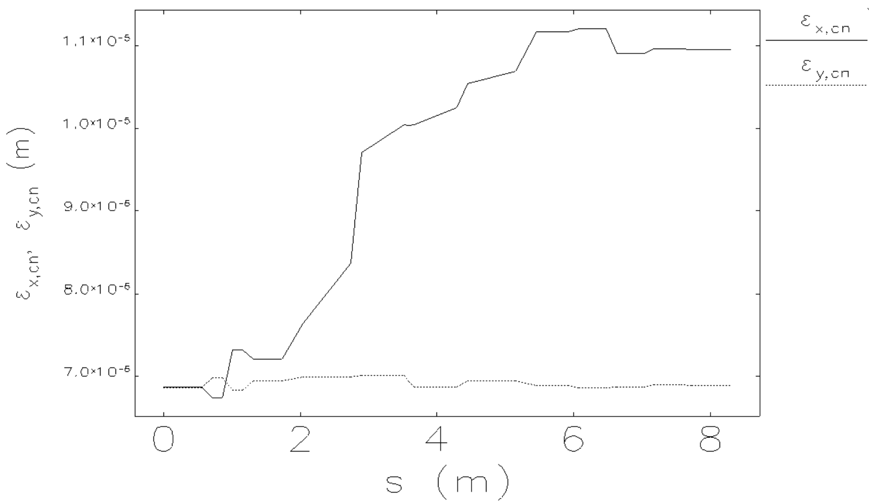
```
x = 2.93e-04 m   x' = 3.78e-04
y = 2.51e-04 m   y' = 6.03e-04
s = 1.04e-03 m   δ  = 1.46e-03
```

Projected emittance within FWHM

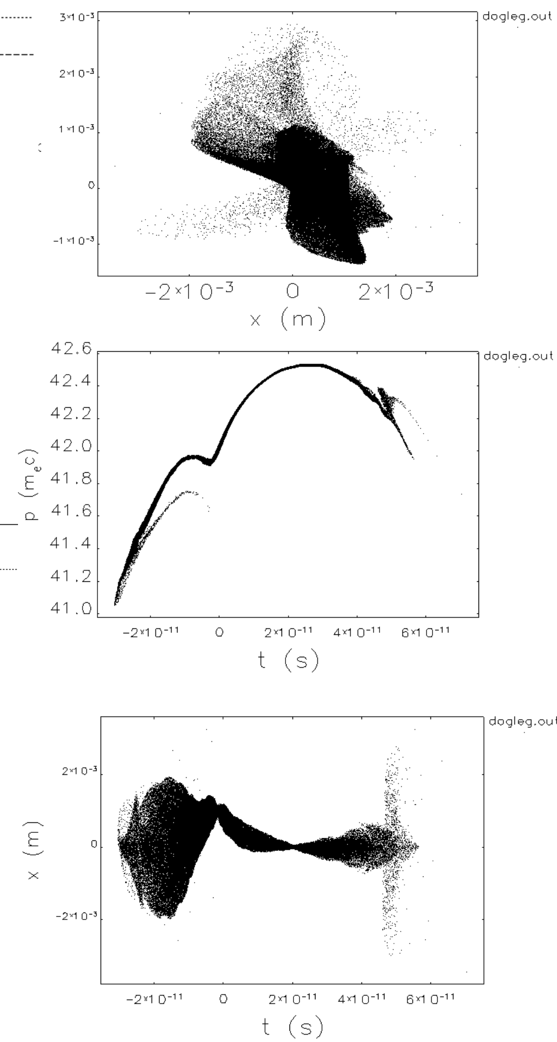
$$\varepsilon_y = y_{rms}^2/\beta\gamma = 1.6\ \text{mm}-\text{mrad}$$

