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Paul Scherrer Institut
Sven Reiche

Electron Beam Requirements for Seeded FELs

SASE vs Seeded FEL

In Comparison to SASE FELs, seeded FELs offer the improvement:

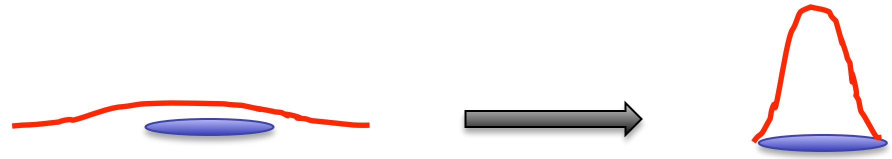
1. **Control/Improvement of the Longitudinal Coherence**
2. **Improved Brilliance**
3. **Energy Stability of FEL Output Pulse**
4. **Spectral Stability at Selected Frequency**
5. **Synchronization with External Source (Pump-Probe)**
6. **Ability to Increase FEL Efficiency with Taper**
7. **FEL becomes shorter**

However the desired stability increases the requirement for the electron beam signficantly due to the lack of „self-tuning“ of the SASE Process

Synchronization to External Seed Signal

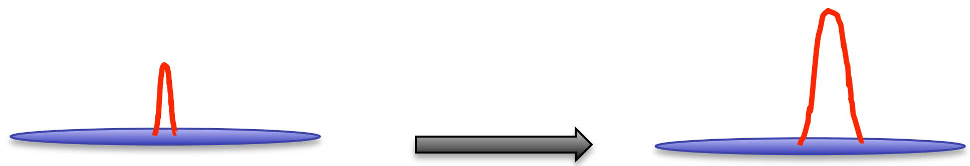
Seed pulse must be shorter than electron bunch length

Otherwise FEL pulse length is defined by electron bunch length, including bunch arrival jitter



Seed pulse must be longer than cooperation length

Pulse will be stretched by FEL process. Identical performance than single spike SASE operation

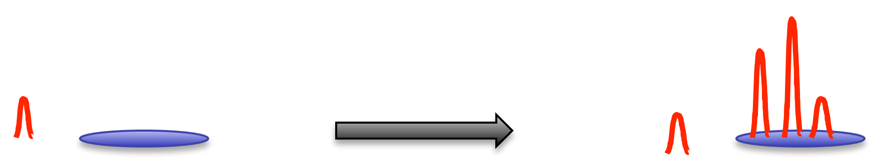


Goal is mutual exclusive to maximum brilliance

Maximum brilliance is given by bunch length and requires a seed signal longer than bunch length

Arrival time jitter must be less than bunch length

Otherwise there is a chance of missing overlap. Bunch will laser in SASE mode



Electron Bunch Length (Short Wavelength)

Design Goal:

Saturation power and length (final radiator) should be competative to SASE FEL

Example: 1 nm FEL requires about E=2 GeV, I=2 kA, and ε_n<1 μm

Bunch Length Limitations:

Short Seed Pulse (HGHG, HHG):

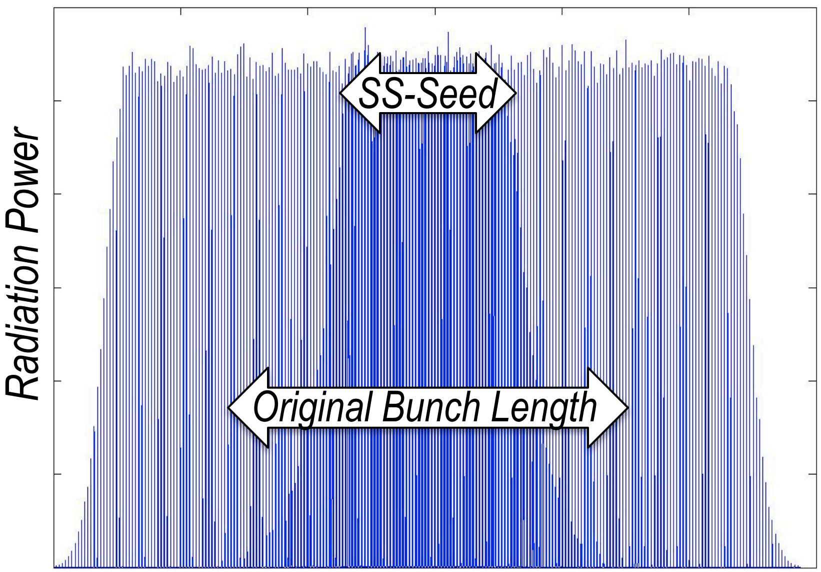
- Safety margin for arrival time jitter (~50 fs)
- Slippage at longest wavelength (~20 fs)
- Fresh bunch methods

