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Paul Scherrer Institute

Sven Reiche

Overview of Seeding Methods for FELs

Outline

- General Features of Seeded FEL
- SASE FEL as a Background Process
- Direct Seeding Methods
- Electron Beam Manipulations
- Cascades and Hybrid Configurations
- Self-Seeding Methods
- Summary

Advantage of Seeded FELs

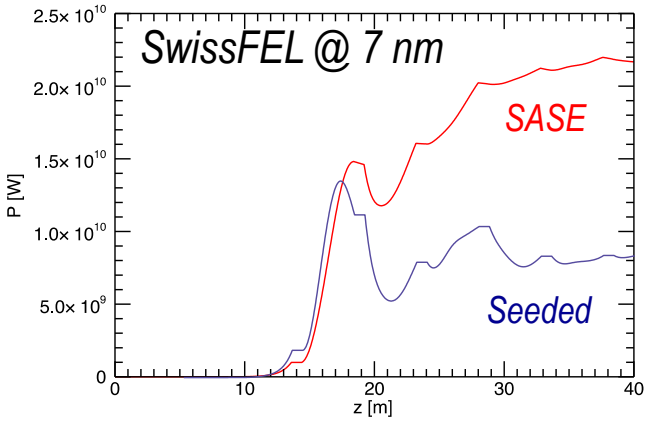
In Comparison to SASE FELs seeded FELs can offer the improvement:

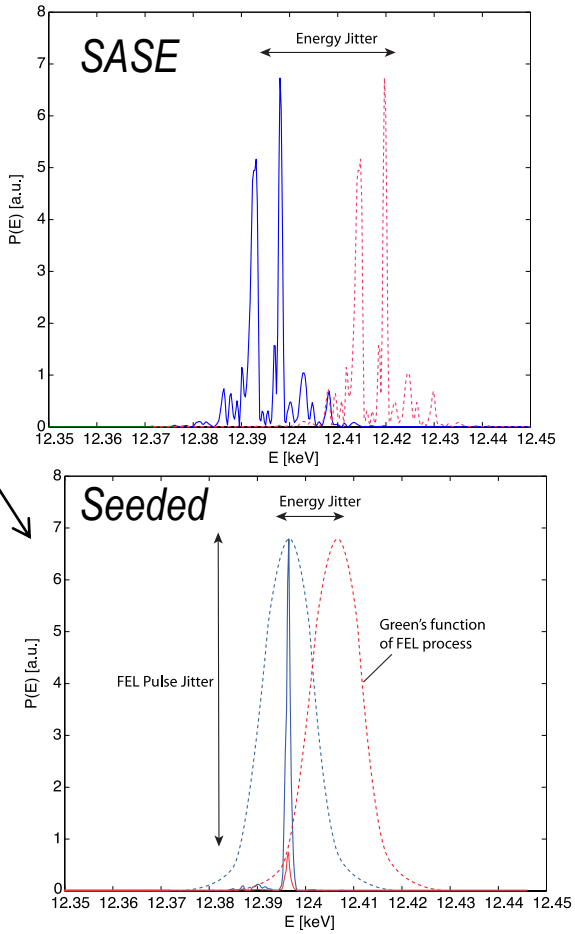
1. **Control/Improvement of the Longitudinal Coherence**
2. **Improved Brilliance**
3. **Energy Stability of FEL Output Pulse**
4. **Spectral Stability at Selected Frequency**
5. **Synchronization with External Source (Pump-Probe)**
6. **Ability to Increase FEL Efficiency with Taper**
7. **FEL becomes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





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

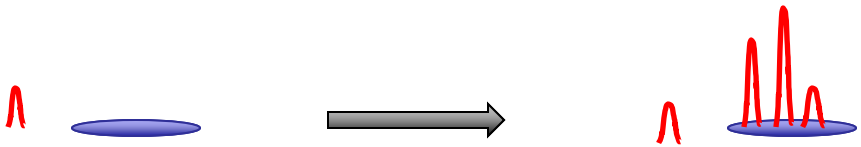
Pulse will be stretched by FEL process.
Identical performance than single spike SASE operation

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

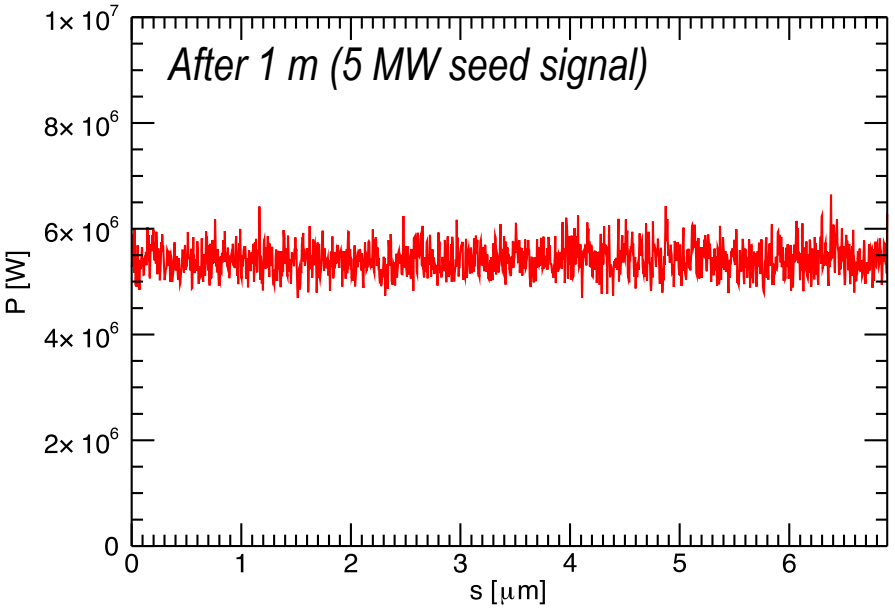
Otherwise there is a chance of missing overlap. Bunch will laser in SASE mode

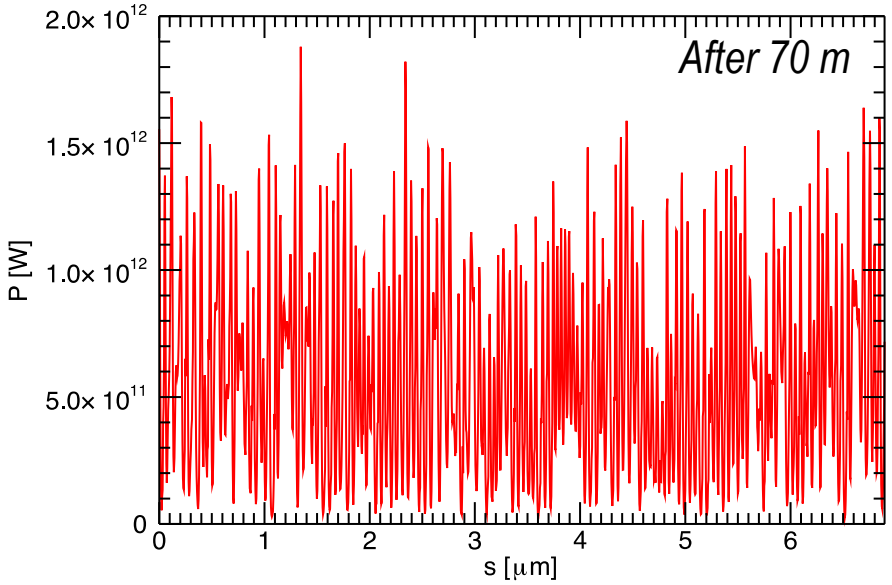


Post Saturation Tapering

- 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

Example: LCLS (self-seeded)





Shot Noise and Seeding Efficiency

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

Towards shorter wavelengths the typical beam energy increases and the shot noise signal gets larger

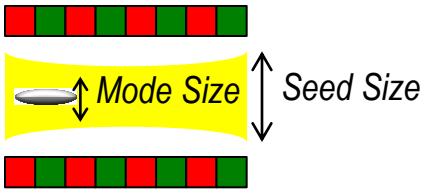
Example: 5 nm @ 2 GeV → P_{sn} ~ 100 W

(N_λ: #electrons/wavelength, ρ: FEL Parameter)

