CONTROL OF ELECTRON BEAM LONGITUDINAL PHASE SPACE WITH **A NOVEL COMPACT DE-CHIRPER** FOR PAL-XFEL

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K. Bane, Z. Huang, G. Stupakov (SLAC)
P. Emma, Marco Venturini (LBNL)

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- **Collaborative R&D with SLAC and LBNL**

  K. Bane, Z. Huang, G. Stupakov (SLAC)

  P. Emma, Marco Venturini (LBNL)

- **Beam test with a prototype dechirper at Injector test facility at PAL on August 5th – 9th , 2013**

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Beam Test on Aug. 5 ~ 9, 2103

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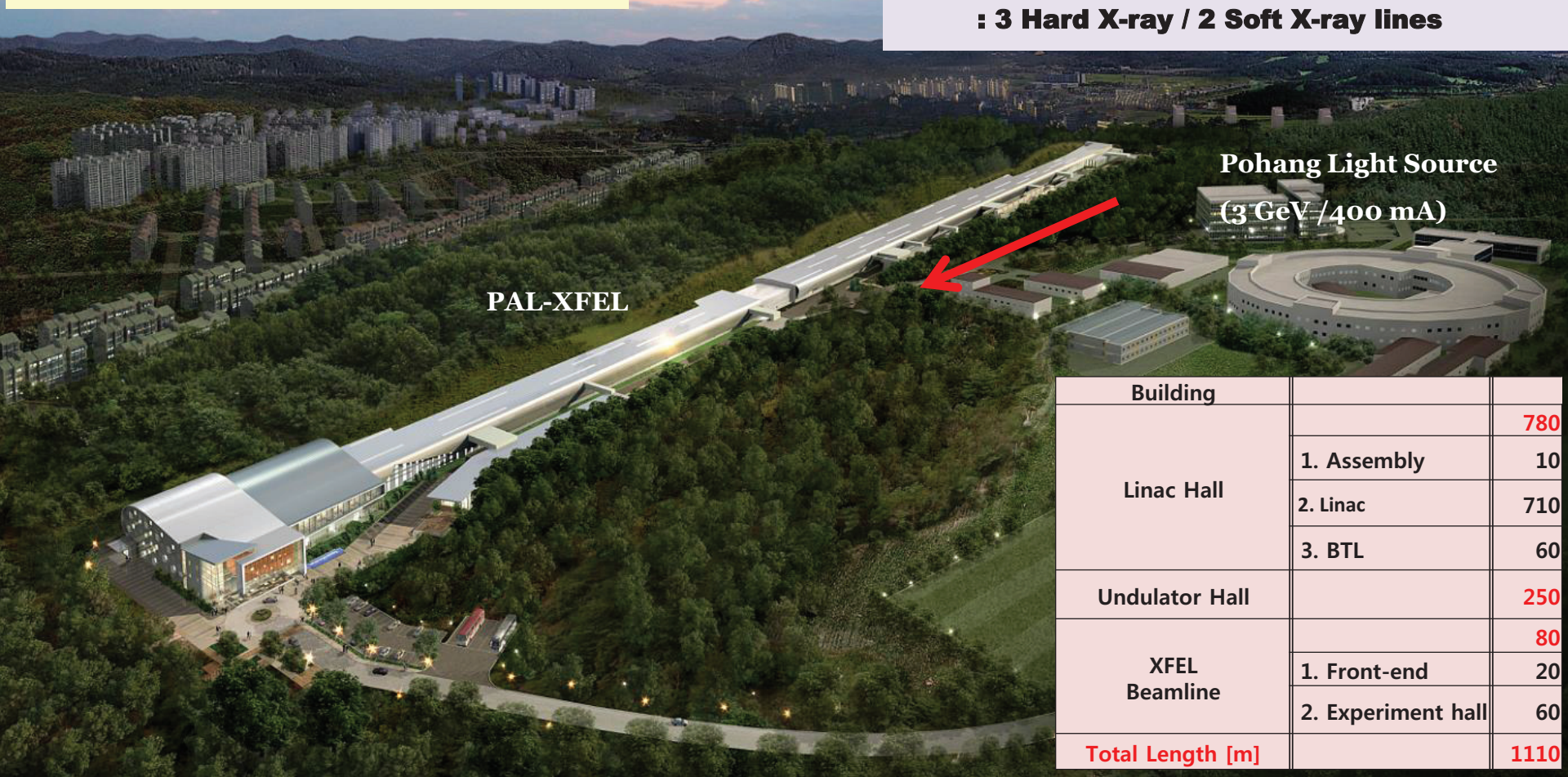
Korean 4-th generation Light Source: PAL-XFEL

0.1-nm Hard X-ray 10-GeV XFEL

- **Project Period: 2011 ~ 2015**
- **Total Budget: 400 M$**
- **Accelerator Length: 1.1 km**

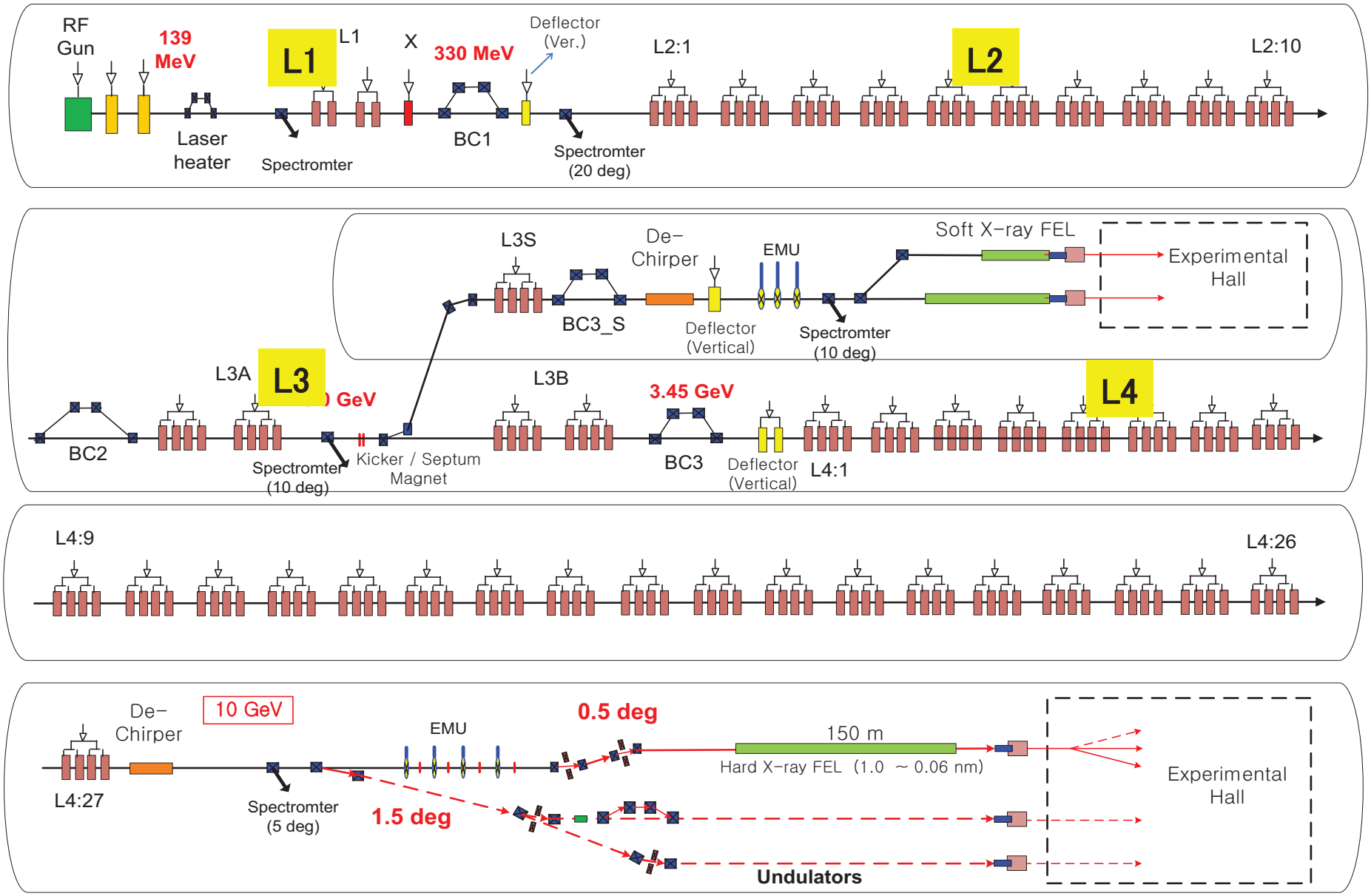
- **Wavelength**
  - **Soft x-ray: 10 nm ~ 1 nm**
  - **Hard X-ray: 1.0 ~ 0.1 nm**
    - **Extendable to 0.06 nm**
- **Undulator Beamline**

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



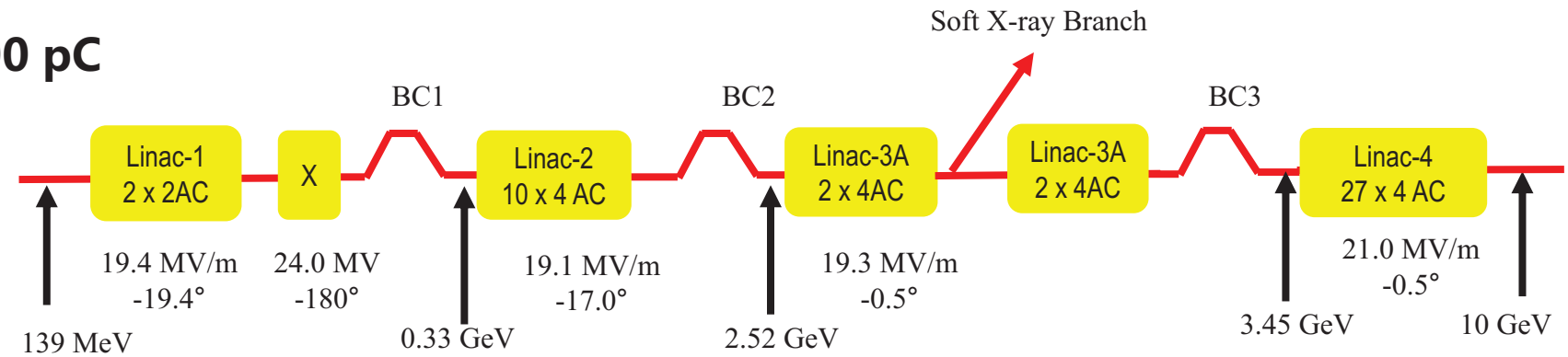
Building		
Linac Hall		780
	1. Assembly	10
	2. Linac	710
	3. BTL	60
Undulator Hall		250
XFEL Beamline		80
	1. Front-end	20
	2. Experiment hall	60
Total Length [m]		1110

