Noise and Coherence properties of HHG for FEL seeding

Brian Sheehy, Sep 10 , 2007, FEL Frontiers 07 Workshop

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- **HHG as a potential seed source for FEL**
- **Issues in its Deployment**
- **Modeling HHG**
- **Some results on noise and coherent shaping**

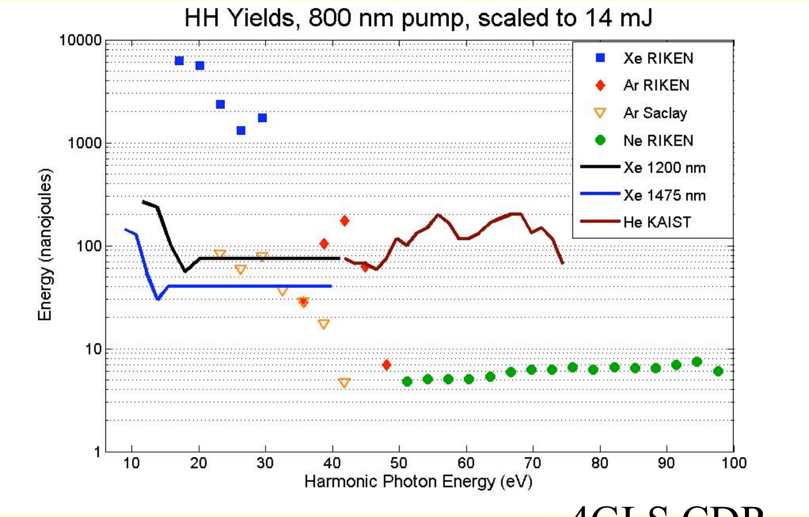
HHG as a potential FEL seed

- Two Options
  - Seed a cascade at as high a frequency as possible
    - reduce noise, complexity of design, expense
  - Seed at the output wavelength
    - take fullest advantage of control over the optical field
    - presently limited to longer wavelengths

- Advantages
  - Coherence
  - Tunability
  - Synchronization
  - Potential to extend pulse-shaping to shorter wavelengths
    - Coherent Control / Optimal Control
  - Potential exploitation of attosecond structure

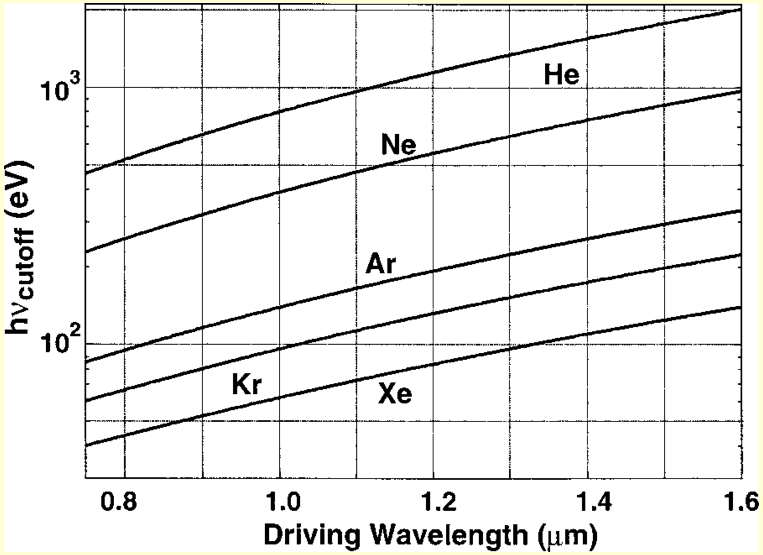
Deployment Issues

- Sufficient pulse energy
  - nJ direct seeding, μJ cascaded
- Wavelength Range
- Tunability
- Synchronization
- Attosecond Structure
- Spatial coherence
- Noise and Coherence



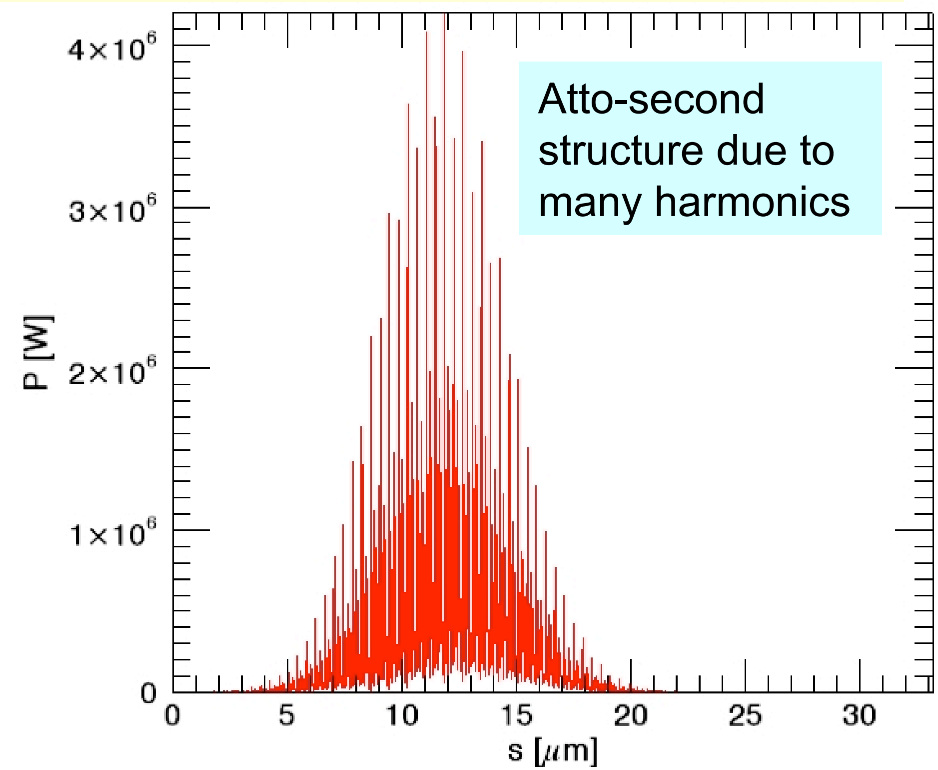
4GLS CDR

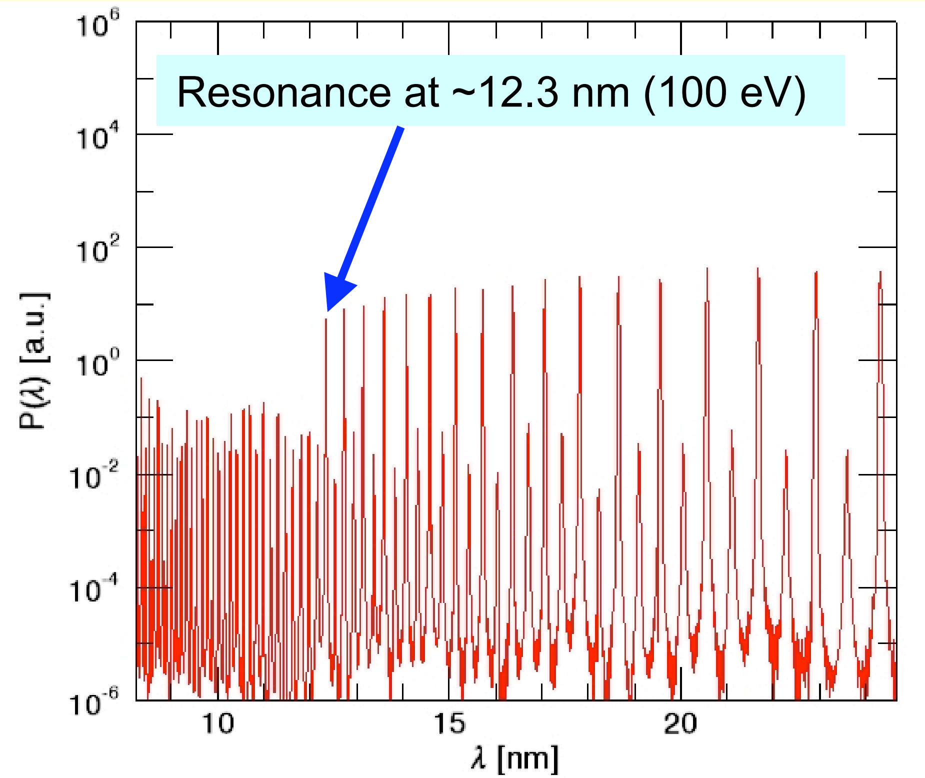
There is a growing recognition that the conditions on HHG for FEL seeding are specific enough to require theoretical and experimental programs targeted to that application.



Shan and Chang PRA **65** 011804 (2001)

Genesis simulation

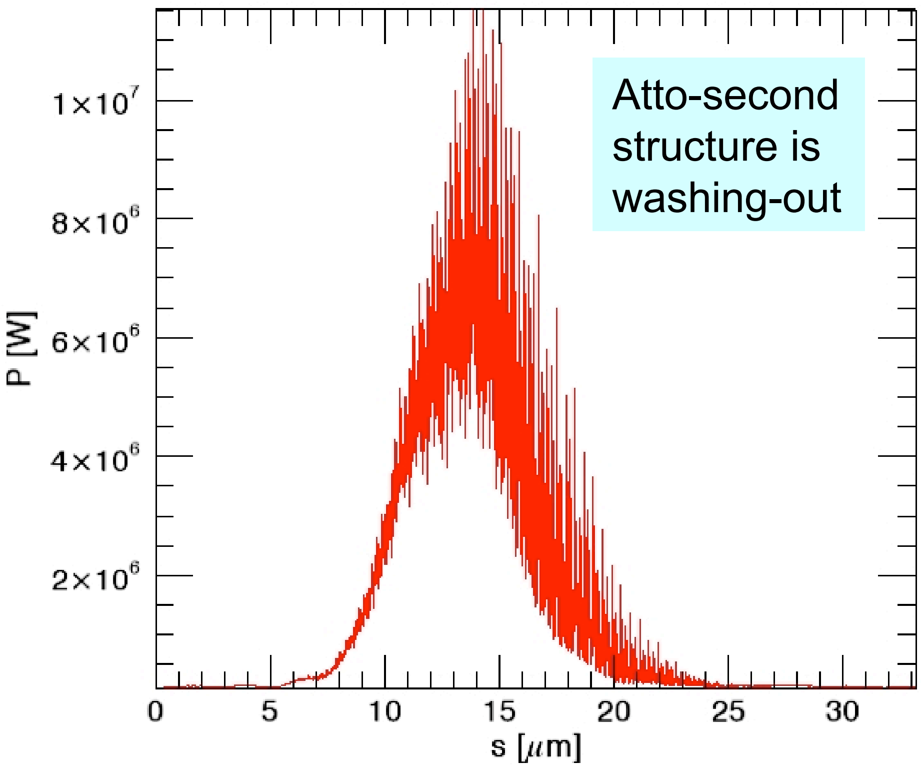


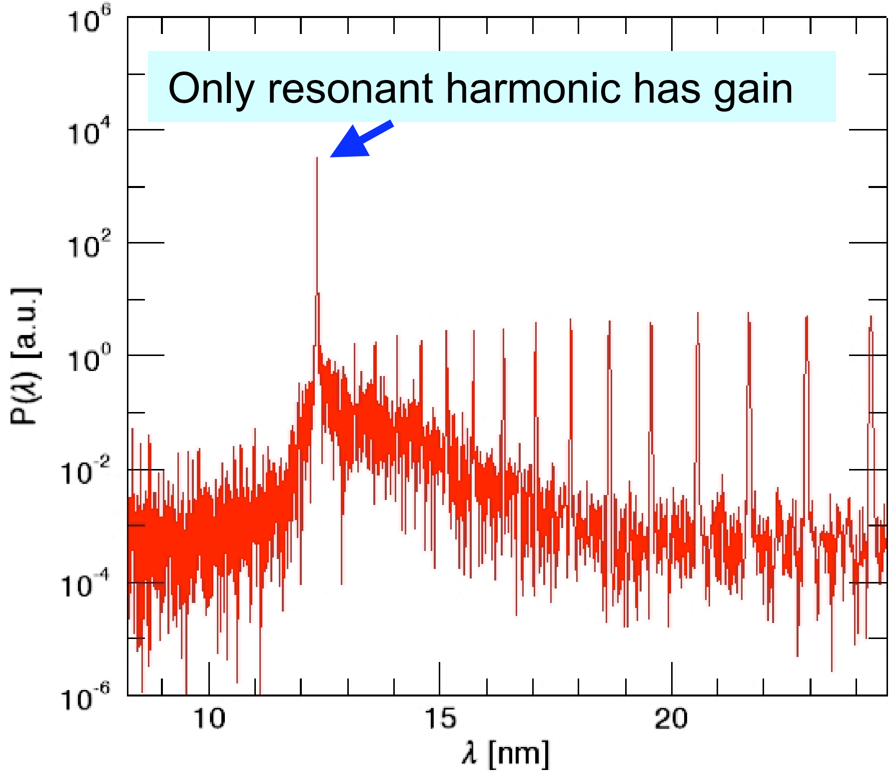


HHG seed field at entrance to FEL

XUV-FEL parameters but with uniform current I=1.5 kA

Genesis simulation





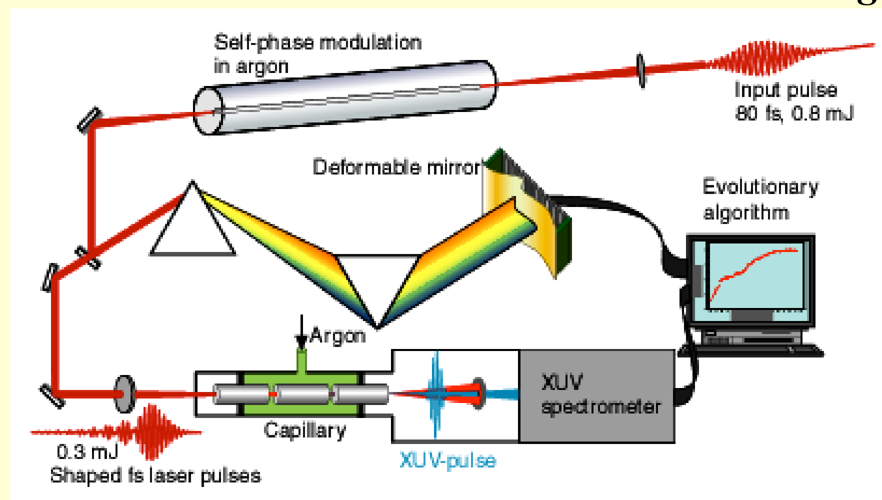
HHG seeded field at z~16 m

Noise and Coherence

Gustav Gerber Uni Wuerzburg

How does noise on the fundamental Affect the harmonic?

