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

Method	Disadvantage
Pulse slicing of chirped FEL pulse with monochromator	Inefficient
Pulse compression of chirped FEL pulse with dispersive optics	Wide bandwidth
HGHG schemes with short seed pulse	Slippage in early stages, background
HGHG schemes with a SASE seed (contrast method)	Background
Electron beam manipulation (slit in dispersive section, ESASE scheme with short pulse, 2-stage of energy modulated beam with slight detuning)	Background

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 ρ-Parameter (1D):

$$\rho_{theo} = 6.7 \cdot 10^{-4}$$

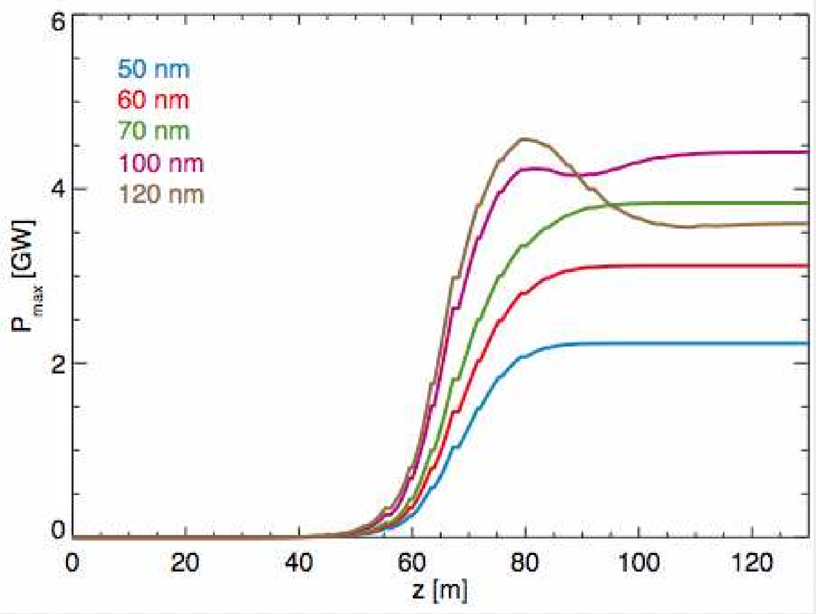
- Effective ρ-Parameter, derived from simulation, including emittance and energy spread effects:

$$\rho = \frac{\lambda_u}{4\pi\sqrt{3}} \cdot \left(\frac{dP}{Pdz} \right) = 4.8 \cdot 10^{-4}$$

