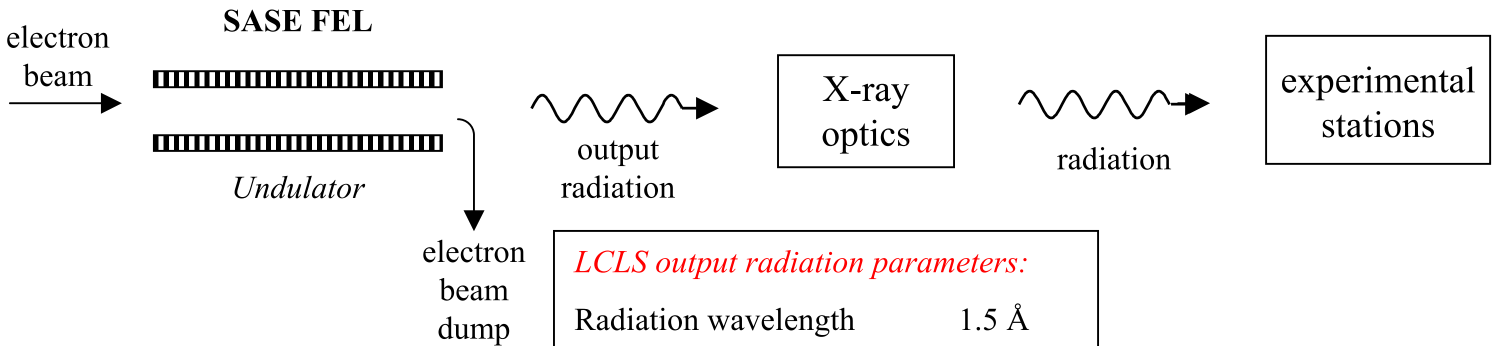
Two-Stage Chirped-Beam SASE-FEL for High Power Femtosecond X-Ray Pulse Generation

C. Schroeder*, J. Arthur^, P. Emma^, S. Reiche*, and C. Pellegrini*

^ Stanford Linear Accelerator Center
* UCLA

Schematic of SASE X-ray FEL:



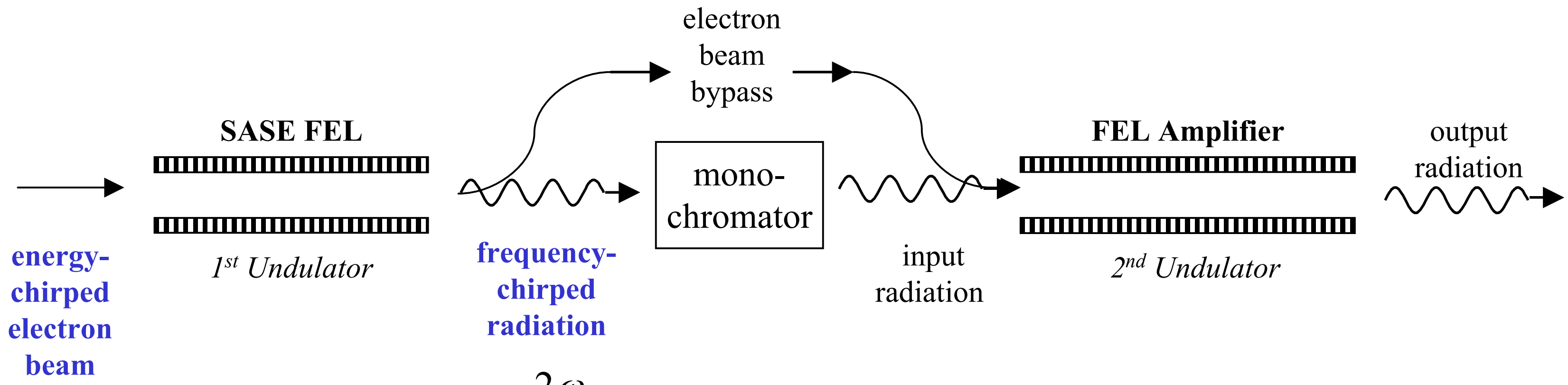
LCLS output radiation parameters:

