The 2014 International Free Electron Laser Conference

Phase-merging enhanced harmonic generation
A novel seeded concept

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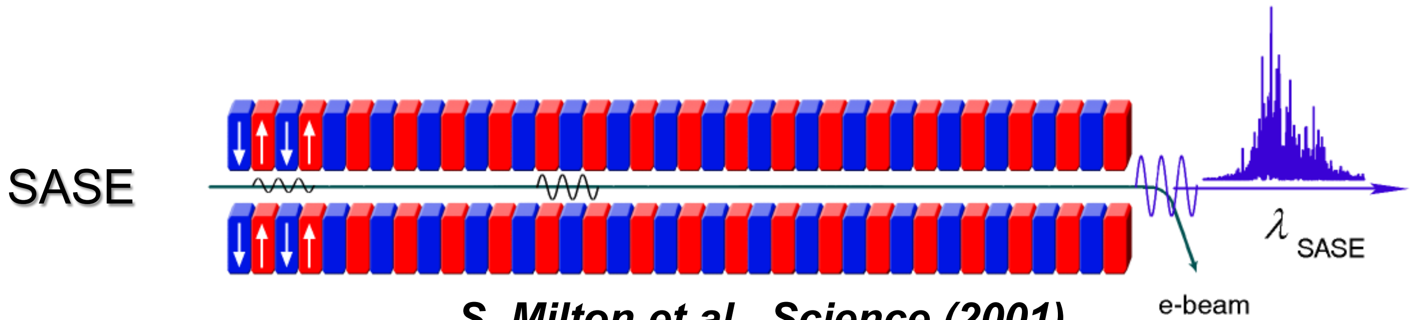
SINAP 中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

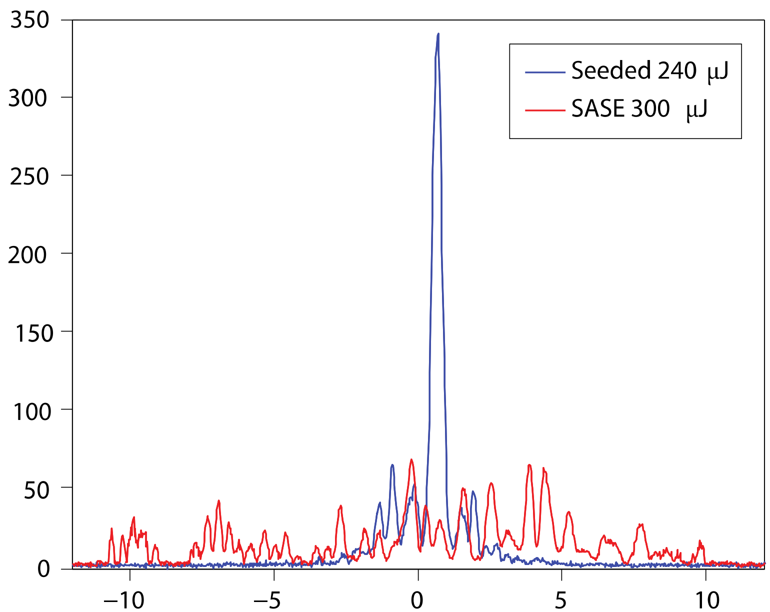
Outline

- **Introduction, & seeding**
- **Phase-merging Enhanced Harmonic Generation (PEHG)**
  - ✓ Phase-merging phenomenon & single-particle dynamics
  - ✓ Alternative schemes
  - ✓ PEHG-FEL and its characteristics
- **PEHG for light sources**
  - ✓ Soft x-ray free-electron laser (SXFEL) @ Shanghai
  - ✓ PEHG-assisted ultrafast pulse generation
  - ✓ Coherent harmonic generation on storage-ring
  - ✓ PEHG & coherent Thomson scattering
- **An experiment proposal at SDUV-FEL**
- **Summary & Outlook**

SASE & advanced schemes



S. Milton et al., Science (2001)

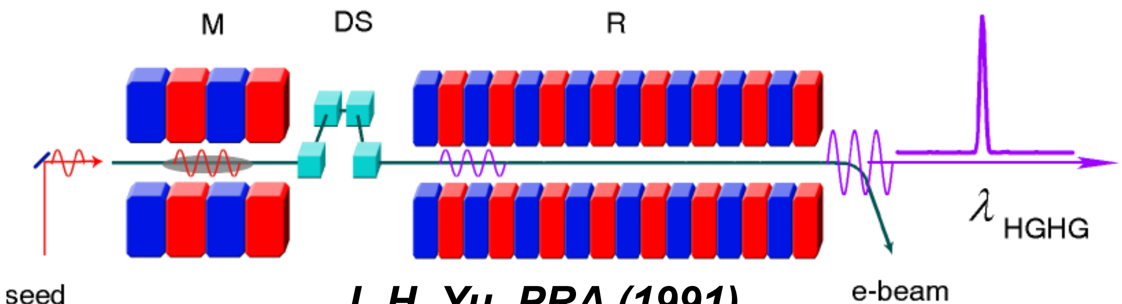


- **Self-seeding**
- **Purified SASE, i-SASE, HB-SASE**
- **FEL amplifier driven by XFELO**

J. Amann et al., Nat. Photonics 6, 693 (2012).
D. Xiang et al., PRST-AB 16 (2013) 010703
B. McNeil et al., PRL 110, 134802 (2013).
J. Wu et al., IPAC13, Shanghai.
H. Deng, C. Feng, IPAC13, Shanghai.

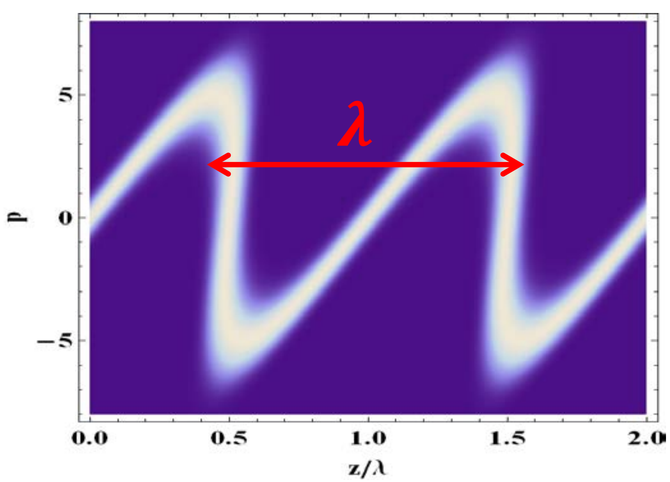
Laser seeding, High-gain harmonic generation

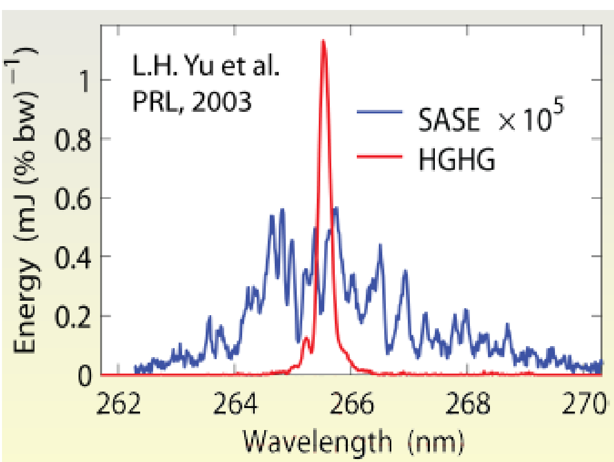
- Induced energy modulation at longer wavelength is changed into harmonic content after compression with a chicane.
- A selected harmonic is picked up with a succeeding undulator.
- FERMI user facility



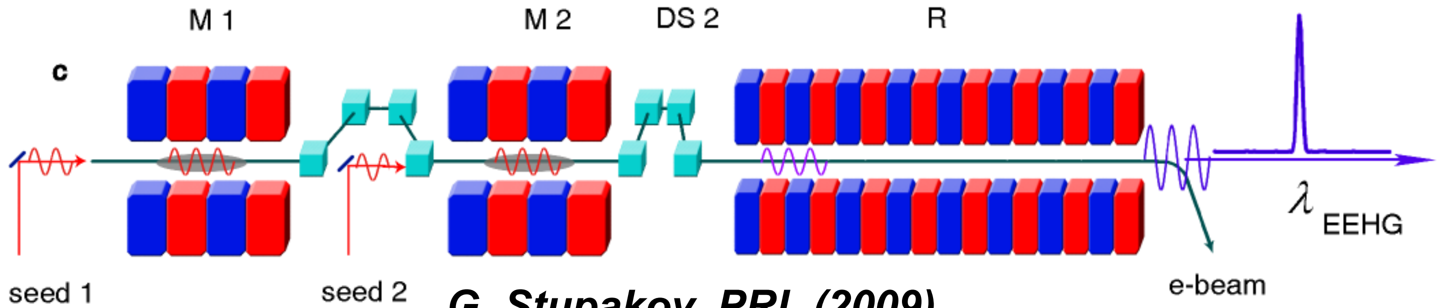
L.H. Yu, PRA (1991)

