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A comparison study of high harmonic characterization in EEHG operation of SDUV-FEL

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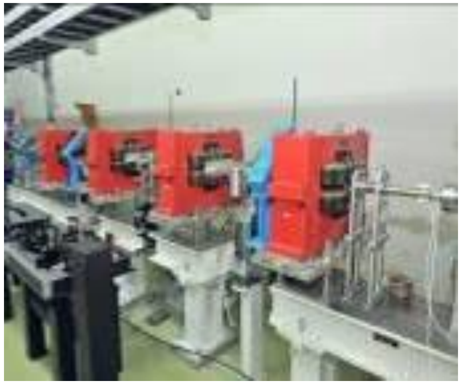
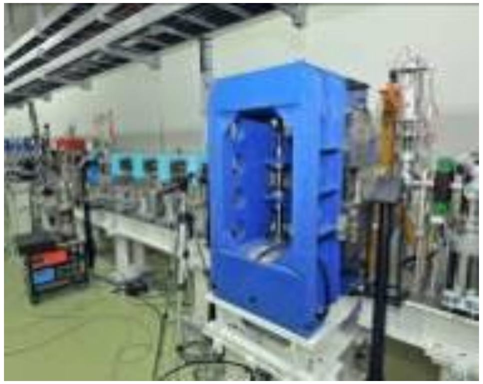
Introduction & Motivation

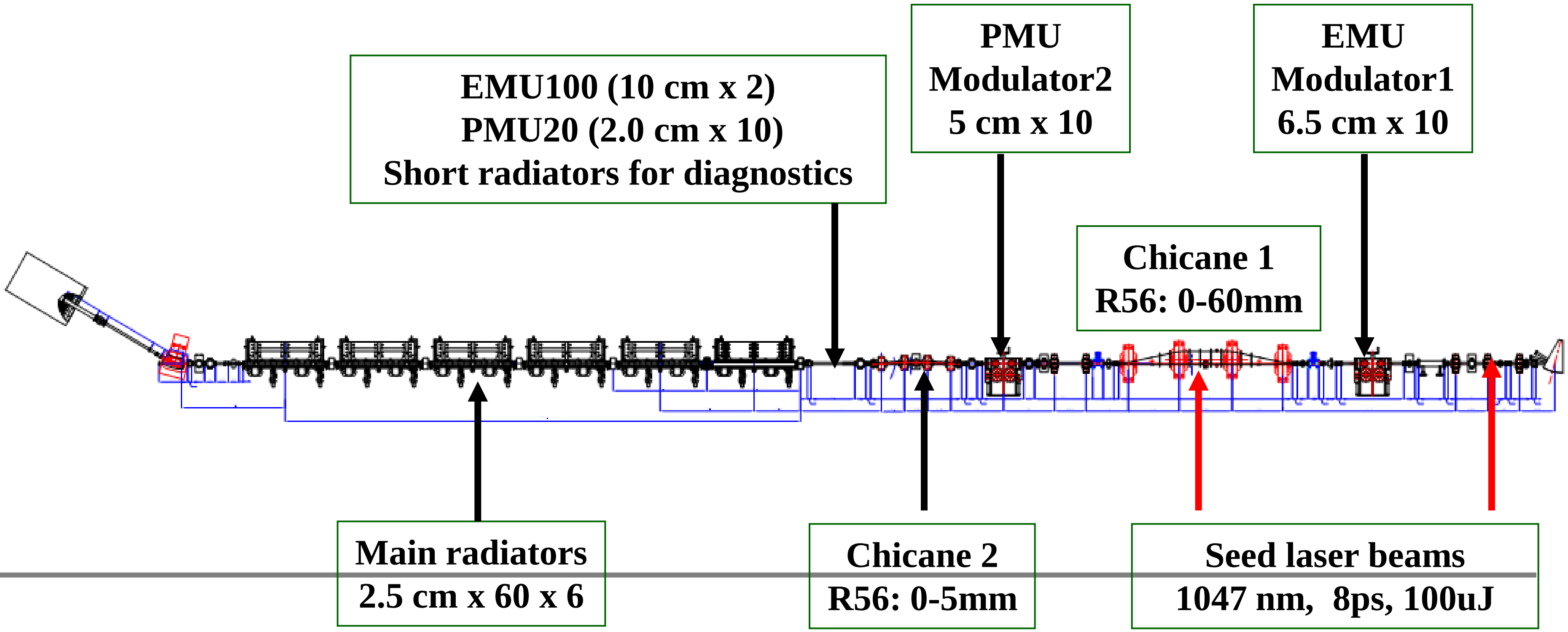
- Seeded FEL .vs. SASE
- Echo enabled harmonic generation (EEHG)
- EEHG commissioning at SINAP
- EEHG commissioning in SLAC



