X-band Based FEL proposal

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Outline

- Introduction
- Proposed layout
  - S-Band injector+X-Band main accelerator
  - All X-Band layout
- Injectors
- Beam Dynamics requirements
- Main accelerating section
- Sample FEL simulatin
- Conclusion

FEL Requirements

- Ångstrom wavelength range
  - To study spatial resolution to resolve individual atoms in molecules, clusters and lattices.
- Tens to hundreds of femtosecond pulse duration.
  - Temporal resolution of dynamic process (change in the molecular structures or transition)
- High peak brightness
- High photon density

} > 10^{12} photons /pulse

- Europian XFEL
  - $\lambda_{FEL} \rightarrow 0.5$ Å
  - E=20GeV
  - Q=1nC
  - σ_z=24μm
  - ε≈1.4 mm
- Swiss FEL
  - $\lambda_{FEL} \rightarrow 0.8$ Å
  - E=5.8GeV,
  - Q=200pC
  - σ_z=7μm
  - ε≈ 200nm - 500nm
- Proposal of Ch. Adolphsen et al. shows concept for X-band
  - E=6GeV Q=250pC σz=8μm ε≈400nm-500nm

Example of Basic Parameters

Parameter	Unit	Parameter
Beam energy	GeV	6
Bunch charge	pC	250
Electron Energy	GeV	6
Emittance	μm	<0.5
Peak Current	kA	3
Energy Spread (sliced)	%	0.01
Undulator Period	mm	15
FEL wavelength	nm	0.1
Und. Strength	#	1
Mean Und Beta	m	15
Sat. Length	m	~60
Sat. Power	GW	~1
Pulse Length	fs	~15
Photons/Pulse	#	$\sim 5 \times 10^{10}$

Design considerations

- Resonanat wavelength of an FEL

$$\lambda_{FEL} = \frac{\lambda_u}{2\gamma^2}\left(1 + K_u^{\ 2}\right)$$

λ_u → undulator period lenth,
K_u → undulator strenght =0.94 B[T] λ_u[cm]
γ → electron beam energy

- FEL power grows exponentially with undulator distance

$$P_{1D} \propto \exp\left(\frac{z}{L_G}\right)$$

Gain Length

$$L_G = \lambda_u / \left(4\sqrt{3}\pi\rho\right)$$

Pierce parameter

$\rho \sim$ radiation power/beam power

Peak Current

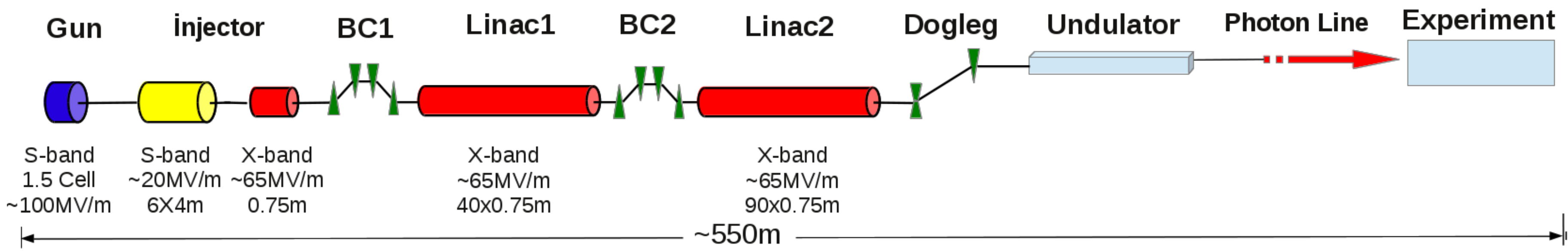
$$\frac{1}{\ }\left[I \ \lambda^2 K^2 f_B^{\ 2} \right]^{1/3}$$

Requires large period length and high undulator strength and small beam energy

Typical undulator period $\lambda_u = 15mm$	undulator period $\lambda_u = 25mm$
Typical undulator strength $K_{RMS} = 1$	undulator strength $K_{RMS} = 1.5$
$E = 6 \text{ GeV} \Rightarrow \lambda_{FEL} \approx 1 \text{ Å}$	$E = 10 \text{ GeV} \Rightarrow \lambda_{FEL} \approx 1 \text{ Å}$

Proposed Layout-1

S-Band based injector + X-Band based main accelerator

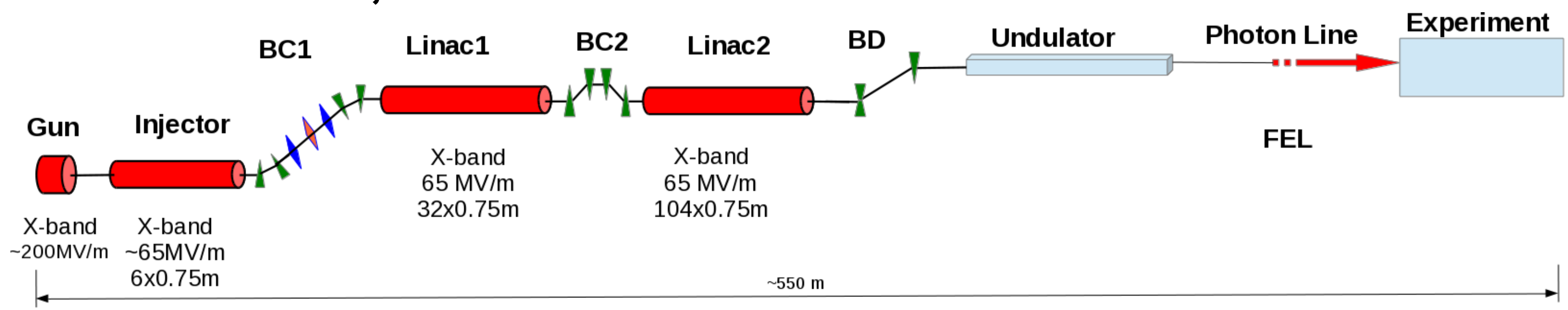


- <u>It consist of</u>

- RF photocathode gun → S band structure delivering beam @7 MeV with 250 pC charge, 9ps (800µm) lengt and 0.25 mm rad emittance
- Injector → consist of S-band structures and one X-band structure as linearizer, accelerating beam up to 300 MeV
- Two main linacs → consist of X-band modules, accelerating beam in two stage 0.3 GeV → 2 GeV and 2 GeV → 6 GeV
- Two bunch compressors , Beam delivery lines , Undulator(s), Laser transport line (s)

Proposed Layout-2

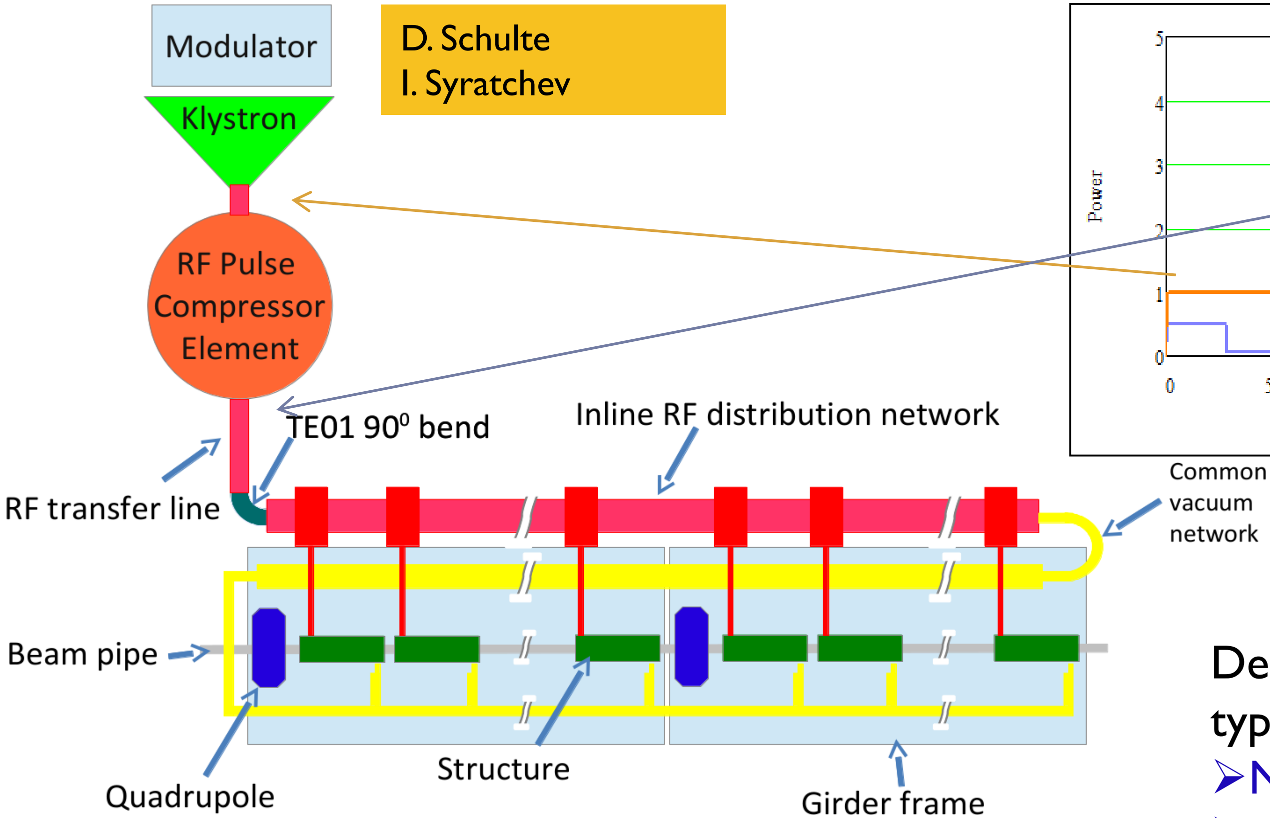
All X-Band based injector and main accelerator

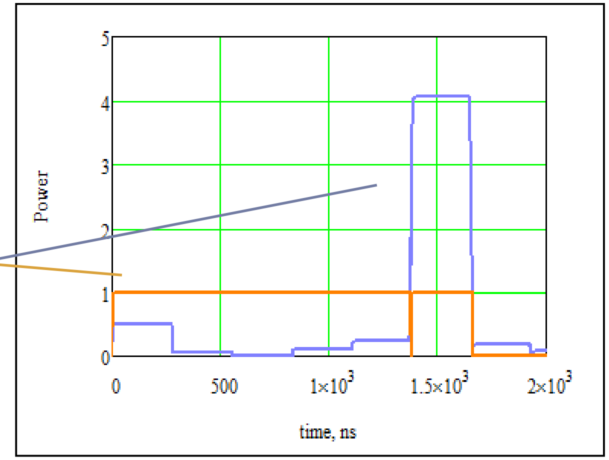


- <u>It consist of</u>

- RF photocathode gun → X band structure delivering beam @7 MeV with 250 pC charge, 2.5 ps (200µm) lengt and 0.45 mm rad emittance
- Injector → consist of X-band structures and one X-band structure to optimize chirp, accelerating beam up to 200 MeV
- Two main linacs → consist of X-band modules, accelerating beam in two stage 0.2 GeV → 1.5 GeV and 1.5 GeV → 6 GeV
- Two bunch compressors , Beam delivery lines , Undulator(s), Laser transport line (s)

Main Linac Module Layout





Depending on compressor type we can adjust

- N klystron
- N structure

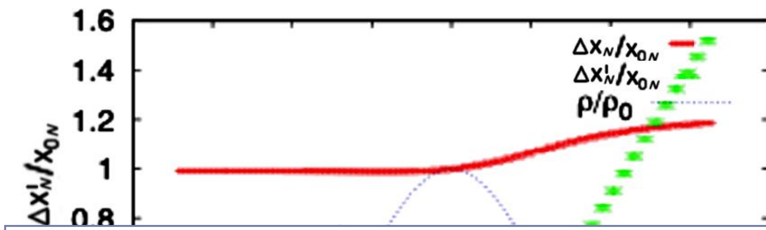
- **In case of using SLED type of pulse compressor**
  - **50 MW, 1.5 μs input power is compressed to 150 ns with 460 MW**
- This unit should provide ~516 MeV acceleration beam loading.
- Need ~14 RF structures.

