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Paul Scherrer Institut

Sven Reiche

Expected Performance of Seeded FELs

Advantage of Seeded FELs

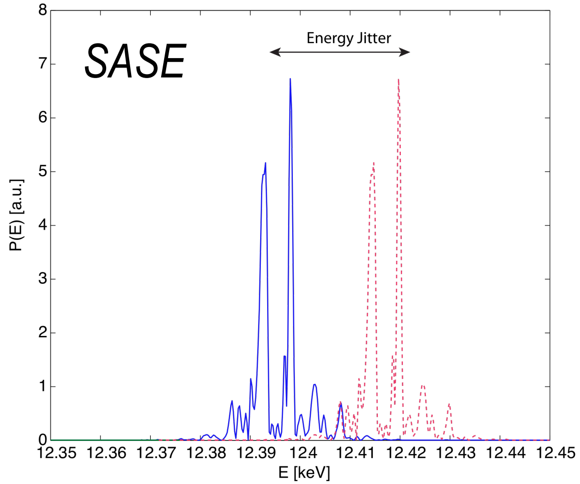
In Comparison to SASE FELs, seeded FELs offer the improvement:

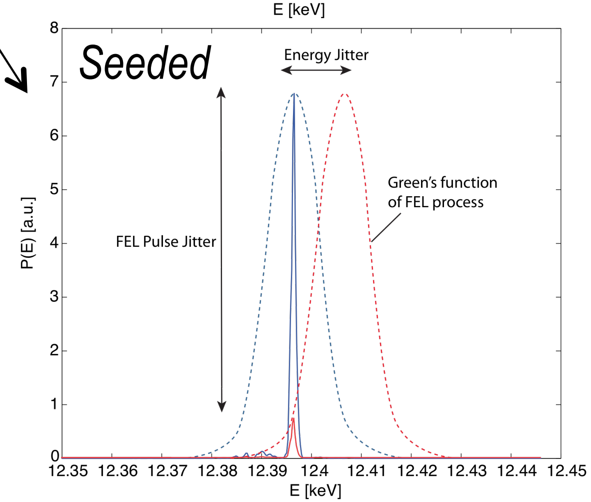
1. **Control/Improvement of the Longitudinal Coherence**
2. **Improved Brilliance**
3. **Energy Stability of FEL Output Pulse**
4. **Spectral Stability at Selected Frequency**
5. **Synchronization with External Source (Pump-Probe)**
6. **Ability to Increase FEL Efficiency with Taper**
7. **FEL becomes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

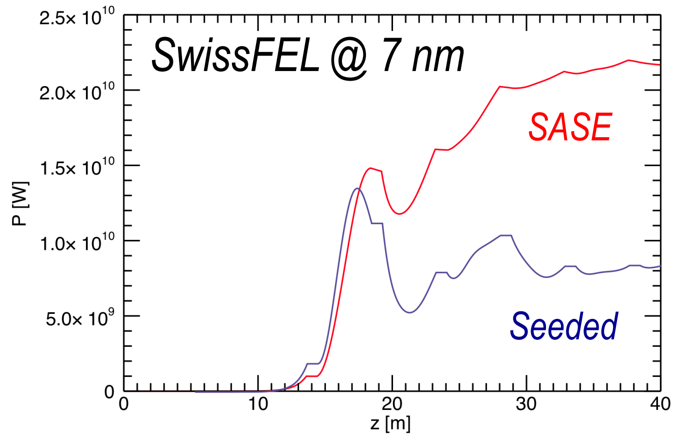
Disadvantage of Seeded FELs

FEL Performance gets more sensitive to electron beam fluctuation:

SASE FEL	Seeded FEL
Energy Jitter shifts central wavelength but keeps photon number almost unchanged	Huge fluctuation in output power when energy jitter becomes comparable to FEL bandwidth
FEL performance unchanged from arrival time	Temporal overlap problems unless seed signal is longer
Power growth flattens at saturation with a slight growth	Post Saturation Oscillation of FEL power







