# X-band RF driven hard X-ray FELs

**Yipeng Sun**

ICFA Workshop on Future Light Sources March 5-9, 2012

SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY

# Motivations & Contents

Motivations

❖Develop more compact (hopefully cheaper) FEL drivers, L→S→C→X-band (successful LCLS run 20-250pC)

❖X-band more efficient in manipulating longitudinal phase space due to shorter wavelength and stronger L-wake

➢An X-band RF driven Hard X-ray FEL Design with Optics based longitudinal phase space linearization

➢A low charge X-band RF driven Hard X-ray FEL

➢An LCLS injector + X-band RF Hard X-ray FEL

➢Tolerance studies

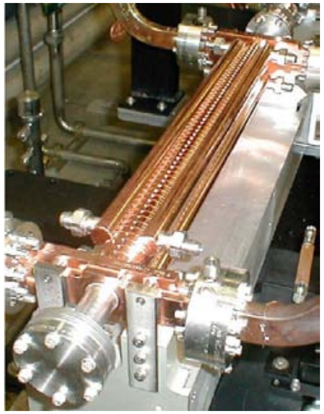
➢Summary

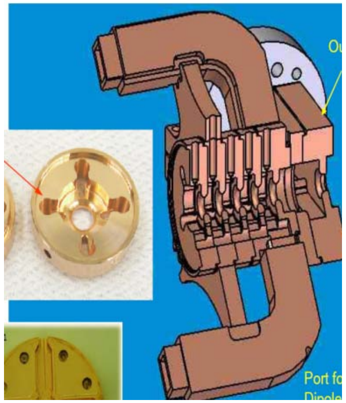
# X-band RF and photoinjector

H60 or T56 structure
11.4 GHz, 80-100MV/m

Tor Raubenheimer

1. Special applications, i.e. deflectors, linearizers, etc where wavelength is important
2. Energy efficiency is better at short wavelength offering possibility of high repetition rate operation
3. Stronger wakefields and larger dE/dt due to gradient and frequency allow better control of longitudinal phase space
4. High gradient rf linacs are shorter (and hopefully cheaper)





Suppressed dipole mode and T-wakes

C. Limborg-Deprey et al., An X-Band gun Test Area at SLAC, PAC 11, MOP015 (2011).

Longitudinal electric field
1.6 cell S-Band gun [red]
and the 5.6 cell X-Band gun

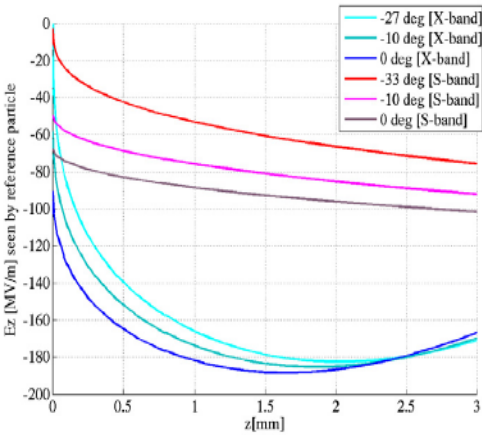
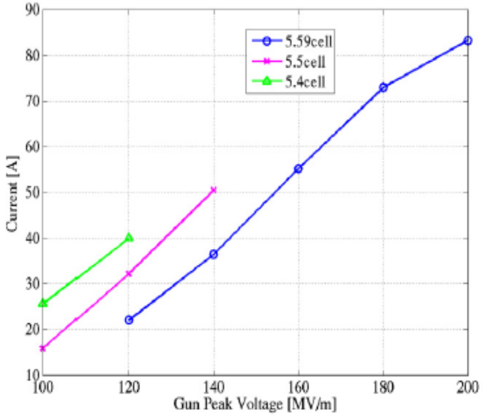



Table 1: Results From Optimizations of the XTA beamline.

| Q [pC] | $\varepsilon_{x,100\%}$, $\varepsilon_{x,95\%}$ [mm-mrad] | $\sigma_l$ [mm] | $Q/\sigma_l/\varepsilon$ /1e3 |
|---|---|---|---|
| 250 | 0.38/0.25 | 0.228 | 4.39 |
| 250 | 0.42/0.28 | 0.184 | 4.85 |
| 100 | 0.362/0.265 | 0.116 | 3.25 |
| 20 | 0.1/0.075 | 0.109 | 2.44 |
| 10 | 0.070/0.052 | 0.105 | 1.83 |
| 10 | 0.092/0.076 | 0.055 | 2.39 |
| 10 | 0.140/0.118 | 0.042 | 2.01 |
| 1 | 0.022/0.016 | 0.080 | 0.78 |
| 1 | 0.042/0.036 | 0.025 | 1.11 |

> 2 times brightness of S-band

Peak current for reduced peak voltage



# General bunch compressor design for longitudinal phase space linearization

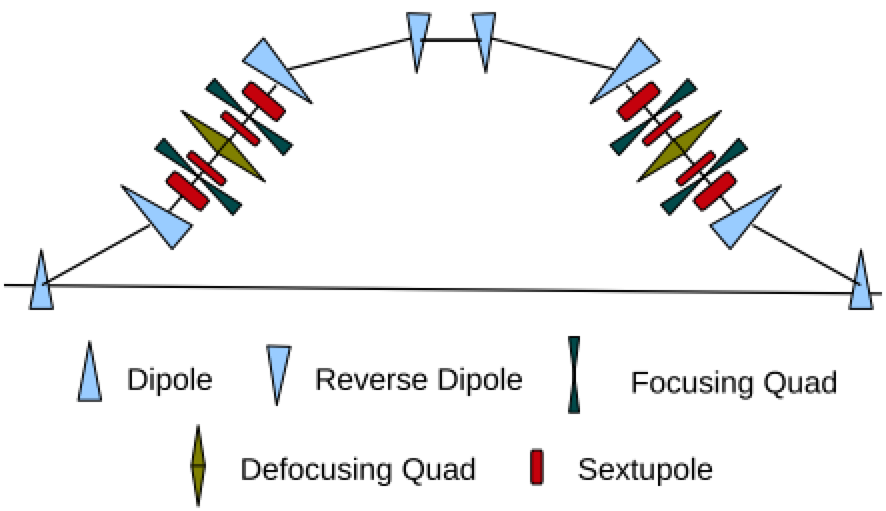
Motivation: Develop alternative for harmonic RF based longitudinal phase space linearization → optics linearization

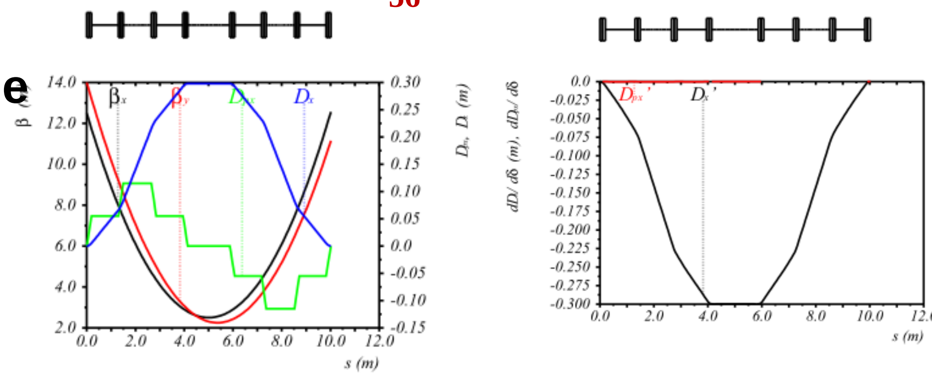
$$R_{56} = \int_0^{s0} \frac{R_{16}}{\rho_0} ds$$

$$T_{566} = \int_0^{s0} \left[ \frac{T_{166}}{\rho_0} + \frac{1}{2} R_{26}^2 + \frac{1}{2} \left(\frac{R_{16}}{\rho_0}\right)^2 \right] ds$$

