FEL seeding possibilities for the NGLS

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SLAC
Introduction

While the NGLS design will include SASE beamlines, the emphasis is on seeded FELs.

Concerns over timing, consistency and high average power motivate many of the design and parameter choices:

- Superconducting RF for high rep rate and less jitter
- Short-bunch option so seed laser can overlap entire bunch
- Energy spread far below typical FEL bandwidth

Will present an overview of requirements, scaling laws, and operating techniques for seeding without “fresh bunch”

- start with simple modulator + radiator scheme
- later will look at optical klystrons
- review the various influences of energy spread on the FEL design
NGLS concept

High Repetition Rate Electron Source

2.0 - 2.5 GeV CW SC LINAC

Capability for 10/20 FEL beamlines
Basic Definitions

Energies given in terms of gamma factor, $\gamma$
Energy spread $\sigma_\gamma$
Will modulate by $\gamma_M$, apply $R_{56}$ to bunch beam
At harmonic number $N$, get initial bunching $b_0$
Focus on radiator section:
- 1D Pierce parameter and gain length $\rho = \lambda_u/(4\pi\sqrt{3} L_{1D})$
- undulator period $\lambda_u$, output wavelength $\lambda_s$, undulator parameter $a_u$
- a key parameter will be $\rho \gamma/\sigma_\gamma \equiv N_0$

similar to Ming Xie parameter $\eta_\gamma = \frac{\sigma_\gamma}{\sqrt{3} \rho_\gamma}$
NGLS Parameters

Still in flux: baseline parameters
2.4 GeV energy, 100 keV energy spread
1 kA peak current
0.8 micron normalized slice emittance
Bunches ranging from 1 ps to <100 fs
  half of bunch length intended to be uniform, ‘usable’
  \( N_0 = 17.5 \) at 1 nm, with 24 mm undulator period
Nominal peak current may be reduced
  for SASE, clearly better if can obtain reduced emittance
  for seeded, need to consider if energy spread or emittance more important to reduce
Expected Behavior

FEL performance sharply degrades when energy spread (including modulation) > ργ

harmonic number will be limited to \( N \sim \gamma_M/\sigma_\gamma < N_0 \)

• otherwise bunching will saturate at low value

Normal HGHG seeding, generated bunching is

\[
b_0 = J_N(x)e^{-(x\sigma_\gamma/\gamma_M)^2/2} \approx 0.675 N^{-1/3}e^{-(N\sigma_\gamma/\gamma_M)^2/2}
\]

where \( x = kR_{56}\gamma_M/\gamma \) and set to the peak of the Bessel function for large \( N \),

\[
j'_{N,1} \sim N + 0.8N^{1/3} \quad J_N(j'_{N,1}) \sim 0.675 N^{-1/3}
\]
Modulation Limit

Energy bandwidth prevents electrons from slipping by a wavelength in less than a gain length:

\[
\frac{\sigma_\gamma}{\gamma} \frac{1 + a_u^2}{\gamma^2} L_{1D} \lesssim \lambda_s
\]

using resonance condition, same as \(\sigma_\gamma/\gamma \ll \rho\)

assume initially energy spread not critical

else cannot usefully modulate

From Ming Xie scaling, estimate \(L_M \approx L_0 \left(1 + \frac{1}{2} \frac{\gamma_M^2}{\rho^2 \gamma^2}\right)\)

Saturation length for HGHG is \(L_{\text{sat}} \approx 2L_M \ln \left(\frac{3b_{\text{sat}}}{b_0}\right)\)

• keep short, compare to shot noise saturation
• factor 3 similar to factor 9 reduction for laser power
• set \(b_{\text{sat}} \sim 1\)
Optimum Seeding

Shortest saturation length is

\[ L_{\text{sat}} = 2L_{1D} \left[ \left( 1.5 + \frac{1}{3} \ln N \right)^{1/2} + \frac{N}{2N_0} \right]^2 \]

