ICFA mini-workshop on Nonlinear dynamics and Collective effects

Phase-merging enhanced harmonic generation and its advances

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19-22 Sept. 2017, Arcidosso, Italy

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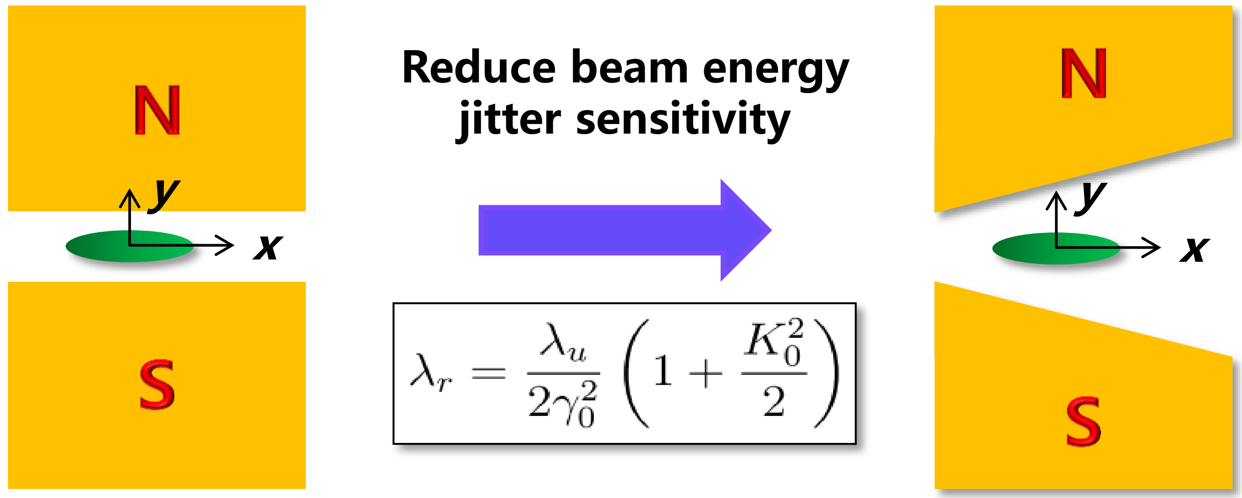
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

Outline

- Introduction, & TGU background
- Phase-merging Enhanced Harmonic Generation (PEHG)
- Advanced concepts
- TGU activities at SINAP
- Summary & Outlook

Transverse Gradient Undulator (TGU)



$$\lambda_r = \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_0^2}{2}\right)$$

- T. I. Smith, et al., Reducing the sensitivity of a free-electron laser to electron energy. Journal of Applied Physics, **50** (1979) 4580.
- N. Kroll, et al., Theory of the transverse gradient wiggler. IEEE Journal of quantum Electronics, **17** (1981)1496.

- Z. Huang, et al, Compact X-ray FEL from a Laser-Plasma Accelerator Using a Transverse-Gradient Undulator. Physical Review Letter, **109** (2012) 204801.
- G. Fuchert, et al., A novel undulator concept for electron beams with a large energy spread. Nucl. Instr. and Meth. A. **672** (2012) 33.

TGU for FEL resonance compensation

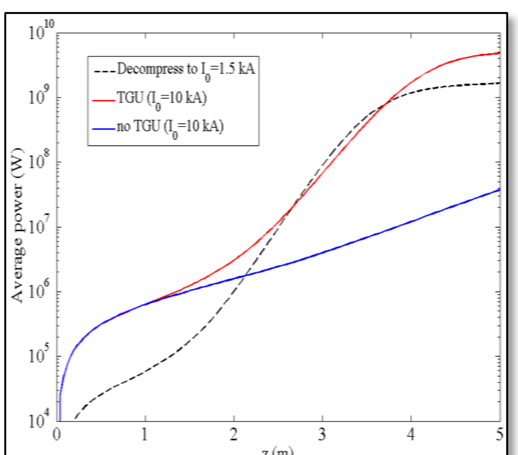
- TGU with linear gradient of α
- Sort beam energy by dispersion η

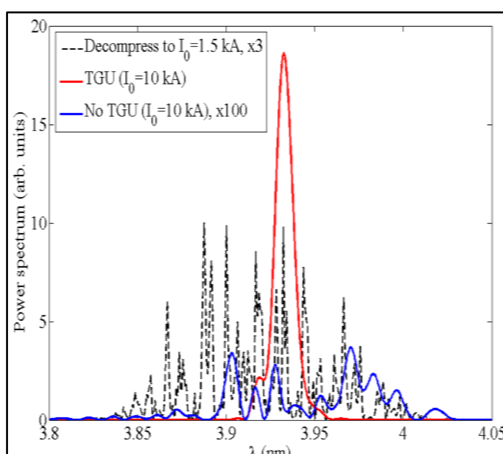
$$\frac{\Delta K}{K_0} = \alpha x \qquad x = \eta \frac{\Delta\gamma}{\gamma_0}$$

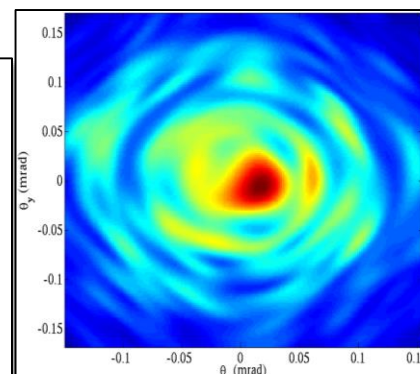
- Optimized resonance relationship

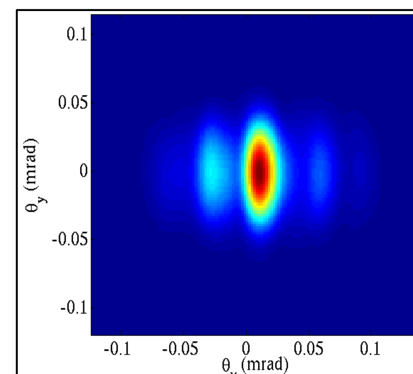
$$\eta = \frac{2 + K_0^2}{\alpha K_0^2}$$

- 1GeV, 10kA, 1% energy spread;
- 0.1μm emittance; 5 fs (50 pC)
- 5-m SC undulator， K = 2;
- Transverse gradient α = 150 m^{-1}
- Radiation wavelength 3.9 nm
- 1cm transverse dispersion
- Transverse beam size 100×15μm



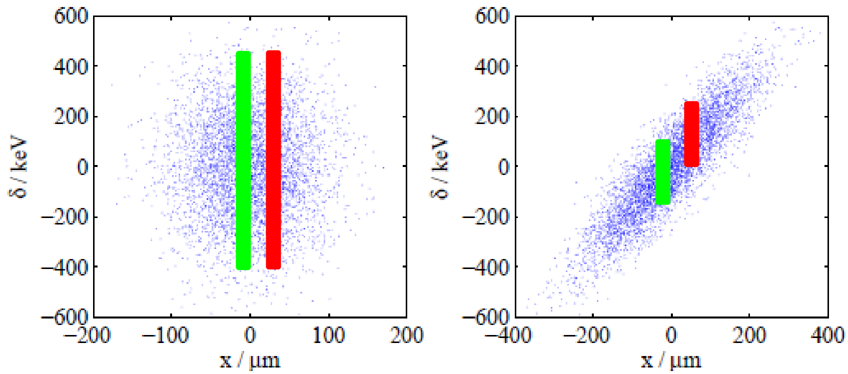


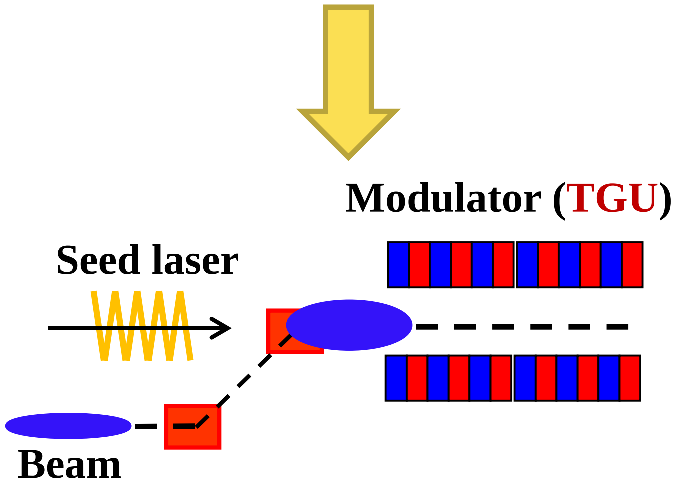




Z. Huang, et al., PRL, 2012.

Motivation & How the idea starts





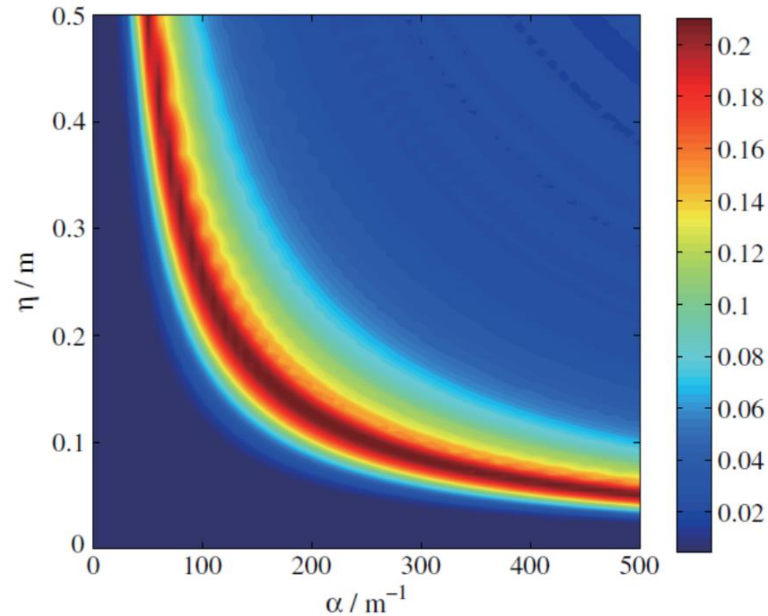


FIG. 2 (color online). Optimization of the transverse gradient α of the modulator and the transverse dispersion η of the dogleg by 1D simulation, in order to find the optimal bunching factor of the 30th harmonic for the cooled HGHG.

