

Manipulation of electron beam phase space

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Outline

On the one hand:

One can tailor the electron beam distribution at high precision for various applications;

On the other hand:

Beam manipulation has to obey basic rules as well as technological limitations.

☞ Electron beam manipulation (symplectic)

- 2D beam manipulation
- 4D beam manipulation

☞ Electron beam manipulation (non-symplectic)

☞ Summary

Electron beam manipulation (symplectic)

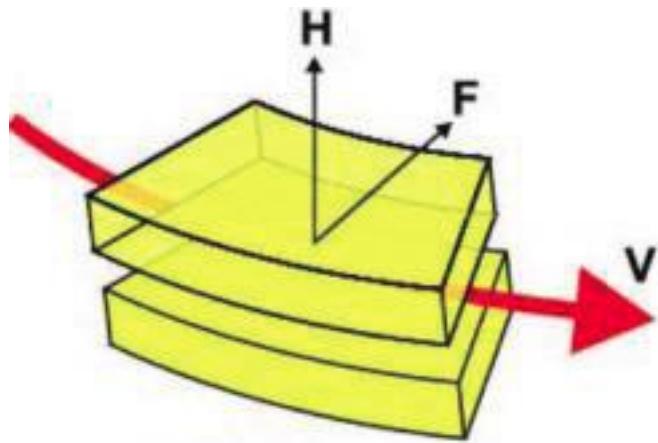
In mathematics, a symplectic matrix is a $2n \times 2n$ matrix M with real entries that satisfies the condition:

$$M^T \Omega M = \Omega,$$

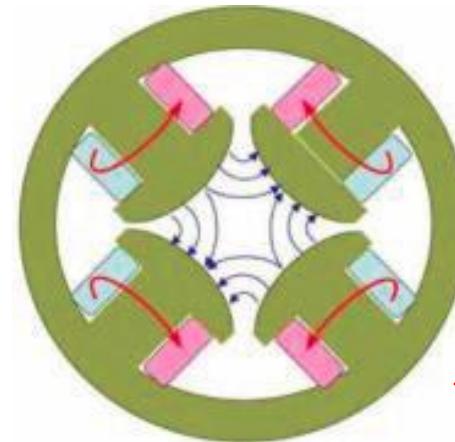
where M^T denotes the [transpose](#) of M and Ω is a fixed $2n \times 2n$ [nonsingular, skew-symmetric](#) matrix. Typically Ω is chosen to be the [block matrix](#)

$$\Omega = \begin{bmatrix} 0 & 1 & & & & \\ -1 & 0 & & & & \\ & & \ddots & & & \\ & & & 0 & & \\ & & & & 0 & 1 \\ & & & & -1 & 0 \end{bmatrix}$$

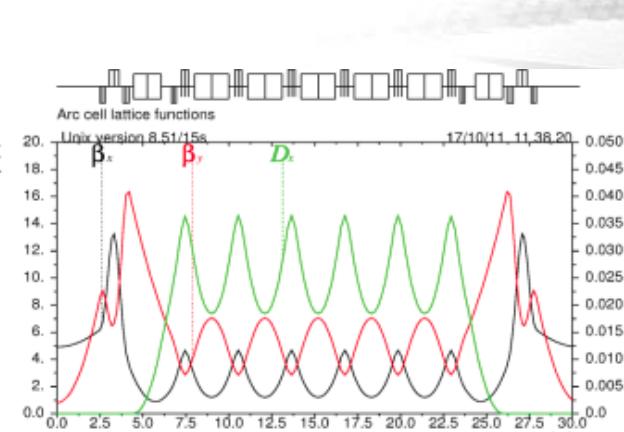
2D manipulation (transverse plane)



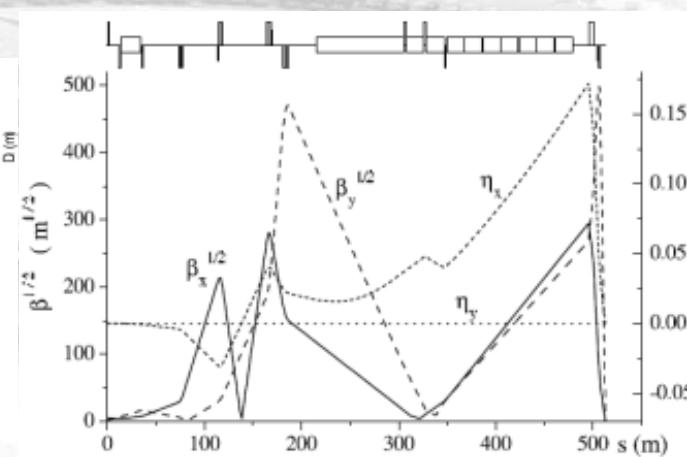
Bend



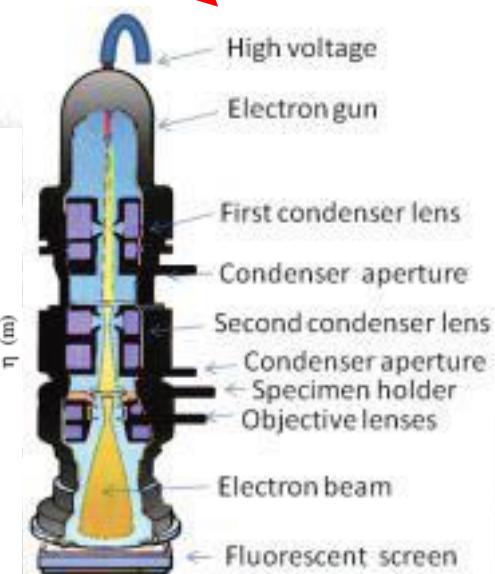
Quadrupole



7-bend achromat for ultimate storage ring

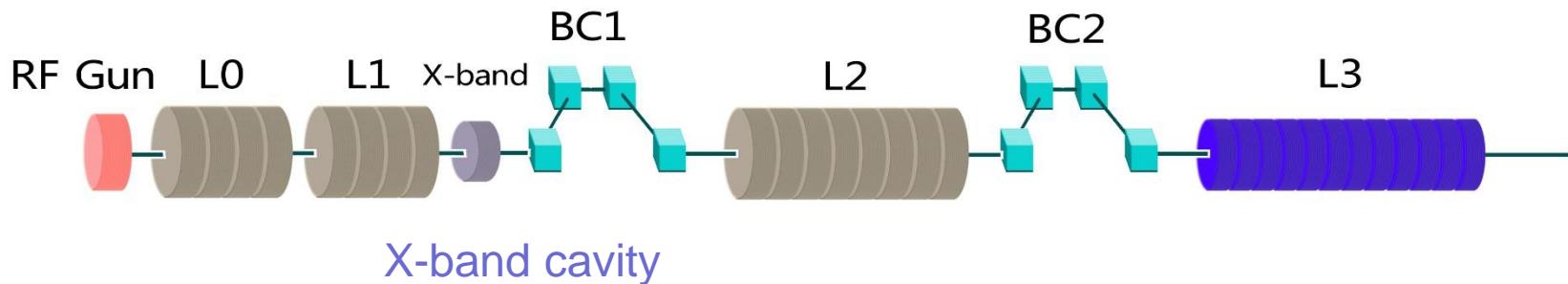


Linear collider

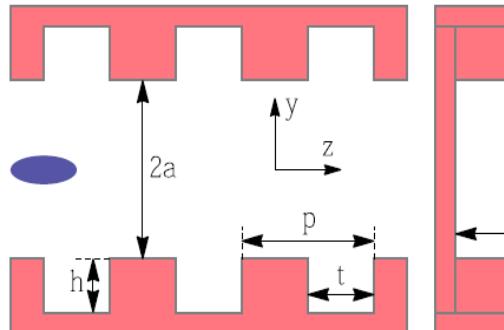


Electron microscope

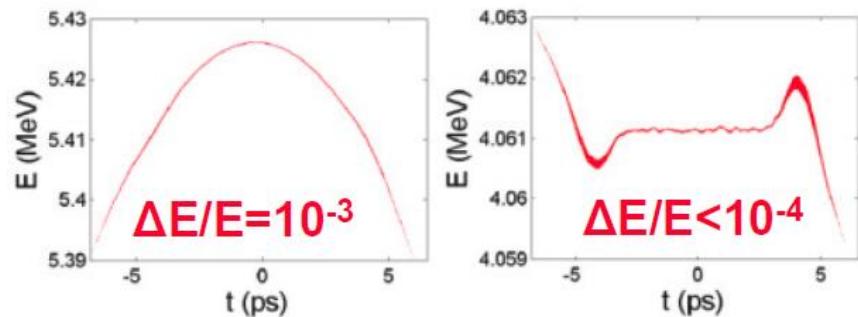
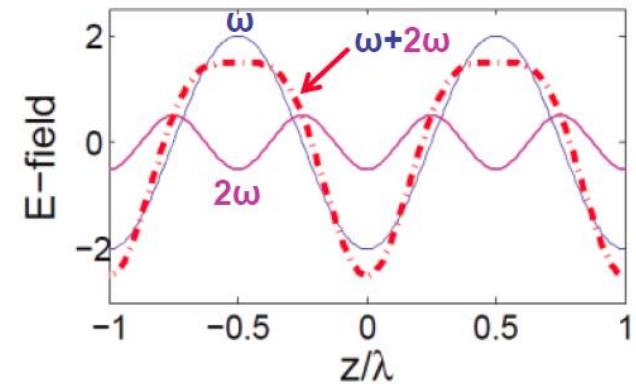
2D manipulation (longitudinal plane)



Phase space linearizer

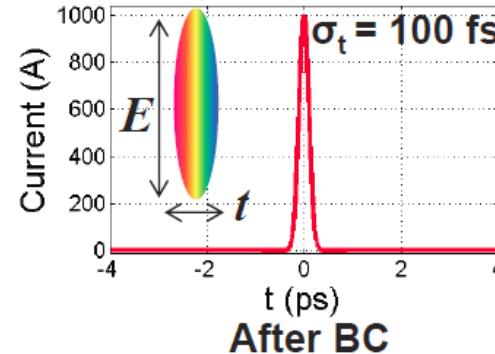
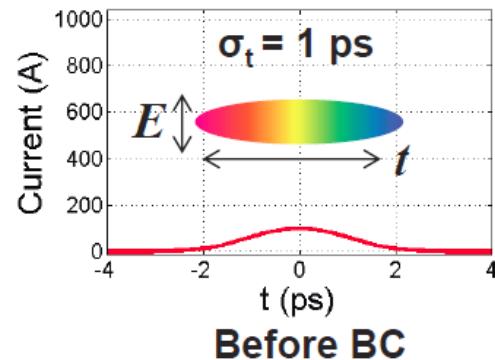


Corrugated structure

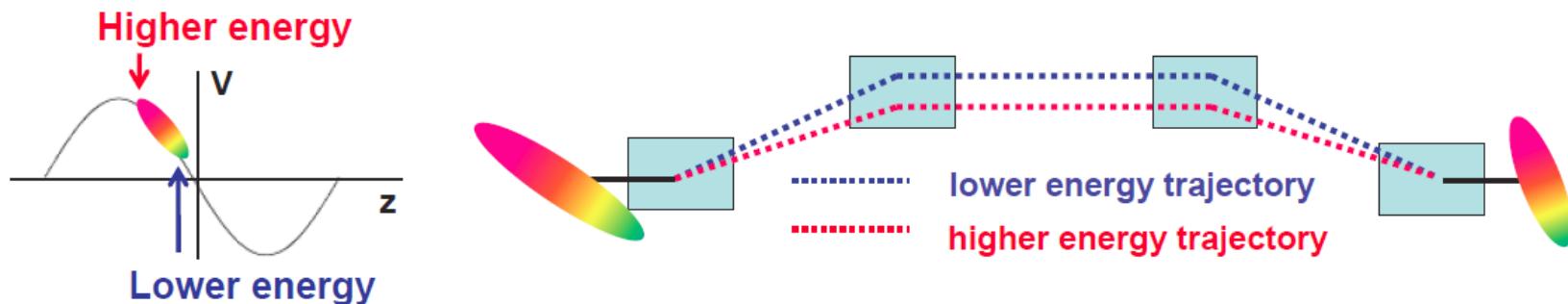


2D manipulation (longitudinal plane)

