Generating Intense Fully Coherent Soft X-Ray Radiation Based on a Laser-Plasma Accelerator

Chao Feng, H. X. Deng, D. Wang, Z.T. Zhao

Shanghai Institute of Applied Physics

D. Xiang

Shanghai Jiao Tong University

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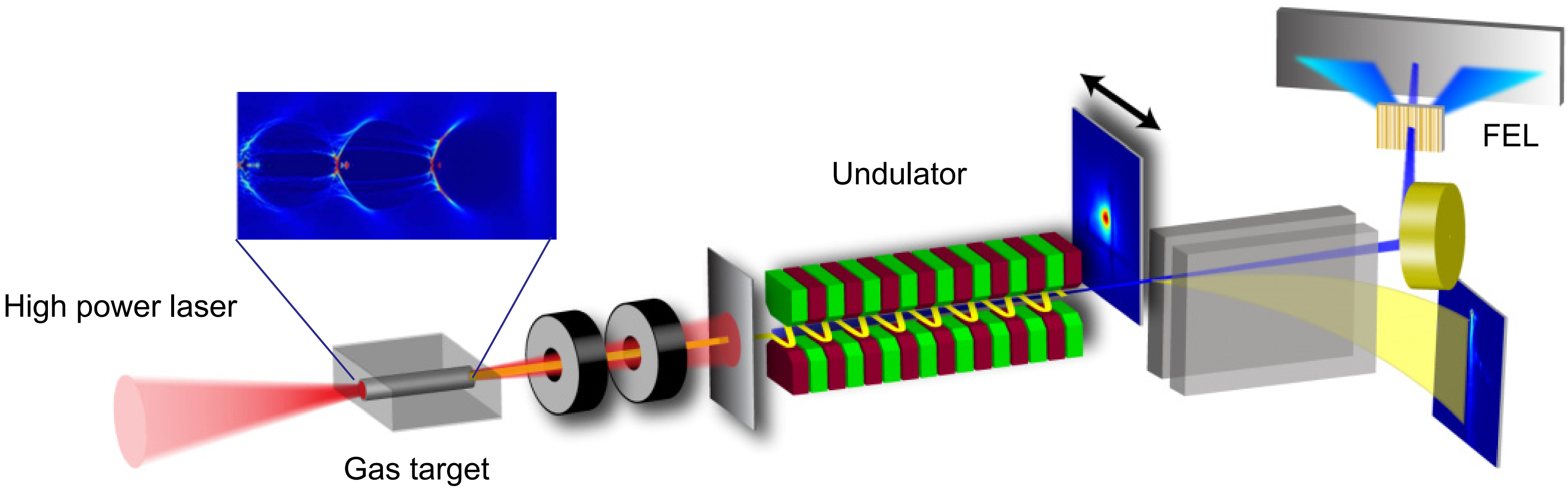
Outline

- ☞ LPA based FEL and problems
- ☞ CHG with angular modulation
- ☞ Inducing angular modulation with a normal seed laser pulse
- ☞ Performance of the proposed method
- ☞ Conclusions and prospects

LPA based FEL and problems



Electron beam from LPA	
Beam energy	~GeV
Peak current	~10 kA
Transverse emittance	<0.1 μm
Energy spread	~1%

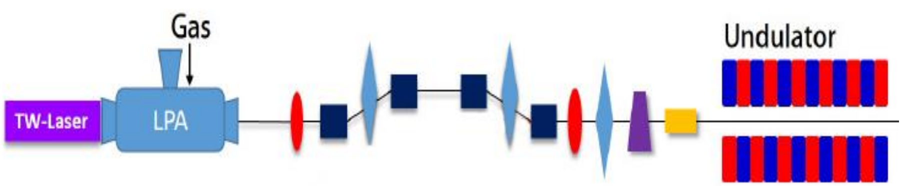
The beam energy spread is much larger than the Pierce parameter of an X-ray FEL

➢ *S. M. Hooker, Nature Photonics 7, 775–782 (2013).*

Beam manipulation for gain length reduction

The optimized gain length reduction for longitudinal dispersion and transverse dispersion $L_{g,\min}/L_{g0} = (4/3^{3/4})\Delta^{1/2}$.

