



# **Beam Dynamics for 6 GeV X-FEL Design Using X-Band Structure**

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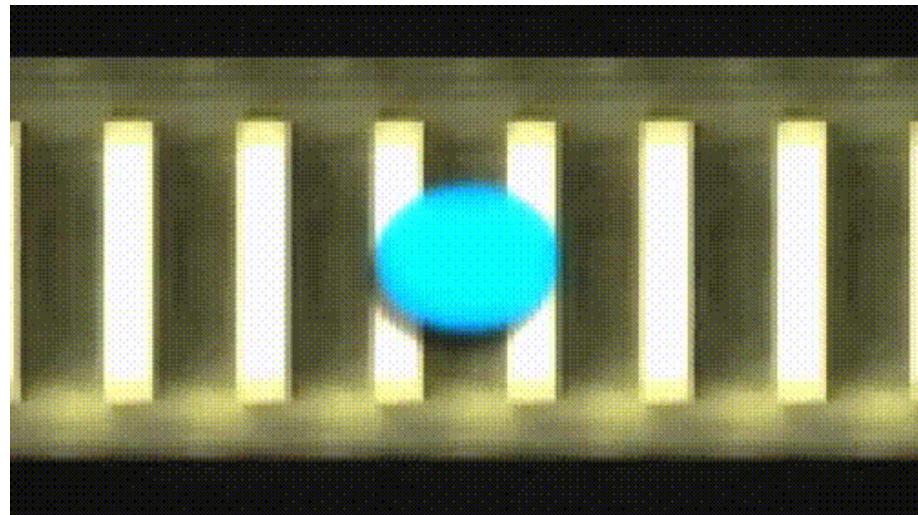
# Outline

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- ▶ Introduction
- ▶ Proposed layout
- ▶ Injector
- ▶ Main accelerating section
  - Transverse beam dynamics
  - Longitudinal beam dynamics
- ▶ Sample FEL simulation
- ▶ Conclusion

# Free electron laser

- ▶ It is produced by the resonant interaction of a relativistic electron beam with a photon beam in an undulator



## Tunable, Powerful, Coherent radiation sources

- First operation of a free-electron laser at Stanford University in 1977
- Today
  - 22 free-electron lasers operating worldwide
  - >20 FELs proposed or in construction

# User 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

## □ European XFEL

- $\lambda_{\text{FEL}} \rightarrow 0.5 \text{ \AA}$
- $E=20\text{GeV}$
- $Q=1\text{nC}$
- $\sigma_z=24\mu\text{m}$
- $\varepsilon \approx 1.4 \text{ mm}$

## □ Swiss FEL

- $\lambda_{\text{FEL}} \rightarrow 0.8 \text{ \AA}$
- $E=5.8\text{GeV}$ ,
- $Q=200\text{pC}$
- $\sigma_z=7\mu\text{m}$
- $\varepsilon \approx 200\text{nm} - 500\text{nm}$

## □ Proposal of Ch. Adolphsen et al. shows concept for X-band

- $E=6\text{GeV}$      $Q=250\text{pC}$      $\sigma_z=8\mu\text{m}$      $\varepsilon \approx 400\text{nm}-500\text{nm}$

# Design considerations

## ► Resonant wavelength of an FEL

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

$\lambda_u$  → undulator period length,  
 $K_u$  → undulator strength  
 $\gamma$  → 0.94 B[T]  $\lambda_u$  [cm]  
→ electron beam energy

## ► FEL power grows exponentially with undulator distance

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

Gain Length  $L_G = \lambda_u / (4\sqrt{3}\pi\rho)$  Pierce parameter  $\rho \sim$  radiation power/beam power

Peak Current  $I$

Emittance  $I_A$

Beta function  $\beta_x$

$$\rho = \frac{1}{4\gamma} \left[ \frac{I}{I_A} \frac{\lambda_u^2 K_u^2 f_B^2}{\pi^2 \varepsilon_x \beta_x} \right]^{1/3}$$

Period length and strength can not be too small

Typical undulator period  $\lambda_u = 15\text{mm}$

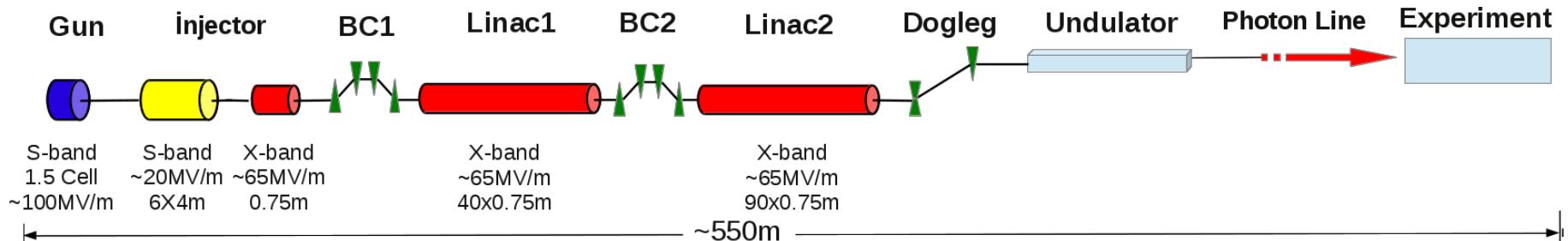
Typical undulator strength  $K = 1.1 - 1.9$

$$E = 6 \text{ GeV} \Rightarrow \lambda_{FEL} \approx 1 \text{ \AA}$$

# Example of Basic Parameters

Parameter	Unit	LCLS	SwissFEL	X-band FEL
FEL wavelength	nm	0.25	0.1	0.1
Bunch charge	pC	250	200	250
Electron Energy	GeV	14	5.8	6
Emittance	μm	0.4 - 0.6	0.4 - 0.6	<0.5
Peak Current	kA	3	2.7	3
Energy Spread	%	0.01	0.01	0.01
Undulator Period	mm	30	15	15
Und. Strength	#	3.5	1.2	1.2
Mean Und Beta	m	30	15	15
Sat. Length	m	60	45	~50
Sat. Power	GW	30	2	~5
Pulse Length	fs	80	13	~15
Photons/Pulse	#	$2 \times 10^{12}$	$3.32 \times 10^{10}$	$\sim 5 \times 10^{10}$

# Proposed Layout



## ► It consist of

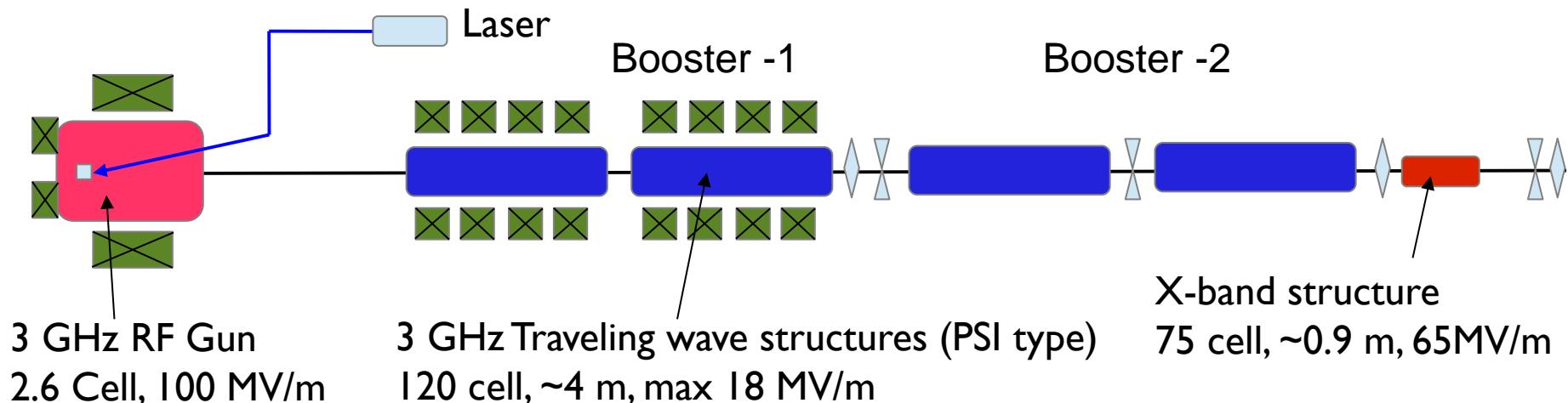
- RF photocathode gun → S band structure delivering beam @7 MeV with 250 pC charge, 2.5 ps ( $800\mu\text{m}$ ) lenght and 0.25 mm rad emittance
- Injector → consist of S-band structures and one X-band structure as linearizer, accelerating beam up to 300 MeV
- Two main linacs → consist of X-band modules, accelerating beam in two stage  $0.3 \text{ GeV} \rightarrow 2 \text{ GeV}$  and  $2 \text{ GeV} \rightarrow 6 \text{ GeV}$
- Two bunch compressors , Beam delivery lines , Undulator(s), Laser transport line

## ► The advantage of using X-band:

- Compact reduction of length with high gradient (SwissFEL  $\sim 750 \text{ m}$ )
- Costs reduction
- Possibility to go to a high repetition rate (up to kHz regime)

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  - ▶ **Injector**
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# RF gun & Injector optimization



Optimization goal →

minimum projected emittance,  
minimum sliced emittance  
minimum bunch length

## Laser parameters

- Laser pulse length?
- Laser spot size?
- ...