Cascaded HGHG:
J. Wu, L. H. Yu, NIMA (2001)
B. Liu et al. Phys. Rev. ST-AB (2013)
E. Allaria, et al., Nat. photonics (2013)

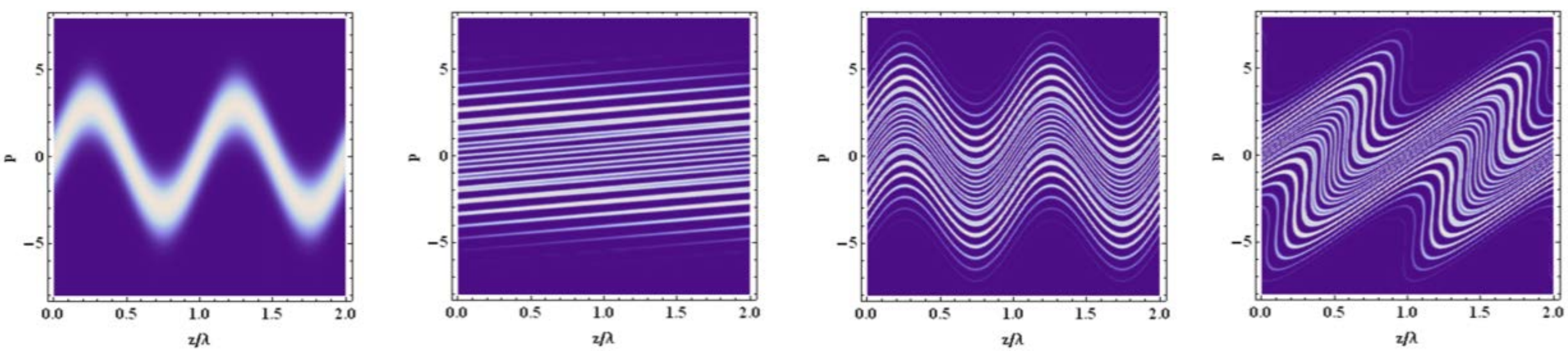




Echo-enabled harmonic generation (EEHG)



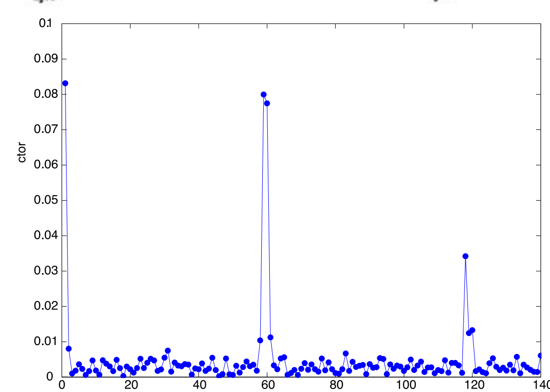
G. Stupakov, PRL (2009)



- ✓ over compression to generate energy bands
- ✓ spacing of bands defines harmonics

High efficiency for bunching

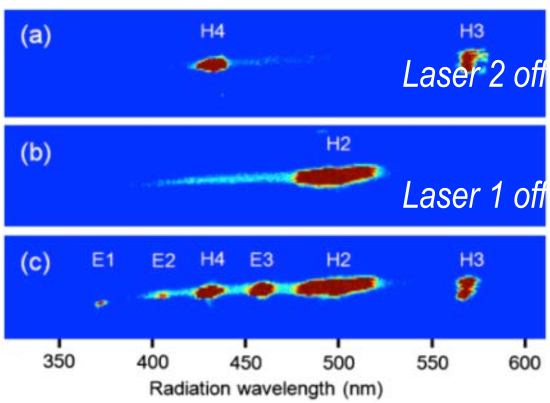
$$b_{\max} = \frac{0.39}{m^{1/3}}$$

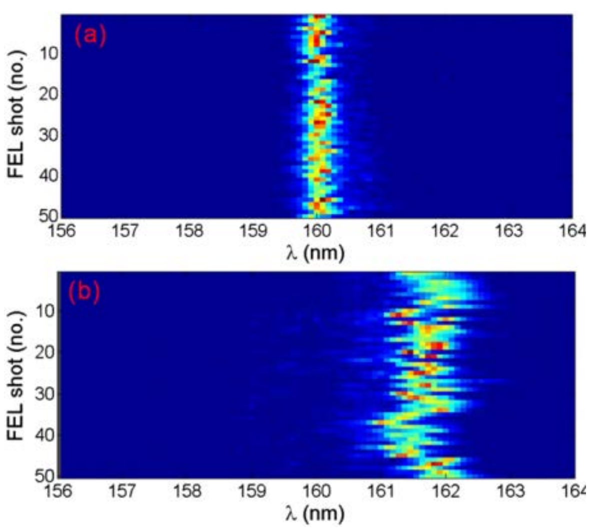


EEHG experiments

D. Xiang et al PRL 105 (2010) 114801

λ_1= 759 nm, λ_2 = 1590 nm

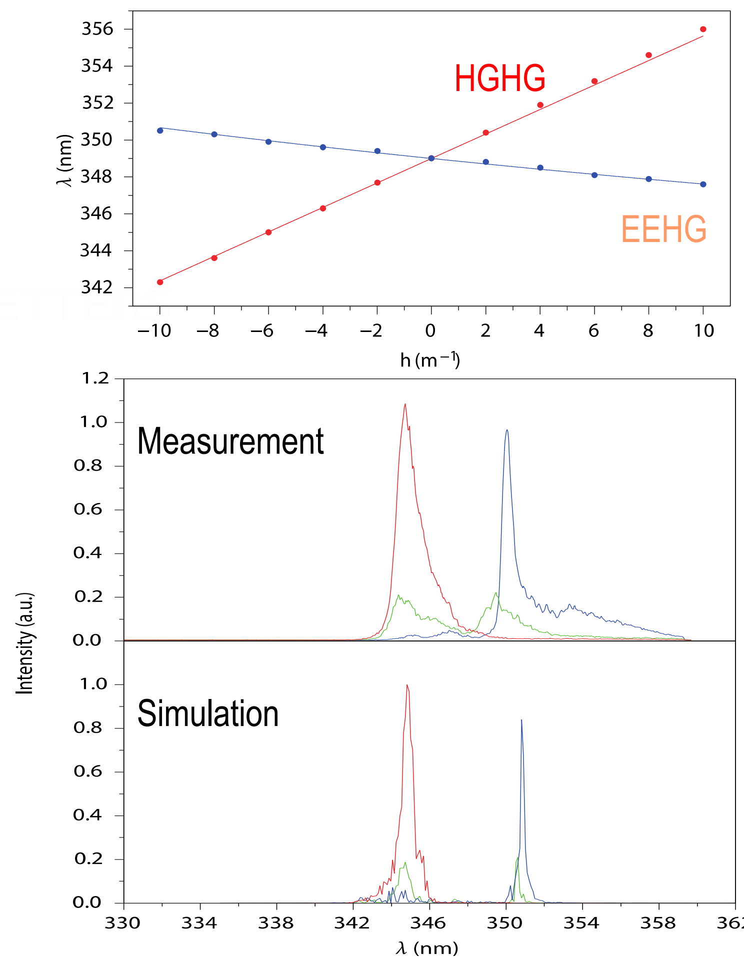




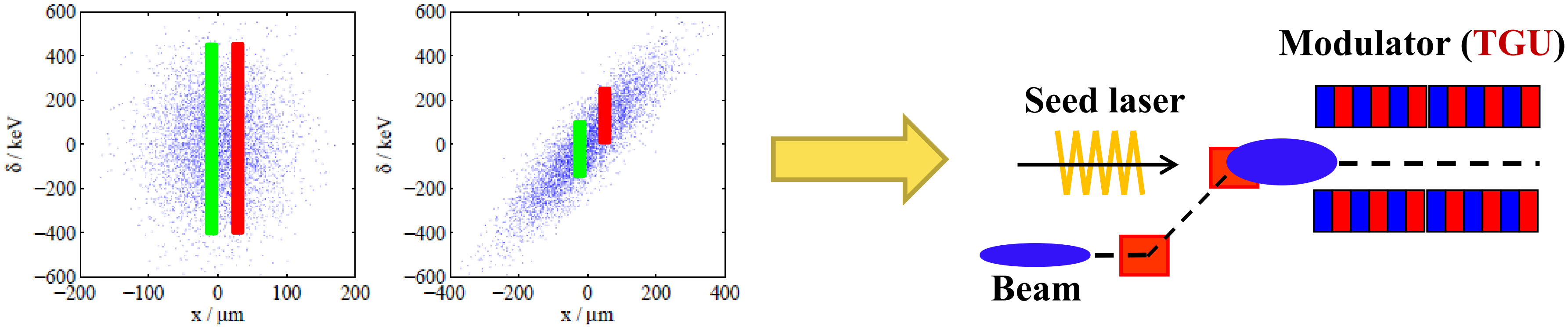
E. Hemsing et al., PRST-AB 17, 070702 (2014)

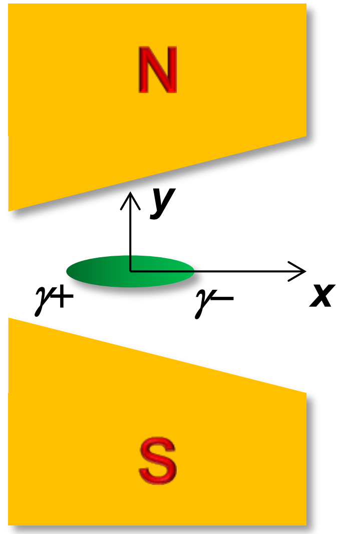
Z.T. Zhao et al Nature Photonics 6 (2012) 360

λ_1= 1047 nm, λ_2 = 1047 nm



Motivation & Initials





- Transverse gradient undulator (TGU)
- Sort e-beam energy by dispersion η

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

- Optimized resonance relationship

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

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

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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

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

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

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

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

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

and N represents the period number of the modulator.