Long Seed Pulse (EEHG, Self-Seeding):

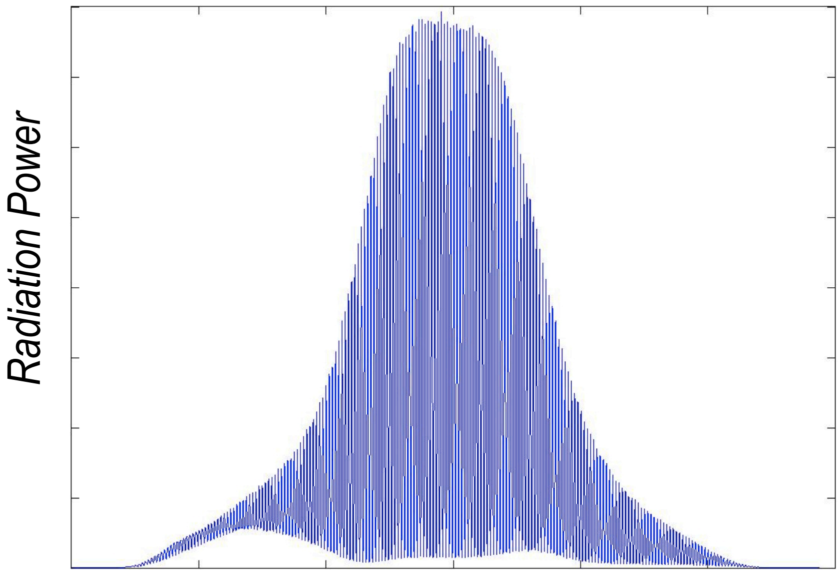
- Streching of the bunch for high harmonics in EEHG
- Reduced enhancement for high resolving filters

