SINAP

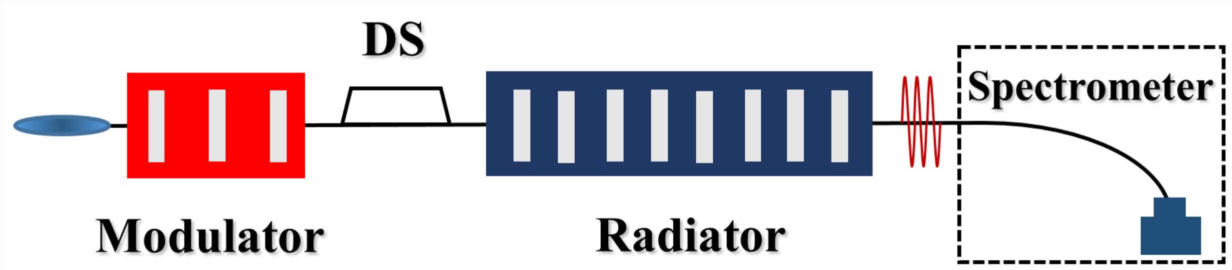
FEL2015 DAEJEON·KOREA

Operating SXFEL in a single-stage high gain harmonic generation scheme

Guanglei Wang

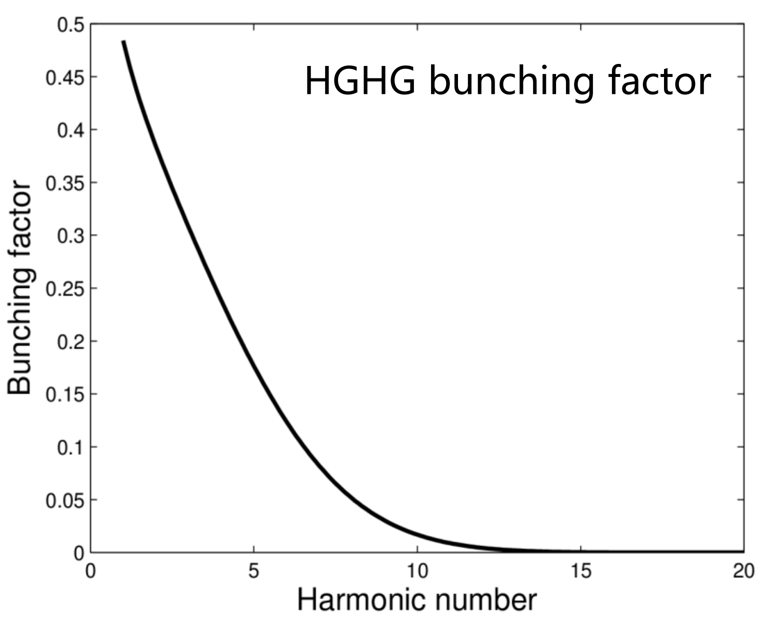
On behalf of the SXFEL and DCLS Team

Principle of HGHG FEL



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

L. H. Yu et al., Science 289, 932 (2000).



Bunching factor: $b_G = J_h(hD\Delta\gamma_s)\exp(-\frac{h^2 D^2 \sigma_E^2}{2})$

Optimal energy modulation : $\Delta\eta = n\sigma$

Limitation : $n\sigma < \rho$

A tradeoff between the energy modulation and the induced energy spread.

Generally, the single-stage harmonic number of HGHG is limited to 5~10.

SXFEL: soft x-ray FEL with seeding

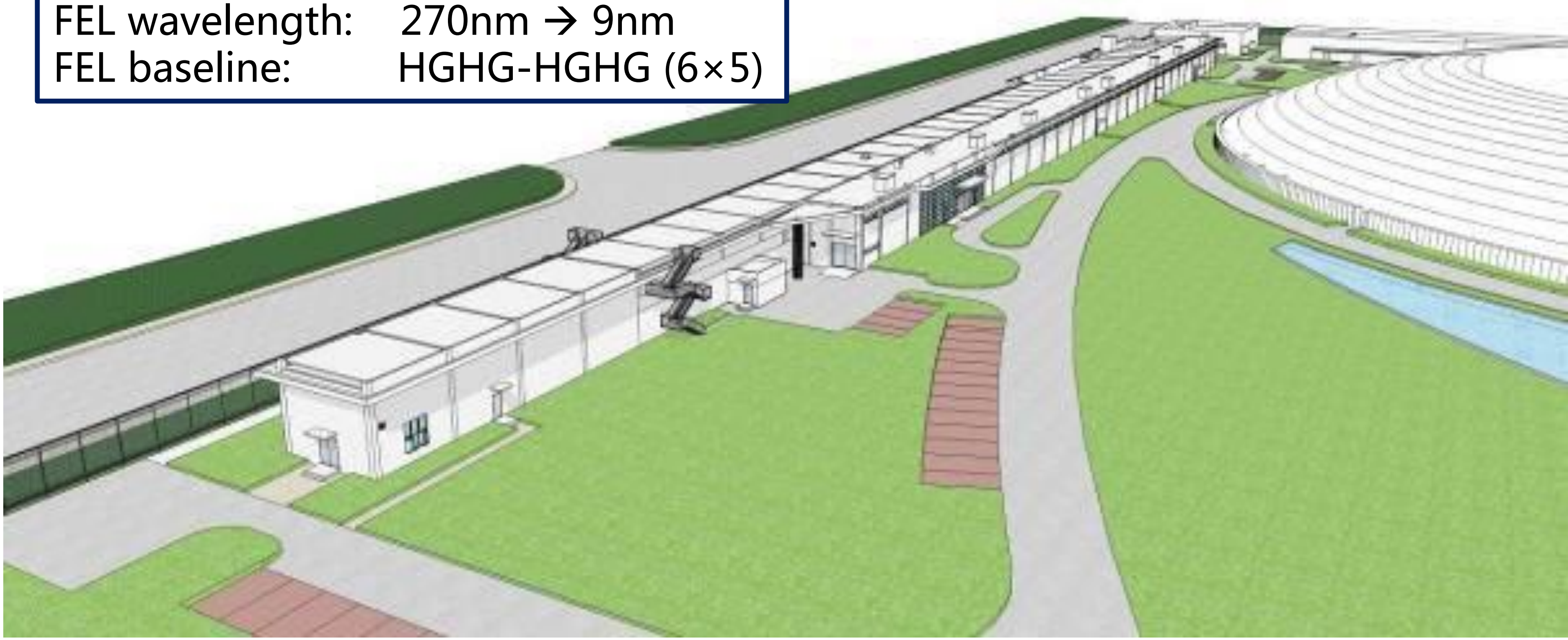
Main goal of the project:

- A R&D prototype of hard X-ray FEL
- User facility in soft X-ray w/ upgrade

Baseline parameters

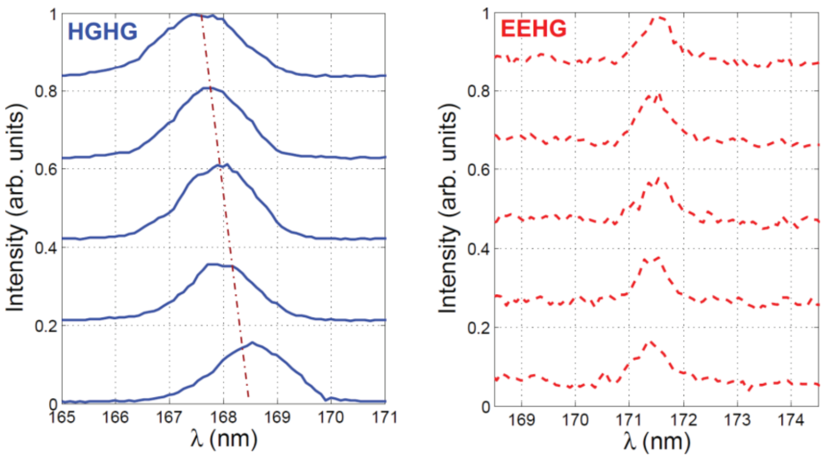
Beam energy:	0.84 GeV
FEL wavelength:	270nm → 9nm
FEL baseline:	HGHG-HGHG (6×5)

