Regenerative Amplifier FEL

from IR to X-rays

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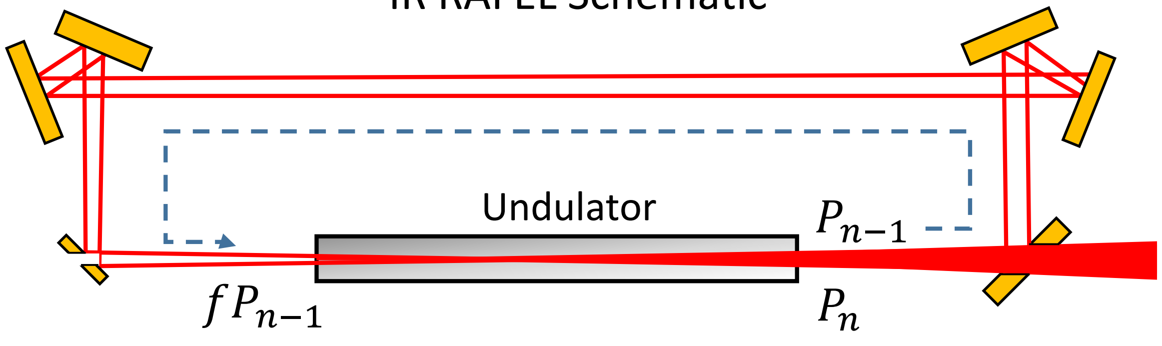
• Gabriel Marcus (SLAC)	Cavity-based X-ray FEL
• Tor Raubenheimer (SLAC)	LCLS-II parameters
• Dilling Zhu (SLAC)	Cavity-based X-ray FEL

Outline

- Infrared RAFEL
- VUV and X-ray RAFEL concepts
- X-ray RAFEL with Bragg reflectors
- RAFEL feedback cavity alignment
- 10-keV RAFEL Genesis simulations
- Out-coupling methods
- X-ray absorption in the out-coupler
- Distortion due to localized heating
- Summary

Infrared Regenerative Amplifier FEL

IR RAFEL Schematic

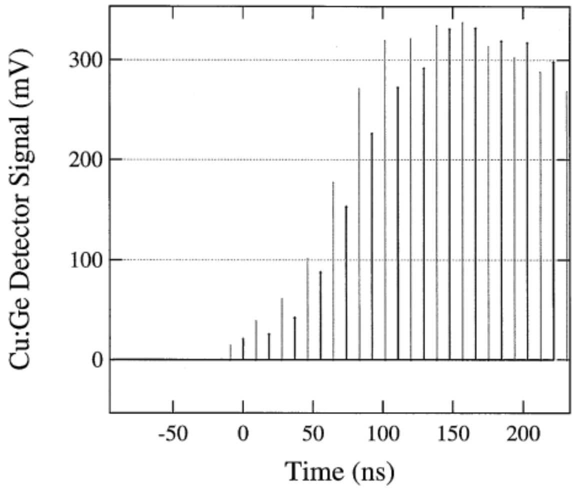


f	Fraction of power returned to the undulator
P_{n-1}	Power at the end of (n-1)th pass
P_n	Power at the end of nth pass

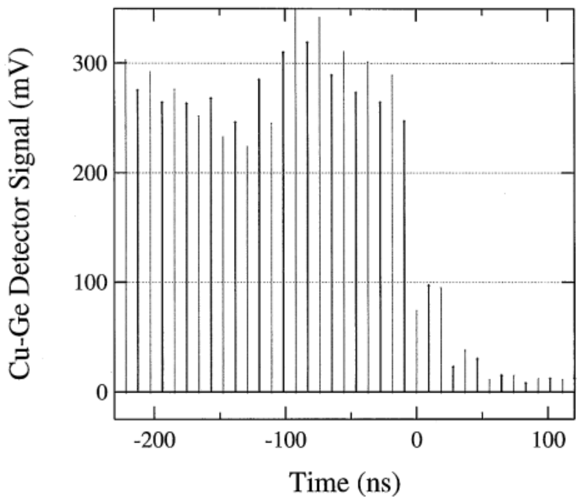
Small feedback x exponential gain = High power

$$P_n = (fP_{n-1})\frac{1}{9}e^{\frac{L_u}{L_G}}$$

Build-up



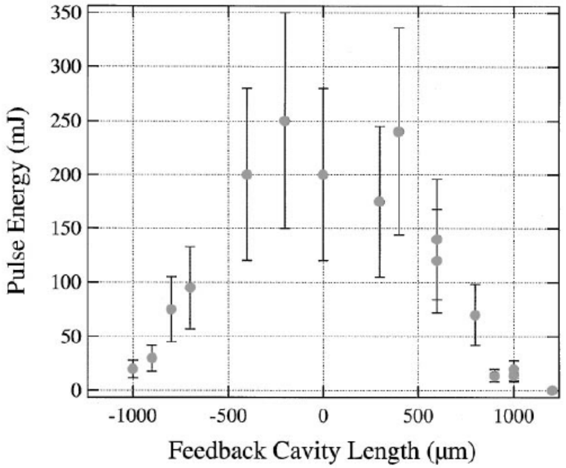
Ring-down



Cavity length detuning is approximately the electron bunch length divided by the number of passes