H. Deng*, C. Feng, PRL (2013).

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Phase-merging: single-particle dynamics

- We first derive the mechanism behind such kind of schemes from single-particle dynamics. Practically for a given wavelength of the seed laser, the resonant beam energy should be

$$\gamma_r(x) = \gamma_0 + \alpha\eta \frac{K_0^2}{K_0^2+2}(\gamma - \gamma_0). \quad (1)$$

- Consider a resonant and an arbitrary electron (γ_0', θ_0) and (γ', θ_0) at the exit of the TGU modulator, which is the electron (γ_0, θ_0) and (γ, θ_0-$\Delta\varphi$) at the entrance of the modulator, respectively. Then,

$$\begin{cases} \gamma_0' = \gamma_0 - \Delta\gamma\sin\theta_0 = \gamma_0 - \Delta\gamma\theta_0 \\ \gamma' = \gamma - \Delta\gamma\sin(\theta_0 - \Delta\varphi/2) = \gamma - \Delta\gamma(\theta_0 - \Delta\varphi/2), \end{cases} \quad (2)$$

- $\Delta\varphi$ is the phase exchange difference of the arbitrary electron with respect to the resonant one.

$$\Delta\varphi = 4\pi N \frac{(\gamma - \gamma_r)}{\gamma_0}, \quad (3)$$

and N represents the period number of the modulator.

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Phase-merging: single-particle dynamics

Combining Eq. (2) and Eq. (3), we can easily derive that

$$\frac{\gamma'-\gamma_0'}{\gamma-\gamma_0} = 1 - \frac{2\pi N\Delta\gamma}{\gamma_0}\left(\frac{\alpha\eta K_0^2}{K_0^2+2} - 1\right). \quad (4)$$

Eq. (4) illustrates a scaling for longitudinal beam phase space control.

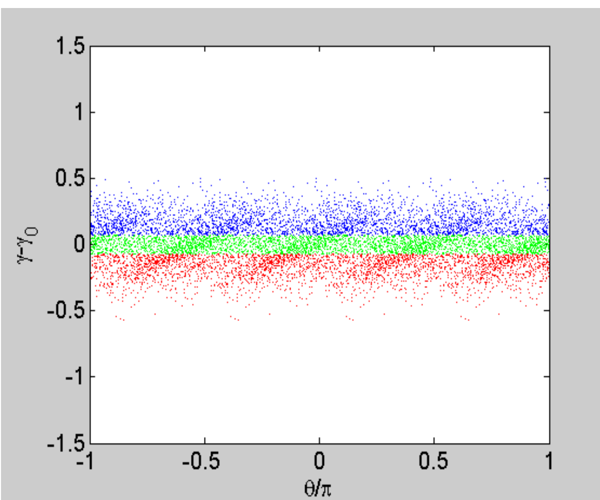
- ✓ **Typical HGHG setup**: the local beam energy spread is amplified by a factor of $2\pi N\Delta\gamma/\gamma_0$ which is usually a relatively small number.
- ✓ **Typical TGU region**: when we increase the αη product and make the right hand of Eq. (4) to be unity, the electron beam energy spread is not changed and almost every electron satisfies the FEL resonant condition.
- ✓ **Phase-merging**: if one further increases αη product properly, the right hand of Eq. (4) can be zero. Although it seems that, the electron beam energy spread is suppressed, **in fact, all the electrons with the same energy merges to an energy-related longitudinal phase**.

Phase-merging: single-particle dynamics

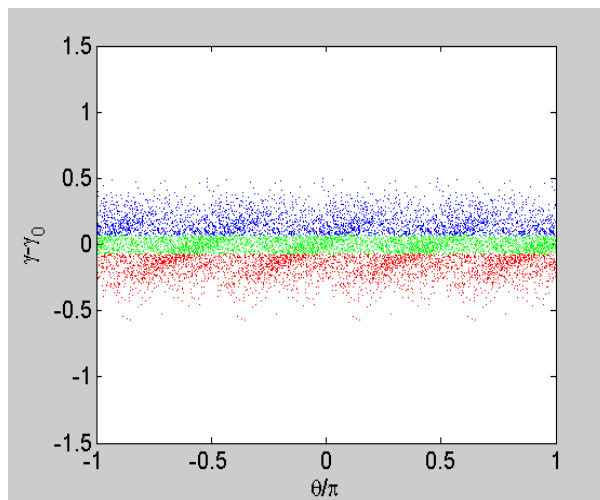
Some practical numbers:

- ✓ Electron beam: E=0.84GeV, 100keV slice energy spread.
- ✓ The modulator parameters: period length 80mm×12, and K=5.8.
- ✓ 265nm seed laser, energy modulation amplitude 500keV.

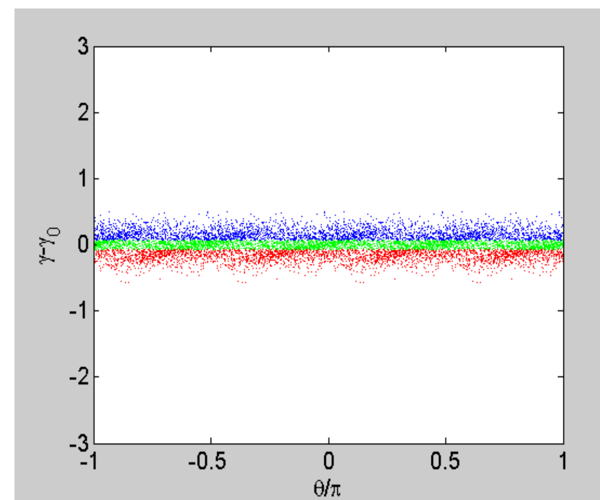
Phase-merging condition: ***αη* = 24**



Standard-HGHG
***αη* = 0**



Phase-merging
***αη* = 24**



Phase-broadening
***αη* = 24, more modulation**

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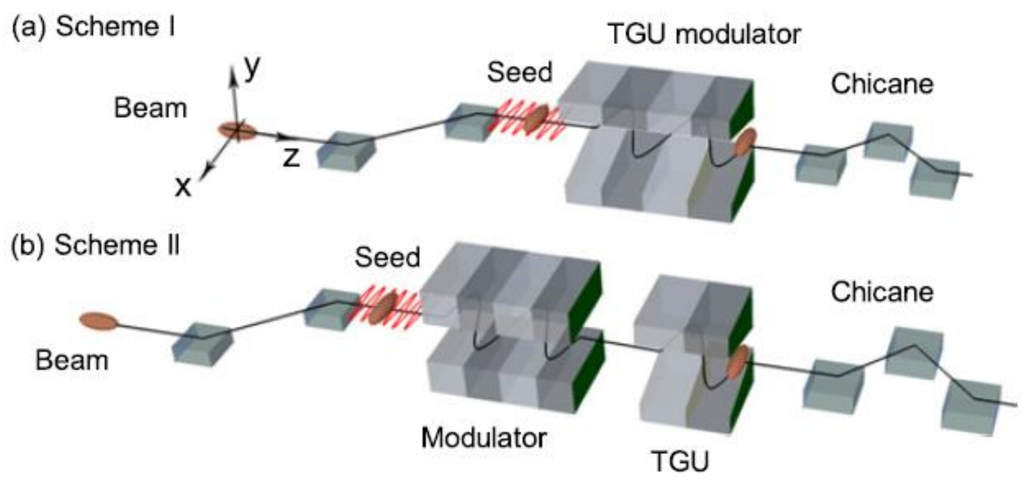
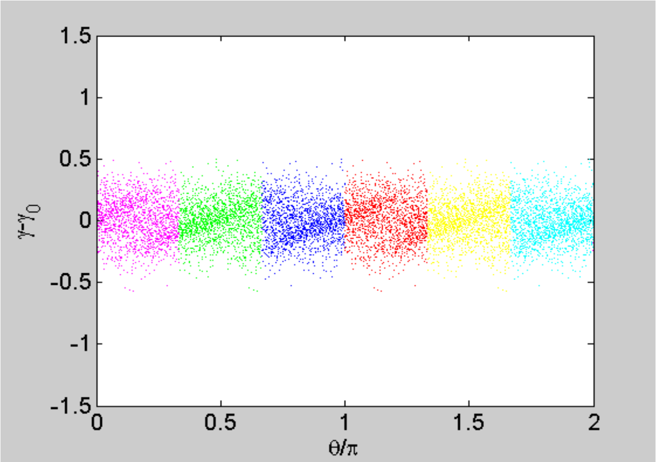
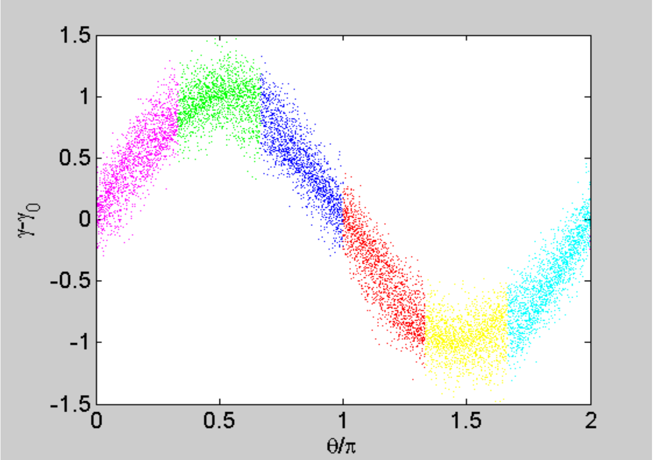
Phase-merging: Alternative scheme I







$$\alpha\eta = -\frac{2\gamma^3\left(n + 0.81n^{1/3}\right)}{nAk_s L_m K_0^2 \sigma_\gamma}$$

