Fully Coherent X-ray Pulses from a Regenerative Amplifier Free Electron Laser

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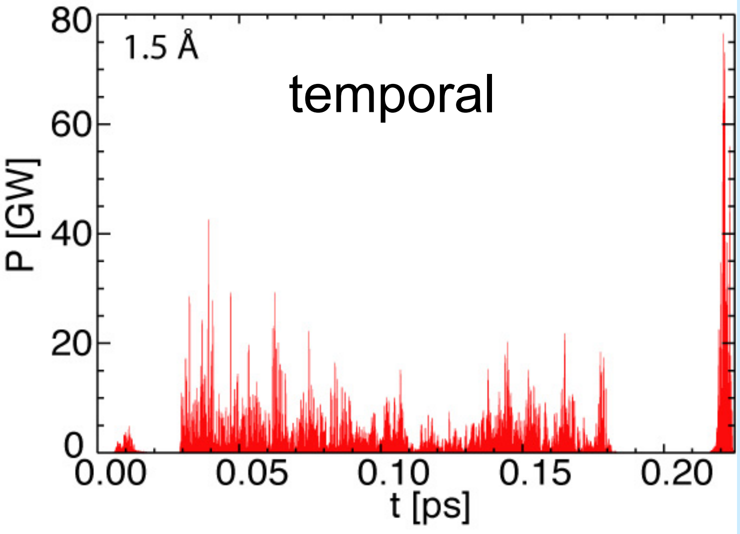
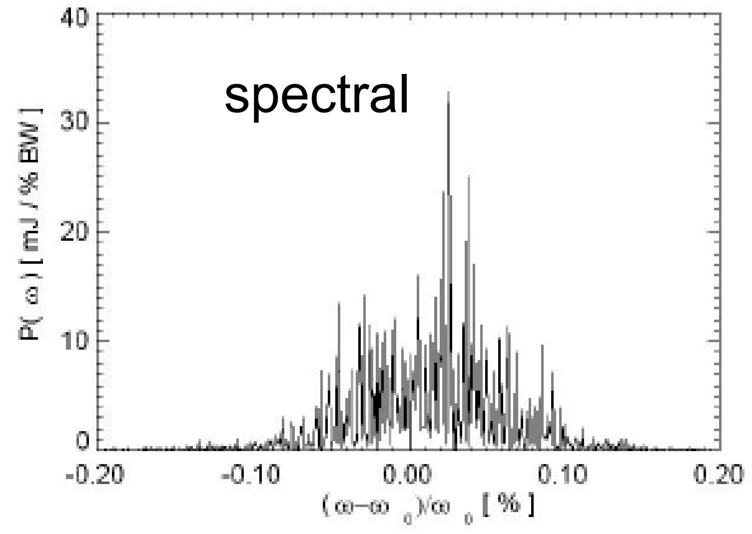
Introduction

- SASE x-ray sources will lay the foundation for next-generation x-ray facilities

- Due to its noisy startup, SASE is transversely coherent but temporally chaotic (LCLS example, from S. Reiche)



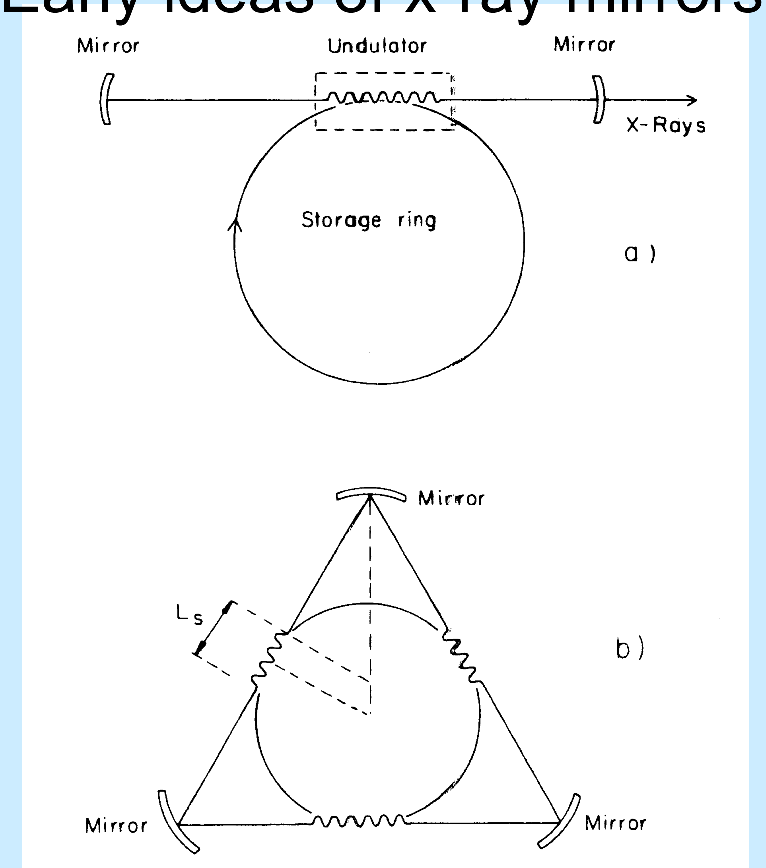


- Monochromator can be used to select a single mode, but flux is reduced (by ~700) and intensity fluctuates 100%

- Various schemes to improve temporal coherence proposed

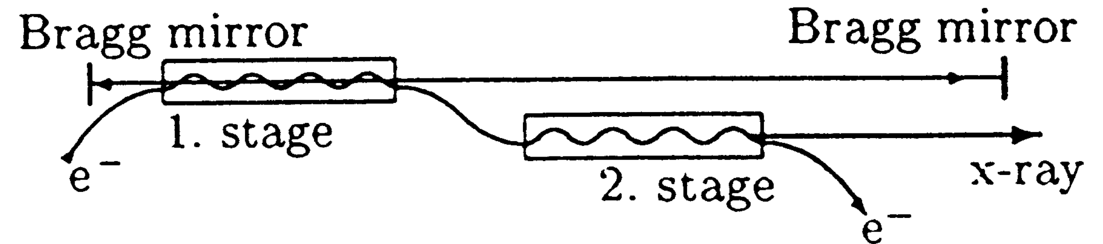
Feedback X-rays

- Early ideas of x-ray mirrors: R. Colella & A. Luccio (1984)



