The 2014 International Free Electron Laser Conference

# Experimental demonstration of spectrum control in a seeded free-electron laser using corrugated device

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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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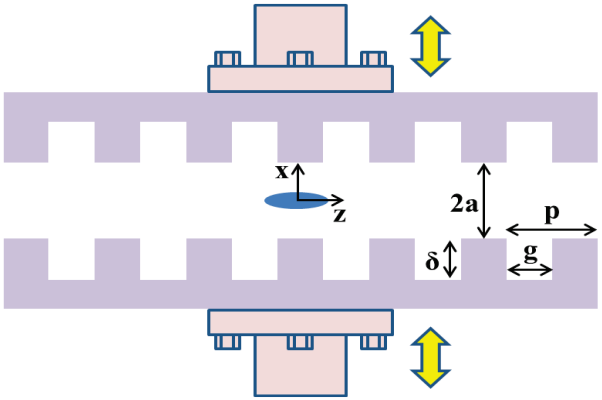
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

# Outline

- Backgrounds
- Proposal & experiment at SDUV-FEL
- Summary and outlook

# Wakefield of corrugated de-chirper

- Undesired time-energy correlation in the beam (e.g., linear energy chirp) may broaden FEL bandwidth and decrease FEL gain. After bunch compressor, the remain beam energy chirp is typically corrected by off-crest acceleration & wakefield in a following LINAC.

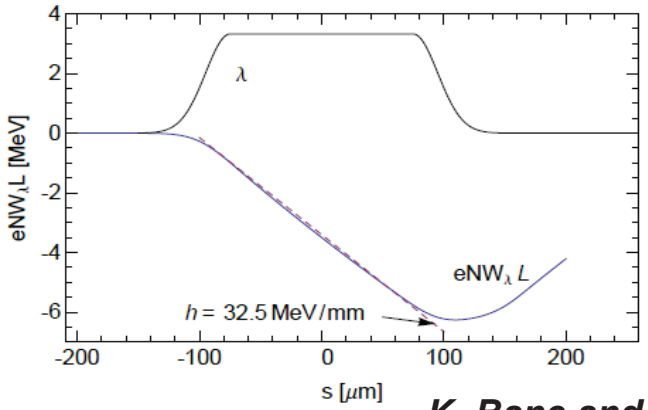



$$W_\lambda(s) = -\int_0^\infty W(s')\lambda(s-s')\,ds'$$

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

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

- has a near maximal possible amplitude
- has a relatively large oscillation




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

*K. Bane and G. Stupakov, NIMA, 690, 106 (2012)*

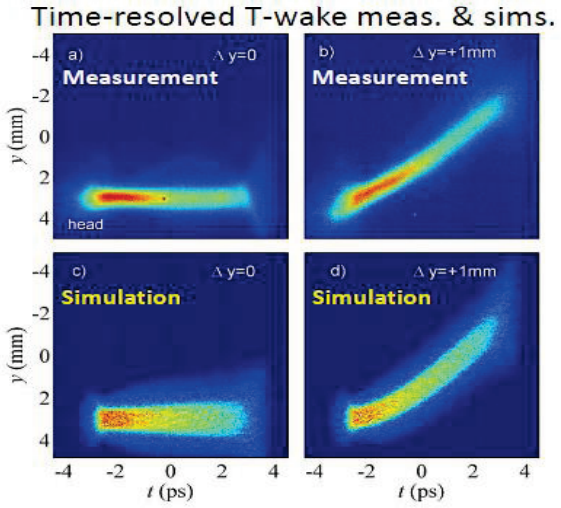
# Development of corrugated structures

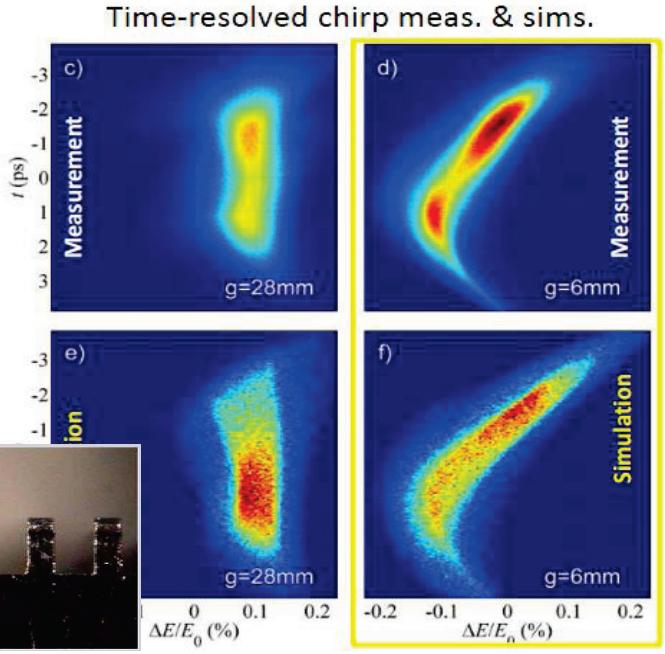
- Theoretical study for “corrugated structure” by K. Bane and G. Stupakov, which is initially motivated for NGLS case.
  - ✓ K. Bane and G. Stupakov, NIMA, 690, 106 (2012)
- Adjustable gap type of flat geometry ⇒ **better controllability**
  - ✓ Longitudinal wake for flat geometry, PRST-AB, 6, 024401 (2003)
  - ✓ Transverse wake for flat geometry was derived in 2013, SLAC-PUB
- Corrugated structure serves as **a beam linearizer, beam energy stabilizer, & high power Terahertz emitter**.
- Passive de-chirper using beam self-induced wakefield to remove head-to-tail chirp are now seriously considered at LCLS, PAL-XFEL & SWISS-FEL.
- Proof-of-principle experiments have been proposed and demonstrated.

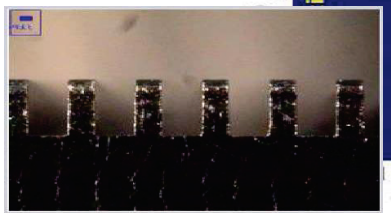
# Corrugated de-chirper test at PAL-ITF

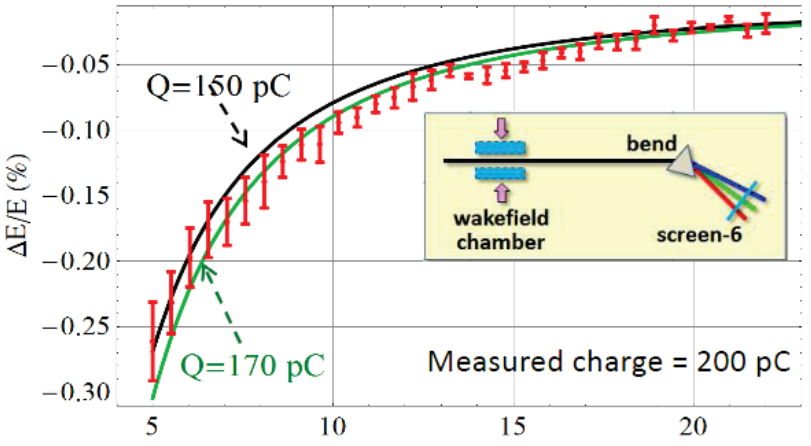
We demonstrates the feasibility to employ a dechirper for precise control of the beam phase space in the next generation free electron lasers.