$$\delta L \sim \frac{l_e}{n_p}$$

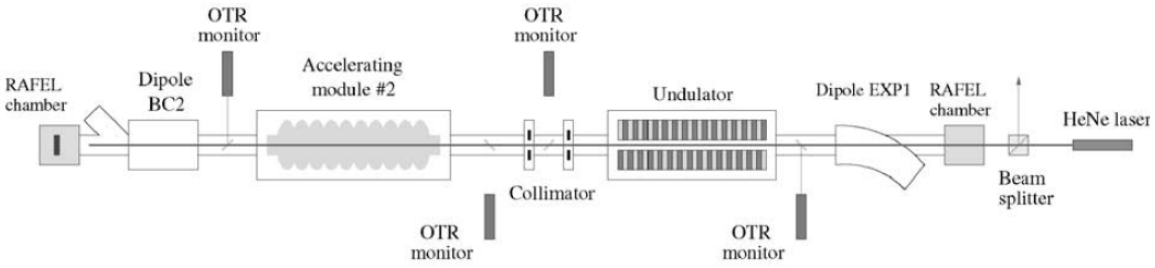
Cavity length detuning



D.C. Nguyen et al., Nucl. Instr. Meth. Phys. Res. A429 125-130 (1999).

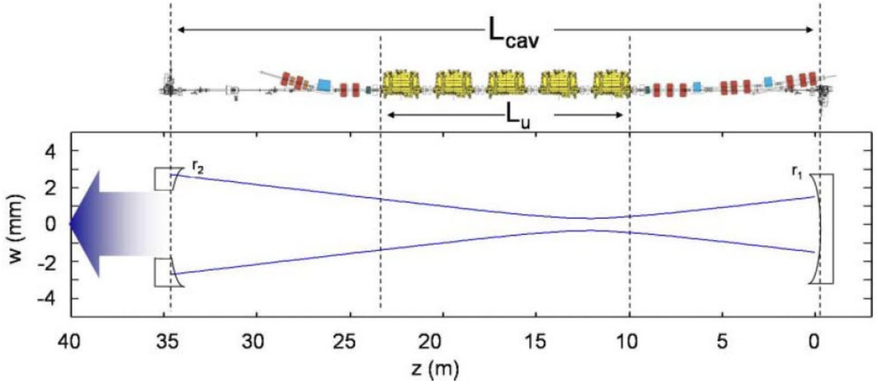
VUV and X-ray RAFEL Concepts

DESY VUV RAFEL



B. Faatz et al., Nucl. Instr. Meth. Phys. Res. A429 424-428 (1999)

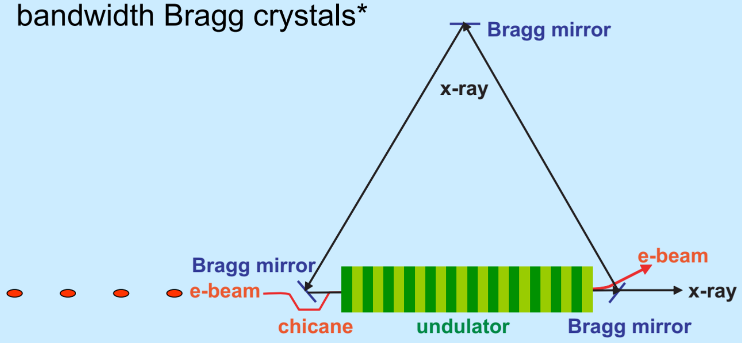
4GLS VUV-FEL



B.W.J. McNeil et al., New Journal of Physics, 9, 239 (2007)

LCLS X-ray RAFEL

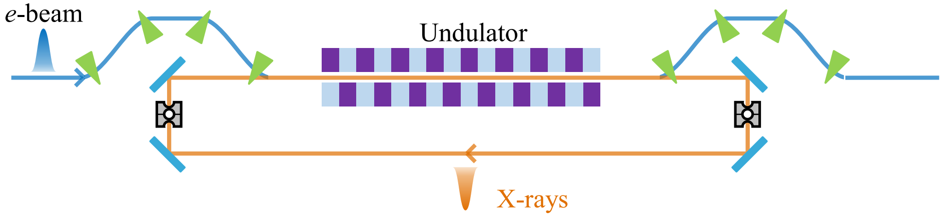
- We propose and analyze an x-ray RAFEL using narrow-bandwidth Bragg crystals*