CSR Simulation for Electron Beam with Low Energy Spread

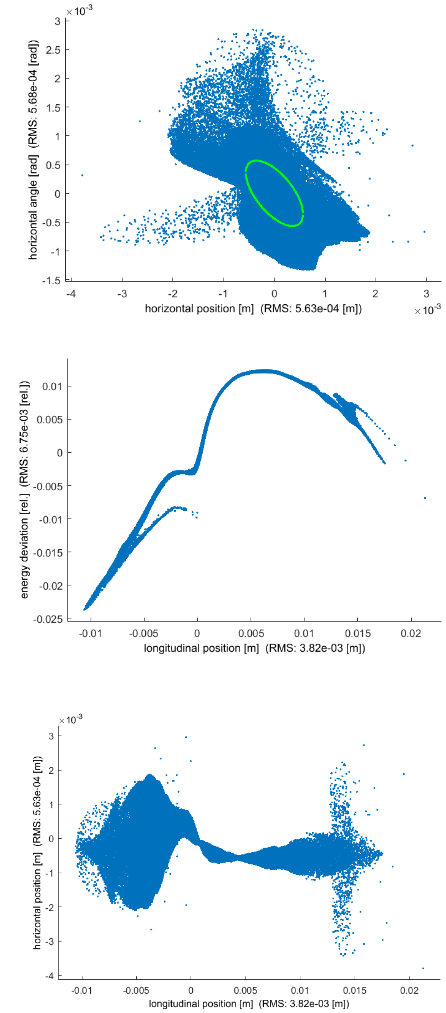




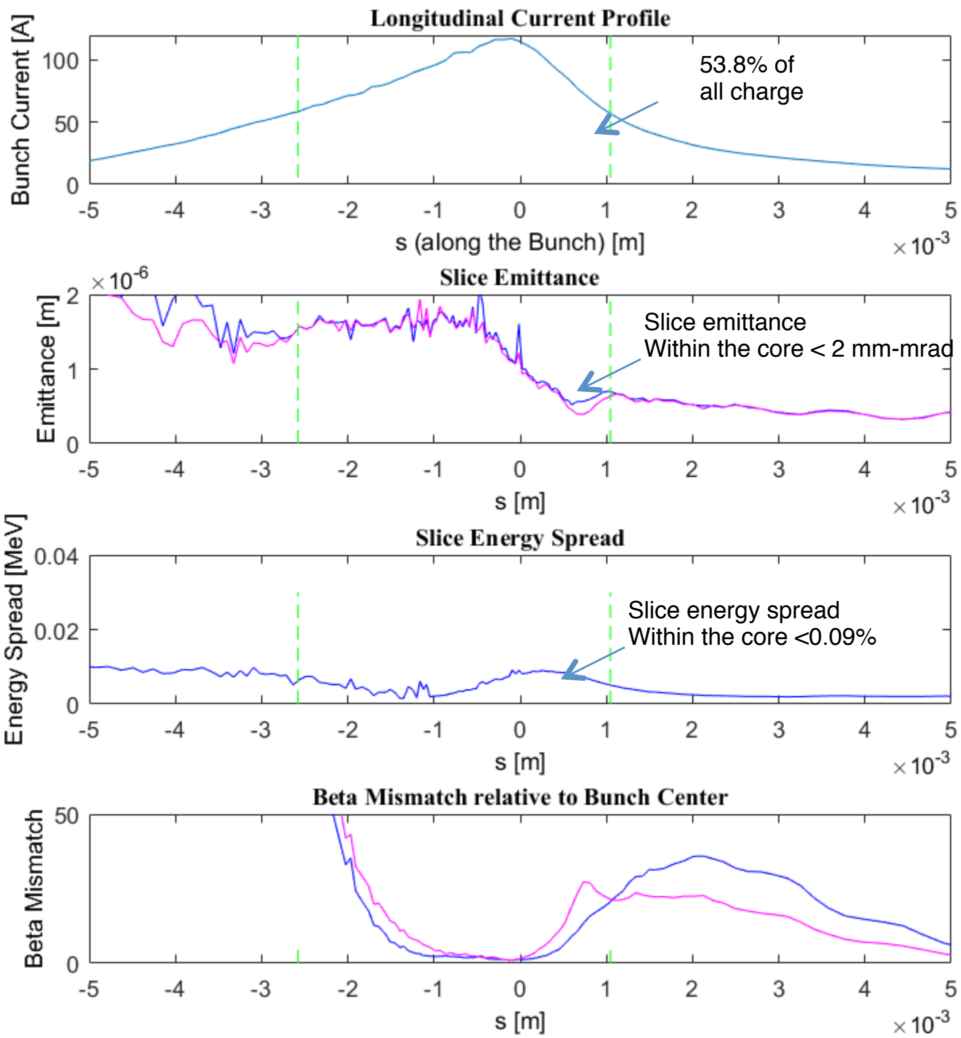
Elegant results



CSRtrack (1D) results



CSR Simulation for Electron Beam with Low Energy Spread Cont.