------ Paul Emma



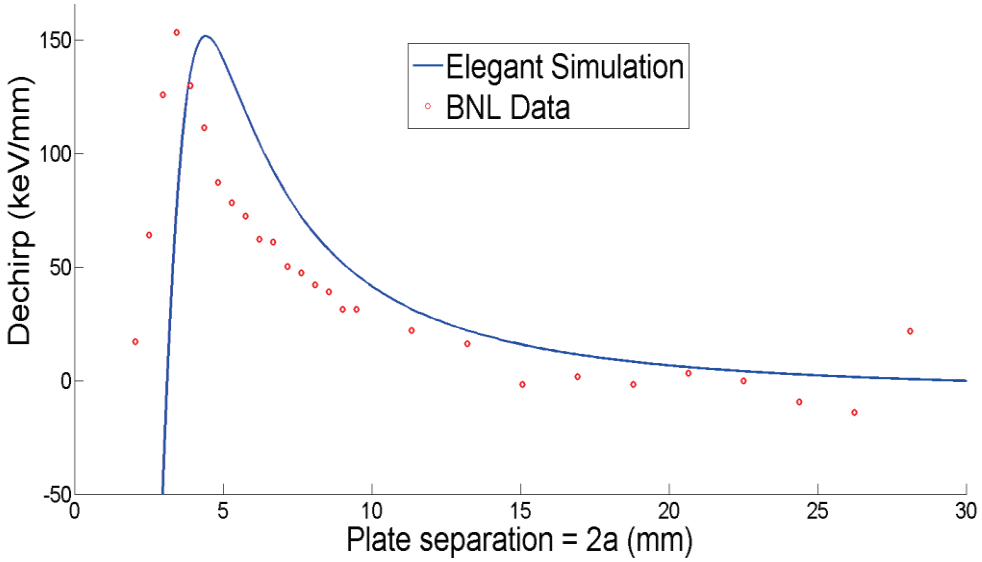



*P. Emma, M. Venturini, K. L. F. Bane, et al., Phys. Rev. Lett. 112, 034801 (2014)*

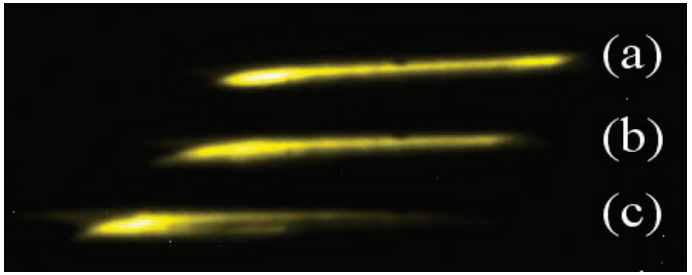
# Corrugated de-chirper test at BNL-ATF

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]

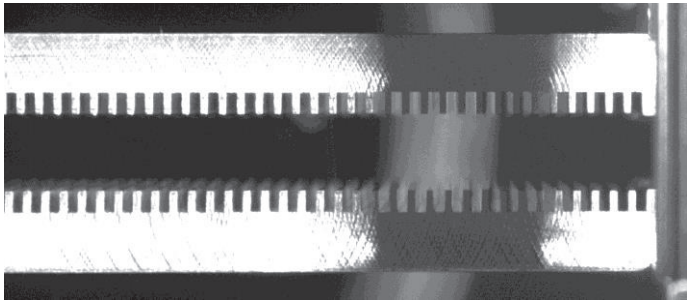
Full-scale test at LCLS with 2 meter long sections planned for 2015. [2]




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

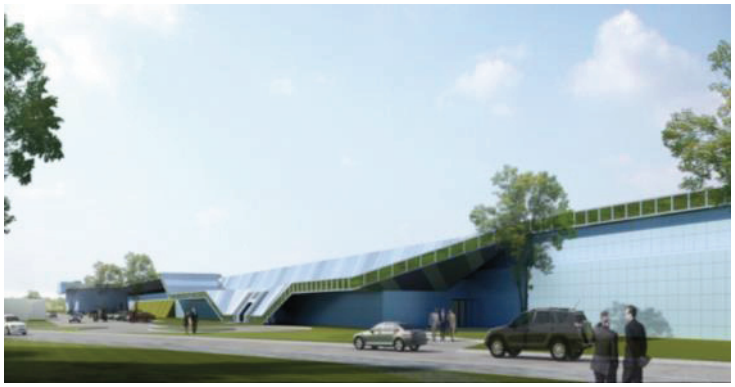
[2] M. Harrison, et al. "Mechanical Design for a Corrugated Plate Dechirper System for LCLS," FEL'14 THP033

# About SDUV-FEL

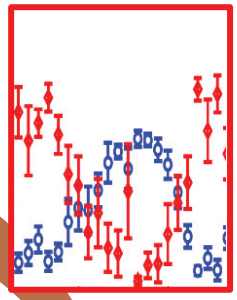
- Shanghai Deep Ultraviolet Free-Electron Laser (SDUV-FEL) started as a 262nm SASE / 88nm HGHG FEL test setup around 2000.
- Funding partially supported by
  - ✓ Chinese Academy of Sciences / CAS
  - ✓ Ministry of Science and Technology of China / MOST
  - ✓ National Natural Science Foundation of China / 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.

# 2. Proposal & experiment at SDUV-FEL

SDUV-FEL

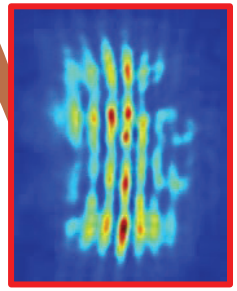


DCLS、SXFEL、XFEL



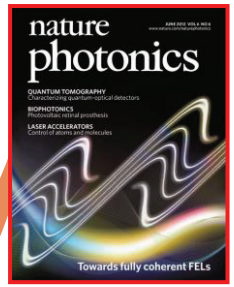
Crossed-planar undulator demonstration

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



HGHG & cascaded HGHG

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



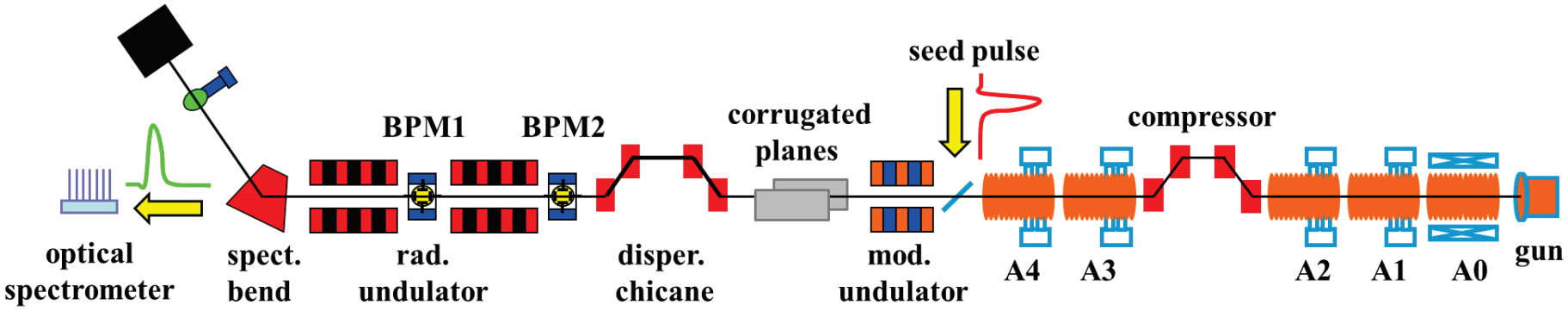

First lasing of Echo-FEL

Nature Photonics
06, 360 (2012)

