X-Ray FEL Oscillator: Review

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XFELO Science Workshop

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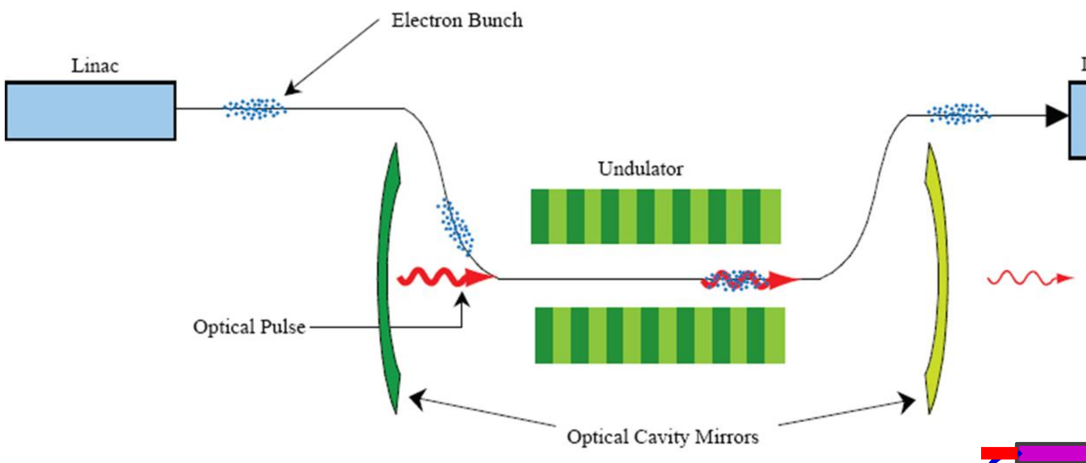
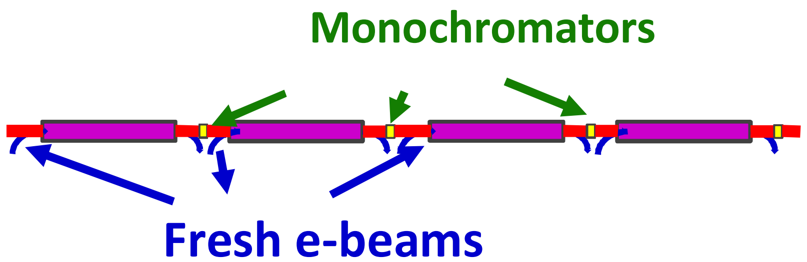
SLAC National Accelerator Laboratory

Menlo Park, CA

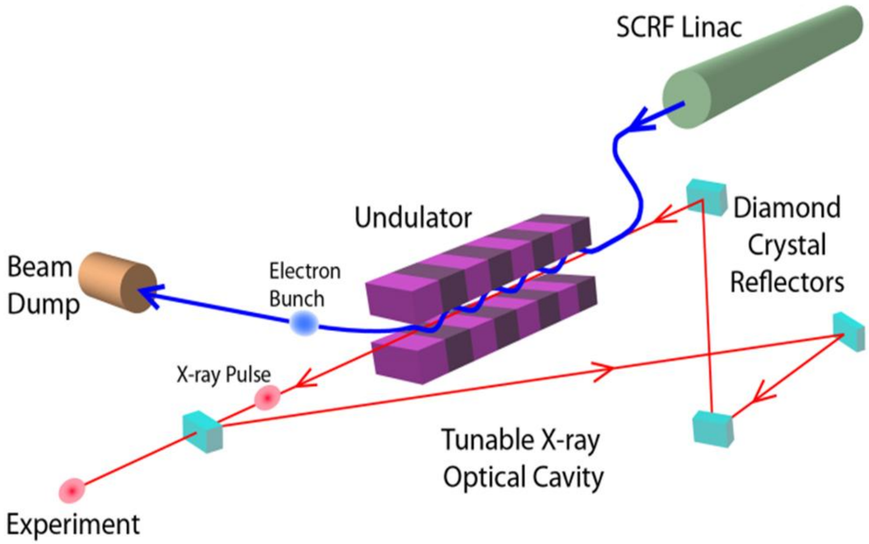
Free Electron Laser Oscillator (FELO)





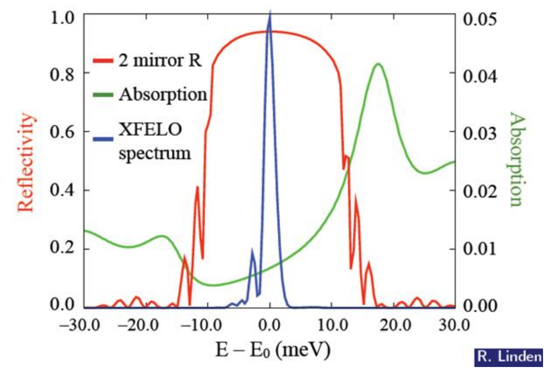
- A low-gain device with a low-loss x-ray cavity
- Optical pulse formed over many electron passes
  - The FELO output is stable even with electron beam fluctuation
- An FELO may be regarded as an infinite sequence of undulator, mode shaper, and fresh e-beam