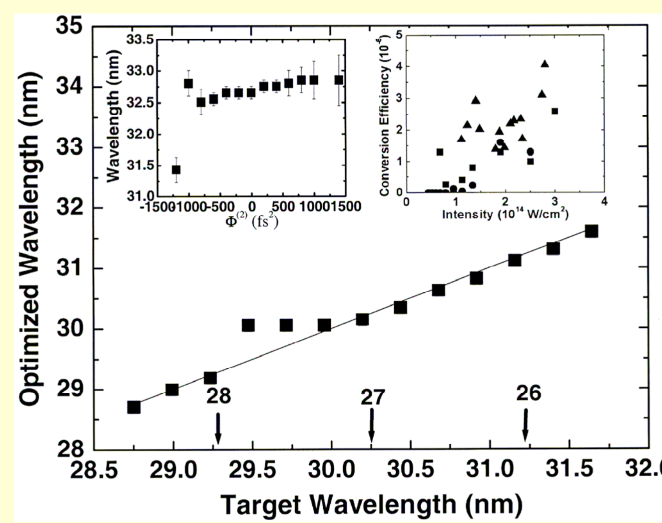
In HGHG there is a well known n^2 growth in the noise of the fundamental in the n^{th} harmonic. What happens to the noise in HHG?



We know that we can tune the harmonics using adaptive pulse shaping, and that it works better than simple chirping.

Can we shape the harmonic through the fundamental?

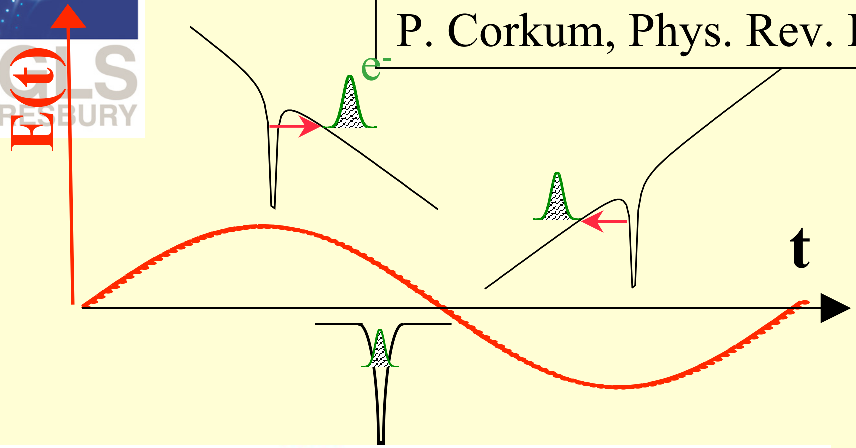
How does the shaping of the fundamental transform in the harmonic?



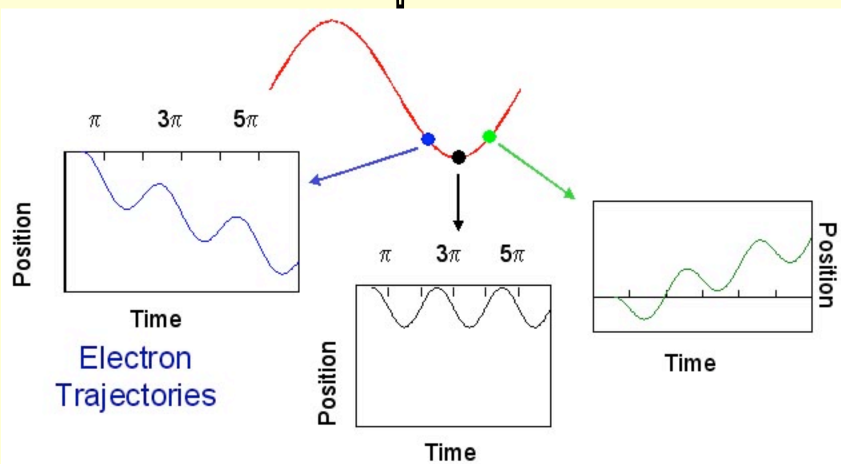
(Reitze et al Opt Lett 2004)

The Three-Step Model

Kulander, Schafer, and Krause *SILAP III* (1993)
P. Corkum, Phys. Rev. Lett. 71, 1994 (1993).

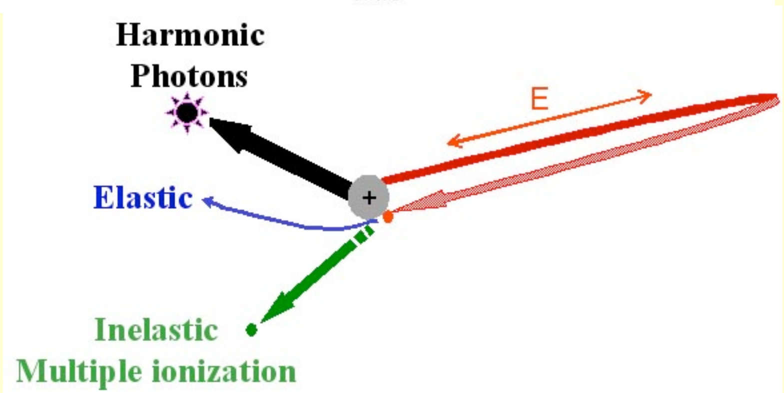


Optical Field Ionization



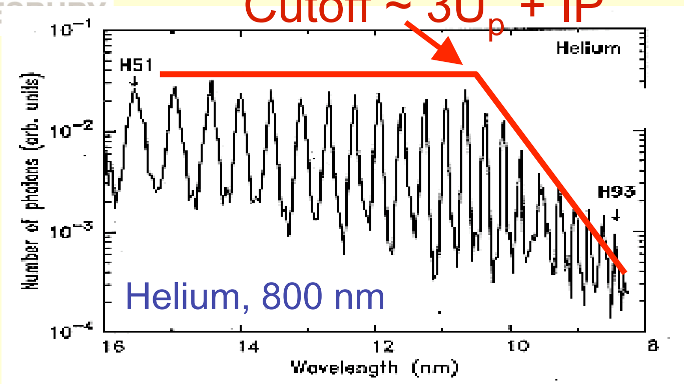
Free electron moving in the optical field. Its average kinetic energy is U_p, a scaling parameter of the dynamics

$$U_p \propto I\lambda^2$$



Some electrons return and interact with the core

Three-Step Model continued

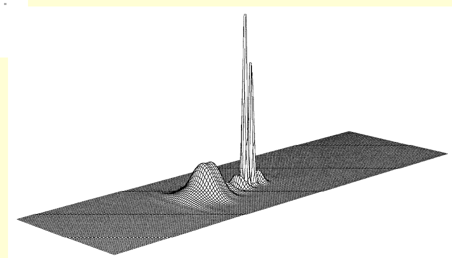


L'Huillier et al, Lund

Approximate cutoff position is given by classical mechanics*

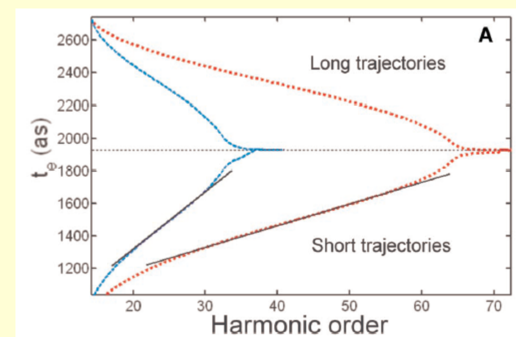
**Shorter pulses non-adiabatic effects push cutoff higher*

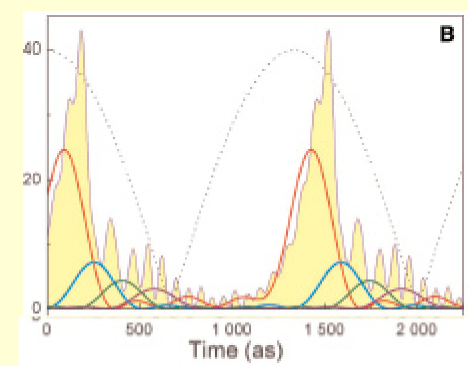
** ignoring macroscopic phase matching*



Quantum treatments:

- TDSE *Kulander, Schafer*
  - single electron, wave function propagation on grid
- Strong Field Approximation *Lewenstein*
  - ionization from simplified core
  - free electron propagation (in E field) outside of core
  - faster, complex polarizations, multiple frequencies
- Quantum Path Distributions/ Path Integral Formalism *Gaarde & Schafer, Salieres & Lewenstein*
  - insight into phase matching and time-frequency anaylsis





Mairesse et al Science 302, 1540 (2003)

ABC Model

(Asymptotic Boundary Condition)
Gordon & Kaertner 2006 (PRA 73 042505)

A very simple idea: In choosing the form of the difference equation used to approximate any differential equation near a singularity, constrain the coefficients of the discretized operators so that the solution of the difference equation near the singularity matches the analytically known asymptotic solution near the singularity

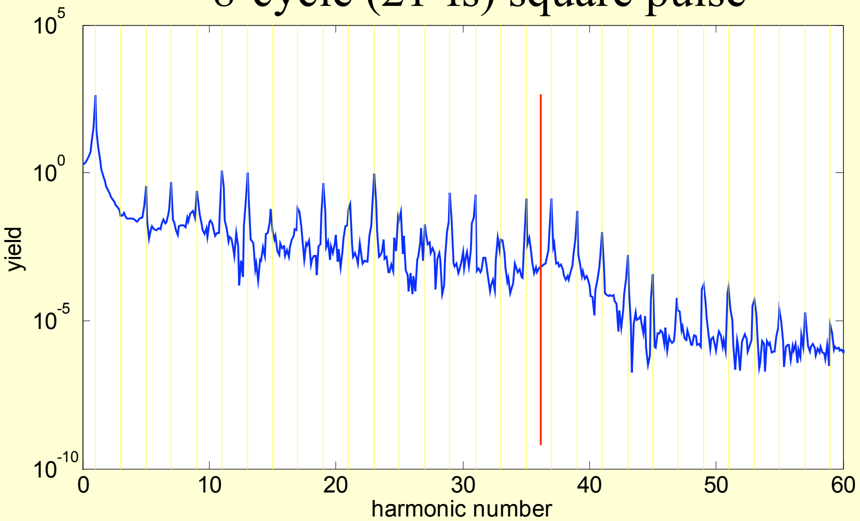
> order of magnitude speed improvement

We've developed a parallel code based on their work, which allows us to process longer pulses in a reasonable time, and should allow us to do some macroscopic averaging using a full quantum treatment of the atomic response. However, we can gain some insights into relevant questions already with just the single atom response…

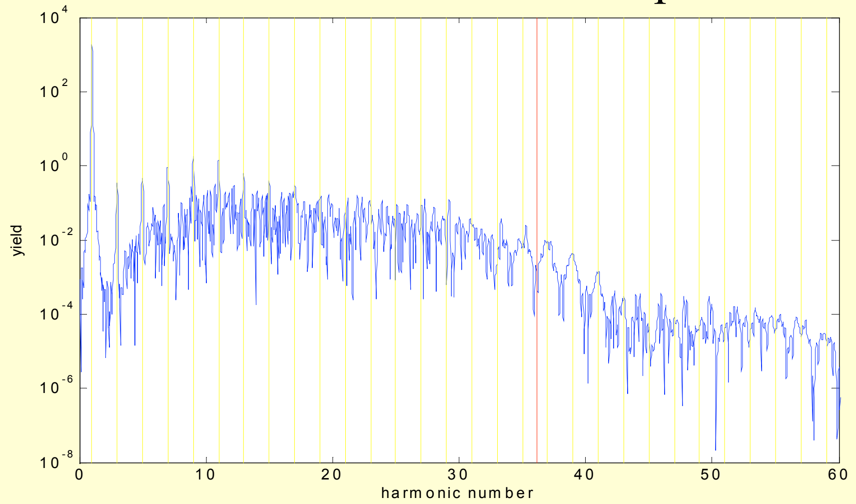
Non adiabatic effects

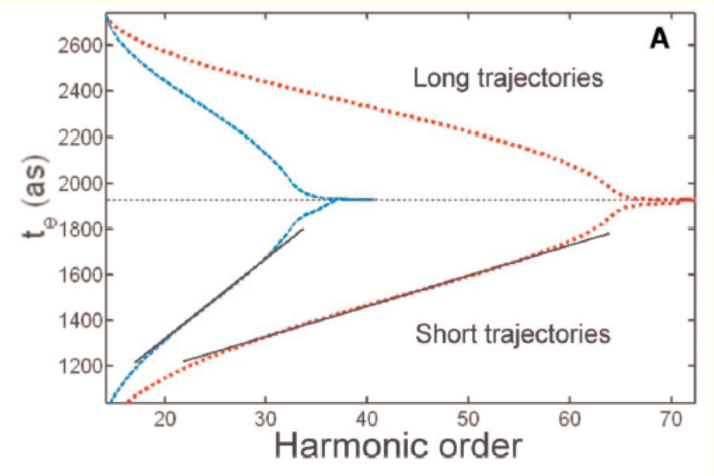
Phases of a given harmonic arising from short and long trajectories respond differently to nonadiabatic change in pulse intensity, and interfere.

