X-Ray FEL Oscillator

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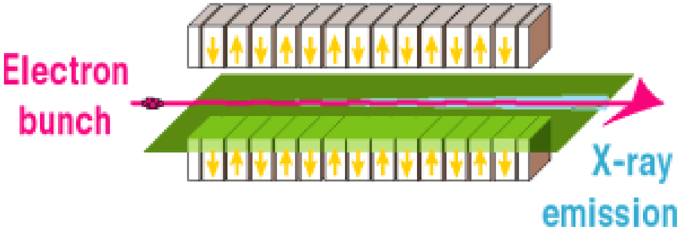
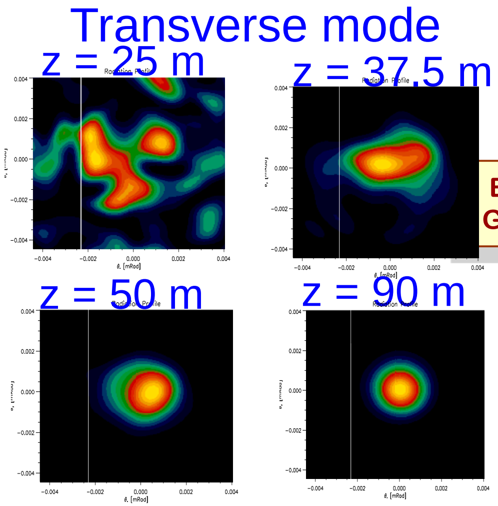
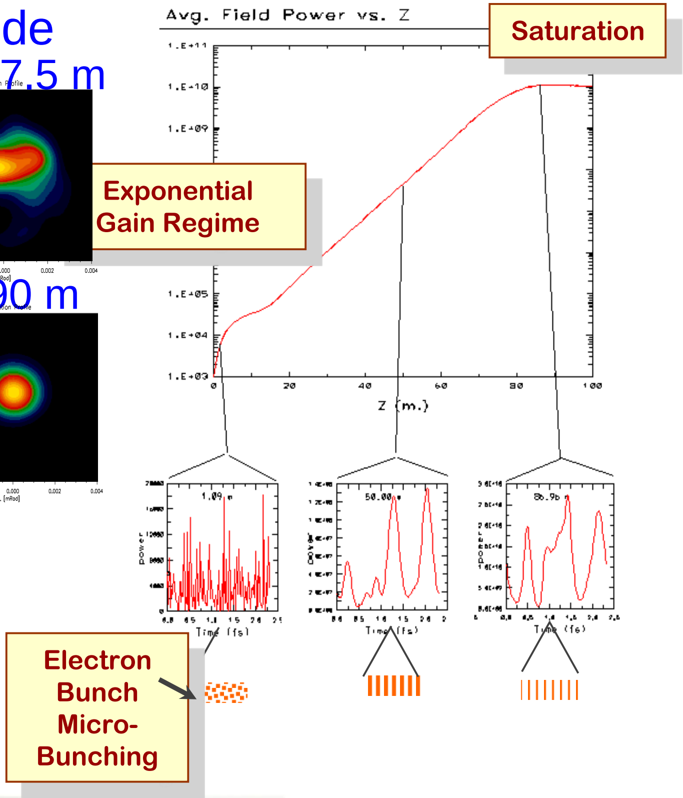
CERN Accelerator School

Hamburg, Germany

Hard X-Ray ($\lambda \leq$ Å) FEL: Self-Amplified Spontaneous Emission (SASE)