Under construction, See Bo Liu, WEA02

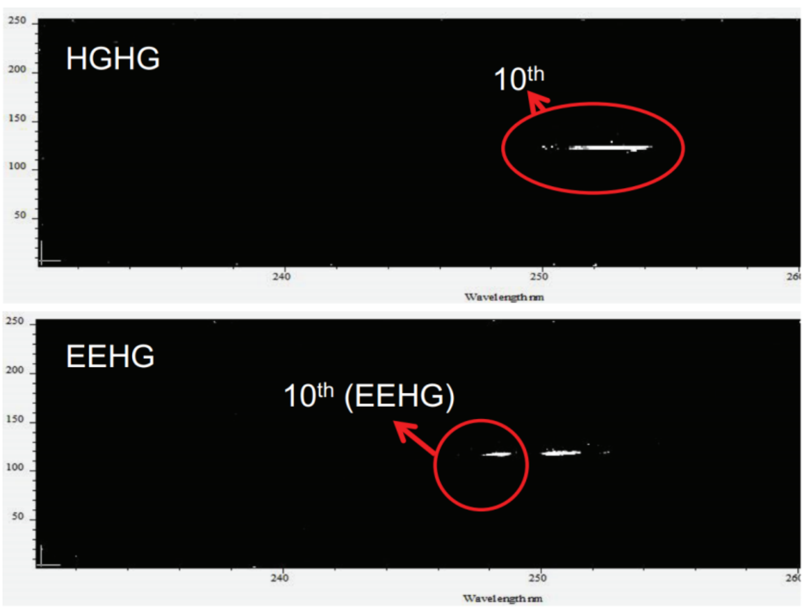


Status of HGHG FEL

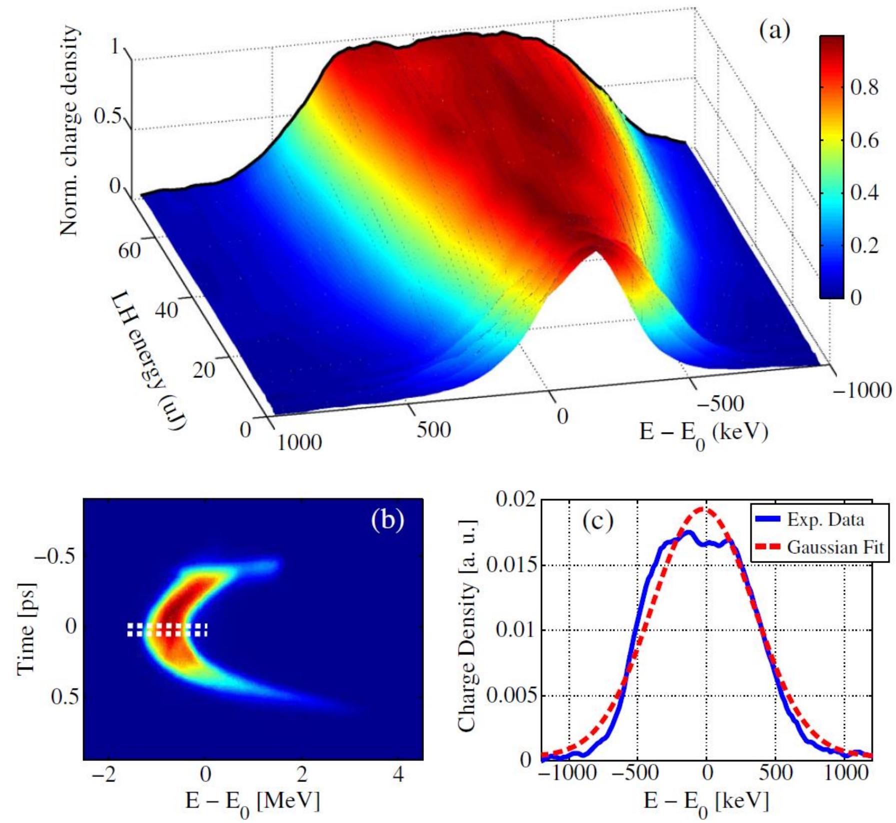
NLCTA@14th



SDUV-FEL@10th



FERMI@15th



assuming perfectly Gaussian pulses. We obtained several tens of microjoules of FEL emission from the 4th harmonic of the seed (65 nm) down to the 13th harmonic (20 nm). Clear evidence of coherent emission was also observed at the 15th harmonic (17 nm). The measured harmonic conversion slightly exceeds the

E. Ferrari, et al., Phys. Rev. Lett. 112, 114802 (2014).

Status of seeded FEL schemes

	EEHG	PEHG	HGHG
Configuration	M+D+M+D+R	D+M+D+R	M+D+R
Harmonics predicted	10~100	10-100	5-10
Harmonics Experimentally demonstrated	3rd - 45th (SLAC/SINAP)	NA (SINAP)	2nd - 15th (BNL/SINAP/SLAC/FERMI)
User operation	NA	NA	√
SXFEL operation (30th harmonic) with single-stage	√	√	?