8-cycle (21-fs) square pulse



24 fsec fwhm Gaussian pulse





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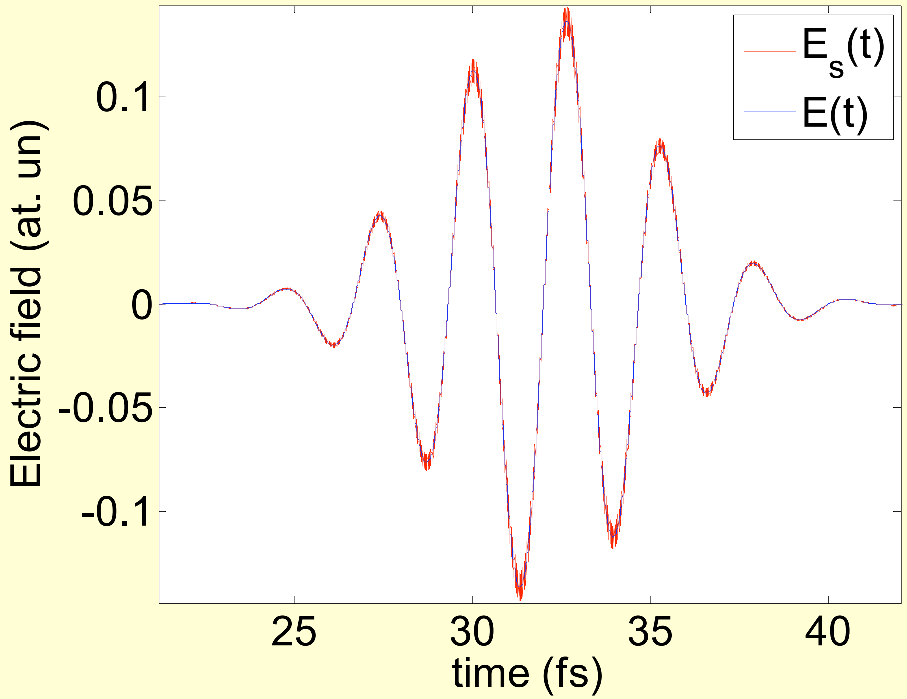


Noise

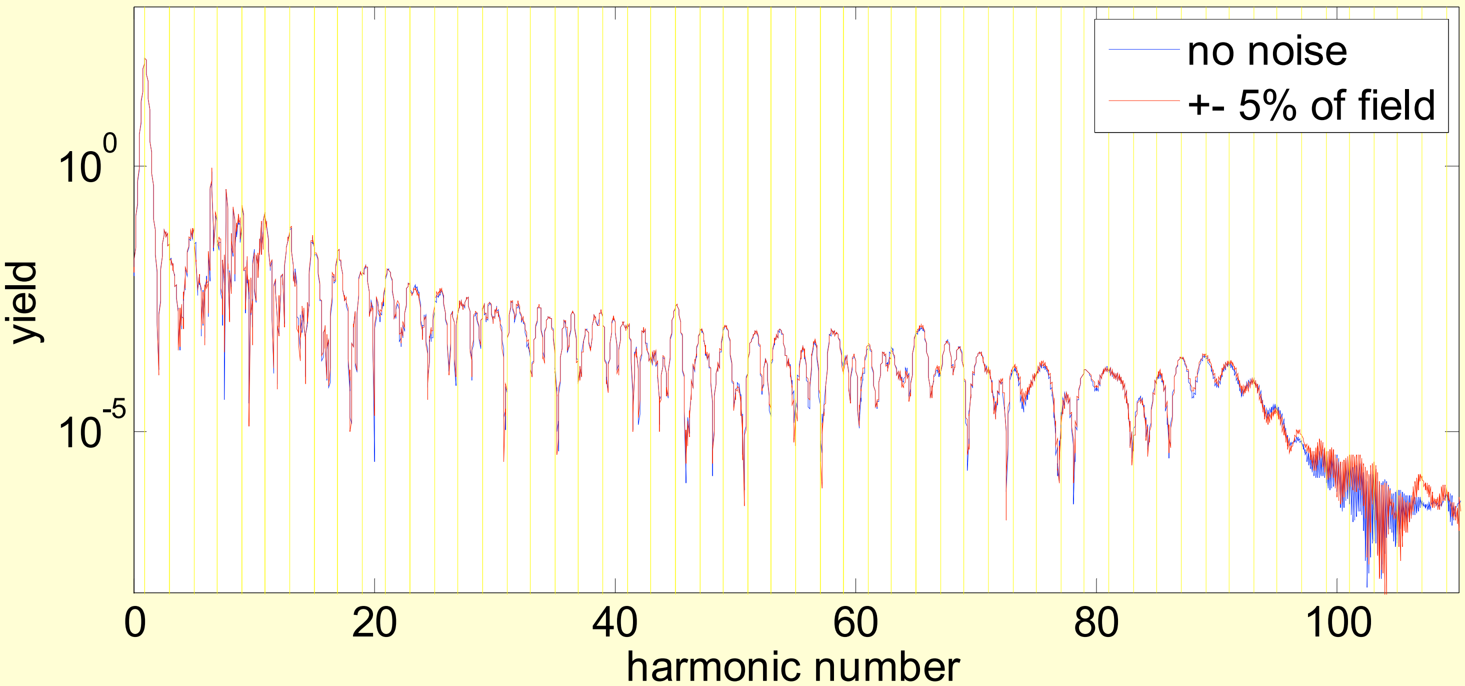
$$E(t) = E_0 e^{-(t-t_0)^2/\tau^2} \sin\left[\omega(t-t_0)+\phi_0\right]$$

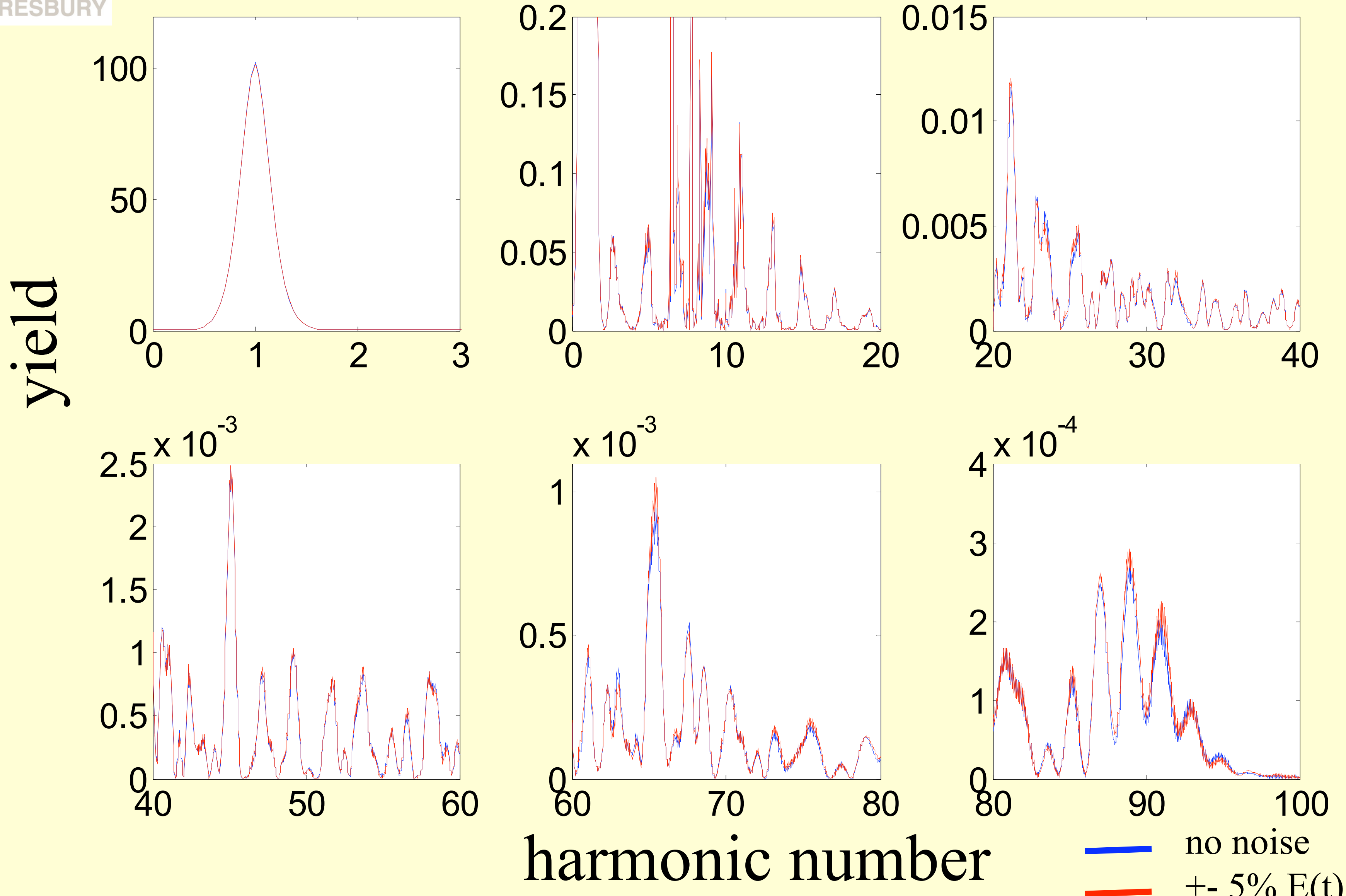
$$E_s(t) = \left[1+\alpha s(t)\right]E(t)$$

$s(t) \equiv$ stochastic variable

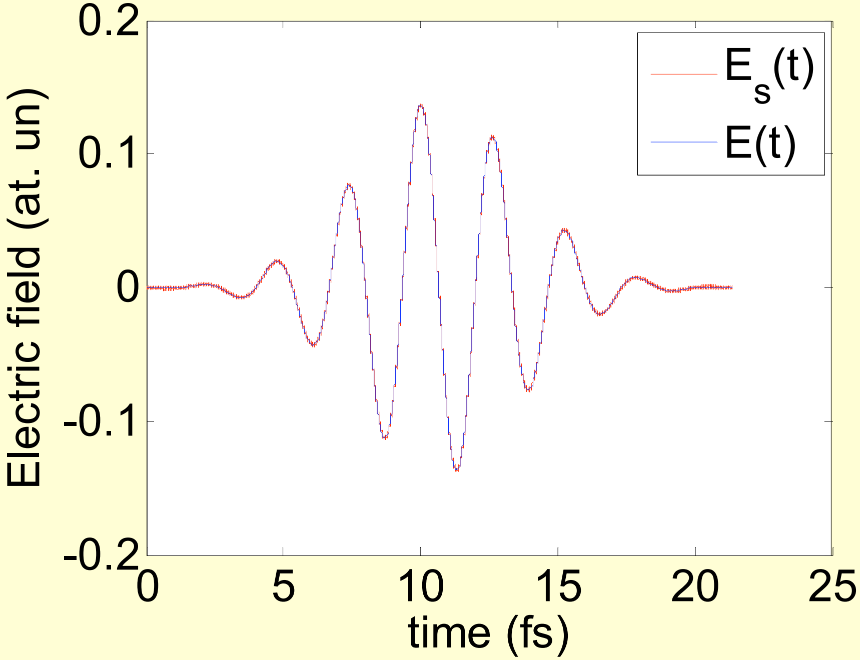
(white noise on [-1,1], change on each time step),

$\alpha = 0.05$, τ such that FWHM Intensity = 5 fsec





yield
harmonic number
x 10^-3
x 10^-3
x 10^-4
no noise
+- 5% E(t)



