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Using the optical-klystron effect to increase and measure the intrinsic beam energy spread in free-electron laser facilities

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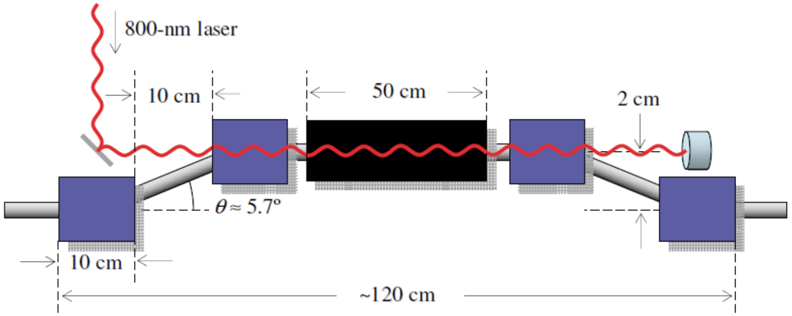
Introduction

- Microbunching instability needs to be suppressed in free-electron laser (FEL) facilities to avoid beam quality degradation causing reduction of FEL performance
- Typical cure: increase the (intrinsic beam) energy spread before 1st bunch compressor with a "laser heater" [*E. Saldin, E. Schneidmiller and M.Yurkov, NIMA 528, 355 (2004)*]

LCLS laser heater design

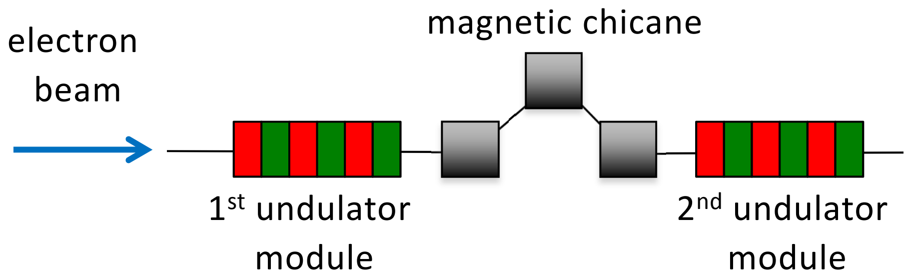
Z. Huang et al, PRSTAB 7, 074401 (2004)



- The laser heater has been successfully demonstrated at LCLS and FERMI, and it is planned in most of the other present and future projects
- Alternative methods to increase the energy spread without the need of any laser:
  - Superconducting undulator *[J. Arthur et al., SLAC Report No. SLAC-R-593, 2002]*
  - Transverse-deflectors *[C. Behrens, Z. Huang, and D. Xiang, PRSTAB 15, 022802 (2012)]*
  - Phase-mixing *[S. Di Mitri and S. Spampinati, PRL 112, 134802 (2014)]*
  - Transverse-gradient undulators *[D. Huang et al., PRAB 19, 100701 (2016)]*
- We propose another method to increase the energy spread in FEL facilities. It is based on the optical klystron effect and uses two undulator modules and one magnetic chicane. It can also be employed to measure the initial beam energy spread with high resolution (<1 keV)

Description of the scheme (I)

- The setup is based on the optical klystron effect and uses two undulator modules and a chicane in between.



- The chicane converts the energy modulation created in the first module into bunching.
- This bunching increases the energy modulation in the second module.
- The setup should be placed before the first bunch compression, whose large R_{56} converts the energy modulation in effective energy spread increase.
- Maximum energy spread is proportional to ρ/σ_δ $(\sigma_\delta=\sigma_E/E)$
- Advantages:
  - Little hardware requirements (no need for a laser)
  - Easy to tune (with chicane strength)
  - It allows measurement of initial energy spread (next slide)
  - It works for any wavelength (see next of next slide)

Description of the scheme (II)

- The optimum chicane strength for maximum power gain of the optical klystron depends on the initial energy spread but it is quite insensitive to other beam parameters

$$R_{56*} \approx \frac{\lambda}{2\pi\sigma_\delta}$$

[Y. Ding et al, PRSTAB 9, 070702 (2006)]