- Alternative backscattering geometry may also be used

Z. Huang and R. Ruth, Phys. Rev. Lett. 96, 144801 (2006).

LCLS-II X-ray RAFEL

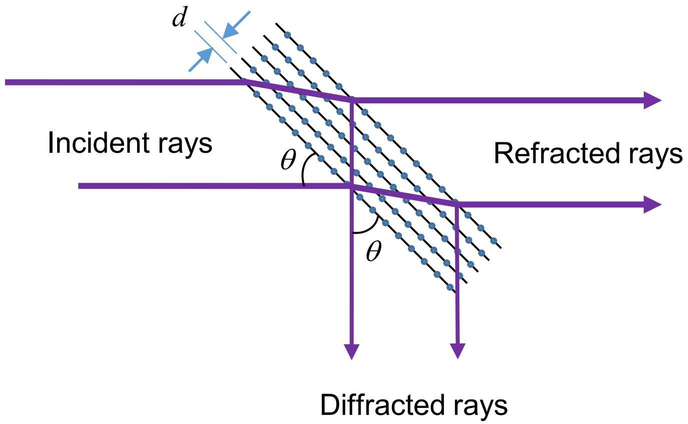


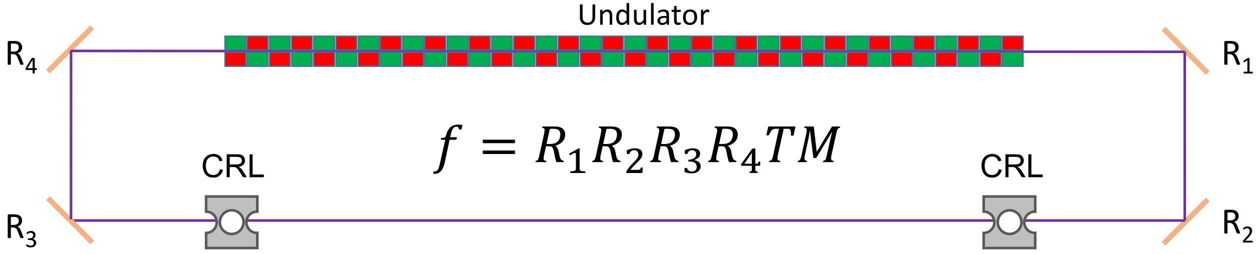
"Cavity-based FEL Research & Development" Talk by Gabriel Marcus FEL19 TUD Session - 17:30 Tuesday

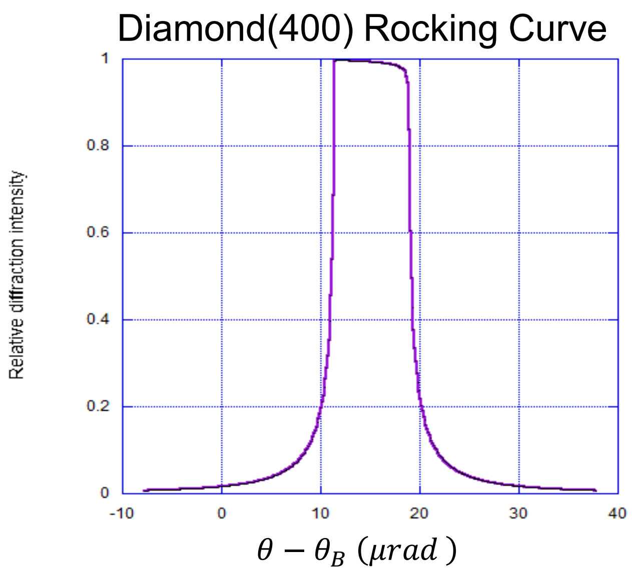
X-ray RAFEL with Bragg Reflectors

Bragg diffraction law

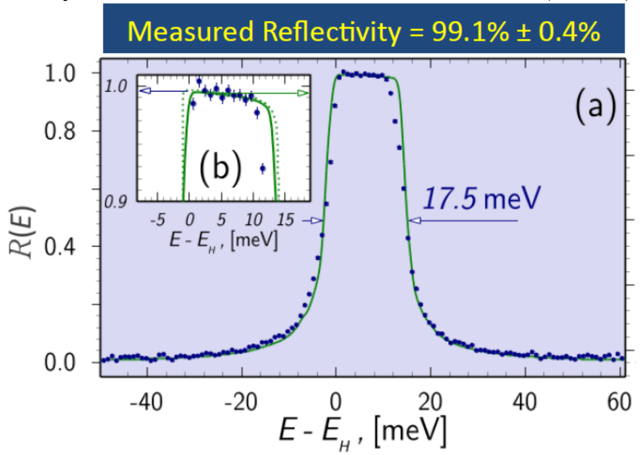
$$n□ = 2d\ sin\theta_B$$







Yu. Shvyd'ko et al., Nature Photonics 5 (2011) 539



Select the feedback fraction and unsaturated SASE power that yield a coherent seed with power exceeding start-up noise in the next pass.