H. Deng*, C. Feng, Phys. Rev. Lett. 111 (2013) 084801.

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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 phenomenon**: 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.

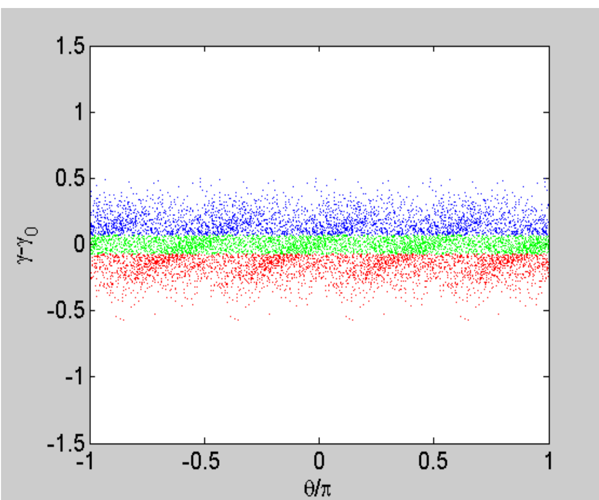
H. Deng, C. Feng, Phys. Rev. Lett. 111 (2013) 084801.*

Phase-merging effect

Some practical numbers:

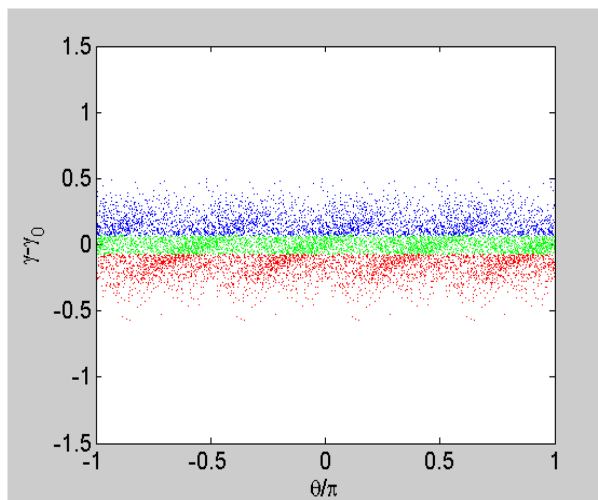
- ✓ Electron beam: *E*=0.84GeV, 100keV slice energy spread.
- ✓ The modulator parameters: period length 80mm × 12, and *K*=5.8.
- ✓ Seed laser wavelength 265nm, energy modulation amplitude 500keV.

Phase-merging condition: $\alpha\eta = 24$



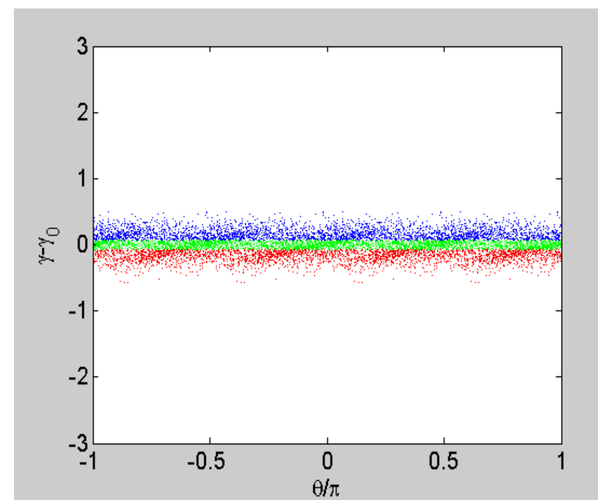
Standard-HGHG

$\alpha\eta = 0$



Phase-merging

$\alpha\eta = 24$



Phase-broadening

$\alpha\eta = 24$, more modulation

Theoretical solution from transfer matrix

$$\begin{pmatrix}\theta(z)\\ \delta(z)\end{pmatrix} = M \begin{pmatrix}\theta(0)\\ \delta(0)\end{pmatrix} \qquad M = \begin{pmatrix} \cos(\Omega z) & \frac{2k_U}{\Omega}(1-Q)\sin(\Omega z) \\ -\frac{\Omega}{2k_U}\sin(\Omega z) & Q+(1-Q)\cos(\Omega z) \end{pmatrix} \qquad Det[M] = 1 - Q(1-\cos(\Omega z))$$

$$\Omega^2 = \frac{\Delta E_e}{E_e}\frac{4\pi}{N_U \lambda_U{}^2} = 0.0974[\mathrm{m}^{-2}], \quad \Omega L = \sqrt{4\pi N_U \frac{\Delta E_e}{E_e}} = 0.2996 \qquad (3.13)$$

The condition for phase merging given by Eq. (3.10) or equivalently by (3.11), is

$$Q = 22.45, \quad \alpha\eta = 23.78 \qquad (3.14)$$

The slope of the phase-merged line is

$$\frac{\delta(L)}{\theta(L)} \equiv s = -\frac{\Omega}{2k_U}\tan(\Omega L) = -6.14\times 10^{-4} \qquad (3.15)$$

K. J. Kim, 4D analysis of phase-merging scheme to improve harmonic efficiency, 2014.

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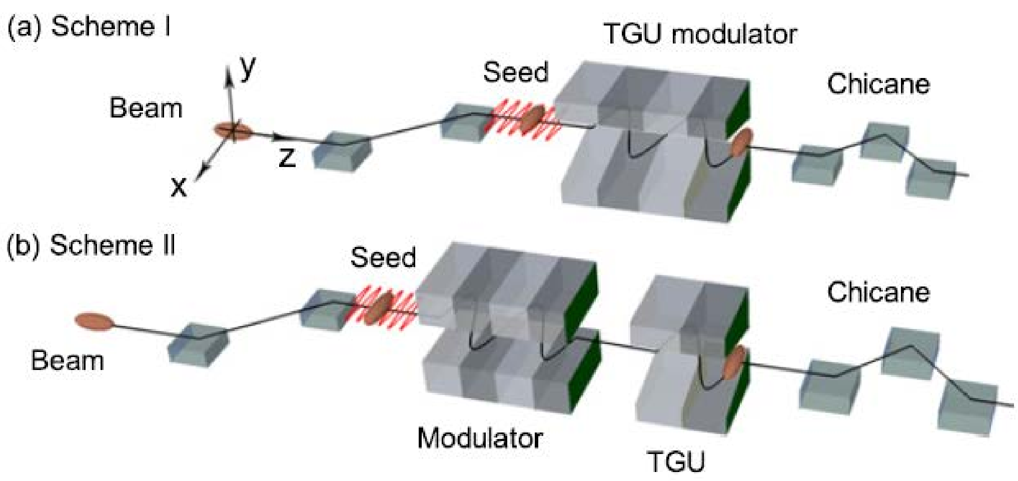
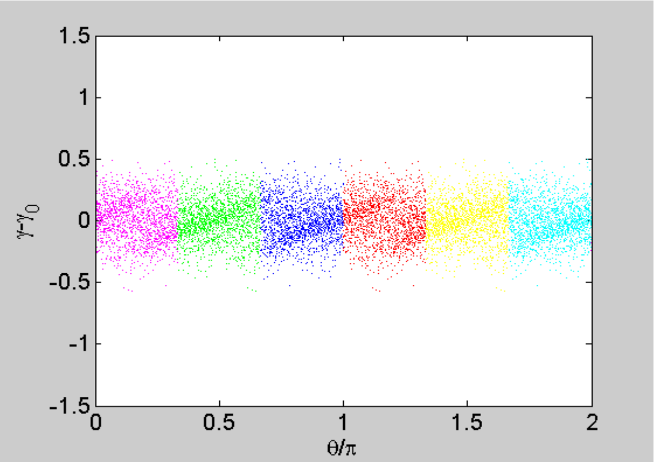
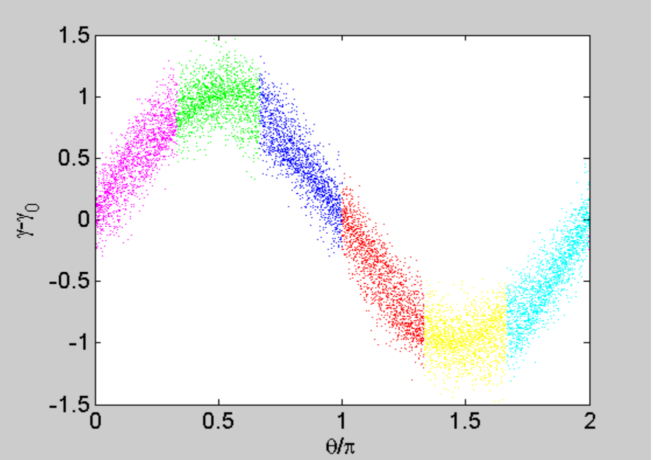
Alternative scheme I