Constant amplitude Noise

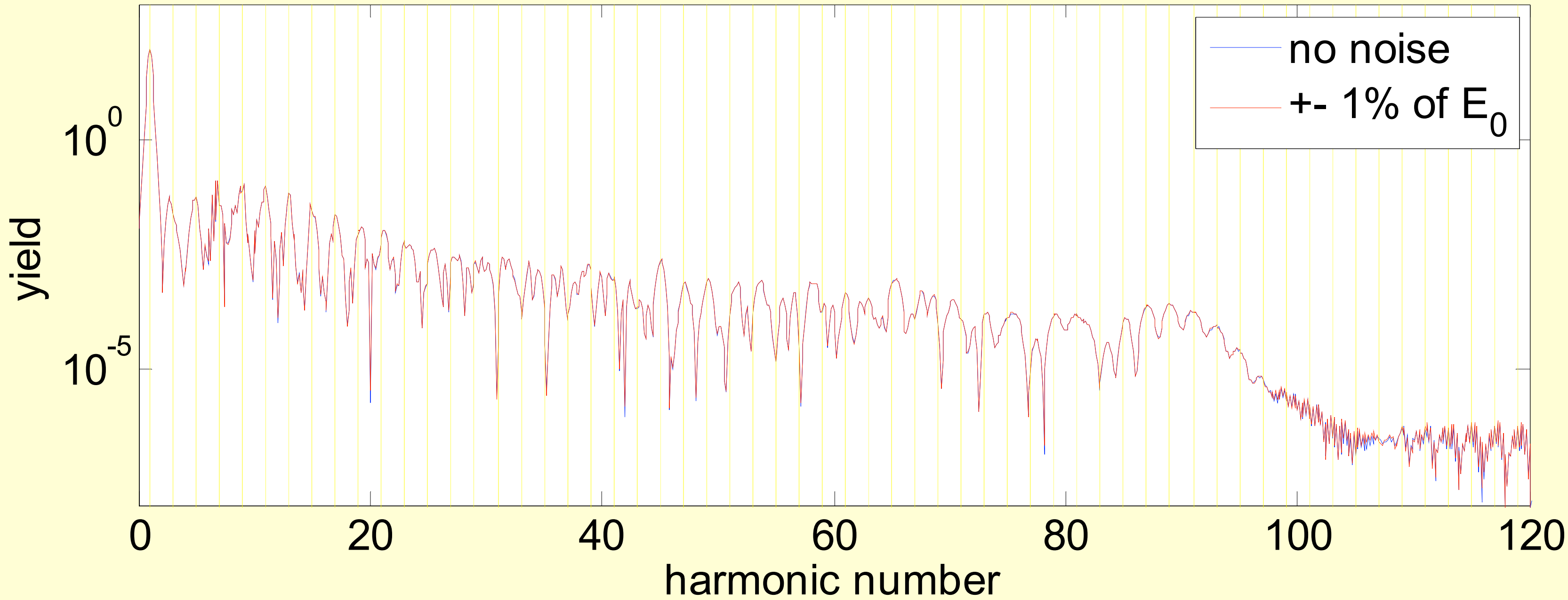
$$E(t) = E_0 e^{-(t-t_0)^2/\tau^2} \sin\left[\omega(t-t_0)+\phi_0\right]$$

$$E_s(t) = E(t) + \alpha s(t) E_0$$

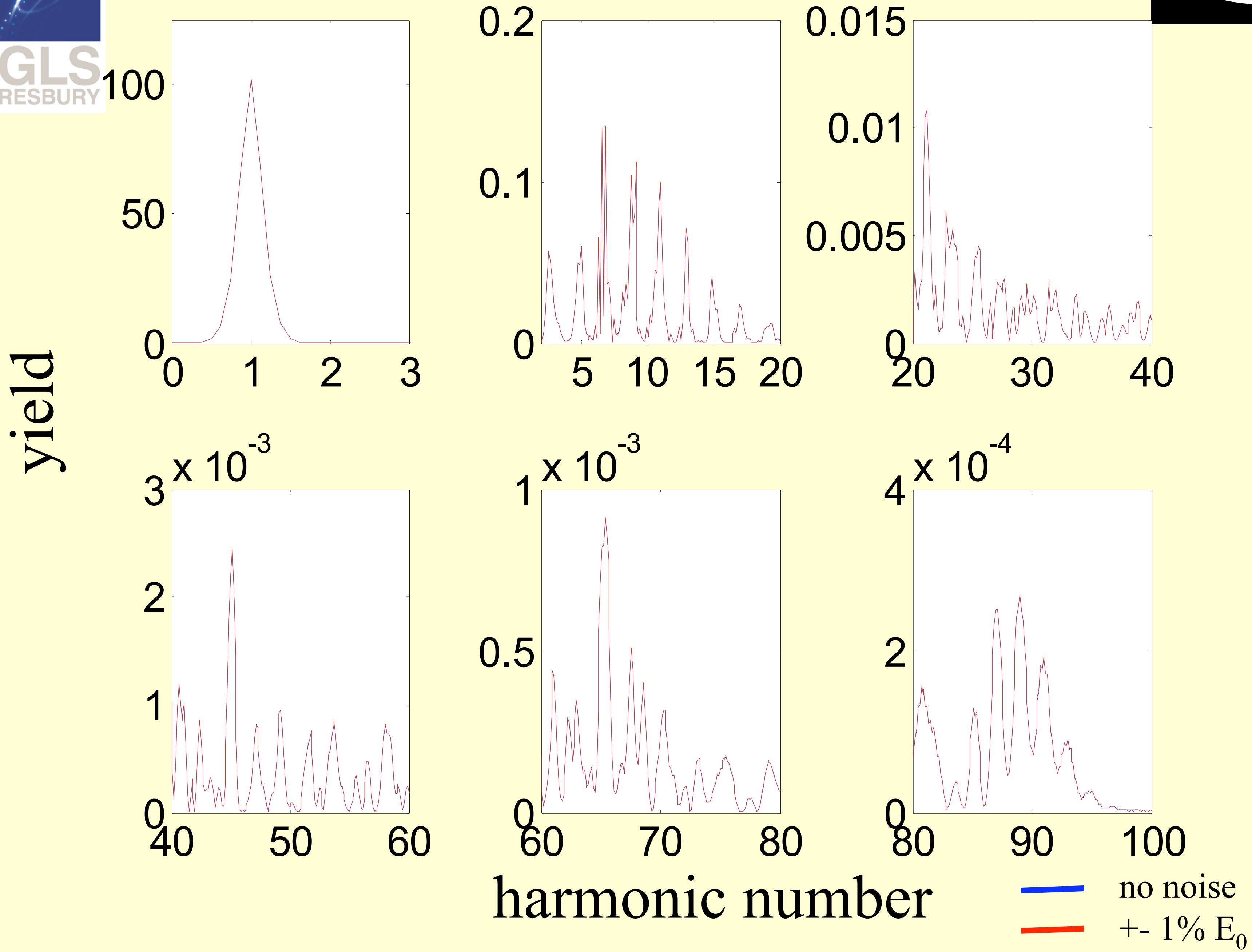
$s(t) \equiv$ stochastic variable

(white noise on [-1,1], change on each time step),

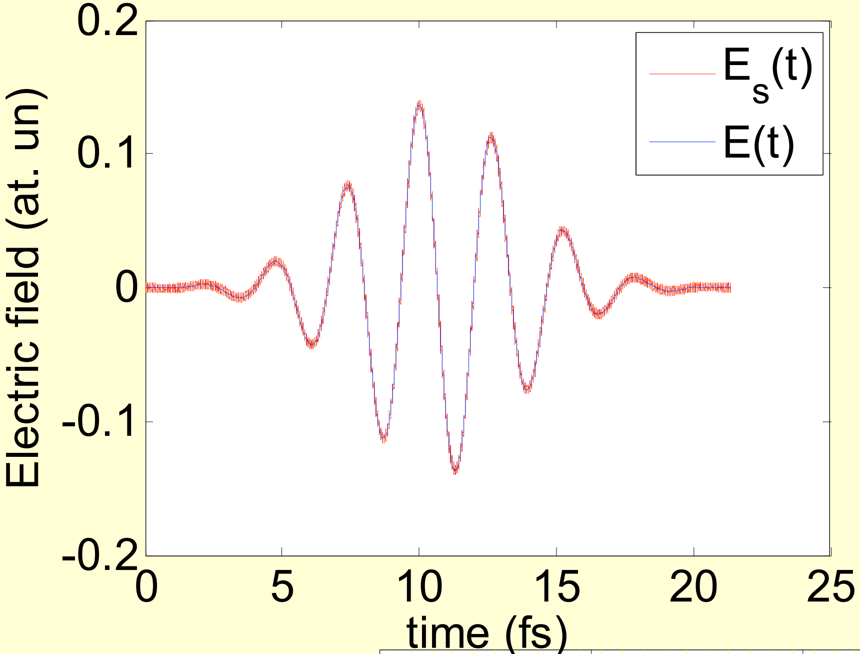
$\alpha = 0.01$, τ such that FWHM Intensity = 5 fsec



Constant amplitude Noise $\alpha = 0.01$



Constant amplitude Noise



$$\alpha = 0.025$$

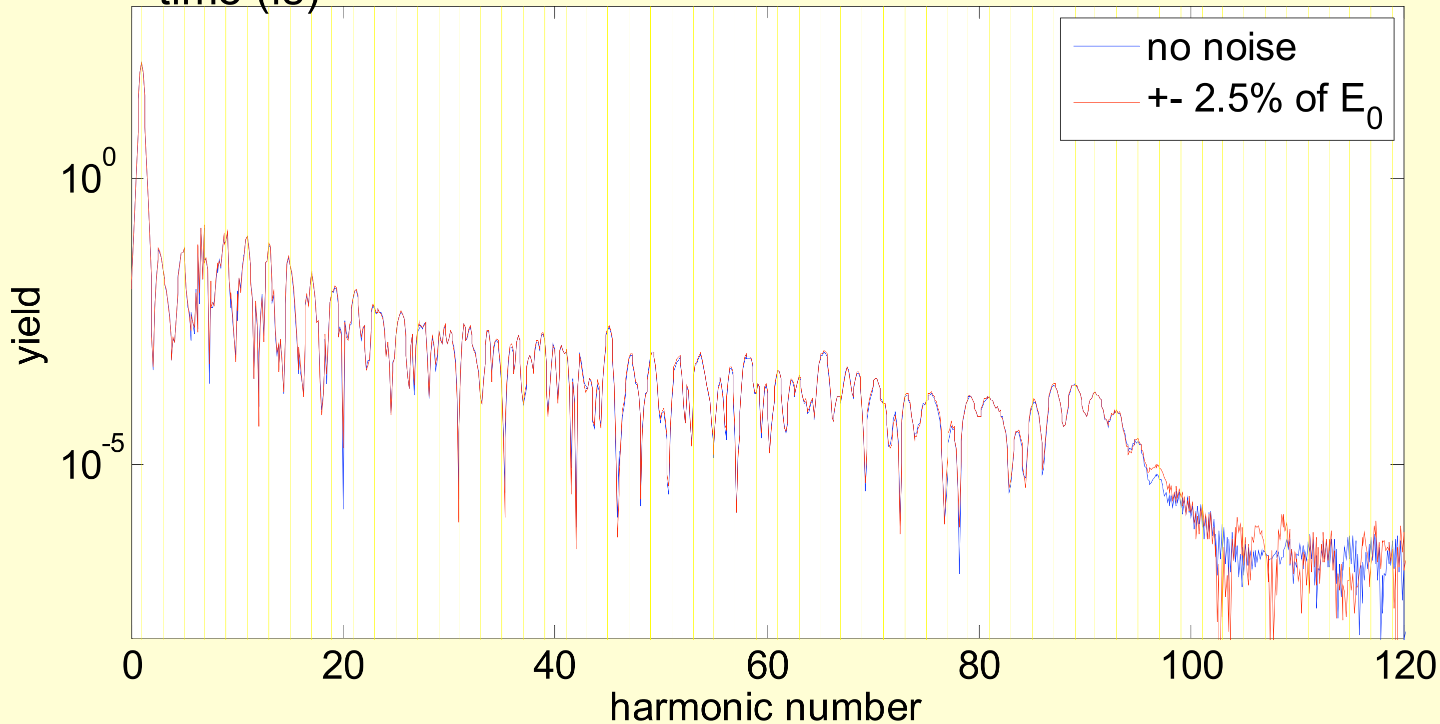
$$E(t) = E_0 e^{-(t-t_0)^2/\tau^2} \sin\left[\omega(t-t_0)+\phi_0\right]$$

