X-ray Spectra and Peak Power Control with iSASE
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Review SASE FEL
- Short longitudinal coherent length leads to spiky temporal and spectral profiles

Review schemes of improving longitudinal coherence
- External seeding
- Mode coupling and mode lock

What is an iSASE
- One-dimensional theory
- Three-dimensional GENESIS simulation
- First experiment on LCLS
- pSASE

Tapered seeded TW FEL for LCLS-II or even LCLS
EMISSION: SPONTANEOUS AND STIMULATED

- Spontaneous:

- Stimulated:

- What does this imply?

The signal has to meet the emitter
Longitudinal / temporal enhancement: photon slips (advances) over electron bunch, the electrons being swept by the same photon wavepacket (which is also growing due to bunching) will radiate coherently due to the resonant condition ⇒ coherence length ⇒ coherent spike

However, the emitter is too fast! almost the same speed as the signal ⇒ short coherent spike ⇒ limiting the “stimulation” within short spike ⇒ 0.5 fs for LCLS, while LCLS FEL pulse duration is about 50 fs for normal operation

FEL group velocity:

\[ v_g = \frac{\omega_r}{k_r + 2k_w/3} \]

Longitudinal speed of electron:

\[ v_l = \frac{\omega_r}{k_r + k_w} \]
Each spike was started **randomly** from shot noise. Coherent Spike duration is normally short than the electron bunch duration. Spiky both in time and frequency!

*Coherent duration*

*K.J. Kim, LBNL Report No. 40672 (1997)*
FREE ELECTRON LASER

Undulator radiation + feedback (on the electron distribution) \(\rightarrow\) instability \(\rightarrow\) Free electron laser

Start from undulator radiation / shot noise \(\rightarrow\) Self-Amplified Spontaneous Emission (SASE) \(\rightarrow\) exponential growth \(\rightarrow\) mechanism for LCLS, SACLA, ...

Start from a coherent seed \(\rightarrow\) Seeded/Self-seeding FEL
Seeding: “If sufficient coherent seed radiation input power is attainable it makes the output power of the FEL amplifier coherent as well. But other aspects of the seed radiation injection approach, as tunability and operating wavelengths range still need to be addressed”.

Phase locking the spikes: “The current prebunching approach may provide more options of frequency tunability and short wavelengths availability.”

Approaches: quoting A. Gover, FEL’06, p. 1, FEL prize lecture: “A third scheme that should be considered for phase locking and increasing the coherence of the radiation in a SASE FEL consists of imposing periodic perturbation on the wiggler (e.g. periodic dispersive sections)”.

“The filtering effect of the periodic structure may be viewed as the analogue of linewidth narrowing of radiation emitted in a Fabri-Perot resonator.”
Do we really need **periodicity**?

Effectively slow down the emitter (electrons) → signal can **meet** the emitter → extend the coherent length

Speed up the longitudinal slippage → amplitude and phase **mixing** → improve longitudinal coherence

Use phase shifter:
Phase Shifter:

- Periodic Constant delay: \( L_{\text{coh}} = (N+1) L_{\text{coop}} \)
- Geometric delay: \( L_{\text{coh}} = 2^N L_{\text{coop}} \)
- Considering energy spread: \( 1, 2, 4, ..., 2^{N-1}, 2^N, 2^{N-1}, ..., 4, 2, 1 \)
- Combination of periodic and geometric: \( 1, 2, 1, 4, 1, 8, 1, 16, 1, 32, ... \)
- Other combination:

The Bottom Line: total slippage comparable to the electron bunch duration

- Periodic delay cleans up the outskirts frequency component
- Geometric delay shrinks the central part of the frequency

We call this improved SASE (\textit{iSASE})

\[ \text{Thompson, McNeil, PRL, 2008} \]
\[ \text{Thompson, Dunning, McNeil, IPAC10, p2257, 2010 with some randomization} \]
\[ \text{Wu, Merinelli, Pelligrini, FEL12, 2012} \]
\[ \text{McNeil, Thompson, Dunning, PRL, 2013} \]
Geometric
1-D THEORY

Maxwell-Vlasov coupled equations

\[
\left( \frac{\partial}{\partial z} - 2ik_\nu \eta \nu \right) F(\nu, \eta; z) = \kappa_1 A(\nu; z) \frac{\partial}{\partial \eta} V(\eta), \quad (1)
\]

\[
\left( \frac{\partial}{\partial z} - i\Delta \nu k_\nu \right) A(\nu; z) = \kappa_2 \int F(\nu, \eta; z) d\eta, \quad (2)
\]

Phase shifter

\[
A(\nu; z + D) = A(\nu; z) e^{i\Delta \nu k_\nu D}, \quad (17)
\]

\[
F(\nu, \eta; z + D) = F(\nu, \eta; z) e^{i\Delta \theta}. \quad (18)
\]
1-D THEORY