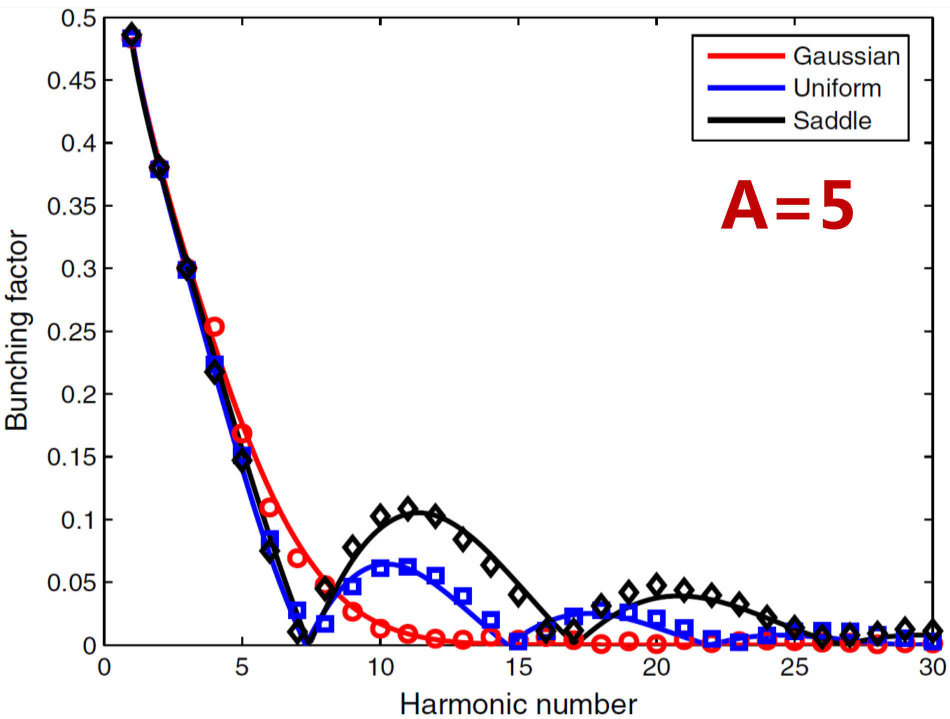
HGHG bunching factor

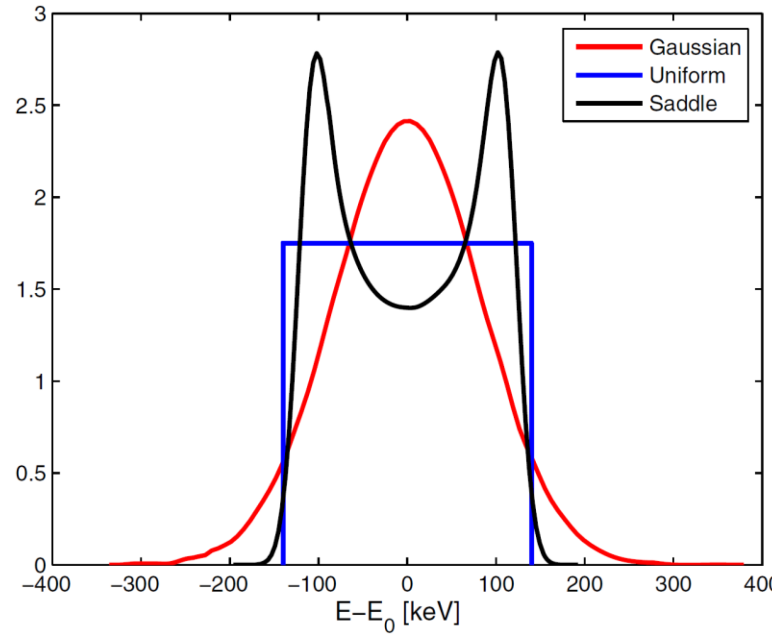
$$b = J_h(h\Delta\gamma_s D)\int d\,p f(p) e^{-ihD\sigma_E p}$$

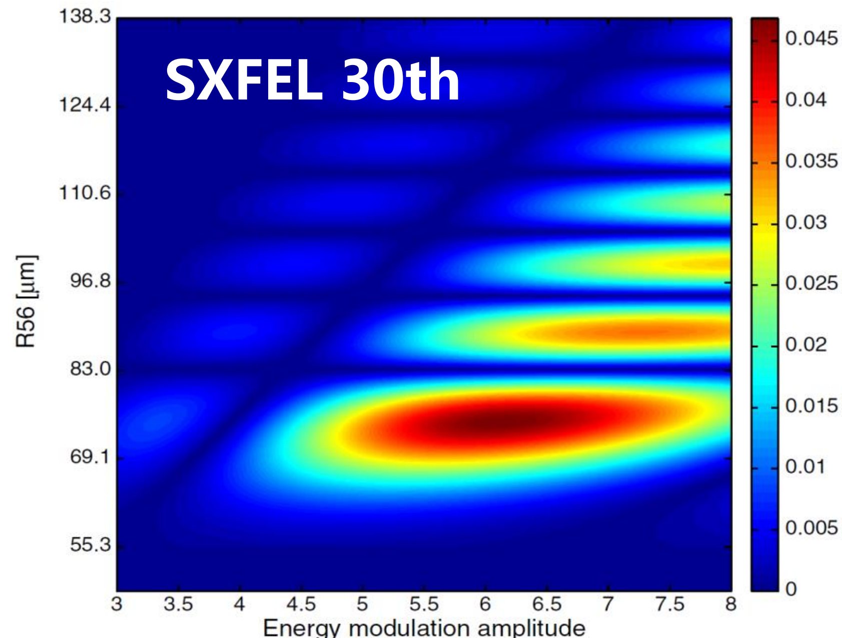
$$b_G = J_h(hD\Delta\gamma_s)\exp(-\frac{h^2D^2\sigma_E^2}{2})$$

$$b_S = |J_h(hD\Delta\gamma_s)\exp(-\frac{h^2\sigma_H^2C^2D^2}{2}) \times J_0(hCD\Delta\gamma_h)|$$

$$b_U = J_h(hD\Delta\gamma_s)|Sinc(hD\,\tau/2)|$$



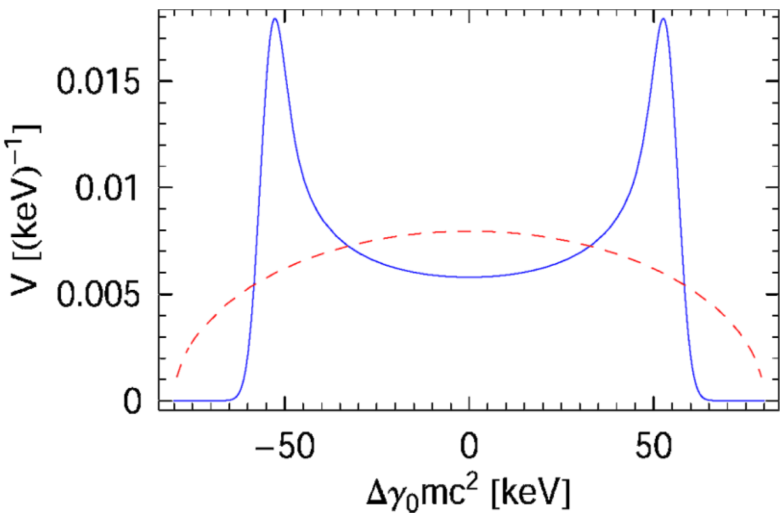




Beam energy distribution in LINAC

$$V(\Delta\gamma_0) = 2\pi \int r dr \int d\, z_0 f_0(z_0, \Delta\gamma_0, r)$$

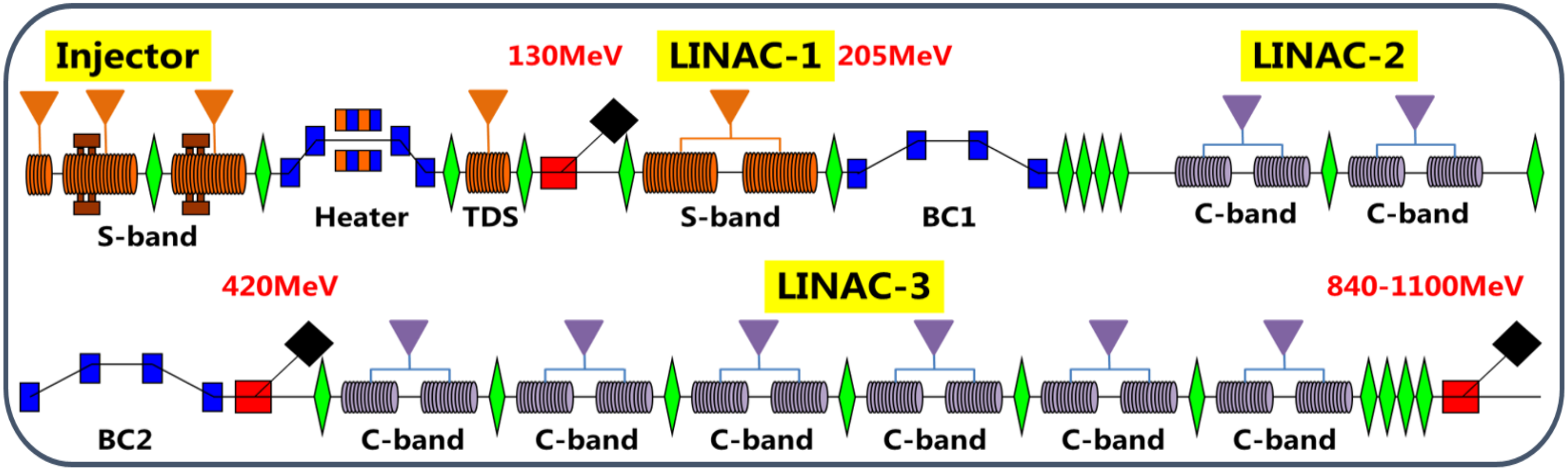
$$= \frac{1}{\pi\sigma_x^2\sqrt{2\pi}\sigma_{\gamma_0}} \int r dr \exp(-\frac{r^2}{2\sigma_x^2}) \int \frac{d\xi}{\sqrt{\Delta\gamma_L(r)^2 - (\Delta\gamma_0 - \xi)^2}} \exp(-\frac{\xi^2}{2\sigma_{\gamma_0}^2})$$



Electron energy distribution after laser heater.