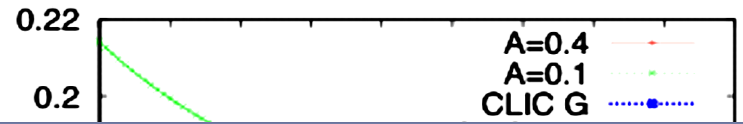
Structure choice;
Transverse wake effect &costs optimization

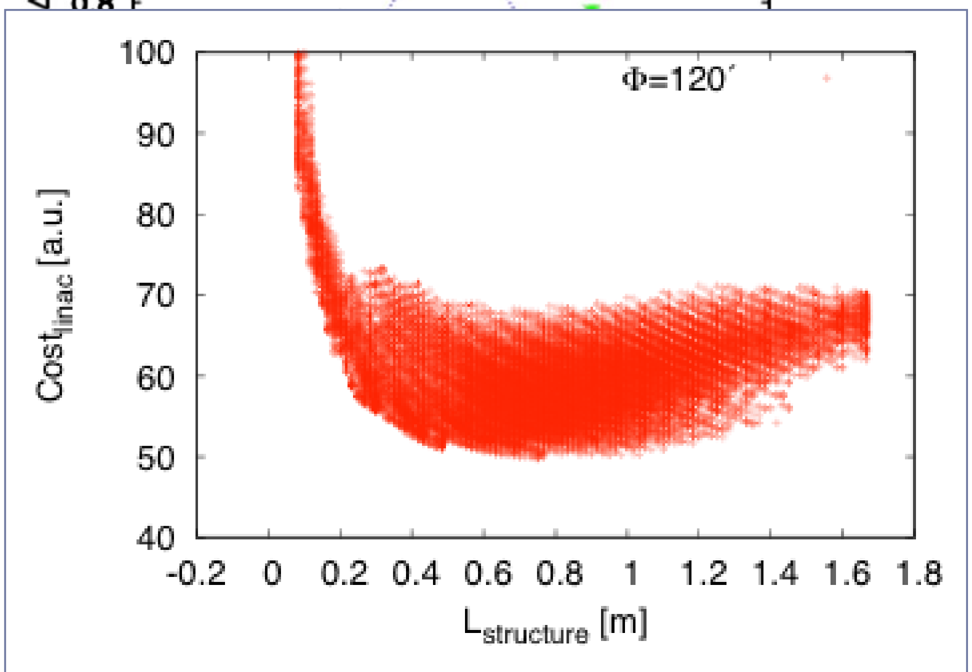
Stability requires small transverse deflection $$\frac{\Delta x}{x_0} \equiv A = Ne^2 \int_0^L \frac{\beta}{2E} \langle W_\perp \rangle ds$$

D. Schulte

Used CLIC lattice and simplified wakefield

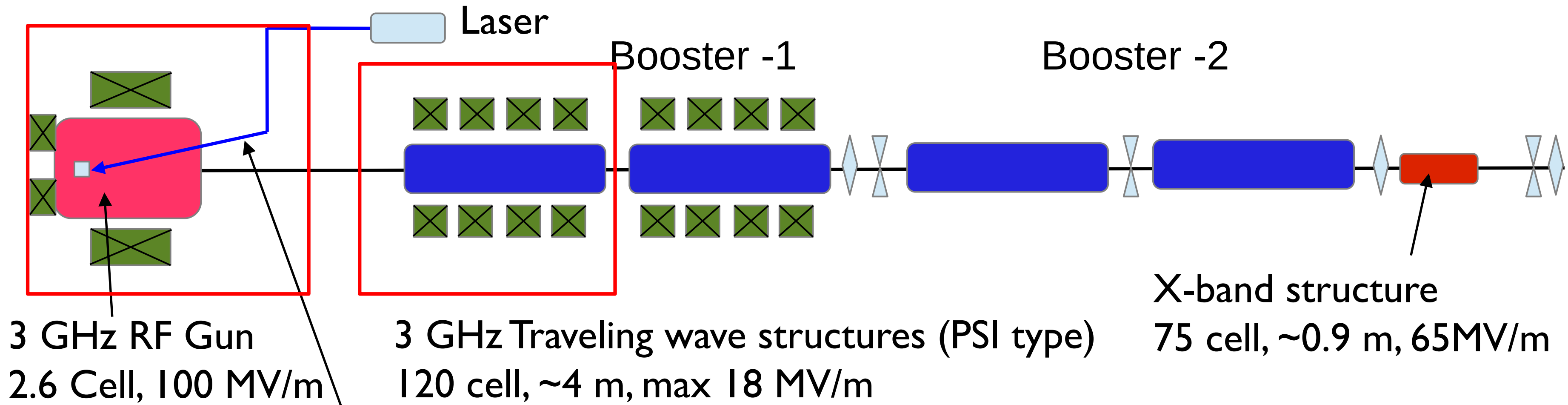


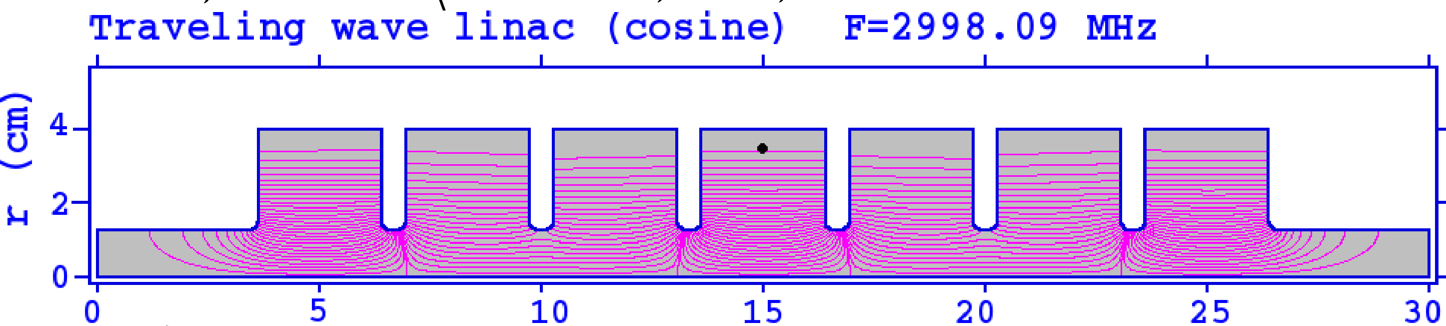


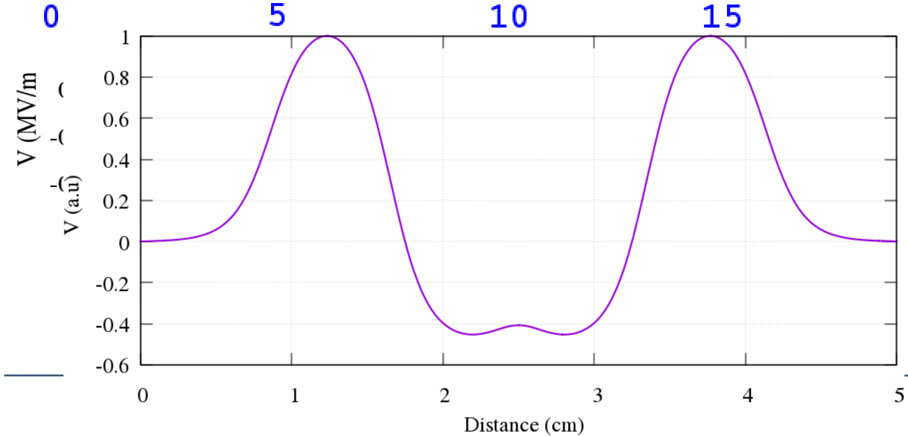


Structures per RF unit	10
Klystrons per RF unit	2
Structure length (m)	0.75
<a>/λ	0.125
Allowed gradient (MV/m)	80+
Operating gradient(MV/m)	65
Energy gain per RF unit (MeV)	488
RF units needed	14
Total klystrons	105
Linac active length m	88