SASE: first stage

Initial conditions:

\[ E_{1\nu}(0) = 0, \quad \int F_{1\nu}(0) d\eta = \frac{1}{N_\lambda} \sum_{j=1}^{N_e} e^{i\nu \omega_1 t_j(0)}, \quad (29) \]

\[ S(\nu) = \frac{1}{\sqrt{2\pi} \sigma_\nu} \exp \left[ -\frac{(\nu - 1)^2}{2\sigma_\nu^2} \right], \]
**1-D THEORY**

- iSASE: second stage
- Short undulator: coherent emission, startup, transient, interference

\[
E_{2\nu}(z) = E_{1\nu}(L_1) \left[ e^{-i\psi} (1 - Be^{i\Delta\theta}) + Be^{i\Delta\theta} \right]
\]

\[
\psi = \Delta \nu k_u z
\]

\[
B \equiv \frac{2\rho}{\Delta \nu \mu_0^2} \left( 1 - \mu_0 e^{i\alpha} \rho k_u z \right)
\]
1-D THEORY

iSASE: second stage

Long undulator: exponential growth, high gain, interference

\[ E_{2\nu}(z) \approx \frac{e^{-i2\rho \mu_0 k_u z} E_{1\nu}(L_1)}{(\mu_0 - \mu_o)(\mu_0 - \mu_d)} \left( \mu_0^2 - \frac{2e^{i\Delta \theta}}{\mu_0} \right) \]

\[ \mu_0 = e^{i2\pi/3} + \frac{\Delta \nu}{6\rho} - \frac{1}{9} e^{i\pi/3} \left( \frac{\Delta \nu}{2\rho} \right)^2 \]

\[ \mu_o = 1 + \frac{\Delta \nu}{6\rho} + \frac{\Delta \nu^2}{36\rho^2} \]

\[ \mu_d = -e^{i\pi/3} + \frac{\Delta \nu}{6\rho} + \frac{1}{9} e^{i2\pi/3} \left( \frac{\Delta \nu}{2\rho} \right)^2 \]
1-D THEORY

Spectrum **narrowing**: neglecting the optical-klystron type power enhancement,

\[
R(\nu) = \frac{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu-\xi)^2} e^{-i\rho k_r \nu R_{56} \xi} e^{i k_r \nu R_{56}/2}}{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu-\xi)^2}}
\]

(22)

For a cold beam, we have

\[
|R(\nu)|^2 = \frac{5 + 4 \cos(\frac{k_r R_{56} \nu}{2})}{9},
\]

(23)
1-D THEORY

SASE

\[ S(\nu) = \frac{1}{\sqrt{2\pi} \sigma_{\nu}} \exp \left[ -\frac{(\nu - 1)^2}{2\sigma_{\nu}^2} \right] \]

iSASE: 2\textsuperscript{nd}-stage

\[ |R(\nu)|^2 S(\nu) \]

Temporal:

\[ E_2(t) = \int \frac{\omega_1 d\nu}{\sqrt{2\pi}} E_{2\nu}(L_2) e^{i\Delta \nu [(k_1 + k_\nu) L_2 - \omega_1 t]} \]
iSASE: multi-stage $\Rightarrow$ step-by-step multiple the $|R(\nu)|^2$

Red: SASE
Blue: 2,2,2,2,2
Green: 4,4,4,4,4
Yellow: 1,2,4,8,16
-- in units of cooperation length
1-D THEORY

Example: periodic vs. geometric

Spectra comparison for three cases: $\delta = 0$ (in units of coherence length), SASE, purple, line width about 1 (in units of $\rho$); $\delta = 3, 3, 3, 3, 3, 3$, iSASE, green, line width about 0.2; $\delta = 1, 2, 4, 8, 16, 32, 64$, iSASE, red, line width about 0.02.
Machine layout:

- First 5 undulator sections on-resonant to establish the FEL wavelength
- From 6th on, even number: 6, 8, ..., 30, and 32 largely detuned (can either be
  random or form a separate spectrum line → two color)
- From 6th on, odd number: 7, 9, ..., 31, and 33 on resonant

Perform proof-of-principle experiment on LCLS for an improved SASE (iSASE)

- Electron bunch: 150 pC, compressed to ~ 3 kA
- 8.45 keV FEE HXSSS
- 13.825 GeV electron energy
No-post saturation taper: 1.21 mJ

- Taper profile on left: optimized for the gain taper (-31 MeV), and spectrum on right (FWHM 15 eV, **limited** by the FEE HXSSS)
iSASE: 0.4 mJ

Taper profile on left, and spectrum on right (1.5 – 4 eV)
ISASE: TWO-COLOR

- iSASE: about 0.4 mJ
- Taper profile on left, and spectrum on right
SASE VS iSASE

- Spectrum
  - Similar peak height
  - Integrated power

Set 1: SASE

Set 5: iSASE

Multi-shot Experiment: SASE (red) and iSASE (blue)