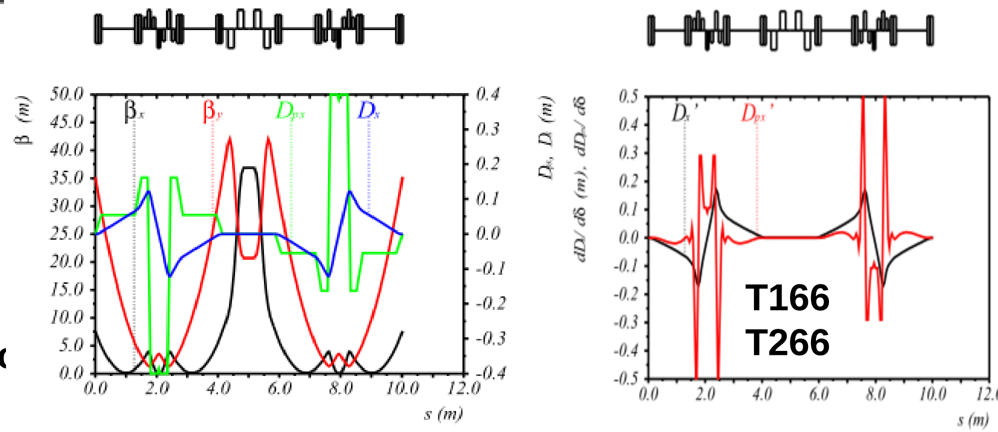
***$R_{56}$ = -30 mm  T566 = 45 mm***

**4-Dip. Dogleg*2**, $R_{56}$ **tunable**, $T_{566}$ **tunable**




***$R_{56}$ = +30mm or -30mm  T566 tunable***



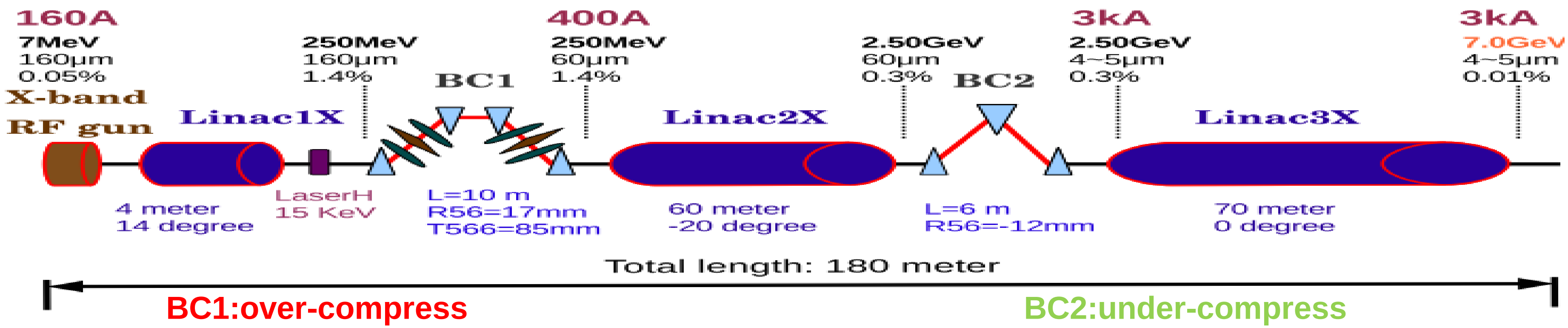

**Bunc**

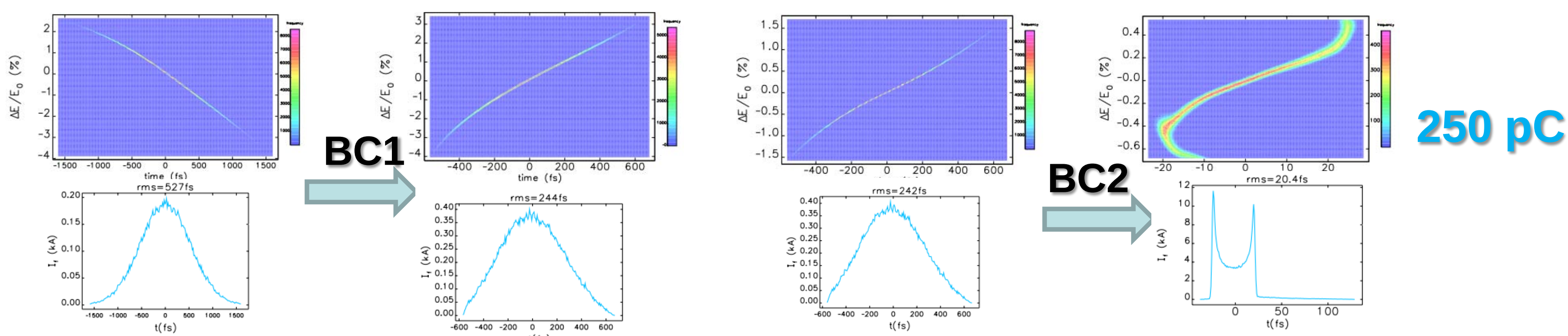
NATIONAL ACCELERATOR LABORATORY

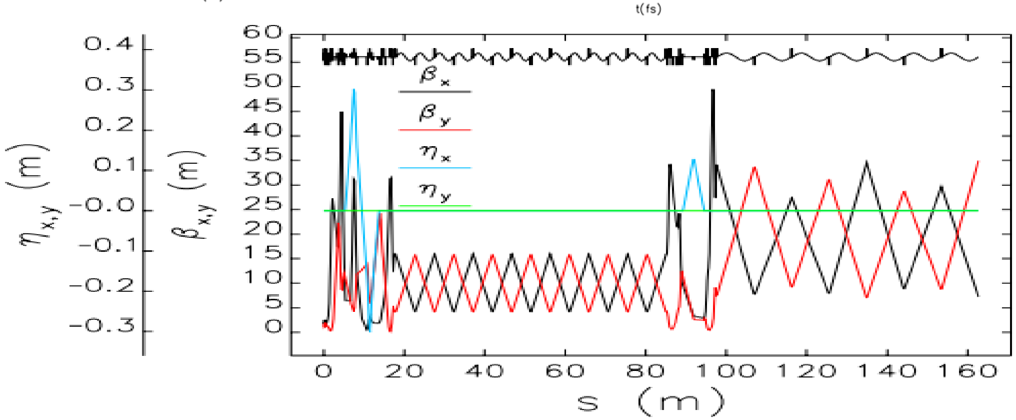
**Yipeng Sun et al.**, SLAC-PUB-14628

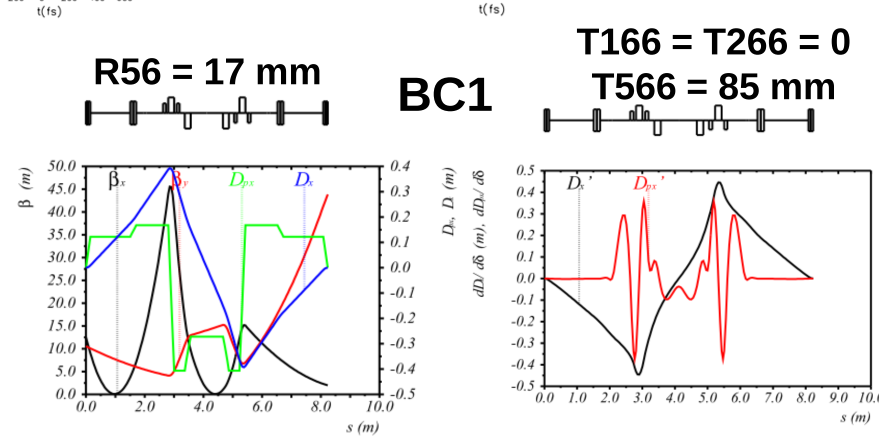
# An X-band RF Based Hard X-ray FEL Design with Optics Linearization (1)