A hard X-ray FEL oscillator; XFELO



- Proposed by R. Collela and A. Luccio at 1983 BNL workshop by using Bragg reflectors as high reflectivity normal incidence mirrors
  - The same WS where BNP proposed SASE
  - Taking into account of the advances in accelerator (ERL)and x-ray optics, it was "resurrected" in 2008 by KJK, Y. Shvyd'ko, and S. Reiche
- Tuning is possible with the four-crystal, zigzag cavity
  - R. M.J. Cotterill (1968, ANL); KJK and Y. Shvyd'ko (2009)
- Electron beam with a constant, ~ MHz rep rate will be ideal

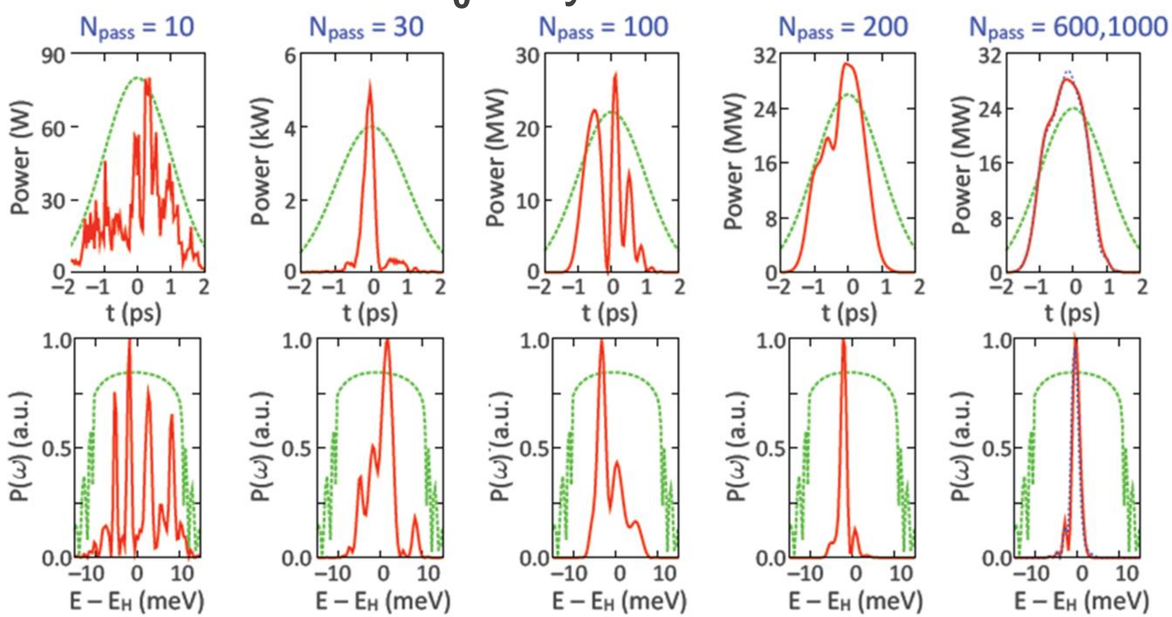
Temporal and spectral evolution



- As the roundtrip pass number *n* increases
  - The spectral width decreases: $\Delta\omega/\omega \propto 1/\sqrt{n}$
  - The pulse width decreases: $\Delta z \propto 1/\sqrt{n}$
- Evolution stops when $\Delta z \times \Delta\omega/\omega \to \lambda$
- → The limiting spectral width (the super-mode theory)

$$\frac{\Delta\omega}{\omega} \to \sqrt{\frac{1}{2N_u}\frac{\lambda}{\Delta z|_0}}$$ =(gain BW □ "transform limited BW")$^{1/2}$

- However, the full transform limit $\Delta\omega/\omega=\lambda/\Delta z_0$ may be achieved with nonlinear saturation:

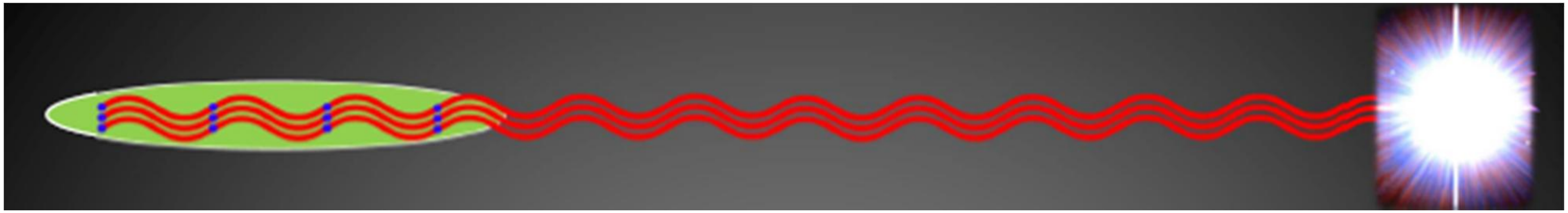


XFELO: $\lambda/\Delta z$ ~ 10^{-7} for λ=1Å and Δz=1 ps

An X-Ray FEL Oscillator is fully coherent and stable

- **Full transverse and longitudinal coherence**
- **Transform limited BW: $\Delta\hbar\omega =$ (3-10) meV for (0.3-1) ps pulse length**
- **10^8-10^9 γ's /pulse, or 10^{14}-10^{15} γ's /second**
- **Complete polarization control with crossed U**

