Towards an x-ray FEL oscillator

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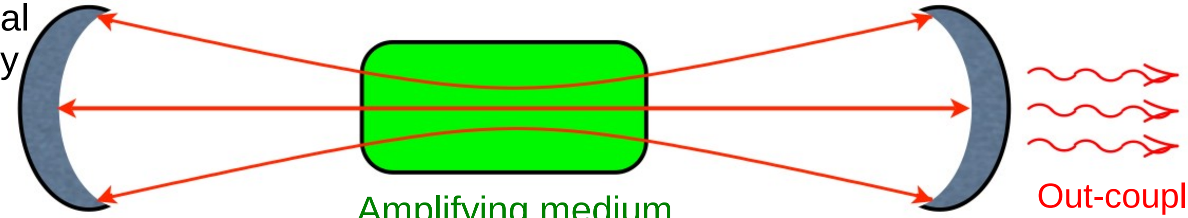
X-ray FEL oscillator is comparable to optical laser

Traditional laser oscillator



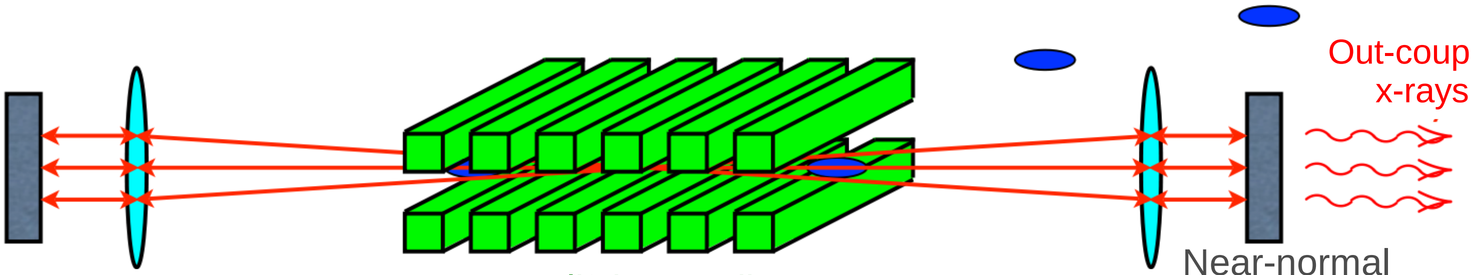
Optical cavity

Amplifying medium
(Glass, fiber, gas,...)

Out-coupled
laser light

Replace amplifier and optical cavity with components that work at x-ray wavelengths

X-ray FEL oscillator (XFELO)†



Out-coupled
x-rays

Focusing element
(Grazing incidence mirror, compound refractive lens, ...)

Amplifying medium = FEL
(Undulator + electron beam)

Near-normal reflector
(Diamond Bragg crystal)

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† R. Colella and A. Luccio, Opt. Comm. **50**, 41 (1984)
K.-J. Kim, Y. Shvyd’ko, and S. Reiche, PRL **100**, 244802 (2008)

XFELO is complementary to high-gain FELs based on self-amplified spontaneous emission (SASE)

Characteristic	SASE	XFELO
Pulse duration	1 to 200 fs	200 to 2000 fs
Photons/puse	~10^{12}	~10^{9}
Energy BW	~ 10 eV	~10^{-2} eV
Coherence	Transverse	Fully
Repetition rate	Variable	~ MHz
Stability	1-100% depending chosen BW	< 1%
Brightness	~10^{32}	~10^{32}

XFELO Science

1. Inelastic x-ray scattering
2. Nuclear resonant scattering
3. X-ray photoemission spectroscopy
4. Hard x-ray imaging
5. X-ray photon correlation spectroscopy

…

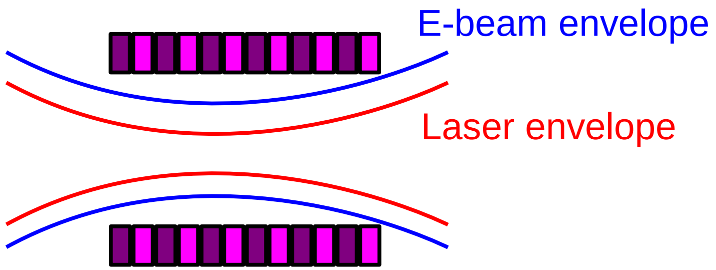
XFELO will revolutionize techniques pioneered at 3rd generation light sources, and complement the capabilities of SASE FELs

Linear gain in an XFELO

- Electron beam requirements
  - High brightness: $\varepsilon_x \leq 0.3$ μm, $\Delta\gamma/\gamma \leq$ few × 10^{-4}
  - Relatively low intensity: $I_{\text{peak}} \sim 10 - 200$ A
  - Moderate duration: 0.2 – 5 ps
  - Repetition rate = c/(cavity length) ~ MHz
- Undulator parameters: K ~ 1 and $N_u \sim 10^3$

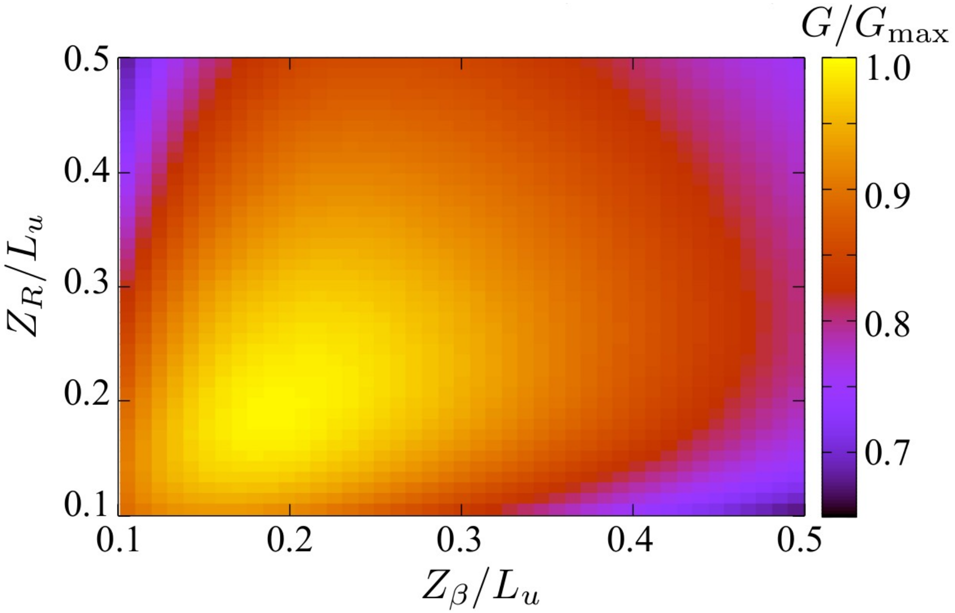
Single pass gain ~ 0.3 to 2

Gain is maximized when the electron and laser beams have maximal overlap

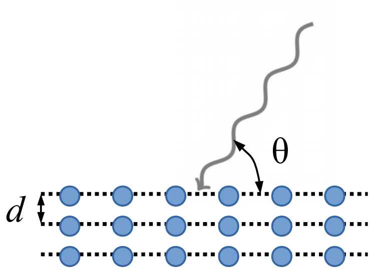


And when the beam nearly matches the spontaneous radiation "mode" size

$$Z_\beta = Z_R \sim \frac{L_u}{\pi}$$



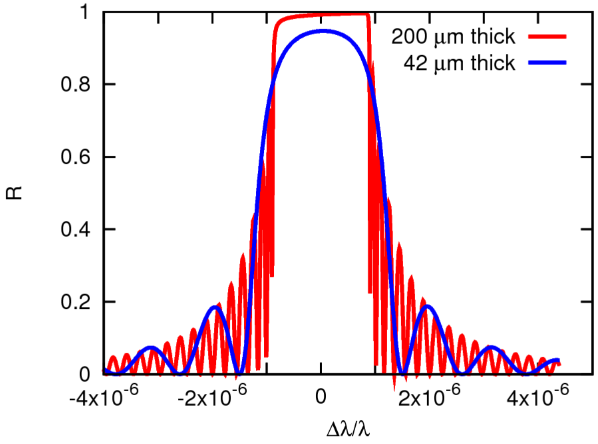
Bragg mirrors for near-normal reflection