more flexible, smaller *αη* & better performance

C. Feng, H. Deng, D. Wang, Z. Zhao, New J. Phys. 16 (2014) 043021*

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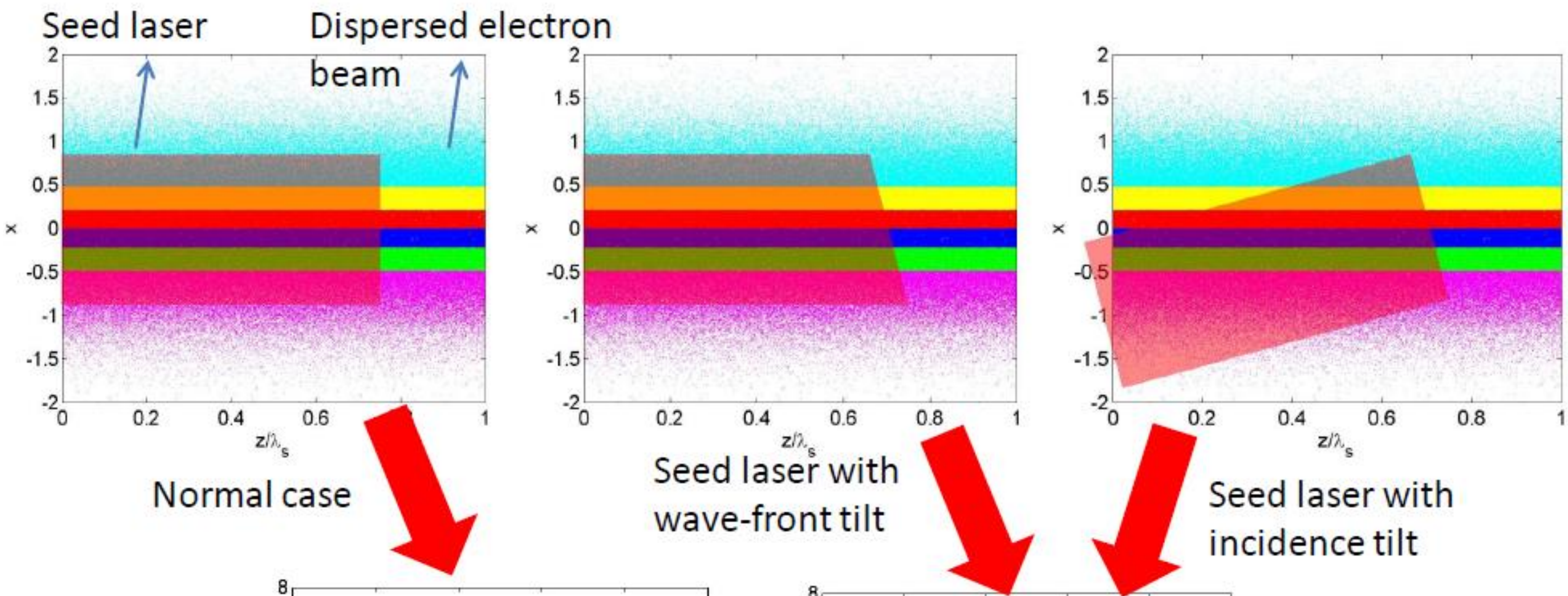
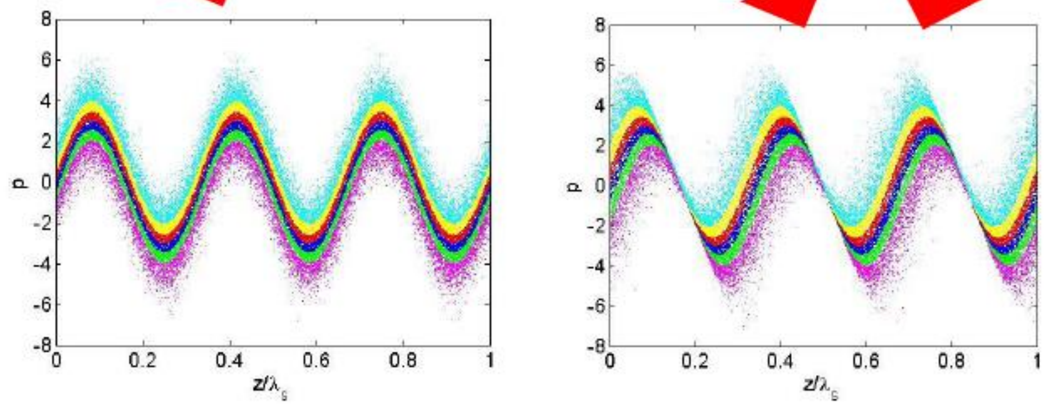
Phase-merging: Alternative scheme II





TGU is not necessary

C. Feng, T. Zhang, H. Deng, Z. Zhao, Phys. Rev. ST-AB. 17 (2014) 070701*

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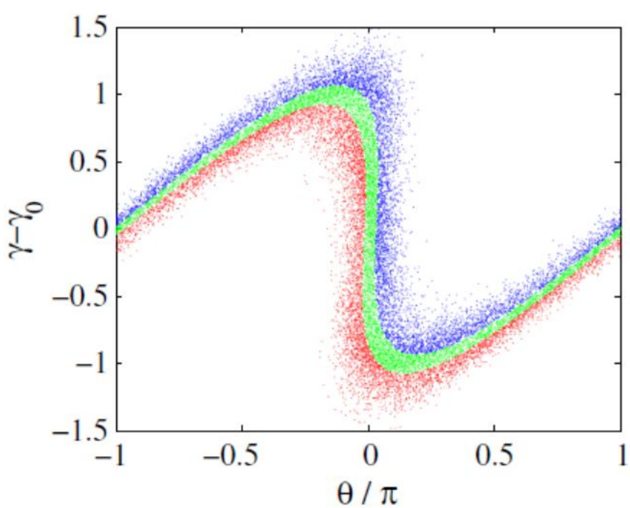
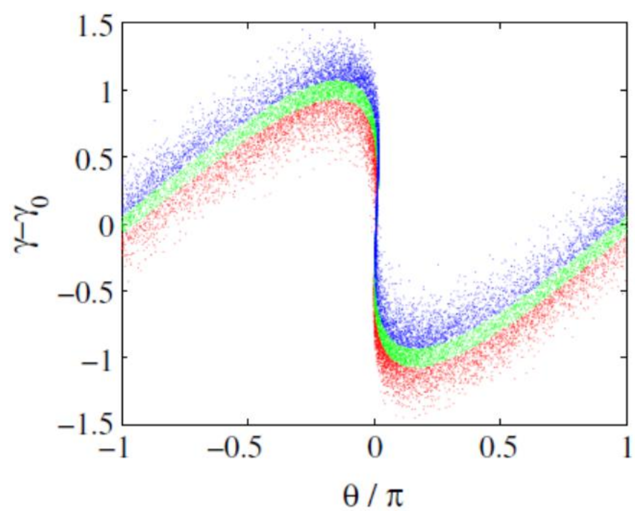
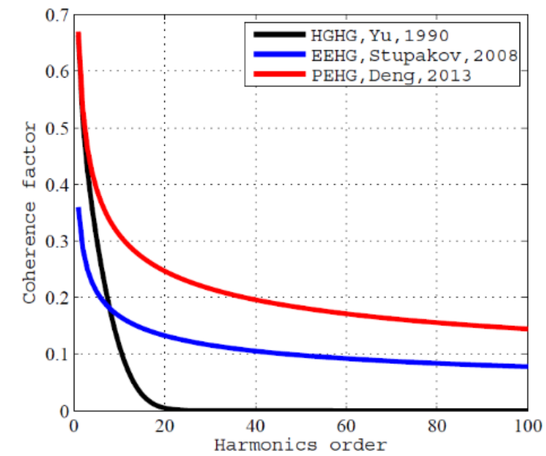
Phase-merging Enhanced Harmonic Generation (PEHG)







HGHG bunching

$$b_n = e^{-\frac{n^2 D^2 \delta^2}{2}} J_n(nD\Delta\gamma)$$

PEHG bunching

$$b_n = J_n(nD\Delta\gamma)$$

HGHG/EEHG/PEHG bunching

- 1D results: The maximum bunching scales as $0.67/n^{1/3}$
- 1D result: The maximum bunching is independent on the energy modulation
- A 3D theory and s2e simulation should be done.

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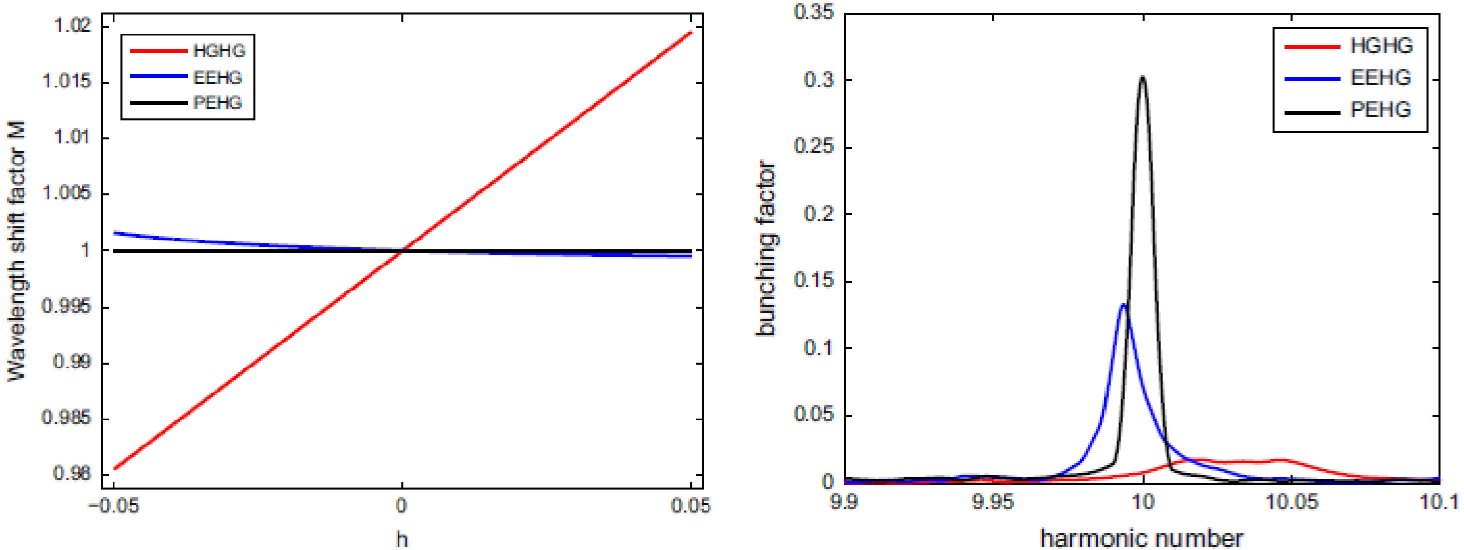
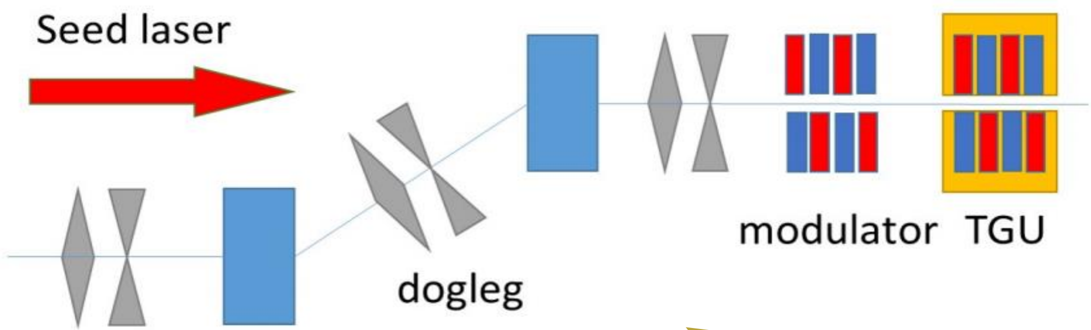
PEHG：Zero response to beam energy chirp

$$a_{HGHG} = \frac{k}{1+hB} \qquad a_{EEHG} = \frac{n+mK(1+hB_1)}{1+hB} \qquad a_{PEHG} = \frac{k}{1+h(TD+B)}$$