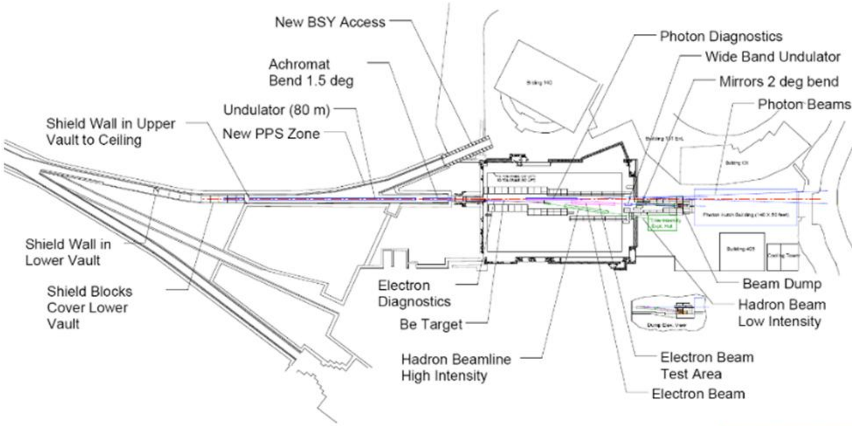
→100-fold higher spectral flux, 10,000-fold higher brightness than USR

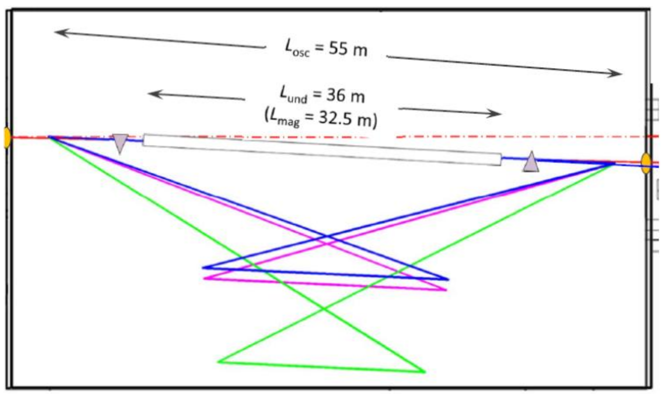


Electron energy can be reduced for a harmonic XFELO for high-quality electron beam (H. X. Deng and Z. M. Dai)

- **Operation at fundamental:**
  - $\lambda=\lambda_U (1+ K^2/2)/2\gamma^2$
  - SASE: $E_e \geq 8$ (SLAC:14) GeV for high exponential gain
  - Oscillator: $E_e \geq 7$ GeV (gain need only overcome the roundtrip loss)
- **Operation at harmonics h:**
  - $\lambda_h=(\lambda_U / h)(1+ K^2/2)/2\gamma^2$
  - Oscillator: Madey's theorem→ gain ∝ *h* →E_e ~ 4 GeV, h=5,7 gives sufficient gain/pass
  - At this energy SASE produces negligible harmonic power of hard x-rays
- **Harmonic XFELO can produce hard x-rays with lower E-beam energy→ reduced size and cost**

4 GeV LCLS II SCRF linac can drive 5th harmonic XFELO





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

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

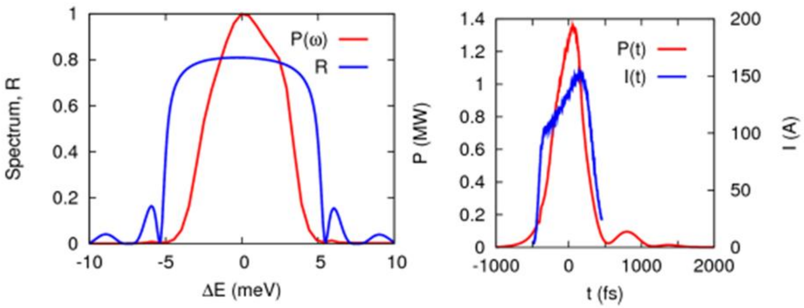
E_{ph} = 9.13 keV, $2\vartheta_r$ = 17.0º, C* (333)

An LCLS-II based XFELO

Major Parameters

	Parameter	Value	Units
Electron bunch	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	
Optical cavity	Loss/round trip	15	%
X-ray pulse	5th harmonic energy	14.4	keV
	X-ray pulse length (FWHM)	500	fs
	Spectral BW (FWHM)	5	meV
	Pulse rep rate	1-2	MHz
	# of photons/pulse	3	10^8