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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

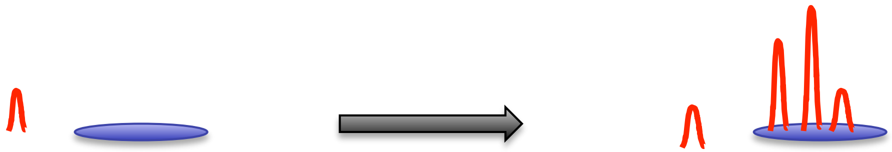
Pulse will be stretched by FEL process. Identical performance than single spike SASE operation

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

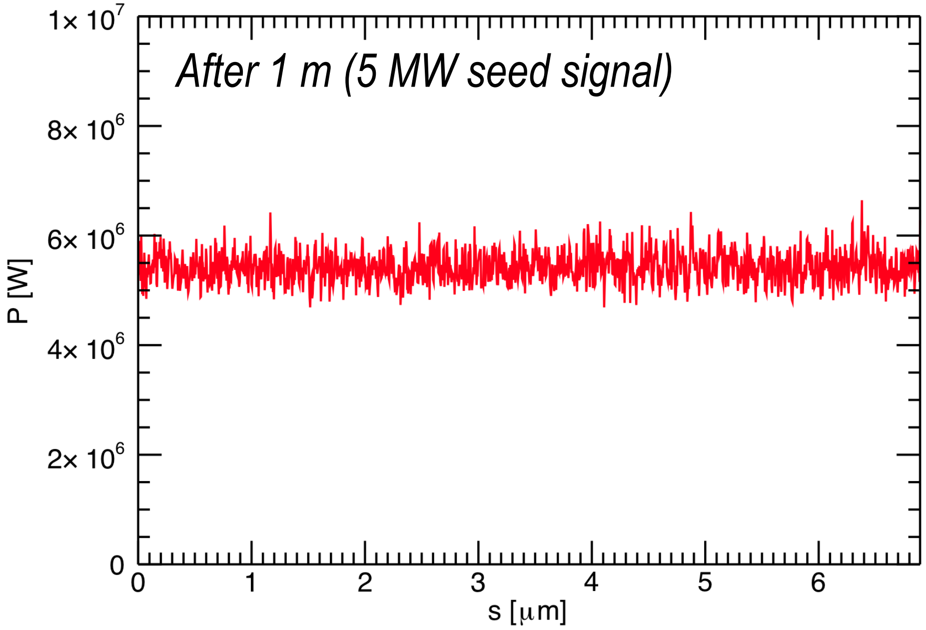
Otherwise there is a chance of missing overlap. Bunch will laser in SASE mode