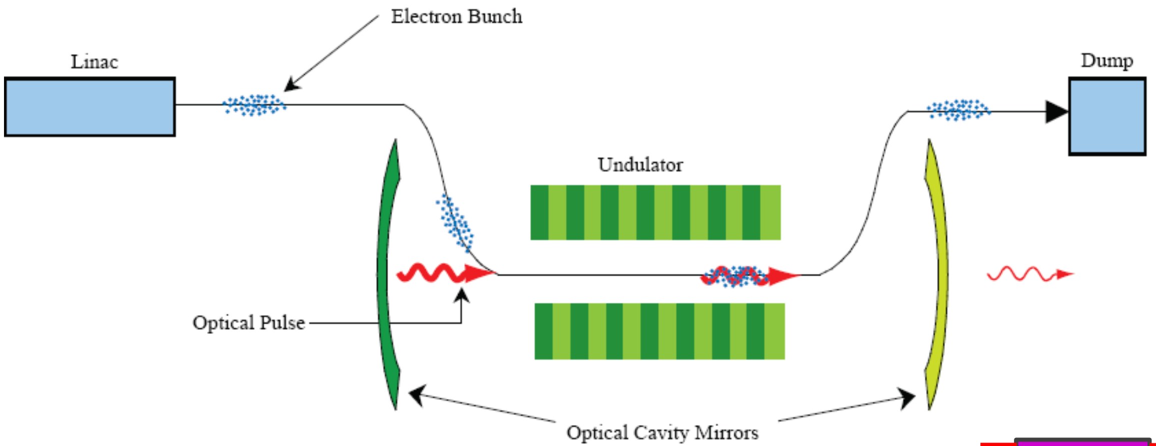


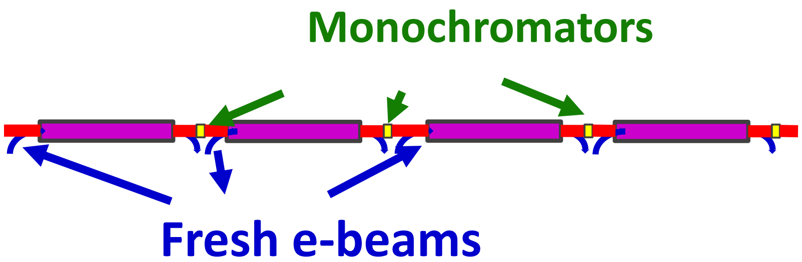




- *Excellent time resolution ($\Delta\tau$ ~ fs)*
- *High transverse coherence*
- *Limited temporal coherence ($\Delta\omega/\omega$ ~$10^{-3} \rightarrow 10^{-5}$)*
- *LCLS, SACLA, Euro-XFEL, Swiss XFEL, PAL-XFEL, FERMI (soft x-ray),..*

Free Electron Laser Oscillator (FELO)

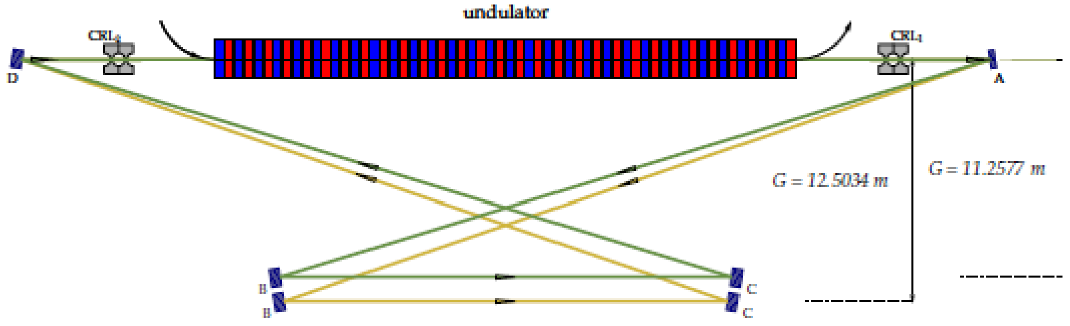




- A low-gain device with a low-loss x-ray cavity
- Optical pulse formed over many electron passes
  - The FELO output is stable even with electron beam fluctuation
- An FELO may be regarded as an infinite sequence of undulator, mode shaper, and fresh e-beam

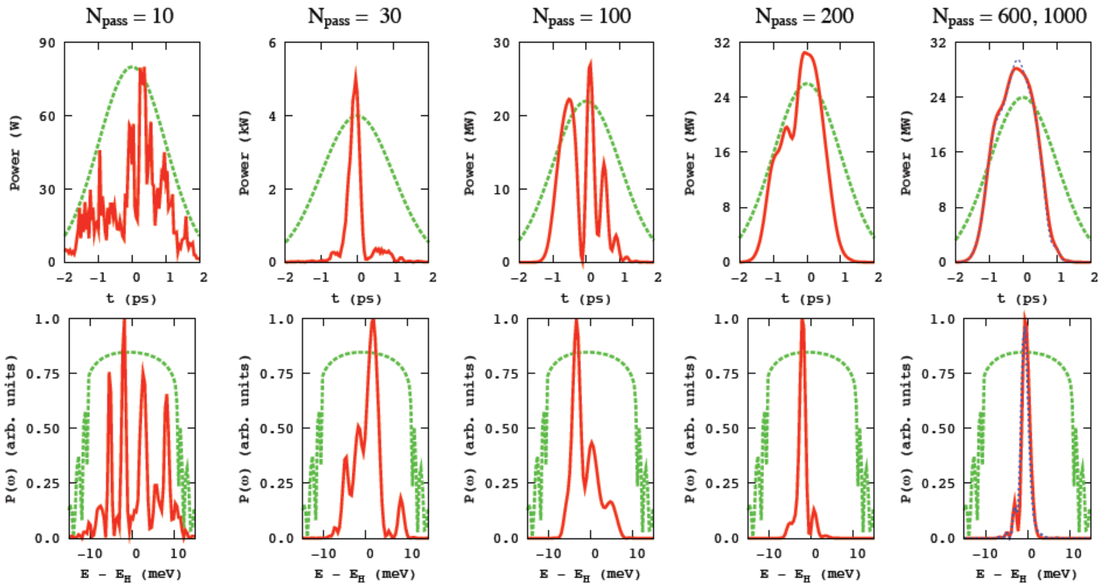
An FELO for hard X-Rays; XFELO

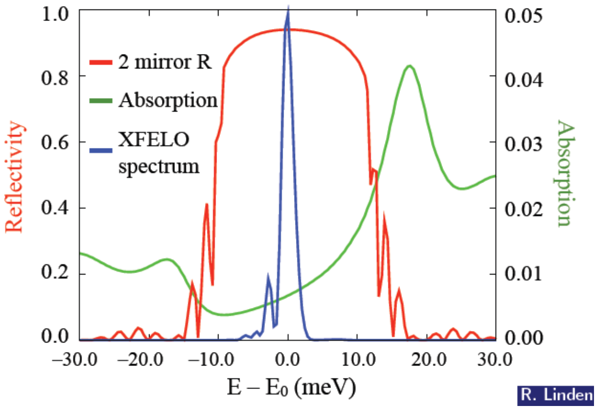
- XFELO was first proposed by R. Collela and A. Luccio at 1983 BNL workshop by using Bragg reflectors as high reflectivity normal incidence mirrors
  - The same WS where BNP proposed SASE
  - Taking into account of the advances in accelerator (ERL)and x-ray optics, it was "resurrected" in 2008 by KJK, 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

