Physics of Free-Electron Lasers

Optical Architectures

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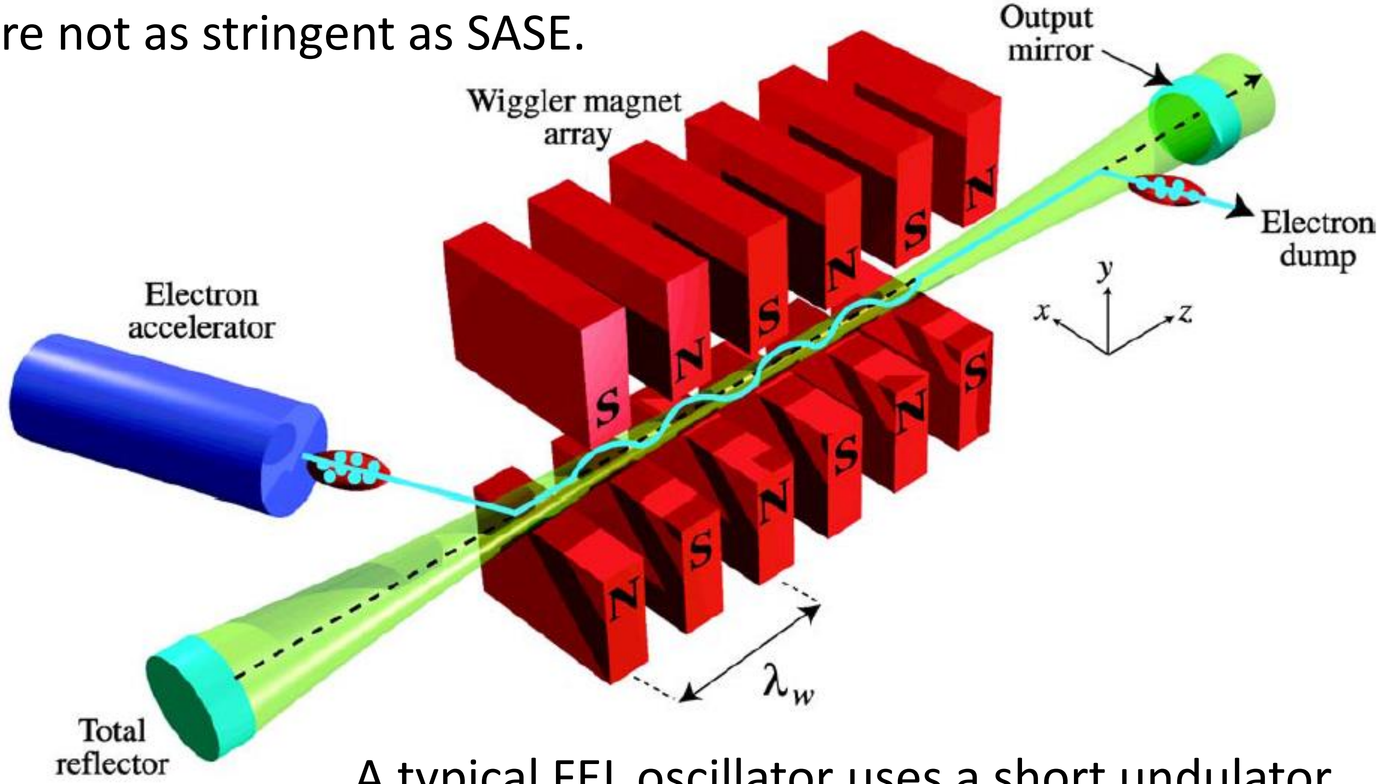
Optical Architectures

1. Oscillator
2. Regenerative Amplifier
3. Seeded Amplifier
4. Self-Amplified Spontaneous Emission
5. Other SASE Schemes
    - Self-seeded SASE
    - xSASE (x = e, i, p, HB, modelocked, etc.)
6. Harmonic Generation
    - Harmonic Bunching
    - HGHG

Elements of an FEL Oscillator

The first FEL was an oscillator. The electron beam requirements for FEL oscillators are not as stringent as SASE.



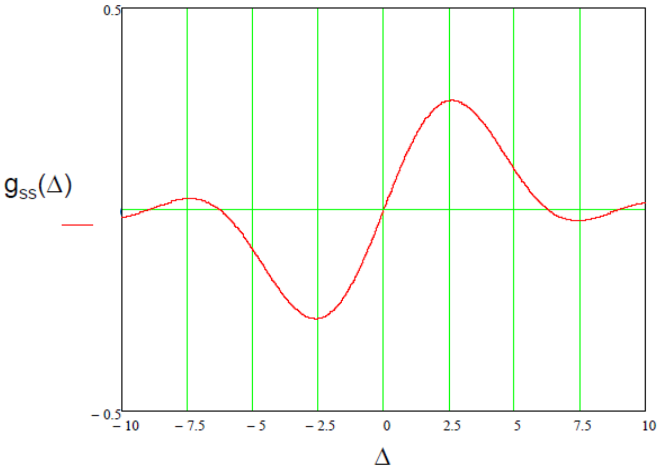
A typical FEL oscillator uses a short undulator (sometimes called a wiggler) and a high-Q optical resonator to trap the FEL pulses in 100s of passes.

FEL Oscillator Glossary

Small-signal gain (SSG)	Single-pass amplification factor minus 1. In the low-gain regime, SSG is typically expressed in %. For example, 50% SSG equals 1.5X gain per pass.
Large-signal gain (LSG)	Single-pass gain is reduced from SSG (low power) to the LSG (high power) at saturation. Saturated LSG = optical cavity loss per pass.
Optical resonator	A series of curved mirrors with at least one mirror partially transmitting to allow the FEL power to exit the resonator.
Optical cavity length	The length of the optical cavity trapping the FEL pulses. It must be set so the pulse overlaps with a new electron bunch in each pass.
Efficiency	FEL pulse energy outside the optical cavity divided by the energy in each electron bunch. FEL oscillator efficiency scales with $1/N_u$.

Small-signal Gain

- The SSG peaks at a longer wavelength than the resonant wavelength (at fixed beam energy) or at higher beam energy than resonant (at a fixed wavelength)



Detuning

$$\Delta = \pi N_u \eta = 2\pi N_u \frac{\Delta\lambda}{\lambda}$$

Maximum SSG occurs at $\Delta_{peak} = 2.6$

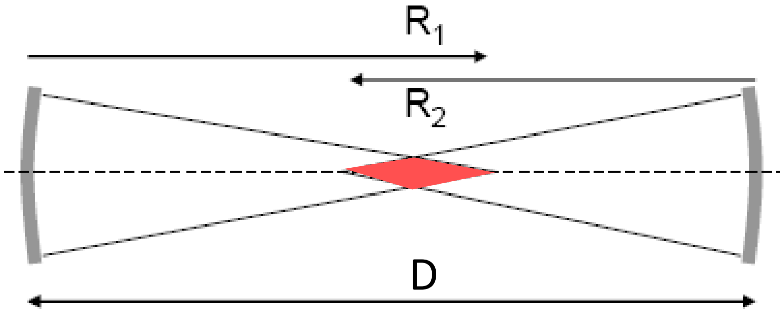
$$\left(\frac{\Delta\lambda}{\lambda}\right)_{peak} = \frac{0.414}{N_u}$$

- The SSG scales with the cube of the product of rho and N_u (thus, SSG scales linearly with peak current). SSG at the peak of the gain curve is given by

$$G_{ss} = \frac{(4\pi N_u \rho)^3}{\pi} = \frac{2N_u^3}{\gamma^3}\frac{\hat{K}^2\lambda_u^2}{\sigma_b^2}\frac{I_{pk}}{I_A}$$

Near-concentric Resonator

- The simplest optical resonator consists of two mirrors, one total reflecting and the other partially transmitting to out-couple the FEL power, separated by a distance D. The sum of the radii of curvature, R_1 and R_2, should be more than D. The distance $R_1 + R_2 - D$ (red) is a measure of the resonator's stability.