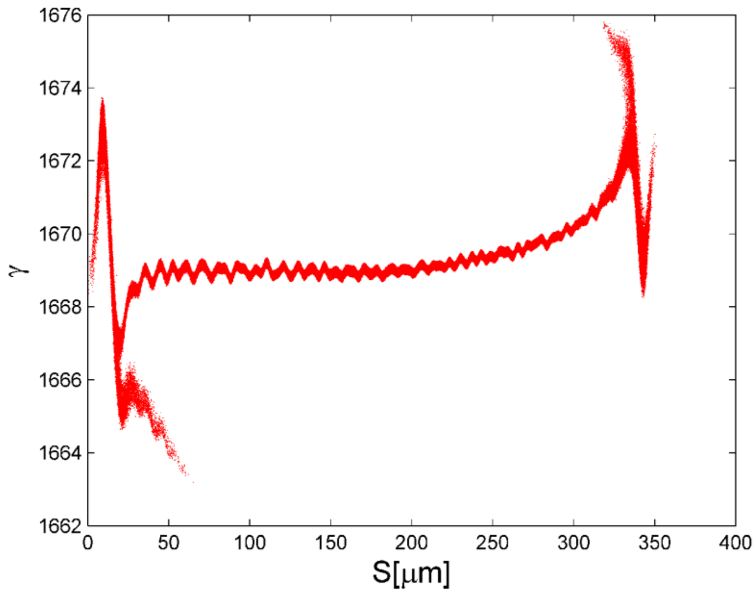
- A large laser spot (blue solid curve)
- A matched laser spot (red dashed curve).