- The initial energy spread can be found by finding the chicane strength that maximizes the optical klystron effect
- The method has a resolution better than 1 keV.
- Slice measurement is possible with energy chirp and collimator (or slotted foil)
- Similar to another method that also uses two undulator sections and a chicane, but requires also a laser *[C. Feng et al., PRSTAB 14, 090701 (2011)]*

- The method is based on SASE → it works for any wavelength (unlike the laser heater). Which wavelength to choose?
  - Not too short (at a given energy, shorter wavelength corresponds to lower K and therefore to worse FEL performance)
  - Not too long (R_{56*} and therefore chicane dimensions increase with wavelength)
  - Avoid wavelengths for which the microbunching gain is high

Numerical example for SwissFEL

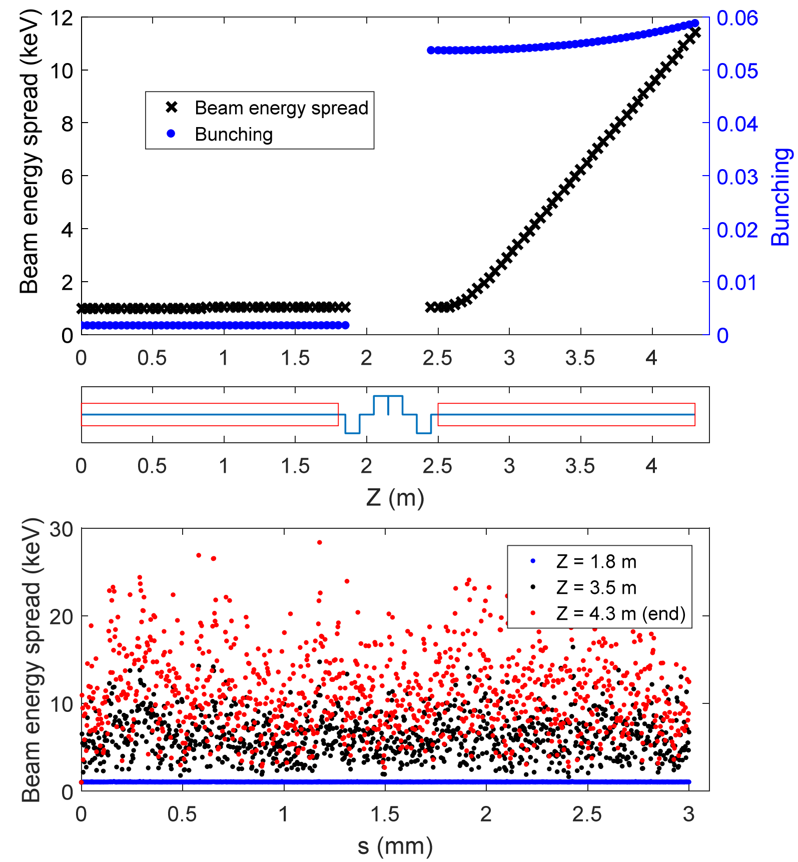
- Simulations performed with Genesis 1.3
- Results are averaged over 5 random seeds

Simulation parameters

e^- charge	200 pC
Current	20 A (flat profile)
e^- Energy	150 MeV
Norm. Emittance	200 nm
Energy spread (rms)	0.5 – 2 keV
Optics (x & y)	β = 10 m, α = 1
Undulator modules	λ_u=40mm L = 1.8m
Wavelength	600 nm
R_{56}*	7.2 – 28.6 mm

Dipole length = 0.1m, drift between magnets = 0.1 m. Total length is 0.6m.
R_{56} of 30 mm can be reached with a magnet strength of 1.5T
The whole setup can be placed in about 4 m (similar to laser heater)