Number of Particles: 200001 Charge: 2 nC
Position: 8.3153 m Beam Energy: 21.491 MeV

FWHM (distance between green bars): 3.62e+03 μ m (12.1 ps)
Charge within FWHM: 53.8 %
Projected Emittance: $\gamma\epsilon_x$ = 1.04e-05 m $\gamma\epsilon_y$ = 7.69e-06 m
Optics @ I_{peak}: α_x = 3.16 β_x = 0.894m α_y = 1.75 β_y = 6.23m

RMS Values for all Particles:

```
x = 5.63e-04 m    x' = 5.68e-04
y = 3.24e-04 m    y' = 5.68e-04
s = 3.82e-03 m    δ  = 6.75e-03
```

RMS Values within FWHM:

```
x = 2.99e-04 m    x' = 4.95e-04
y = 3.49e-04 m    y' = 2.87e-04
s = 9.55e-04 m    δ  = 2.25e-03
```

Projected emittance within FWHM

$$\varepsilon_y = y_{rms}^2 / \beta\,\gamma = 0.8\ \text{mm}-\text{mrad}\,\varepsilon$$

Summary

- A start to end simulation model the entire beam line from the generation of the photo electrons to the transport of electron beam to FEL section.
- We have generated electron beam that have low emittance, peak current ~100 and core energy spread <0.1%.
- Lattice matching for dogleg injector was optimized by using Elegant.
- Achromatic effect induced emittance growth in the dogleg section can be large for electron beam with large energy deviation.
- CSR effect was simulated using Elegant and CSRtrack code, emittance growth due to CSR effects is negligible compare with achromatic effect.

References

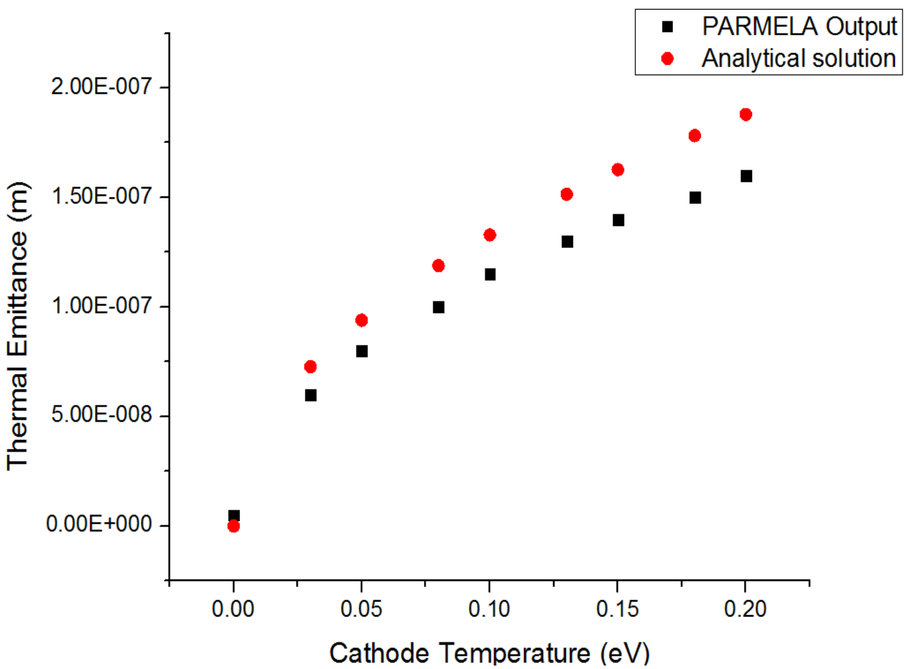
- [1] V. N. Litvinenko, and Y. S. Derbenev, Physical Review Letters 102 (2009).
- [2] G. Wang and V. N. Litvinenko, Influence of e-beam Parameters on Coherent Electron Cooling, these proceedings.
- [3] Y. Hao , and V.N. Litvinenko, Simulation Study of Electron Response Amplification in Coherent Electron Cooling
- [4] Yichao Jing , Vladimir N. Litvinenko, Yue Hao , and Gang Wang, Model Independent Description of amplification and saturation using Green's Function

