The 12th Symposium on Accelerator Physics

Free-electron laser spectrum control using corrugated structure at SDUV-FEL

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On behalf of FEL physics group

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Shanghai Institute of Applied Physics, the Chinese Academy of Science

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SINAP 中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

Outline

- Introduction
- Corrugated structure theory
- Overview of previous experiments
- About SDUV-FEL
- Proposal & experiment at SDUV-FEL
- Summary & outlook

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Worldwide hard X-ray FEL facilities

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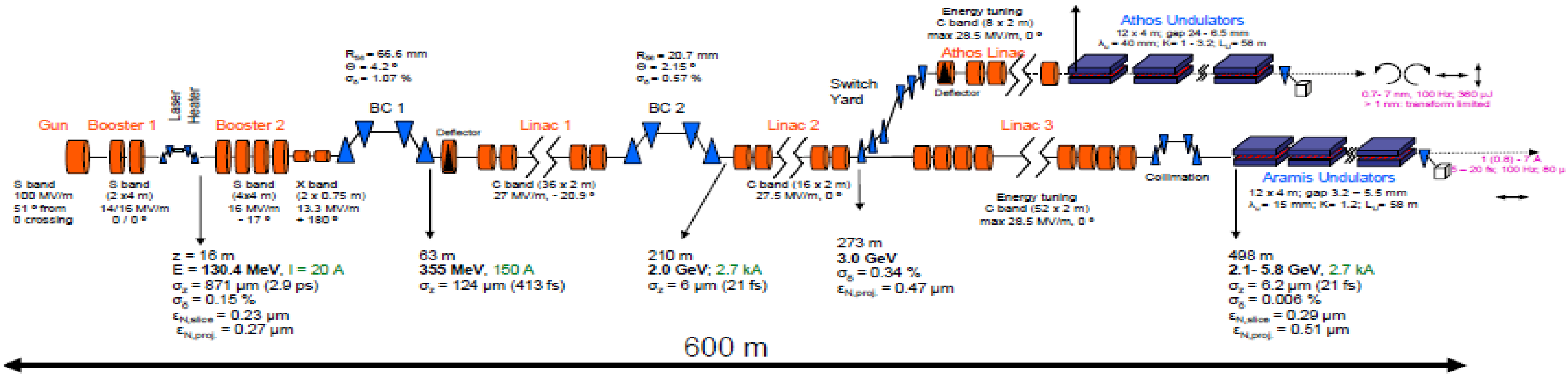
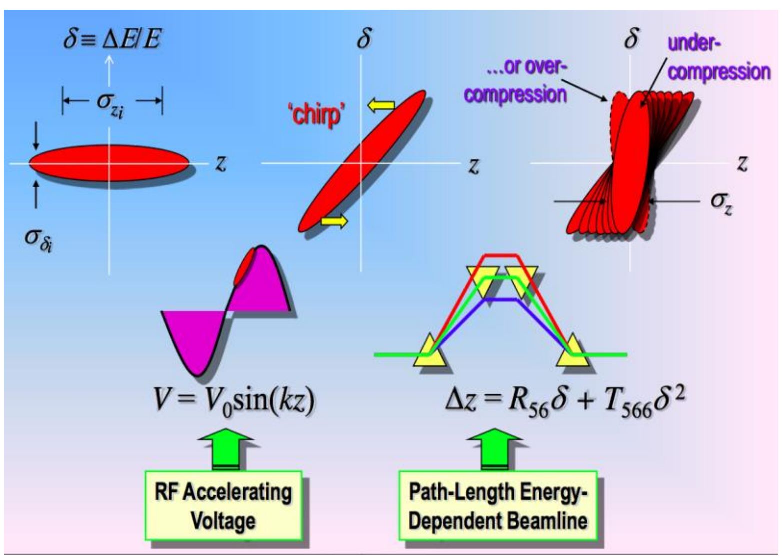
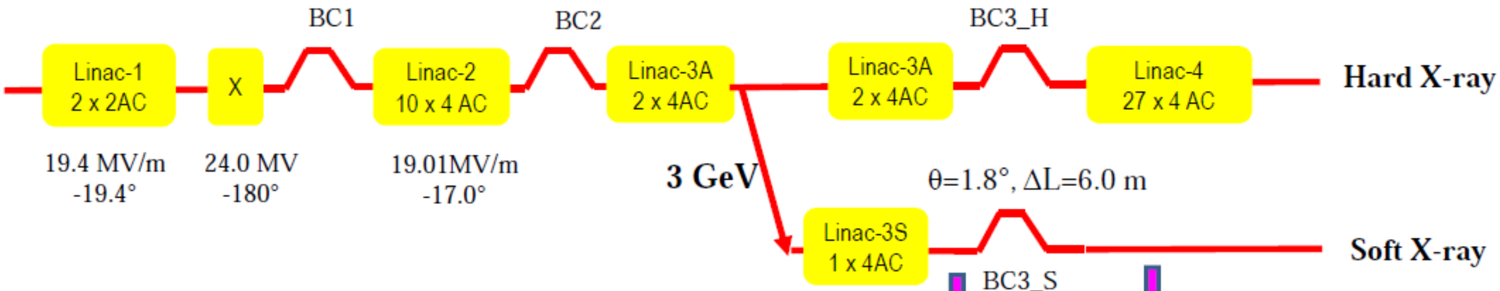
LINAC based free-electron laser



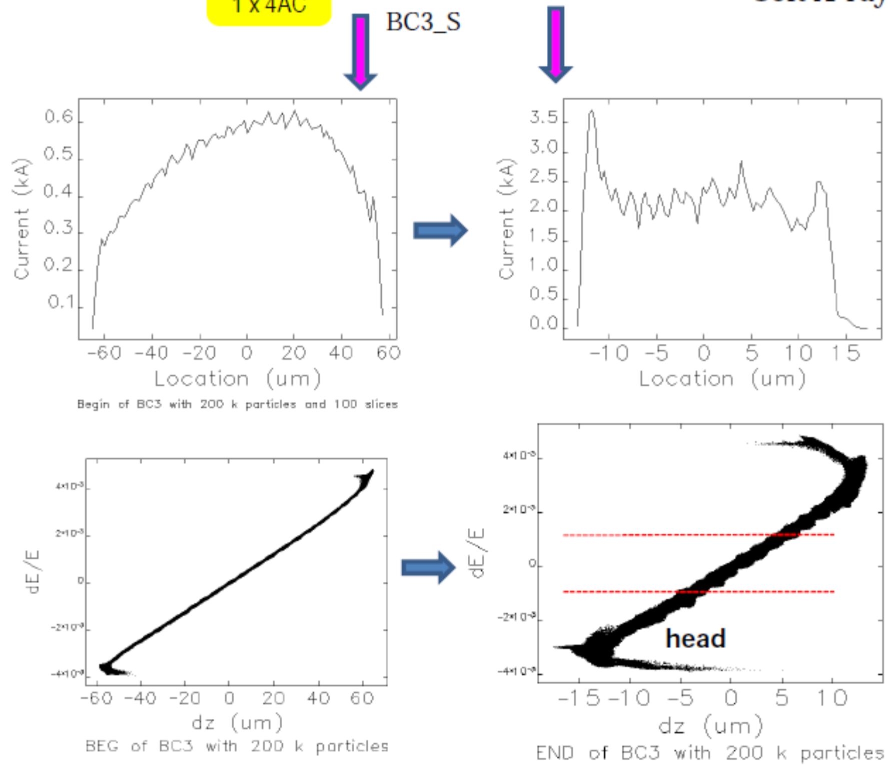


- In typical LINAC-based FELs, undesired time-energy correlation in the beam (linear energy chirp & nonlinear RF curvature) is left, which may broaden FEL bandwidth and decrease FEL gain.
- The remain time-energy correlation should be removed before FEL undulator.
  - ✓ Off-crest acceleration & wakefield in a following LINAC for de-chirper
  - ✓ Harmonic cavity used for nonlinear RF curvature compensation

PAL-XFEL, Soft x-ray FEL line

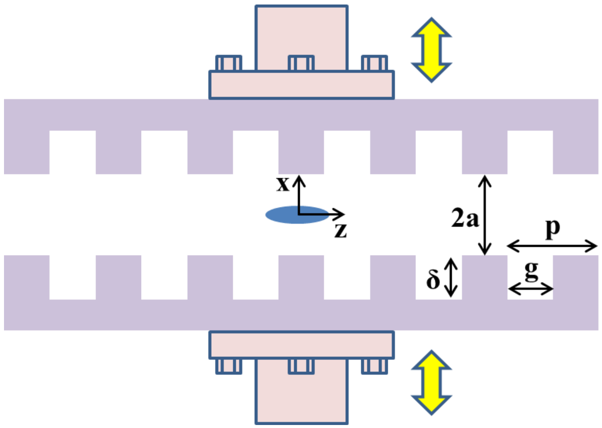


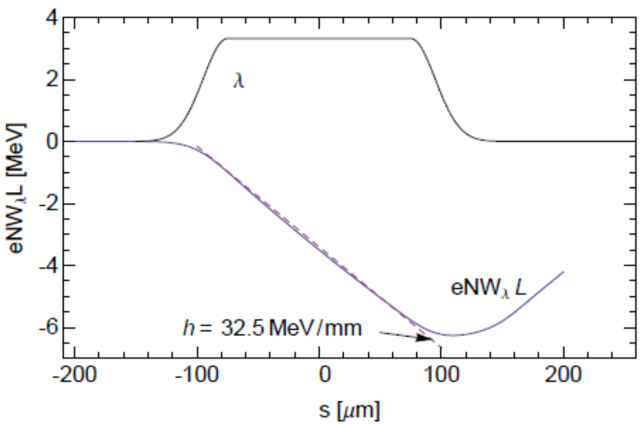
- Energy chirp after final compression (4 x10^{-3}) is larger than FEL parameter (1 x10^{-3})
- There is a limited space before undulator. So, we need a strong longitudinal wake structure



Slide from H. S. Kang

Corrugated pipe & wakefield





$$W_\lambda(s) = -\int_0^\infty W(s')\lambda(s-s')\,ds'$$

$$W(s) = 2\varkappa H(s)\cos ks$$

$$k = \sqrt{\frac{2p}{a\delta g}} \qquad \varkappa = \frac{Z_0 c}{2\pi a^2}$$

- **has a near maximal possible amplitude for a given aperture**
- **has a relatively large oscillation, even with a small aperture.**

a [μm]	δ [μm]	p [μm]	g [μm]	L [m]	k [mm^{-1}]	$\varkappa$ [MV/nC·m]	$(1-\eta)$
3000	450	1000	750	6.65	1.4	2.0	0.68