They recognize x-ray outcoupling may be a problem (extremely thin crystal, 0.1% of total power leaks out)

- B. Adams & G. Materlik (FEL1996), feedback x-rays and switch out microbunched beams

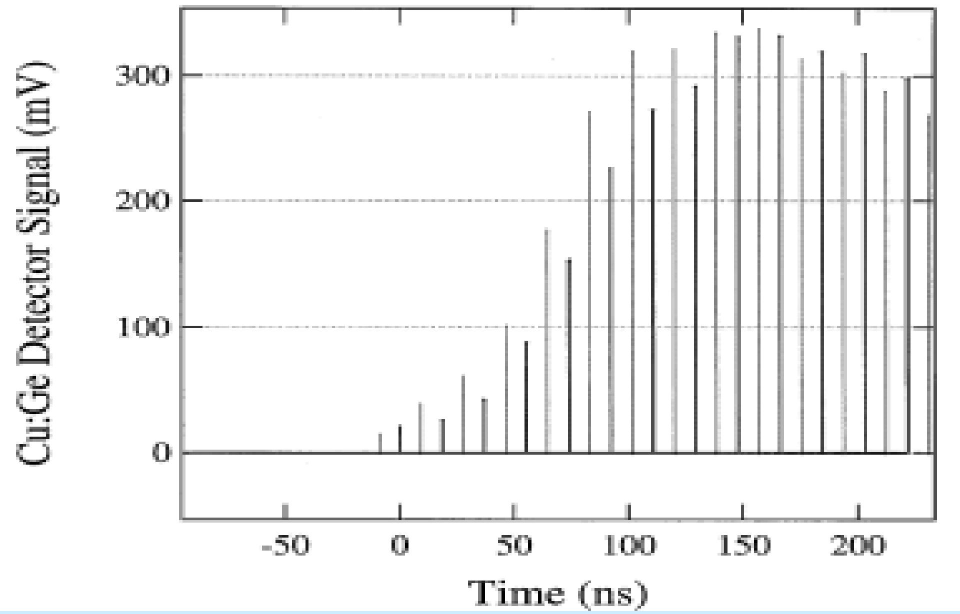


Regenerative Amplifier FEL (RAFEL)

- RAFEL: high-gain, small feedback (high extraction efficiency)
- Demonstrated in IR (~16 μm, LANL) (FEL1998)

First lasing of the regenerative amplifier FEL

Dinh C. Nguyen*, Richard L. Sheffield, Clifford M. Fortgang, John C. Goldstein,
John M. Kinross-Wright, Nizar A. Ebrahim