$$\alpha\eta = -\frac{2\gamma^3\left(n + 0.81n^{1/3}\right)}{nAk_sL_mK_0^2\sigma_\gamma}$$

more flexible, smaller *αη* & better performance

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

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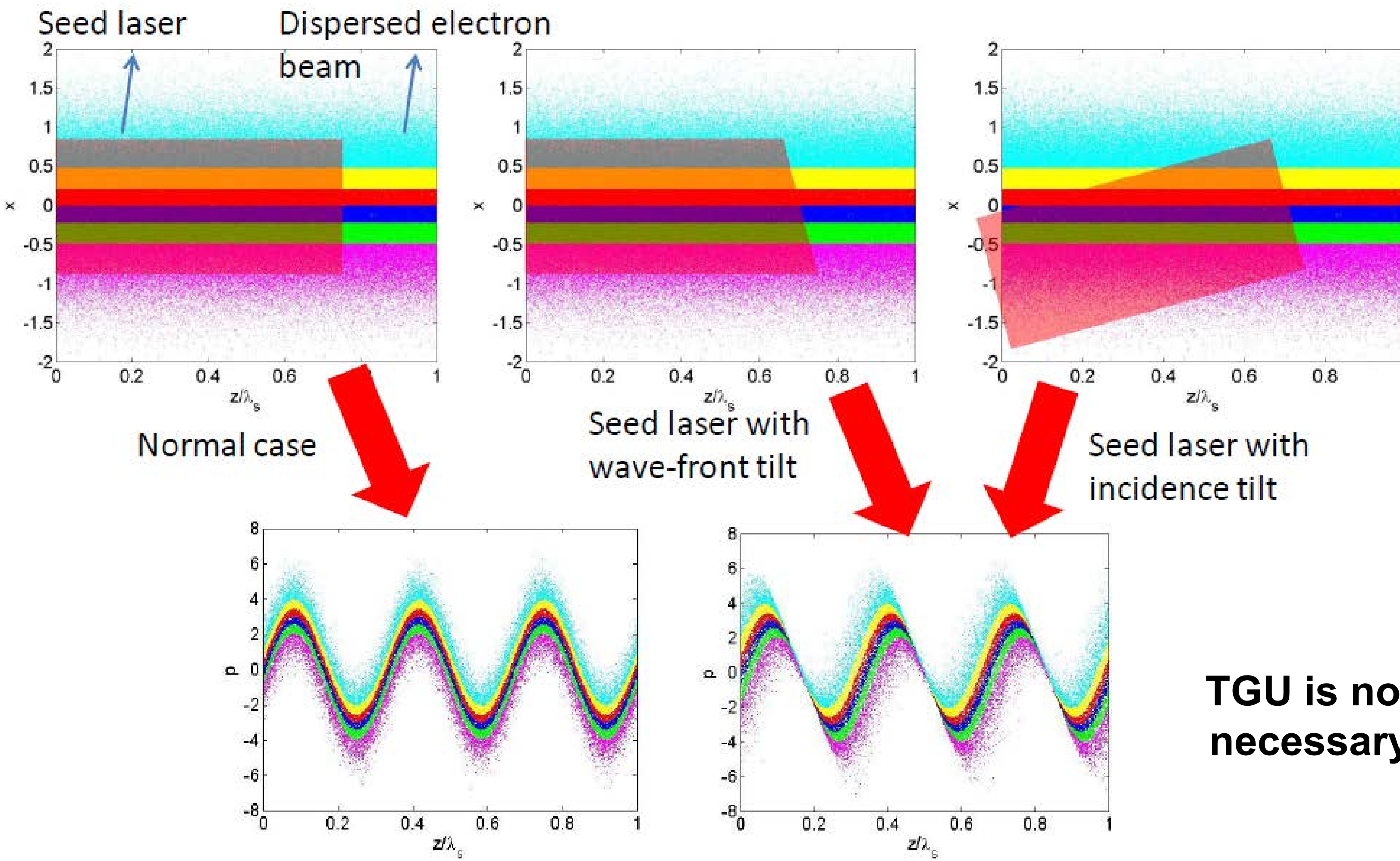
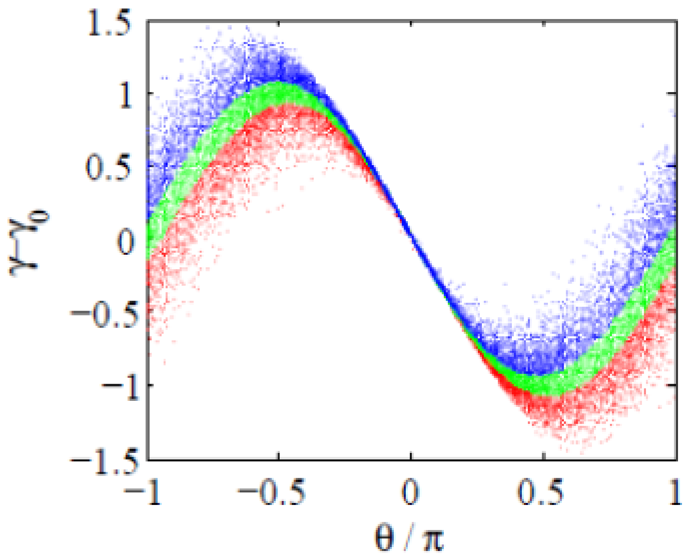
Alternative scheme II

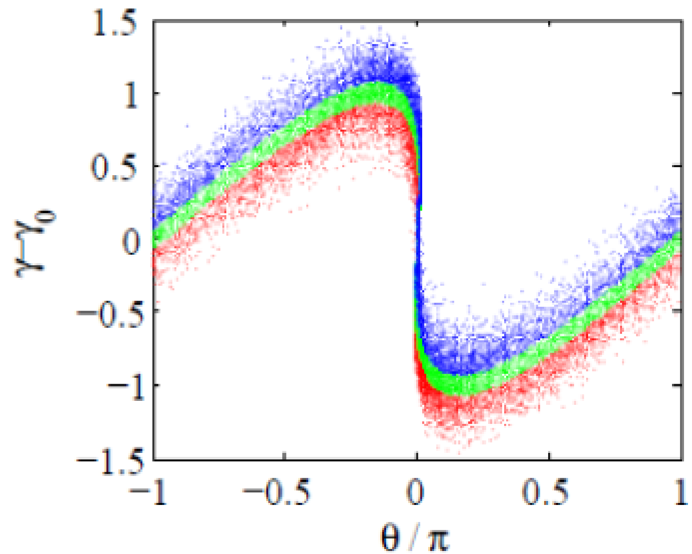


TGU is not necessary

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

Phase-merging Enhanced Harmonic Generation (PEHG)





HGHG bunching

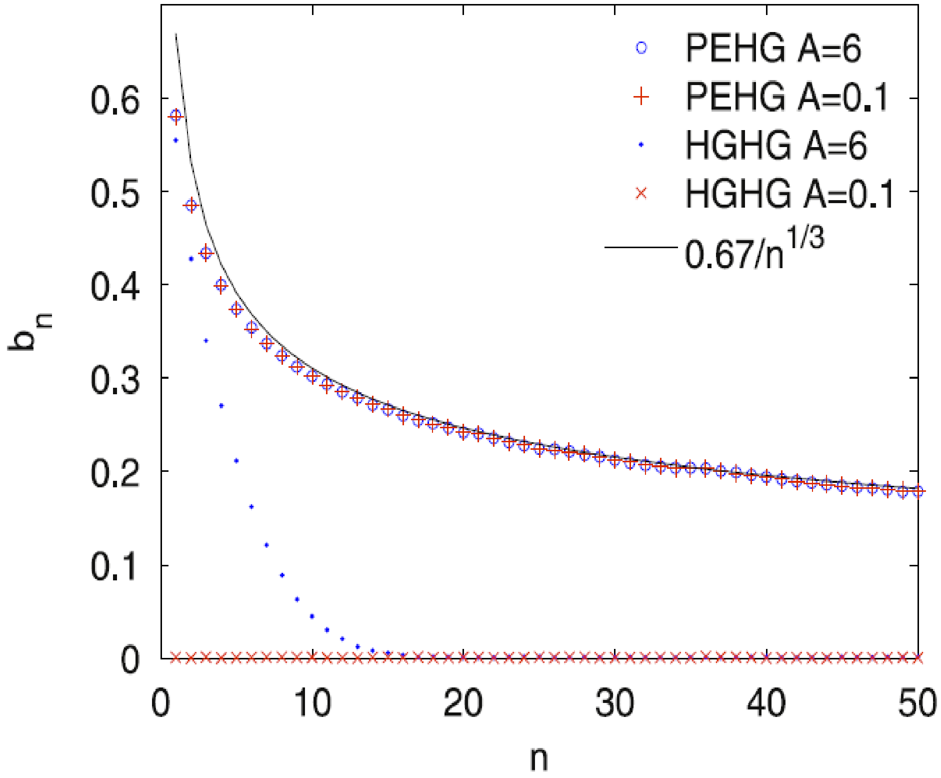
$$b_n = e^{-\frac{n^2D^2\delta^2}{2}} J_n(nD\Delta\gamma)$$