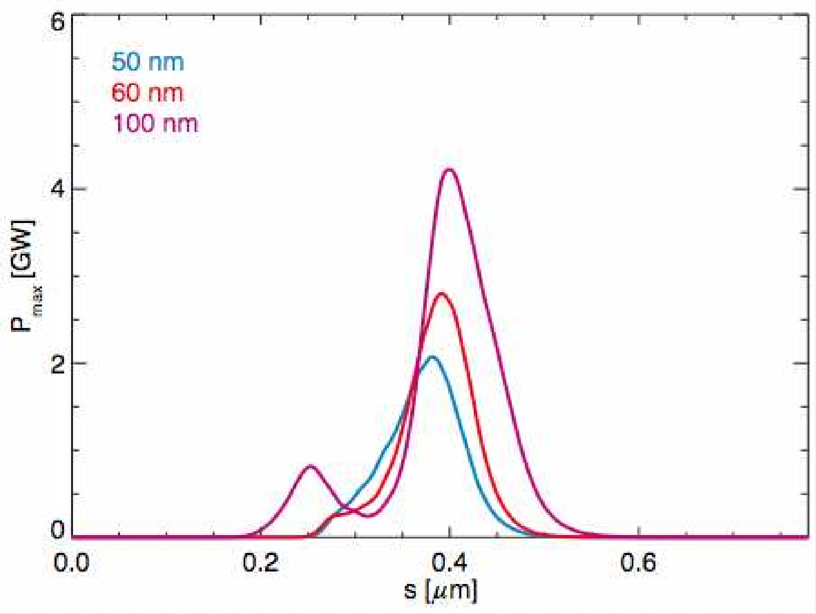
Dependence on Bunch Length

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

Max Power for Various rms Bunch Lengths

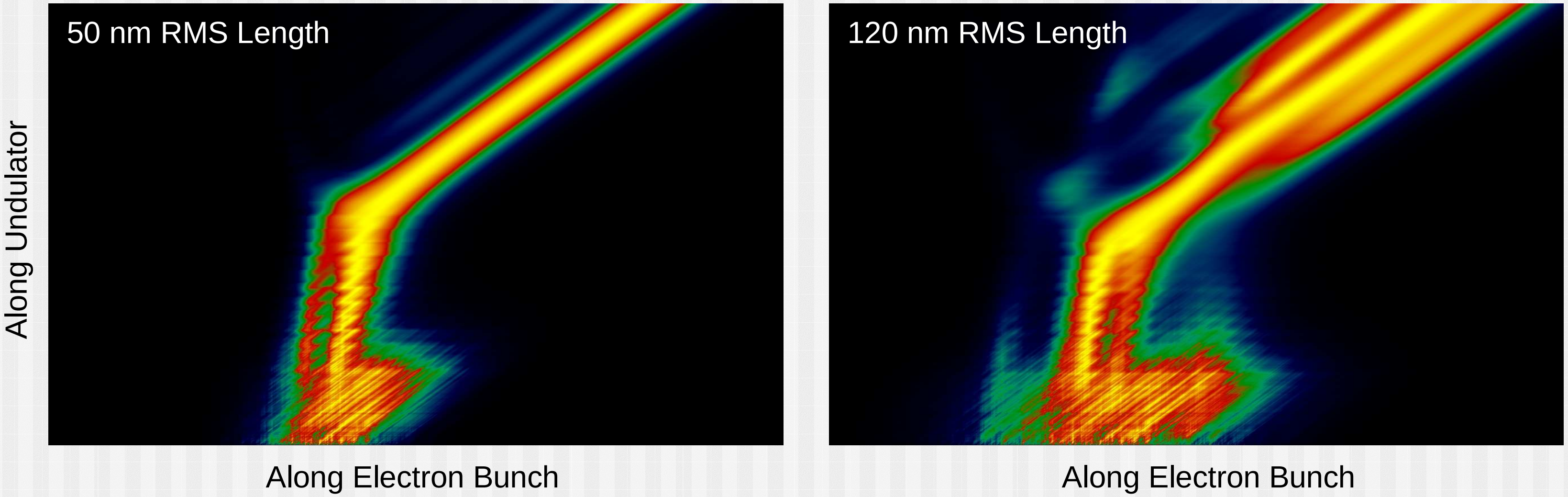


Radiation Profile at Saturation (z=80m)



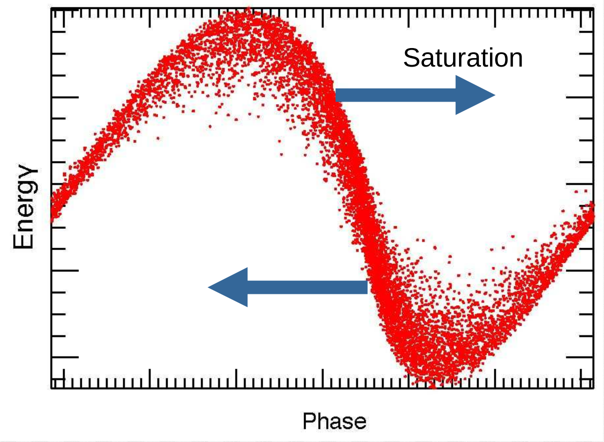
Deep Saturation Behavior

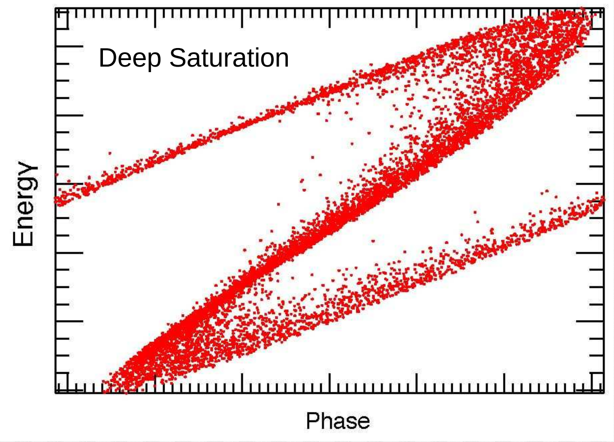
- Best results for pulses, which slips out of the electron bunch before reaching saturation.
- Long electron bunches continue to emit on a comparable radiation level, stretching the pulse while short pulses are ‘quiet’



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).