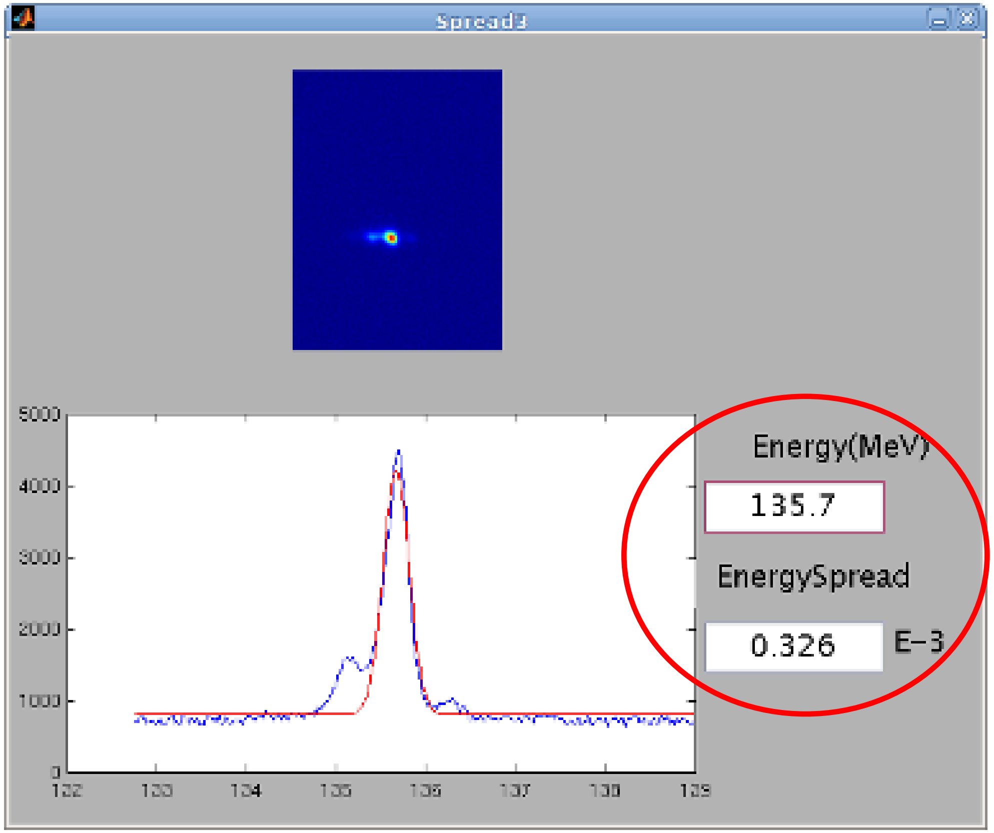


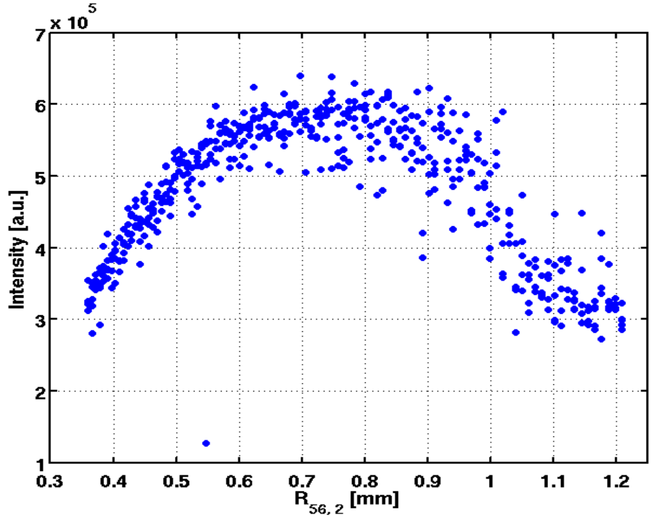

SINAP EEHG setup

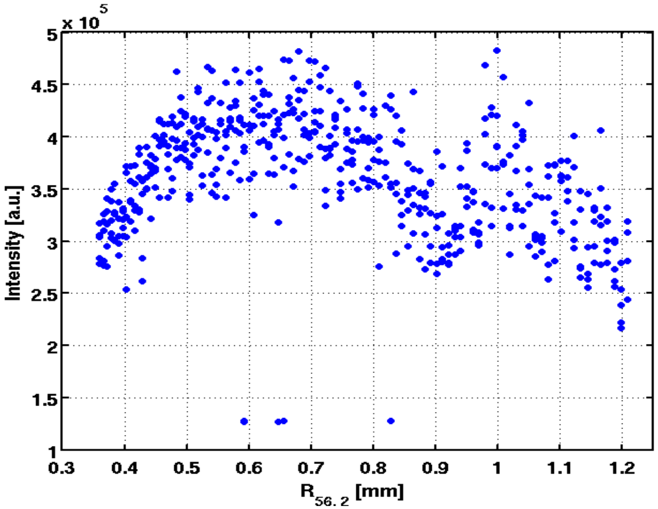
- SDUV-FEL is a test facility for seeded FEL
  - Originally designed for HGHG
  - After modifications, well suited for double-modulator FEL test



SINAP EEHG results

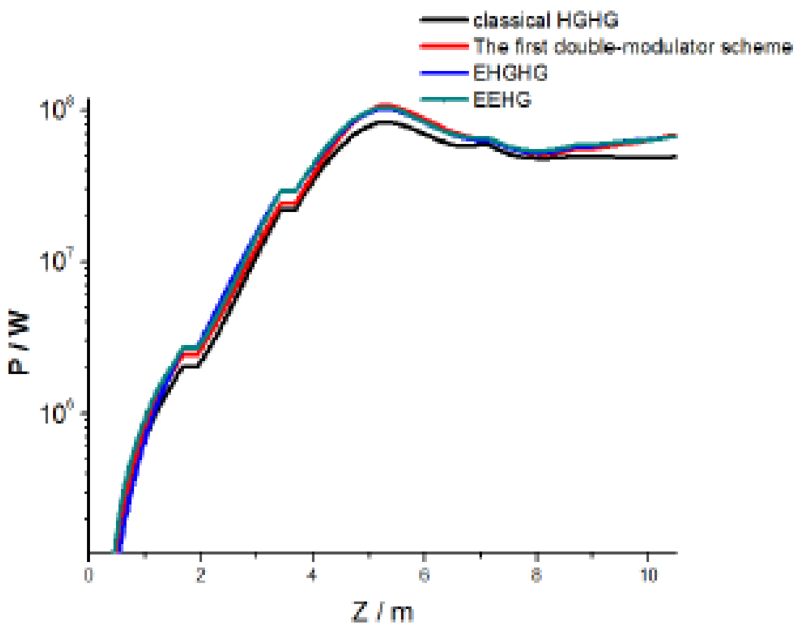




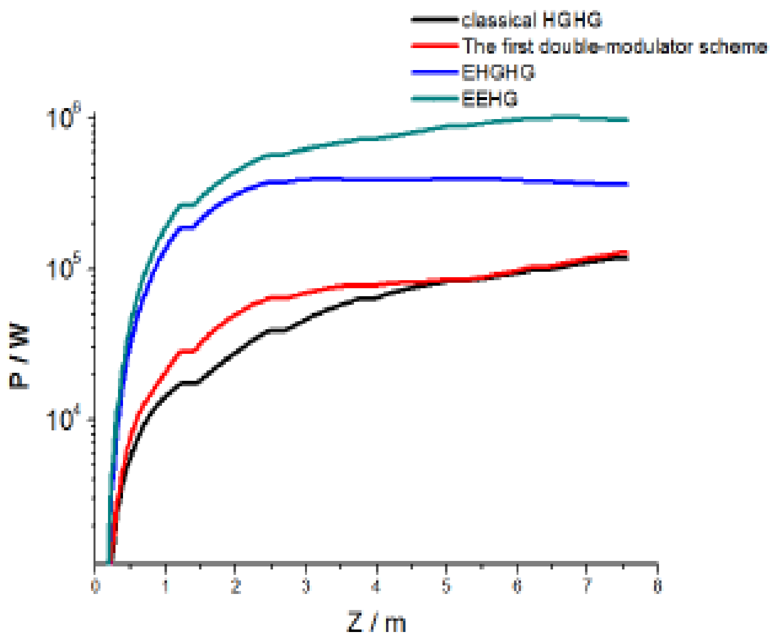


HGHG .vs. EEHG .vs. Other schemes

- EEHG observed in SINAP & SLAC are both low harmonics.
- Low harmonics, HGHG & EEHG have an even similar performance.
- High harmonics, EEHG shows its unique status. Need demonstration.