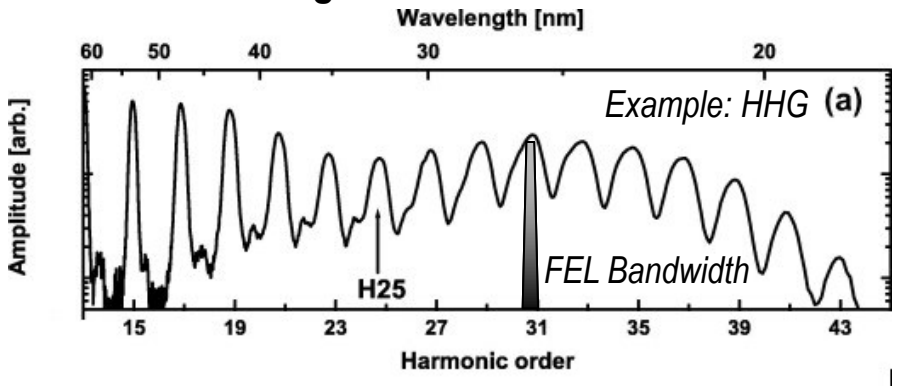
Coupling to Growing Mode

$$P = \frac{P_0}{9} e^{z/L_g}$$

Coupling to FEL Mode



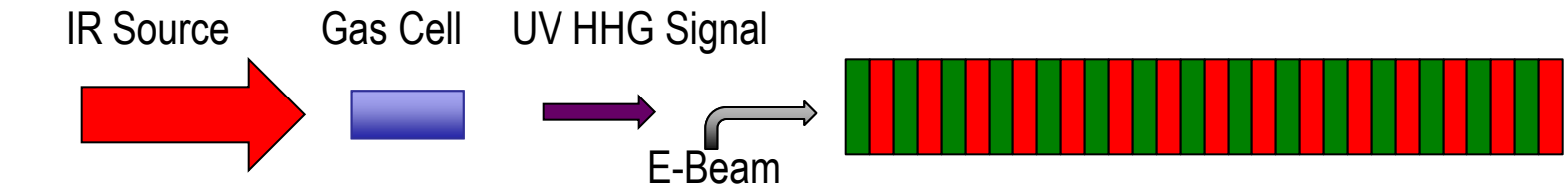
Matching FEL Bandwidth

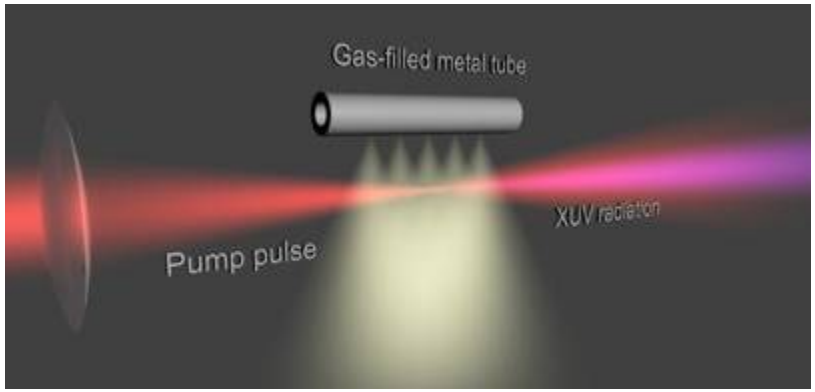


Seed Power	x	Transport Loss	x	Growing Mode	x	FEL Mode	x	Bandwidth	>	Contrast	x	Shot Noise
		<10%		11%		<50%		10-100 %		>10		

P_{seed} > 2000 P_{sn}

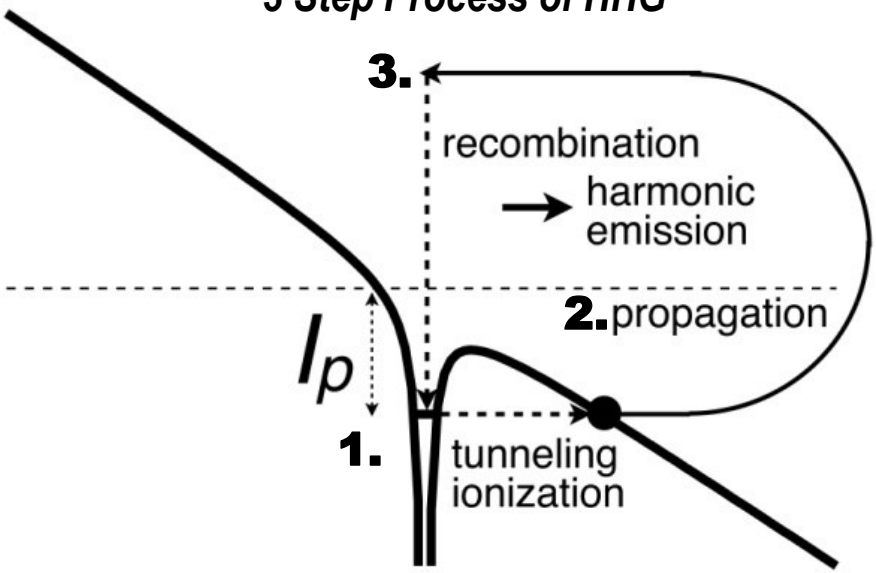
High Harmonic Generation (HHG) Seeding

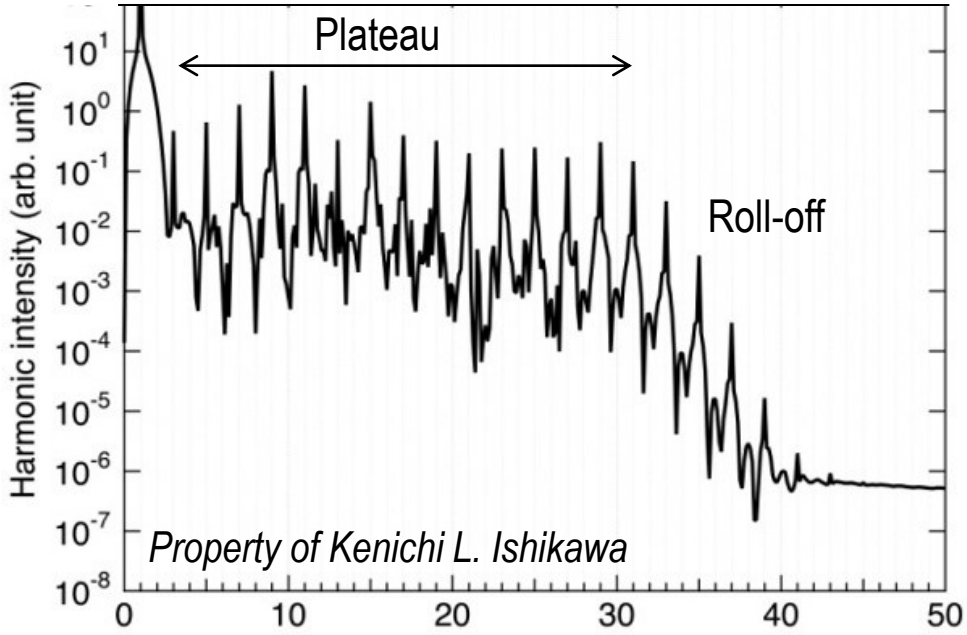




- 3 step process in noble gases
- High energetic photons, phase locked to drive laser
- Coherence properties inherited from drive laser
- Limited to short pulses due to ionization of gas