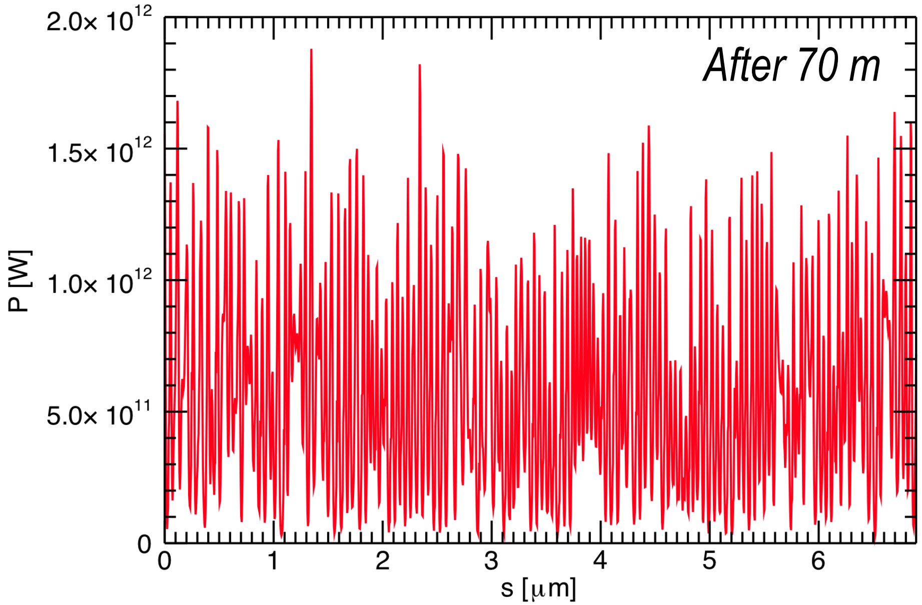


Post Saturation Tapering

- Well-defined input signals allows to optimize the tapering profile
- However side-band instability will modulate profile envelope
- Slippage effects stops the trapping of the electrons
- Effective tapering about the saturation length of SASE process.

Example: LCLS (self-seeded)





Seeding Methods

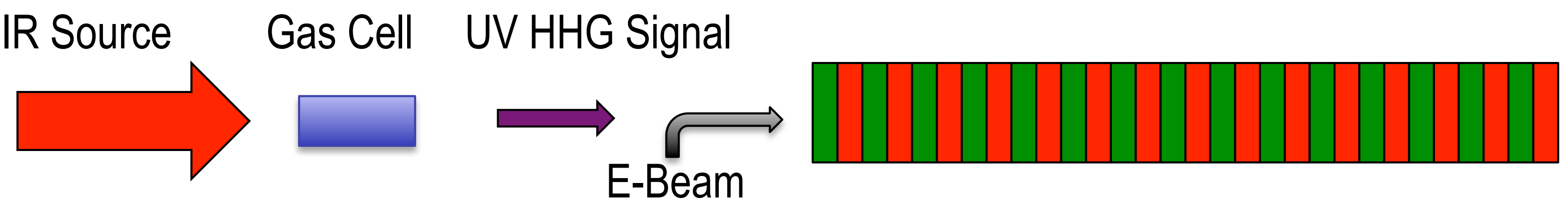
High Harmonic Generation Seeding
Direct Seeding

High Gain Harmonic Generation Seeding
Long wavelength and harmonic conversion
-*Same Bunch*
-*Fresh Bunch*

Echo-Enable Harmonic Generation
Manipulation of electron distribution

Self-Seeding
Filtered output of SASE FEL
-*Monochromator*
-*Stopband Wakefield*

HHG Seeding



HHG Seeding has the advantage that it generates a radiation field at the resonant wavelength, based on a HHG process in noble gas.

But:

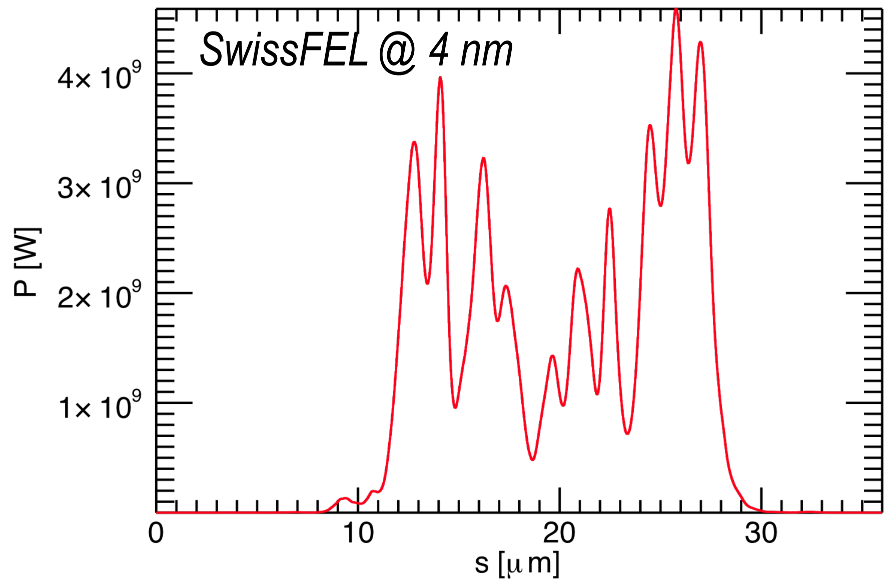
- Efficiency of HHG drops exponentially below 10 nm, limits to very short seed pulses.
- Shot noise, defining minimum seeding power, grows with shorter wavelength.