## Gun parameters

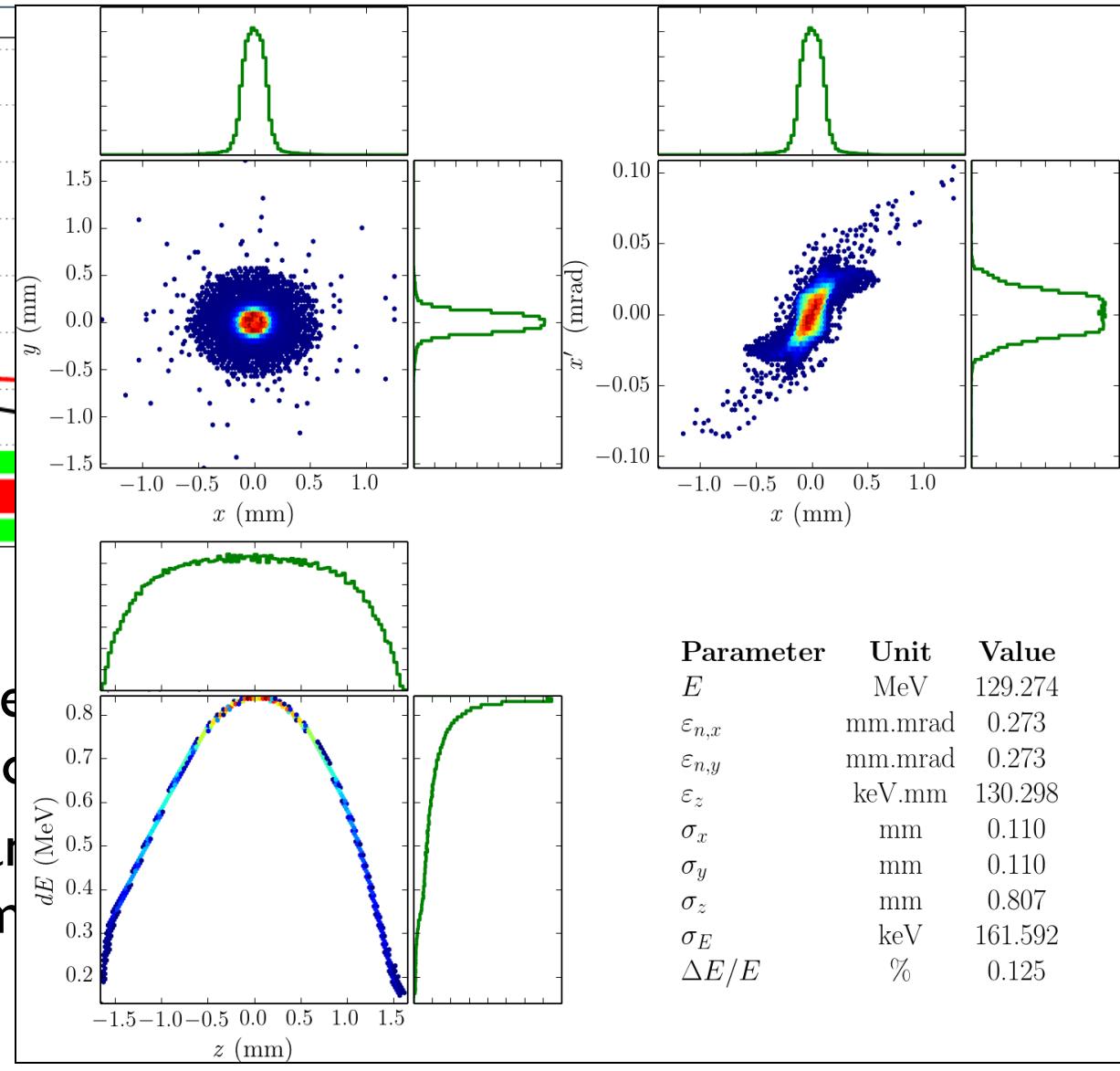
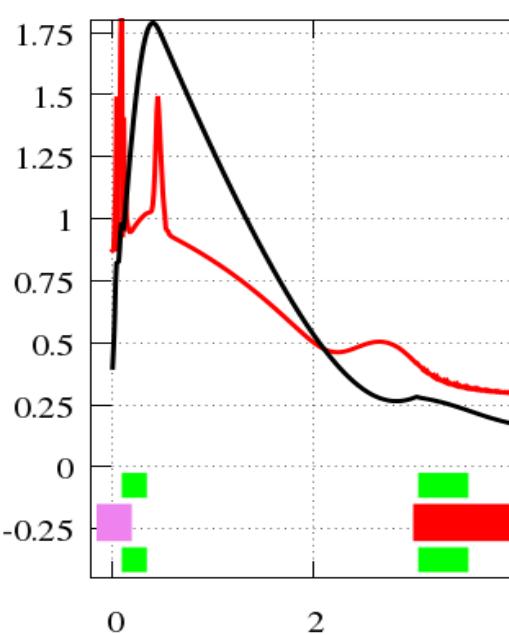
- Gradient-phase?
- Bunch charge?
- Solenoid fields and positions?
- ...

## Injector structure

- Gradient?
- Position of structure?
- Position of structure?
- ....

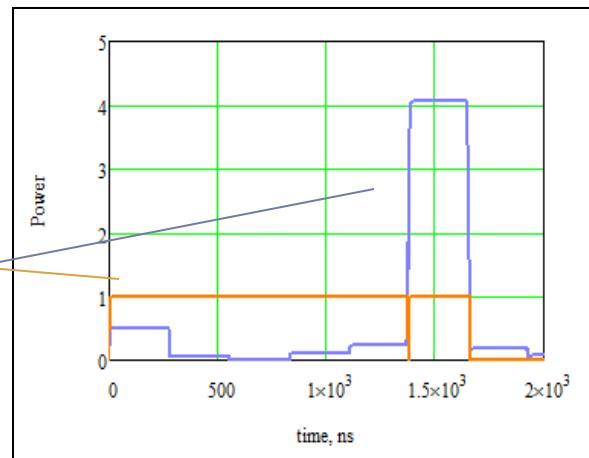
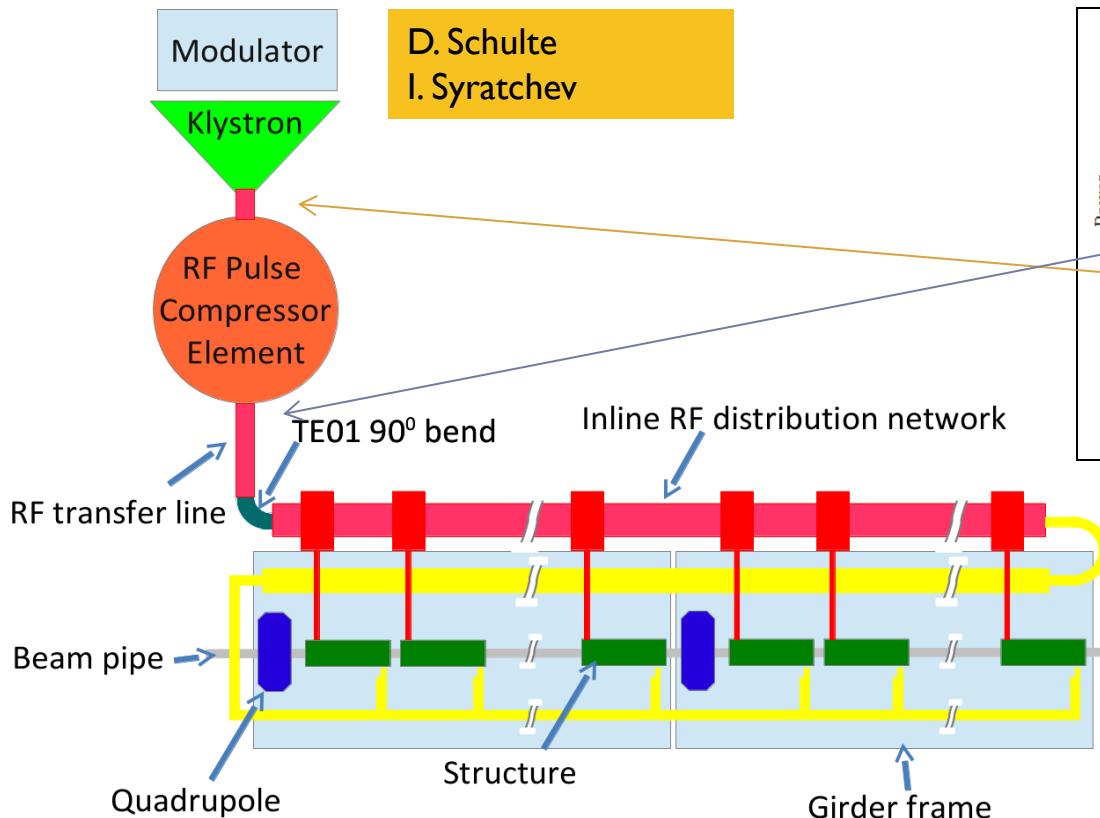
# Injector Optimization

