Three Bunch Compressor Scheme for SASE FEL

HeungSik Kang

Pohang Accelerator Laboratory

XFEL Requirements

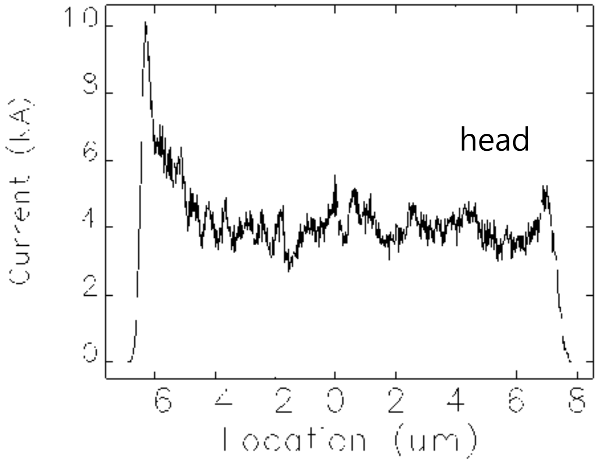
- Photon beam requirements from users
  - Wavelength : 0.1 nm
  - Photon Flux : > 1 x 10^{12} photons / pulse (brightness ~ 1x10^{33})
    - FEL power (29 GW) x Pulse length (60 fs FWHM) = 1 x 10^{12} photons / pulse
    - As many electrons in a pulse as possible should contribute to SASE FEL interaction

- Electron beam requirements

1. Transverse emittance

$$\frac{\varepsilon_n}{\gamma} < \frac{\lambda_r}{4\pi}$$

* Projected emittance: 0.5 μm-rad for 0.2 nC beam



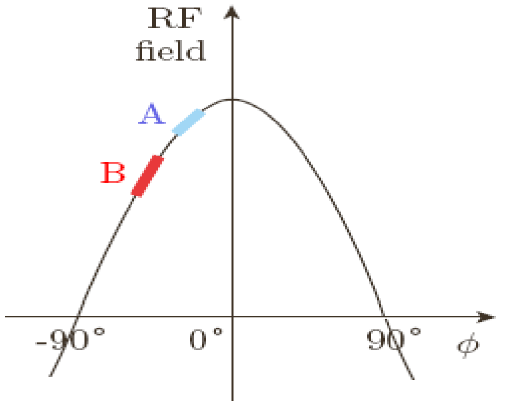
End of BC3 with 200 k particles and 100 slices

2. Energy spread

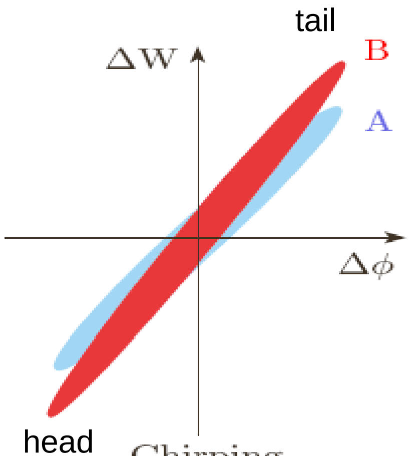
$$\boxed{\sigma_\delta < \rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_N}\left(\frac{K}{\gamma}\right)^2\right)^{1/3}}$$

* Correlated energy spread < FEL parameter

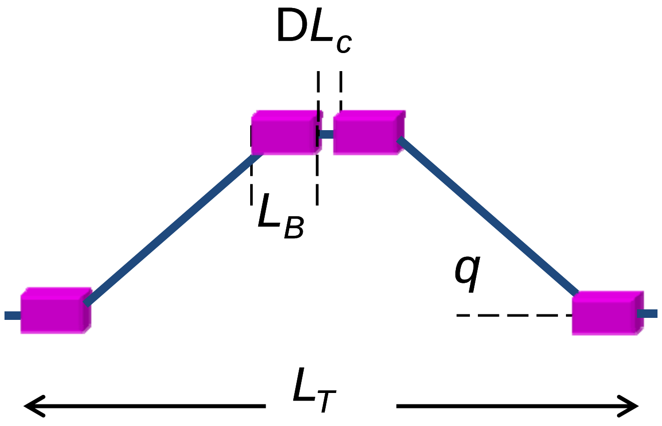
Bunch Compression



Phase



Chirping



$$R_{56} \approx -2\theta^2\left(\frac{L_T}{2}-\frac{4}{3}L_B-\frac{\Delta L_c}{2}\right)$$

Bunch length σ_z

$$\sigma_z = \langle z^2 - \langle z\rangle^2\rangle^{1/2} = \sqrt{(1+hR_{56})^2\,\sigma_{z_i}^2 + (aR_{56}\sigma_{\delta_i})^2} \approx |1+hR_{56}|\sigma_{z_i}$$

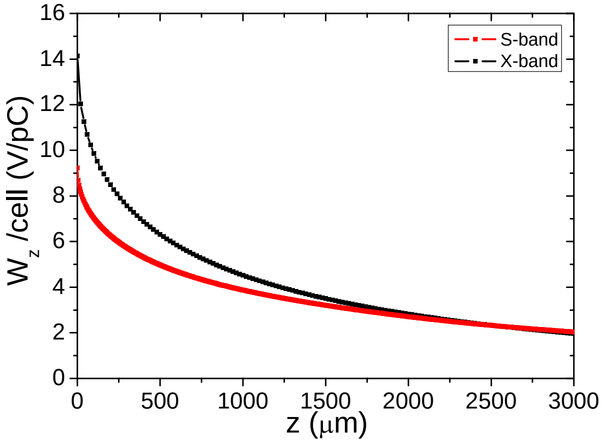
σ_z , σ_{zi} are given variables, and ***h* x R_{56} = constant.**

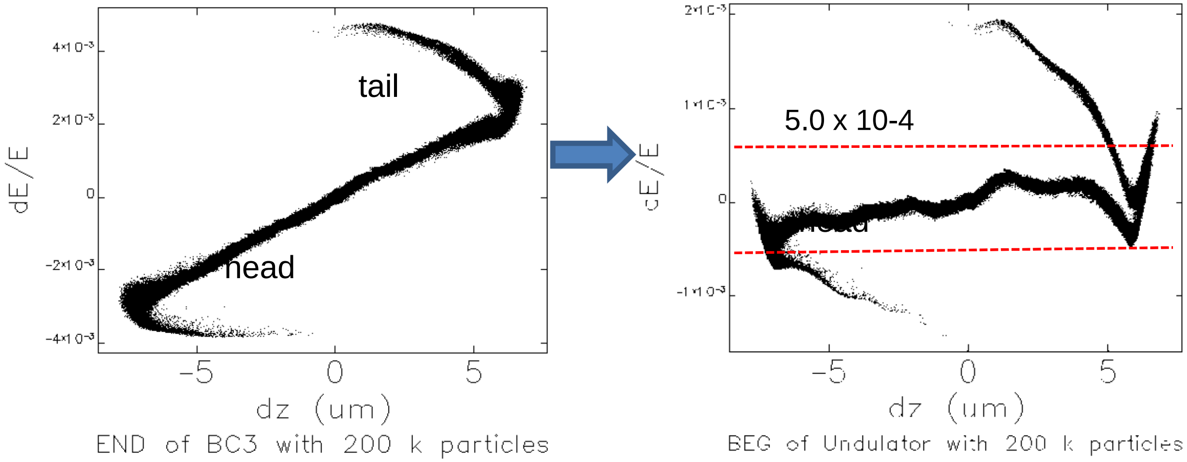
Energy chirp *h* and R_{56} are to be carefully chosen considering emittance growth and correlated energy spread.