$$P_{sn} = \frac{3\sqrt{4\pi}\rho^2 P_{beam}}{N_\lambda \sqrt{\ln(N_\lambda/\rho)}} \propto \frac{\gamma}{\sqrt{a - \ln\gamma}}$$

Typical shot noise power @ 5nm: 1kW
Minimal seed power level: $100xP_{sn}$=100kW
Seed length of 10 fs →

Energy in harmonic at undulator entrance: > 1nJ

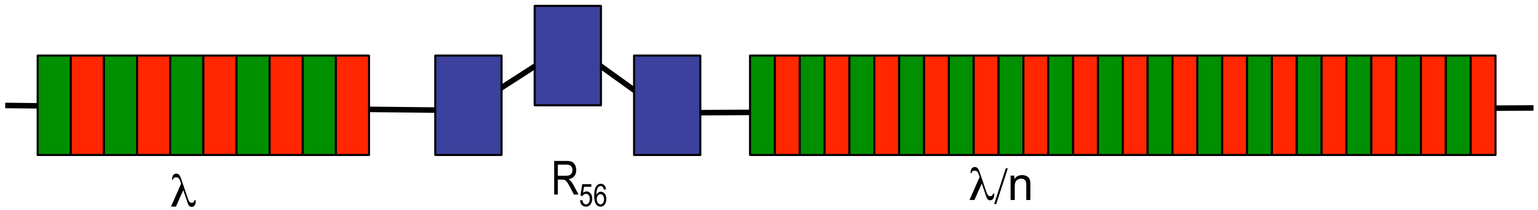
Very Difficult to use below 10 nm

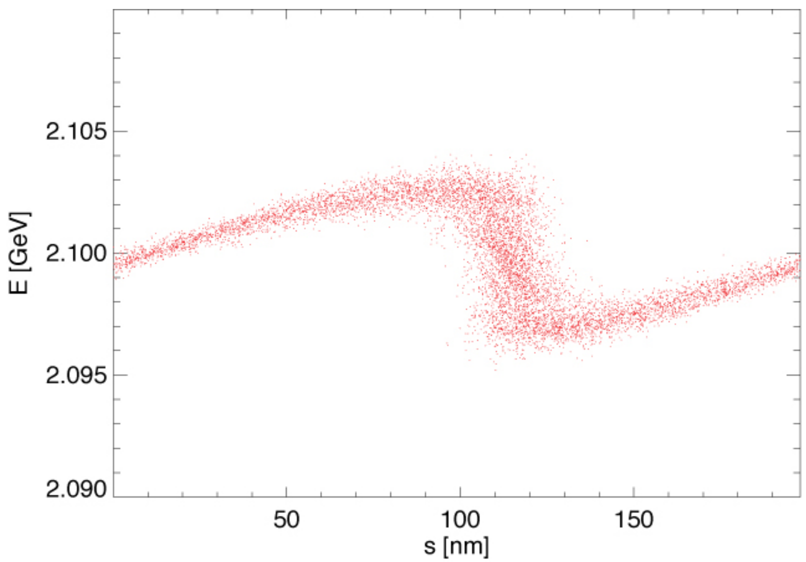


HGHG- Basic Principle

Induced energy modulation at longer wavelength is changed into rich harmonic current content after compression with a chicane.

A selected harmonic is picked up with a succeeding undulator.