XFEL-GB



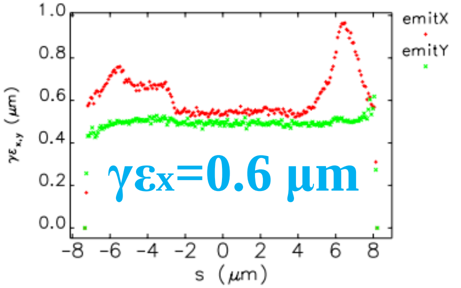



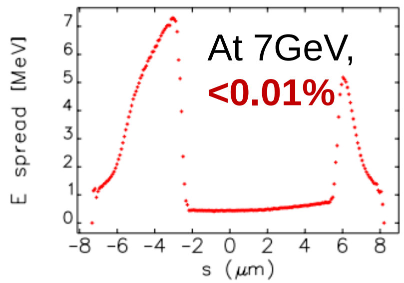



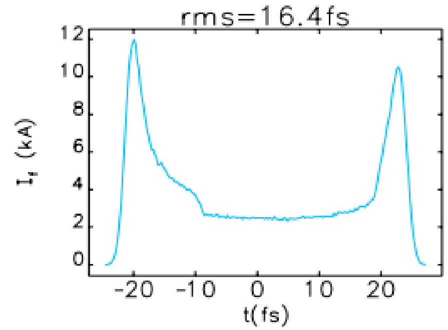
# An X-band RF Based Hard X-ray FEL Design with Optics Linearization (2)

Electron beam at linac3 end

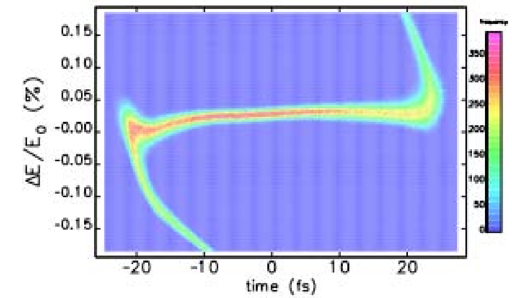
**7 GeV** 50fs, **$I_{peak}$> 3kA**



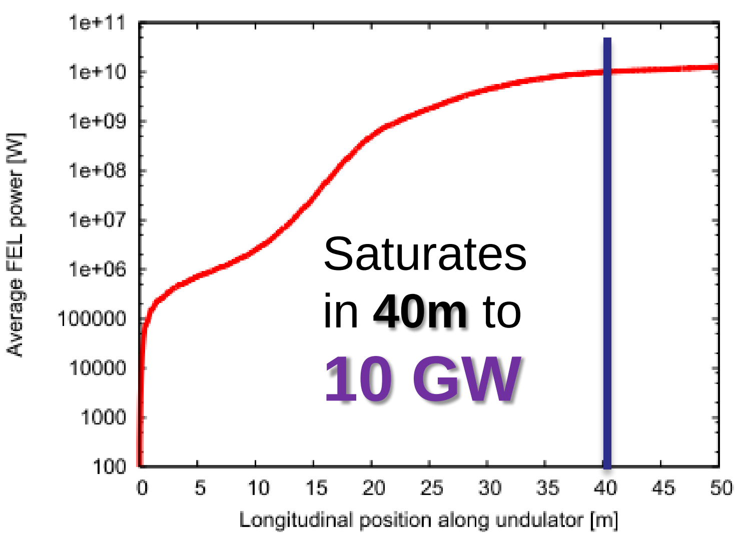



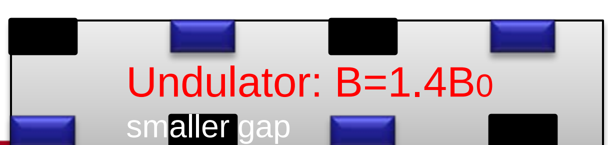




**Flat energy profile**




FEL performance (w/o tapering)



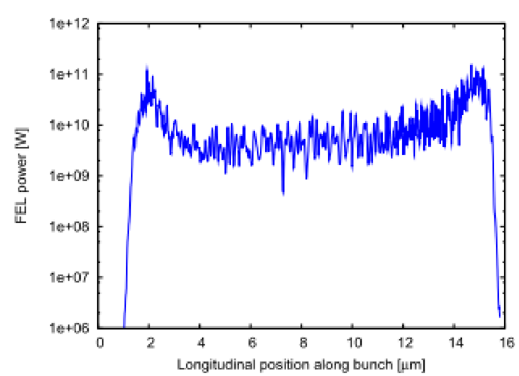




FEL at photon energy 9 keV, wavelength1.5 Å

LCLS Undulator with period $\lambda_w$ **= 1.5 cm**

beta-function ~ 20 m

**Power over 10 GW in 50 fs**




**Narrow bandwidth at 0.15 nm, 1E-3**

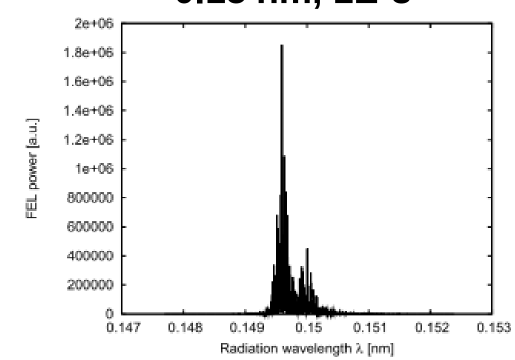



Figure 20: FEL power spectrum at undulator 40 m.

# Elegant simulation conditions

Ideal machine:

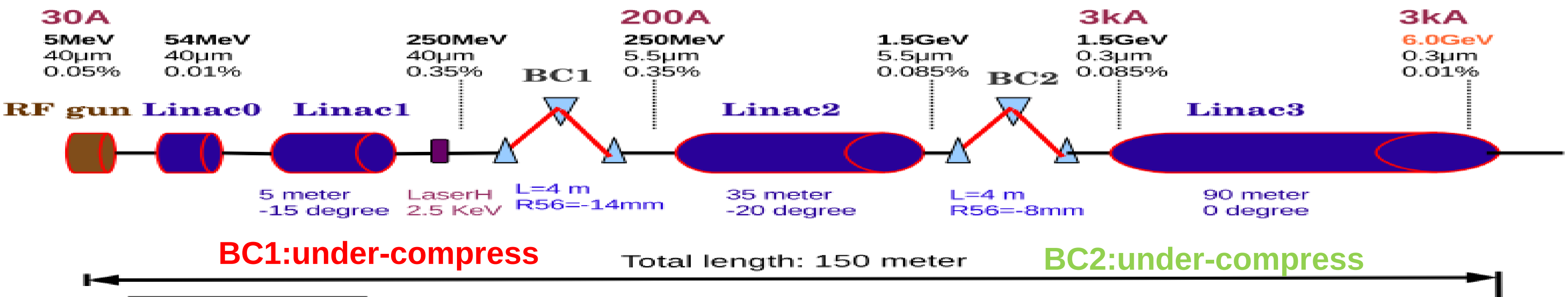
✓In Elegant, transverse and longitudinal wake of (S)X-band cavities
✓1D coherent synchrotron radiation (CSR) and ISR in all bends
✓longitudinal space charge (LSC) in drifts
✓CSRDRIFT between all bends with the "USE_STUPAKOV" option
✓CSR induced steering removed by 'center' element in Elegant
✓CSR induced dispersion no corrected
✓NO misalignment
✓1 million macro-particles
✓Initial bunch from ASTRA simulation, or generated using ASTRA simulated parameters