Wake in Accelerating Structures

Wake in Accelerating structures cancel energy chirp after compression

(Karl L.F. Bane, “Short-range dipole wakefields in accelerating structures for the NLC”)





END of BC3 with 200 k particles

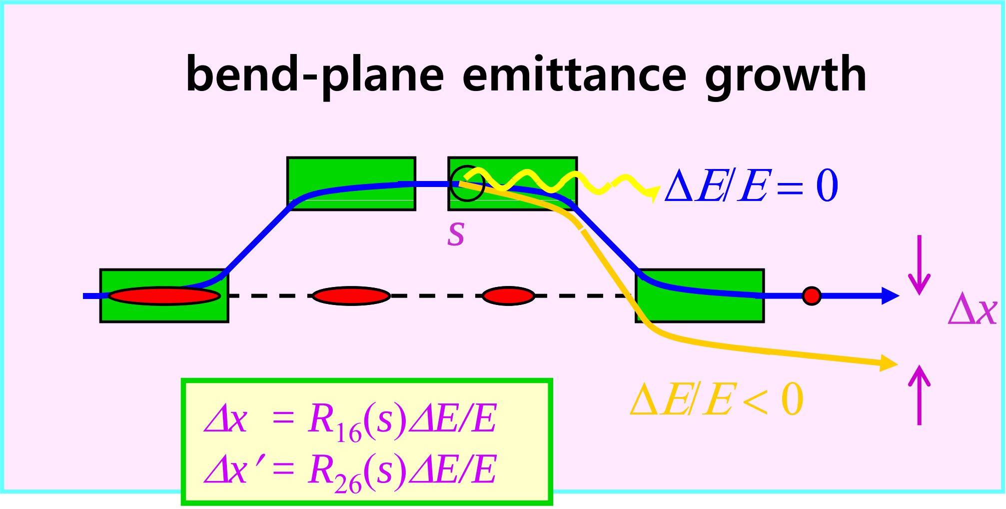
BEG of Undulator with 200 k particles

- If the bunch current after bunch compression is given, the length of accelerating structures determines the required energy chirp.
- A short linac requires a smaller energy chirp than a long linac like LCLS, which means a short linac requires a larger R56 than a long linac.
- A large R56 may give birth to large emittance increase at the bunch compressor due to CSR

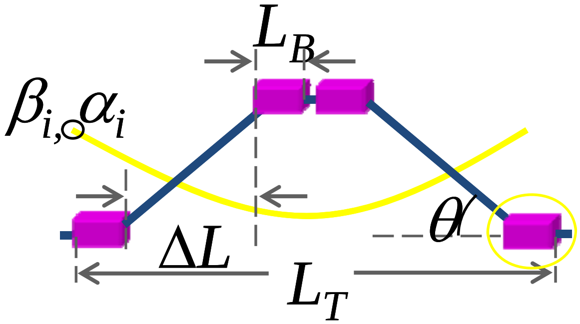
Coherent Synchrotron Radiation

Courtesy P. Emma

- **CSR generates energy spread in bends**
- **Causes bend-plane emittance growth (short bunch worse)**



Energy spread in bends causes transverse position spread after bends ⇒ *x*-emittance growth



$$\frac{\epsilon}{\epsilon_0} \approx \sqrt{1+\frac{(0.22)^2}{36}\frac{r_e^2N^2}{\epsilon_N\beta_i\gamma}\left(\frac{\theta^5 L_B}{\sigma_z^4}\right)^{2/3}\left[L_B^2\left(1+\alpha_i^2\right)+9\beta_i^2-6\alpha_i\beta_i L_B\right]}$$

$N = 6\times10^9$, $\theta = 30$ mrad (1.72°) , $L_T = 20$ m, $\varepsilon_N = 1$ μm,
$\gamma mc^2 = 4$ GeV, $\sigma_z = 20$ μm ⇒ $\Delta\epsilon/\epsilon_0 \approx 25\%$

- A large bend angle gives birth to a large emittance increase.
- A higher beam energy is preferred in the bunch compressor

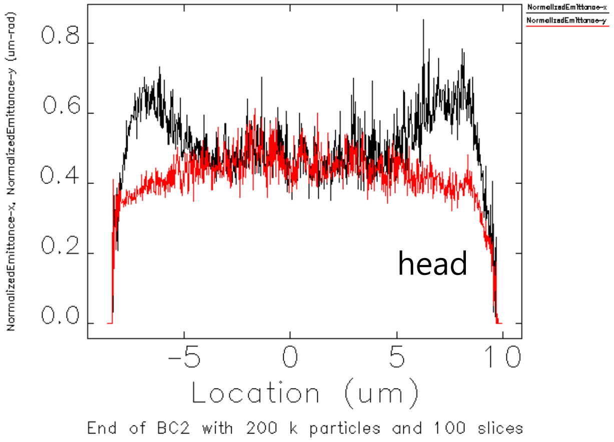
Incoherent Synchrotron Radiation Emittance Growth

Incoherent synchrotron radiation (ISR) in chicane bends at **high** energy *E*, generates uncorrelated energy spread, diluting phase space in horizontal plane (dilutes ‘slice’ emittance) …

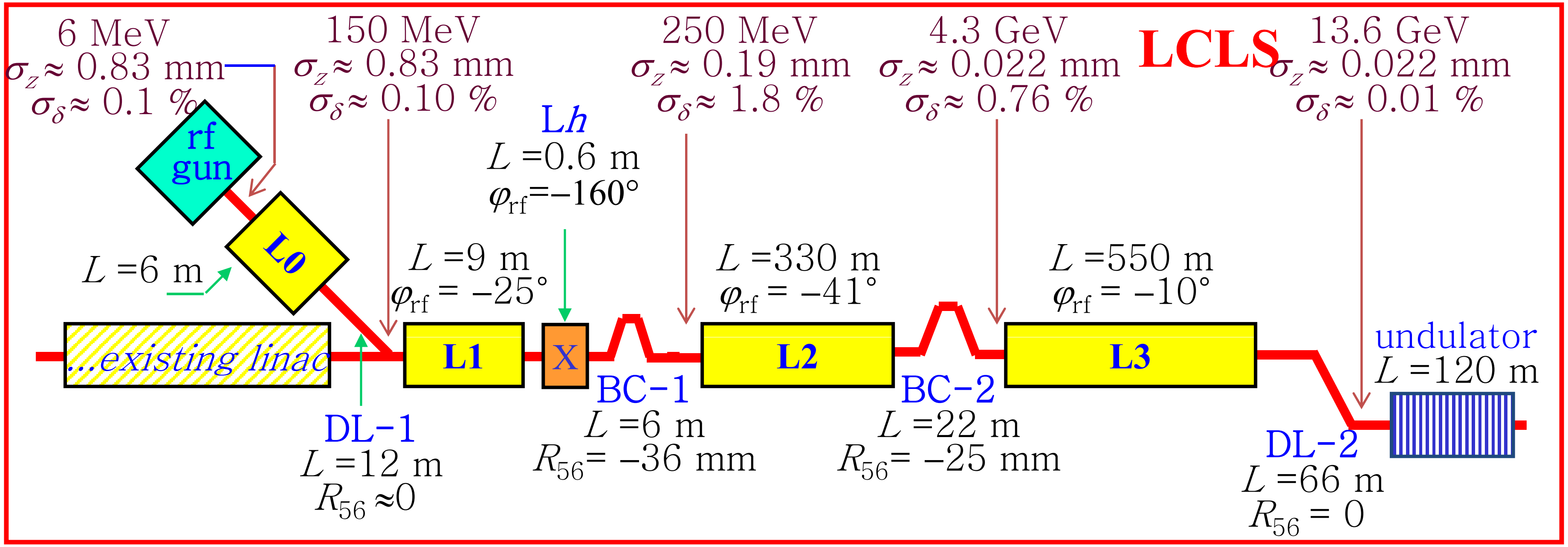
T. Raubenheimer

$$\boxed{\frac{\Delta\varepsilon}{\varepsilon_0} \approx aE^6 \frac{\left|\theta^5\right|}{\varepsilon_N L_B^2}\left[\Delta L + L_B + \frac{\widehat{\beta}+\breve{\beta}}{3}\right],\ a \cong 8\times10^{-8}\,\mathrm{m}^2\cdot\mathrm{GeV}^{-6}}$$

Chicane bends should be weak and long (L_B), and beam energy should be as low as possible.

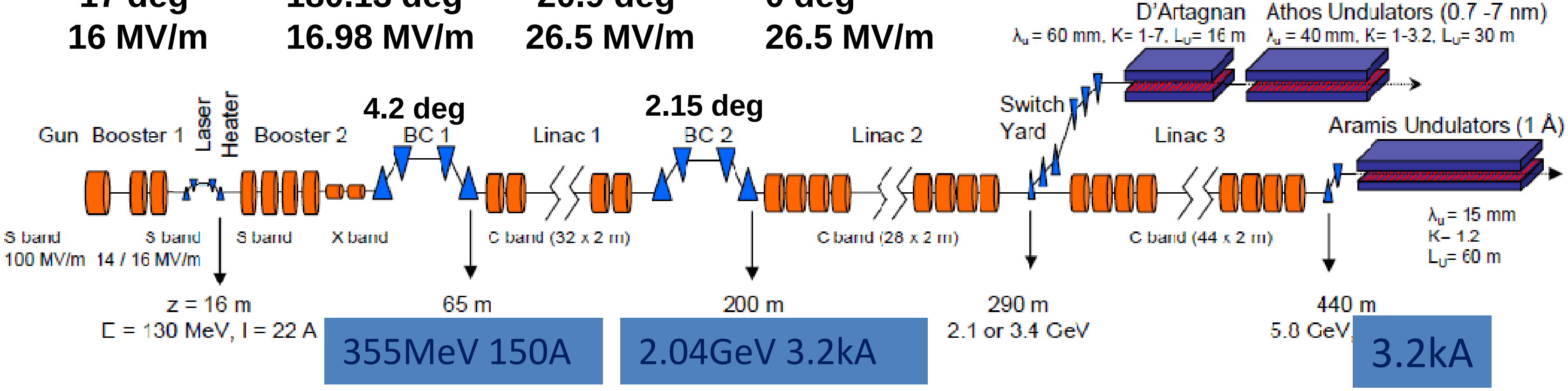


Two Bunch Compressor Scheme



SwissFEL

Booster 2:	X-Band:	Linac 1:	Linac 2/3:
-17 deg 16 MV/m	180.13 deg 16.98 MV/m	-20.9 deg 26.5 MV/m	0 deg 26.5 MV/m