- A dispersive element is required for manipulation in longitudinal plane

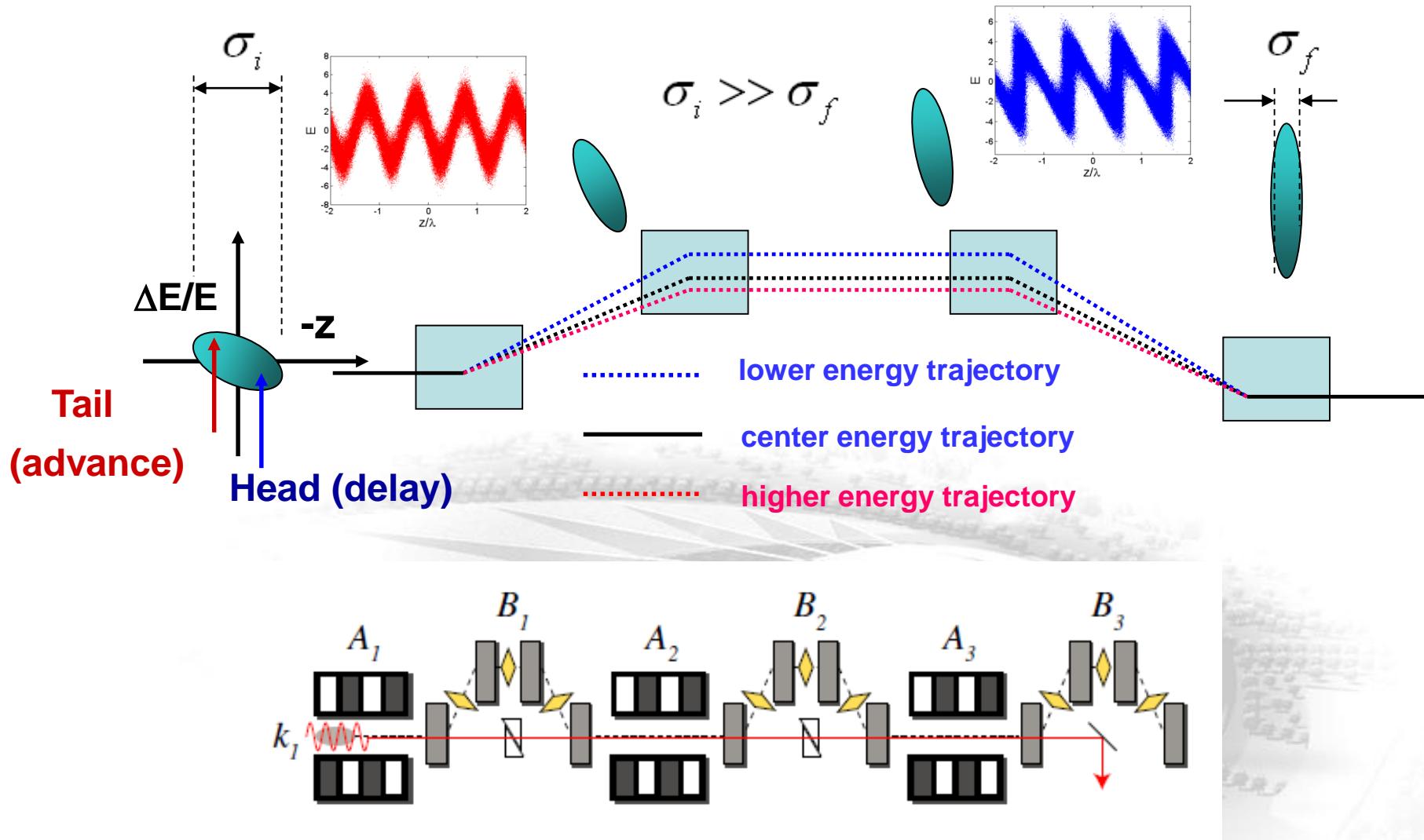


Bunch compression



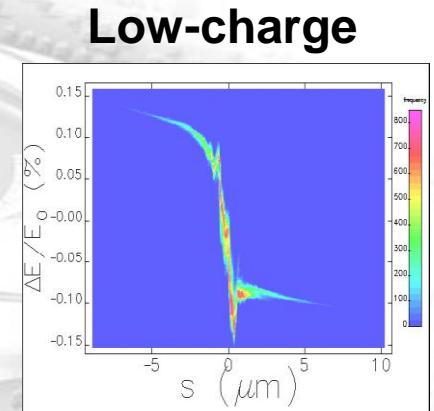
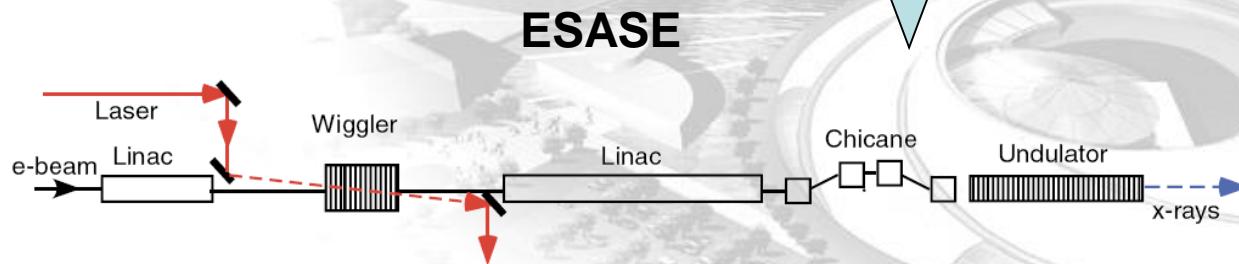
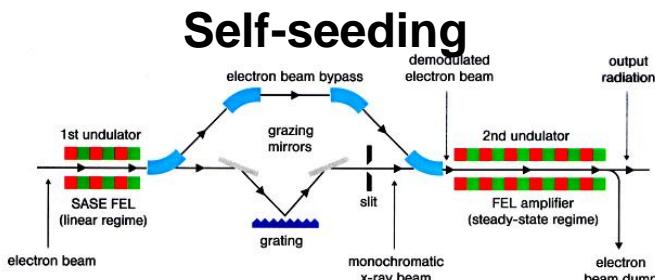
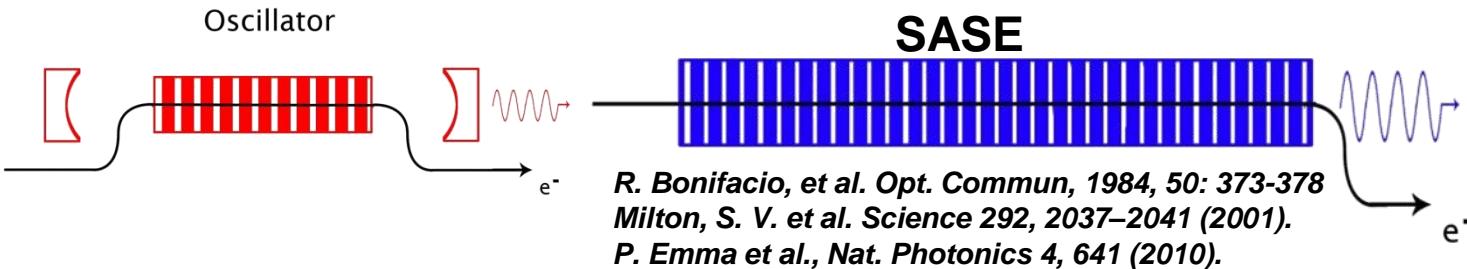
Low energy electrons slow down; high energy electrons catch up

2D manipulation (longitudinal plane)



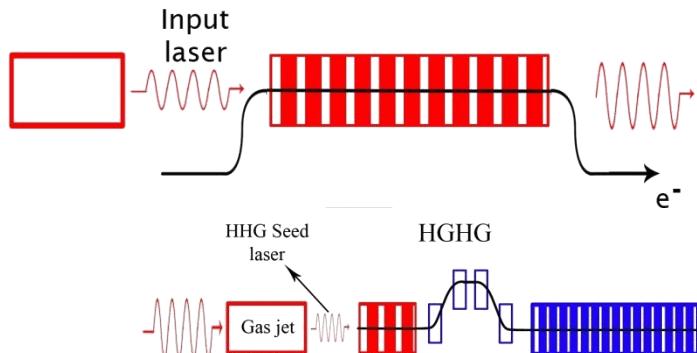
Manipulate the longitudinal phase space at the optical wavelength scale

FEL schemes (without seed)



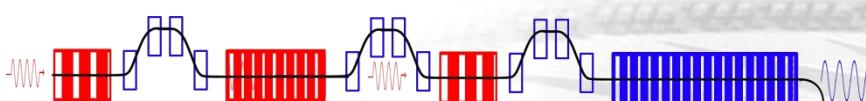
FEL schemes (with seed)

Amplifier



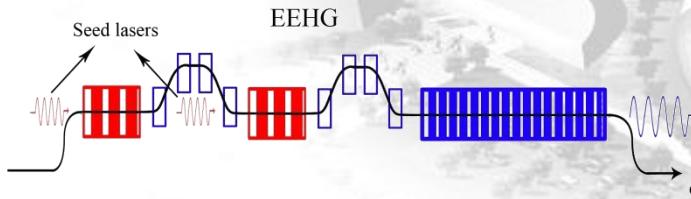
L. Giannessi et al. Phys. Rev. Lett. 108, 164801 (2012)

Cascaded HGHG



Yu L H, Ben-Zvi I. Nucl Instr Meth A, 1997, 393: 96–99

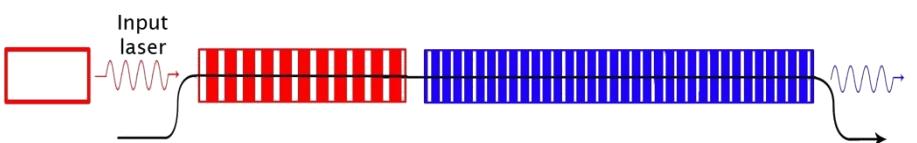
B. Liu, et al. Phys. Rev. ST Accel. Beams 16, 020704 (2013).



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

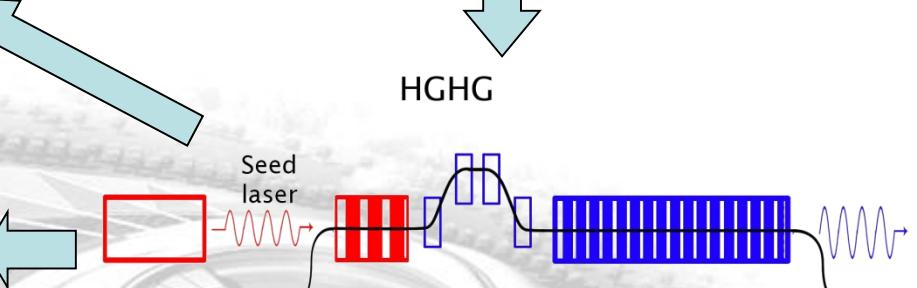
Z. T. Zhao, D. Wang, J. H. Chen et al., Nat. Photonics 6, 360 (2012).

Two wiggler



R. Bonifacio, et al. Nucl. Instrum. Methods A 296, 787 (1990).

HGHG

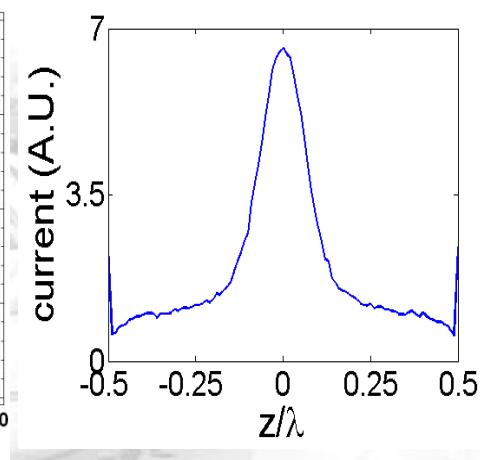
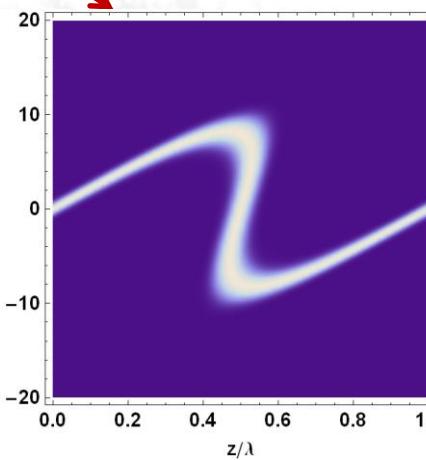
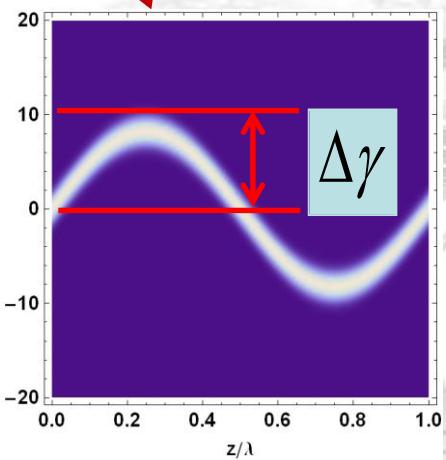
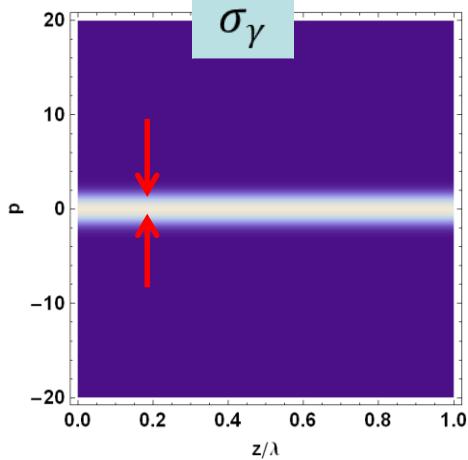
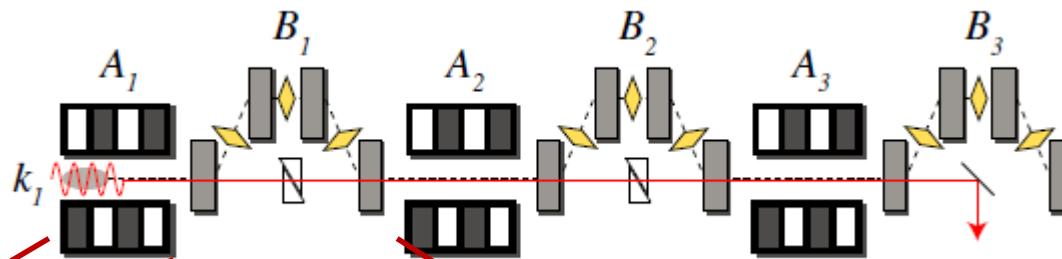


L. H. Yu. Phys. Rev. A, 1991, 44: 5178–5193
L. H. Yu, et al., Science 289, 932 (2000).



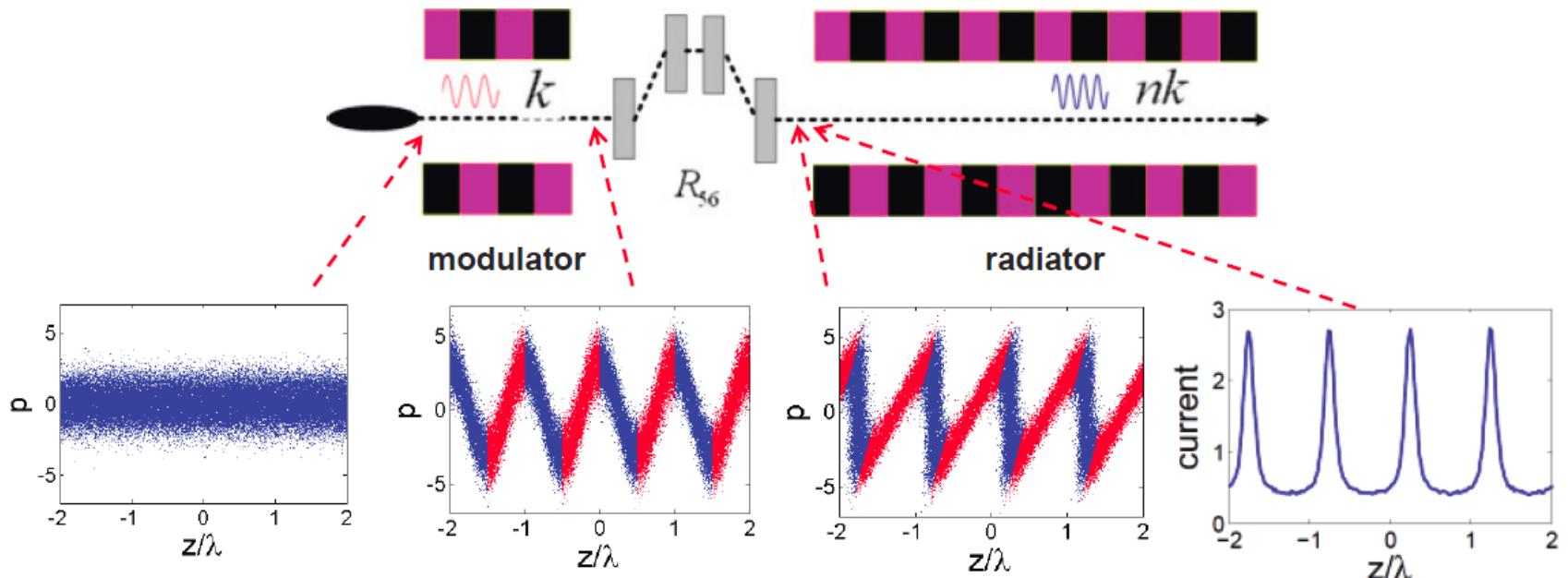
High-gain harmonic generation (HGHG)

Beam slicing, enhanced SASE, HGHG



High-gain harmonic generation (HGHG)