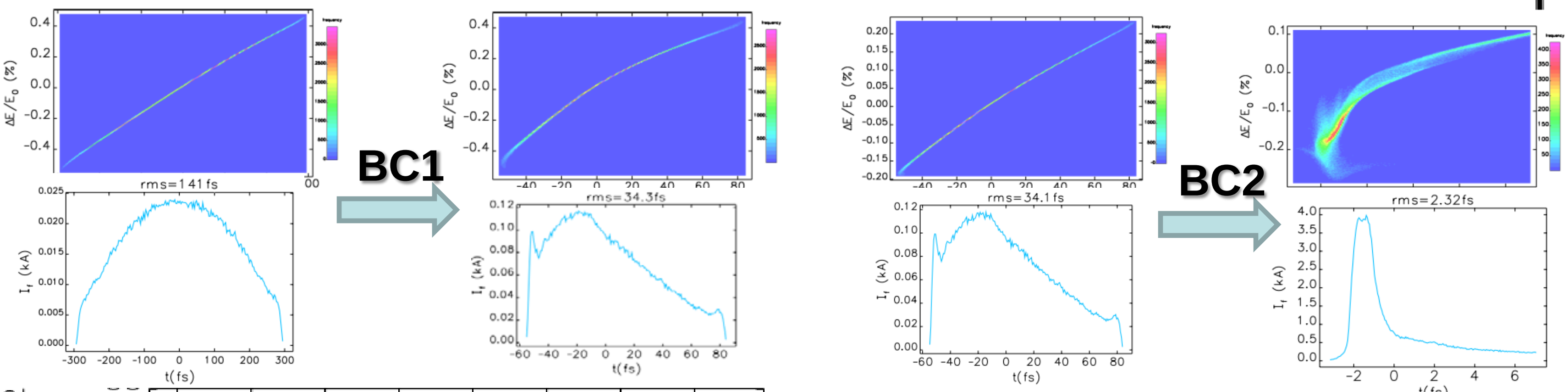
Tolerances:

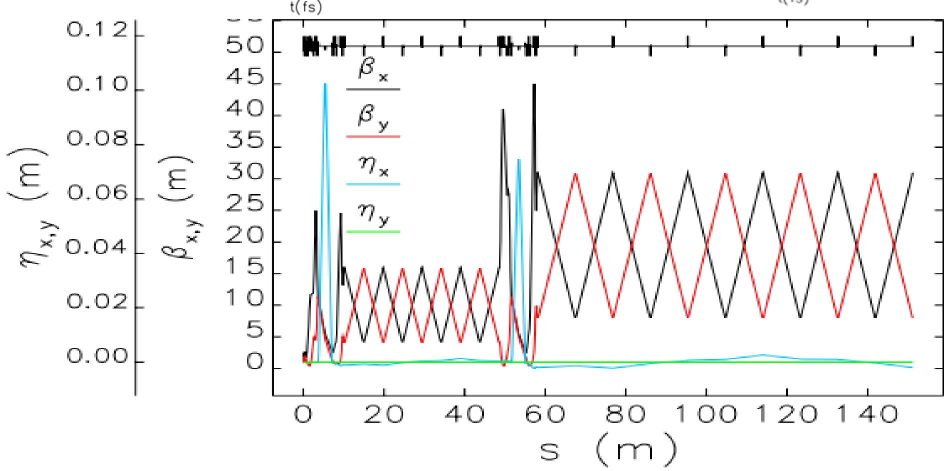
✓Quad and Sextupole: 200 **μm** + 200 **μrad RMS**
✓RF & BPM-Quad: 200 **μm RMS**
✓1-to-1 or DFS steering
✓Timing jitter, correlated for all RF between gun laser

# Another two X-band RF Based Hard X-ray FELs (1-1)

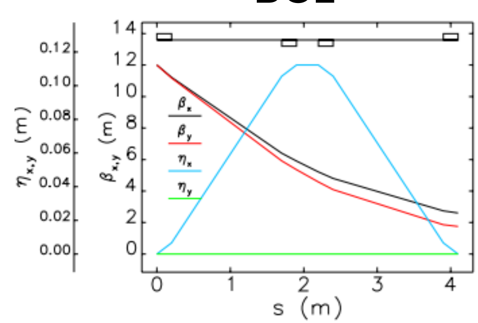
**10 pC** **XFEL-LowC**



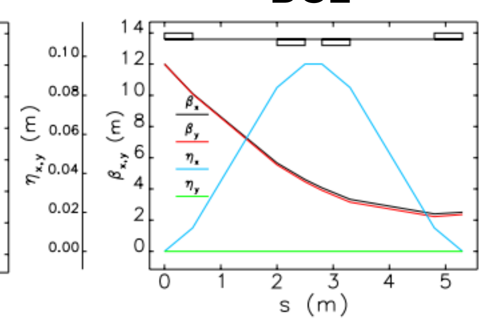




BC1

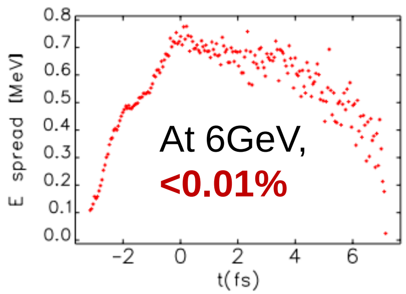


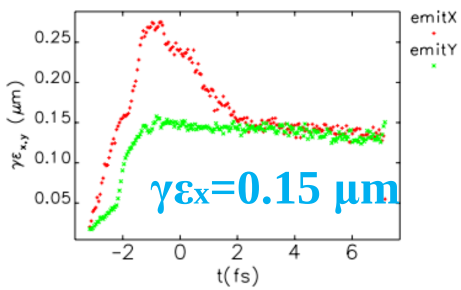

BC2



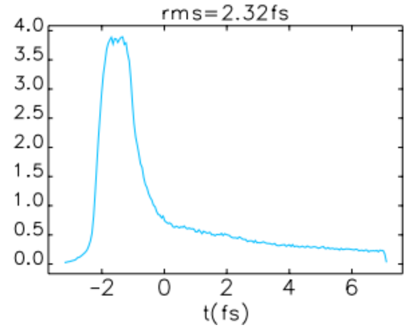
# Another two X-band RF Based Hard X-ray FELs (1-2)