$$P_{SASE} \sim 10^7 - 10^8\ W$$

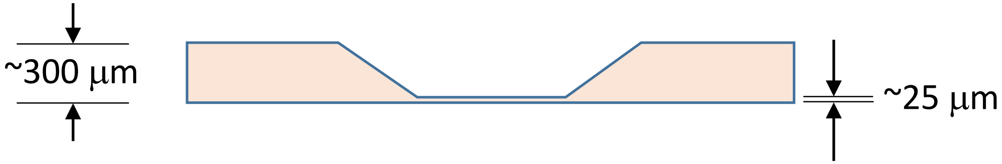
$$P_{sn} \sim 10^4 - 10^5\ W$$

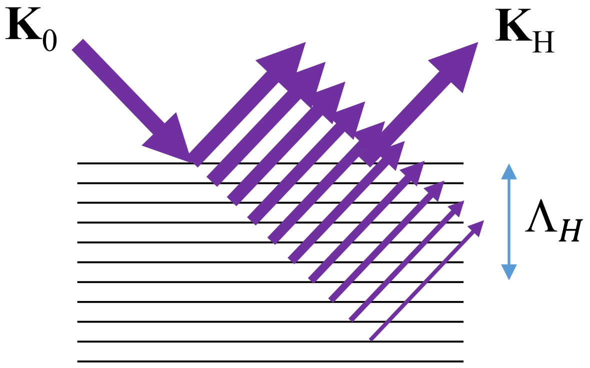
$$\Rightarrow \quad f > 10^{-3}$$

Symmetric Bragg 45° Reflectors

Bragg Crystal	Photon Energy (keV)	Darwin Width FWHM (µrad)	Energy Width FWHM (eV)	σ Polarization Extinction Length Λ_H (µm)	Thickness* for R = 95% (µm)
Diamond (111)	4.2573	59.4	0.25	1.1	5.0
Diamond (220)	6.9521	19.4	0.14	1.98	8.9
Diamond (311)	8.1521	8.80	0.072	3.74	16.8
Diamond (400)	9.8318	7.56	0.074	3.63	16.3
Diamond (331)	10.714	4.26	0.046	5.89	26.5
Diamond (422)	12.042	4.41	0.053	5.03	22.6

Preparation of diamond drumheads





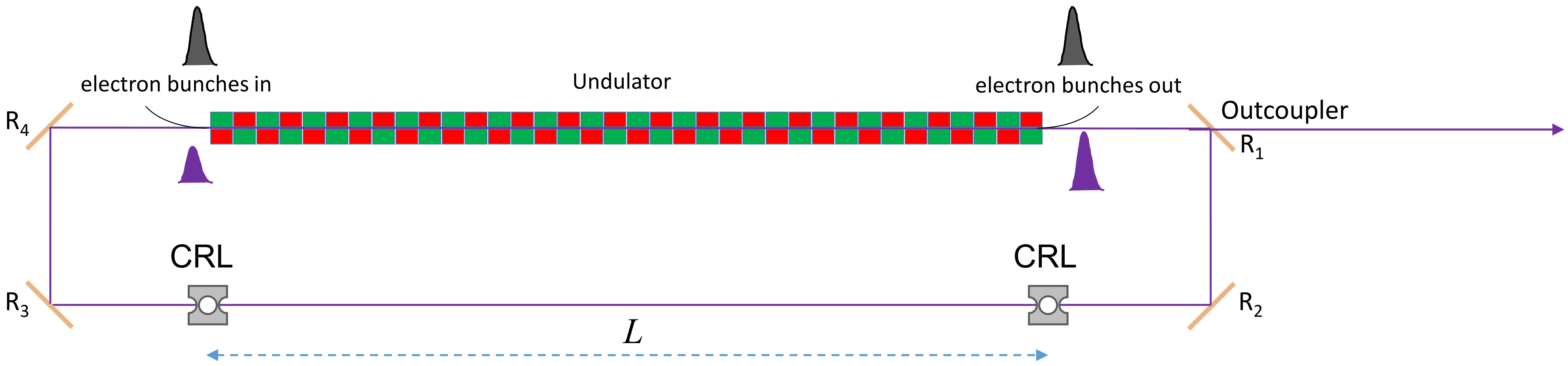
Extinction length ~ 10^5 *d*

* Shvyd'ko equation $R(0) \approx 1 - 4\,exp\left(\frac{t}{\Lambda_H}\right)$

T. Kolodzie, P. Vodnala, S. Terentyev, V. Blank and Y. Shvyd'ko, *J. Applied Crystallography*, **2016**, 49, 1240–1244

RAFEL Feedback Cavity Alignment

The reinjected X-ray pulse has to overlap with the electron bunch both longitudinally and transversely.