Filtering by crystals expedite and stabilize the development of the ultra-narrow spectrum. Spectrum saturation takes much longer than intensity saturation





An X-Ray FEL Oscillator is fully coherent and stable

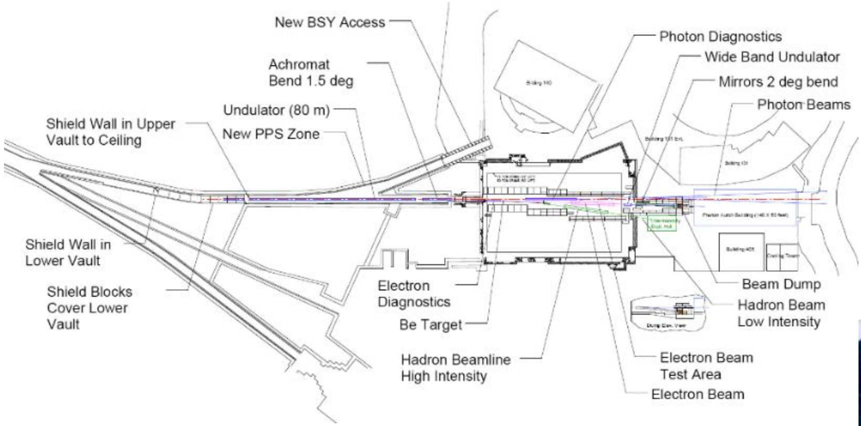
- **Full transverse and longitudinal coherence**
- **Transform limited BW: $\Delta\hbar\omega =$ (3-10) meV for (0.3-1) ps pulse length**
- **10^8-10^9 γ's /pulse, or 10^{14}-10^{15} γ's /second**
- **Complete polarization control with crossed U**

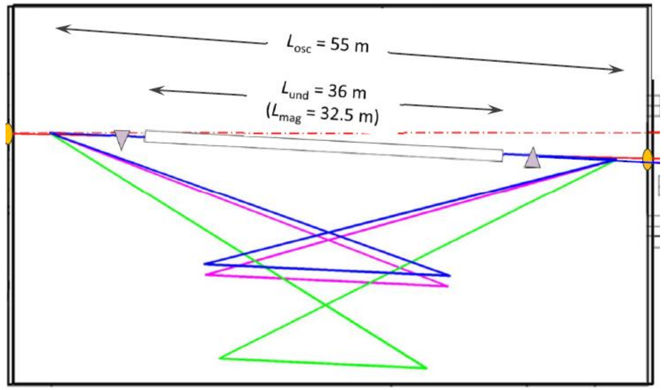
→ **100-fold higher spectral flux, 10,000-fold higher brightness than USR**

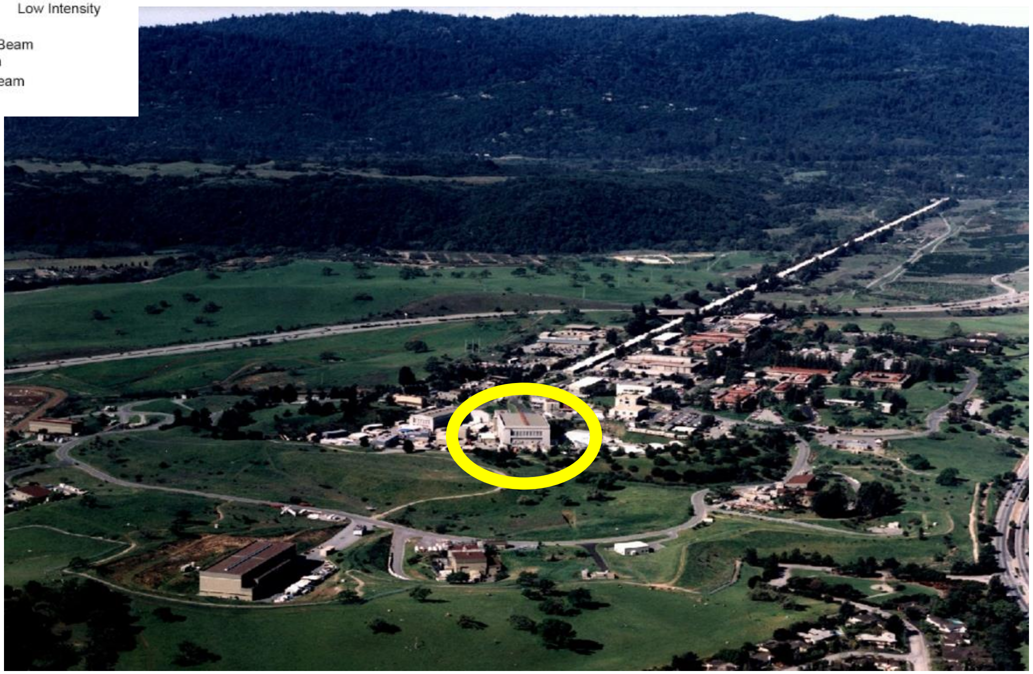
Electron energy can be reduced for a harmonic XFELO for high-quality electron beam *(H. X. Deng and Z. M. Dai)*