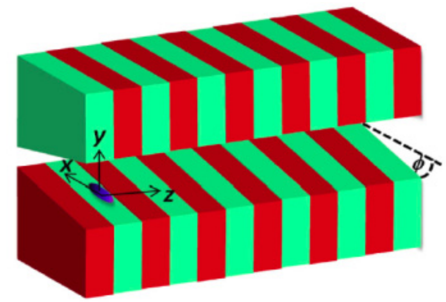
Decompression (longitudinal dispersion)



Advantage:
1. Simple scheme
2. Good transverse coherence

disadvantage:
1. Increase pulse duration
2. Reduce temporal coherence

TGU (transverse dispersion)



Advantage:
1. Short pulse length
2. Good longitudinal coherence
3. Stable central wavelength
4. Direct seeding or self-seeding

Potential disadvantage:
1. Loss of transverse coherence

- *A. R. Maier, et al., Phys. Rev. X.2, 031019 (2012).*
- *Z. Huang, Y. Ding, and C.B. Schroeder, PRL 109, 204801 (2012).*
- *C.B. Schroeder, et al., Proceedings of FEL2013, New York, NY, USA*

An alternative method: CHG with angular modulation

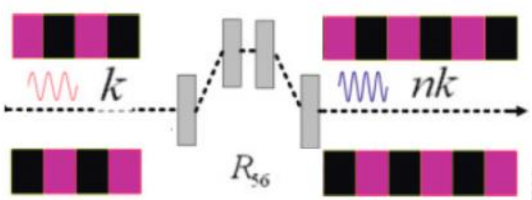
The output power of coherent harmonic radiation (CHG) is insensitive to the beam energy spread:

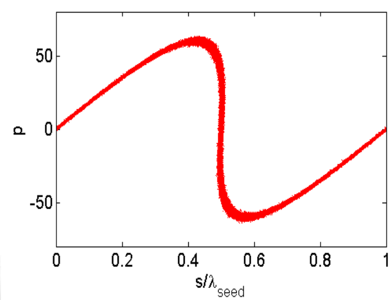
$$P_{CHG} \approx \frac{(Z_0 K[JJ] L_r I b_n)^2}{32\pi\sigma^2\gamma^2}$$

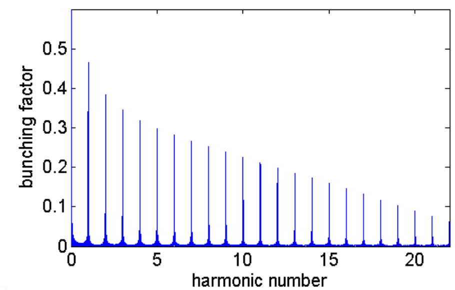
Radiator length is very short ~2 gain lengths.