S-band based Injector

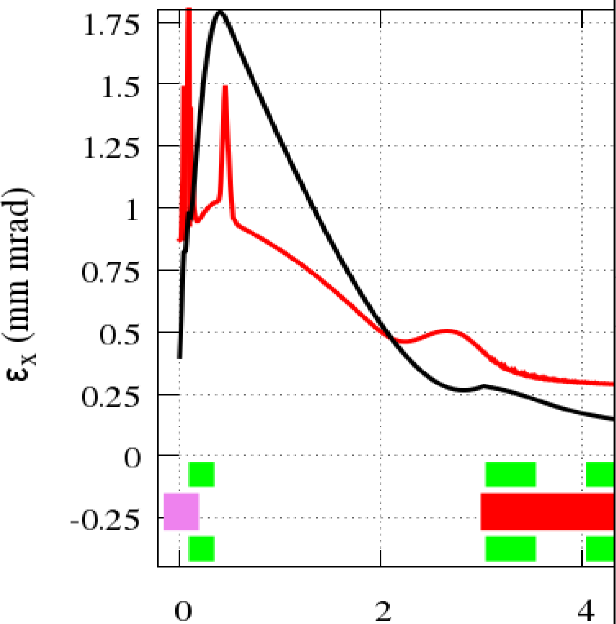


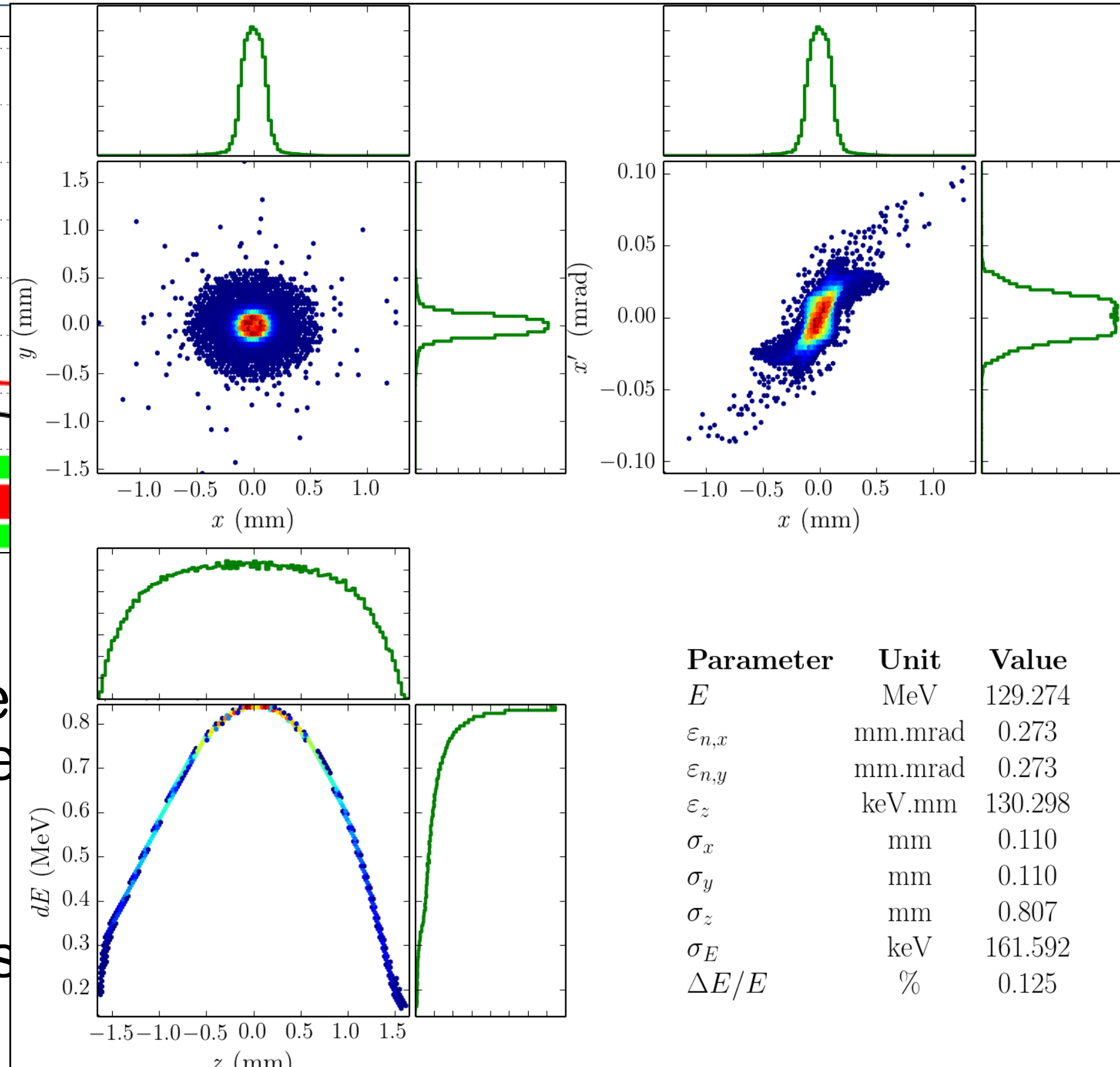




Parameter	Value	Unit
Frequency	3	GHz
Gradient	20	MV/m
Total lengt	4	m
Cell number	117+2	#

S-band Injector Optimization



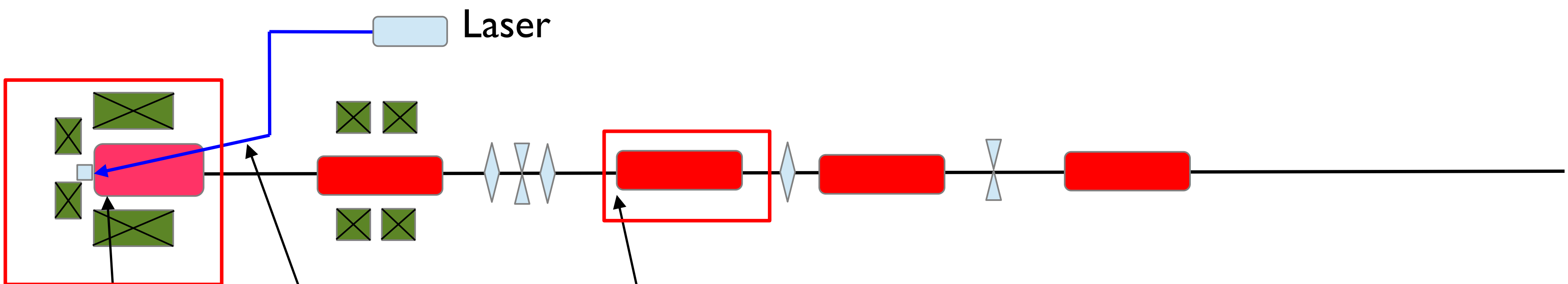


Parameter	Unit	Value
E	MeV	129.274
$\varepsilon_{n,x}$	mm.mrad	0.273
$\varepsilon_{n,y}$	mm.mrad	0.273
ε_z	keV.mm	130.298
σ_x	mm	0.110
σ_y	mm	0.110
σ_z	mm	0.807
σ_E	keV	161.592
$\Delta E/E$	%	0.125

z mm

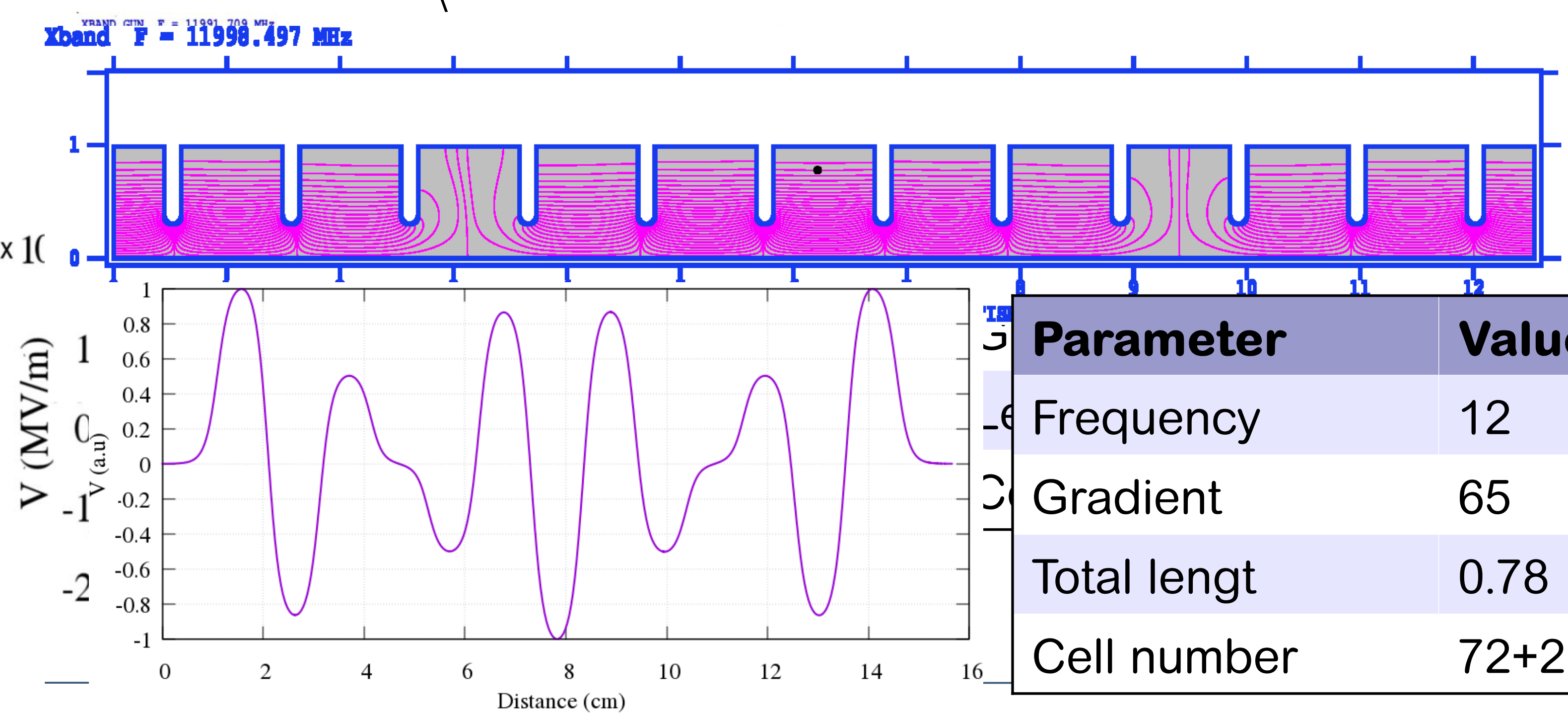
- Acceptable proje emittance has bee observed
- Sliced emittance optimized with mis parameter..