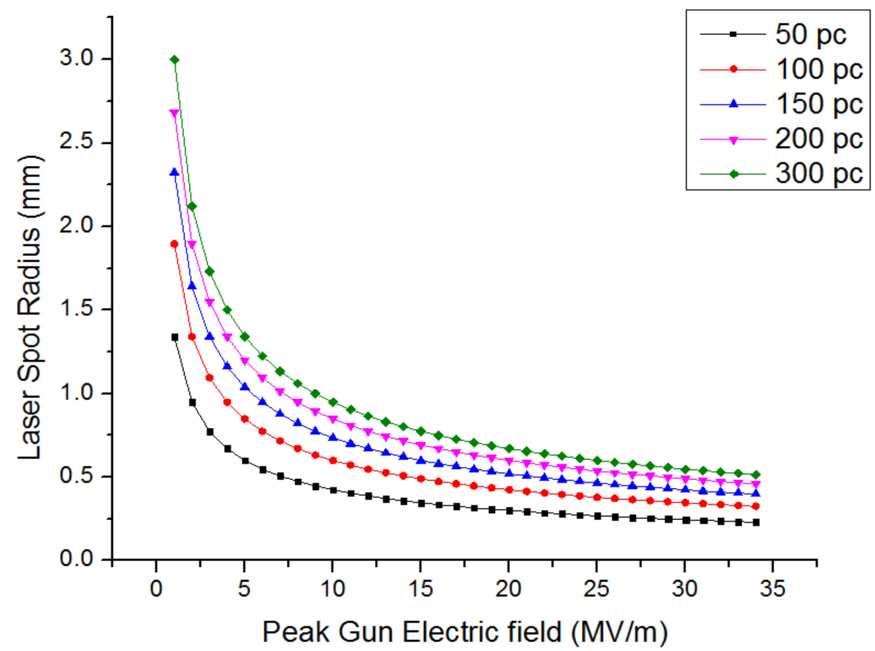
Back up

Thermal Emittance

emittance $\varepsilon_{thermal} = \sigma_x \sqrt{k_B T / mc^2} = \sigma_x \sqrt{\langle v^2 \rangle} / c$