$$E_s(t) = E(t) + \alpha s(t) E_0$$

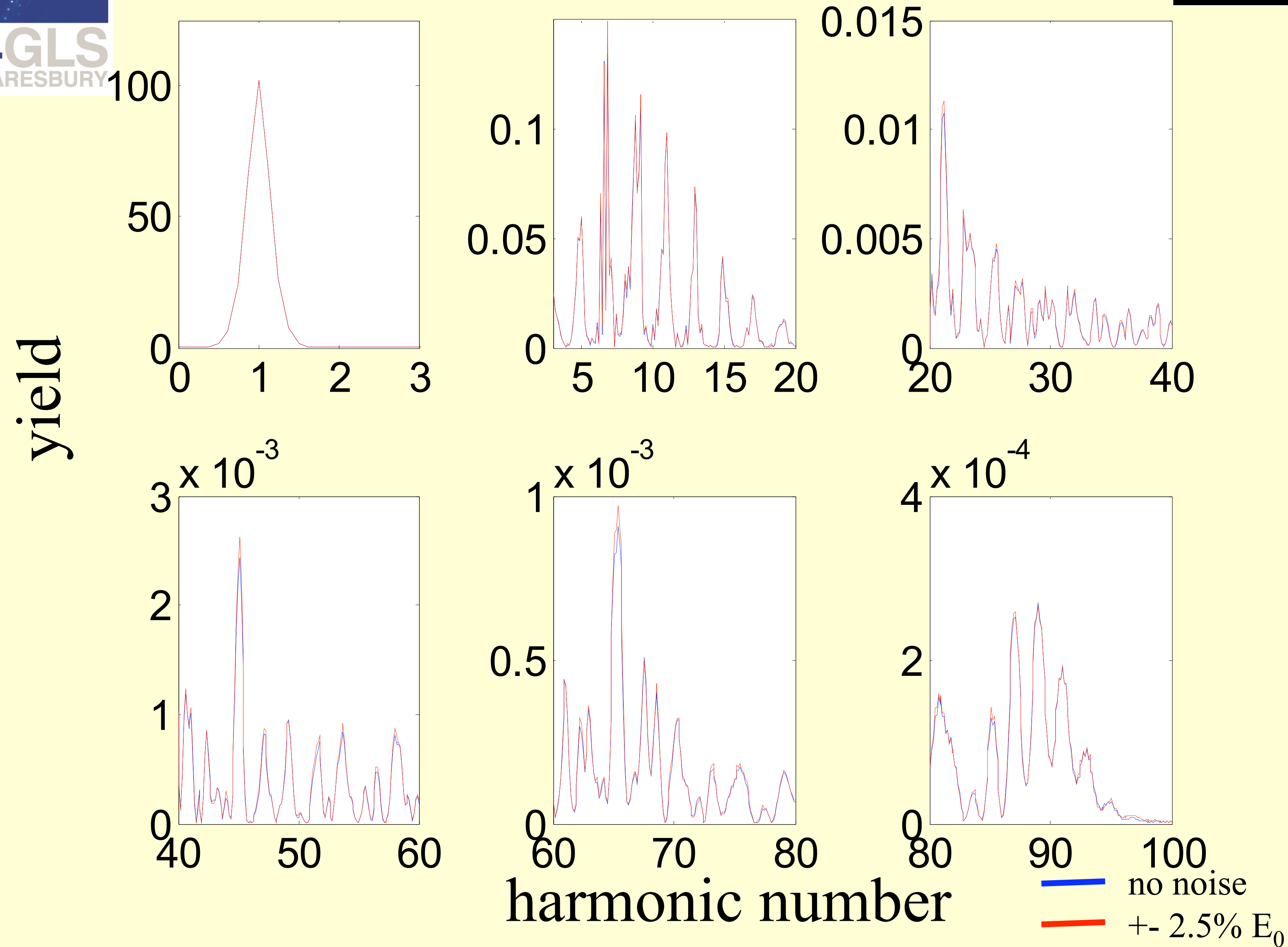
$s(t) \equiv$ stochastic variable

(white noise on [-1,1], change on each time step),

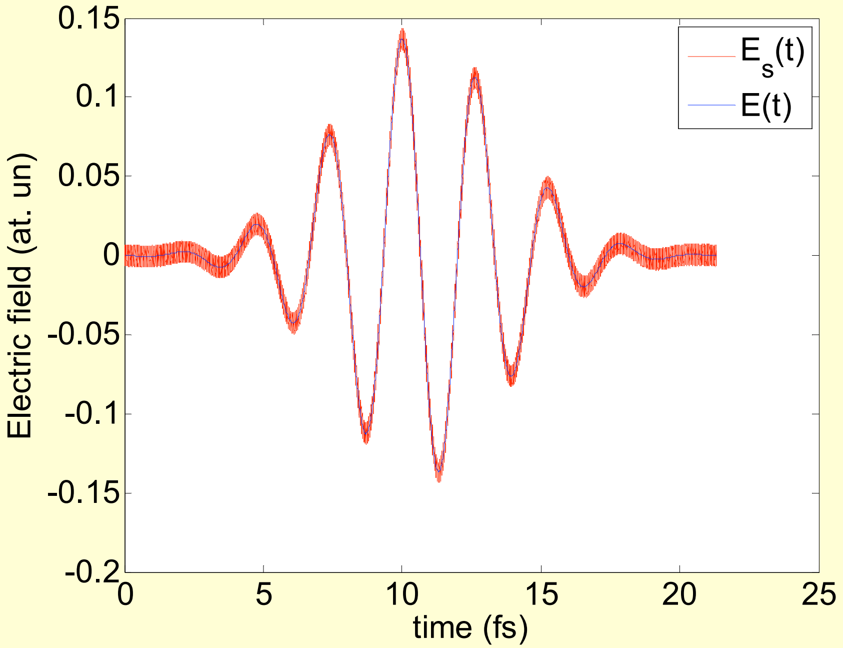
$\alpha = 0.025$, τ such that FWHM Intensity = 5 fsec



Constant amplitude Noise $\alpha = 0.025$



Constant amplitude Noise



$$\alpha = 0.05$$

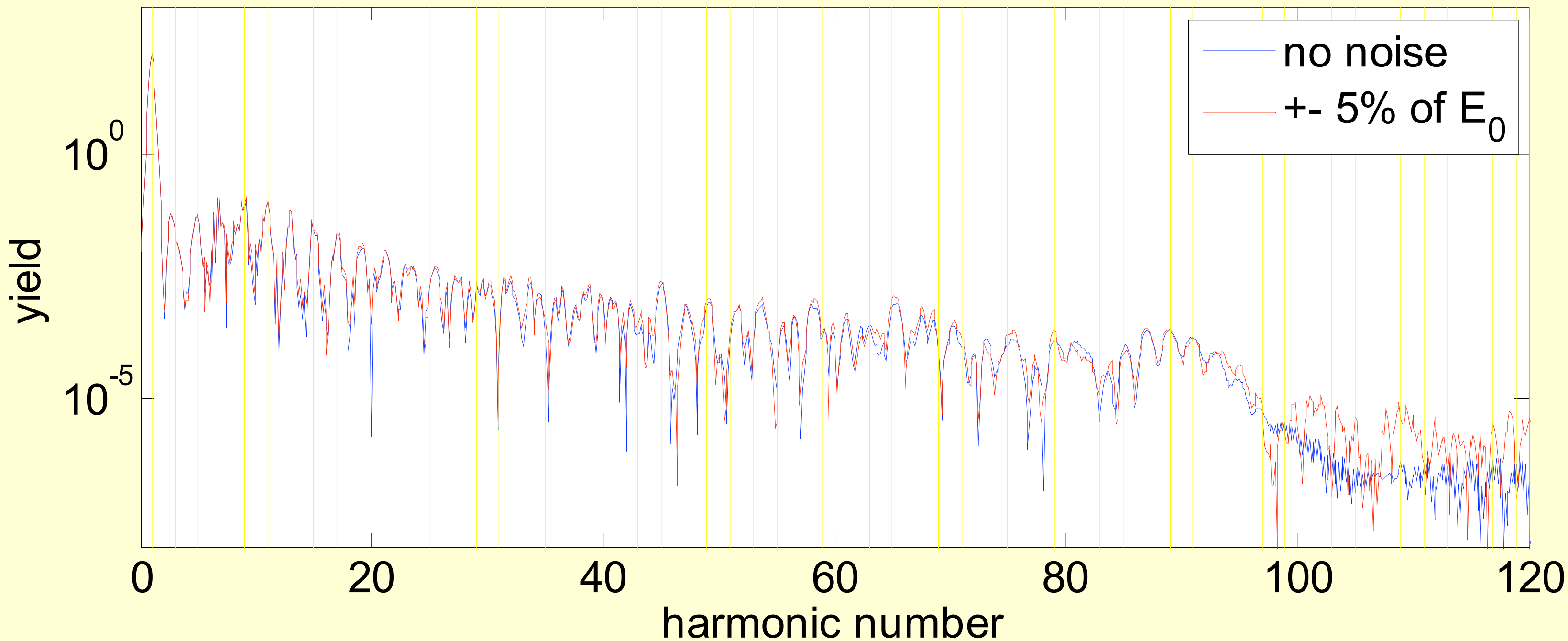
$$E(t) = E_0 e^{-(t-t_0)^2/\tau^2} \sin\left[\omega(t-t_0)+\phi_0\right]$$

$$E_s(t) = E(t) + \alpha s(t) E_0$$

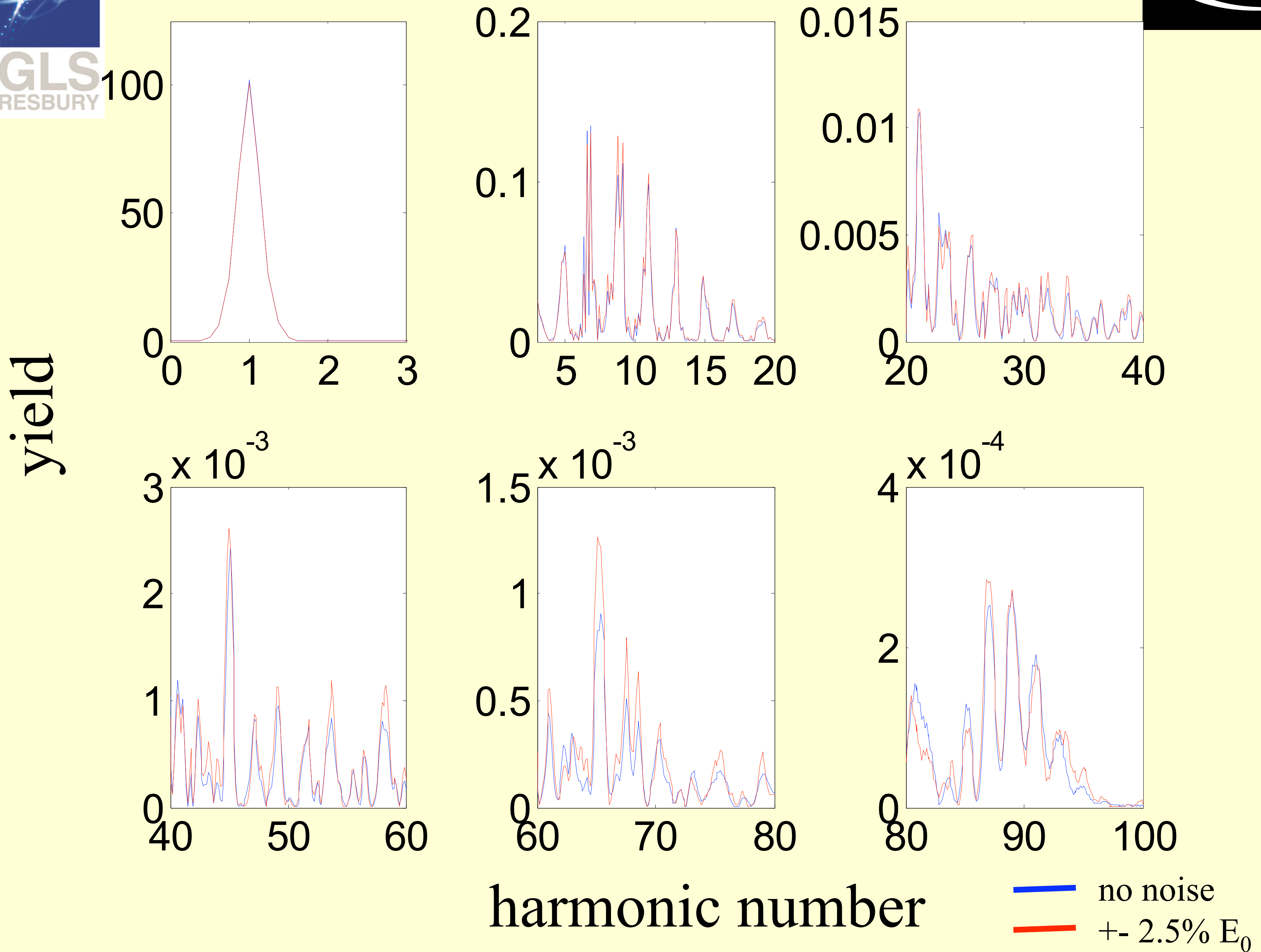
$s(t) \equiv$ stochastic variable

(white noise on [-1,1], change on each time step),

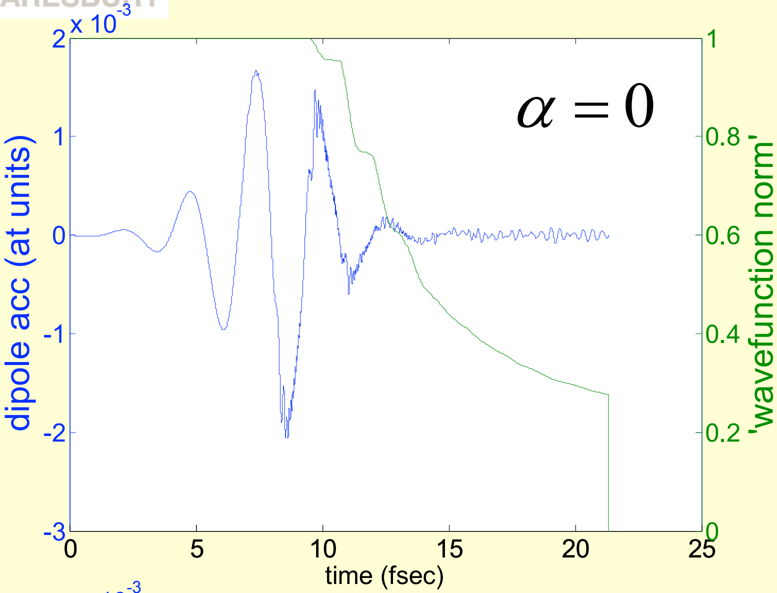
$\alpha = 0.05$, τ such that FWHM Intensity = 5 fsec