Example: Radiation Profile of EEHG at 1 nm for SwissFEL

Start of Radiator



First Saturation

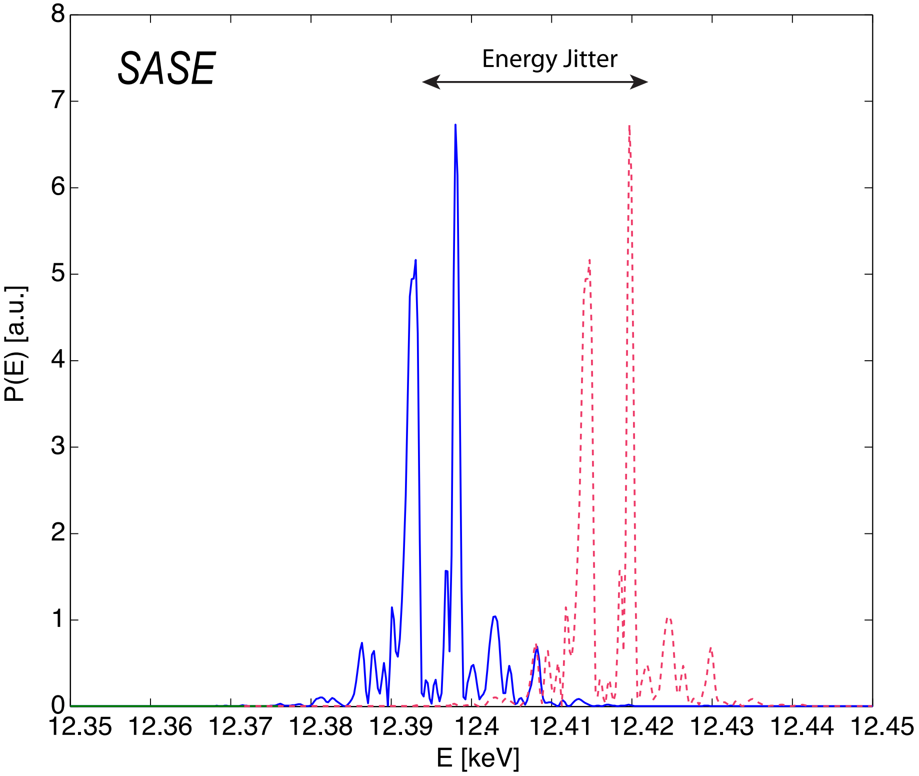


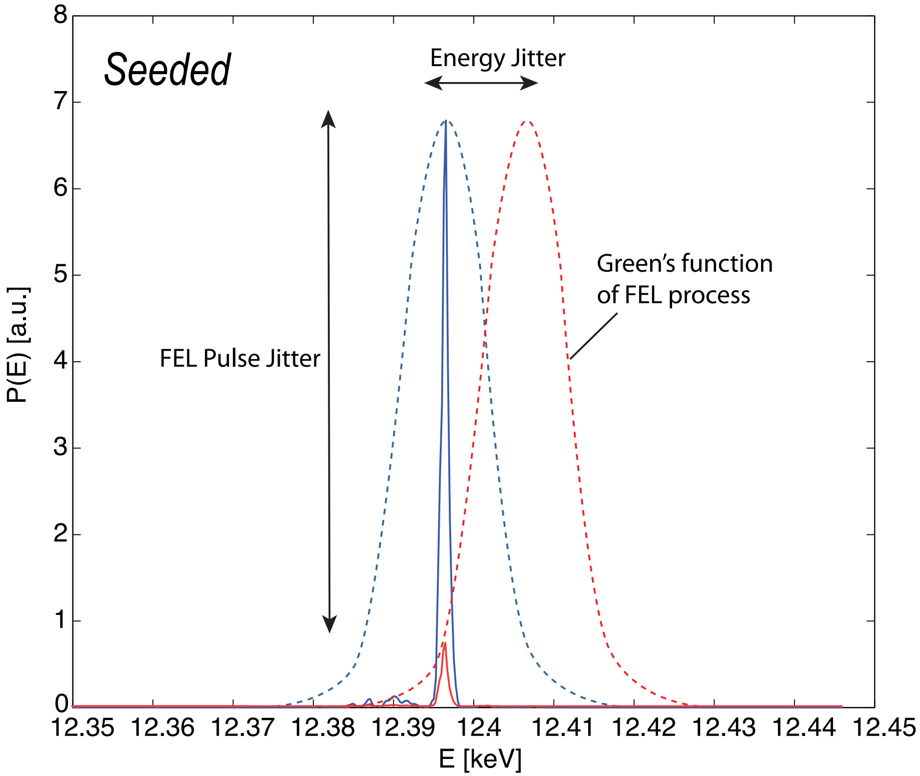
Energy Stability

Unlike SASE FELs the seeded FELs are sensitive to detuning effects. Resonance condition has to stay within the bandwidth:

$$\frac{\Delta E}{E} << \rho$$

Effect can be enhanced in cascaded HGHG schemes, somehow mitigated in fresh bunch techniques