Bunching:

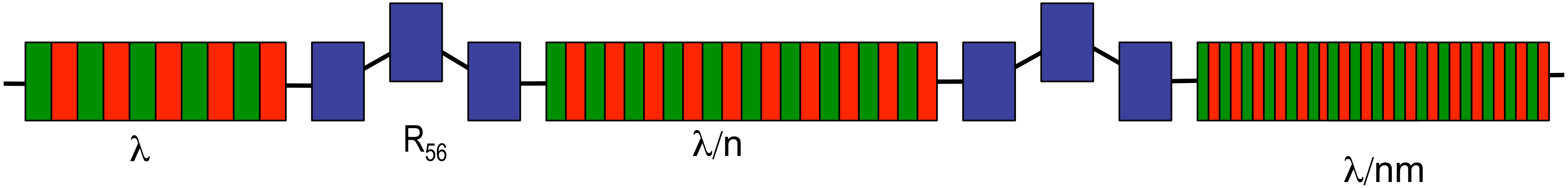
$$b_n = J_n\left(\frac{n}{\lambda} R_{56} \frac{\Delta E}{E}\right) e^{-\frac{1}{2}\left(\frac{n}{\lambda} R_{56} \frac{\sigma_E}{E}\right)^2}$$

$$\Delta E \approx n \cdot \sigma_E$$

Limit:

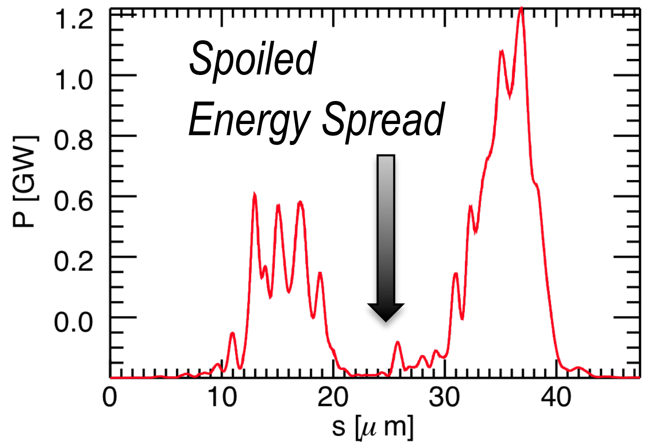
$$\frac{\Delta E}{E} = \frac{n\sigma_E}{E} < \rho$$