- A measure of stability for the optical resonator is the g factor $g_i = 1 - \frac{D}{R_i}$

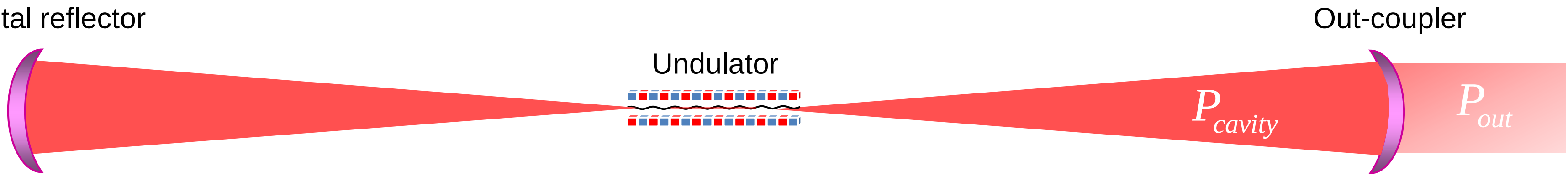
- For a near-concentric resonator, stability requires g_1 and g_2 to be

$$g_1 g_2 \leq 1$$

- For symmetric resonators, stability requires $\left| g \right| \leq 1$

Out-coupling Fraction

- The simplest optical resonator consists of two mirrors, one total reflecting and the other partially transmitting to out-couple the FEL power.



$$P_{out} = \Gamma_{oc} P_{cavity}$$

- Optimum out-coupling (in %) is estimated from G_{ss} (also in %) by

$$\alpha_{opt} = 2\times10^{-7} G^3 - 2.9\times10^{-4} G^2 + 0.2G - 0.024$$

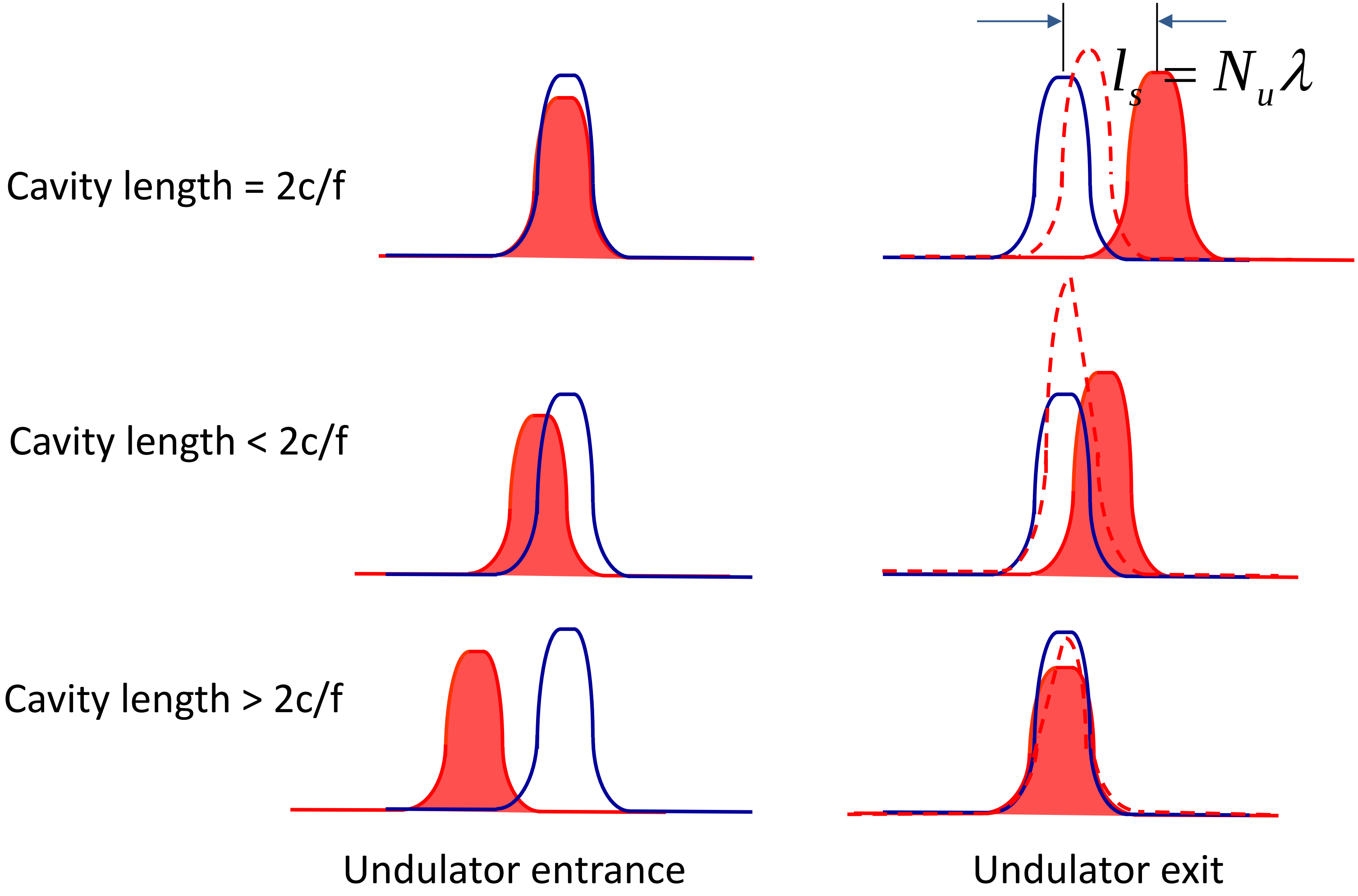
- Output power at optimum out-coupling

$$P_{out} \approx \frac{1}{2.3N_u}\left(\frac{IE_b}{e}\right)$$

Slippage

Slippage in an oscillator FEL establishes longitudinal coherence over many passes.

Slippage in small-signal regime (red dash) is 1/3 slippage at saturation (red solid).