The 3rd harmonic



The 10th harmonic

Yan Jun et al., Proceedings of FEL2009, Liverpool, UK. 406~409

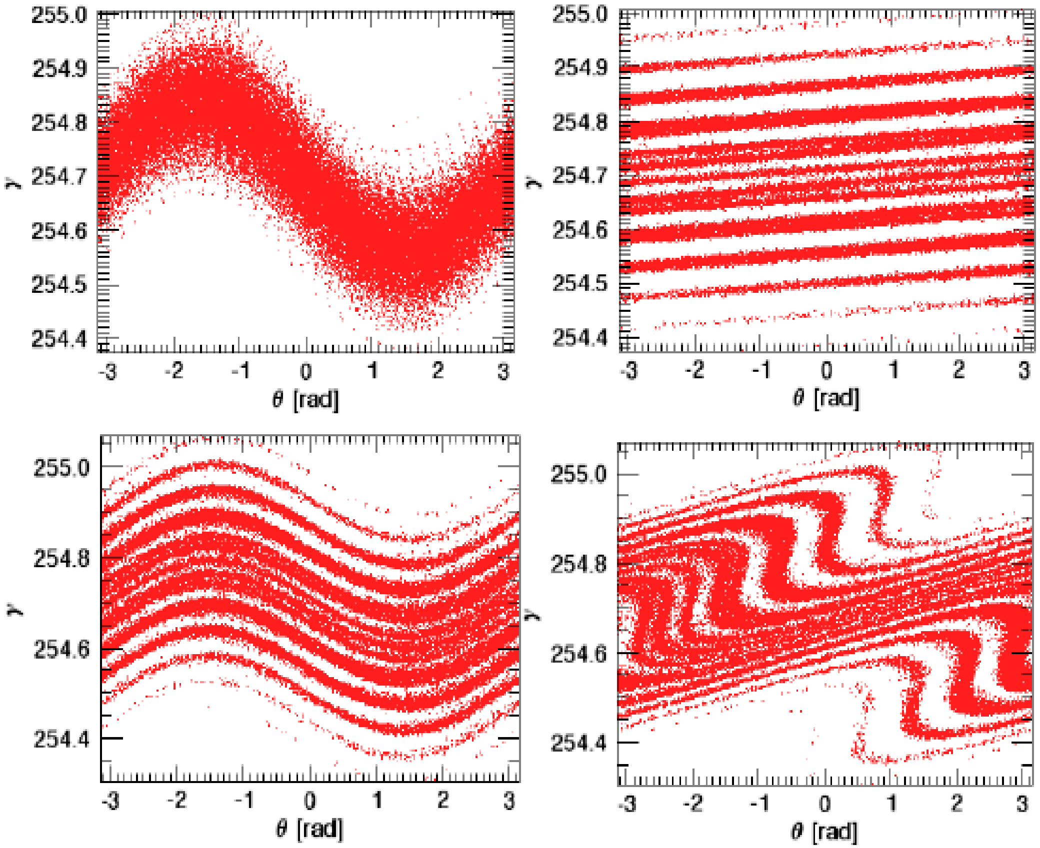
Comparison analysis of high harmonics

- **Beam parameters**
  - **135MeV, 200pC, 100A (Compressed)**
  - **200um, 10mm-mrad**
  - **30keV energy spread**

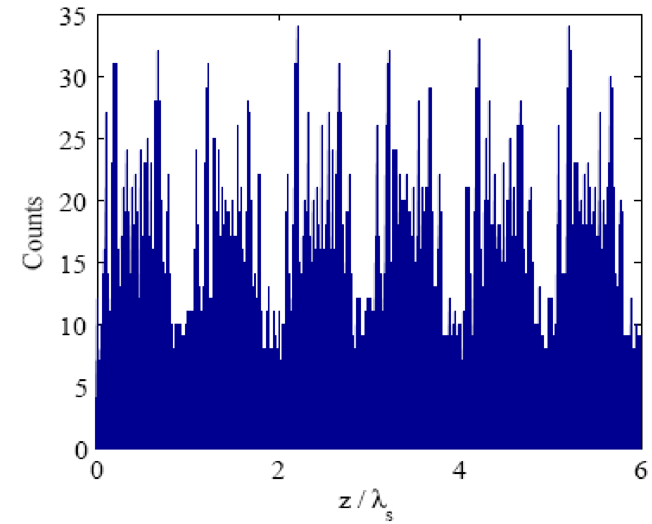
- **Chicanes**
  - **1st R56 = 5.500mm**
  - **2th R56= 0.523mm**

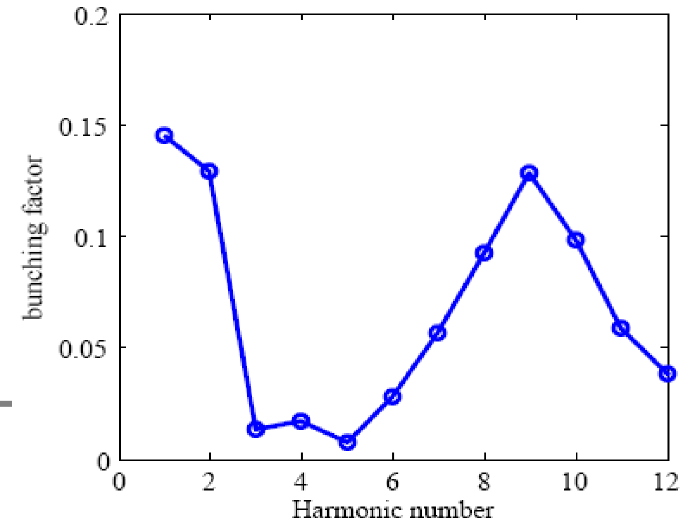
- **Main undulator**
  - **25mm period, 1.5m length per segment, K=1.4**