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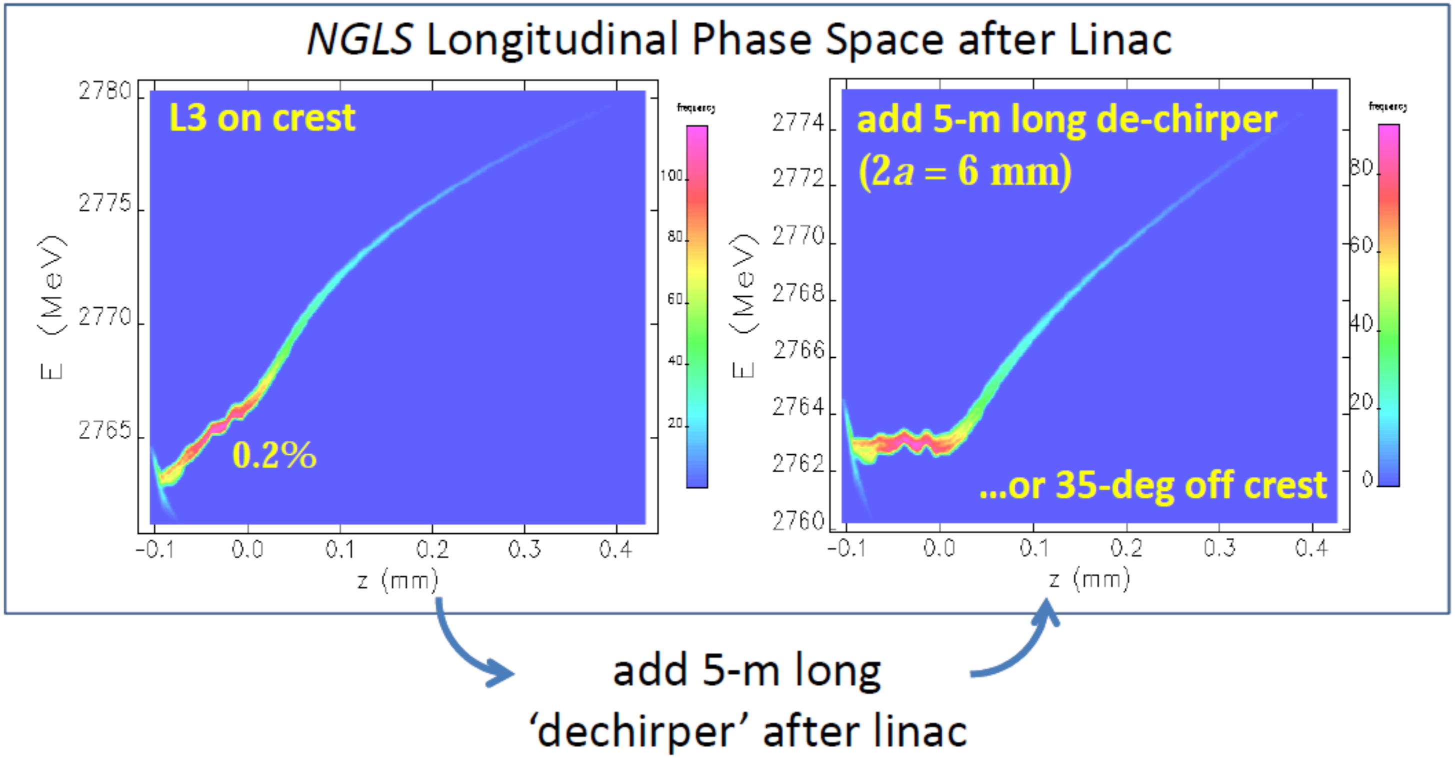
De-chirper motivation in NGLS



'Dechirper' in ***NGLS*** allows L3-linac (~200 m) to run on crest, rather than 35-deg off crest, saving one entire cryo-plant (M$...)

Courtesy P. Emma

History of corrugated structures

- 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
- Theoretical study for "corrugated structure" 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, SLAC-PUB
- Vertical offset control capability of the flat geometry makes it possible to minimize the effect of **dipole wake**. Flat geometry introduces **quadrupole wake**, which is not present at round geometry.
- Passive de-chirper using beam self-induced wakefield to remove head-to-tail chirp are now seriously considered at LCLSII, PAL-XFEL & SWISS-FEL.

Passive beam energy linearizer

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 034401 (2010)

Passive longitudinal phase space linearizer

P. Craievich

Sincrotrone Trieste–ELETTRA, Trieste, Italy
(Received 23 September 2008; published 30 March 2010)

We report on the possibility to passively linearize the bunch compression process in electron linacs for the next generation x-ray free electron lasers. This can be done by using the monopole wakefields in a dielectric-lined waveguide. The optimum longitudinal voltage loss over the length of the bunch is calculated in order to compensate both the second-order rf time curvature and the second-order momentum compaction terms. Thus, the longitudinal phase space after the compression process is linearized up to a fourth-order term introduced by the convolution between the bunch and the monopole wake function.

Proceedings of LINAC2012, Tel-Aviv, Israel TUPB022

A PASSIVE LINEARIZER FOR BUNCH COMPRESSION

Q. Gu#, M. Zhang, M. H. Zhao, SINAP, Shanghai, China

Abstract

In high gain free electron laser (FEL) facility design and operation, a high bunch current is required to get lasing with a reasonable gain length. Because of the current limitation of the electron source due to the space charge effect, a compression system is used to compress the electron beam to the exact current needed. Before the bunch compression, the nonlinear energy spread due to the finite bunch length should be compensated; otherwise the longitudinal profile of bunch will be badly distorted. Usually an X band accelerating structure is used to compensate the nonlinear energy spread while decelerating the beam. But for UV FEL facility, the X band system is too expensive comparing to other system. In this paper, we present a corrugated structure as a passive linearizer, and the preliminary study of the beam dynamics is also shown.

above the cut-off frequency of the cylindrical pipe will be excited. The longitudinal point charge wakefield of this mode is approximatelywritten as,

$$W(s) = 2 \cdot \chi \cdot H(s) \cdot \cos(k \cdot s). \quad (1)$$

The χ is the loss fact by

$$\chi = \frac{Z_0 \cdot c}{2 \cdot \pi \cdot a}, \quad (2)$$

the H(s) is a unit step function by,

$$H(s) = \begin{cases} 1, s \geq 0 \\ 0, s < 0 \end{cases}, \quad (3)$$

and the k is the wave number of the fundamental mode by

P. Emma did simulations for corrugation parameters similar to those used in the PAL experiment: P. Emma, NGLS Technical Note 32, 2012.

One needs to get a shorter wavelength of the wakefield mode, compared with the de-chirper case.

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Passive beam energy stabilizer

Table 2 Average energy stability under different energy chirp conditions

L3 phase	dE/E (0.1% normalization)			
	−23.9°	−22°	−20°	−18°
−5°	0.785 4	0.669 4	0.637 2	0.604 7
−2°	0.778 6	0.661 4	0.630 1	0.599 6
−1°	0.778 2	0.660 9	0.630 3	0.600 9
0°	0.778 6	0.661 6	0.631 7	0.603 6
2°	0.781 9	0.665 9	0.638 0	0.612 9
5°	0.793 6	0.680 8	0.656 9	0.637 6

M. Zhang, X. Li, H. X. Deng, Q. Gu, High Power Laser and Particle Beams, 26, 015106 (2014)

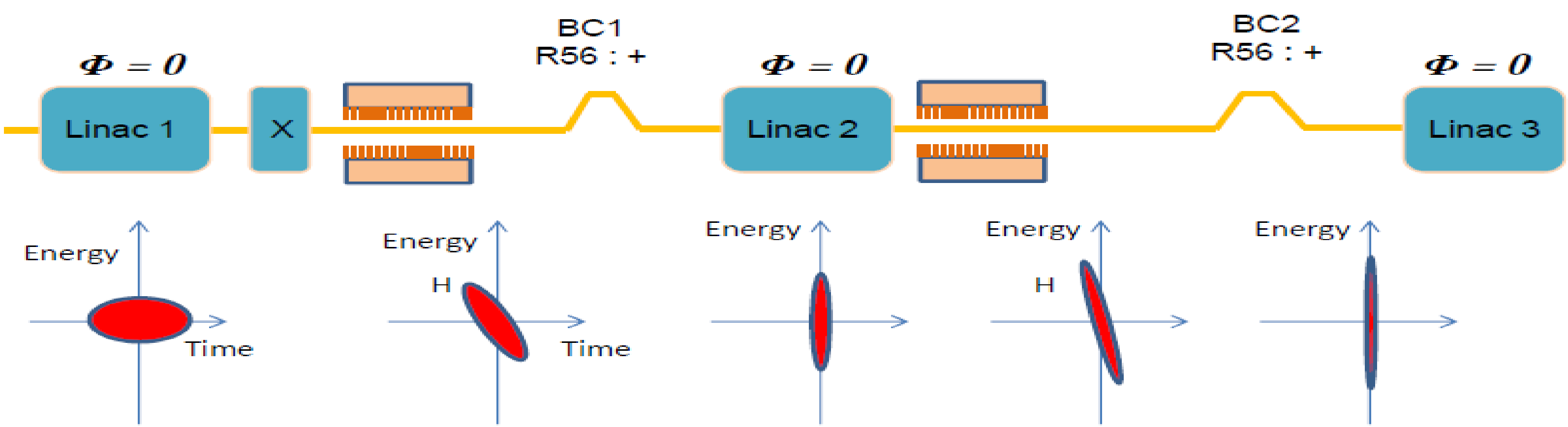
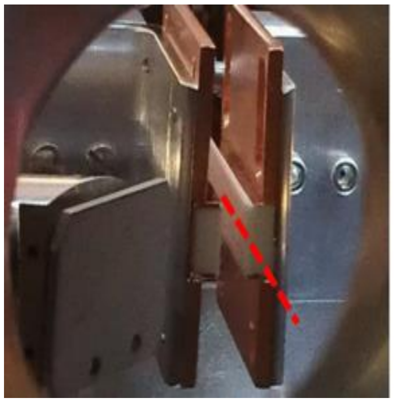
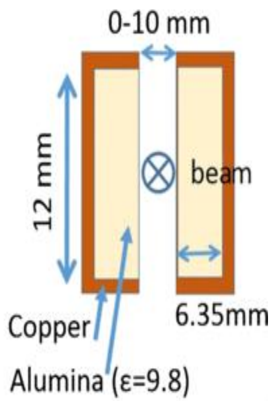