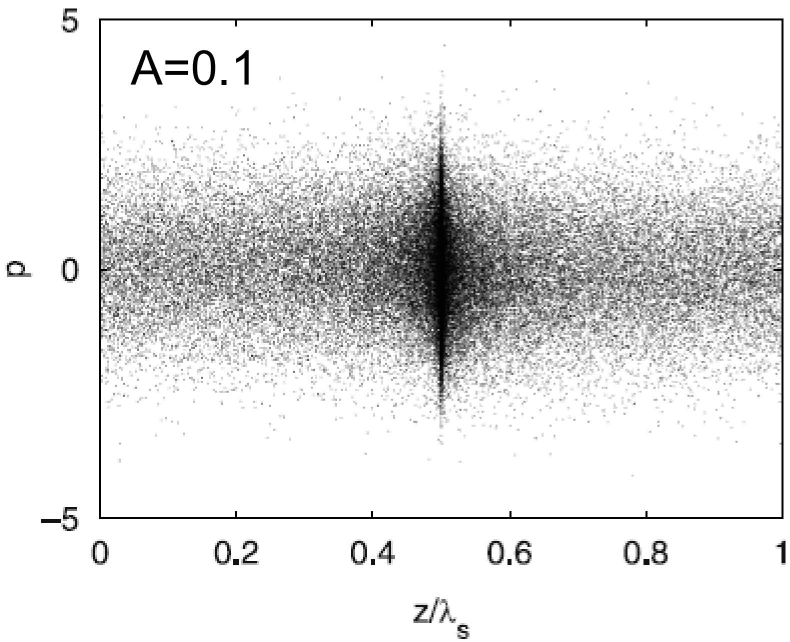
PEHG bunching

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

- The maximum bunching factor scales as $0.67/n^{1/3}$
- The maximum bunching factor is independent on the energy modulation

Phase-merging Enhanced Harmonic Generation (PEHG)



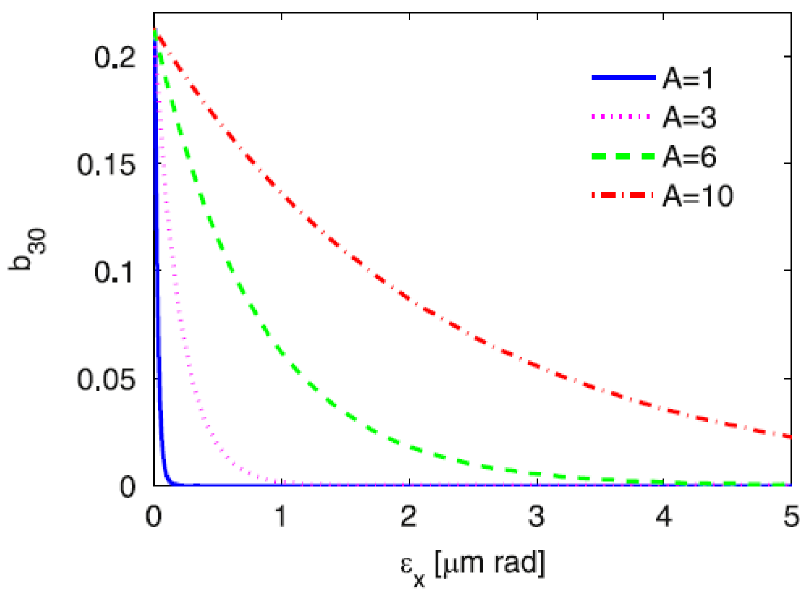


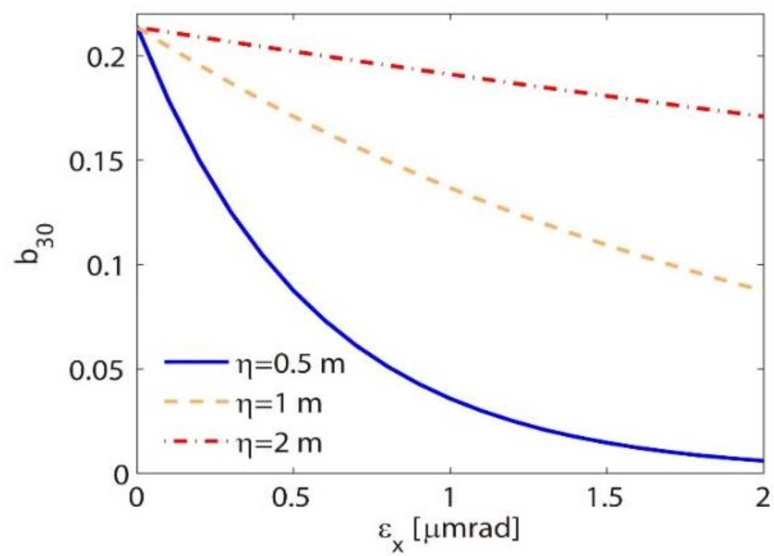
Bunching factor with transverse emittance

$$h_{PEHG}(\zeta, p, \chi) = \frac{N_0}{2\pi} \exp\left\{-\frac{1}{2}\left[p - A\sin(\zeta - T\chi - Bp)\right]^2\right\} \times \exp\left[-\frac{1}{2}\left\{\chi - D\left[p - A\sin(\zeta - T\chi - Bp)\right]\right\}^2\right]$$

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

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

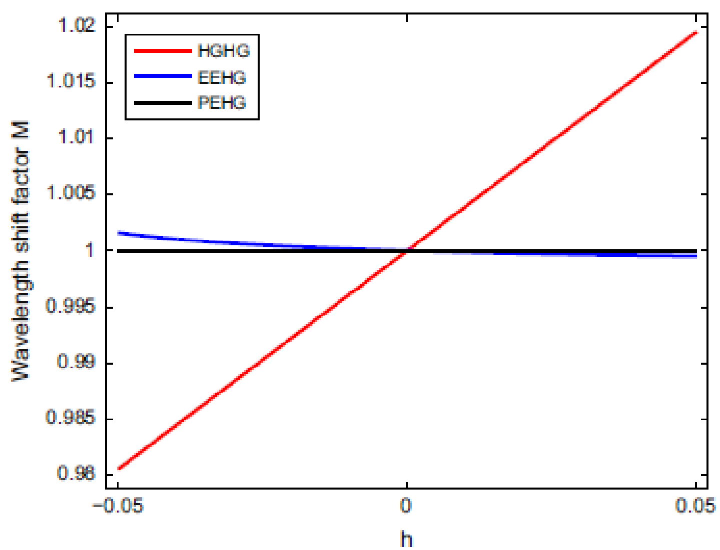


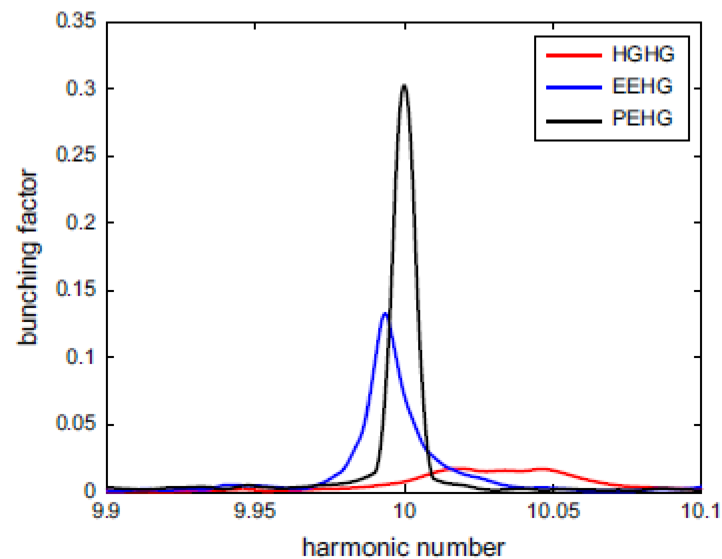


C. Feng, H. Deng*, D. Wang, Z. Zhao, New J. Phys. 16 (2014) 043021

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.