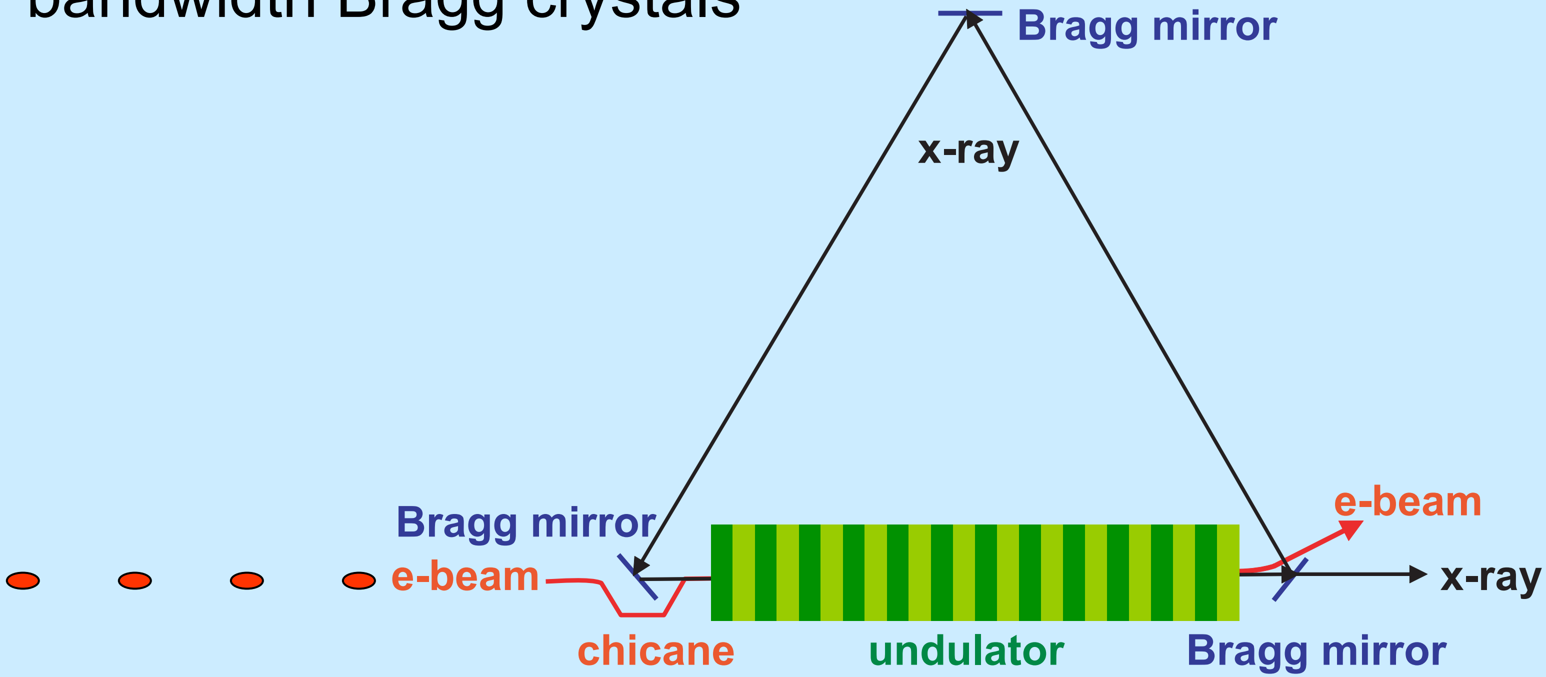
- Proposals for VUV FELs

  DESY: B. Faatz et al., NIMA 1999

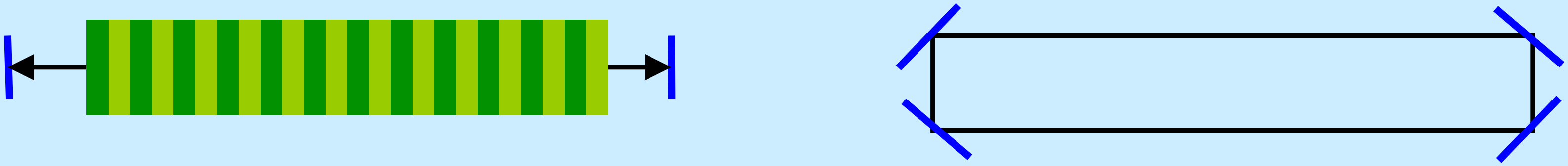
  Daresbury 4GLS: N. Thompson et al., FEL2005

X-ray RAFEL

- ➢ We propose and analyze an x-ray RAFEL using narrow-bandwidth Bragg crystals*



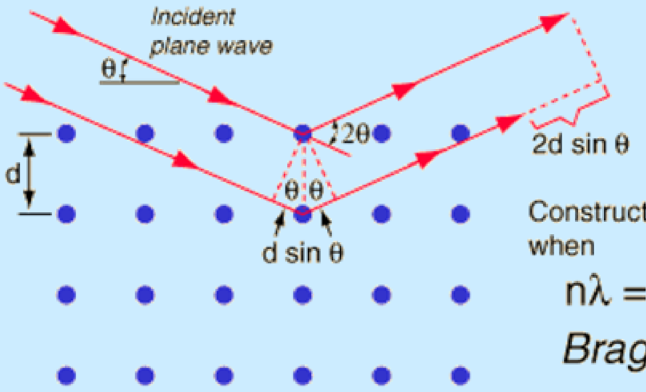
- ➢ Alternative backscattering geometry may also be used