- **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 $\propto h$ →$E_e \sim 4$ 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)

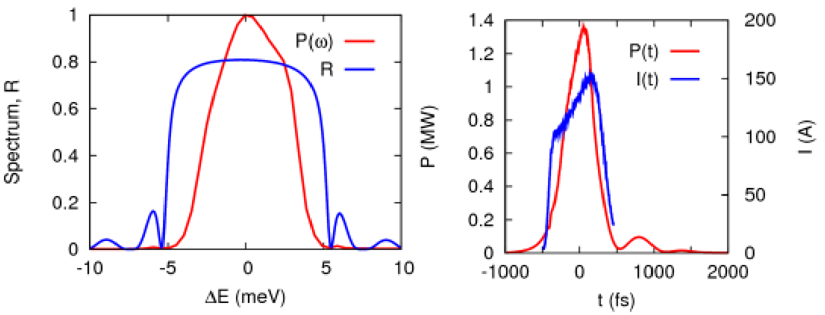
E_{ph} = 13.8 keV, $2\vartheta_r$ = 29.3º, C* (355)

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

Performance of LCLS-II based XFELO

	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	5^{th} 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

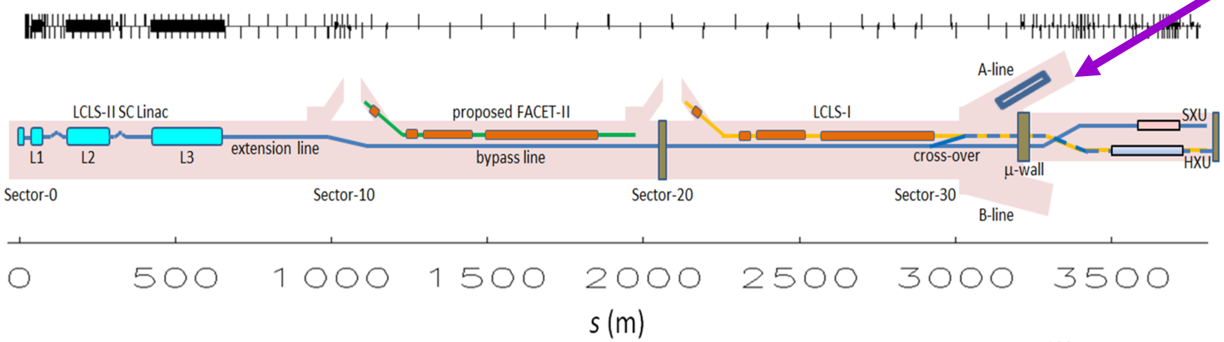


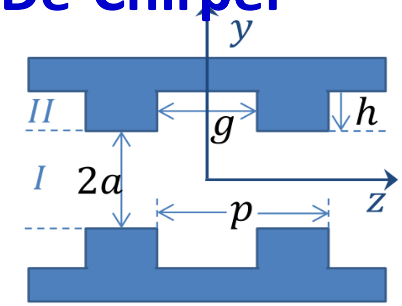
Technical Issues

- 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**

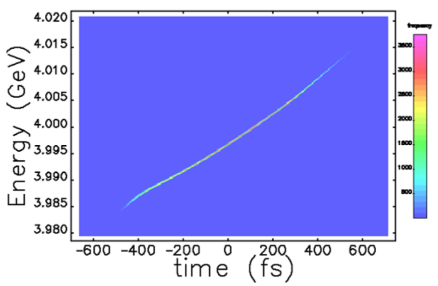
Injector Design: For I_p <100 A, the small emittance & energy spread from the gun can be maintained thru the injector. A de-chirper removes the energy slope from bunchers (W. Qin, Y. Ding, K. Bane,..)

