Increasing the Seeded FEL to Noise Contrast Ratio

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Motivation

The bandwidth of seeded FELs is often limited by shot noise, especially for low seed power.

Is there a simple way to improve the contrast ratio?

Seeding begins from a pure electromagnetic field, shot noise is primarily a density variation.

Both drive the fastest growing modes, main difference is coherence and bandwidth.

A monochromator at the end of the FEL can be used to favor the desired coherent mode, but reduces output.

An appropriately designed modulator in an optical-klystron (OK) configuration at the very beginning of the FEL can enhance the coupling of laser seeds to the growing mode over that of density fluctuations; call it a Superseed Section.

Modulator sections in FELs

Basic configuration: modulator + chicane + radiator

| laser seed | | chicane |
| modulator | | radiator |

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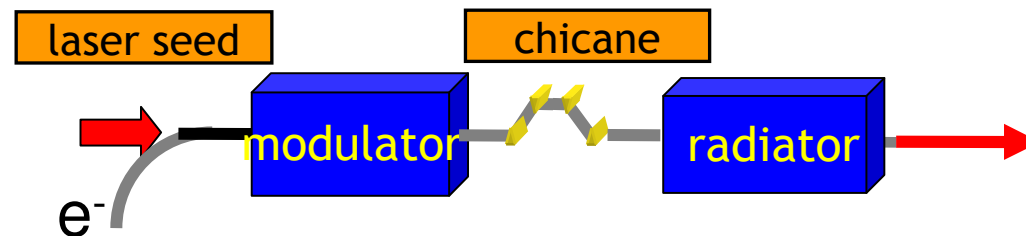
Similar to configurations already used for:

- optical klystron (N.A. Vinokurov and A.N. Skrinsky, INP **77**-59)

- DOK, improved gain length (V.N. Litvinenko, NIMA 1991)

- HGHG (L.H. Yu, Phys. Rev. A 1991)

- EEHG (G. Stupakov, Phys. Rev. Lett. 2009)

Here, we give a motivation to use this configuration even when not
going to higher harmonic or trying to shorten undulator

Some basic linear analysis: 1D, monoenergetic

Scaled variables: laser field, density and energy modulation

$$a_s \qquad \delta\theta = \Re e\ \xi_\theta e^{i\theta_0}\alpha/\rho_{1D}^2 \qquad \delta\eta = \Re e\ \xi_\eta e^{i\theta_0}\alpha/\rho_{1D}$$

with

$$\alpha \equiv \frac{a_u}{1+a_u^2}\left[J_0\left(\frac{a_u^2/2}{1+a_u^2}\right) - J_1\left(\frac{a_u^2/2}{1+a_u^2}\right)\right]$$

evolve according to

$$a_s' = 2k_u\rho_{1D}\xi_\theta \qquad \xi_\theta' = 2k_u\rho_{1D}\xi_\eta \qquad \xi_\eta' = 2ik_u\rho_{1D}a_s$$

with 3 modes: growing |+>, stationary |0>, and damped |->
express as $(a_s, \xi_\theta, \xi_\eta)$: $|+\rangle = (1, e^{i\pi/6}, e^{i\pi/3})$

$$|0\rangle = (1, -i, -1) \qquad |-\rangle = (1, e^{i5\pi/6}, e^{-i\pi/3})$$

Laser seed vs shot noise

Now express laser seed, pure $a_{\rm s} = (1, 0, 0)$, etc.

pure seeding:

$$\frac{1}{3}\left(|+\rangle + |0\rangle + |-\rangle\right)$$

pure density mod:

$$\frac{1}{3}\left(e^{-i\pi/6}|+\rangle + i|0\rangle - e^{i\pi/6}|-\rangle\right)$$

pure energy mod:

$$\frac{1}{3}\left(e^{-i\pi/3}|+\rangle - |0\rangle + e^{i\pi/3}|-\rangle\right)$$

all have 1/9 of "power" coupled to growing mode

Applying dispersion can enhance some of these modes more than others, or even lead to interference.