** Z. Huang & R. Ruth, PRL96, 144801 (2006)*

Diamond crystals as Bragg Mirrors

- Bragg's law

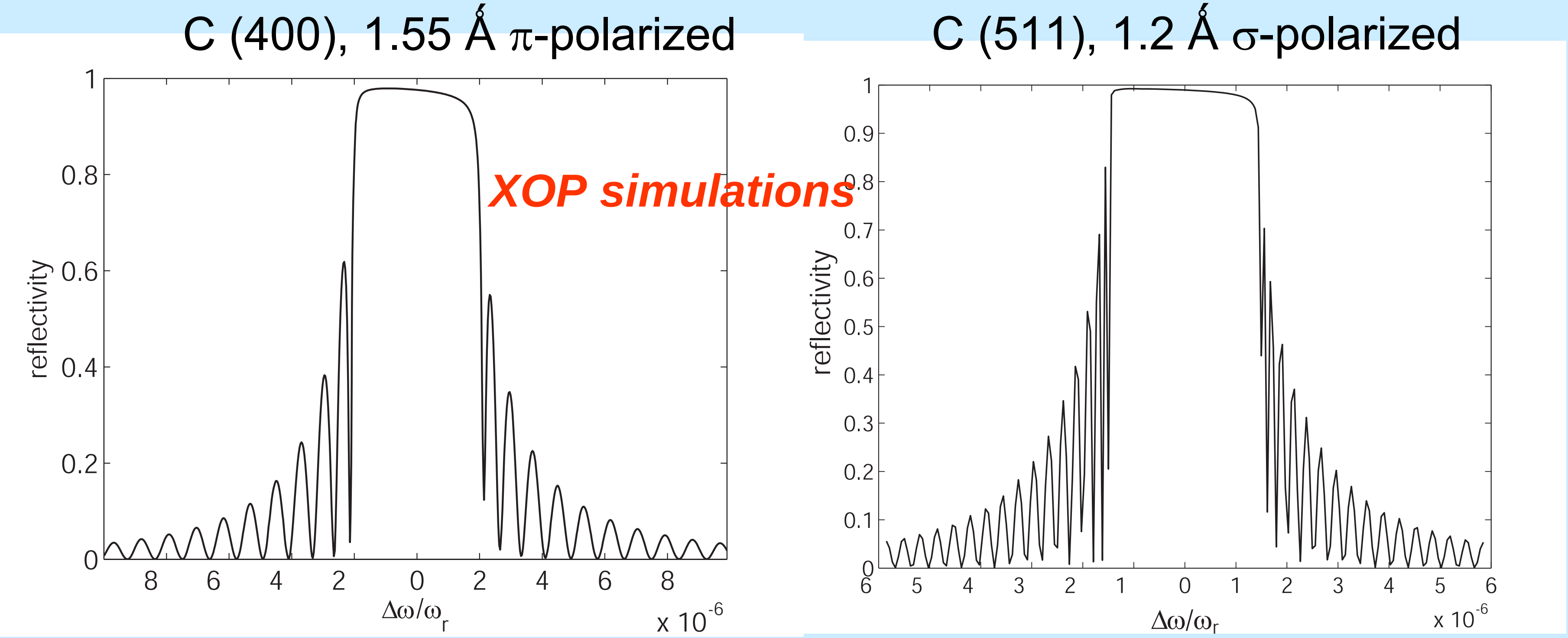


Constructive interference when

$n\lambda = 2d \sin\theta$

Bragg's Law

- Diamond (high heat load, low absorption) at 60 degree


C (400), 1.55 Å π-polarized

C (511), 1.2 Å σ-polarized

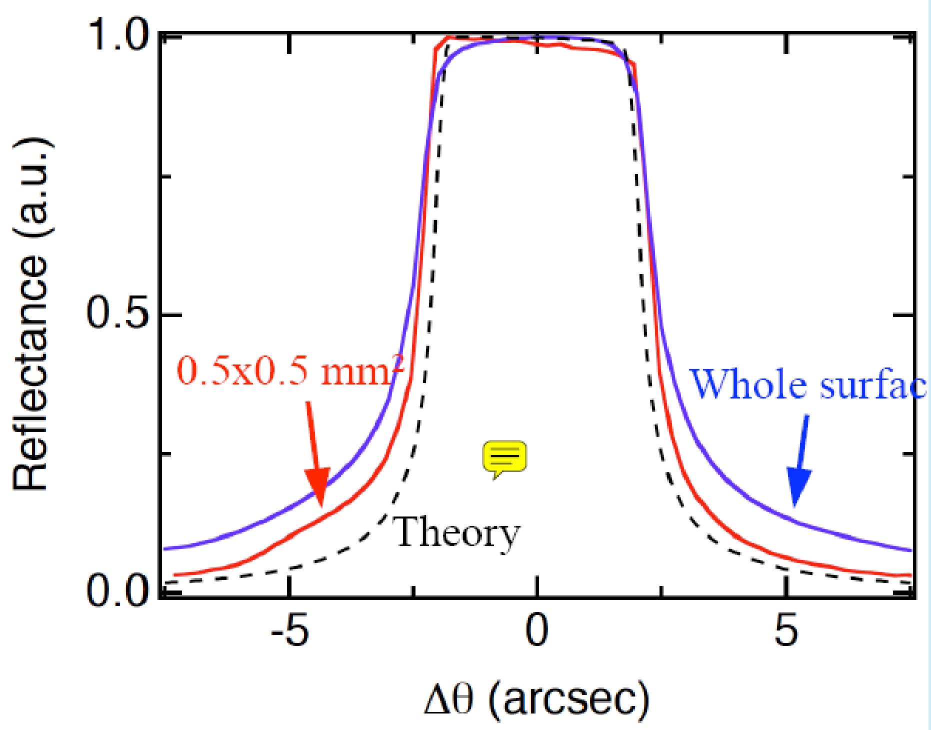
XOP simulations

Measured rocking curves

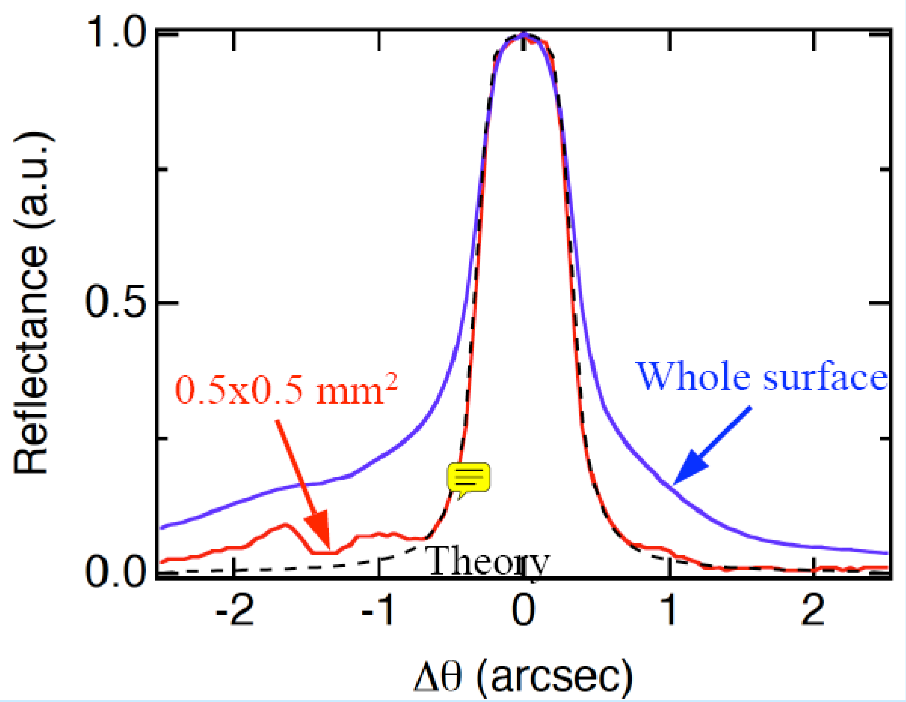
Diamond workshop @ ESRF, May 24-25, 2004

Tamasaku et al: "Characterization of synthetic IIa diamonds at SPring-8"