3 Step Process of HHG





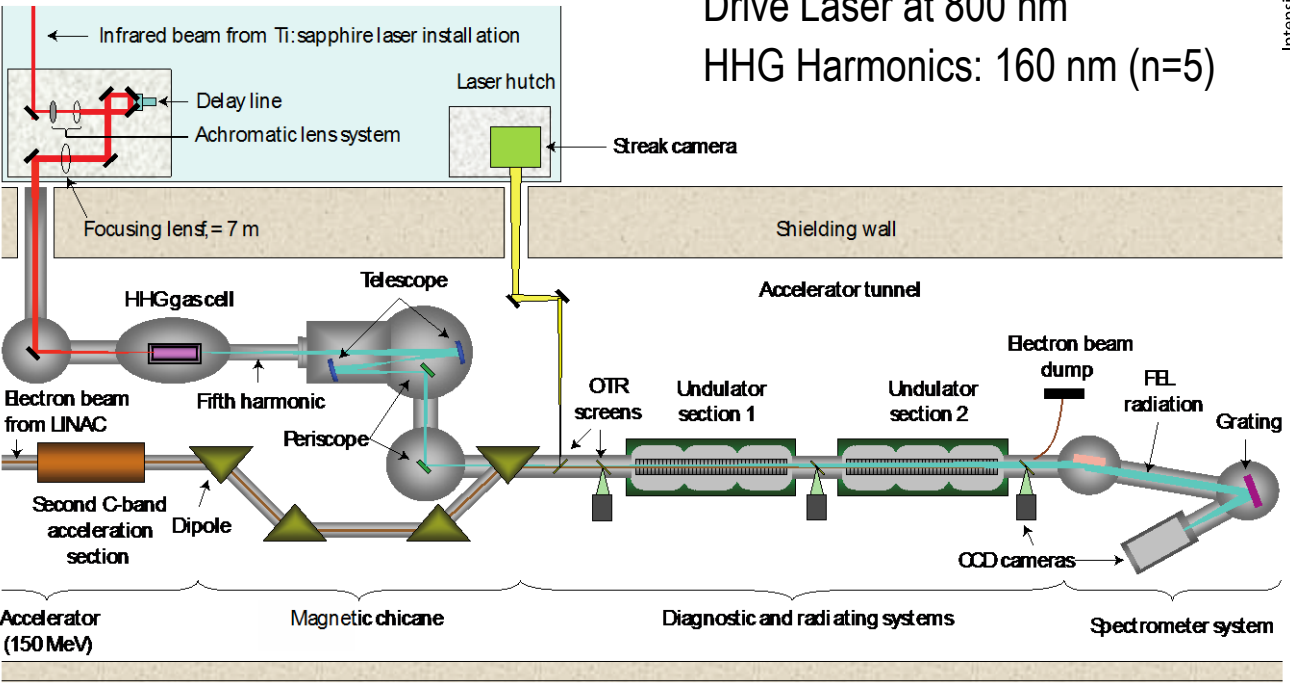
Proof-of-Principle Experiment

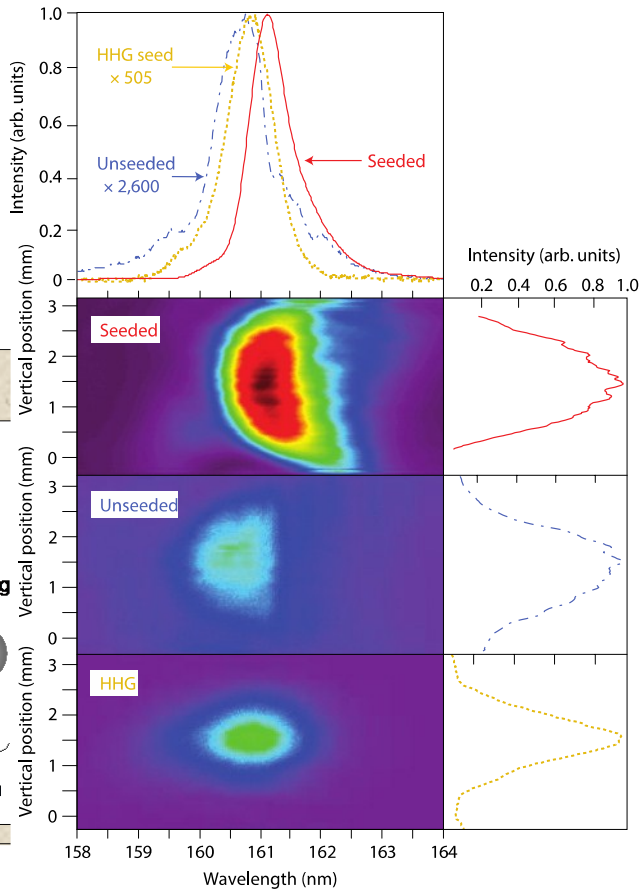
G. Lambert et al, Nature Physics Vol. 4 (2008) 296

Test Injector at SCSS (Spring 8)

Drive Laser at 800 nm

HHG Harmonics: 160 nm (n=5)





HHG Seed is amplified by a factor of about 500

SASE signal is 2600 times weaker than seeded FEL(good contrast of seed to shot noise)

Comments on HHG Seeding

HHG sources as seeds for FEL have been demonstrated at various experiments with the current record of 39 nm [*C. Lechner, et al, Proc of FEL Conference 2012*]

However further progress requires significant R&D in the source development:

- Decrease the wavelength (extending the plateau of the HHG process)
- Increase the efficiency of HHG process to overcome increasing shot noise power
- Control/preserve the phase front and mode content of the HHG source
- Control the bandwidth of a given harmonic to match FEL bandwidth

Wavelengths below 20 nm difficult to achieve

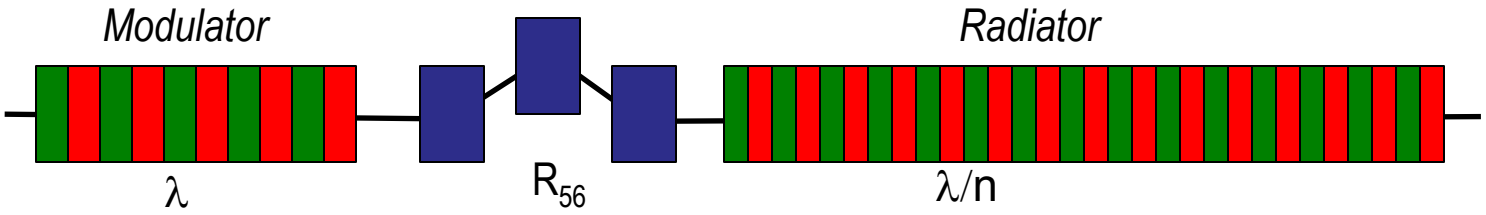
Best for sync FEL pulse to external signal

Very little increase in brightness
(Single-spike SASE might be better alternative)

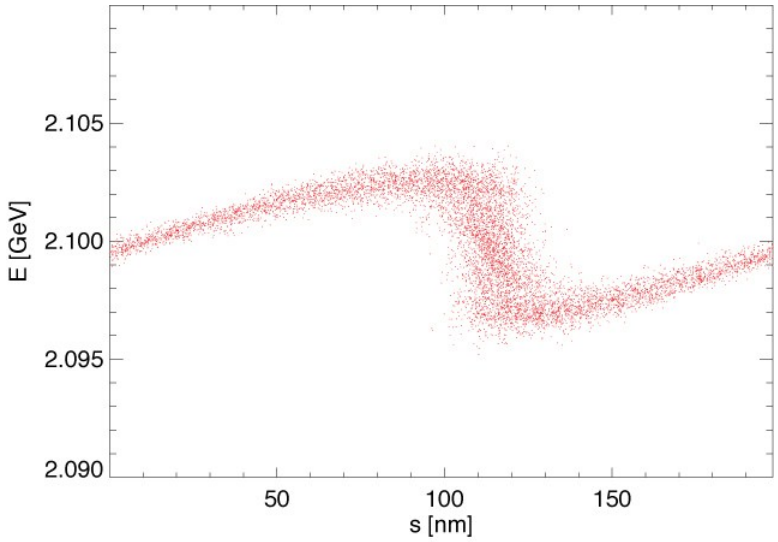
High Gain Harmonic Generation (HGHG)

- Induced energy modulation at longer wavelength is changed into rich harmonic current content after compression with a chicane.
- To avoid smearing out the energy modulation must be larger than intrinsic energy spread
- A selected harmonic is picked up with a succeeding undulator.

Theory: L.-H. Yu, Science 289 (2000) 932



Phase Space at Radiator Entrance



Bunching:

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

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

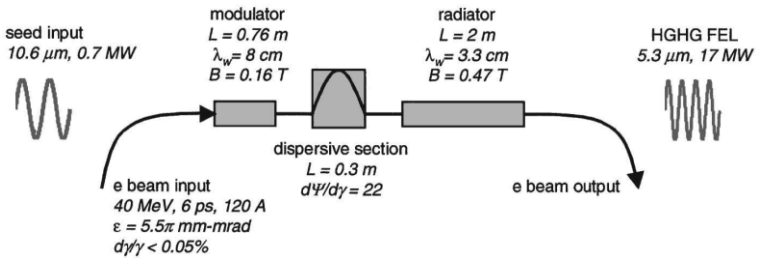
Limit:

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

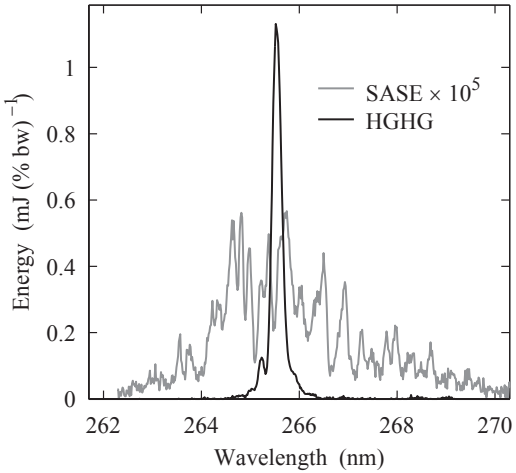
HGHG Experiments

Proof-of Principle Experiment (SDL)

A. Doyuran et al, PRL 86 (2001) 5902

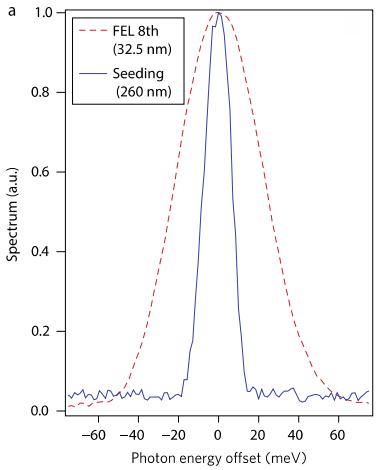


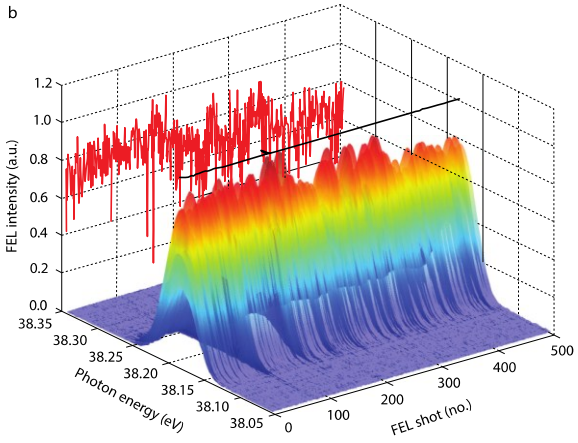
L.-H. Yu et al, NIMA 528 (2004) 436

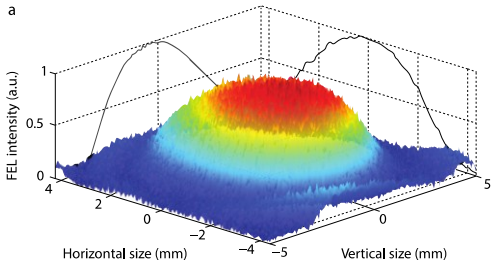


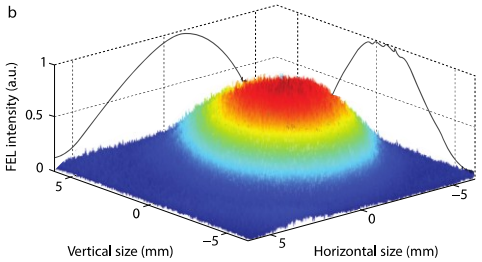
FERMI @ Elettra – User Facility based on HGHG