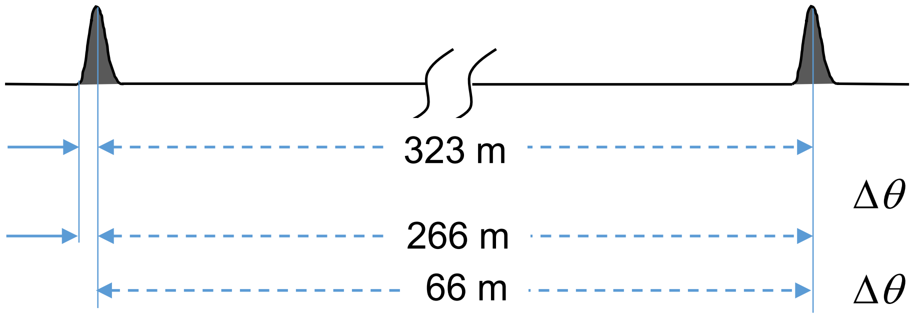


Cavity length dimension accuracy $\delta L \sim \frac{l_e}{n_p}$

Bragg mirror angular accuracy

$$\Delta\theta < \frac{w_r}{L}$$

l_e



LCLS-II @ 929 kHz ~5 μm

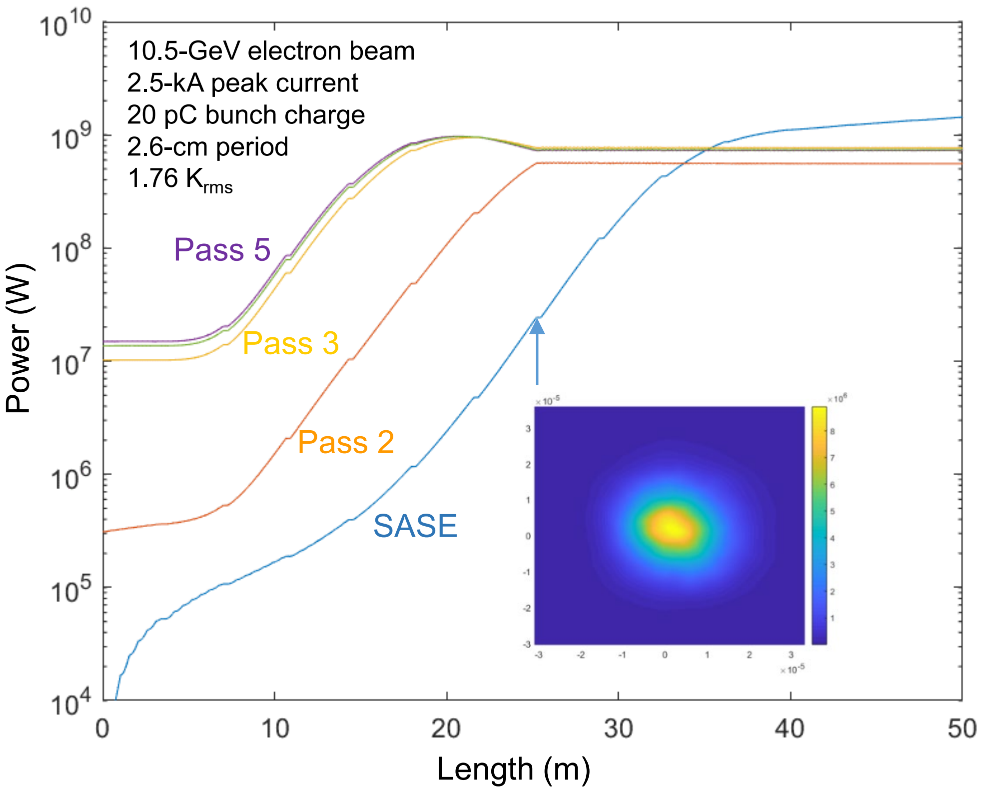
EuXFEL @ 1.128 MHz ~15 μm

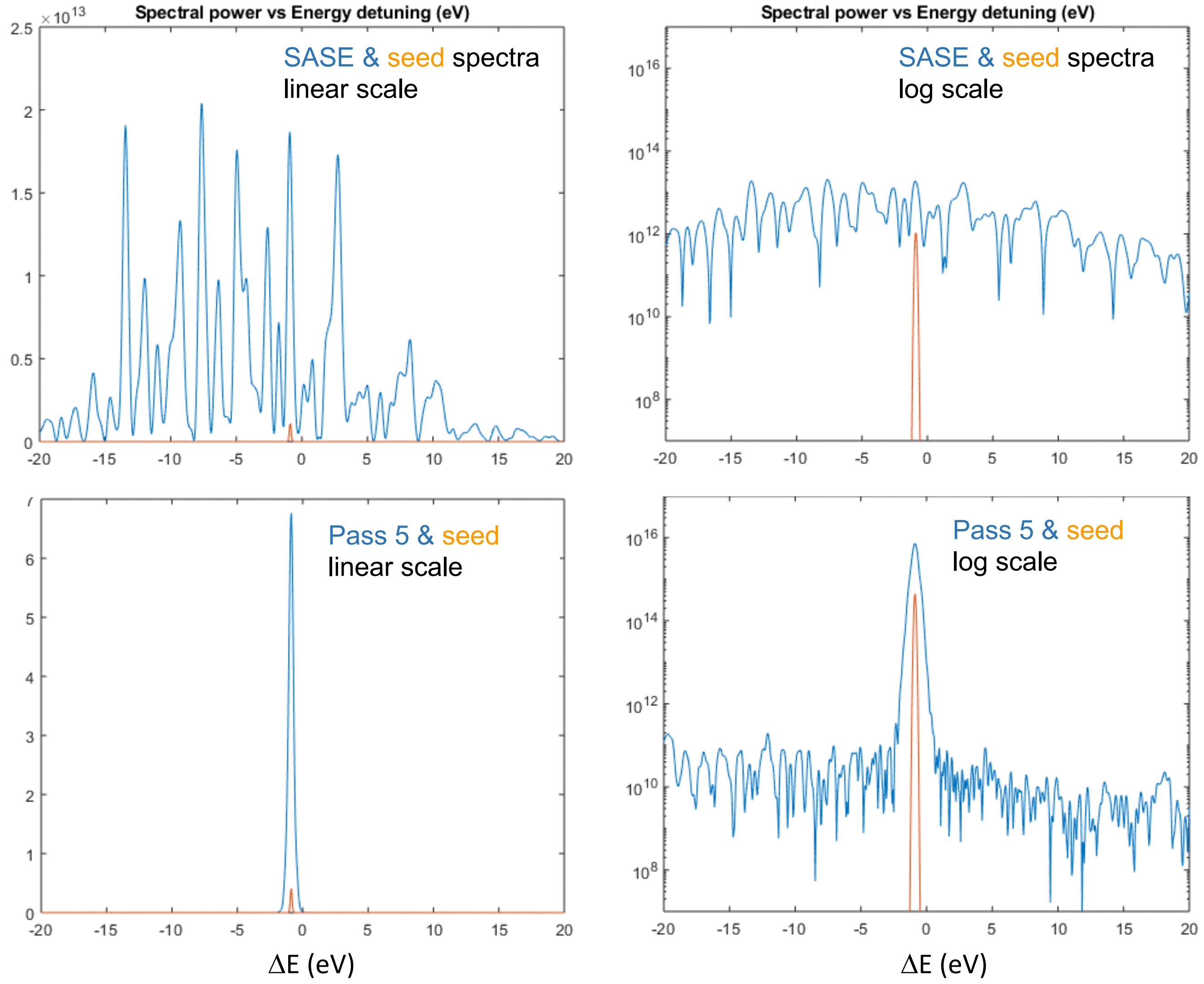
@ 4.512 MHz

$\Delta\theta < 0.5$ μrad

$\Delta\theta < 2$ μrad

10-keV RAFEL Genesis Simulations

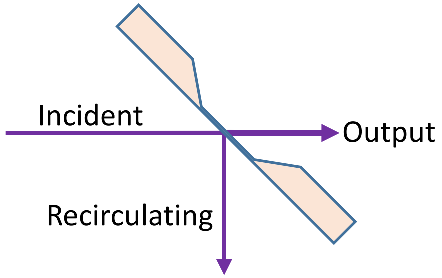




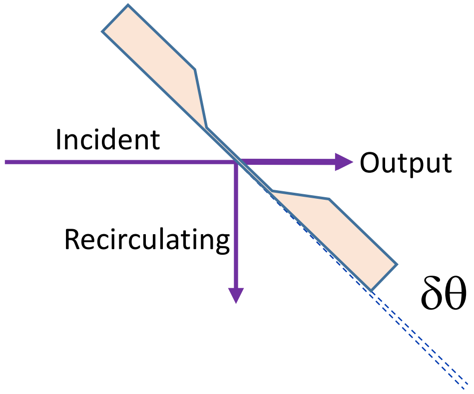
RAFEL reaches saturation at the end of Pass 3
SASE is suppressed by two orders of magnitude
RAFEL spectral power is 10^5 above SASE in Pass 5
FWHM bandwidth at the end of Pass 5 is 0.5 eV

Out-coupling Methods

1. Out-coupling through a very thin membrane
   - Bragg reflectivity scales linearly with thickness for thin membranes.
   - Diffraction width scales inversely with thickness for thin membranes.

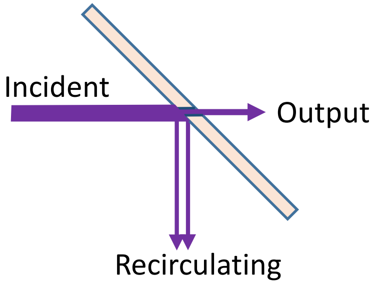


2. Out-coupling with a tilted thin membrane
   - Feedback cavity is aligned with the out-coupler tilted at a small angle $\delta\theta$ (~5 μrad) off the Bragg angle.

