Prospects of Cascaded Harmonic Generation FELs*

G. Penn
Lawrence Berkeley National Laboratory

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Outline

Harmonic generation by cascade of multiple harmonics

- Planned facilities and design studies

Fundamental noise issues and challenges

- Phase errors and energy variations
  - made worse with high harmonic numbers
- Simulation noise associated with energy spread
- Strategies

Comparison of conventional laser and HHG as seeds

Conclusions and future outlook

Collaborators

LBNL Center for Beam Physics

- Bill Fawley, Sasha Zholents, Jonathan Wurtele

FERMI@Elettra collaborators (non-LBNL)

- Giovanni De Ninno, Enrico Allaria, Fulvio Parmigiani, Bruno Diviacco
- Max Cornacchia
- Bill Graves – MIT Bates

Earlier work on LUX design study

Assistance from Sven Reiche, UCLA

- GENESIS simulation program

and many others

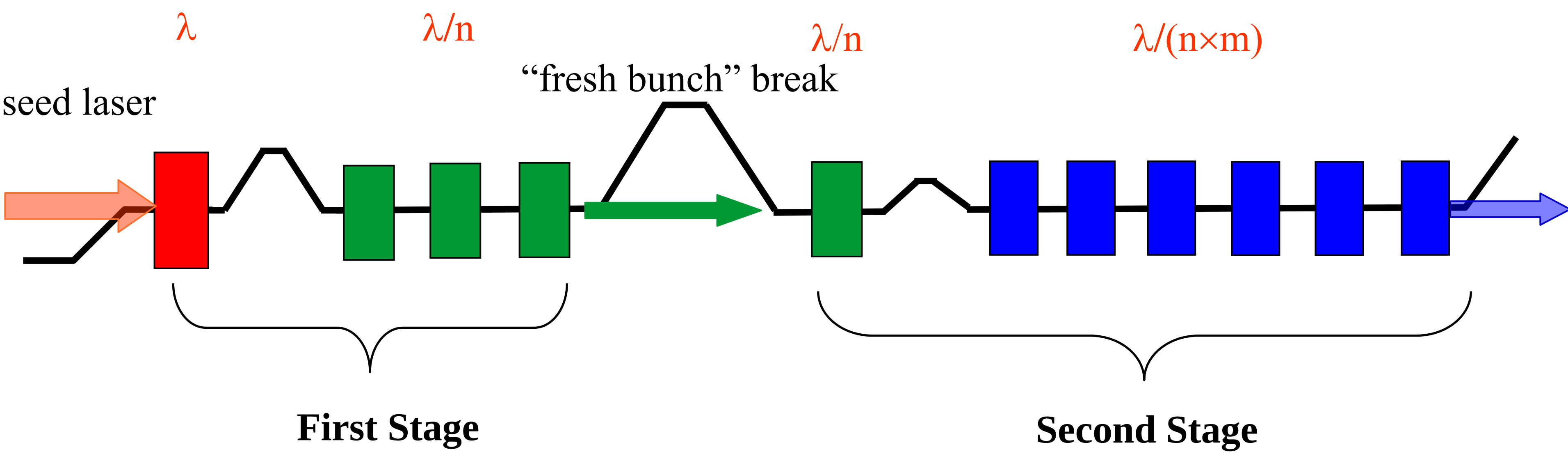
FERMI@Elettra

Parameters

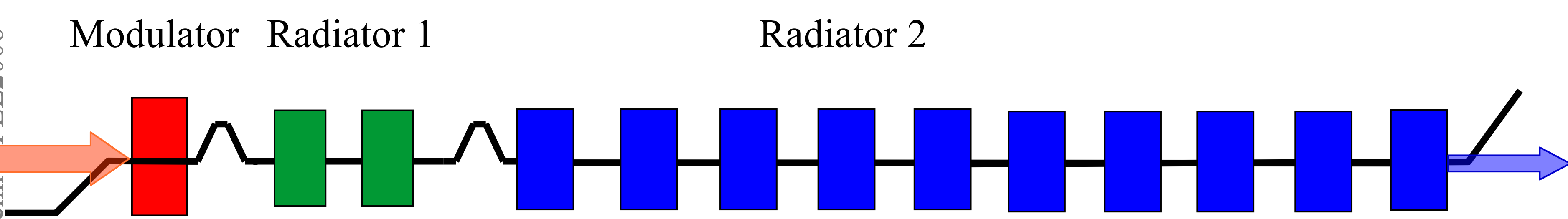
- 1.2 GeV beam, 1.5 micron emittance
- current can range from 400 A to 1 kA, depending on charge and compression
- laser for FEL seed: tunable 240–360 nm, up to 100 MW peak power, up to 1 ps pulse duration
- 2 beamlines:
  - FEL-1 has one harmonic stage, output from 100 nm to 40 nm
  - FEL-2 has two harmonic stages, output from 40 nm to 10 nm
- considering “fresh-bunch” and “whole-bunch” for FEL-2

FEL-2 Options

Fresh-bunch:



Whole-bunch:



Multi-Stage Cascades

BESSY:

- 1 – 2.3 GeV electron beam, 1750 A, 1.5 micron emittance, 200 keV energy spread
- Laser seed: short pulses, 15 fs rms, ~ 1 GW peak power
- Considering up to four harmonic stages, possible wavelengths ranging from 50 nm to as low as 1.2 nm
- Expect a few μJ of energy per pulse

LUX design study at LBNL:

- 1.1 – 3.1 GeV electron beam, 500 A, 2 micron emittance, 200 keV energy spread
- Laser seed: 100 fs or shorter, ~ 100 MW peak power
- Up to four harmonic stages, 40 nm to 1 nm

Phase Noise Multiplication

Energy samples before and after energy modulation + bunching

Each energy bunches at a different phase (phase space preserved)

Related to:

- sensitivity to energy spread
- sensitivity to energy variation
- macroparticle noise, even with quiet load, $\approx n\Delta_\gamma/N_\gamma\gamma_M$