Electron beam at linac3 end **6 GeV**

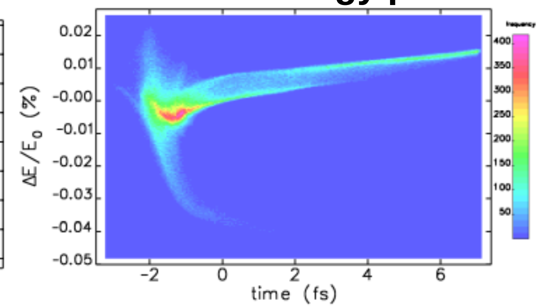


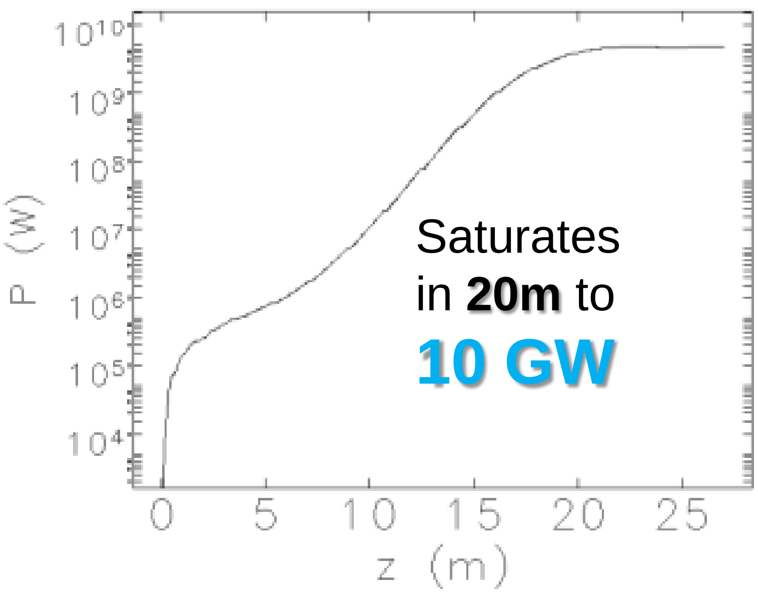

**2fs**, **$I_{peak}$> 3kA**




**Flat energy profile**




FEL performance (**w/o tapering**)

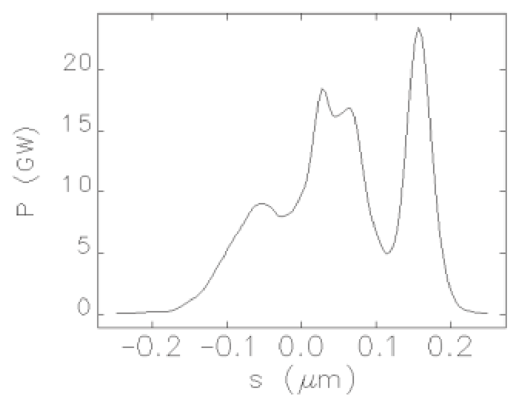



FEL at photon energy 8 keV, wavelength 1.5 Å

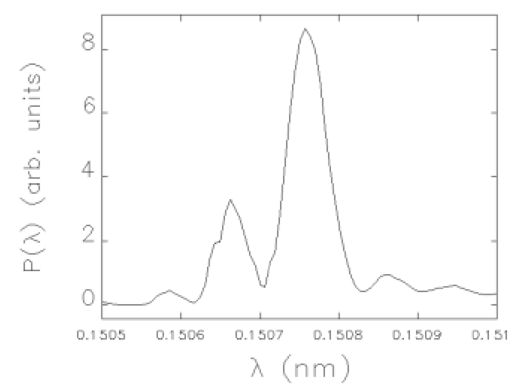
LCLS Undulator with period $\lambda_w$ **= 1.5 cm**