PAL-XFEL Layout

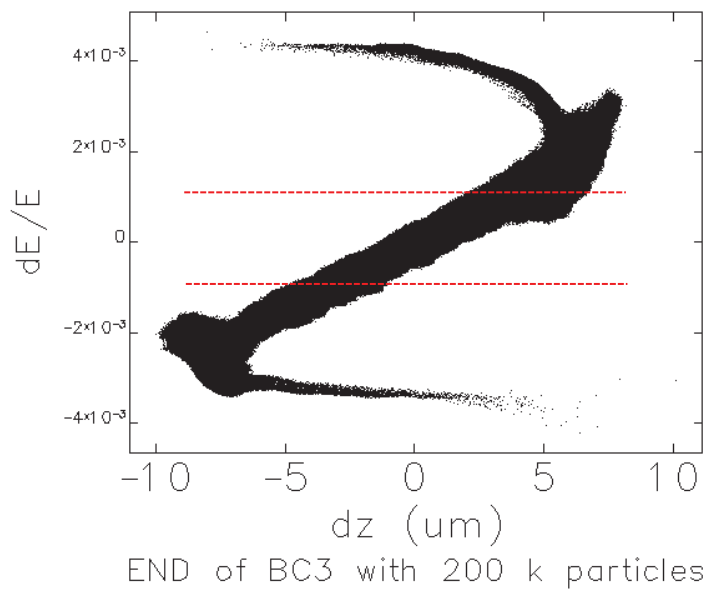


Start-to-End Simulation for Hard X-ray FEL Line

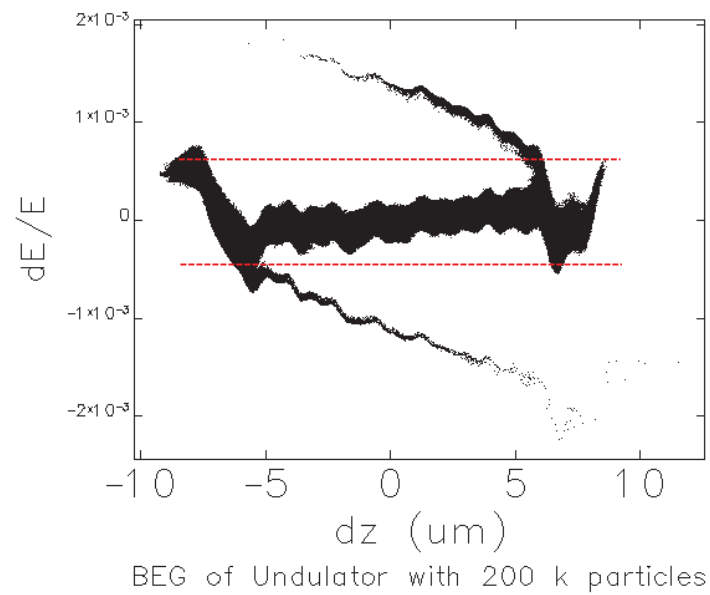
200 pC



After BC3



At the linac end



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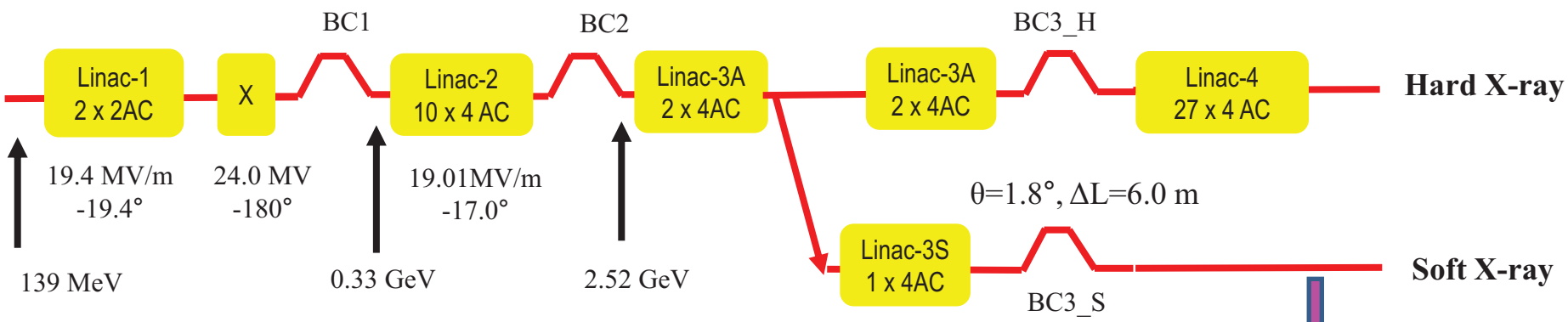
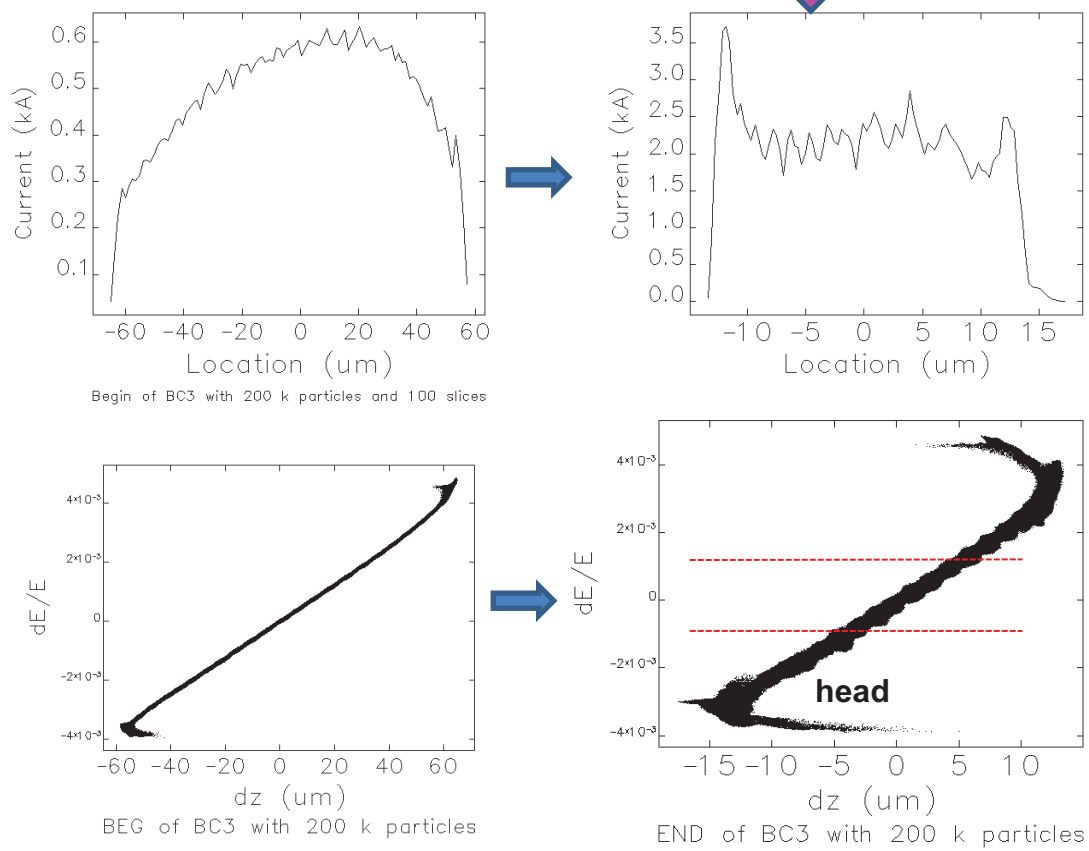
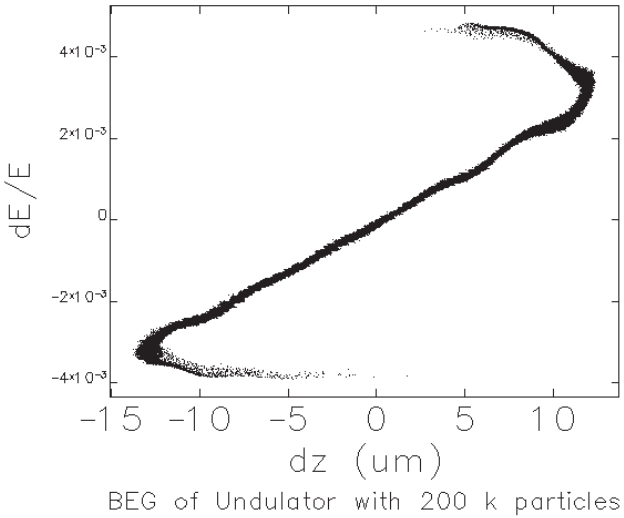
Start-to-End Simulation for Soft X-ray FEL Beamline

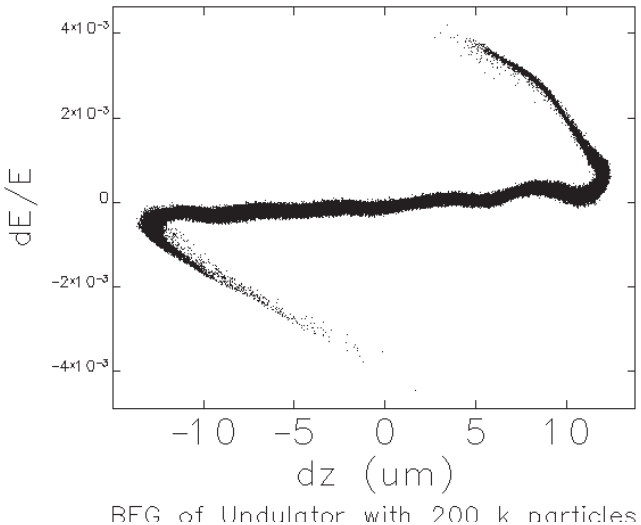


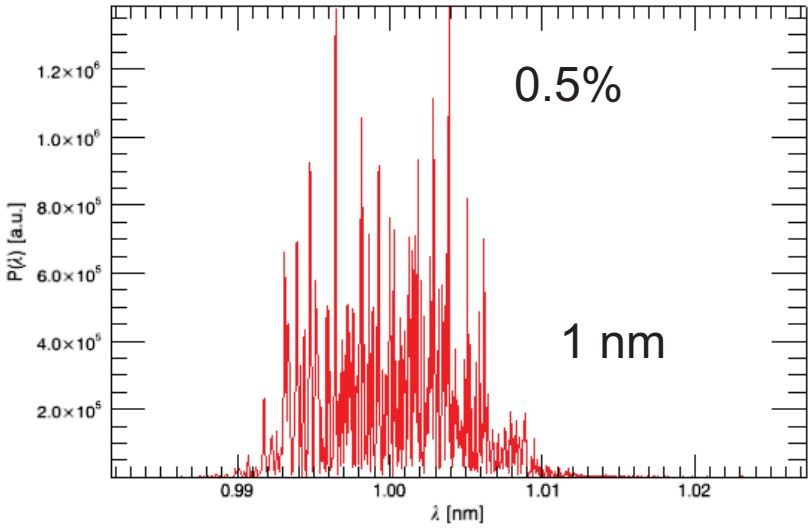
- energy chirp after final compression (4 x10^{-3}) is larger than FEL parameter (1 x10^{-3})
- There is a limited space before undulator. So, we need a strong longitudinal wake structure

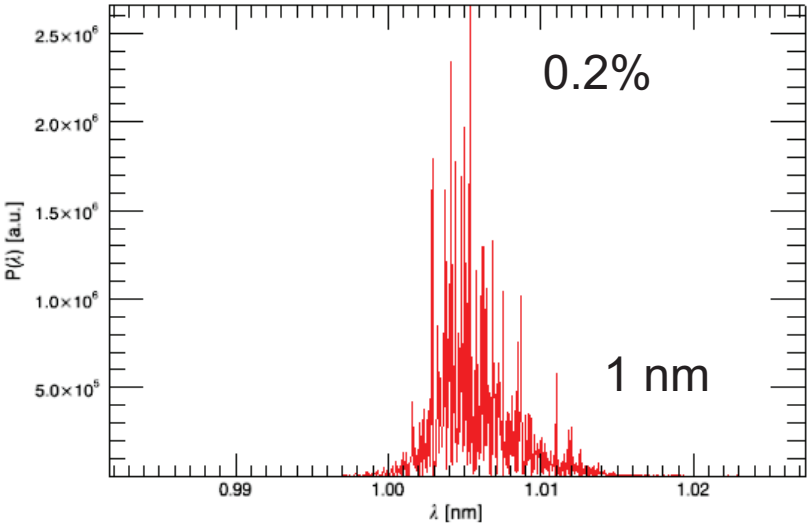


SASE Bandwidth vs. Energy chirp









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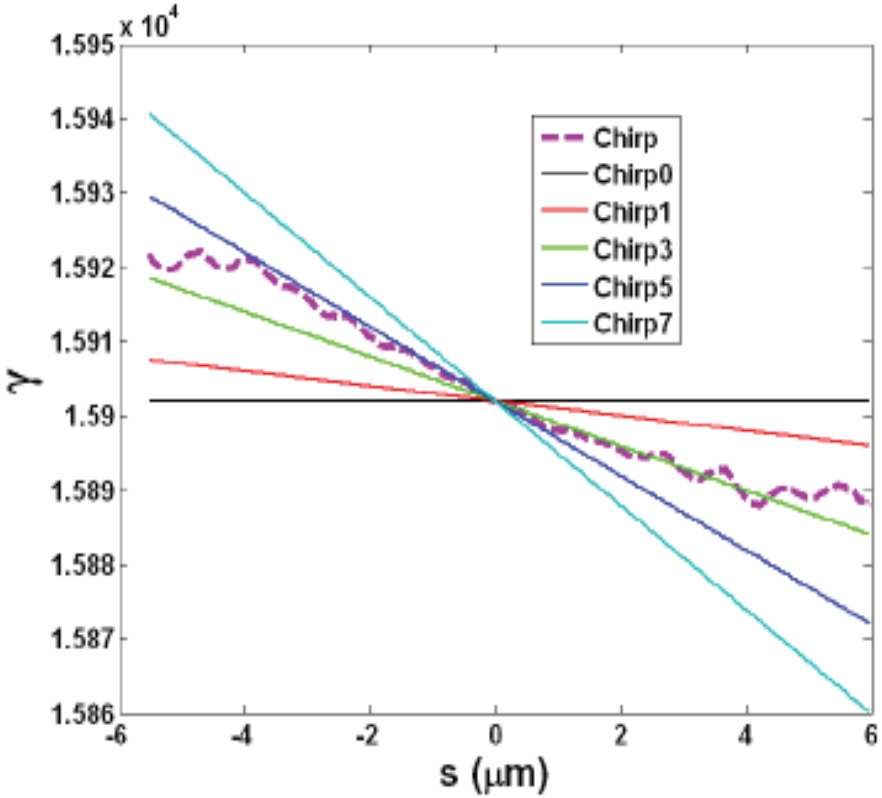
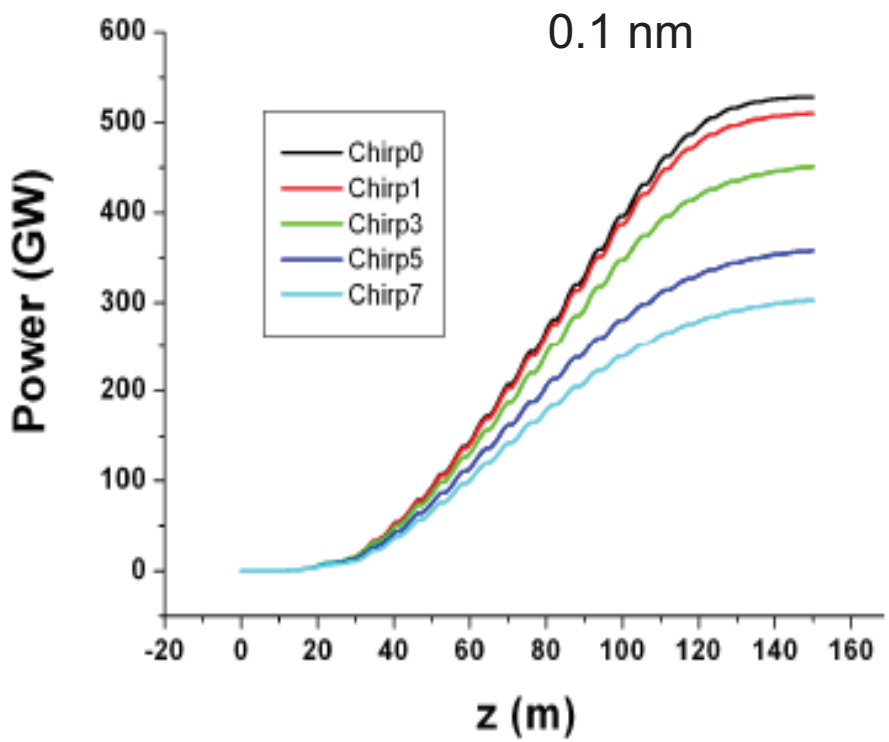
Self-Seeding FEL Power vs. Energy chirp