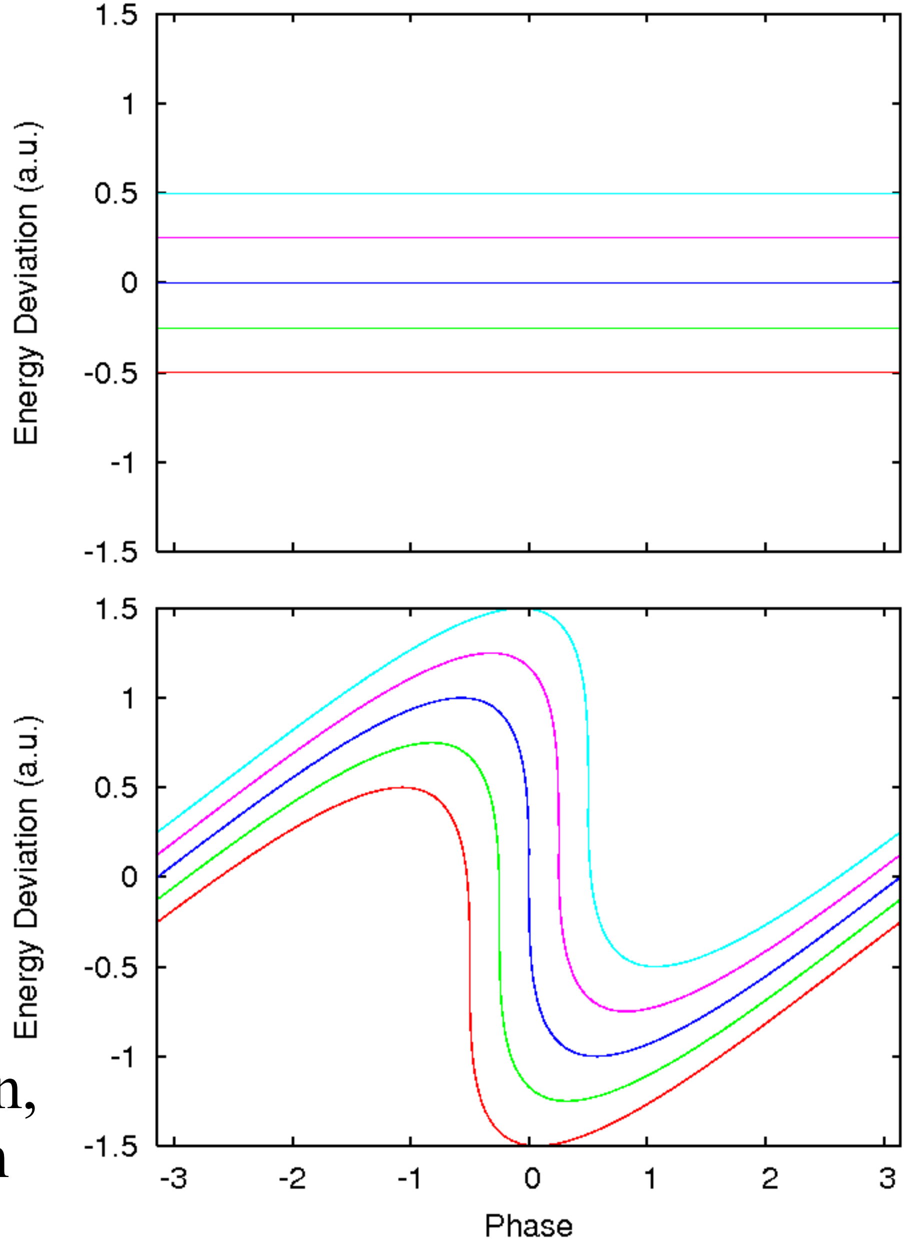
  n = harmonic #

  Δ_γ = energy spread

  N_γ = # of energies sampled

  γ_M = energy modulation

Note: phase corresponds to position, increases towards head of bunch

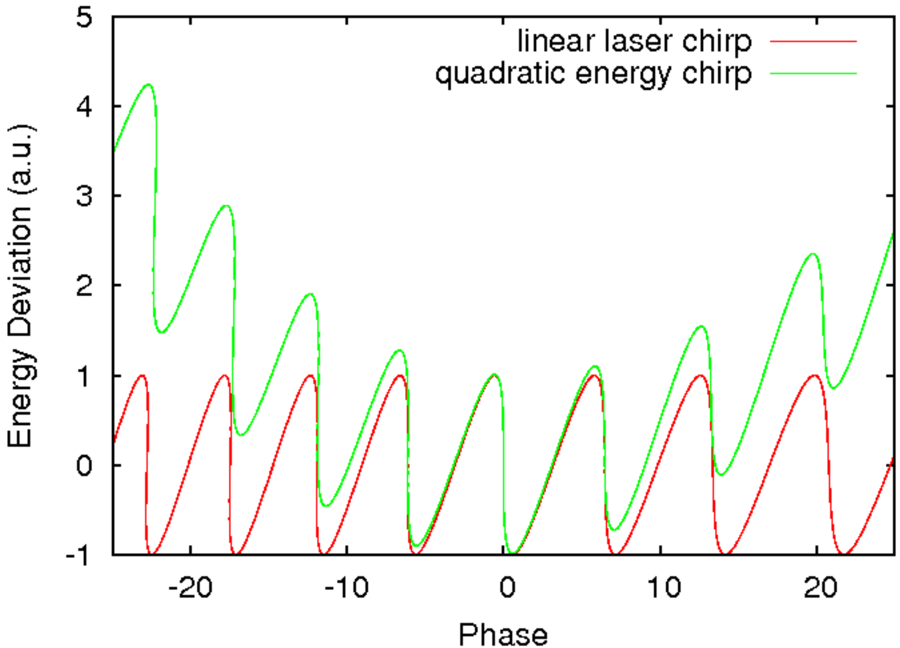


Energy + Frequency Chirp

Similar model as above, more periods

A variation in energy across the bunch acts like a phase variation in the laser seed

- a laser chirp could counteract a slow energy variation
- more rapid variations lead to power fluctuations as well
- very small-scale variations smoothed out by slippage