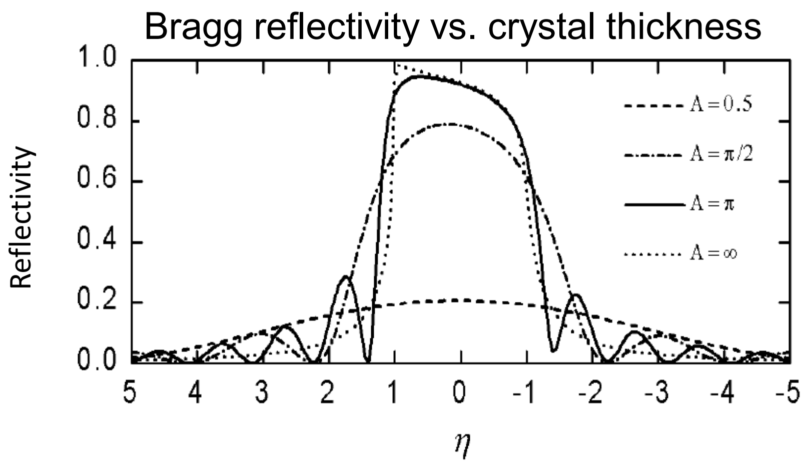


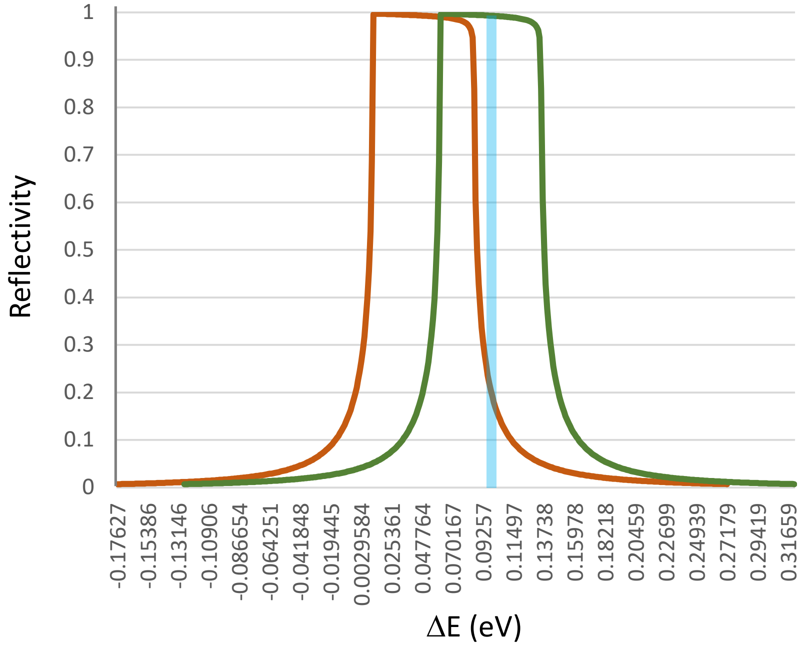
3. Out-coupling by heating the Bragg crystal
   - Raising the Bragg crystal temperature shifts the diffraction peak to lower photon energy.

4. Out-coupling through a diamond pinhole
   - Hole-coupling works at longer wavelengths.



H.P. Freund et al., arXiv:1905.06279 (2019).





X-ray Absorption in the Out-coupler

Bragg Crystal	Photon Energy (keV)	Extinction Length* Λ_H (μm)	Thickness for R ~ 50% (μm)	Absorption Length L_a (μm)	Absorption in 45° Out-coupler
Diamond (111)	4.2573	1.09	2.2	77.46	3.9%
Diamond (220)	6.9521	1.98	4.0	312.1	1.8%
Diamond (311)	8.1521	3.74	7.5	836.1	1.3%
Diamond (400)	9.8318	3.63	7.3	1,519	0.7%
Diamond (331)	10.714	5.89	11.8	1,999	0.8%
Diamond (422)	12.042	5.03	10.1	2,907	0.5%

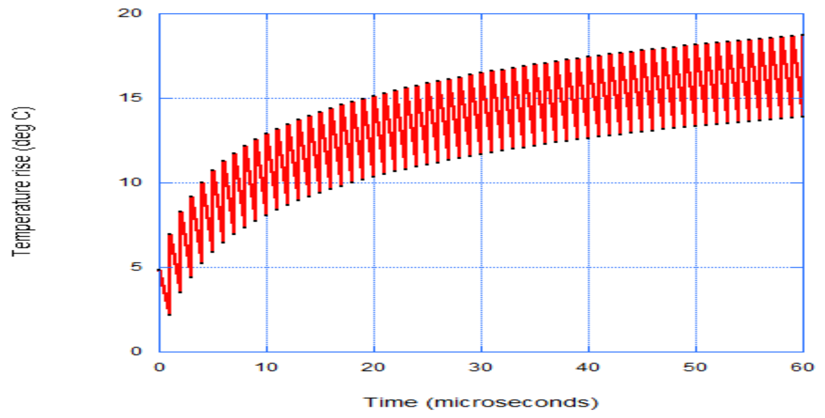
Absorbed energy per pulse

$$W_{abs} = W_0\left(1 - e^{-\frac{t}{La\, sin\theta_B}}\right)$$

W_0 → Incident X-rays energy

For the 10-keV RAFEL with X-ray pulse energy of 140 μJ irradiating a π(50μm x 50μm x 10μm) volume, the absorbed energy is 1 μJ / pulse.

Plot of temperature rise versus time



* Y. Shvyd'ko and R. Lindberg, *Phys. Rev. ST Accel. Beams,* **15** 100702 (2012).