- High-Gain Harmonic Generation (HGHG)
- Single modulator-chicane system

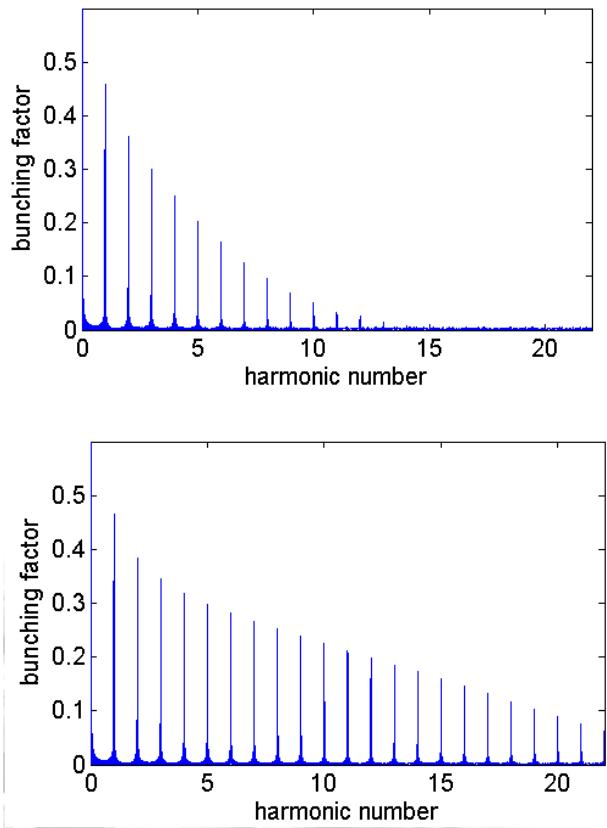
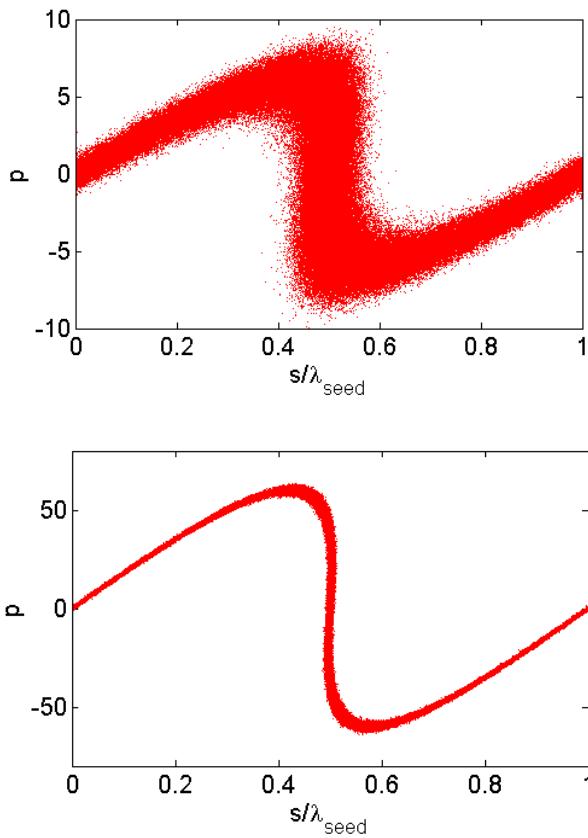
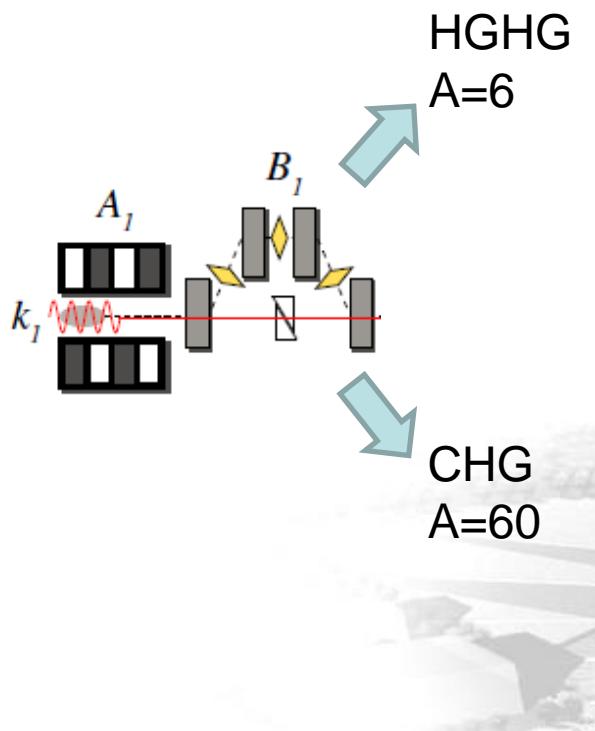


- ❖ Energy modulation in a modulator
- ❖ Energy modulation converted to density modulation
- ❖ Coherent radiation at nk amplified to saturation in a radiator
- ❖ Harmonic number $n \approx \Delta E / \sigma_E$

Yu et al., Science, 2000

Yu et al., PRL, 2003

High-gain harmonic generation (HGHG)



Energy modulation amplitude:

$$A = \Delta\gamma / \sigma_\gamma$$

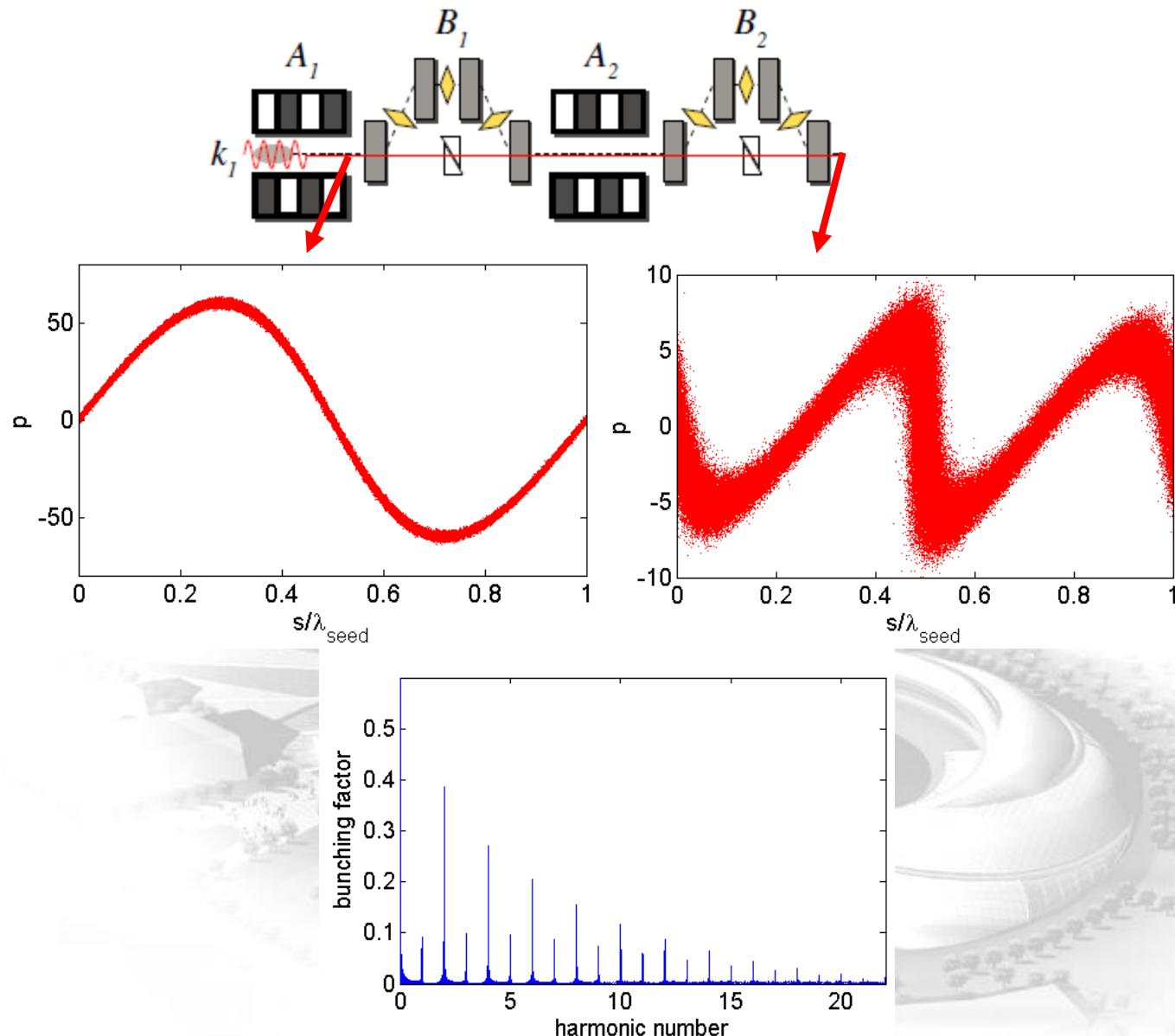
dispersion:

$$B = R_{56} k_1 \sigma_\gamma / \gamma$$

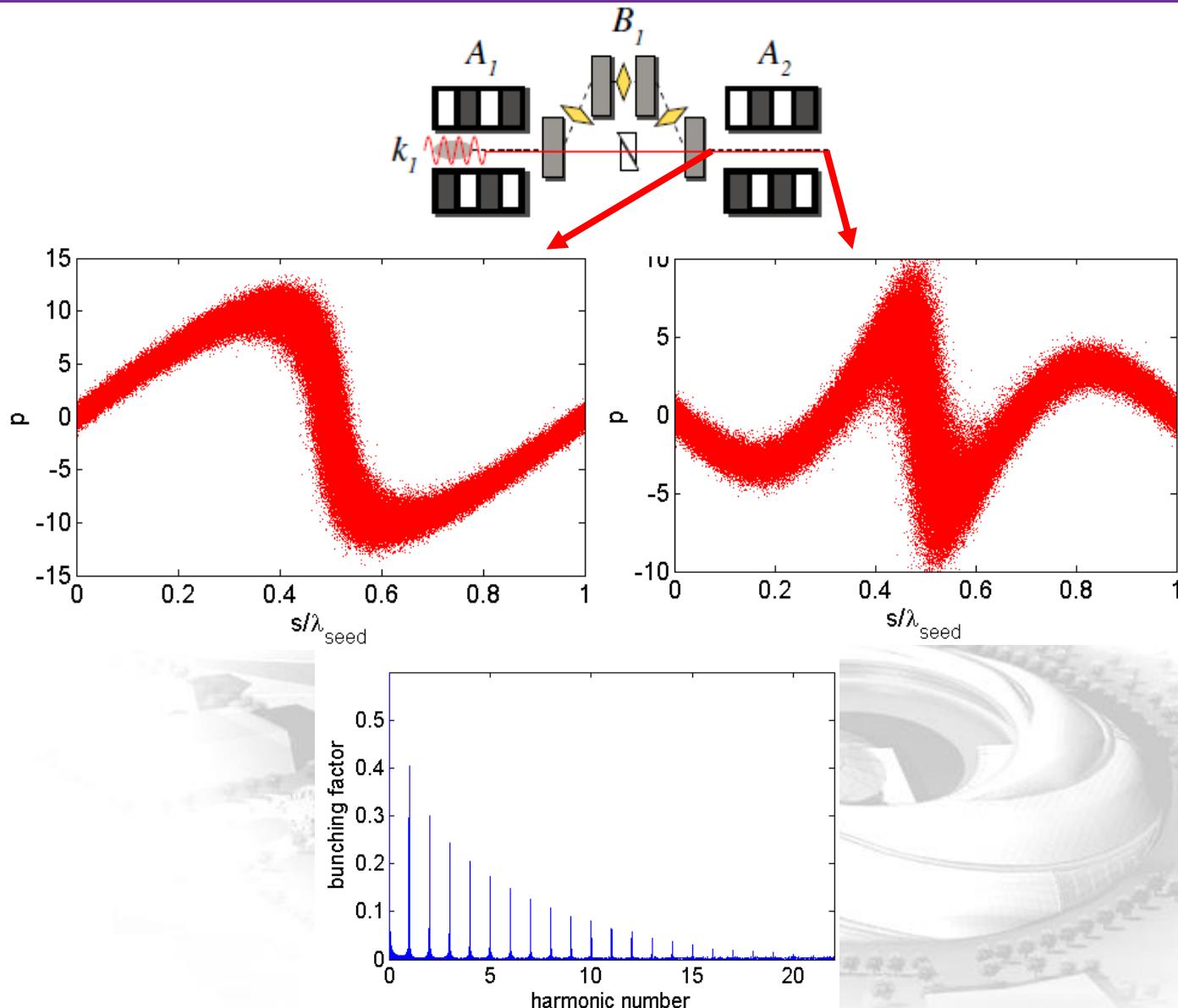


bunching: $b_k = J_k(kAB) \exp(-\frac{1}{2}k^2 B^2)$

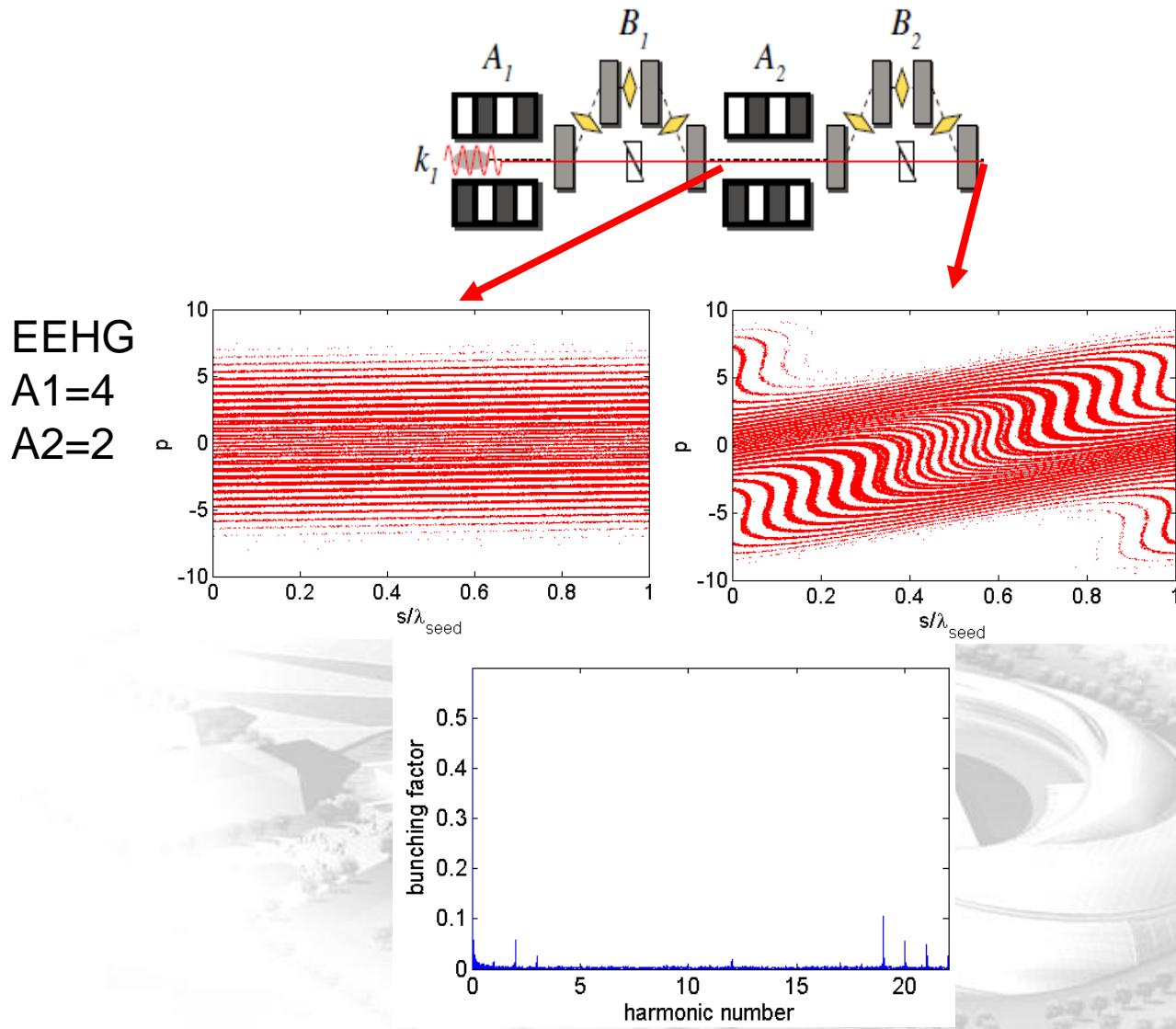
Silence scheme (2007)



Enhanced HGHG (2008)