Initial nth harmonic bunching factor

Energy modulation

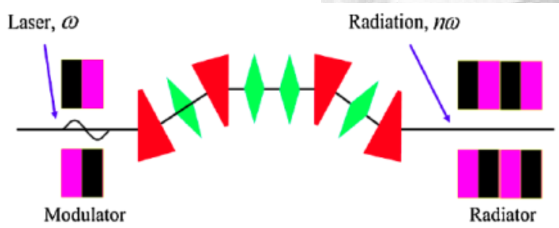


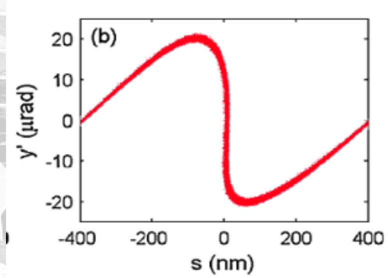


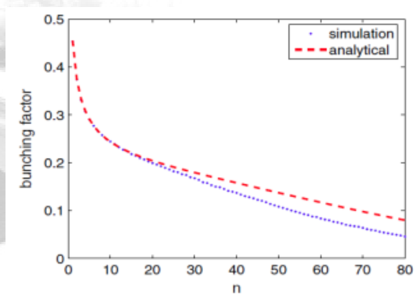


Angular modulation

Seed laser operating in the TEM01 mode



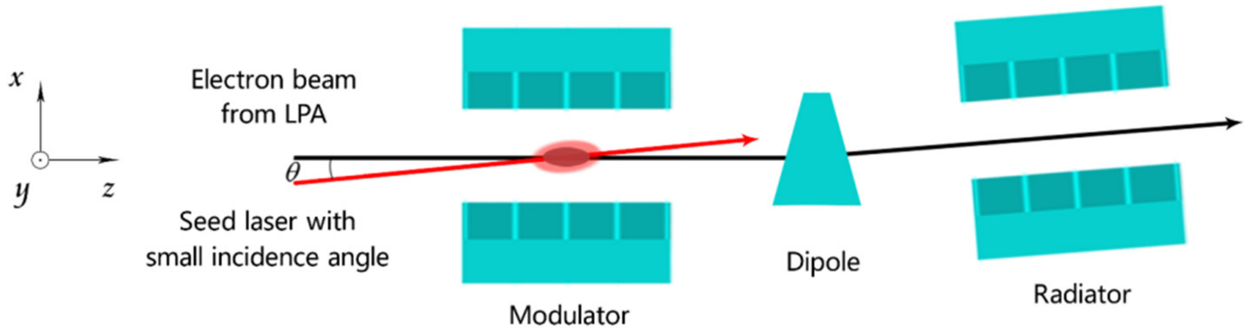




- Very high peak power of the seed laser is needed (~TW)
- May not suitable for UV seed lasers

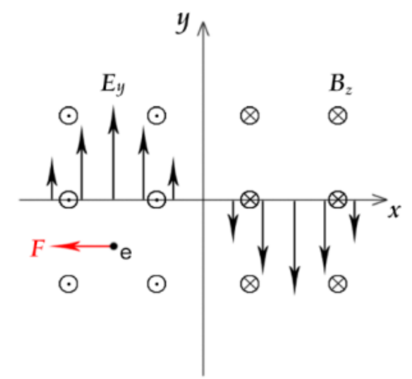
- L.H. Yu, Phys. Rev. A 44, 5178-5193 (1991).
- D. Xiang, and W. Wan, Phys. Rev. Lett. 104, 084803 (2010).

Inducing angular modulation with a normal seed laser pulse



$$E_y = E_0 \sin(\omega t + k_z z + k_x x + \varphi),\ E_x = E_z = 0,$$

$$\Rightarrow \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},\ B_x = -\frac{E_y \cos\theta}{c},\ B_z = \frac{E_y \sin\theta}{c},$$



For a small incidence angle θ

Energy modulation amplitude

$$\frac{\Delta\gamma}{\gamma} = \frac{e}{\gamma m c^2}\int_0^{L_m/c} E_y \cdot v_y dt,$$

Angular modulation amplitude

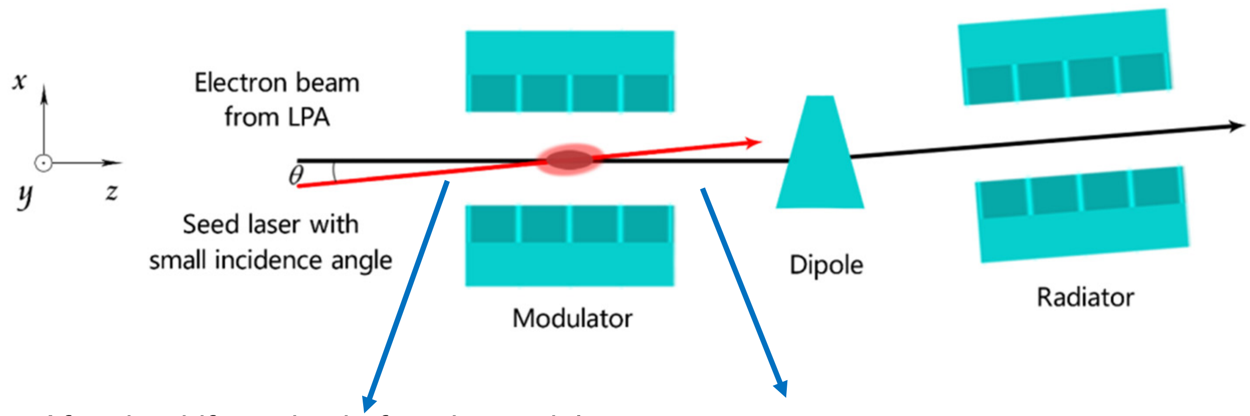
$$\Delta x' \approx \frac{1}{c}\int_0^{L_m/c} \frac{e}{m\gamma} B_z \cdot v_y dt \approx \frac{\tau e}{\gamma m c^2}\int_0^{L_m/c} E_y \cdot v_y dt,$$