Z. Huang, et al., Phys. Rev. ST Accel. Beams 7, 074401 (2004).

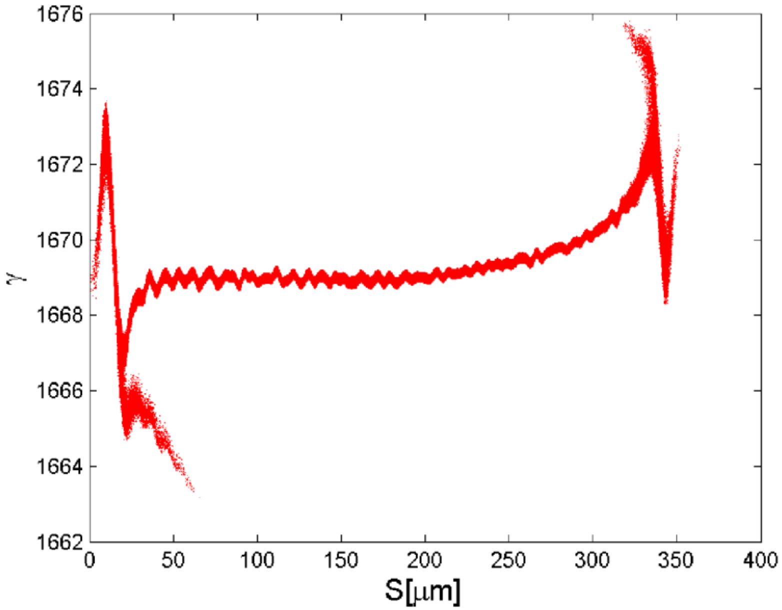


Beam energy distribution in LINAC

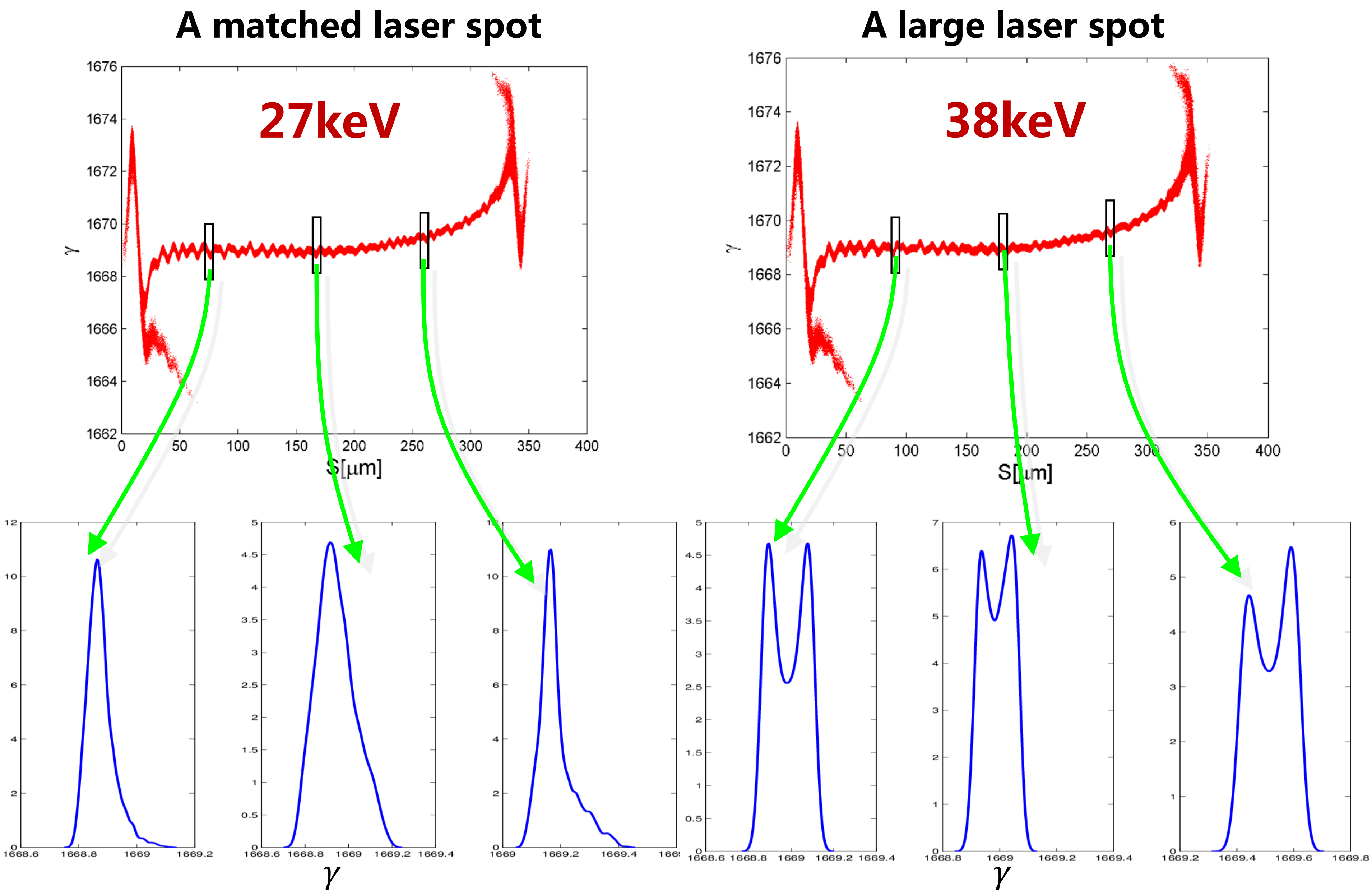
A matched laser spot



A large laser spot

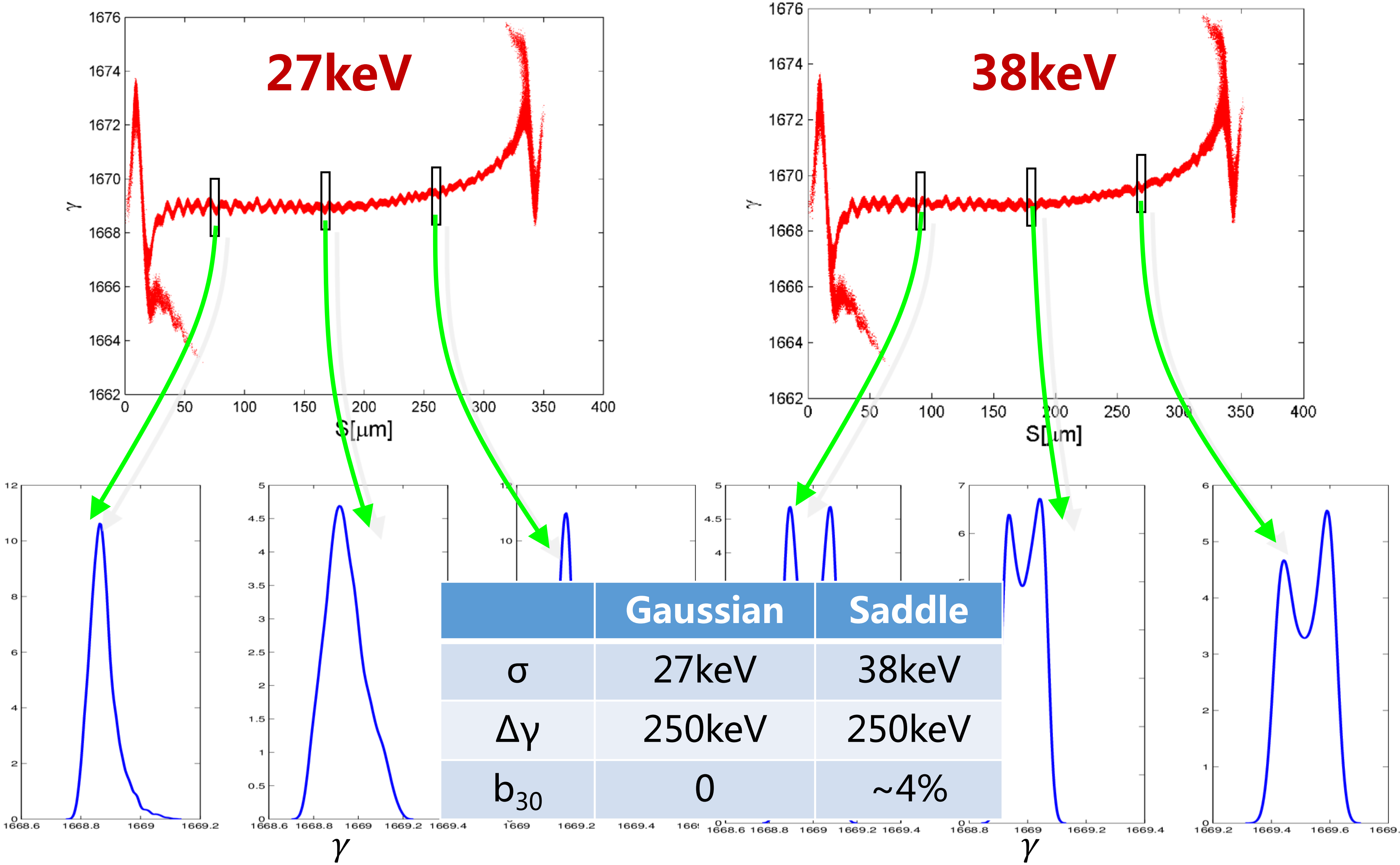


Beam energy distribution in LINAC



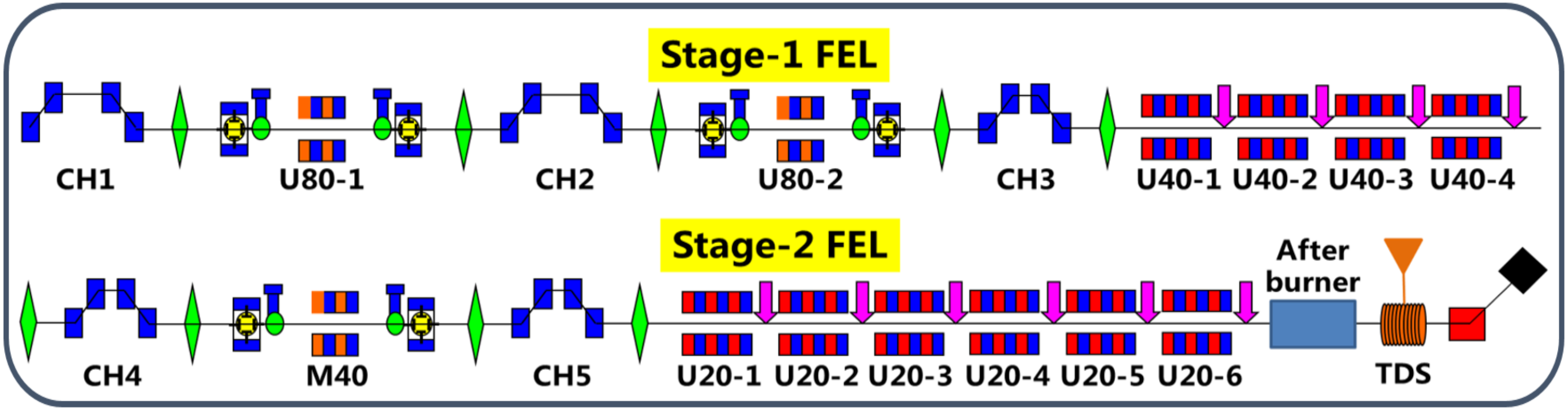
Beam energy distribution in LINAC

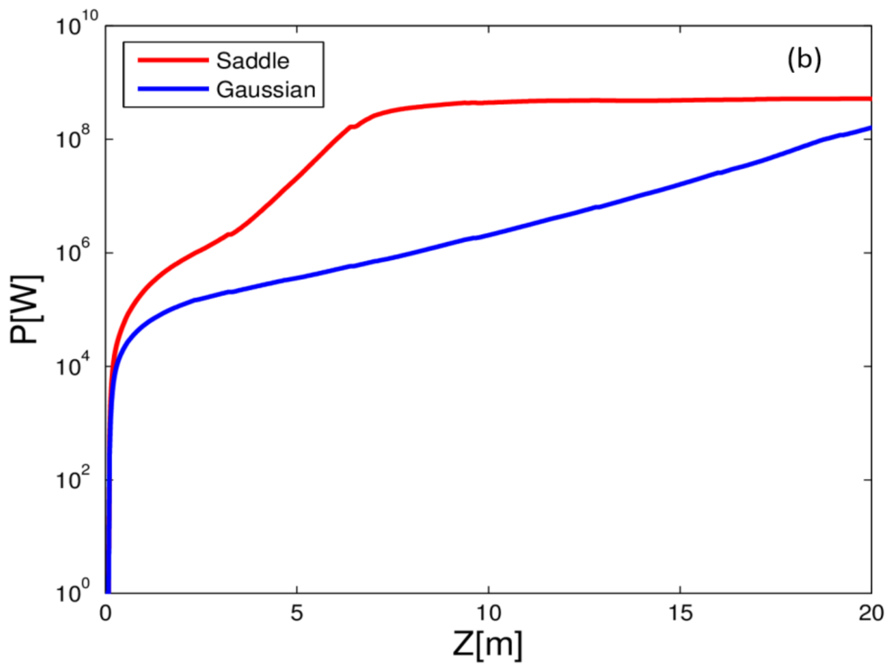
A matched laser spot | **A large laser spot**

