Coherence Requirements for Various Seeding Schemes

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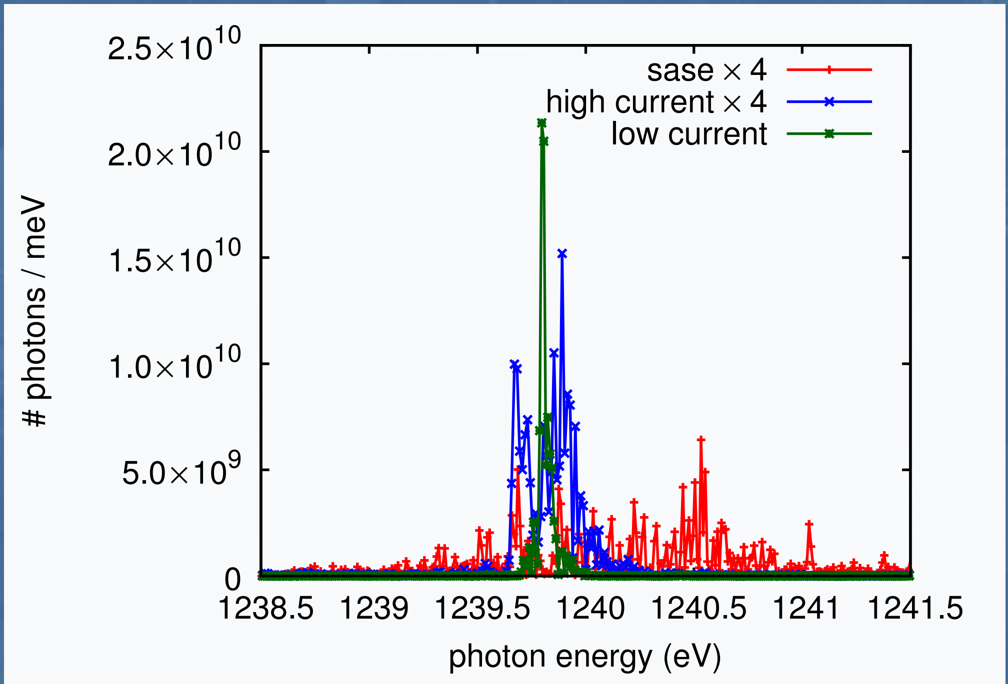


Coherence is a major goal of seeding

Laser seed phase errors

- multiplied by harmonic jump
- straightforward and unavoidable, not considered here
- small effect from laser seed power profile

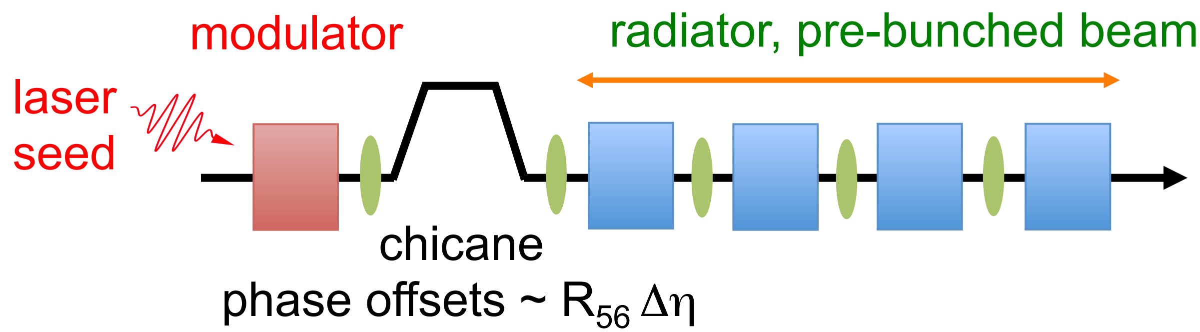
Shot noise

- required seed power grows with square of harmonic

Electron beam slice variations (scale > L_{coop})

- focus on slice energy
- peak current and emittance weaker

Start with HGHG



Phase variations from energy profile dominated by chicane

$$\Delta\theta = \frac{2\pi}{\lambda_r} R_{56}\,\Delta\eta$$

$\Delta\eta$ = rel slice energy offset

$$\Delta z = R_{56}\,\Delta\eta$$

avoids confusion when wavelength changes

(arbitrary sign choices, ‘normal’ chicane $R_{56}>0$)

Phase Errors Still Grow after Chicane

initial bunched beam → radiation phase

a good fit is

$$\Delta\theta \simeq \begin{cases} \frac{2\pi}{\lambda_u} L_u \Delta\eta \,, & L_u < 4.5 L_g \\ 1.2\, \frac{2\pi}{\lambda_u} \left(L_u - \frac{3}{4} L_g\right) \Delta\eta \,, & L_u > 4.5 L_g \,. \end{cases}$$

by analogy, define as

$$\Delta z \equiv R_{\mathrm{rad}}^{\mathrm{FEL}} \, \Delta\eta$$

shorthand: "R value" for radiator with pre-bunching

R^{FEL} for prebunched beams

$$R_{\rm rad}^{\rm FEL} \simeq \begin{cases} \frac{\lambda_r}{\lambda_u} L_u \, , & L_u < 4.5 L_g \\ 1.2 \, \frac{\lambda_r}{\lambda_u} \left(L_u - \frac{3}{4} L_g \right) \, , & L_u > 4.5 L_g \end{cases}$$

levels off at ~ $1.2 \, L_{\rm sat} \lambda_r / \lambda_u$ after saturation

R_{56} for undulators is $L_u (1 + a_u^2)/\gamma^2 = 2 L_u \lambda_r / \lambda_u$

- low gain, R^{FEL} is half of R_{56} from beamline
- L_u is magnetic length
  - more accurate, use $L_u + L_{drift}/(1+a_u^2)$

same result for modulator

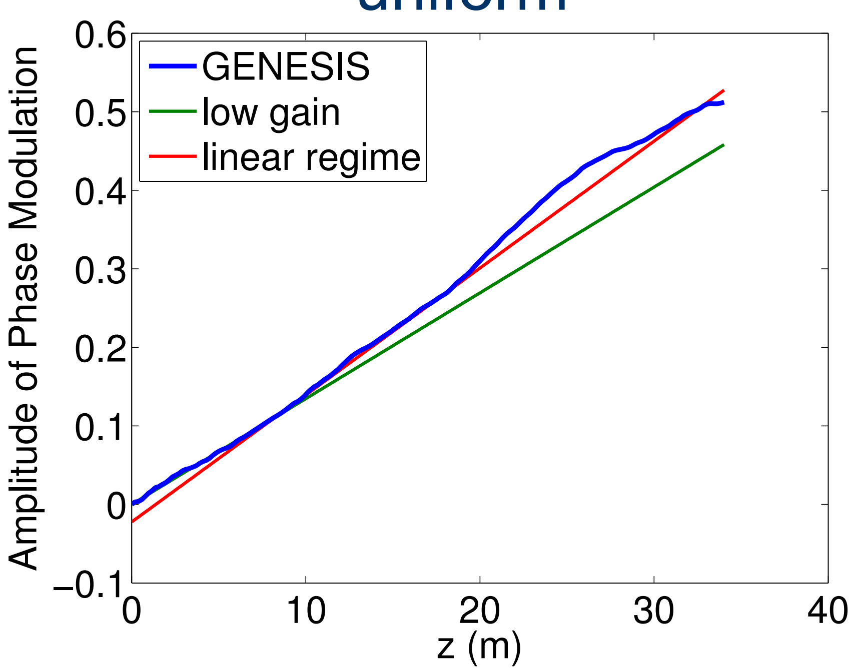
- initial radiation field → modulation phase