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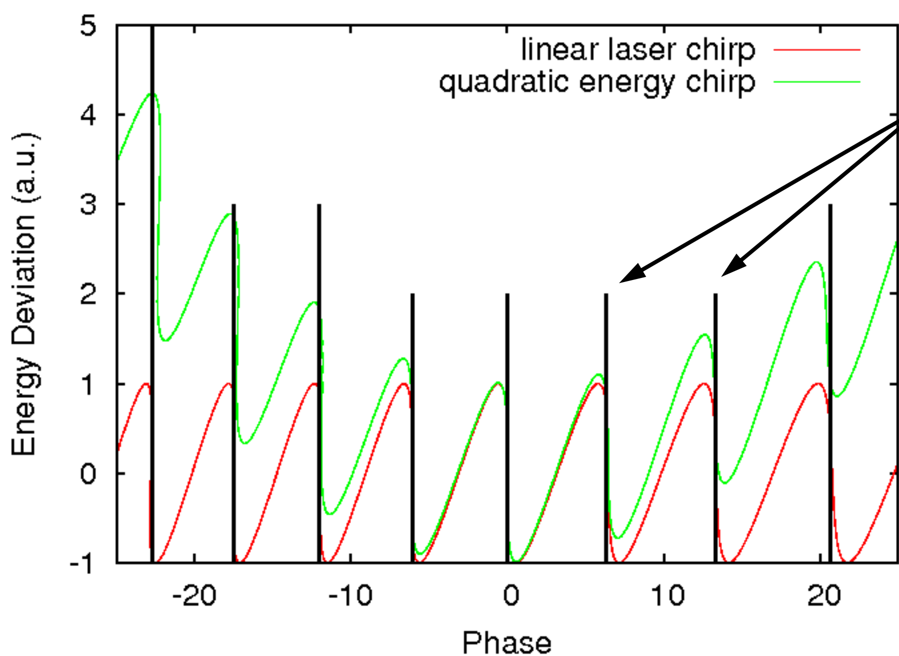
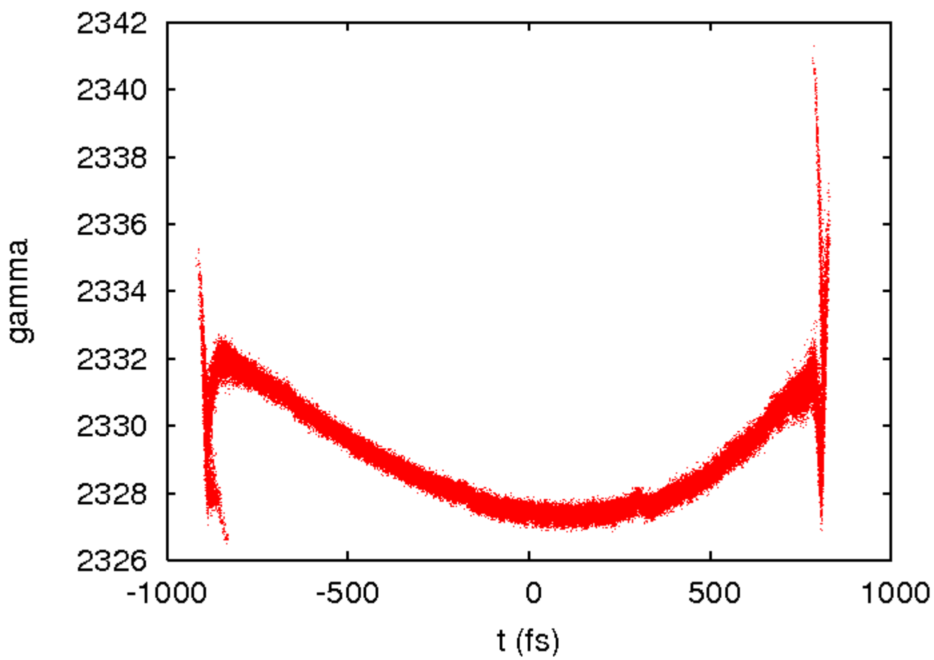
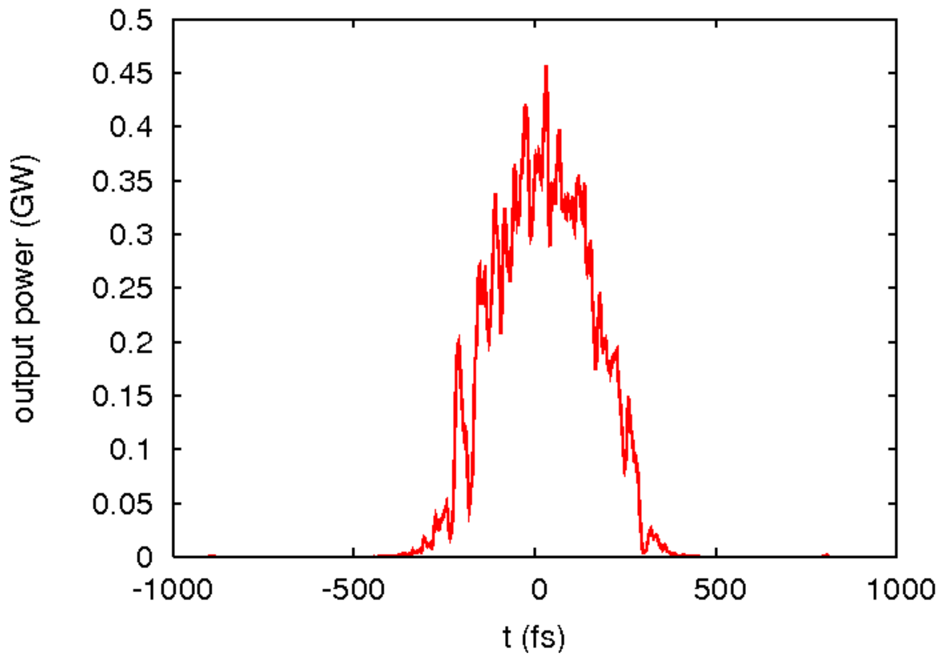