Usually a soft optimum in \( \gamma_M \) unless harmonic > \( N_0 \)
then instead of \( N\sigma_\gamma \) being good enough, shifts to

\[ \frac{\gamma_M}{\sigma_\gamma} \sim \left( \frac{NN_0}{\sqrt{1.5 + 0.33 \ln N}} \right)^{1/2} \]

Not reasonable to expect \( \ln N \) term to be much help.
N=8 examples

LBNL parameters:
undulator for 1 nm:  2.4 cm period, $a_u=0.9143$
  beta function $\approx 20$ m
  resulting $\rho = 5.2 \times 10^{-4}$
  $N_0 = 17.5$, reduced to 12 by 3D effects

8th harmonic to 1 nm, optimum $\gamma_M \sim 1$.

modulator has 5 cm period, $a_{u,mod}=2.460$, same beta function
  resulting $\rho_{mod} = 1.3 \times 10^{-3}$
  $\rho_{mod}\gamma = 6$, rough estimate of achievable modulation $\gamma_M$
  avoid overbunched distribution
Saturation occurs when $\sigma_\gamma = 3$
This limit is just a bit bigger than $\rho_\gamma = 2.4$
If start above this level, final bunching is limited and tends to drop from starting value, never recovers. Still enough power to consider using for ‘fresh bunch’. SASE saturates at $\sim 40$ m.

3 different energy modulations: $\gamma_M = 2, 4, 8$; for largest $\gamma_M$, the bunching only decreases, never recovers. $\gamma_M = 1$ corr to 30 MW seed power
Now consider a weak laser seed, that has to be amplified in an optical klystron to generate the required energy modulation.

\[
\frac{d\gamma_M}{dz} \simeq (JJ) \left( \frac{4P_L e a_u^{2,\text{mod}}}{mc^2 I_A \sigma_{\text{seed}}^2} \right)^{1/2}
\]

The gain length is usually shorter than the Rayleigh length. To get an energy modulation \(\sim 0.3 \sigma_\gamma\) in 1 gain length requires

\[
P_L > \frac{1}{12} \left( \frac{L_{\text{mod}}}{L_{1D,\text{mod}}} \right)^2 \frac{\sigma_\gamma^2}{\gamma^2 \rho_{\text{mod}} \gamma} \frac{1}{\sigma_{\text{beam}}^2} \frac{mc^2 I_{\text{peak}}}{e}
\]

with \(mc^2 I/e \, [\text{MW}] = 0.511 \, I \, [\text{A}]\)
Weak Laser Seed (2)

Here we used two expressions for the 1D FEL parameter,

\[ \rho_{\text{mod}} = \frac{\lambda_{u,\text{mod}}}{(4\pi \sqrt{3} L_{1D,\text{mod}})} \]

and

\[ \rho_{\text{mod}} = \left( \frac{\lambda_{u,\text{mod}}^2 a_{u,\text{mod}} I/I_A}{32\pi^2 \gamma^3 \sigma_{\text{beam}}^2} \right)^{1/3} \]

If the seed laser disperses faster than a gain length, the seed power will have to be increased to compensate.

Note that as the energy modulation is of order the energy spread, and could be smaller, the total energy spread is barely affected. No fresh bunch should be needed.
Amplification of Seed vs Noise

Maximum amplification of weak seeds when \( R_{56} = \lambda_s \gamma / 2\pi \sigma_\gamma \)

The laser seed is amplified linearly with modulator length, the bunching noise quadratically and out of phase with initial bunching, and energy spread by \( N_0 \).

Then seeding is most efficient when initial modulator length \( \approx L_{1D} (6/N_0)^{1/2} \), assuming \( N_0 \) is big.

Amplification factors: \( (2N_0)^{1/2} \) for laser, \( 2^{1/2} \) for bunching, and \( N_0 \) for modulation.

Expect energy modulation from noise to start \( 1/N_0 \) smaller than density modulation, so wind up comparable.