Prebunched beam: fit to simulations

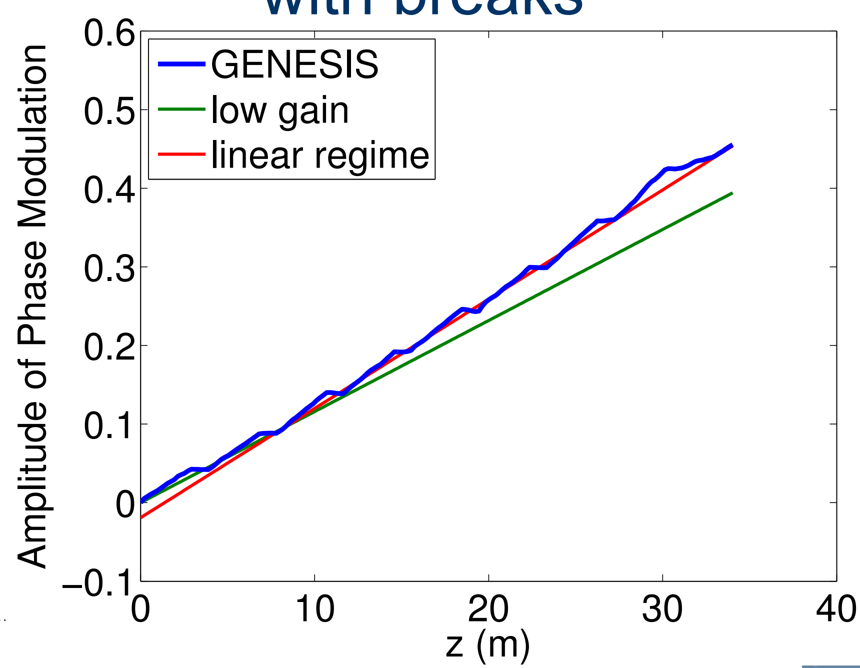
- e-beam: 2.4 GeV, 0.6 micron, 600 A, 250 keV spread
- und: 20 mm pd, 3 m sections, tuned for 1 nm output

100 keV energy modulation is applied: track phases

uniform



with breaks



after saturation, phase modulation levels off

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Close to 1D FEL theory

3 modes, only 1 growing

growth rates up to linear in $\Delta\eta$:

$$\Gamma_+ = \frac{1}{2L_{1D}}\left(1+\frac{i}{\sqrt{3}}\right) - \frac{4}{3} i k_u \, \Delta\eta$$

$$\Gamma_0 = \frac{1}{2L_{1D}}\left(1+\frac{i}{\sqrt{3}}\right) - \frac{4}{3} i k_u \, \Delta\eta$$

$$\Gamma_- = \frac{1}{2L_{1D}}\left(-\frac{2i}{\sqrt{3}}\right) - \frac{4}{3} i k_u \, \Delta\eta$$

initial mix for bunching with no modulation or field

differences from numerical fit:

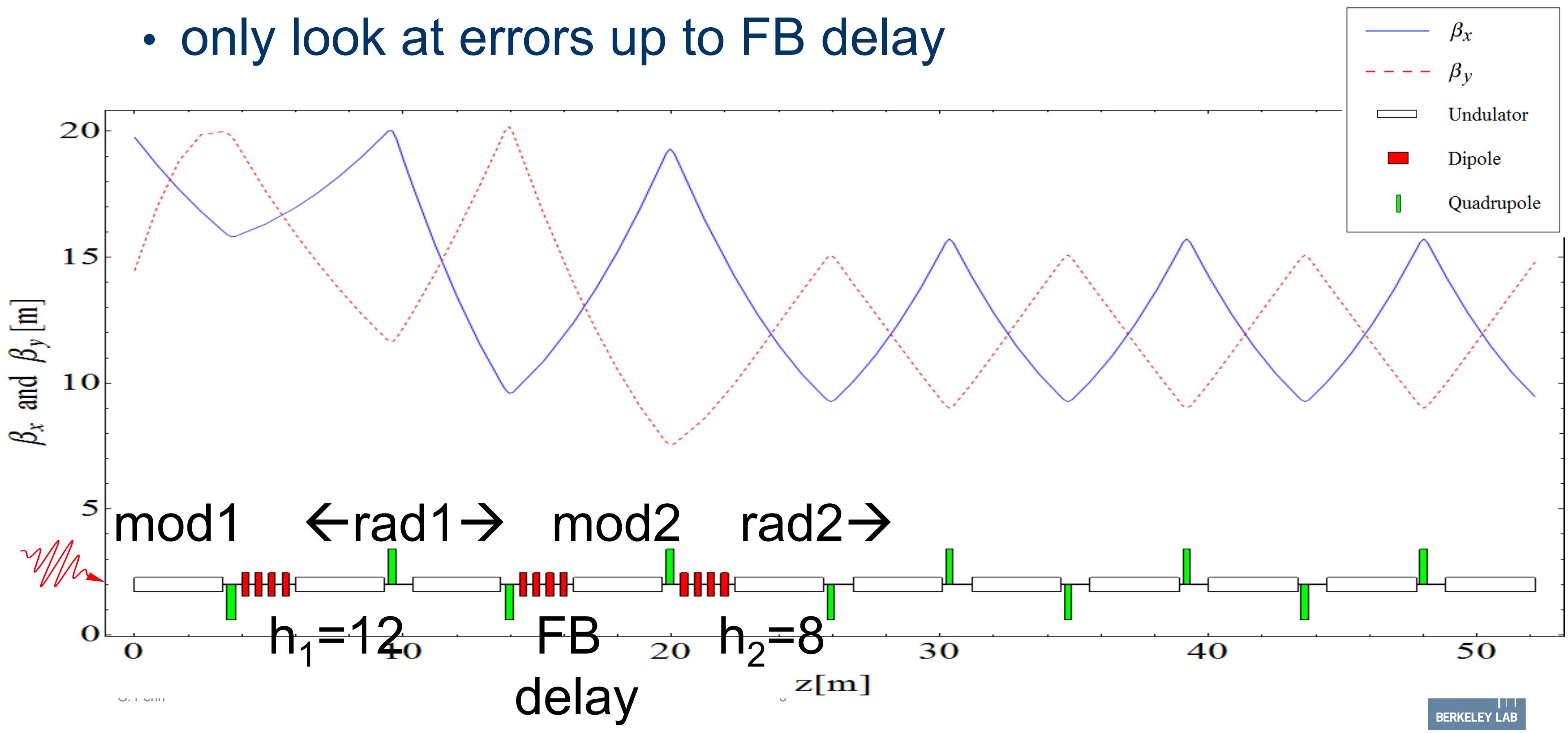
- replace L_g with L_{1D}, and 1.2 factor with 2 × 2/3

2/3 because bunch & modulation affected by dispersion, but not radiation; 4/3 → 1.2 due to diffraction?