$$\Delta x' \approx \tau \frac{\Delta\gamma}{\gamma},\quad \tau = \theta$$

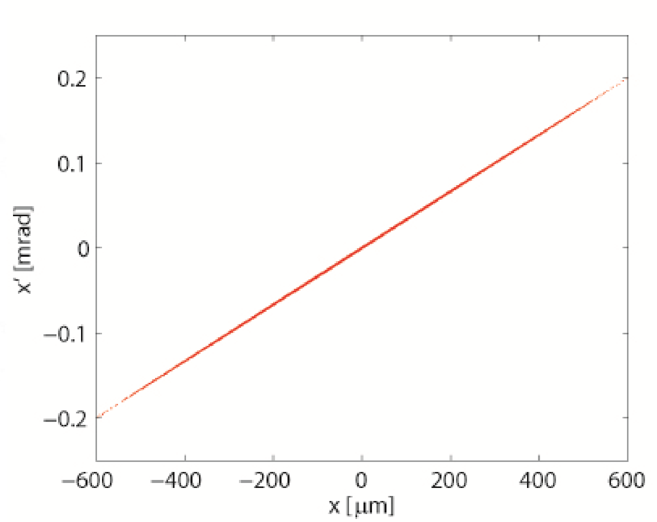
After the interaction

$$\Delta\gamma(x,s)/\gamma = A_m \sin(k_z s + k_x x),\ \Delta x'(x,s) \approx A_a \sin(k_z s + k_x x),\ A_a = \tau A_m$$

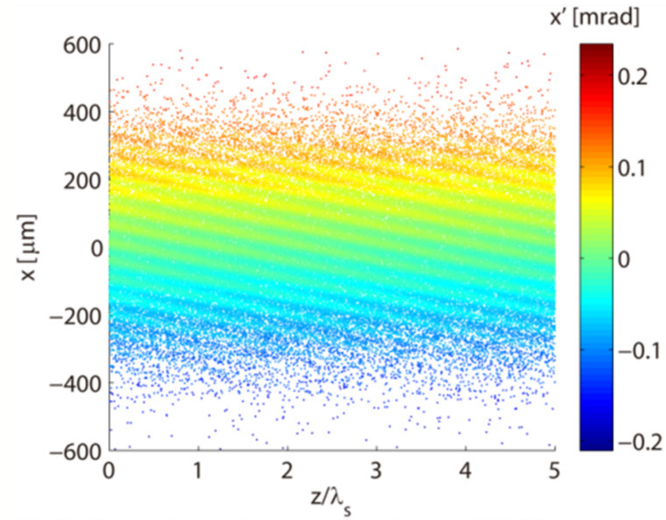
Inducing angular modulation with a normal seed laser pulse