X-band based Injector



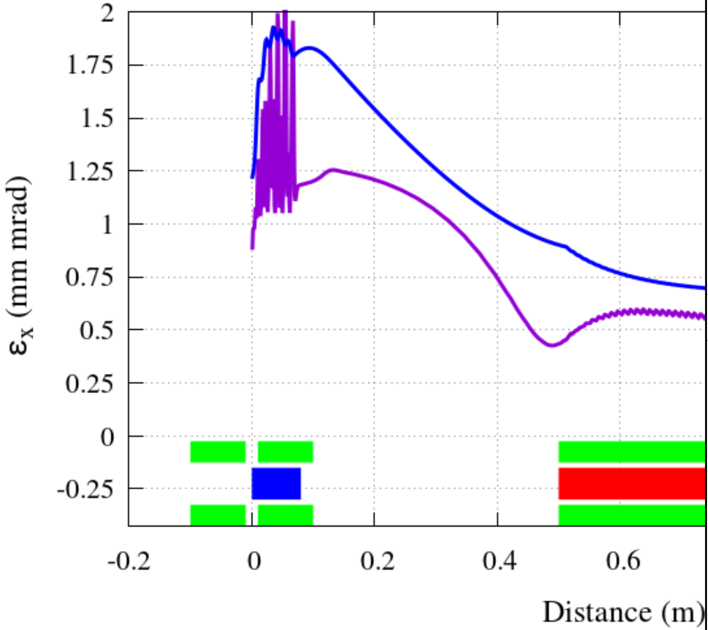
12 GHz RF Gun
5.6 Cell, 200 MV/m

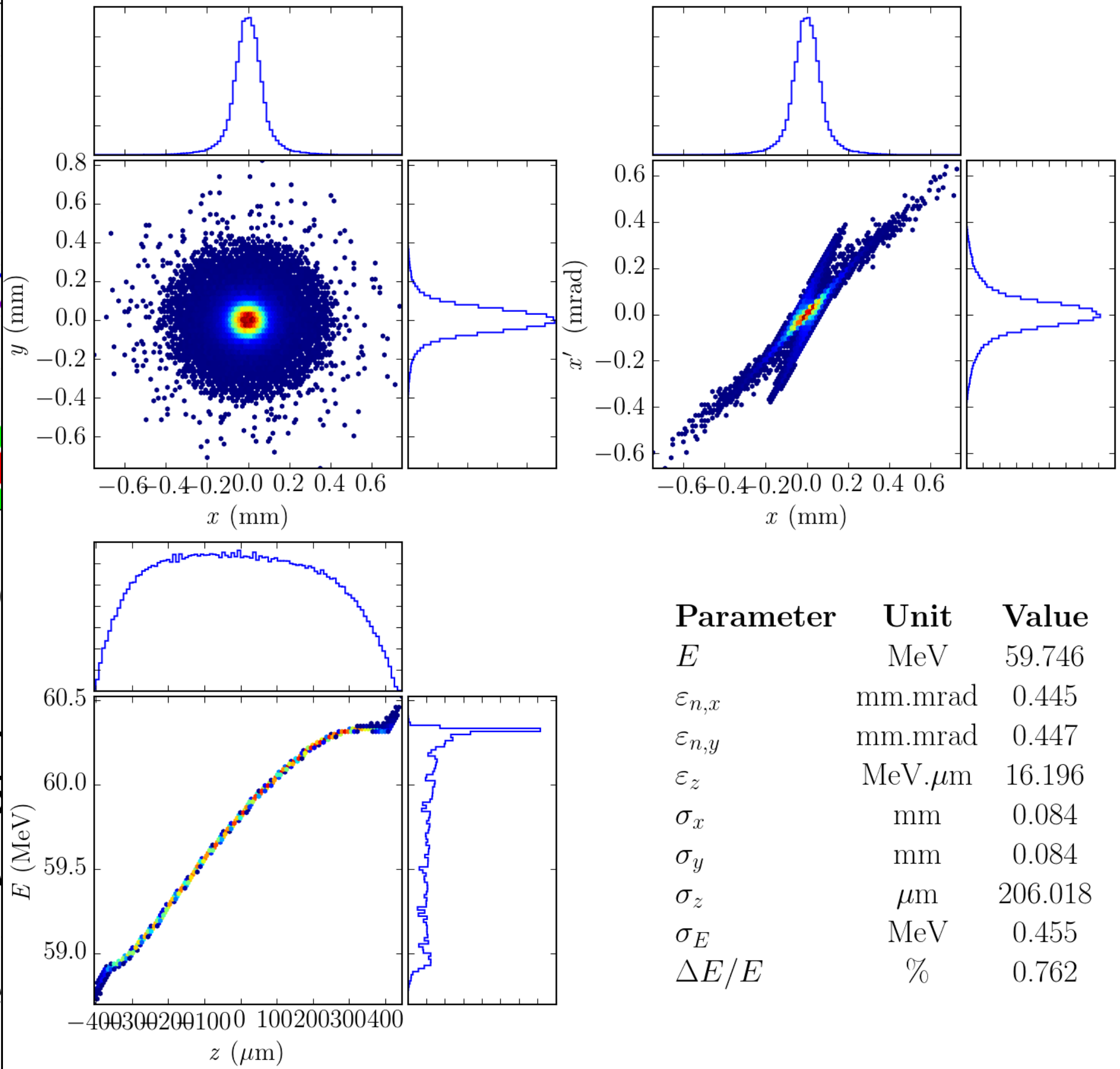
12 GHz Traveling wave structures
75 cell, ~0.9 m, 65MV/m, 150 degree



Parameter	Value	Unit
Frequency	12	GHz
Gradient	65	MV/m
Total lengt	0.78	m
Cell number	72+2	#

X-band Injector Optimization





Parameter	Unit	Value
E	MeV	59.746
$\varepsilon_{n,x}$	mm.mrad	0.445
$\varepsilon_{n,y}$	mm.mrad	0.447
ε_z	MeV.μm	16.196
σ_x	mm	0.084
σ_y	mm	0.084
σ_z	μm	206.018
σ_E	MeV	0.455
$\Delta E/E$	%	0.762

- For better projected emittance x band structur are very close to gun. (0.5
- Projected emittance is tw worse than s-band based
- Sliced emittance is close

Wake poetantials ↔ Bunch charge distribution

- FEL gain mechanism requires
  - Minimum sliced emittance
  - Minimum sliced energy spread

Instability is driven by strong wake field of high frequency structure.

To reduce the wake effect → Optimize charge distribution

Transverse wake potential

$$V_\perp(s) = \int_{-\infty}^{s} ds' \lambda(s') W_\perp(s - s')$$

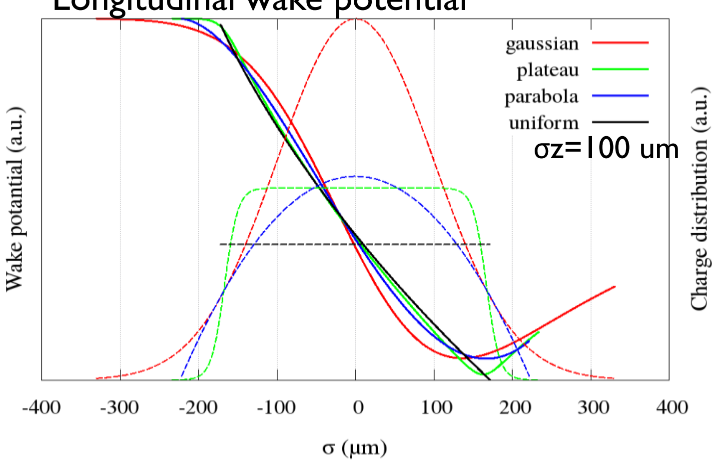
Causes transverse deflection along bunch

Lo

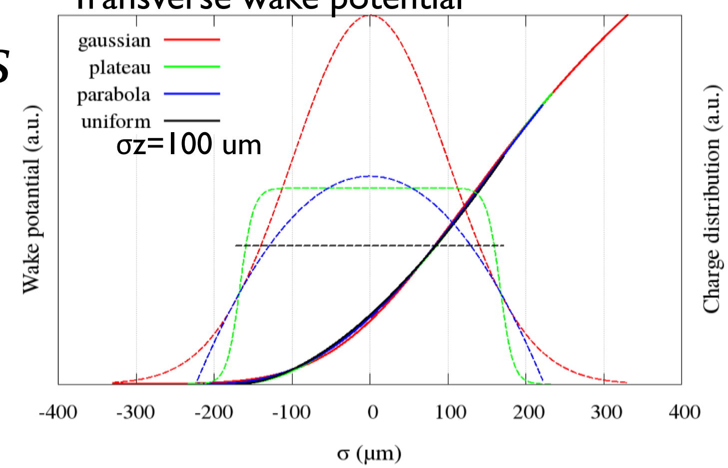
$$\int_{-\infty}^{s} ds' \lambda(s$$

e

Longitudinal wake potential



Transverse wake potential



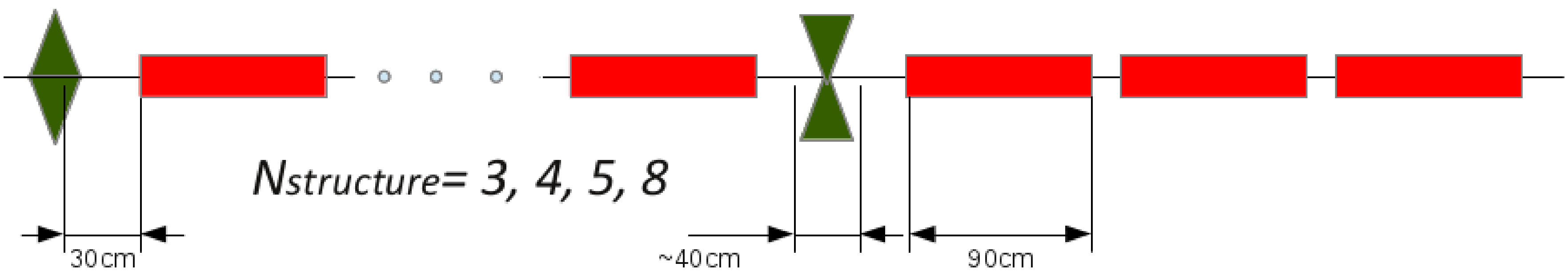
- For both transverse and longitudinal case
  - uniform bunch distribution and no tail is preferred
  - Bunch distribution is fixed in injector → try to make it uniform on bunch compressors

Transverse beam dynamics

- The transverse deflection of beam is proportional

$$\Delta x_N \propto \int_0^L \frac{\beta(s')}{E(s')} ds', \qquad \Delta x'_N \propto \int_0^L \frac{\beta(s')}{E(s')} ds',$$ → Minimize β functions

- FODO type of lattice is proposed
- In order to optimize phase advance per cell and minimize β functions we propose different number of structures per one FODO cell



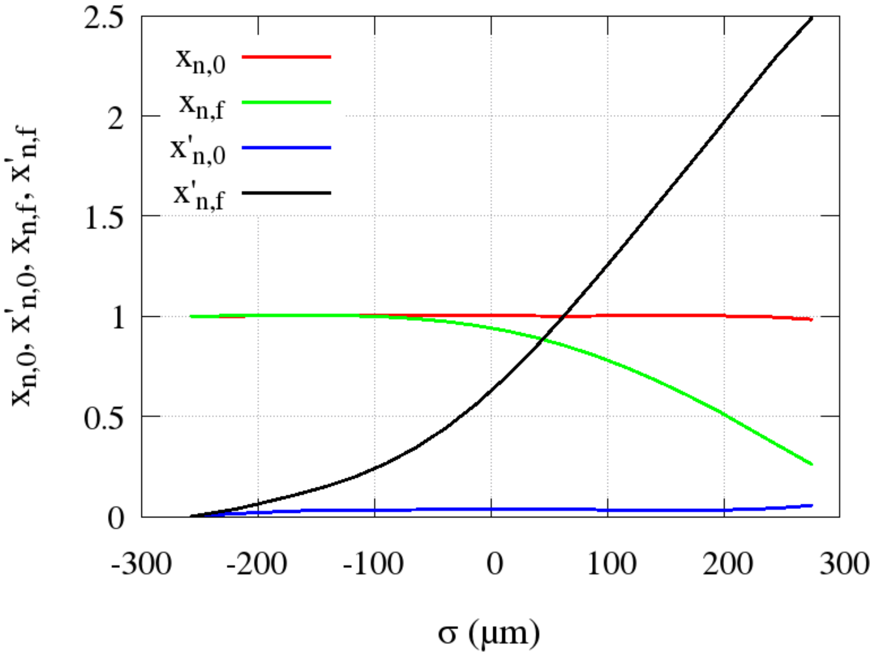
The most critical section is the injector and linac 1 since the energy is low and bunch length is long