Centers of bunches line up

FERMI@Elettra examples

Preliminary linac studies yielded parabolic energy profiles

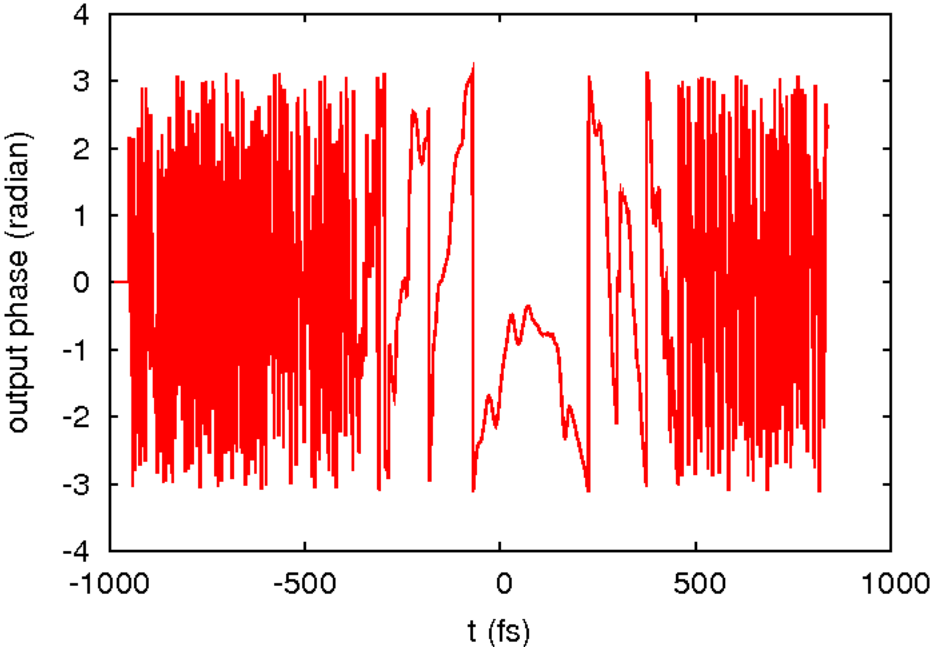


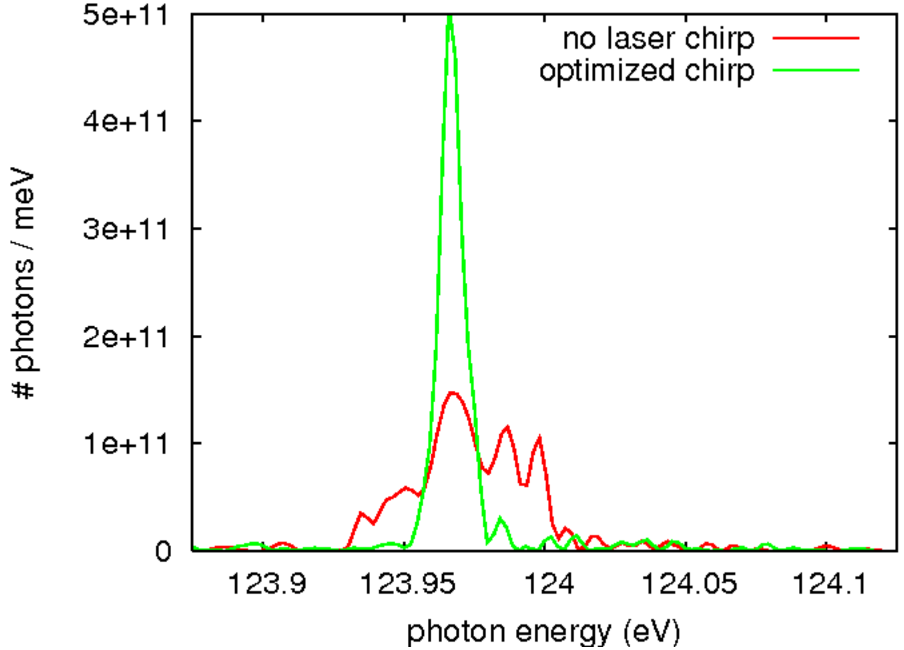


simulated using GENESIS

- long electron bunch, 500 A central current
- sample power profile for FEL-2 whole-bunch at 10 nm, 0.1 mJ energy per pulse

FERMI@Elettra spectra





Phase (modulo 2π) shows strong quadratic variation

- reflected in broad, fluctuating spectrum
- cancellation by linear chirp in seed laser very effective, yields sharp peak
- demonstrates importance of flat electron beam profile

Harmonic FEL Challenges

Short wavelengths

- Energy spread must be small
- Smaller FEL parameter (ρ): constrains energy jitter
- For moderate beam energies, challenges with resonant undulator design:

$$\lambda_U = \frac{2\gamma^2}{1 + a_U^2}\lambda_r$$

(a_U = rms undulator strength)

High harmonic numbers

- Large *n* in single stage requires small energy spread
- Many stages yield a complicated design
- Phase noise is amplified, as is sensitivity to energy chirp
  - even for harmonic cascade
- Numerical simulations require more resources and care