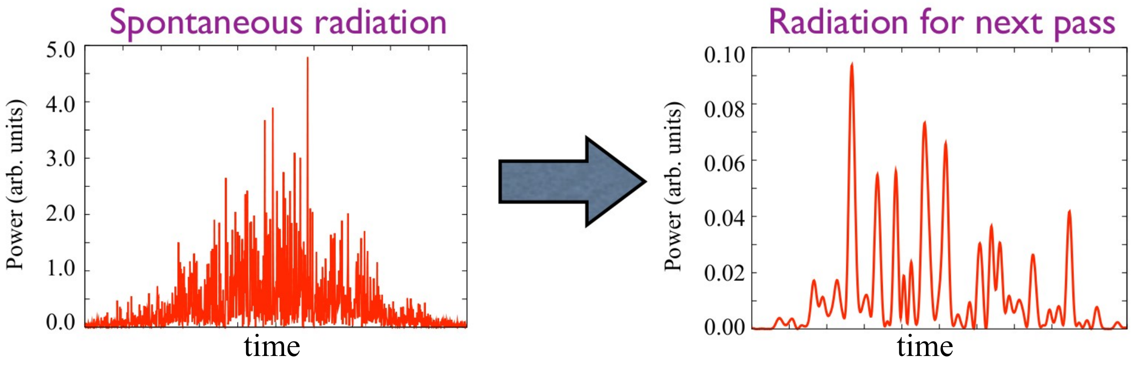


Bragg crystals work via coherent scattering of photons whose wavelength approximately satisfies Bragg's Law, $\lambda = 2d\cos\theta$

Many crystal planes contribute, $N_p \sim 10^5 - 10^8$, and the region of high reflectivity has a bandwidth $\Delta\lambda/\lambda \sim N_p^{-1} < 10^{-5}$

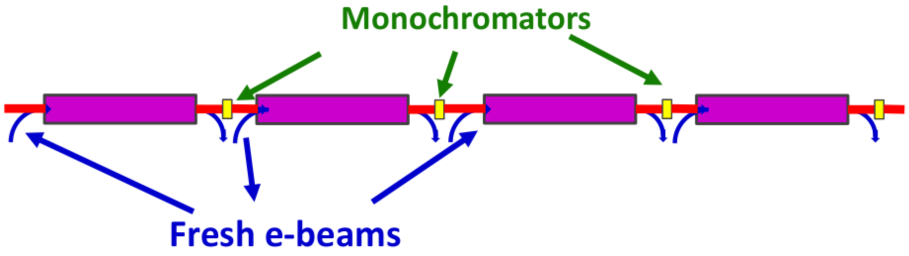
Dominant effects of Bragg crystals are frequency filtering and losses



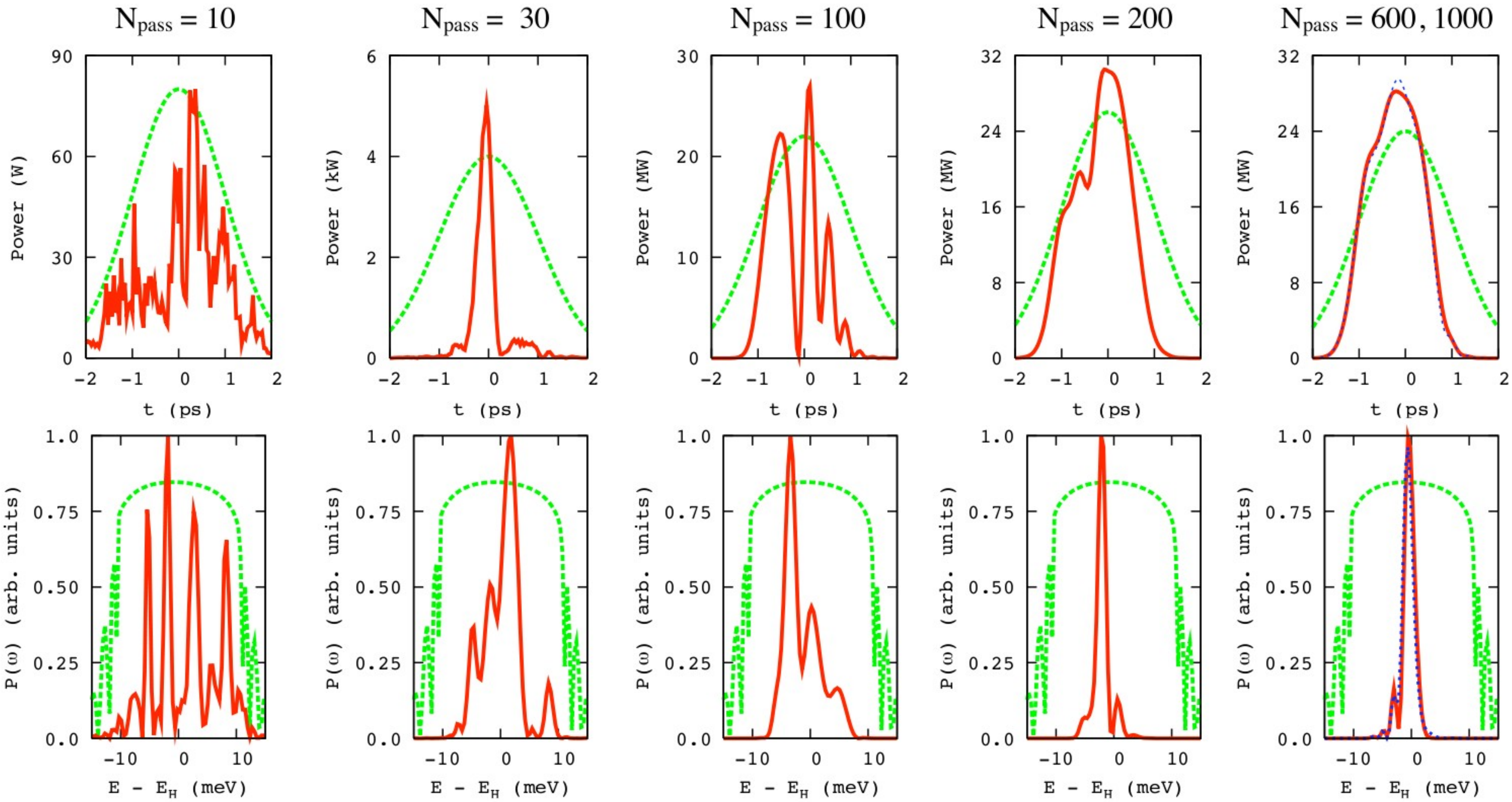


X-ray power builds and bandwidth decreases over many passes

"Infinite chain" of self-seeded FELs



Temporal and spectral profile evolution



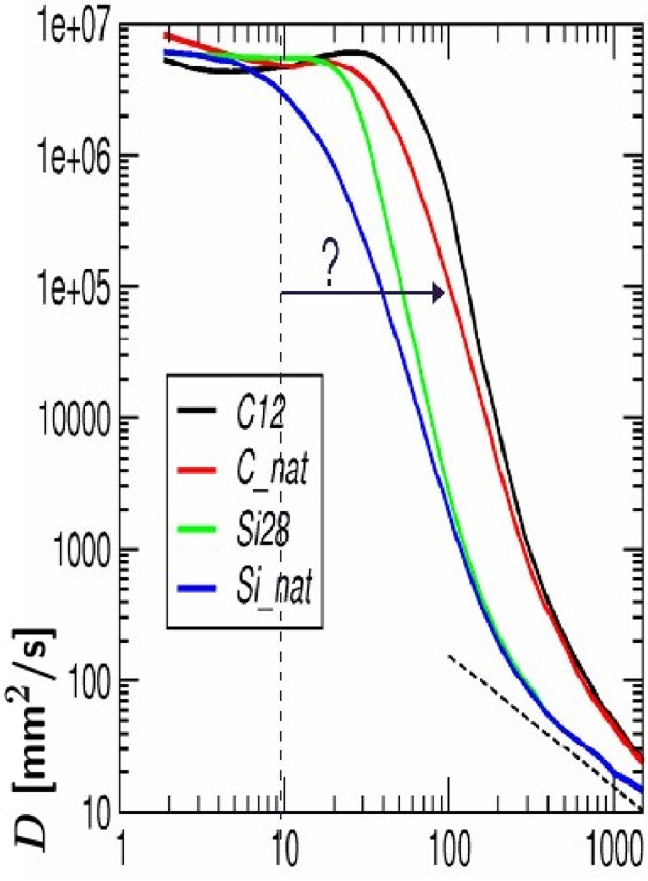
All this relies on high-quality Bragg crystals.

Can real-world diamond crystals approach this ideal performance?