2-stage HGHG example

2.4 GeV, 200 nm seed laser, 150 keV σ_E, fresh-bunch

- offsets before and after fresh bunch uncorrelated
- only look at errors up to FB delay



Sensitivity to energy offsets

Total effect:

$$R^{\mathrm{FEL}} = R^{\mathrm{FEL}}_{\mathrm{mod}} + R_{56} + R^{\mathrm{FEL}}_{\mathrm{rad}}$$

26.5 μm = 9 μm + 16 μm + 1.5 μm

- first chicane usually largest term

$$R_{56} \approx \frac{\lambda_{\mathrm{seed}}}{2\pi\eta_M}$$

η_M = rel energy modulation, typically ≤ ρ_{FEL}

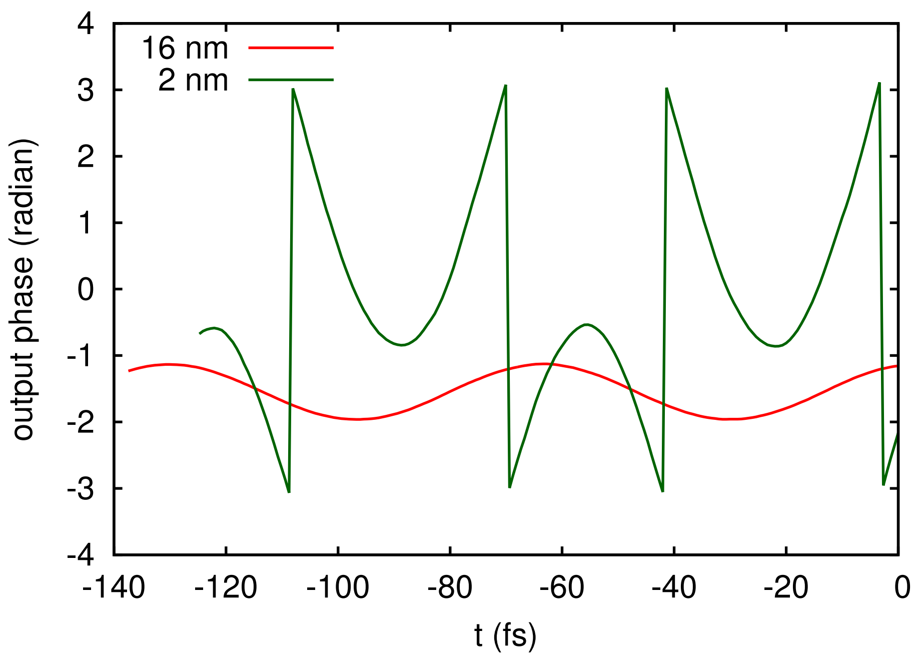
- energy modulation of 3.5 MeV yields R_{56}=16 μm
- also some bunching in modulator

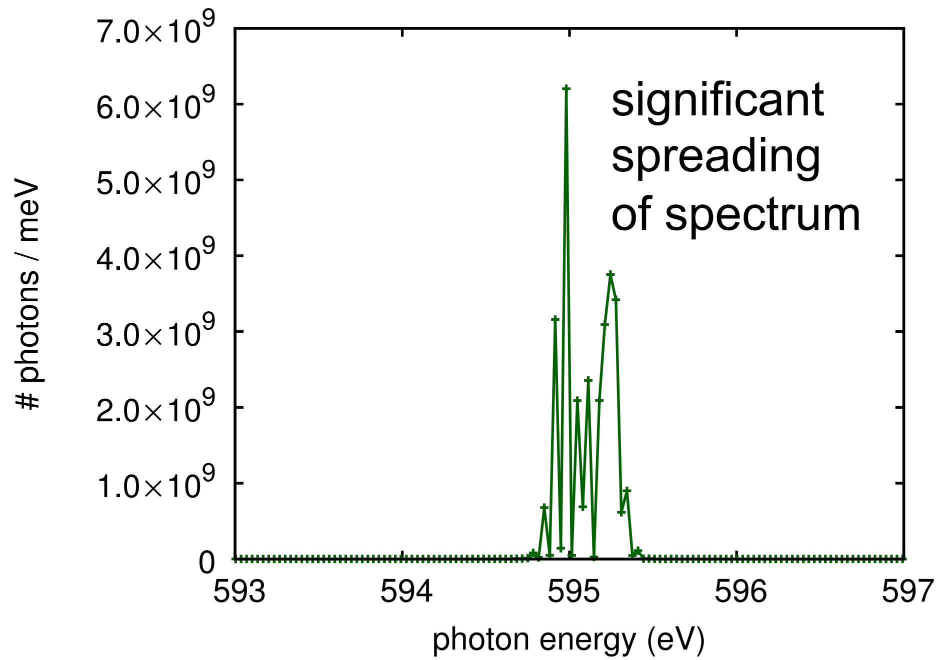
Output Phase and Spectrum

100 keV offsets: 1.1 nm shifts in location of microbunch

1st stage (16 nm) and 2nd stage (2 nm)

- at 2 nm > +/- 3 radian; R^{FEL}= 23 μm



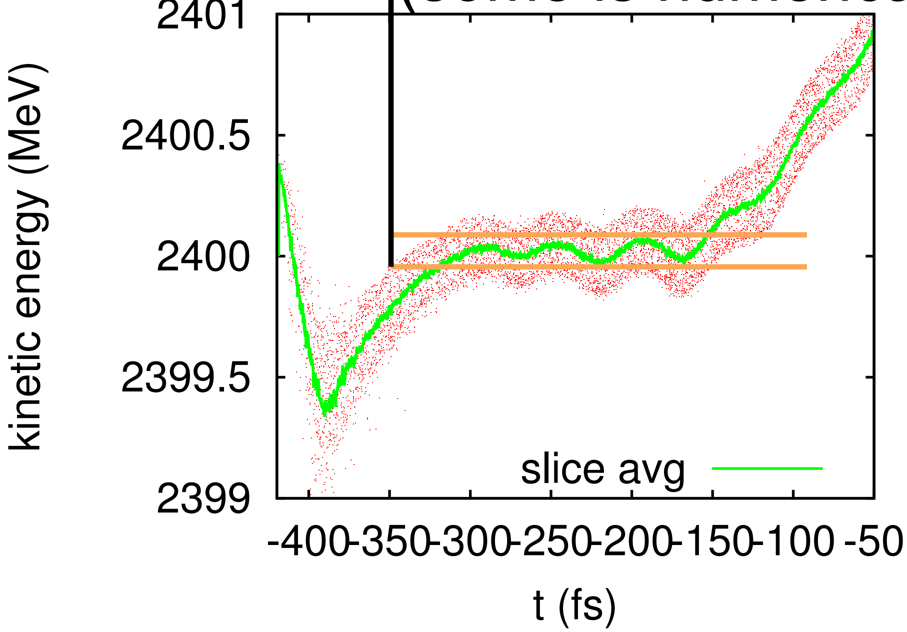


using avg phase; on-axis phase looks a little worse

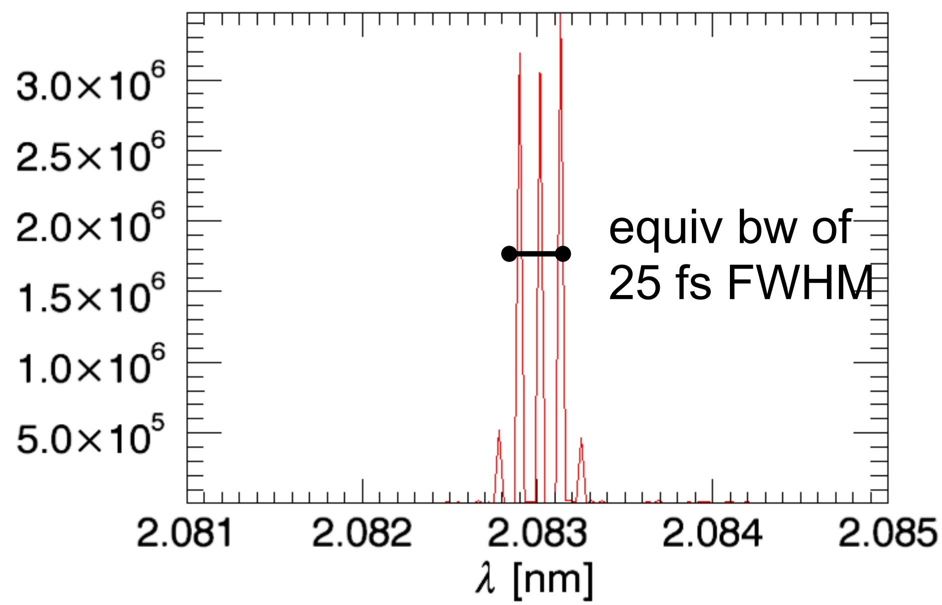
Simulated beam from RF gun

not an accurate estimate of microbunching

ripples ≤ 120 keV
(some is numerical)



spectrum with ±1.5 radian
phase modulation 120 fs pd



How to get more tolerance to chirp?