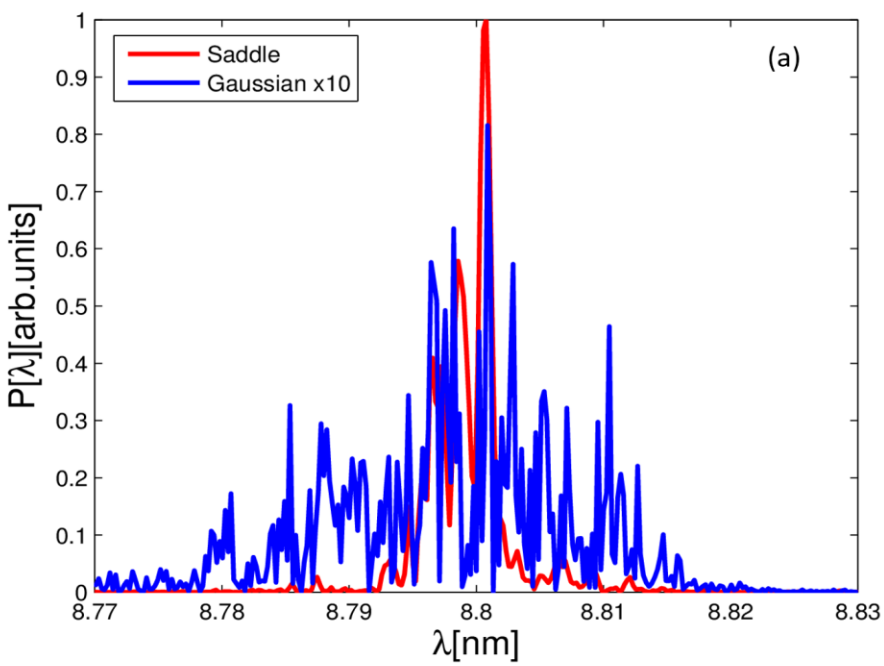


	Gaussian	Saddle
σ	27keV	38keV
Δγ	250keV	250keV
b_{30}	0	~4%

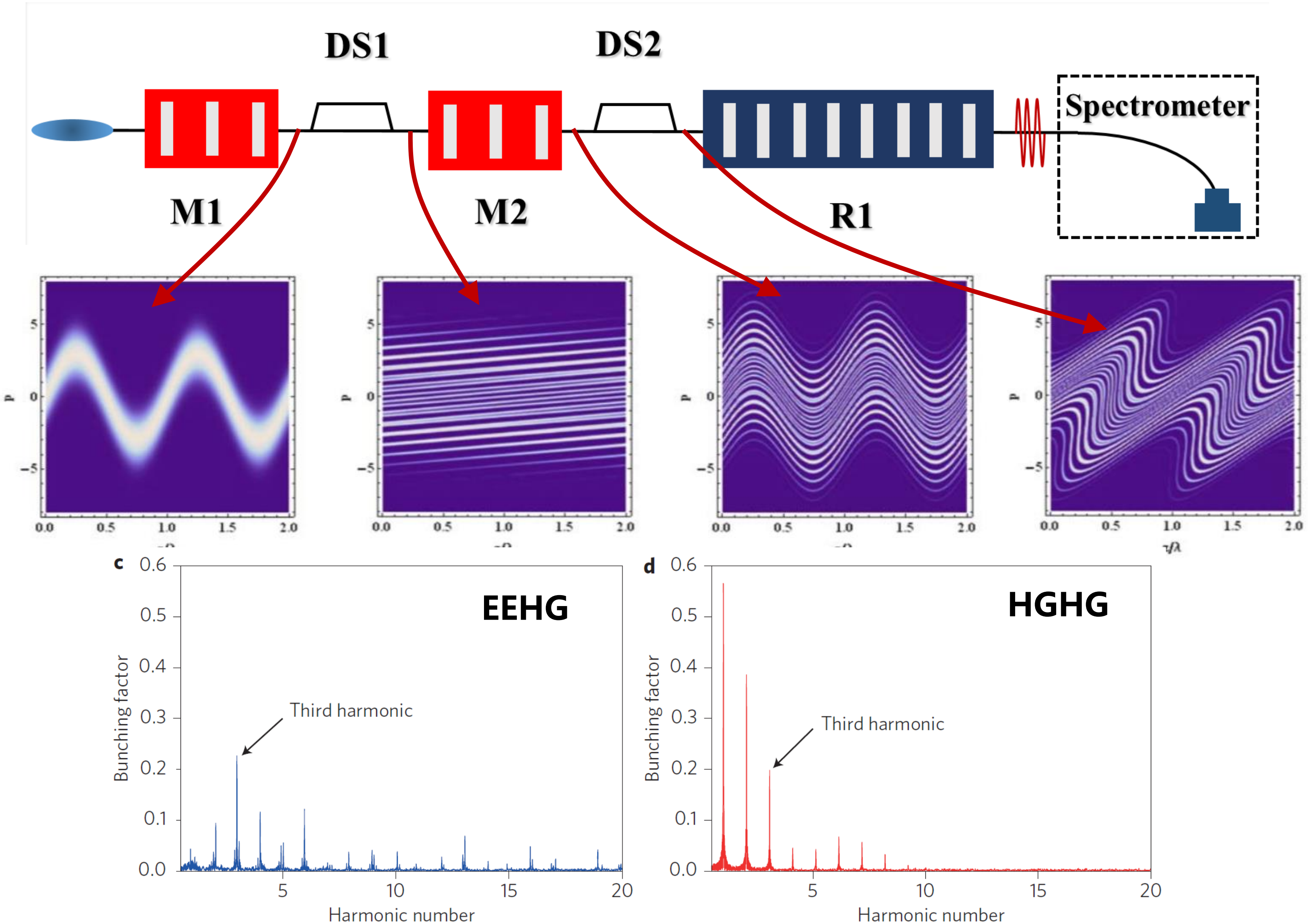
Operating SXFEL with single-stage HGHG







Principle of EEHG FEL



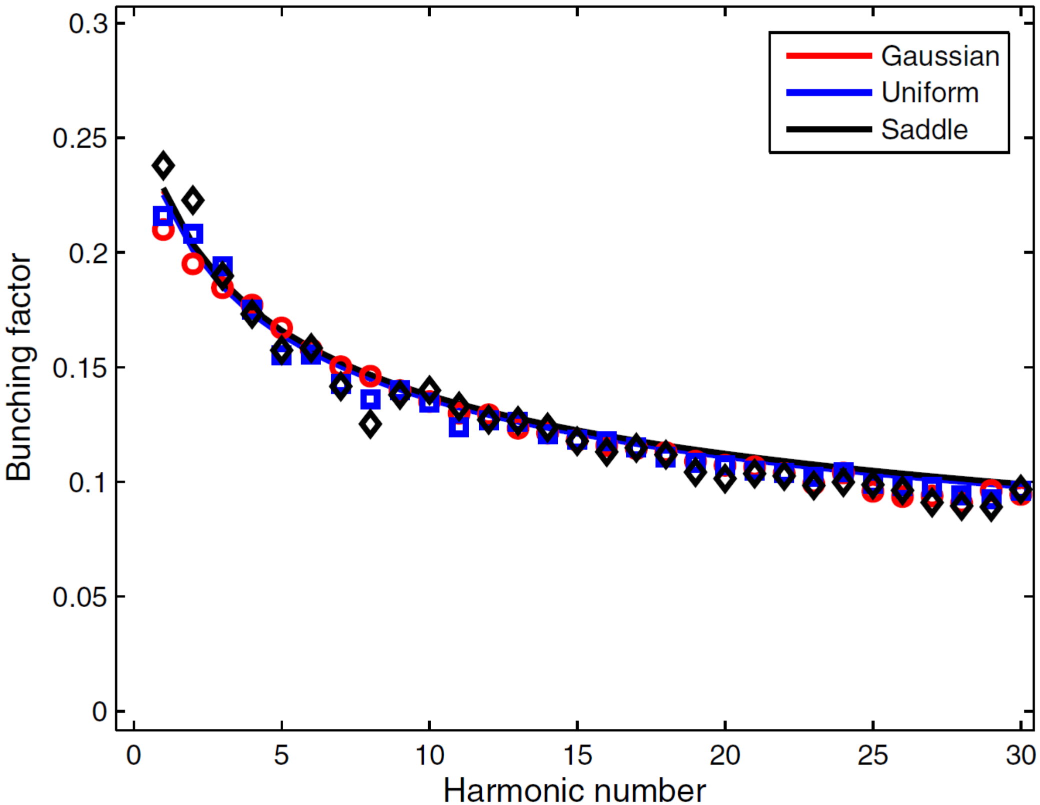
G. Stupakov, Phys. ReV. Lett. 102, 074801 (2009).

Beam energy distribution in EEHG

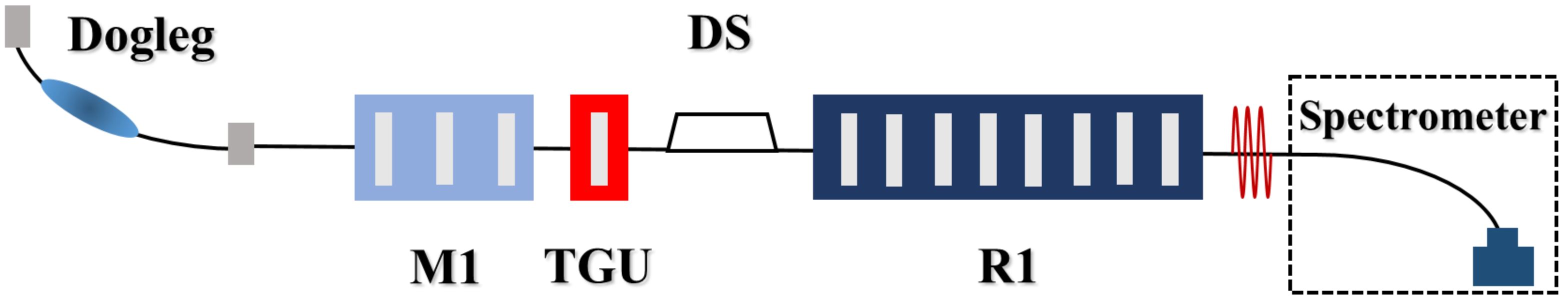
$$b_G = |\exp(-\frac{1}{2}(nB_1 + (m+n)B_2)^2)J_m(-(m+n)A_2B_2)J_n(-A_1[nB_1 + (m+n)B_2])|$$