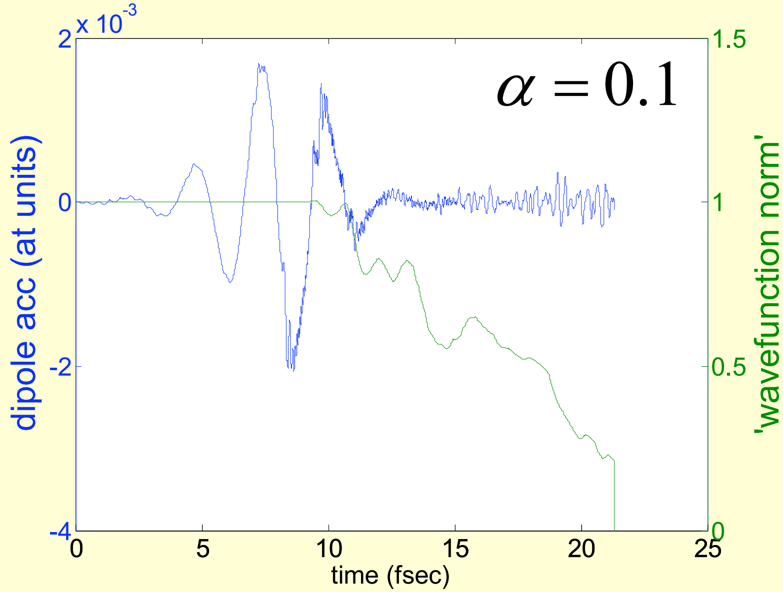


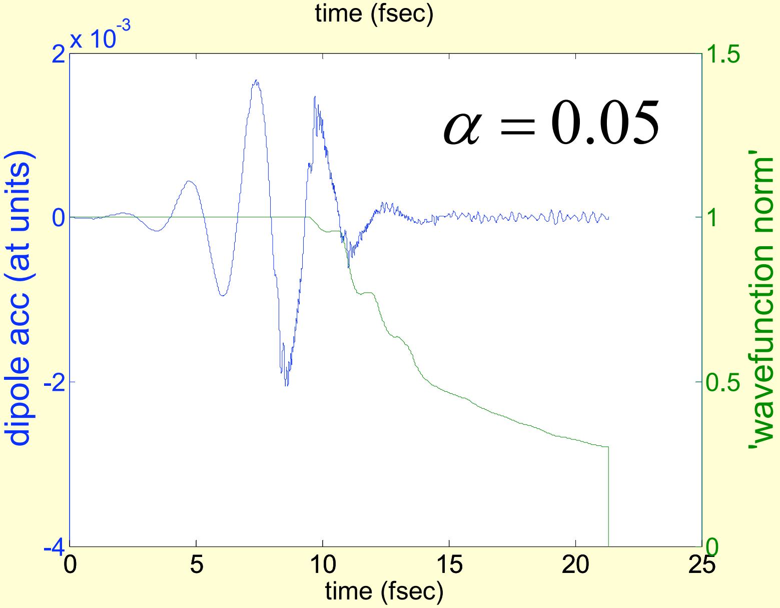
Constant amplitude Noise $\alpha = 0.05$



Sign of instability in the calculation





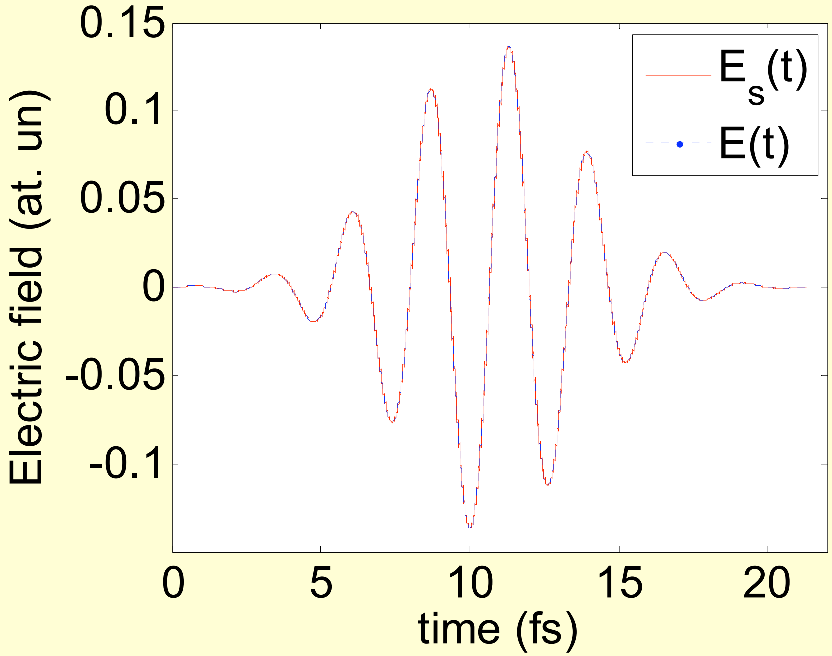


pseudoprobability $P = \sum_{jk} \frac{(\phi_{jk}^n)^* \phi_{jk}^{n+1} + \phi_{jk}^n (\phi_{jk}^{n+1})^*}{2}$

is conserved except for absorption at boundaries.

i.e $$\frac{dP}{dt} \leq 0$$

Discontinuous phase fluctuations



$$\alpha = 1^\circ$$

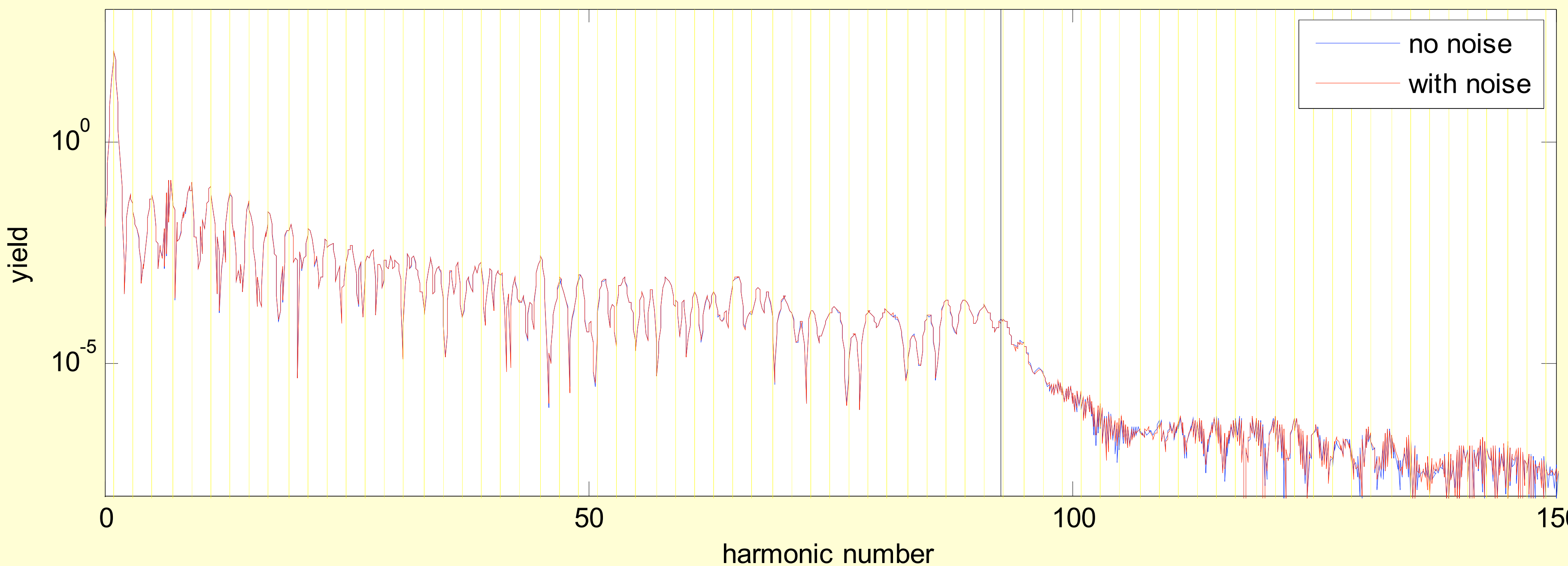
$$E(t) = E_0 e^{-(t-t_0)^2/\tau^2} \sin\left[\omega(t-t_0)+\phi_0\right]$$

$$E_s(t) = E_0 e^{-(t-t_0)^2/\tau^2} \sin\left[\omega(t-t_0)+\phi_0+\alpha s(t)\right]$$