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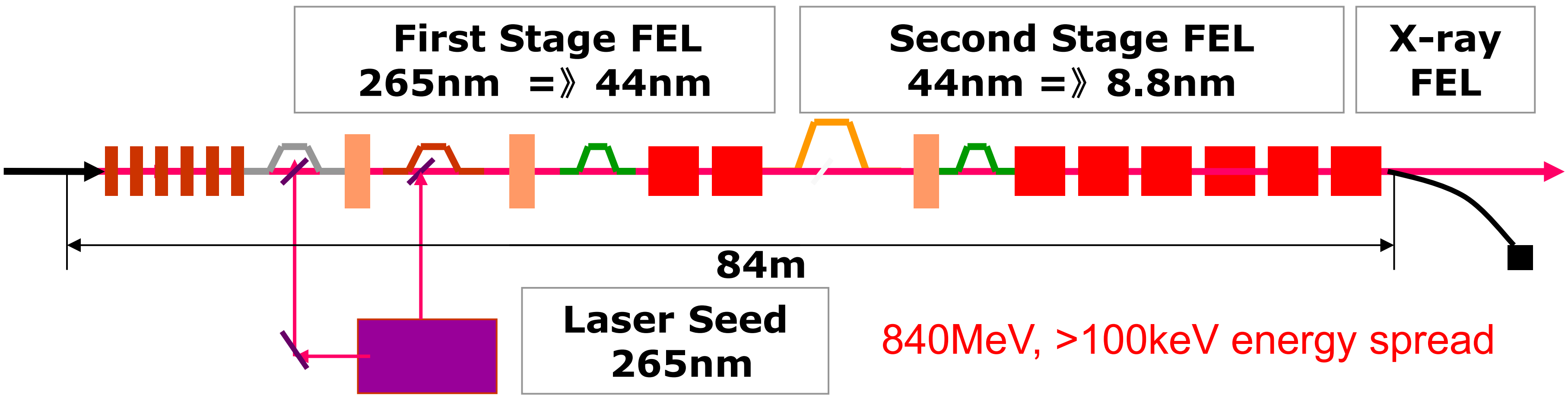
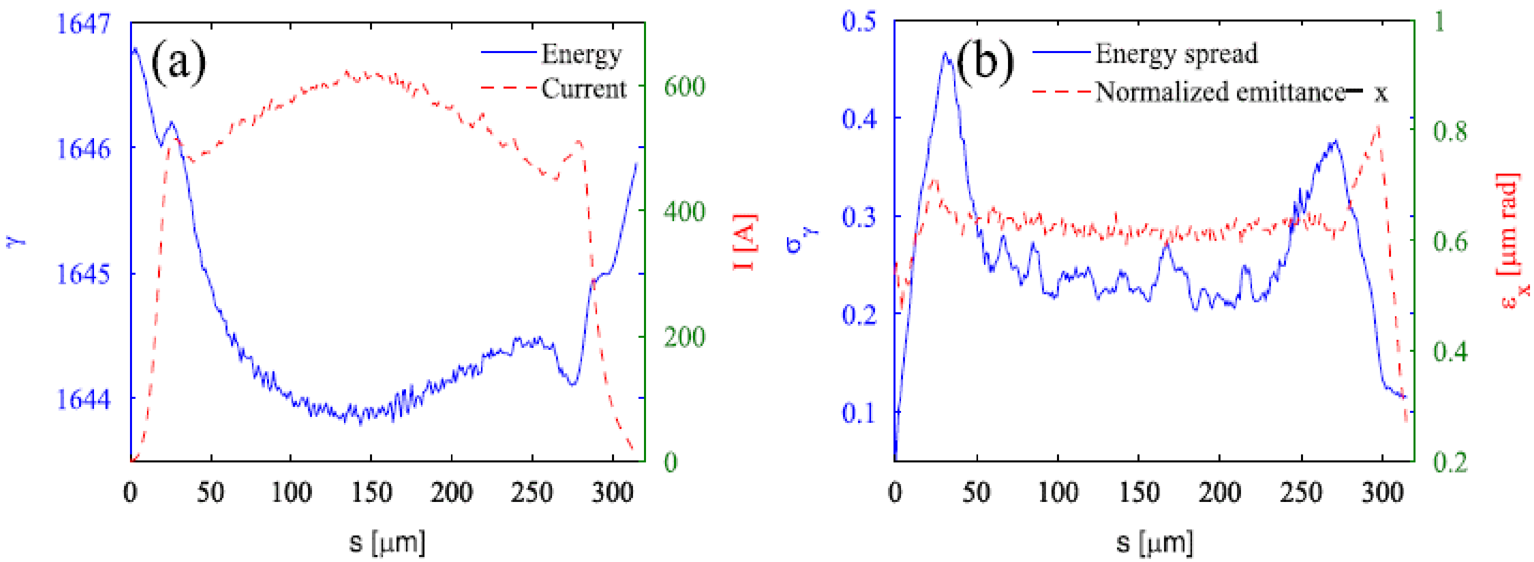
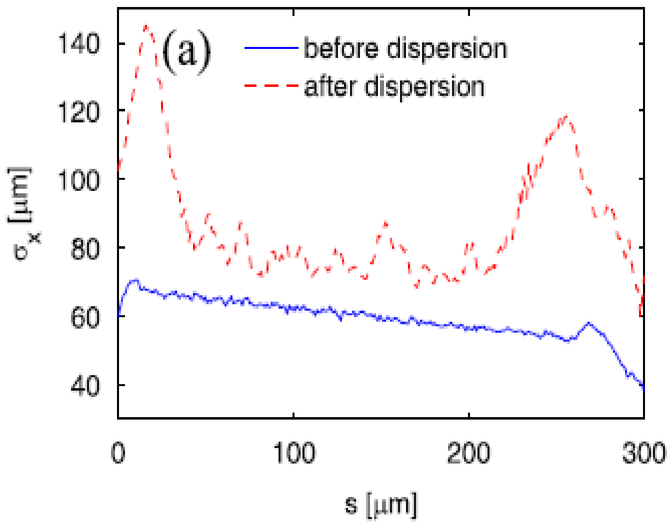
Shanghai soft x-ray free electron laser (SXFEL)



840MeV, >100keV energy spread



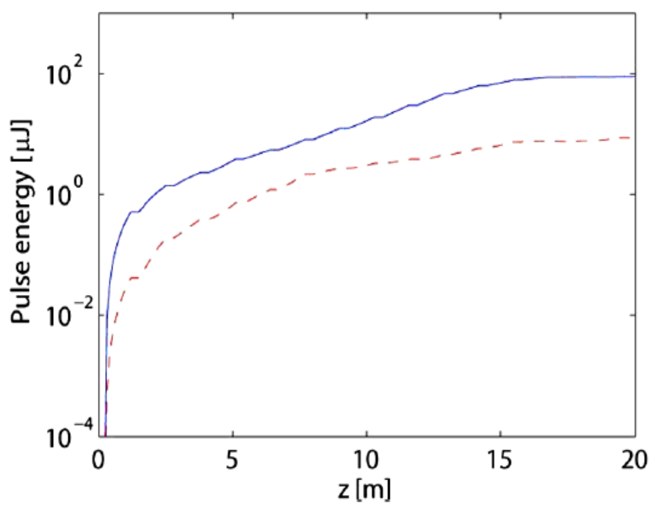
Shanghai soft x-ray free electron laser (SXFEL)

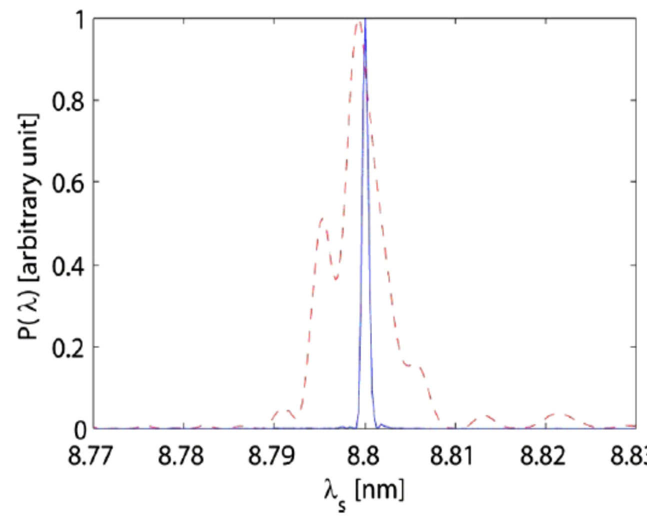


PEHG at 30th harmonic of 265nm.
The peak power at 9nm is 400MW.