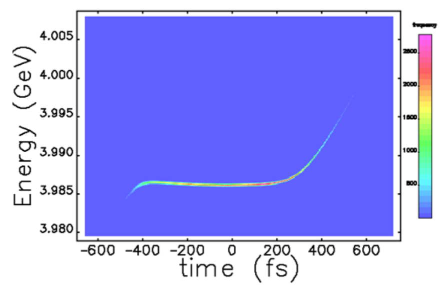
De-Chirper

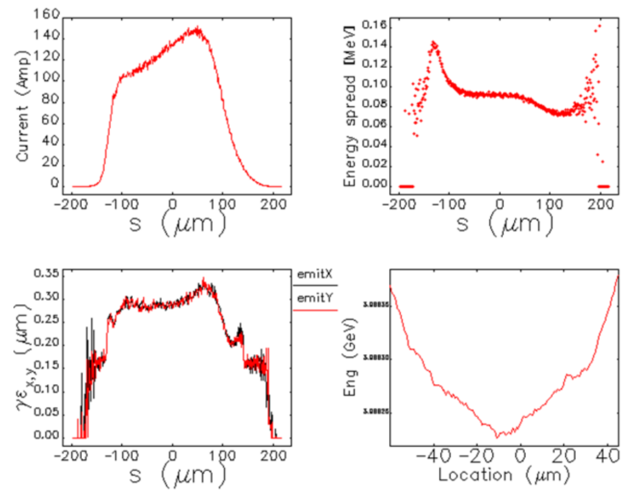




Before and after de-chirper

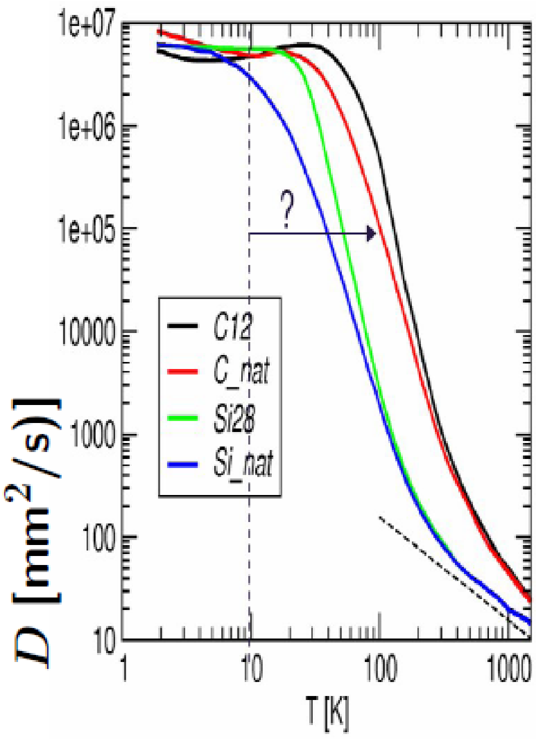




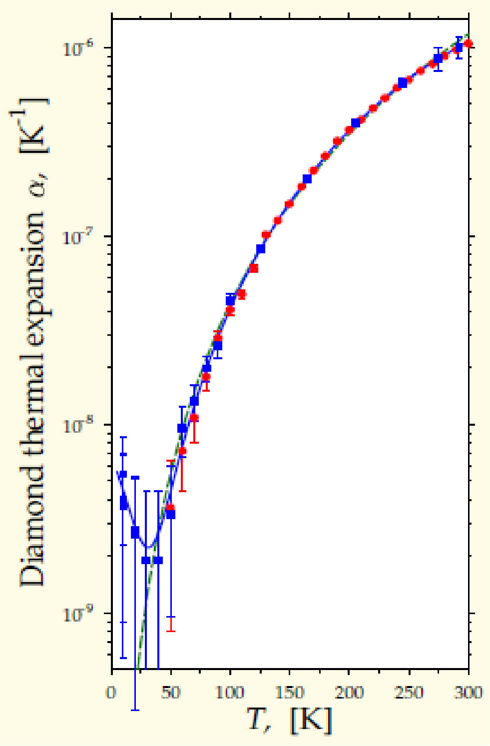


Diamond: Excellent Thermo-Mechanical Properties

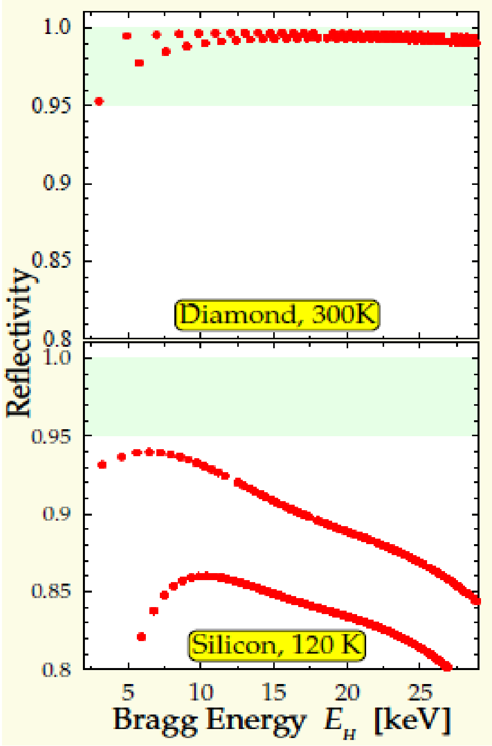
Ultra-high thermal diffusivity at low temperatures	Ultra-low thermal expansion at low temperatures	Record high reflectivity for hard x-rays
$\simeq 10^5$ mm^{-2}s @ 100 K	$\simeq 10^{-8}$ K^{-1} @ 100 K	Theory: $> 99\%$