Radiation wavelength	1.5 Å
Mean peak power	7.7 GW
Bandwidth	$2 \cdot 10^{-4}$
Intensity fluctuations	6 %
Pulse duration, rms	67 fs

Disadvantages of standard SASE FEL configuration:

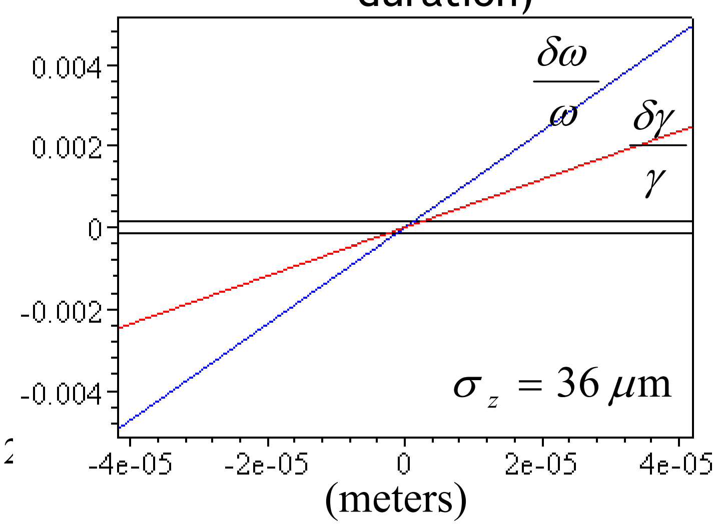
- Shot-to-shot fluctuations of radiation power after monochromator will increase with increasing photon energy resolution.
- Conventional x-ray optical elements (monochromator) may suffer damage due to the high output radiation power.
- Large shot-to-shot fluctuations in mean electron beam energy (0.1%) results in shot-to-shot fluctuations of resonant radiation frequency.

Two-stage chirped pulse seeding for short pulse production:

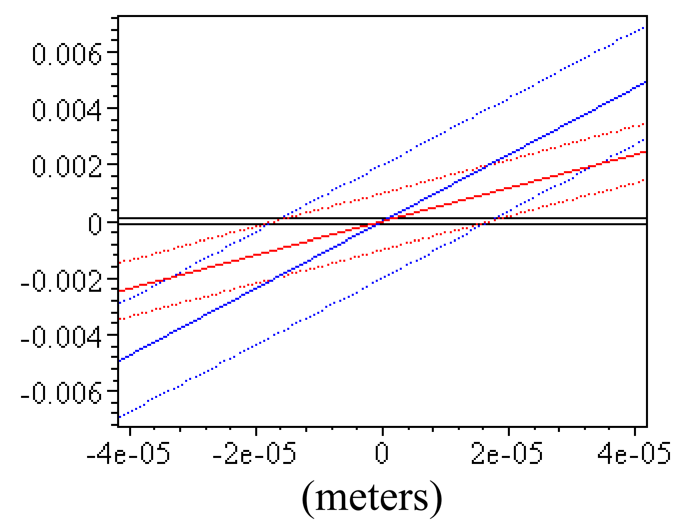


Resonant condition: $\omega = \frac{2\omega_u}{\gamma_\perp^2}\gamma^2$

Pulse duration selection:
(monchromator bandwidth and amount of chirping define pulse duration)



Stabilize central frequency:
(shot-to-shot jitter in mean electron beam energy)



Two-stage LCLS FEL Parameters:

LCLS FEL Parameters:

Radiation wavelength	1.5 Å
FEL parameter	$4.7 \cdot 10^{-4}$
Undulator type	planar
Undulator period	3 cm
Peak magnetic field	1.32 T
Undulator strength parameter	3.71
Repetition rate	120 Hz

Electron Beam Parameters:

Electron energy	14.3 GeV
Norm. beam emittance	1.1 mm mrad
Average beta function	18 m