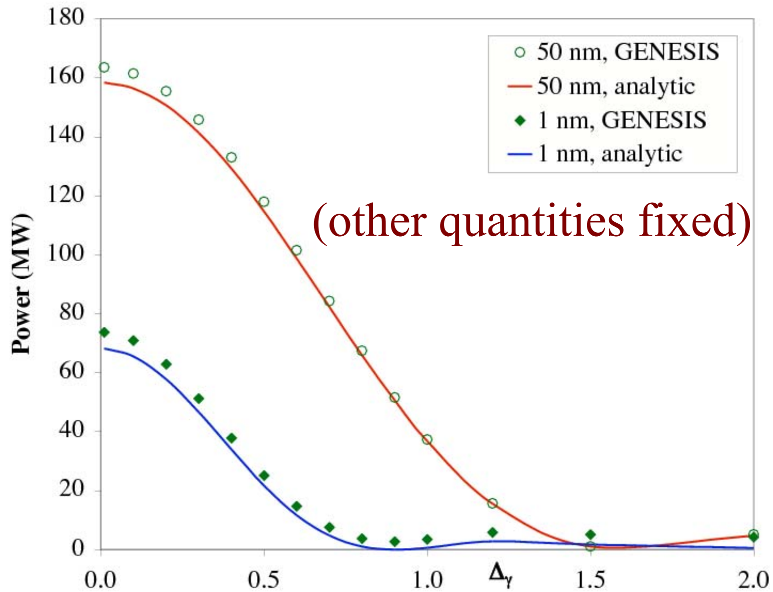
Short Wavelengths

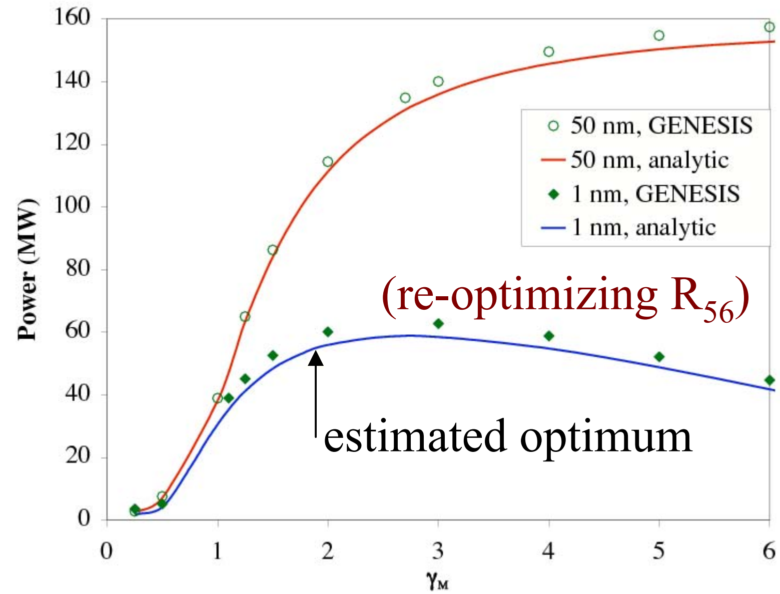
Shorter wavelengths are more sensitive to energy spread

- too little modulation ⇒ not enough bunching
- too much modulation ⇒ debunches in < gain length

Comparison of simulations and analytic theory (LUX study)

 – 3.1 GeV electron beam, 500 A, 2 micron emittance, 0.2 MeV nominal energy spread, 20 – 25 m beta function





Short Wavelengths (2)

Parameters "squeezed" at shorter wavelengths

- if debunching is faster than gain, will not reach saturation
- trapping condition for electrons in ponderomotive well

Rough requirement: $\gamma_M \leq \gamma\, \lambda_U / 16\, L_G$

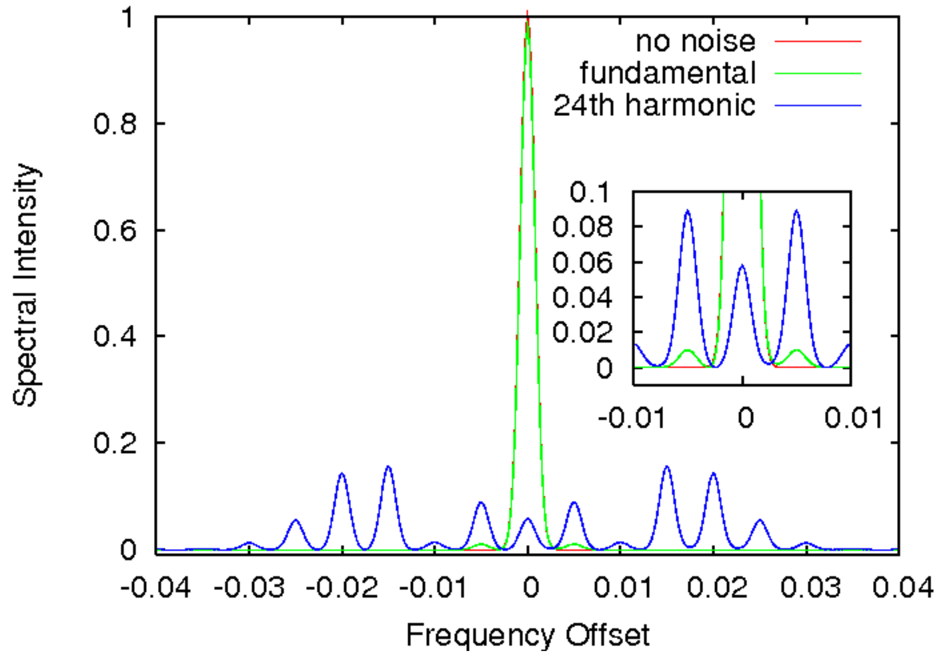
- also require $\gamma_M \geq (n-1)\, \Delta_\gamma$
- energy modulation γ_M, energy spread Δ_γ, gain length L_G, harmonic number n, undulator period λ_U

Energy spread must be small for high harmonics, long gain lengths, low energies

Can relieve harmonic number effect by using multiple stages, with "fresh-bunch" approach to fix growth in Δ_γ

High Harmonics

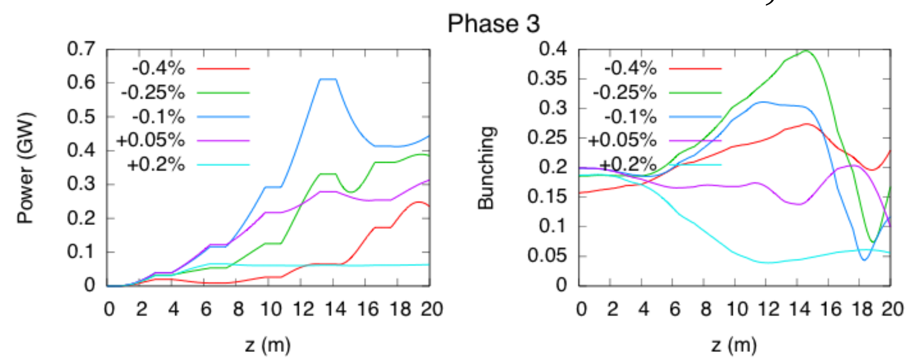
Consider an oscillating phase error, +/- 0.2 radian (for original wavelength)