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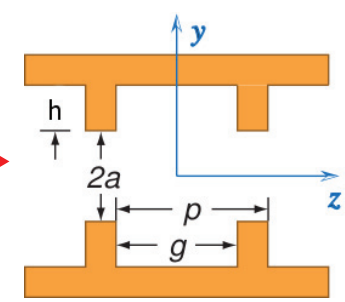
A history of Corrugated Structure As a Dechirper

- ✓ A smooth-pipe as a dechirper was considered for PAL-XFEL (THOA4, FEL2011).
- ✓ A **corrugated structure with flat geometry** was selected for PAL-XFEL (TUPPP062, IPAC2012).
- ✓ "Dechirper R&D meeting" was held at Nara in Japan on 29 August 2012
- ✓ Dechirper R&D group was organized by Paul Emma in 2012
- ✓ PAL prepared a prototype of 1-m long flat geometry dechirper in 2012 and 2013
- ✓ Theoretical study for "corrugated structure with flat geometry" by K. Bane and G. Stupakov
  - K. Bane and G. Stupakov, NIMA, 690, 106 (2012)
  - Longitudinal wake for flat geometry, PRST-AB, 6, 024401 (2003)
  - Transverse wake for flat geometry was derived in 2013
- ✓ Beam test was done at ITF, PAL on 5-10 August 2013.

  - K. Bane, G. Stupakov (SLAC)

  - P. Emma, Marco Venturini (LBNL)

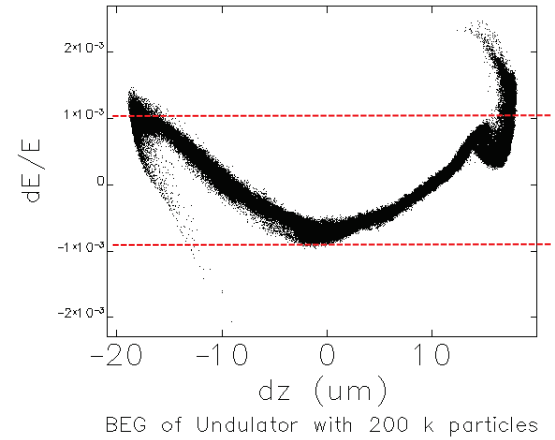
Beam



Why we choose **Flat Geometry** for Dechirper

Smooth pipe vs. Corrugated pipe

- Smooth, resistive pipe shows a large non-linearity, while corrugated pipe shows linear
- If we use S-band accelerating structure, the total length required is approximately **16 times** as corrugated pipe.



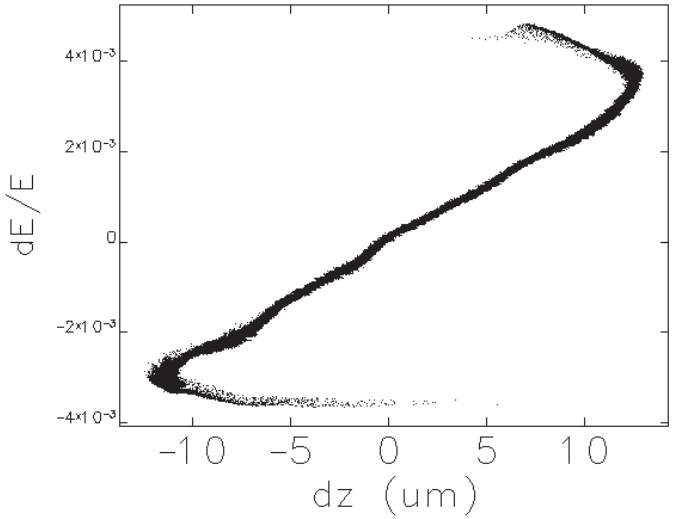
Round geometry vs. Flat geometry

- Required chirp is different for a different bunch length and charge → Round geometry dechirper lacks controllability
- Adjustable gap type of flat geometry → better controllability
  - Wake reduces to a factor of $\pi^2/16$ from round geometry
  - Movable gap : 1 ~ 30 mm full gap
- Vertical offset control capability of the flat geometry makes it possible to minimize the effect of **dipole wake**.

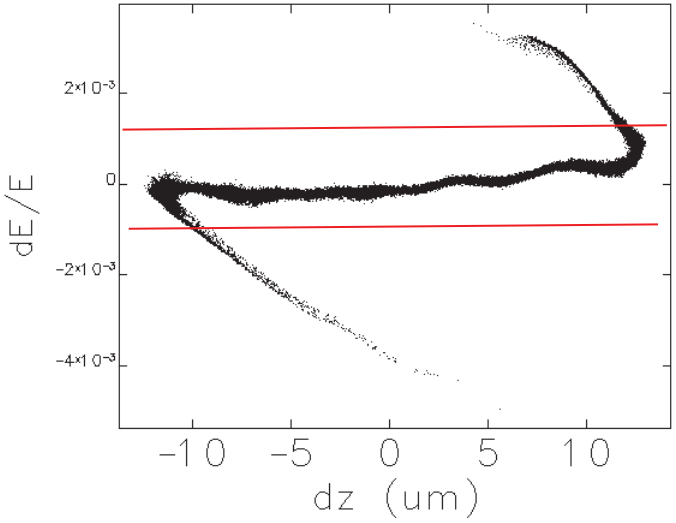
Simulation of longitudinal wake

for Soft X-ray FEL line (3.15 GeV, 200 pC)

Corrugated pipe with radius of 2.5 mm and L=20 m



END of BC3 with 200 k particles



BEG of Undulator with 200 k particles

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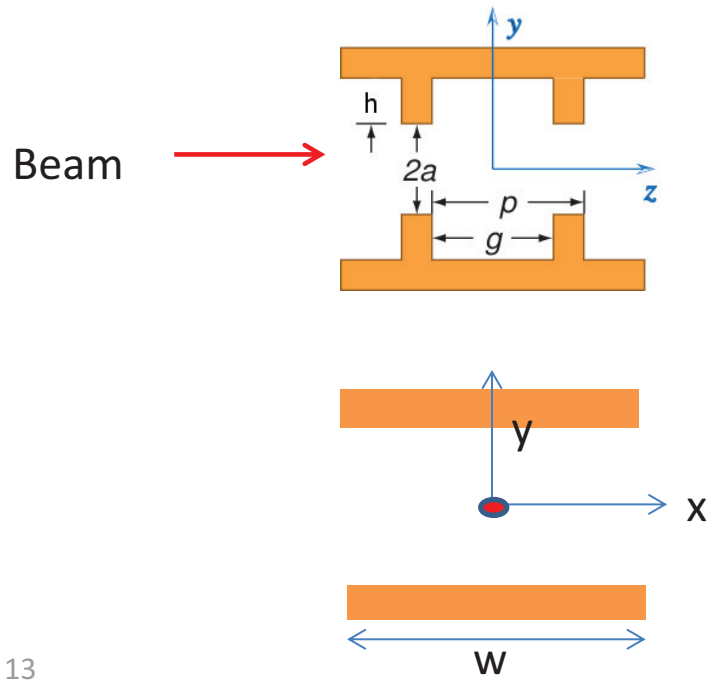
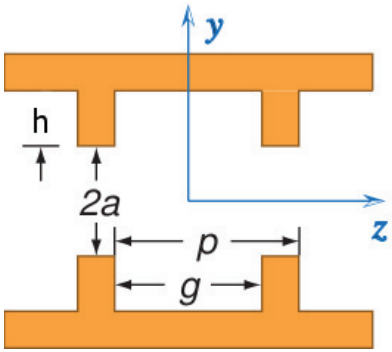
Issues of Flat Geometry

	Round geometry with radius *a*	Flat geometry with half gap *a*	Flat geometry with half gap 0.785 *a*
Longitudinal wake	1	$\pi^2/16 = 0.616$	1
Dipole wake	1	1 / 2.62 = 0.38	1
Quadrupole wake	0	1	2.6

- Effect of dipole wake is similar
- Flat geometry introduces **quadrupole wake**, which is not present at round geometry

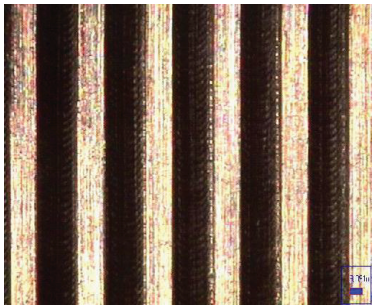


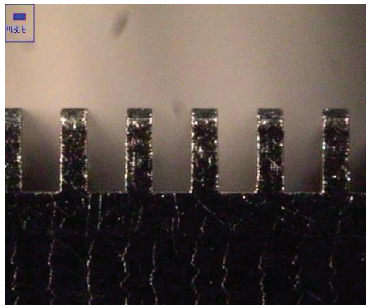
Corrugation Parameters for Dechirper



	A Test module at PAL-ITF	PAL-XFEL Soft XFEL line
Beam energy, GeV	0.07	3.15
Half gap, a [mm]	4	2.5
corrugation period, p [mm]	0.5	1.0
corrugation depth , h [mm]	0.6	0.5
Wall distance, g [mm]	0.3	0.5
Width of plate [mm]	50	50
Length [m]	1	20
Gap of two plates [mm]	1 ~ 30	1 ~ 30

After Chemical Cleaning





DECHIRPER TEST AT ITF

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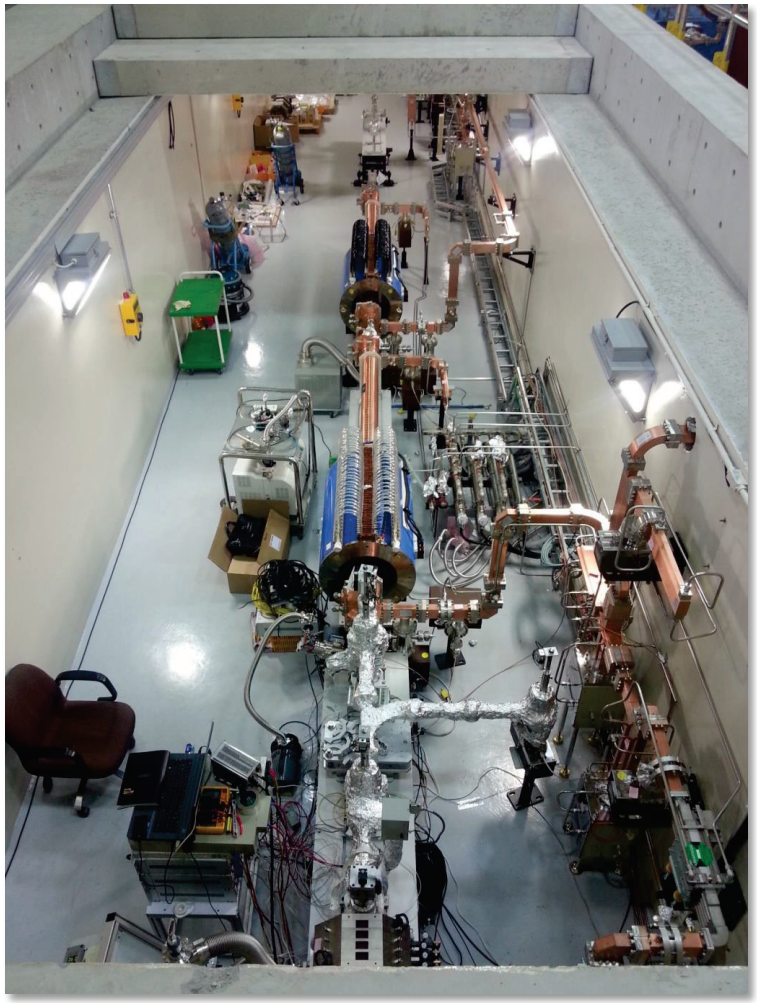
Injector Test Facility