***Undulator 1**:* (L_1 = 43.20 m)

Peak current	3.4 kA
Bunch duration, rms	120 fs
Uncorrelated energy spread, rms	0.006 %
Correlated energy chirp (FWHM)	0.5 %

Undulator 2: (L_2 = 51.84 m)

Peak current	4.0 kA
Bunch duration, rms	103 fs
Uncorrelated energy spread, rms	0.008 %

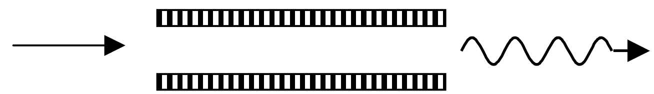
First Undulator:

SASE FEL

1st Undulator

(energy-chirped) electron beam

(frequency-chirped) radiation



$$L_1 = 43.2 \text{ m} < L_{\text{sat}}^{\text{SASE}}$$

Input Electron Beam Parameters:	
Peak current	3.4 kA
Bunch duration, rms	120 fs
Energy spread, rms	0.006 %
Energy chirp (FWHM)	0.5 %

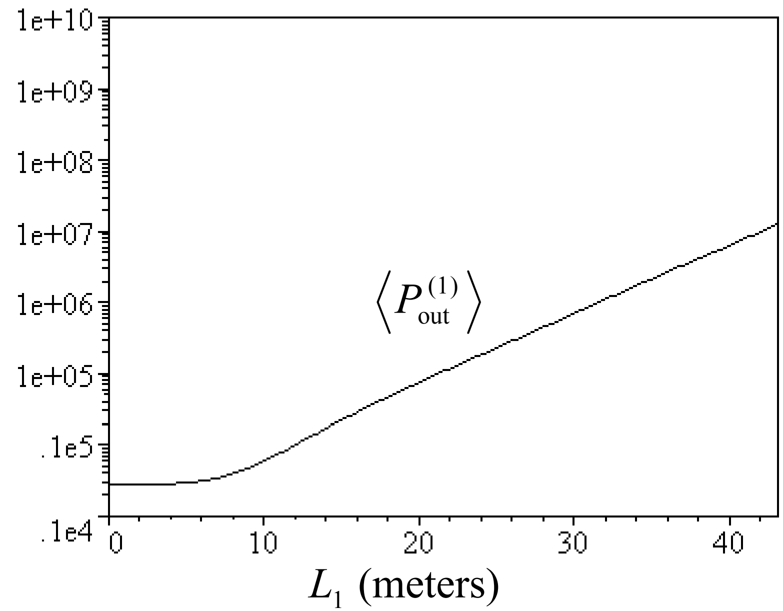
Output Radiation Parameters:	
Mean peak power	13 MW
Frequency chirp	1 %
FEL bandwidth	$2.7\cdot10^{-4}$
Rayleigh range	40 m

Require:

$$\left\langle P_{\text{out}}^{(1)} \right\rangle << P_{\text{sat}}$$

1. Reduce damage to optical elements of monochromator.
2. Energy spread of electron beam after the first undulator will satisfy

$$\sigma_\gamma \approx \rho \sqrt{\frac{\left\langle P_{\text{out}}^{(1)} \right\rangle}{P_{\text{sat}}}} < \rho$$



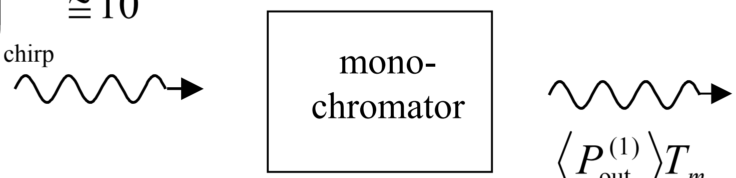
$$\frac{\left\langle P_{\text{out}}^{(1)} \right\rangle}{P_{\text{sat}}} \cong 10^{-3}$$