EEHG phase space & modulation frequency



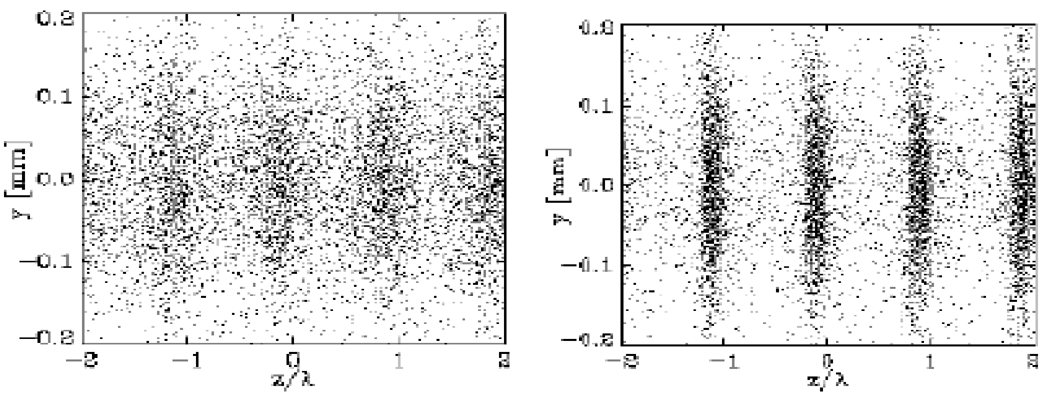
Optimized at 9th harmonic of seed laser





How to character the bunched beam

- Free Electron Laser process: further amplification to saturation
- Coherent radiations: rigid beam, fixed bunching
  - Coherent Transition Radiation (CTR)
  - Coherent Synchrotron Radiation (CSR)
  - Coherent Uudulator Radiation (CUR)



Typical FEL process

In the case of no suitable undulator

$$P(\omega) = kb^2(\omega)$$

$$b(\omega) = < e^{-iwt_j} >$$

- Aluminum foil
- Dipole
- Undulator *

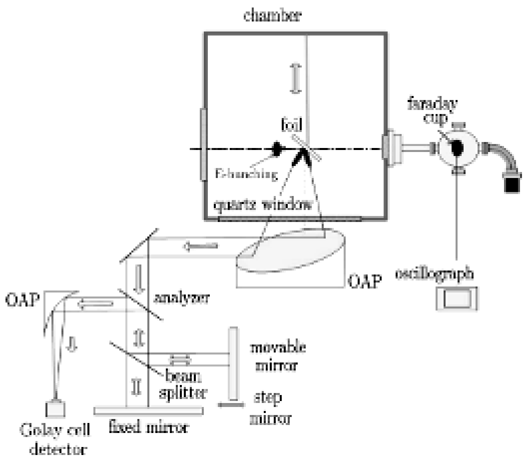
Deng haixiao, Chinese Physics C, ***34*** *(2010) 1649-1605*

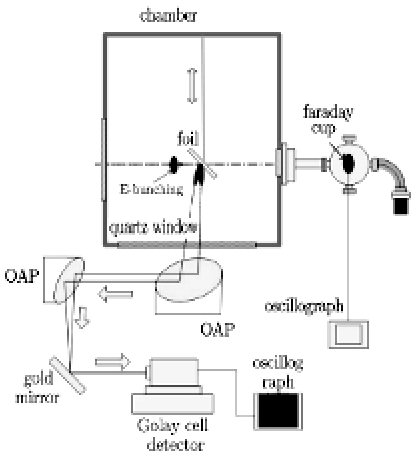
1. Coherent Transition Radiation

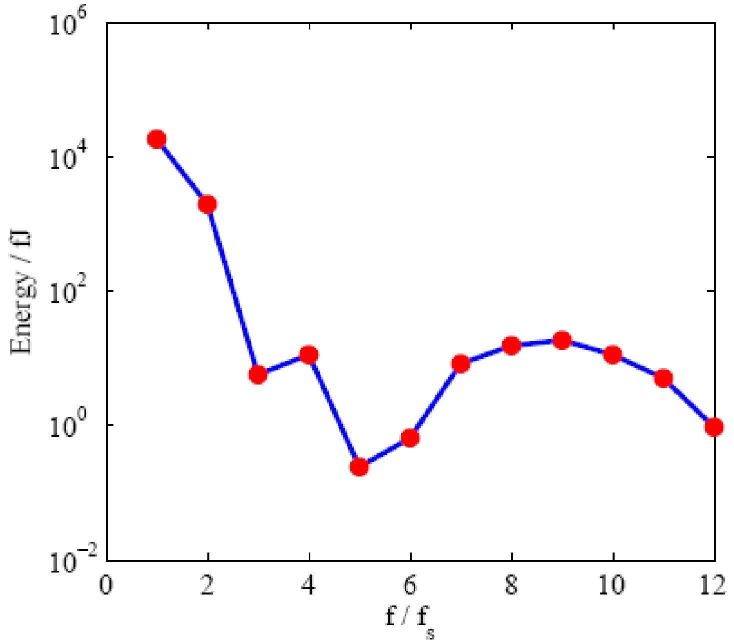
$$f(x,y,z)=\frac{N_b}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}-\frac{z^2}{2\sigma_z^2}}$$

$$\times[1+\sum_{n=1}^{\infty}b_n\sin(nk_r z)]$$

$$U_n=\frac{nhc\alpha(N_b b_n)^2}{8(\pi)^{3/2}\sigma_z}\left(\frac{\gamma}{nk_r}\right)^4\left(\frac{\sigma_x^2+\sigma_y^2}{\sigma_x^3\sigma_y^3}\right)$$







Theoretical CTR spectrum

EEHG signal from CTR: 19fJ

2. Coherent Synchrotron Radiation

Beam dynamics

$$\frac{d\gamma_j}{dt} = e\mathbf{v}_j \times \mathbf{B} \cdot \mathbf{v}_j = 0$$