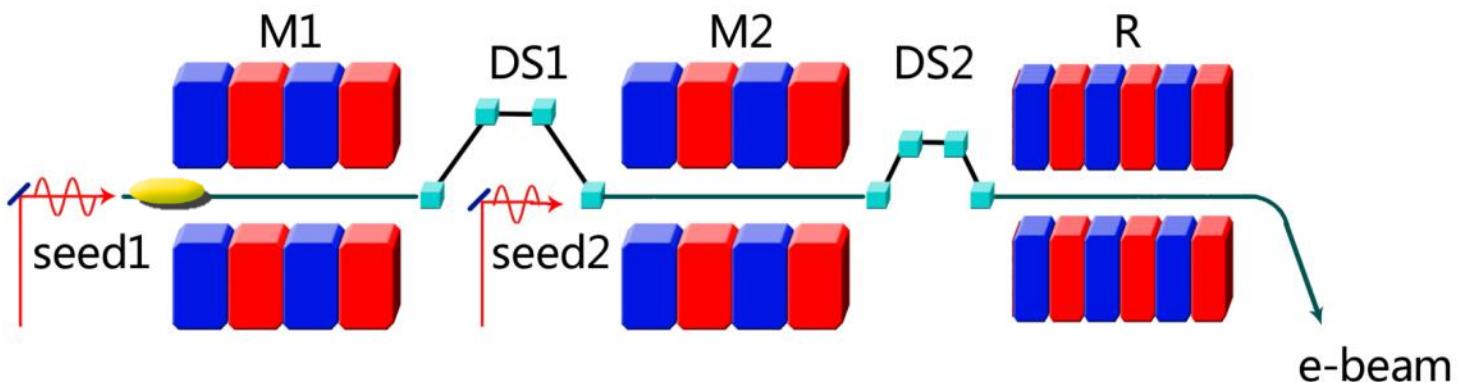
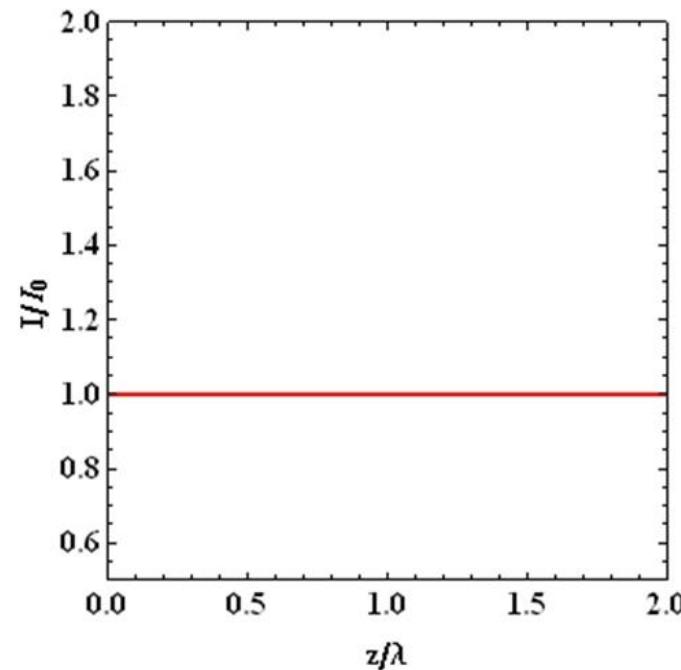
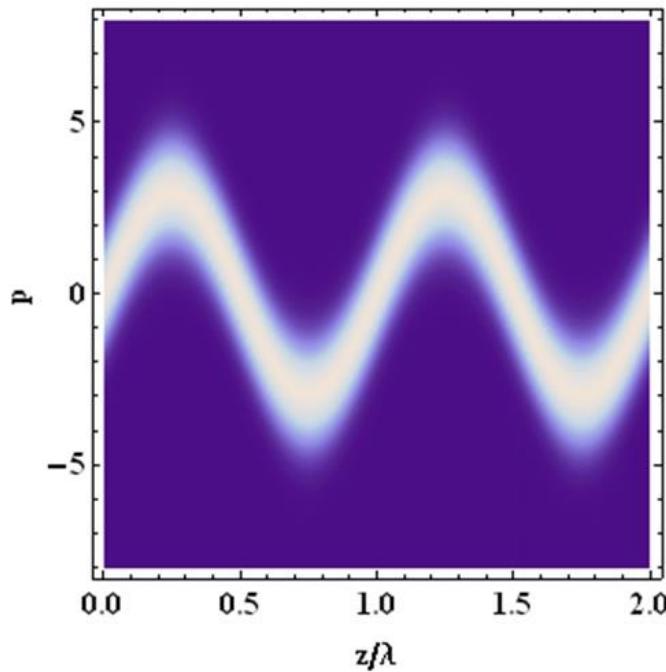
Echo-enabled harmonic generation (2009)



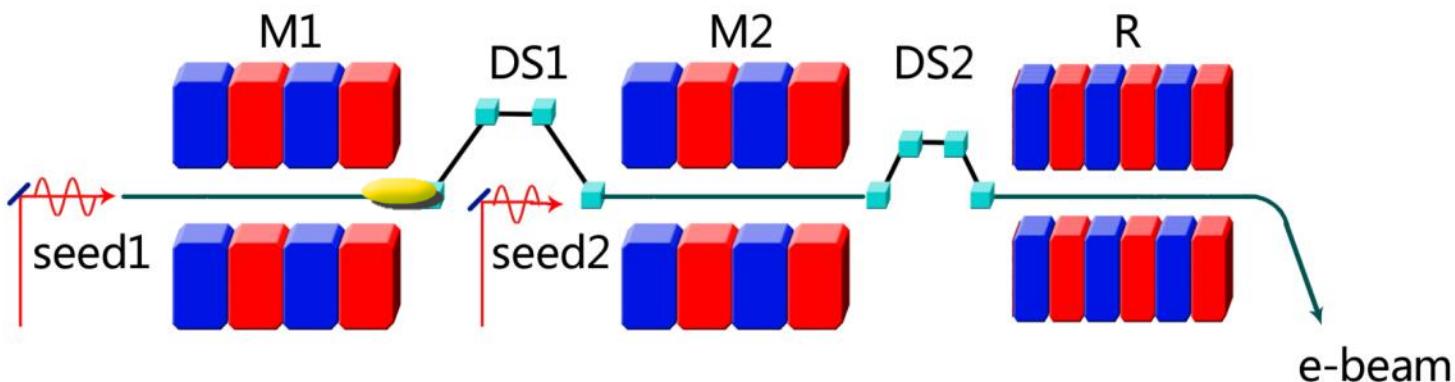
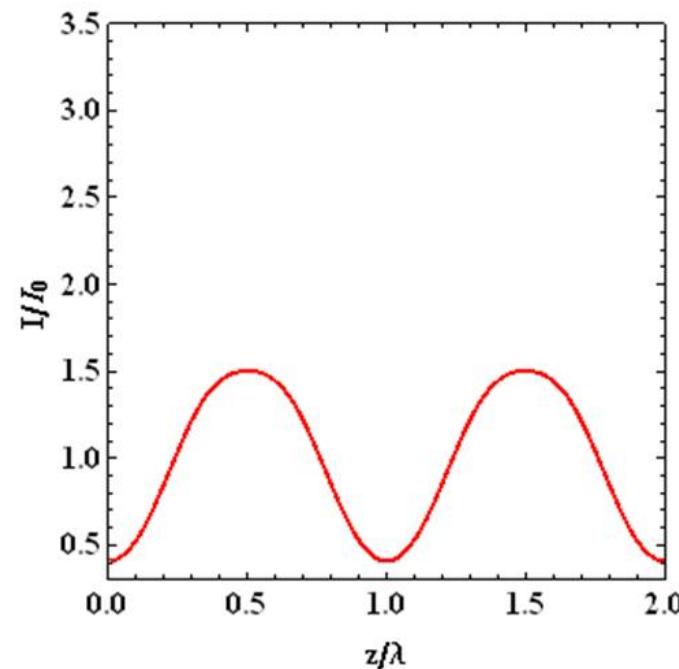
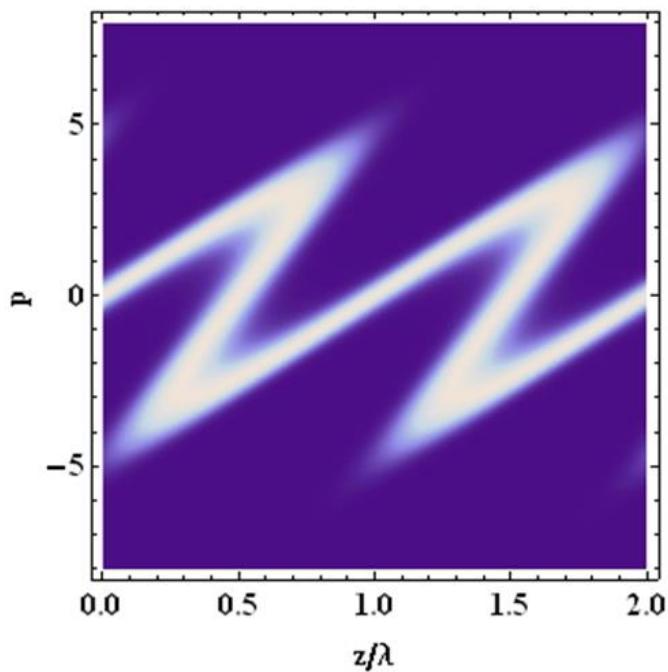
G. Stupakov, Phys. Rev. Lett. 102 (2009) 074801.

D. Xiang and G. Stupakov, Phys. Rev. ST Accel. Beams 12 (2009) 030702.

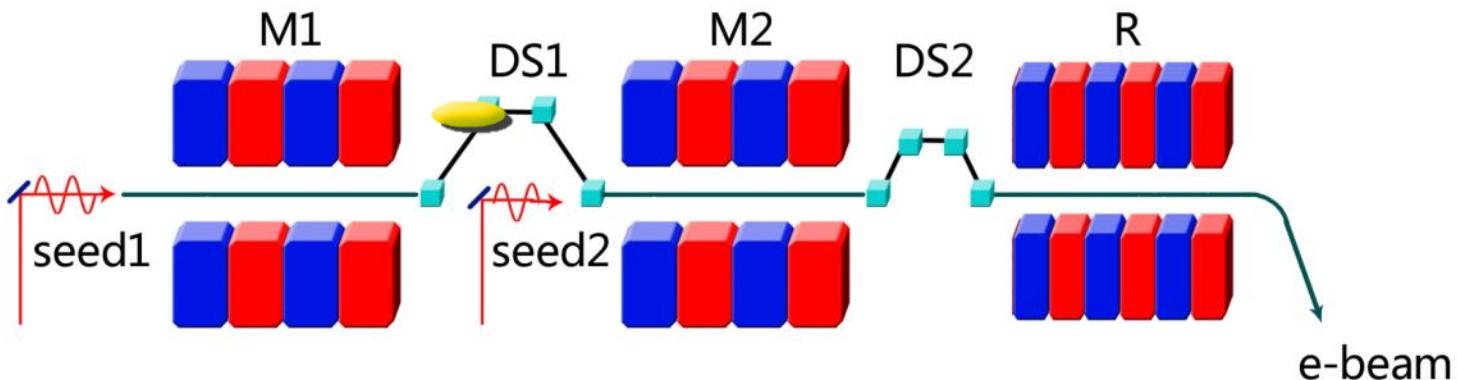
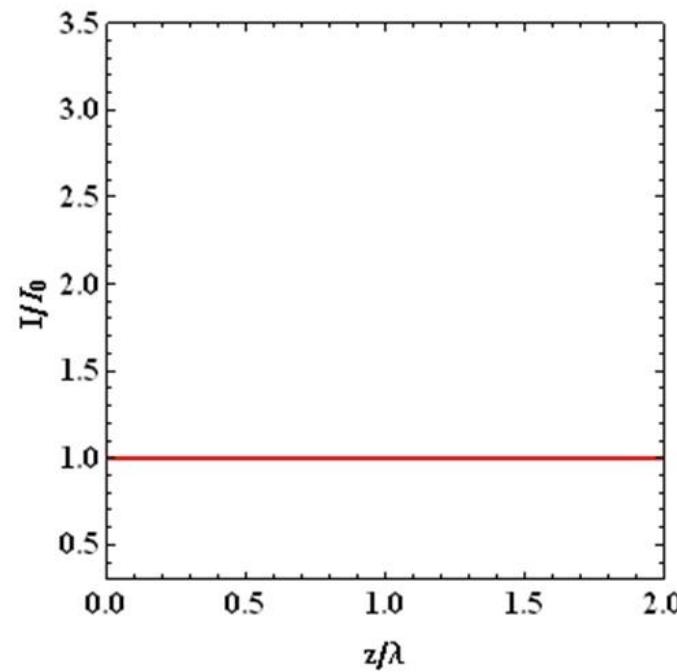
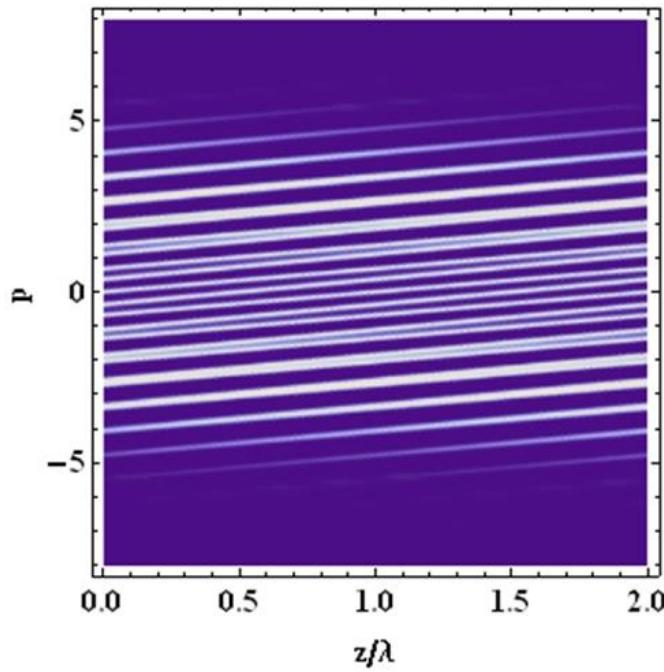
EEHG principle