Image charge field $E_s = Q / \pi r^2 \varepsilon_o$



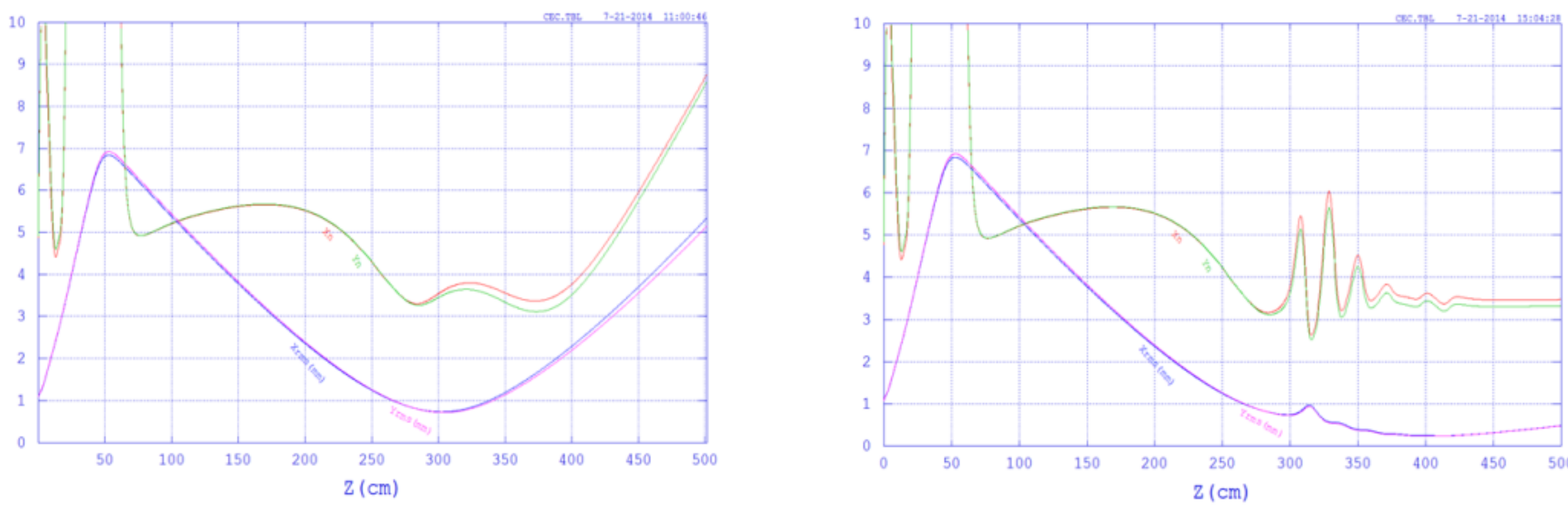


mean transverse energy of 35meV was used in simulation

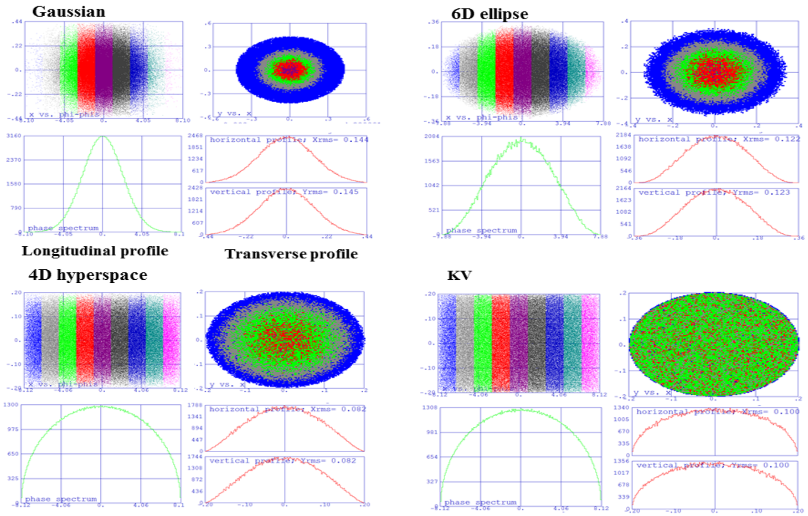
Emittance Compensation Theory

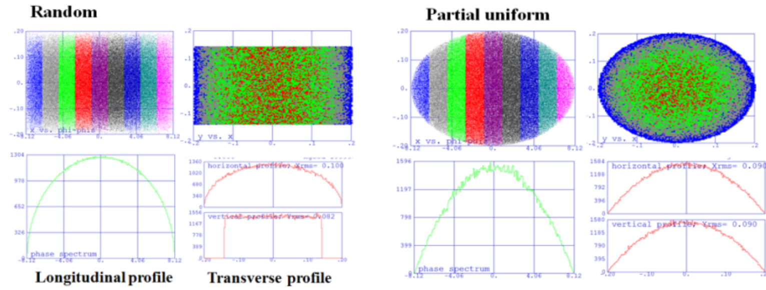
$$\sigma_r''(\zeta)+K_r\,\sigma_r(\zeta)=\boxed{\frac{I(\zeta)}{2I_0(\beta\gamma)^3\sigma_r(\zeta)}}+\boxed{\frac{\varepsilon_{n,intrinsic}^2(\zeta)}{(\beta\gamma)^2\sigma_r^3(\zeta)}}$$