Courtesy of H. Sinn

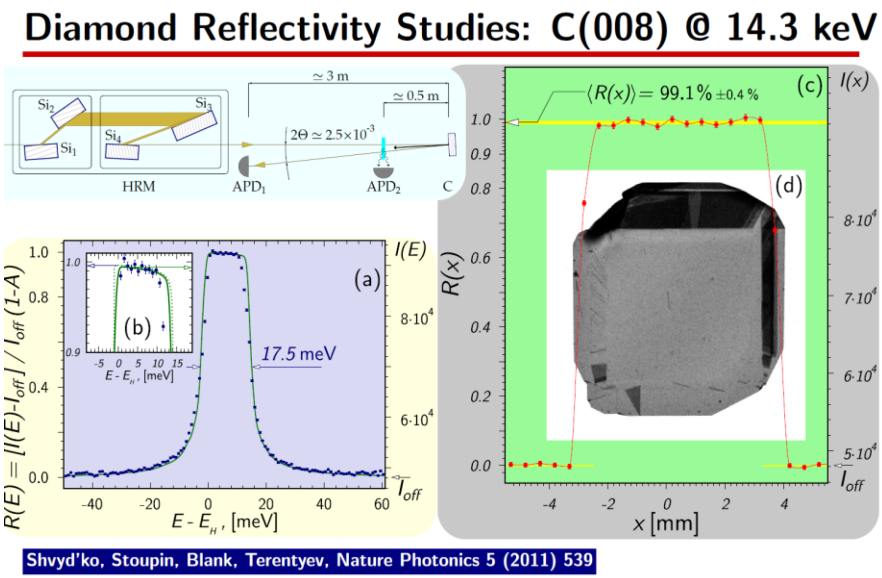


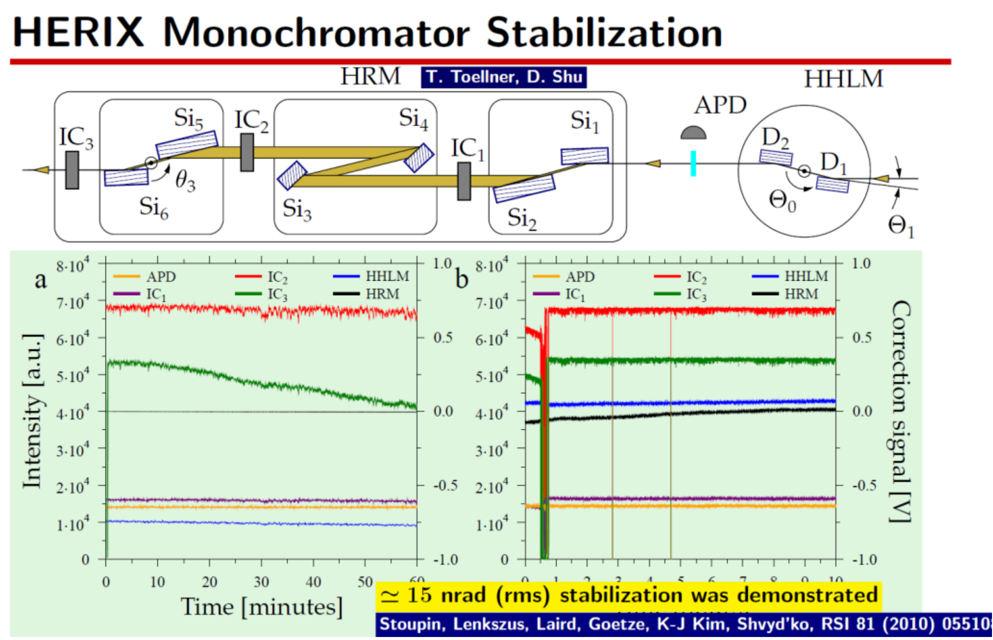
S. Stoupin, Yu. Shvyd'ko PRL (2010)



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

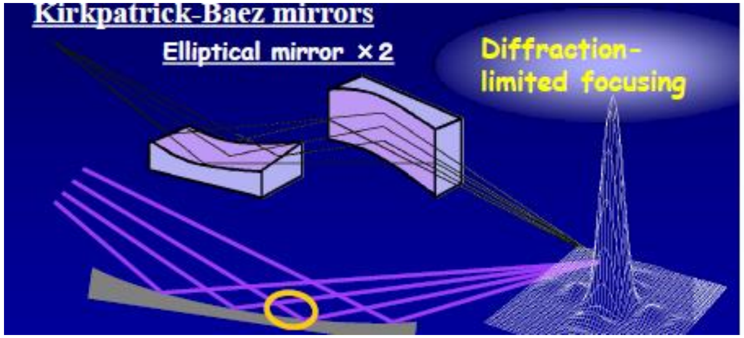
TISNCM diamonds tested for reflectivity & Crystal stabilization works at 1 Hz BW



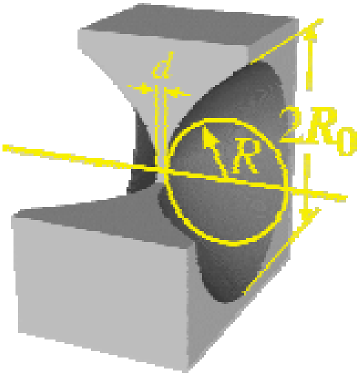


Focusing optics for X-ray cavity

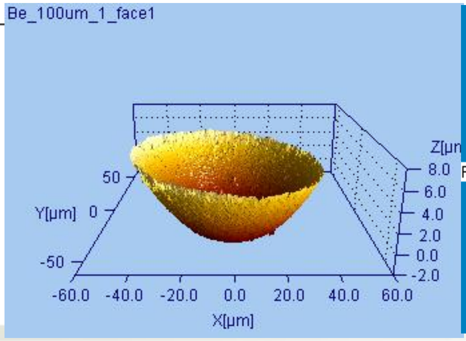
- **Grazing incidence KB mirrors are being perfected at JTEC, but are large & heavy.**