$\epsilon_x$  (mm mrad)



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# Main Linac Module Layout



Depending on compressor type we can adjust  
➤ N klystron  
➤ N structure

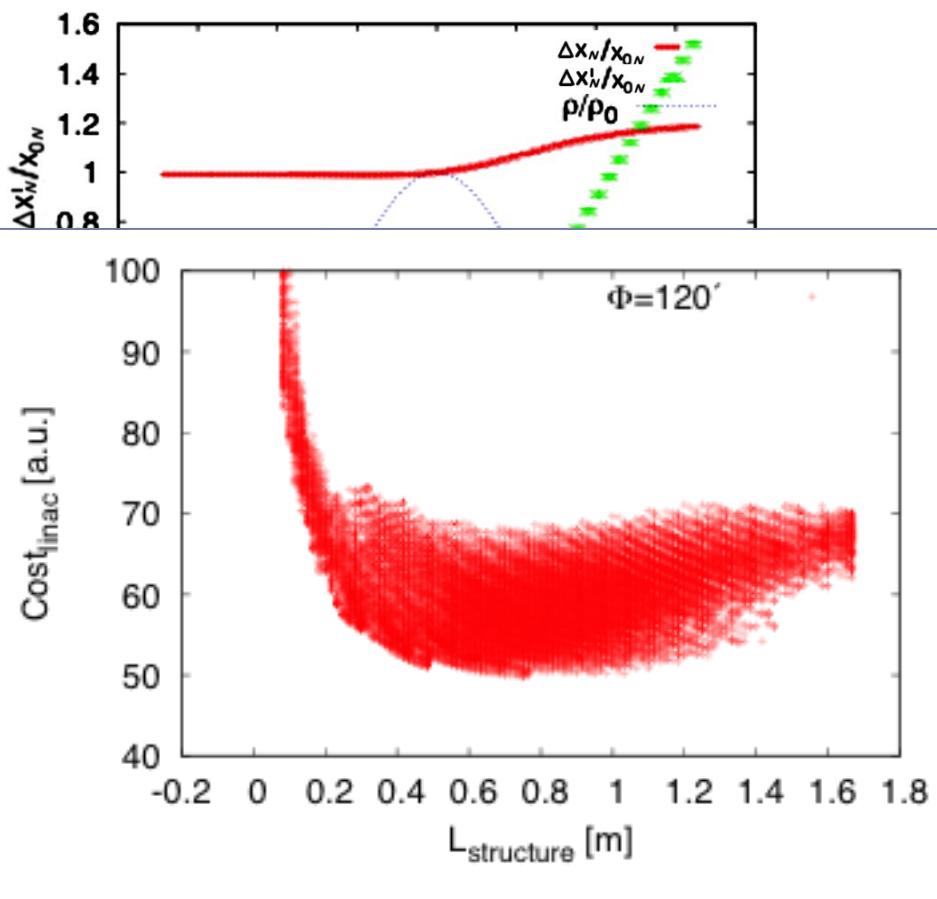
- ▶ In case of using SLED type of pulse compressor
  - 50 MW, 1.5  $\mu$ s input power is compressed to 150 ns with 460 MW
  - This unit should provide ~516 MeV acceleration beam loading.
  - Need 12 RF structures.

# Structure choice; Transverse wake effect & costs optimization

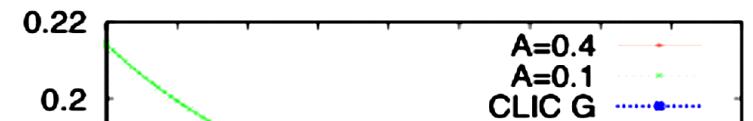
Stability requires small transverse deflection

D. Schulte

Used CLIC lattice and simplified wakefield



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



Structures per RF unit	10
Klystrons per RF unit	2
Structure length (m)	0.75
$\langle a \rangle / \lambda$	0.125
Allowed gradient (MV/m)	80+
Operating gradient (MV/m)	65
Energy gain per RF unit (MeV)	488
RF units needed	12
Total klystrons	24
Linac active length m	88

# Wake potentials $\leftrightarrow$ Bunch charge distribution

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

Transverse wake potential

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

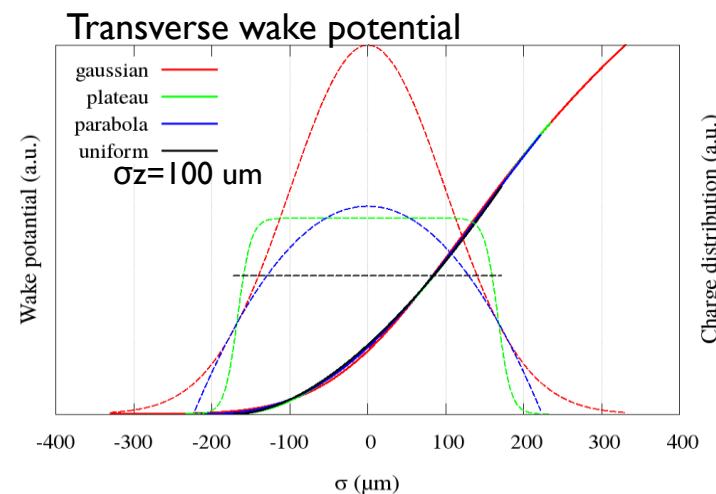
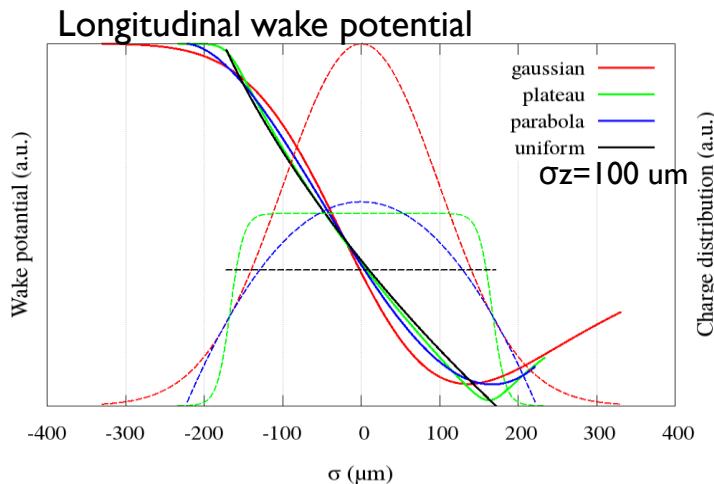
Causes transverse deflection along bunch