After the drift section before the modulator

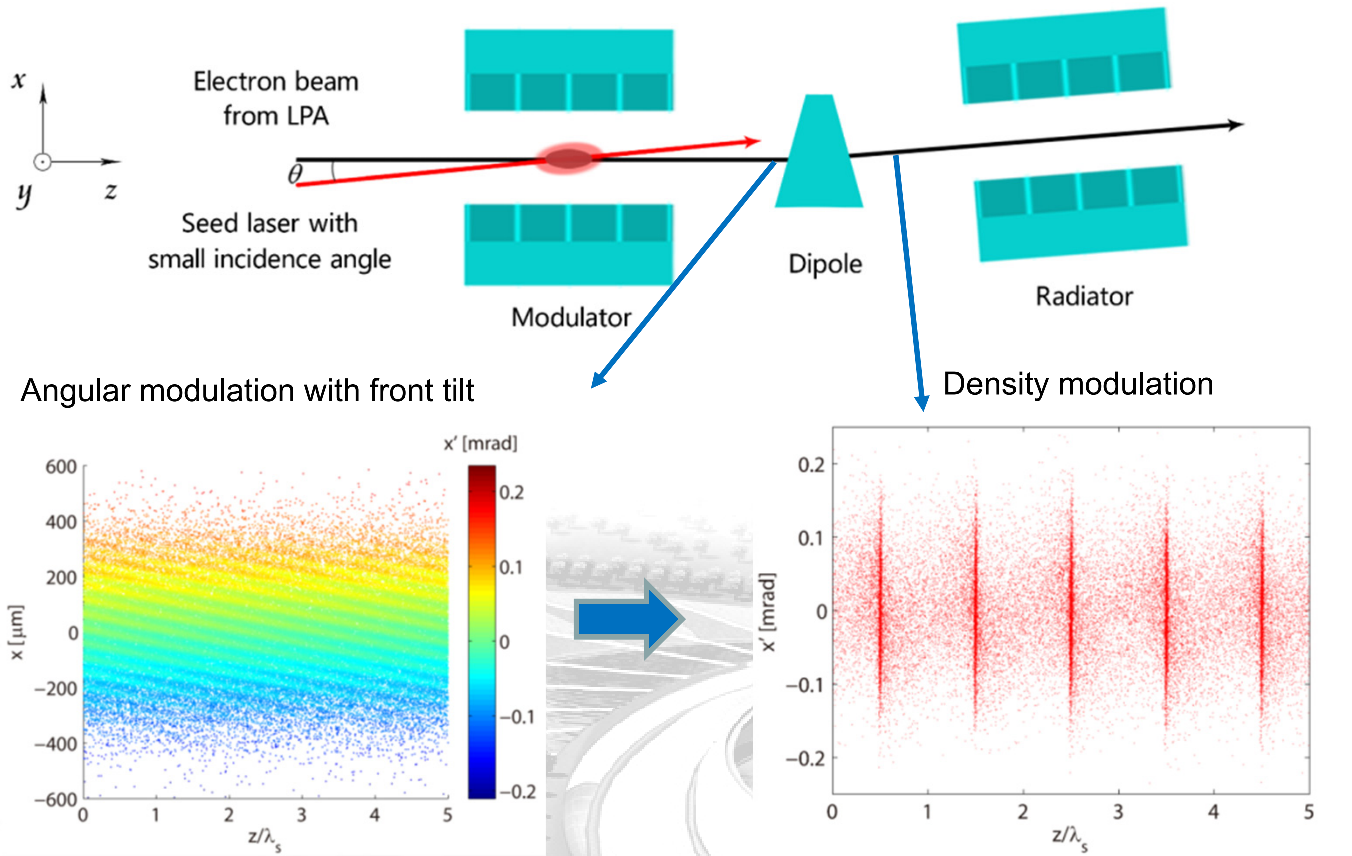


Angular modulation with front tilt



After the interaction $\Delta\gamma(x,s)/\gamma = A_m \sin(k_z s + k_x x),\ \Delta x'(x,s) \approx A_a \sin(k_z s + k_x x),\ A_a = \tau A_m$

Inducing angular modulation with a normal seed laser pulse



The angular modulation can be converted into density modulation by a weak dipole.
The laser induced energy modulation amplitude and angular modulation amplitude is much smaller than the initial beam energy spread and transverse divergence.

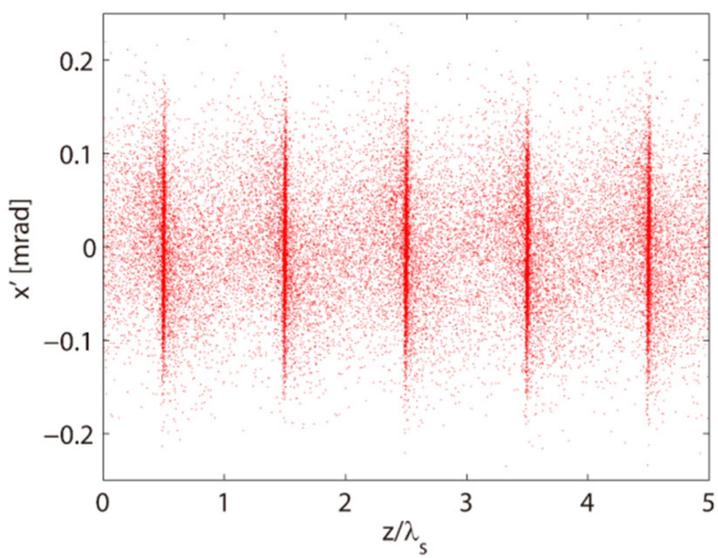
The bunching factor at nth harmonic of the seed $b_n = J_n[-nk_s DL_2 A]\exp\{-(1/2)[nk_s(a\sigma_x + b\sigma_{x'})]^2\}$