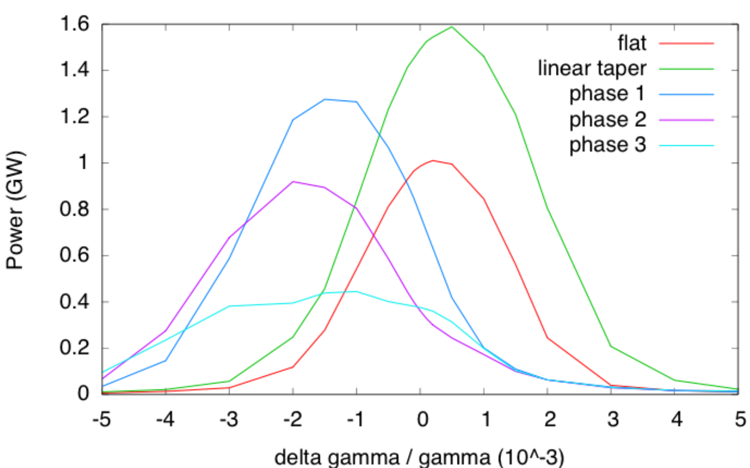
- Fundamental, barely noticeable effect on spectrum
- 24th harmonic, huge degradation
- Scales with square of harmonic $\left(\frac{P_N}{P_S}\right)_{\text{out}} \simeq n^2 \left(\frac{P_N}{P_S}\right)_{\text{in}}$

Energy Jitter Sensitivity

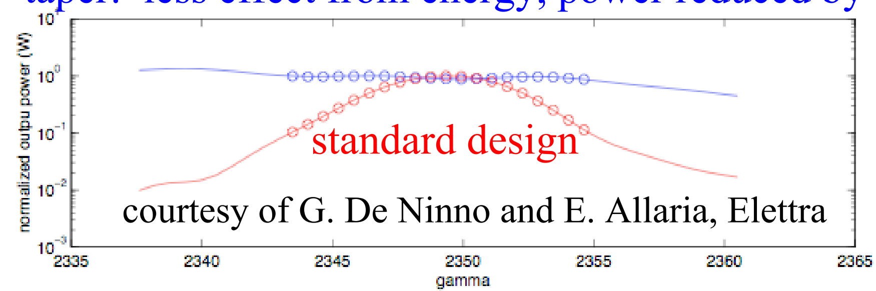
- For small FEL parameter, energy jitter in electron beam is problematic and hard to correct for
- Problem affects all experiments (higher output jitter and reduced photon production)
- Can yield some improvements by oversized tapering of undulator parameter, introducing phase shifts, or even a pseudorandom variation in undulator strength; can also use shorter undulator, with severe drop in output power.



FERMI examples at 10 nm



"random" taper: less effect from energy, power reduced by 30



Strategies for Fresh-bunch

"Fresh-bunch" configuration, with delay section, maintains low energy spread, reduces required undulator, and avoids large gain (with noise amplification)

- can attempt large harmonic jump at first stage
- penalty is complexity, sensitivity to timing jitter, and restricts duration of output pulse
- in cascade, can reduce # of delay sections, for example by alternating fresh-bunch and whole-bunch

Example: from LUX design study, 2.1 GeV beam, 3 harmonic stages from 200 nm to 2.5 nm final output