More modulation, weaker chicane?

- modulator already contributes a lot
- self-bunching (no chicane) degrades performance

Negative R_{56} chicane?

- have to unwind bunching from modulator

$$-18\ \mu\text{m} = 9\ \mu\text{m} - 29\ \mu\text{m} + 2\ \mu\text{m}$$

- more complex, usually not tunable

either way, get less than 50% improvement

- needs further study

Optical Klystron: new constraints

similar configuration, just no harmonic jump

- saturate sooner
  - V.N. Litvinenko, NIMA **304** (1991) 463
- low-power HHG seeds
  - M. Gullans *et al.*, Opt. Commun. **274** (2007) 167
- oscillators, …
  - G. Dattoli *et al.*, J. Quan. Elec. 31 (1995) 1584

optimal bunching when $kR_{56}\sigma_\eta \sim 1$

- but phase errors are $kR_{56}\Delta_\eta$, order unity when $\Delta_\eta \sim \sigma_\eta$
- if only care about power, use *slice* energy spread
- if care about coherence, use harmonic × Δ_η

(typically, Δ_η ~ projected energy spread)

Self-seeding and R^{FEL}

only post-monochromator stage has an impact

- initial radiation → final radiation phase
- same analysis, different dependence

$$R_{\mathrm{ss}}^{\mathrm{FEL}} \simeq \begin{cases} 0\,, & L_u < 1.5 L_g \\ 1.2\,\frac{\lambda_r}{\lambda_u}\left(L_u - \frac{3}{2}L_g\right)\,, & L_u > 1.5 L_g\,. \end{cases}$$

also close to 1D theory:

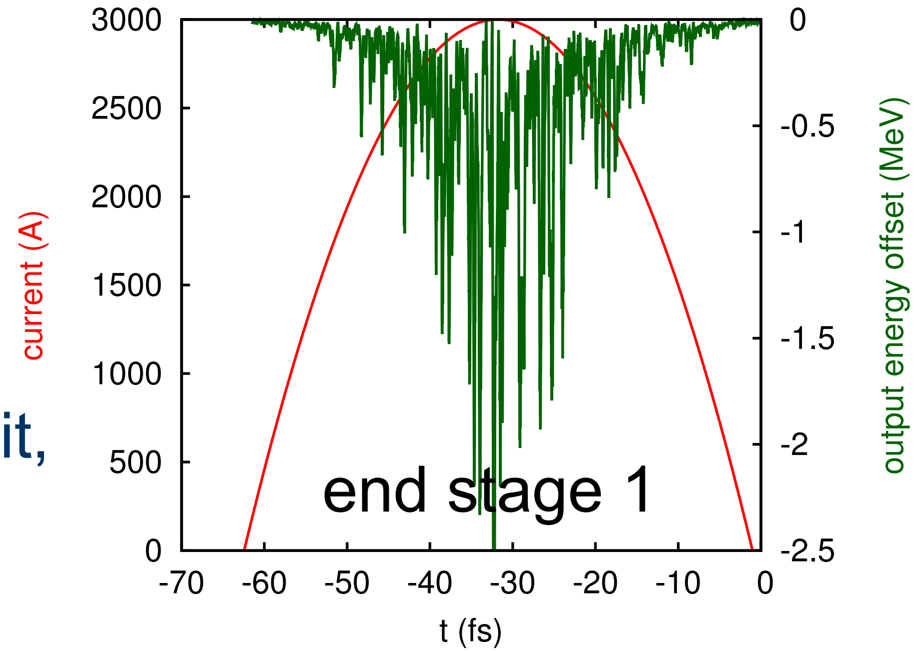
- low gain, no change in phase by definition of low gain
- linear regime would have 4/3 instead of 1.2

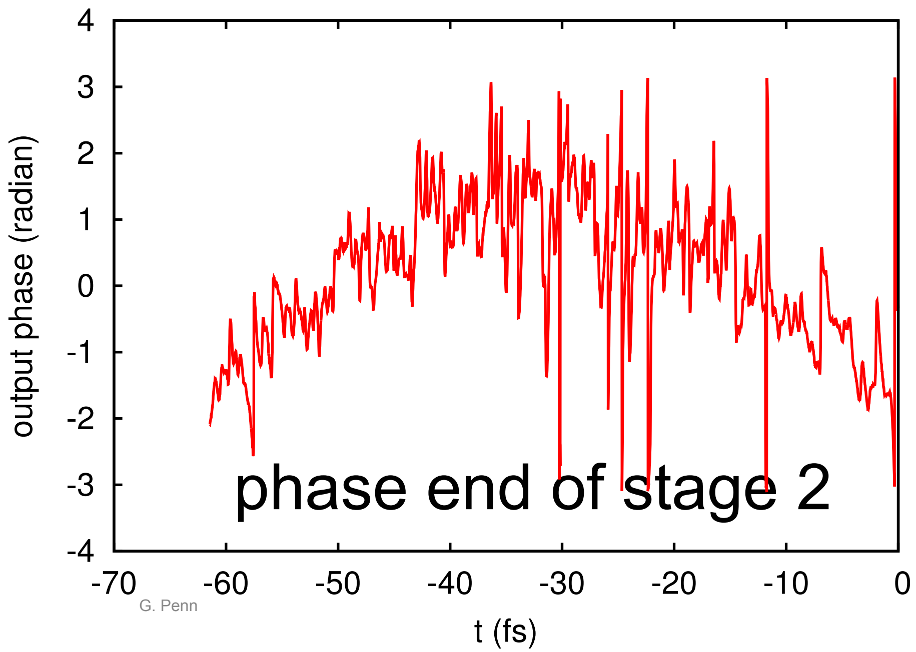
LCLS HXRSS self-seeding

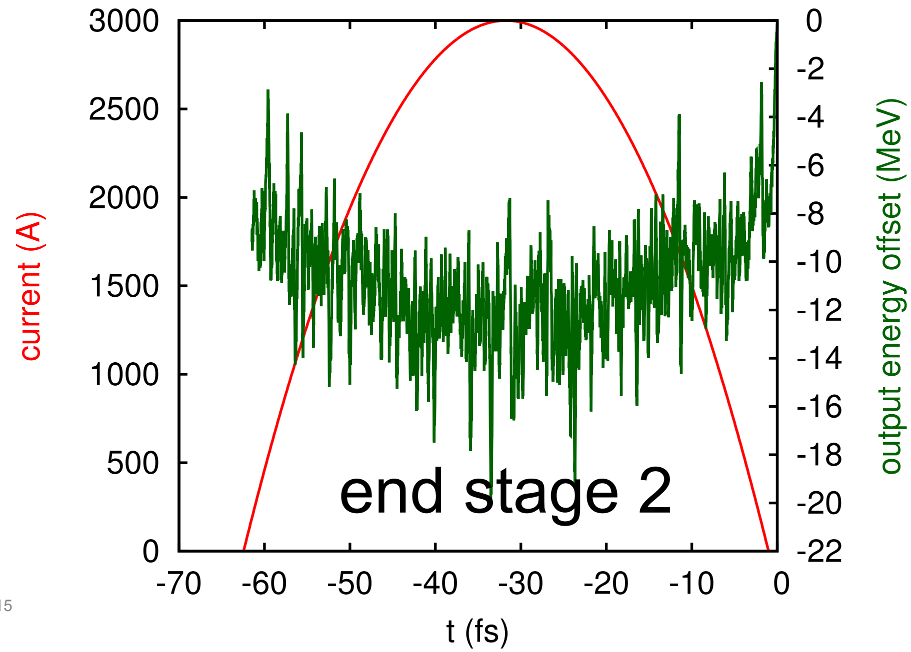
electron beam:

- 13 GeV, 3 kA, 0.4 μm emit, parabolic profile

radiate at 0.15 nm







EEHG has intriguing result

In echo scheme, mixing two waves:

- output k_x=pk_2-mk_1 p, m integers; k=2π/λ
- smaller phase errors in bunching than HGHG*

$$\Delta\theta = (k_x R_2 - m k_1 R_1)\,\Delta\eta$$

- so

$$R_{\text{echo}}^{\text{FEL}} = R_2 - m R_1 \lambda_x / \lambda_1$$

- two terms can partly cancel, but bunching

$$b \propto J_m\left[(k_x R_2 - m k_1 R_1)\,\eta_{M1}\right]$$

- if arg=0, no bunching

η_{M1} is 1st relative energy modulation

* D. Xiang and G. Stupakov, PRST:AB **12** (2009) 030702

EEHG less sensitive to energy offsets

usually m=1, Bessel function yields soft optimum

$$|k_x R_2 - k_1 R_1| \simeq 1.8/\eta_{M1}$$

very good scaling, almost cancels

- ratio of terms is $1.8\,(\eta_{M2}/\eta_{M1})\,(\lambda_2/\lambda_x)$
- R^{FEL} goes like output wavelength, not seed wavelength

$$R_{\mathrm{echo}}^{\mathrm{FEL}} = R_2 - mR_1\lambda_x/\lambda_1$$

Easy control over sign of R^{FEL}

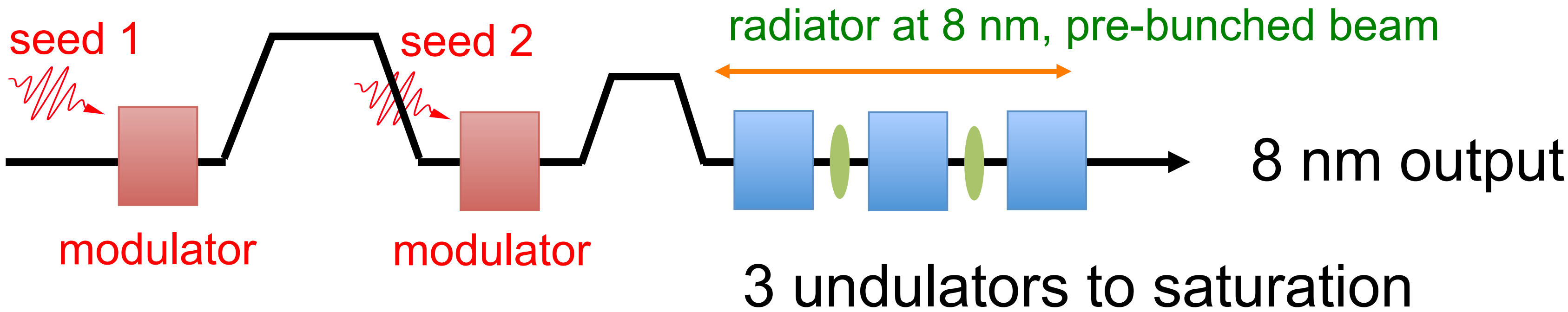
useful feature, EEHG has two optimal settings for R_1

- for given $\Delta\eta$, can choose sign of $\Delta\theta$
- can look like negative R_{56}
  - get this for free by mixing two frequencies
  - single electrons at higher energy shift to front, but *regions* of high current are shifted back in phase

tunable: just cannot have $R^{FEL} = 0$, else $b=0$

- bunching scales linear or better with R^{FEL}

Use EEHG to tolerate big energy offsets



beam: 2.4 GeV, 0.6 μm emit, 150 keV σ_E

200 nm seeds, 300 keV modulation

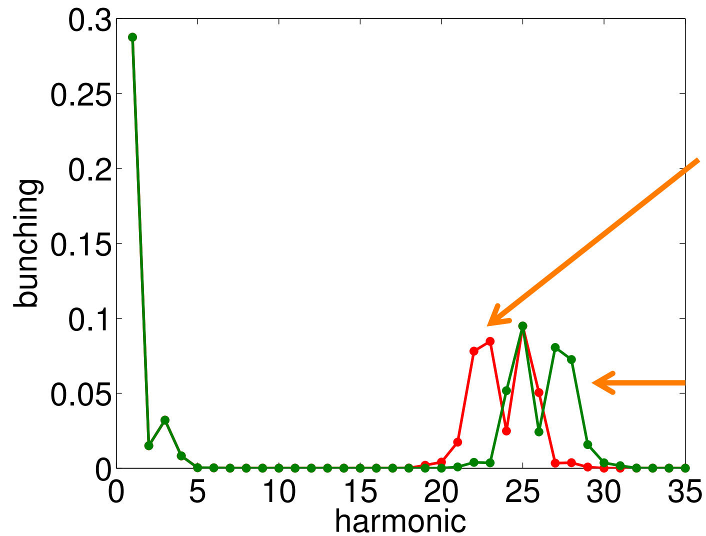
R_1=7.5 mm, R_2=280 micron

optimum $|R_2 - R_1\lambda_x/\lambda_1|$ = 14 micron (with energy spread)

- close to HGHG case
- ~ 1/10 energy modulation

Harmonics, bunching, and R^{FEL}

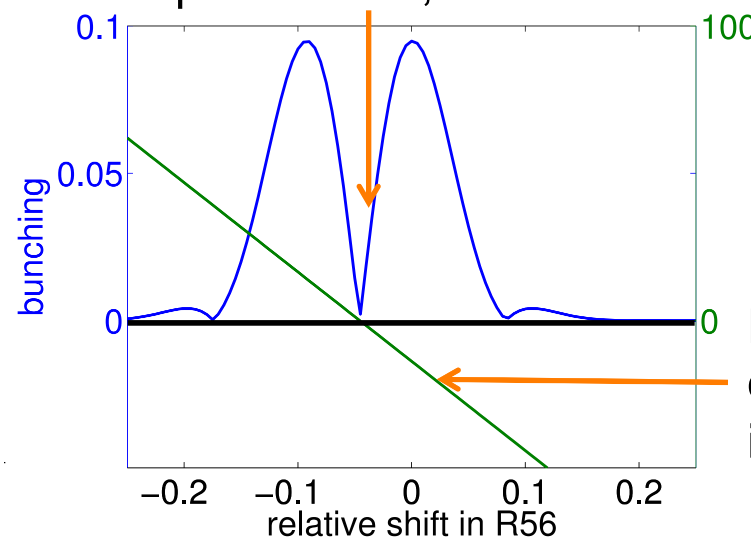
2 choices to optimize bunching:



25th harmonic, bunching and R^{FEL} vs ΔR_1

radiator adds 4 μm

includes energy spread
neglects scattering



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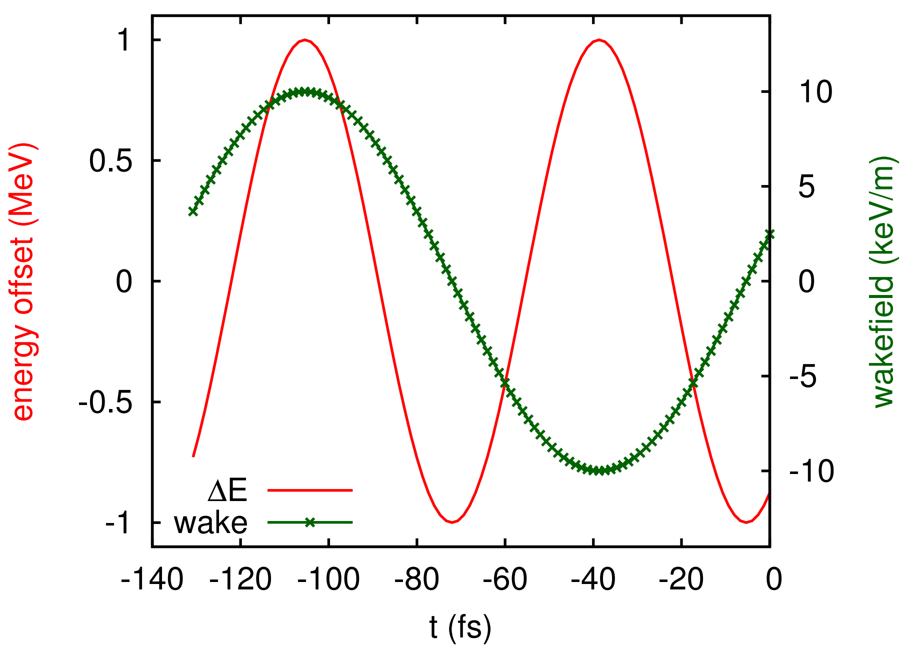
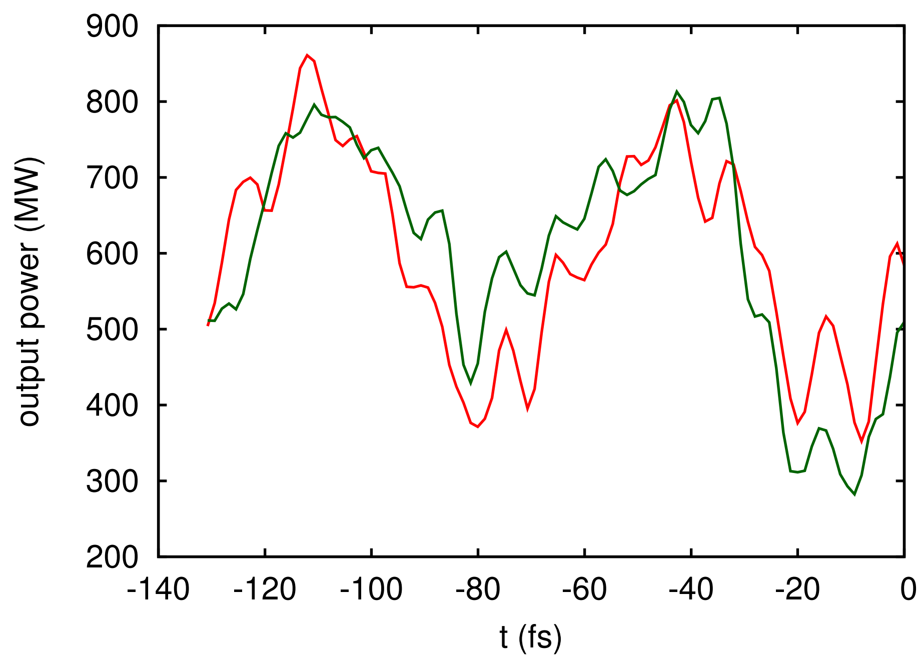
EEHG simulations at 8 nm

consider initial energy modulation +/- 1 MeV

- optional +/- 10 keV/m wakefield

includes ISR and rough IBS models





red: just energy modulation green: added wakefield

Residual Phase Errors

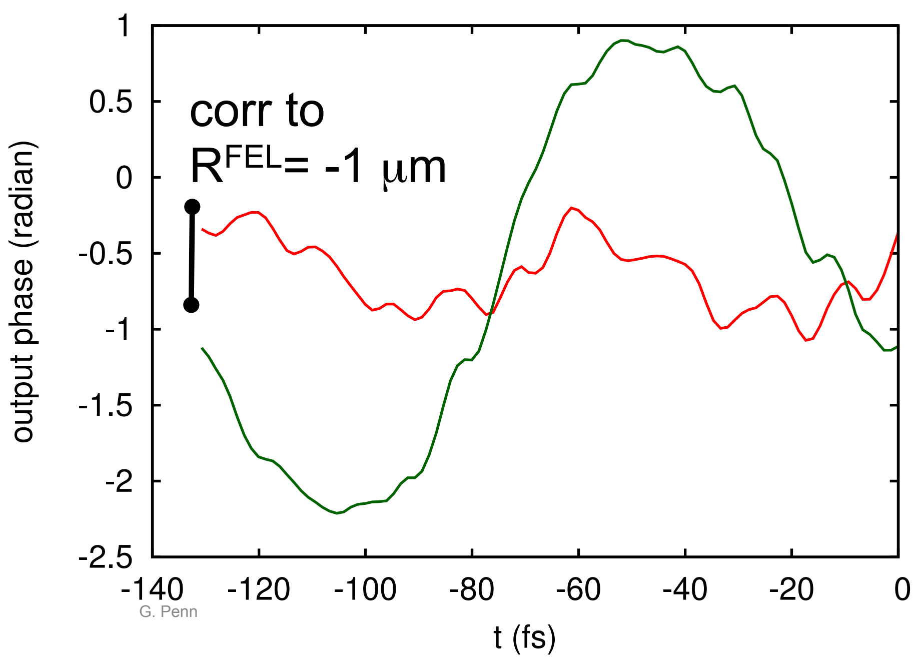
due to slippage, phase errors misaligned with energy

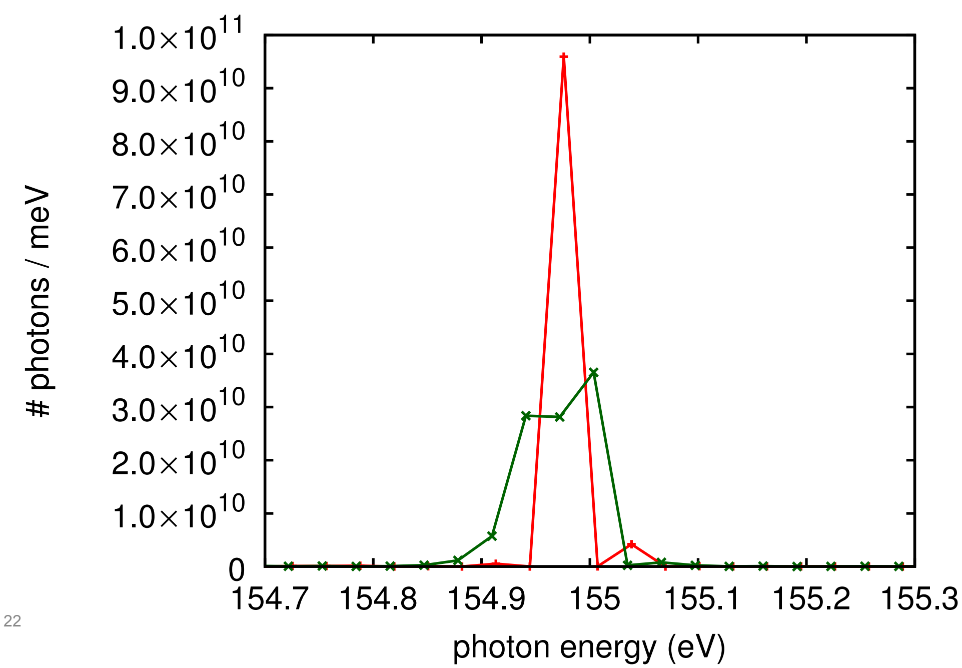
- but if slippage > modulation scale length, acts like σ_E