ITF Tunnel

ITF Modulator / Klystron

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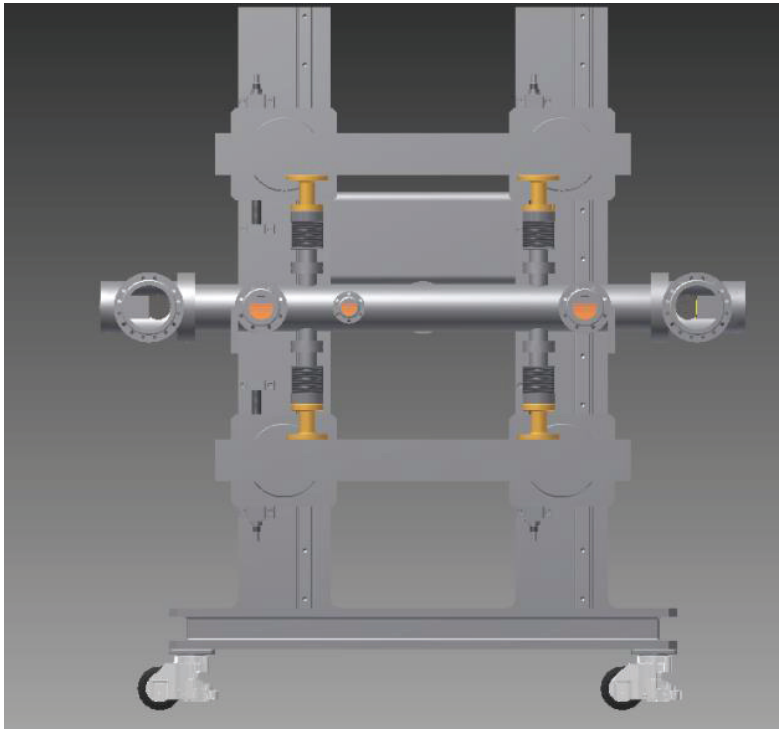
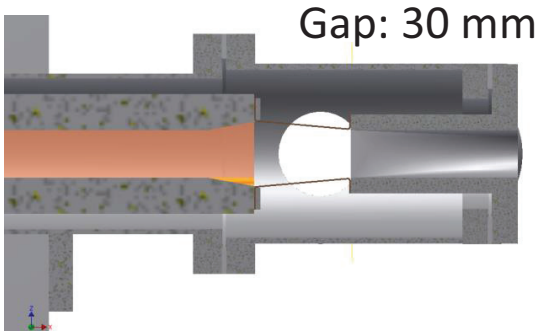
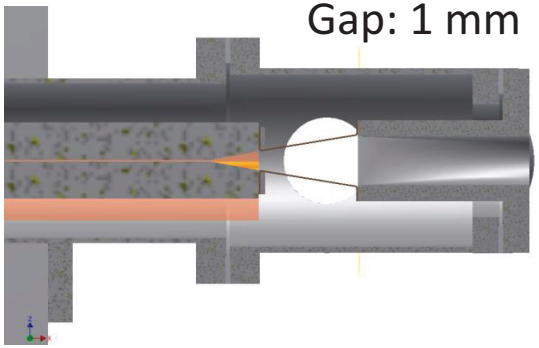
One-meter long proto-type dechirper

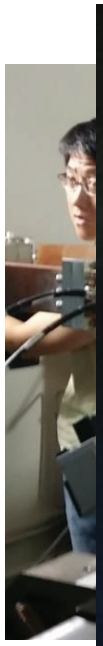


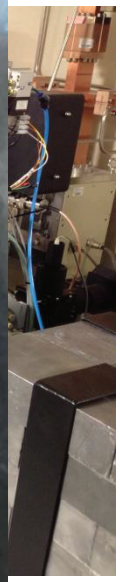
- Upper and lower corrugation pates are independently movable.
- Vertical offset is variable





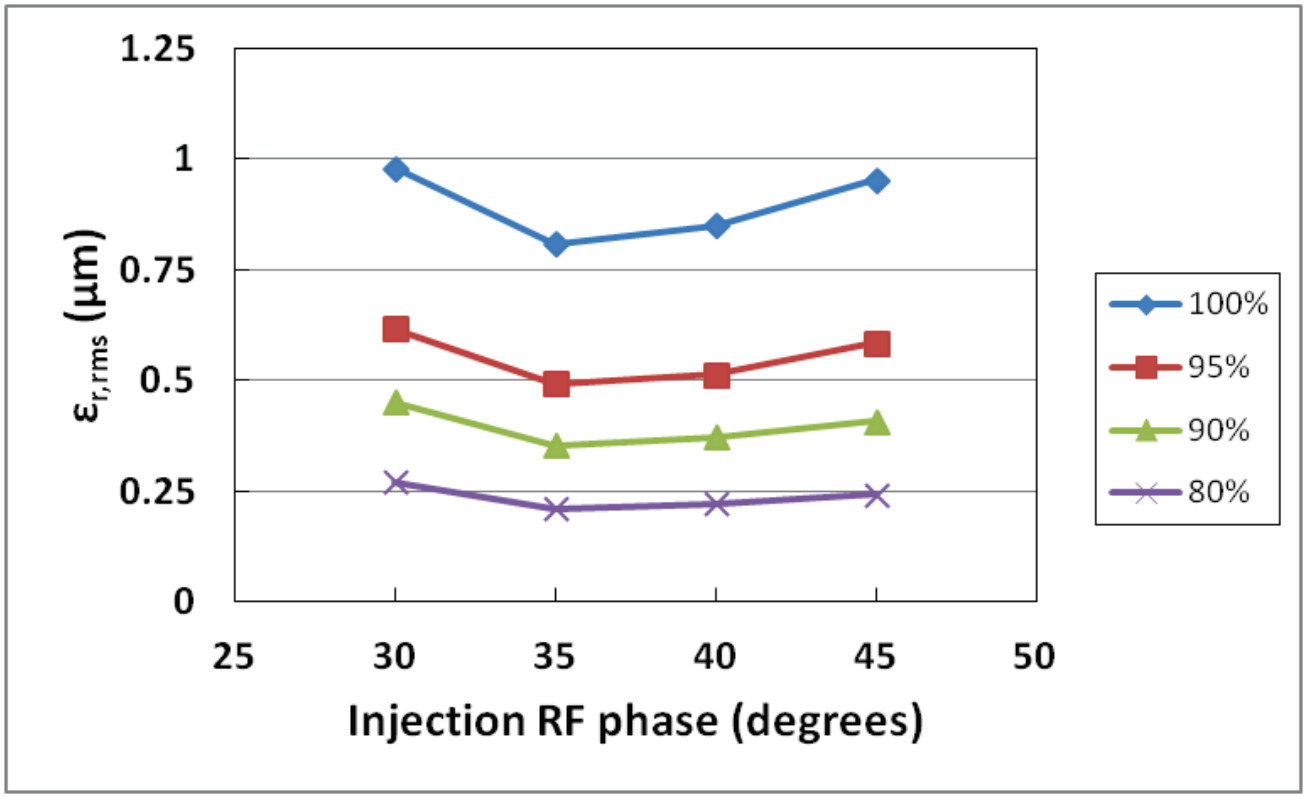
Dechirper Test at ITF (August 5–9, 2013)





Emittance measurement (70 MeV, 0.2 nC)

gun phase & gun solenoid 스캔 결과



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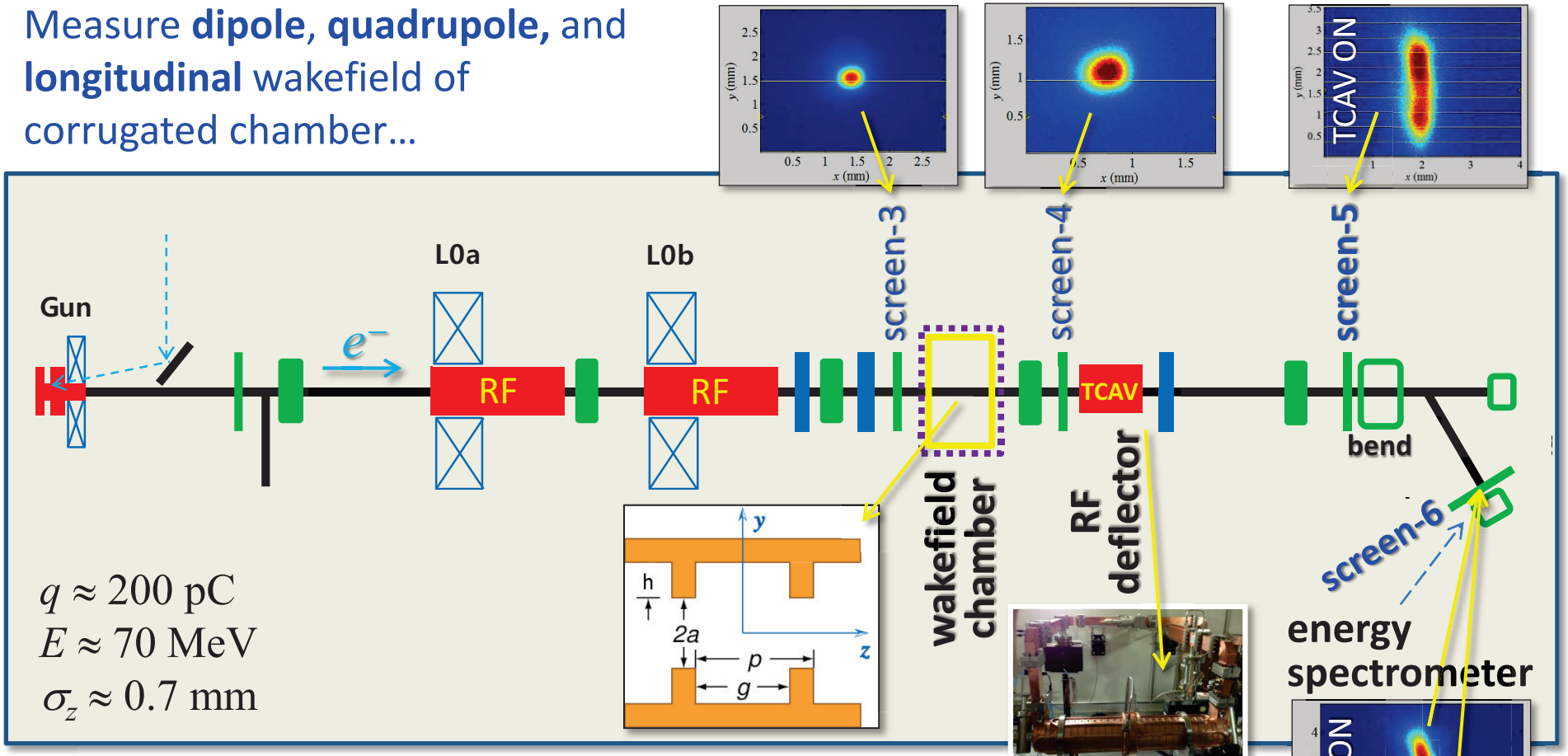
Wakefield Experiment and Beamline Layout at *PAL-ITF*