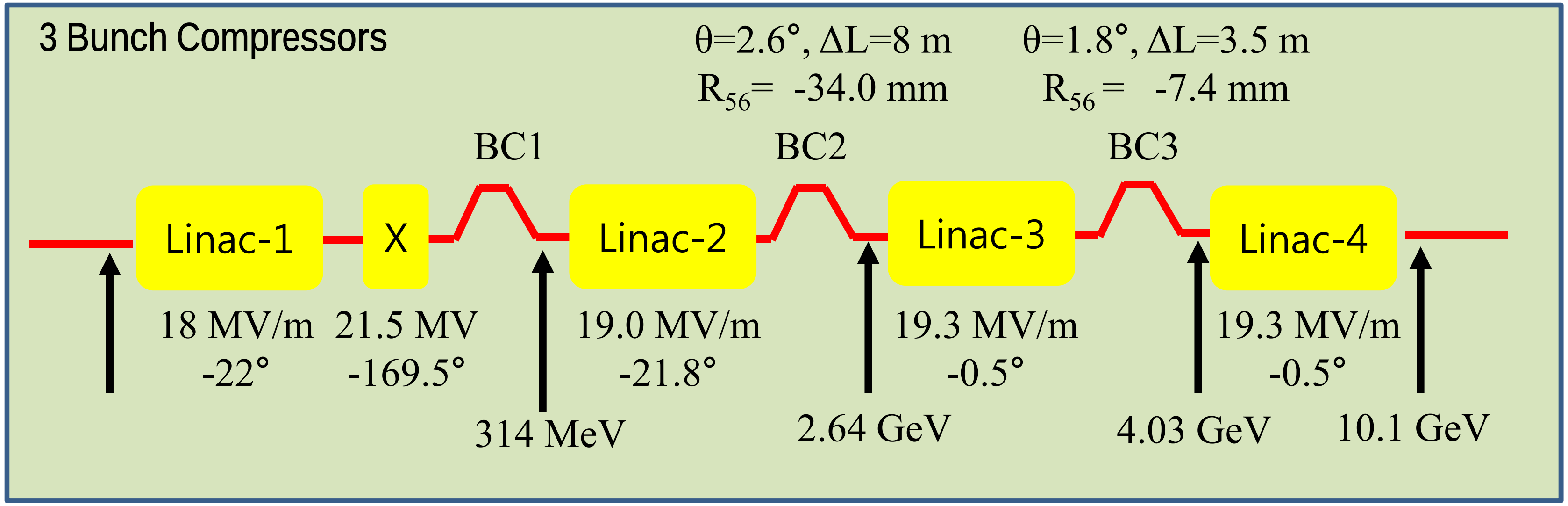
Three Bunch Compressor Scheme

- A short Linac → small energy chirp → big R56 → big bend angle in chicane → large emittance increase due to CSR and ISR

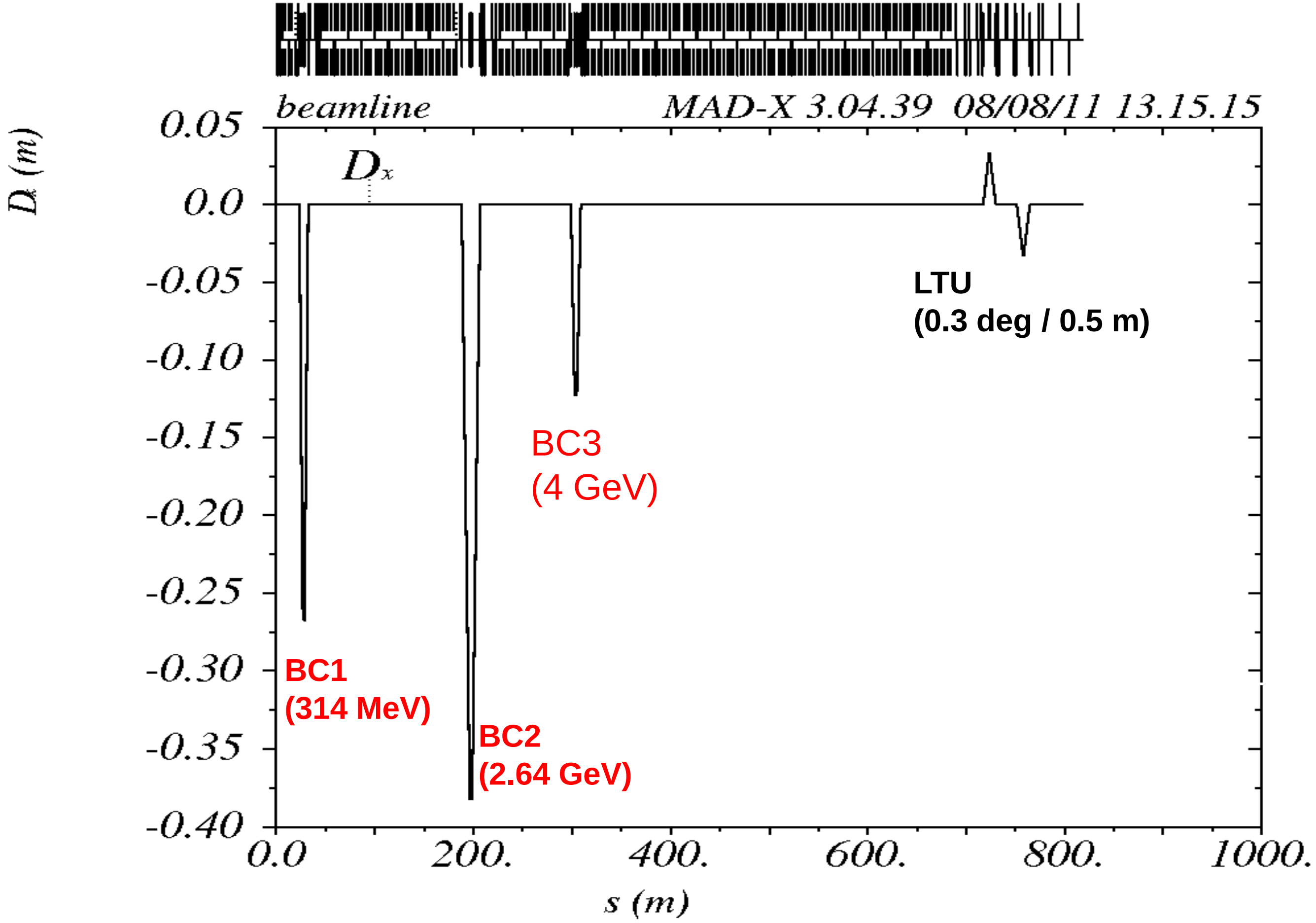
h x R_{56} = constant = h x R_{56}

- 2^{ND} BC in Two BC Scheme is splited into two.
- 3^{rd} BC has a small R56 to minimize CSR effect