beta-function ~ 15 m

**Power over 10 GW in 2 fs**

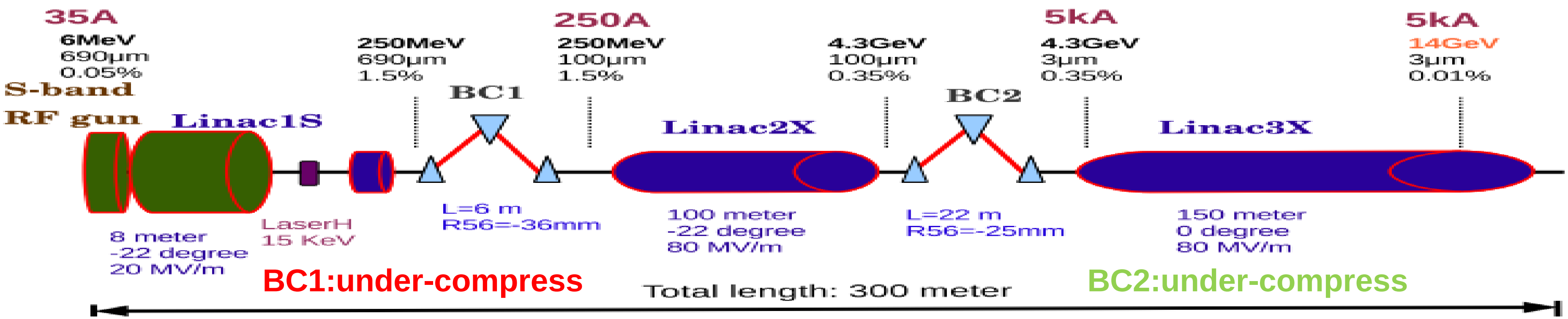


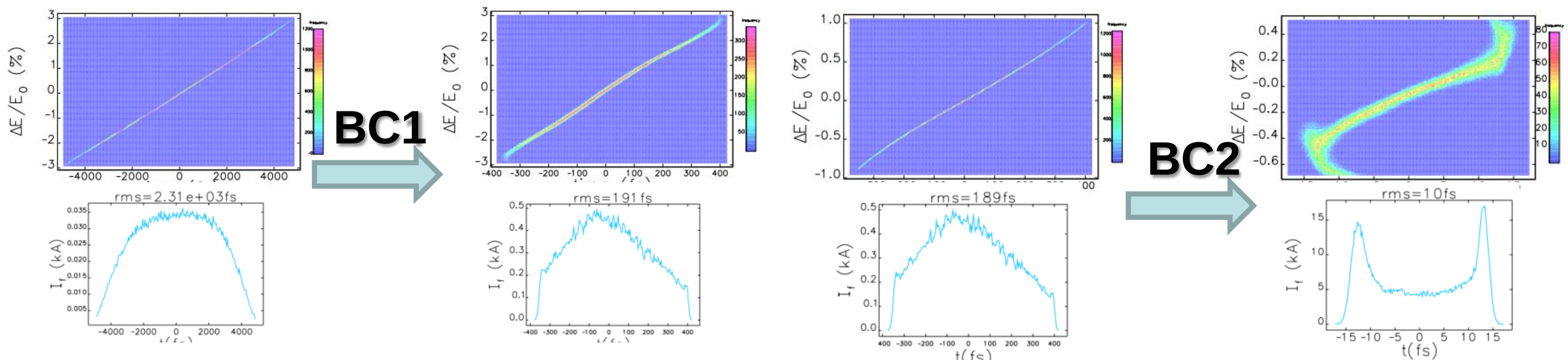

**Narrow bandwidth at 0.15 nm, 1E-4**

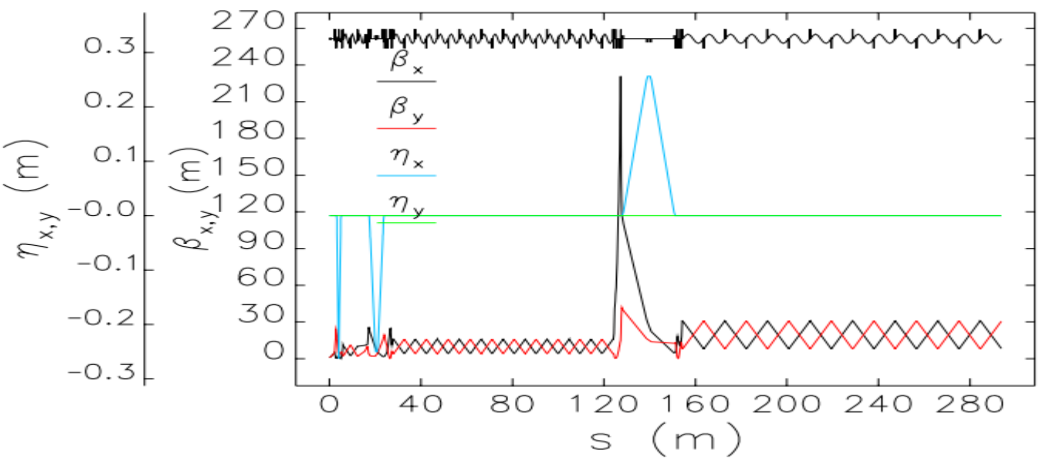


# Another two X-band RF Based Hard X-ray FELs (2-1)

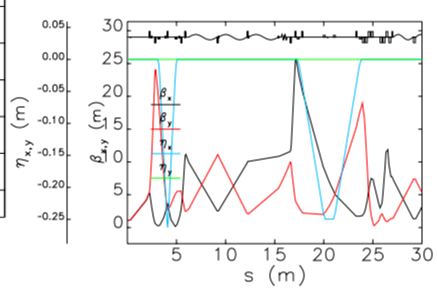
**250 pC** XFEL-LCLSinj



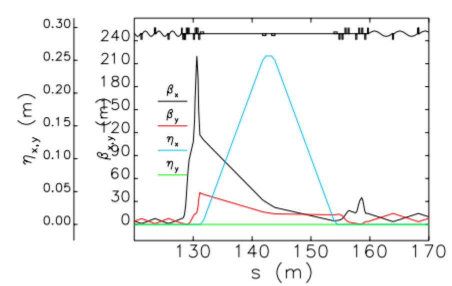




LCLS BC1

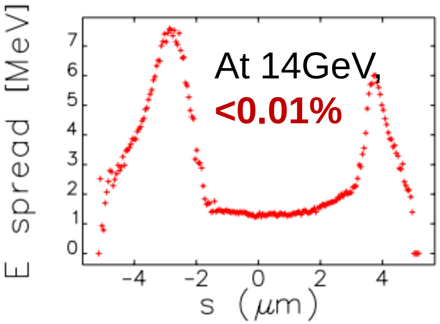


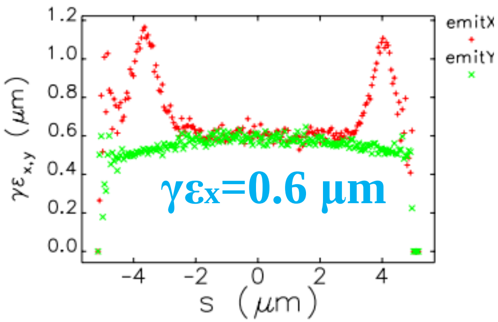

LCLS BC2



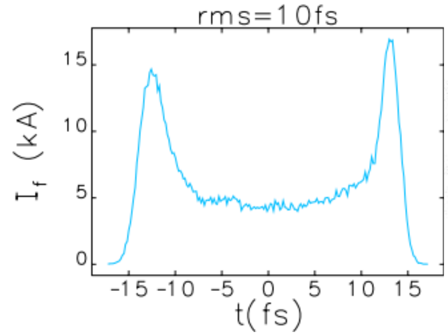
# Another two X-band RF Based Hard X-ray FELs (2-2)

Electron beam at linac3 end

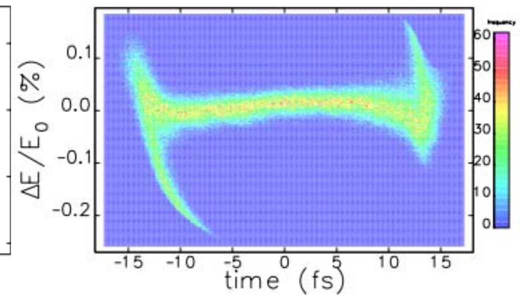


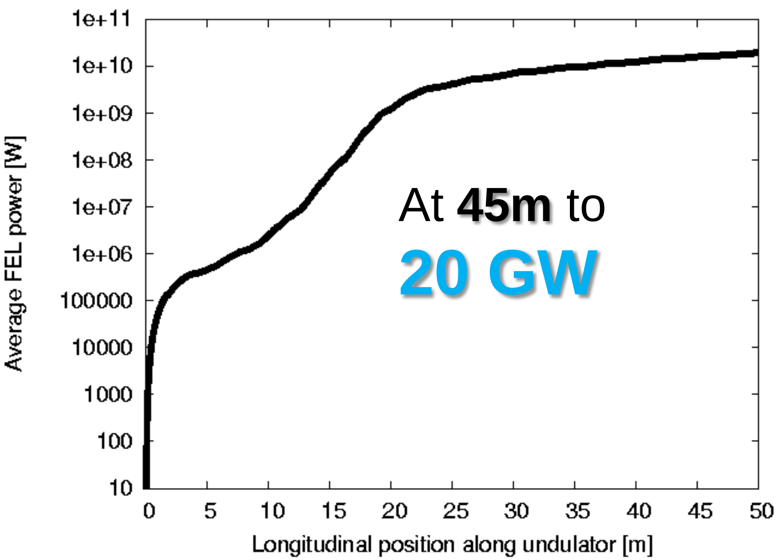

**30fs**, $I_{peak}$> 5kA




**Flat energy profile**




FEL performance (w/o tapering)

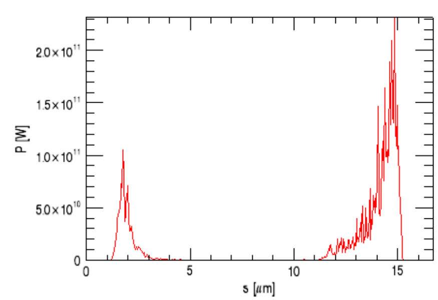



FEL at photon energy 8 keV, wavelength 1.5 Å

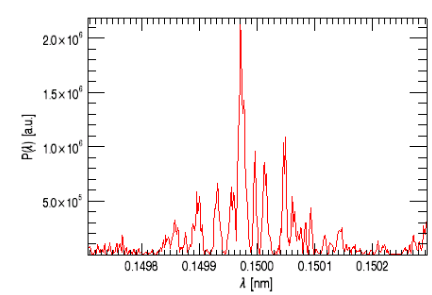
LCLS Undulator with period $\lambda_w$ **= 1.5 cm**