Si 220(b=20.9)-C 111 @9.44 keV

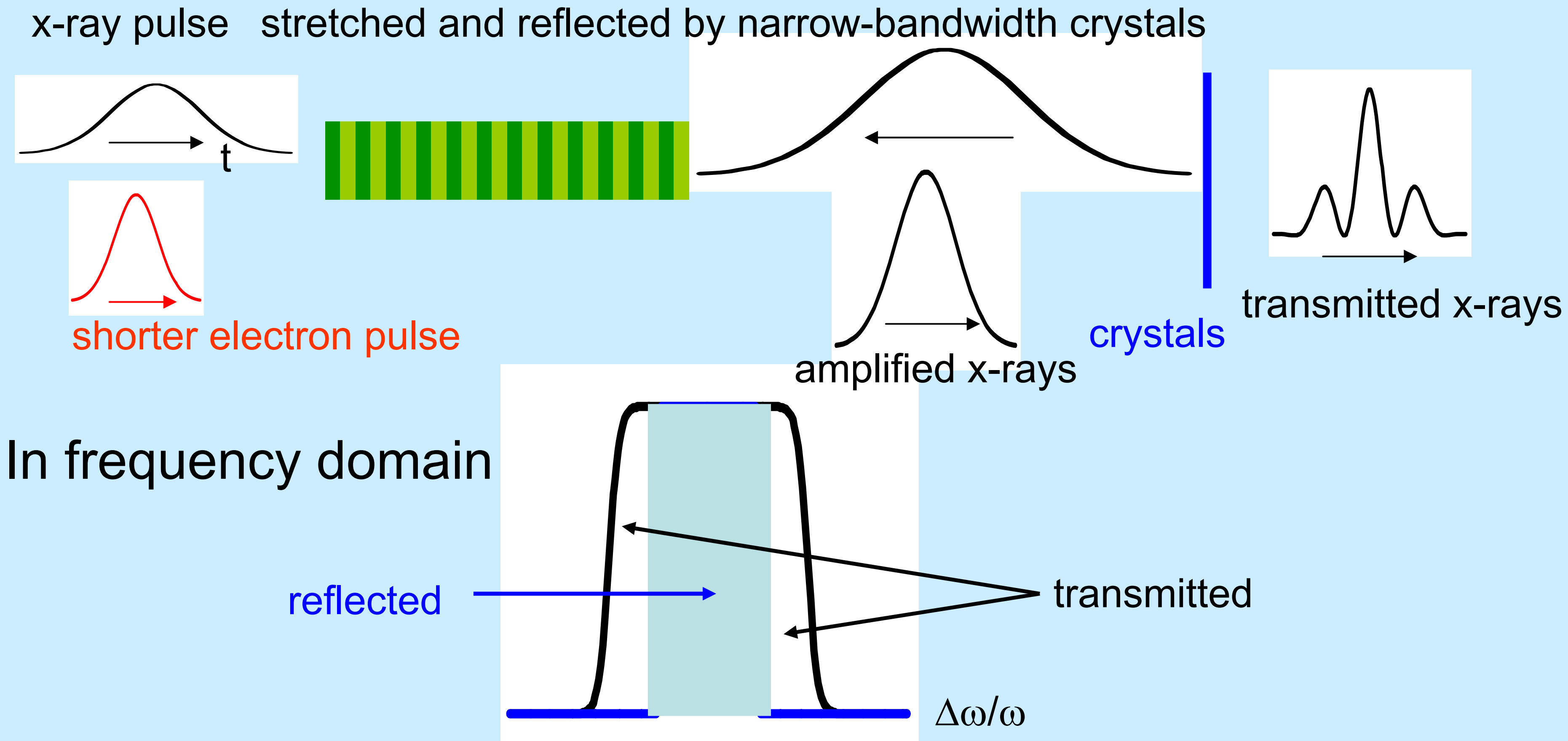


Si 531(b=20.9) - C 004 @19.74keV



Frequency-domain extraction scheme

- If crystal reflects ~100% within narrow bandwidth, how can power be extracted out of the cavity?
- Use bunch shorter than the reflected x-ray pulse: FEL interaction ➔ amplify and spectrally broaden the radiation
  ➔ Power transmitted outside the feedback bandwidth



1D analysis

- Radiation slippage (~ 0.1 μm) << bunch length (~10 μm)
➔ field gain factor proportional to local beam current

$$g(t) \approx g_0 \exp\left(-\frac{t^2}{2\sigma_\tau^2}\right)$$

rms bunch length

- Radiation field at undulator end of nth pass

$$E_n^a(t) \approx E_n(t) g(t) + \delta E_n(t)$$

radiation field at undulator begin

SASE generated by nth bunch

- Signal is spectrally filtered and fed back to (n+1)th pass

$$E_{n+1}(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} e^{-i\omega t} \int_{-\infty}^{\infty} dt' E_n^a(t') e^{i\omega t'} f(\omega)$$

narrow-band filter function

- SASE term starts the process, but can be ignored for n>>1 as the feedback signal dominates

Round-trip gain and extraction efficiency

- Look for an exponentially growing solution with *n*

$$E_n(t) = \Lambda^n A(t) e^{-i\omega_r t}$$

- Get an integral equation for gain Λ and mode profile A(t)

$$\Lambda A(t) = \sqrt{R}\sigma_m \int_{-\infty}^{\infty} \frac{dt'}{\sqrt{\pi}} e^{-\sigma_m^2 (t-t')^2} g(t') A(t')$$

peak reflectivity   rms bandwidth of crystals

- A Gaussian fundamental mode has the largest round trip power gain

$$G_{eff} = |\Lambda|^2 = G_0 R \frac{\sqrt{1+8\sigma_m^2\sigma_\tau^2}-1}{\sqrt{1+8\sigma_m^2\sigma_\tau^2}+1}$$