 - weaker chicane BC3 → less CSR



Three Bunch Compressor Scheme

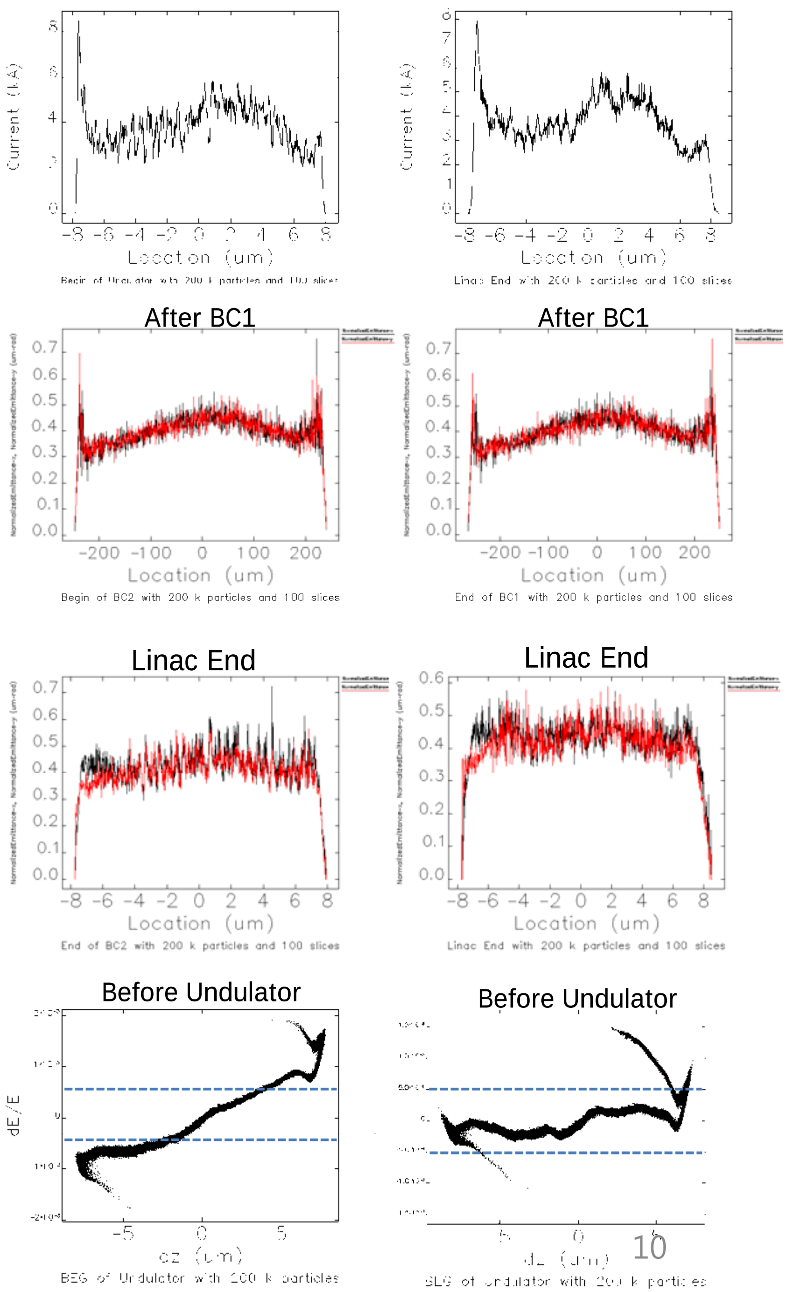


- 3 Bunch compressor Scheme
  - gives a better beam parameter than two bunch compressors

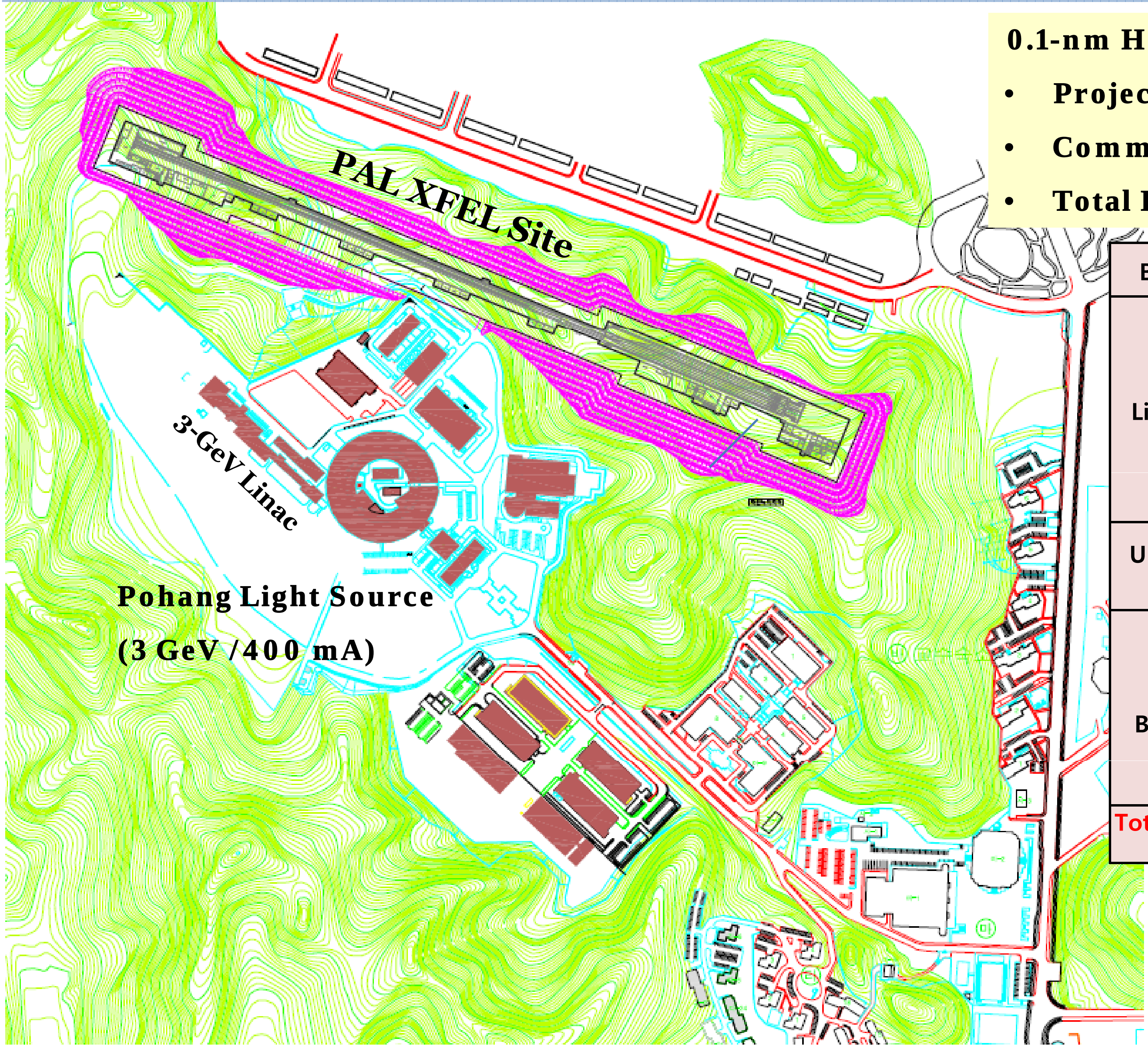
		Two Bunch compressors	Three BCs
BC1 (420 MeV)	Bend Angle [deg]	4.5	4.5
	Distance bet. Two dipoles [m]	3.2	3.2
	R56 [cm]	-4.11	-4.11
BC2 (2.8 GeV)	Bend Angle [deg]	2	2.6
	Distance bet. Two dipoles [m]	11	8
	R56 [cm]	-2.75	-3.4
BC3 (4 GeV)	Bend Angle [deg]		1.8
	Distance bet. Two dipoles [m]		3.5
	R56 [cm]		-0.74
L1 phase [deg]		-18	-18
L2 phase [deg]		-27.5	-18.6
X-band phase [deg]		-166	-166
LTU (dogleg) dipole bend angle / length		0.5 deg / 1.9 m	0.3 deg / 0.5 m
Correlated energy spread		> 5 x 10-4	< 5 x 10-4
Emittance increase by CSR		small	small

2 BCs

3 BCs



PAL XFEL Project



0.1-nm Hard X-ray 10-GeV XFEL

- **Project Period: 2011 ~ 2014**
- **Commissioning: 2015**
- **Total Budget: 400 M$**

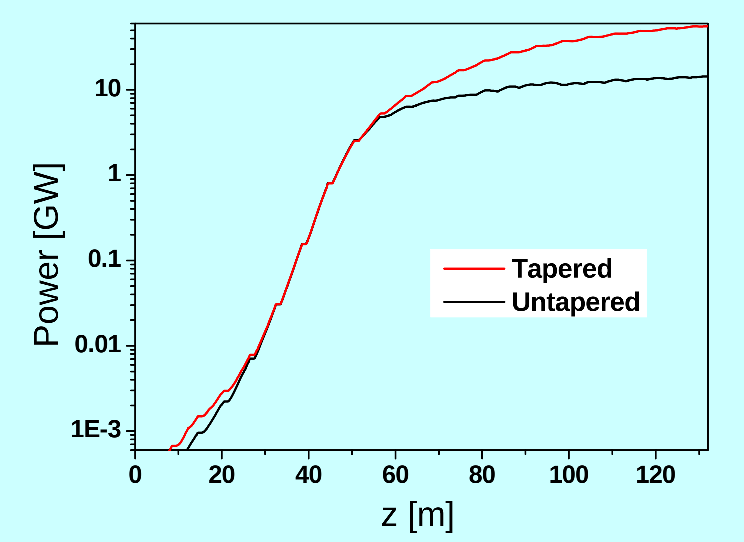
Building		
Linac Hall		830
	1. Assembly	20
	2. Linac	700
	3. BTL	110
Undulator Hall		200
XFEL Beamline		80
	1. Front-end	20
	2. Experiment hall	60
Total Length [m]		1110

Major Parameters of PAL XFEL

	FEL wavelength [nm]	0.1
Electron Linac	Beam energy [GeV]	10
	Beam charge [nC]	> 0.2
	Beam emittance [mm-mrad]	< 0.5
	Injector Gun	Photocathode RF-gun
	Peak current at undulator [kA]	> 3
	Repetition rate	120 Hz
	Number of Bunch	Single
	Linac Structure	S-band
Undulator	Undulator type	Out-vacuum
	Undulator Period [cm]	2.46
	Undulator Gap [mm]	6.8
	Undulator parameter, K	2.076
	Saturation Length [m]	56
FEL	FEL Radiation Power [GW]	> 29
	Photon beam length [fs]	60
	FEL Photons/pulse	> 1.0 E+12