G. Wang, C. Feng, H. Deng, T. Zhang, D. Wang, NIMA, 753 (2014) 56-60.*

PEHG：three-dimensional theory



$$b_n = J_n[nAB]e^{-(1/2)n^2(T_1^2+T_2^2)}$$

$$T_1 = k_s\tau\sigma_x \qquad T_2 = k_s\tau L\sigma_{x'}$$

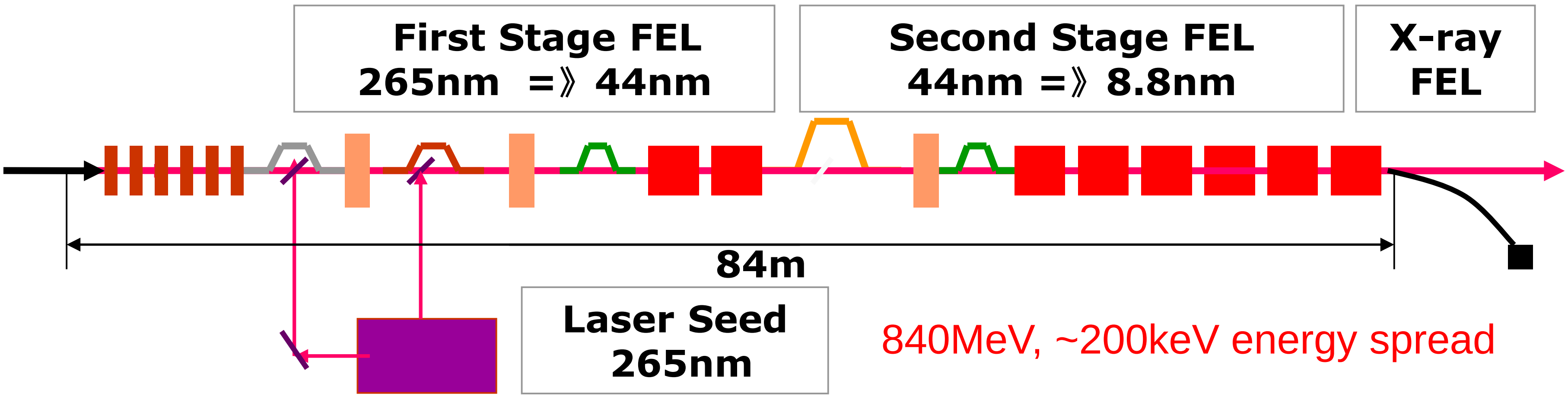
$$\begin{cases} L = L_d + L_m + L_T/2 \\ L_0 = L_T/2 + L_c \end{cases}$$

$$R_D = \begin{bmatrix} 1 & L_d & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi_d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad R_M = \begin{bmatrix} 1 & L_m & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & h & 1 \end{bmatrix} \quad R_{TGU} \approx \begin{bmatrix} 1 & L_T & 0 & \tau L_T/2 \\ 0 & 1 & 0 & \tau \\ \tau & \tau L_T/2 & 1 & \tau^2 L_T/6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

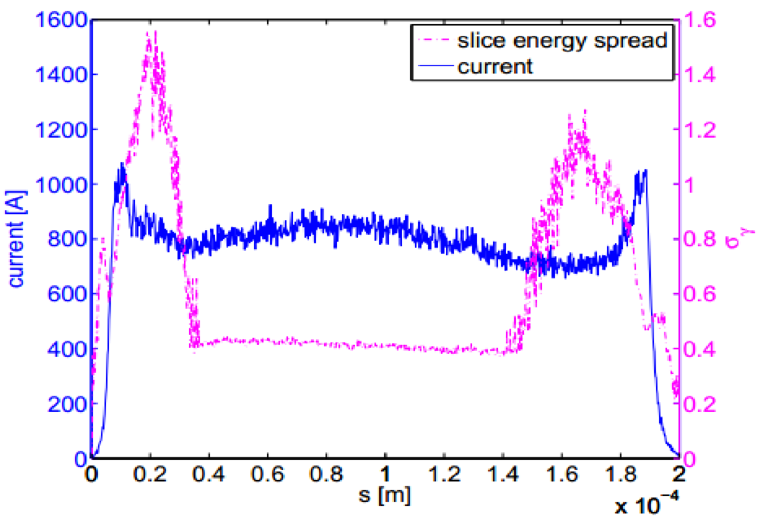
$$\begin{bmatrix} 1 & L + L_T + 2L_c & L_T/2h\tau & \eta + \tau L_0(1 + h\xi_d) \\ 0 & 2 & h\tau & \tau(1 + h\xi_d) \\ \tau & \tau L & 0 & 0 \\ 0 & h\eta & h & 1 + h\xi_d \end{bmatrix}$$

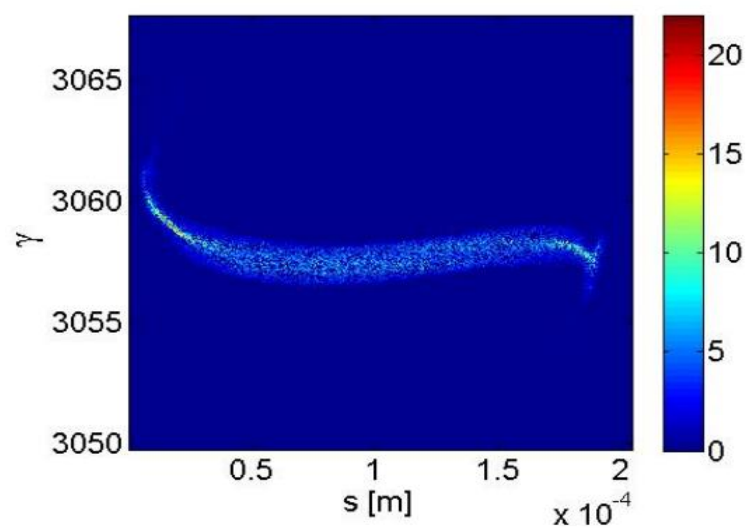
$$b_n = J_n[nAB]e^{-n^2k_s^2\tau^2 L\varepsilon_x}$$