X-ray pulse profile

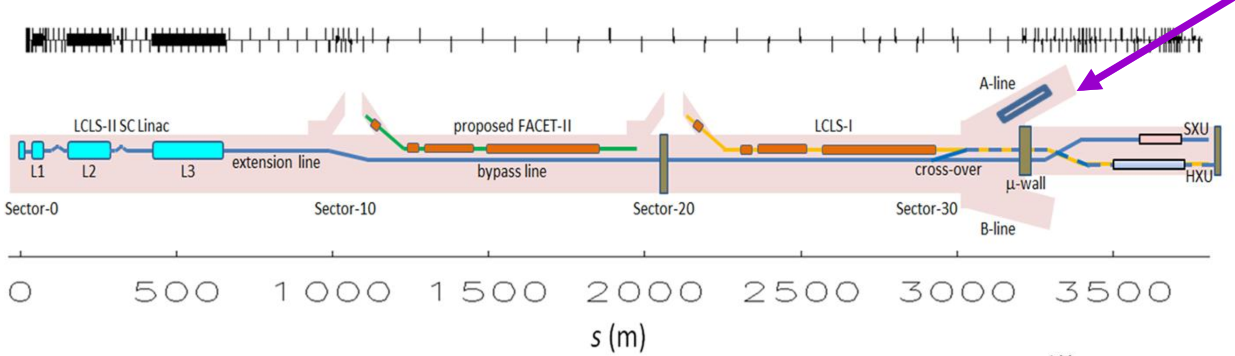


Technical Issues

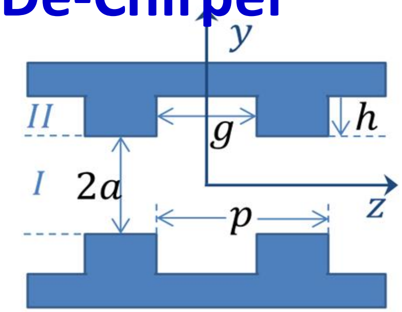
- Electron injector producing the required beam qualities
- Diamond reflectivity and thermo-mechanical properties
- Stability of x-ray cavity
- Low-loss x-ray focusing optics
  - Curved, grazing incidence mirror
  - Be CRL
- **Diamond survival under intense x-ray environment**

Injector Design: For I_p <100 A, the small emittance & energy spread from the gun can be maintained thru the injector. A de-chirper removes the energy slope from bunchers

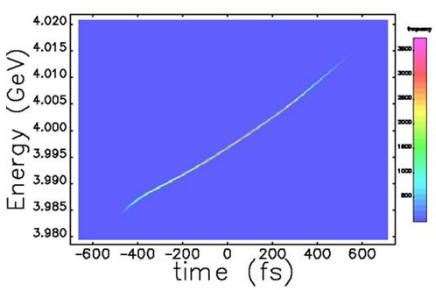
(W. Qin, Y. Ding, K. Bane,..)

