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

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)

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

\[ a_s \delta \theta = \Re \xi \xi_0 e^{i \theta_0} \alpha / \rho_{1D}^2 \quad \delta \eta = \Re \xi \eta e^{i \theta_0} \alpha / \rho_{1D} \]

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

\[ a'_s = 2k_u \rho_{1D} \xi \quad \xi'_\theta = 2k_u \rho_{1D} \xi_\eta \quad \xi'_\eta = 2ik_u \rho_{1D} a_s \]

with 3 modes: growing |+>, stationary |0>, and damped |->

express as \((a_s, \xi_\theta, \xi_\eta)\):

\[ |+\rangle = (1, e^{i\pi/6}, e^{i\pi/3}) \]

\[ |0\rangle = (1, -i, -1) \quad |\rightarrow\rangle = (1, e^{i5\pi/6}, e^{-i\pi/3}) \]
Laser seed vs shot noise

Now express laser seed, pure $a_s = (1, 0, 0)$, etc.

pure seeding:
$$\frac{1}{3} (|+\rangle + |0\rangle + |−\rangle)$$

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 $\frac{\sigma_\eta/\rho_{1D}}{\xi_\eta}$ weighting factor for $\xi_\eta$ narrow energy range.
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 $\xi$ 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 $|R_{56}| < \lambda_s/2\pi\sigma_n$

- 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 $L_{\text{mod}} << L_G$

- assume $R_{56}$ still below energy spread limit $\lambda_s/2\pi \sigma_\eta$
- then improved contrast is
  $$(2.8 \frac{L_G}{L_{\text{mod}}})^2 / (1+x^2), \quad x = 16.6 \frac{\lambda_s L_G^3}{\lambda_u R_{56} L_{\text{mod}}^2}$$
- 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 $\rho_{1D}/\sigma_\eta$
- but $L_{\text{mod}}/L_G = (24\sigma_\eta/5\rho_{1D})^{1/2}$
- 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

\[ \rho_{1D} = 2 \times 10^{-3}, \] 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

\[ \frac{\sigma_\eta}{\rho_{1D}} = 0.04 \], 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 \[ \frac{\sigma_\eta}{\rho_{1D}} \]

- 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

$R_{56} \sim 60$ 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 $\sigma_\eta/\rho_{1D}$

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