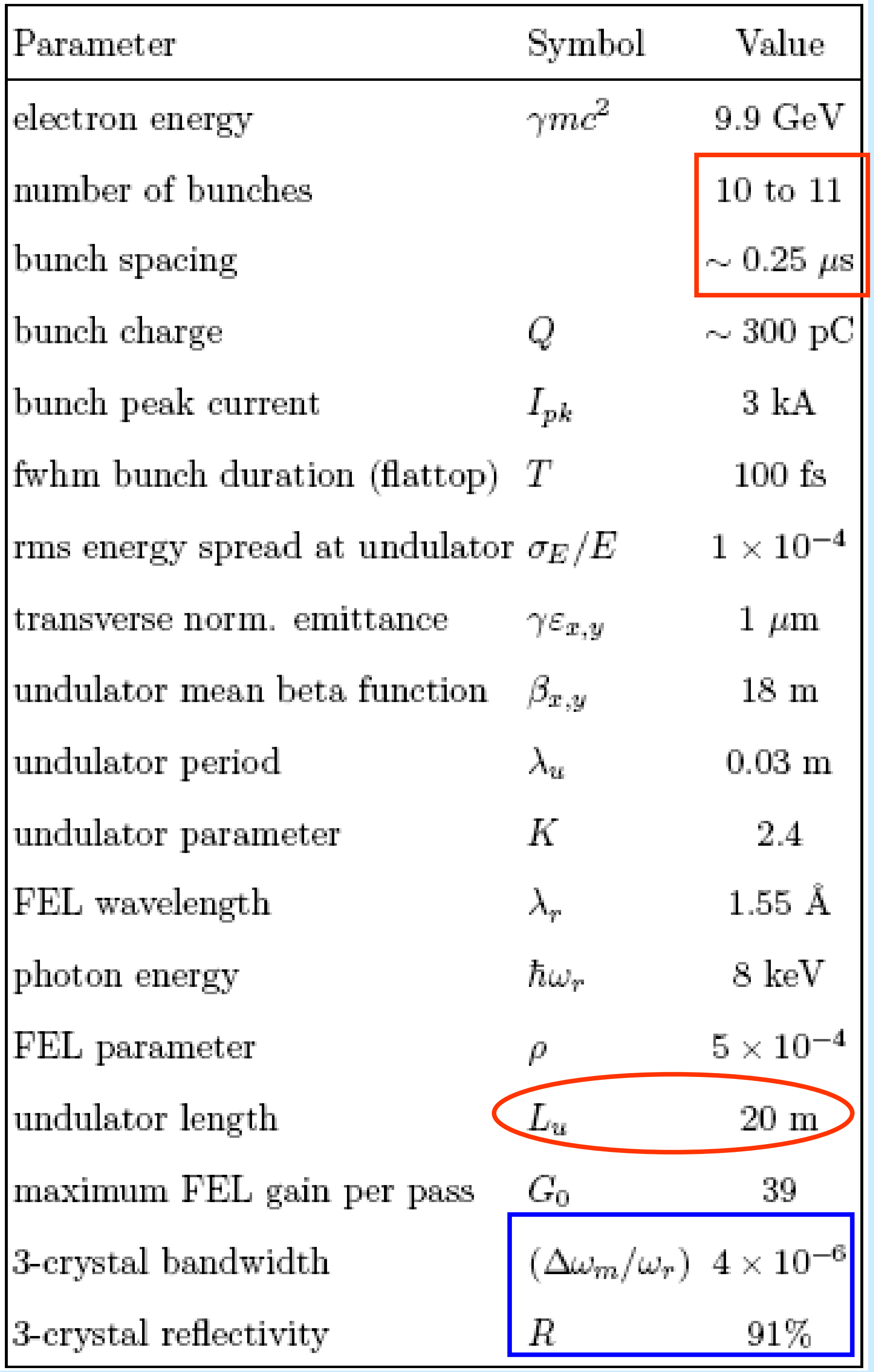
FEL peak power gain = $|g_0|^2$

- Assume no absorption by crystals, maximum extraction efficiency

$$\eta = 1 - R\sqrt{\frac{\sqrt{1+8\sigma_m^2\sigma_\tau^2}-1}{\sqrt{1+8\sigma_m^2\sigma_\tau^2}+1}}$$

A possible RAFEL configuration for LCLS

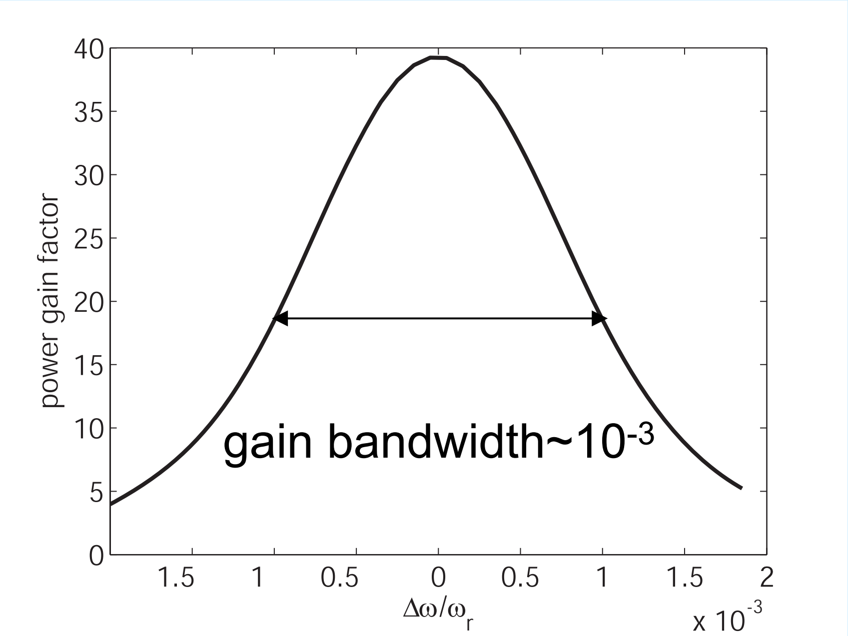
- Use LCLS linac but without SLED (~3.5 μsec rf pulse)
- Maximum LCLS energy without SLED is ~10 GeV
- Adjust undulator K (≈2.4) for FEL wavelength at 1.55 Å
- Use a 20-m undulator instead of >100 m for SASE