- Wavelength
  - Soft x-ray: 1 nm ~ 10 nm
  - Hard X-ray: 0.7 ~ 0.1 nm
    - Extended to 0.06 nm
- Photon beam Length
  - Nominal : 30 ~ 100 fs (200 pC)
  - Short : < 5 fs (20 pC)
  - Ultra short: < 0.5 fs by ESASE scheme
- Undulator Beamline

  : 3 Hard X-ray / 2 Soft X-ray lines



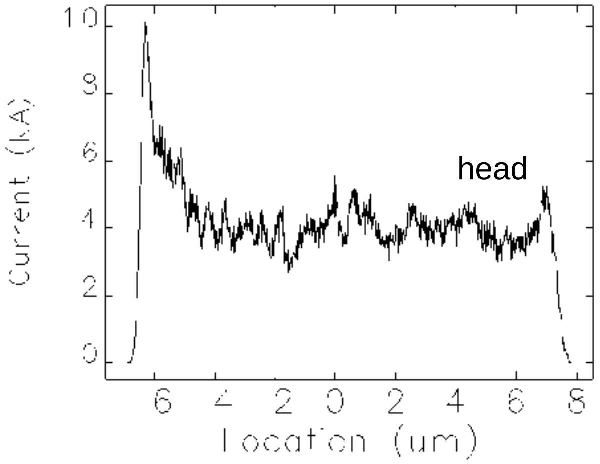
Radiation Power of 0.1 nm @Z=132 m

- Untapered : 14 GW (4.7E+11 photons)
- Tapered : 55 GW (1.8E+12 photons)

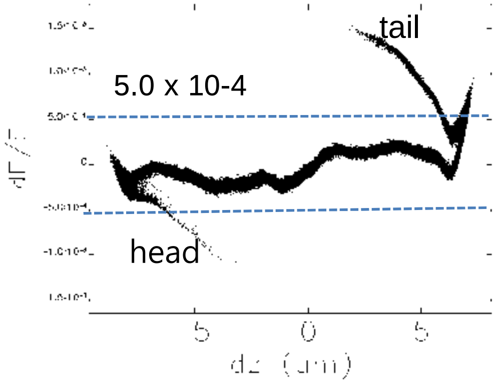
Linac and BTL Design

- **3 Bunch Compressors: t**he beam emittance is well preserved along the Linac and BTL by reducing CSR effect, and the correlated energy spread is controlled well below the FEL parameter.

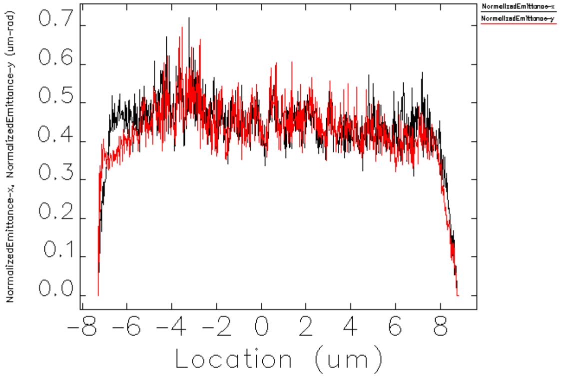
- Beam Current profile has a shape without horn at the head, which can help reduce the resistive wall wake effect in small gap undulator.