Longitudinal wake potential

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

Causes energy change along bunch

To reduce the wake effect  $\rightarrow$  Optimize charge distribution



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

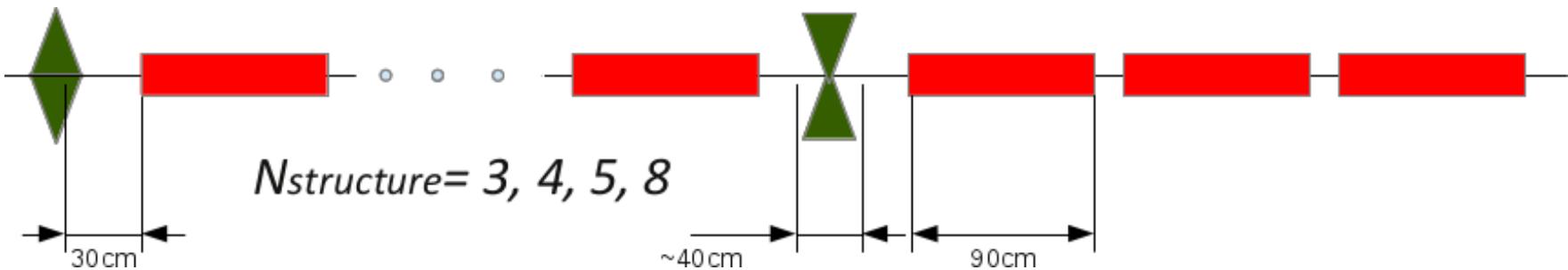
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# Transverse beam dynamics

- ▶ The transverse deflection of beam is proportional

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

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

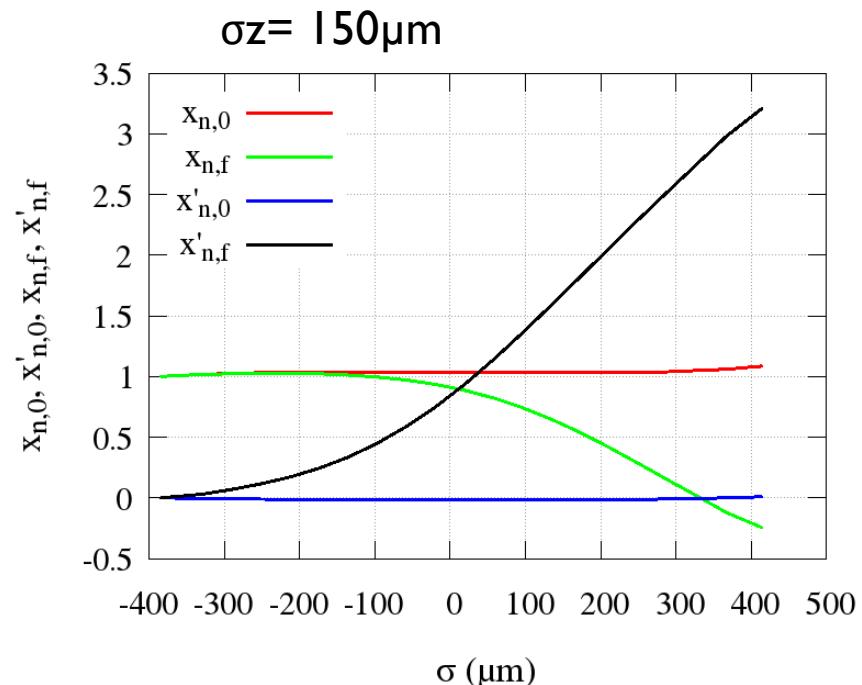
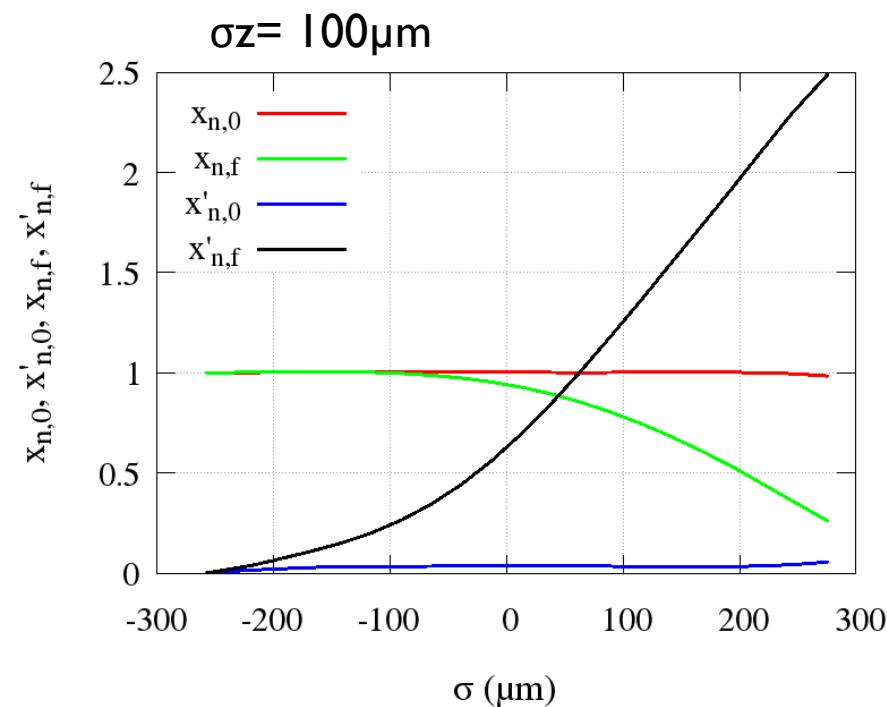


The most critical section is linac I since the energy is low and bunch length is long

# Transverse deflection in Linac I

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

The lattice houses 10 structure per FODO cell.

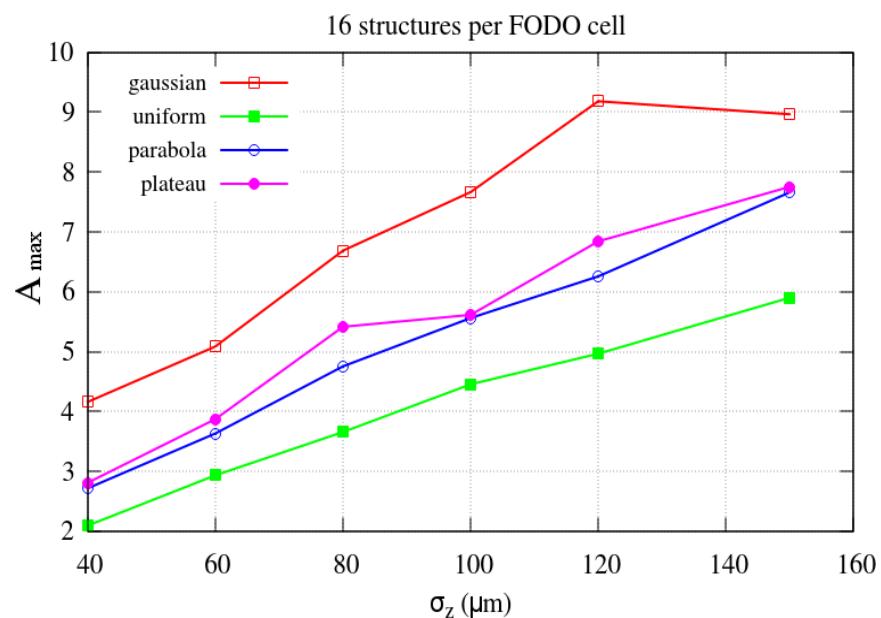
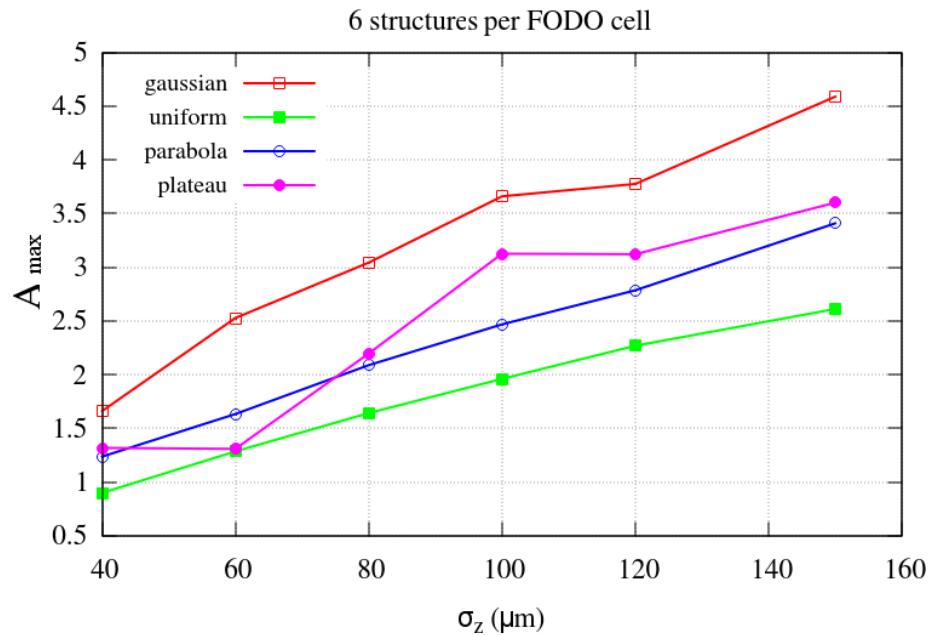