Should reduce phase noise by \( (2N_0/3)^{-1/2} \)

With this “superseed” scheme, can lower laser requirements
SASE beamlines have no reason to push on low energy spread
Only a few examples have large $N_0$ at lowest wavelengths; but for seeding at long wavelength, can be very large
• at least allows modulation to be done efficiently
• will quote factor with 3D effects

<table>
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<th>Expt</th>
<th>Energy (GeV)</th>
<th>$\lambda_s$ (nm)</th>
<th>$N_0$</th>
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<td>202</td>
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<td>FLASH TTF2</td>
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200 nm laser seed: aim for 20th harmonic at 10 nm and for 50 mm undulator period $N_0=40$, including 3D effects. 80 MW peak power, modulate by 2 MeV after 20 m, 2.6 GW power variations: 0.5% in power, 0.05 radian in phase.

Current profile at maximum spike.
HGHG from HHG laser

40 nm laser seed: aim for 20th harmonic
  at 2 nm and for 24 mm undulator period,
  \( N_0 = 20 \), including 3D effects
version 1) 20 MW peak power, modulate by 1.2 MeV, current spike 7.4 kA
generates 3% bunching, after 21 m reaches 1.9 GW; 0.1 radian phase variation

version 2) 0.5 MW peak power, use “superseed” design
modulator is 0.25 m long; after 100 micron \( R_{56} \), 5% bunching at harmonic
after 21 m reaches 1.1 GW, with 0.1 radian phase variation

note: rad size in 2nd part of opt klystron
increases rapidly, as does power;
uniform enough for EEHG at long wavelengths?

potential problem:
  short modulator won’t fully smooth out HHG spikes,
  so can’t trust GENESIS results
Echo-Enabled HG

Allows for high harmonics with much smaller energy modulation, moderate increase in peak currents

Gain length not significantly impacted (if $N_0$ is already around 10+)

Can still benefit from low energy spread by radiating at harmonic of typical spacing between microbunches

spacing is roughly

$$\Delta z \approx \frac{\lambda_1 \lambda_2 \gamma}{4\pi R_1 \gamma M_2}$$

because spacing is not uniform, lose some efficiency

• but can be easier than trying for shorter spacing

Unlike optical klystron configurations, bunch current does not affect initial bunching at harmonic

Typically requires very large input seed power and long chicanes. “superseed” idea may lose effectiveness at very high harmonics?
Two-color EEHG Seeding

After generating “shredded” phase space, separate sections of electron bunch can be seeded independently.

For fixed initial modulation and $R_{56}$, tune solely through second modulation and $R_{56}$

tuning range is fixed by range of energy modulations

Additional benefits:

- pump/probe timing controlled by laser seeds
- consistent with attosecond pulses
- if two seeds are split from single pulse, output will retain correlations
  - timing, profile
  - if carrier-phase stabilized, will share that phase
Two-color Example

Use 200 nm for initial modulation, long pulse
Two short 800 nm pulses for attosecond pulse generation
  target wavelengths 3.03 nm and 2.27 nm
Very small beta function, 1 m
Because of long chicanes, will have to focus with strong doublets
Modulators and radiators are all short, 2 m or less

Model with idealized modulator
No transverse gradient, but includes:
  • slippage for short pulse
  • random energy losses in chicane

example beamline: large breaks for chicanes
Two-pulse Results

Two pulses, ~0.2 fs FWHM, > 350 MW peak power

~100 nJ energy in each pulse

typical bunching profile at harmonic
Sensitivity to Modulations

Have looked at shot noise fluctuations; coherent effects yield stronger perturbations.

If the electron beam has an energy modulation imposed on it, with period $\lambda_e$, this will cause fluctuations and increase the output bandwidth through frequency modulation.

Use as an example an 8 nm seed being converted into 1 nm output.

Phase oscillation is $\Delta \varphi = R_{56} \left( \Delta \gamma / \gamma \right) \left( 2 \pi / \lambda_s \right) \exp\left[-\lambda_c / \lambda_e\right]$
where $\lambda_c$ is the slippage or coherence length in the radiator, here $\sim 0.8$ $\mu$m.