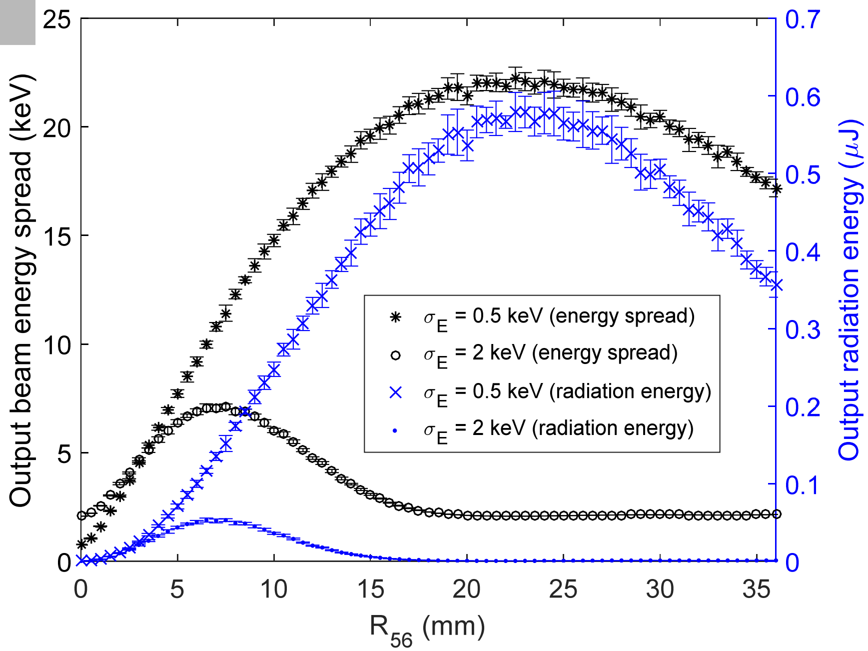
Energy spread and bunching along the lattice (initial energy spread = 1 keV and R_{56} = 10mm)



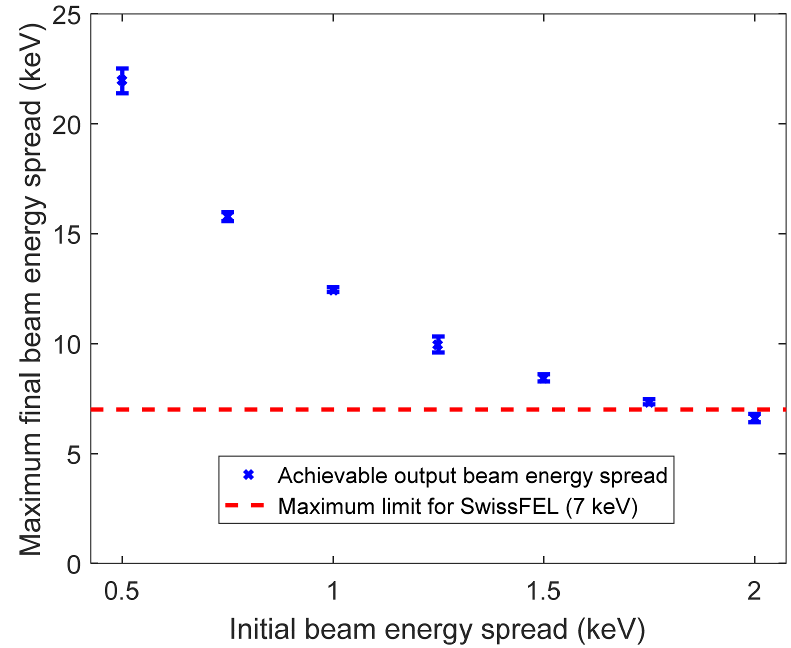
- Chicane converts energy modulation in the first stage to bunching
- Bunching helps to increase the energy spread in the second module

Numerical example for SwissFEL

Output energy spread and radiation energy as a function of the chicane R_{56} (for an initial energy spread of 0.5 and 2 keV)