Transverse deflection in Linac 1

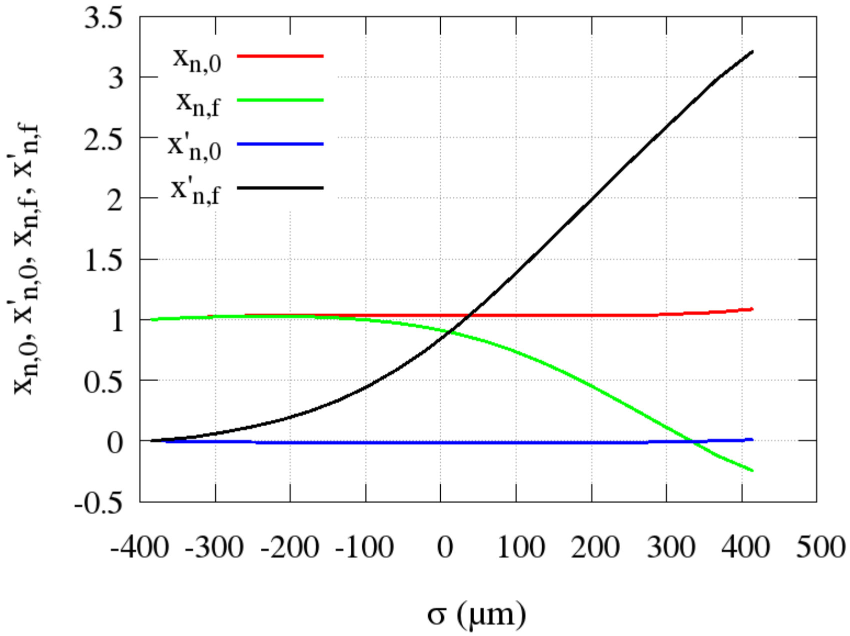
Plots show the transverse deflection of coordinate (x) and angle (x’) of slices along the bunch in linac 1 for a Gaussian bunch.

The lattice houses 10 structure per FODO cell.

σz= 100μm



σz= 150μm

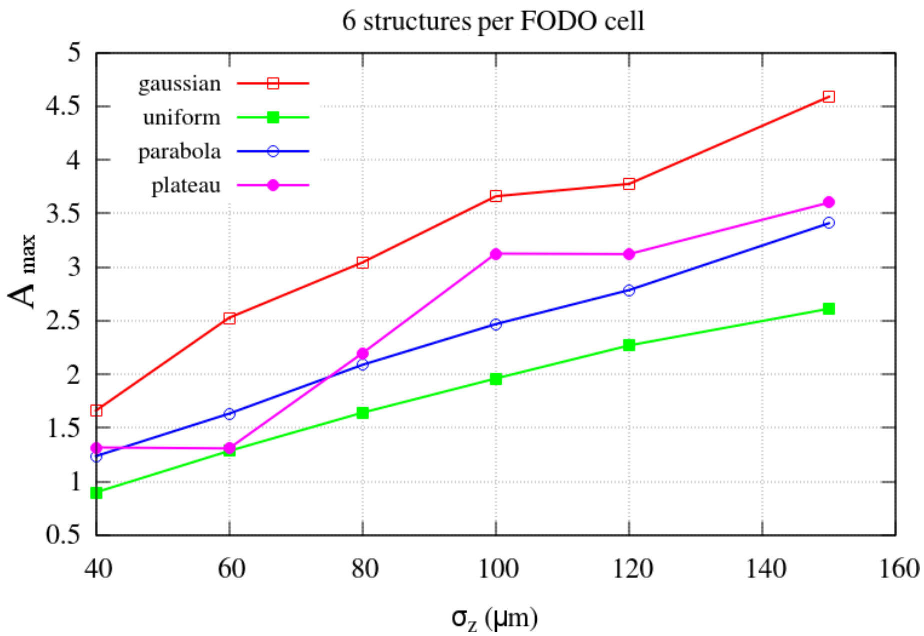


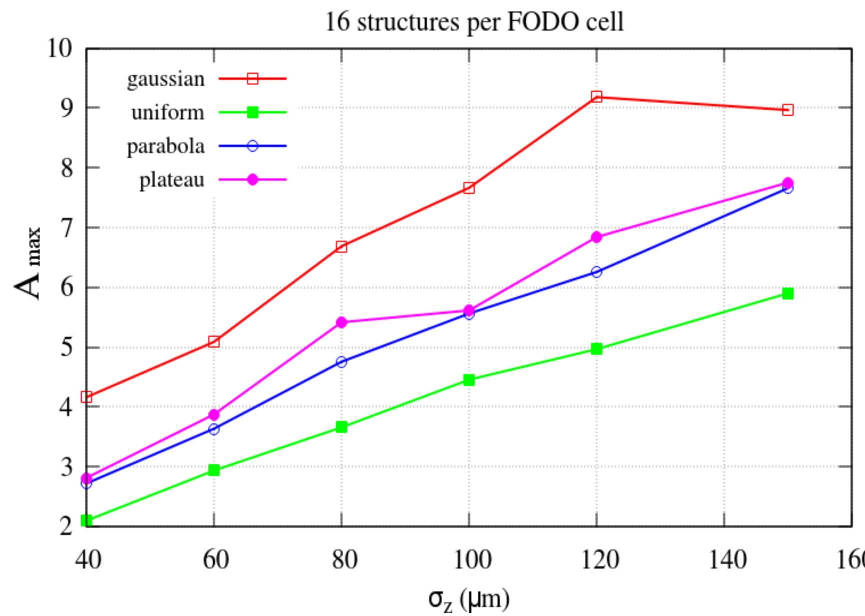
For compression of lattices and bunch profile we check

$$Amp_x = \frac{1}{x_N(0)}\sqrt{x_N^2(L) + x_N'^2(L)}.$$

The amplification on Linac - 1

- The amplification for different bunch charge distribution on a lattice that has FODO cell with 6 structure per cell and 16 structure per cell

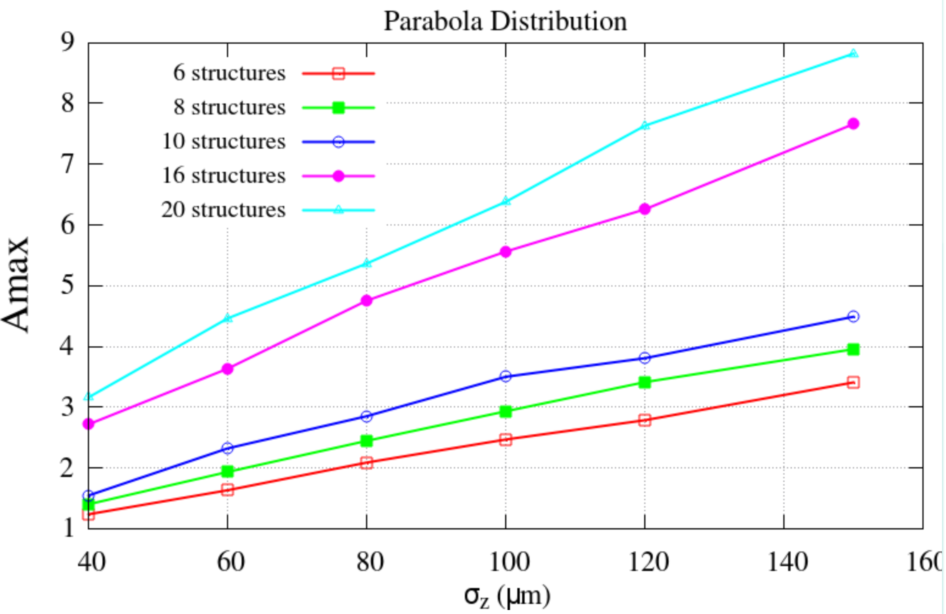


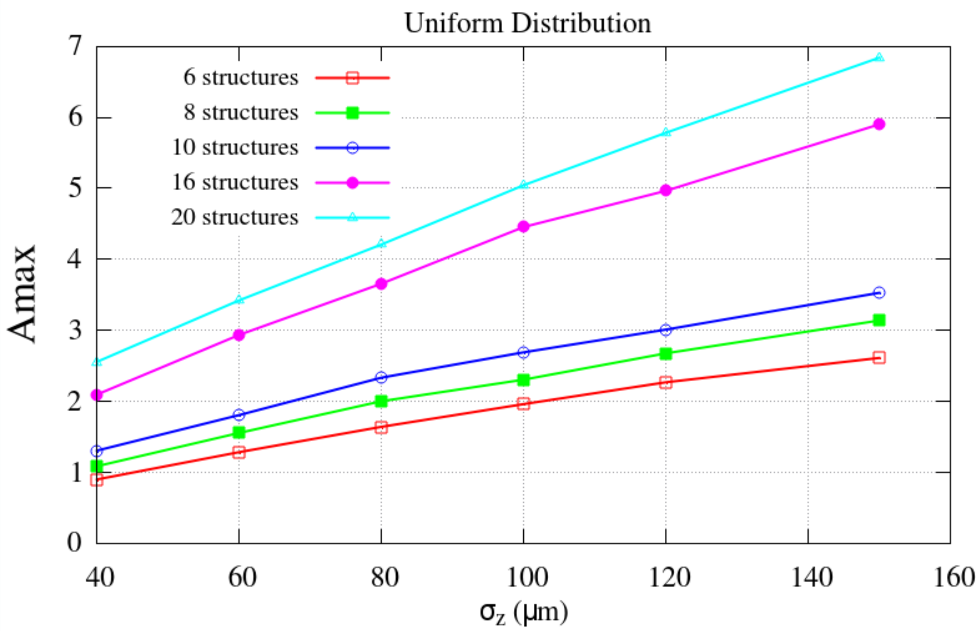


- The uniform charge distribution has lowest amplification.
- In order to get lower amplification factor than 1.5 we need to have bunch length **σz < 70 μm**

The amplification on Linac – 1 (compression rate)

- The amplification of uniform and parabolic charge distribution on different type of lattices