$$\frac{d}{dt}\left(\frac{m v_x}{\gamma_j}\right) = e(v_y B_z - v_z B_y)$$

$$\frac{d}{dt}\left(\frac{m v_y}{\gamma_j}\right) = e(v_z B_x - v_x B_z)$$

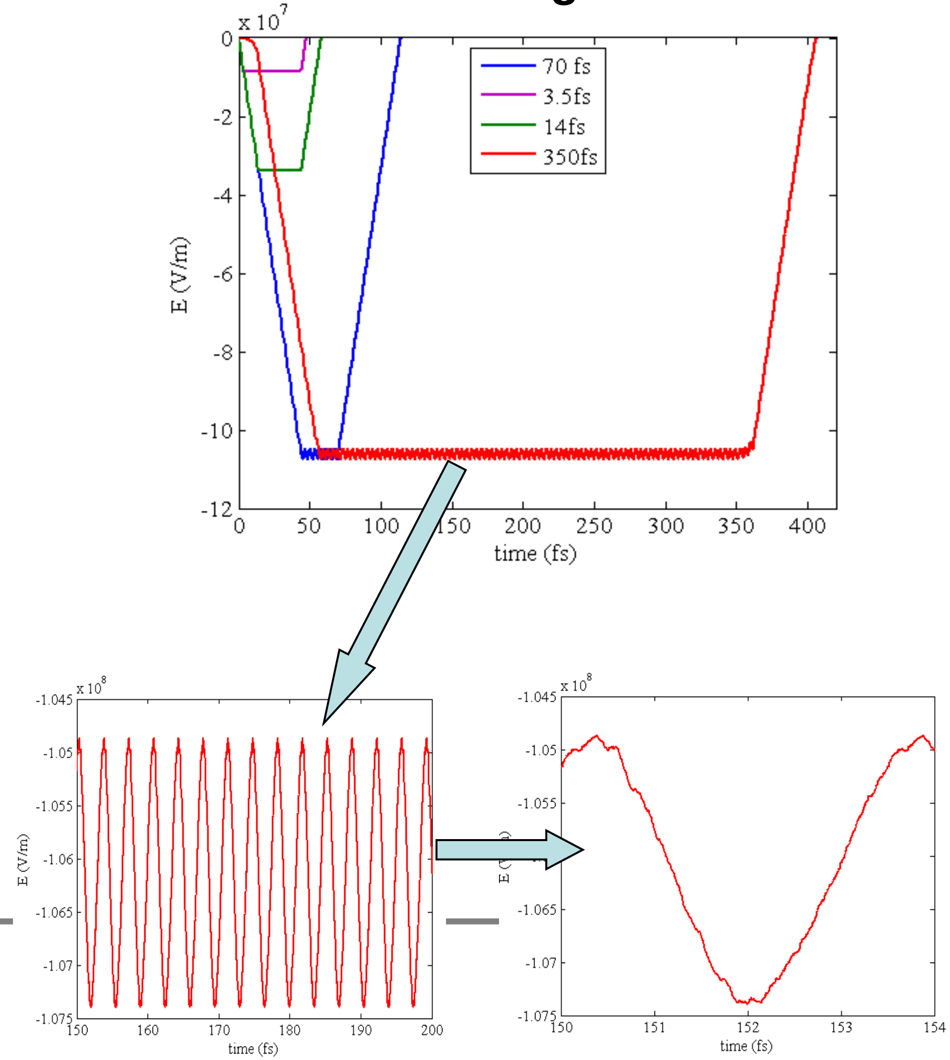
$$\frac{d}{dt}\left(\frac{m v_z}{\gamma_j}\right) = e(v_x B_y - v_y B_x)$$

CSR calculation

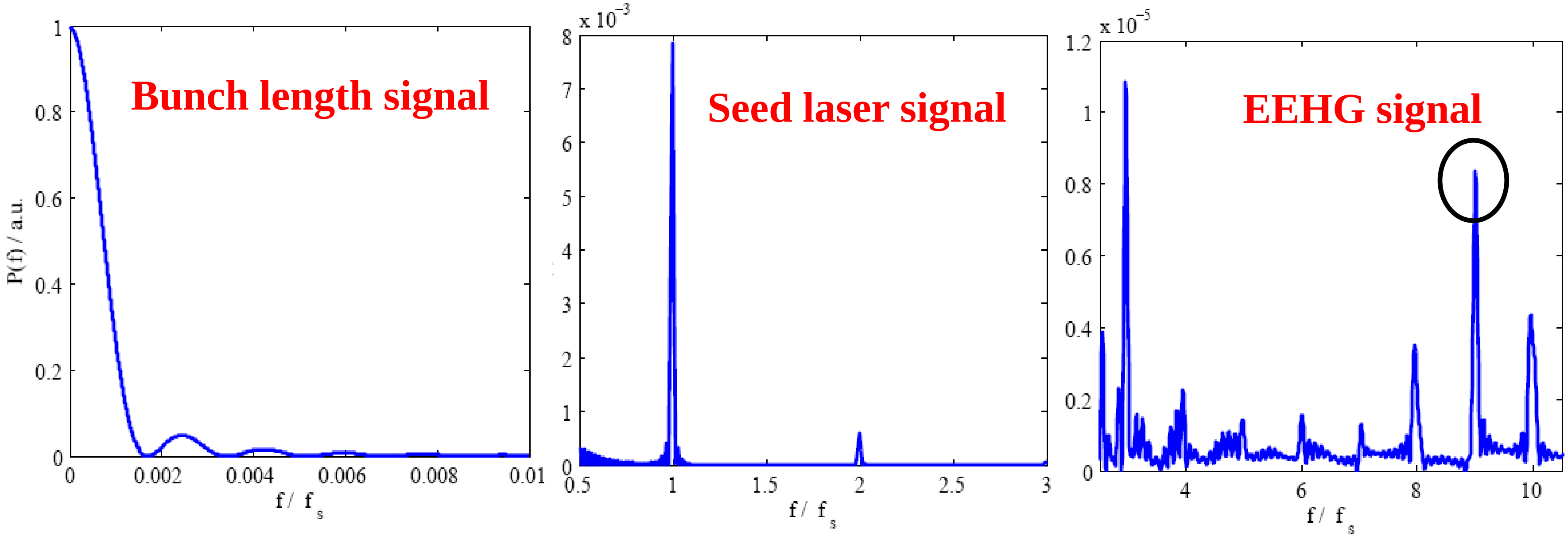
$$E_j(t') = \frac{e}{4\pi\varepsilon_0 c^2 r} \frac{\vec{n} \times [(\vec{n} - \frac{\vec{v}}{c}) \times \vec{v}']}{(1 - \frac{\vec{v} \cdot \vec{n}}{c})^3}$$