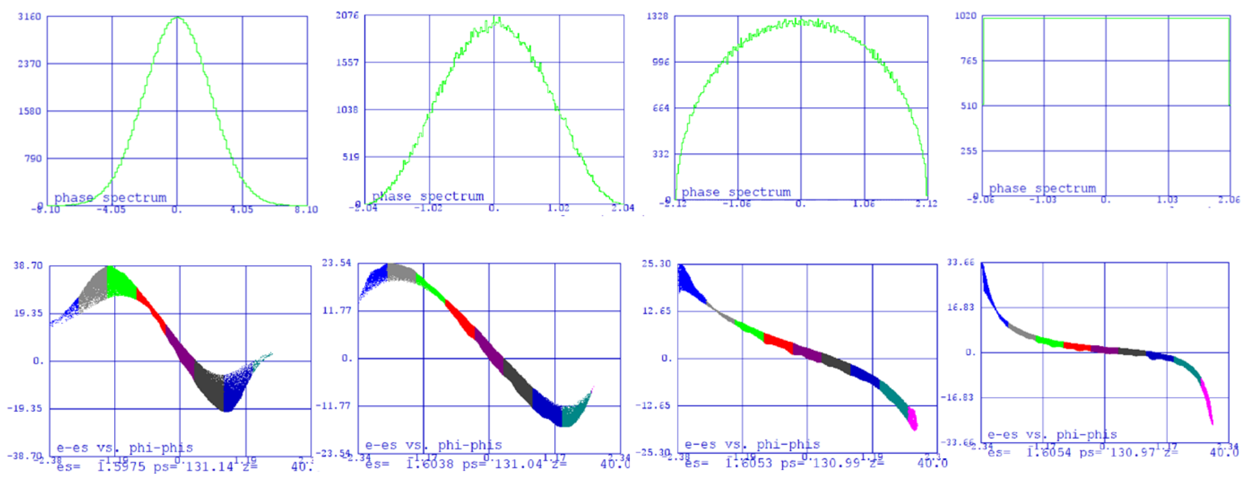
Space charge dominated | Emittance dominated