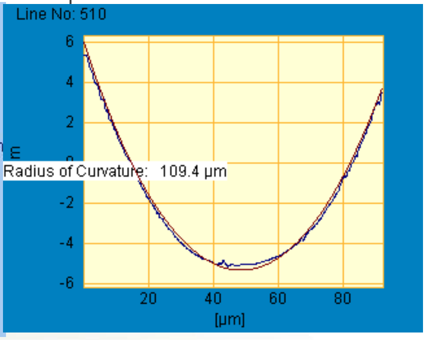


- **Be-CRL can be a low-loss device for large focal length application (>20m)**

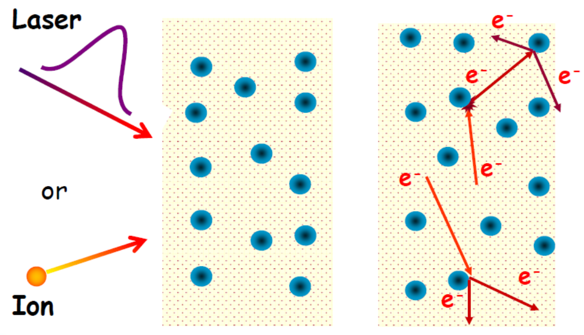


For 14.4 keV, f = 21.1 m, d=30 um σ_r = 28 um,
Crystalline Be, IF 1 grade: *Tr* = 99.74%
PS20 E grade (atten. length 60% of IF-1): *Tr* = 99.56%





Estimates for Damage Thresholds
(N. Medvedev)

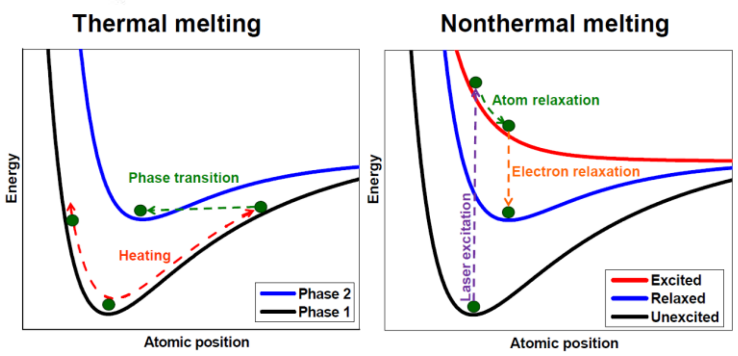


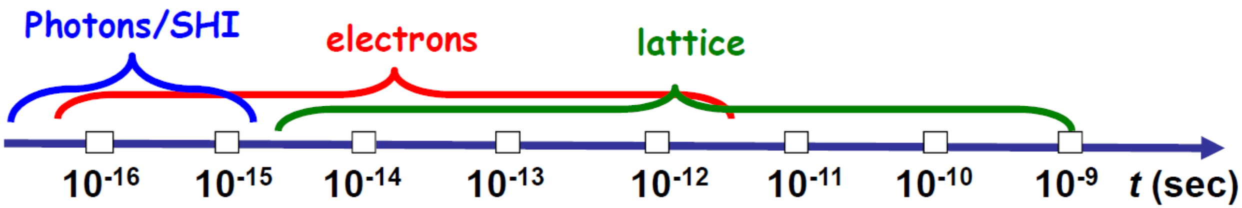
Single shot effects:

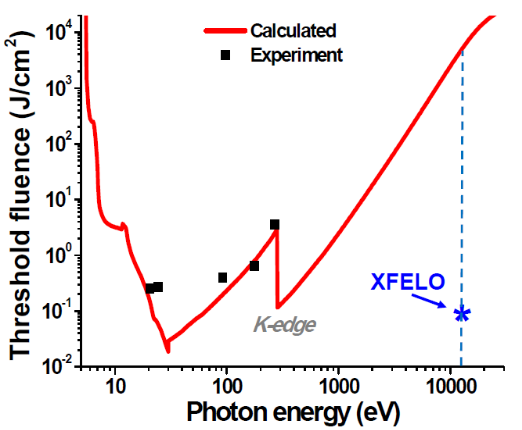
- ✗ 1) Nonequilibrium electron kinetics ~100 fs
- ✗ 2) Nonthermal melting ~150 fs (0.7 eV/atom, N_e~1.5%)
- ✗ 3) Thermal melting ~1-10 ps