HGHG Cascade – Same Bunch

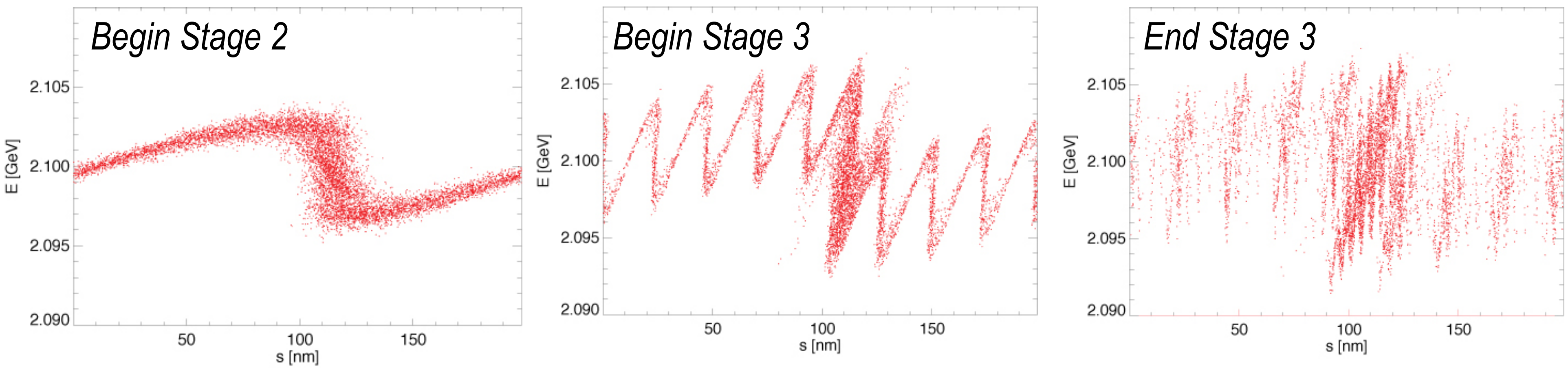


Needed for short bunched (or high peak current)
Rely on the FEL process to build up energy modulation
VERY sensitive to beam jitter:

- FEL performs weaker → bunching is lost
- FEL performs stronger → energy spread is spoiled
- Errors are accumulative in multi stage configuration

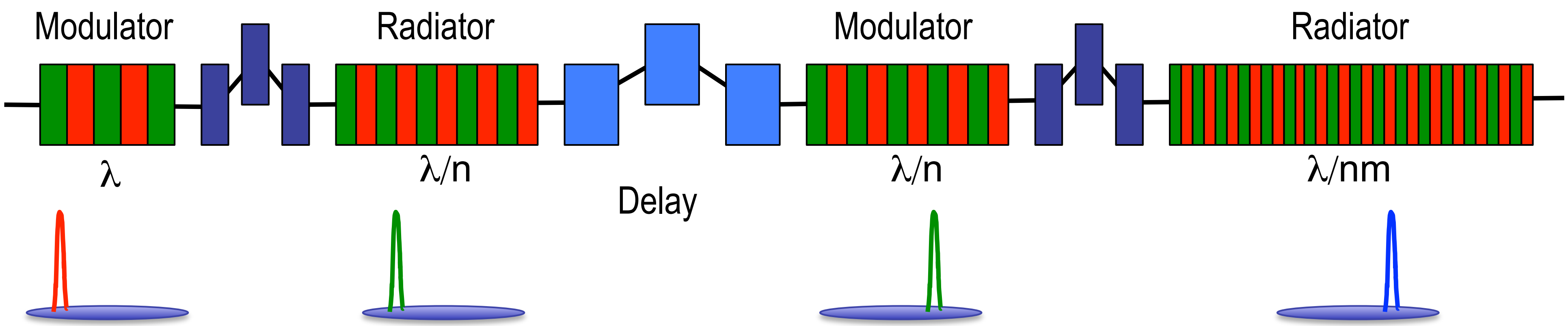


SwissFEL Design Study (200 nm → 22.2 nm →4.4 nm)



Practical Limit around 10 nm (2 cascade)

HGHG Cascade – Fresh Bunch



Benefits of:

- Radiator can run into saturation → more stable against beam parameter jitter
- Energy spread is not acumulated → better performance of final radiator

Disadvantage:

- Seed pulse must be short
- Bunch must be long, typically reduced current and thus reduced power level at saturation
- No long final radiator
- Strong demands on electron beam quality (uniformity, arrival time)

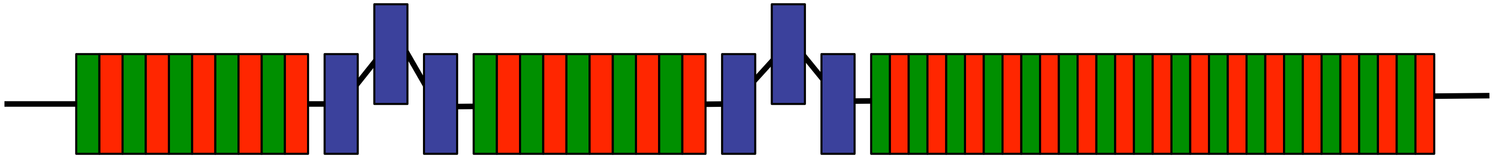
Example:

100 fs jitter + 25 fs pulse + 50 fs delay + 25 fs pulse second stage = 200 fs pulse length (flat top)