Power oscillation: at large wavelength, just power shift due to alterations in local energy, in this case about 8%
- gradually increases as wavelength $\lambda_e$ approaches $\lambda_s$, to 23%, then sharply decreases at shorter wavelengths

Large harmonic number will drive a large $R_{56}$, small output wavelength
no additional effects unless beam variation lies within some undulator’s bandwidth.
For initial energy perturbation
\[ \gamma = \gamma_0 (1 + d_\gamma \sin k_e z) \]
the phase varies as
\[ \phi = \phi_0 (1 - d_\phi \sin k_e z) \]
and the power typically varies as
\[ P = P_0 (1 + d_p \cos 2k_e z) / (1 + d_p) \]
though for short wavelengths it can switch to
\[ P = P_0 [1 + d_p \sin (k_e z + \theta)] \]
where \( \theta \) is a small, constant phase offset.

For long periods and uniform pulses, the Fourier series is proportional to
\[ \left( 1 + \frac{d_p}{2} e^{2ik_e z} + \frac{d_p}{2} e^{-2ik_e z} \right) \sum_{n=-\infty}^{\infty} J_n(d_\phi) e^{-in k_e z} \]
For small perturbations, this gives sidebands at \( \pm k_e \) with height \( d_\phi^2 / 4 \),
and at \( \pm 2k_e \) with height \( d_p^2 / 4 \); for longer \( \lambda_e \), the relative heights stay the same,
but the sidebands move closer to the fundamental.

If \( d_\phi \approx 2.4 \), the fundamental is suppressed.
Sensitivity to Beam Variation

Example with 0.5 micron period in energy variation, at ± 100 keV. Phase oscillation is ± 0.3 radian, power osc is ± 23%. At longer wavelengths, the sidebands get bigger but move closer in.
Example with 2 micron has worst spectrum. Energy variation ± 100 keV. Resulting phase oscillation ± 0.9 radian. Power osc ± 8%. Sidebands are large.
Large Phase Variation

Example with 2 micron, energy variation ± 270 keV.
Resulting phase oscillation ± 2.4 radian
power osc ± 60%.
Fundamental almost completely suppressed, because $J_0(2.4) \approx 0$. 
EEHG and energy modulations

For long scale lengths, energy modulation acts like chirp. EEHG is not more sensitive to chirp than HGHG (Z. Huang et al, FEL 2009 proceedings)

At short wavelengths (< seeding wavelength), not very severe

- because of phase space manipulations, energy modulation just acts like increased energy spread
- additional microbunches (at high and low energy), and some wobble in microbunch location

Could have problems for wavelengths on order of slippage distance

- resonant perturbations can alter harmonic components
- long period more likely to have high amplitude, effective energy spread can be >> slice energy spread
- hardest case to simulate, need many particles
Noise in Electron Bunch

Shot noise is as expected; energy modulations below 1 micron are also near shot noise levels

Some artifacts from long wavelength chirps, both linear and non-linear

- easier to think of as separate from modulations or bunching
- jitter comes from different effects (RF errors, etc)

Detailed profile information provided by Ji Qiang
Noise in Electron Bunch

Expect at most to need to include effect of linear chirp or parabolic variation when looking at wavelengths < 1 micron (spectrum is for 100 micron slice)

from slope in current?
Summary

FEL types:
- SASE definitely favors reduced current by improving emittance; smaller energy spread not a help
- EEHG, smaller current does not affect bunching at harmonic, but final radiator would be longer
  - smaller energy spread reduces required input laser
- Optical klystron sensitive to beam current, will need to retune; reduced energy spread significantly helps performance

0.3 – 1 GW power feasible at 1 kA, even for attosecond pulse
- required parameters (esp. beta function) for attosecond case are quite demanding, may give up some power instead

Energy chirp ok if doesn’t jitter
- quadratic part yields fluctuations from timing jitter