PEHG：SXFEL start2end results

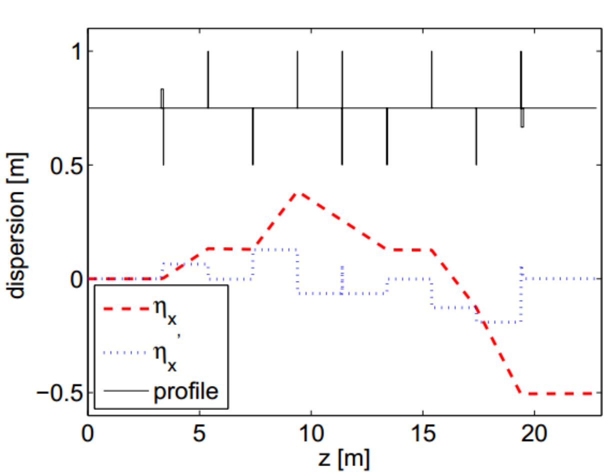


840MeV, ~200keV energy spread

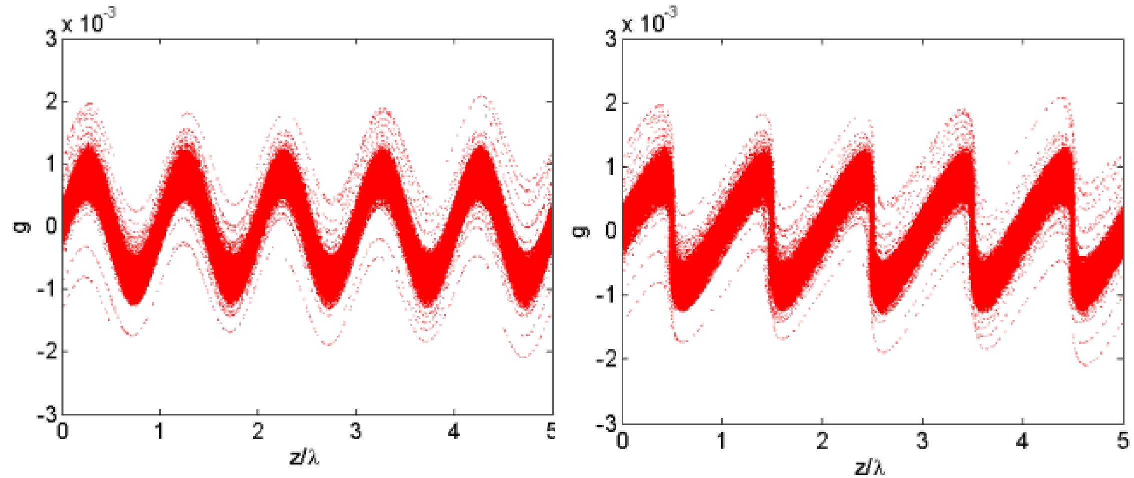




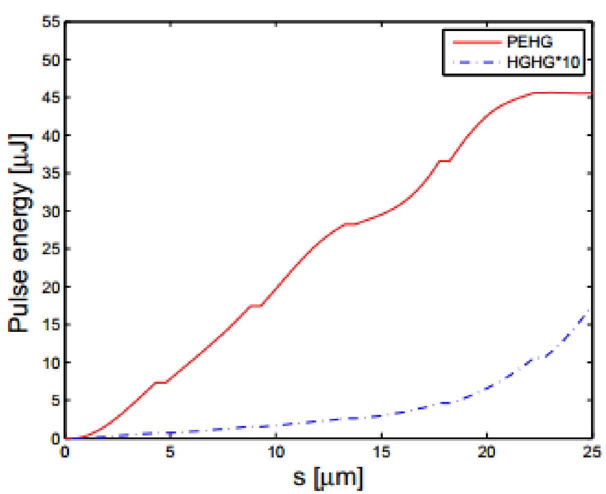
PEHG：SXFEL start2end results

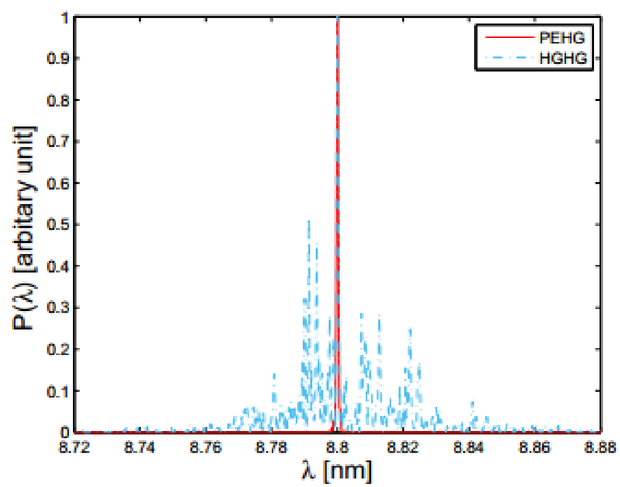


Specially designed Dogleg



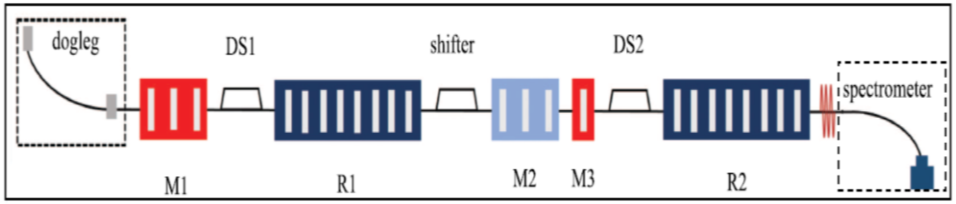
Beam phase space before and after TGU



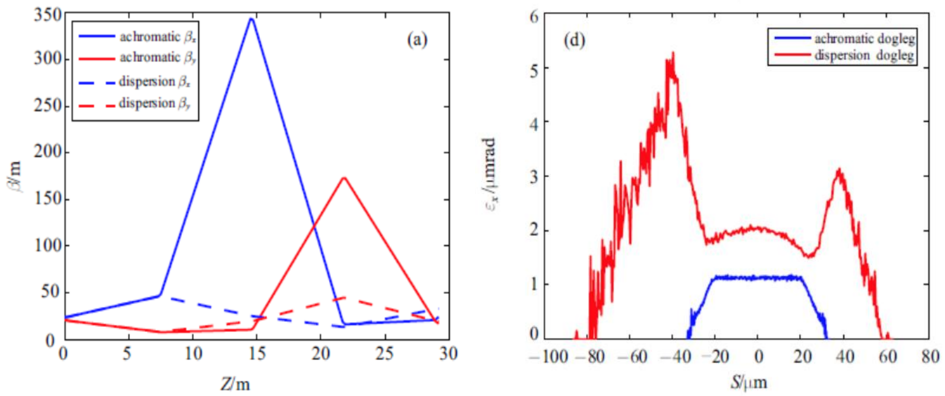


Zheng Qi et al., submitted to NIMA, 2017

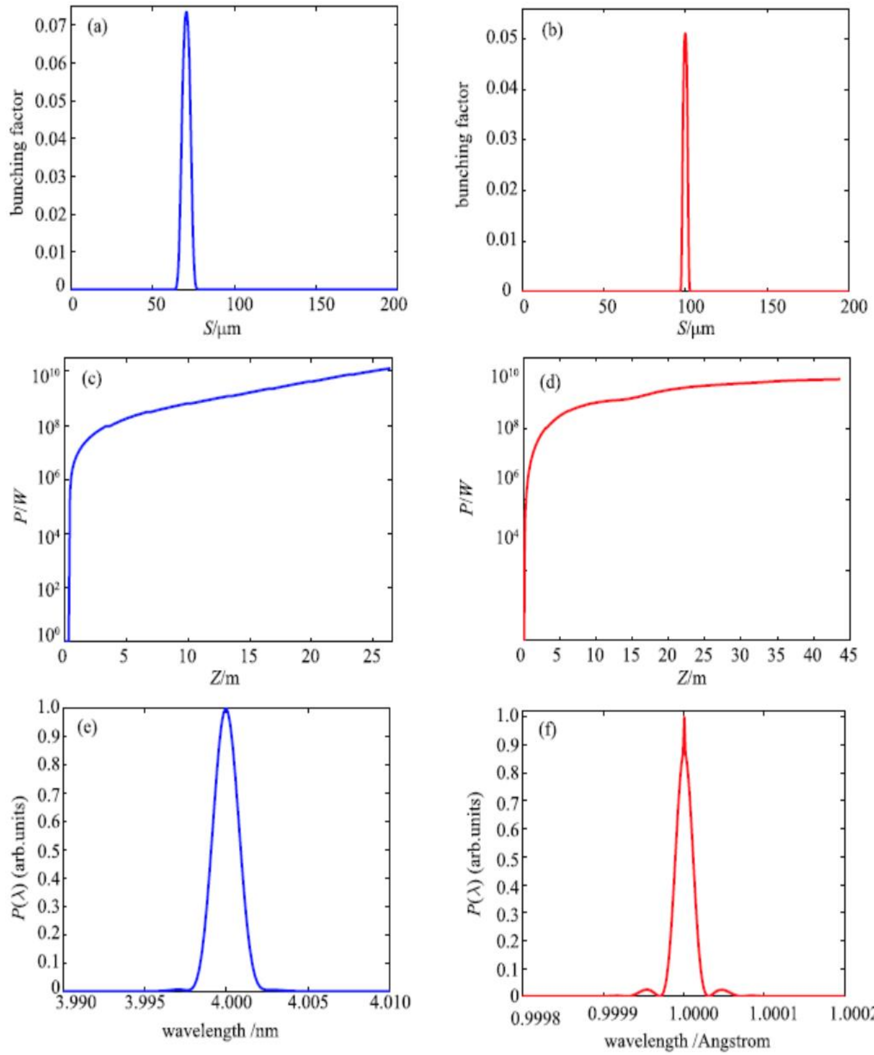
Two-stage PEHG to hard X-ray ?



Two-stage PEHG



Beam optics and emittance growth in the switch yard



G. Wang et al., Chin. Phys. C (2016)

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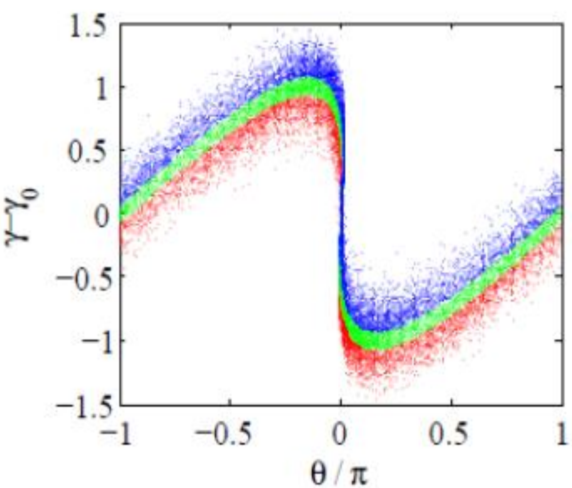
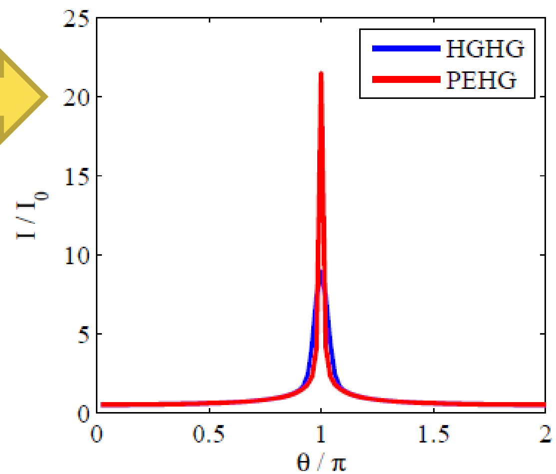
PEHG-assisted ultrafast pulse generation

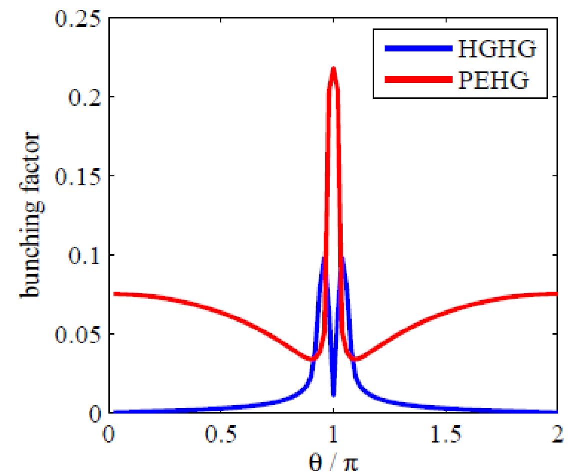
According to beam density modulation theory, current & bunching factor distribution during one seed wavelength can be expressed as

$$I_n(\theta_0, N_2) = 1 + \frac{2n}{\pi}\sum_{m=1}^{\infty} p_m b_m$$

$$B_n(\theta_0, N_2) = \frac{\sum_{m=1}^{\infty} q_m b_m}{\frac{\pi}{n} + 2\sum_{m=1}^{\infty} p_m b_m}$$







H. Deng et al, Chin. Phys. C 2010
K. Li, C. Feng, H. Deng, et al, 2017, in preparation.

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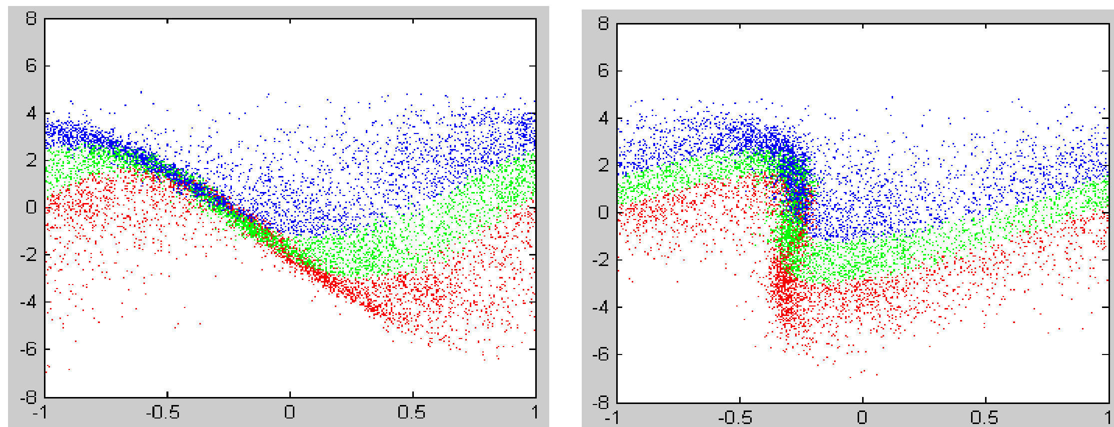
Coherent harmonic generation at storage ring



Main parameters

Beam energy: 600MeV
Energy spread: 0.6MeV
Emittance: 17.5nm-rad
Coupling: 3%
Seed laser: 800nm
Seed modulation: 1.2MeV
Radiation: 133nm

$\alpha\eta \approx 6.5$

Considering the small vertical emittance, each bunch was proposed to be vertically dispersed only after it undergoes sufficient damping. Then under an optimal condition, the bunching factor of the 6^{th} harmonic is enhanced to 23.0% by PEHG from 1.8% in OK setup.