25 fs Seeded pulse over 200 fs background (partially amplified SASE signal)

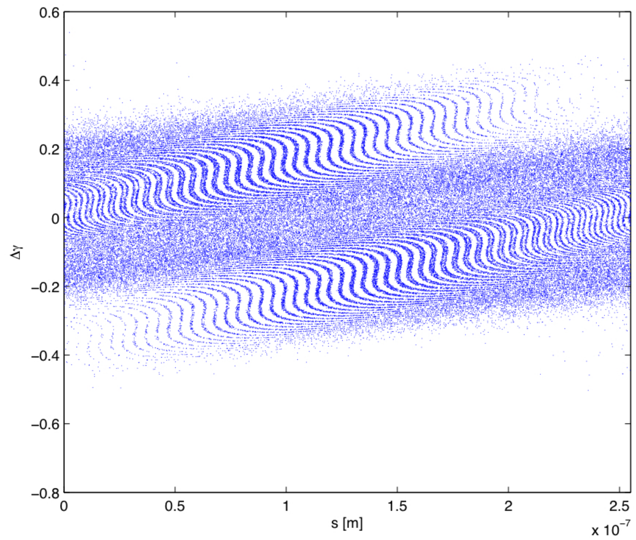
Practical Limit around 5 nm

Echo Enable Harmonic Generation



- Novel scheme with double modulation to generate a high frequency bunching in current

- Strong bunching at very high harmonics: $$b_{\max} = \frac{0.39}{m^{1/3}}$$



But:

- Higher harmonics require stronger modulation and/or compression
  - Stronger compression imposes limit by CSR and hard photons
  - Stronger energy modulation limited by FEL bandwidth
- Problems with intra-beam scattering and residual chirp

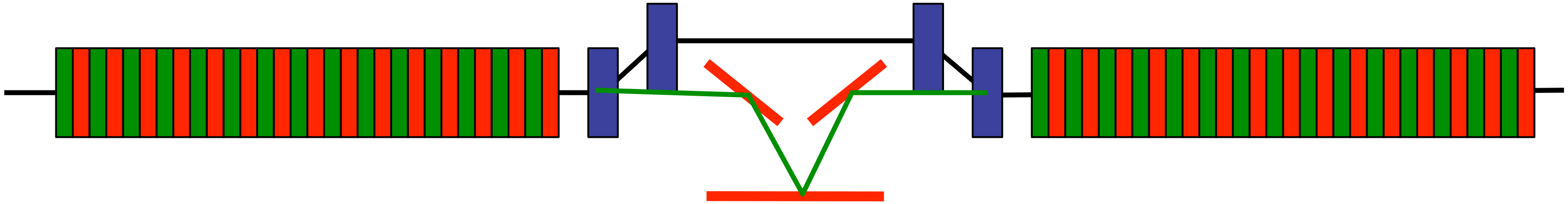
- Harmonics higher than 100 are getting difficult to realized:
  - Requires about 100 energy bands in phase space
  - Mixing of at least 100 slices in first stage

260 nm Seed Laser → lengthening by 26 microns

Very promising for longer wavelength, smart ideas for shorter (e.g. 2nd harmonic peak)