$$E(t) = \sum_j E_j(t'_j)$$

CSR signal



2. Coherent Synchrotron Radiation



Parseval's theorem

$$\int P(t)dt = \frac{1}{2\pi}\int P(\omega)d\omega$$

EEHG signal from CSR: 85pJ

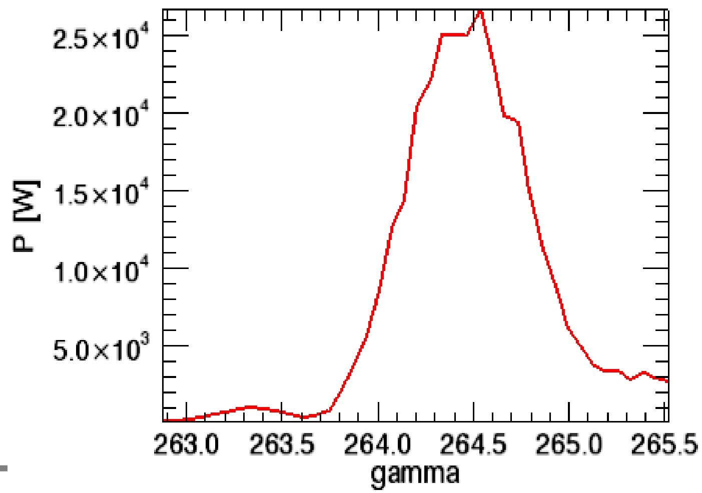
3. Coherent Undulator Radiation

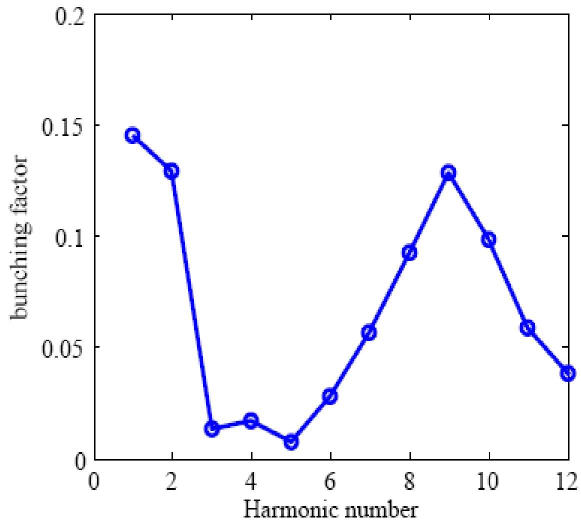
$$f(x,y,z)=\frac{N_b}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}e^{-\frac{x^2}{2\sigma_x{}^2}-\frac{y^2}{2\sigma_y{}^2}-\frac{z^2}{2\sigma_z{}^2}}\times[1+\sum_{n=1}^{\infty}b_n\sin(nk_r z)]$$

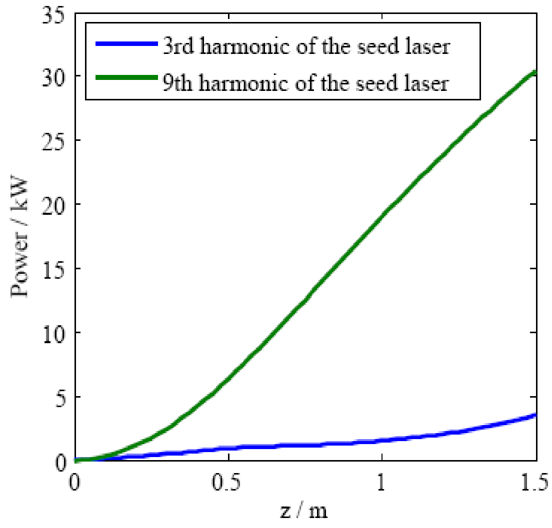
$$\frac{\partial}{\partial z}E_m(z)=\frac{eK[JJ]_m}{4\gamma m_0 c^2}b_m(z)$$

$$U_m=\frac{Z_0(IKb_m[JJ]_m l)^2\sigma_z}{5\pi(\sigma_x{}^2+\sigma_y{}^2)\gamma^2 c}$$

EEHG bunches beam at 9th harmonic of seed
Radiator is resonant at the 3rd harmonic of seed