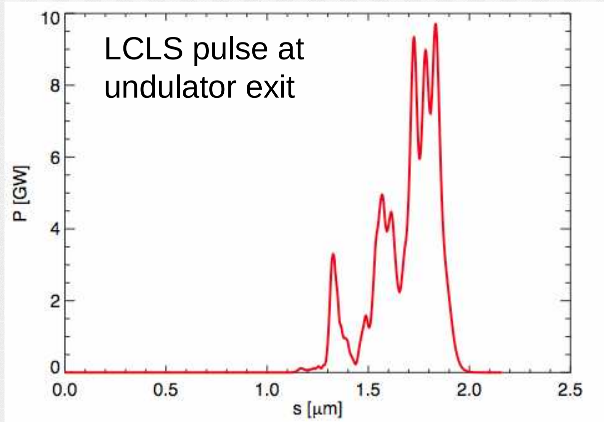


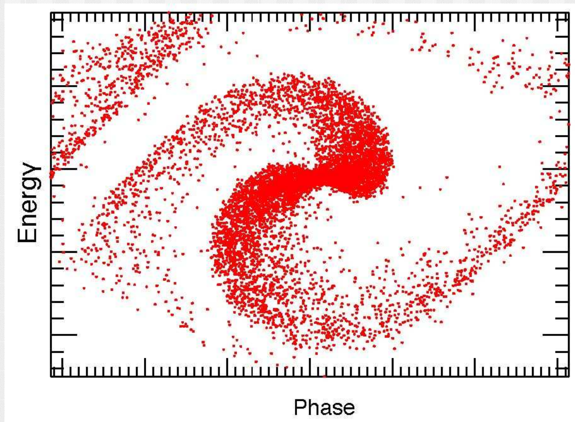


Deep Saturation Behavior (cont')

- 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.

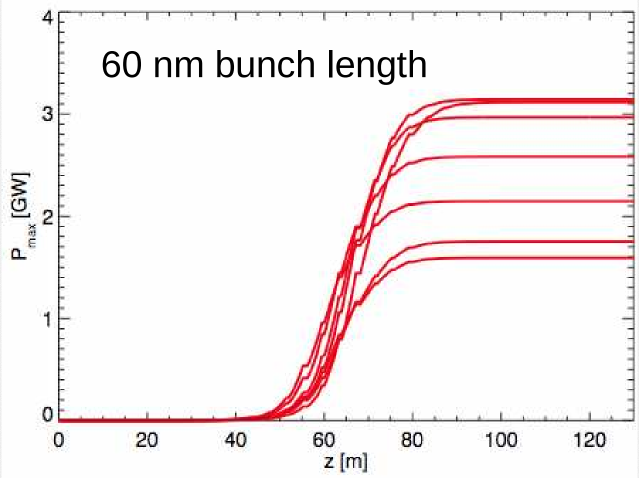


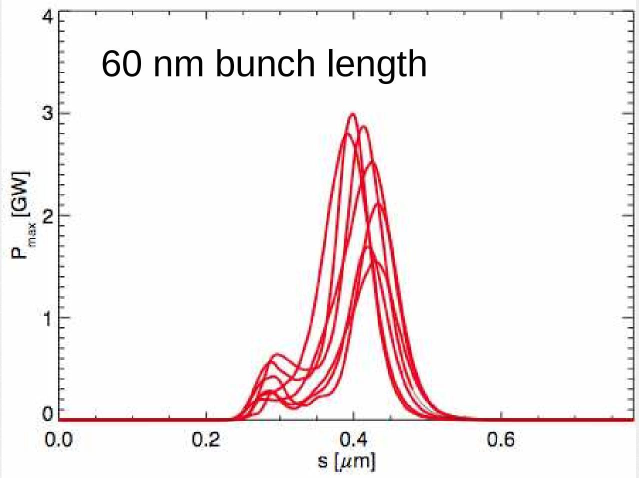


Shot-shot Stability

- 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:

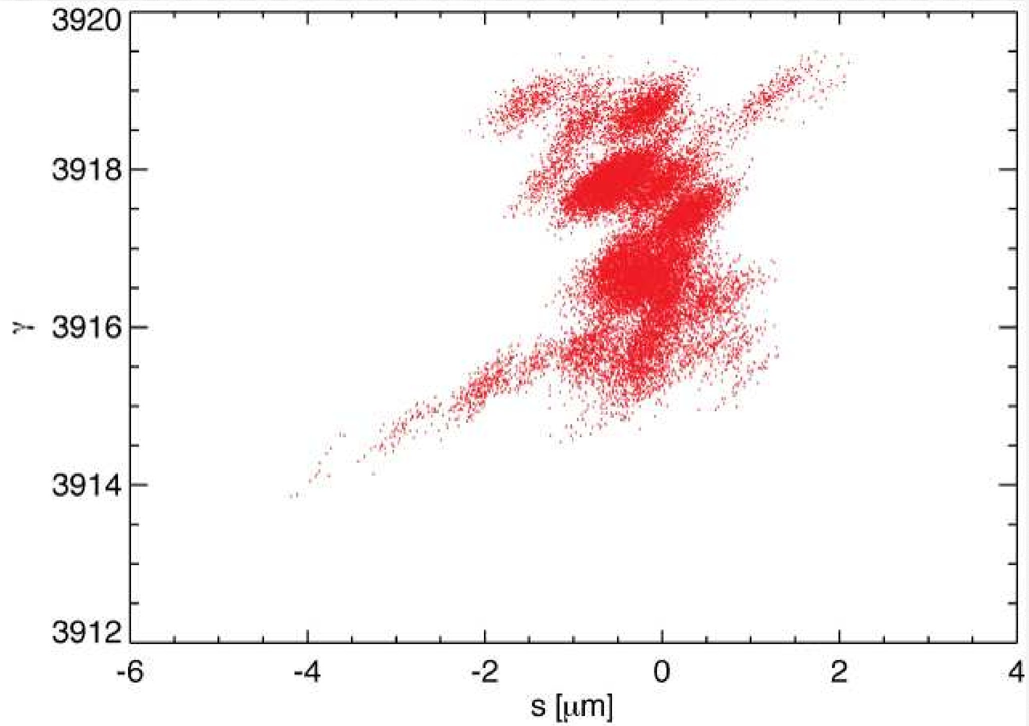
$$\boxed{\sigma_b \leq 2L_c}$$

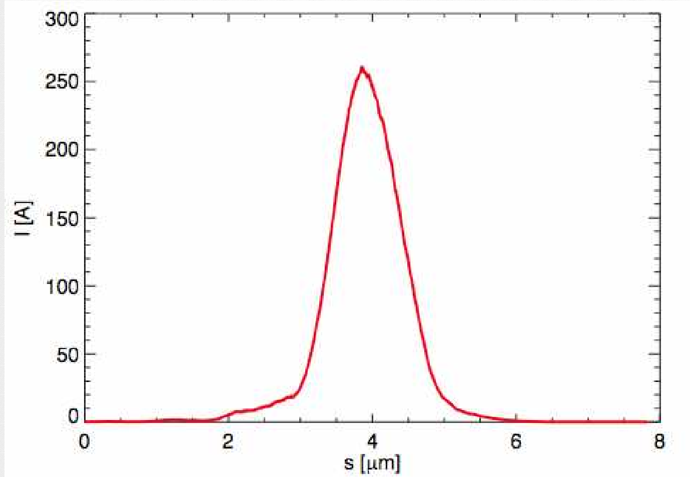


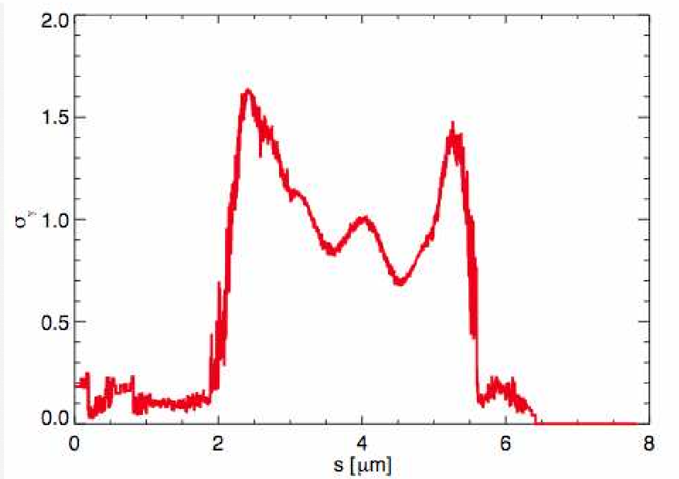


Start-end Simulation: SPARX

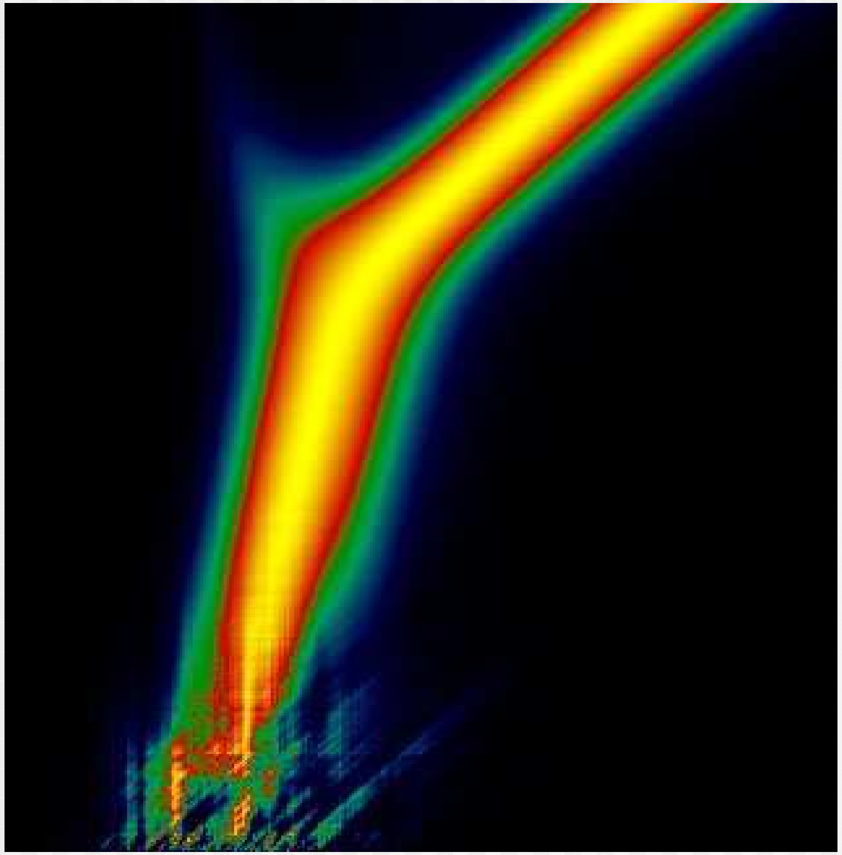
- Beam energy extended to 2 GeV -> resonant wavelength is 3 nm.