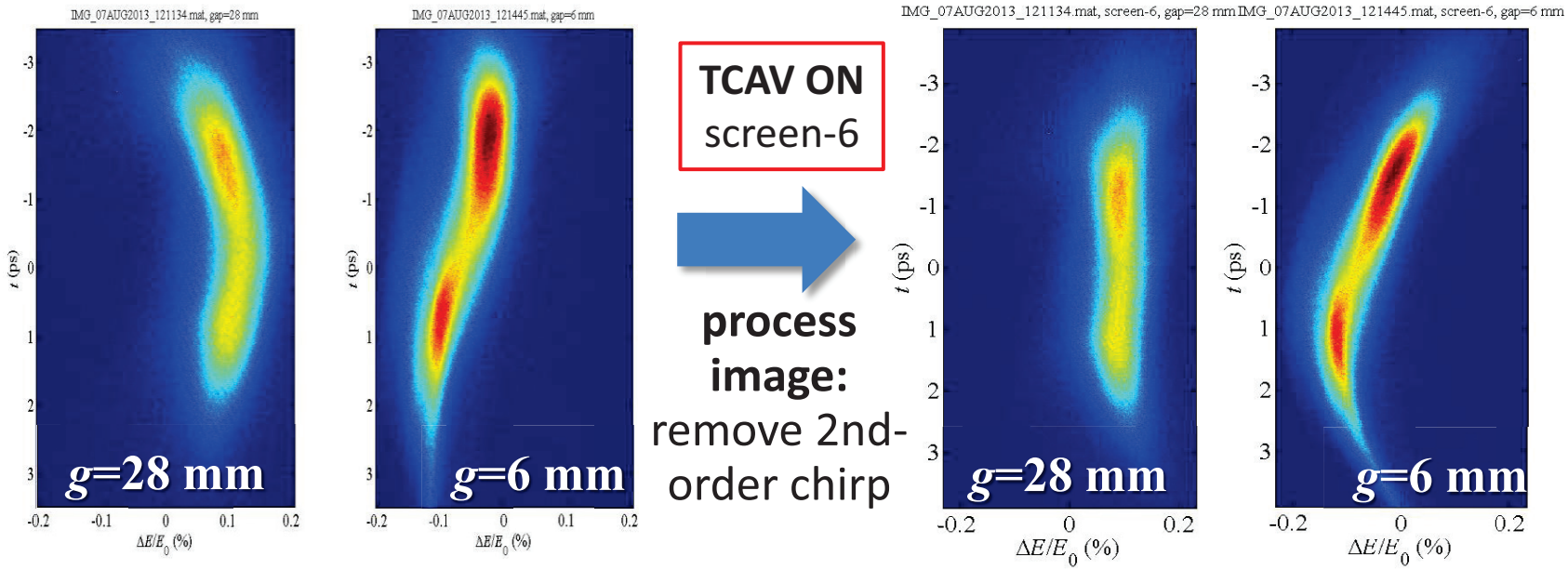
Measure **dipole**, **quadrupole,** and **longitudinal** wakefield of corrugated chamber…



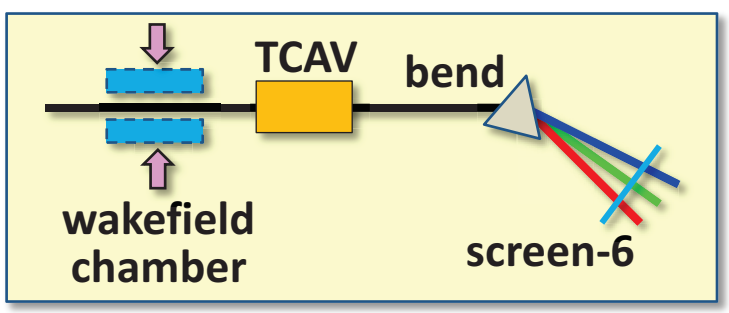
- Beam size and centroids measured on YAG screens
- Spectrometer bend allows energy loss and energy spread measurements
- RF deflector allows time-resolved measurements
- Dechirper gap and offset are varied

Longitudinal Wakefield Chirp – Simulation & Measurement

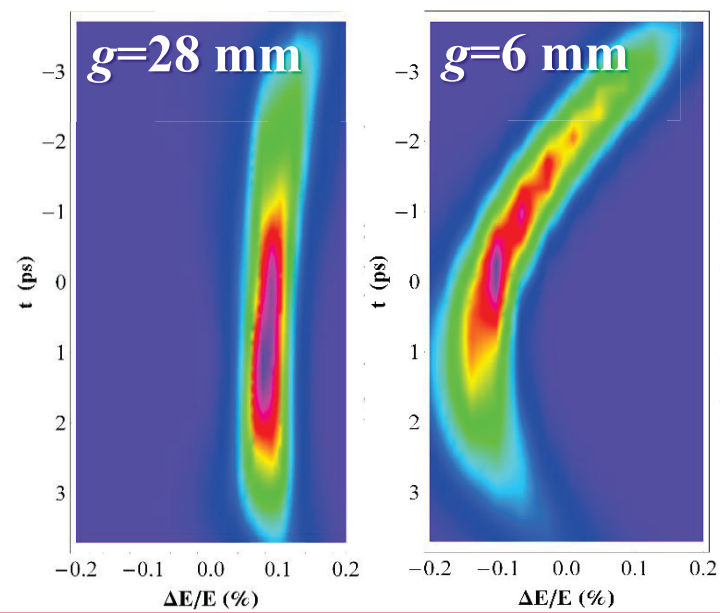
Measurement



(all plots same scales)

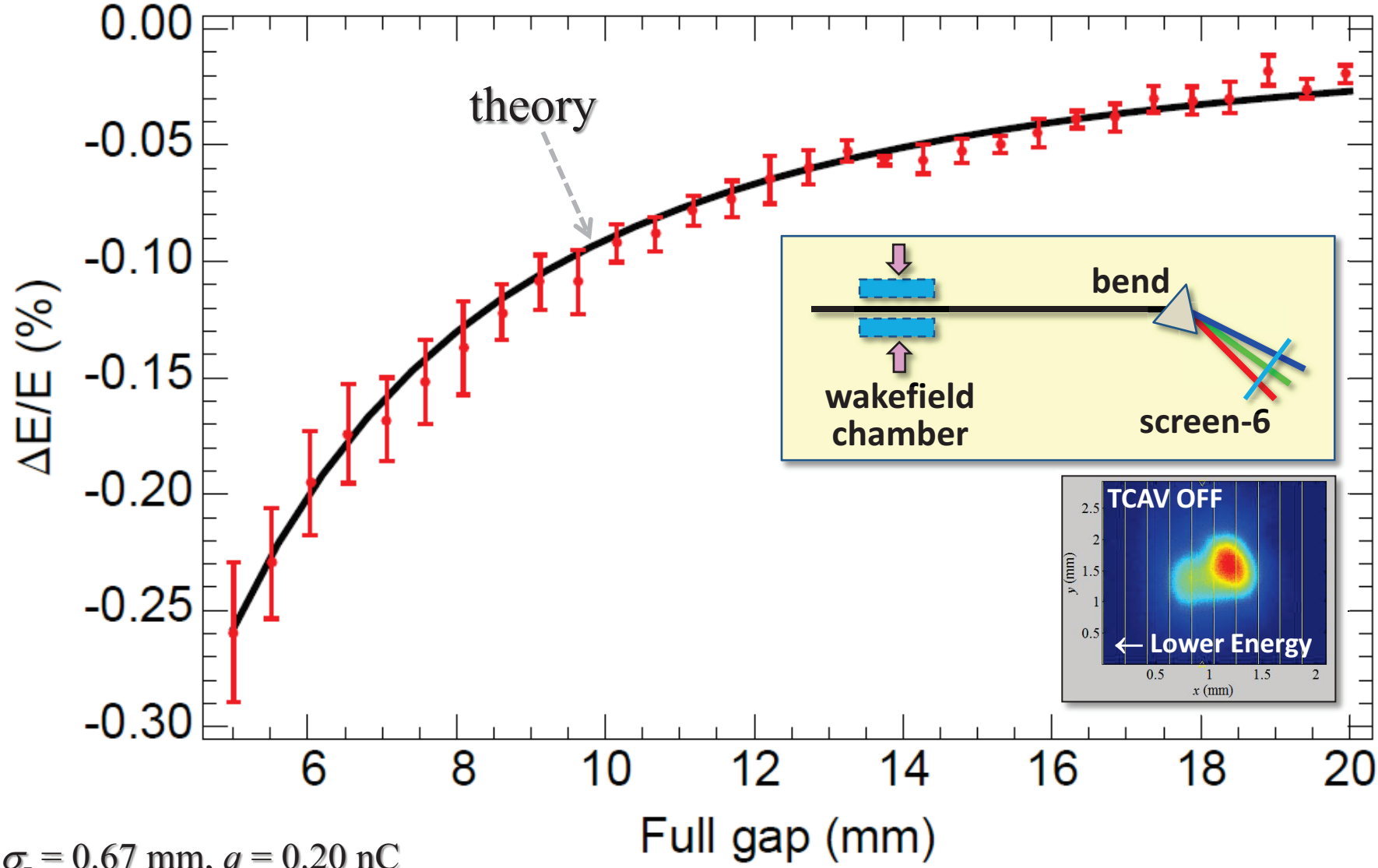


Simulation *(Elegant)*



$\sigma_z = 0.67$ mm, $q = 0.20$ nC

Energy Loss vs. Dechirper Gap - Theory & Measurement



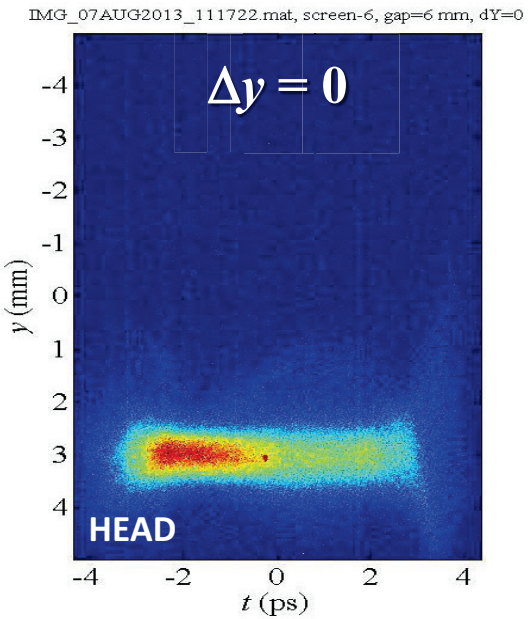
$\sigma_z = 0.67$ mm, $q = 0.20$ nC

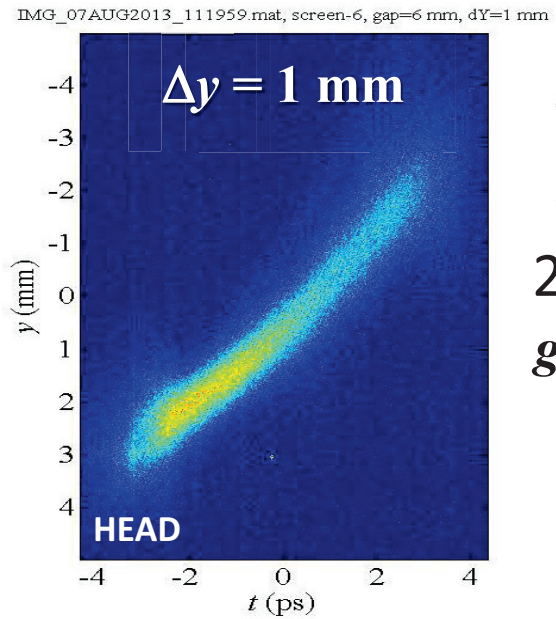
- Four data sets are averaged (**red** points) with rms spread/√3 as error bar
- No free parameters used here

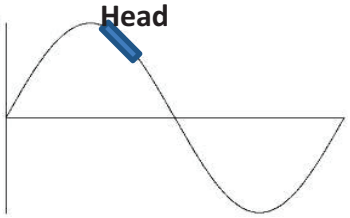
Dipole Wakefield – Simulation & Measurement

Measurement

RF Chirp
screen-6



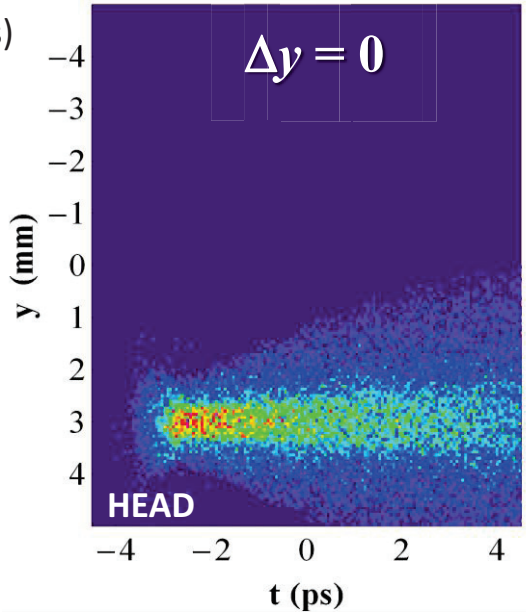


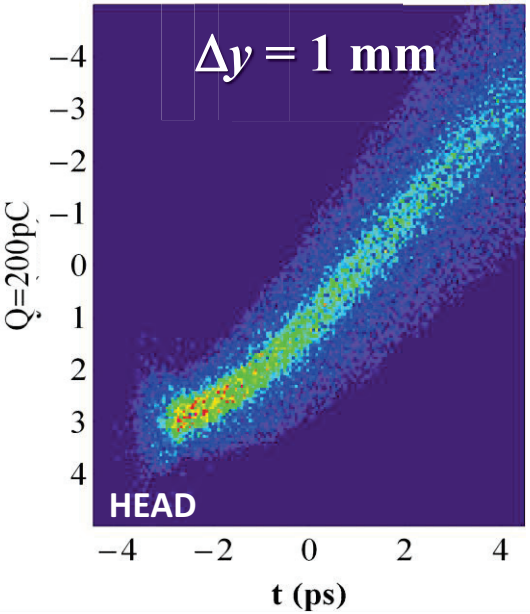


200 pC
$g = 6$ mm

Simulation (*Elegant*)