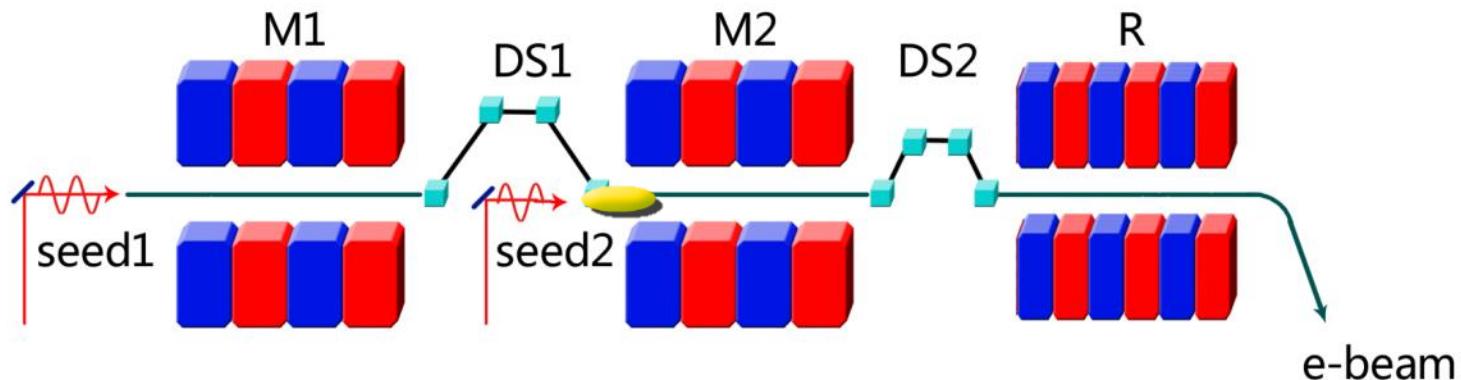
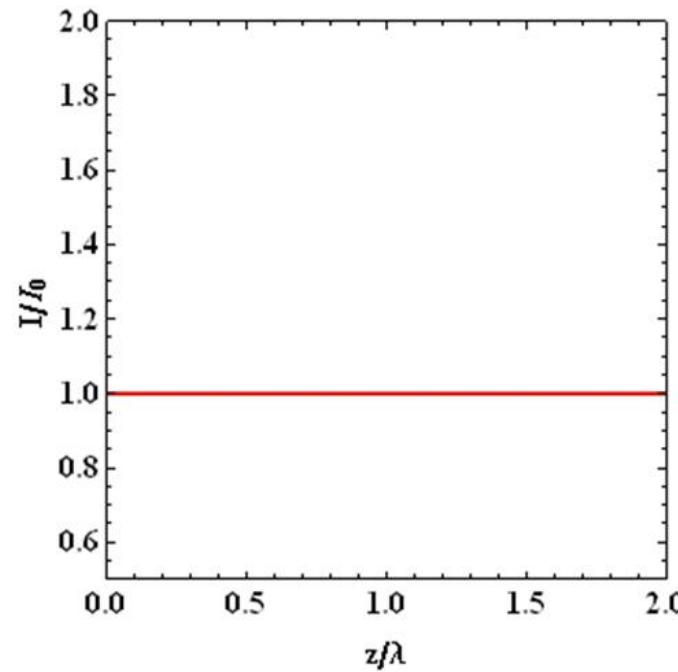
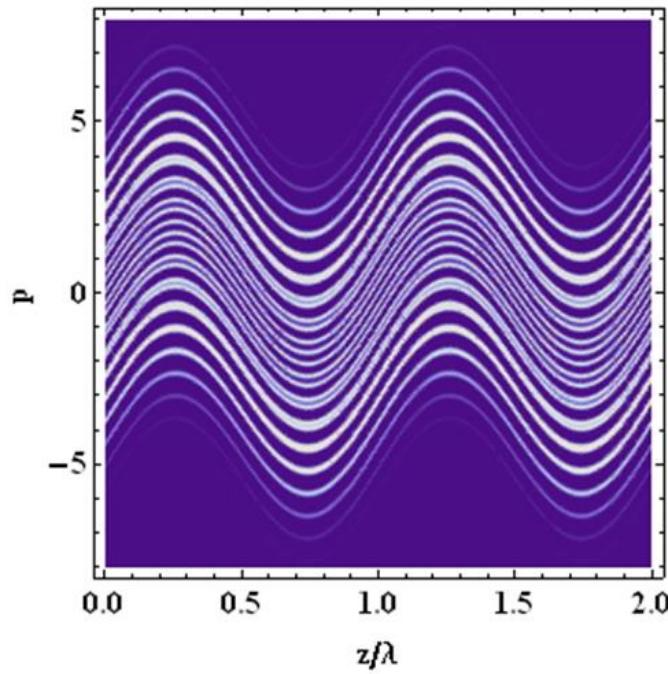
EEHG principle



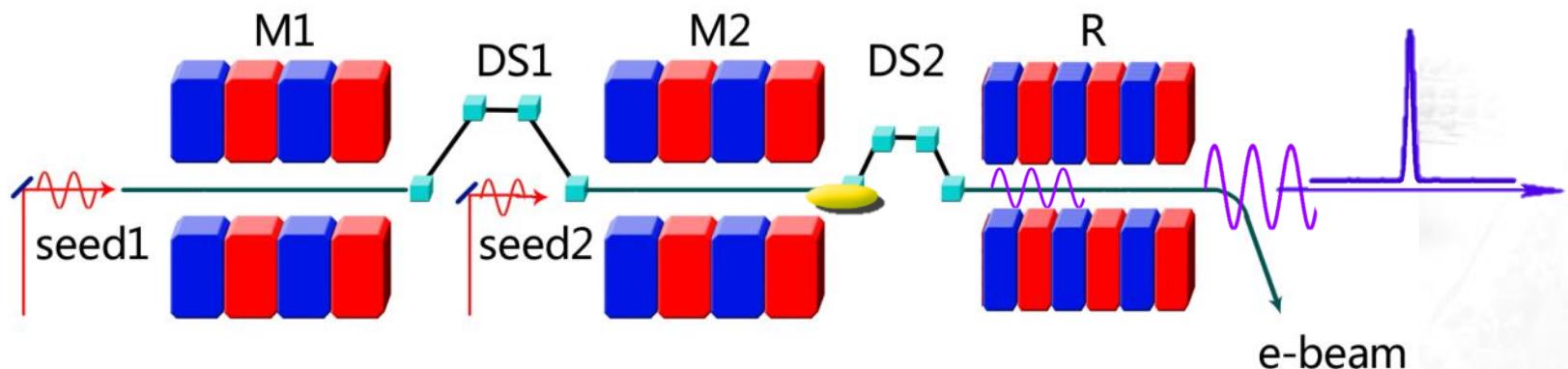
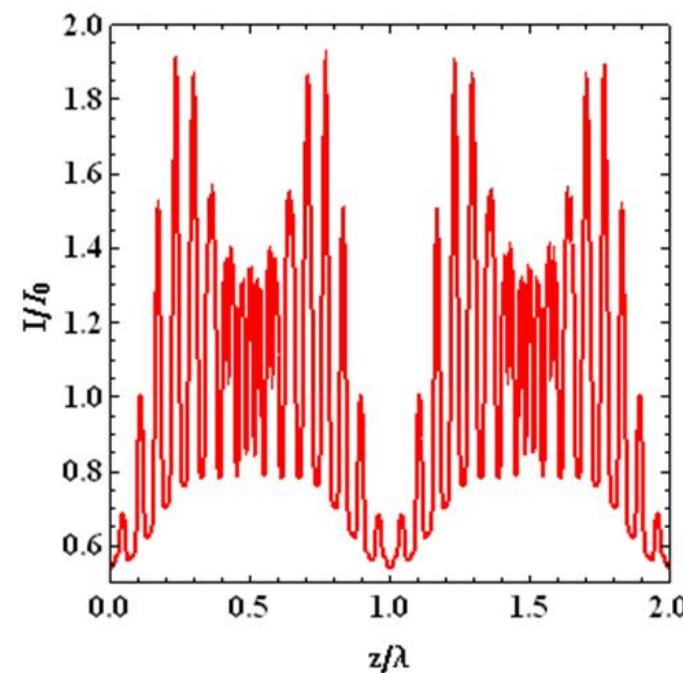
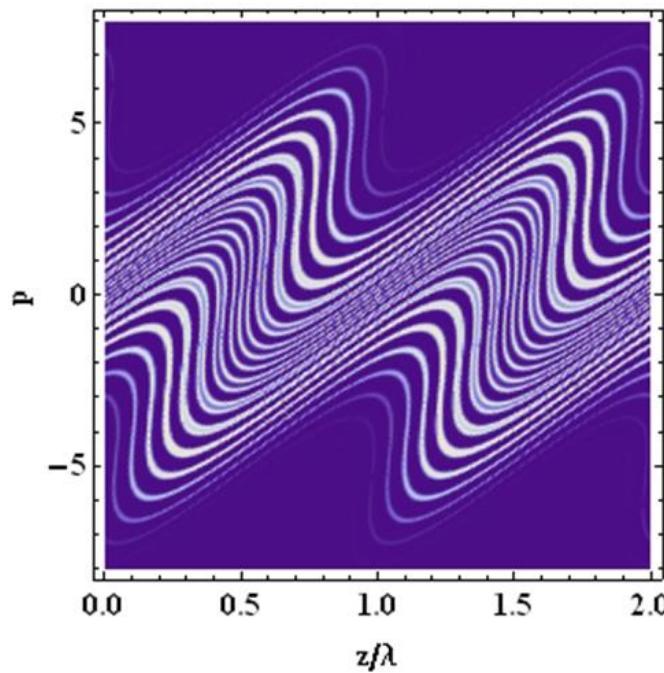
EEHG principle



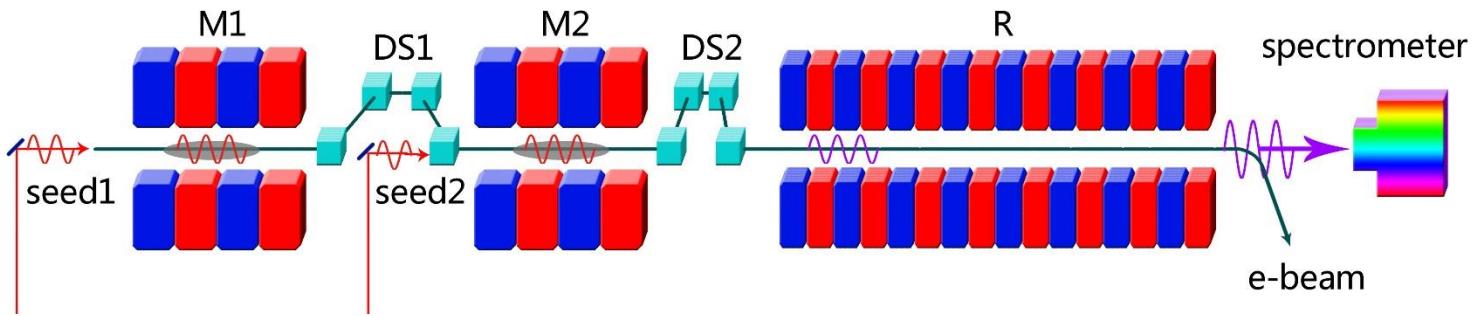
EEHG principle



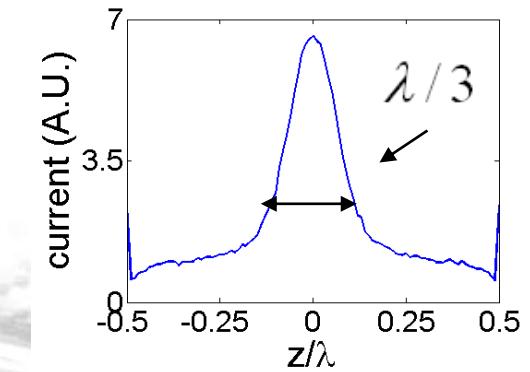
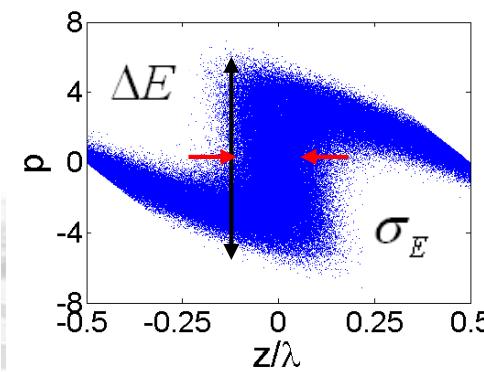
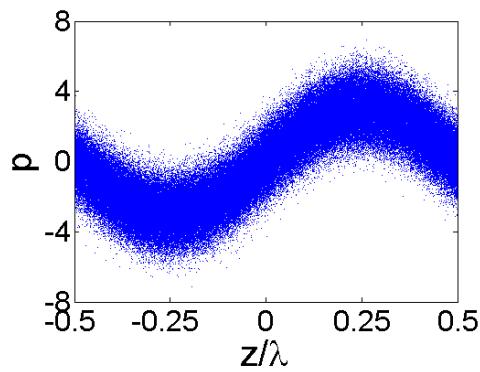
EEHG principle



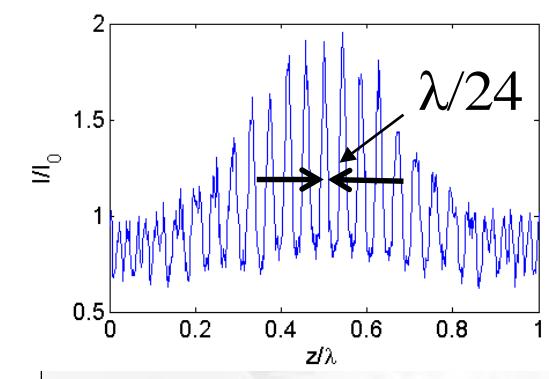
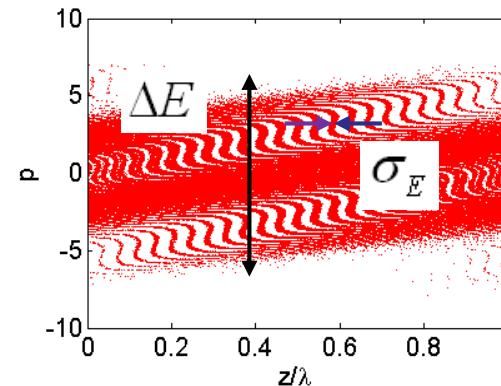
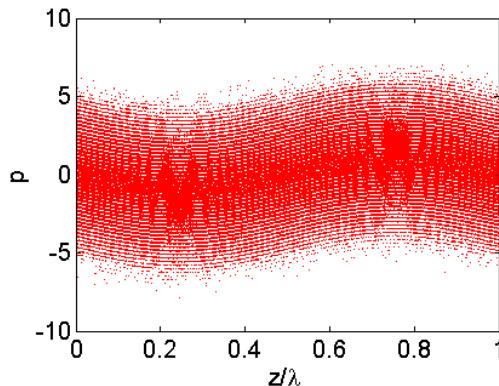
EEHG principle



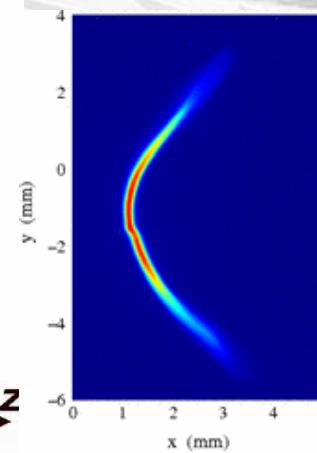
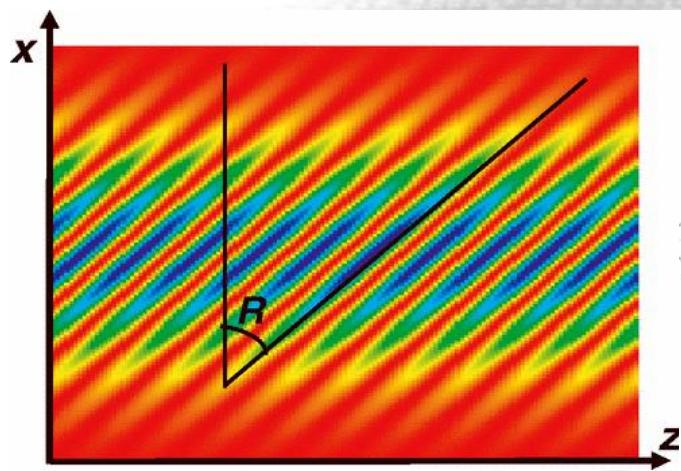
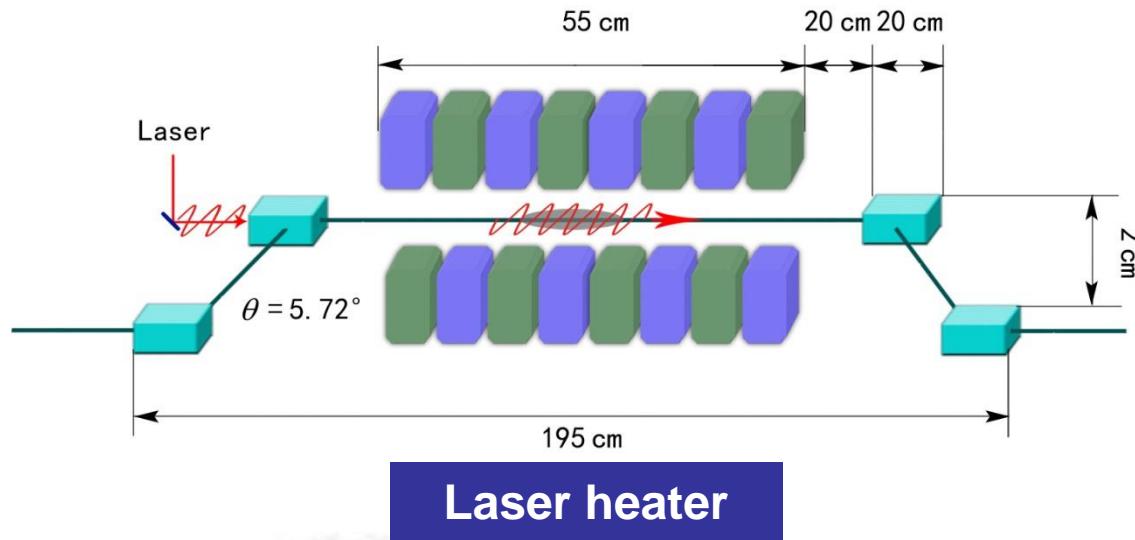
HGHG
A=3