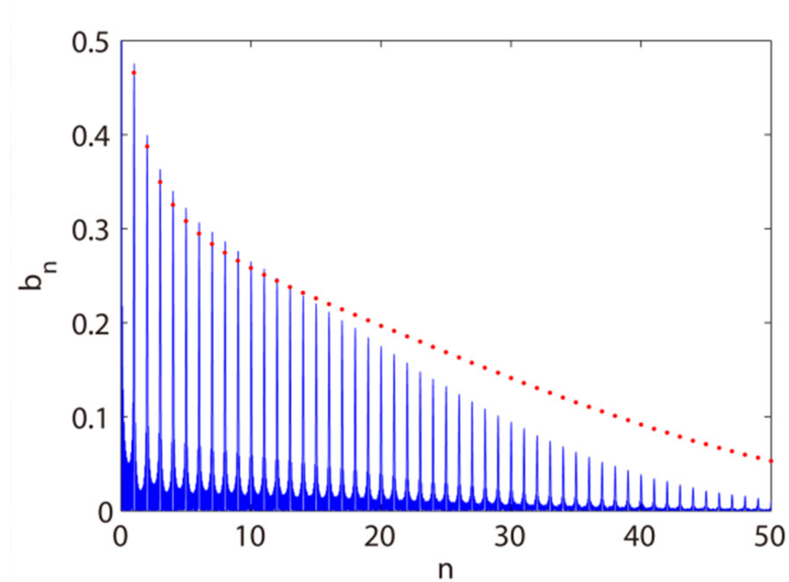
Maximal value approach $0.67/n^{1/3}$, much larger than a conventional CHG

Performance of the proposed method

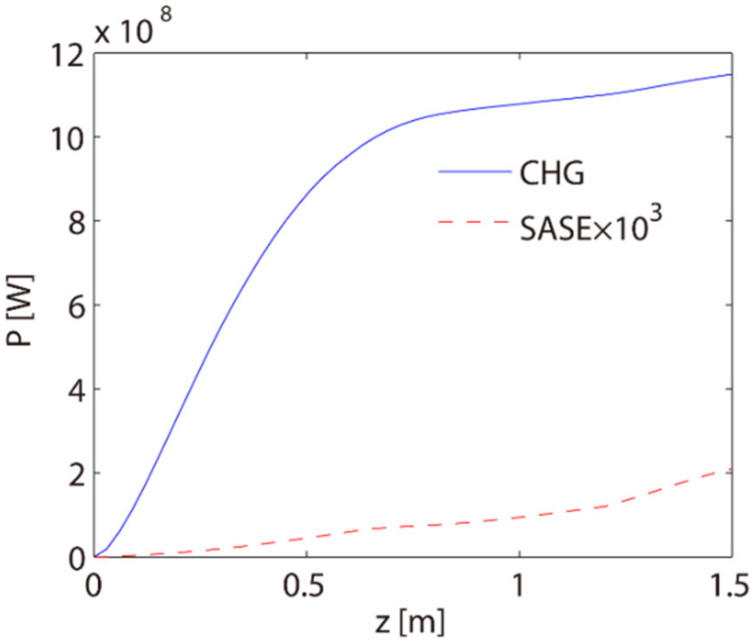
Electron beam from LPA	
Energy	1 GeV
Normalized emittance	0.1 μm
Initial transverse beam size	1 μm
Energy spread	1%
Bunch length (rms)	3 fs
Peak current	10 kA

Beam line	
Drift section before modulator	3 m
Seed laser	260 nm/5 GW
Incidence angle	4.7 mrad
Modulator (sub harmonic)	8 cm*2
Drift section after modulator	1 m
Dispersion	R_{12}=5 cm, R_{52}=8.8*10^{-5} m
Radiator	3 cm*50