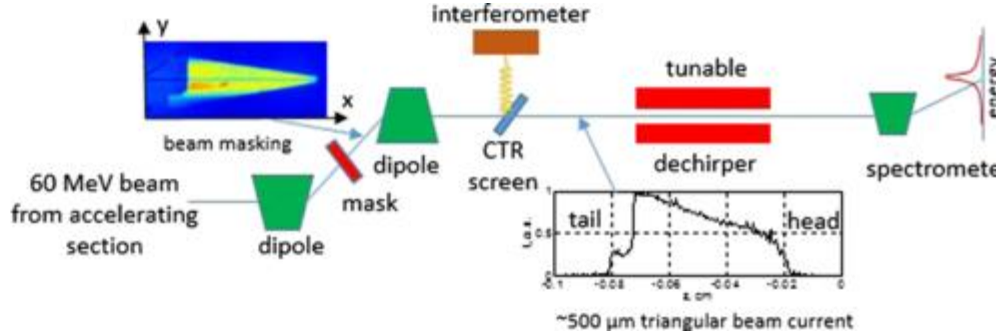
Figure from H. S. Kang

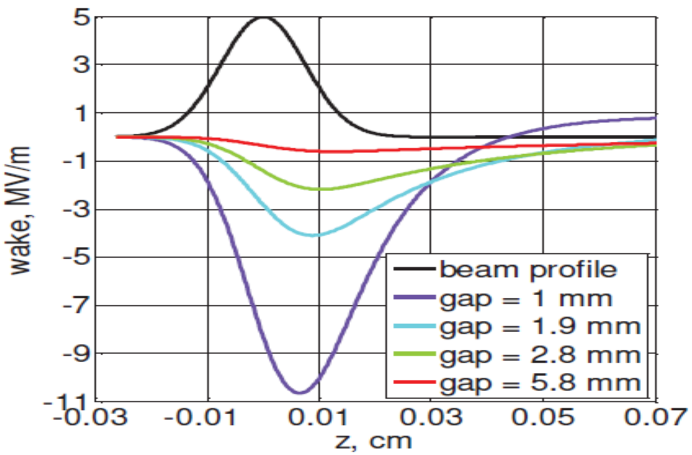
On-crest acceleration improves beam energy jitter

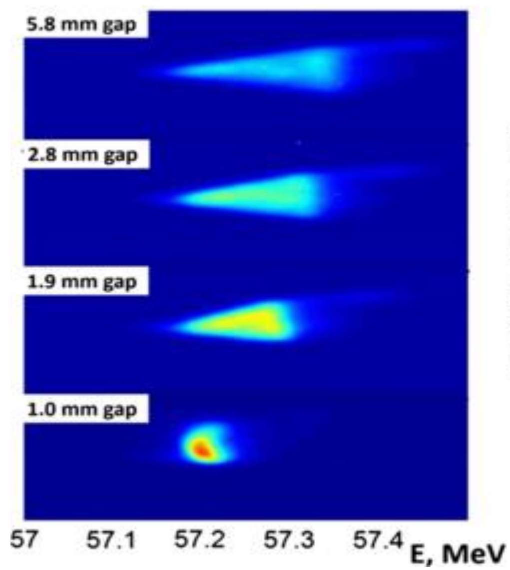
Dielectric de-chirper at BNL-ATF

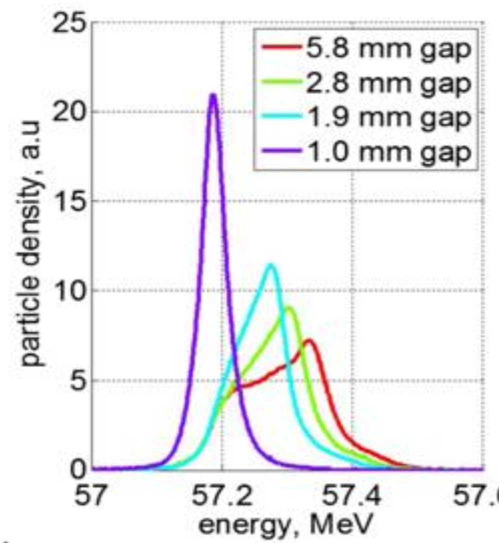






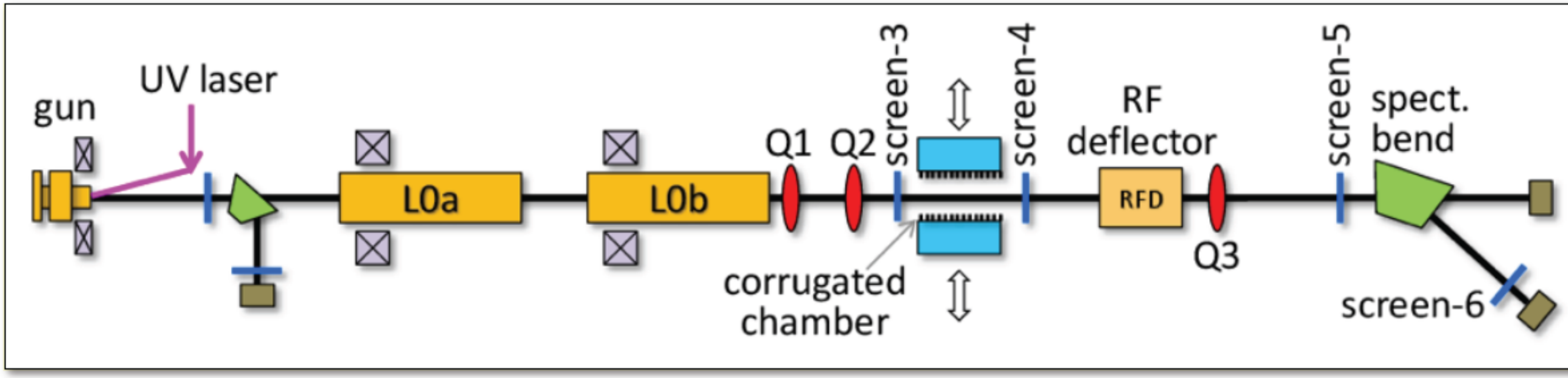






S. Antipov, C. Jing, M. Fedurin et al., Phys. Rev. Lett. 112, 114801 (2014)

Corrugated de-chirper test at PAL-ITF



- S-band, 1.6-cell RF Gun (~200 pC)
- Two 3-m S-band RF structures (L0b ~off)
- 1-m S-band vert. RF deflector (RFD)
- Electron spectrometer (30 deg, hor.)
- All quads off
- 1-m long *rectangular* ‘dechirper’
- 4 main YAG screens

$E = 70$ MeV
$Q = 200$ pC (?)
$\gamma\varepsilon_{x,y} = 0.5\text{-}1$ µm
$\beta_{x,y} \approx 20\text{-}50$ m
$f = 10$ Hz
$\sigma_z = 0.45$ mm rms

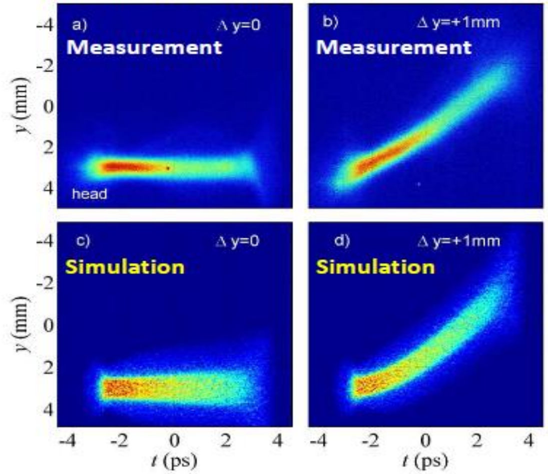
Slide from H. S. Kang

Corrugated de-chirper test at PAL-ITF

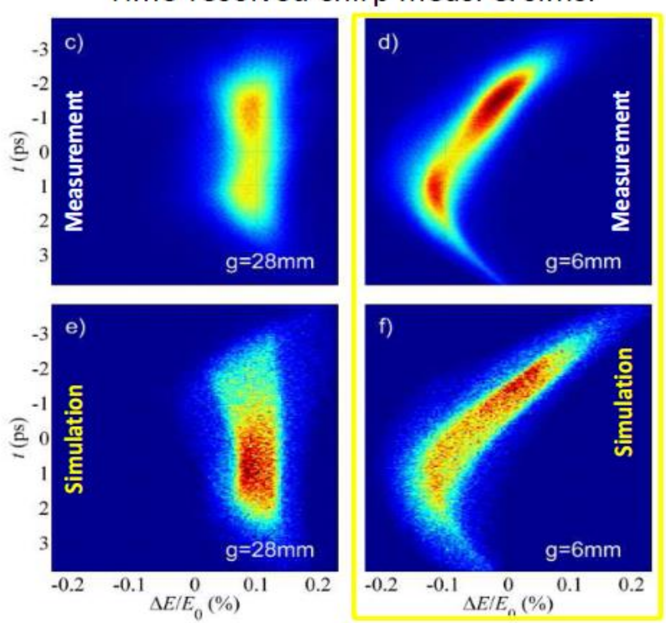
We demonstrates the feasibility to employ a dechirper for precise control of the beam phase space in the next generation free electron lasers.

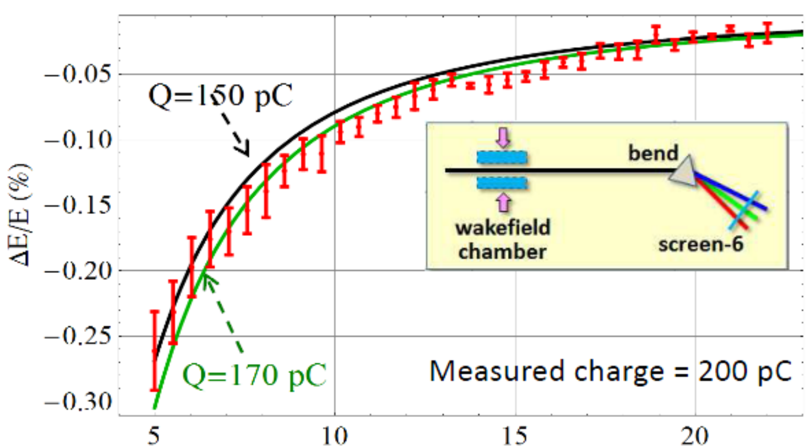
------ Paul Emma

Time-resolved T-wake meas. & sims.



Time-resolved chirp meas. & sims.