$$b_U = |Sinc(\tau(nB_1 + (m+n)n\,B_2/2))J_m(-(m+n)A_2B_2)J_n(-A_1[nB_1 + (m+n)B_2])|$$

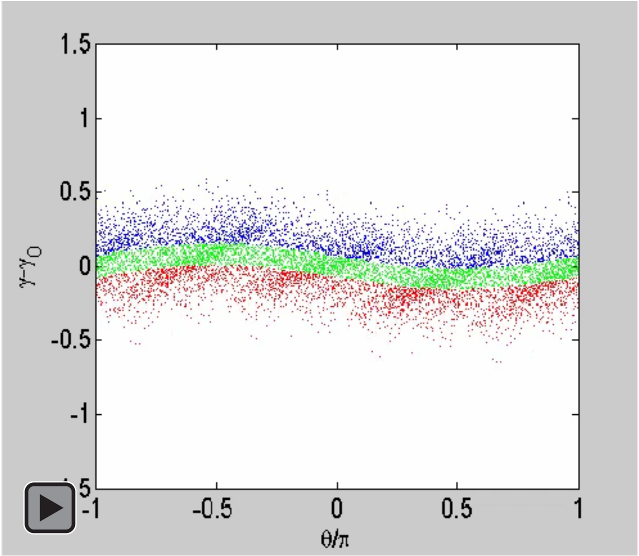
$$b_S = |\exp(-\frac{1}{2}[(nD_1 + (m+n)D_2)C\sigma_H]^2)J_m(-(m+n)A_2B_2)J_n(-A_1[nB_1 + (m+n)B_2]) \times J_0(-C\Delta\gamma_h[(m+n)D_2 + nD_1])|$$

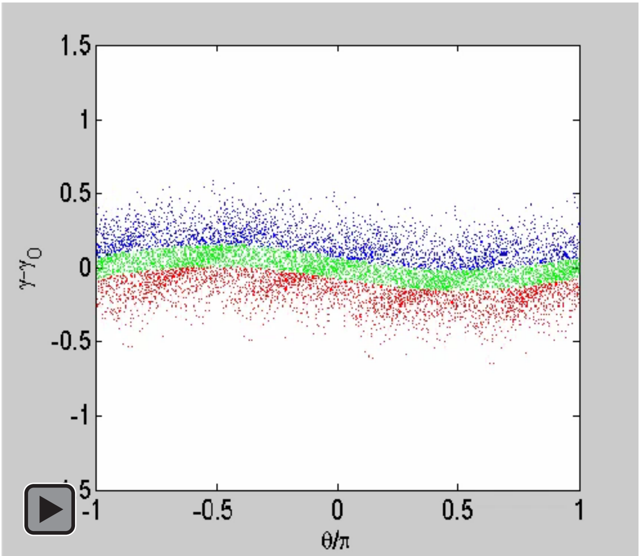


Principle of PEHG FEL



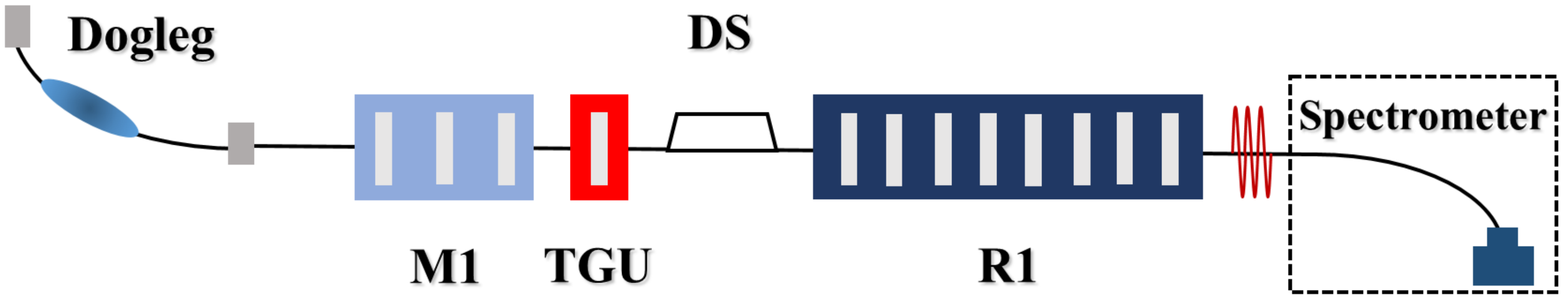
- The maximum bunching factor scales as $0.67/n^{1/3}$.
- The maximum bunching is independent on the energy modulation.
- Zero response to beam energy chirp.