Energy Stability Example

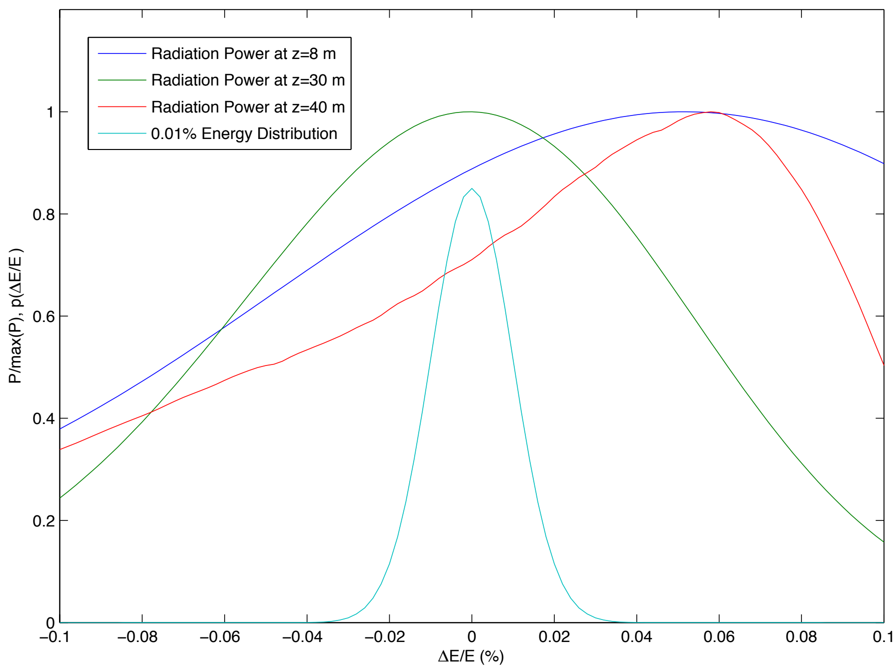
SwissFEL Soft X-ray Beamline ATHOS:

- Wavelength 1 nm
- Seed power 1 kW
- Saturation length 38 m

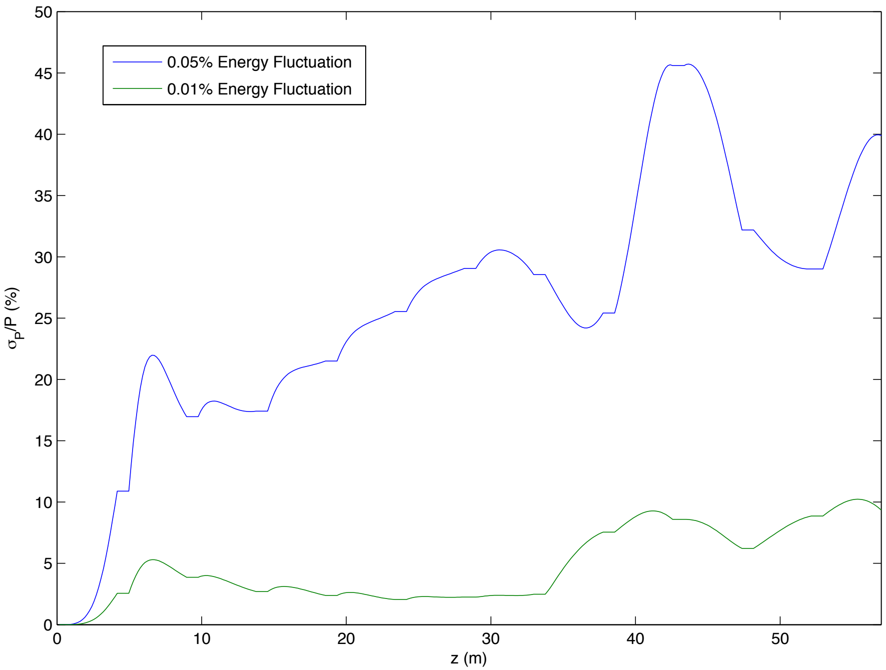
$$\rho = 10^{-3}$$

Energy Fluctuation	0.01 %	0.05 %
Power Fluctuation	5 %	25 %

Detuning Curves



RMS Fluctuation



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Electron Energy Spread

- Energy spread is typically bound to the peak current mostly by means of bunch compression:

Example: 20 A, 1 keV spread → 3000 A, 150 keV spread

- For SASE FEL the spread has to satisfy the condition:

$$\frac{\sigma_\gamma}{\gamma} << \rho$$

Laser heater, HGHG and EEHG are increasing the energy spread, which has taken into acount:

- **HGHG** roughly by the harmonic number:

$$A = \Delta\gamma / \sigma_\gamma \approx n$$

- **EEHG** roughly by the rms of the modulation amplitudes

$$\sqrt{A_1^2 + A_2^2} \approx 2 - 10$$

High Risk at short wavlengths, which require high current and mitigation for microbunch instabilities (Laser Heater)

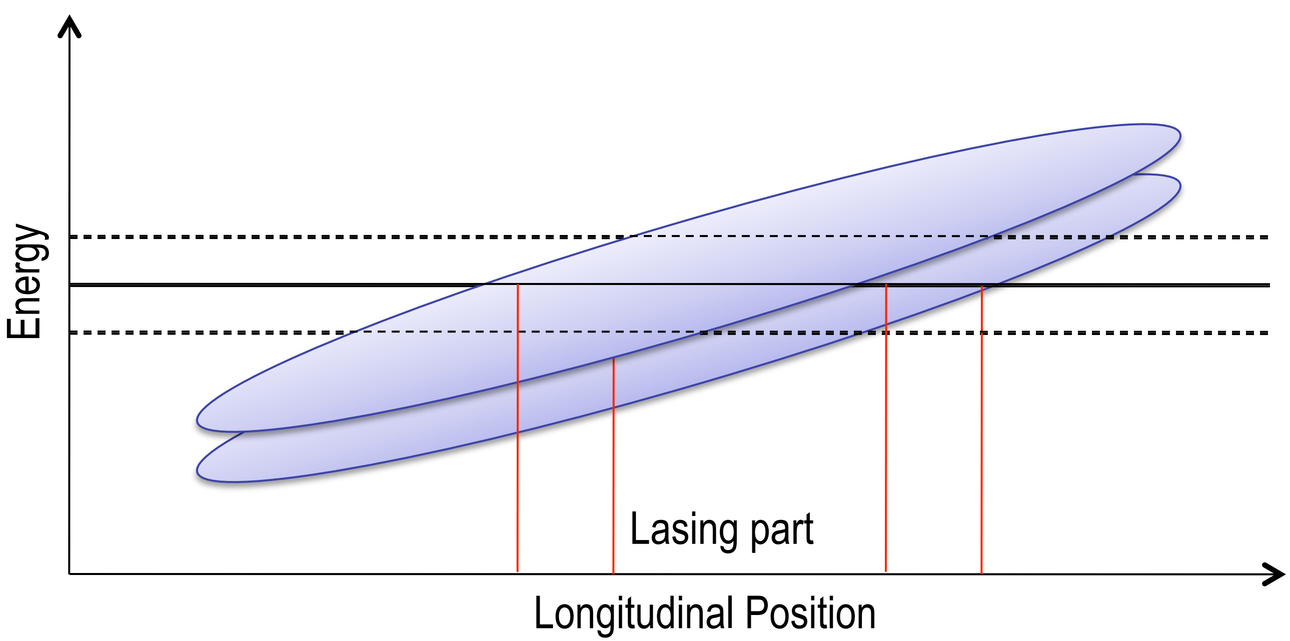
Electron Energy Chirp

Benefits:

- Makes FEL insensitive to energy jitter for long seeds, though translate energy jitter to arrival time jitter
- Linear chirp shifts resonant condition in HGHG and EEHG but can be completely compensated

Disadvantages:

- Quadratic and higher order terms disrupts homogenity of seed mechanism
- Restricts lasing part of the bunch
- Can severely alter profile for large R_{56}



Electron Beam Charge and Current Stability

- Most seeding schemes are affected by fluctuation in the beam current as SASE FELs (1D Model):

$$\frac{\Delta P}{P} = \frac{4}{3}\frac{\Delta I}{I}$$

- When the jitter in current and pulse length is correlated (compression jitter) then the dependence is weaker for the pulse energy: $\Delta E/E = (1/3)\ \Delta I/I$