wakefields generate uncorrected phase errors

- thanks to Paul Emma for pointing this out

different radiated power generates extra energy offsets





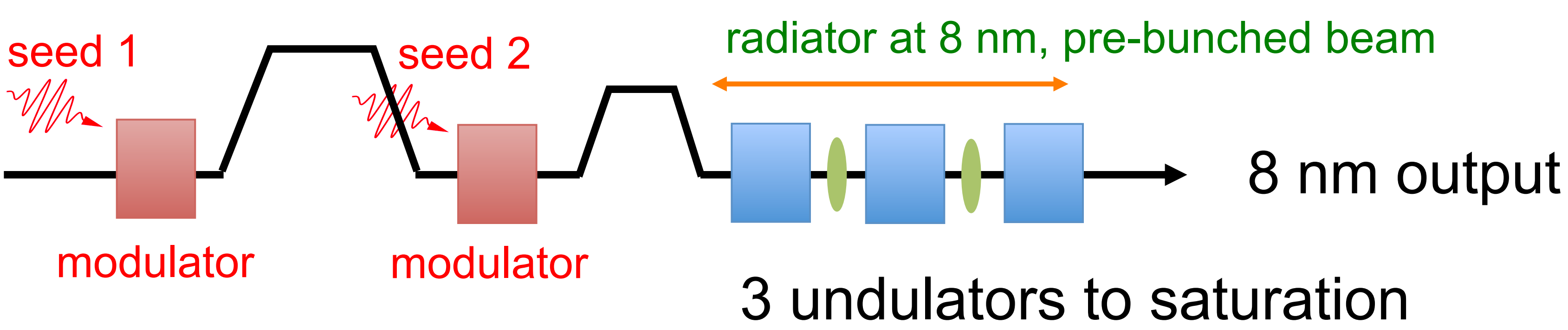
Push to 2 nm

tweak design to reach 2 nm, using EEHG+HGHG

try not to use fresh bunch

- otherwise slice energy before/after uncorrelated
- could use fresh bunch and just accept phase offsets from after delay

earlier design



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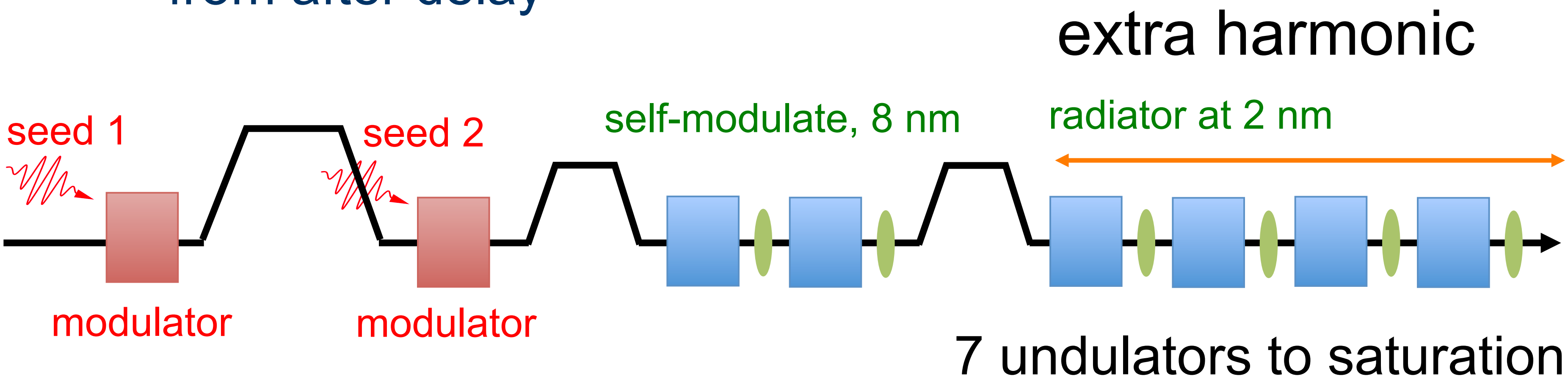

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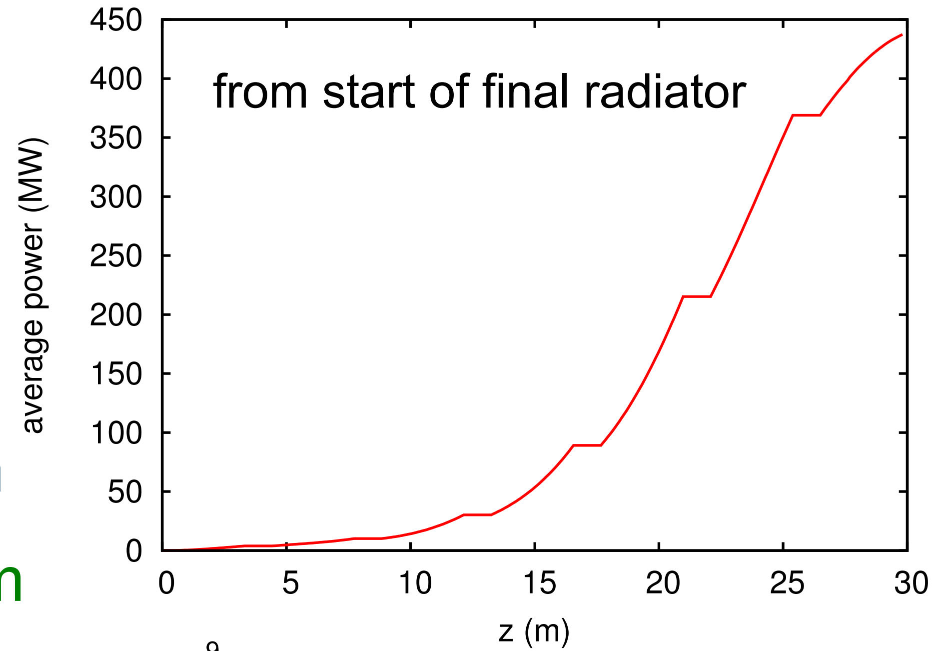
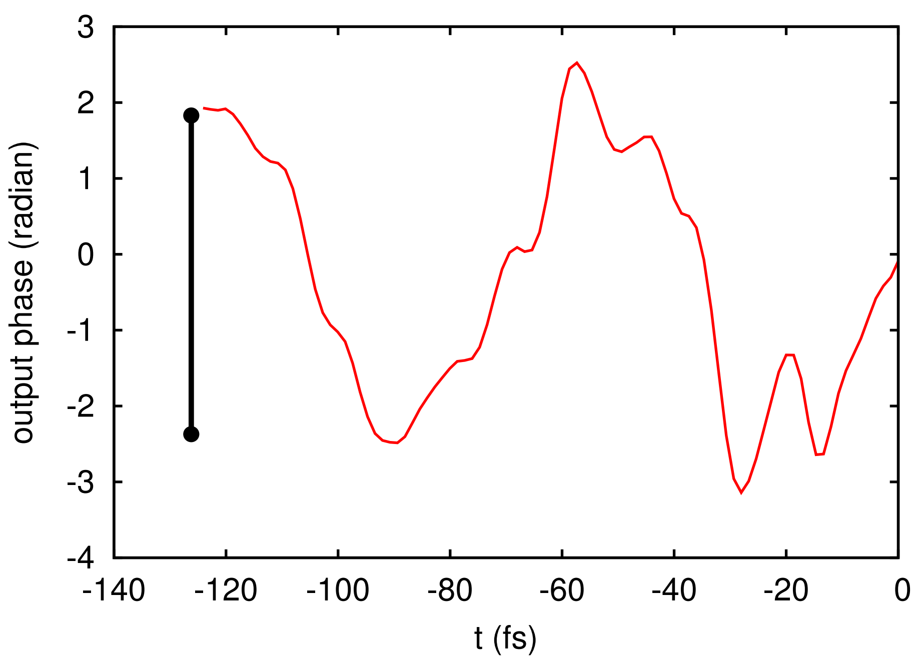
Results at 2 nm