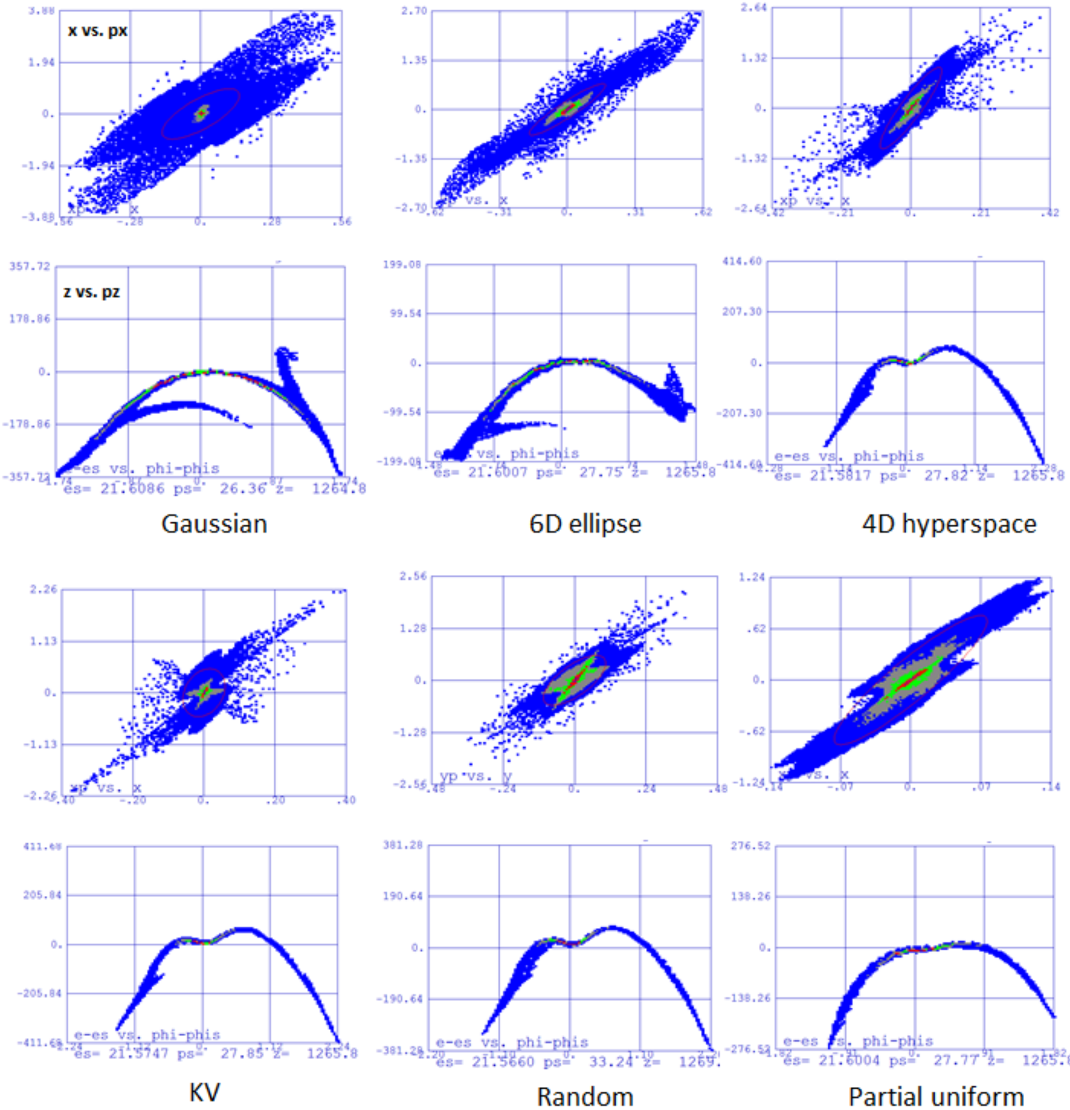


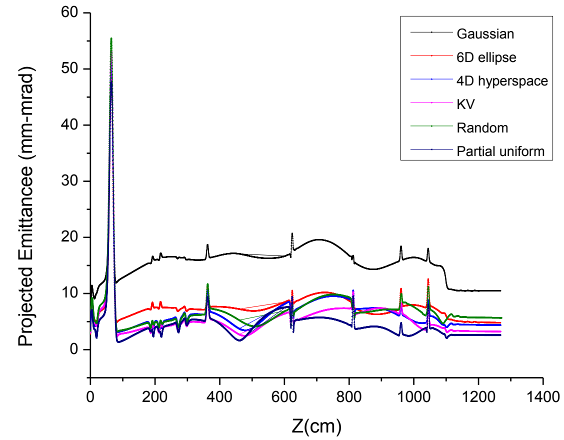
PARMELA simulation of emittance compensation for photoinjetor, transverse rms beam size and normalized emittance, with (right) and without (left) accelerator structure

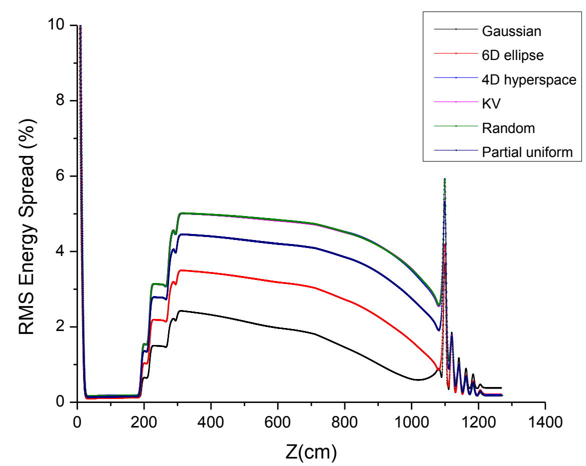

Gaussian
6D ellipse
Longitudinal profile
Transverse profile
4D hyperspace
KV


Random
Partial uniform
Longitudinal profile
Transverse profile


phase spectrum
phase spectrum
phase spectrum
phase spectrum
e-es vs. phi-phis
es= 1.5975 ps= 131.14 z= 40.
e-es vs. phi-phis
es= 1.6038 ps= 131.04 z= 40.0
e-es vs. phi-phis
es= 1.6053 ps= 130.99 z= 40.0
e-es vs. phi-phis
es= 1.6054 ps= 130.97 z= 40.0


x vs. px
z vs. pz
Gaussian
6D ellipse
4D hyperspace
KV
Random
Partial uniform


Gaussian
6D ellipse
4D hyperspace
KV
Random
Partial uniform
Projected Emittancee (mm-mrad)
Z(cm)


Gaussian
6D ellipse
4D hyperspace
KV
Random
Partial uniform
RMS Energy Spread (%)
Z(cm)