Expect to enhance stray energy modulations, but unless generated by instabilities starts lower by factor σ_η / ρ_{1D} weighting

narrow energy range   factor for ξ_η

Design considerations:

Crucial that modulator be shorter than a gain length:

- after growing mode gets large, distinction between laser seed and shot noise modes is gone
- keep slippage shorter than coherence length

however, ratio of a_s to ξ_η implies should be of order gain length

- instead, use R_{56} to get enhanced bunching, discard radiation
- saves worrying about phase matching laser field into radiator

Energy spread sets constraint $|R_{56}| < \lambda_s/2\pi\sigma_\eta$

- higher than this, microbunches will be smeared by > 1 radian
- decoupling shot noise from growing mode, if possible, requires complicated setup and $|R_{56}|$ having opposite sign of simple chicane
- will use a straightforward chicane to get some improvement in contrast
- avoid overbunching the energy modulation induced by laser seed

Limits

Some simple limits when $R_{56} >> \lambda_s/2\pi\rho_{1D}$ and $L_{mod} << L_G$

- assume R_{56} still below energy spread limit $\lambda_s/2\pi\sigma_\eta$

- then improved contrast is

   $(2.8 \, L_G/L_{mod})^2 / (1+x^2),$ $x=16.6 \, \lambda_s L_G{}^3/\lambda_u R_{56} L_{mod}{}^2$

- in practice, energy spread limit to R_{56} will limit improvement, prevents going to small x

- for fixed R_{56}, optimum modulator length is to have x=1

Set R_{56} to the maximum allowed by the energy spread, $R_{56}=\lambda_s/2\pi\sigma_\eta$

- see improvement of up to 0.8 ρ_{1D}/σ_η

- but $L_{mod}/L_G = (24\sigma_\eta/5\rho_{1D})^{1/2}$

- this won't be small unless $\sigma_\eta < \rho_{1D}/100$, so typical gain in contrast will be less impressive

Most useful for beams with very low energy spread and high brightness.

Numerical Example using GENESIS:

Based on 30 nm HHG seeding paper:

M. Gullans et al., Optics Comm. 2007

electron beam parameters:

- 1 GeV energy, 75 keV energy spread
- 500 A current
- 1.2 micron emittance, ~60 micron spot size (natural focusing)
- undulators: 30 mm period, a_u=2.58, resonant for 30 nm
- weak laser seed, 1 kW, assume focused so Z_R=1.2 m
    - 75 micron min. spot size

ρ_{1D} = 2 ×10^{-3}, 3D gain length L_G=0.8 m

simple amplifier saturates after 14 m with 1.3 GW power

base configuration: 0.6 m modulator, chicane with R_{56}=60 micron

- radiator, 11.4 m to saturation with 1.3 GW power
- laser field exiting modulator is blocked