Parameter	Symbol	Value
electron energy	γmc^2	9.9 GeV
number of bunches		10 to 11
bunch spacing		$\sim 0.25\ \mu s$
bunch charge	Q	~ 300 pC
bunch peak current	I_{pk}	3 kA
fwhm bunch duration (flattop)	T	100 fs
rms energy spread at undulator	σ_E/E	1×10^{-4}
transverse norm. emittance	$\gamma\epsilon_{x,y}$	1 μm
undulator mean beta function	$\beta_{x,y}$	18 m
undulator period	λ_u	0.03 m
undulator parameter	K	2.4
FEL wavelength	λ_r	1.55 Å
photon energy	$\hbar\omega_r$	8 keV
FEL parameter	ρ	5×10^{-4}
undulator length	L_u	20 m
maximum FEL gain per pass	G_0	39
3-crystal bandwidth	$(\Delta\omega_m/\omega_r)$	4×10^{-6}
3-crystal reflectivity	R	91%

Gain simulation and calculation

- Genesis 3D FEL gain scan



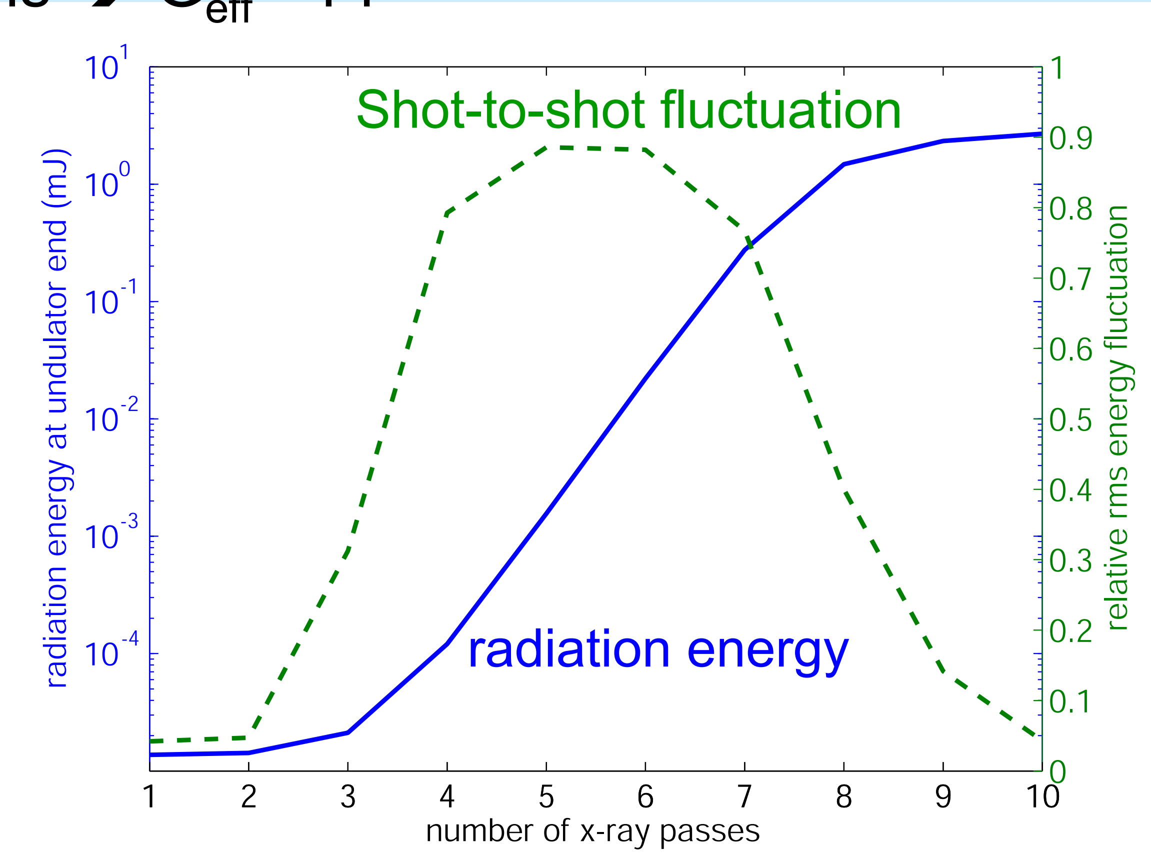
- With G_0=39, use Gaussian FWHM widths for flattop current and reflectivity widths ➔ round-trip G_{eff} =16 (theory)

- We develop 1D time-dependent RAFEL simulation (SASE+ narrow-band feedback)

- Use a larger energy spread in 1D code to reproduce 3D gain

1-D simulation results

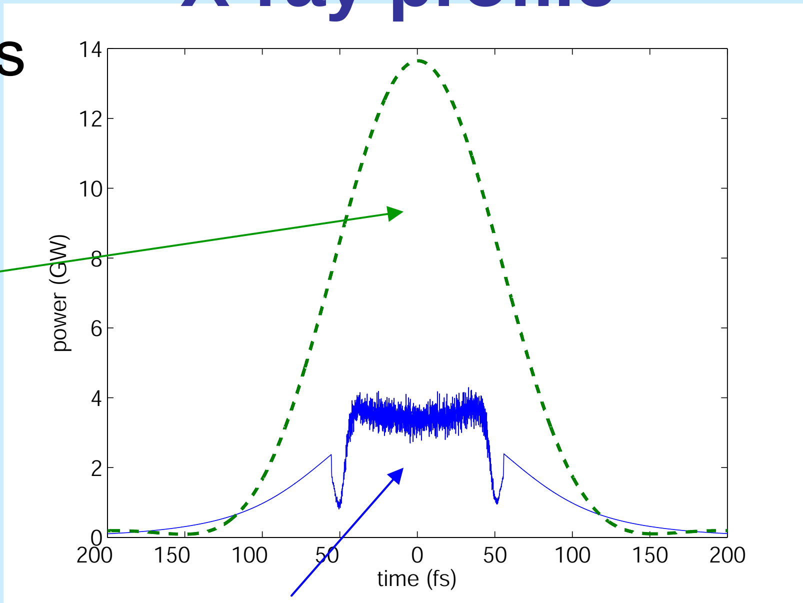
- ➢ Simulations use nearly flattop current and reflectivity functions ➔ G_{eff} =14