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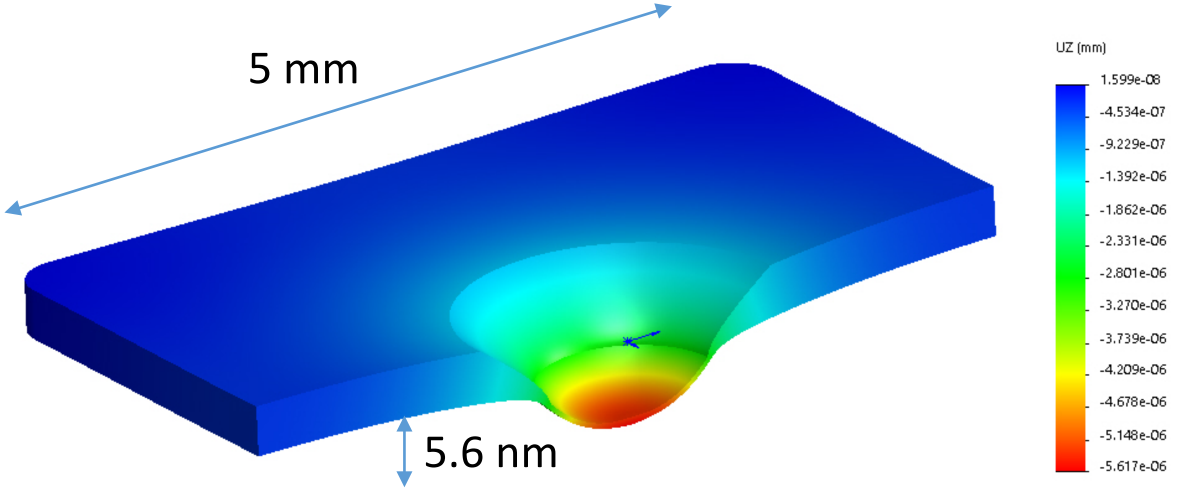
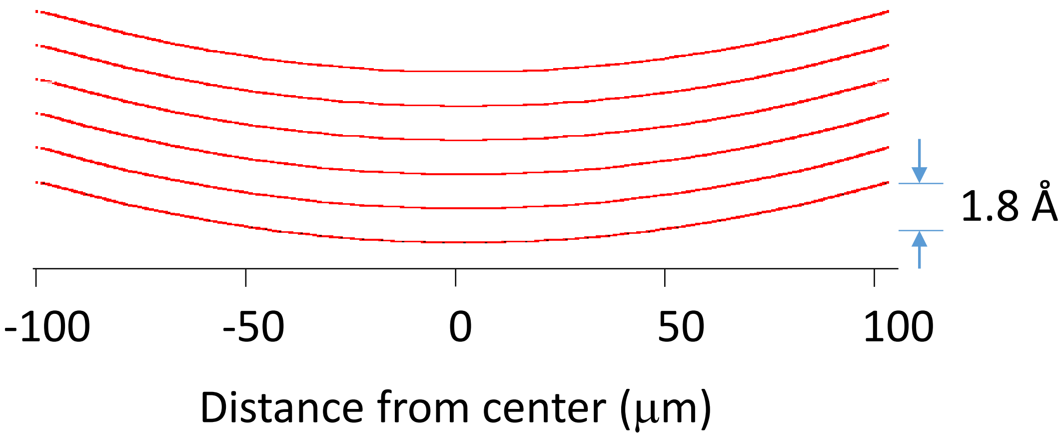
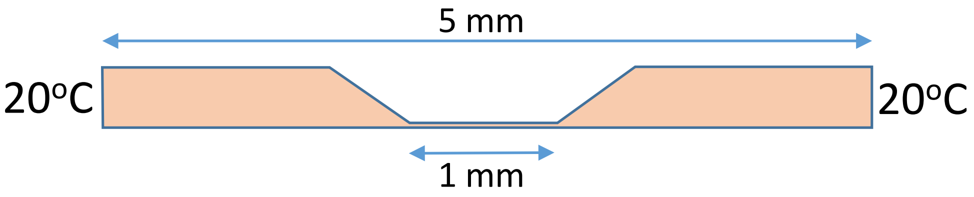
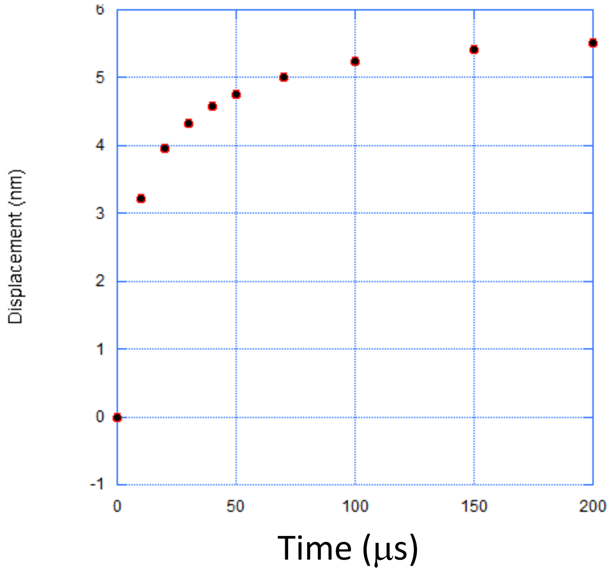
Distortion due to Localized Heating







Center displacement vs time with 1 W deposited in 100 μm diameter spot



Summary

- The RAFEL with diamond Bragg reflectors is a feasible approach to a temporally coherent X-ray FEL with narrow linewidth (~5 x 10^{-5} relative).
- Optical alignment of the RAFEL feedback cavity, though not as challenging as an XFELO cavity, is difficult due to the sub-μrad angular alignment accuracy.
- Genesis simulations show that with only 6% feedback fraction, a 10-keV X-ray RAFEL using seven 3.4-m undulators can saturate in two passes after SASE.
- We suggest a number of options to out-couple the intra-cavity power and to mitigate the thermal distortions due to X-ray absorption in the out-coupler.

Thank you for your attention