Simulation Results

We ignored slippage in linear analysis, but all GENESIS runs are time-dependent

σ_η / ρ_{1D} =0.04, small number but not quite in ideal limit

Note GENESIS does not model shot noise energy modulation. but the relative importance of this term is also given by σ_η / ρ_{1D}
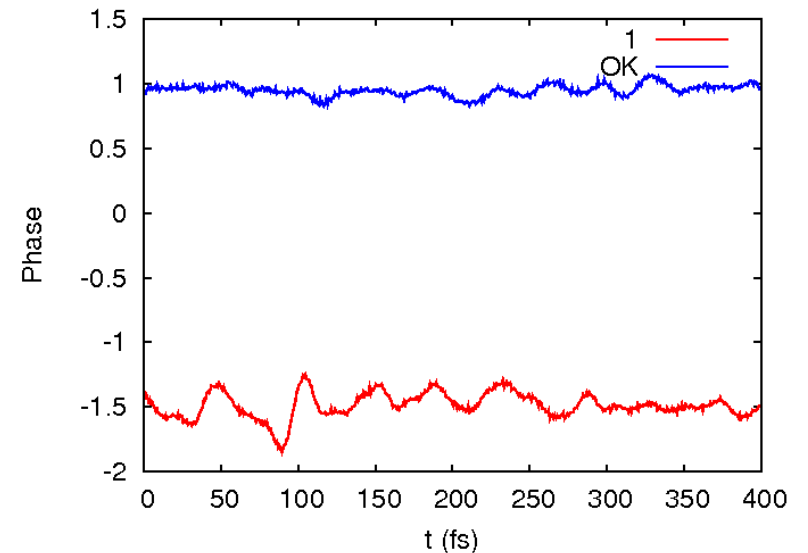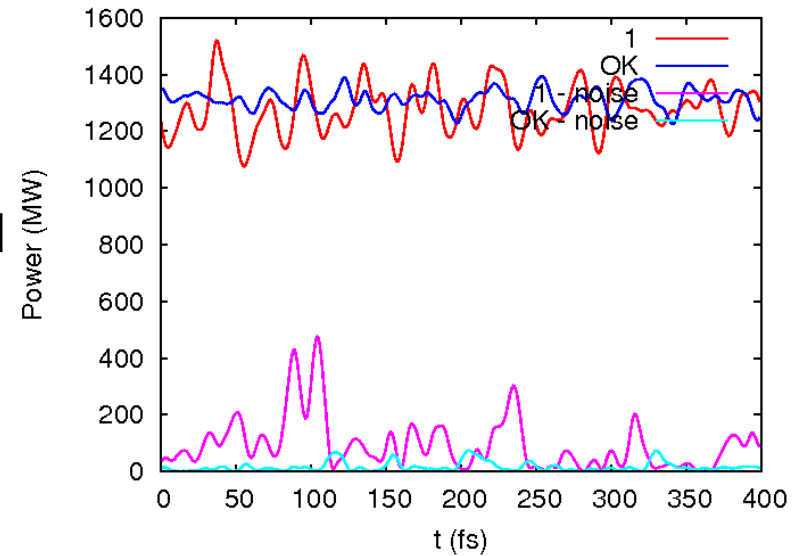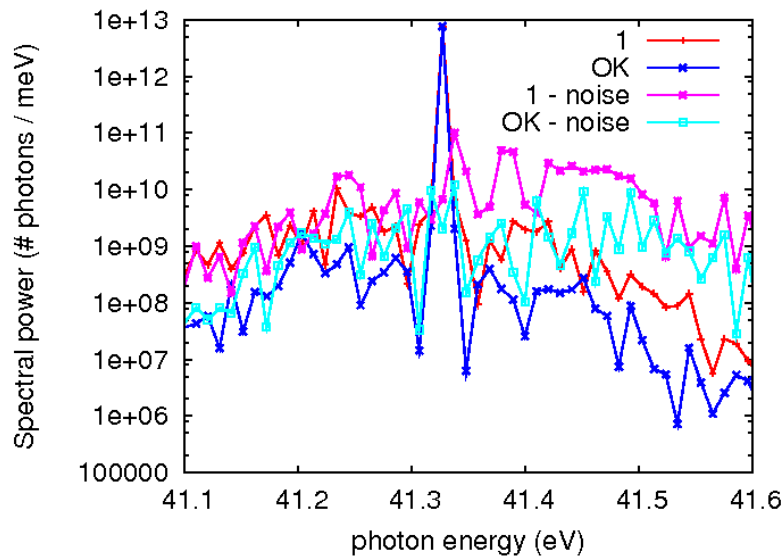
* safe to ignore as a contributor to SASE

Simulate 0.4 ps of uniform beam with uniform seed, also repeated with no input seed

Nominal Case

Reduces effect of shot noise from both seeded and unseeded cases.

At saturation length, background noise reduced from 95 MW to 17 MW, more than factor 5 improvement

Low Energy Spread Example

Same parameters as before but reduced energy spread to 15 keV and used modulator length 0.3 m. Better match to limiting case above.