Diamond crystals have superior material properties

Ultra-high thermal diffusivity

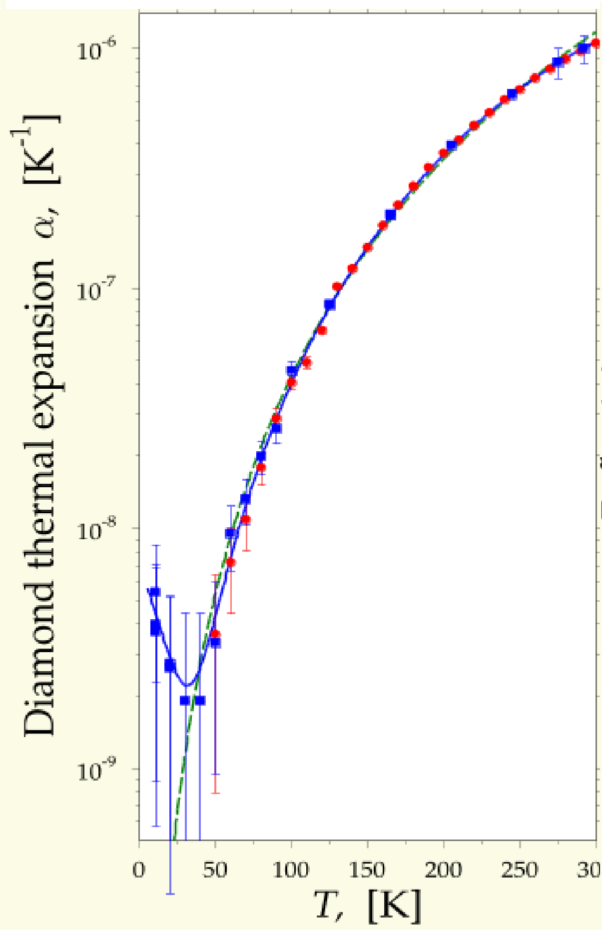
~ 10^5 s/mm^2 @ 100 K



Courtesy H. Sinn

Ultra-low thermal expansion

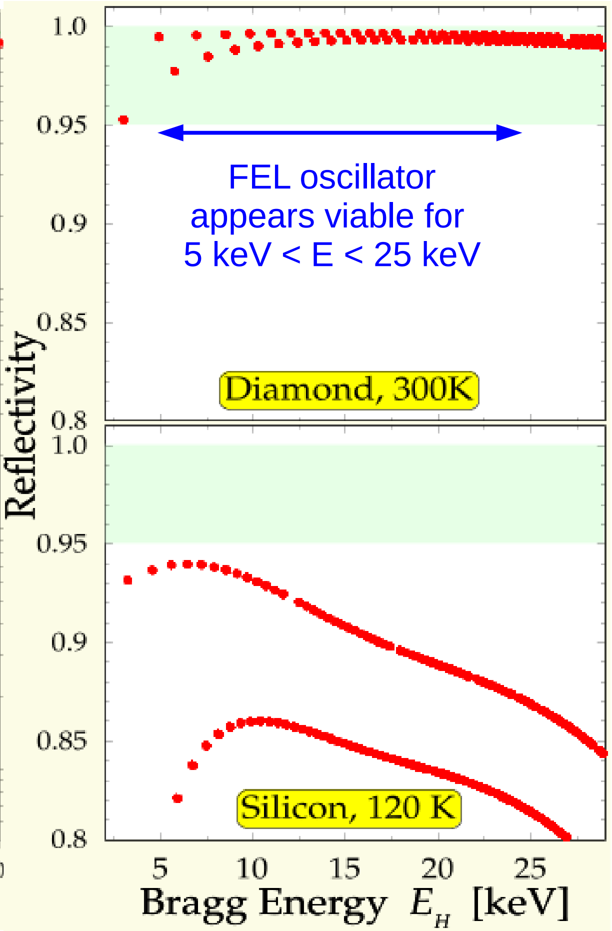
~ 10^{-8} K^{-1} @ 100 K



S. Stoupin and Yu. Shvyd'ko, *Phys. Rev. Lett.* **104**, 085901 (2010)

Record-high reflectivities

Theory: > 99% possible

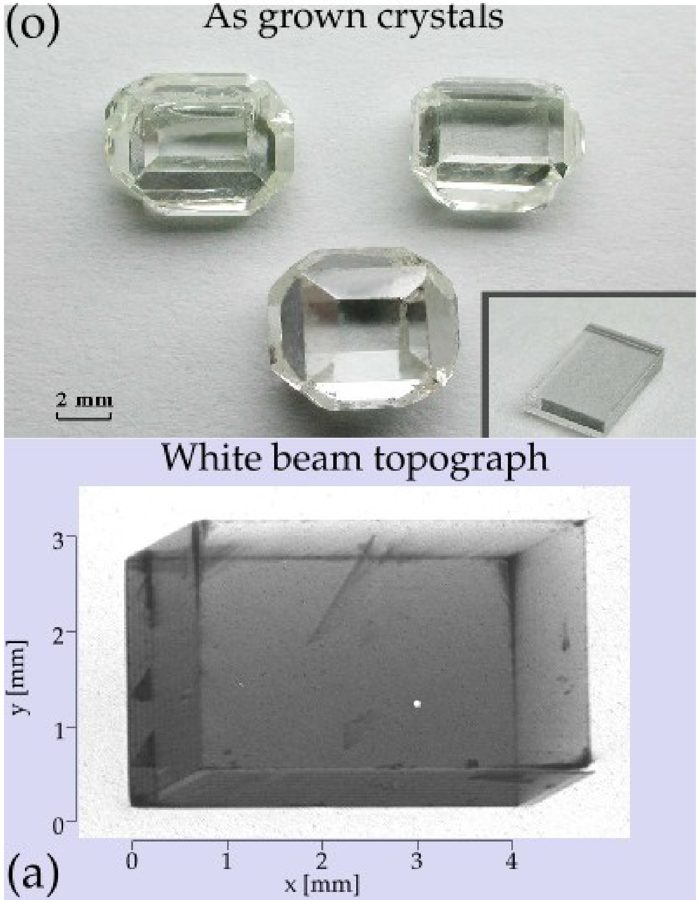


FEL oscillator appears viable for 5 keV < E < 25 keV

Yu. Shvyd'ko, S. Stoupin, A. Cunsolo, A.H. Said, and X. Huang, *Nature Phys.* **6**, 196 (2010)

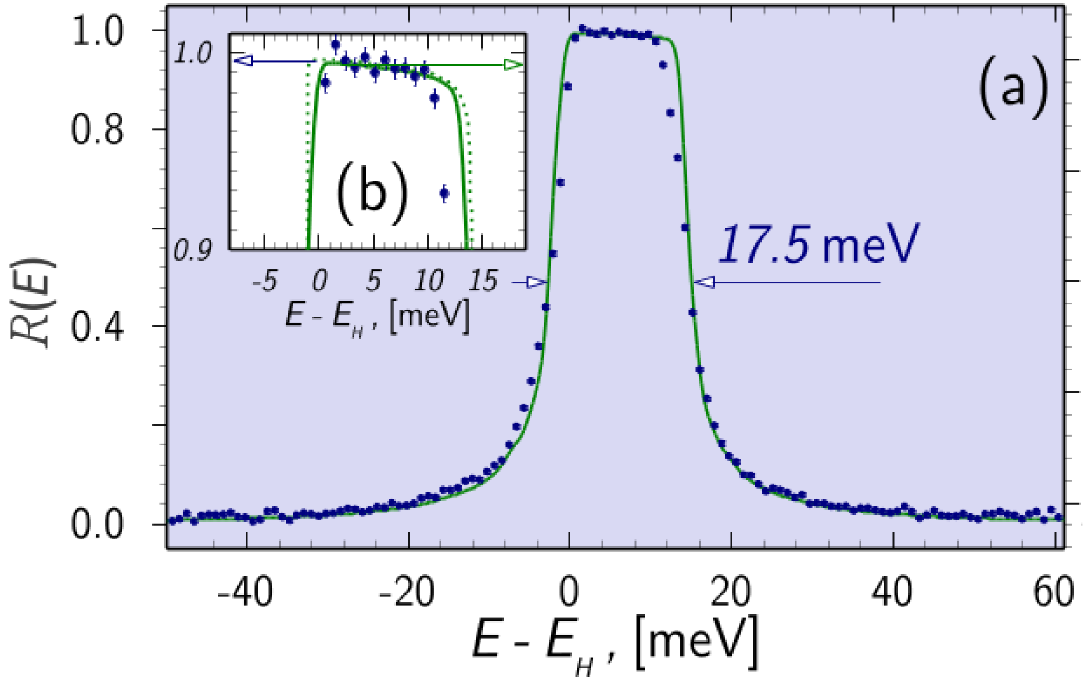
Reflectivity of TISNCM† synthetic diamond was measured to be > 98% @ the APS

† Technological Institute for Superhard Novel Carbon materials, Russia



There exist regions whose area > 1 mm^2 that are free of dislocations and stacking faults