$l_s = N_u \lambda$

Cavity length = 2c/f

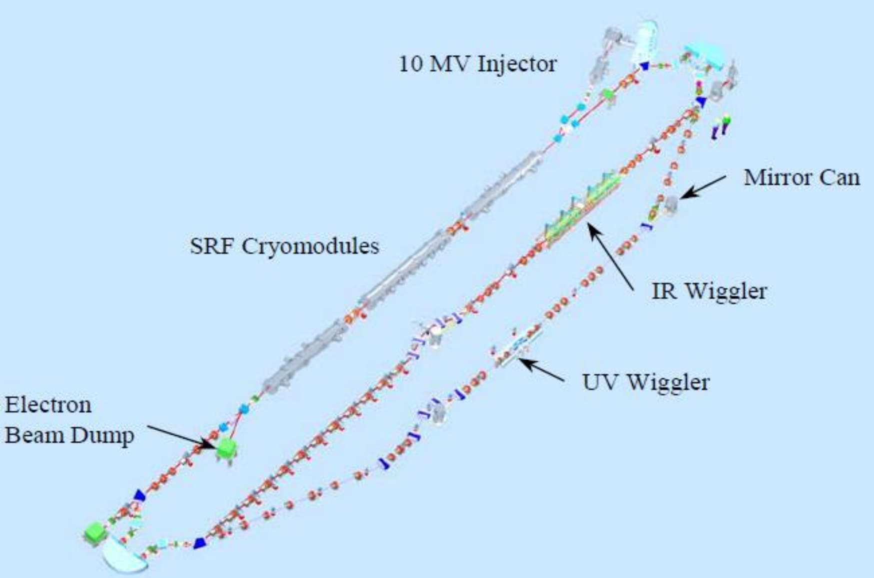
Cavity length < 2c/f

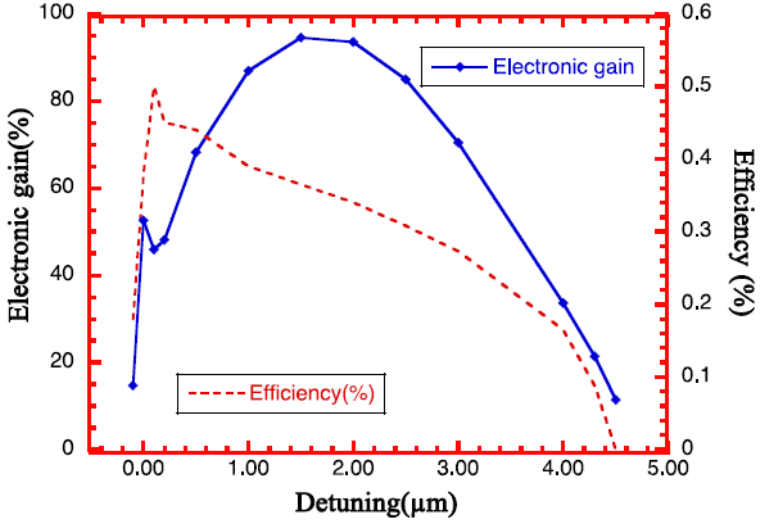
Cavity length > 2c/f

Undulator entrance

Undulator exit

FEL Oscillator with Energy Recovery





Jefferson Laboratory UV FEL produces 140 W

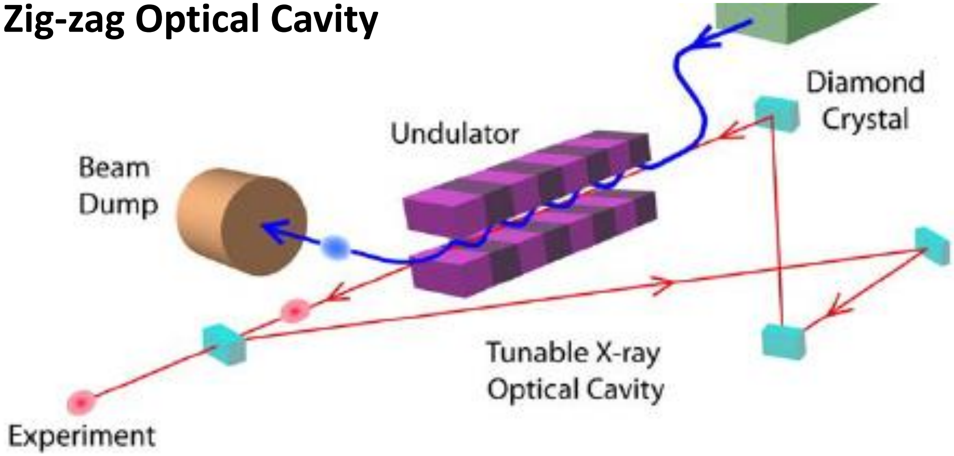
e^- beam energy (MeV)	135
repetition rate (MHz)	4.68-74.85
Q_{bunch} (pC)	60
σ_z (psec)	0.11
I_{peak} (A)	240
maximum I_{ave} (mA)	5
$L_{wiggler}$ (m)	1.98
L_{period} (cm)	3.3
N_{period}	60 (APS undulator A prototype)
K_{wig}	0.5-1.51
gap (mm)	11.5
L_{cavity} (m)	32.04

Optical cavity must be set to the correct length to maximize gain and efficiency (FEL power/electron beam power). Typically, gain is maximized at slightly larger (more negative) detuning than efficiency.

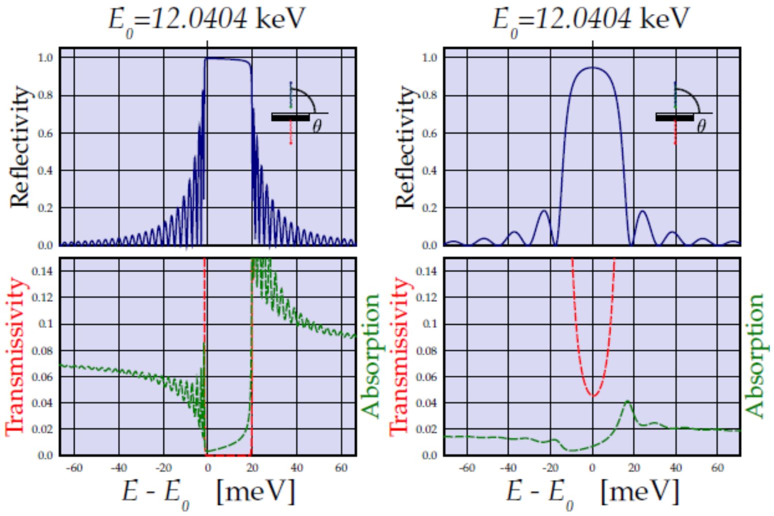
Reference: “The Jlab UV FEL Demo,” by S. Benson et al., Proceedings IPAC 2012, New Orleans, LA, Paper WEYB03

XFEL Oscillator

Zig-zag Optical Cavity



Diamond Mirror Reflectivity



C(4 4 4); L = 0.2 mm; T = 300 K

C(4 4 4); L = 0.042 mm; T = 300 K

XFELO Parameter

γmc^2	7 GeV
Q	25 pC
I_{peak}	10 A
$\varepsilon_{x,n}$	0.2 mm-mrad
$\Delta\gamma mc^2$	1.4 MeV
L_{und}	52 m
G	0.36
R_{tot}	0.85
crystal	C(4 4 4)

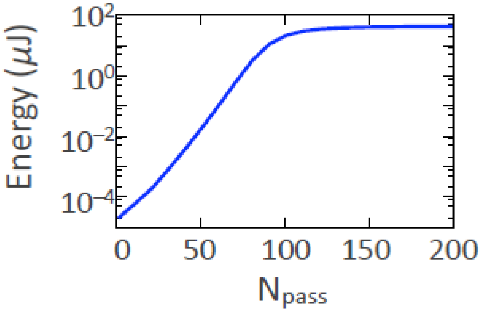
P_{out}	1.7 MW
Photons/ pulse	1.1×10^9
ΔE_{FWHM}	1.95 meV
Δt_{FWHH}	1.58 ps