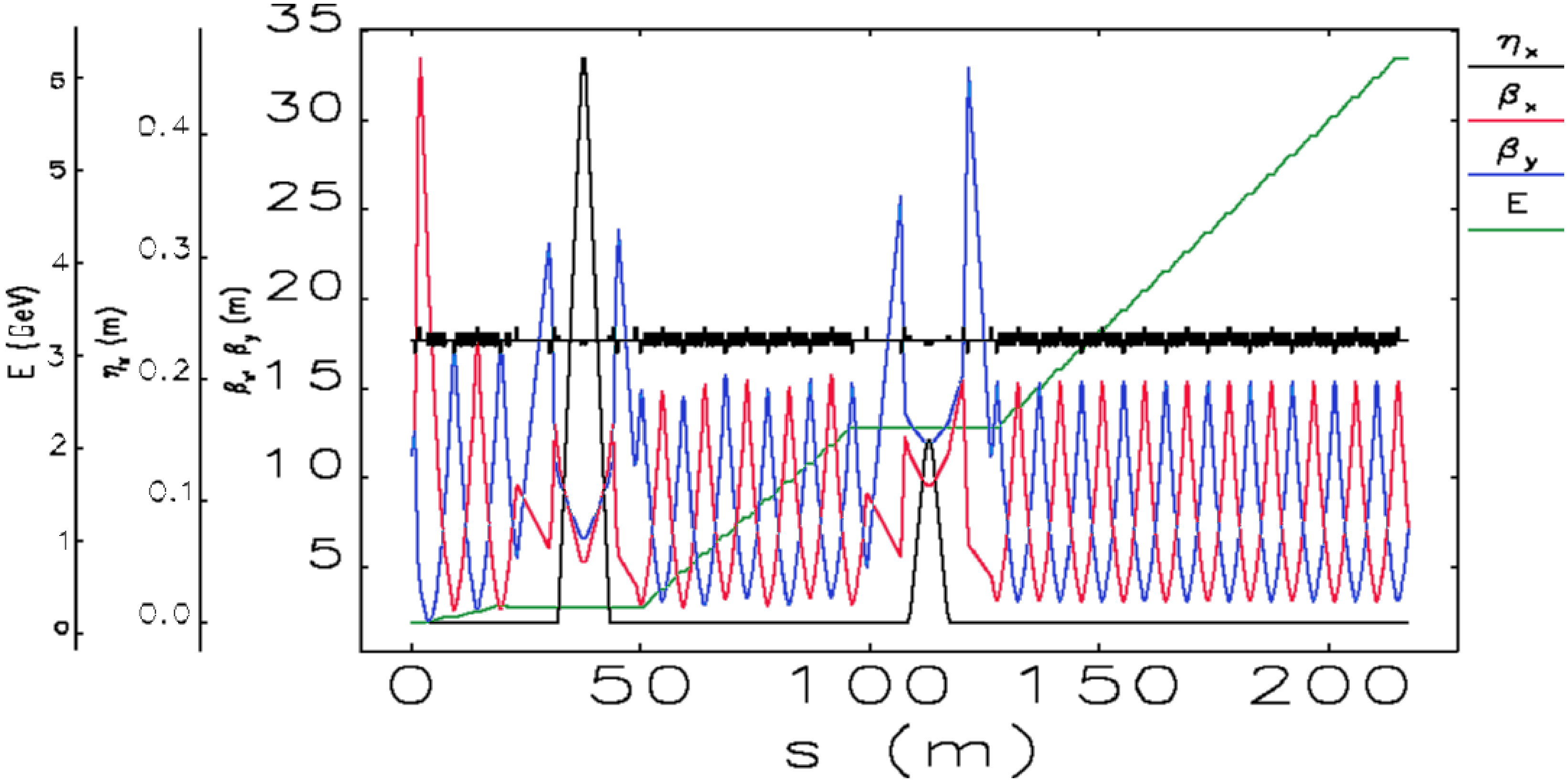


In order to get lower amplification factor less than 2

- The bunch length must be less than 80 μm
- Number of structures per FODO must be less than 8

The lattice for Layout 1

- We have proposed FODO type of lattice on which 8 structures located in one cell



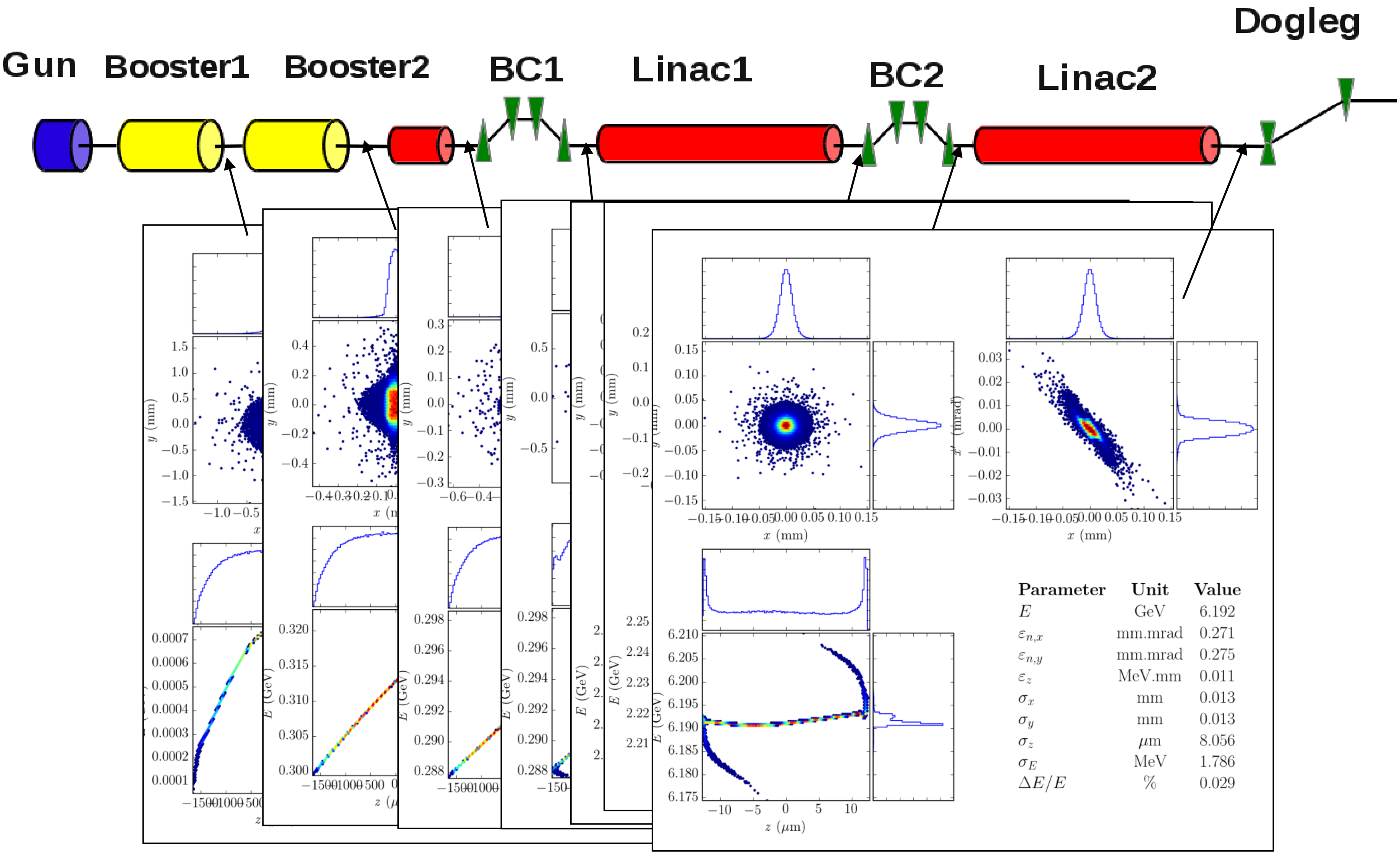
Linac 1: 40 x-band strcuture, phase 25 degre

Linac 1: 80 x-band strcuture, phase 3 degre

BC1 R56=-0.082

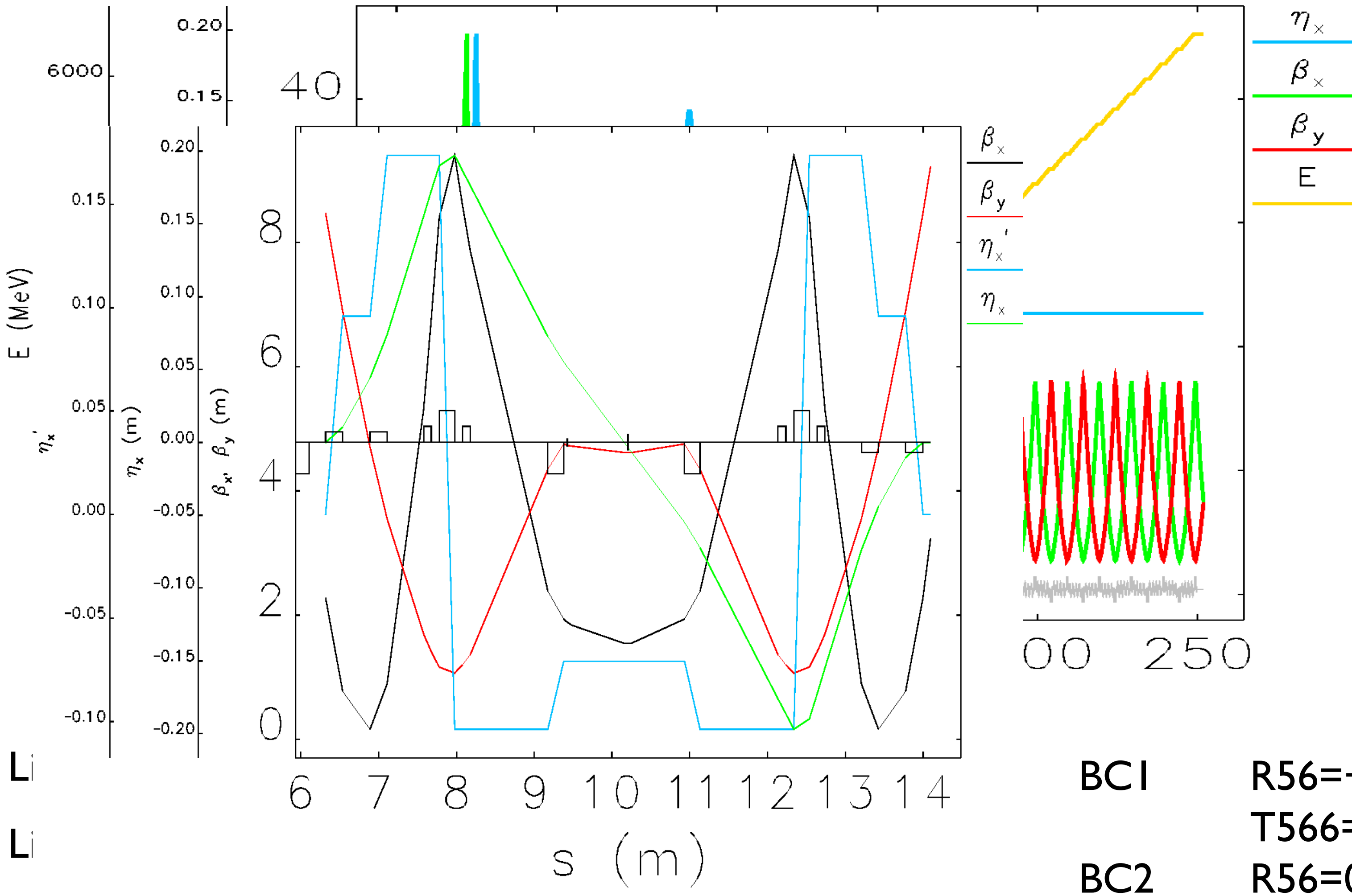
BC2 R56=-0.011

Layout -1
Longitudinal phase space along beam line



The lattice for Layout 2

- Same as S+X band based we have proposed FODO type of lattice on which 8 structures located in one cell