H. X. Deng*, and C. Feng, Phys. Rev. Lett. 111 (2013) 084801.
C. Feng, H. X. Deng* et al., New Journal of Physics, **16** 043021.

Principle of PEHG FEL



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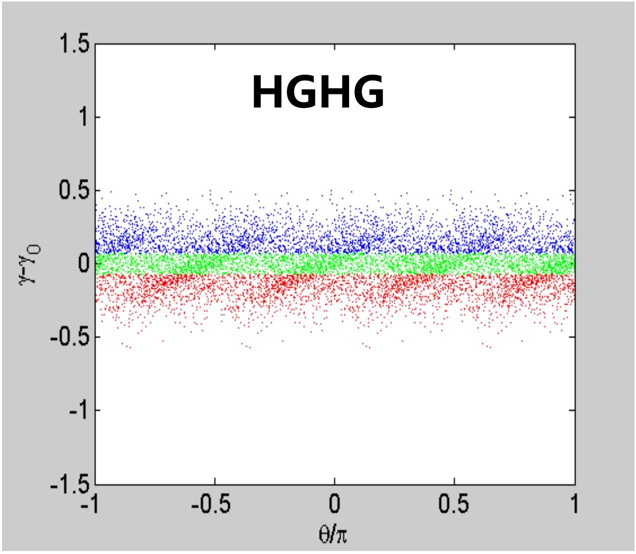
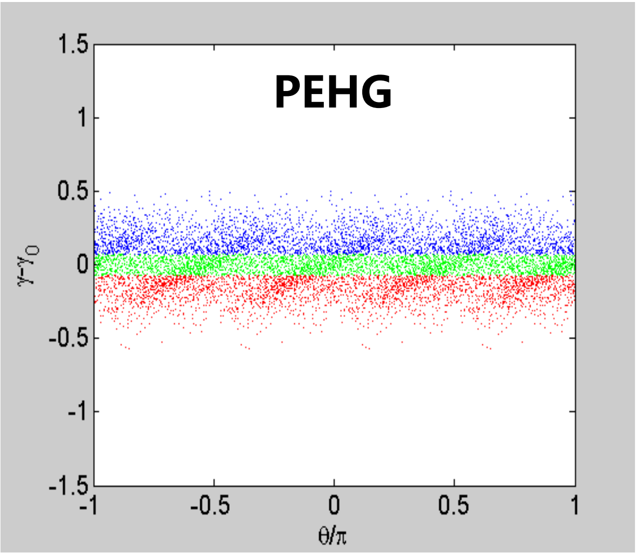




H. X. Deng*, and C. Feng, Phys. Rev. Lett. 111 (2013) 084801.
C. Feng, H. X. Deng* et al., New Journal of Physics, **16** 043021.

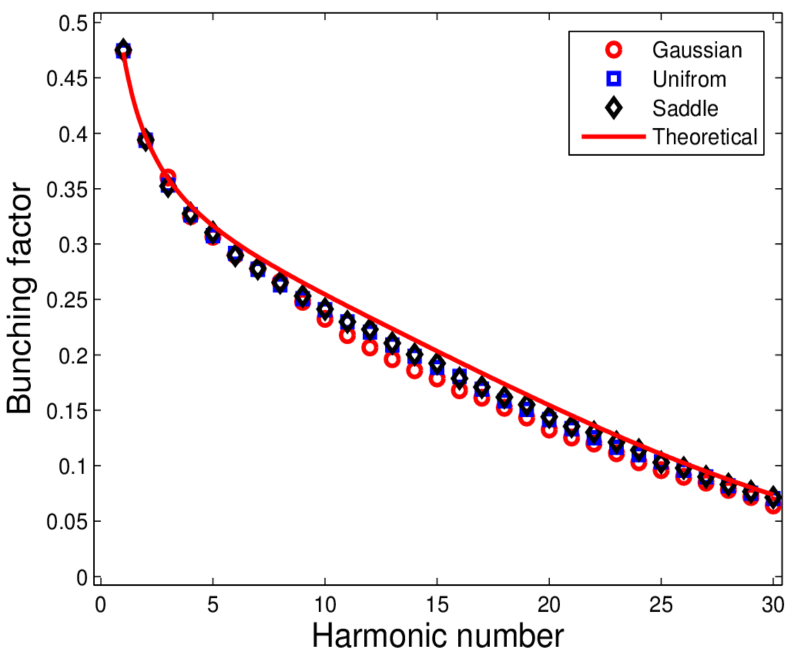
Beam energy distribution in PEHG

- **Ideally, PEHG is immune to different energy distributions.**

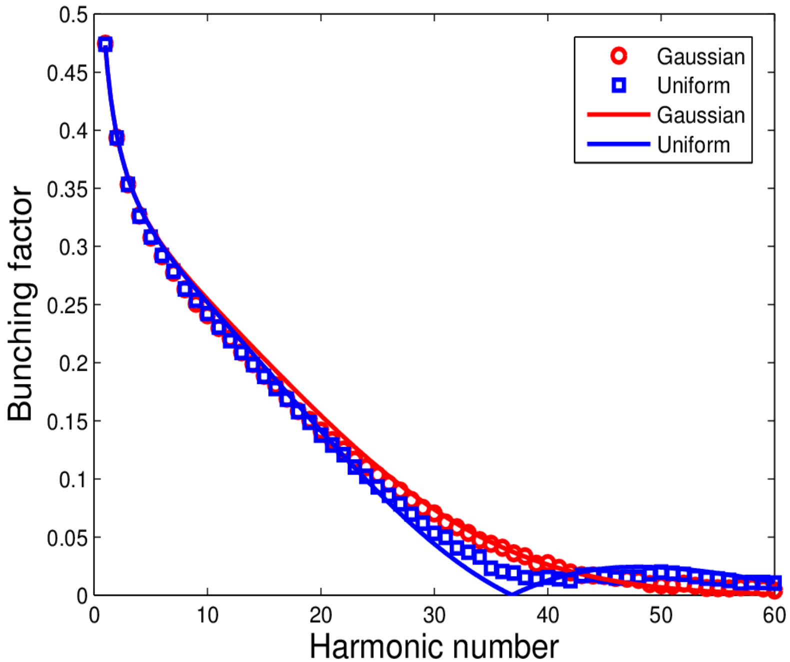
$$h_{PEHG}(\zeta,p,\chi)=$$
$$\frac{N_0}{2\pi}\exp\{-\frac{1}{2}[p-A\sin(\zeta-T\chi-Bp)]^2\}\exp[-\frac{1}{2}\{\chi-D[p-A\sin(\zeta-T\chi-Bp)]\}^2]$$

$$b=J_h(hD\Delta\gamma_s)\exp(-\frac{h^2D\sigma_x^2}{2\eta^2})$$

$$\frac{\sigma_x}{\eta}=\sigma_{eff}$$



Energy spread



Conclusion

- For HGHG-FEL, uniform and saddle beam energy distribution could induce a useful & controllable bunching factor oscillation.
- Thus, the 30^{th} or even higher harmonic operation is possible with a moderate energy spread controlled by laser heater.
- EEHG and PEHG is almost zero response to energy distribution.
- Quietly related to many issues, e.g., LINAC setup; machine flexibility; accuracy of beam energy spread measurements; commissioning experiments.

THANK YOU
FOR
YOUR ATTENTION