Expected good performance down to 5 nm

Self-Seeding

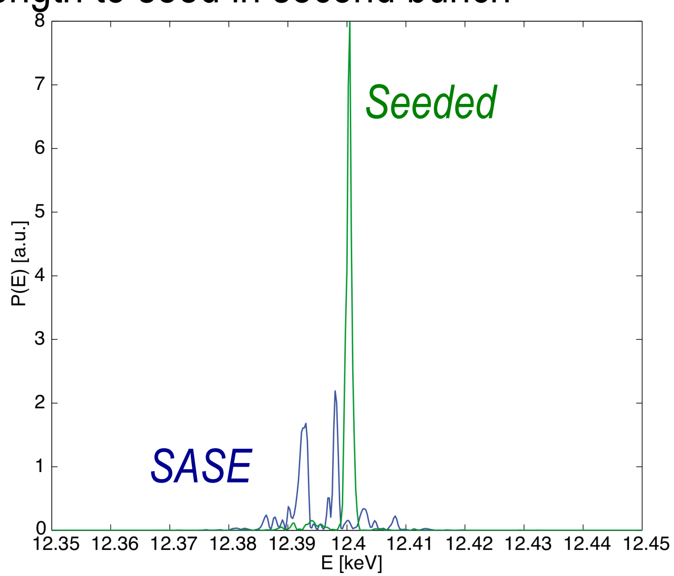


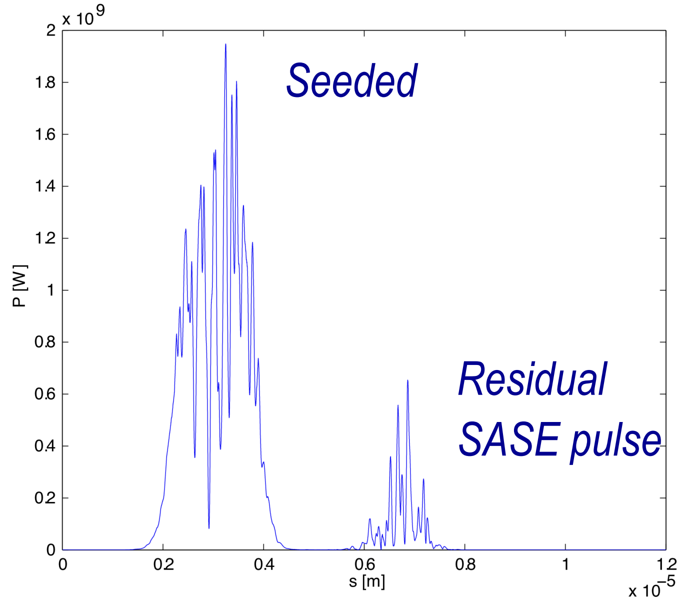
•Seed derived from SASE FEL and monochromatic device.
•No intrinsic problem with wavelength and robustness of SASE FEL.

But in soft X-ray range the intersection is long (about 20 m). In hard X-ray the stopband of Bragg crystal can be used to delay central wavelength to seed in second bunch

Required length about 1.5 the saturation length of SASE FEL

Bunching removed but not energy modulation and spread →Profile distortion in second stage





Limitation on wavelength given by availability of monochromators

Comparison

	FLASH II (~5 nm)				SwissFEL(~1 nm)			
	HHG	**HGHG**	**EEHG**	**Self Seed**	**HHG**	**HGHG**	**EEHG**	**Self Seed**
Brilliance increased	Maybe	Good	Good	Best	Maybe	Good	Good	Best
Energy Stability	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe
Spectral Stability	Maybe	Yes	Yes	Best	Maybe	Yes	Yes	Best
Synchronization	Best	Good	No/Maybe	No	Best	Good	No/Maybe	No
Monochromator needed	Maybe	Yes	Yes/Maybe	No	Maybe	Yes	Yes/Maybe	No
Temporal Shape	Best	OK	Good	OK	OK	Bad	OK	OK
Signal/ Background	Poor	Poor	Good	Good	Poor	Poor	Good	Good
Length vs SASE Length	<1	~1	<1	>1.5	~1	1 – 1.5	~1	>1.5
Complexity of Operation	Normal	High	Very High	Normal	High	Very High	Very High	Normal
Tunability	Normal	Complex	Complex	Normal	Complex	Complex	Complex	Normal

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Summary

Seeding is very promosing to improve the quality of FEL as a user facility.

Several methods are proposed for seeding.

Except for the synchronization with external signal, self-seeding is most promising and robust method with no inherent limitation below 5 nm.

Seeding at very short wavelength are very limited. More experimental results are very welcome