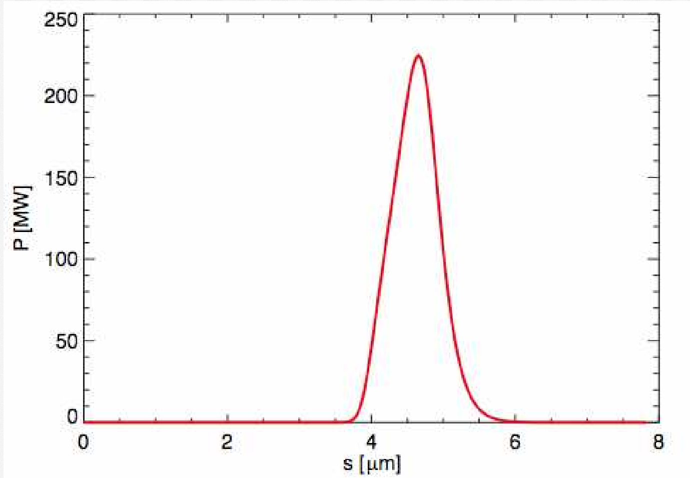


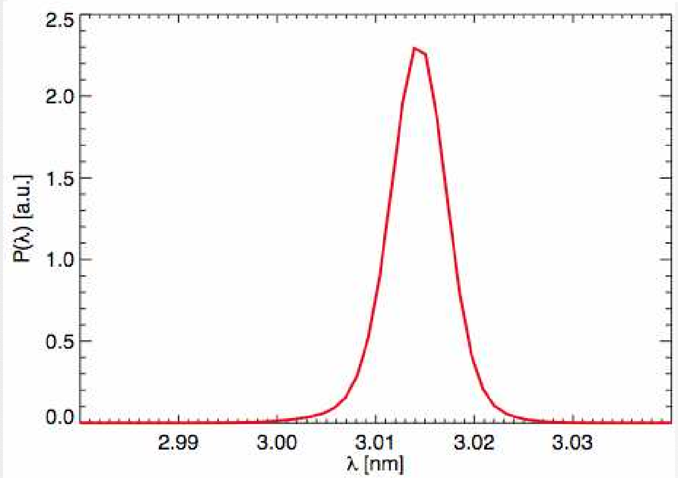




SPARX - FEL Performance







SPARX - FEL Performance

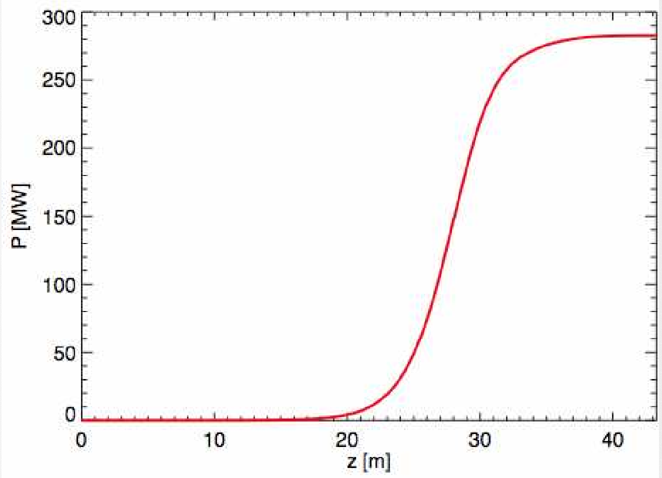
- Single spike operation
- Stable profile and spectrum, even in deep saturation.