FWHM bandwidth:
SASE (red) -- 17 eV
iSASE (blue) -- 5 eV
SASE VS ISASE

FEL power vs spectrum width

Histogram spectrum width

Histogram spectrum width

Number of counts

Number of counts

Spectrum FWHM width (eV)

Spectrum FWHM width (eV)
Purified SASE

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Purified self-amplified spontaneous emission free-electron lasers with slippage-boosted filtering

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FIG. 2. Schematic layout of a pSASE FEL.
LCLS-II base line has phase shifters, so schemes to improve longitudinal coherence of SASE

Variable gap undulator → Tapered FEL to reach TW
An FEL is characterized by the FEL parameter, \( \rho \), giving:

- the exponential growth, \( P = P_0 \exp(z/L_G) \), where \( L_G \sim \lambda_U / 4\pi\rho \)
- The FEL saturation power \( P_{\text{sat}} \sim \rho P_{\text{beam}} \)

For the LCLS-II electron beam: \( I_{pk} \sim 4 \text{ kA}, E \sim 14 \text{ GeV} \), \( P_{\text{beam}} \sim 56 \text{ TW} \), FEL: \( \rho \sim 5 \times 10^{-4} \), \( P_{\text{sat.}} \sim 30 \text{ GW} \ll 1 \text{ TW} \)

Overall, the peak power at saturation is in the range of **10 to 50 GW** for X-ray FELs at saturation.

The number of coherent photons scales almost linearly with the pulse duration, and is \( \sim 10^{12} \) at 100 fs, \( 10^{11} \) at 10 fs.
What happens when the FEL saturation is achieved

- Centroid energy loss and energy spread reaches $\rho$.

- Exponential growth is no longer possible, but how about coherent emission? Electron microbunching is fully developed

As long as the microbunching can be preserved, coherent emission will further increase the FEL power

- Maintain resonance condition $\rightarrow$ tapering the undulator

- Coherent emission into a single FEL mode – more efficient with self-seeding scheme

- Trapping the electrons
Near the saturation point, start changing the undulator period and magnetic field along the undulator length to adjust to the energy of a reference electron

\[ \lambda = \frac{\lambda_U(z)[1 + K(z)^2]}{2\gamma_R(z)^2} \]
Maximum FEL intensity (>400 uJ) responses well to strong undulator taper

40 pC bunch length < 10 fs, maximum peak power > 40 GW
**EXPERIMENT VS SIMULATION: ENERGY JITTER, TAPER SCAN**

- **Taper scan for 5.5 keV**

- **Simulation for energy jitter:** blue (on-energy), black (+0.1 %), red (-0.1 %), magenta (-0.2 %)

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FEL and Beam Phys. Dept. (ARD/SLAC), J. Wu, jhwu@slac.stanford.edu, 02/04/2013
Work with LCLS-II type system

- Electron beam parameters -- Energy: 13.5 GeV; Emittance: 0.3 μm-rad; slice energy spread: 1.3 MeV; peak current: 4 kA; β-function: 15 m
- Photon beam parameters – Energy: 8 keV;
- Undulator – period: 3.2 cm; magnetic length: 3.4 m; break distance: 1 m

iSASE scheme

- Break introduces 5 optical periods
- For each magnetic segment, the slippage between the photon beam and the electron beam is 106 optical periods, and we regard this as the coherent length
- For iSASE, we introduce
  - Additional 400 optical periods in the breaks; or
  - Additional 400, 800, 1600, 3200 optical periods in the breaks

As comparison, a self-seeding FEL with input seed power of 0.2 MW
**FEL power gain curves:**

- Effective startup power of iSASE is about 0.2 MW
- For 1 MW Self-seeding → reach TW
- Improve startup power
iSASE: Energy jitter of ± 0.1 %

- **Shift** in central frequency following the electron centroid energy
- Yet, spectral width and power level is essentially NO change
iSASE prepared seed: narrow bandwidth → close to transform limited

\[
P_{\text{FEL}}(\lambda) = 3.9 \times 10^7 e^{-[(\lambda - 0.1500)^2 / (2(3.23 \times 10^{-6})^2)]}
\]

FWHM Bandwidth: 5.1E-05
iSASE: narrow bandwidth → close to transform limited
Self-seeding: Energy jitter of ± 0.1 % → 100 % fluctuation

SASE: Energy jitter of ± 0.1 % → Stable
A TUNABLE NARROW BANDWIDTH FEL

- iSASE: Energy change of ± 0.1%
- FEL central frequency change ± 0.2% following the electron centroid energy
- Yet, spectral width and power level is essentially NO change

8 keV iSASE FEL with energy jitter: On-Energy (black), 0.1% (red), -0.1% (blue)

Simulation

FEL and Beam Phys. Dept. (ARD/SLAC), J. Wu, jhwu@slac.stanford.edu, 05/15/2013
Improved SASE (iSASE) to control the FEL spectrum

Coherent seed either from iSASE or Self-seeding can respond to the taper well and lead to TW FEL

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