Advantages of EEHG:

- ✓ enhance FEL brightness
- ✓ simplify facility design





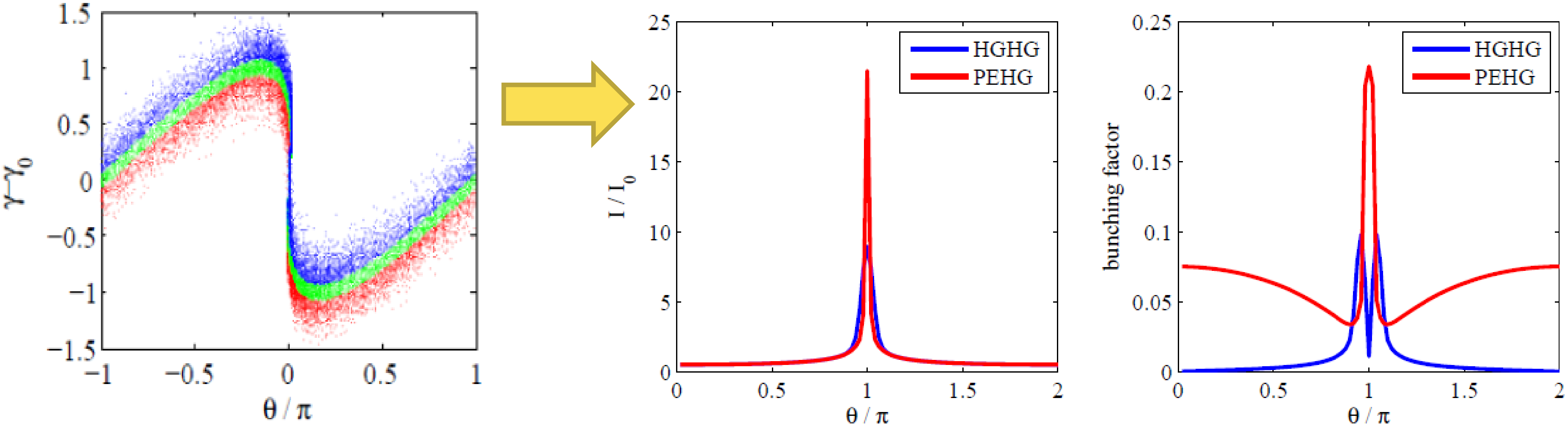
Blue: PEHG , Red: two-stage HGHG

PEHG-assisted ultrafast pulse generation

According to beam density modulation theory (H. Deng et al, Chin. Phys. C 2010), the current & bunching factor distribution in one seed wavelength is

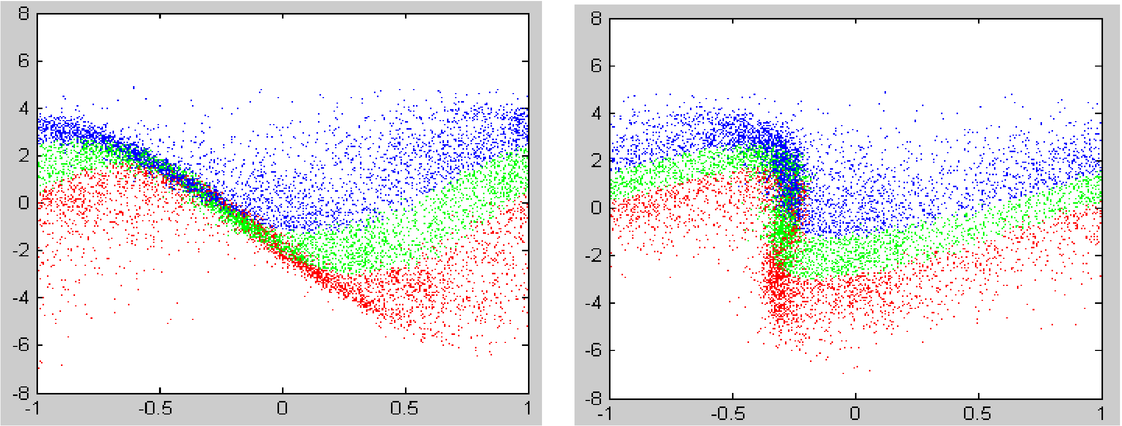
$$I_n(\theta_0, N_2) = 1 + \frac{2n}{\pi}\sum_{m=1}^{\infty} p_m b_m$$

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



H. Deng, C. Feng, T. Zhang et al, 2014, in preparation.

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 6th harmonic is enhanced to 23.0% by PEHG from 1.8% in OK setup.

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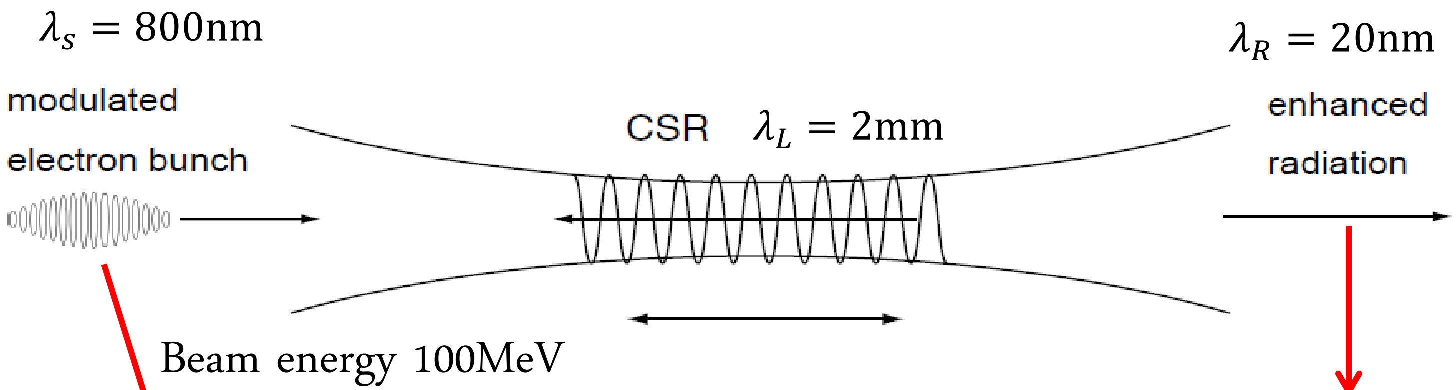
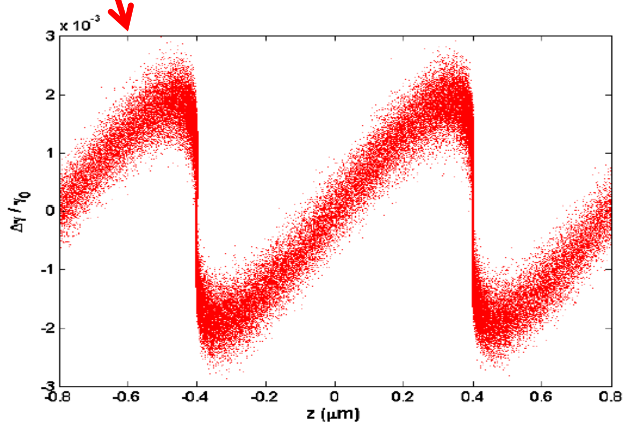
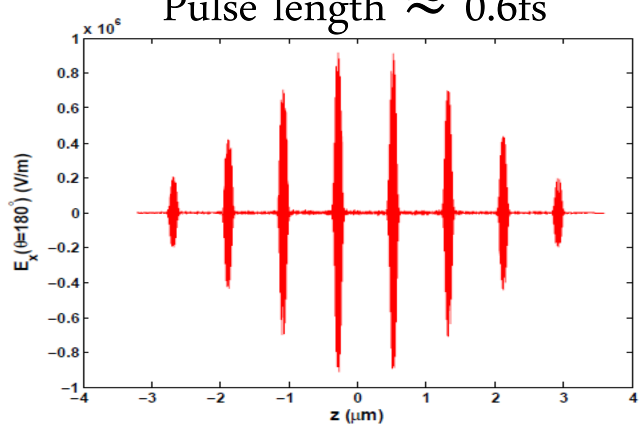
PEHG & coherent Thomson scattering





Ultra-short longitudinal density modulation (by PEHG)

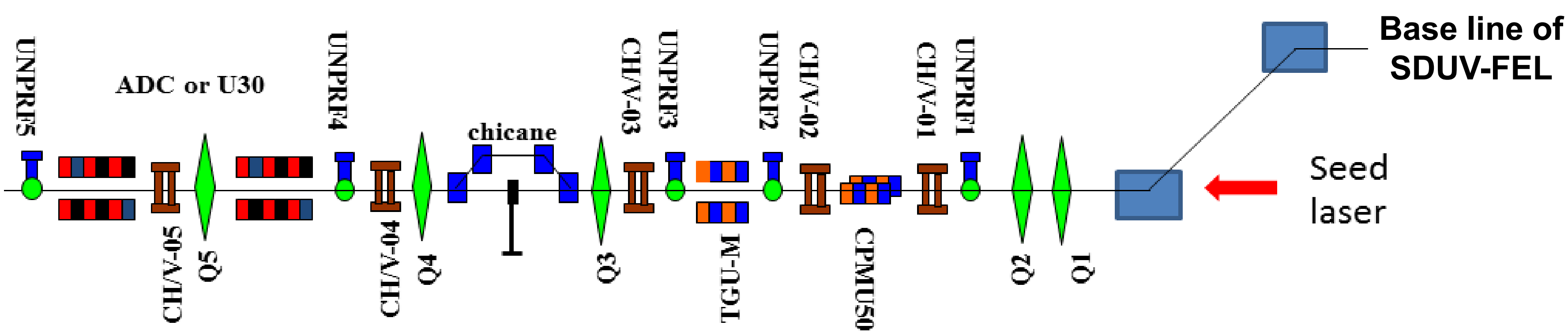


Enhanced radiation pulse (by coherent Thomson scattering)