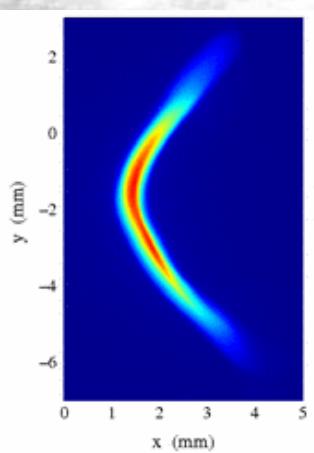
EEHG
A1=3
A2=1



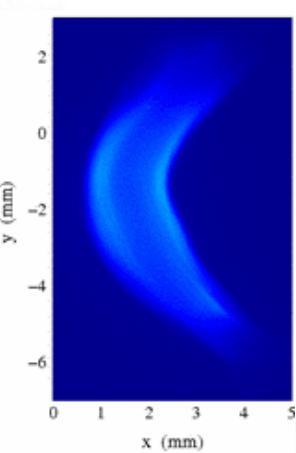
4D manipulation



(a) no heating



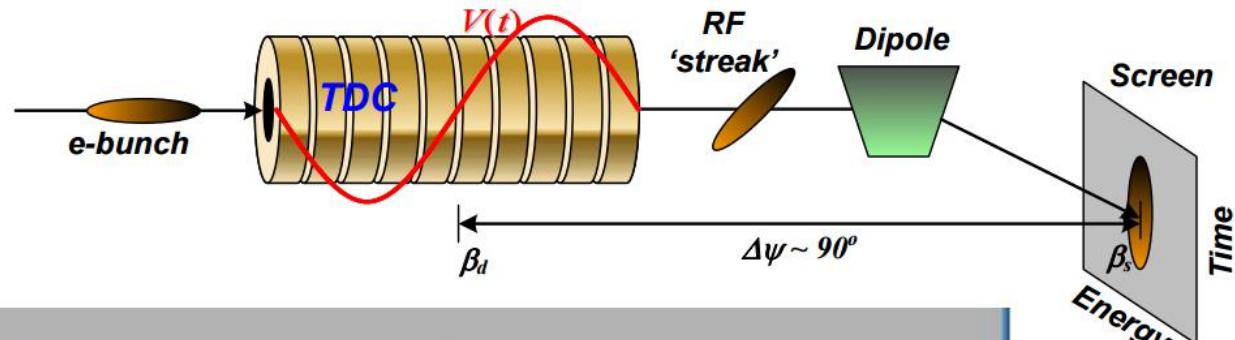
(b) nominal heating



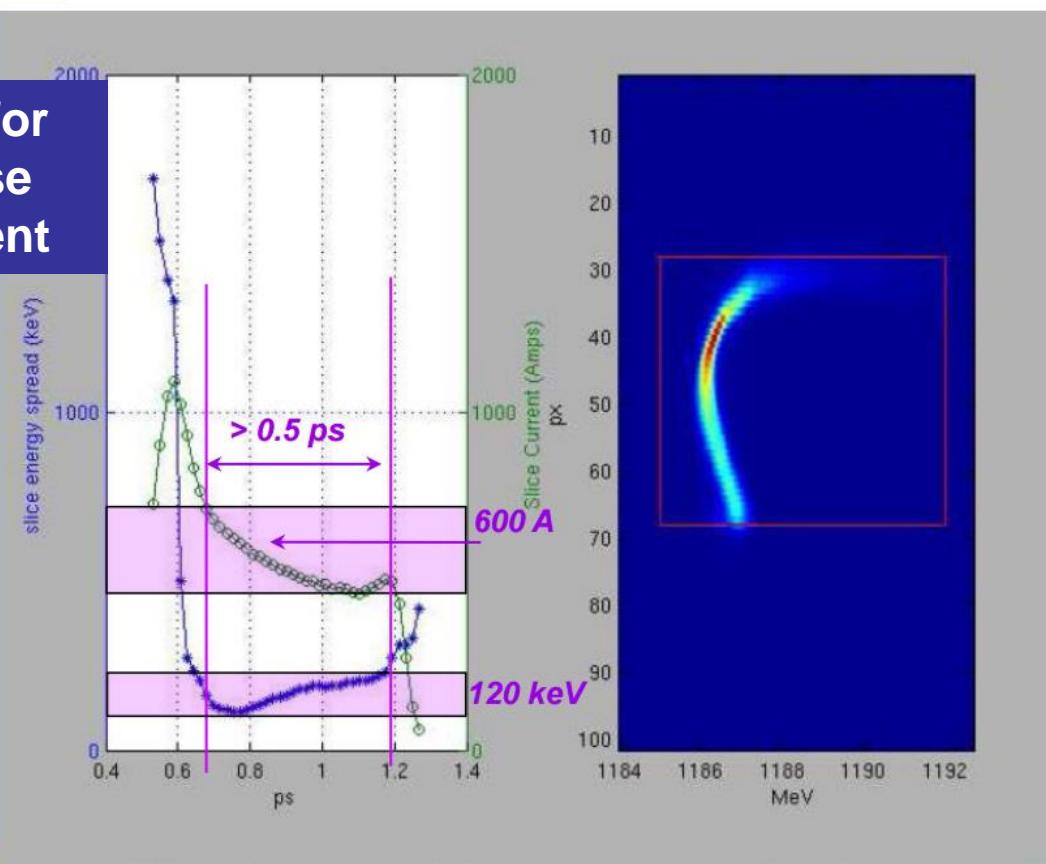
(c) maximum heating

4D manipulation

Slice beam analysis
made @1.2 GeV
using a
high energy
TDC

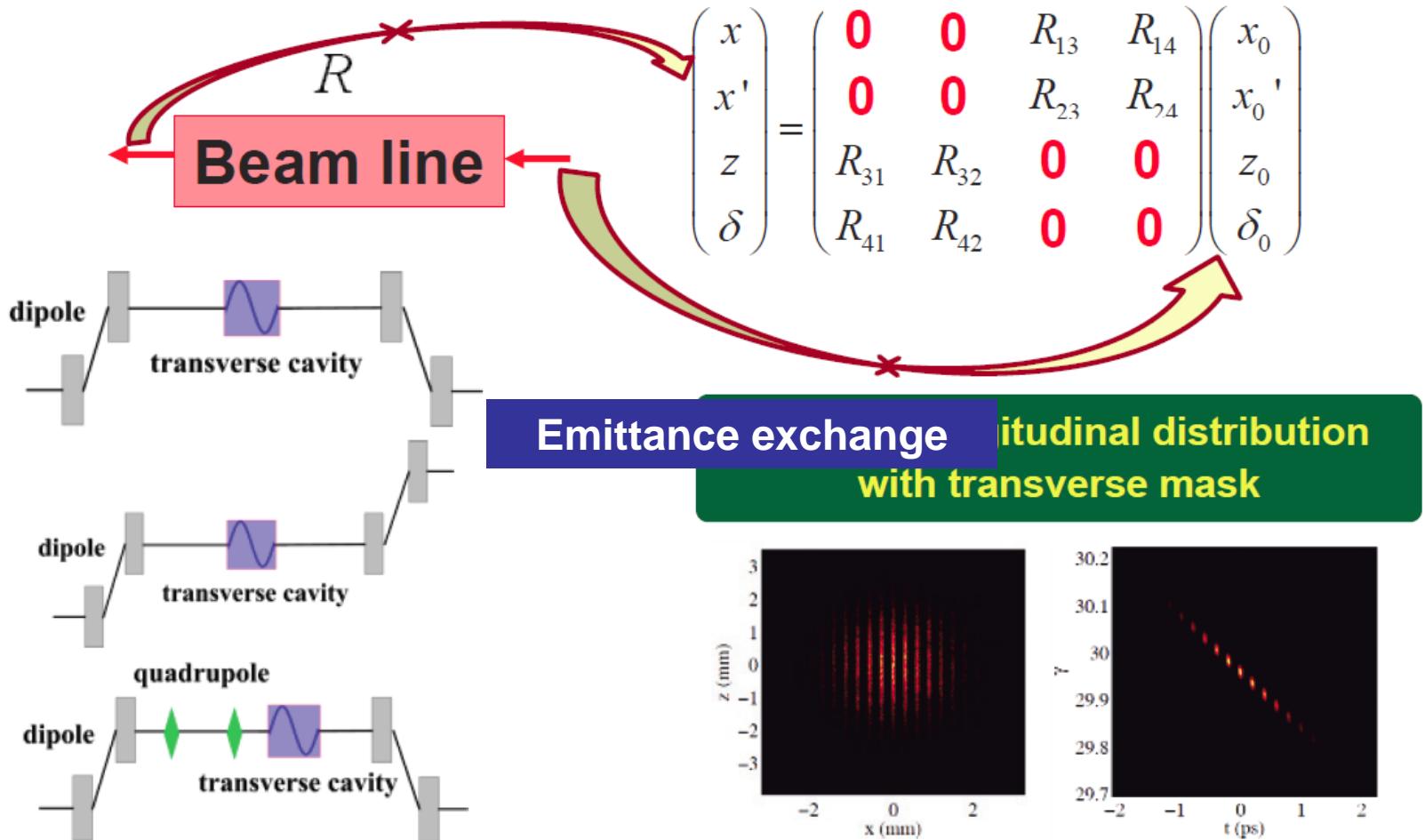


Deflecting cavity for
longitudinal phase
space measurement



Courtesy of
G. Penco

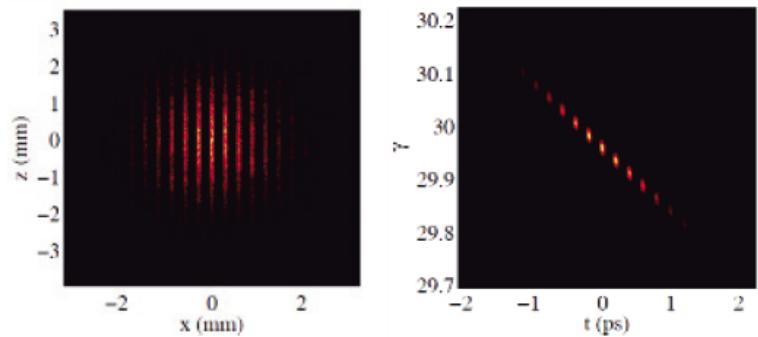
4D manipulation



Cornacchia and Emma PRST-AB, 5, 084001 (2002);

Emma et al., PRST-AB, 9, 100702 (2006);

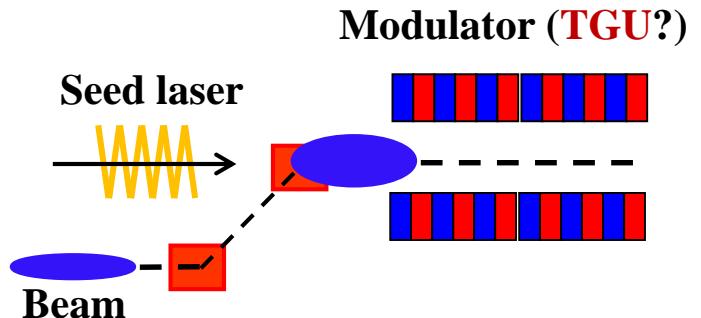
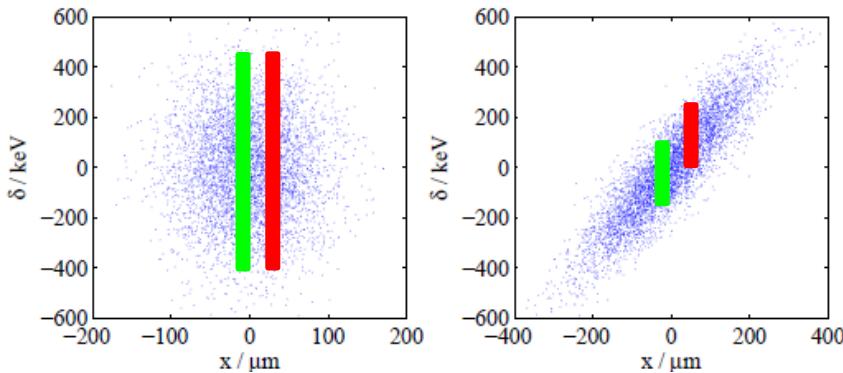
Xiang and Chao, PRST-AB, 14, 114001 (2011)



Sun and Piot, Linac08; Sun et al., PRL, 105, 234801 (2010); Ruan et al., PRL, 106, 244801, (2011); Piot et al., PRST-AB, 14, 022801 (2011); Jiang et al., PRL, 106, 114801 (2011)

Phase merging enhanced harmonic generation (PEHG)

Motivation & Initials



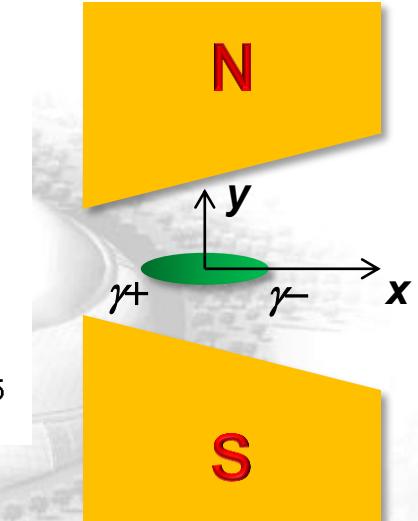
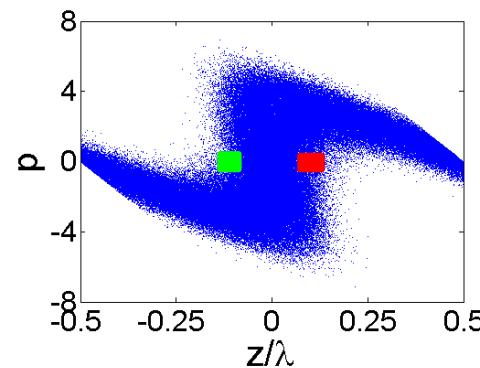
- Transverse gradient undulator (TGU)
- Sort e-beam energy by dispersion η

$$\frac{\Delta K}{K_0} = \alpha x$$

$$x = \eta \frac{\Delta \gamma}{\gamma_0}$$

- Optimized resonance relationship

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



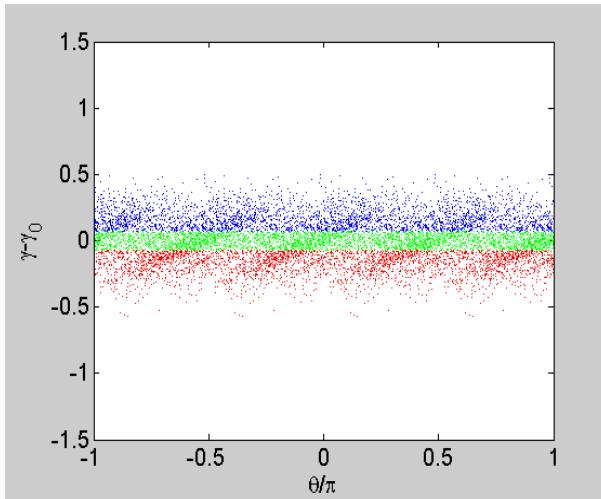
Phase merging enhanced harmonic generation (PEHG)