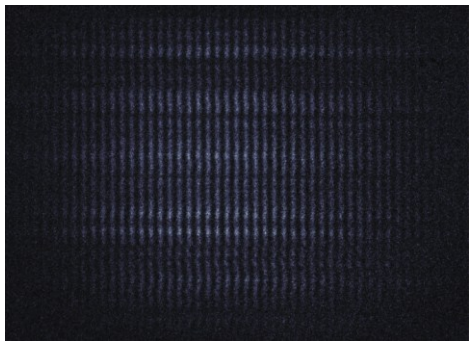
E. Allaria et al, Nature Photonics. 6 (2012) 699

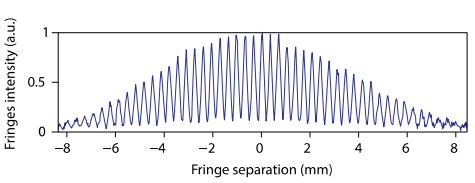






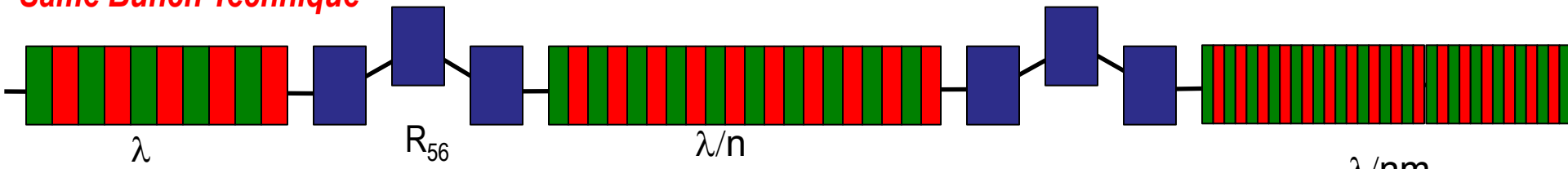




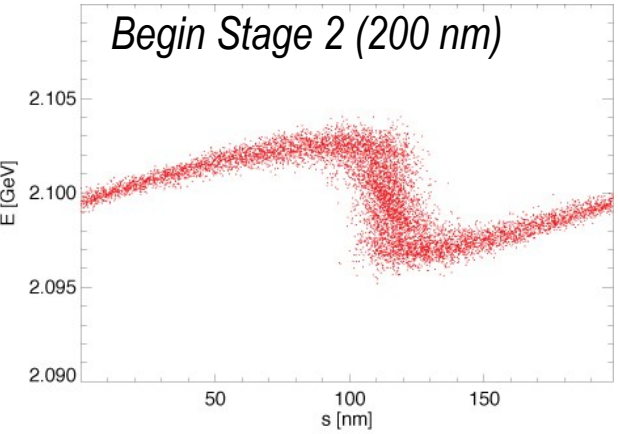


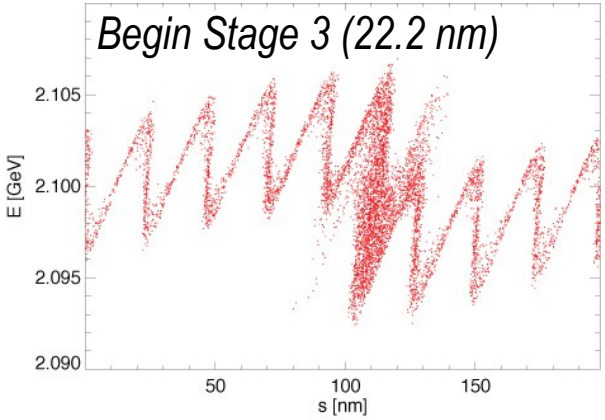
Cascading HGHG

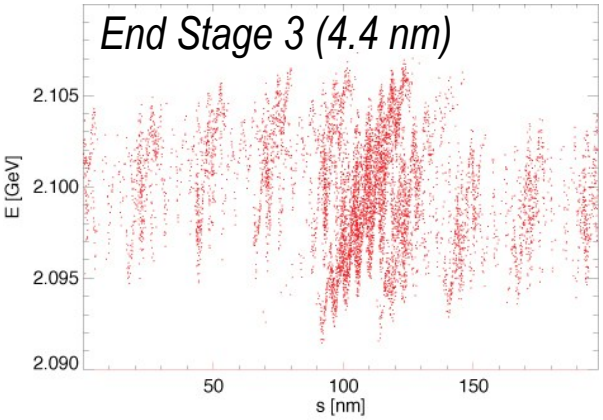
Same Bunch Technique



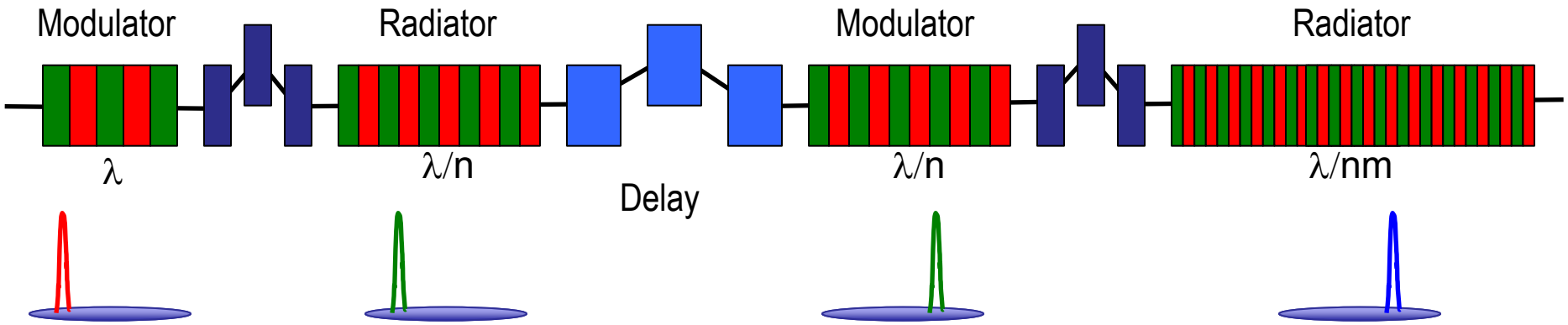
SwissFEL Design Study (200 nm → 22.2 nm →4.4 nm)







Fresh Bunch Technique (e.g. FEL II at FERMI@Elettra)



Comments on HGHG

Strong progress in the last year mostly due to the success of FERMI. Wavelengths down to 4 nm have been achieved.

However an HGHG FEL cannot be optimized much for pulse energy:

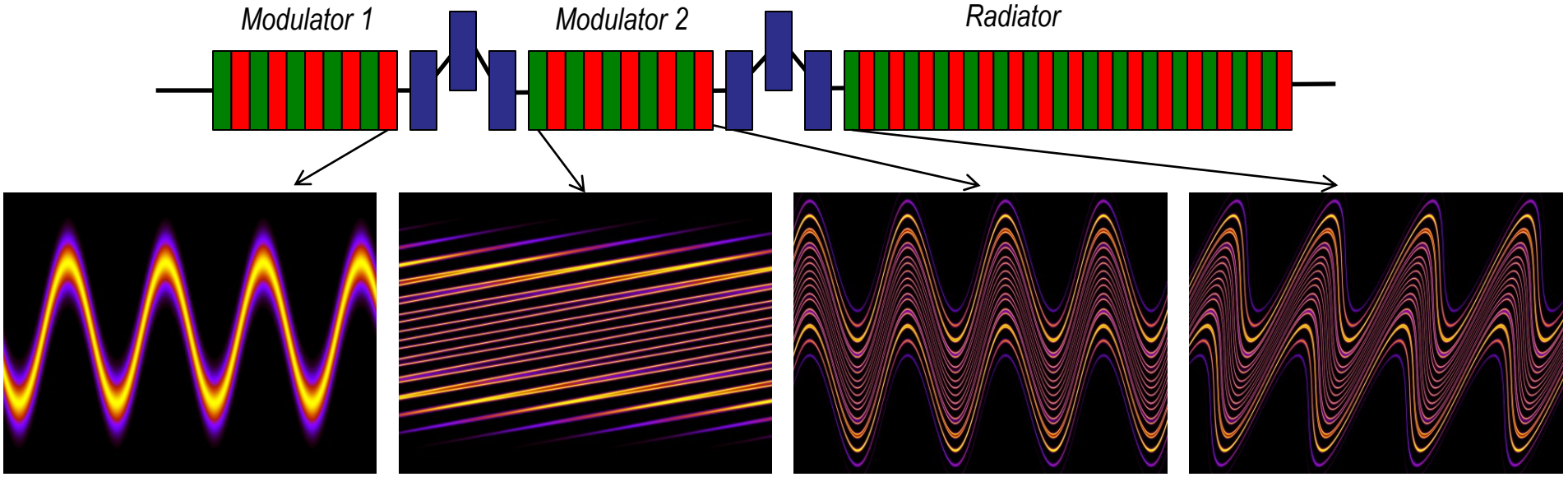
- Only fresh bunch feasible for cascades due to the tremendous sensitivity of same bunch cascades
- Long bunches reduces the current and thus the saturation power
- Only a subsection of the bunch contribute to the final radiation stage (similar to HHG seeds)
- Energy spread of initial beam has to be less than in SASE case, limiting the use of laser heaters in the injector and machine.