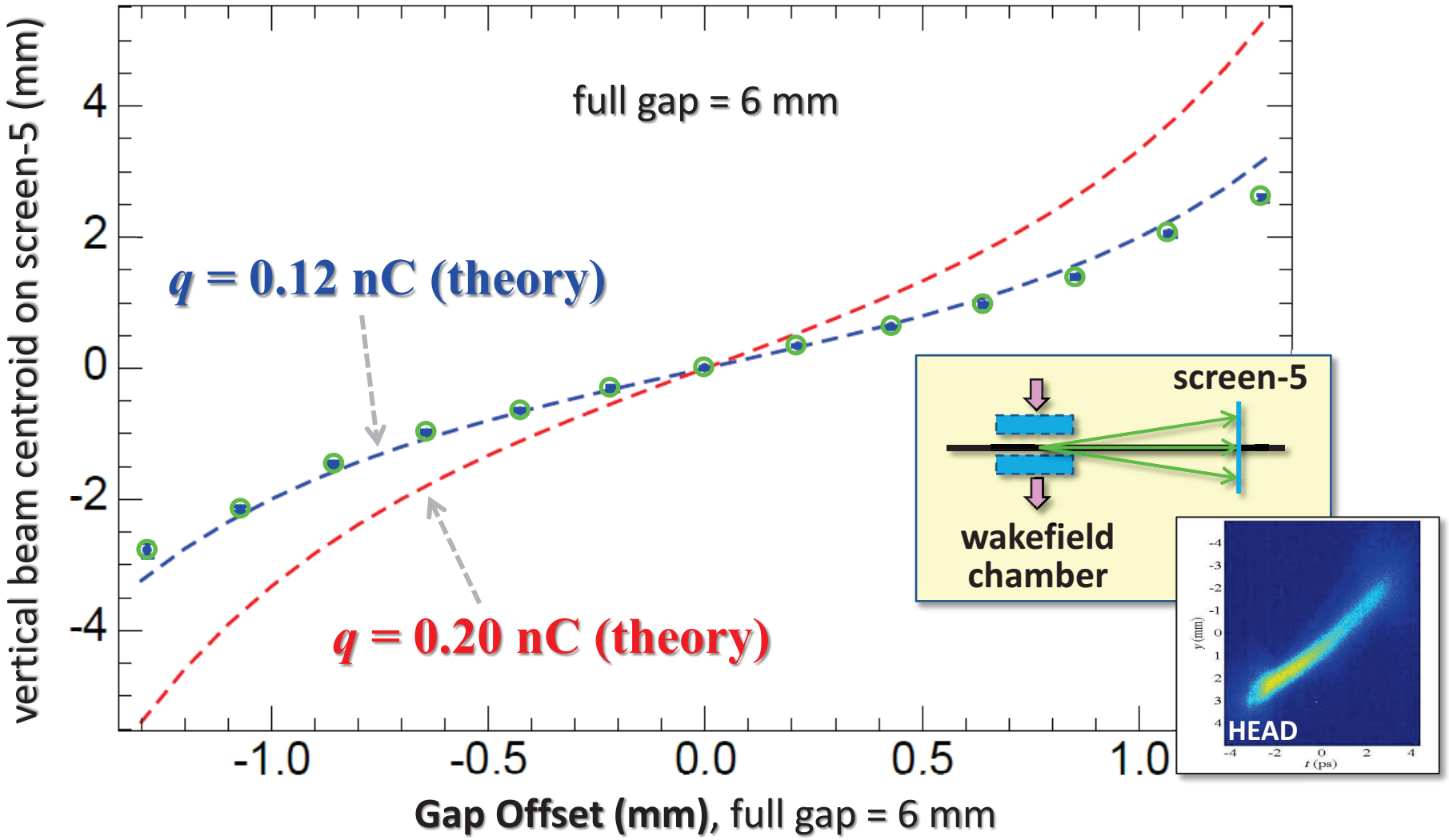
(all plots same scales)





200 pC
$g = 6$ mm

Dipole Wake vs. Dechirper Offset - Theory & Measurement

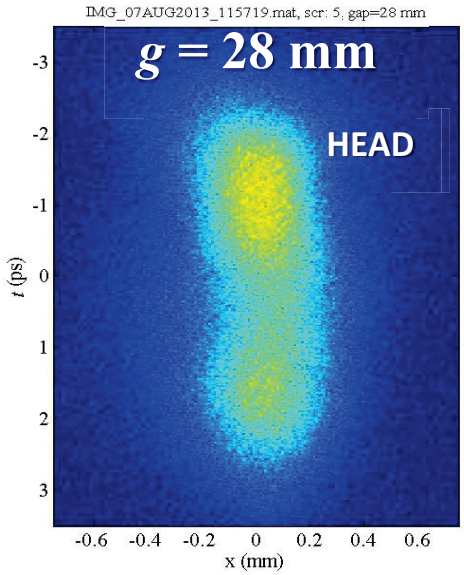


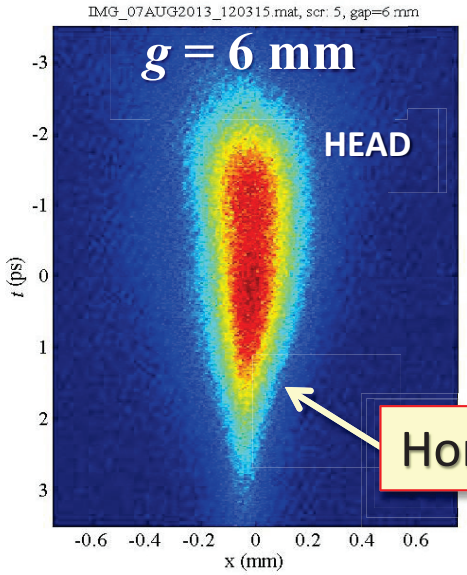
- Data are **green** points showing *y*-centroid kick on screen-5 vs. gap **offset**
- Measured kicks **~half** of that expected (**?**)
- Higher-order dipole wake also fits well to theory (with 0.12-nC charge)

Quadrupole Wakefield – Simulation & Measurement

Measurement

TCAV ON
screen-5



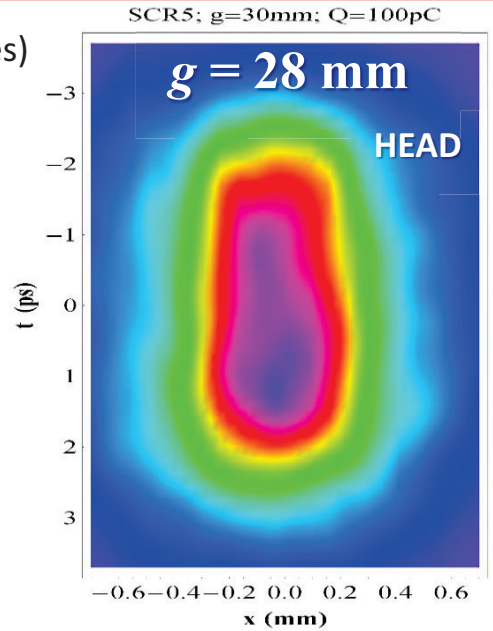


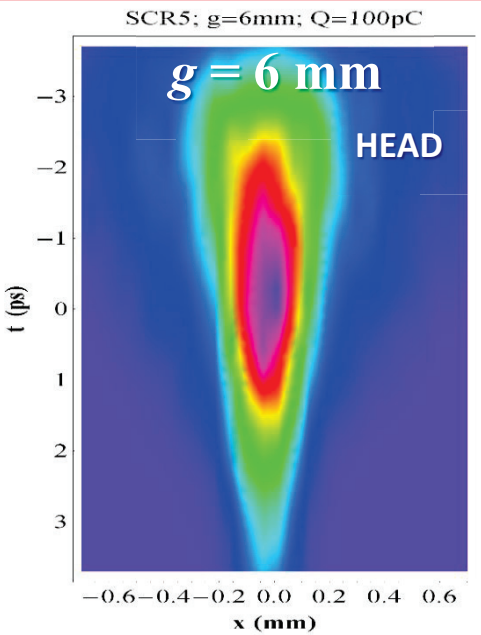
200 pC

Hor. focusing of tail

Simulation (*Elegant*)

(all plots same scales)

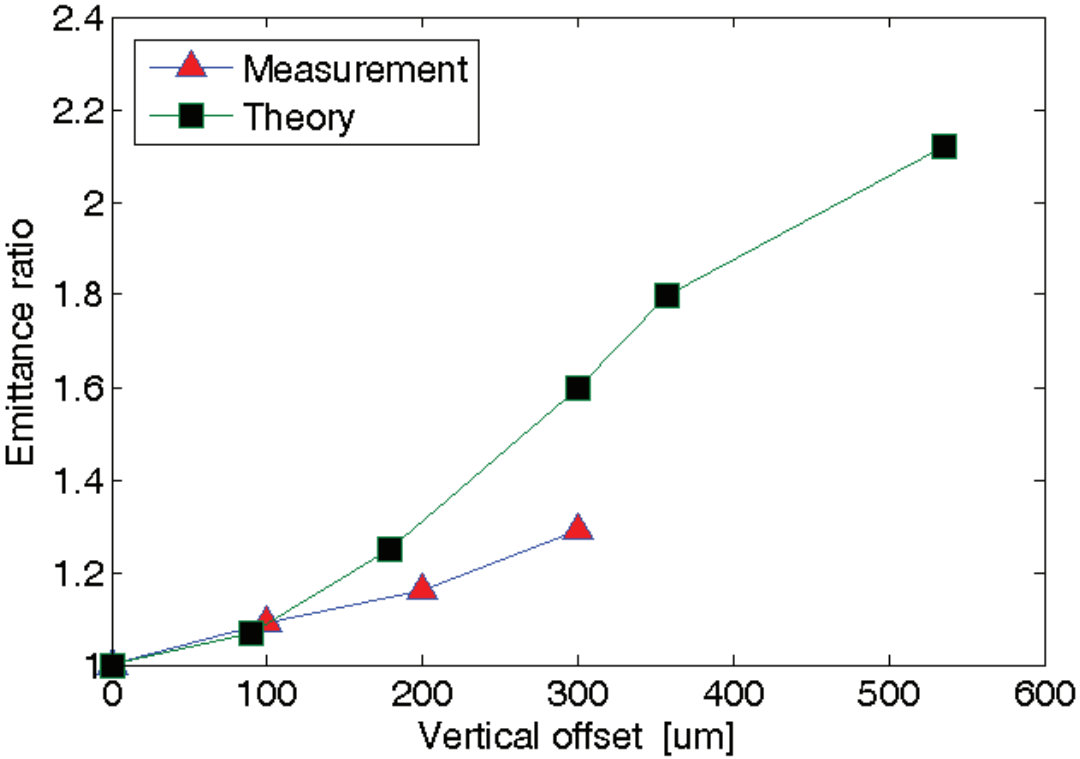




Simulation uses only <u>100</u> pC to get agreement – quad wake is too weak by ~2?