Phase-merging effect

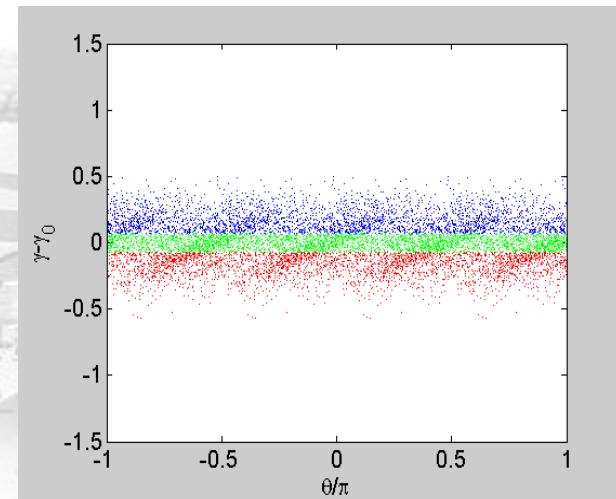
Some practical numbers:

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

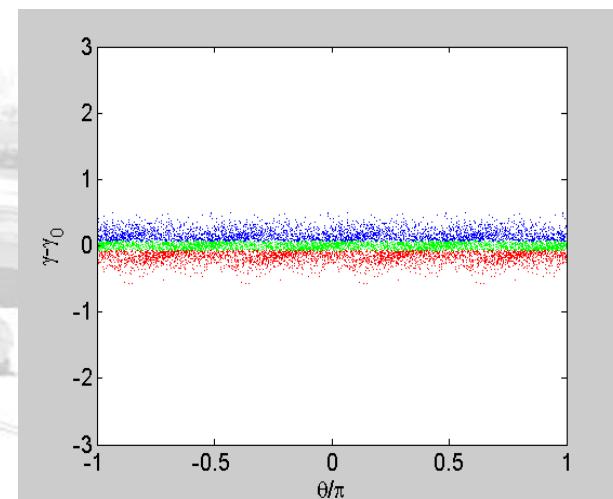
Phase-merging condition: $\alpha\eta = 24$



Standard-HGHG
 $\alpha\eta = 0$

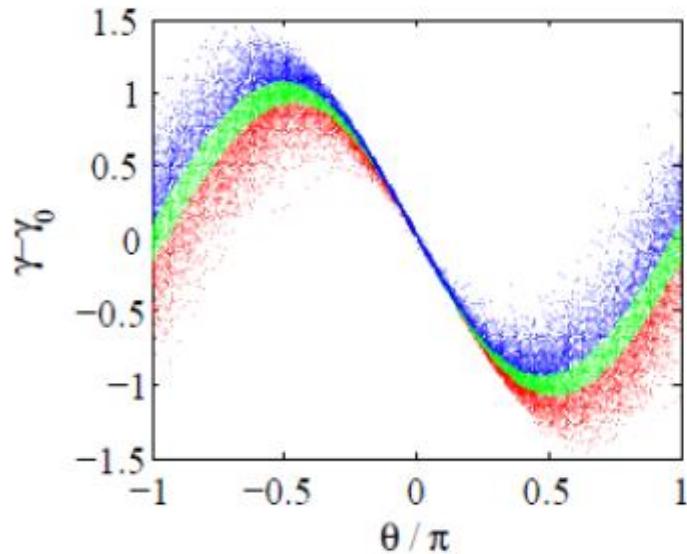


Phase-merging
 $\alpha\eta = 24$



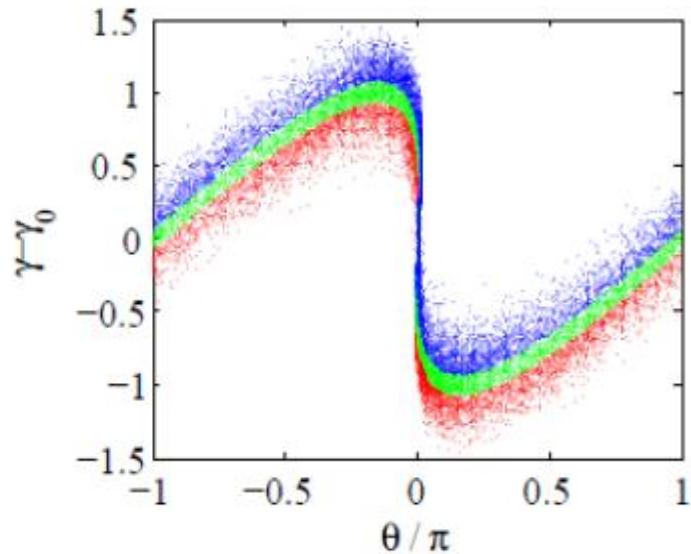
Phase-broadening
 $\alpha\eta = 50$

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

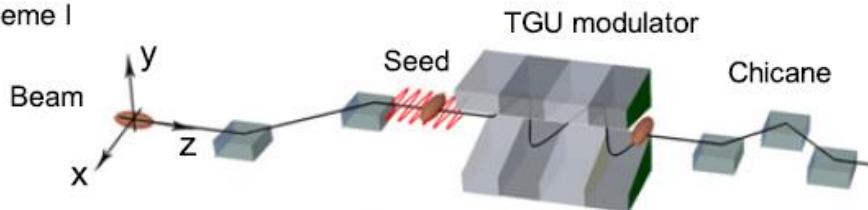
$$b_n = J_n(nD\Delta\gamma)$$

- The maximum bunching factor scales as $0.67/n^{1/3}$

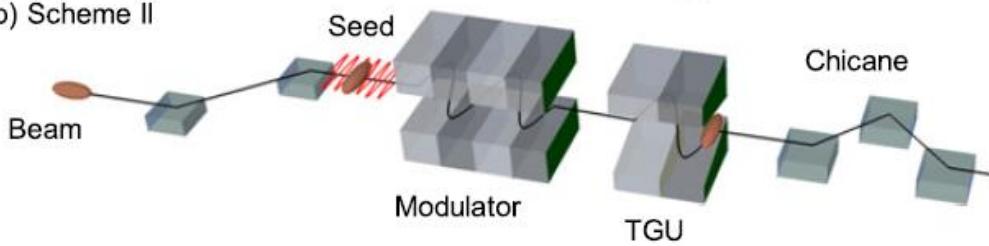
Phase merging enhanced harmonic generation (PEHG)

Alternative scheme I

(a) Scheme I

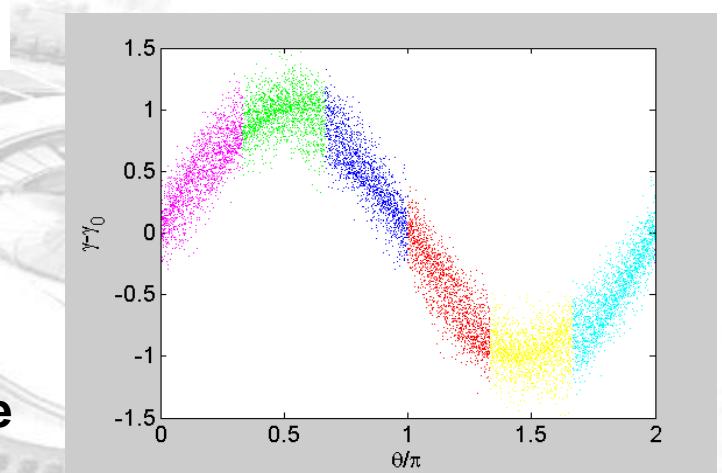
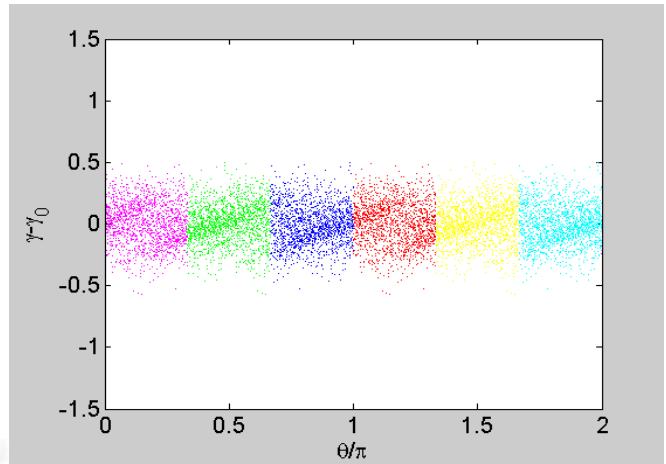


(b) Scheme II



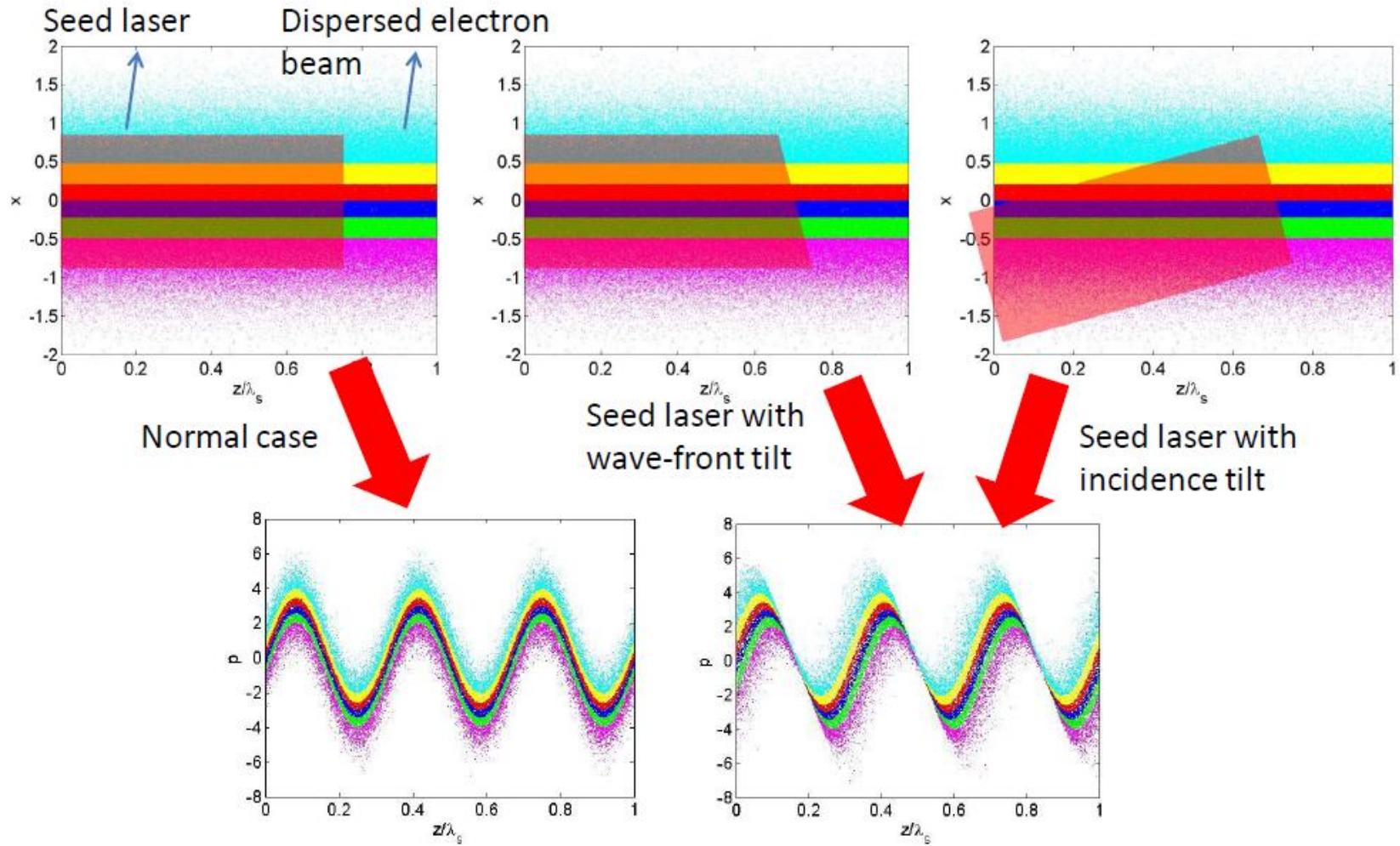
$$\alpha\eta = -\frac{2\gamma^3(n + 0.81n^{1/3})}{nAk_sL_mK_0^2\sigma_\gamma}$$

more flexible, smaller $\alpha\eta$ & better performance

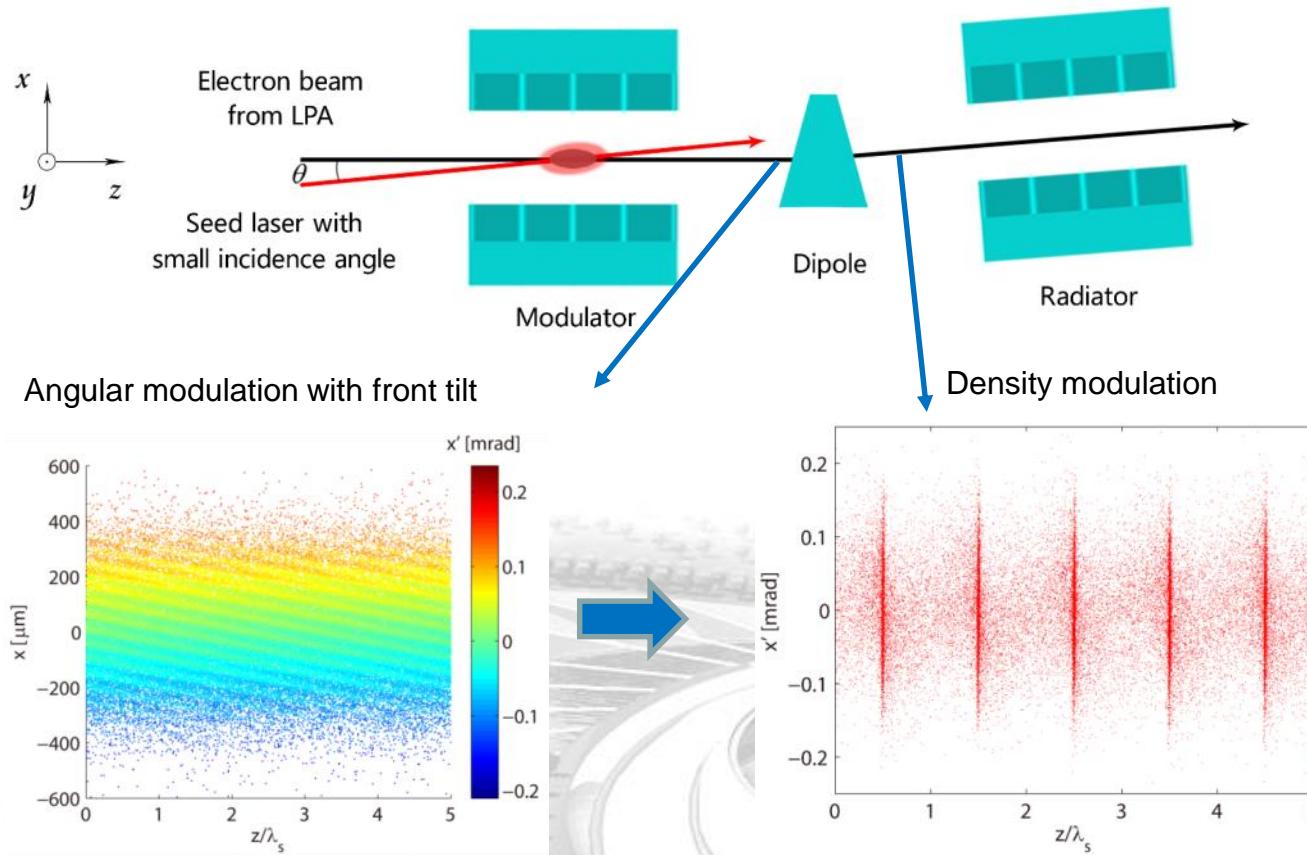


Phase merging enhanced harmonic generation (PEHG)