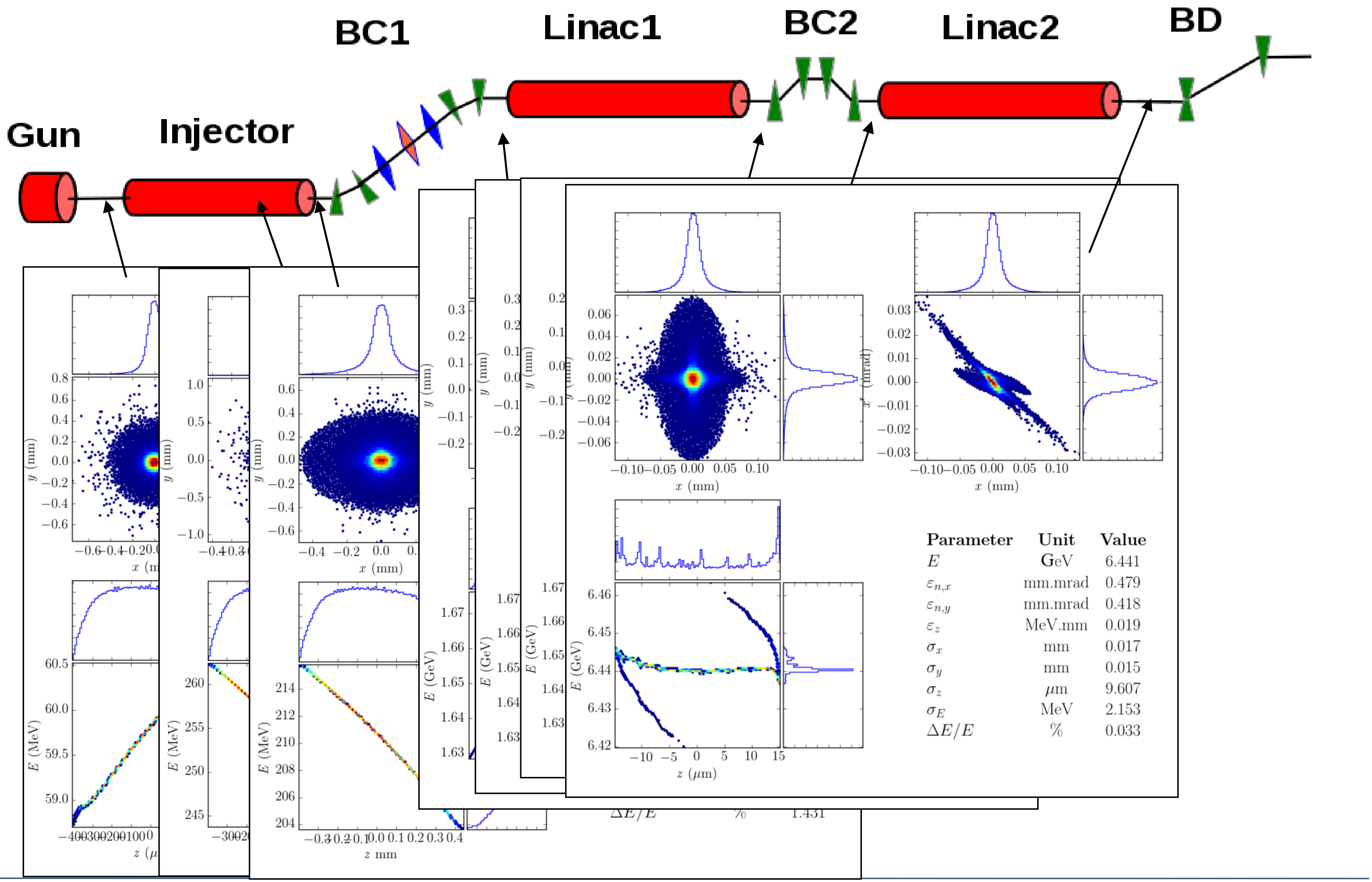


Li

Li

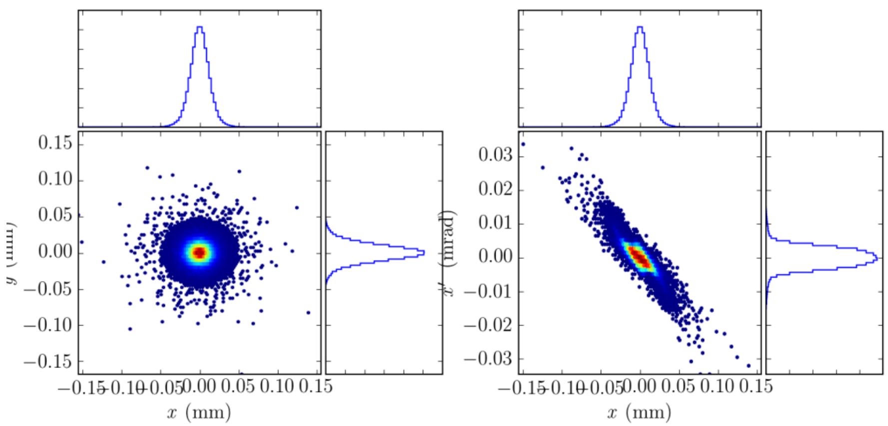
BC1	R56=+0.001
	T566=0.04
BC2	R56=0.011

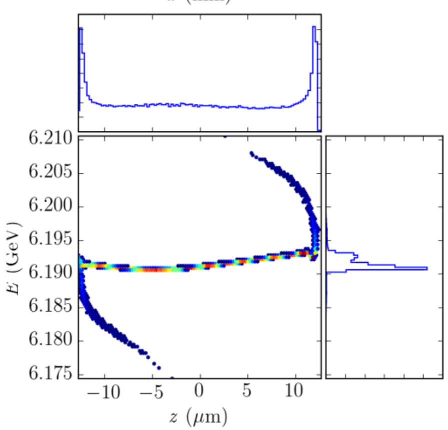
Layout -2
Longitudinal phase space along beam line



Comperasion

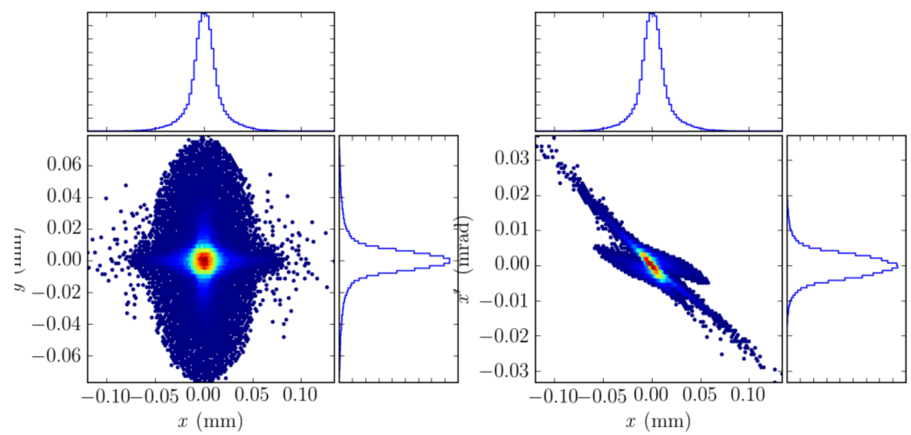
Final bunch @ S+X band layout

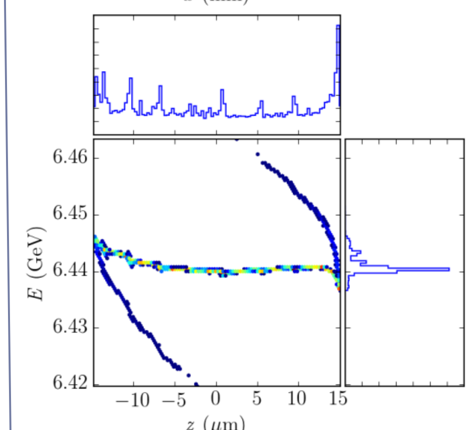




Parameter	Unit	Value
E	GeV	6.192
$\varepsilon_{n,x}$	mm.mrad	0.271
$\varepsilon_{n,y}$	mm.mrad	0.275
ε_z	MeV.mm	0.011
σ_x	mm	0.013
σ_y	mm	0.013
σ_z	μm	8.056
σ_E	MeV	1.786
$\Delta E/E$	%	0.029