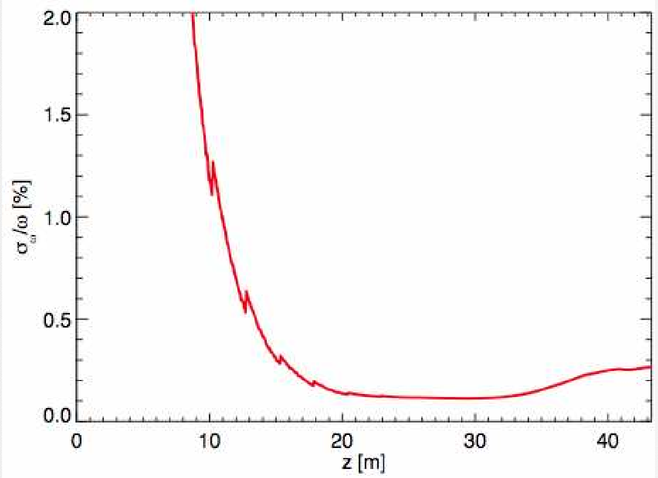
$$\sigma_z = 420\,\mathrm{nm}$$

$$\frac{\sigma_k}{k} = 1.5 \cdot 10^{-3}$$

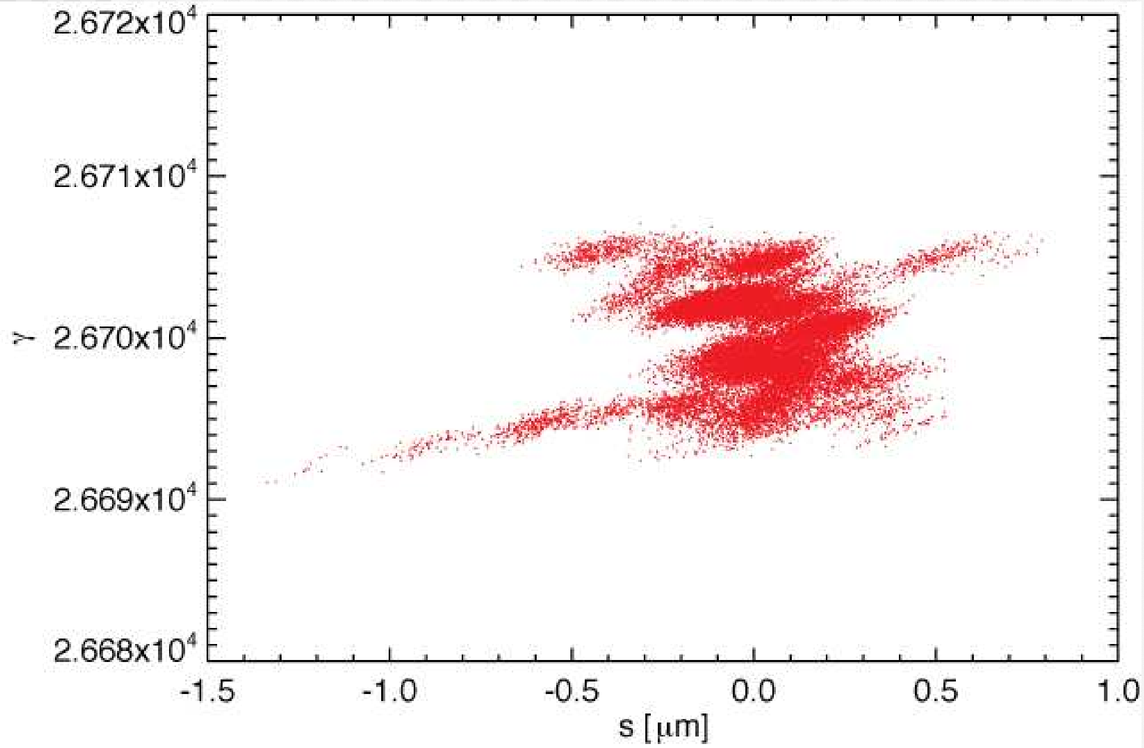
$$\sigma_z \cdot \sigma_k = 1.3$$

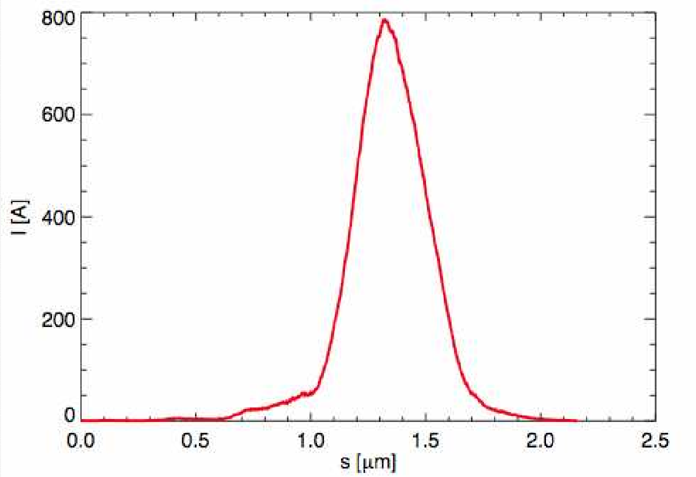
- Fourier Limit: $\sigma_z . \sigma_k = 0.5$