At saturation length, background noise reduced from 97 MW to 6.1 MW, factor 16 improvement. Close to predicted factor 19.
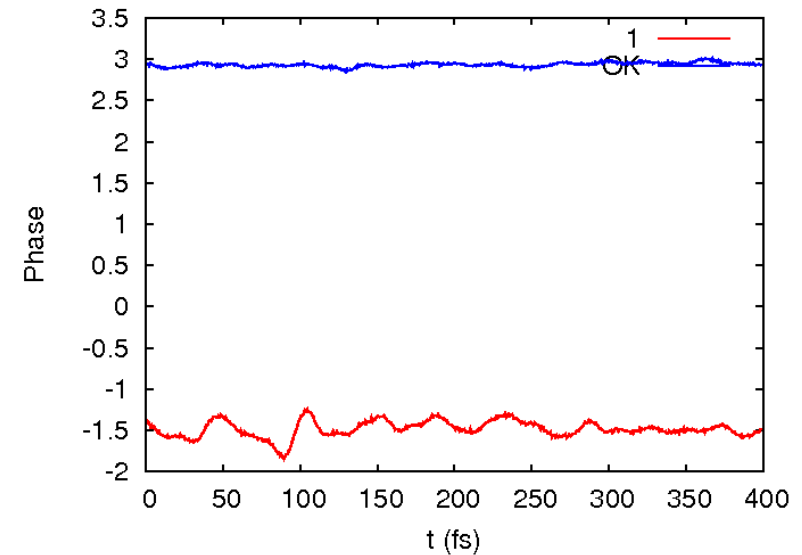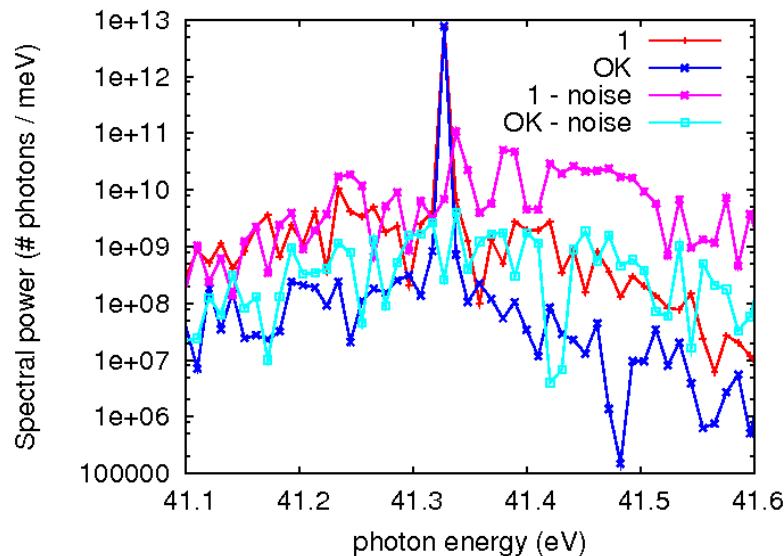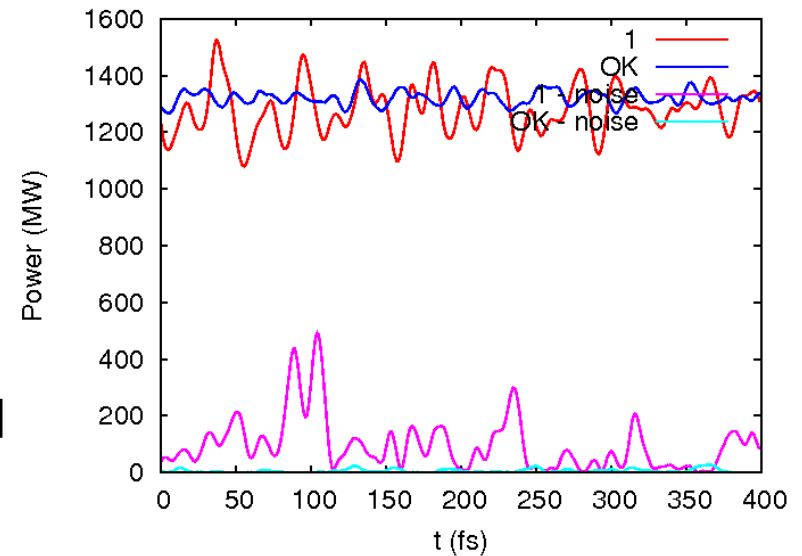
Performance Scaling in Test Case