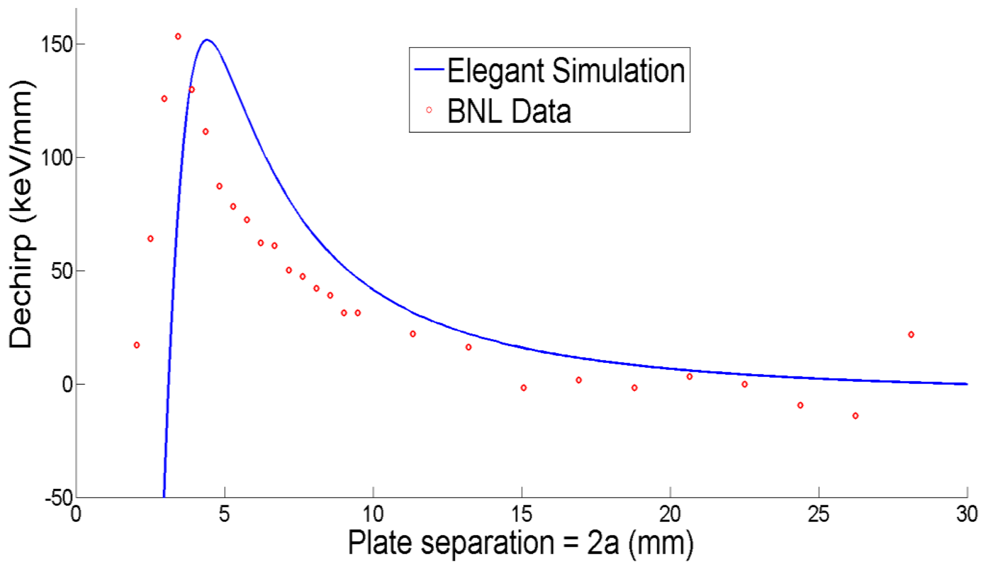


P. Emma, M. Venturini, K. L. F. Bane, et al., Phys. Rev. Lett. 112, 034801 (2014)

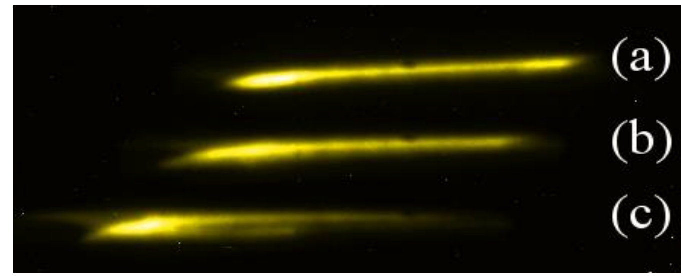
Corrugated de-chirper test at BNL-ATF

An 18cm long pair of aluminum plates with 1mm corrugations removed ~50% of 400keV/mm chirp from 58MeV beam with 3.4ps bunch length. The plot below shows the amount of chirp removed at various plate separations. [1]

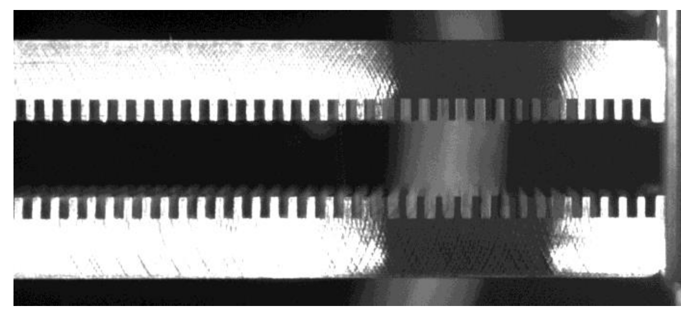
Full-scale test at LCLS with 2 meter long sections planned for 2015. [2]



Slide from M. Harrison



Spectrometer measurements with different gaps (a) 30 mm (b) 9 mm (c) 3.4 mm.



Side view of corrugated de-chirper plates

[1] M. Harrison, et al. "Further Analysis of Corrugated Plate Dechirper Experiment at BNL-ATF," FEL'14 THP034
[2] M. Harrison, et al. "Mechanical Design for a Corrugated Plate Dechirper System for LCLS," FEL'14 THP033

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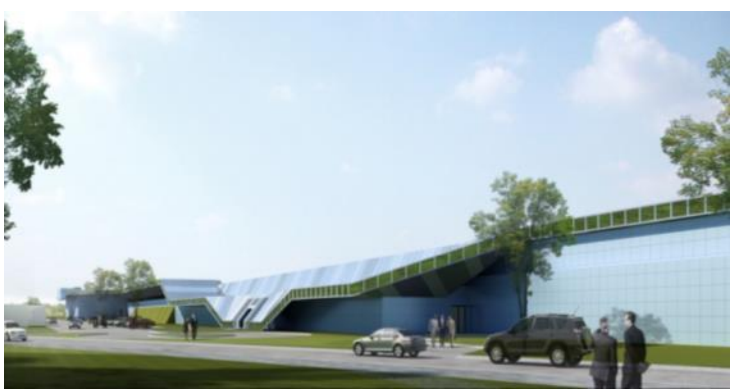
SDUV-FEL program

- Shanghai Deep Ultraviolet Free-Electron Laser (SDUV-FEL) started as a 262nm SASE / 88nm HGHG FEL test setup around 2000.
- Funding partially supported by
  - ✓ Chinese Academy of Sciences / CAS
  - ✓ Ministry of Science and Technology of China / MOST
  - ✓ National Natural Science Foundation of China / NSFC
- Collaborating between USTC, IHEP, TUB and SINAP.
- 2009.04, LINAC commissioning started.
- Currently, it is a test bed for FEL novel principles & key technologies for future X-ray FELs.

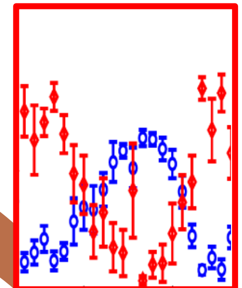
SDUV-FEL Experiment Hall

4. About SDUV-FEL

SDUV-FEL

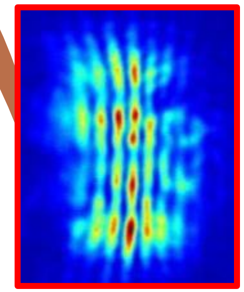


DCLS、SXFEL、XFEL



Crossed-planar undulator demonstration

Phys. Rev. ST-AB 16, 020704 (2014)

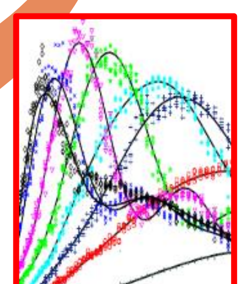


HGHG & cascaded HGHG

Phys. Rev. ST-AB 17, 020704 (2013)

First lasing of Echo-FEL

Nature Photonics 06, 360 (2012)



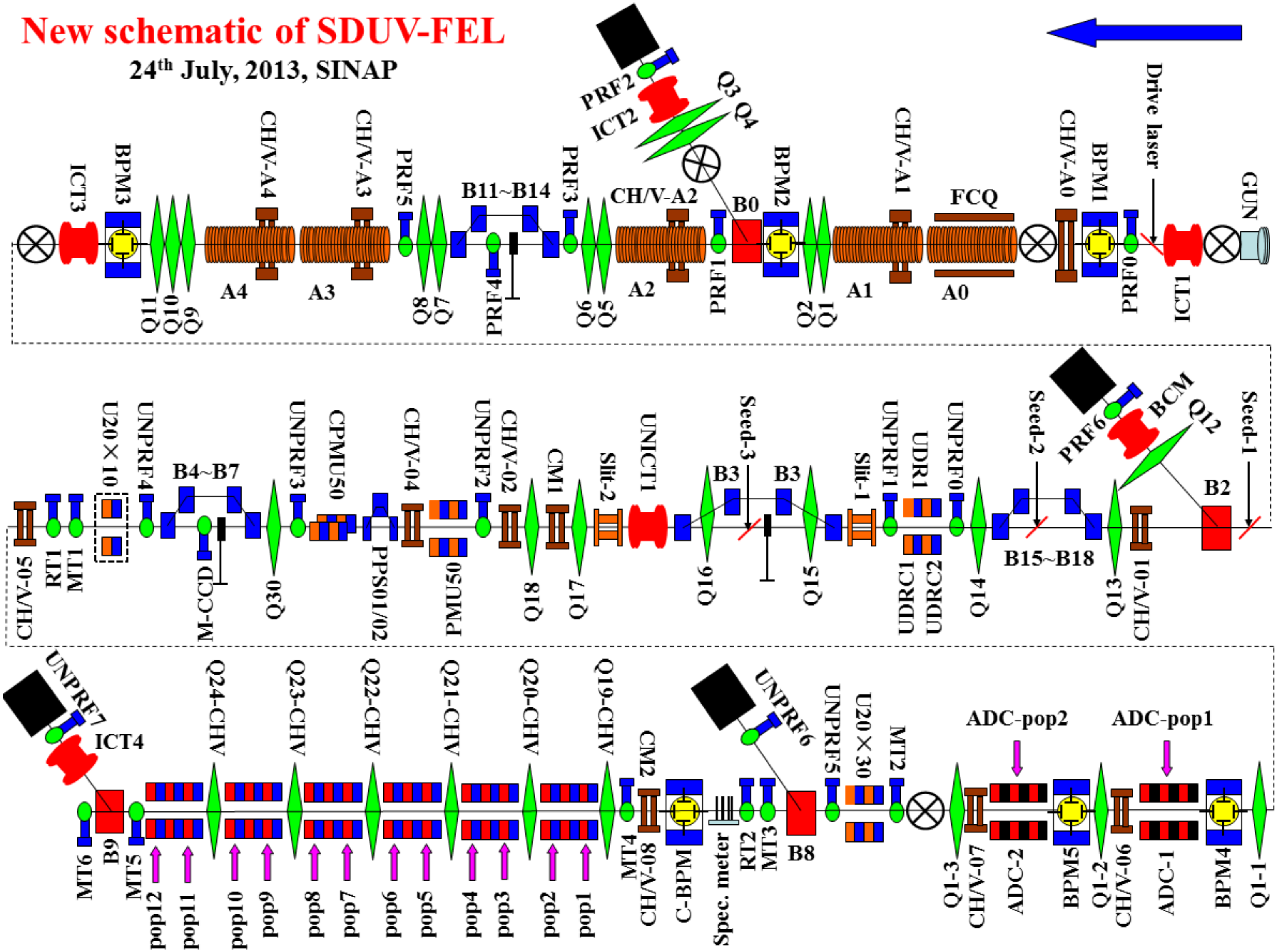
keV sliced energy spread measurement

Phys. Rev. ST-AB 14, 090701 (2011)