End of BC3 with 200 k particles and 100 slices

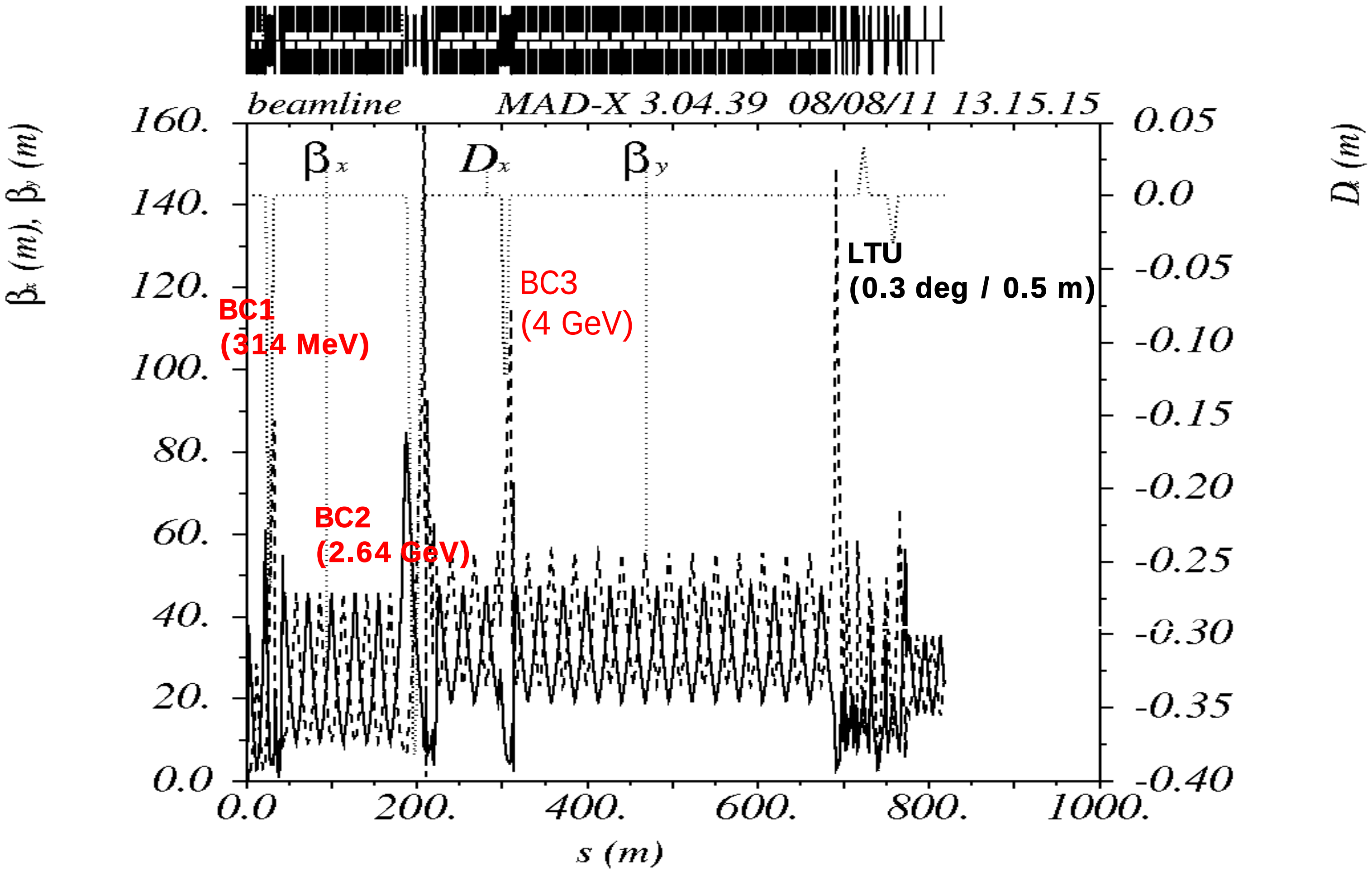


BEG of undulator with 200 k particles

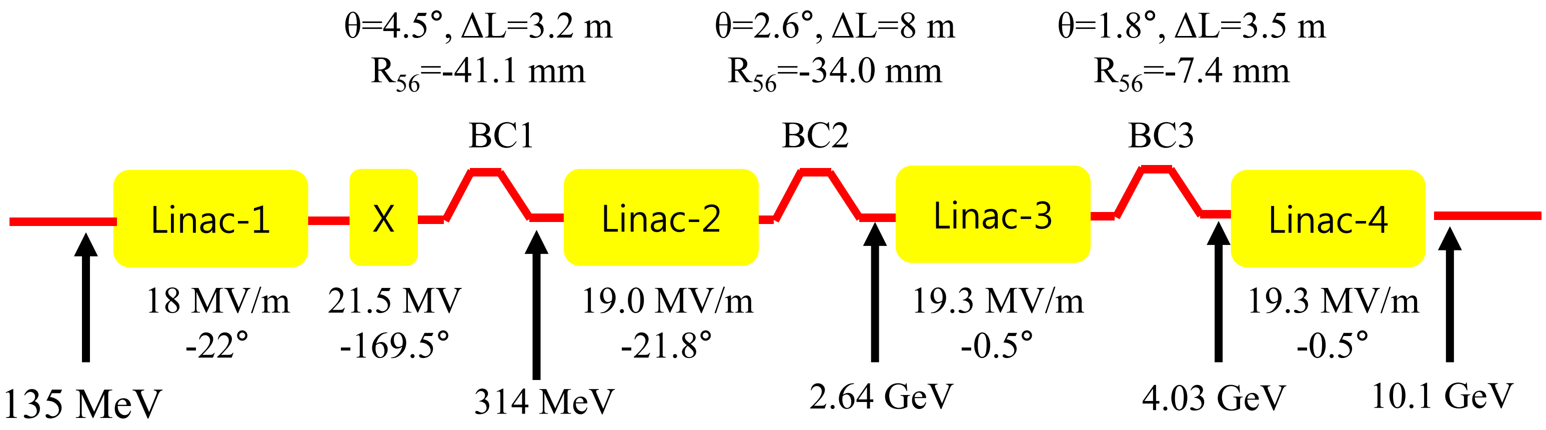


Begin of Undulator with 200 k particles and 100 slices

Linac & BTL Lattice



Start-to-End Simulation



θ=4.5°, ΔL=3.2 m
R_{56}=-41.1 mm

θ=2.6°, ΔL=8 m
R_{56}=-34.0 mm

θ=1.8°, ΔL=3.5 m
R_{56}=-7.4 mm

BC1

BC2

BC3

Linac-1

X

Linac-2

Linac-3

Linac-4

18 MV/m
-22°

21.5 MV
-169.5°

19.0 MV/m
-21.8°

19.3 MV/m
-0.5°

19.3 MV/m
-0.5°

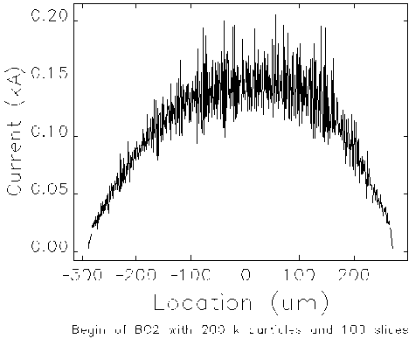
135 MeV

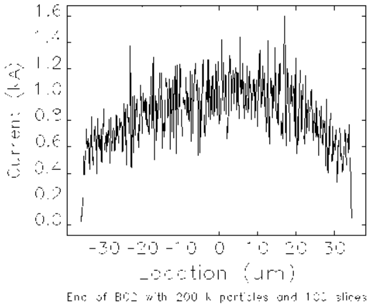
314 MeV

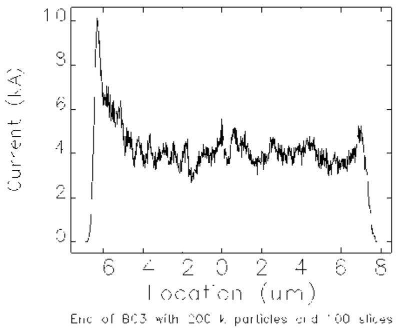
2.64 GeV

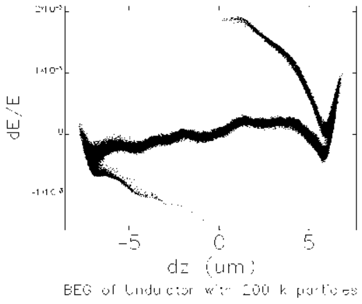
4.03 GeV

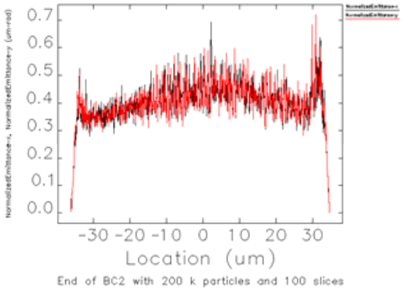
10.1 GeV

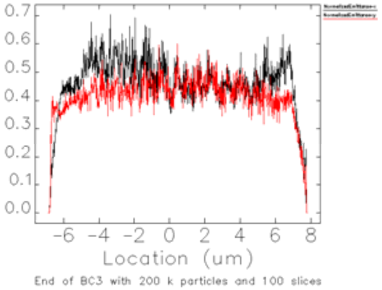


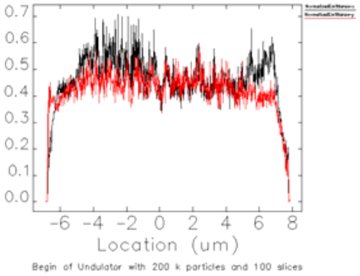












L1: 2 Kly / 4 AC
L2: 11 Kly / 44 AC
L3: 6 Kly / 24 AC
L4: 26 Kly / 104 AC

TOLERANCE BUDGET

- P_{sen} is value of sensitivity-individual table.

Parameter	# of klystron	sym bol	ΔI/I0 = +10% (P_{sen})	$<\Delta E/E_0>$ = +0.1%(P_{sen})	ε_{nx} = +5% (P_{sen})	Tolerance (rms)	unit
Mean L1 rf phase	3	φ_1	-0.17	2.1	-0.12	0.05	deg.
Mean X rf phase	1	φ_X	0.26	-3.9	0.19	0.05	deg.
Mean L2 rf phase	11	φ_2	-0.33	1.46	-0.23	0.1	deg.
Mean L3 rf phase	6	φ_3	-23.8)	96.5	-17.4	0.1	deg.
Mean L4 rf phase	26	φ_4	87053.0	58.6	-3938.99	0.1	deg.
Mean L1 rf voltage	3	V_1	2.4	8.5	4.04	0.05	%
Mean X rf voltage	1	V_X	1.7	-14.7	0.67	0.05	%
Mean L2 rf voltage	11	V_2	-57.7	1.43	-12.6	0.1	%
Mean L3 rf voltage	6	V_3	-25.0	1.76	-17.9	0.1	%
Mean L4 rf voltage	26	V_4	18555.7	0.87	-6455.36	0.1	%
B.C.-1 angle	-	θ_1	0.34	-4.7	0.18	0.01	%
B.C.-2 angle	-	θ_2	0.2	-3	0.17	0.01	%
B.C.-3 angle	-	θ_3	1.7	25.1	1.10	0.01	%
Sum [Σ(tolerance)^2/P_{sen}^2]			**0.45**	**0.16**	**0.66**		

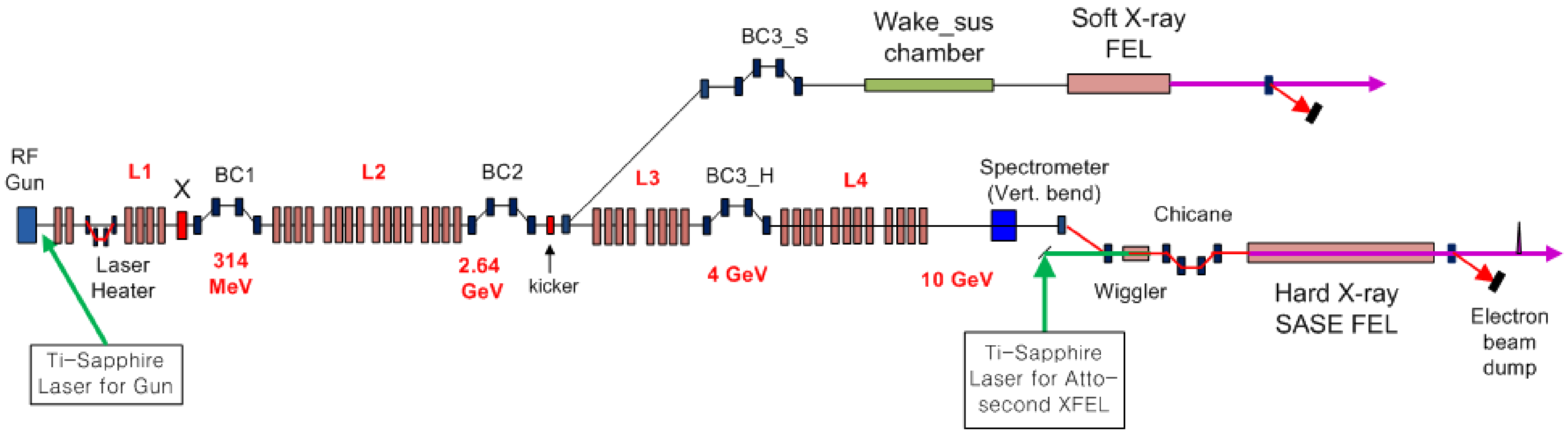
$$\sqrt{\sum(0.44+\frac{(tolerance)^2}{P_{sen}}}=1.05\ \ for\ \ \varepsilon_{nx}$$

(Emittance growth is most tough criterion.)