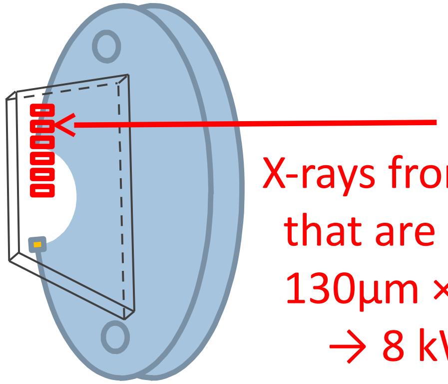
Measured Reflectivity = 99.1% ± 0.4%



Reflectivity curve width and maximum agree with dynamical diffraction theory

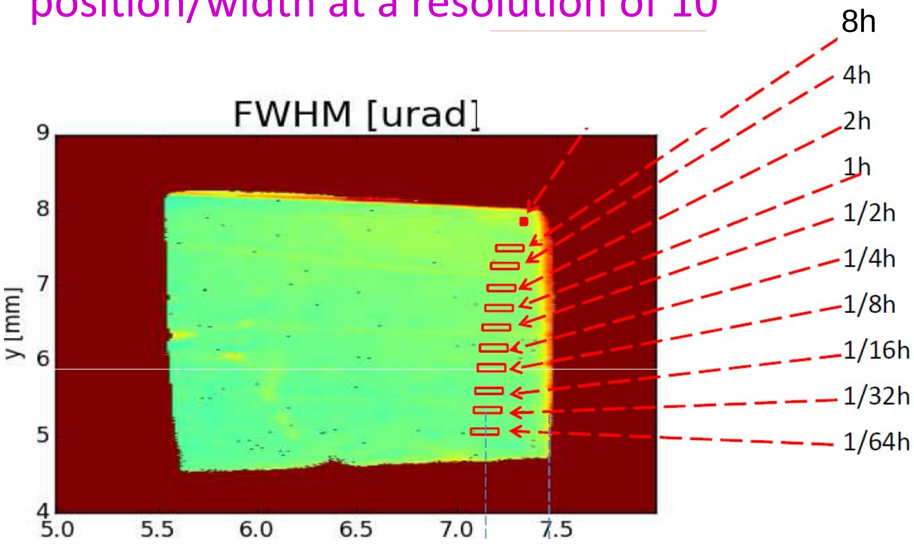
Yu. Shvyd’ko, S. Stoupin, V. Blank, and S. Terentyev, *Nature Photonics* **5**, 539 (2011)

Tests of diamond resiliency under XFELO conditions

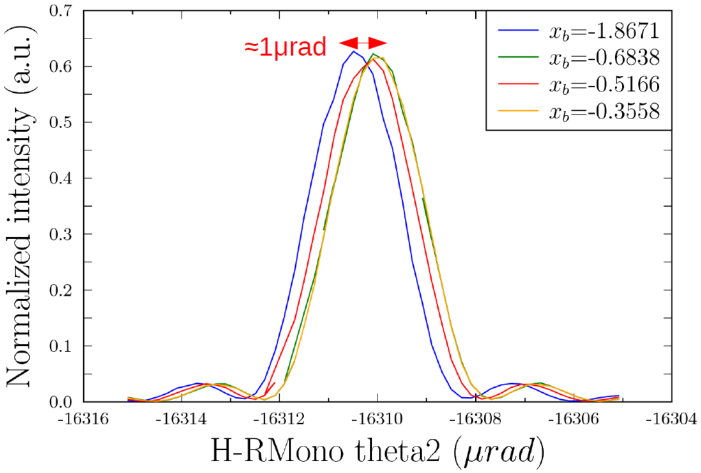


X-rays from APS 35 ID-B that are focused to a 130μm × 30μm spot → 8 kW/mm^2

Double crystal topography indicates no changes in the rocking curve position/width at a resolution of 10^{-6}

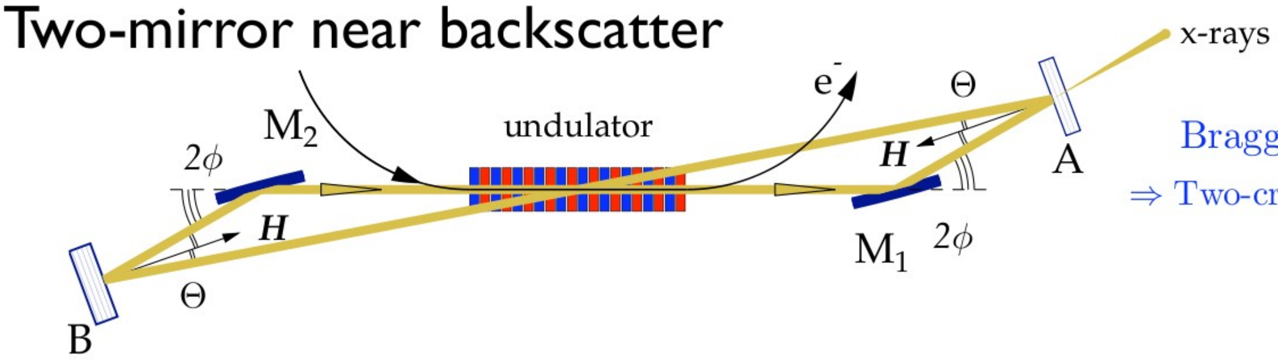


High resolution measurements showed a shift in peak reflectivity at a level of 10^{-8}



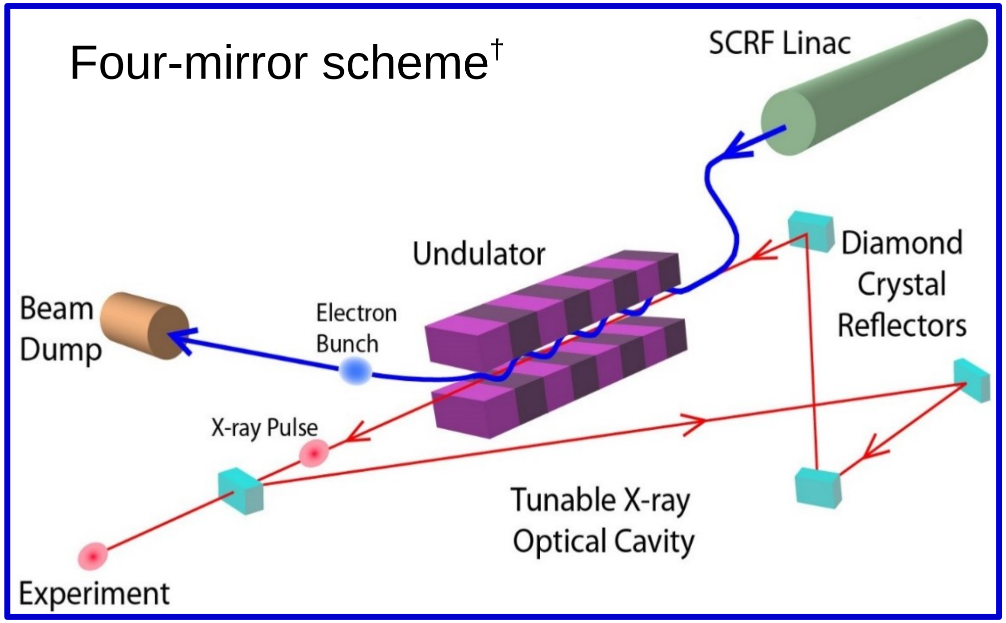
- The measured ~1 meV shift could be compensated for in XFELO with feedback
- Annealing at 600 C eliminated shift
- Believe that the shift is caused by impurities
- Next experiment will test this theory using an improved vacuum (< 10^{-8})

X-ray cavity configurations



Bragg's Law $E = E_H \cos\Theta$

$\Rightarrow$ Two-crystal scheme is not tunable



† K.M.J. Cotterill, Appl. Phys. Lett. **12**, 403 (1968)
K.-J. Kim and Yu. Shvyd'ko, Phys. Rev. ST-AB **12**, 030703 (2009)

Cavity looks like a wrapped-up version of the standard 4-bounce monochromator

By changing angles on all crystals one can tune the photon energy

Can we stabilize the cavity to the required tolerance?

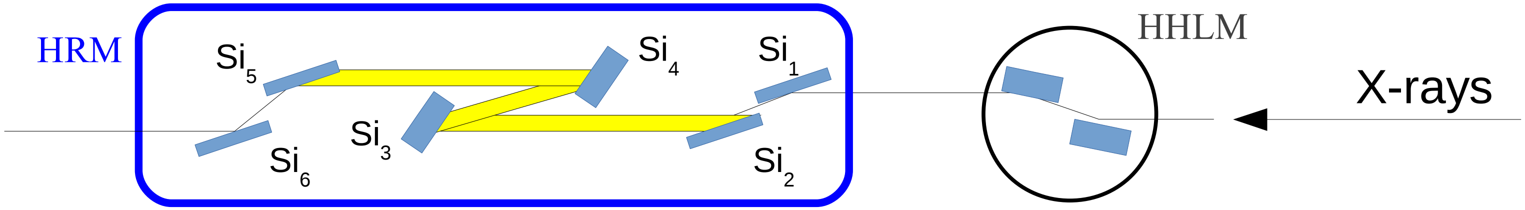
What focusing elements can we use?