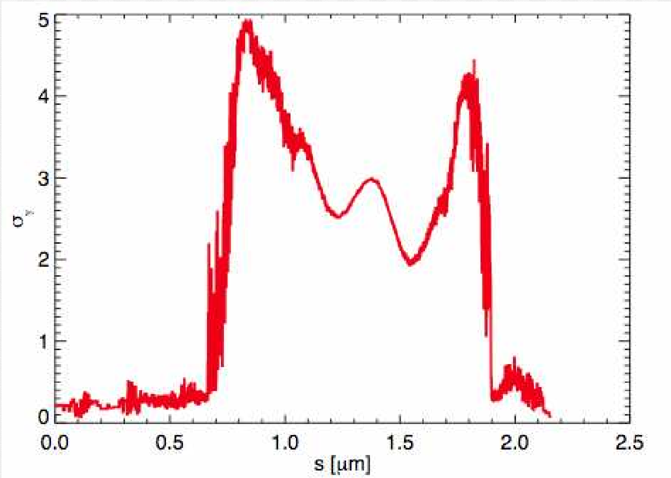




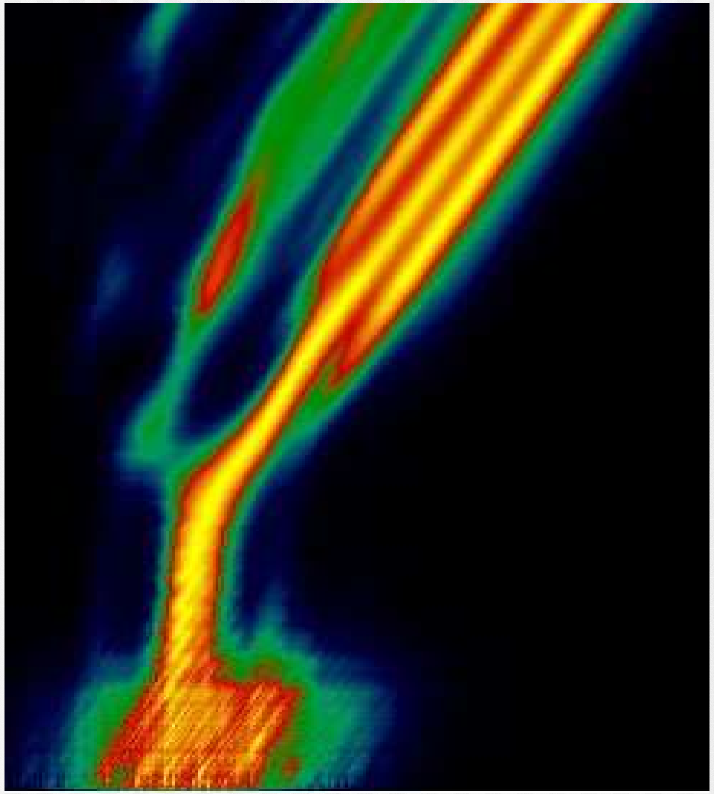
Start-end Simulation: LCLS

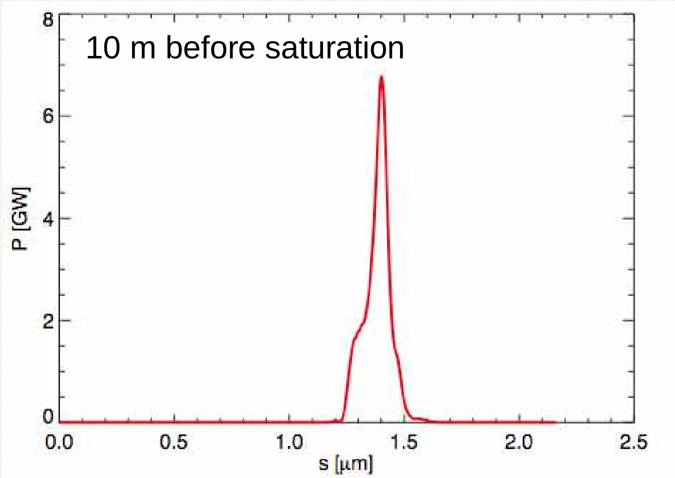


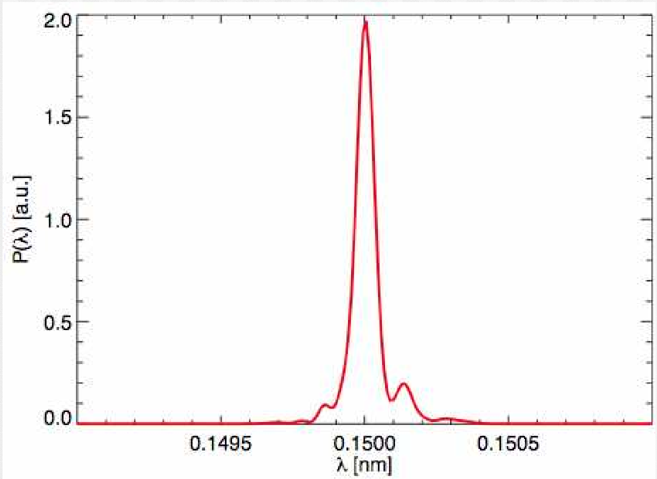




LCLS - FEL Performance

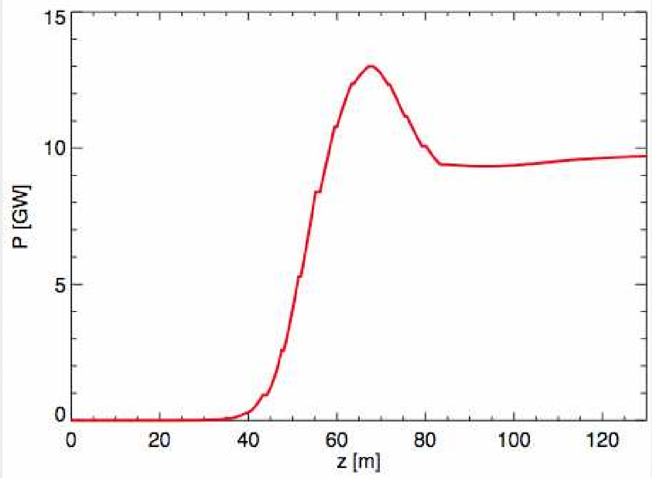


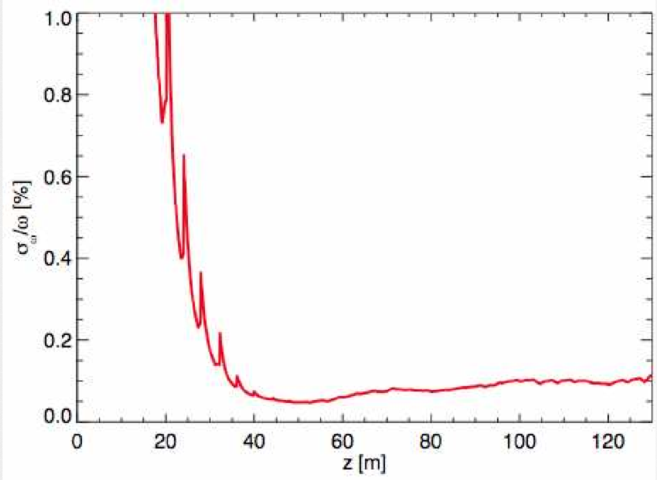




LCLS - FEL Performance

- 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: $\sigma_z . \sigma_k = 6.2$





LCLS - Optimizing