- ➢ Radiation energy saturates at around 9th pass, relative energy fluctuation comes down from 90% to ~5% (SASE single mode always fluctuates 100%)

X-ray profile

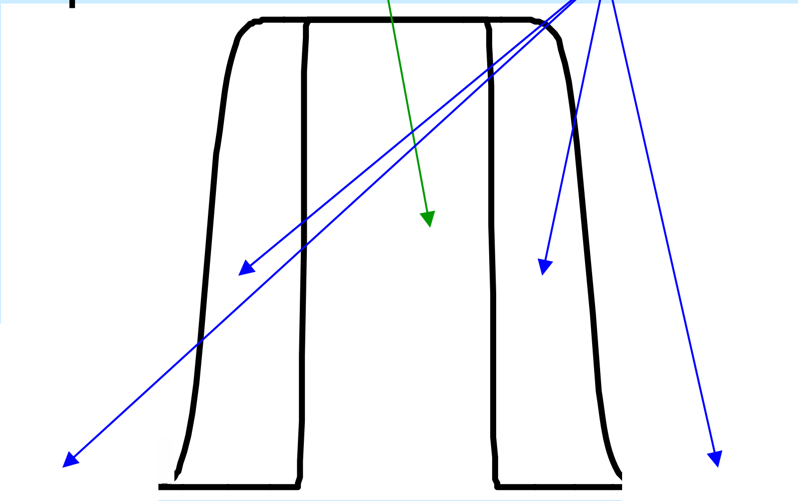
- End of 10th pass



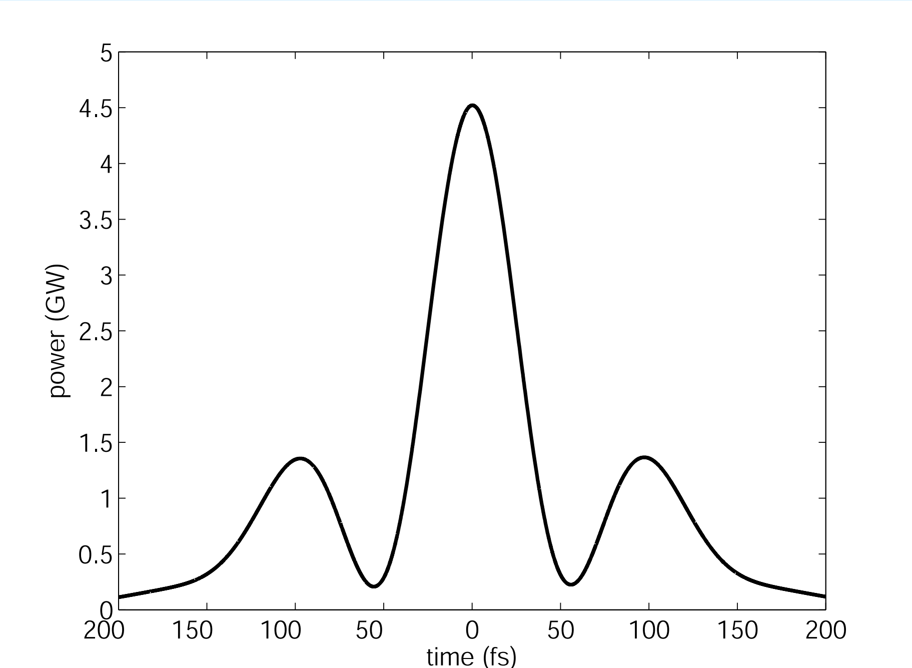
reflected x-ray

transmitted x-ray (82% transmission for a 100-μm diamond)

- Spectrum



Broadband SASE can be filtered by another monochromator



Radiation energy dose and damage issue

Comparison of LCLS SASE and RAFEL power and energy

X-ray properties	**SASE**	**RAFEL**
Pulse length (fwhm)	200 fs	100 fs transmitted (150 fs reflected)
FEL pulse energy	2 mJ (one pulse)	2 mJ (last 2 saturated pulses)
FEL peak power	10 GW	4 GW out (14 GW in cavity)
FEL photon energy	~ 8 keV	8 keV
Absorption in 100-μm diamond crystal	18 % of 10 GW = 1.8 GW	18 % of 4 GW = 0.72 GW
Beam transverse area	~ $(50\ \mu m)^2$ (100 m away)	~ $(22\ \mu m)^2$
Energy dose on crystal	0.004 eV/atom	0.002 eV/atom × 2 pulses (?)
Spontaneous power (over large beam area)	70 GW	3.6 GW × 10 bunches

Melt dose level of C (graphite) is 0.9 eV/atom, more than two orders of magnitude higher than both SASE and RAFEL doses on diamond

Discussions

➢ FEL gain bandwidth ~ 10^{-3}, need energy uniformity of the bunch train within ±0.05% (some beam loading compensation for about 1 mA macropulse current)

➢ Time jitter: don’t care overall bunch train jitter, do care bunch-to-bunch spacing jitter (±100 fs relative jitter requires 11-bunches of 2.5 μsec to reach saturation at 1.55 Å)

➢ Crystals need slight bending to provide necessary transverse focusing and pointing stability of x-rays

➢ Switch out cavity x-ray power
(suggested by J. Hastings, D. Rees)

➔ rotate the crystal by ~10 μrad in 0.25 μsec

➔ change the lattice spacing by a laser (more suitable for silicon crystals)

Summary

- We discussed a narrow-bandwidth RAFEL as a candidate for a fully coherent x-ray laser

- It may offer two to three orders of magnitude improvement in temporal coherence and spectral brightness over SASE x-ray sources

- Multi-bunch & x-ray feedback allows for a much shorter undulator and may be adapted in LCLS with s-band linacs

- May be more easily adapted in superconducting linacs with planned multi-bunch operation in a long rf pulse → relaxed beam and jitter requirements