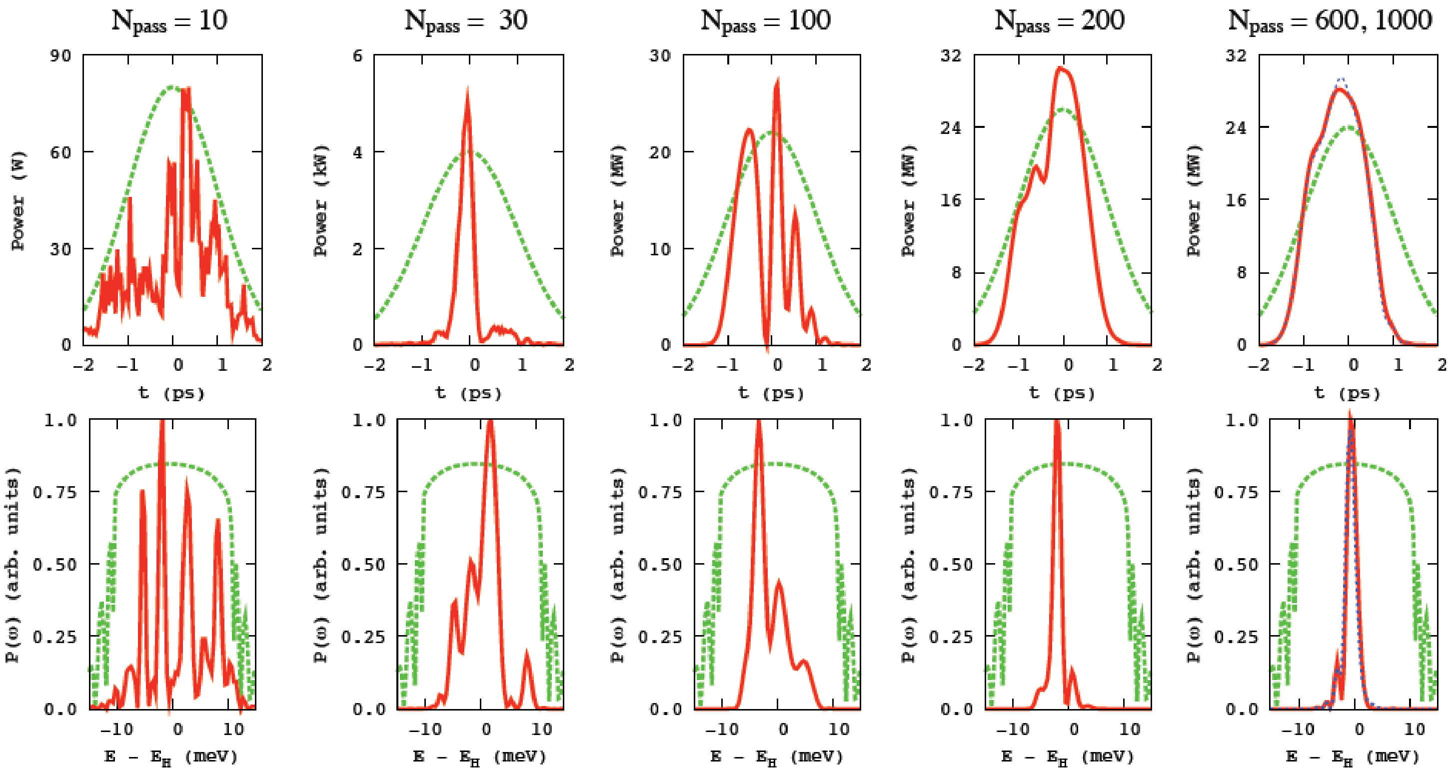
Reference: "XFELO Parameters," by R. Lyndberg et al., Future Light Source 2012, TJNAF, Wednesday talk.

Line-narrowing in XFELO

Evolution of the XFELO spectral output as a function of the number of passes, as modeled with GINGER. The spectral output gets narrower at large N_{pass}.

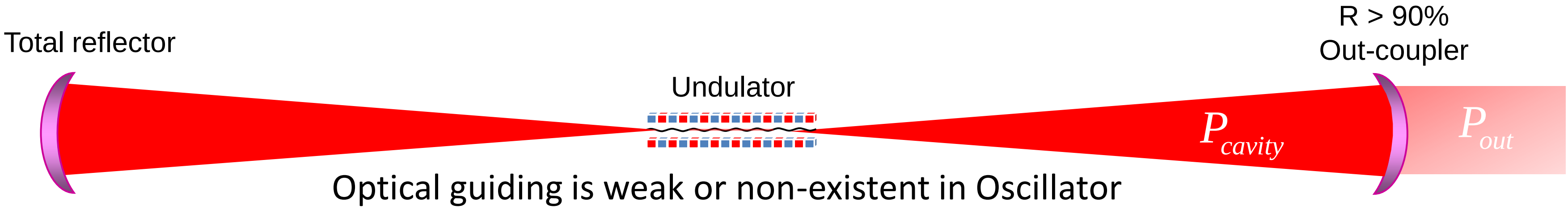
from R. Lindberg's presentation at FLS 2012





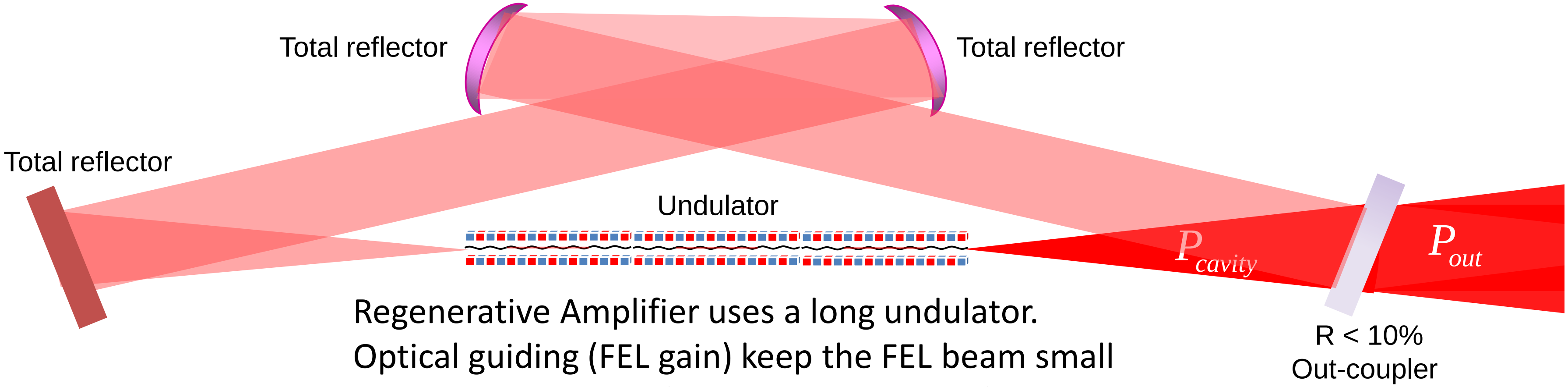
Regenerative Amplifier

Oscillator: Low gain, high Q. The high-Q cavity determines the FEL optical mode and coherence.



Optical guiding is weak or non-existent in Oscillator

Regenerative Amplifier : High gain, low Q. The low-Q cavity provides an optical seed for amplification . The optical mode is determined by the electron beam's properties and FEL gain.



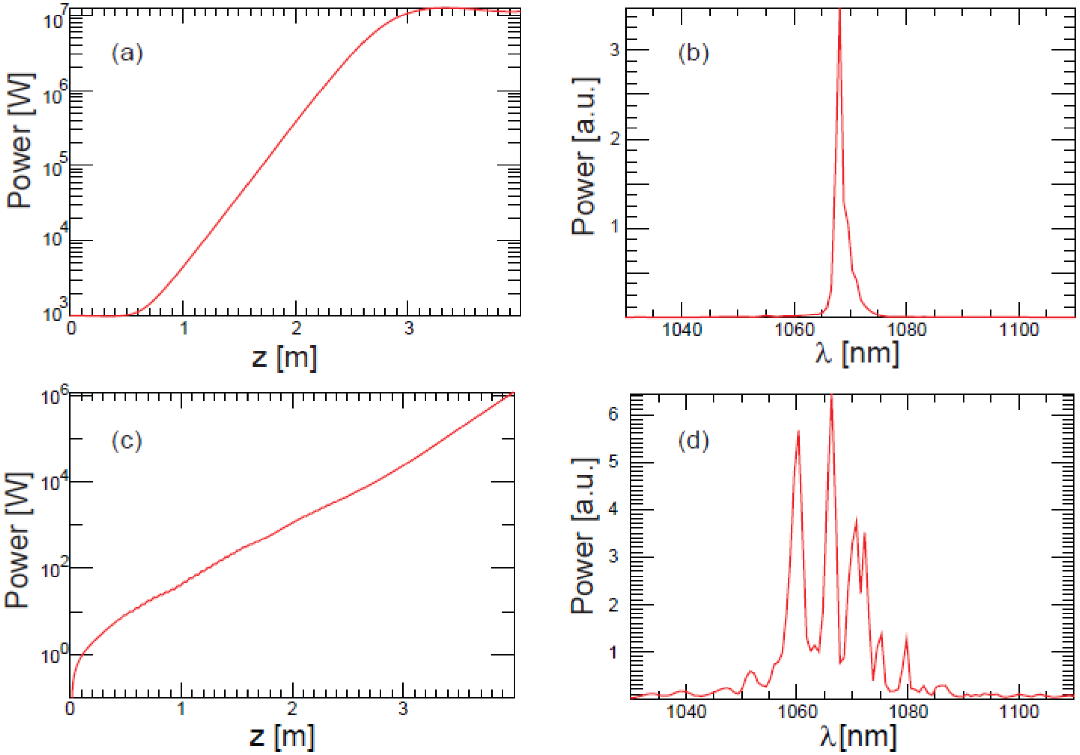
Regenerative Amplifier uses a long undulator.
Optical guiding (FEL gain) keep the FEL beam small along the undulator (only in one direction).