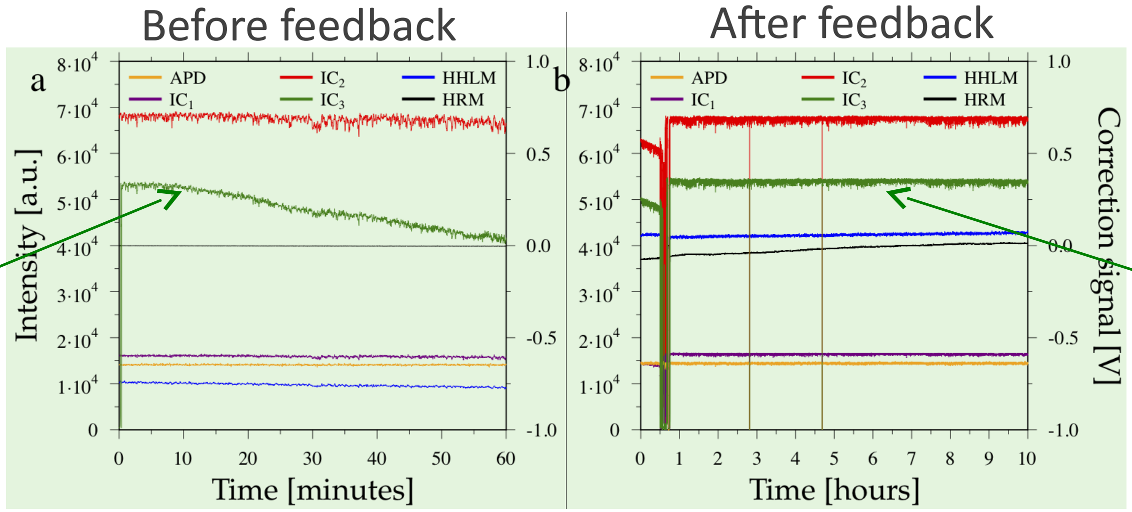
Cavity stabilization proof of principle

To preserve radiation-electron beam overlap and FEL gain, we require:

1. Cavity length stability $\delta L < 3$ μm (relatively easy)
2. Crystal angular stability $\delta\theta \sim 10$ nrad (less straightforward)

Null detection feedback (LIGO): proof of principle experiment @ APS





"Wandering" crystal

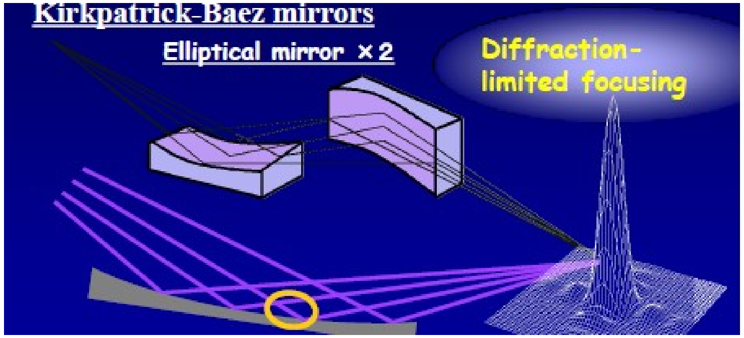
Stabilized crystal

Crystal stability of ~ 15 nrad rms was shown at the APS HERIX monochromator

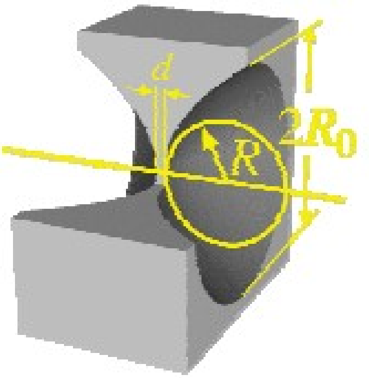
Stoupin, Lenkszus, Laird, Goetze, Kim, and Shvyd'ko, *Rev. Sci. Instrum.* **81**, 055108 (2010)

Focusing elements for an XFELO

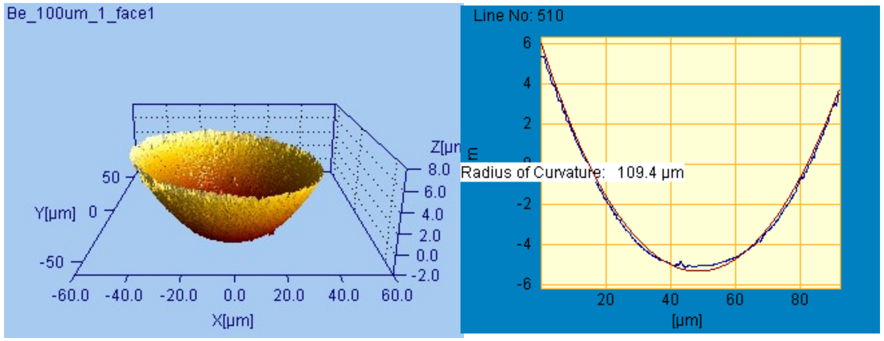
- Grazing incidence Kirkpatrick-Baez mirrors are being perfected at JTEC, but they are long, heavy, difficult to control, and result in a non-coplanar XFELO geometry



- Grazing incidence mirrors that focus in both planes are possible in theory, but manufacturing such mirrors with micron-scale surface roughness is very difficult
- Beryllium compound refractive lens (CRL) can be a low-loss focusing element for applications requiring long focal lengths ($f > 20$ m)

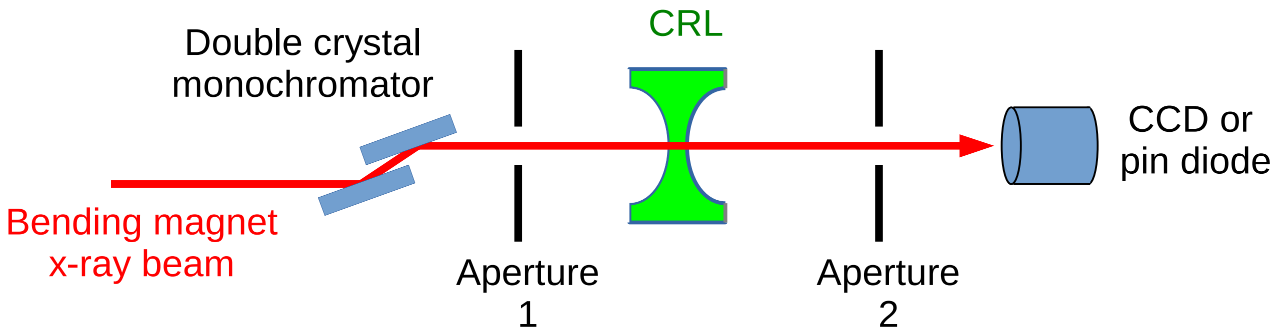


APS metrology of Be CRL

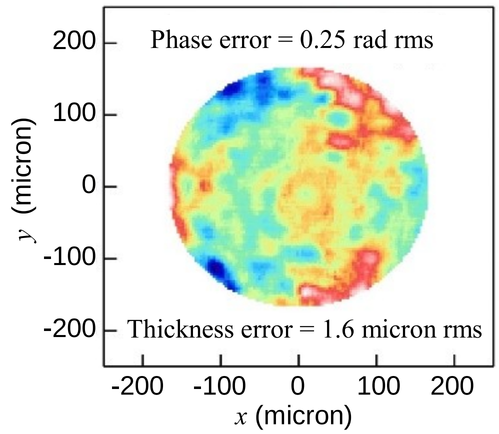


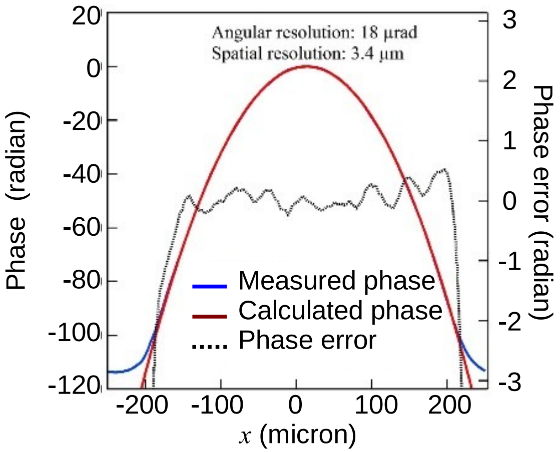
99.5% transmission @ 14.4 keV (theory for $d = 30$ µm)

Beryllium compound refractive lens test @ APS



1. Transmission of Beryllium CRL with $f = 50$ m was measured to be ~99%
2. Wavefront measurement data shows < 1 micron surface errors





3. Be-CRL endurance was tested as a byproduct of diamond crystal experiments, in which a 25 micron thick window was exposed to 3 kW/mm^2 x-rays

Measurements by S. Stoupin, J. Kryziwinski, T. Kolodziej, Y. Shvyd'ko, D. Shu, X. Shi

XFELO operating at a harmonic of the fundamental can significantly decrease electron beam energy[†]

- Madey's theorem says that in the low-gain limit $G_h \propto \frac{\partial}{\partial \omega} \mathcal{S}_{\text{spont}}(\omega)$

  and it turns out that gain can be larger at higher harmonics
  (fixed e-beam energy, number of undulator periods, etc.)