Final bunch @ All X-band layout



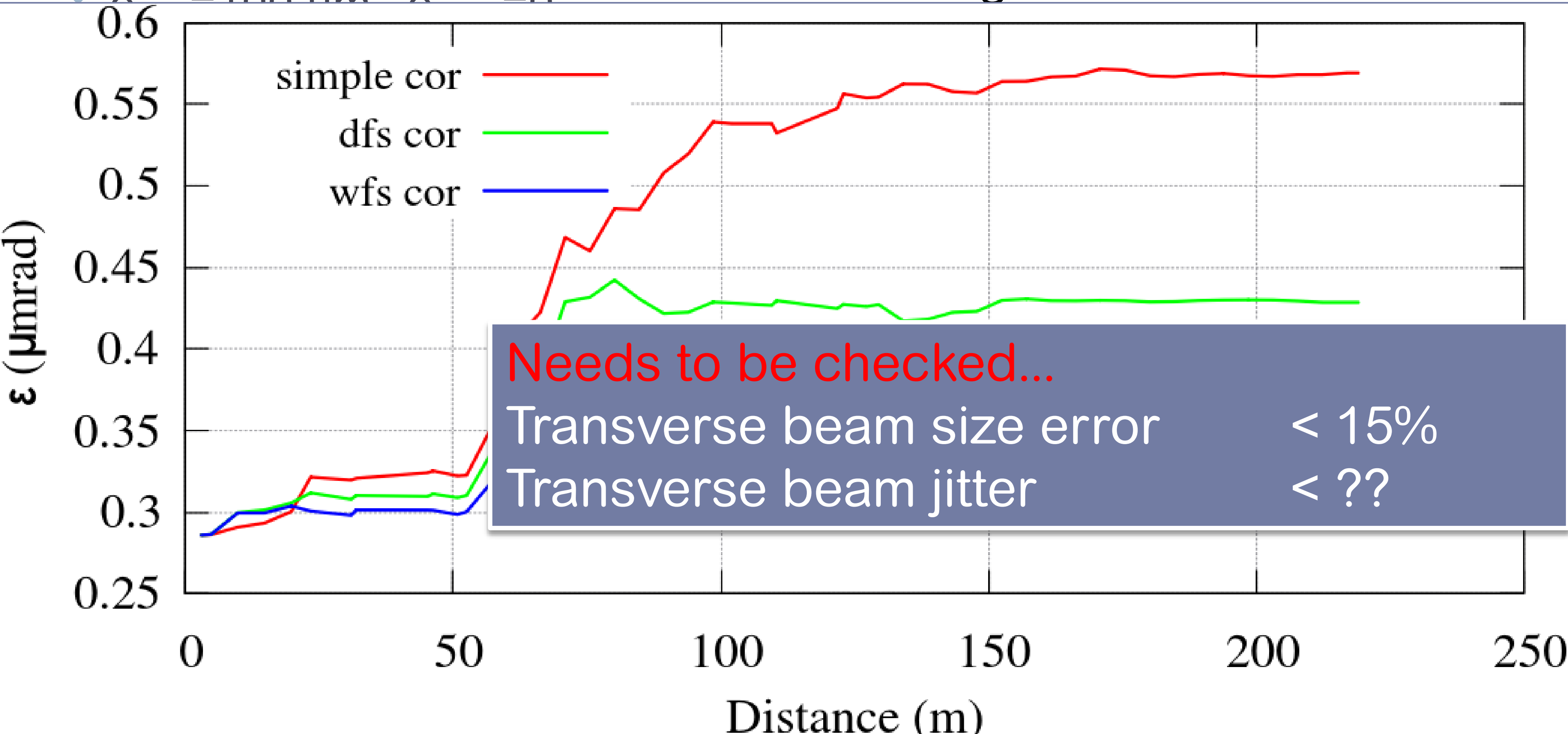


Parameter	Unit	Value
E	GeV	6.441
$\varepsilon_{n,x}$	mm.mrad	0.479
$\varepsilon_{n,y}$	mm.mrad	0.418
ε_z	MeV.mm	0.019
σ_x	mm	0.017
σ_y	mm	0.015
σ_z	μm	9.607
σ_E	MeV	2.153
$\Delta E/E$	%	0.033

Emittance growth due to missalingment for S+X-band layout

Assumed all elements are scattered along beamline with an rms error

- Quadrupoles ;
- S-band structures are located on single frame



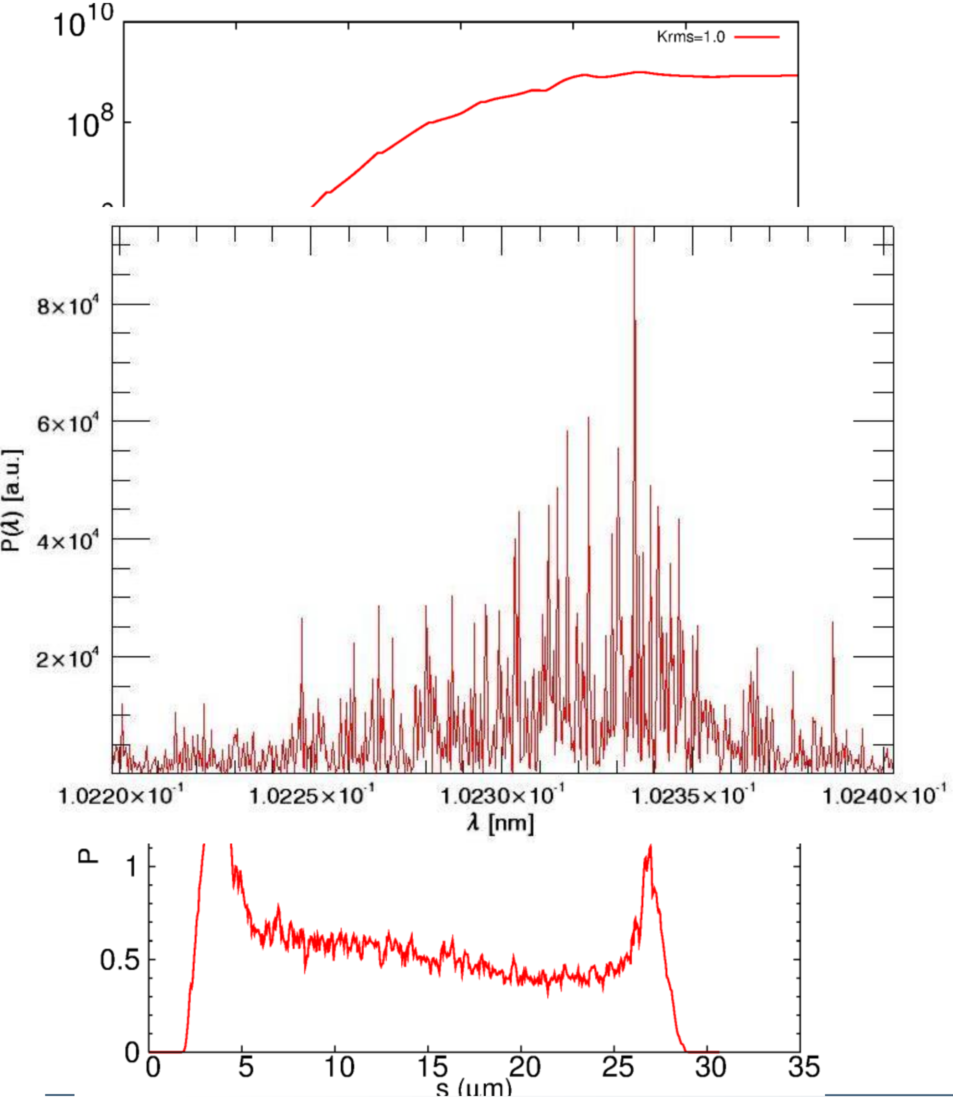
Needs to be checked...

Transverse beam size error < 15%

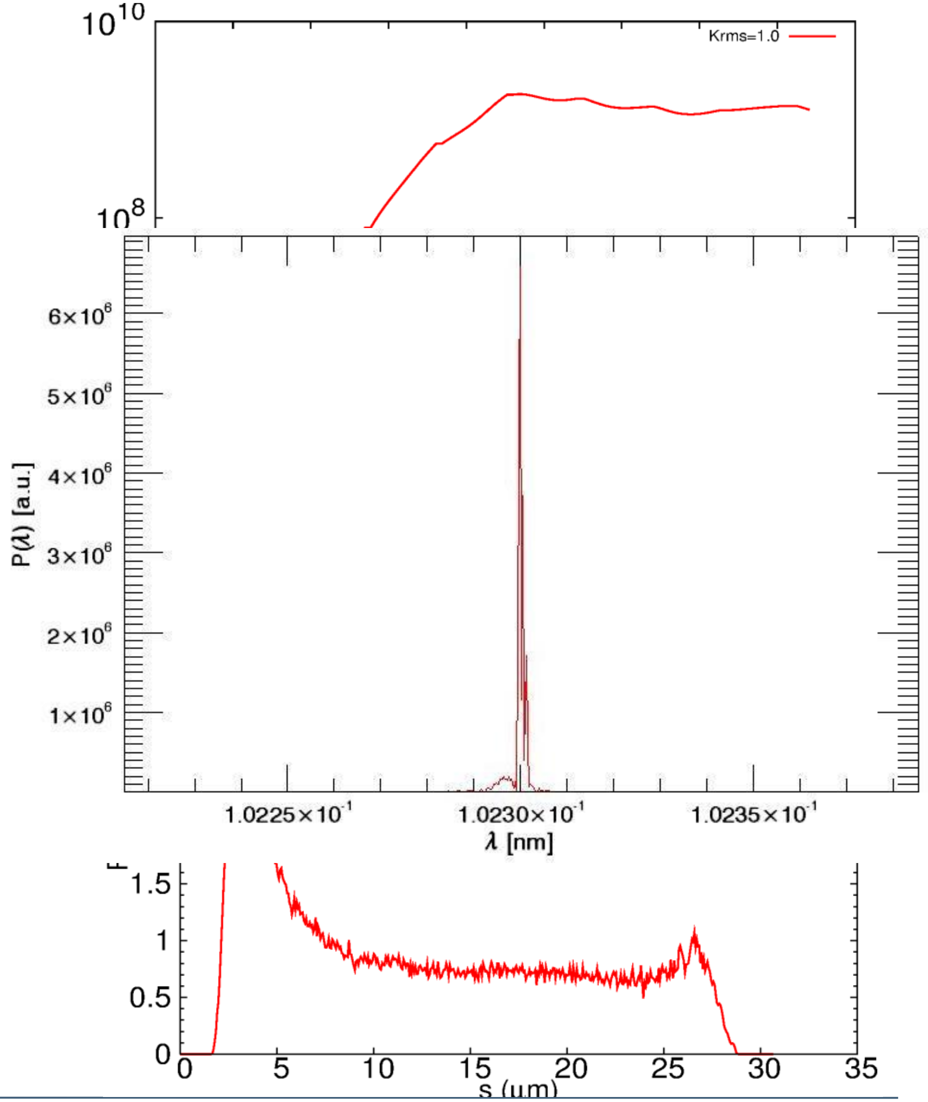
Transverse beam jitter < ??

Sample FEL simulation for 1 Å FEL
(FODO type of lattice housing 2x4m undulator)

For SASE mode



For Seeded mode



Conclusion

- An injector based on S-band and X-band based structures has been preliminary designed
- The beam dynamics issues for Main linac sections based on CLIC X-Band structure has almost been complated
- We have shown that CLIC X-Band structure is sufficient to generate FEL
  - Incase of using the structure with given a/λ effective length
    - 8 structures per one FODO cell with <β>=8m fulfills transverse stability requirements agains transverse wakefields.
- All X-band layout will be useful for going hih repetition rate up to 500 Hz..
  - However the gun still under developlopment @ SLAC
- For S-band based injector layout the beam proporties are much better.
  - S-band based injector is used in many laboratories
- Previously we have shown that
    - $\delta G_{rf}=0.05\%$ and $\delta\Phi_{rf}=0.05^{\circ}$ errors seems to fulfill the longitudinal requirements
- Needs to be checked
    - Dipole and Quadrupole field errors
    - CSR effect
    - The effect of transverse beam jitter and size oscillations to FEL perfomance
    - ….

Thank you for your attention!