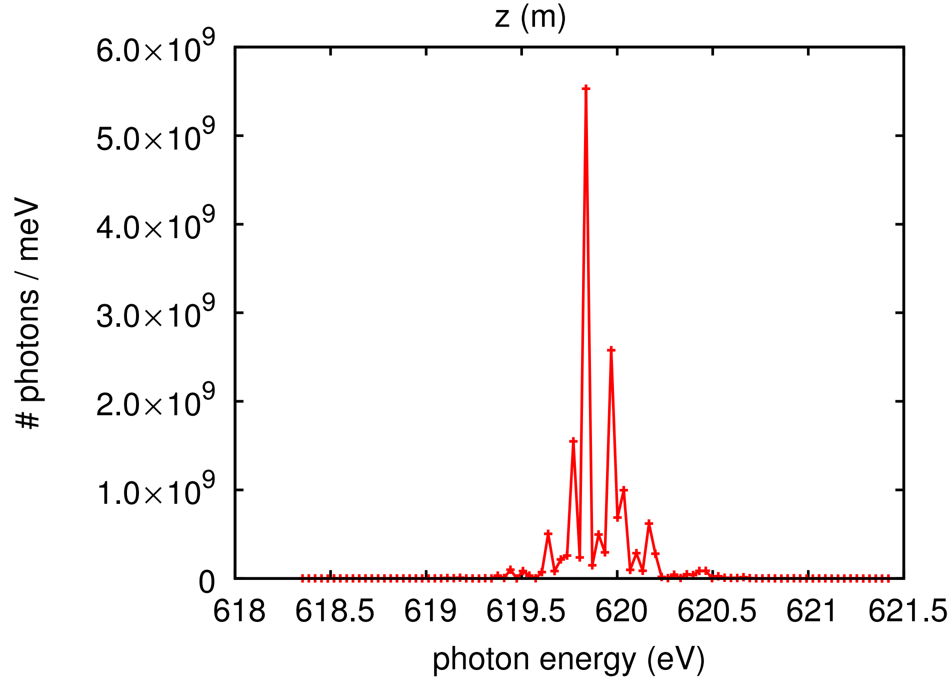
no wakes

equivalent to R^{FEL} ~ -1.5 μm

compare to HGHG, 23 μm







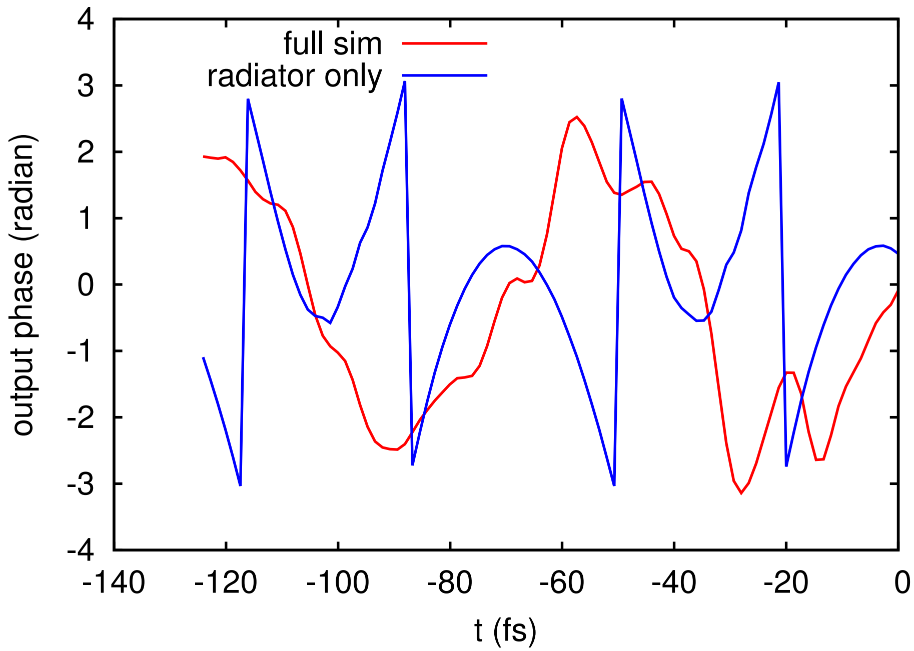
Results at 2 nm

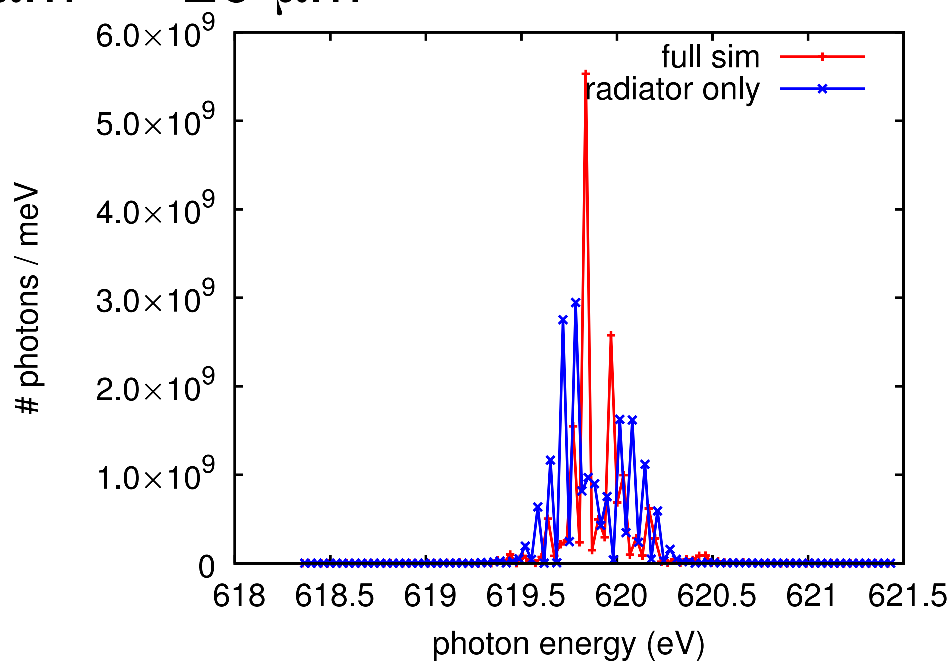
compare to "perfect" bunching at start of radiator

R^{FEL} for radiator alone is ~ 3 μm

improvement ~ $\left|\sin(\pi L_{\text{shift}}/L_{\Delta E})\right|$

3 μm   20 μm





Quick Summary

rough scalings for different configurations:

- HGHG or OK, $\Delta\theta \sim (\lambda_{seed}/\lambda_{out})\, \Delta\eta/\eta_M > (\lambda_{seed}/\lambda_{out})\, \Delta\eta/\rho$
  - want $\Delta\eta < \rho\, /\, (\lambda_{seed}/\lambda_{out})$
- selfseed or radiator, $\Delta\theta \sim$ (# gain lengths) $\Delta\eta/3\rho$
  - want $\Delta\eta < \rho \times 3$ / (# gain lengths)
- EEHG, $\Delta\theta \sim (\lambda_x/\lambda_{out})\, \Delta\eta/\eta_{M1} \rightarrow \Delta\eta < \eta_{M1}\, (\lambda_{out}/\lambda_x)$
- other slice variations, $\Delta\theta \sim$ (# gain lengths) $\Delta\rho/3\rho$
- one region reaches saturation first: ~ 1 radian
  - energy loss ~ ρ over a few gain lengths

slice energy spread barely has any effect

"killer app" for echo scheme?

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