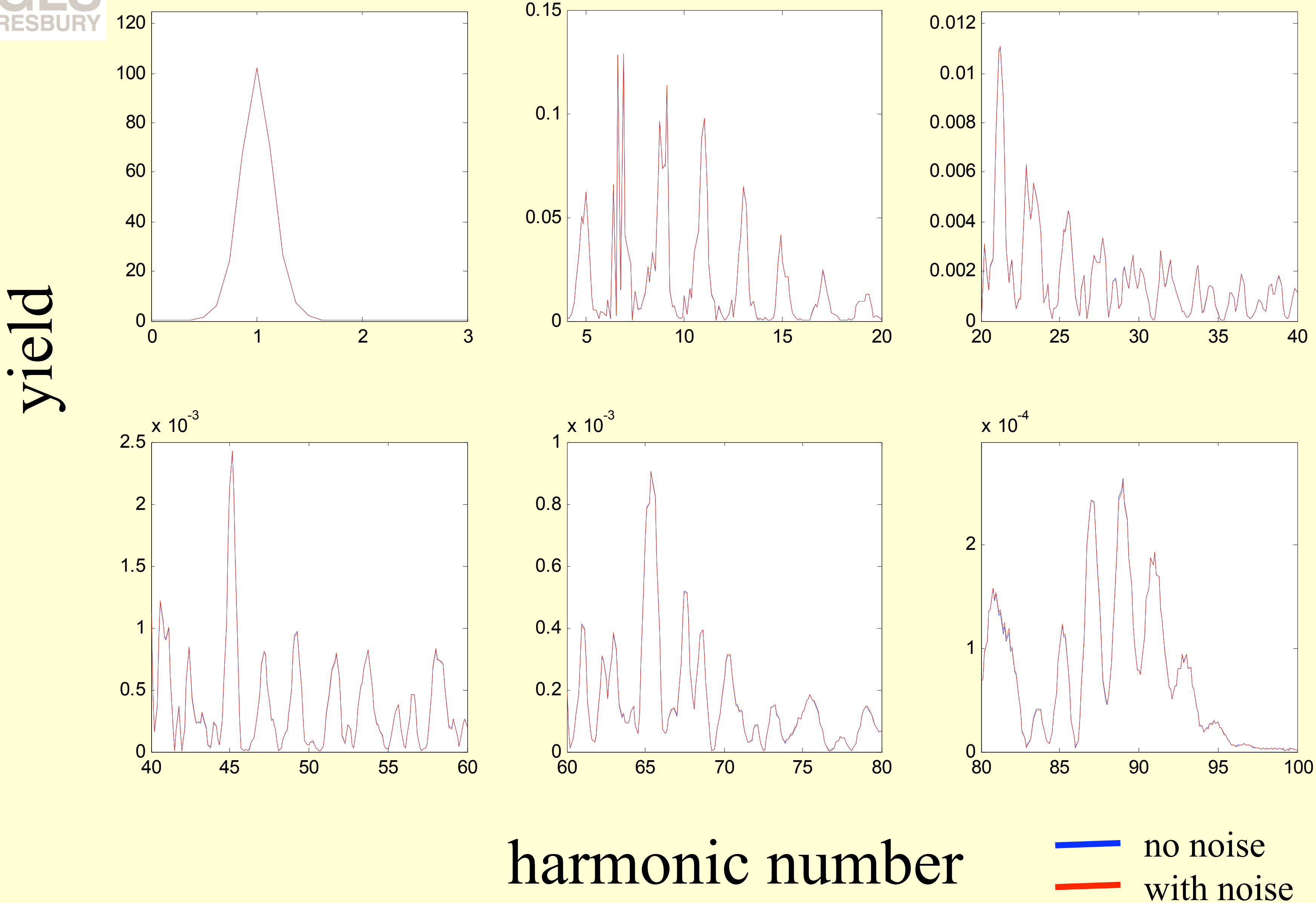
$s(t) \equiv$ stochastic variable

(white noise on [-1,1], change on each time step),

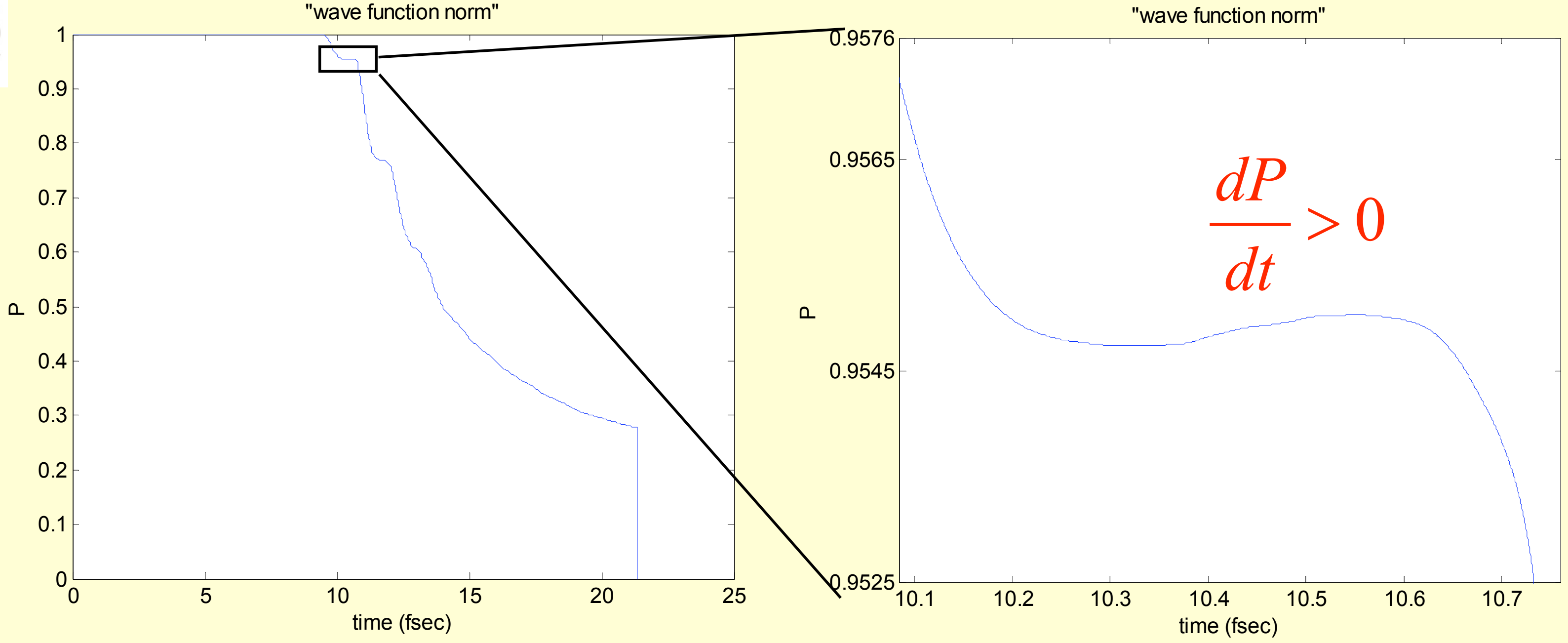
$\alpha = 1^\circ$, τ such that FWHM Intensity = 5 fsec



Discontinuous phase fluctuations $\alpha = 1^\circ$



Discontinuous phase fluctuations $\alpha = 1^\circ$



- Some instability in the calculation already apparent
    - can't push α much higher
- no sign of rapid noise growth in harmonics up to 95
    - would expect large bandwidth growth, noisy spectrum

Noise Summary

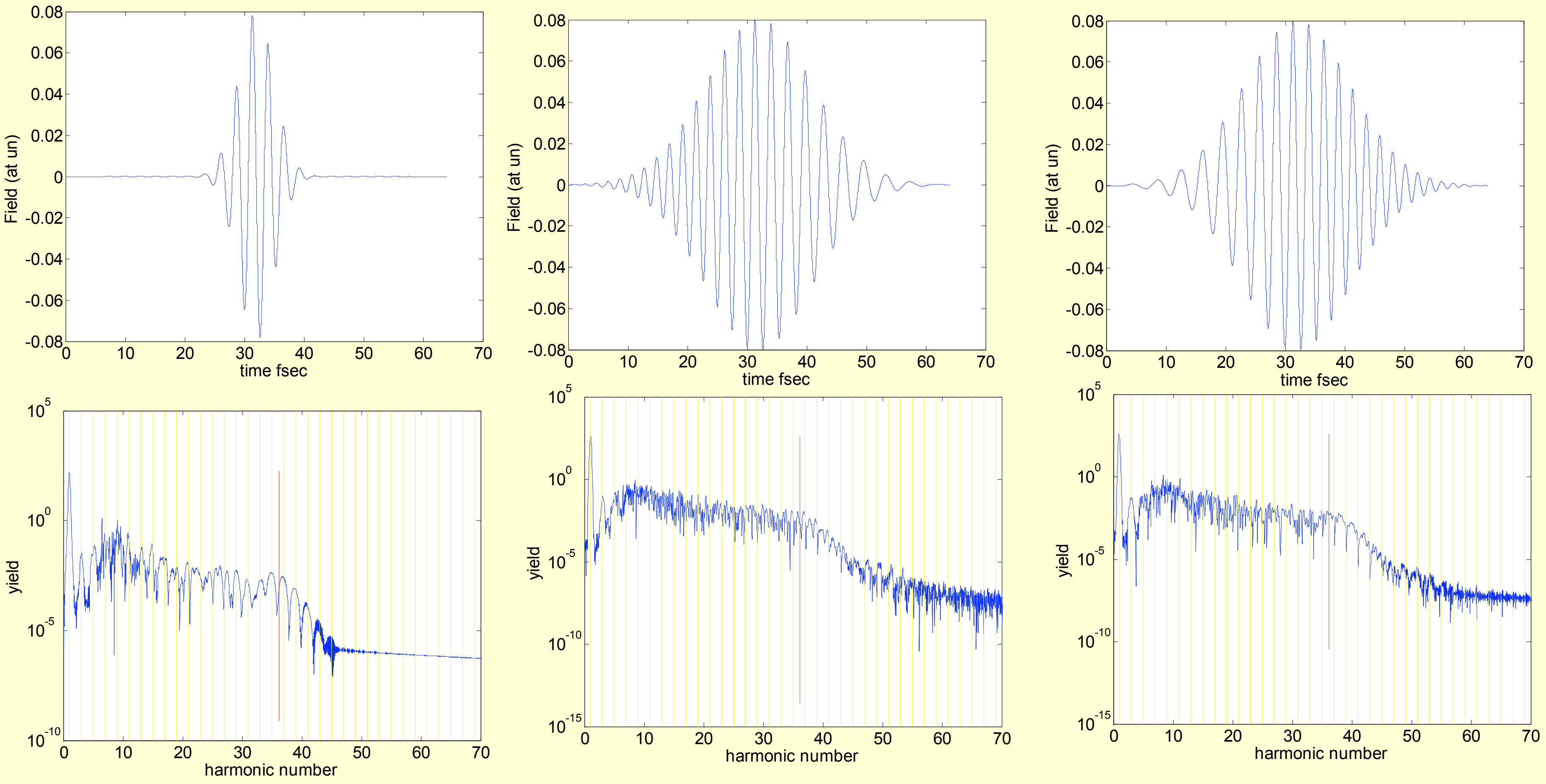
- Harmonics are very robust to the noise studied
  - could be even much better than indicated here
    - stability of calculation question
    - macroscopic phase matching

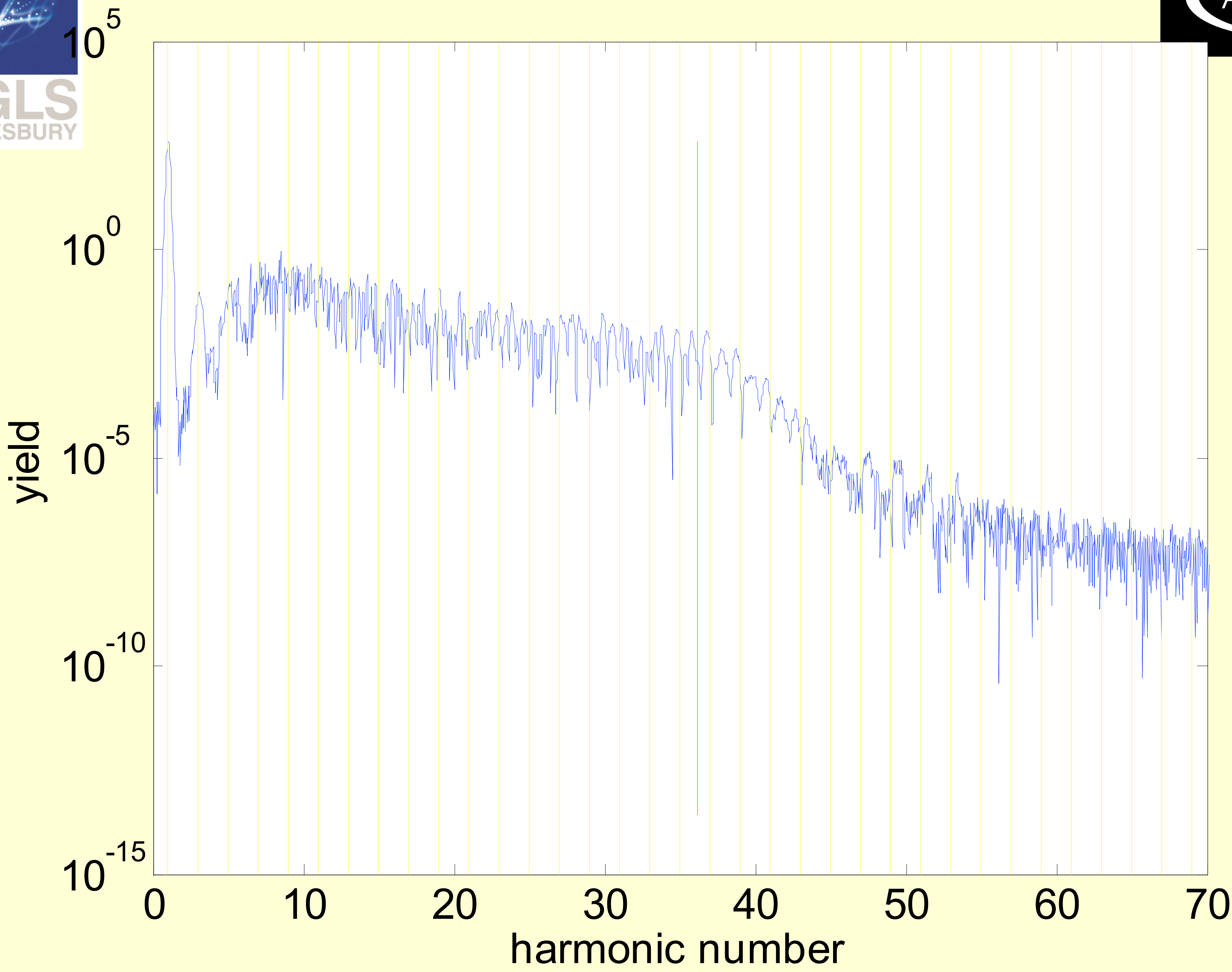
- magnitude of noise tried is large compared to lasers
  - e.g lasers with a contrast of $<10^{-6}$ are used in plasma X-ray sources
  - I still need to use a better model of fast phase noise

- Maybe it’s not too surprising:
  - (photon picture) HHG is not a classical amplifier: quantum system, ladder of dressed states, does not store phase noise of “pump”. Compare to HGHG where noise is encoded in the modulation of the the electron bunch.
  - (wave packet picture) relies on an interference persisting over several cycles; perhaps the relevant criterion is: perturbation of tunneling & recurrence times from noise << wave packet spread?