beta-function ~ 15 m

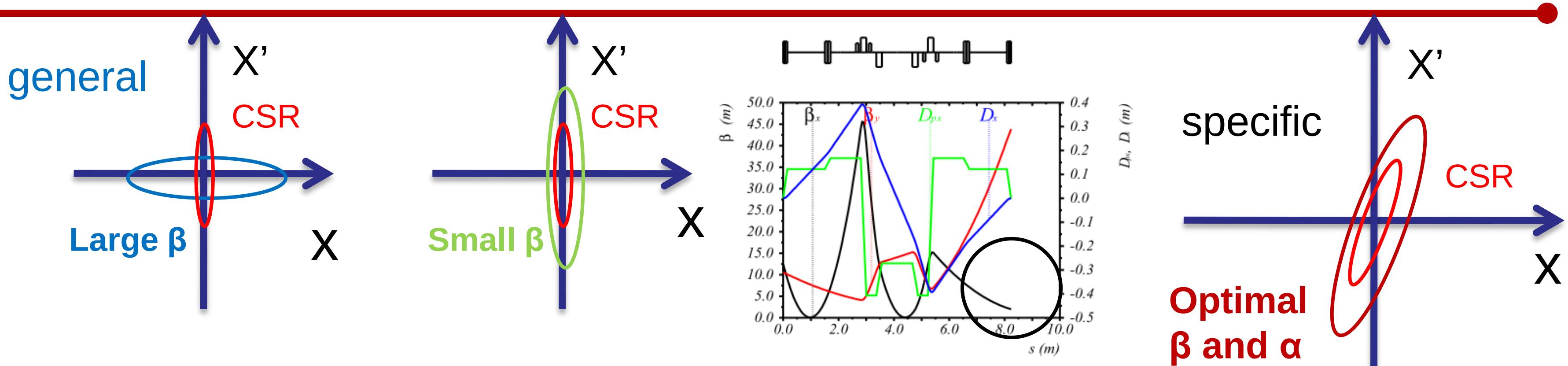
**Power over 5 GW in 30 fs**



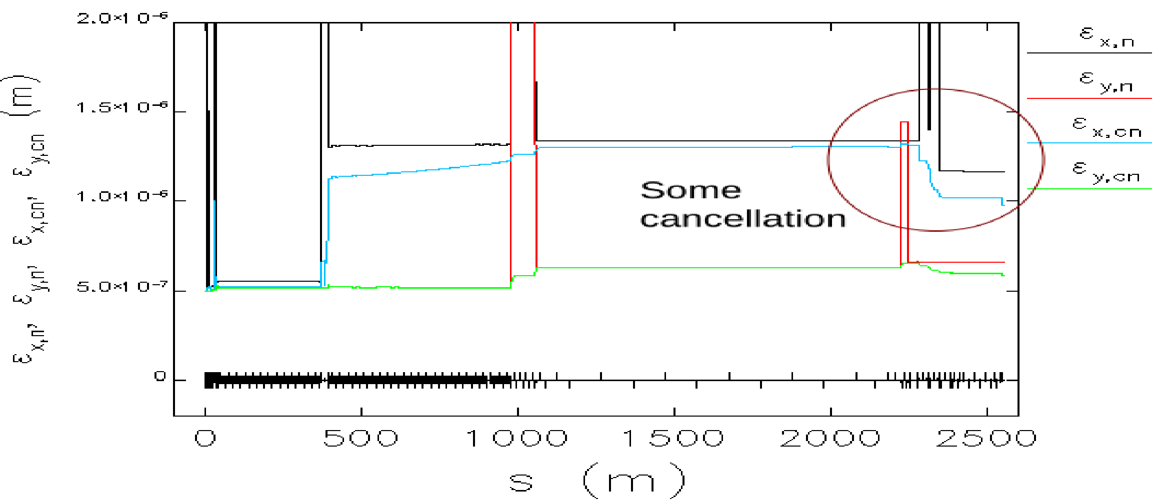

**Narrow bandwidth at 0.15 nm, 2E-3**



# CSR minimization in general




- Short CSR interaction time, shorter dipole length→ fast turn over full compression
- Large transverse beam size, transverse suppression of CSR impacts (in the direction of radiation, the effective projected bunch length is longer)
- Horizontal phase space matching
- Long range CSR cancellation between bending systems (phase advance and TWISS in bending system) (horizontal phase space matching for two double-horns)




LCLSII BC2 and LTU arc
Final horizontal projected emittance decreased from **1.63** micron to **1.16** micron

# Tolerances: timing jitter and charge jitter

Random error→ sum small
Correlated: all RF and gun laser

Estimated from FEL 1-D theory

$$L_G \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

$$L_{sat} \approx \lambda_u/\rho \approx 18 L_G$$

$$P_{FEL,sat} \approx \rho \times P_e$$

$$K = B[T] \cdot \lambda_u[cm]$$

$$\rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\epsilon_N}\left(\frac{K}{\gamma}\right)^2\right)^{1/3}$$

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

**XFEL-GB**

Table 2: Peak current and FEL performance with timing jitter

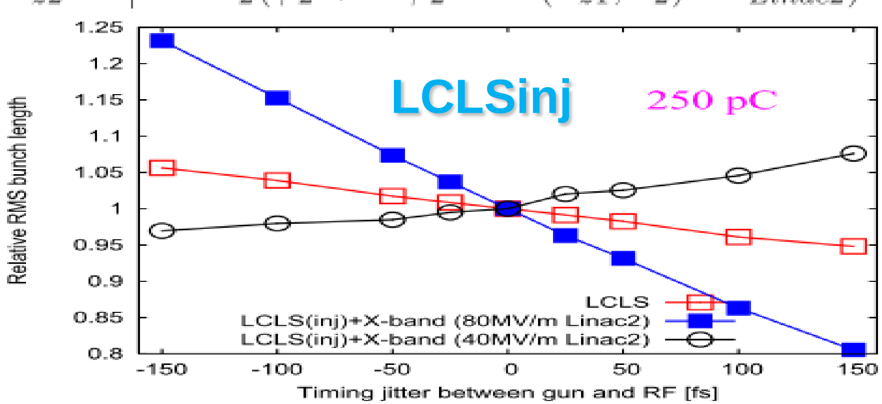
| timing jitter | $\Delta I_{pk}$ | $\Delta L_G$ ($L_{sat}$) | $\Delta P_{FEL,sat}$ |
|---|---|---|---|
| 25fs | 0.6% | 0.3% | 99.7% |
| 50fs | 2% | 1% | 99% |

**XFEL-LowC**

| | Ipk | LG | PFEL,sat |
|---|---|---|---|
| 50fs timing | 18% | 7% | -7% |
| 4% charge | 4% | 2.5% | -6% |

$$\frac{\Delta\sigma_{zf}}{\sigma_{zf}} = -\frac{\Delta C}{C_0} = (C_0 \mp 1)\Delta\phi_{rf}\cot\phi_{rf} \approx C_0\frac{\Delta\phi_{rf}}{\phi_{rf}}$$

$$\sigma_{z2} = \left[1 - k_2(\phi_2 + \Delta\phi_2 - D(\sigma_{z1}, k_2)\cdot L_{Linac2})R_{56(2)}\right]\cdot\left[1 - k_1(\phi_1 + \Delta\phi_1)R_{56(1)}\right]\cdot\sigma_{z0}$$




**Tuning Linac2 length/gradient**
stronger longitudinal wakefield in Linac2 to cancel the timing jitter effect, a longer total accelerator length and a higher total cost employing more RF cavities. tradeoff between the tolerated timing jitter.

# Tolerances: BC1 alignment

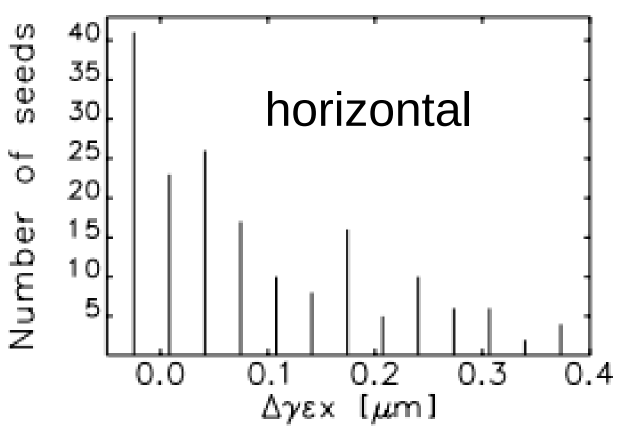
- **200 µm** (RMS) random offsets are generated on all the quadrupoles and sextupoles in BC1
- **200 µm** for the offset between BPM electrical center and quadrupole magnetic center
- An RMS roll angle error of **200 µrad** is also applied on all the quadrupoles and sextupoles in bunch compressor one