Simulation results obtained using GENESIS 1.3

Monochromator: femtosecond radiation pulse generation

$$\left(\frac{\Delta\lambda}{\lambda}\right)_{\mathrm{chirp}} \cong 10^{-2}$$

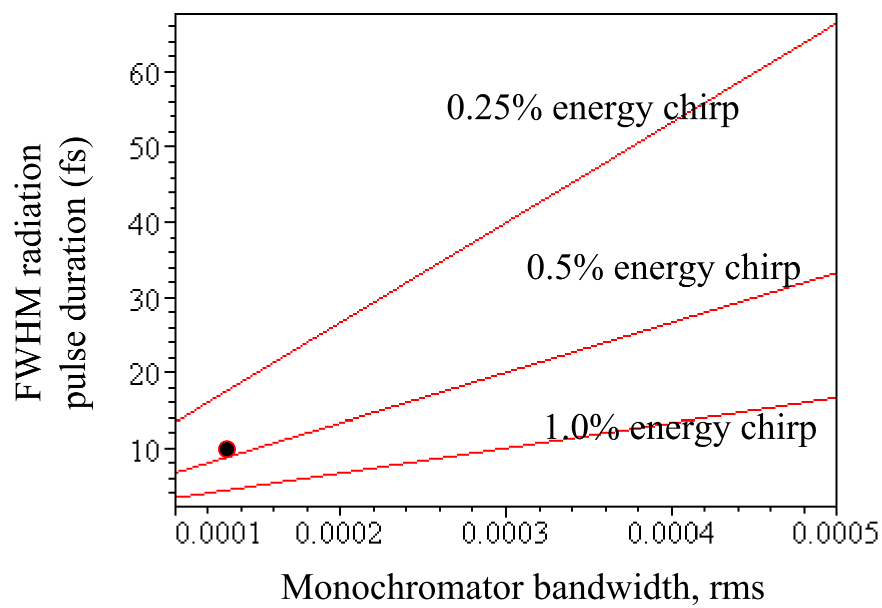
$$T_m = 41\,\%$$



$$\left\langle P_{\mathrm{out}}^{(1)} \right\rangle T_m$$

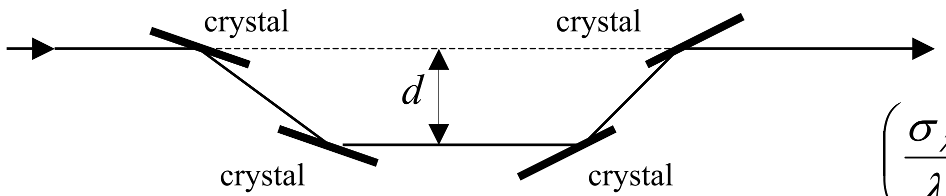
$$L_{\mathrm{FWHM}} \cong 8.7\ \mathrm{fs}$$

$$\left(\frac{\sigma_\lambda}{\lambda}\right)_{\mathrm{rms}}^{(\mathrm{mono})} \cong 1.3\mathrm{x}10^{-4}$$



Monochromator:

Bandwidth selection by Bragg diffraction in crystals [e.g., Ge(111)]:



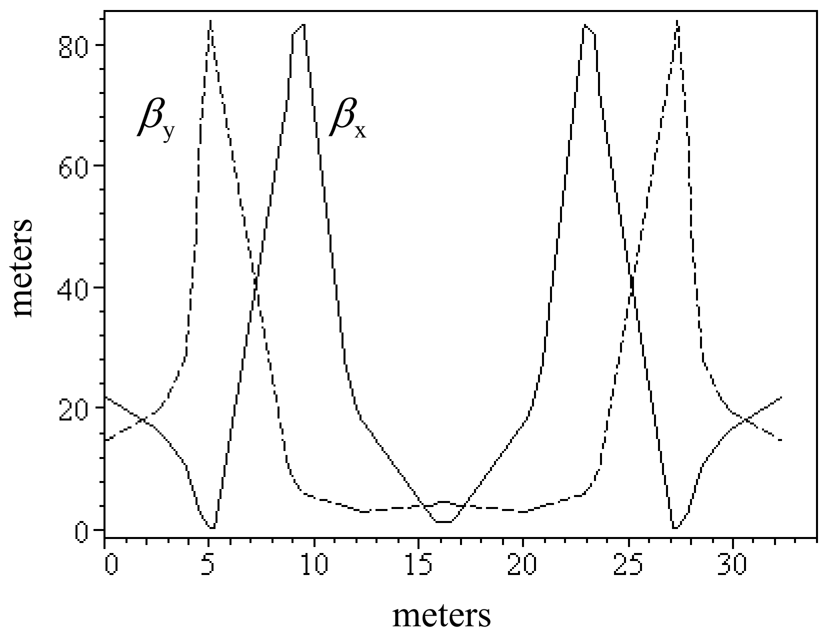
$$\left(\frac{\sigma_\lambda}{\lambda}\right)_{\text{rms}}^{(\text{mono})} \cong 1.3\text{x}10^{-4}$$