- This conclusion applies if the energy spread is sufficiently small:

$$h\frac{\sigma_\gamma}{\gamma} \lesssim \frac{1}{2\pi N_u}$$

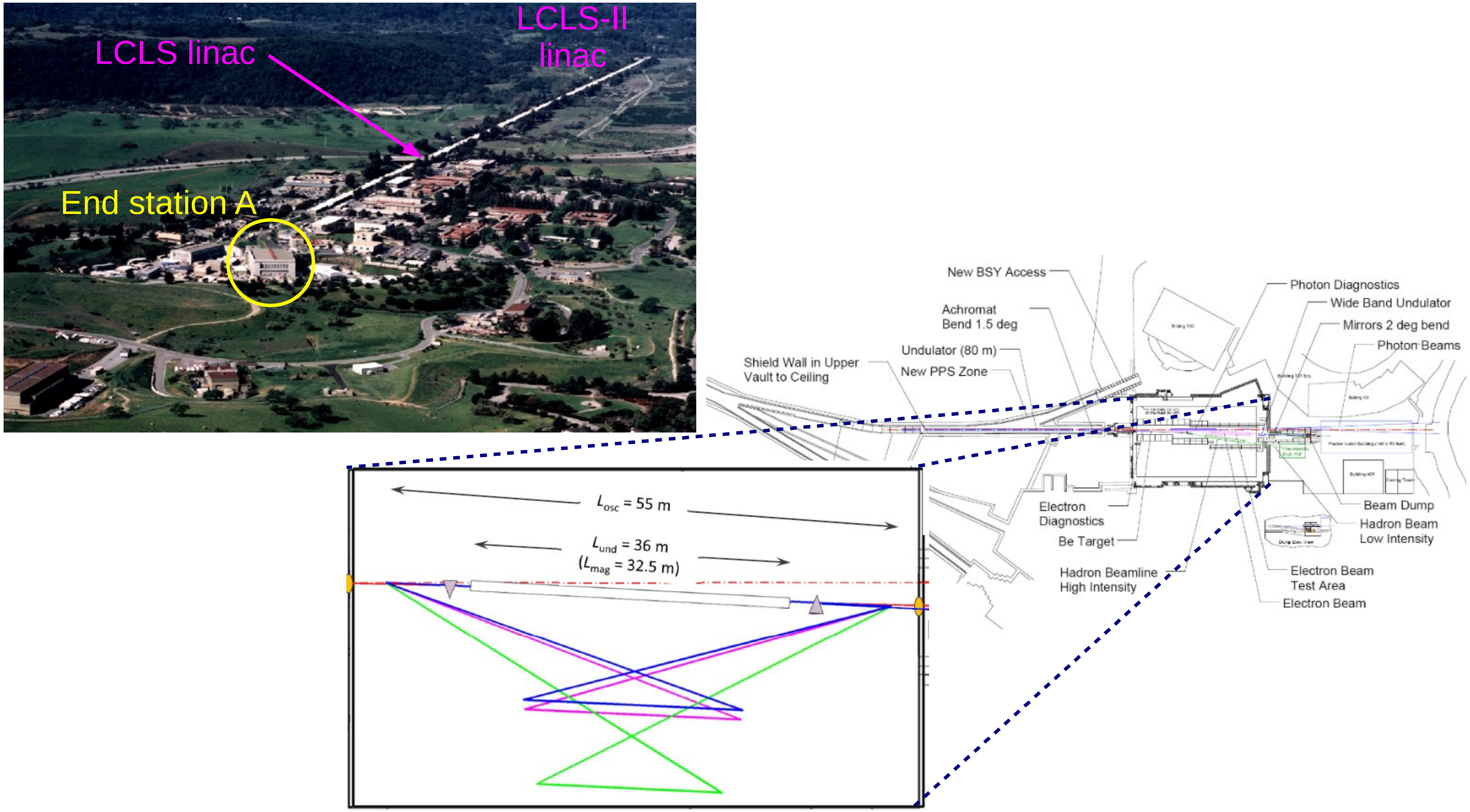
Variation of the resonance energy at harmonic h must be small

- For an XFELO, this typically means that $\Delta\gamma/\gamma < 2\times10^{-4}/h$

- Harmonic lasing may make an XFELO possible with low charge operation at the 4 GeV superconducting linac planned for LCLS-II

[†] J. Dai, H. Deng, Z. Dai, Phys Rev. Lett. **108**, 034802 (2012)

Possible layout of harmonic XFELO at LCLS-II



E_{ph} = 14.4 keV, $2\vartheta_r$ = 18.4º, C* (337)

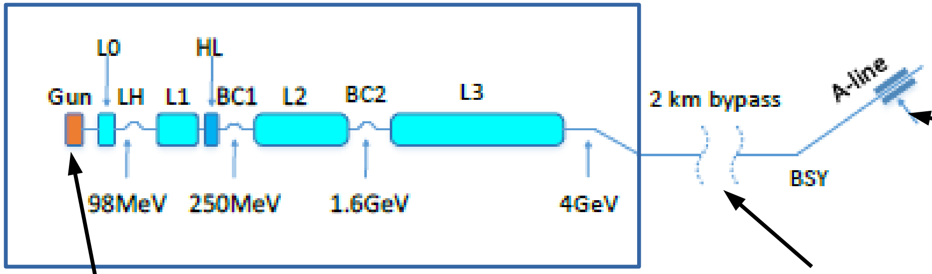
E_{ph} = 13.8 keV, $2\vartheta_r$ = 29.3º, C* (355)

E_{ph} = 9.13 keV, $2\vartheta_r$ = 17.0º, C* (333)

From T. Maxwell et al. (SLAC)

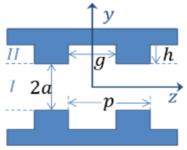
Electron beam profile optimization (simulation)

LCLS-II SRF linac operating @ ~MHz



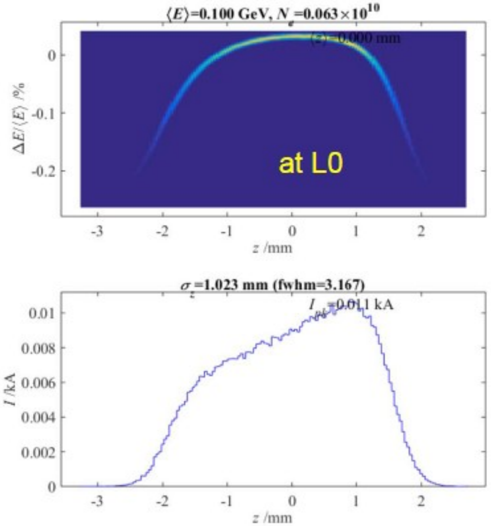
End station A
(XFELO)