Emittance increase due to dipole wake

(A Test module at PAL-ITF)

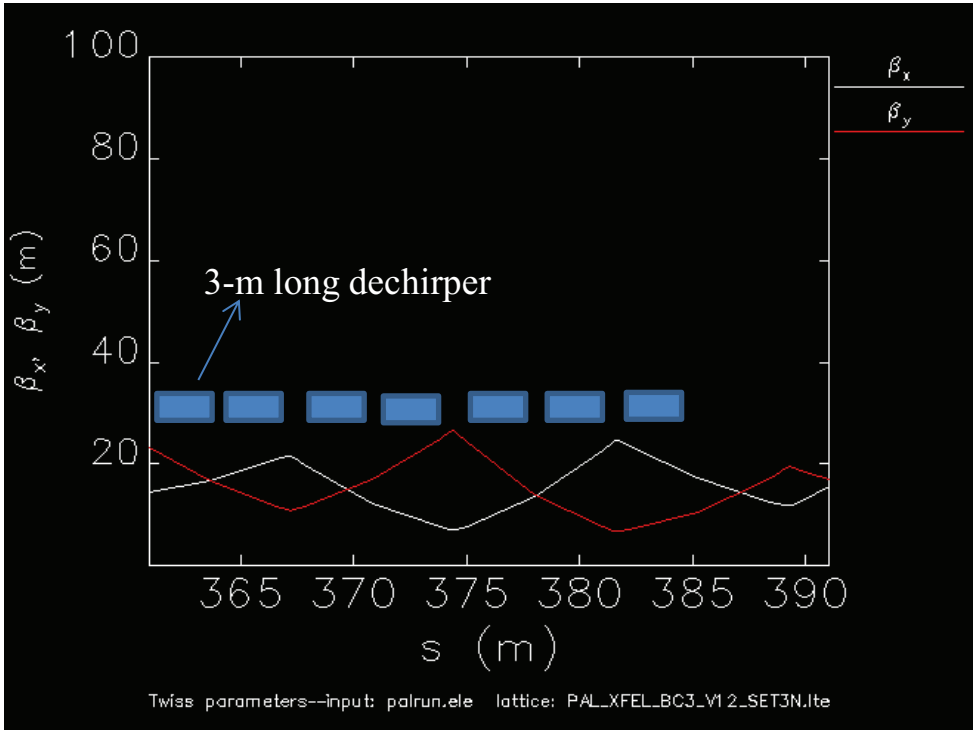


- Beam energy : 70 MeV
- Bunch length (rms) : 400 um
- Dechirper length : 1 m
- Betatron function : 35 m
- Transverse beam size (rms) : 360 um

Elegant simulation for dipole wake
(PAL-XFEL Soft-XFEL line)

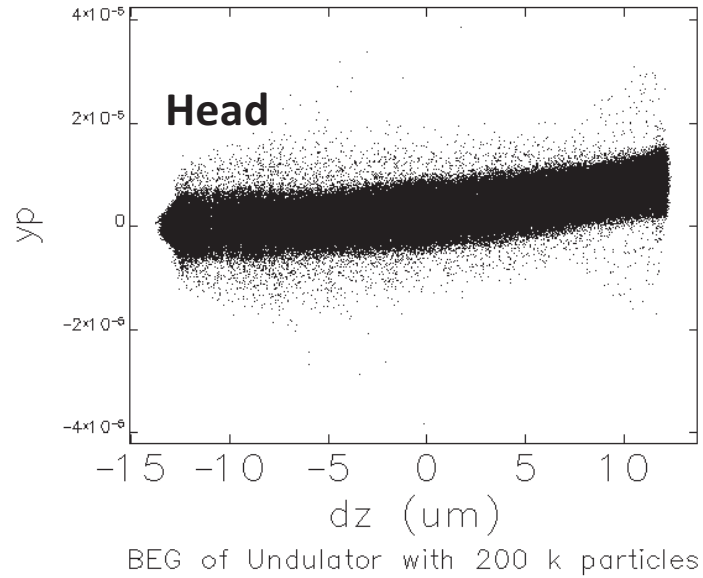
- Beam energy : 3.15 GeV
- Beam charge : 200 pC
- Bunch length (rms) : 8.7 um
- Dechirper length : 20 m
- Dechirper gap (2a) : 5 mm
- Betatron function : 20 m
- Transverse beam size (rms): 40 um

Betatron function at dechirper



Betatron phase between two quads: $\pi/6$

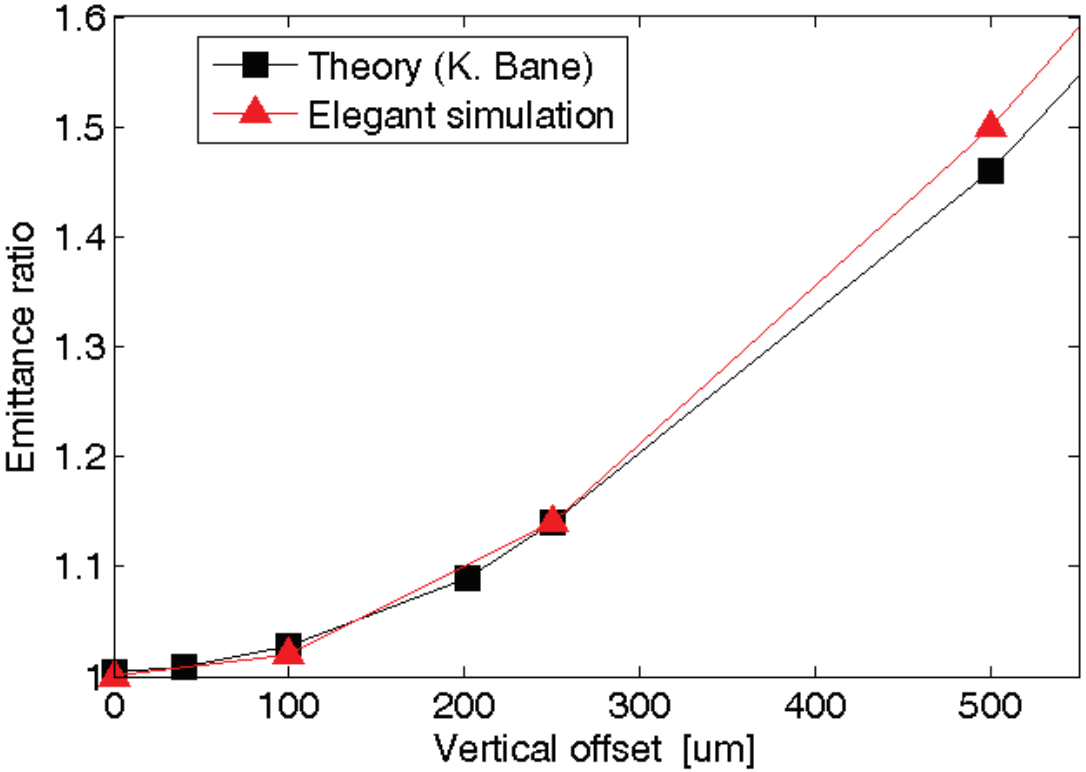
Vertical offset : 1 mm



- No growth in slice emittance
- Projected emittance growth appears

Emittance increase due to dipole wake

(PAL-XFEL Soft-XFEL line : 3.15 GeV)



- Beam energy : 3.15 GeV
- Bunch length (rms) : 8.7 um
- Dechirper length : 20 m
- Betatron function : 20 m
- Transverse beam size (rms): 40 um

- Vertical offset control capability of the flat geometry is easy to minimize the emittance growth due to **dipole wake**.

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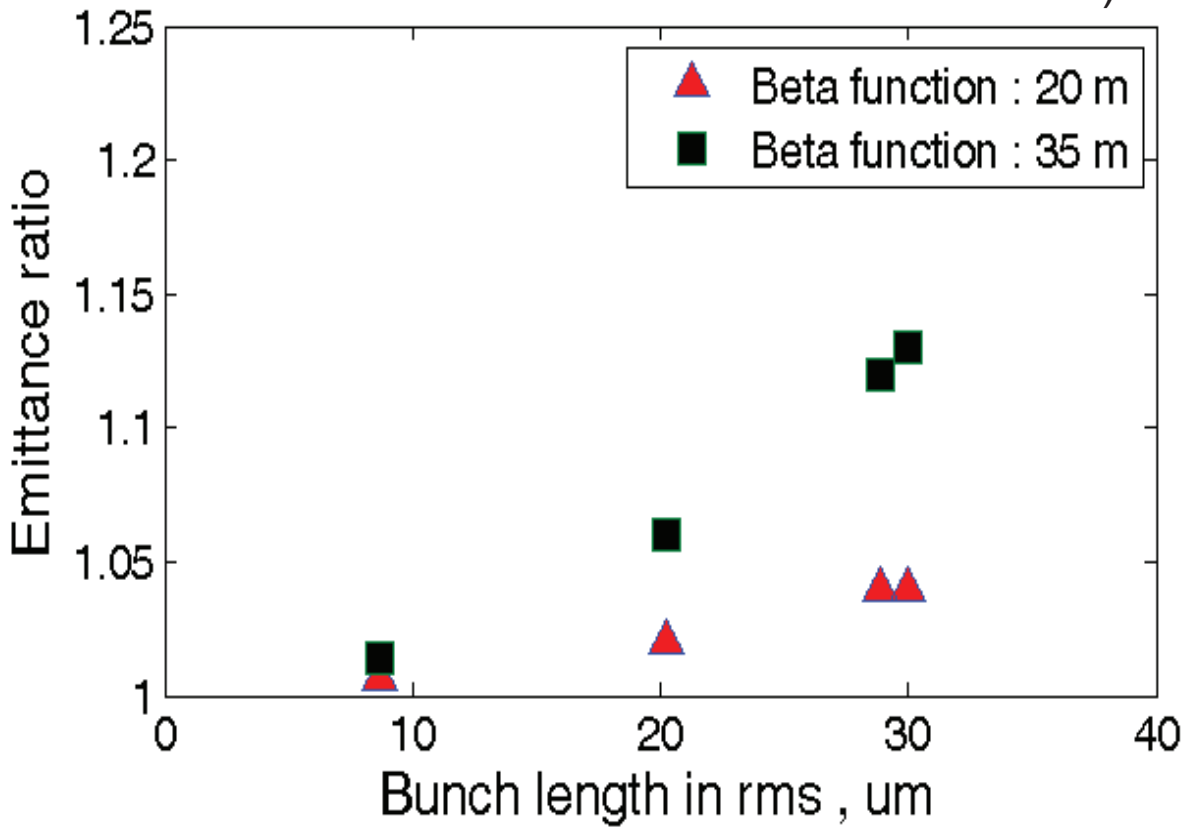
Emittance increase due to quadrupole wake
(PAL-XFEL Soft-XFEL: 3.15 GeV)

Beam energy : 3.15 GeV
Dechirper length : 20 m
Dechirper gap (2a): 5 mm

K. Bane's calculation)



Operation bunch length in the Soft X-ray FEL : 5 ~ 15 um (rms)

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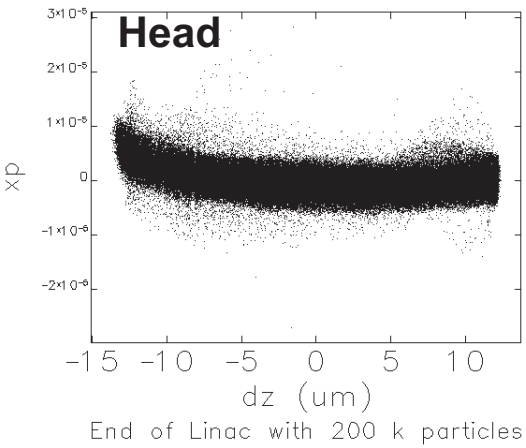
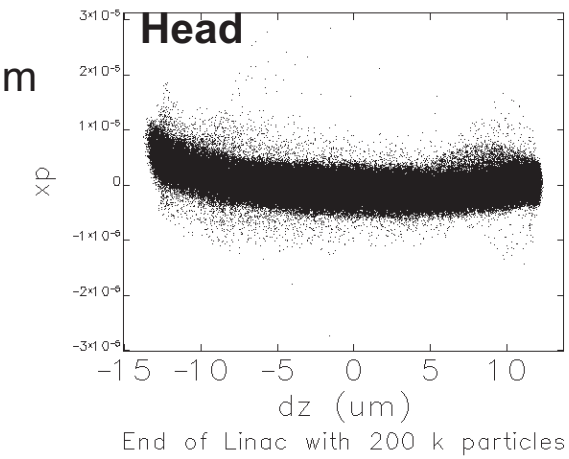
Elegant simulation of Qadrupole wake
for PAL-XFEL Soft-XFEL line (3.15 GeV)

Without Q-wake

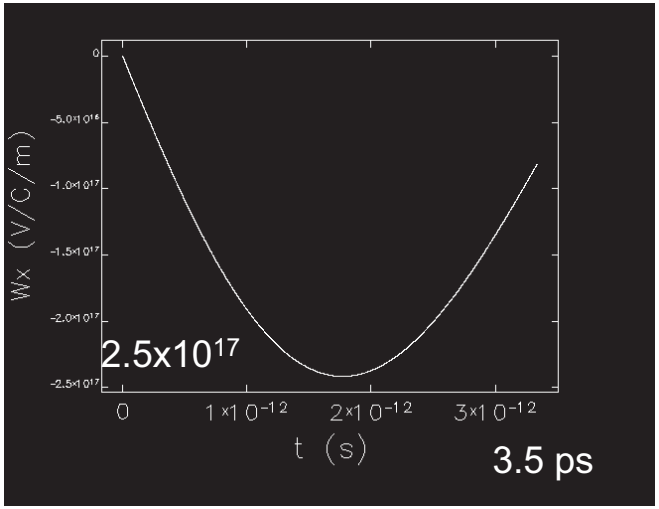
- Beam energy : 3.15 GeV
- Bunch length (rms) : 8.7 um
- Dechirper length : 20 m
- Betatron function : 20 m
- Transverse beam size (rms): 40 um