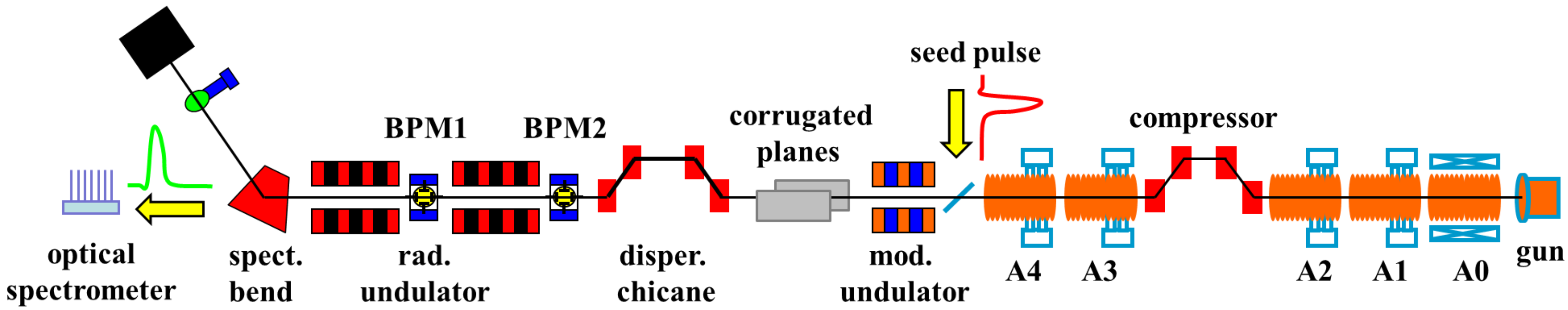
4. About SDUV-FEL

New schematic of SDUV-FEL

24th July, 2013, SINAP



Corrugated experiment proposal at SDUV-FEL



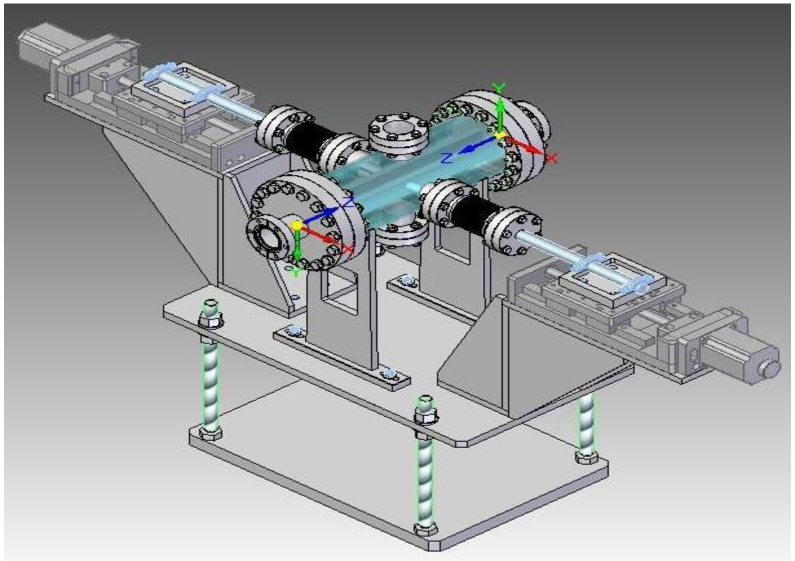
- So far, only dechirper experiment was carried out at BNL and PAL, & they are just beam experiments.
- In SDUV-FEL proposal, we will fight for the first operation of corrugated device in a real FEL facility.
- SDUV-FEL method: Spectrum of beam energy & seeded FEL.

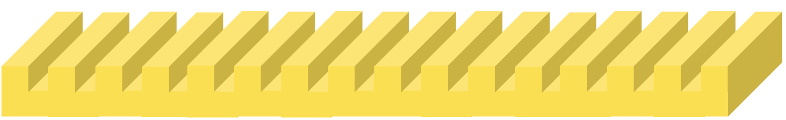
Work supported by NSFC (No. 11175240, 11205234 and 11322550) and Major State Basic Research Development Program of China (2011CB808300).

Main experiment parameters

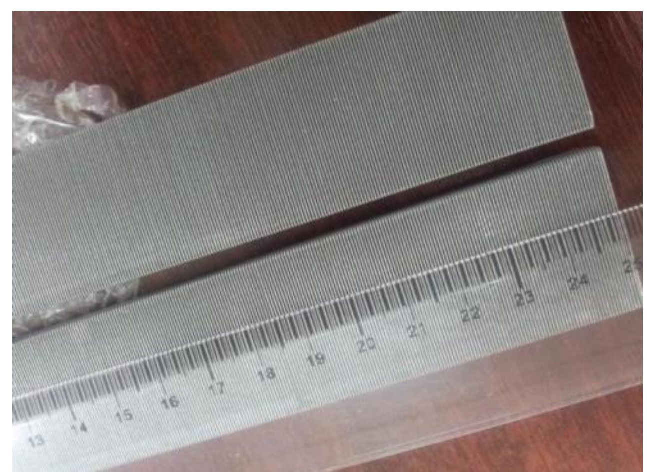
Electron Beam			
Beam Energy [MeV]	~140	Slice Energy Spread [keV]	1
Bunch length [ps]	8.8	Normalized Emittance	4~6 mm·mrad
Total Charge [pC]	100	Transverse Beam Size	~200 μm
Modulator (EMU65)			
Period Length [m]	0.065	Period Number	10
Radiator (ADC)			
Period Length [m]	0.04	Period Number	40*2
Seed Laser System			
Wavelength [nm]	1047	Time Duration (FWHM) [ps]	~ 8.0
Peak Power [MW]	~ 10	Rayleigh Length [m]	~ 3.0
Corrugated structures			
Total Length [m]	0.3	Separation [mm]	0 ~ 30

Corrugated device design & manufacture

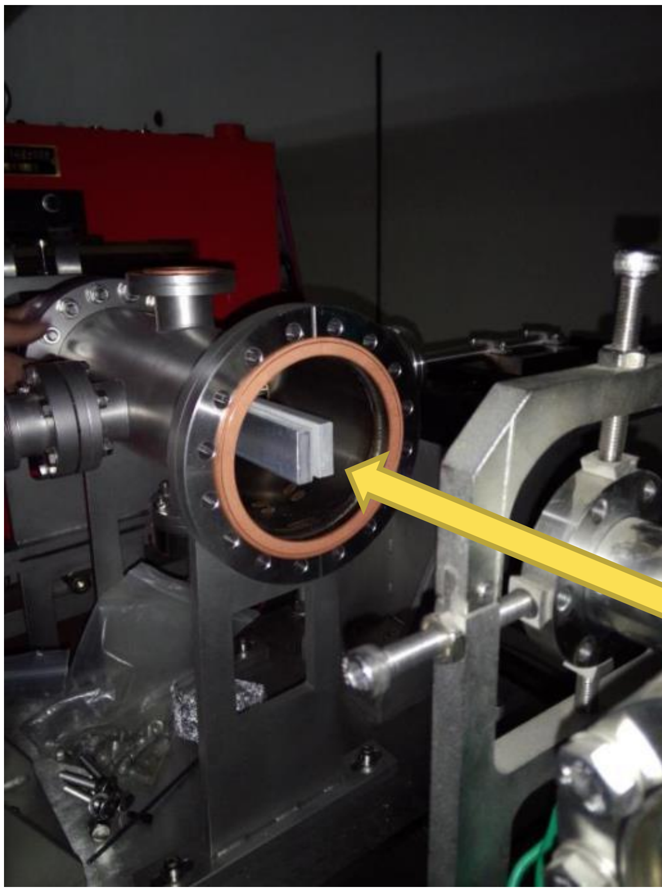


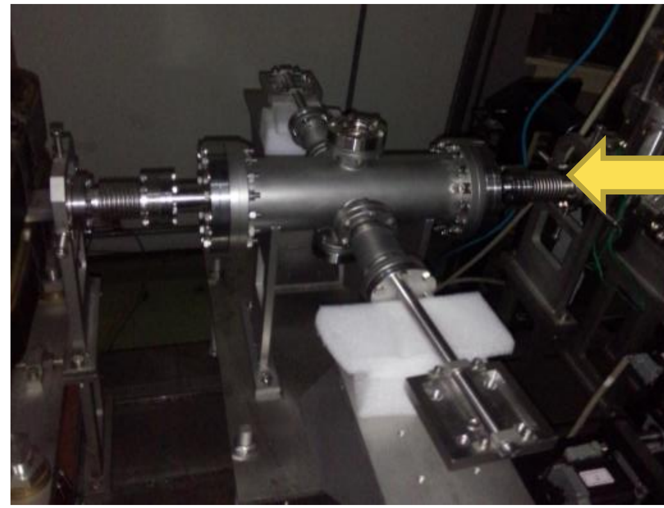


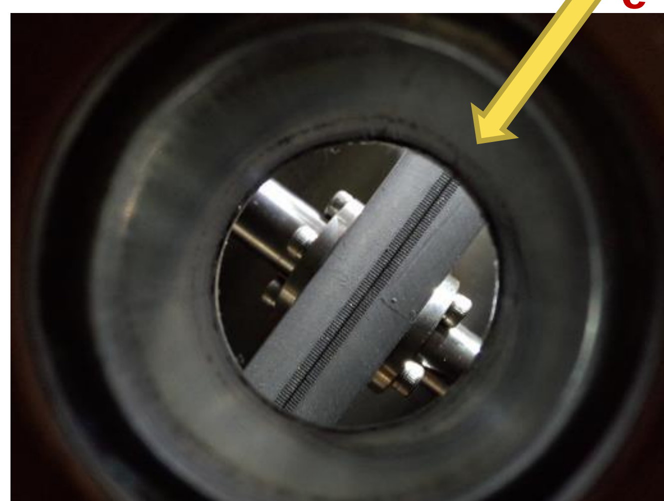
Material	Aluminum
depth δ	2.0mm
corrugated width g	0.3mm
period p	0.6mm
length	300mm
width	30mm