Wavelengths down to 1 nm seems feasible

Good for sync FEL pulse to external signal

Not optimized for pulse energy.

Echo-Enabled Harmonic Generation

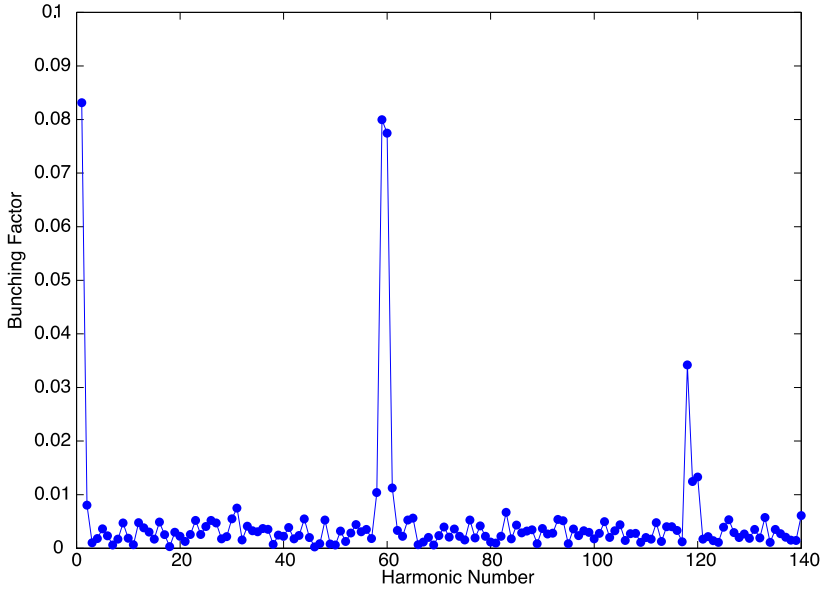


Basic Idea [*D. Xiang and G. Stupakov, PR STAB 12 (2009) 030702*]:

- First stage: Modulation and overcompression to generate energy bands
- Second stage: HGHG principle but spacing of bands defines harmonics

High efficiency for bunching

$$b_{\max} = \frac{0.39}{m^{1/3}}$$

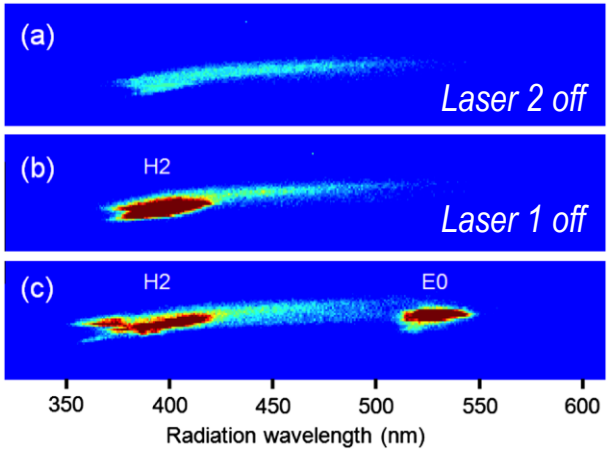


Experiments for EEHG

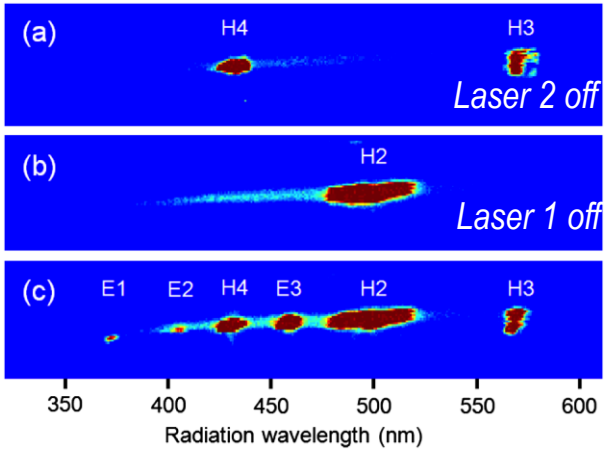
[*D. Xiang et al PRL 105 (2010) 114801*]

λ_1= 759 nm, λ_2 = 1590 nm

Little Chirp



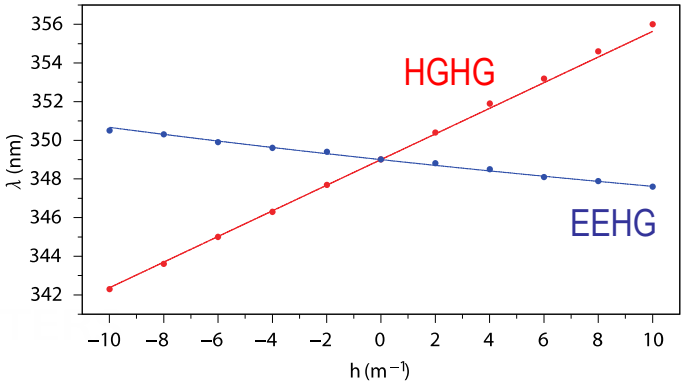
Strong Chirp

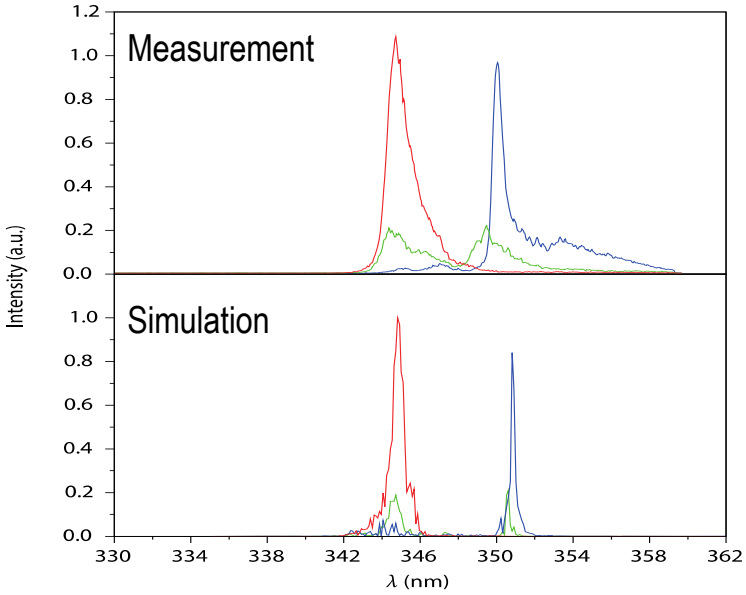


[*Z.T. Zhao et al Nature Photonics 6 (2012) 360*]

λ_1= 1047 nm, λ_2 = 1047 nm

Wavelength vs chirp





Wavelength Limit of EEHG

Although scaling towards shorter wavelength is promising, there are practical reasons for the higher harmonic numbers:

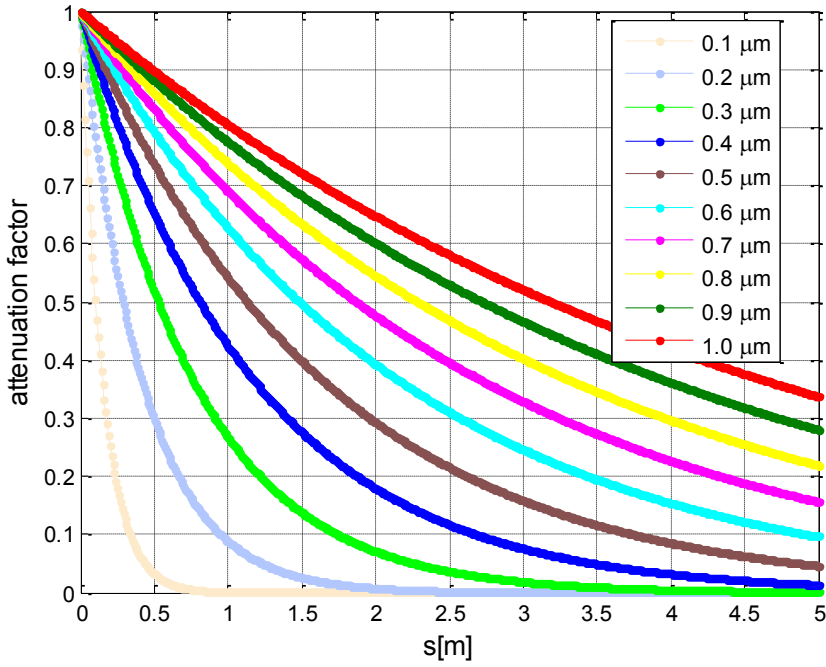
- Total width of energy modulation is limited by FEL process ($\Delta\gamma/\gamma<\rho$)
- Number of lines defines harmonic *m* with an average line spacing of $\delta\gamma/\gamma < \rho/m$
- Hyperfine structure can be blurred out by:
  - Quantum Fluctuation of the incoherent emission in modulator and chicane
    - Favors low magnetic field and long chicanes
  - Intrabeam scattering [G. Stupakov, FEL 2011]
    - Favors compact chicanes