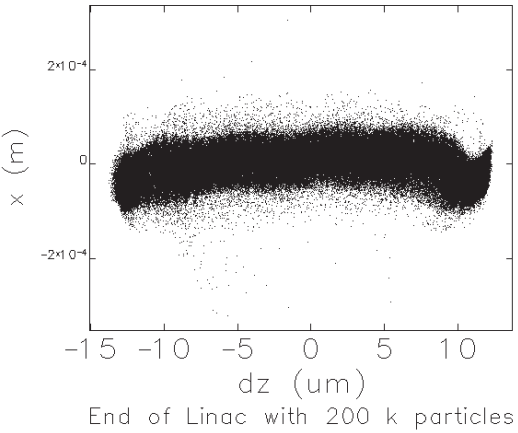
With Q-wake

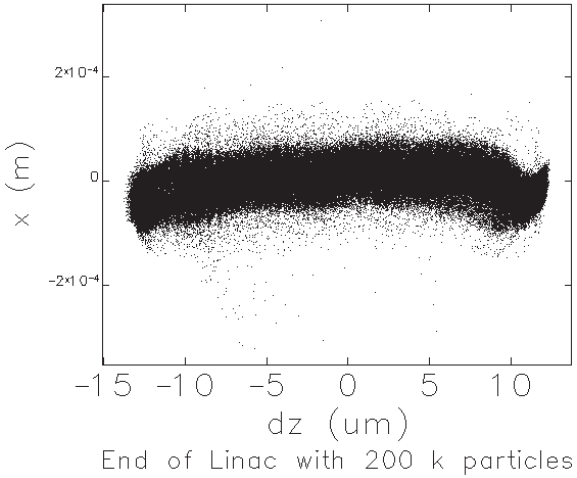




Wake for a=2.5 mm / L= 1 m

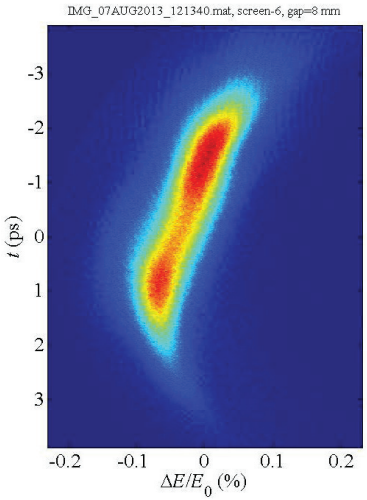






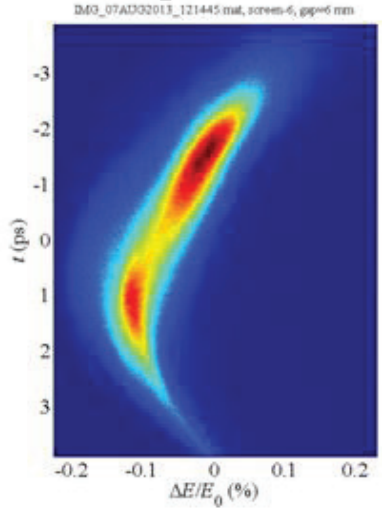
Working as a Linearizer

Gap: 8 mm



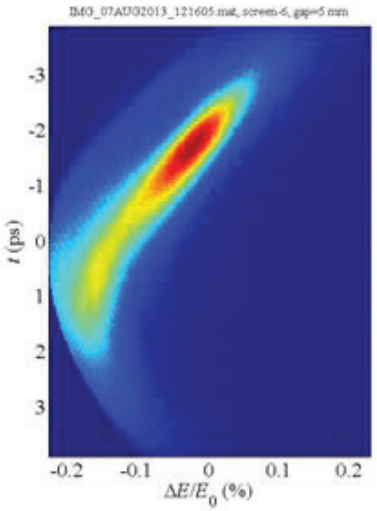
Wakefield wavelength : 6.6 (1.65 mm)

Gap : 6 mm

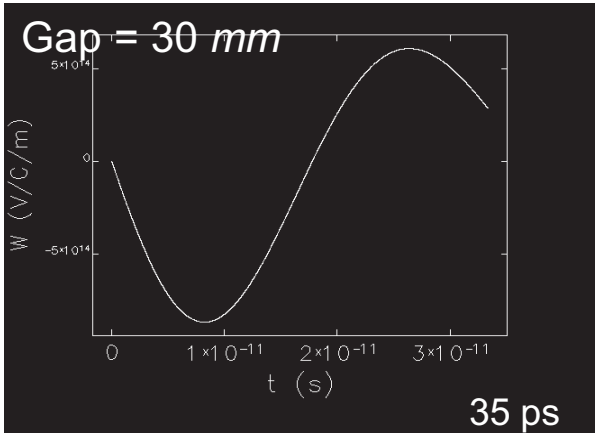


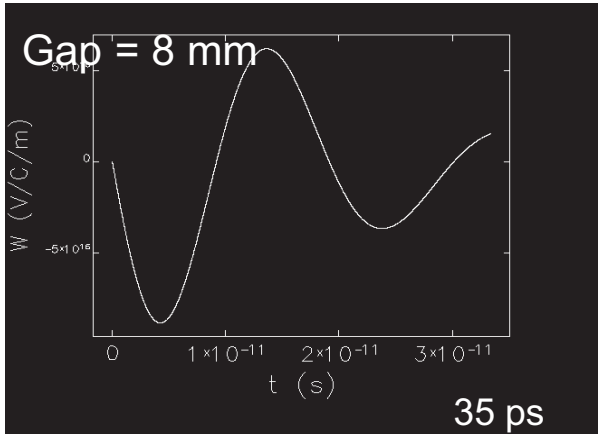
5.8 (1.45 mm)

Gap : 5 mm



5.2 (1.3 mm)



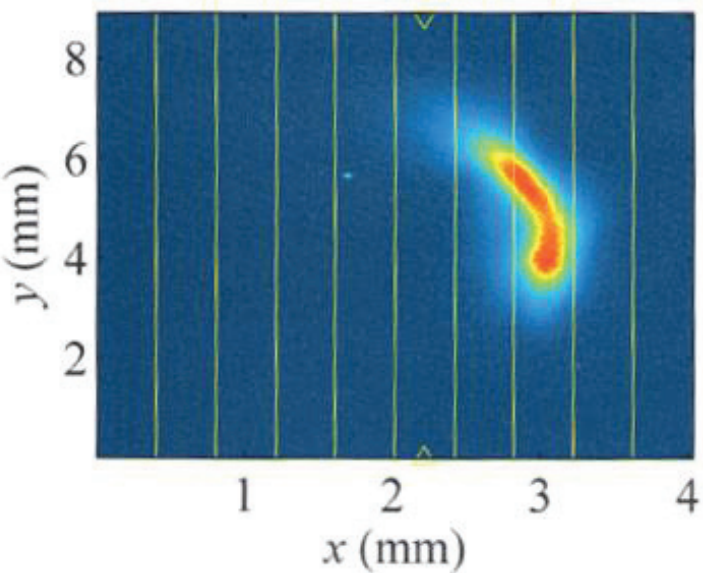


- Measured bunch length (rms): 0.67 mm
- Quadratic wake seems to be effective if bunch length is smaller than a quarter of wakefield wavelength.

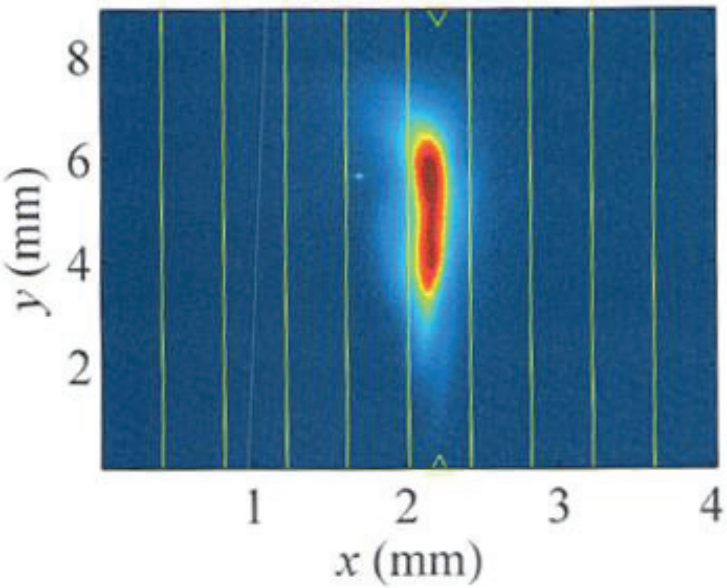
Working as a Linearizer

: Screen 6 and TCAV ON

Gap: 28 mm



Gap: 6 mm



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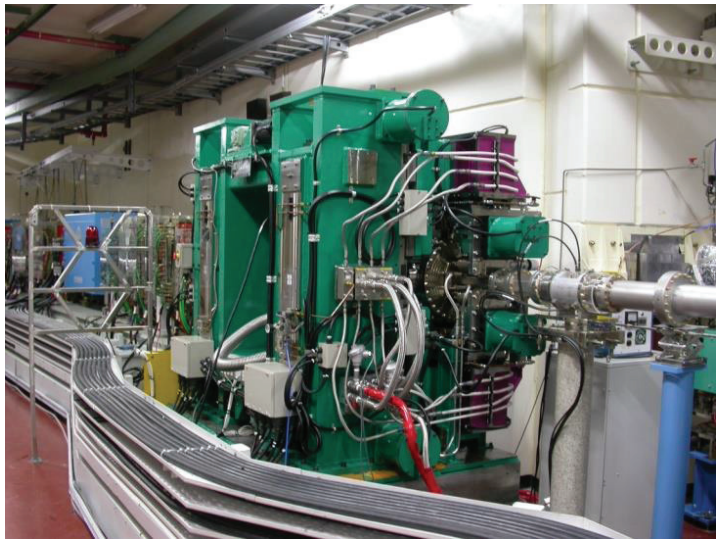
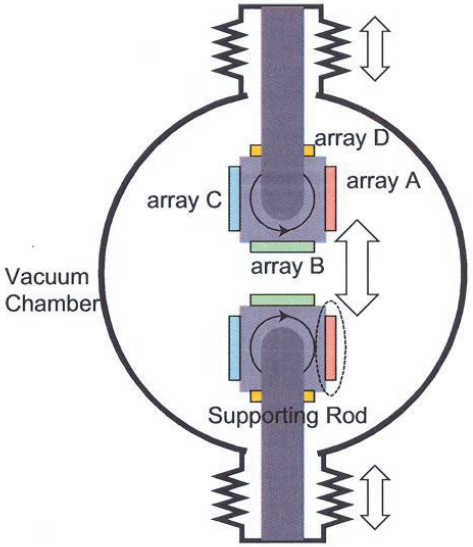
RIVXUN: Revolver In-Vacuum X-ray UNdulator

H. S. Kang, THOAFI02, EPAC2006



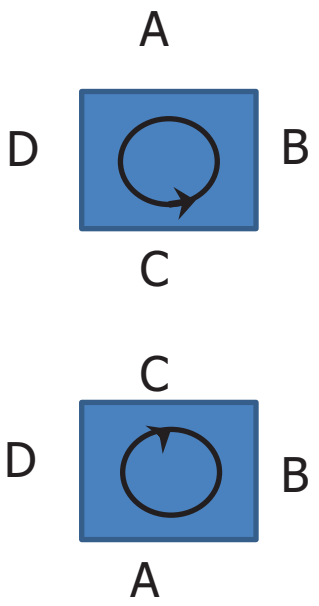
- Permanent magnet structure is a revolving type with four arrays, which provides 4 different undulator periods of 10, 15, 20, and 24 mm.
- ***Made by Spring-8*** **(Kitamura et al. NIMA 467, 110 (2001)**
- **Operational at PLS since 2004**



Array	Undulator Period [mm]	Number of period
C, c	10	101
B, b	15	67
A, a	20	50
D, d	24	42

Revolving Dechirper

- X-band RF linearizer can control a large variations of energy curvature depending on the beam parameters.
- Single corrugation Dechirper lacks controllability
- A revolving type with four corrugations (A,B, C, and D) can provide higher flexibility as X-band RF.



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Dechirper against Microbunching Instability

- A more de-chirper is added to increase an energy chirp and, therefore, decrease R56 for bunch compression.
- It may reduce microbunching instability gain.

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

σ_z , σ_{zi} are given variables, so $h \times R_{56}$ = constant.

$h \times R_{56}$ = constant = $h \times R_{56}$

without dechirper with dechirper

Simulation study is under way

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Summary

- Longitudinal wakefield-induced energy loss agrees quite well with theory
- Linear energy chirp also agrees reasonably well and therefore can be controlled ("dechirper")
- Transverse wakefields (dipole and quadrupole) are ~2-times weaker than expected (preliminary results)
- Even though the flat geometry introduces **quadrupole wake**, its effect is negligible in case of short bunch.
- Vertical offset control capability of the flat geometry is easy to minimize the emittance growth due to **dipole wake**.
- Possibility of working as a linearizer and mitigating the MBI will be investigated.

Thank you for your attention