- Criterion: $$\sqrt{\sum(0.44+\frac{(tolerance)^2}{P_{sen}}}<1$$

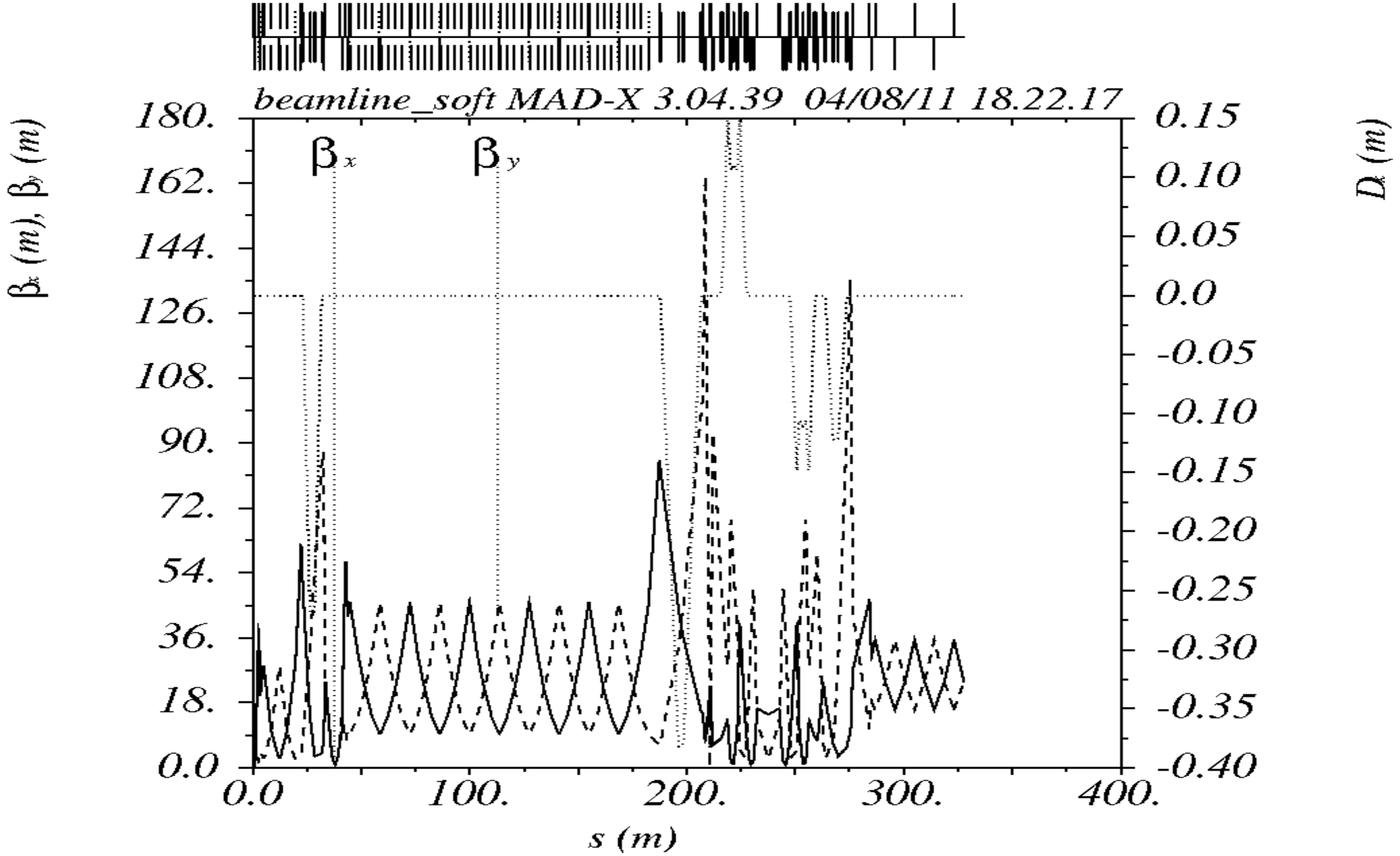
(0.44 is portion for unconsidered variable. It is determined by referring LCLS CDR)

lattice for Soft X-ray Line



- ◆ L1, X, BC1, L2, and BC2 has the same parameters as Hard X-ray
- ◆ No need of pulse-by-pulse RF phase control
- ◆ Very flexible in control of bunch current by changing the BC3_S bend angle
  - ❖ Switching by a kicker and a septum magnet
  - ❖ Orbit variation from the switching by kicker is acceptable for Soft X-ray FEL beamline
    - ▪ Simultaneous operation is feasible for Soft X-ray and Hard X-ray FEL