keV sliced energy spread measurement

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

# Corrugated experiment proposal at SDUV-FEL

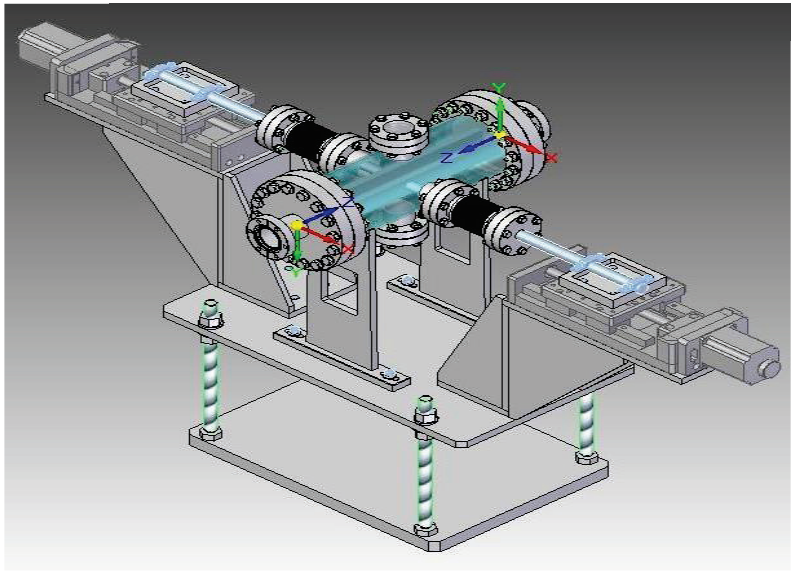



- To date, de-chirper experiments were carried out on LIANCs at PAL & BNL, However they are just beam experiments.
- In SDUV-FEL proposal, we fight for the first operation of corrugated device in a real FEL facility.

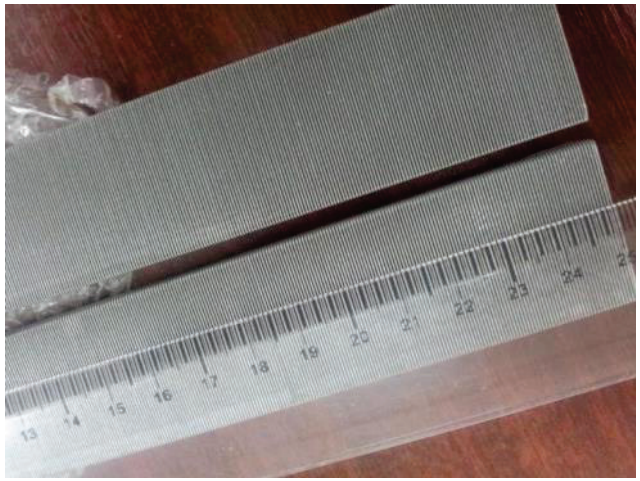
Work supported by NSFC (11175240, 11205234 and 11322550) and Major State Basic Research Development Program of China (2011CB808300).

# 2. Proposal & experiment at SDUV-FEL

## Corrugated device design & manufacture

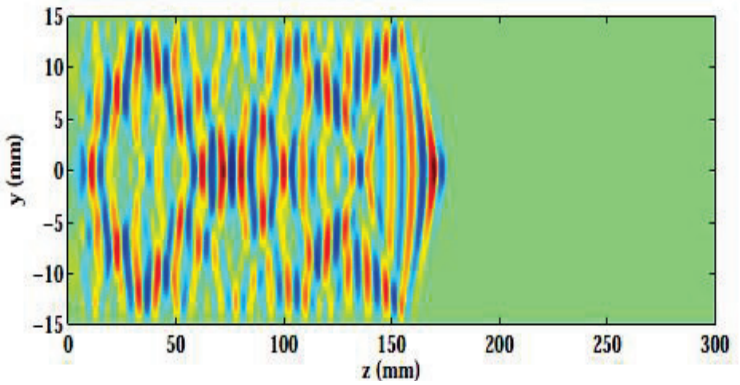


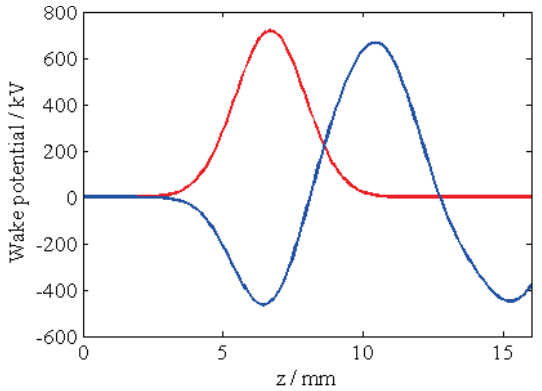
| Material | Aluminum |
|---|---|
| depth δ | 2.0mm |
| corrugated width g | 0.3mm |
| period p | 0.6mm |
| length | 300mm |
| width | 30mm |



# 2. Proposal & experiment at SDUV-FEL

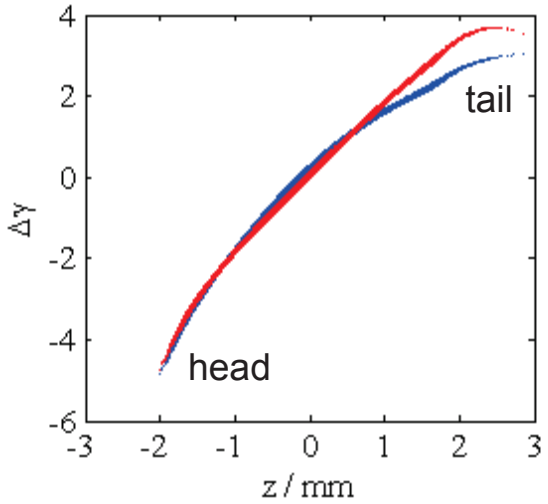
## Wakefield & beam dynamics



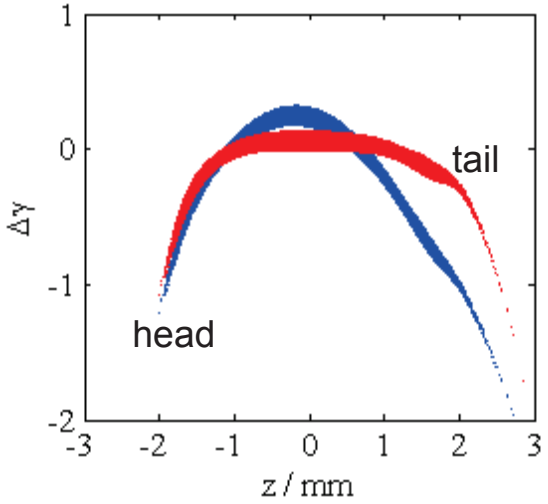




Courtesy
Dan Wang

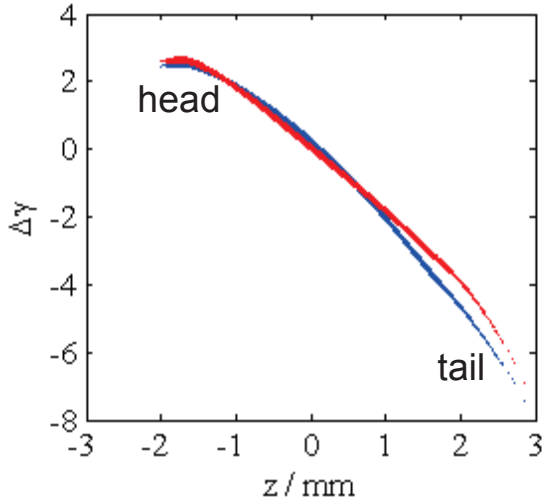
**CST calculation of wakefield of the corrugated structures used at SDUV-FEL**