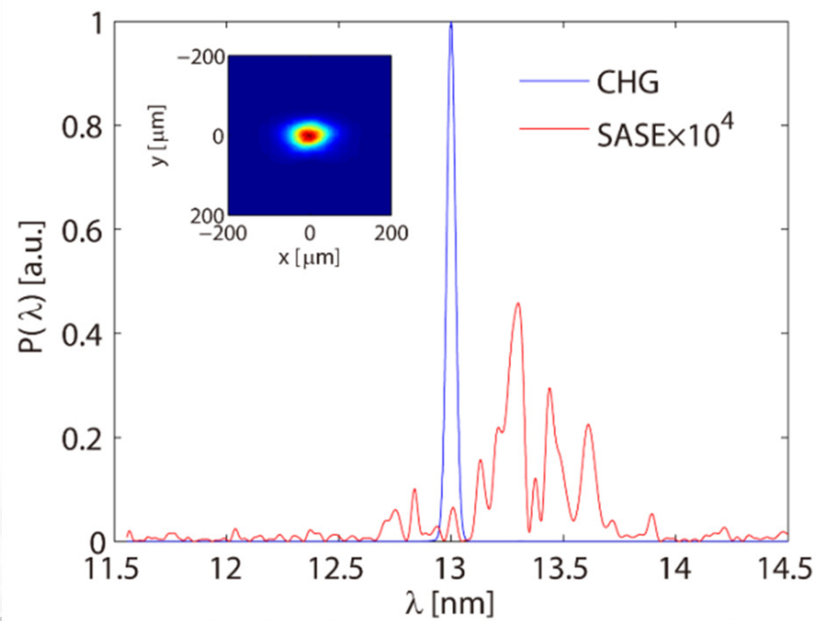




Performance of the proposed method



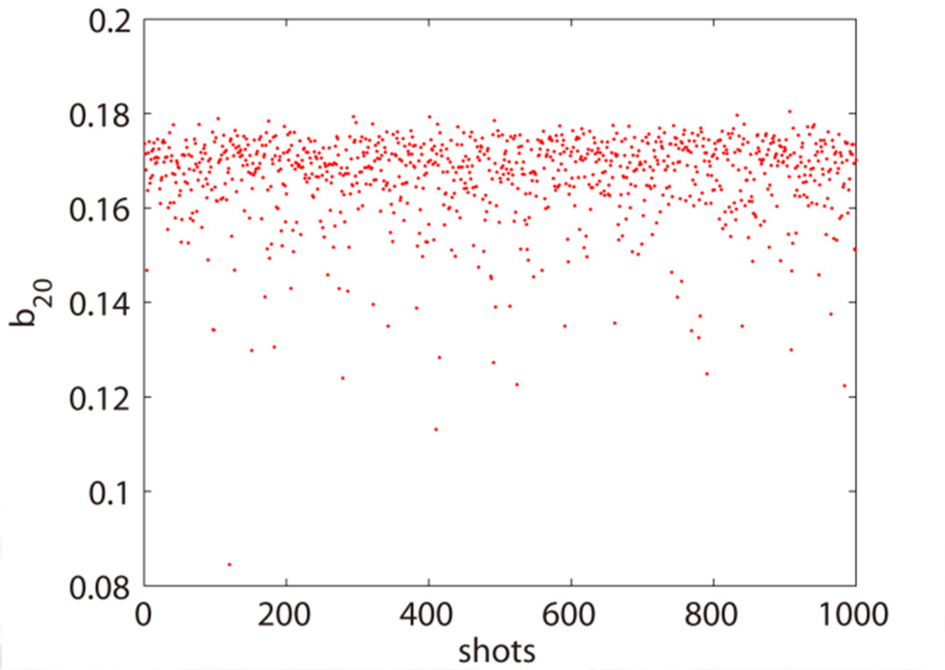
Gain curves@13 nm (peak power)



Output spectra@13 nm

After a 1 m long radiator, the output peak power is around 1 GW, which is comparable to the saturation power of a soft x-ray facility based on the conventional linear accelerator. The output bandwidth of CHG is about 0.3%, which is quite close to the transform-limited

Performance of the proposed method



The sensitivity of the 20th harmonic bunching factor to the instability of the machine has been studied by introducing normal random fluctuations of the laser power of 5%, incidence angle of 0.1%, and dipole magnetic field of 0.01%.

Conclusions and Prospects

- A new method for directly imprinting strong coherent micro-bunching on the electron beam with large intrinsic energy spread is proposed and demonstrated with 3D simulations.
- Besides LPA, the proposed scheme also has other potential applications involving the use of electron beam with large intrinsic energy spread from storage rings, especially the ultimate storage rings..
- It may also be used to enhance high harmonic bunching and improve the output spectrum of a seeded high gain FEL.
- In order to extend the proposed scheme to shorter wavelength, e.g. in the "water window" or even sub-nanometer wavelength regions, one may need to increase the seed laser power or reduce the horizontal emittance of the electron beam from LPA for further increasing the harmonic up-conversion efficiency. Further investigations on these topics are ongoing.


Thanks for your attention!!!