Parameters: 500 A, 2 micron emittance, 200 keV σ_E, 20 m β

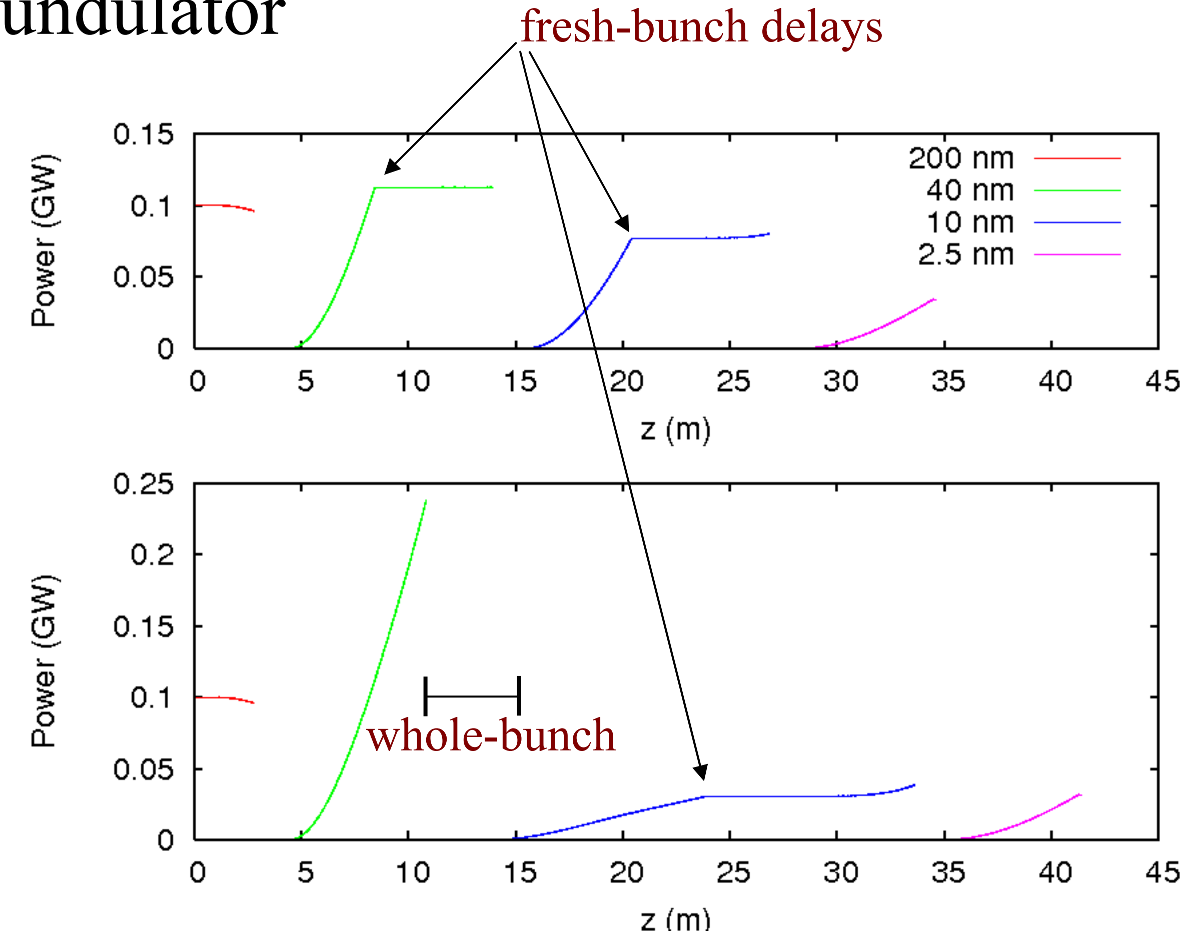
Fewer Fresh-bunch Delays

Results using single delay chicane + one whole-bunch

- essentially same output as from two delay chicanes, 31 MW instead of 34 MW
- requires 6 m more undulator

standard design,
slice beam in thirds:

whole-bunch
then fresh-bunch,
slice beam in half:



HHG-seeded FELs

- HHG sources offer an opportunity to shorten the harmonic cascade
- Low peak power can be accommodated by first amplifying the signal in an optical-klystron configuration
- There is not much information on HHG longitudinal coherence
- As already seen, desired HHG properties go beyond requiring that the pulse be transform-limited

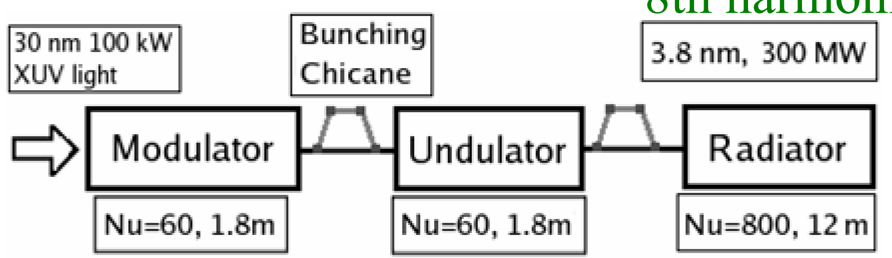
Consider a 30-nm wavelength HHG, versus 240-nm laser

HHG configuration

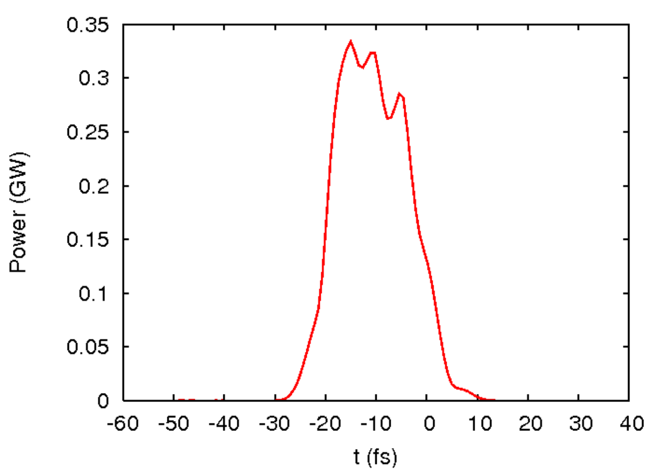
- First modulator is split into two stages, to amplify low-power seed with optical klystron
- Result is more initial bunching than could be practically achieved with a single modulator

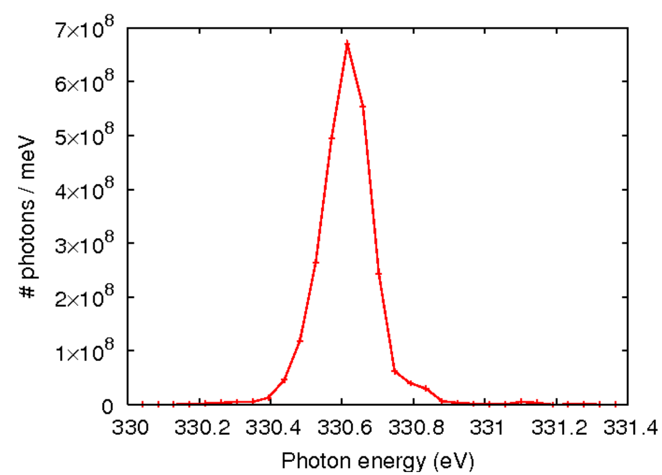
1 GeV beam
500 A
1.2 micron emittance
75 keV energy spread
$\beta \sim 6$ m