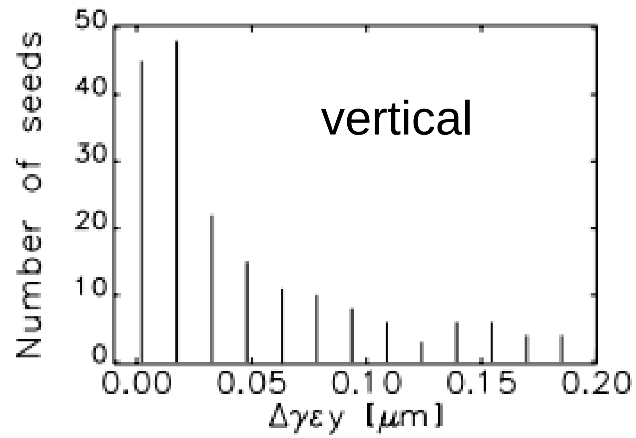
Table IV: Bunch compressor magnets parameters (3*cm* radius).

| *Name* | Bend [*kGauss*] | Quad [*kG*] | Sextupole [*kG*] |
|---|---|---|---|
| 250pC BC1 (250MeV) | 1.7-4 | 1.7 | 0.18 |

Table II: Bunch compressor TWISS parameters.

| *Name* | $K_Q$ 0.2m $[m^{-2}]$ | $K_S$ 0.1m $[m^{-3}]$ | $Q'_x$ | $Q'_y$ | $\beta_{x,max}$ | $D_{x,max}$ |
|---|---|---|---|---|---|---|
| 250pC BC1 | 7.4 | 50 | -1.72 | -0.9 | 45 | 0.4 |



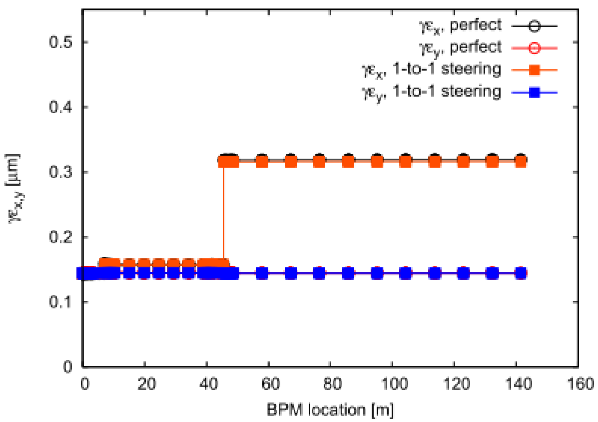

- One to one steering, **200 random seeds**
- An average growth of **0.15** µm and **0.06** µm are found in horizontal and vertical projected normalised emittance, respectively

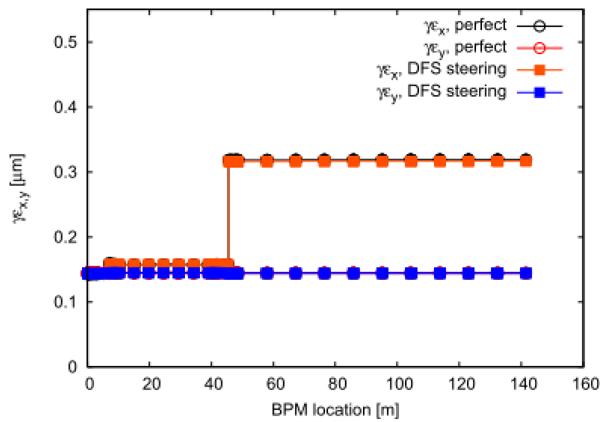
SLAC NATIONAL ACCELERATOR LABORATORY

# Tolerances: linac alignment

Stronger X-band T-wake than S-band, easier with low charge and shorter bunch

- ➢**200 µm** (RMS) random offsets are generated on all the quadrupoles and RF in linac
- ➢**200 µm** for the offset between BPM electrical center and quadrupole magnetic center
- ➢An RMS roll angle error of **200 µrad** also applied on all the quadrupoles



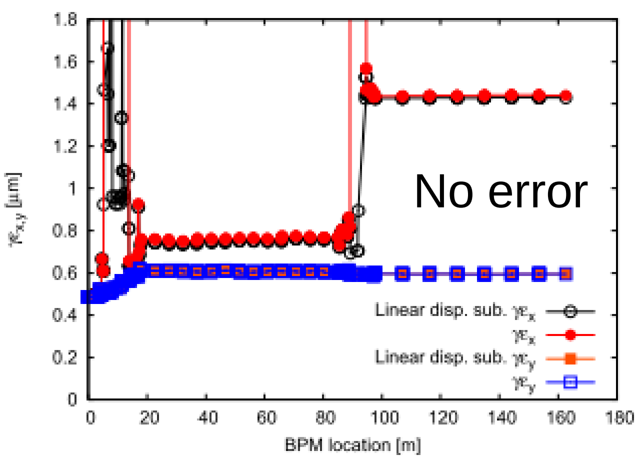

XFEL-LowC

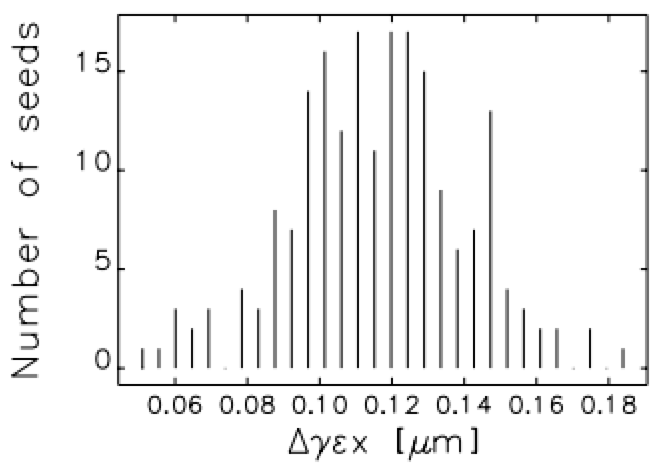
**10 pC**

Average of 200 seeds

1-to-1 or DFS

negligible




XFEL-GB

**250 pC**

200 seeds

1-to-1

0.12 um growth

# Summary

- General bunch compressor design for longitudinal phase space linearization (tolerance acceptable)→ alternative for harmonic RF
- Three X-band RF driven Hard X-ray FELs, achieve/exceed LCLS-like performance in **25% overall length or less**
- X-band tolerance acceptable from 10-250 pC

| Parameter | Sym. | LCLS | XFEL-GB | XFEL-LowC | LCLSinj | unit |
|---|---|---|---|---|---|---|
| bunch charge | $Q$ | 250 | 250 | 10 | 250 | pC |
| Energy | $E$ | 14 | 7 | 6 | 14 | GeV |
| N. emittance | $\gamma\varepsilon_{x,y}$ | 0.6 | 0.6 | 0.15 | 0.6 | µm |
| peak current | $I_{pk}$ | 3.0 | 3.0 | 3.0 | 5.0 | kA |
| Slice espread | $\sigma_E/E$ | 0.01 | 0.01 | 0.01 | 0.01 | % |
| Pulse length | $\Delta T$ | 60 | 50 | 2 | 30 | fs |

I would like to thank the following people for their great help and useful discussions:

C. Adolphsen , K. Bane, A. Chao, Y. Cai, Y. Ding, J. England, P. Emma, Z. Huang, C. Limborg, Y. Jiao, Y. Nosochkov, T. Raubenheimer, M. Woodley, W. Wan, J. Wu

# Thank you for your patience!

NATIONAL ACCELERATOR LABORATORY