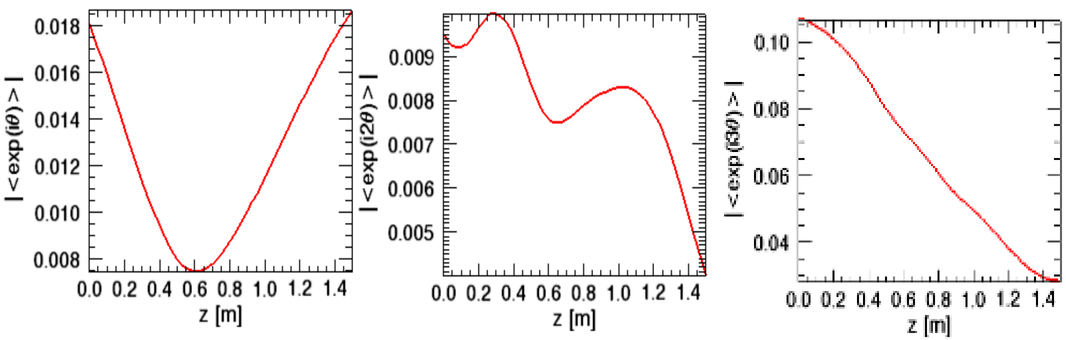
EEHG signal from CUR: 64nJ

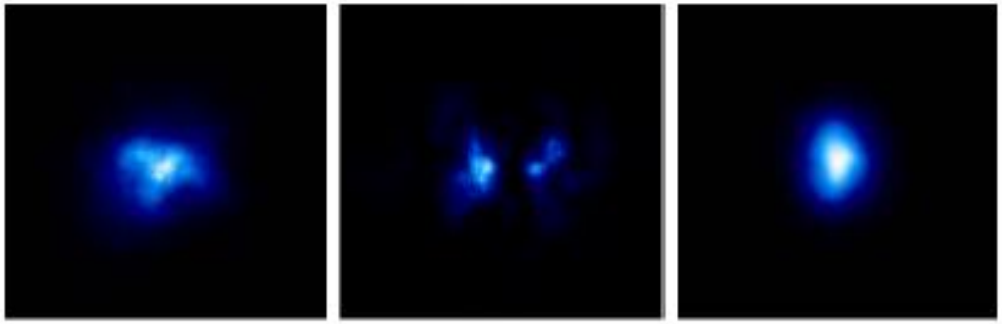
3. Coherent Undulator Radiation

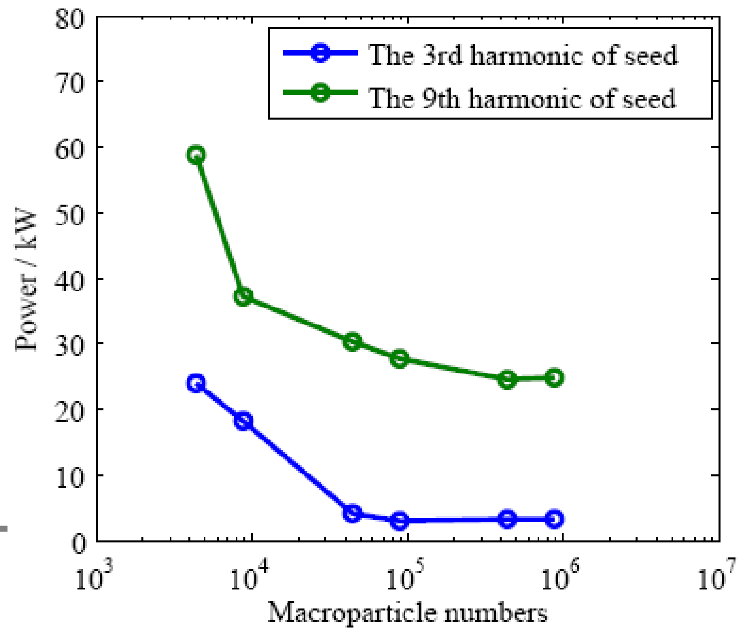
	The 3rd harmonic	The 9th harmonic
Theory	9 nJ	120 nJ
Simulation	8 nJ	64 nJ

Possible Reasons for difference

- bunching variation
- Transverse effects
- Numerical errors





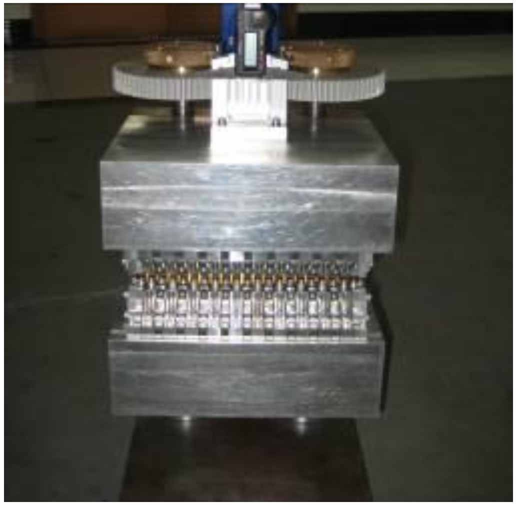


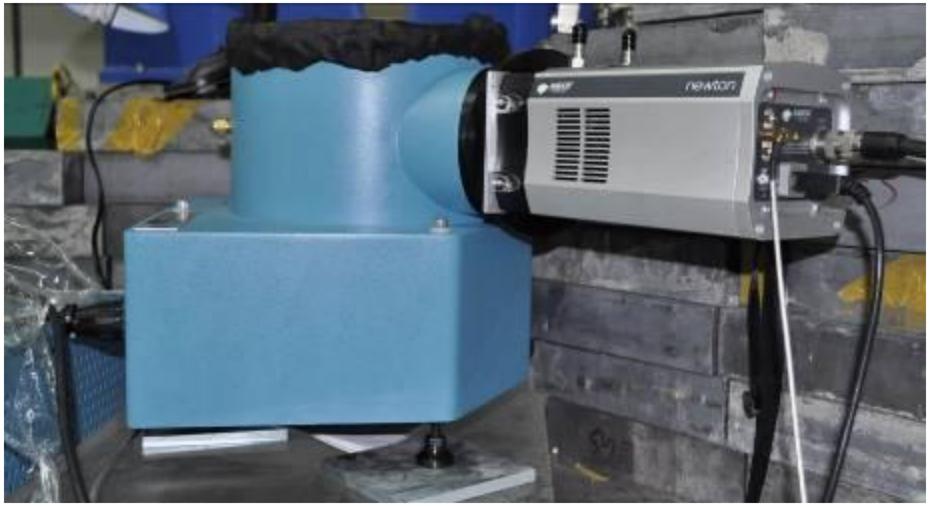
A short comparison

	Radiation source	EEHG wavelength	EEHG energy	Noises region	Noise energy	SNR
CTR	Aluminum foil	VUV 116.3 nm	~ 19fJ	THz IR	~ 100uJ ~ 20pJ	$\times 10^{-10}$ $\times 10^{-3}$
CSR	Dipole in Chicanes	VUV 116.3 nm	~ 85pJ	THz IR	~ 10uJ ~ 80nJ	$\times 10^{-7}$ $\times 10^{-3}$
CUR	SDUV radiator	VUV 116.3 nm	~ 64nJ	UV~VIS SE	~ 8nJ ~ 5nJ	$\times 10^{+1}$ $\times 10^{+1}$
FEL	A suitable undulator	VUV 116.3 nm	~ 48uJ	SE	~ 35nJ	$\times 10^{+3}$

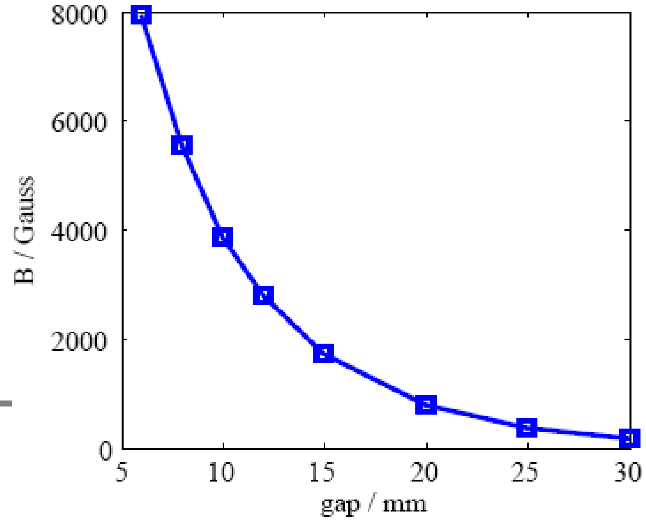
**   CTR, SE & FEL results are from brief theoretical estimation*
*** CSR & CUR results are from simulations*
**** First approximation, and transport efficiency of different radiation not included*