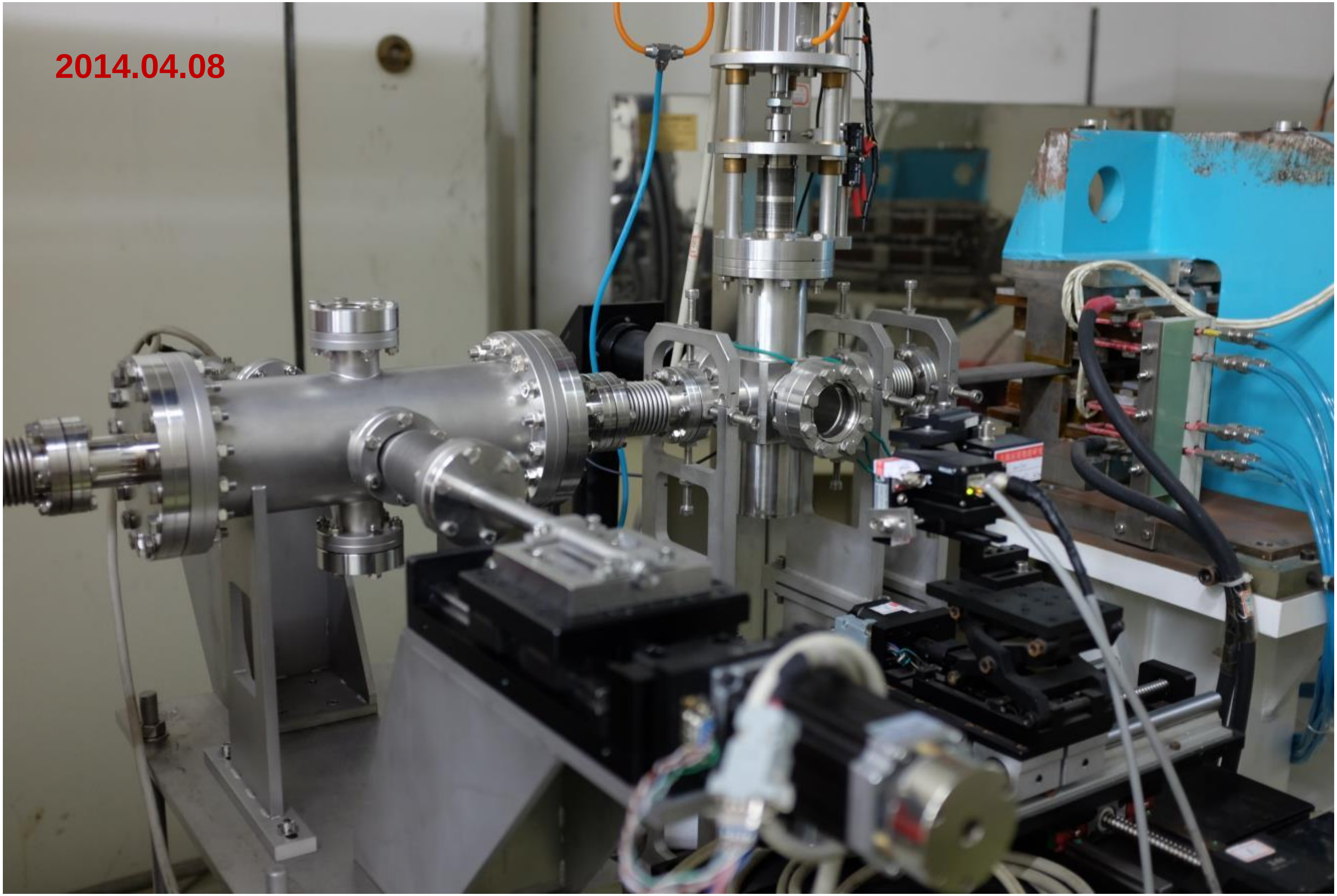
Corrugated device assembly & alignment



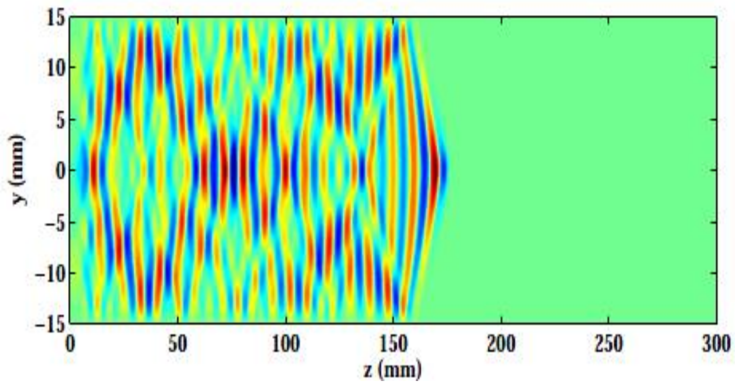


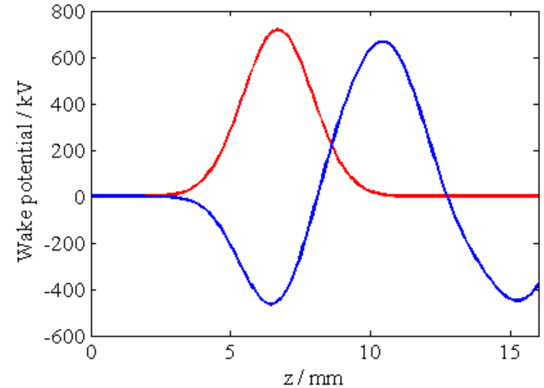


5. Proposal and experiment at SDUV-FEL



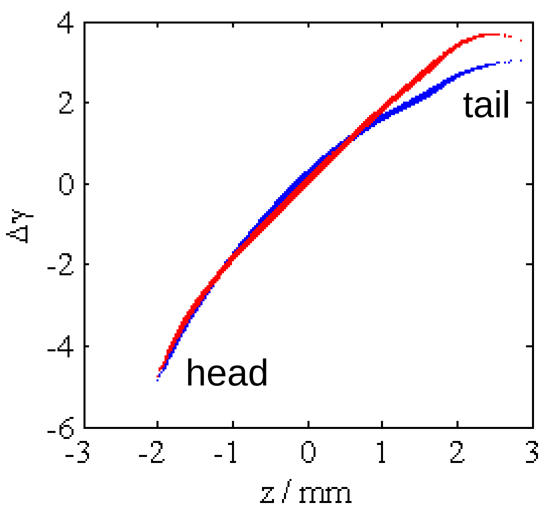
Wakefield & beam dynamics



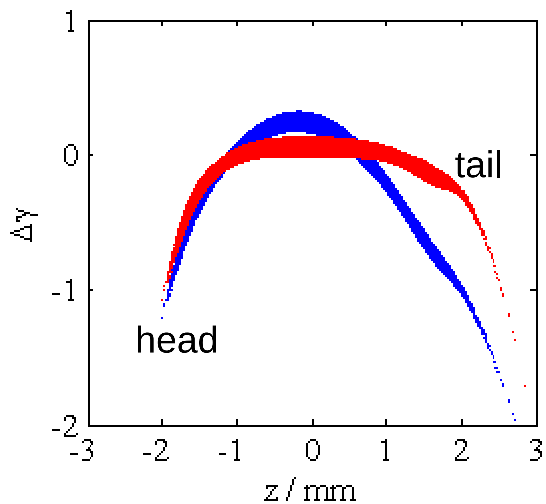


Courtesy Dan Wang

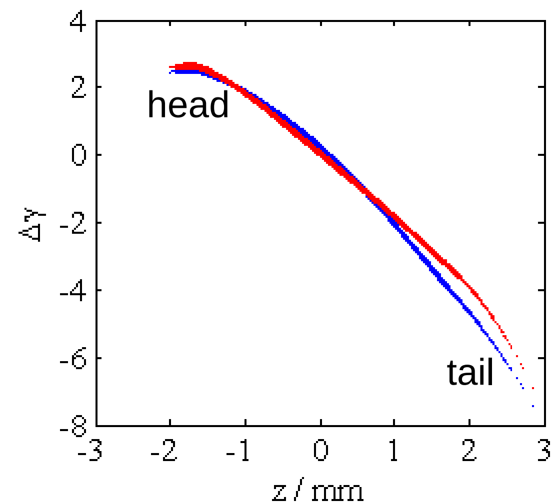
CST calculation of wakefield of the corrugated structures used at SDUV-FEL



φ3, φ4 = -25°

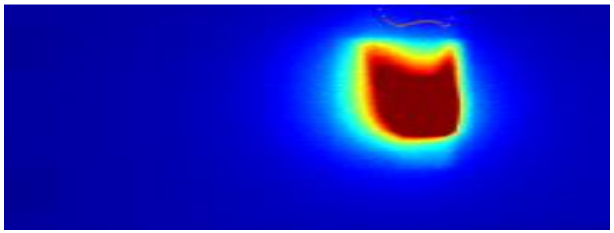


φ3, φ4 = 0°

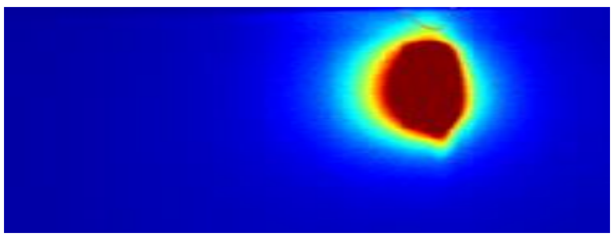


φ3, φ4 = 25°

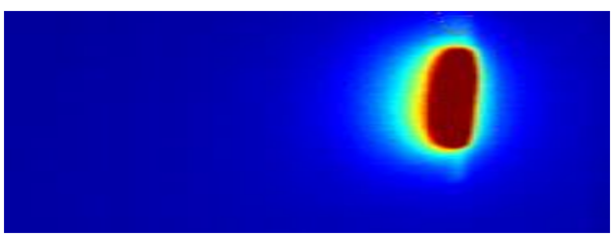
Beam energy spread suppression measurement