Wavelength limit at about 1 nm

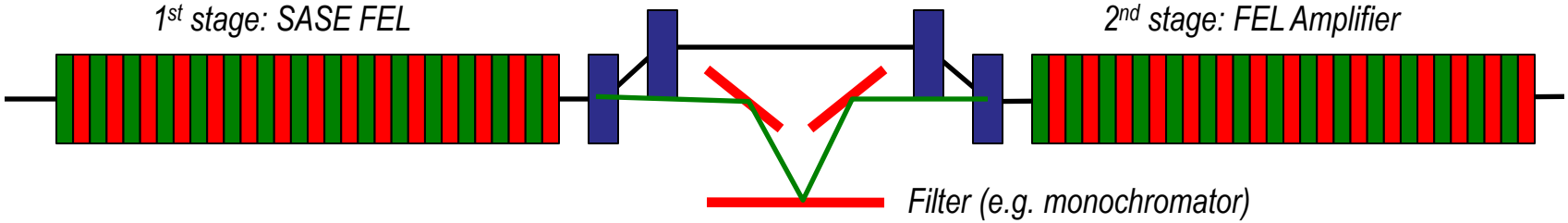
Good control of electron chirp

1st chicane can lengthen bunch

Dependence of IBS on emittance @ 1 nm



Self-Seeding



Basic Idea:

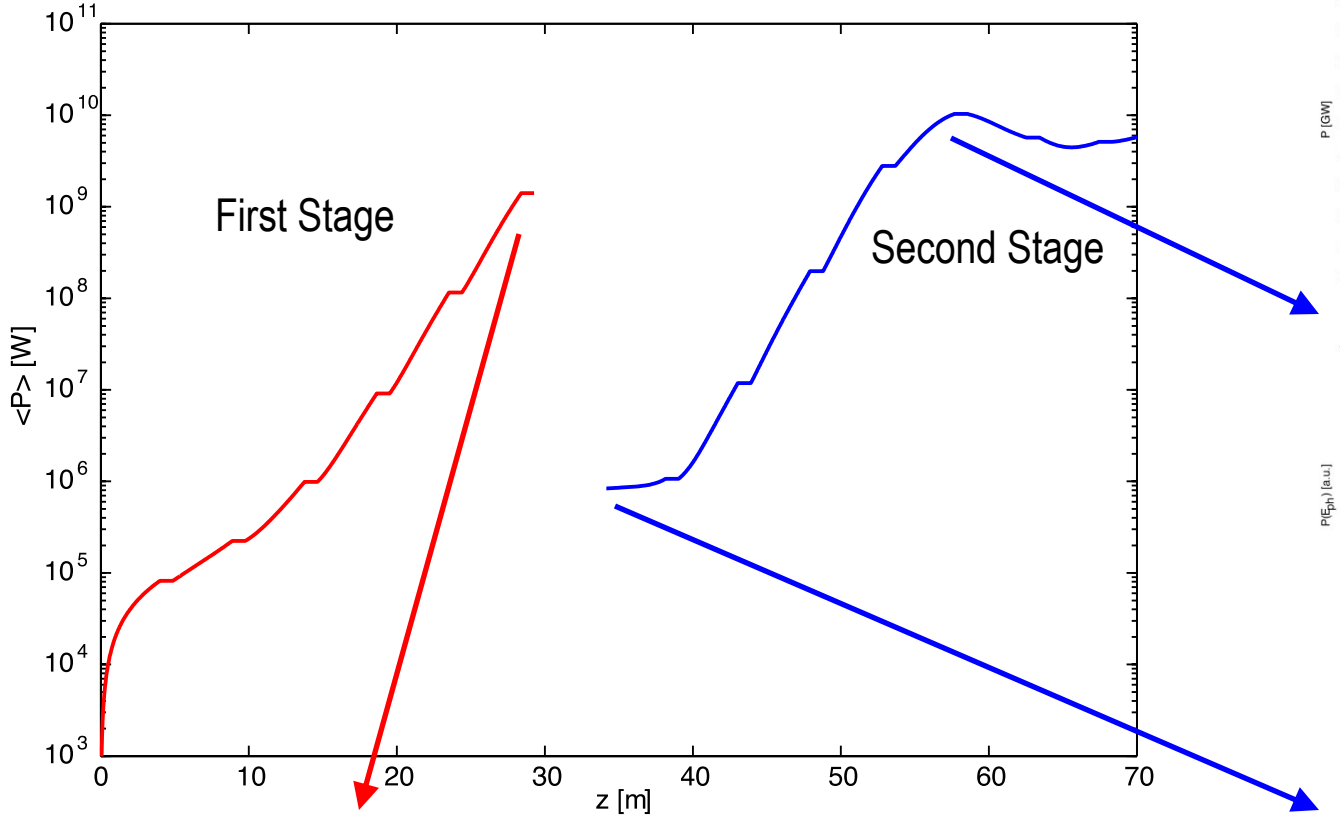
- 1st stage operates as SASE FEL, but stopped before saturation
- Radiation is filtered, introducing longitudinal coherence
- Delay of radiation field is matched with delay electron beam with a magnetic chicane. The chicane removes also any induced bunch, removing the imprint of SASE in the bunch (quasi fresh bunch)
- Beam and radiation are overlapped in a second stage, operating as an FEL amplifier.

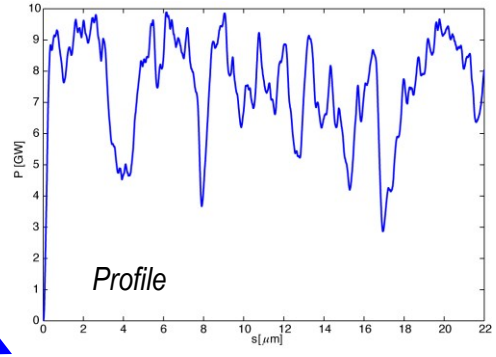
First proposed for soft X-ray FEL FLASH *[J. Feldhaus et al, Opt. Comm 140 (1997) 341]* but never realized due to the strong delays in the photon and electron path.

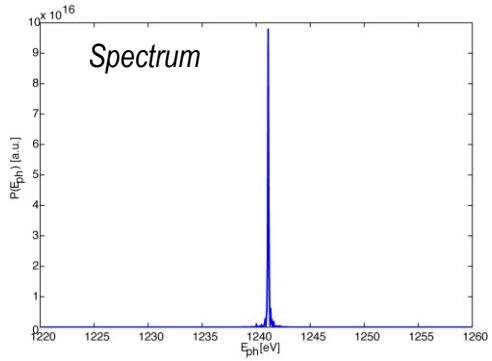
Idea brought up again for hard X-ray [*G. Geloni, Jour. Of Modern Optic 58:16 (2011) 1391*], using the transmission around the stop band of a Bragg reflection (see next slide).

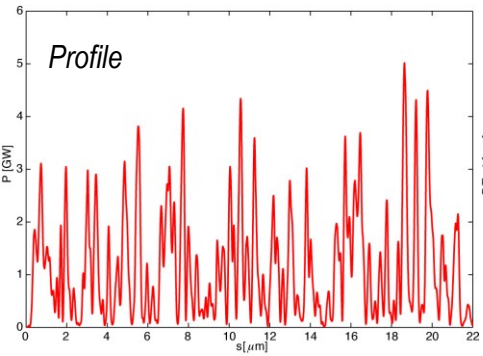
More compact design for soft X-ray [*Y. Feng, LCLS*] makes self-seeding feasible for longer wavelength

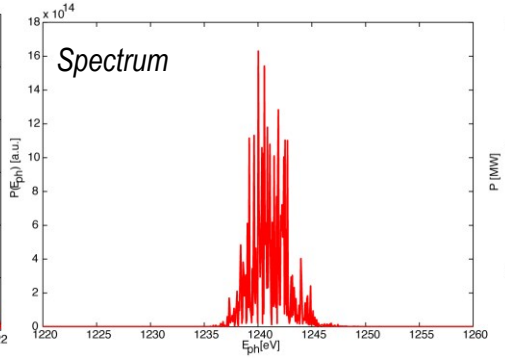
Example Performance for SwissFEL at 1 nm