More advanced schemes are proposed by C. Feng, et al., for EUV lithography

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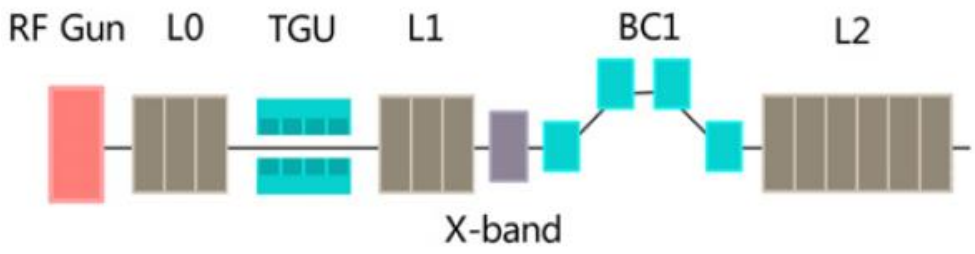
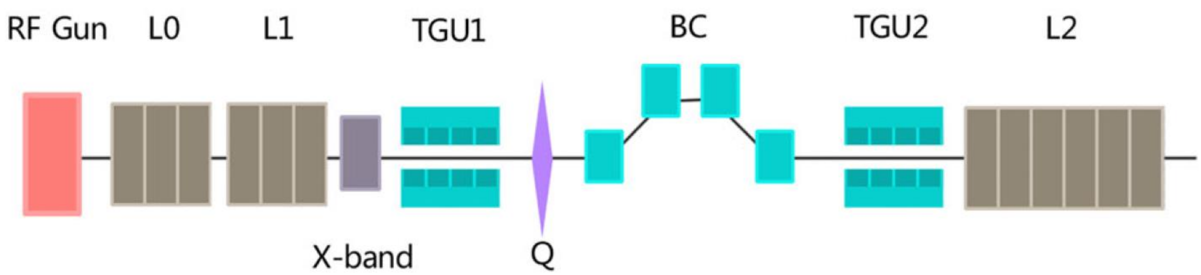
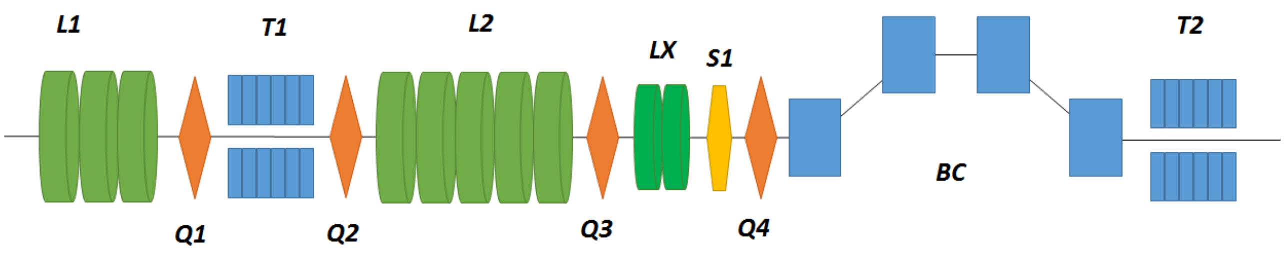
TGU-assisted MBI suppression



C. Feng et al., New J. Phys. 17, 073028 (2015).



D. Huang et al., Phys. Rev. Accel. Beams 19, 100701 (2016).



T. Liu et al., Phys. Rev. Accel. Beams 20, 082801 (2017).

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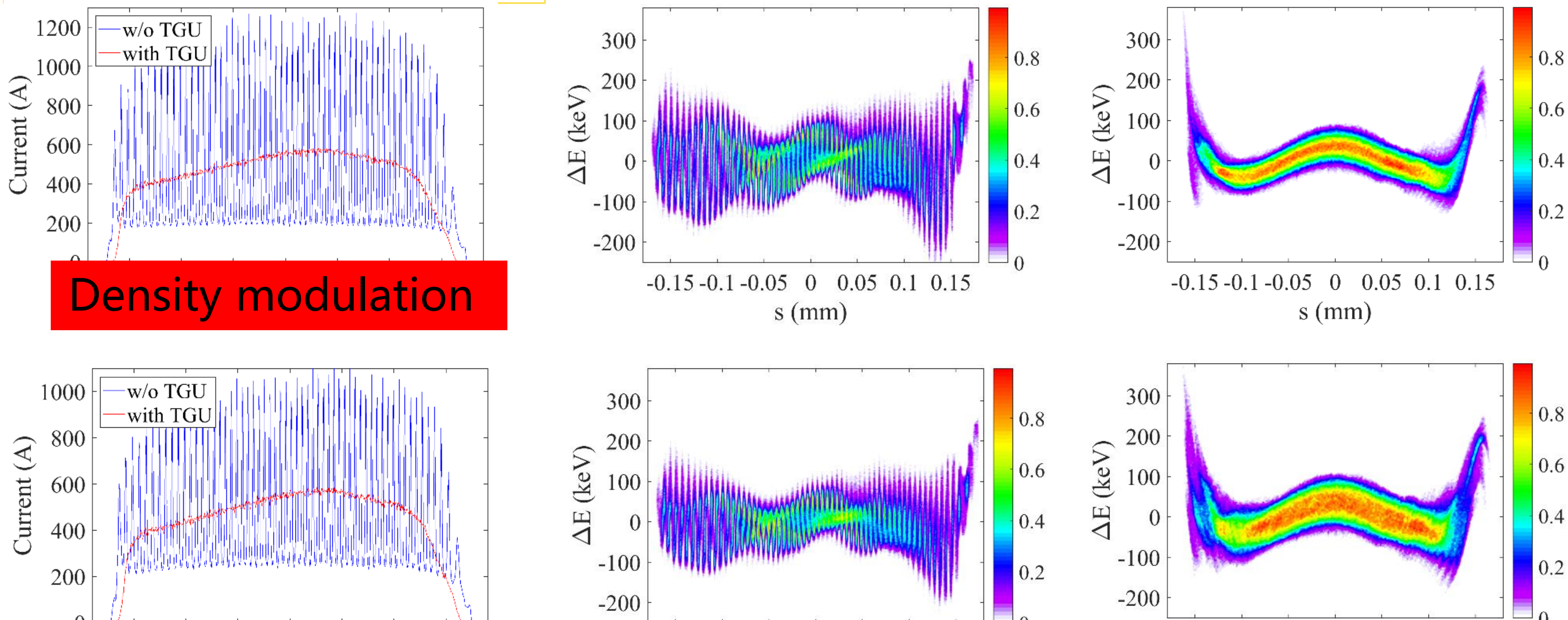
TGU-assisted MBI suppression