8th harmonic



Output from 25 fs FWHM seed

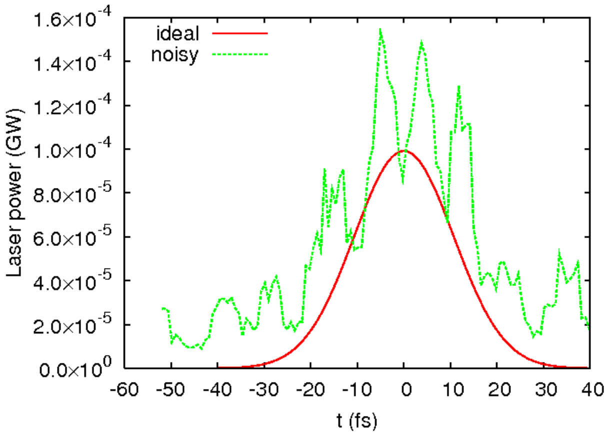


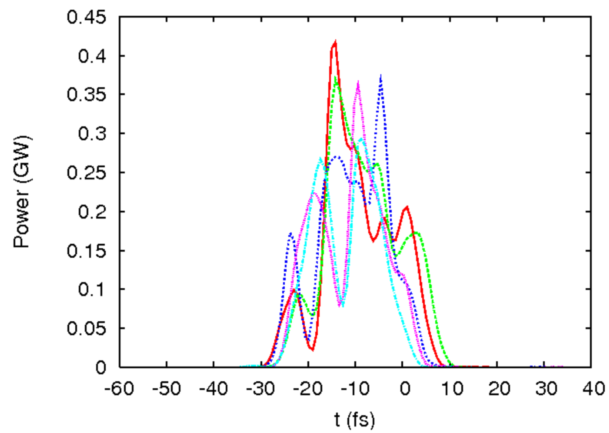


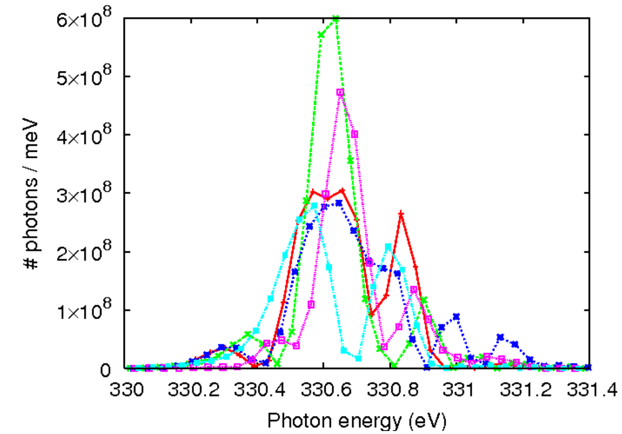
- Model seed noise as flat-top power spectrum

HHG noise sensitivity

FEL output jitter with 200 W per 0.1% bandwidth seed noise

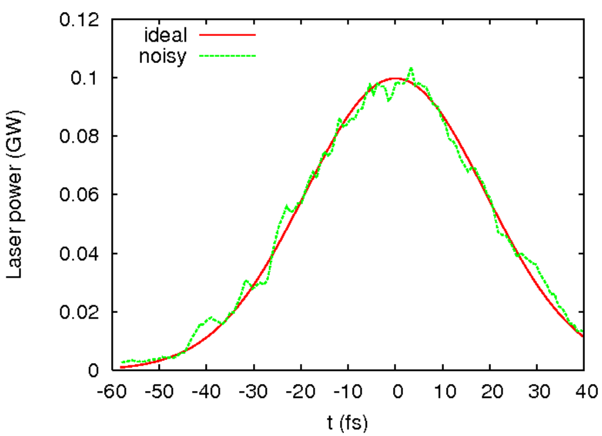


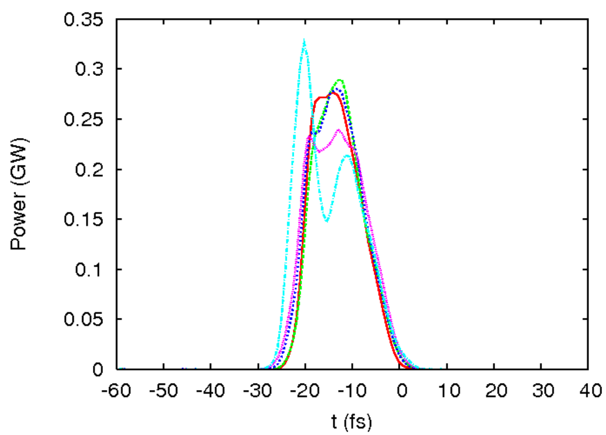


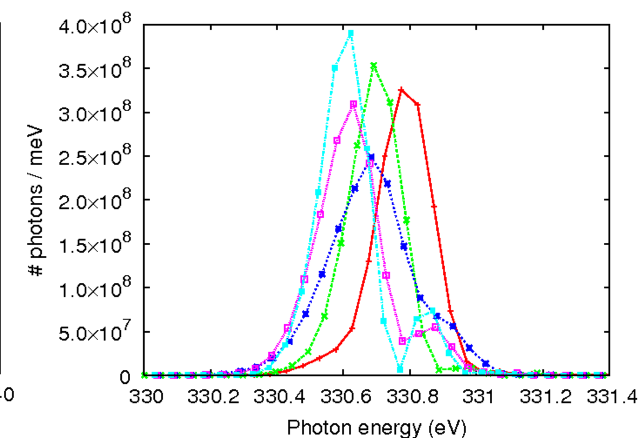


seed = 53 kW / 0.1% bw

Using 240 nm laser, jitter with 1 kW per 0.1% bw noise







seed = 12 MW / 0.1% bw

noise barely visible

output noise most apparent in the spectrum

Simulation Noise

When performance is weak and energy spread is large, it is especially hard to get simulation results to converge

- example from HHG studies, vary particle loading only
- bunching $b = |\langle \exp i\Psi \rangle|$, where Ψ is phase

Seed Wave-length (nm)	σ_E (keV)	ε_N (micron)	Initial Bunch at 3.8 nm (%)	Avg Power (MW)	σ_{Power} (MW)	σ_{Phase} (rad)
30	150	1.2	0.9	82	53	2.22
30	75	1.8	2.9	90	12	0.22
30	75	1.2	4.3	295	10	0.16
240	75	1.2	6.4	241	14	0.17

Conclusions

The good news:

- Current ability to control undulator phase noise seems to fit needs
- Can be shorter than SASE, with distinct benefits, but more complex
- Developments in HHG seeds may simplify future seeded FELs

The bad news:

- Sensitive to energy deviations
  - jitter (when FEL parameter is small) as well as energy chirp
- Output fluctuations may always be "large", to some experiments

Looking ahead:

- Laser seeds need closer scrutiny: specifications for phase control (clock-like precision desired even for short pulses)
- Many facilities on the horizon, opportunities for exciting research
- Look for improvements on many fronts
  - electron sources, acceleration, undulator design, sources for seeding, optics

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