R_{56}~60 micron works well for all cases; much larger does not work at all because of energy spread (200 micron ok in low-espread example)

independent of seed power until overbunch at very high power

similar results as long as modulator length not too small or big, then stops working

effect of Superseed section is to make seed input look like it is 5x more powerful, which improves contrast ratio by up to 5
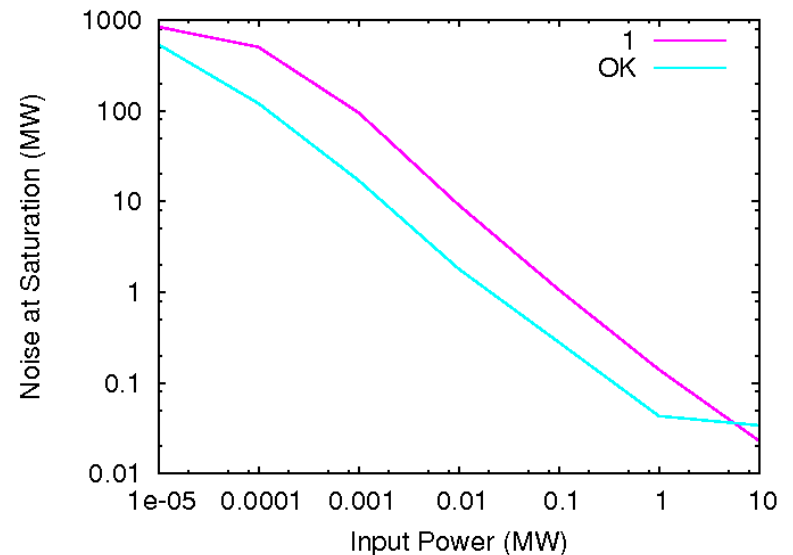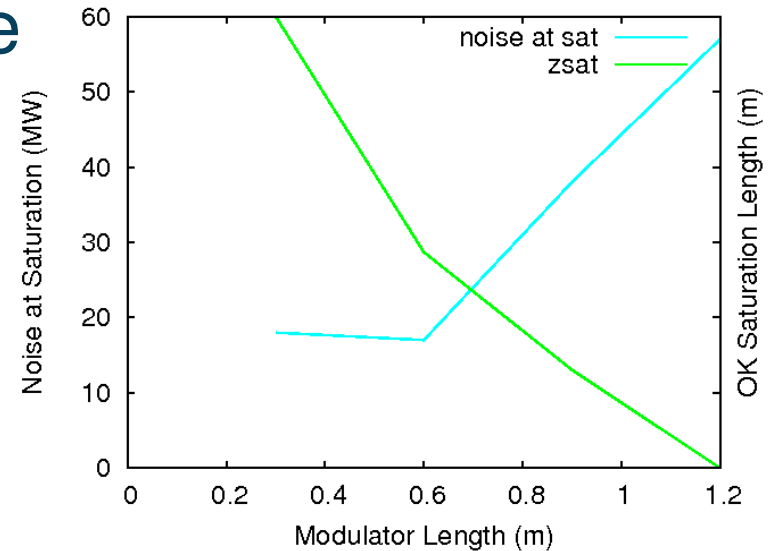
Conclusions

Factor of 5 improvement of contrast ratio in simulations

- regions both inside and outside laser pulse are improved
- a modest improvement, but very little cost to implement
- adds chicane, but reduces total undulator length
- works from moderate seed power down to levels barely above noise
- more improvement by keeping laser field, adding phase shifter?
- is better for more extreme σ_η / ρ_{1D}

No clear downside to implementing this

- weak sensitivity to parameters
- moderate chicane strength (by necessity)
- any increase in contrast should benefit experiments
- complementary to DOK scheme
- if going to higher harmonic, probably little final benefit
  - already helped by nonlinearity in harmonic generation