- Extracting peak current, energy spread and normalized emittance from the 1 pC distribution, steady-state simulations are indicating an effective ρ-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:

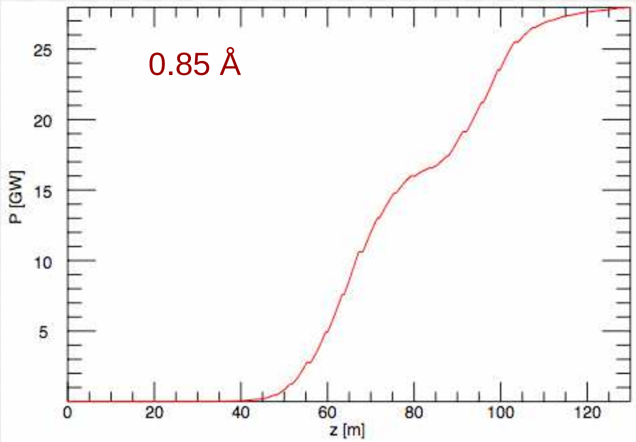
$$\sigma_b \leq 2L_c$$

- The cooperation length can directly be controlled by increasing the beam emittance (larger spot size).

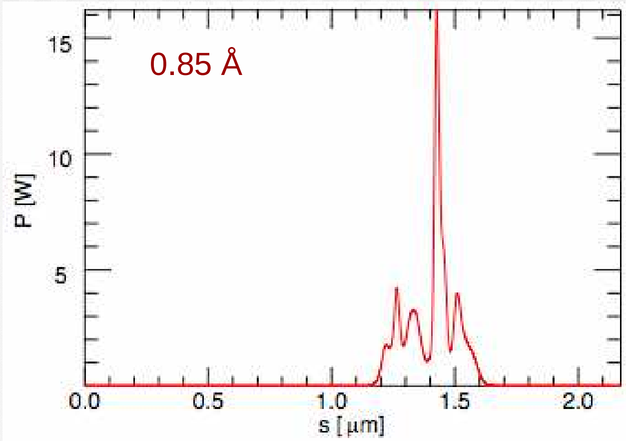
Alternative Utilization of Low Charge Bunch

- 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).