Alternative scheme II



Inducing angular modulation with a normal seed laser pulse



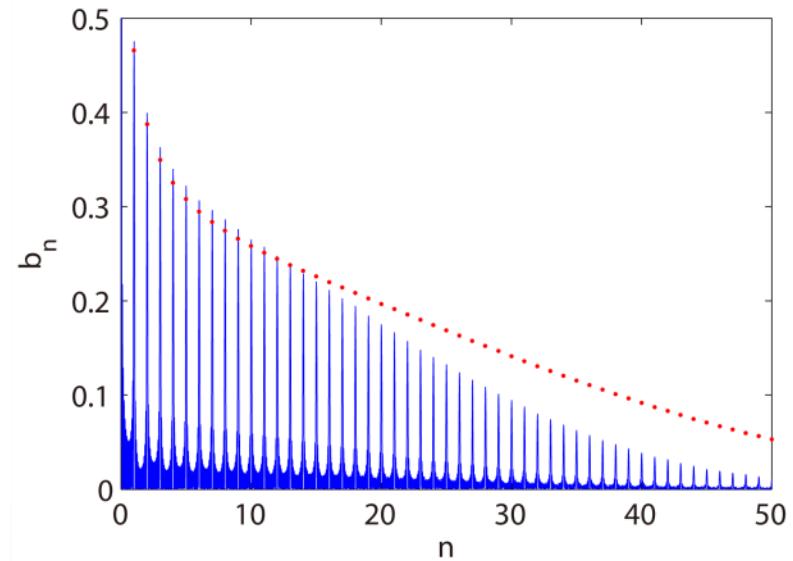
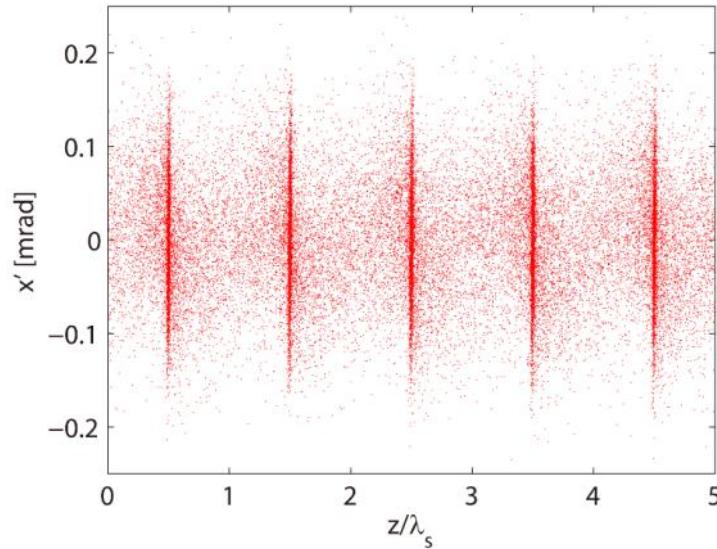
The angular modulation can be converted into density modulation by a weak dipole.

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

Inducing angular modulation with a normal seed laser pulse



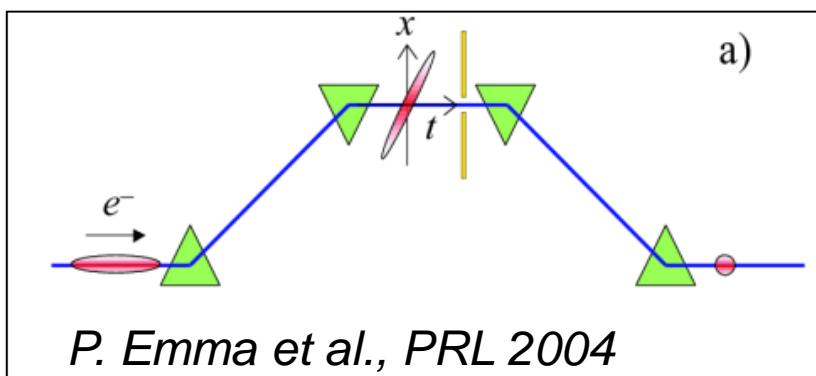
Electron beam from LPA

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

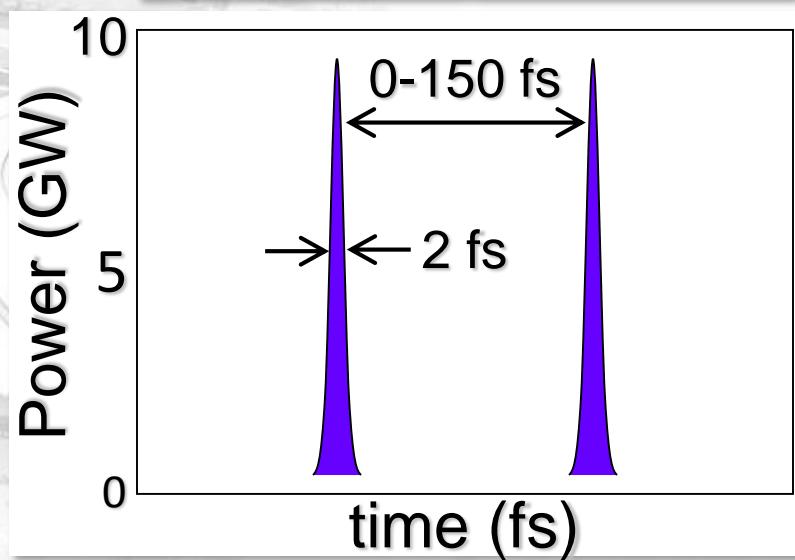
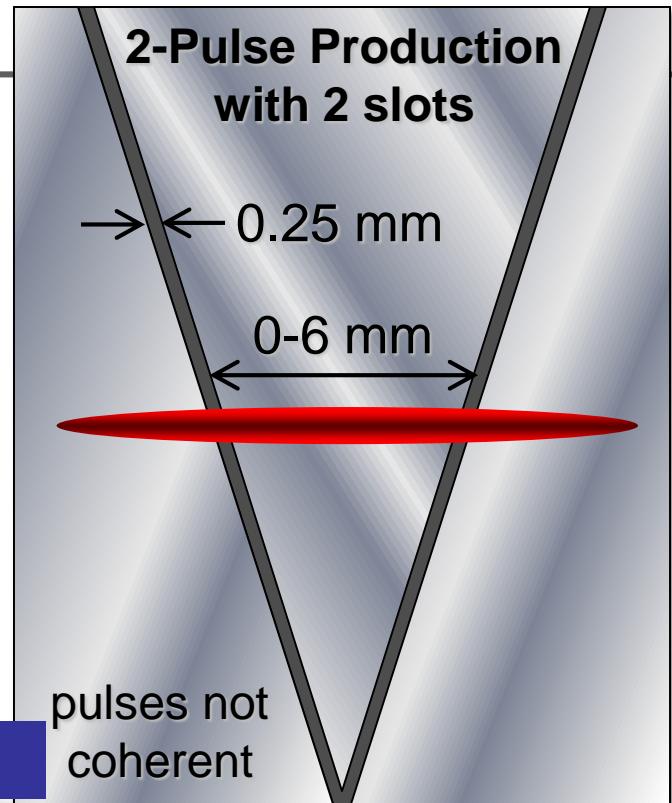
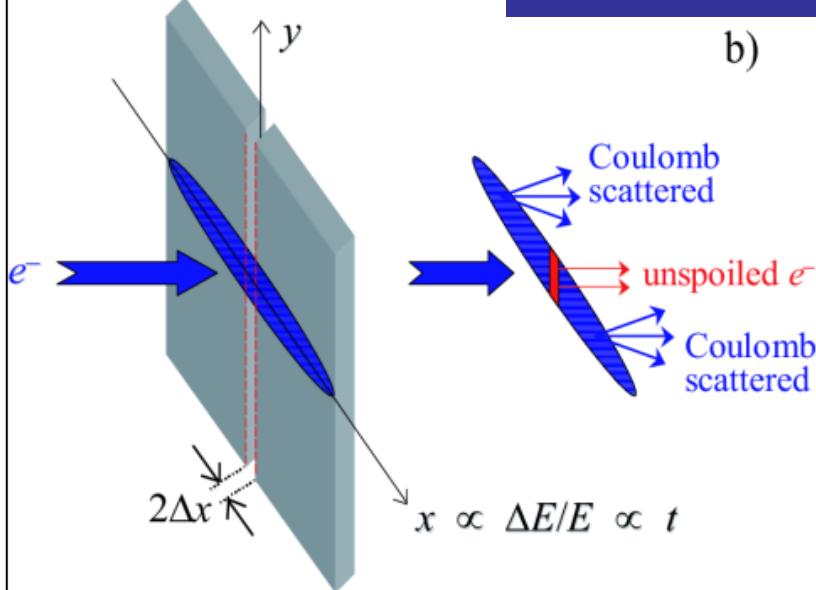
Drift section before modulator	3 m
Seed laser	260 nm/5 GW
Incidence angle	4.7 mrad
Modulator (sub harmonic)	8 cm^*2
Drift section after modulator	1 m
Dispersion	$R_{12}=5 \text{ cm}, R_{52}=8.8*10^{-5} \text{ m}$
Radiator	3 cm^*50

Electron beam manipulation (non-symplectic)

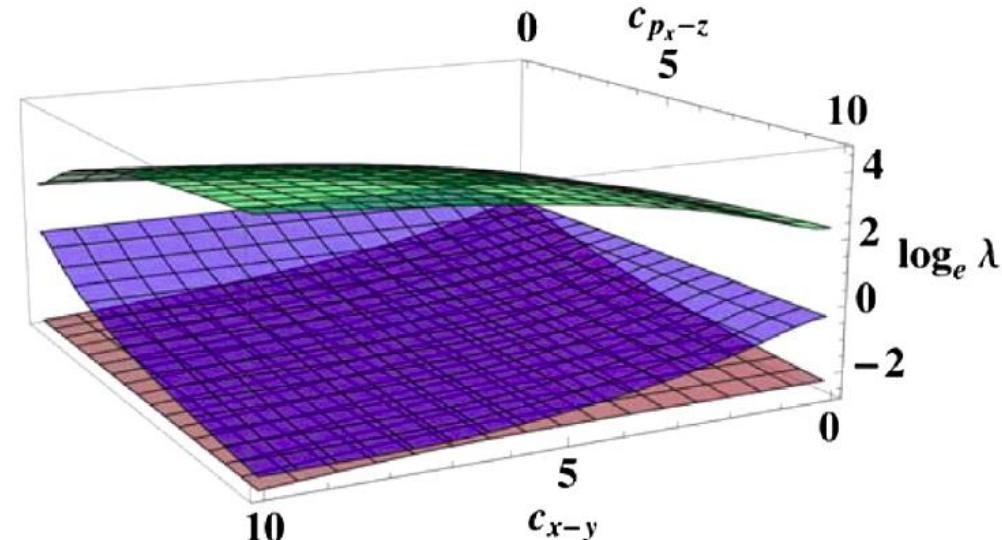
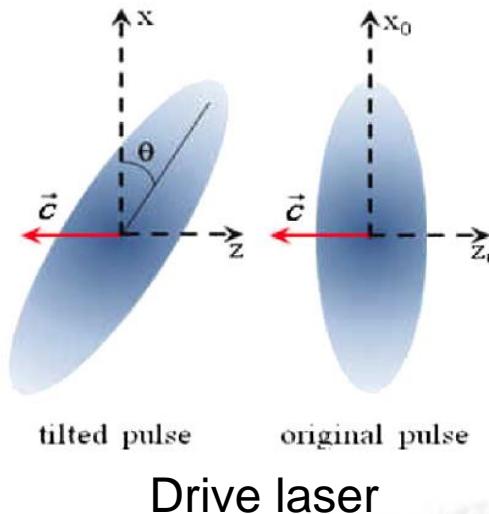


P. Emma et al., PRL 2004

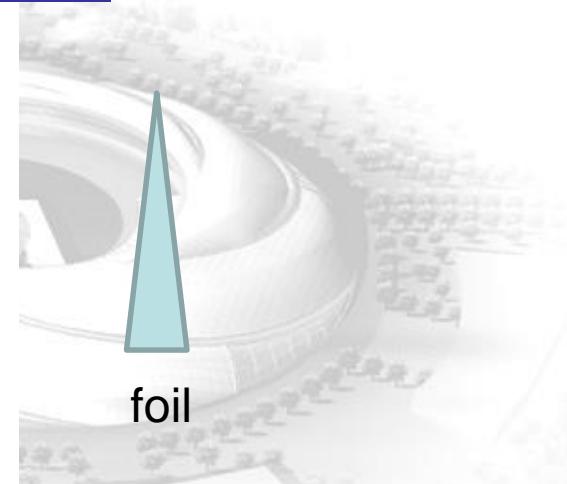
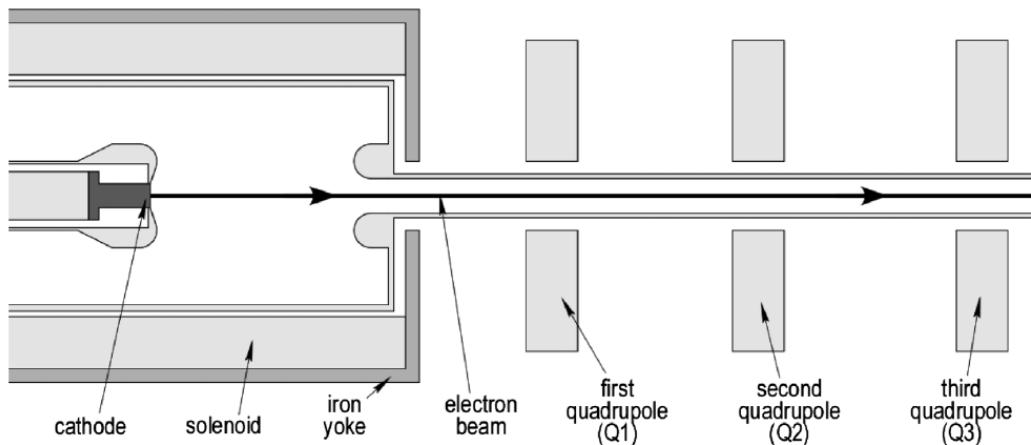
Emittance spoiler



Electron beam manipulation (non-symplectic)



Emittance partitioning



Summary

- 👉 Beam manipulations at beam-length and optical wavelength scales becomes a new focus in accelerator physics and has significantly enhanced the performance of accelerator based scientific facilities.
- 👉 Beam manipulation has to obey basic rules as well as technological limitations. However, if you can break the rules, there are more interesting things can be done.

Thanks!!!