**φ3, φ4 = -25°**

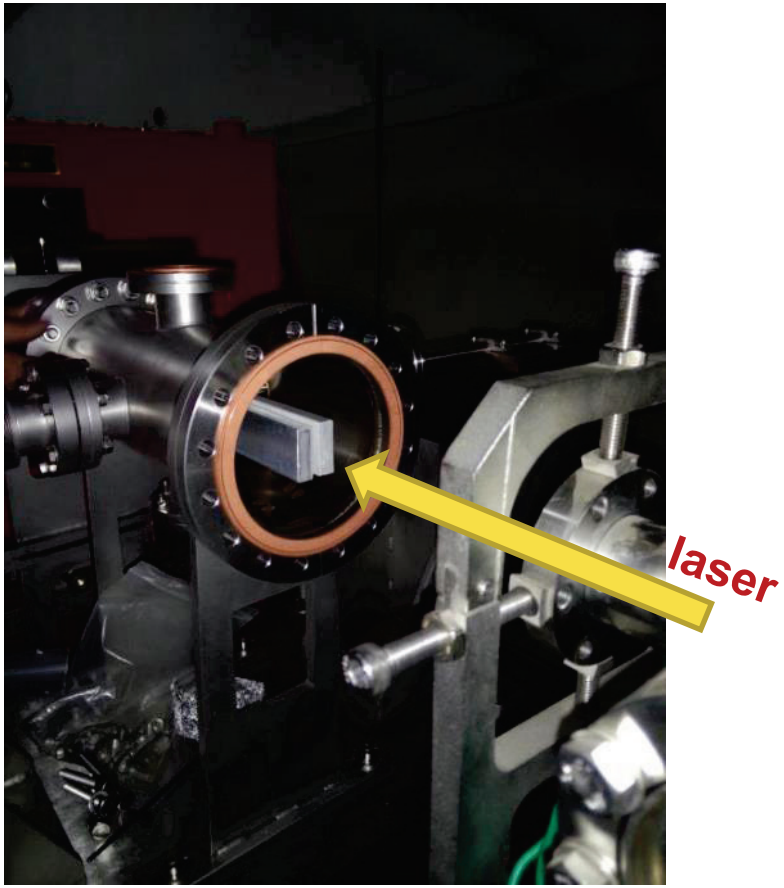


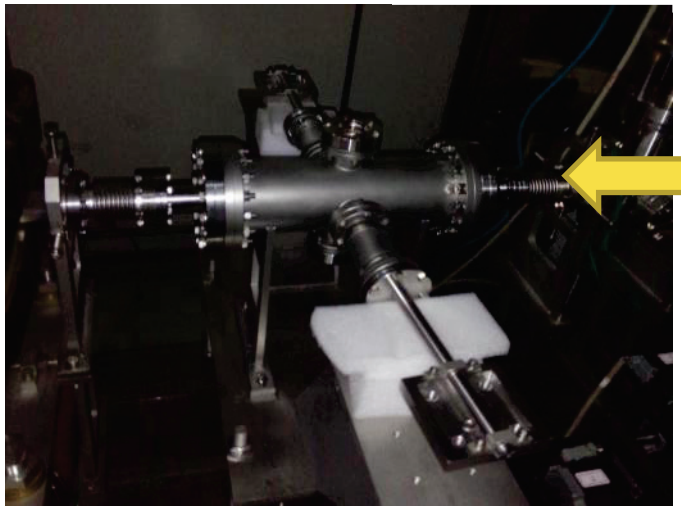

**φ3, φ4 = 0°**

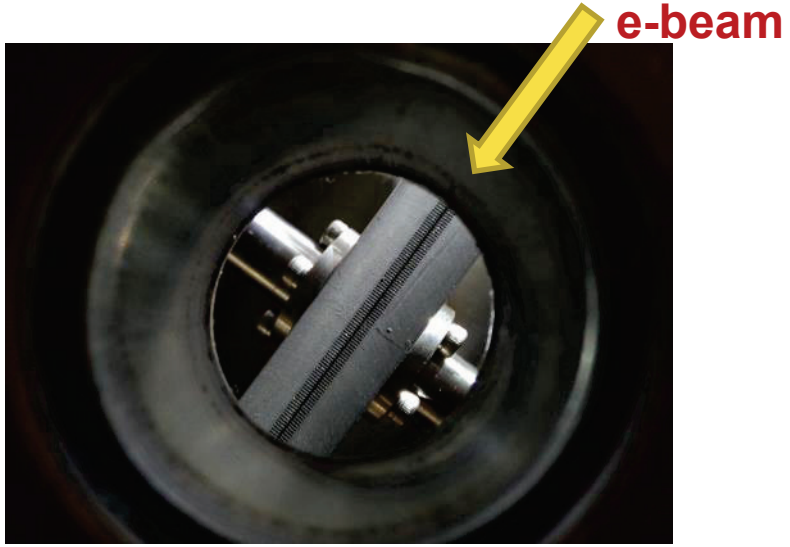



**φ3, φ4 = 25°**

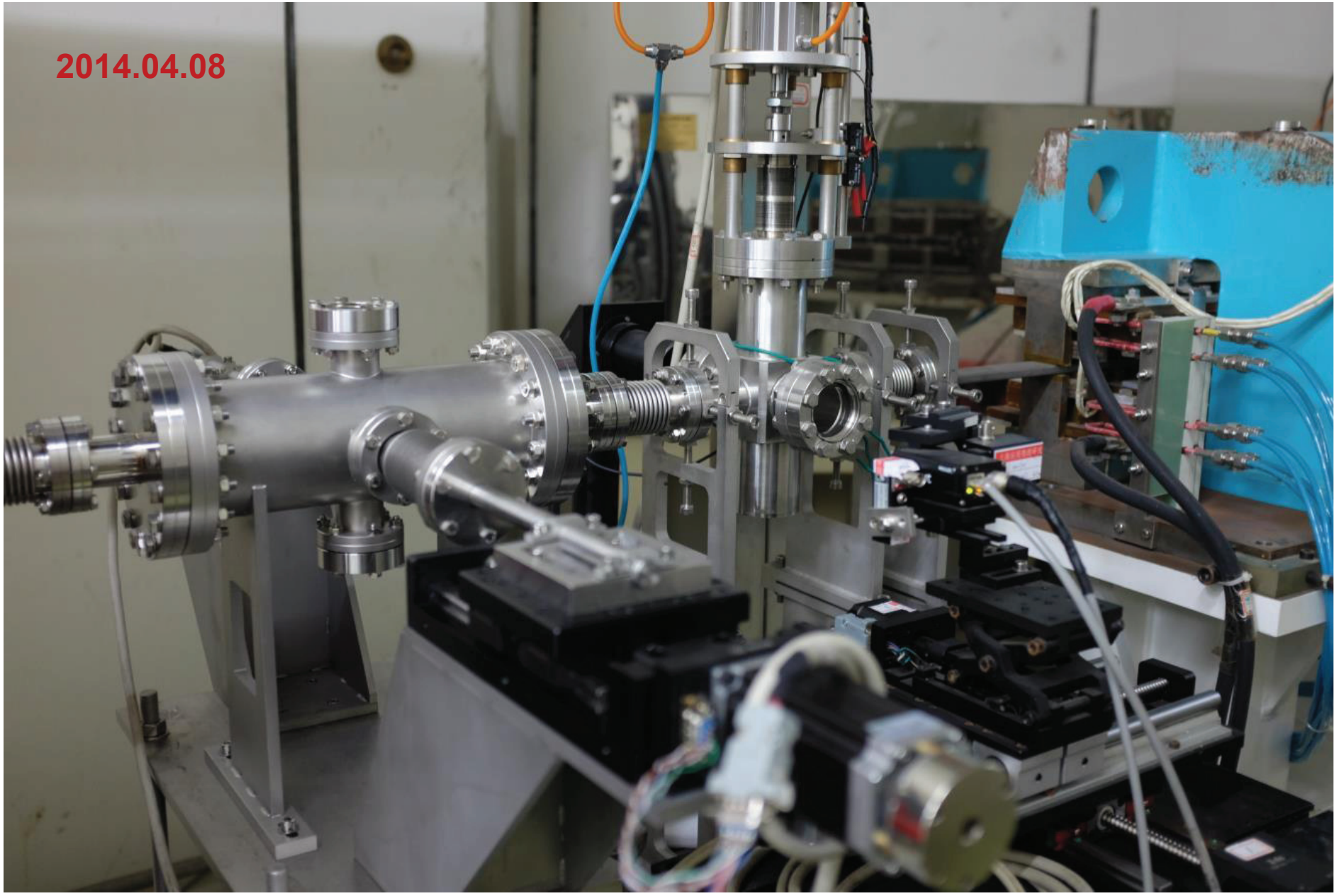
# Corrugated device assembly & alignment