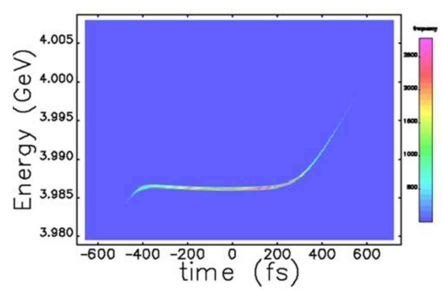


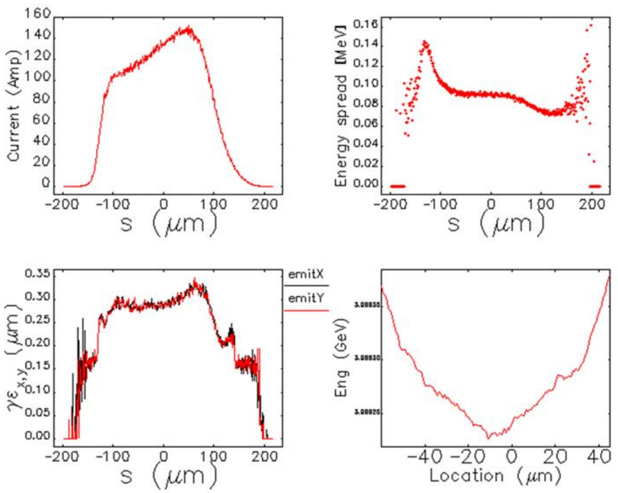
De-Chirper



Before and after de-chirper



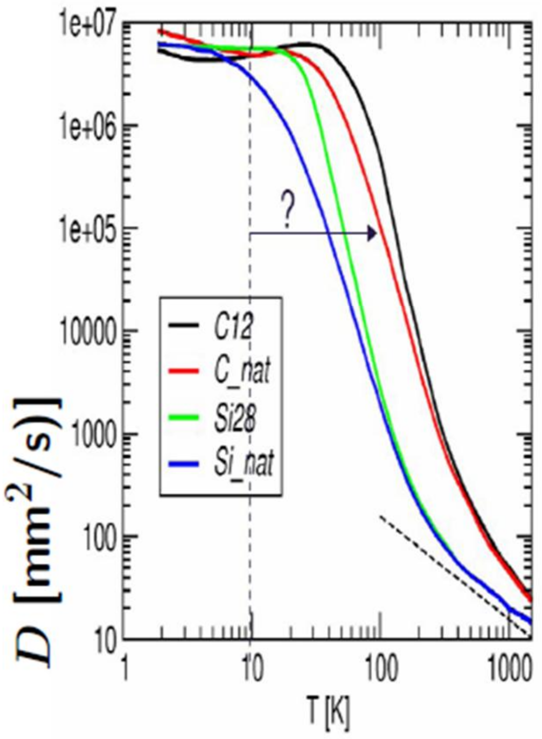




Diamond: Excellent Thermo-Mechanical Properties

Ultra-high thermal diffusivity at low temperatures

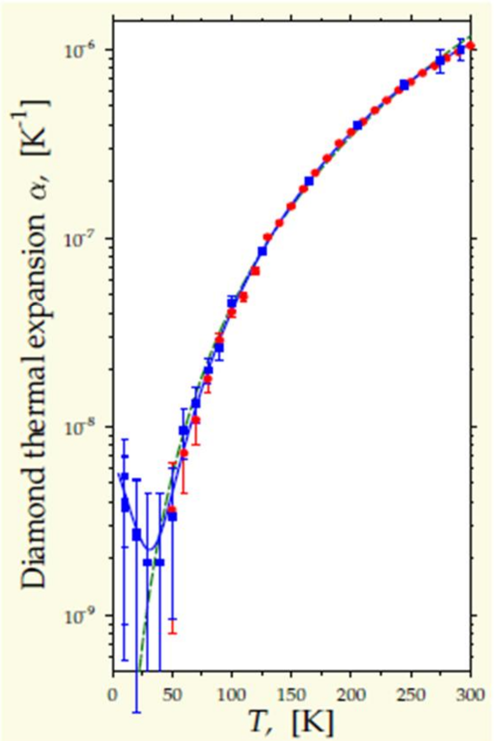
$\simeq 10^5$ mm^{-2}s @ 100 K



Courtesy of H. Sinn

Ultra-low thermal expansion at low temperatures

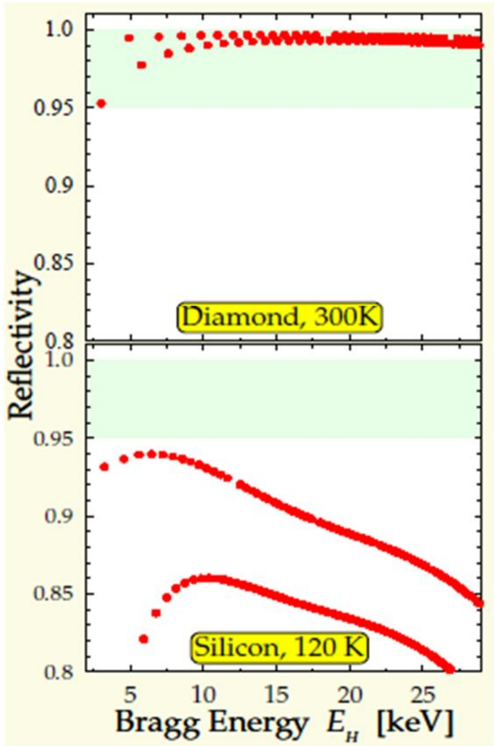
$\simeq 10^{-8}$ K^{-1} @ 100 K



S. Stoupin, Yu. Shvyd'ko PRL (2010)

Record high reflectivity for hard x-rays

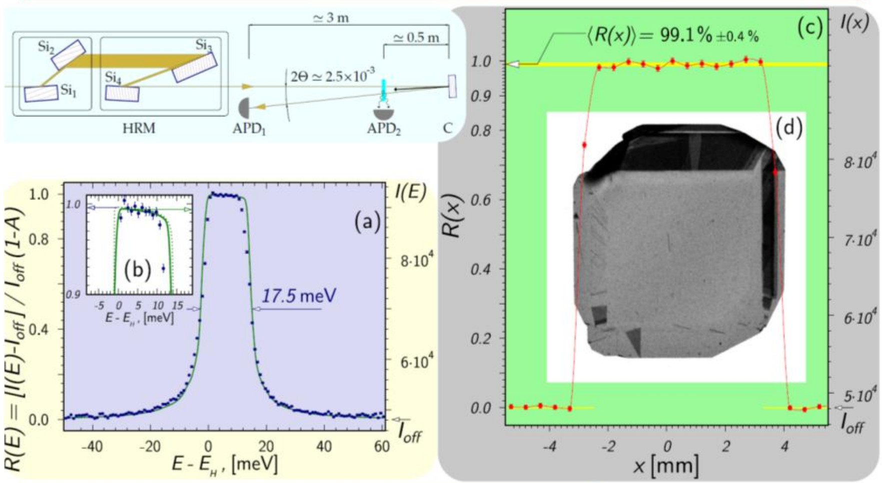
Theory: $> 99\%$



Yu. Shvyd'ko et al Nature Phys. (2010)

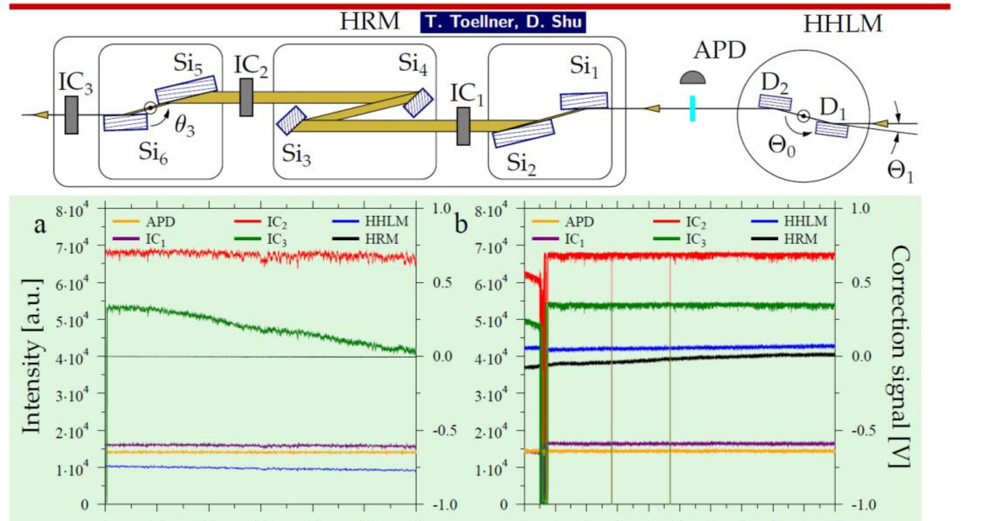
TISNCM diamonds tested for reflectivity & Crystal stabilization works at 1 Hz BW