For compression of lattices and bunch profile we check

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

# The amplification on Linac - I

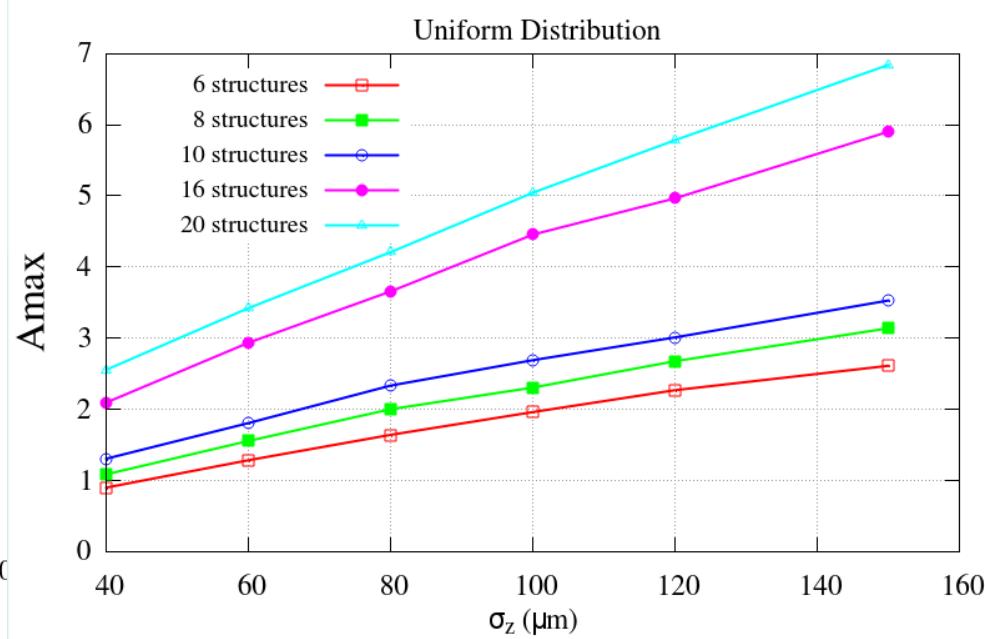
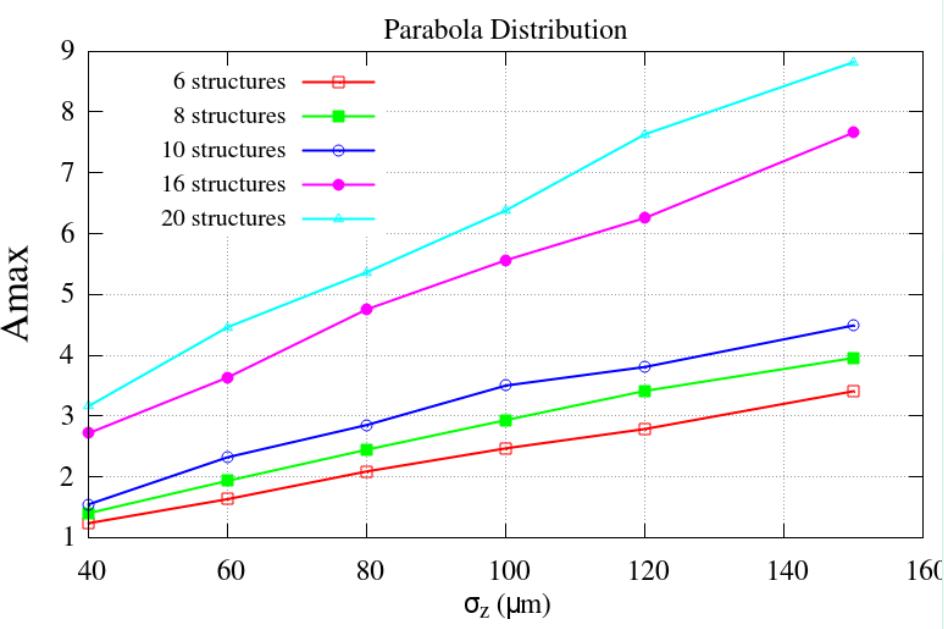
- ▶ The amplification for different bunch charge distribution on a lattice that has FODO cell with 6 structure per cell and 16 structure per cell



- The uniform charge distribution has lowest amplification.
- In order to get lower amplification factor than 1.5 we need to have bunch length  $\sigma z < 70 \mu\text{m}$

# The amplification on Linac - I

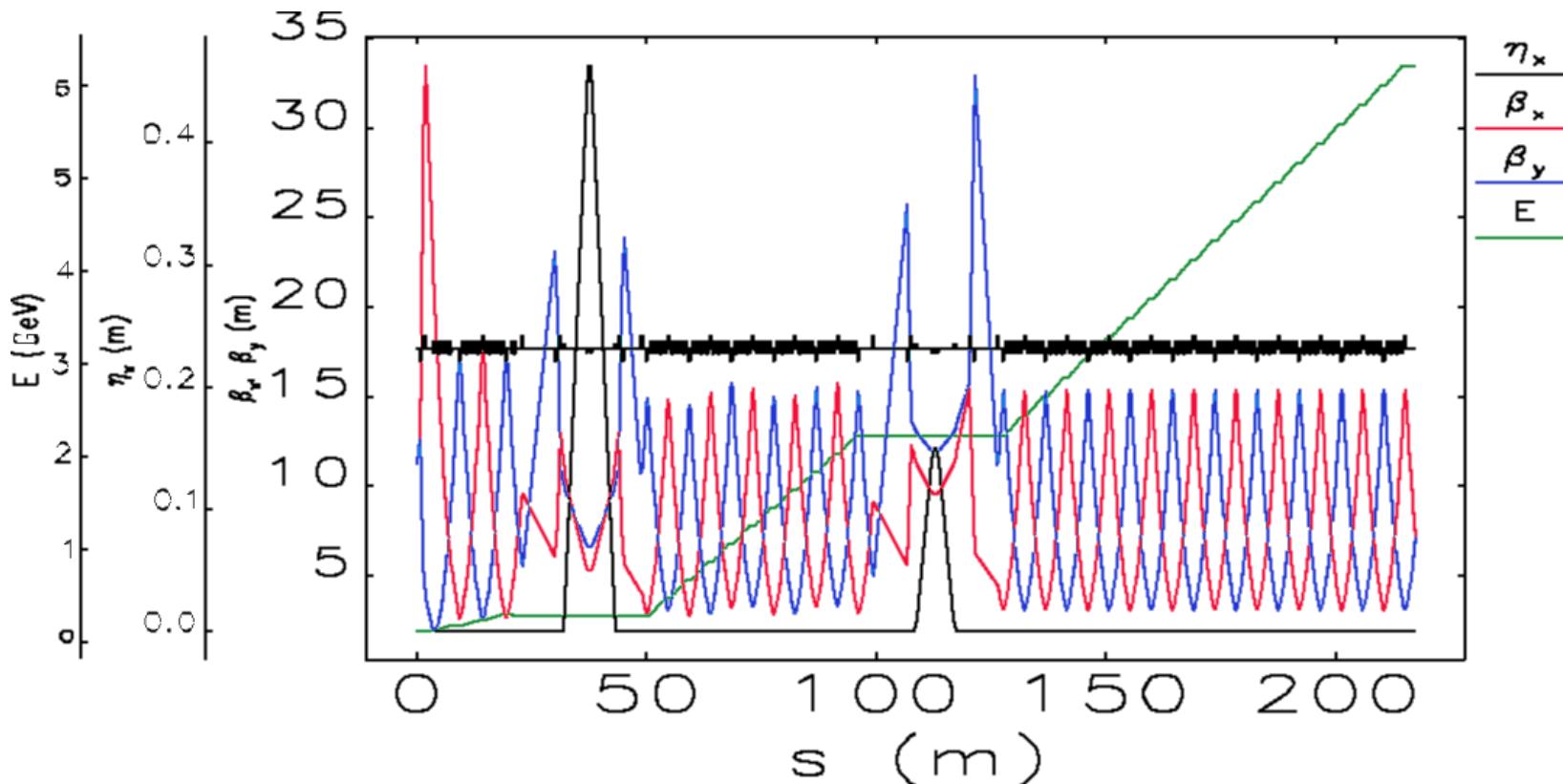
- ▶ The amplification of uniform and parabolic charge distribution on different type of lattices