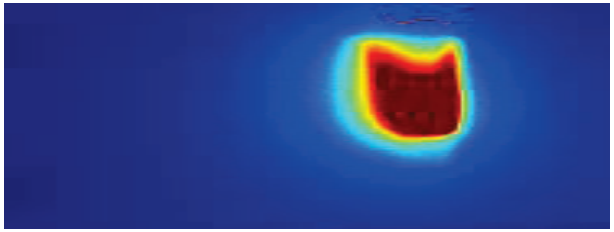



# 2. Proposal & experiment at SDUV-FEL

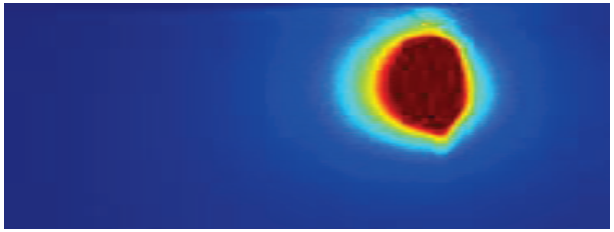


# 2. Proposal & experiment at SDUV-FEL

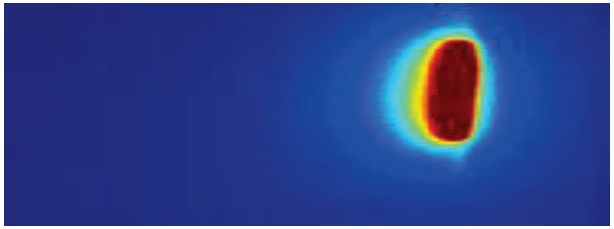
## Beam energy spread suppression measurement