Diamond Reflectivity Studies: C(008) @ 14.3 keV



Shvyd'ko, Stoupin, Blank, Terentyev, Nature Photonics 5 (2011) 539

HERIX Monochromator Stabilization

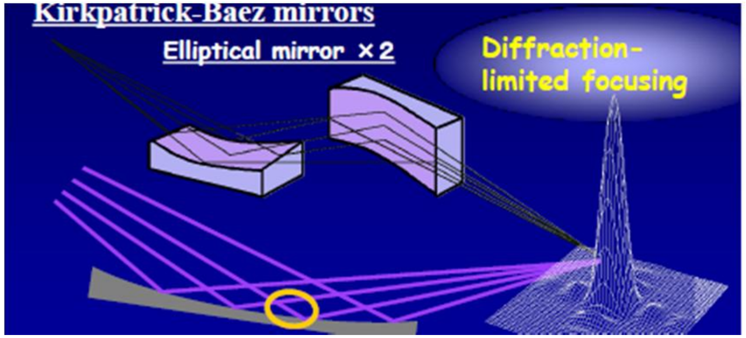


≃ 15 nrad (rms) stabilization was demonstrated

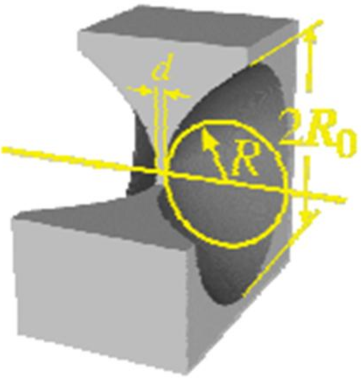
Stoupin, Lenkszus, Laird, Goetze, K-J Kim, Shvyd'ko, RSI 81 (2010) 05510

Focusing optics for X-ray cavity

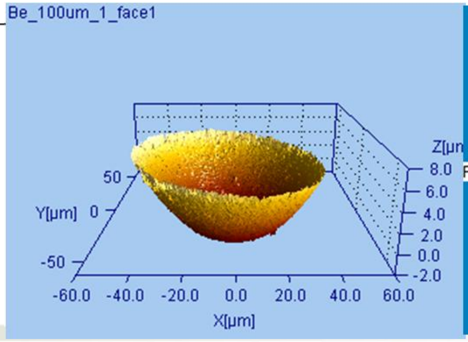
- **Grazing incidence KB mirrors are being perfected at JTEC, but are large & heavy.**

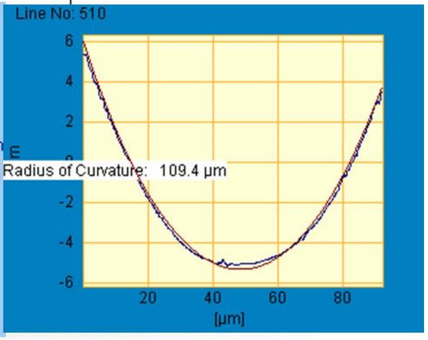


- **Be-CRL can be a low-loss device for large focal length application (>20m)**

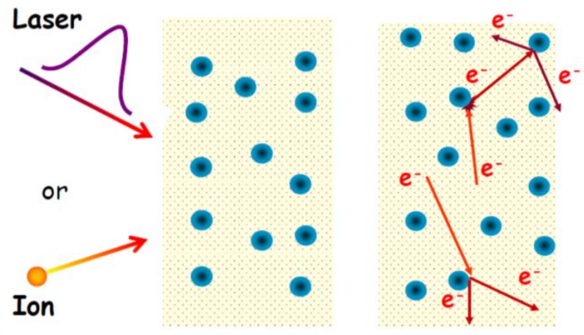


For 14.4 keV, f = 21.1 m, d=30 um σ_r = 28 um,
Crystalline Be, IF 1 grade: *Tr* = 99.74%
PS20 E grade (atten. length 60% of IF-1): *Tr* = 99.56%





Estimates for Damage Thresholds
(N. Medvedev)

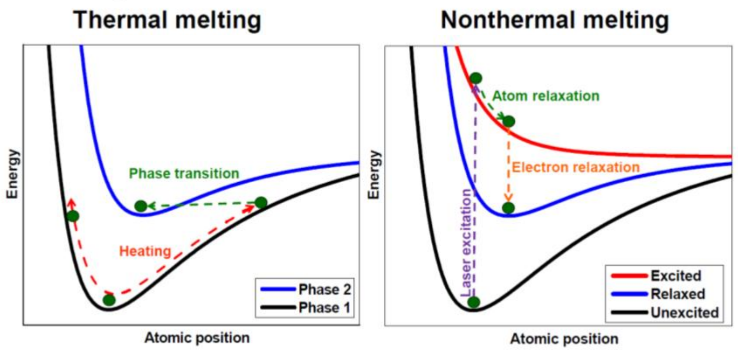


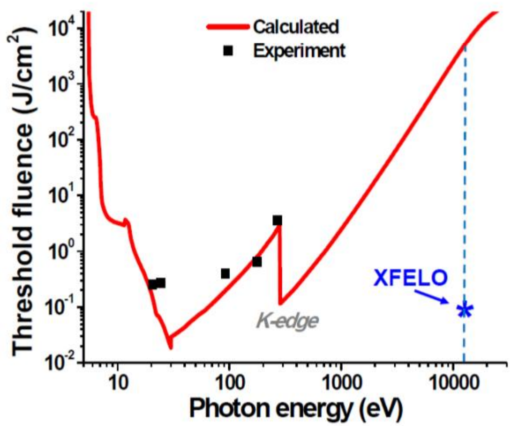
Single shot effects:

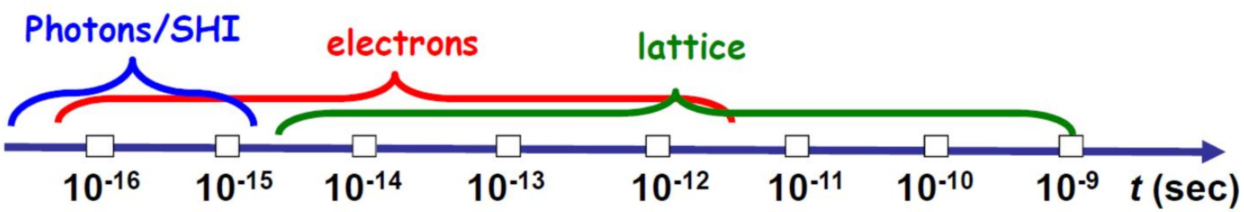
- ✗ 1) Nonequilibrium electron kinetics ~100 fs
- ✗ 2) Nonthermal melting ~150 fs (0.7 eV/atom, N_e~1.5%)
- ✗ 3) Thermal melting ~1-10 ps

Multishot effects:

- ✗ 1) Melting, stresses, fatigue (require heating)
- ✗ 2) Electrons recombine: fluorescence <1 ns
- ✗ 3) Point defects are not produced
- ✓ 4) Surface effects may play a role ~1 μm

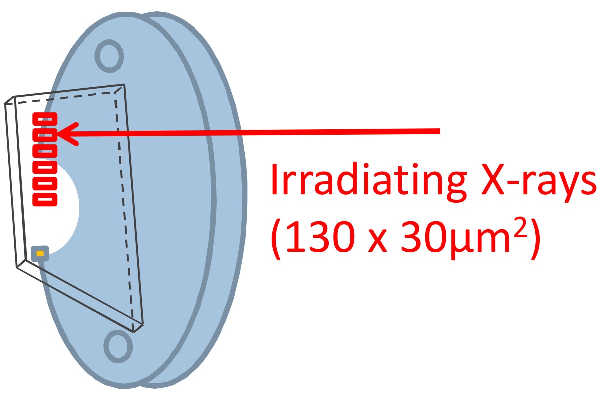


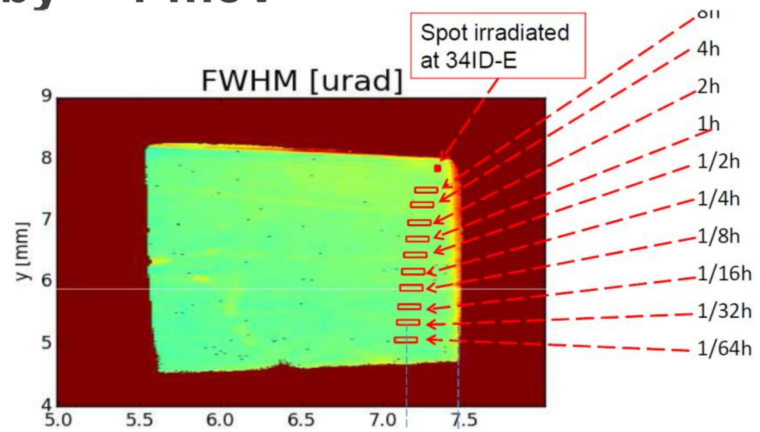


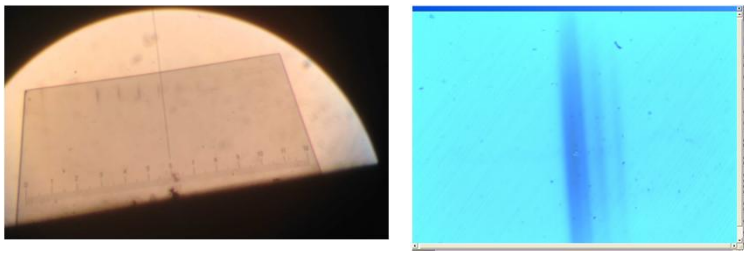


APS experiment for the resilience of diamond under x-ray exposure in an XFELO cavity up to 4 hours (T. Kolodziej, Yuri, Stan, Deming Shu,..)

- **35 ID-B: 8 kW/mm^2 in 120x30 μm^2 spot (~XFELO)**
- **No evidence of damage under medium resolution topography**
- **Possible shifts of rocking curve by < 1 meV**