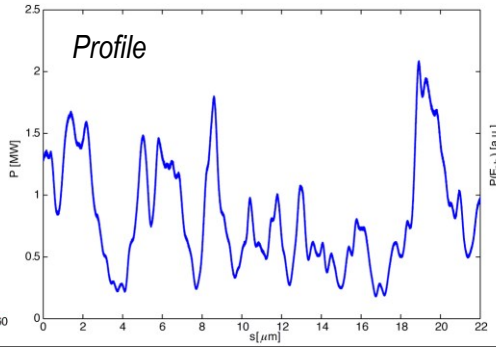


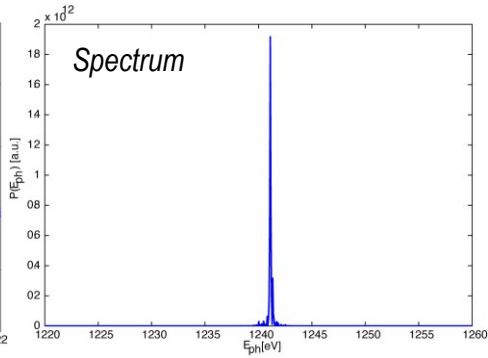




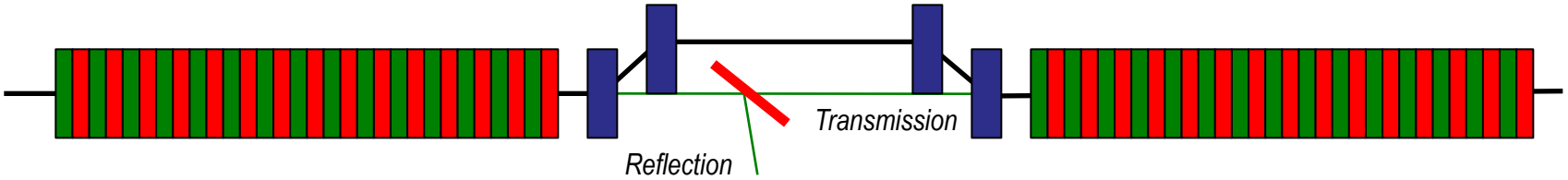




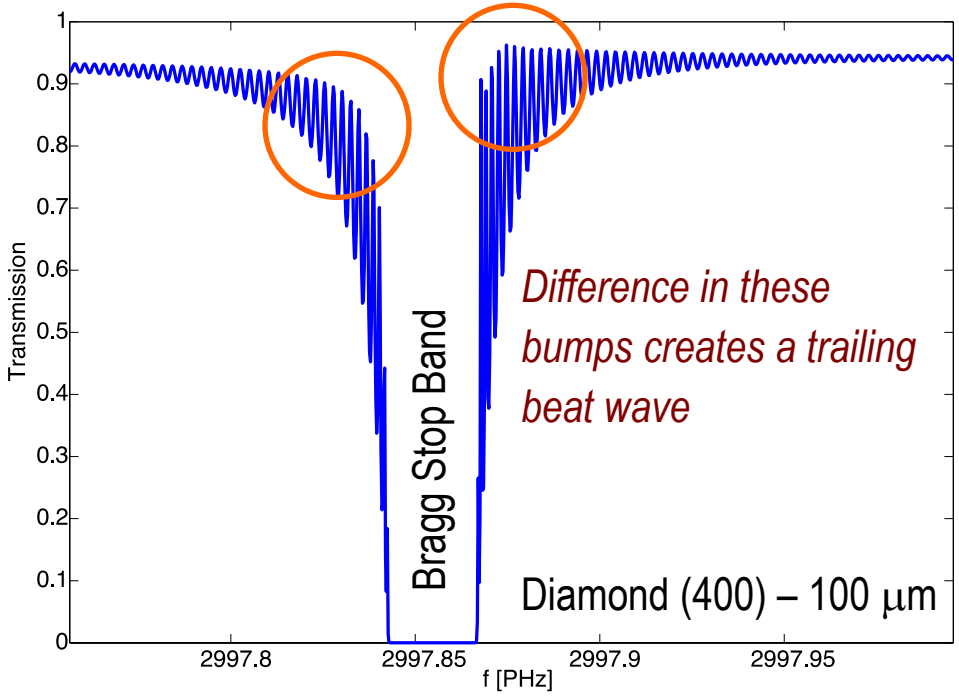




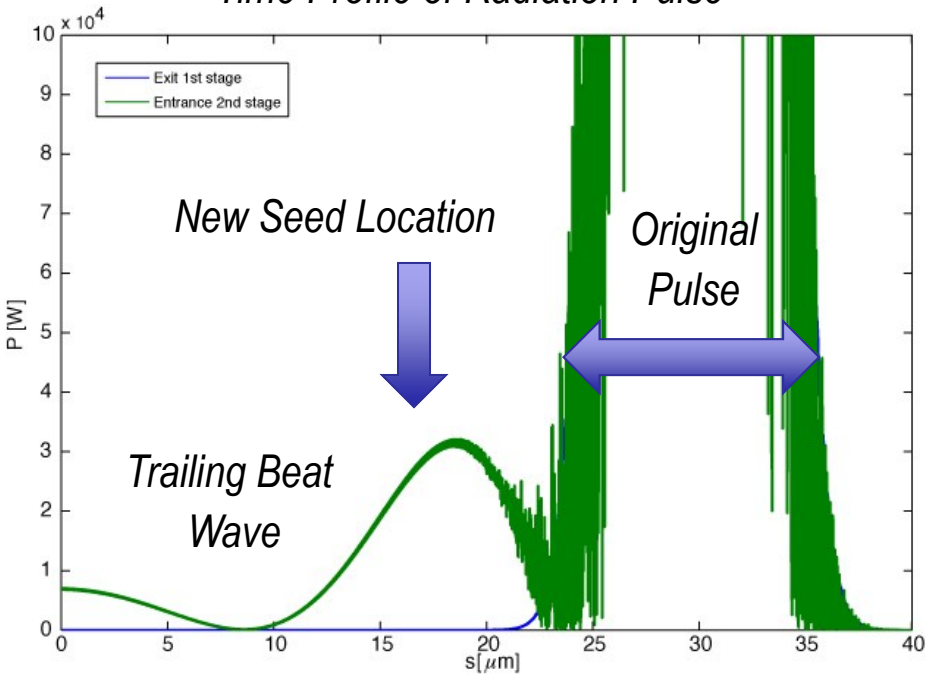
Self-Seeding for Hard X-rays



Transmission



Time Profile of Radiation Pulse



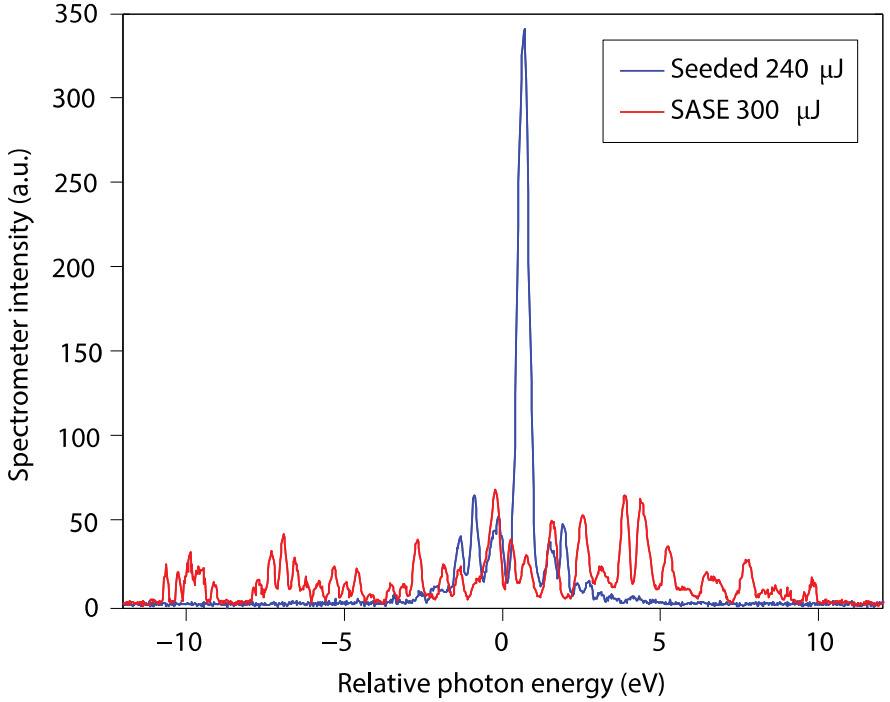
Bunch Delay by Chicane

Proof-of Principle Experiments

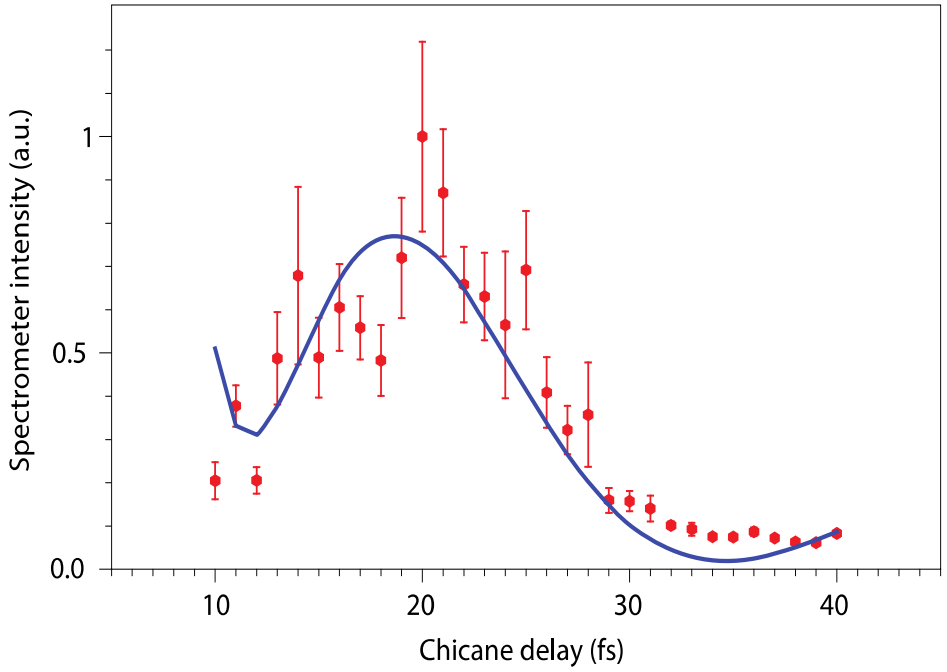
Hard X-ray Self-seeding done at LCLS for 8 keV [*J. Amann et al, Nature Photonics 6 (2012) 693*]