a = 5.0mm

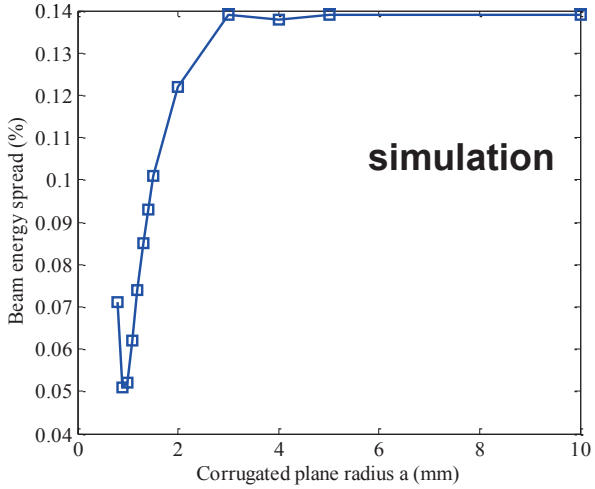


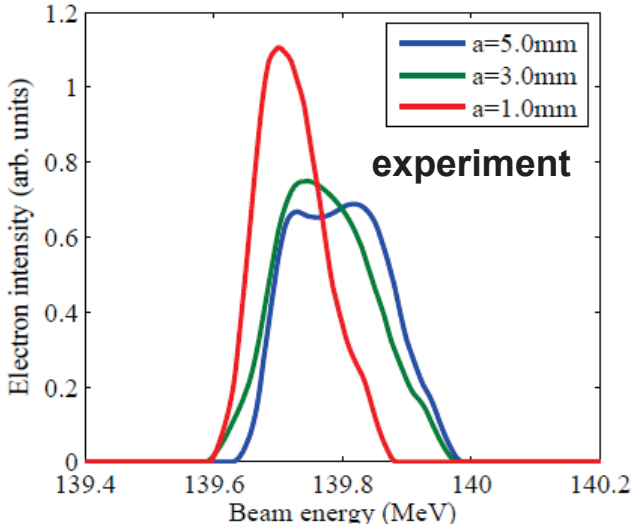
a = 3.0mm



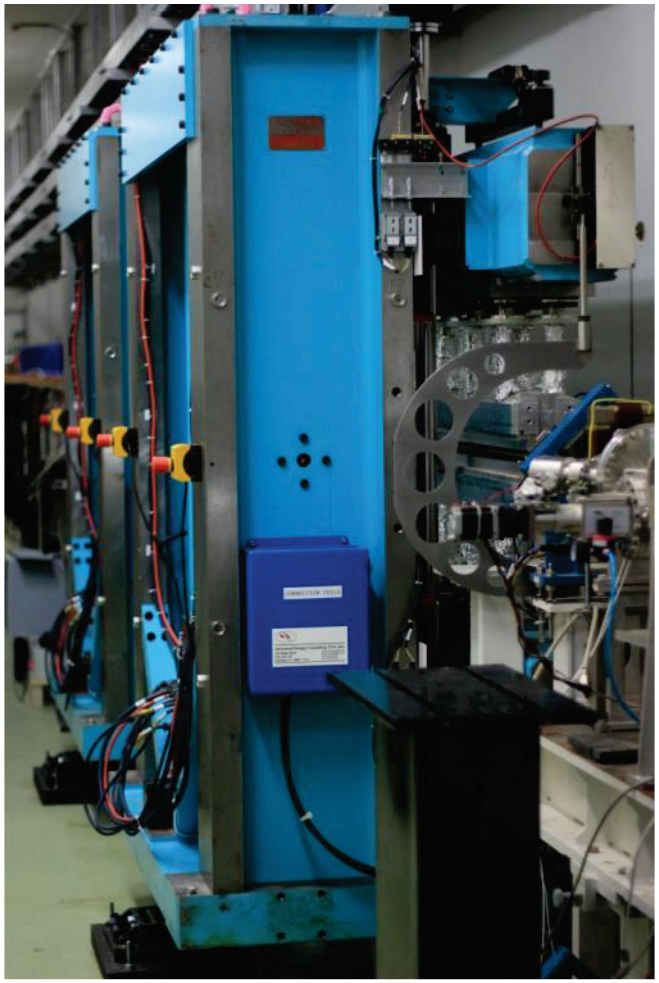
a = 1.0mm

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

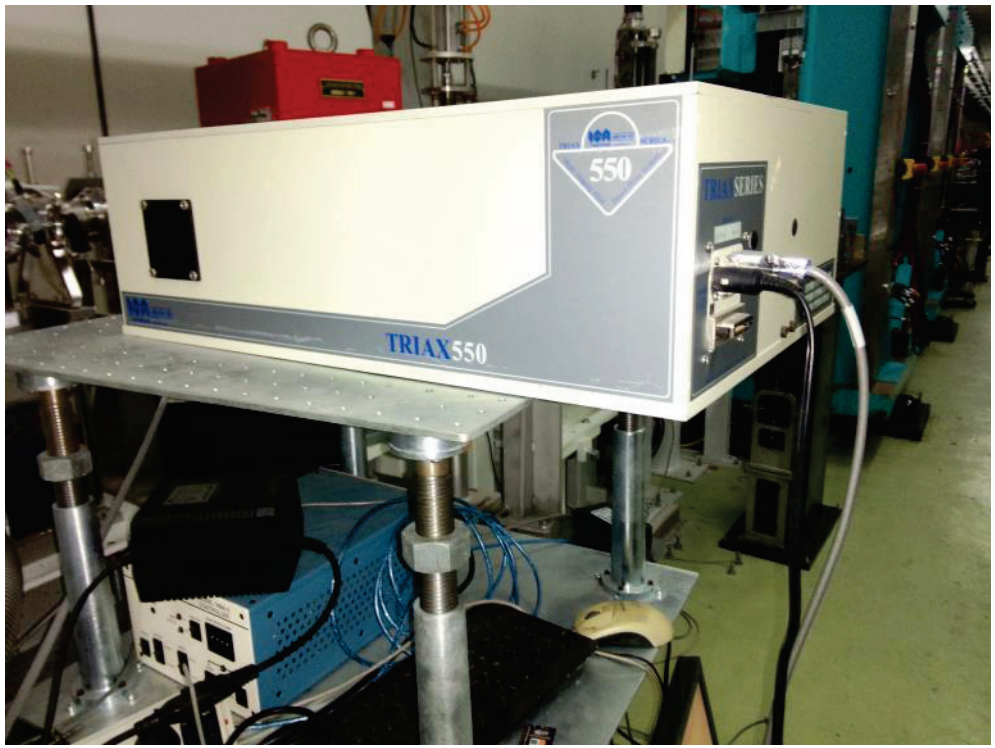


# FEL radiator undulator & spectrometer



40mm*80 periods, with variable gap



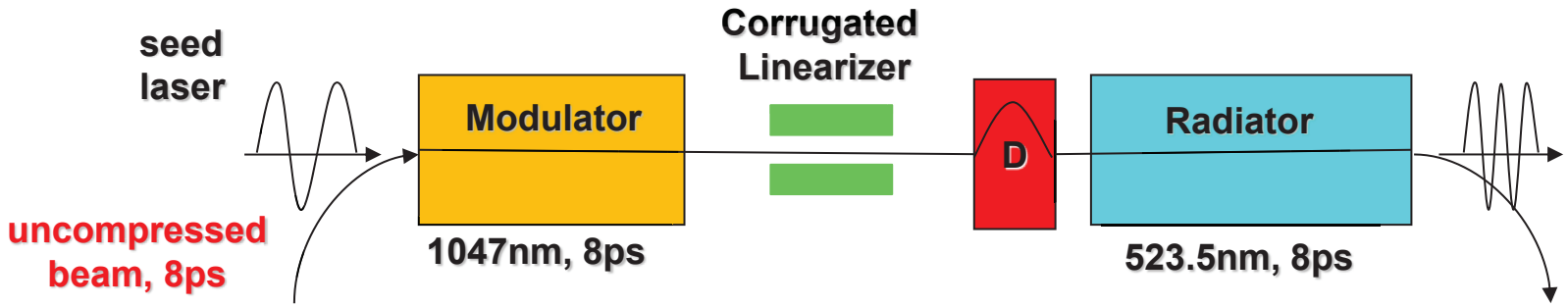

TRIAX550 spectrometer
600 line grating
2.7nm resolution @ 1mm slit (calibrated)

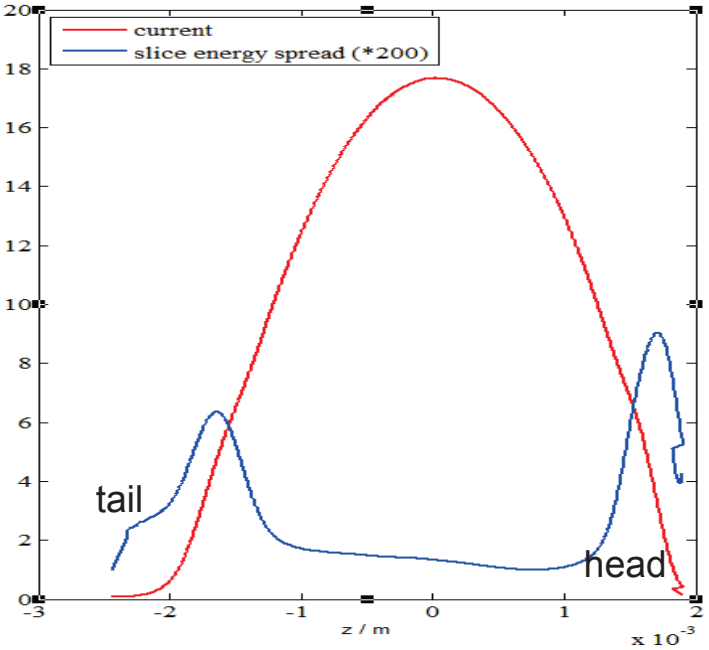
# Main experiment parameters

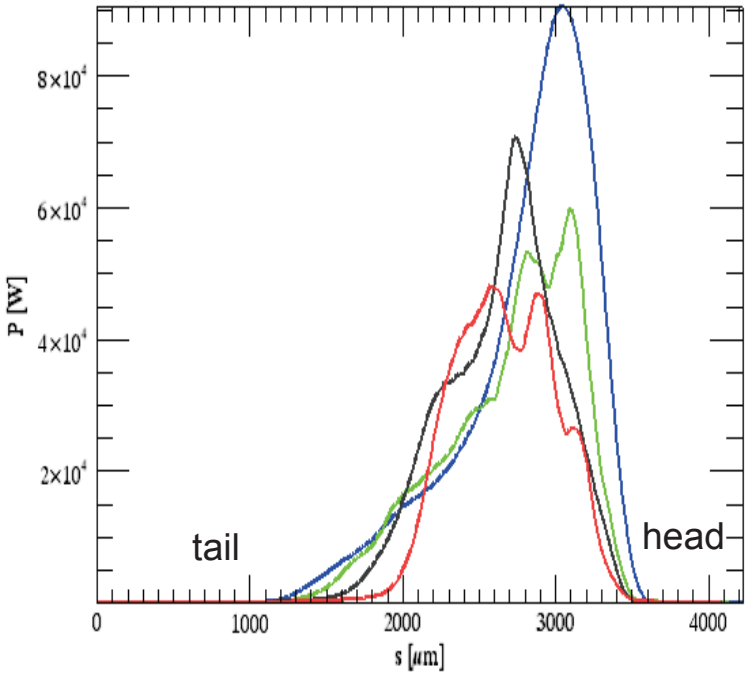
| | | | |
|---|---|---|---|
| **Electron Beam** | | | |
| Beam Energy [MeV] | ~140 | Slice Energy Spread [keV] | 1 |
| Bunch length [ps] | 8.8 | Normalized Emittance | 4~6 mm·mrad |
| Total Charge [pC] | 100 | Transverse Beam Size | ~200 μm |
| **Modulator (EMU65)** | | | |
| Period Length [m] | 0.065 | 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 |