$$\text{path delay} = \Delta L = 2d \tan\theta$$

Monochromator Parameters: Ge(111)

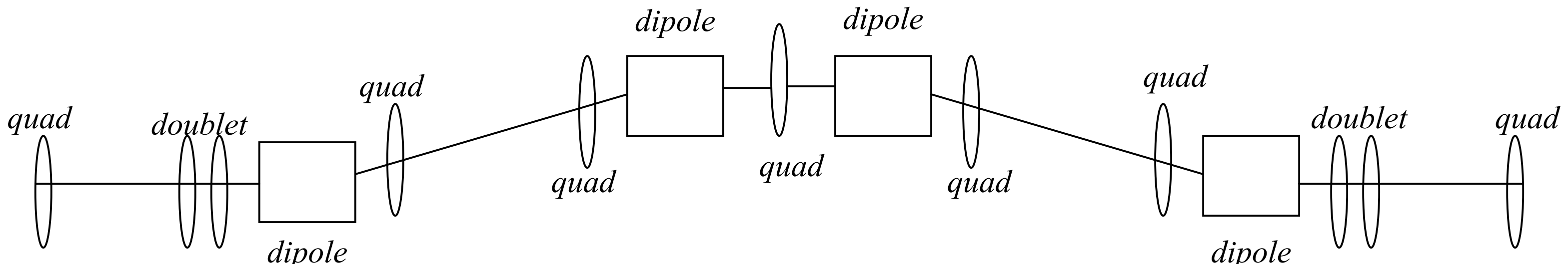
• Nominal photon energy	8.3 keV
• Reflection angle	0.24 rad
• Monochromator bandwidth, rms	$1.3\text{x}10^{-4}$
• Power transmission (0.8/reflection)	$T_m = 41$ %
• Tunability	4.0 – 8.5 keV
• Photon beam path delay	5 mm

Electron Beam Bypass:



Bypass Parameters:	
Total Length	32.4 m
R_{56}	3.6 mm
Path delay	5.0 mm
Maximum displacement	20.5 cm
Deflection angle	1.68 deg
Bend magnetic field	0.4 T
Bend magnet length	3.5 m
Quadrupole strength (max)	82 T/m
Quadrupole length	50 cm

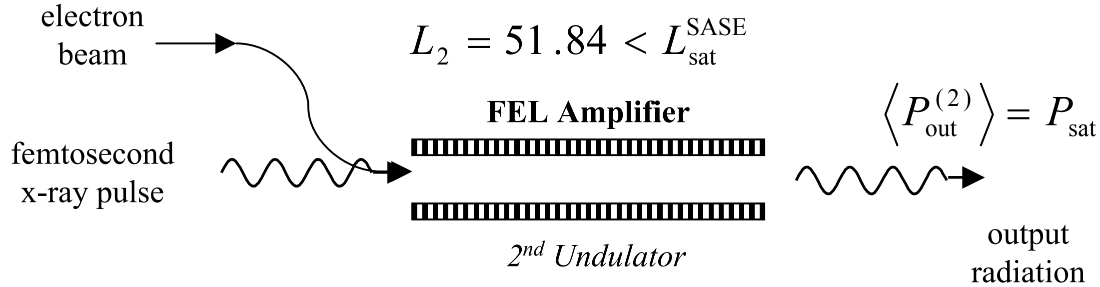
Schematic of non-isochronous achromatic chicane for electron beam bypass:



Second Undulator:

Input Electron Beam Parameters:	
Peak current	4.0 kA
Bunch duration, rms	103 fs
Energy spread, rms	0.008 %

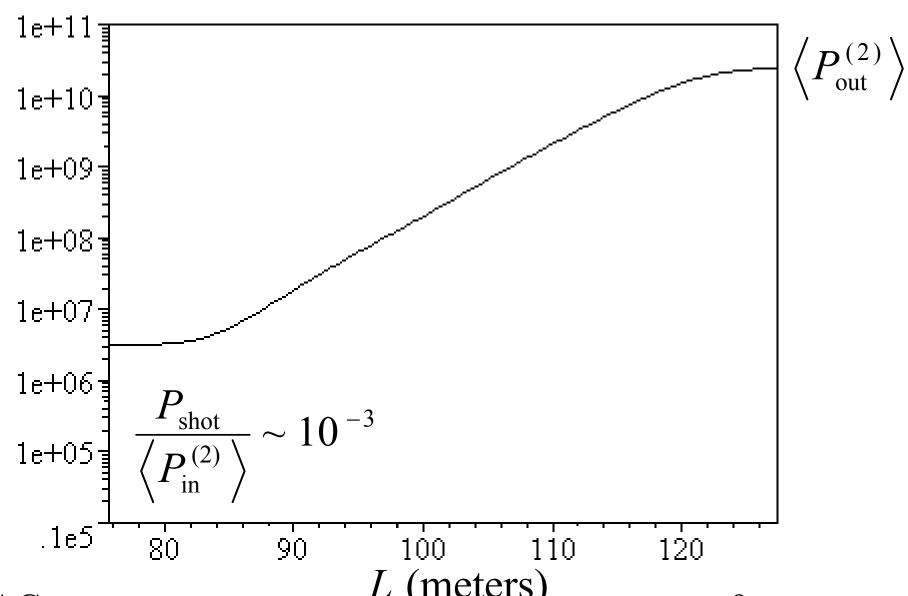
Input Radiation Parameters:	
Mean peak power	3.2 MW
Pulse duration, FWHM	8.7 fs
Bandwidth, rms	$1.3\cdot10^{-4}$
Intensity Fluctuations	30 %



Require:

$$P_{shot} << \langle P_{in}^{(2)} \rangle = \langle P_{out}^{(1)} \rangle T_m T_{diff}$$

Radiation power from monochromator dominates over the shot noise, such that the FEL will amplify the input signal radiation (with bandwidth compared to SASE FEL bandwidth).



Simulation results obtained using GENESIS 1.3

Shot-to-shot fluctuations:

Radiation Probability Distribution after Monochromator:

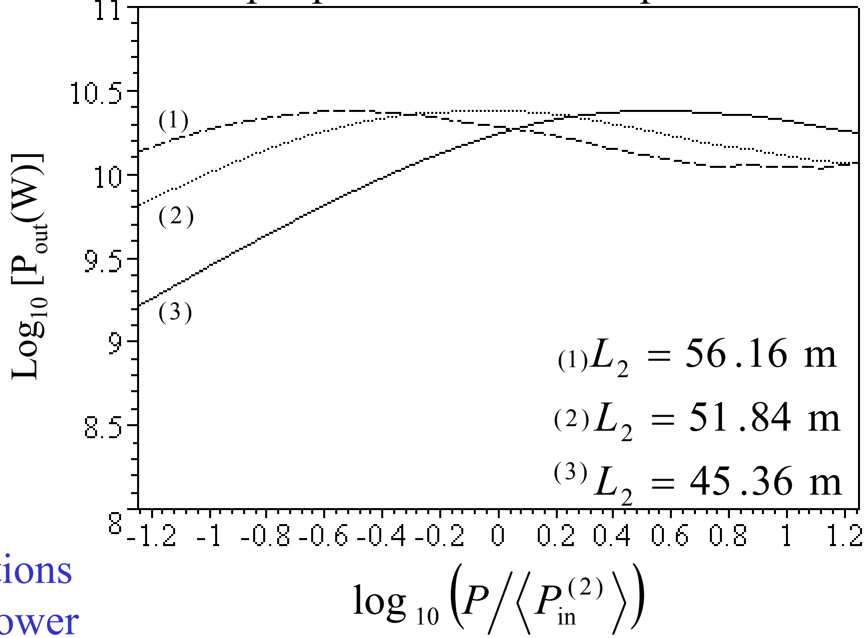
Negative Binomial Distribution

$$p(P) = \frac{\Gamma(P+M)}{\Gamma(P+1)\Gamma(M)} \frac{\left(1+\frac{M}{\langle P_{in}^{(2)}\rangle}\right)^{-P}}{\left(1+\frac{\langle P_{in}^{(2)}\rangle}{M}\right)^{-M}}$$

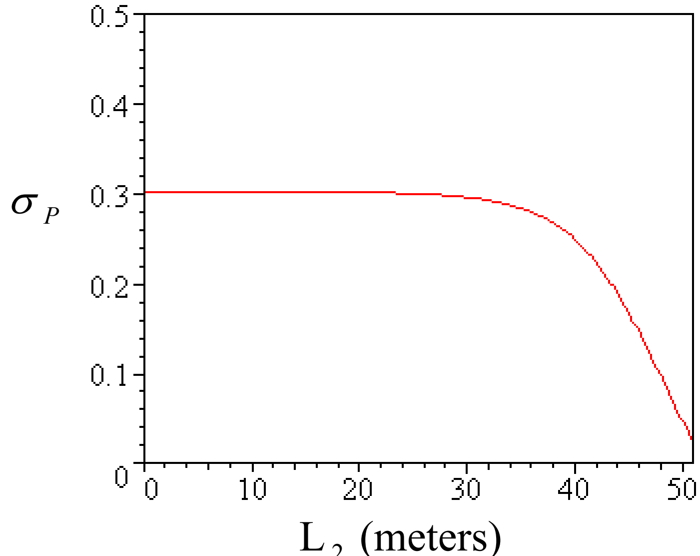
Standard deviation of radiation power into second undulator:

$$\sigma_P = \frac{1}{\sqrt{M}} \approx \sqrt{\frac{2\pi\sigma_c}{L_p}}$$

Dependence of output power on input power for FEL amplifier



Relative rms fluctuations of output radiation power

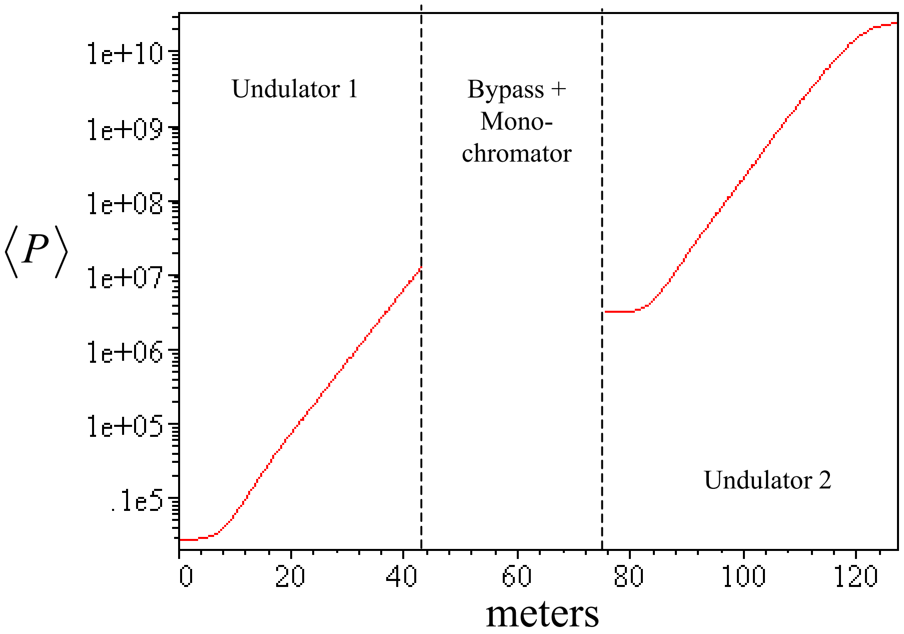


Shot-to-shot fluctuations of output radiation power are reduced by operating the FEL amplifier in the non-linear regime.

Output Radiation Parameters for Two-Stage LCLS:

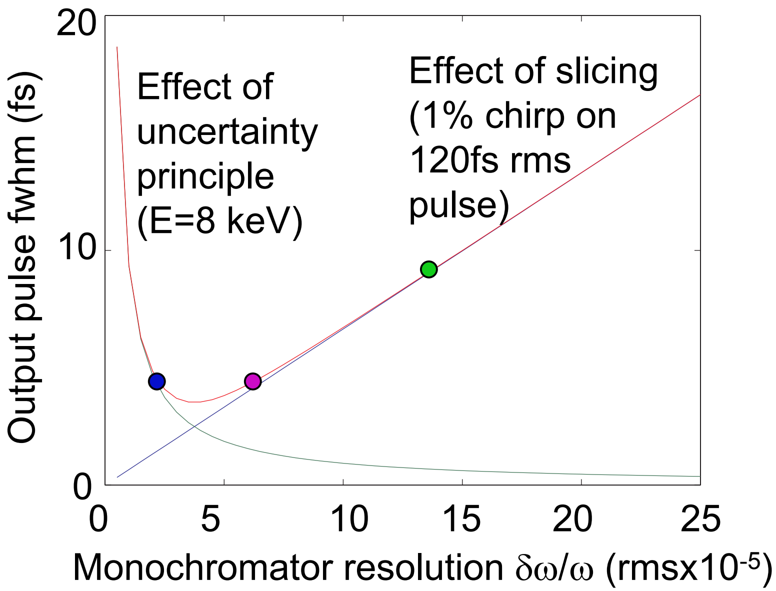
Two-Stage FEL Output Radiation:	
Radiation wavelength	1.5 Å
Bandwidth, FWHM	$3.1 \cdot 10^{-4}$
Pulse duration, FWHM	8.7 fs
Mean peak power	23 GW
Power fluctuations, rms	2 %
RMS spot size	31 μm
RMS angular divergence	0.5 μrad

Mean Peak Radiation Power:



Simulation results obtained using GENESIS 1.3

Monochromator: short pulse limit



Monochromator with smaller bandwidth slices out shorter pulse
$\delta t_{out} = \delta t_{in} \times \delta\omega_{mono}/\delta\omega_{chirp}$

But uncertainty principle gives a limit
$\delta\omega_{mono} \times \delta t_{out} \geq 1/2$

Note that if the uncertainty principle dominates, then the output pulse has complete longitudinal coherence

For LCLS at 8 keV with 1% chirp, the minimum pulse length is about 3.5 fs fwhm, using a monochromator resolution of 3.3×10^{-5} rms.

Some practical monochromator options:

Crystal reflection	rms resolution	Output pulse fwhm
Ge(111)	14×10^{-5}	9 fs
Si(111)	5.7×10^{-5}	4.1 fs
Si(220)	2.5×10^{-5}	4.1 fs

Conclusions

The **Two-Stage Chirped-Beam SASE-FEL offers:**

1. **An attractive way to produce high intensity X-ray pulses in the 10 to 20 fs range**
2. **Improved stability of the central frequency**
3. **Reduced load on optical elements**
4. **It can be built as an upgrade to present LCLS design**