Ultra-short pulse, single coherent spike operation of SASE X-ray FELs

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Motivation

- Ultra short FEL pulses (<10 fs) are of high interest to study fast process in biology, chemistry and material science (e.g. dissociation of OH groups).
- The pulse can be used as a pump and/or probe pulse.
- Short pulses also prevents structural damage to the object under study (e.g. for imaging process of clusters / molecules)
- Short-pulse application mostly do not rely on a high photon count.
- Some applications are sensitive on the photon flux, requiring no long background signal.
Other Methods for Short Pulse Generation

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Operation below 1 nC bunch Charge

- Most FELs are based in its design and operation on a bunch charge of 1 nC, however operating at a low charge has the advantages:
  - Less sensitive to coherent effects
  - Reduced space charge and wakefield effects
  - Increased electron beam brightness
  - Shorter pulse length, less RF curvature.
  - Less variation of electron beam parameters along bunch

- Studies have shown that LCLS is not loosing in its FEL performance by operating at 200 pC, while making the operation of the injector more stable.
Ultra-short Electron Beam Production

- Goal is to operate the FEL in the superradiant regime with a single spike (Bonifacio, et al, '91).
- Bunch charge of 1 pC.
- To keep the injector settings the same, the electron density in the rf gun has to be preserved:
  - Reducing laser pulse length by factor 10.
  - Reducing laser spot size by factor of 100.
- Two Compression stages:
  - 1st stage: velocity bunching,
  - 2nd stage: conventional compression with magnetic chicane at high energy.
- Details have been presented in talk by J.B. Rosenzweig
Basic Beam Parameters:

- Using the LCLS undulator and typical beam parameters for a 1 pC bunch charge:
  - Current: 350 A
  - Emittance: $3 \cdot 10^{-2}$ mm⋅mrad
  - Energy Spread (relative): $3 \cdot 10^{-5}$

- Theoretical $\rho$-Parameter (1D):
  \[
  \rho_{\text{theo}} = 6.7 \cdot 10^{-4}
  \]

- Effective $\rho$-Parameter, derived from simulation, including emittance and energy spread effects:
  \[
  \rho = \frac{\lambda_u}{4\pi\sqrt{3}} \cdot \left( \frac{dP}{Pdz} \right) = 4.8 \cdot 10^{-4}
  \]
Dependence on Bunch Length

- Goal: To find optimum pulse length in relation to the cooperation length \( L_c = \lambda / 4\pi \rho \)
- With \( \rho = 4.8 \cdot 10^{-4} \) the cooperation length is \( L_c = 25 \text{ nm} \)
Deep Saturation Behavior

- Best results for pulses, which slips out of the electron bunch before reaching saturation.
- Long electron bunches continue to emit on a comparable radiation level, stretching the pulse while short pulses are ‘quiet’
Deep Saturation Behavior (cont’)

- At short pulses (<60 nm) further emission after saturation is suppressed, allowing for a stable operation of the single-spike operation.
- The radiation pulse slips out after bunch has reached maximum bunching. Due to lack of the electron ‘field bucket’, the existing bunching decays (overbunching).

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Deep Saturation Behavior (cont’)

- Longer Bunch exhibit in deep saturation:
  - Drop in the radiation power,
  - Broadening of the spectrum due to sideband instability,
  - Trailing spikes from ongoing coherent emission

- Bunching in deep saturation is persistent, when phase space distribution is rotated by more 360 degree.
Shot-shot Stability

- Strong fluctuation from shot to shot due to the nature of the SASE process.
- Many shots have more than one longitudinal mode for a bunch length larger than 50 nm.
- Singe-Spike condition:

\[ \sigma_b \leq 2L_c \]
Beam energy extended to 2 GeV -> resonant wavelength is 3 nm.
SPARX - FEL Performance

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SPARX - FEL Performance

- Single spike operation
- Stable profile and spectrum, even in deep saturation.

\[ \sigma_z = 420 \text{ nm} \]
\[ \frac{\sigma_k}{k} = 1.5 \cdot 10^{-3} \]
\[ \sigma_z \cdot \sigma_k = 1.3 \]

- Fourier Limit: \( \sigma_z \cdot \sigma_k = 0.5 \)
Start-end Simulation: LCLS
LCLS - FEL Performance

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LCLS - FEL Performance

- Drop in maximum power indicates that bunch length is too long.
- In the deep saturation regime electron pulse continues to emit on a high power level, resulting in trailing spikes.
- At saturation: $\sigma_z \sigma_k = 6.2$

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LCLS - Optimizing

- Extracting peak current, energy spread and normalized emittance from the 1 pC distribution, steady-state simulations are indicating an effective $\rho$-parameter of:

\[ \rho = 5.5 \cdot 10^{-4} \]

- The RMS bunch length of the electron bunch is 150 nm, about 3 times too large to fulfill the empirical condition:

\[ \sigma_b \leq 2L_c \]

- The cooperation length can directly be controlled by increasing the beam emittance (larger spot size).
Alternative Utilization of Low Charge Bunch

- The 1 pC bunch has a high beam brightness than the standard LCLS case.
- With modification of the undulator (e.g. reducing the gap) the wavelength range can be extended.

Maximum power

Profile at Saturation
Conclusion

- Low charge operation at 1 pC allows for single-spike operation for VUV and X-ray FELs.
- Condition to be fulfilled:
  \[ \sigma_b \leq 2L_c \]
- Additional control of cooperation length through emittance (e.g. by controlling the laser spot size on cathode).
- Improvement in electron beam brightness allows for extending wavelength range (requires re-optimization of undulator lattice).