# 2. Proposal & experiment at SDUV-FEL

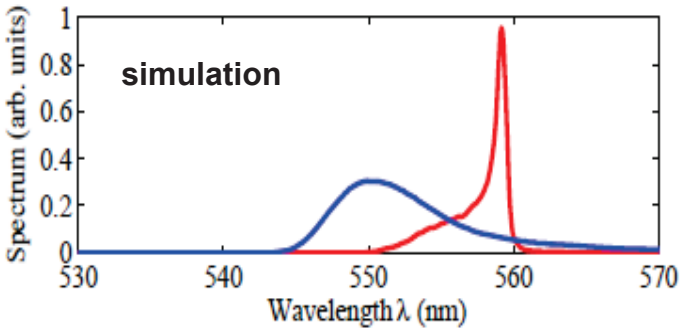
## Start-to-end simulation results



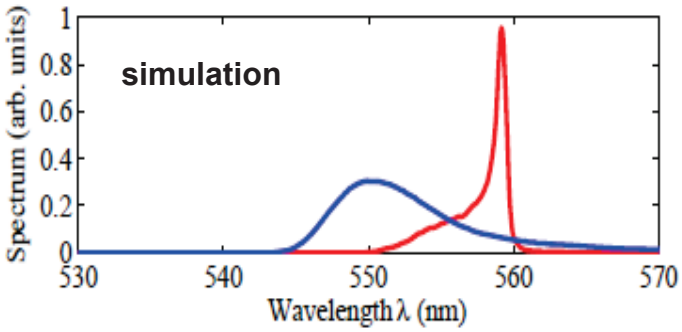



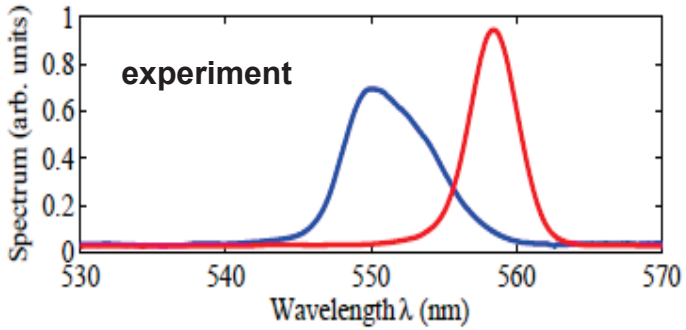
# FEL spectrum measurement




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

# FEL spectrum measurement

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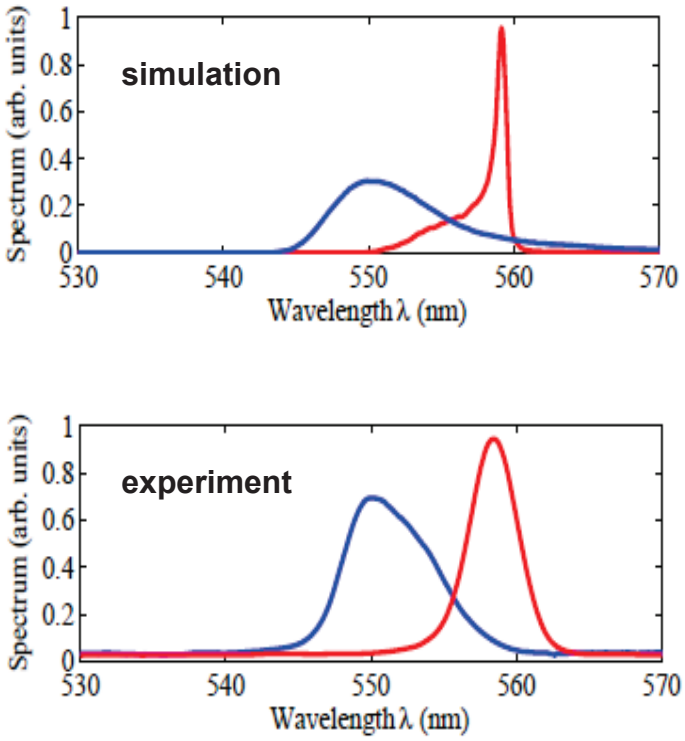
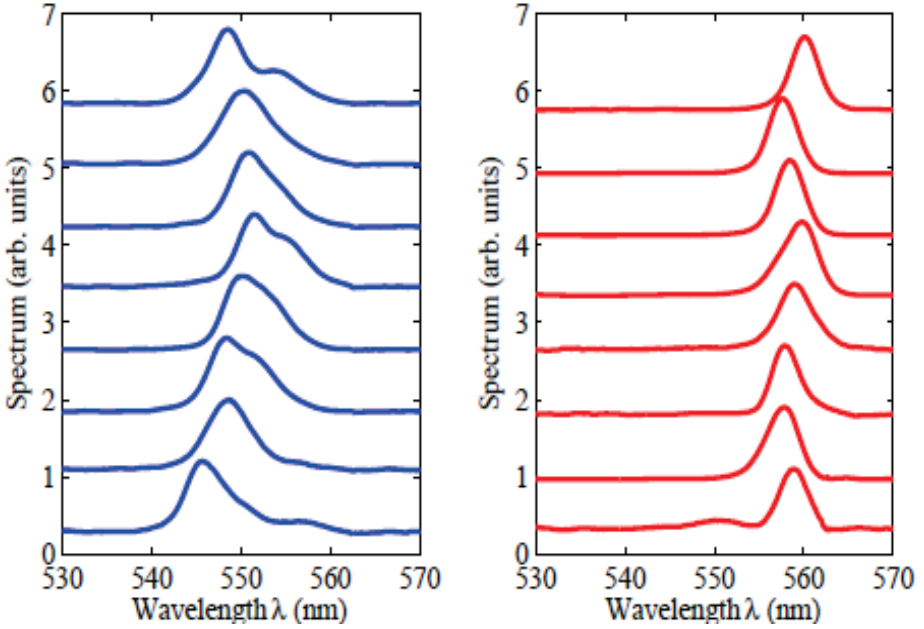
# FEL spectrum measurement




Multi-shots experiment results
$R_{56}$=6.5mm (dispersive section of HGHG)
φ3, φ4 = 25°

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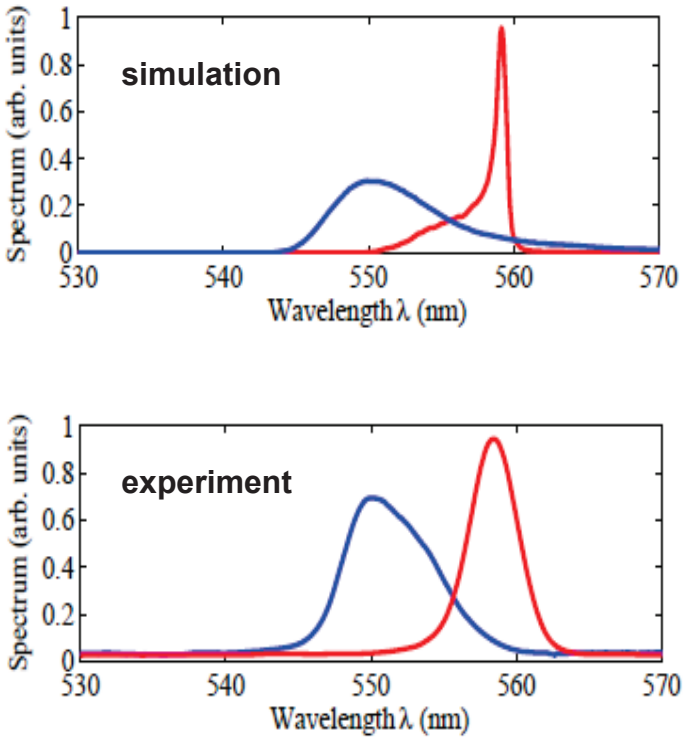
# 2. Proposal & experiment at SDUV-FEL