In order to get lower amplification factor than 1.5 we are allowed to use the FODO lattice with 6 or 8 structure per cell

# The lattice

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



Linac I: 40 x-band strcuture, phase 25 degree

BC1 R56=0.082

Linac I: 80 x-band strcuture, phase 3 degree

BC2 R56=0.011

# Longitudinal phase space along beam line

Dogleg

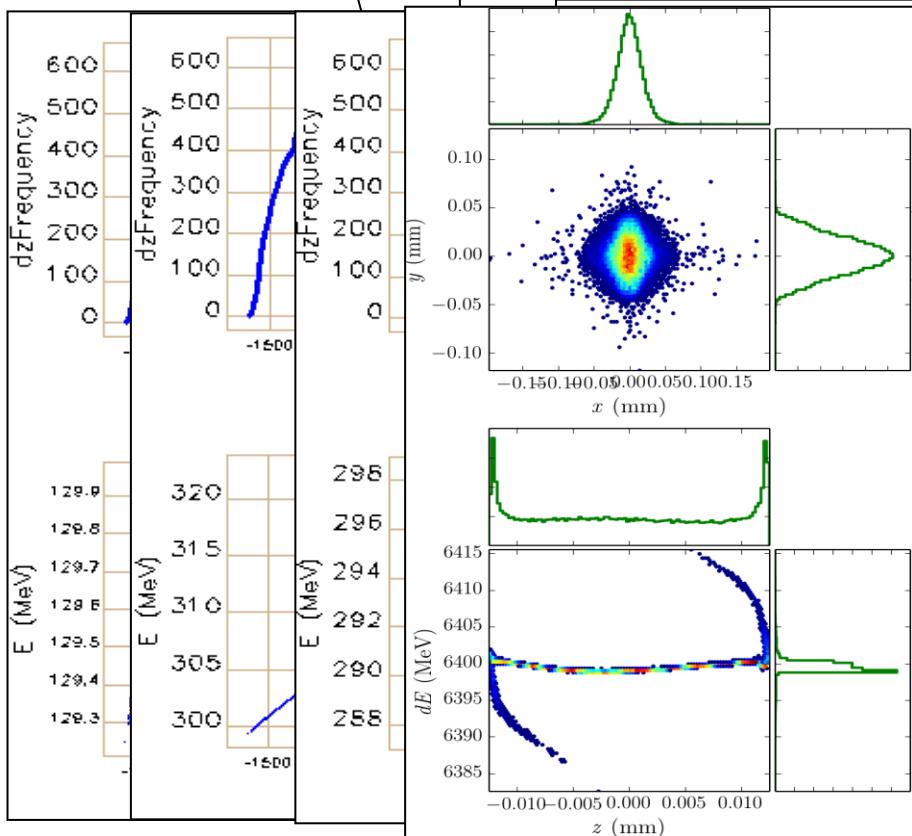
Gun   Booster1   Booster2

BC1

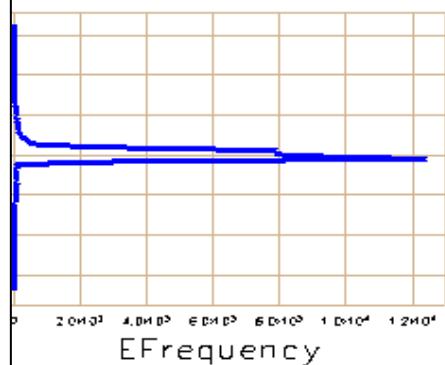
Linac1

BC2

Linac2



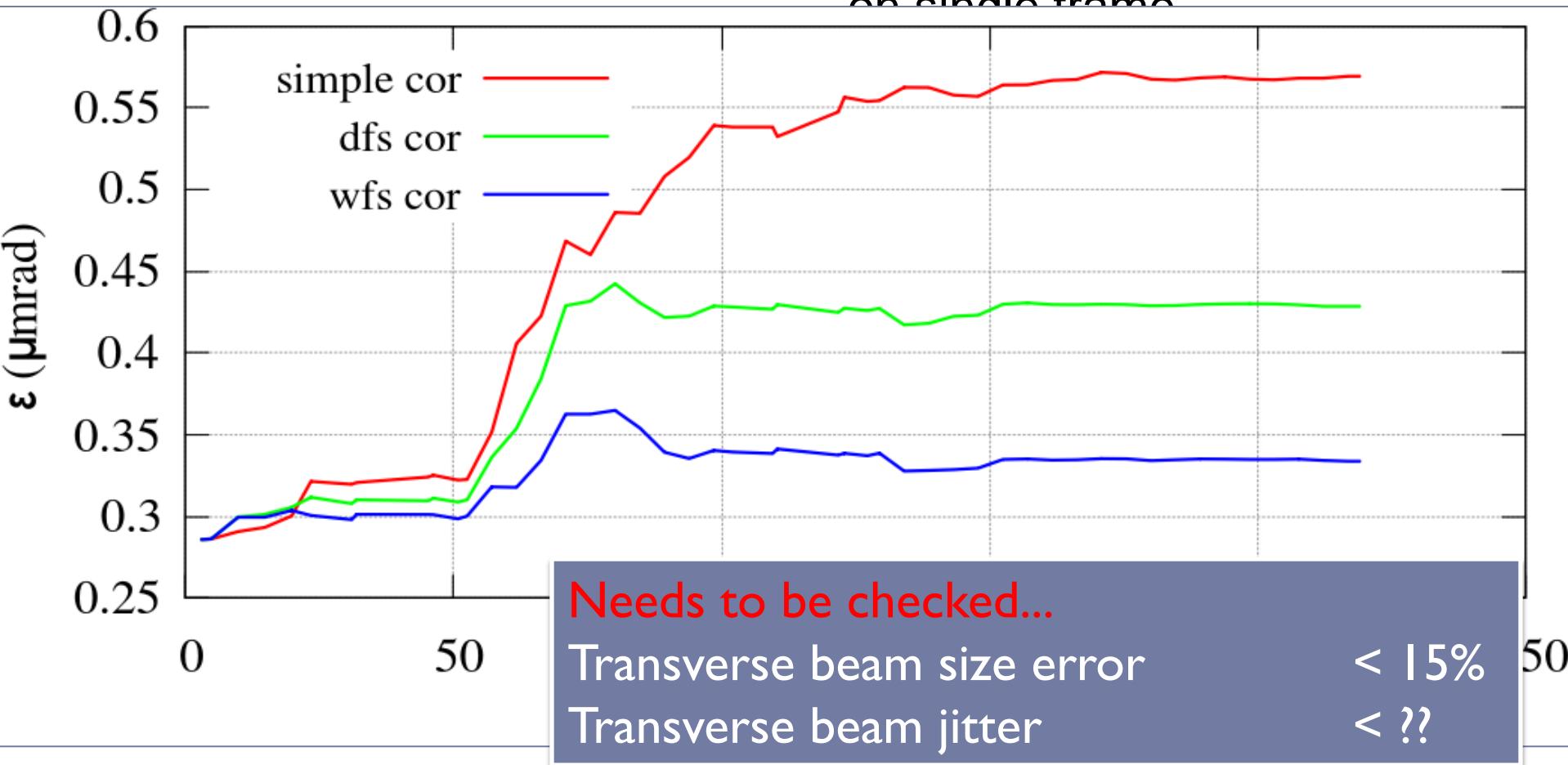
Parameter	Unit	Value
$E$	MeV	6399.589
$\varepsilon_{n,x}$	mm.mrad	0.273
$\varepsilon_{n,y}$	mm.mrad	0.272
$\varepsilon_z$	keV.mm	11.173
$\sigma_x$	mm	0.018
$\sigma_y$	mm	0.018
$\sigma_z$	mm	0.008
$\sigma_E$	keV	1471.241
$\Delta E/E$	%	0.023