Seeded Amplifier

- Initial power loss of 1/9
- Same gain length as SASE
- Seeded L_{sat} < SASE L_{sat}
- Seeded P_{sat} > SASE P_{sat}
- Single-mode spectrum
- Less amplitude fluctuations (coherence length > Δt_b)

Seeded Amplifier Power

Seeded Amp Spectrum



SASE Power

SASE Spectrum

Self-Amplified Spontaneous Emission

- Gain length

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

- Bandwidth at saturation

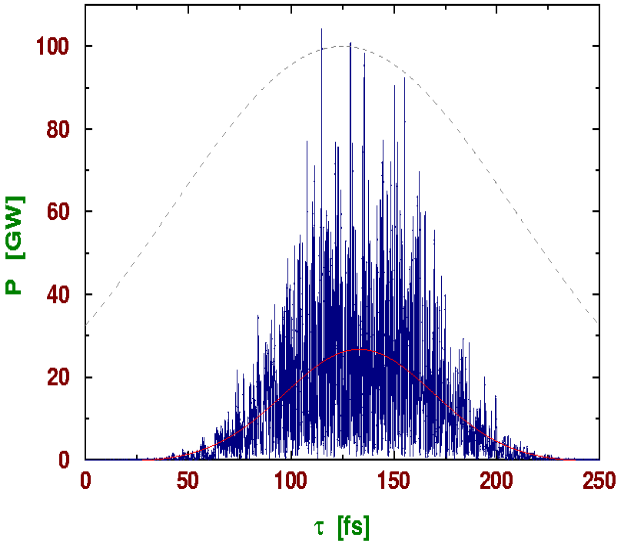
$$\frac{\Delta\omega}{\omega} = \rho$$

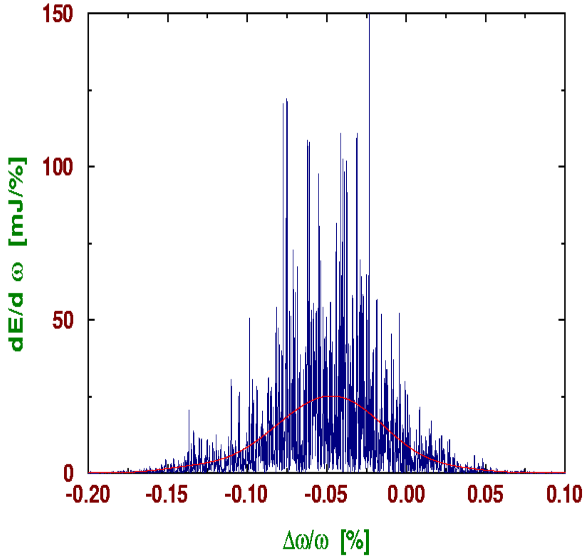
- Coherence length and time

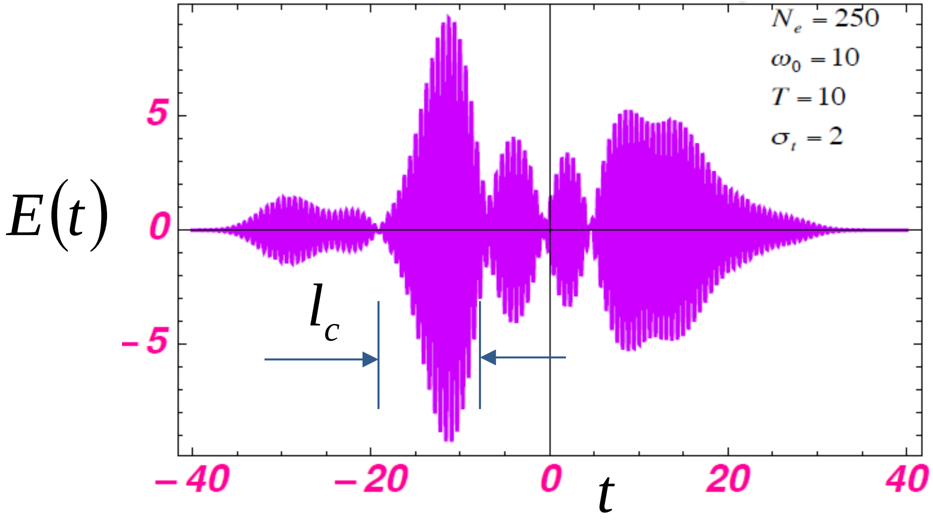
$$l_c = \frac{\lambda}{4\pi\rho} \qquad \tau_c = \frac{l_c}{c}$$

- Number of longitudinal modes

$$M = \frac{\Delta t_b}{\tau_c}$$

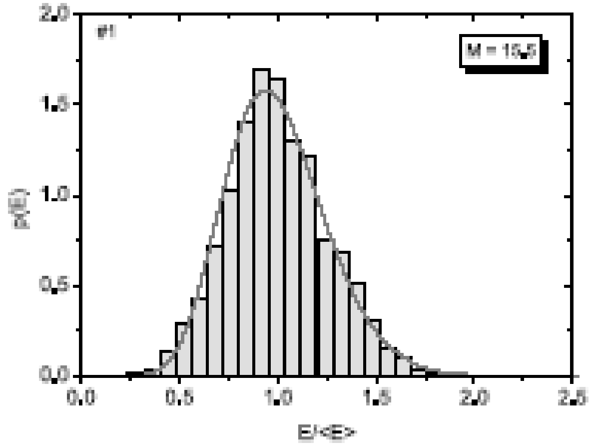




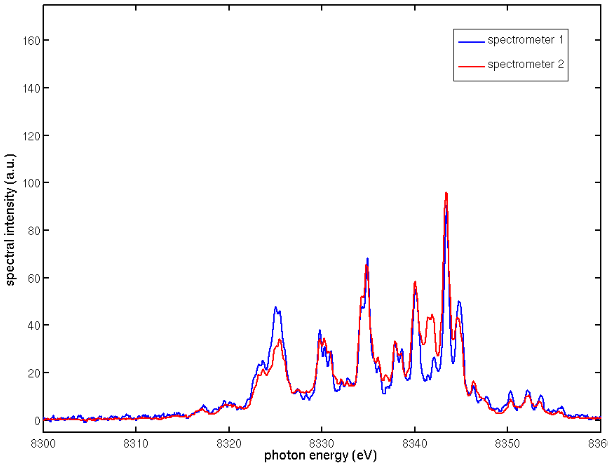


SASE Shot-to-shot Fluctuations

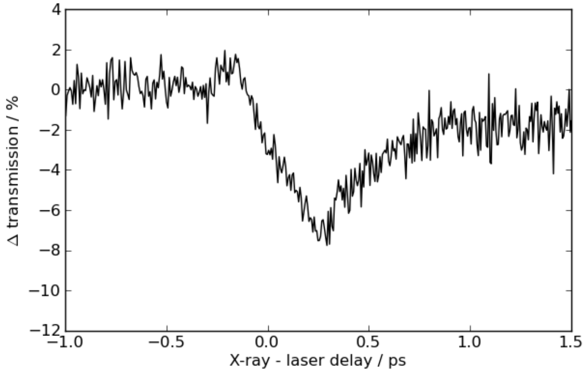
Gamma Distribution



Spectral



Temporal



Shot-to-shot fluctuations of SASE occur in both temporal and spectral domains.