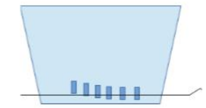


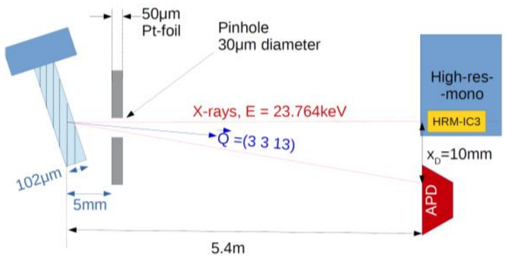


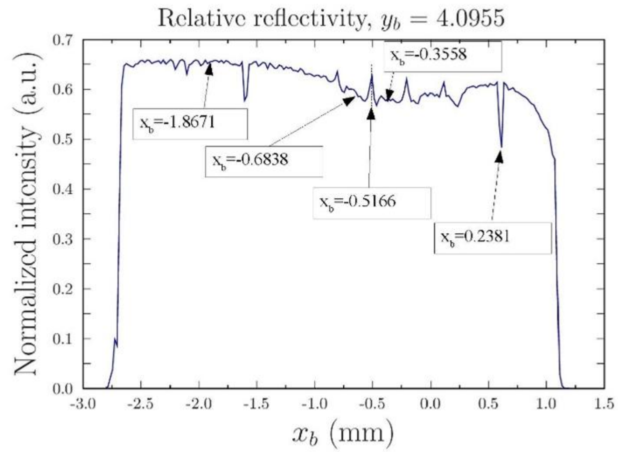


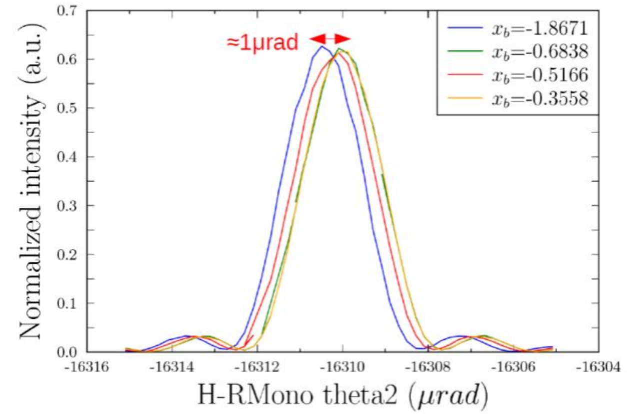
Optical microscope images

HR measurements@ 24 keV



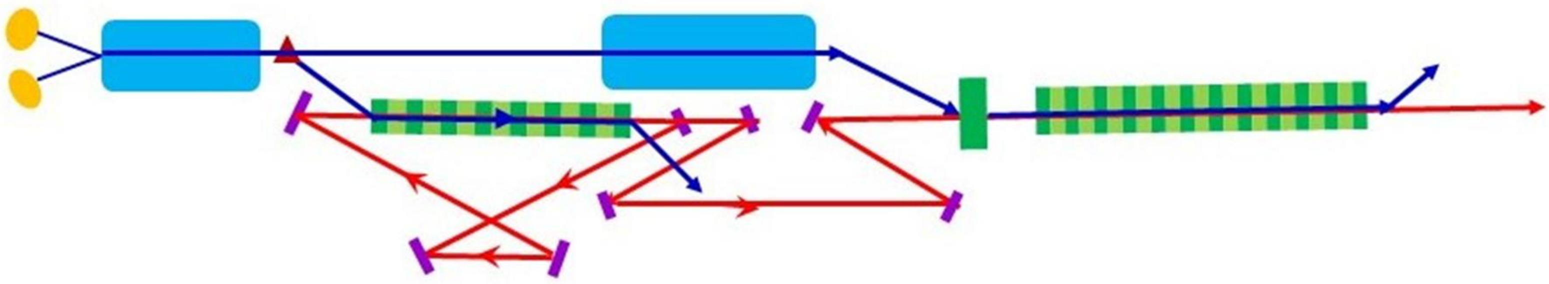






- Scan across irradiated spots show drops in reflectivity
- The drop could be due to the observed shifts of ≤ 0.5 meV in the rocking curves
- If so, the effect can be compensated by FB
- Is the shift due to the adsorption of impurities?
- Irradiation under high vacuum (< 10^{-8}) and further HR reflectivity measurements are planned.

X-Ray MOPA for higher intensity, sub-fs pulse, & higher photon energy



- Two guns produces XFELO and high-gain e-bunches
- Both bunches enter interleaved to the first accelerator and separated after acceleration
- XFELO output pulses are delayed to overlap with the high-gain e-bunches
- A harmonic generation stage may precede the high-gain amplifier
- The high-gain bunches are further accelerated for resonance in the amplifier

Concluding remarks

- An XFELO will enhance the capability of X-ray FEL as a scientific instrument
  - Provide high rep rate hard x-rays of unique properties for LCLS II
  - Complements SASE (ultrafast)
- We have demonstrated:
  - The diamond mirror has high reflectivity, and seems to survive the high-intensity environment.
  - Be-CRL will be a compact and low loss focusing element
  - The specs for placing XFELO elements at 1 Hz BW
- The drive accelerator could be
  - ERL
  - USR with a bypass and kickers, and pulsed operation
  - European XFEL (pulsed or CW) and LCLS II (CW)
- A “perfect” facility with HGXFEL& XFELO), together (XFELO seeding HGFEL), or separately

XFELO Collaboration

ANL/APS, SLAC, C-FEL, Peking U, TISNCM

- General: Zhirong Huang, Jerry Hastings, Jo Frisch, Tim Maxwell, Yuri Shvyd'ko, KJK
- FEL physics/simulation: Ryan Lindberg, Bill Fawley, Yuantao Ding, Gabe Marcus, Tim Maxwell
- Theory/simulation of diamond damage: Nikita Medvedev
- Diamond damage experiment: Yuri, Tomasz Kolodziej, Stan, Vladimir Blank, Sergei Terentyev
- CRL lens: Jacek Krzywinski, Stan Stoupin, Lahsen Assoufid, Xianbo Shi
- Optical cavity mechanical design: Deming Shu, Steve Kearney
- Electron beam: Weilun Qin, Yuantao, Karl Bane, Paul Emma, Tor Raubenheimer, Dieter Walz
- Sciences: Jerry, Yuri, John Arthur,..