S. Chen, K. Ohmi et al., 2014

simulation code: tomsan

PEHG experiment at SDUV-FEL

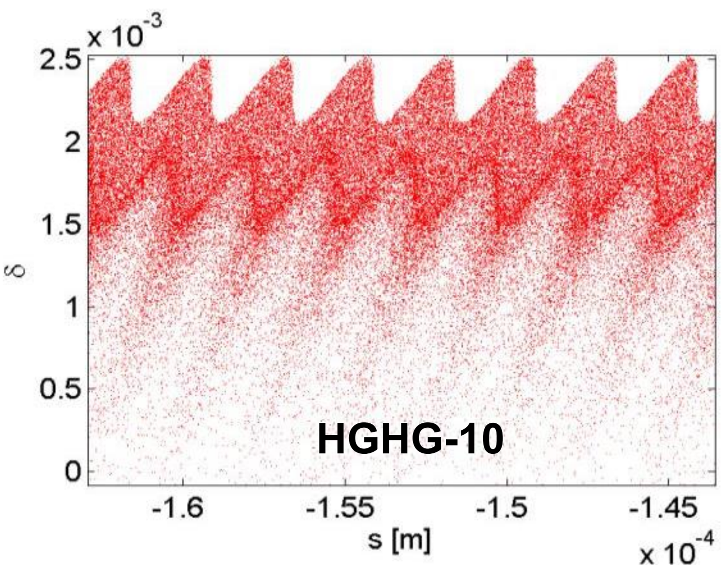


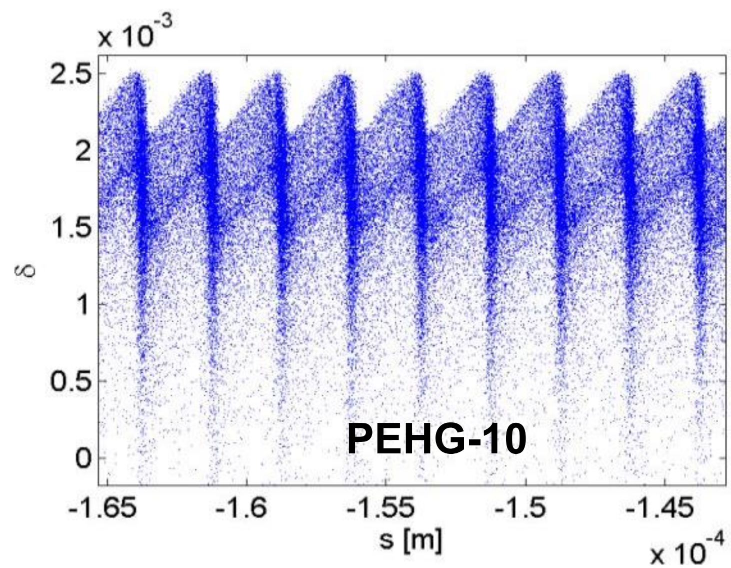
- SDUV-FEL@SINAP is a test bed for FEL novel principles & key technologies for future XFELs.
- A proof-of-principle experiment to demonstrate PEHG is currently being planned at SDUV-FEL.
- A dedicated beam line is proposed to be extracted from the base line of SDUV-FEL, be capable of providing ~2m transverse dispersion.
- Crossed planar undulator is introduced to be more flexible, be able to test different PEHG schemes.

Main parameters & Simulation results

Parameters	Value
Beam energy	160MeV
Beam energy spread	0.1%
Normalized emittance	3mm-mrad
Bunch charge	300pC
Sliced energy spread	10~20keV
Dispersion	1m

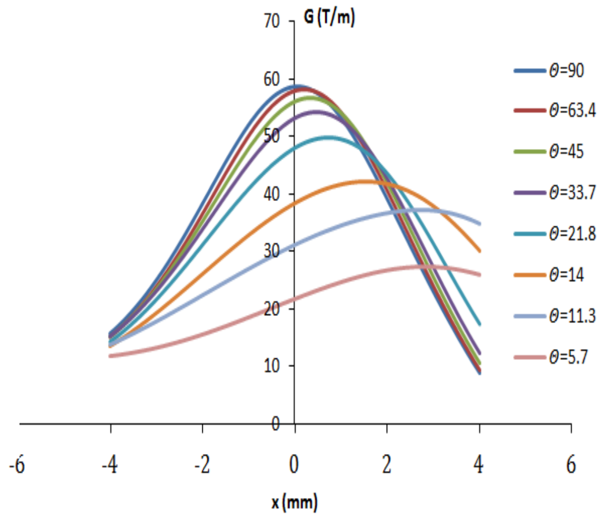
Parameters	Value
Modulator	10*50mm
Seed laser wavelength	2500nm
TGU	10*60mm
Gradient of TGU	36/m
R56 of DS	1~10mm
Radiation wavelength	250nm

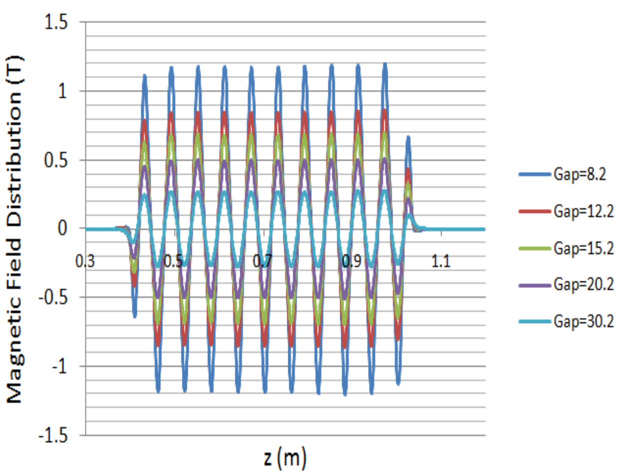


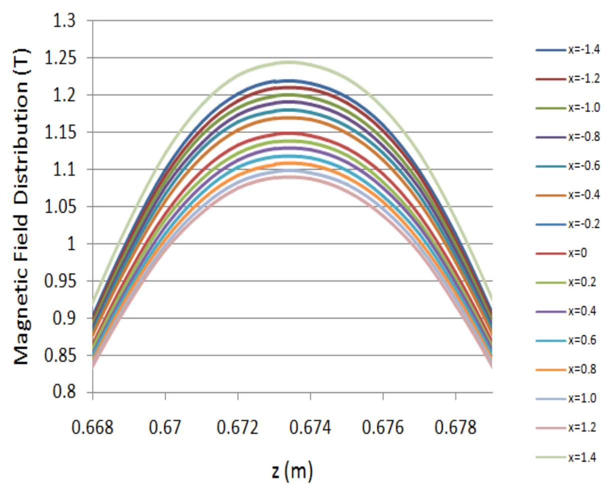


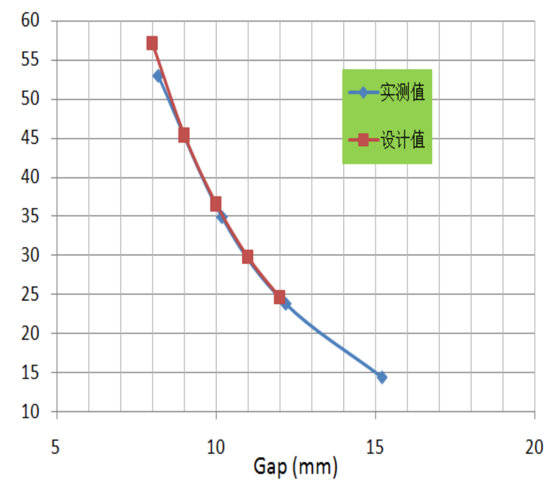
A prototype of TGU60

Chamfer 45°









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Conclusions

- A new phenomenon in laser-beam interaction, so-called “phase-merging” was proposed & studied. Once the door was opened, alternative schemes can be used to achieve the proposed phase-merging phenomenon.
- Phase-merging enhanced harmonic generation (PEHG) FEL is one of the most straightforward application in seeding business. 3D analytical theory and 3D 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).
- Various attractive applications of PEHG is being proposed and studied in light source, i.e., ring-based scheme, coherent Thomson scattering, ultra-fast pulse generation, and polarization control etc.
- A proof-of-principle experiment of PEHG is being planned at Shanghai deep ultraviolet free-electron laser (SDUV-FEL) test facility.

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- Many others.

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Phase-merging Enhanced Harmonic Generation (PEHG)

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Thank you for your attention

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