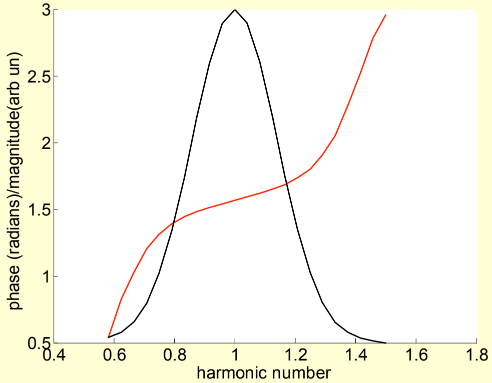
Chirping the fundamental

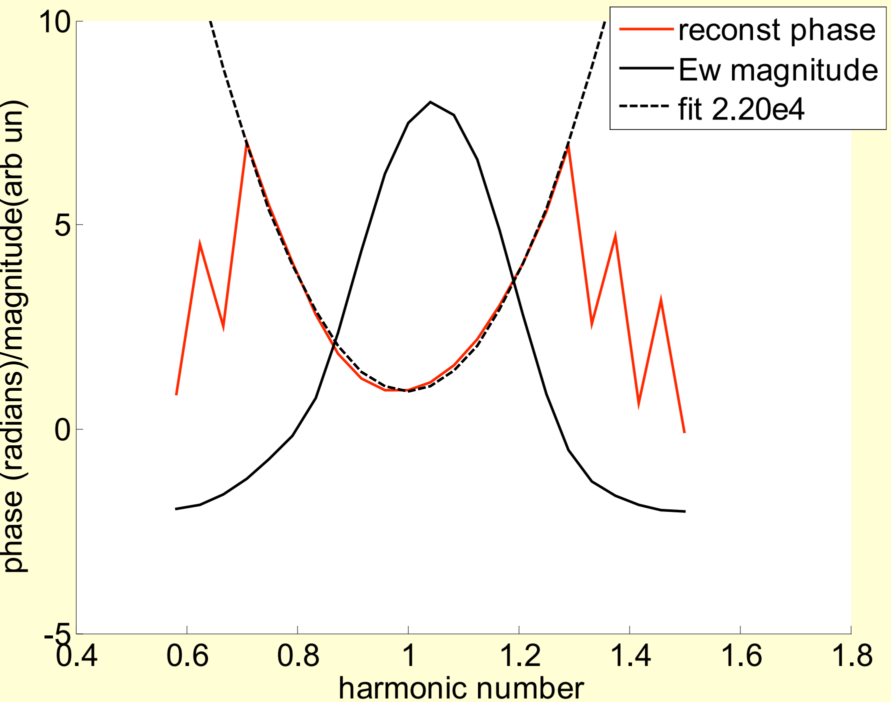
chirp a 5 fsec pulse into a 15 fsec pulse two ways, using equal but opposite chirps.
The spectral chirp to do this is alpha = 2.2e4 a.u = 13 fsec^2

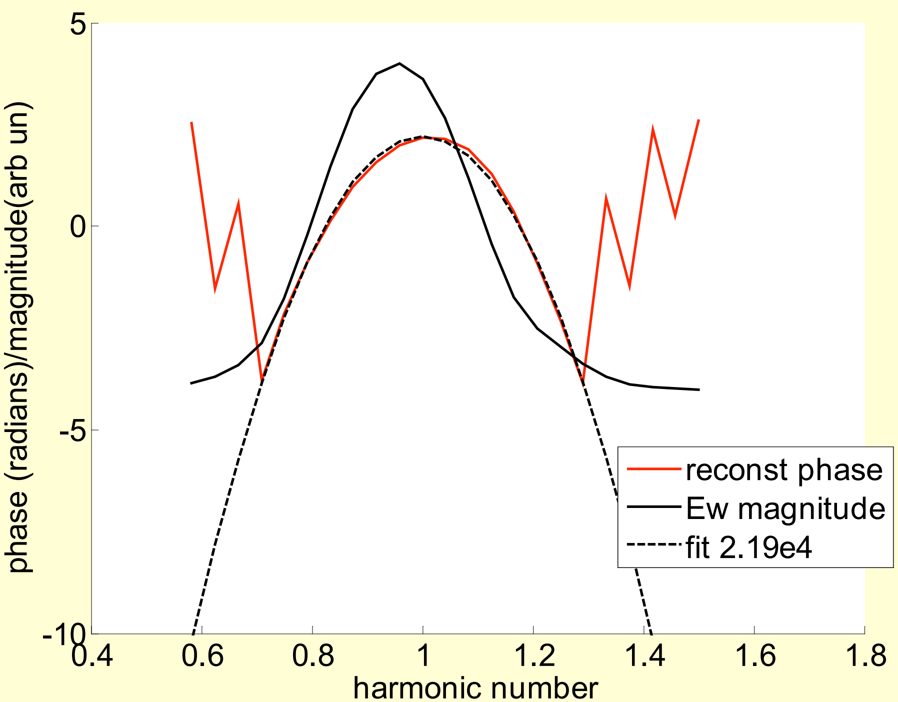




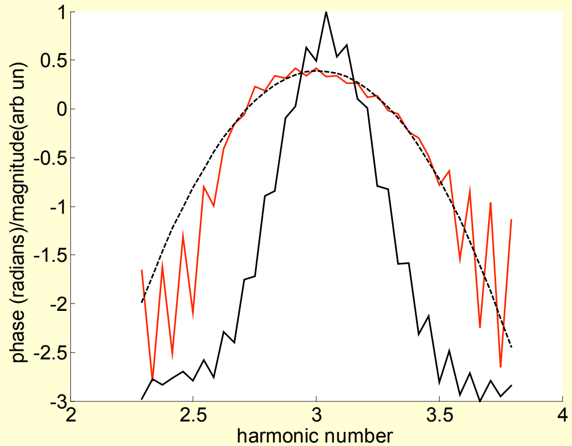
10^5
10^0
10^-5
10^-10
10^-15
yield
0
10
20
30
40
50
60
70
harmonic number

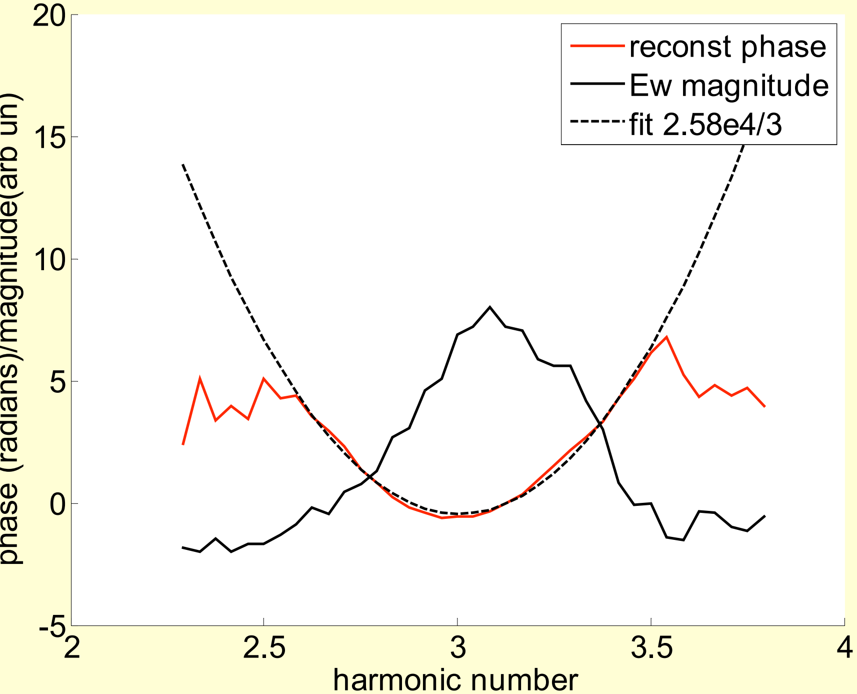


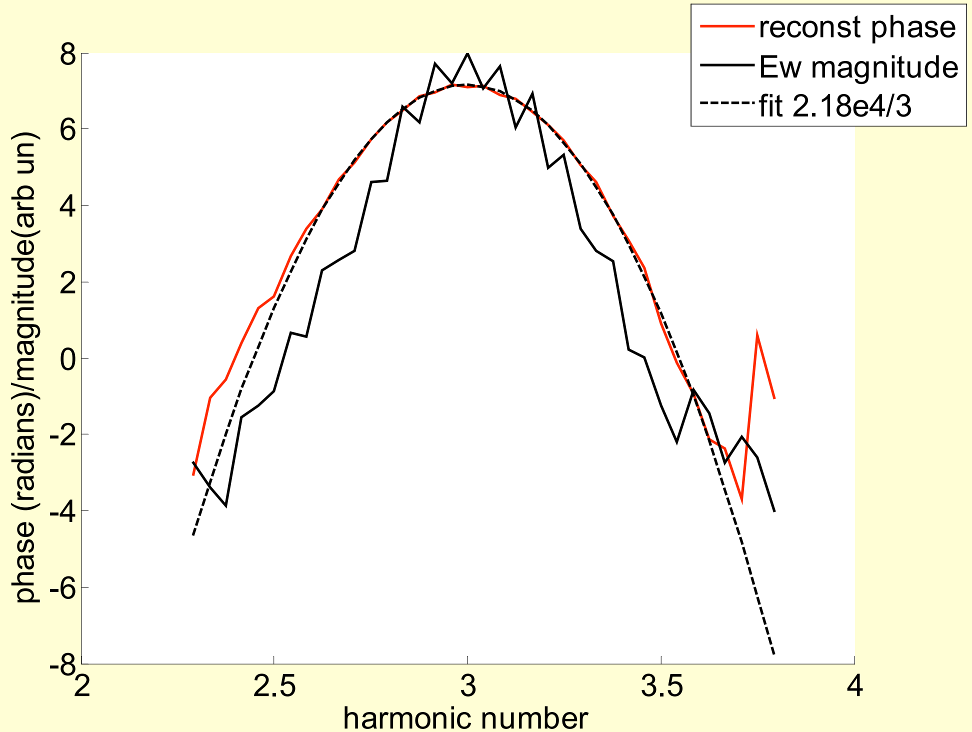




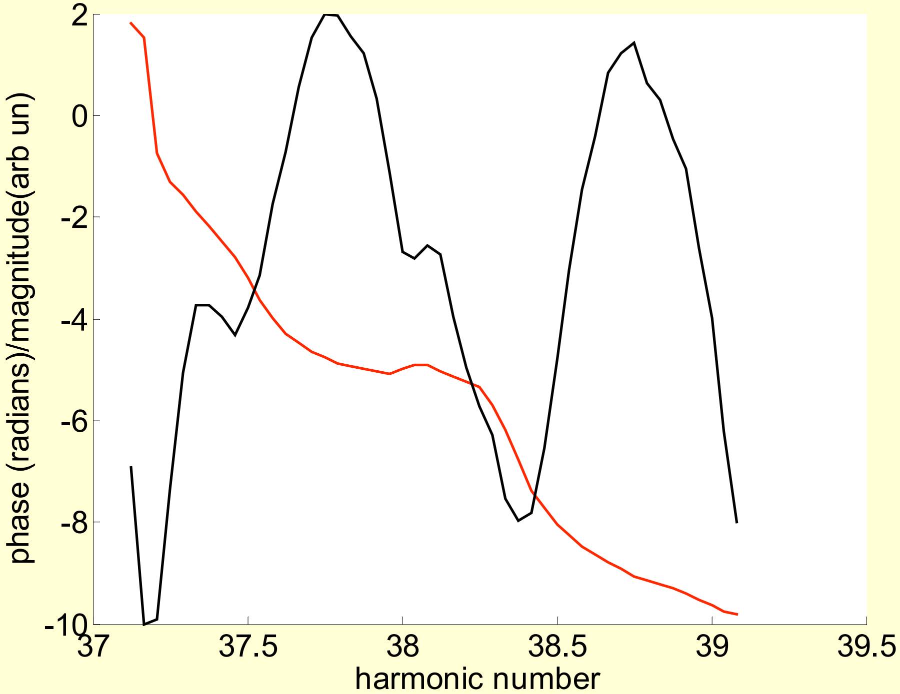
chirp is visible in the radiated fundamental

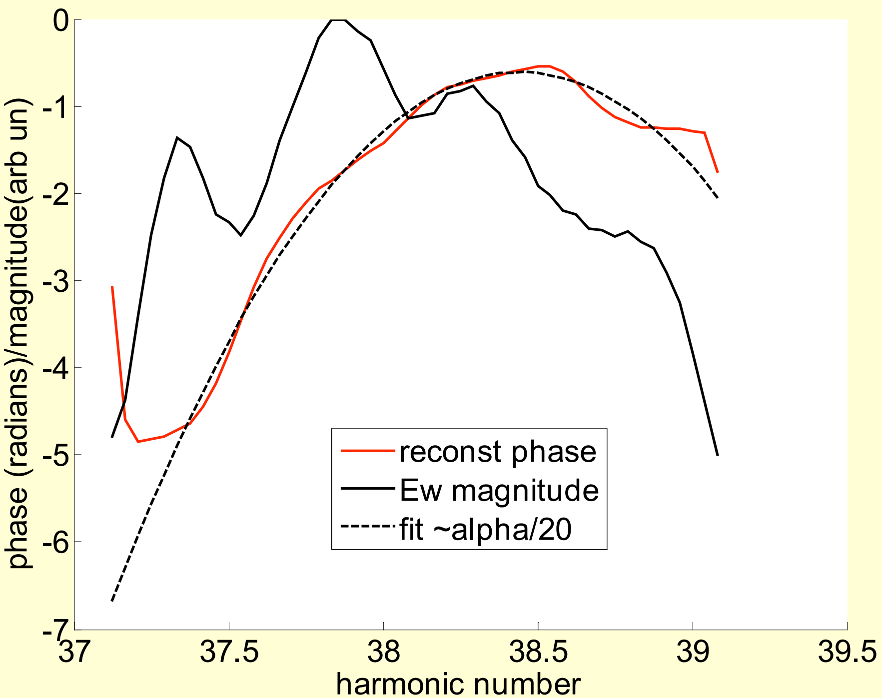






low order harmonics behave approximately perturbatively, but note chirp in the 3rd harmonic of the unchirped pulse (~5x smaller).





Behavior at higher order harmonics is much more complicated

Summary

An appreciation for the versatility of HHG as an FEL seed is growing at about the same pace as the appreciation for the complexities involved.