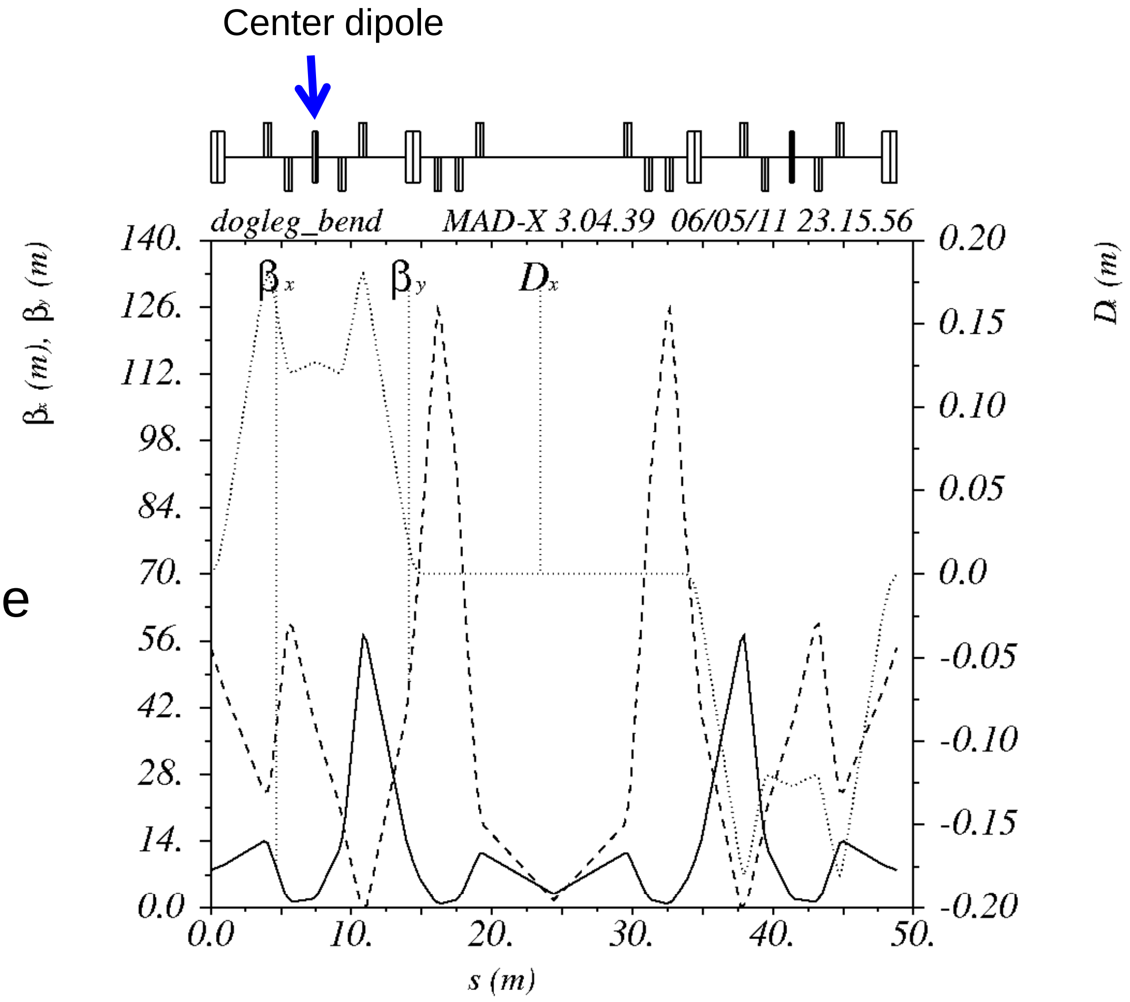
Lattice Design for Soft X-ray Lune



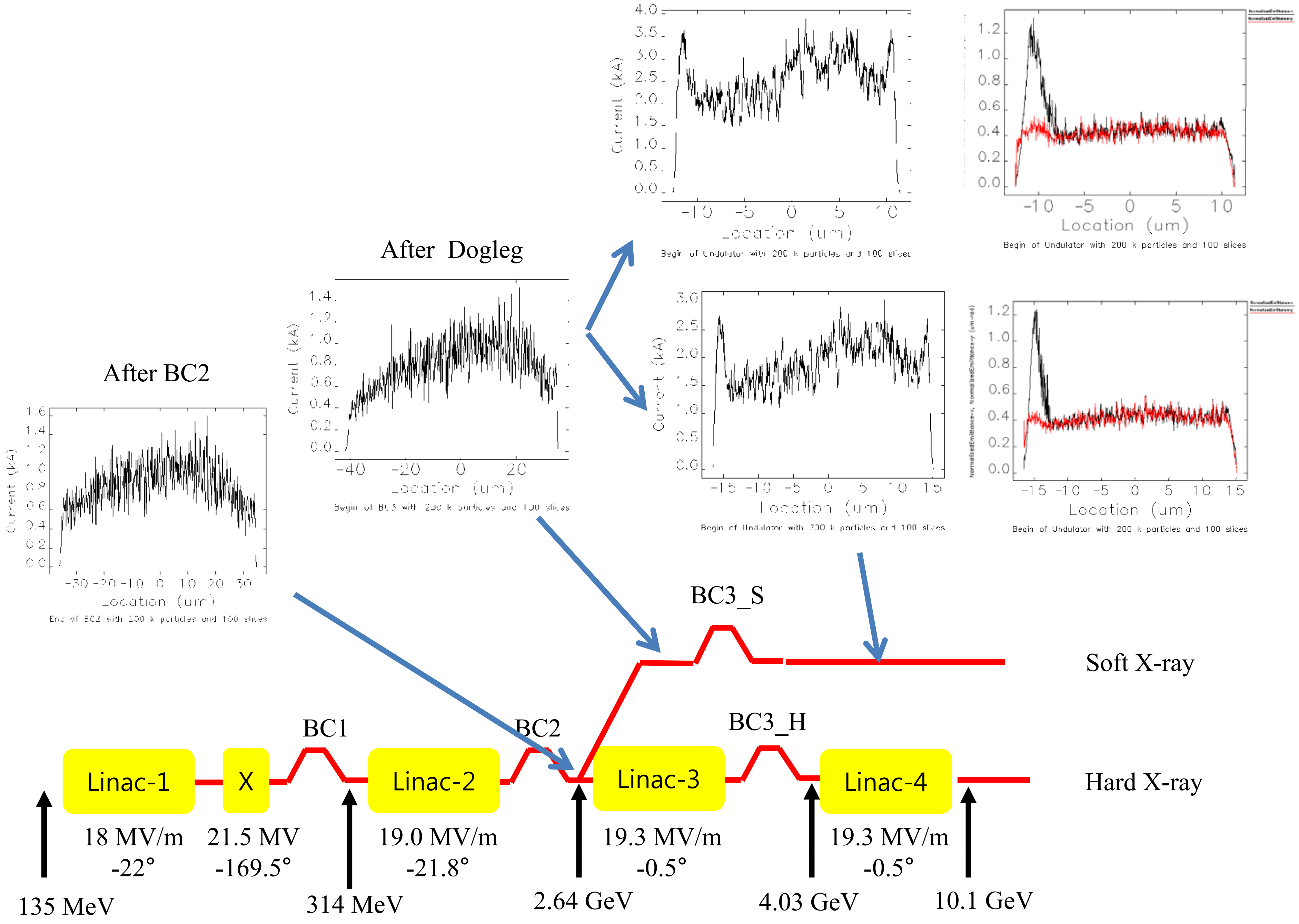
PAL XFEL: HeungSik Kang
(hskang@postech.ac.kr)

R56 Tunable Dogleg Branch for Soft X-ray

- 3-degree bend
- R56 tunable
- Small betas in large angle dipoles

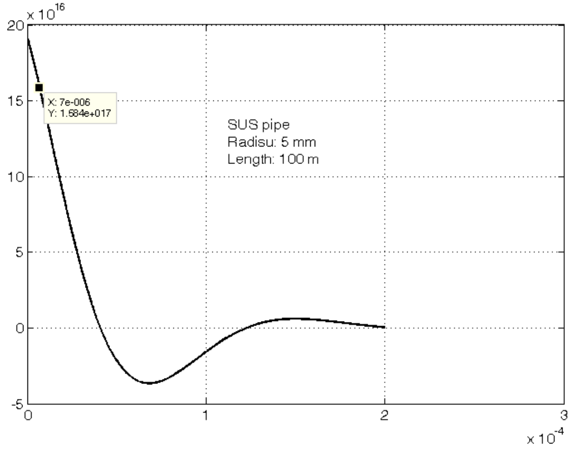

Center dipole

Bend angle [deg]	Bend angle of center dipole	R16	R26	R56
3	0.45	1.9 x 10-8	-2.4 x 10-10	-8.9 x 10-5
3	0.47	1.5 x 10-9	-1.9 x 10-11	-6.1 x 10-6
3	0.48	-8.0 x 10-9	9.8 x 10-11	3.6 x 10-5

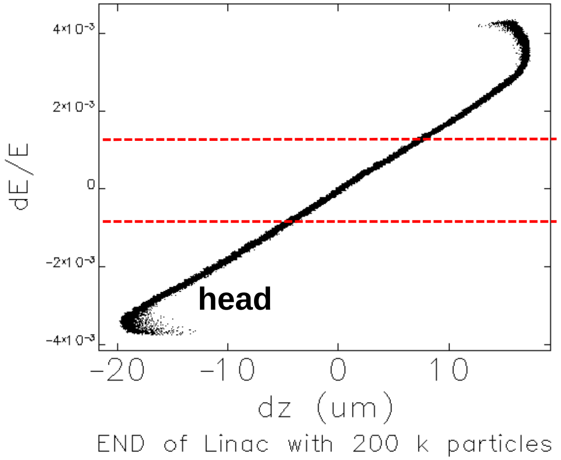

After BC2
Current (kA)
Location (um)
End of BC2 with 200 k particles and 100 slices
After Dogleg
Current (kA)
Location (um)
Begin of BC3 with 200 k particles and 100 slices
Current (kA)
Location (um)
Begin of Undulator with 200 k particles and 100 slices
Location (um)
Begin of Undulator with 200 k particles and 100 slices
BC1
BC2
BC3_S
BC3_H
Linac-1
X
Linac-2
Linac-3
Linac-4
Soft X-ray
Hard X-ray
18 MV/m
-22°
21.5 MV
-169.5°
19.0 MV/m
-21.8°
19.3 MV/m
-0.5°
19.3 MV/m
-0.5°
135 MeV
314 MeV
2.64 GeV
4.03 GeV
10.1 GeV

Reduction of Large Correlated Energy spread
by Resistive Wall Longitudinal wakefield of SS pipe

Resistive Wall wake of 100-m long SS pipe (r=5 mm)

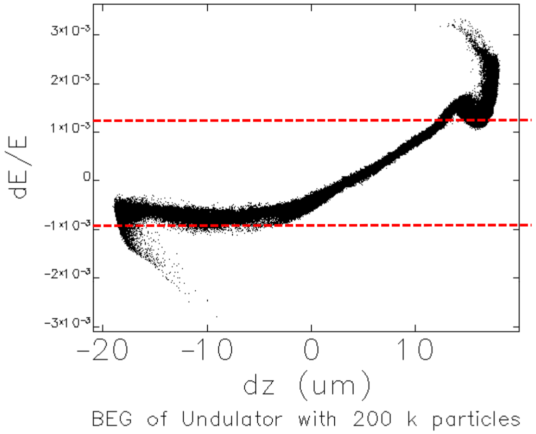


After BC3

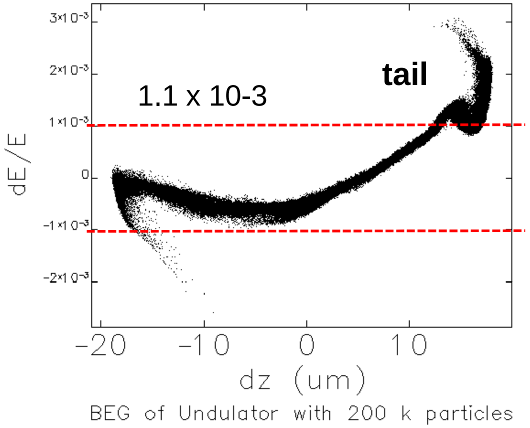


- Large correlated energy spread needs to be reduced at the subsequent Stainless Steel vacuum pipes.
- DC conductivity is only considered in the calculation.

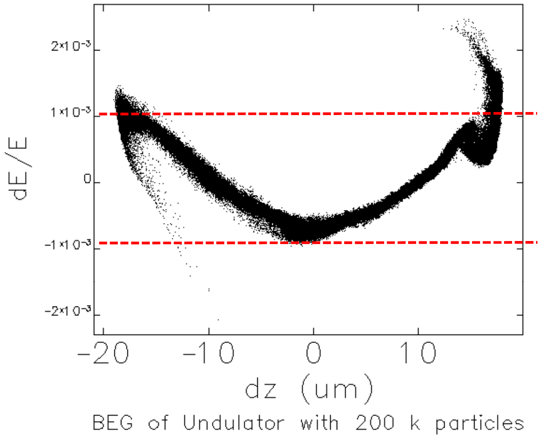
50-m SS pipe (r=5 mm)



65-m SS pipe (r=5 mm)



100-m SS pipe (r=5 mm)



Acknowledgements

Thanks to…

- Paul Emma, Zhirong Huang, and Karl L.F. Bane at ***SLAC***
- Kwang-Je Kim at ***ANL***
- Simone Di Mitri at **Sincrotrone Trieste – ELETTRA Laboratory**