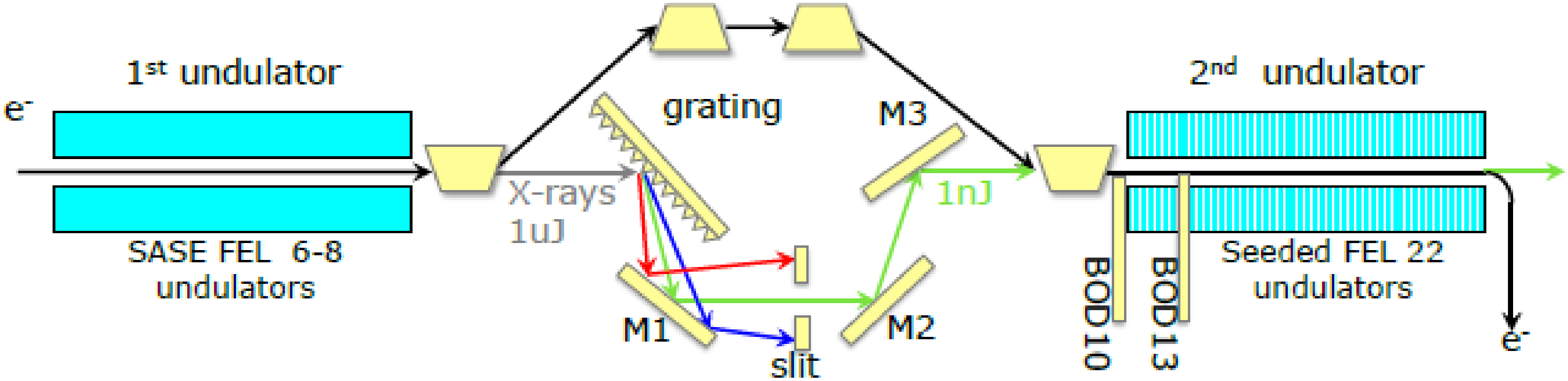
The relative fluctuation of the SASE pulse energy is inversely proportional to the square root of the number of longitudinal modes.

Pulse energy fluctuation

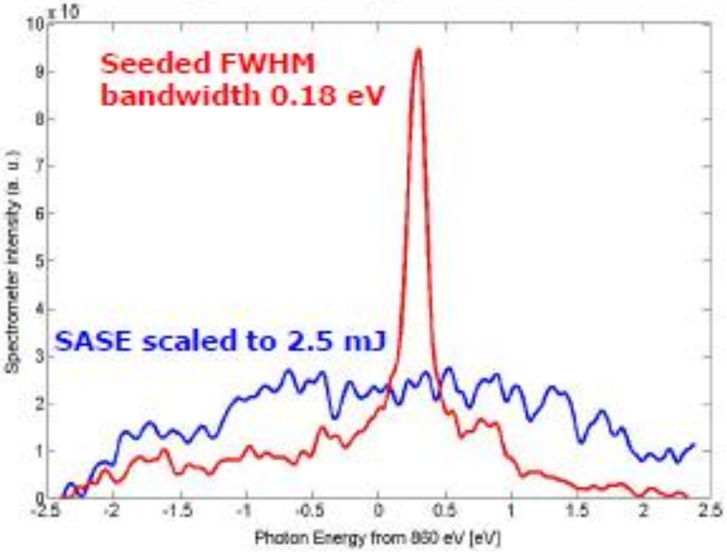
$$\frac{\sigma_W}{W} = \frac{\langle W - \langle W \rangle \rangle}{\langle W \rangle} \propto \sqrt{\frac{1}{M}} = \sqrt{\frac{\tau_{coh}}{\Delta t_b}}$$

Courtesy of the LCLS Team

Soft X-ray Self-Seeding



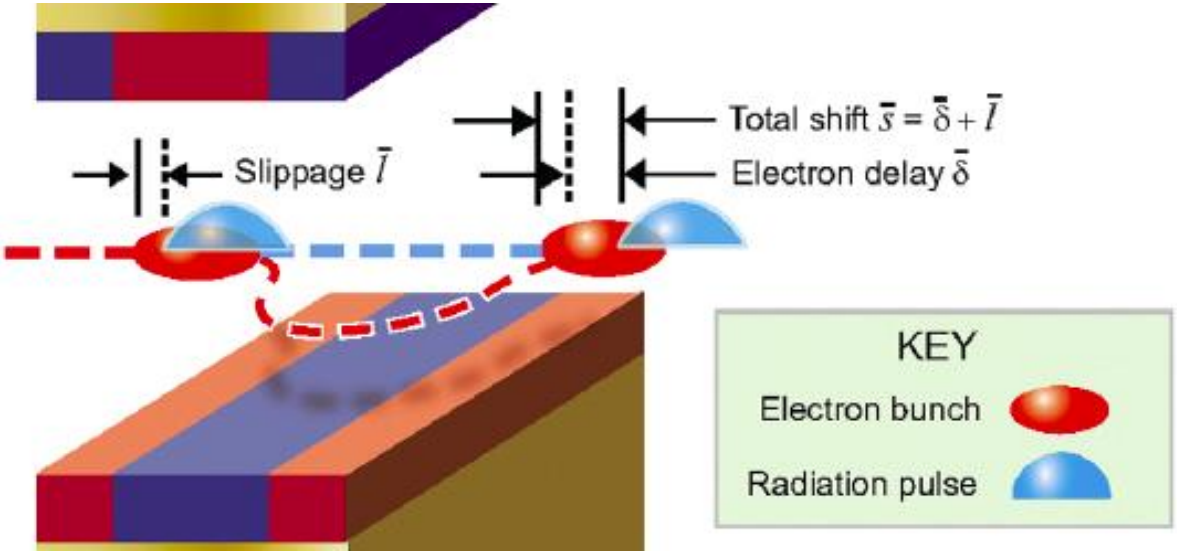
- Use a grating after the 1st undulator section to disperse the SASE radiation
- Select a narrow portion of the SASE spectrum
- Re-inject the spectrally selected radiation as the radiation seed for the 2nd undulator
- Overlap the selected radiation and electron beams in space and time in the 2nd undulator

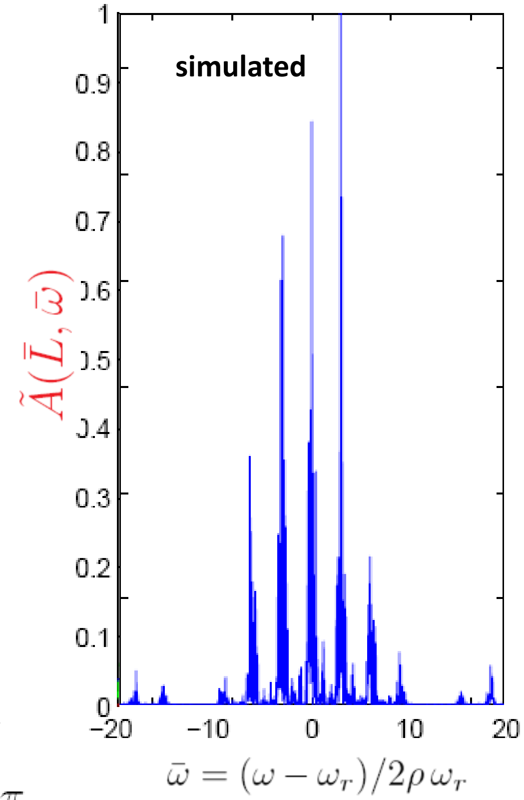


Courtesy of the LCLS Team

Locking the SASE Axial Modes via Repetitive Delays in Chicanes

- Axial modes are synthesised by repeatedly delaying the electron bunch in a magnetic chicane between two undulator modules.
- Produces a sequence of time-shifted copies of the radiation from one module, and hence axial modes are locked.