# Emittance growth due to missaligment

Assumed all elements are scattered along beamline with an rms error

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



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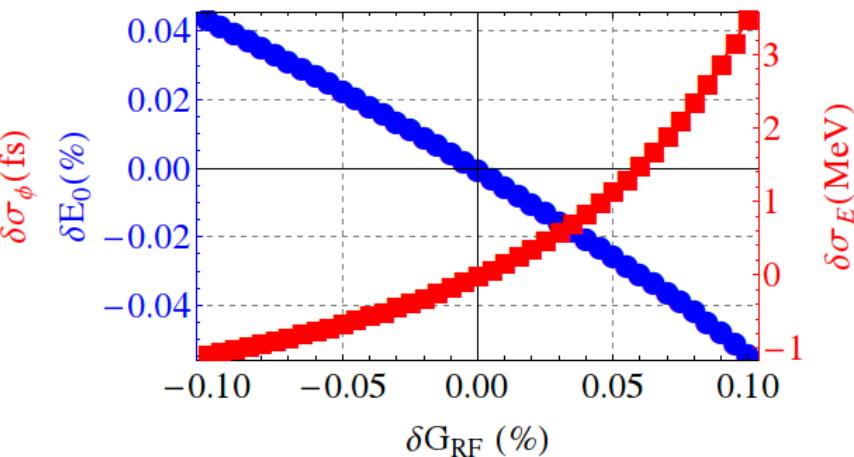
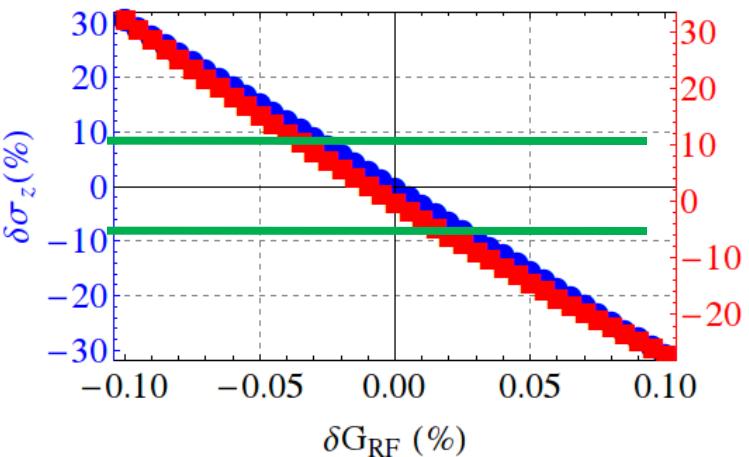
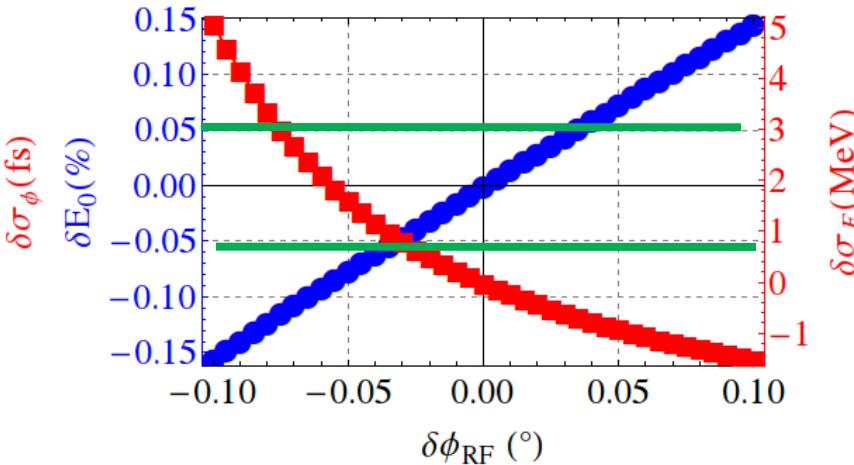
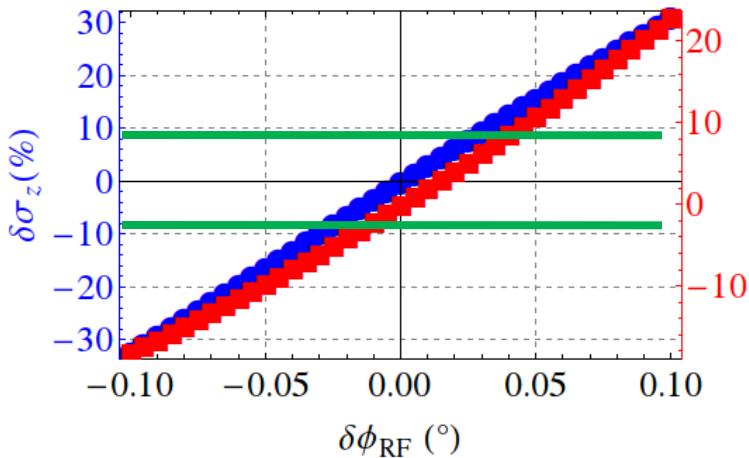
# Longitudinal tolerances

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- ▶ Energy spread < 0.02 %
  - ▶ Energy error < 0.05%
  - ▶ Bunch arrival time jitter < 20 fs
  - ▶ Peak current error < 10 %
  - ▶ Bunch length error < 10 %
- 
- ▶ Most of the numbers were taken from different facilities
    - SwissFEL, European XFEL..
  - ▶ The impact of these errors to FEL performance should be checked..