Maximum final energy spread as a function of initial beam energy spread

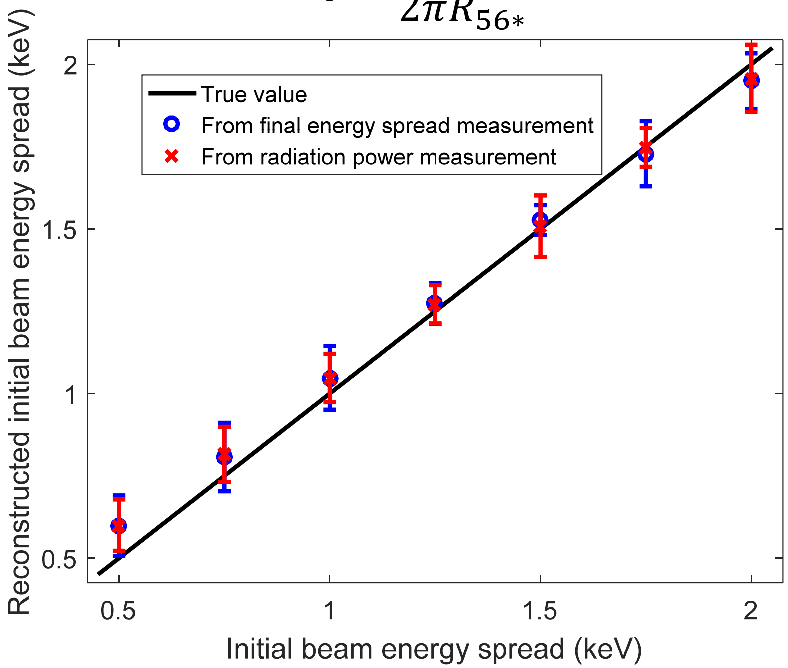


- R_{56} from 0 to R_{56*} acts as a “heater”, R_{56} is a good knob to fine tune the final energy spread
- Achievable energy spread proportional to $1/\sigma_\delta$
- R_{56*} proportional to $1/\sigma_\delta$
- For SwissFEL we can increase the energy spread up to 7 kev or more ☺

Numerical example for SwissFEL

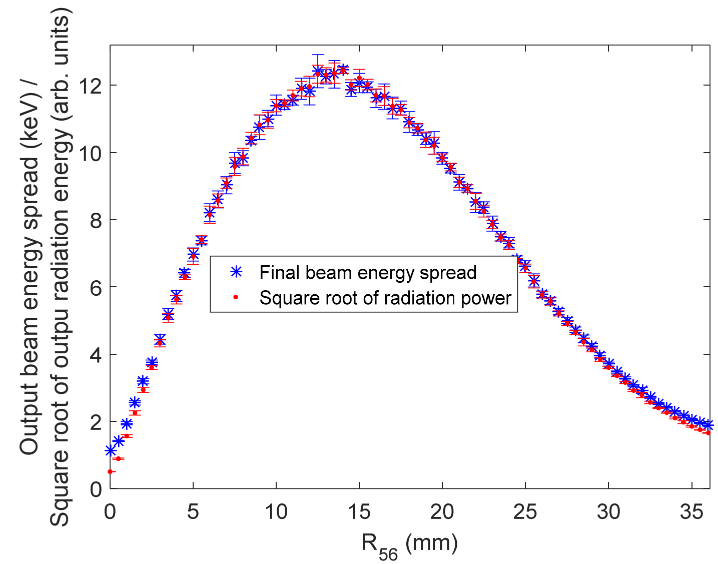
Reconstructed initial energy spread vs true value

$$\sigma_\delta \approx \frac{\lambda}{2\pi R_{56*}}$$



- Results from output energy spread or radiation energy are equivalent
- Statistical errors around 0.1 keV dominated by fit to determine R_{56*}
- Small systematic error (to be improved with 3D simulations)
- Method is robust against beam parameter variations (emittance / current). It also works for more realistic beams

Output energy spread and square root of the radiation energy as a function of the chicane R_{56} (for an initial energy spread of 1 keV)



- Output energy spread and square root of the radiation energy are equivalent.
- Final energy spread can be calibrated with radiation energy (if energy spread can be measured at least at its maximum value)

We have presented a setup based on the optical klystron effect, consisting of two undulator modules and a chicane in between, that can be used in FEL facilities to:

1. **Increase the energy spread → useful to suppress the microbunching instability without the need of any laser**
2. **Measure the initial energy spread with high resolution (<1 keV)**

More information in *[E. Prat et al, PRAB 20, 040702 (2017)]*