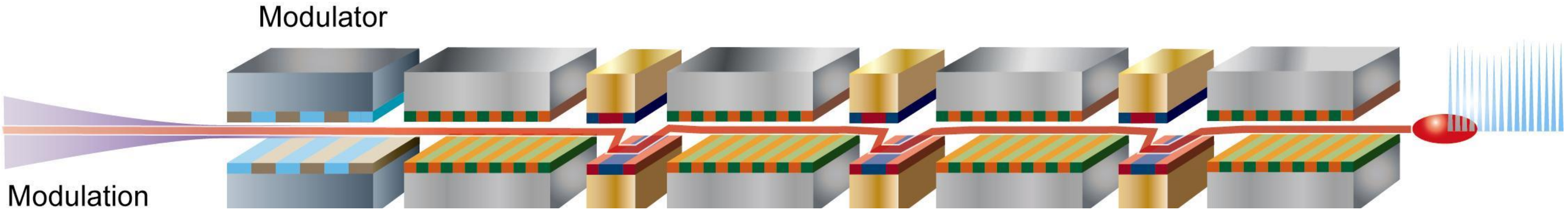
$\bar{s} = \bar{\delta} + \bar{l}$	total delay
δ	delay in chicane
l	slippage in one undulator module
N	number of modules

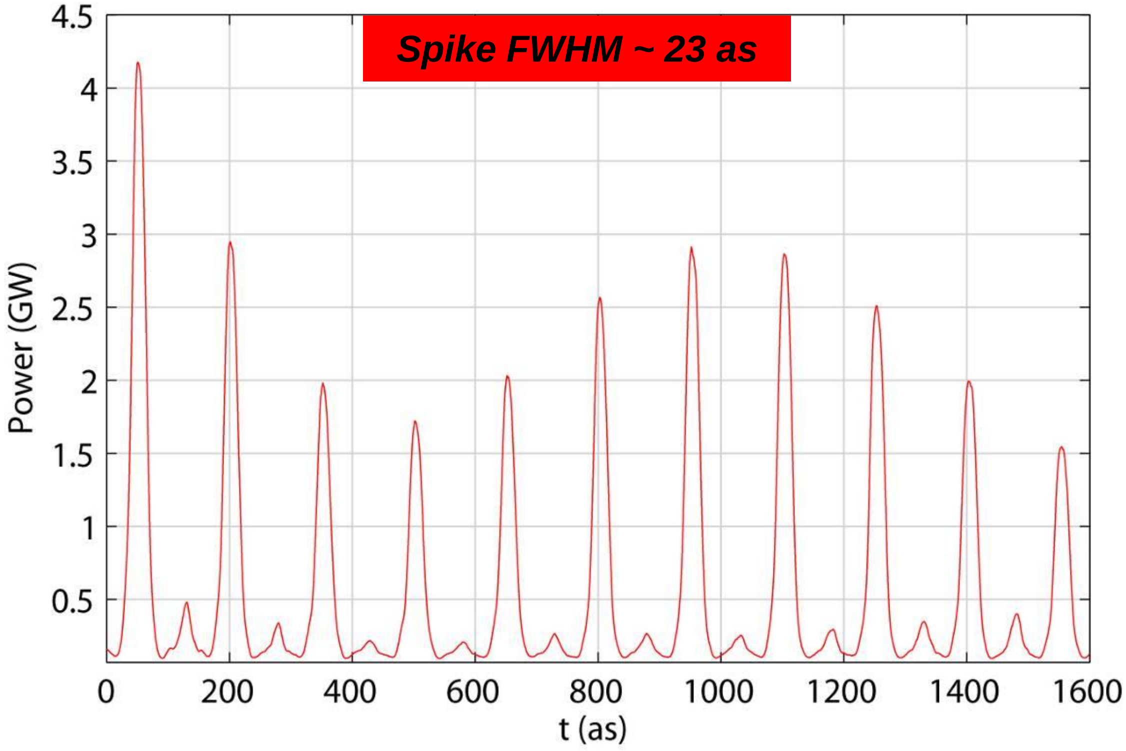
Mode spacing

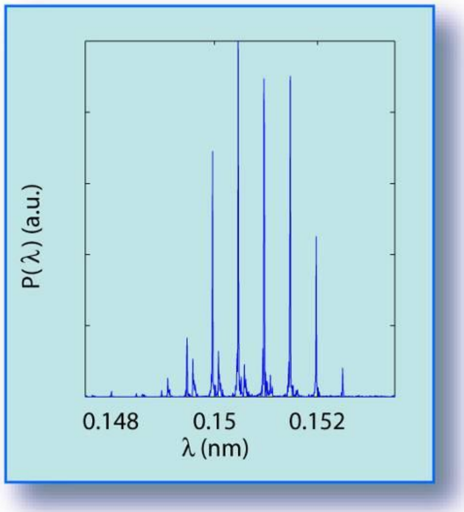
$$\Delta\bar{\omega} = \frac{2\pi}{\bar{s}}$$

Courtesy of N. Thompson

High-brightness SASE



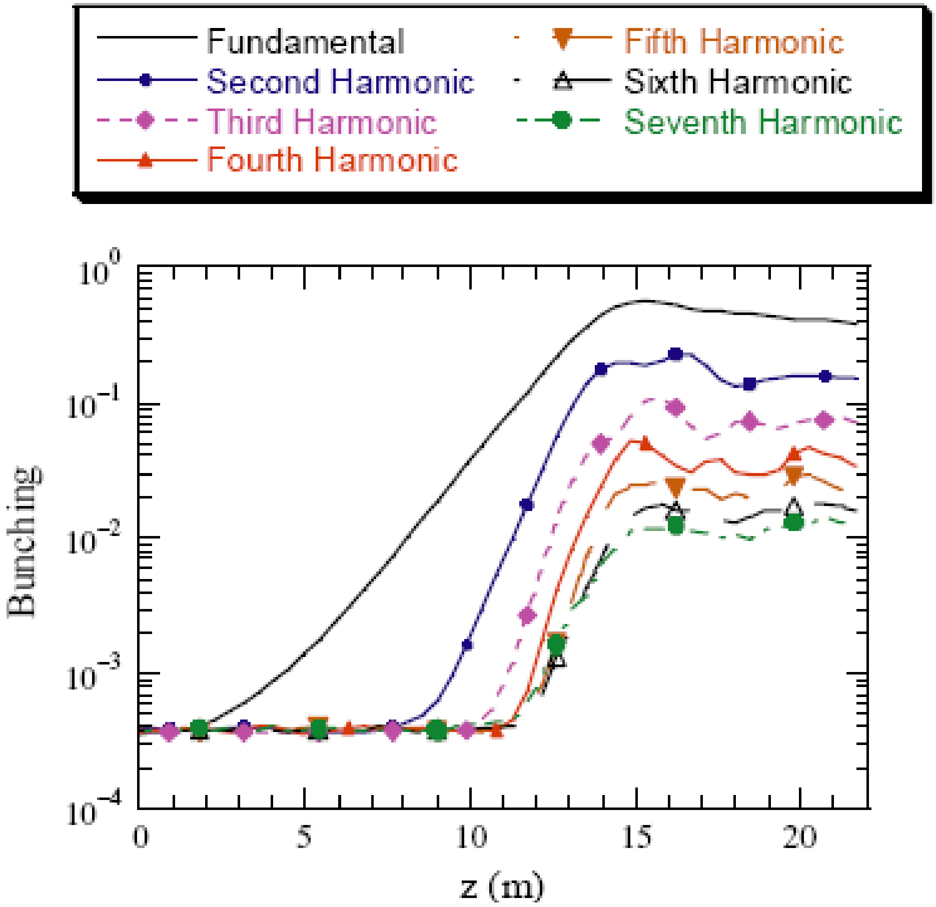

Spike FWHM ~ 23 as



The spectrum is the same as a ring cavity of length s.