Wakefield from corrugated
“dechirper” removes energy chirp

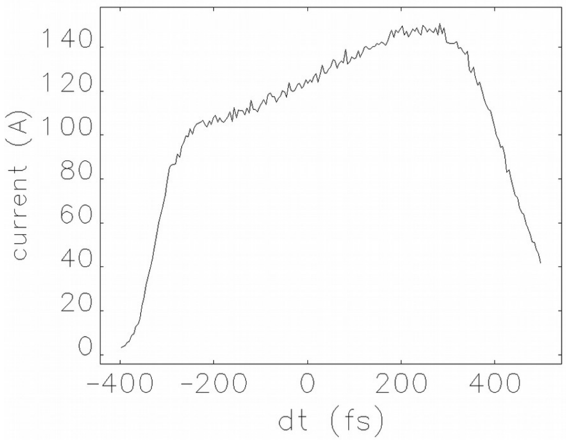


Wakefields induce
correlated energy chirp

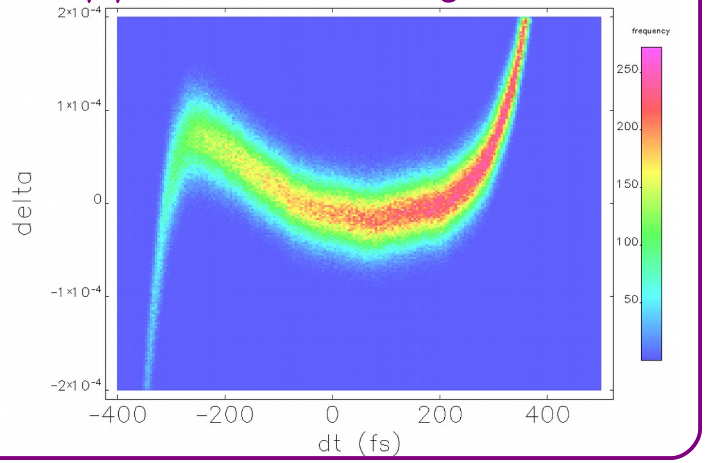
Simulated laser profile on the
cathode optimized to minimize
energy spread @ ESA



Current ~ 120 A



$\Delta\gamma/\gamma < 5\times10^{-5}$ over length ~500 fs

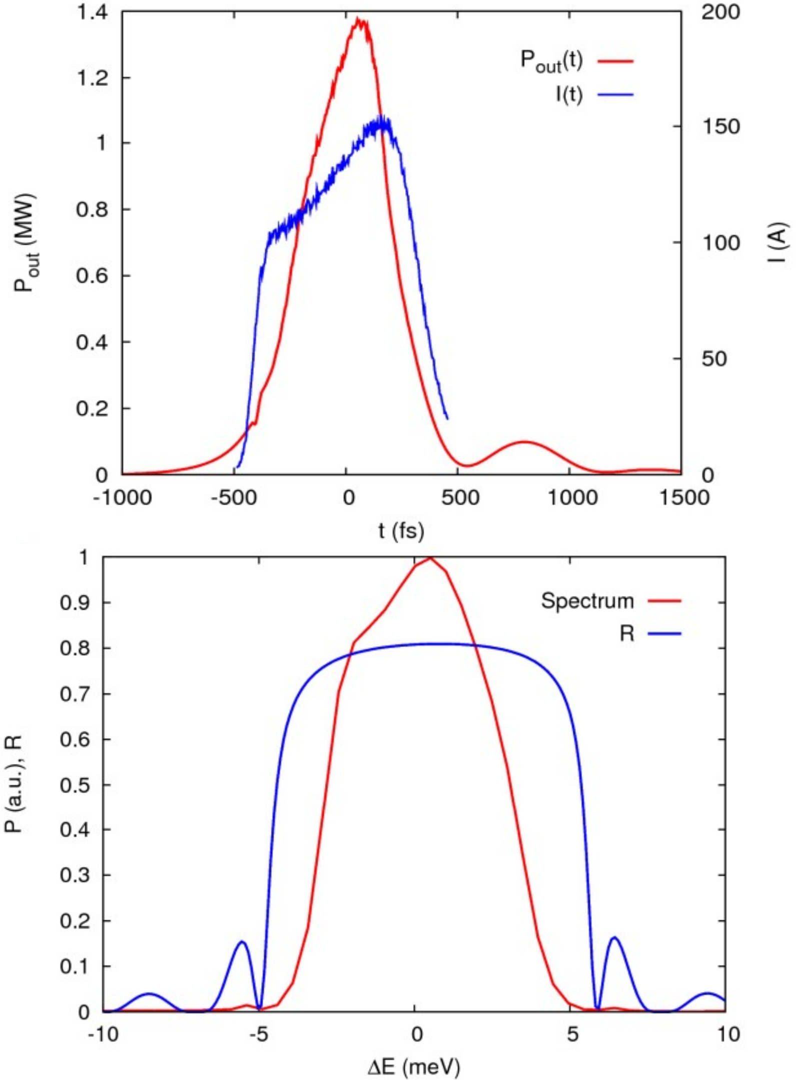


W. Qin (Peking), Y. Ding, K. Bane, et al. (SLAC)

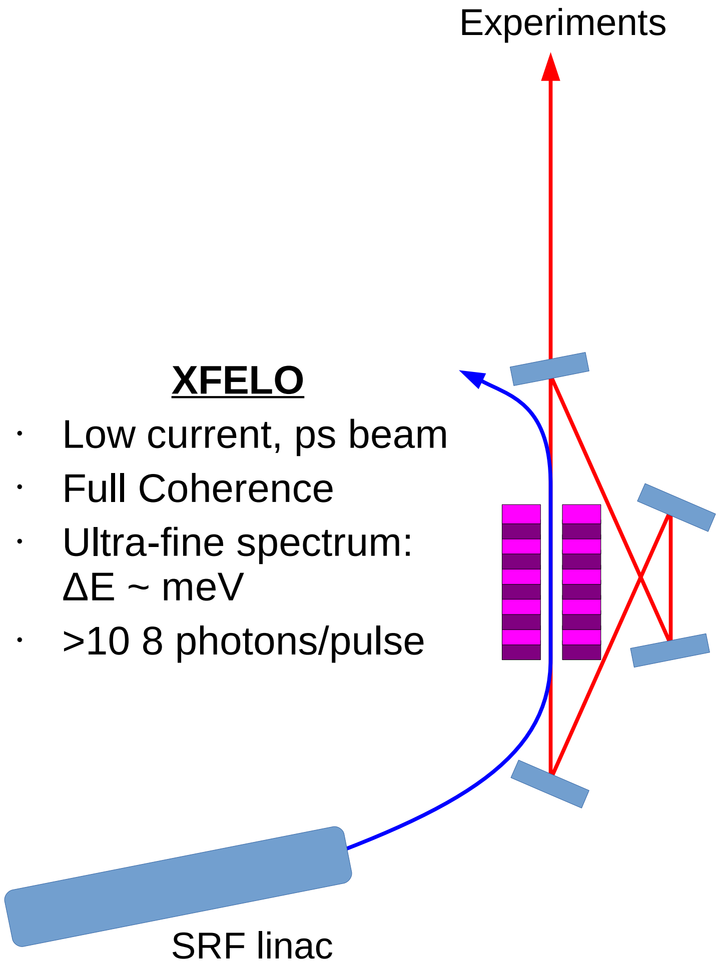
Performance of harmonic XFELO @ LCLS-II

Major Parameters

Parameter	Value	Units
Electron energy	4.0	GeV
Peak current	100-140	A
Bunch charge	100	pC
Bunch length	400	fs
Energy spread	0.1	MeV
Norm. emittance	0.3	μm
Undulator period	2.6	cm
Undulator K	1.433	
# undulator periods	1250	
Loss+Transmission	20	%
Photon energy@5th h	14.4	keV
Spectral BW	5	meV
Pulse length	0.5	ps