a = 5.0mm

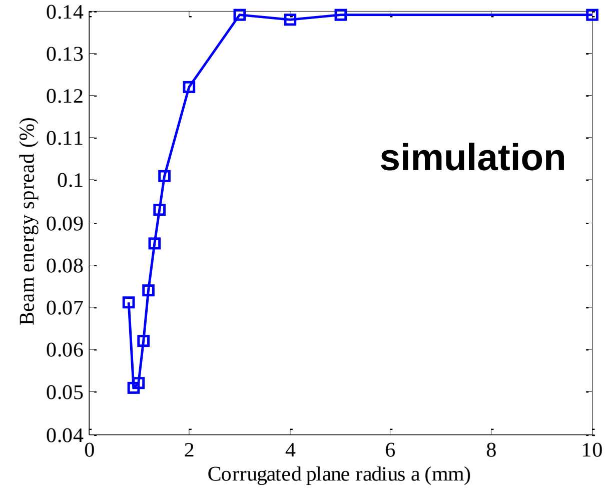


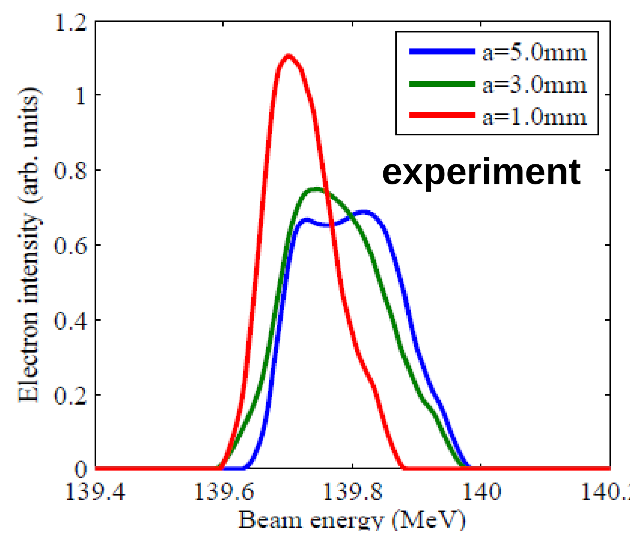
a = 3.0mm



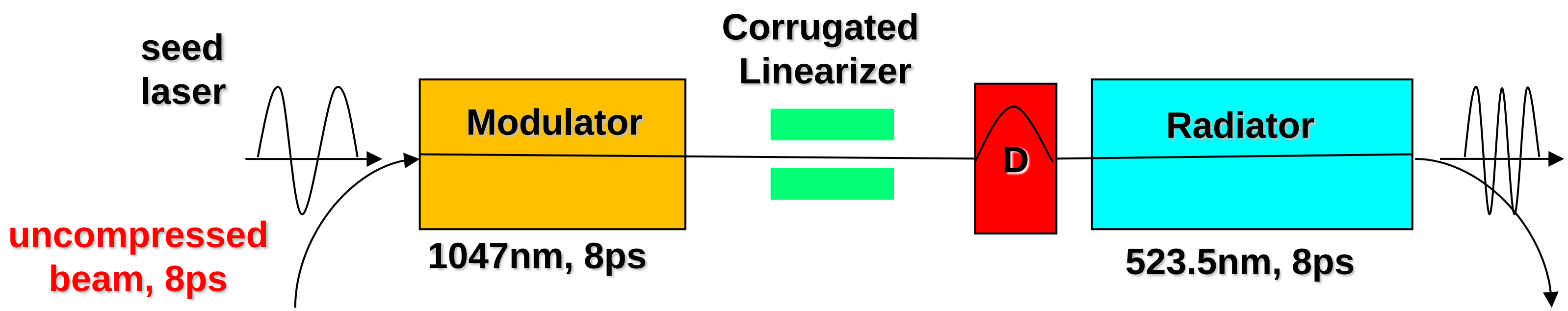
a = 1.0mm

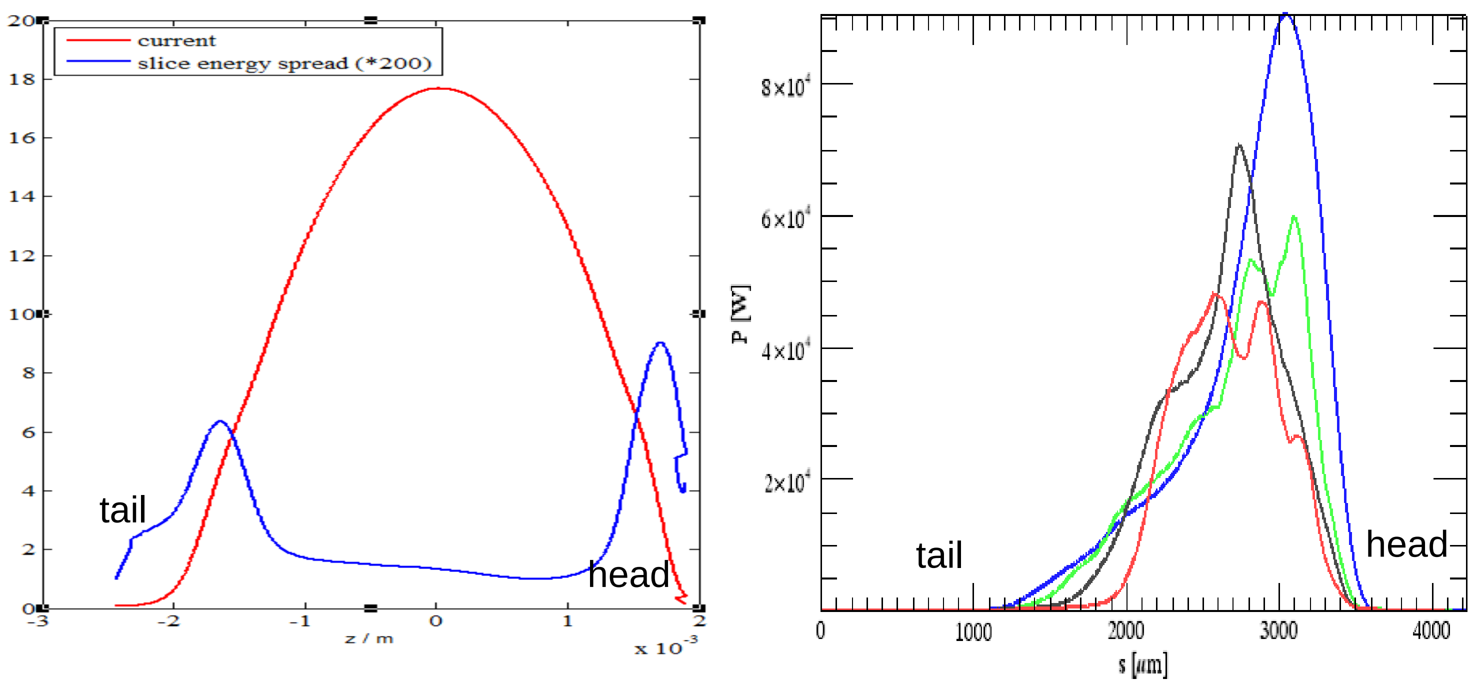
Beam energy spread
$1.1\times10^{-3} \rightarrow 7.5\times10^{-4}$



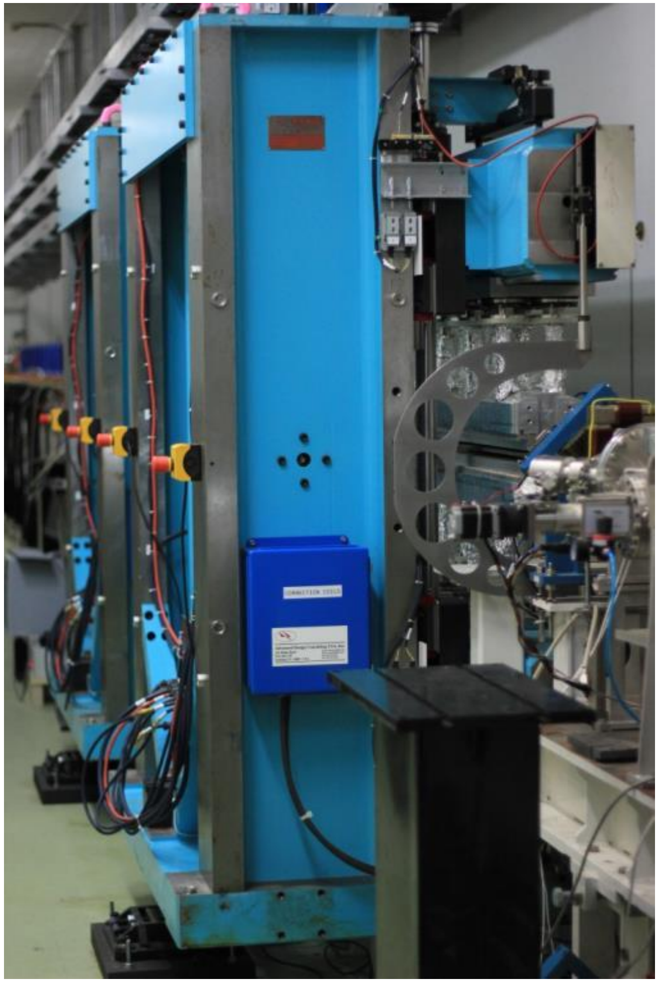


Start-to-end simulation results

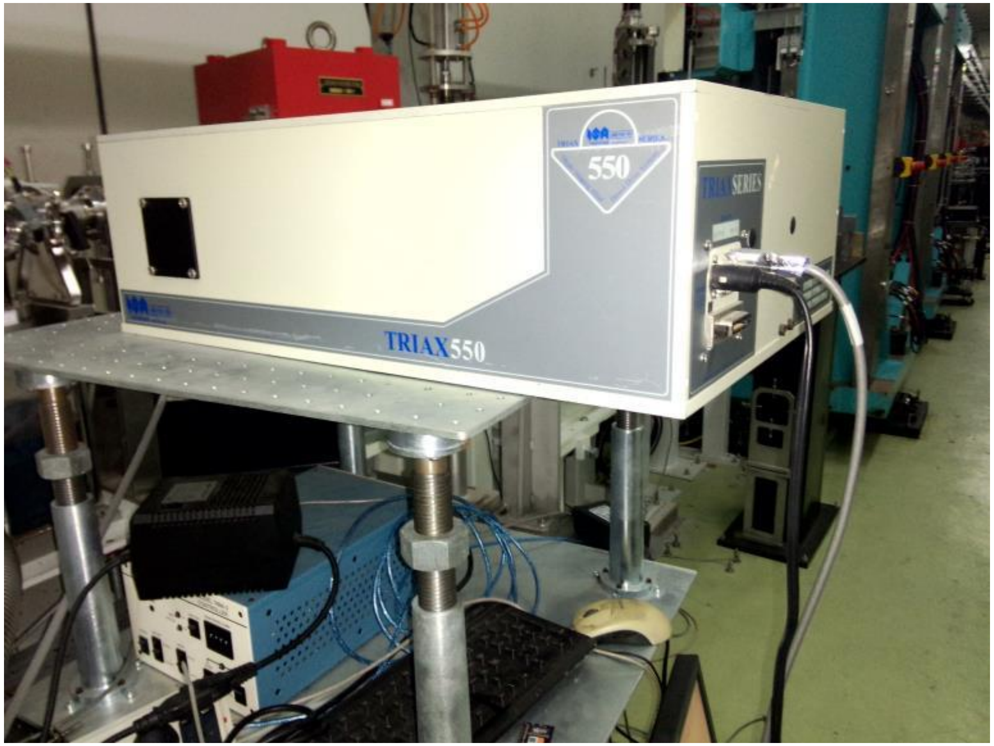




FEL radiator undulator & spectrometer

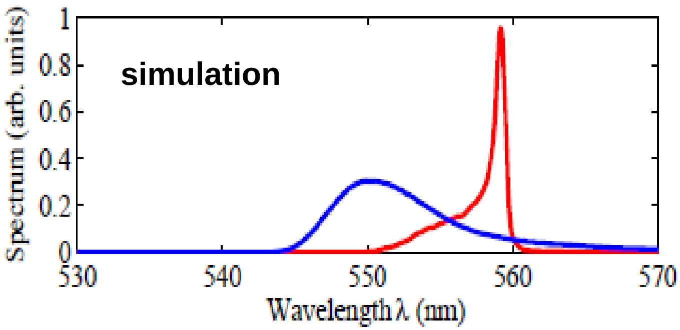


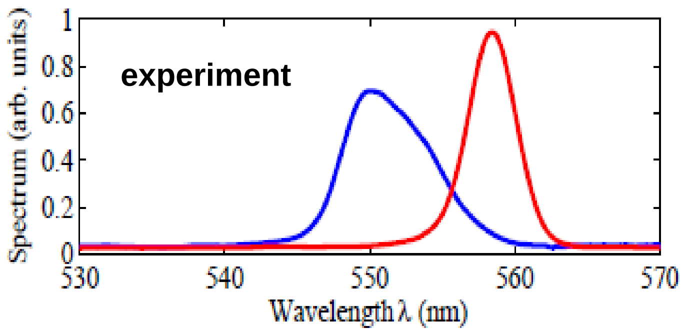
40mm*80 periods, with variable gap



TRIAX550 spectrometer
600 line grating
2.7nm resolution @ 1mm slit (calibrated)