Reference: "Transform-limited X-ray Pulse Generation from a High-Brightness SASE FEL," by B.W.J. McNeil et al., http://arxiv.org/pdf/1212.5816v1.pdf

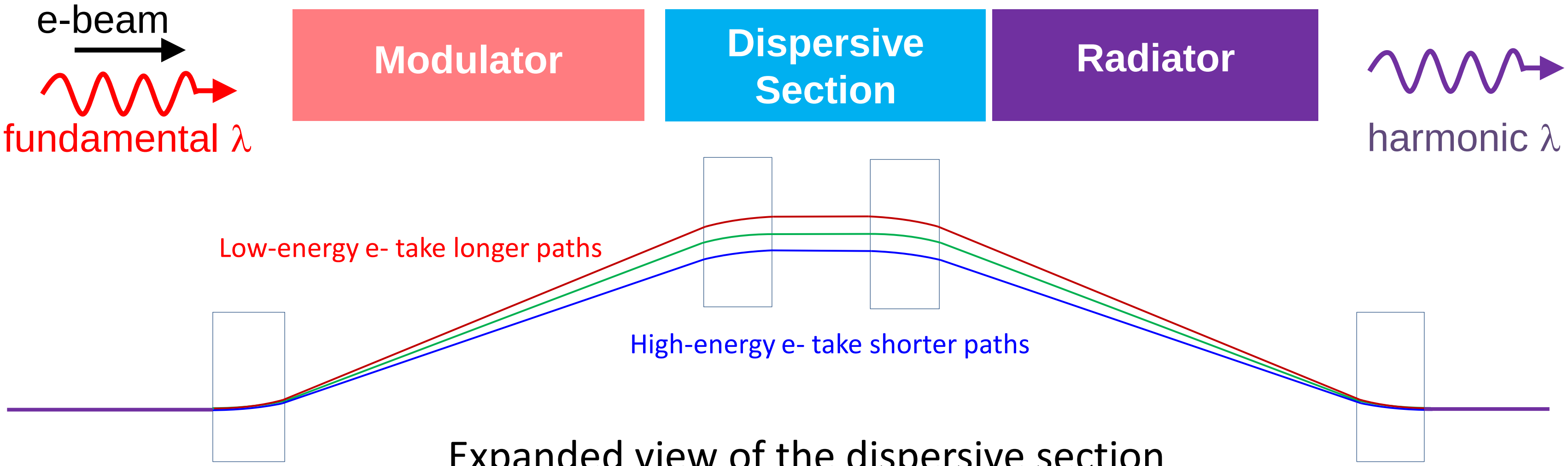
Harmonic Bunching



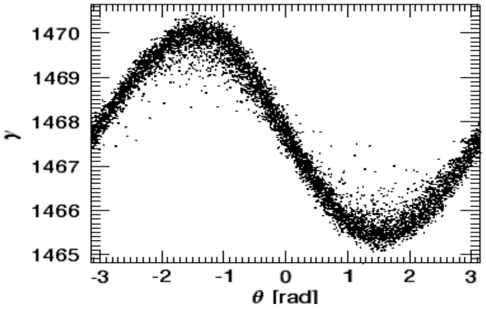
Reference: “Non-linear harmonic generationin FEL,” by H. Freund et al., IEEE J. Quantum Elec. 36(3), 275 (2000).

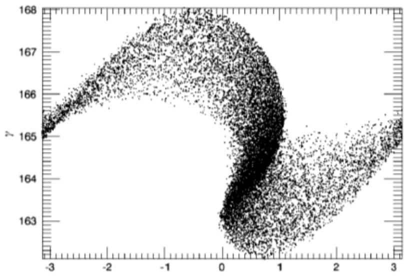
Harmonic bunching occurs later (larger z) but has higher exponential growth rates than the fundamental bunching. The bunching factor decreases with higher harmonics.

High-gain Harmonic Generation



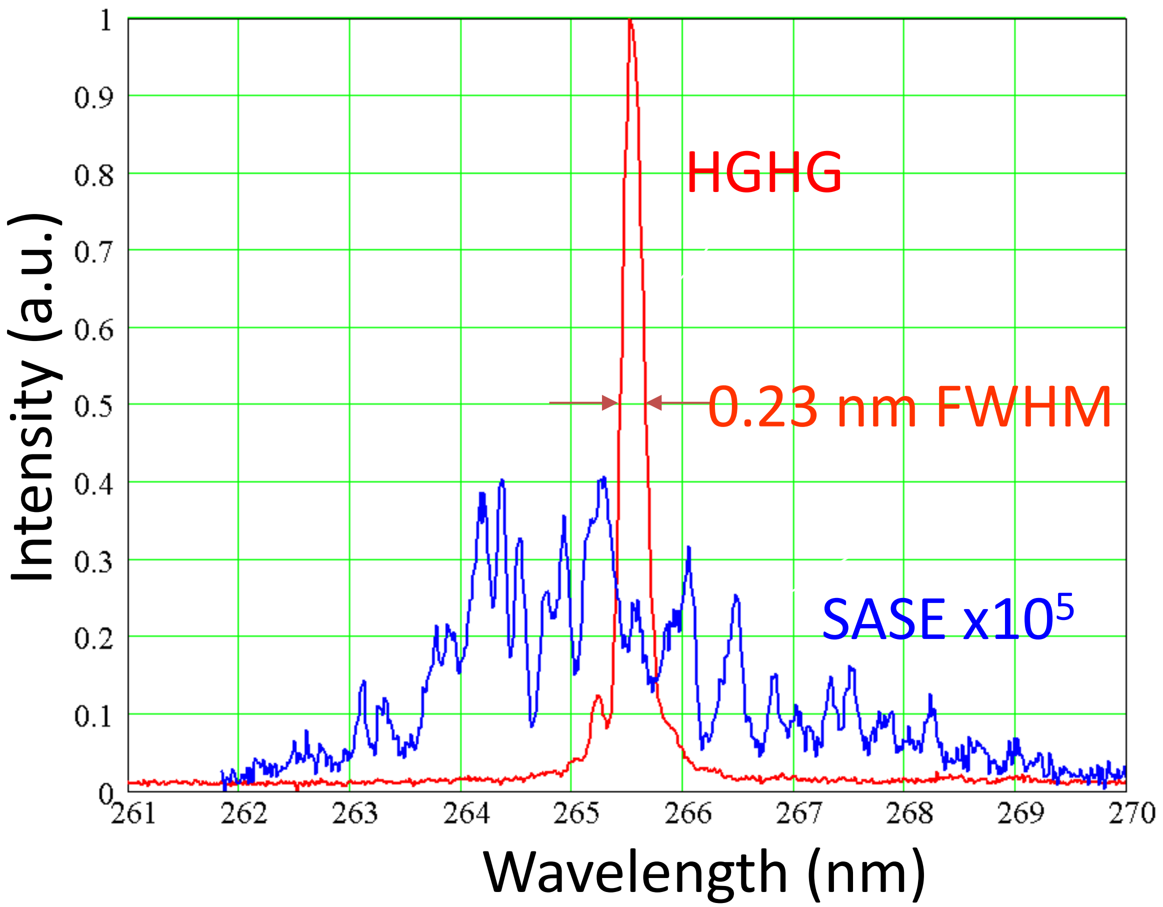
Expanded view of the dispersive section





Dispersive section consists of four dipoles arranged as a chicane to speed up the FEL bunching process. The output density-vs-z plot exhibits high harmonic content.

HGHG and SASE Spectra



Spectra of HGHG (red) and unsaturated SASE (blue) under the same conditions. HGHG exhibits 1-2 narrow spectral lines compared to SASE spiky spectrum.

Summary

- FEL optical architectures cover a wide range of single-pass gain (from less than 2X to 10^7X) and optical feedback (from ~99% to zero feedback)
  - **Oscillator**: low gain, high-Q optical cavity (high feedback)
  - **Regenerative Amplifier** : high gain, low-Q optical cavity (low feedback)
  - **Seeded Amplifier** : high gain, an external laser as seed (no feedback)
  - **SASE** : high gain, spontaneous noise as seed
  - **Seeded SASE** : high gain, SASE from upstream undulators as seed
  - **xSASE** : high gain, segmented undulator with chicanes or wigglers in between
- SASE has significant shot-to-shot fluctuations, temporally and spectrally.
- Harmonic generation is successful at extending the FEL wavelengths to shorter wavelengths without increasing the electron beam energy.