tail head



Density modulation

Energy modulation

w/o TGUs

with TGUs

Courtesy Tao Liu

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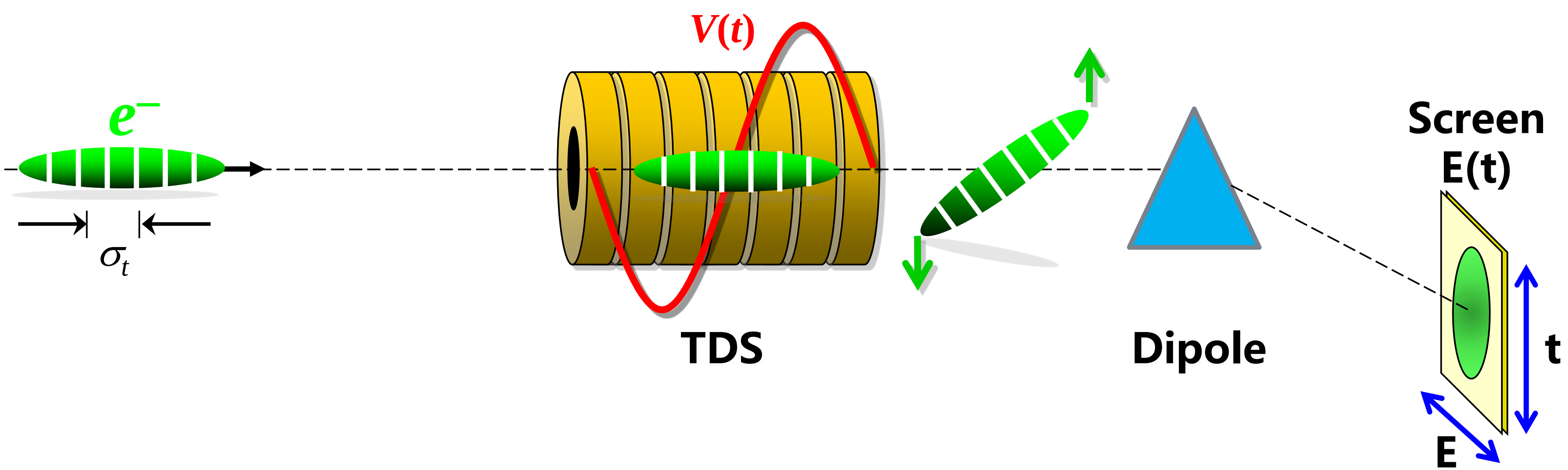
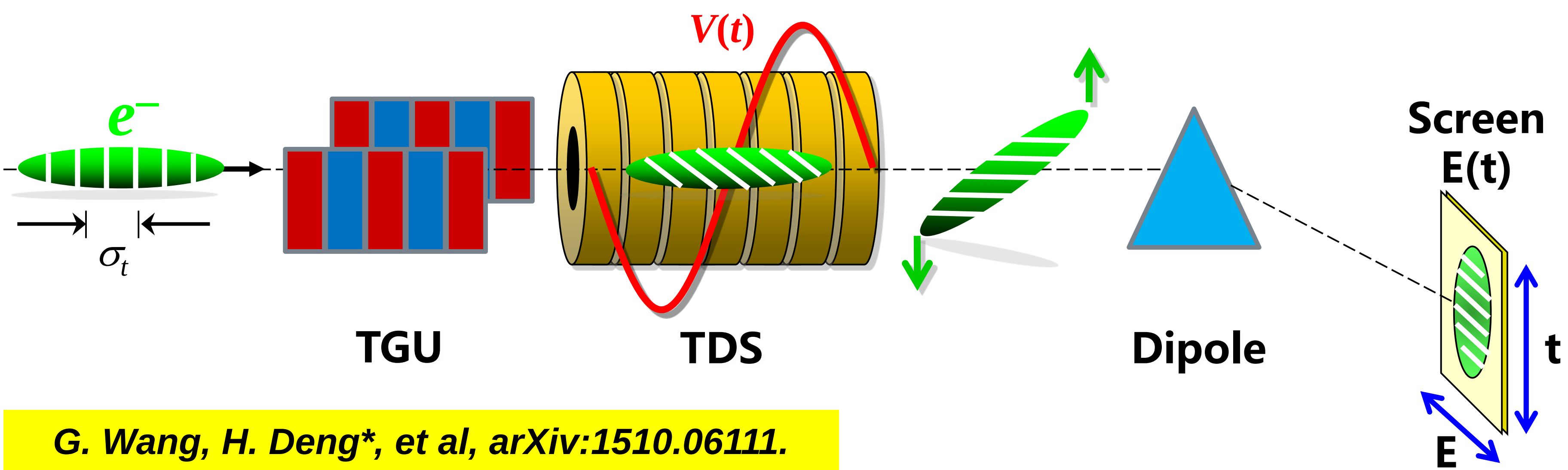
TGU-enhanced transverse deflector

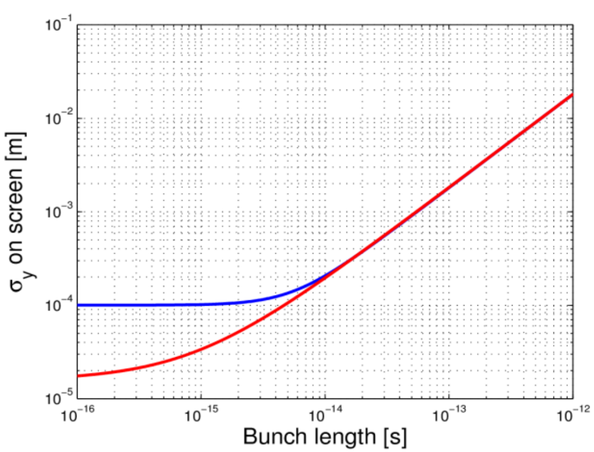


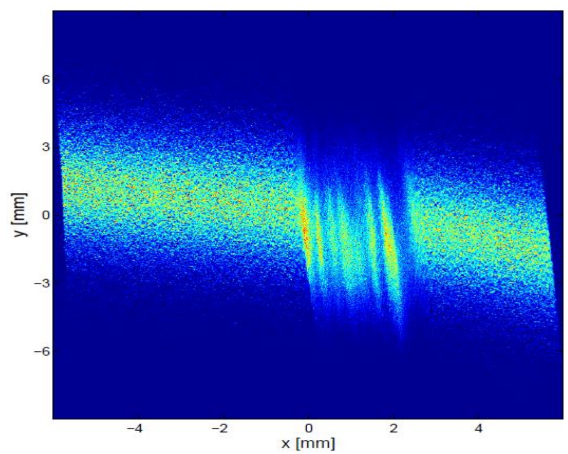
	FLASH	FERMI	LCLS
TDS type	S-band	S-band	X-band
TDS freq.	2856MHz	2998MHz	11424MHz
TDS Voltage	26MV	20MV	48MV
Time resolution	~27fs	~20fs	~1fs

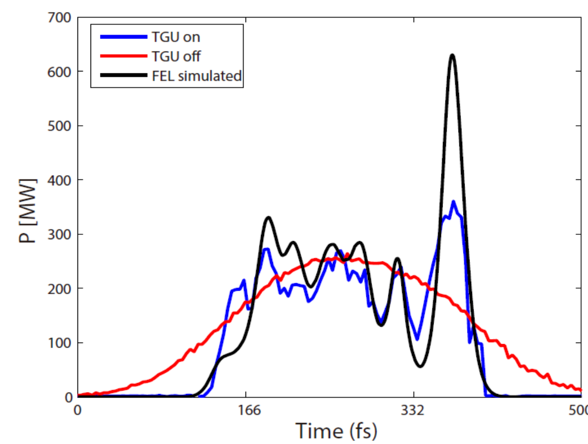
TGU-enhanced transverse deflector



G. Wang, H. Deng*, et al, arXiv:1510.06111.







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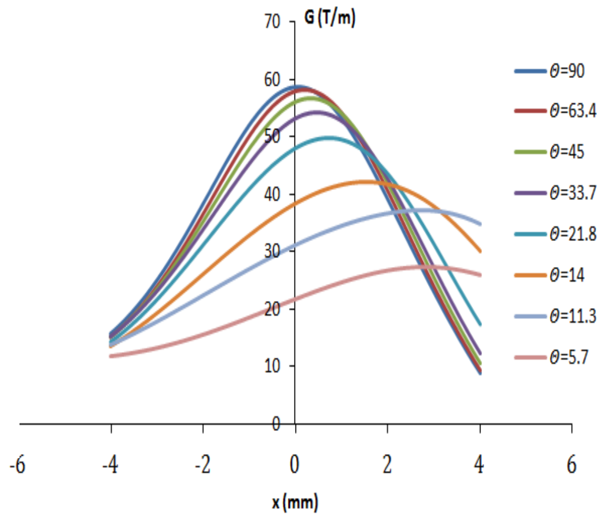
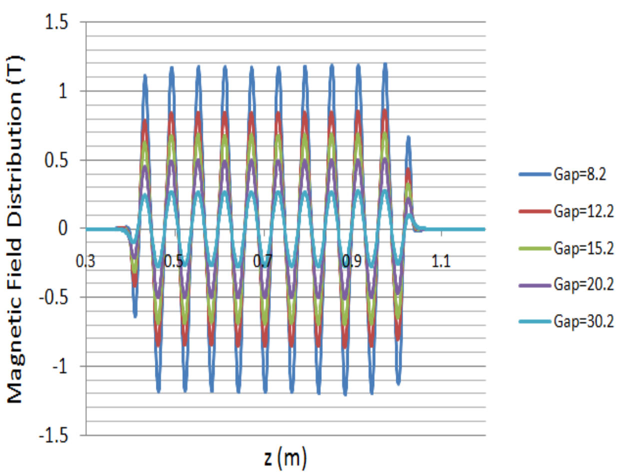
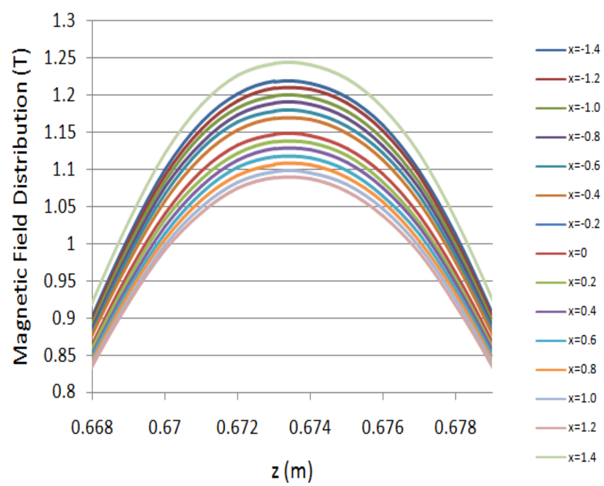
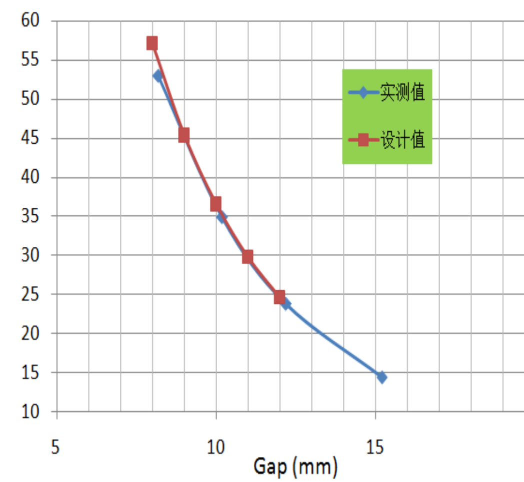
TGU-60 modulator prototype (2013)