## FEL spectrum measurement

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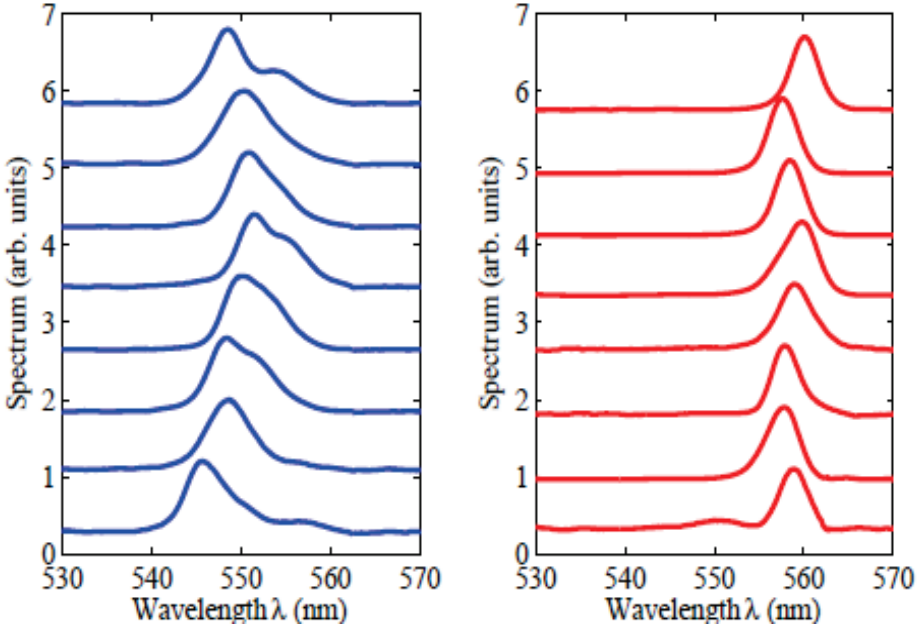


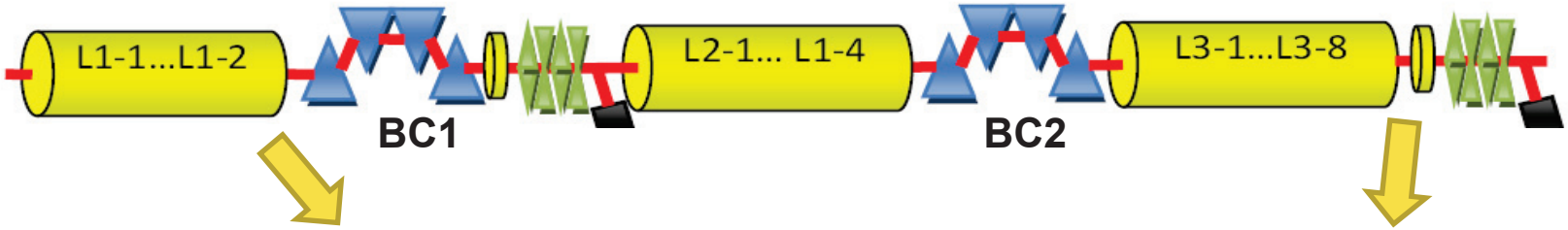

**Blue**：corrugated structure open，**Red**：corrugated structure closed (2mm separation)

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

# 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 $1.1\times10^{-3}$ to $7.5\times10^{-4}$ was observed.
- The experiment results agree well with simulations, which confirms the theory of corrugated structures for FEL improvement.

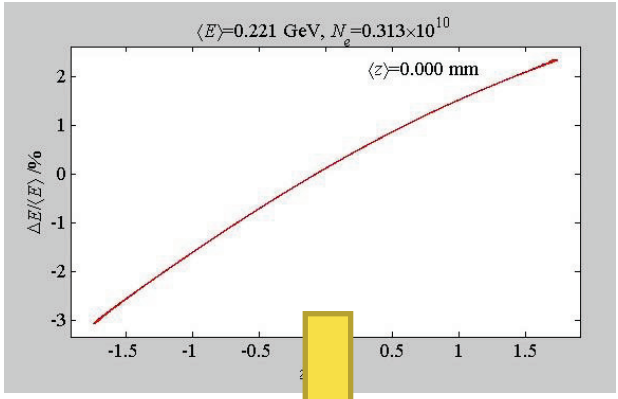
# Corrugated device beam manipulation for SXFEL

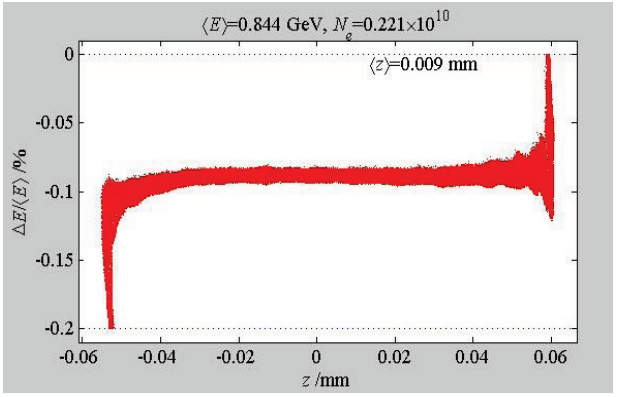


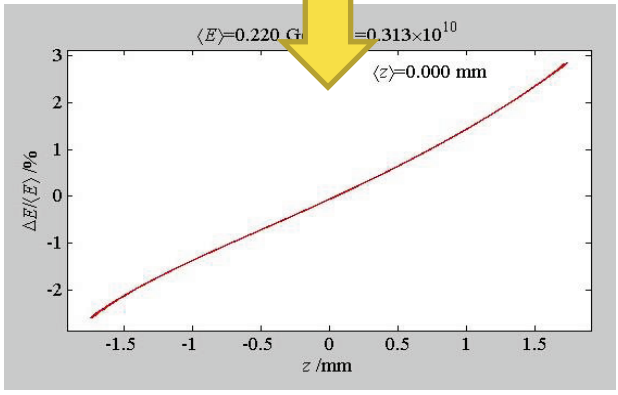

## SXFEL

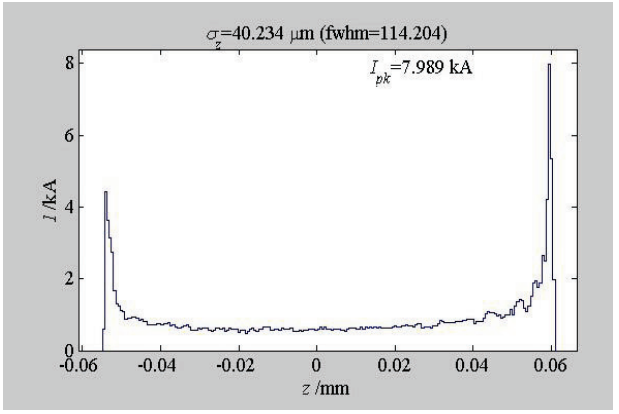
- 840MeV LINAC
- 9nm FEL
- 2-stage HGHG

- 1m corrugated device



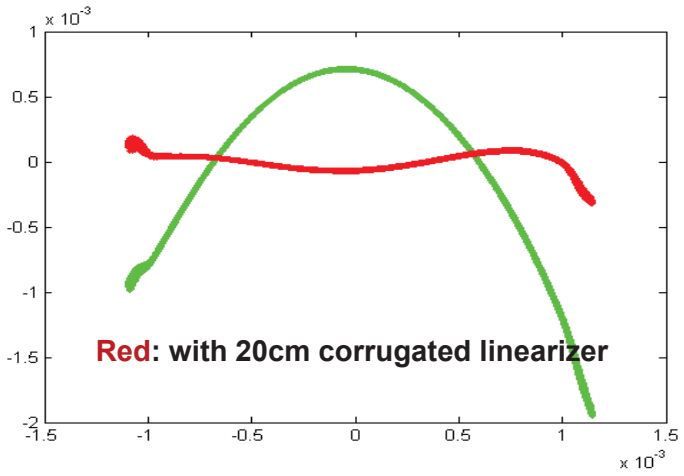
# Energy spread control in MeV UEM

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, Phys. Rev. Appl. 2, 024003 (2014).***
***D. Xiang et al., NIMA 759, 74-83 (2014).***

| 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