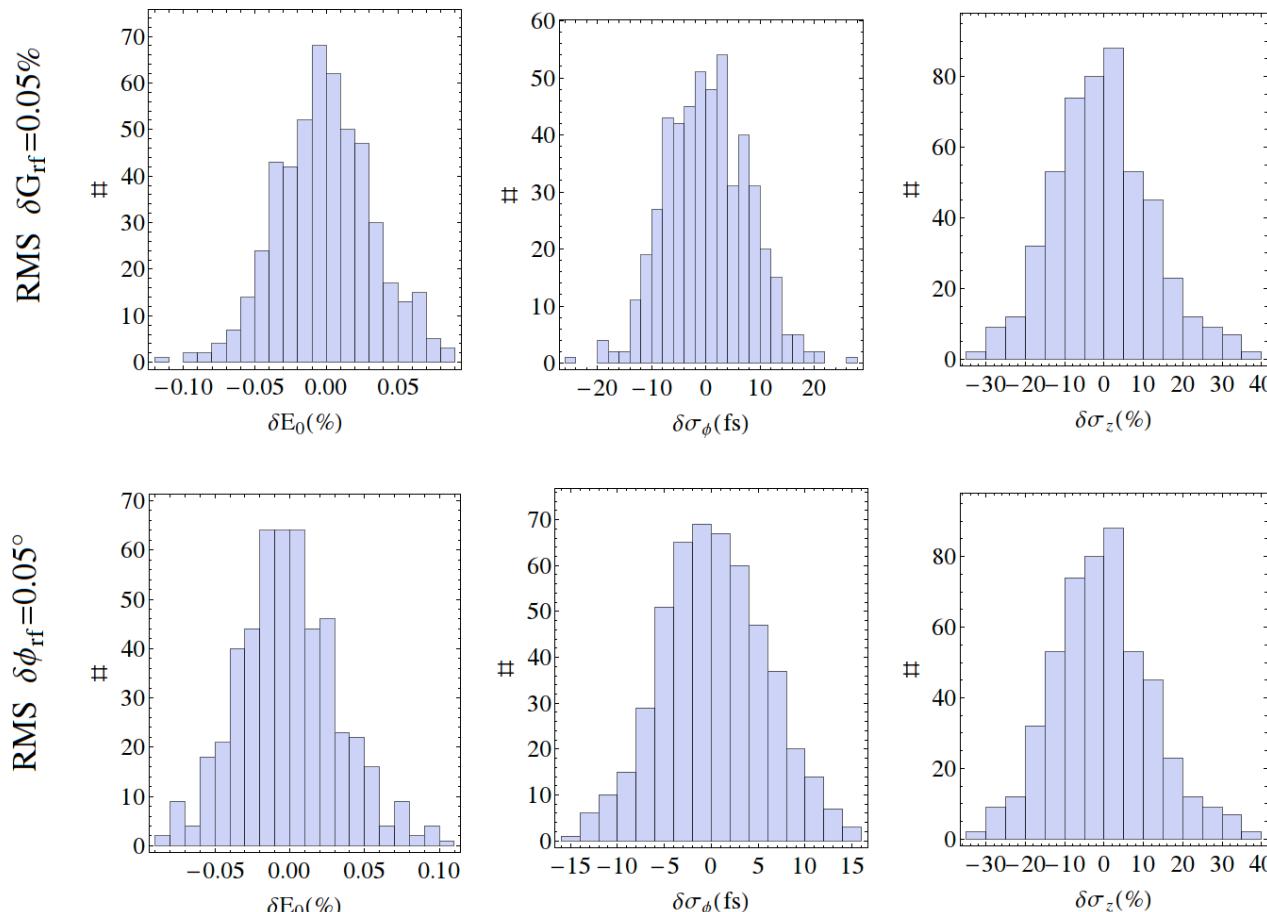
# Longitudinal coherent errors

- We have checked linac coherent phase error ( $\equiv$  beam phase error) and gradient error.



# Longitudinal rms errors $\delta G_{rf}=0.05\%$ $\delta \Phi_{rf}=0.05^\circ$

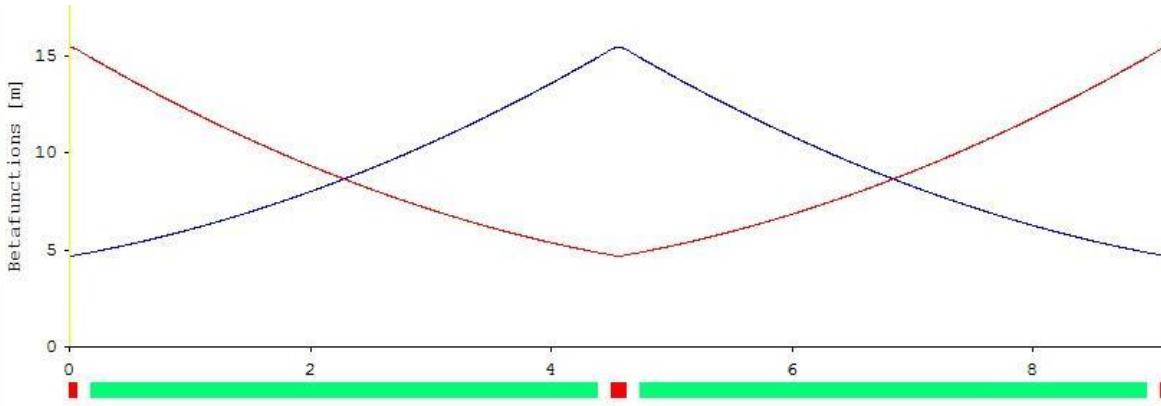
- ▶ Each S-band structure has individual power source
- ▶ Linearizer has its individual power source
- ▶ Each 8 structures are fed by one power source on Linac I and linac 2



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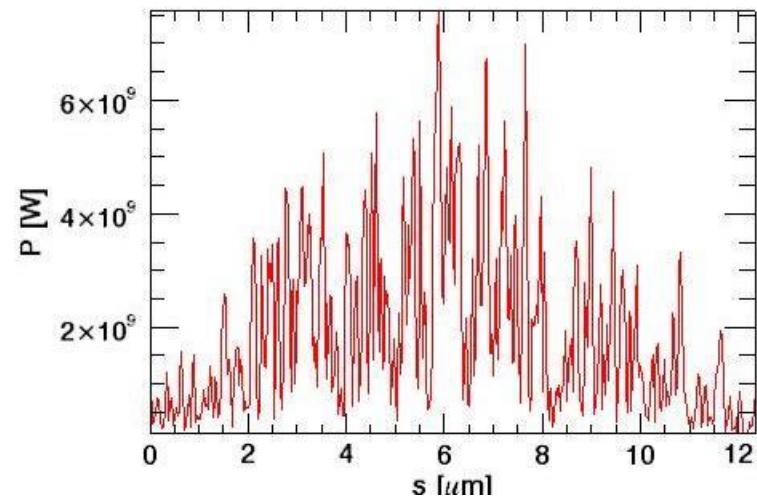
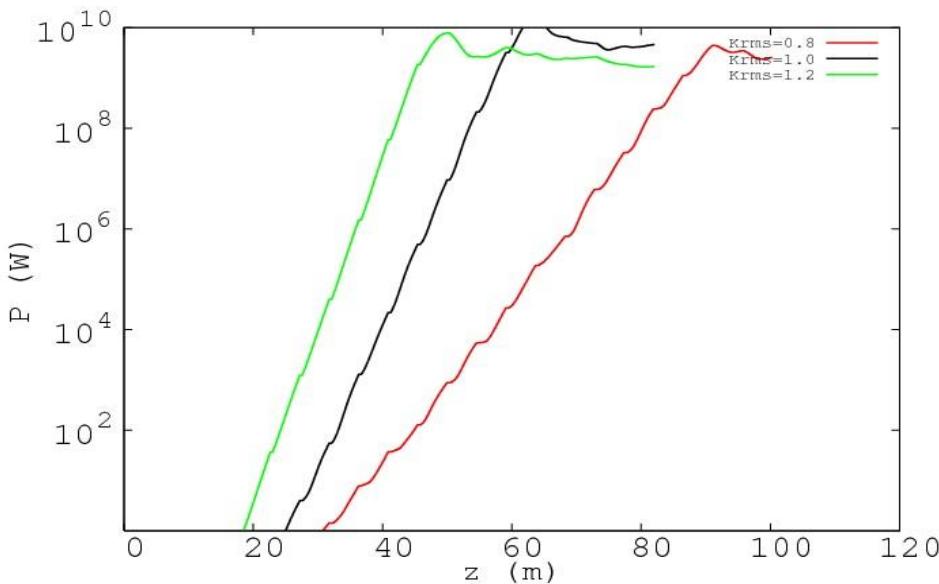
# Sample FEL simulation

- Preliminary simulations has been done for  $1 \text{ \AA}$  FEL



$\lambda_{\text{FEL}} = 15 \text{ mm}$   
 $L_u = 4.2 \text{ m}$   
 $N_{\text{section}} = 14$

$K_{\text{rms}} = 1.2 \rightarrow \lambda_{\text{FEL}} = 1.25 \text{ \AA}$   
 $K_{\text{rms}} = 1 \rightarrow \lambda_{\text{FEL}} = 1.02 \text{ \AA}$   
 $K_{\text{rms}} = 0.8 \rightarrow \lambda_{\text{FEL}} = 0.84 \text{ \AA}$



# Conclusion

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- ▶ An injector based on S band gun and S-band structures has been preliminary designed
- ▶ The beam dynamics issues for Main linac sections based on CLIC X-Band structure has almost been completed
- ▶ We have shown that CLIC X-Band structure is sufficient to generate beam for generating X-FEL
  - Incase of using the structure with given  $a/\lambda$  effective length
    - 8 structures per one FODO cell with  $\langle\beta\rangle=8m$  fulfills transverse stability requirements
  - For longitudinal tolerances
    - $\delta G_{rf}=0.05\%$  and  $\delta \Phi_{rf}=0.05^\circ$  errors seems to fulfill the requirements
  - Needs to be checked
    - Dipole and Quadrupole field errors
    - CSR effect
    - The effect of transverse beam jitter and size oscillations to FEL performance
    - ....

# Thank you for your attention!

Special thanks to  
Daniel Schulte, Igor Syratchev, Walter Wuensch