- Wavelength: 1.5 nm
- Diamond Crystal, using (400) reflection
- Reduction of Bandwidth by factor 40 observed
- Output energy very sensitive to electron energy jitter

Single-Shot Spectrum

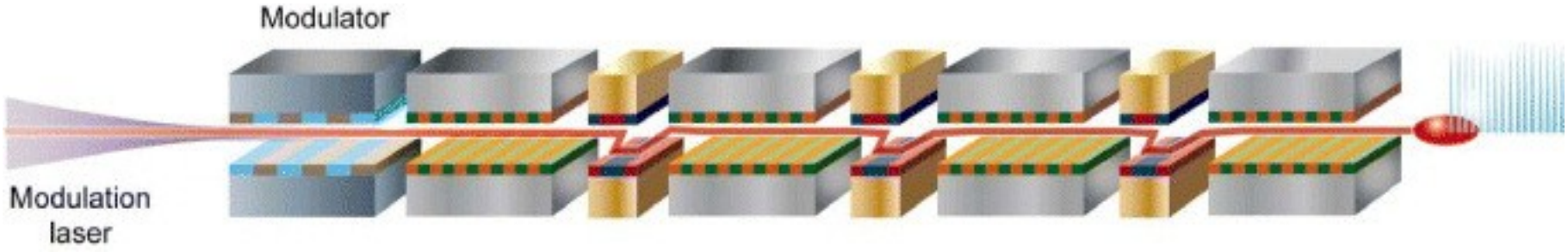


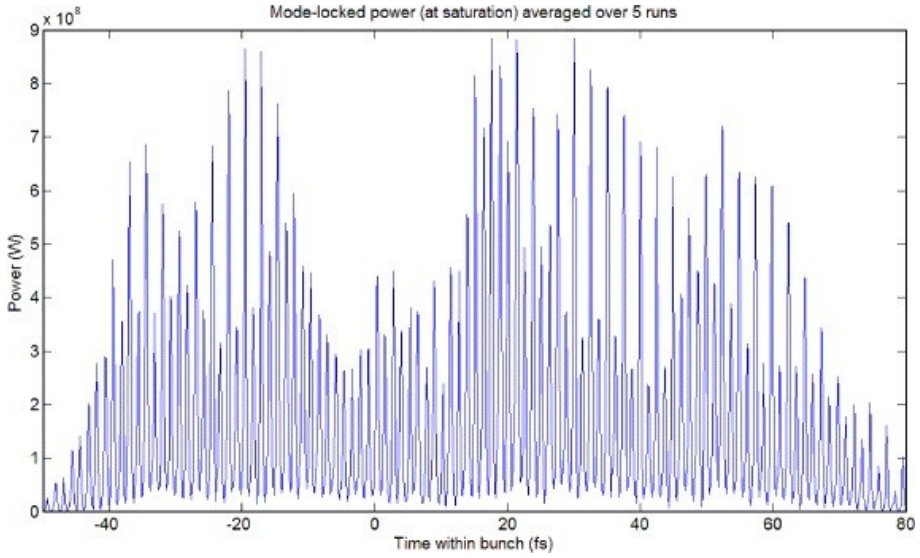
Electron Bunch Delay

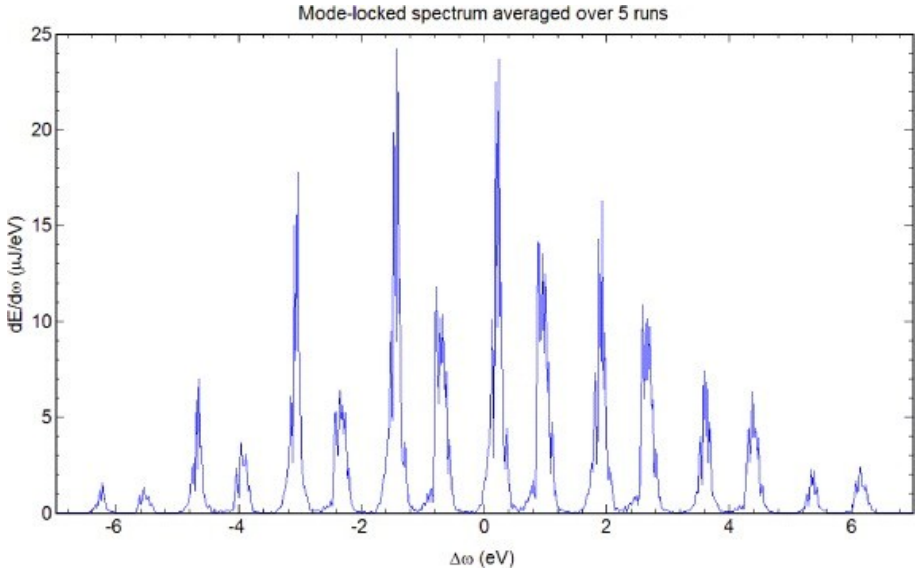


Slippage Enhancing Schemes I

Mode Locked FEL (*N.R. Thompson et al, PRL 100 (2008) 203901*)







- Increase Slippage by delay lines
- Undulator modules shorter than one gain length
- Lock with a modulation synched to slippage per stage
- Single mode selectable by increasing delay (1,2,4,8 etc) → iSASE [*J. Wu et al, FEL Conference 2012*]

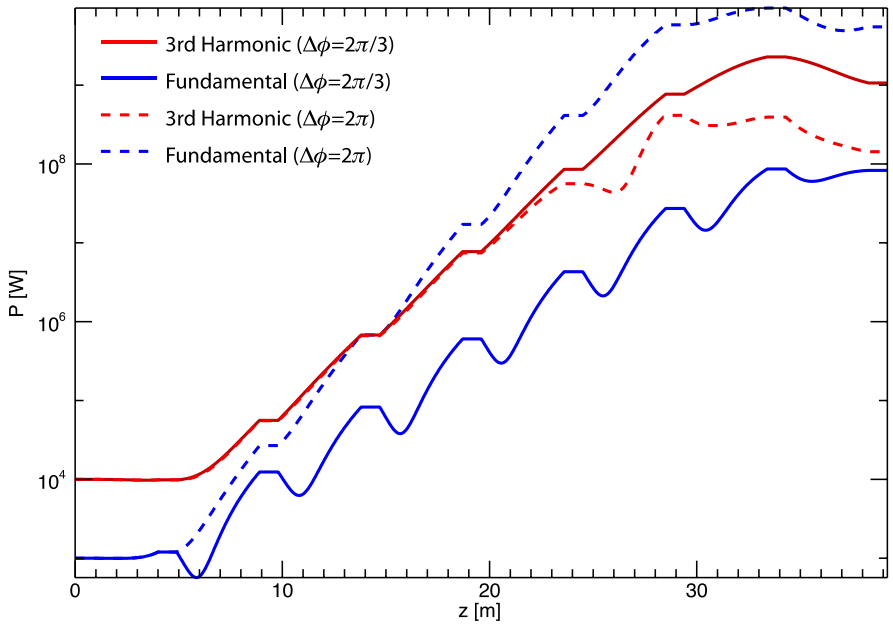
Slippage Enhancing Schemes II

- For high K-values, the FEL is operated at the higher harmonics *n*
- Phase shifter disrupts fundamental by $\Delta\phi = m\,2\pi / n$ with *m* is integer, optimized for best suppression of fundamental.
- Requires rather short undulator modules less than two gain length.

Enhanced slippage and thus narrow bandwidth

Full Undulator: [*E. Schneidmiller, DESY 12-070*]

Sub-section with high harmonic (pSASE): [*D. Xiang et al, PR STAB 16 (2013) 010703*]



Example for SwissFEL Soft X-ray at 2 nm

$$L_g \propto \lambda_u / \left(\lambda_u \, K \, JJ_n\right)^{\frac{2}{3}}$$

λ_u	4 cm	5 cm
K	1	2.3
n	1	3
JJ_n	0.8	0.4
L_g	2.5 m	2.5 m

Comparison and Summary

Method	Direct Seeding (HHG)	HGHG Cas. or EEHG	Self-Seeding
Wave Length Limit	>20 nm	> 1nm	> 0.1 Å
Synchronization	Good	Good	None
Brilliance	Similar to SASE (penalty from seed BW)	Slightly better (penalty from lower current)	Much better than SASE
Pulse Length	~10 fs	10 – 100 fs	As electron bunch
Signal-to-Background	Poor	Moderate - Good	Excellent
Complexity	Moderate (excluding source)	High	Moderate
Electron Beam Requirement	Arrival time and energy stability	Arrival time and energy stability, lower energy spread	Energy stability
Undulator Length	Slightly less than SASE FEL	Comparable and longer than SASE FEL	50% longer than SASE FEL

Summary

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

Several methods are proposed for seeding and sucessfully demonstrated down to 1 Ångtrom.

Except for the synchronization with external signal, self-seeding is most promising and robust method with no inherent limitation below 1 nm.

Seeding at very short wavelength are very limited. Novel ideas emerging to improve performance of seeded FELs