Proposed Measurement & Status

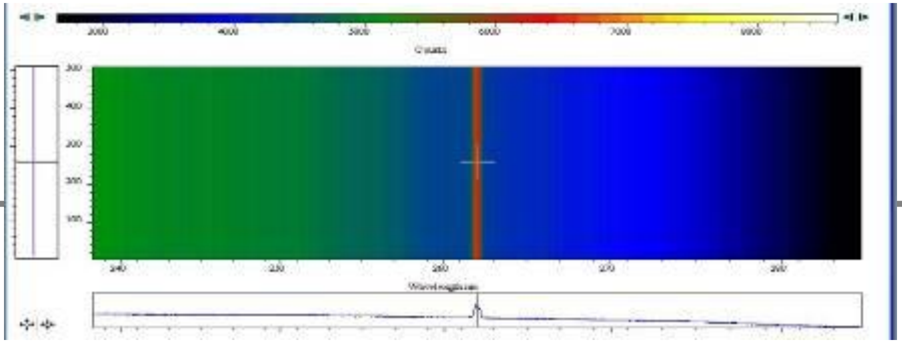




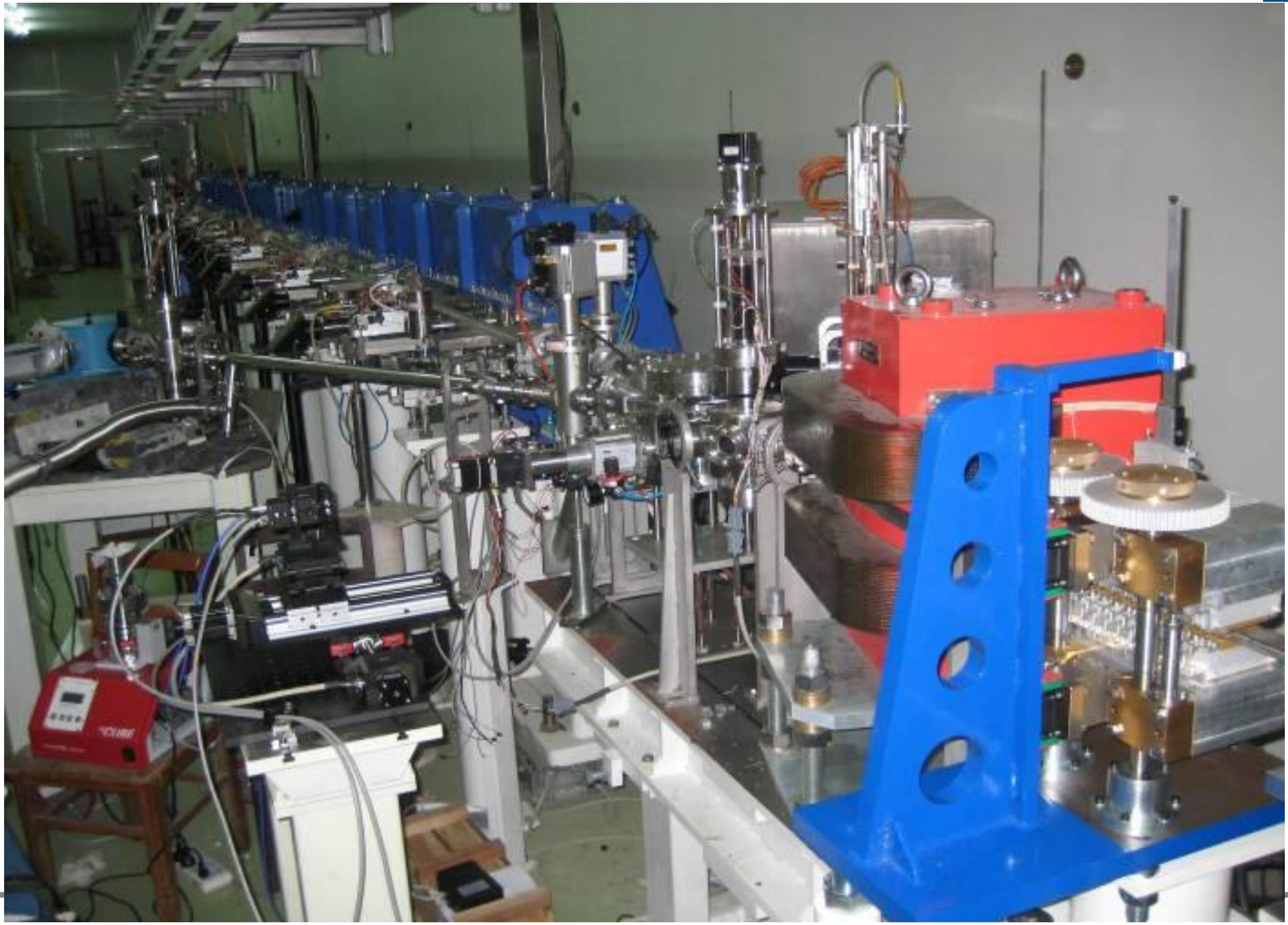
VUV spectrometer（30-300nm）



PMU20 magnetic field measurement



Proposed Measurement & Status



Summary

- **EEHG test has been carried out in SDUV-FEL at SINAP. So far, the experimental results agree well with theoretical predictions.**
- **Higher harmonic microbunching measurement with EEHG technique is of great interest and under way in SDUV-FEL.**
- **In comparison with the CTR & the CSR-based method, the CUR shows extremely strong radiation energy and high SNR, which is very helpful in improving the resolution and sensitivity of the diagnoses.**

Acknowledgement:

- Z. T. Zhao, Z. M. Dai, D. Wang, Q. Gu, B. Liu, G. Q. Lin, D. G. Li
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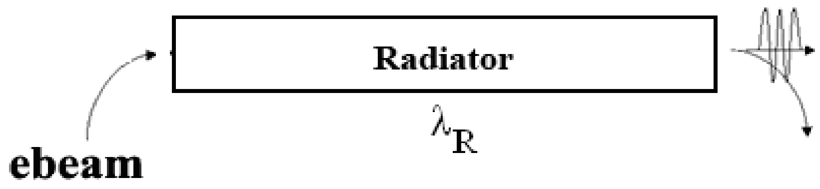
- Q. K. Jia from USTC, W. X. Liu from Tsinghua University


Thank you for your attention
谢谢！

How for the 10th, 11th, 13th harmonic etc?



- Since the radiator is the 3rd, 4th or 5th harmonic of the seed laser, here we can only characterize the 9th, 12th and 15th harmonic of the seed laser?
- No, it is not the story.
- EEHG bunches electron beam on arbitrary harmonic of the seed laser, and just adjust the radiator resonant frequency to 1/3 or 1/5 of the interested harmonic.
  - Harmonic operation technique *
  - Suppression of the fundamental of the radiator radiation
  - A case: the 1st harmonic of the radiator is 11/3-th harmonic of the seed laser, then, the 3rd harmonic of the radiator is the 11th harmonic of the seed laser.

** Deng haixiao et al., FEL proceeding of 2008, Geyongju, Korea*