Chamfer 45°

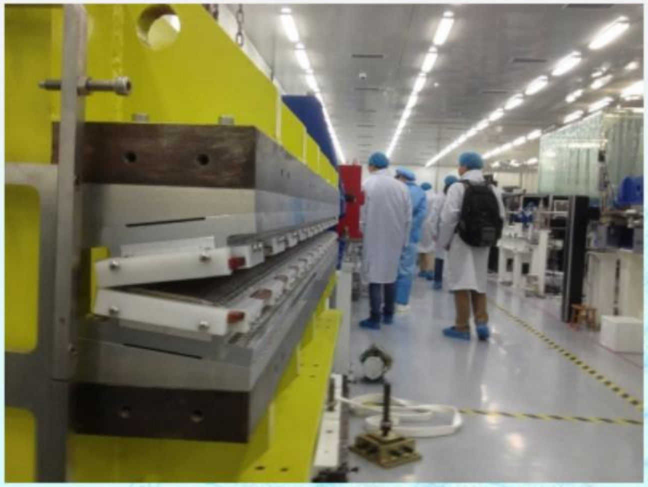




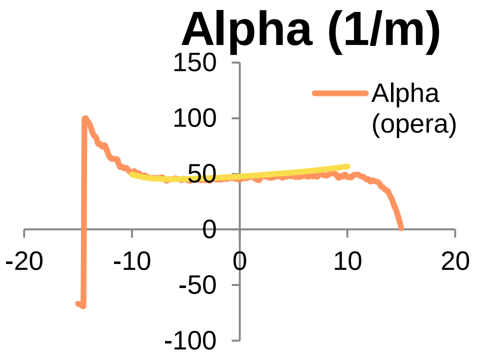


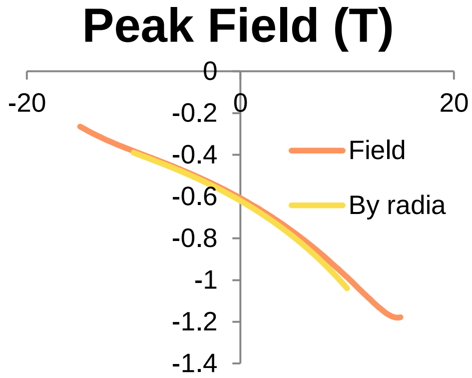


TGU-20 radiator (2016)

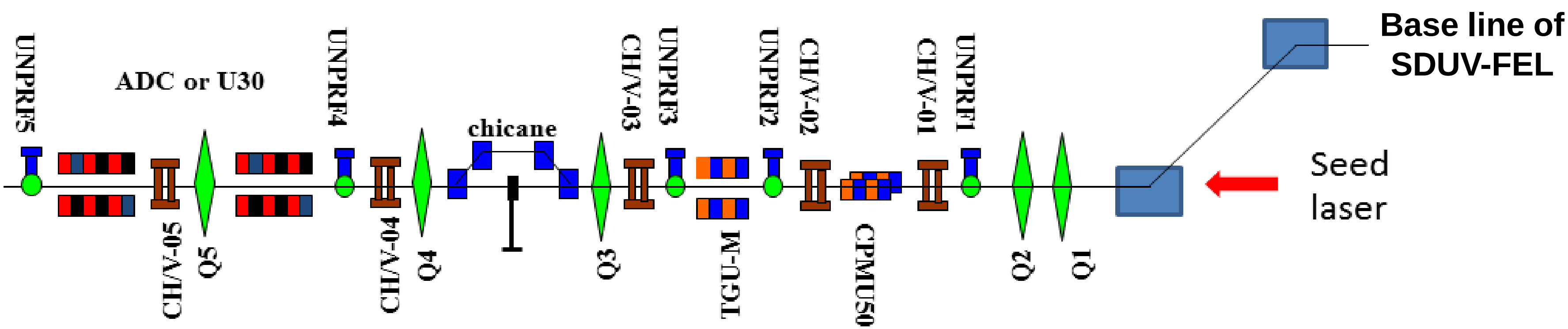


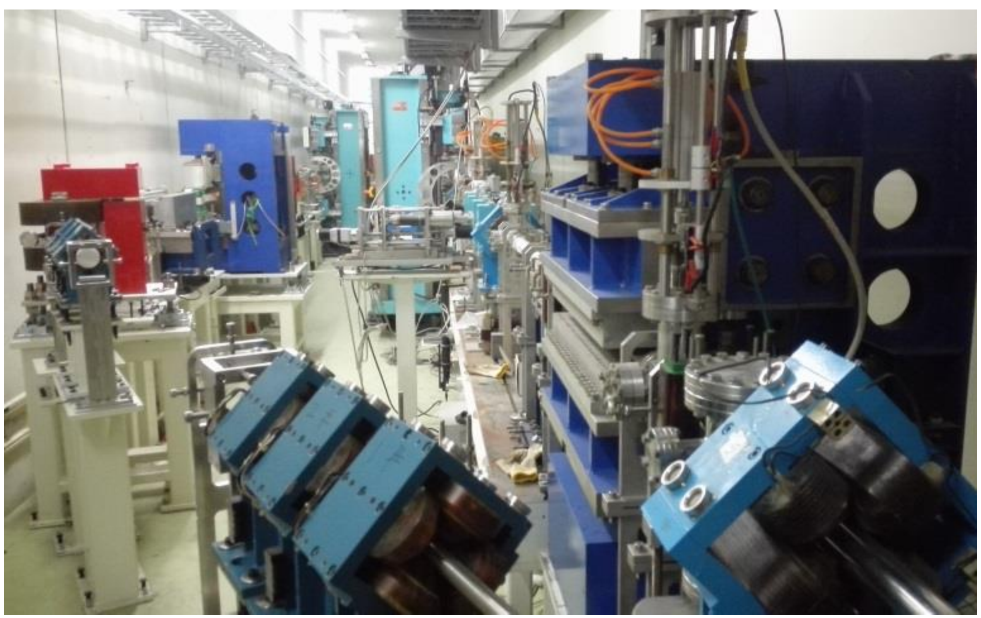
Period length	**20**	**mm**
Segment length	1.5	m
Gap	>7.00	mm
Peak field	0.615	T
K	1.150	
Gradient	50	m^{-1}
Gradient tolerance	±5	m^{-1}





POP experiment of PEHG





- A POP experiment to demonstrate PEHG was planned at SDUV-FEL.
- It is over， but not finished.
- The 2nd undulator lines of DCLS and SXFEL are possible for a POP PEHG operation, and is under consideration.
- It seems that PEHG on storage ring is much more attractive.

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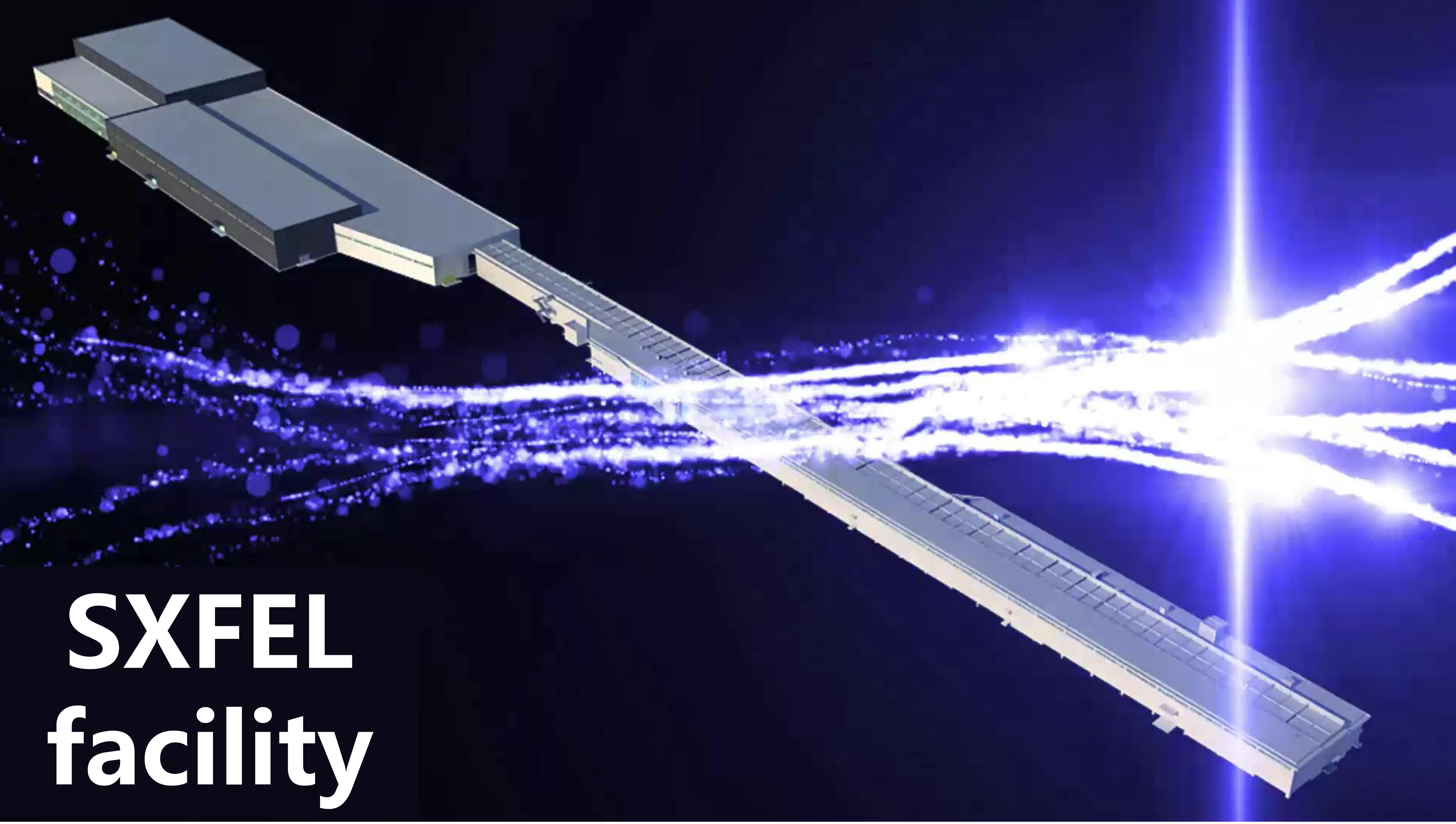
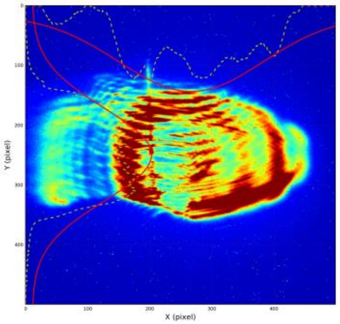
Conclusions

- Phase-merging in laser-beam interaction was proposed & studied. Once the door was opened, alternative schemes can be used to achieve the proposed phase-merging phenomenon.
- Phase-merging enhanced FEL is one of the most straightforward applications in seeding business. The 3D analytical theory and s2e simulations were performed, which demonstrates the feasibility of fully coherent soft-x-ray FEL from the commercial laser using single-stage PEHG technique (30^{th} harmonic or even higher).
- Many advanced concepts of phase-exchange, i.e., transverse-longitudinal coupling is being studied, i.e., ultra-fast pulse generation, ring-based schemes, enhanced TDS and MBI suppression, etc.
- Several TGUs have been successfully manufactured at SINAP. Some proof-of-principle experiments of PEHG is under consideration, with the funding supports from NSFC and MOST of China.





Thanks for attention !