FEL spectrum measurement

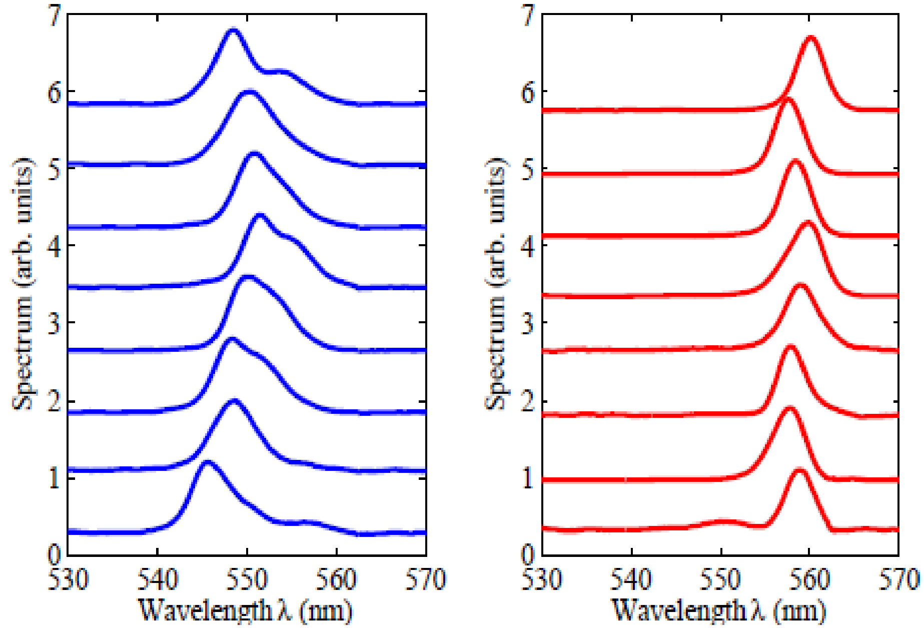




Multi-shots experiment results

R_{56}=6.5mm (dispersive section of HGHG)

φ3, φ4 = 25°



Blue: corrugated structure open, **Red**: corrugated structure closed (2mm separation)

Central wavelength: 8nm redshift **FEL bandwidth: 8nm → 4nm**

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Conclusions

- Corrugated device could be beam de-chirper, linearizer, stabilizer and THz emitter in FEL light sources. Several beam experiments of corrugated structure were carried out on LINACs at BNL & PAL.
- SDUV-FEL is one of the most competitive test FEL facilities, on which the first FEL spectrum control experiment by corrugated device was accomplished more recently.
  - ✓ FEL central wavelength is shifted from 550nm to 558nm.
  - ✓ Seeded FEL bandwidth is reduced from 8nm to 4nm, 50% order.
- When electron beam is accelerated on-crest, beam energy spread suppression from 1.1×10^{-3} to 7.5×10^{-4} was observed.
- The experiment results agree well with simulations, which confirms the theory of corrugated structures for FEL improvement.

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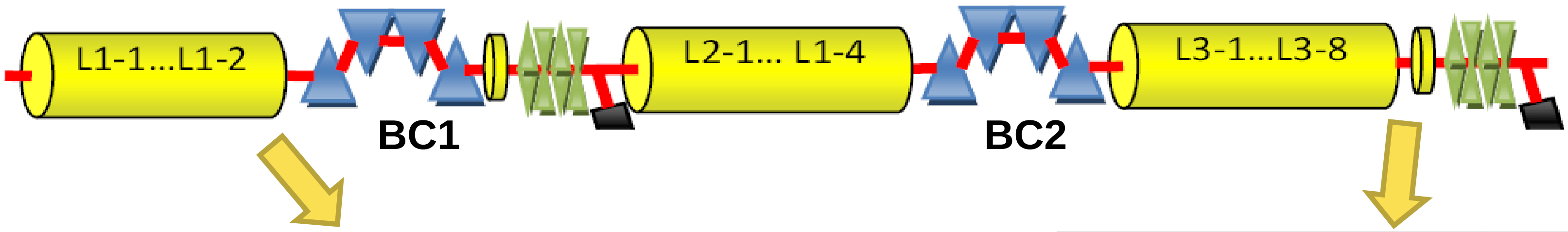
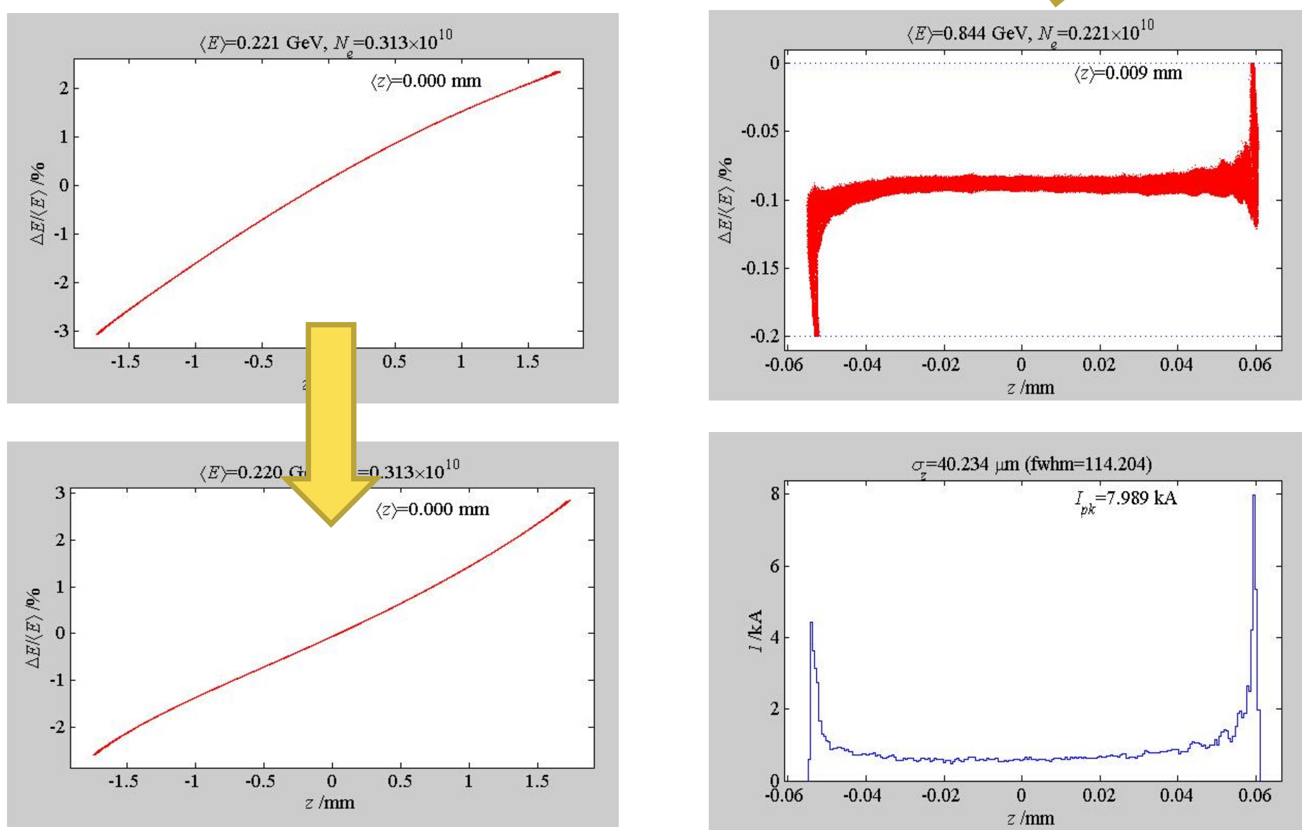
Corrugated device beam manipulation for SXFEL



SXFEL

- **840MeV LINAC**
- **9nm FEL**
- **2-stage HGHG**



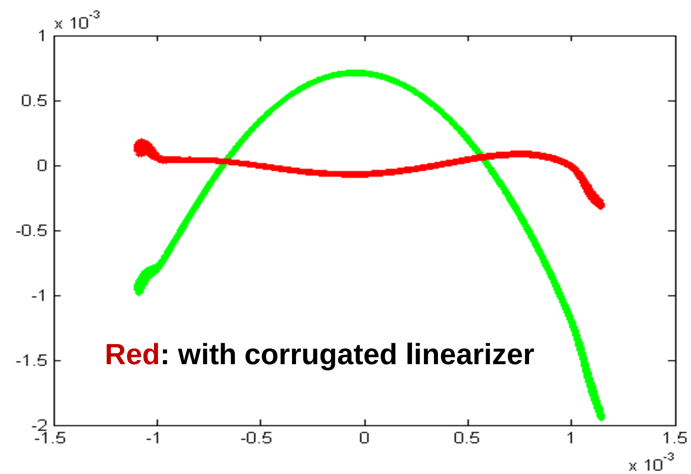
Energy spread control in ps-nm resolution TEM

TABLE I. Requirements on electron source parameters.

	RF photogun	ps MeV TEM
Number of electrons	10^7	$> 10^6$
rms normalized emittance	40 nm	< 10 nm
rms energy spread	10^{-3}	$< 10^{-4}$
FWHM bunch length	< 200 fs	10 ps

R. Li, P. Musumeci, arXiv: 1405. 5969.

Gun type	2.4-cell
Laser pulse (ps)	10
Laser diameter (μm)	100
Therm. emitt. (0.8μmrad/mm)	0.02
Charge (pC)	1
E_{peak} (MV/m)	100



Energy spread: 0.07% → 0.006%

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FEL physics group at SSRF