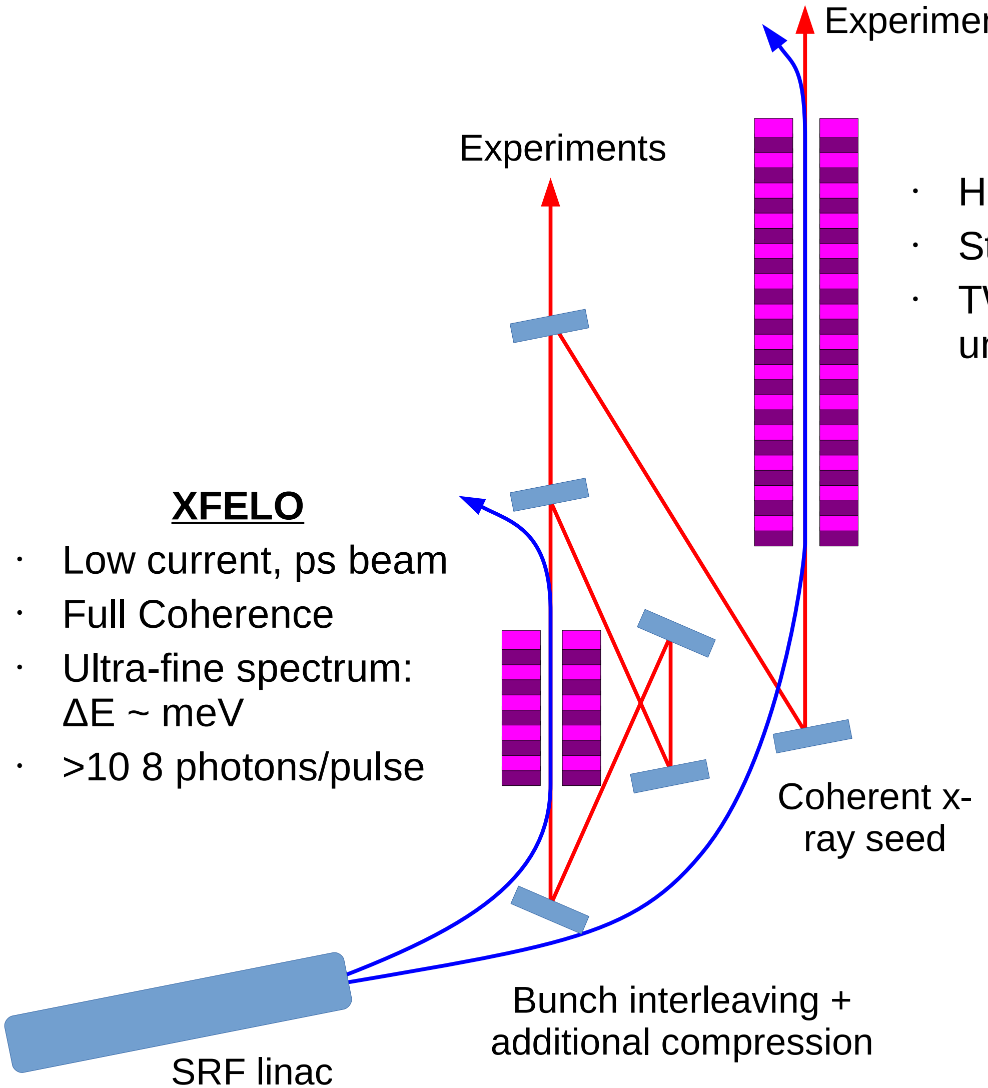
“Ultimate” x-ray generation facility



XFELO

- Low current, ps beam
- Full Coherence
- Ultra-fine spectrum:
  ΔE ~ meV
- >10 8 photons/pulse

“Ultimate” x-ray generation facility



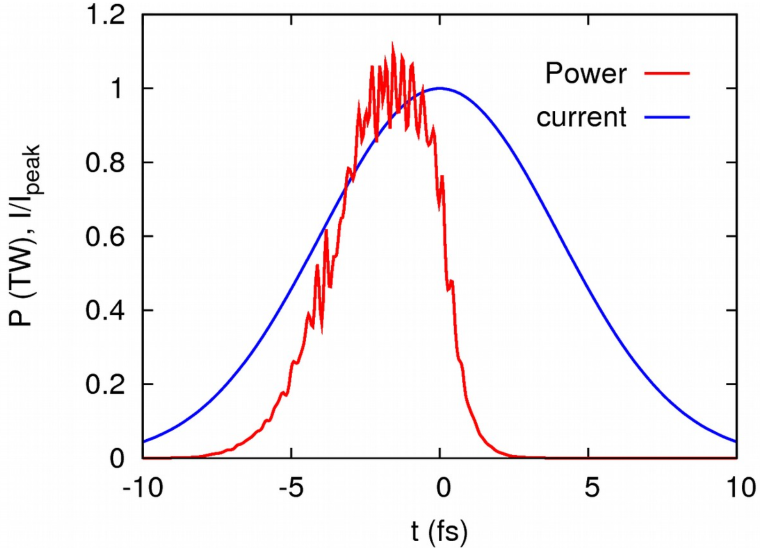
High Gain Amplifier

- High current, fs beam
- Stable, high power fs x-rays
- TW peak powers with undulator tapering

XFELO

- Low current, ps beam
- Full Coherence
- Ultra-fine spectrum: ΔE ~ meV
- >10 8 photons/pulse

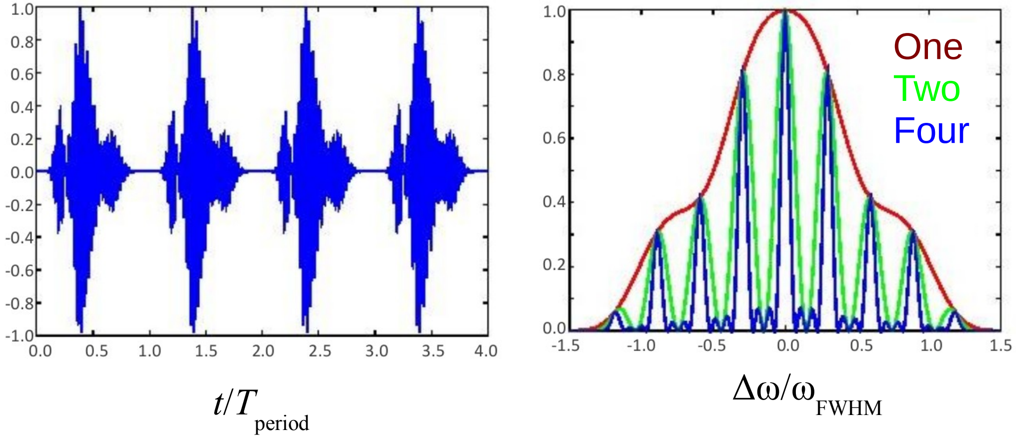
@ z = 200 m for 4 fs (rms) e-beam



@ z = 130 m, P = 0.5 TW
(10^{12} photons in 5 fs)

Frequency stabilized, mode-locked XFELO

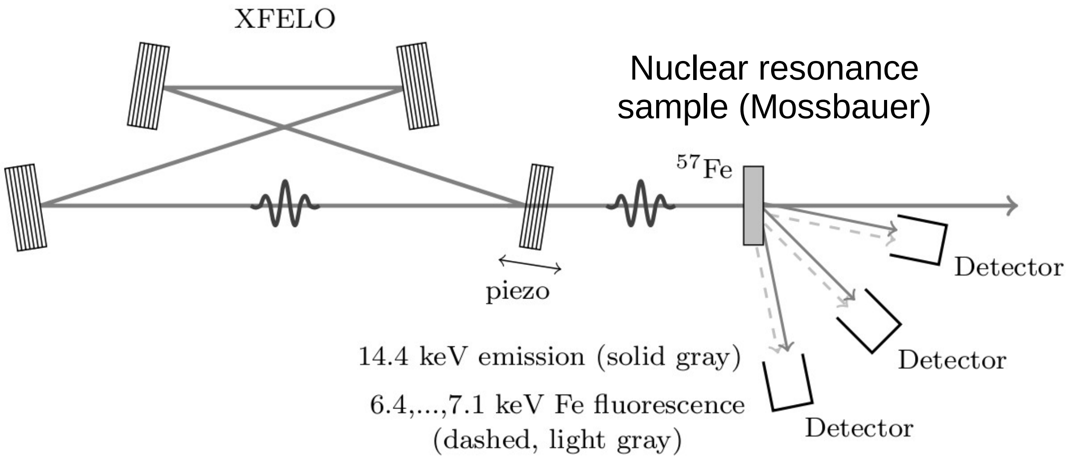
Mode locking

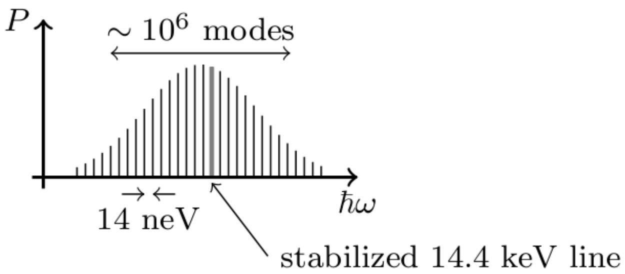


- Total bandwidth set by pulse duration ~1/Δt
- Mode spacing set by periodicity $1/T_{\text{period}}$
- Mode spectral width set by number of modes $1/NT_{\text{period}}$

Relies on phase coherence across all pulses

Can we stabilize the cavity to less than a wavelength and do this for an XFELO?





B. Adams and K.-J. Kim, PRSTAB **18**, 030711 (2015)

Conclusions

- XFELO is a complementary source to SASE FELs: an XFELO is stable with a very narrow bandwidth and comparable brightness
- Many of the XFELO components have been proven, with no show stoppers
  - High brightness electron beam
    $\Delta\gamma/\gamma < 10^{-4}$, $\varepsilon_{x,n} < 0.2$ mm-mrad, $I > 20$ A, $Q > 50$ pC ✓ 🙂
  - High quality undulators with minimal trajectory errors ✓ 🙂
  - High reflectivity Bragg crystals ✓ 🙂
    that can withstand XFELO power densities ? 😐
  - High efficiency focusing elements that induce small phase errors ✓ 🙂
  - Crystal stabilization scheme < 20 nrad ✓ 🙂
    over a ~ kHz bandwidth ? 😐
- XFELO can be used to seed high-gain FEL for intense, fs x-ray pulses
- A mode locked XFELO would bring new optical techniques into x-ray regime