- Current jitter affects also the point of saturation (SASE and Seeded FELs):
  - Strong seed signals mitigate the impact of source point jitter
  - HGHG schemes enhance the fluctuation by a fluctuation of the seed signal in the second stage
    - Further enhanced by cascaded non-freshHGHG cascade
  - Effect on self-seeding mostly negligible due to the inherent strong fluctuation in the second stage

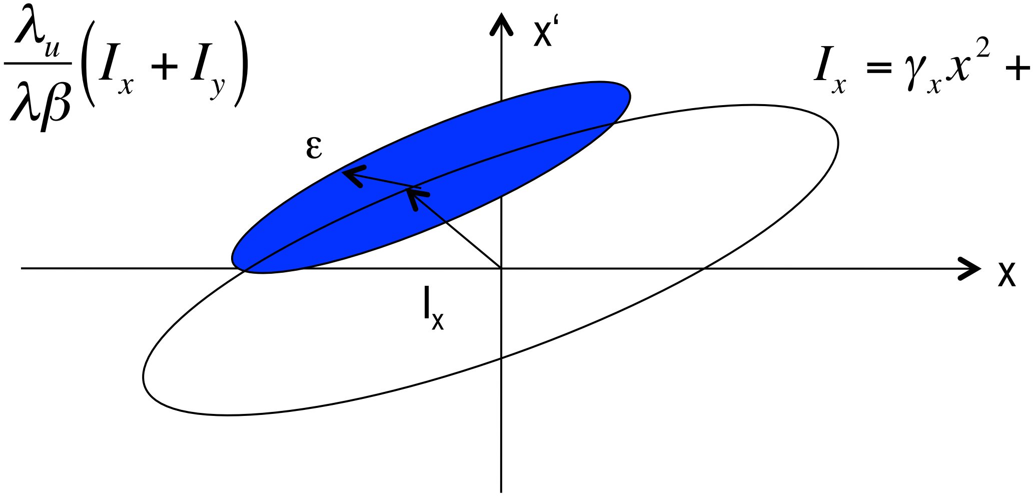
Cascaded HGHG FEL are most sensitive to current jitter. Can be mitigate by fresh bunch techniques

Electron Beam Orbit Stability

- Similar to the SASE process a jitter in orbit degrades the FEL process. More severe at shorter wavelength where the optical mode is smaller.
- Injection error (as well as larger emittance values) needs to be compensated by larger mode size of the seed signal
- The betatron oscillation causes also a red-shift in the resonance condition by:

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda_u}{\lambda\beta}\left(I_x + I_y\right)$$

$$I_x = \gamma_x x^2 + 2\alpha_x x x' + \beta x'^2$$



Normally β is optimized for highest electron density and smallest seed mode size, thus the orbit jitter should be less than the rms beam size or divergence

Summery

	SASE	HHG	HGHG	EEHG	Self-Seeding
Arrival Time	No impact	sensitive	sensitive	Less sensitive	No impact
Bunch Length	As short as possible	Longer than arrival jitter	Longer than arrival jitter +fresh bunch	Stretching possible	As short as resolving power allows
Energy Jitter	Wavelength Jitter	Saturation Length and Power Jitter	Saturation Length and Power Jitter	Saturation Length and Power Jitter	Saturation Length and Power Jitter
Energy Spread	normal	normal	Needs to be smaller by harmonics	Needs to be smaller by up to 10	normal
Chirp	Chirped FEL pulse	Arrival time jitter converts to energy jitter	Wavelength shift, changes current	Strong current changes, overcompressi on	Shorter FEL pulse
Current Jitter	Power jitter	Power jitter	Power and Seed jitter	Power Jitter	Power jitter
Injection Jitter	Red shift	Quasi Energy Jitter	Quasi Energy Jitter	Quasi Energy Jitter	Quasi Energy Jitter

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Seeding Schemes require more stringent requirements on electron beam performance:

- **Energy jitter affects all seeding schemes and must be much smaller than FEL bandwidth**

- **Arrival jitter must be small for laser based seeding schemes, enforcing minimum bunch length**

- **HGHG and EEHG require smaller energy spread than SASE FELs reducing the operation range of laser heater**