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

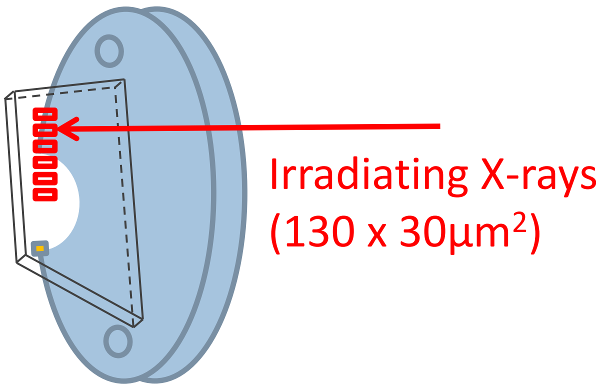


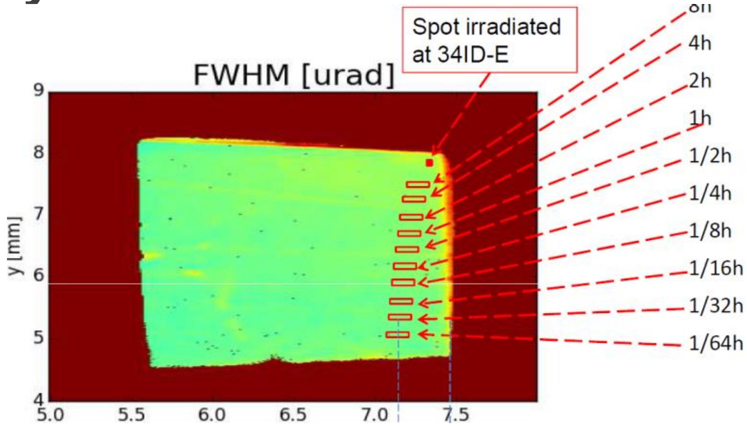


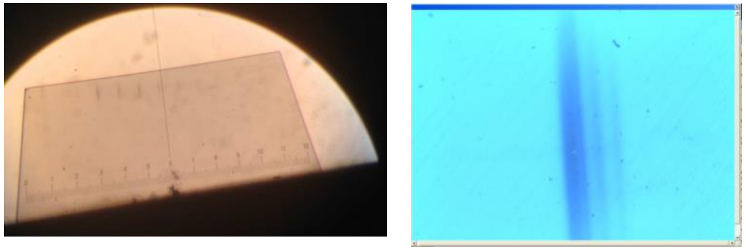


APS experiment for the resilience of diamond under x-ray exposure in an XFELO cavity up to 4 hours (T. Kolodziej, Yuri, Stan, Deming Shu,..)

- **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**



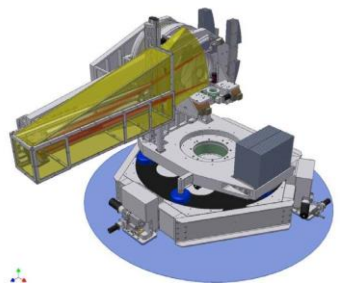




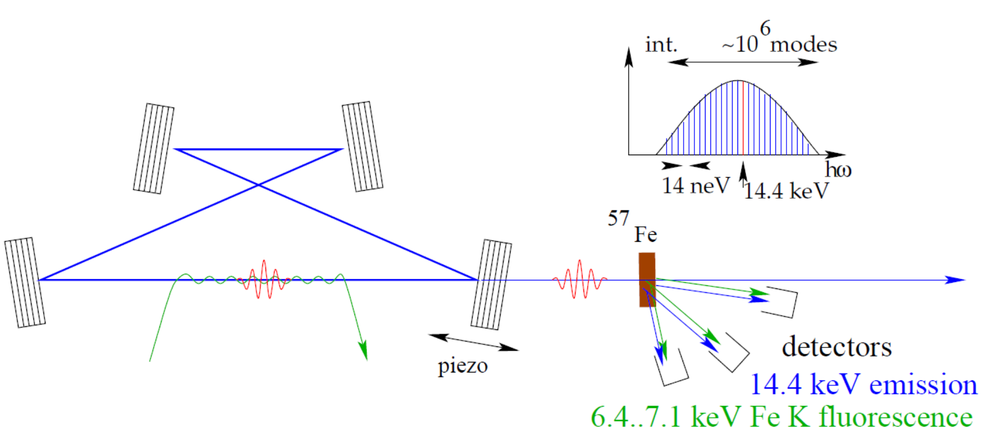
Optical microscope images

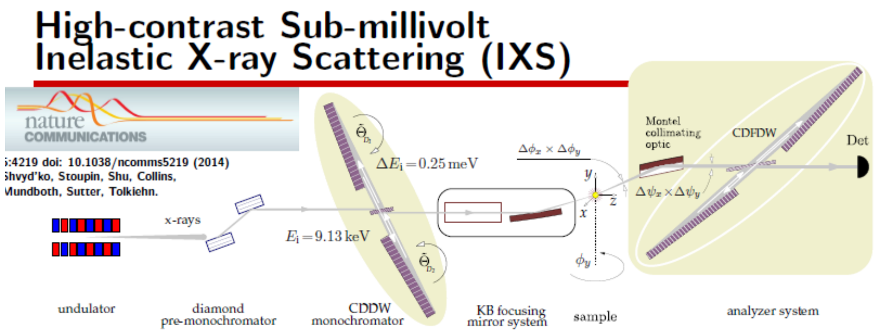
Science with an XFELO

- Enhanced IXS (MR or HR) for elucidating the emergent phenomena of strongly correlated system
  - High Tc Superconductivity,..
- Moessbauer, XPCS,…
- **Nonlinear quantum optics**
- **A science retreat at SLAC in June 29-July 1**



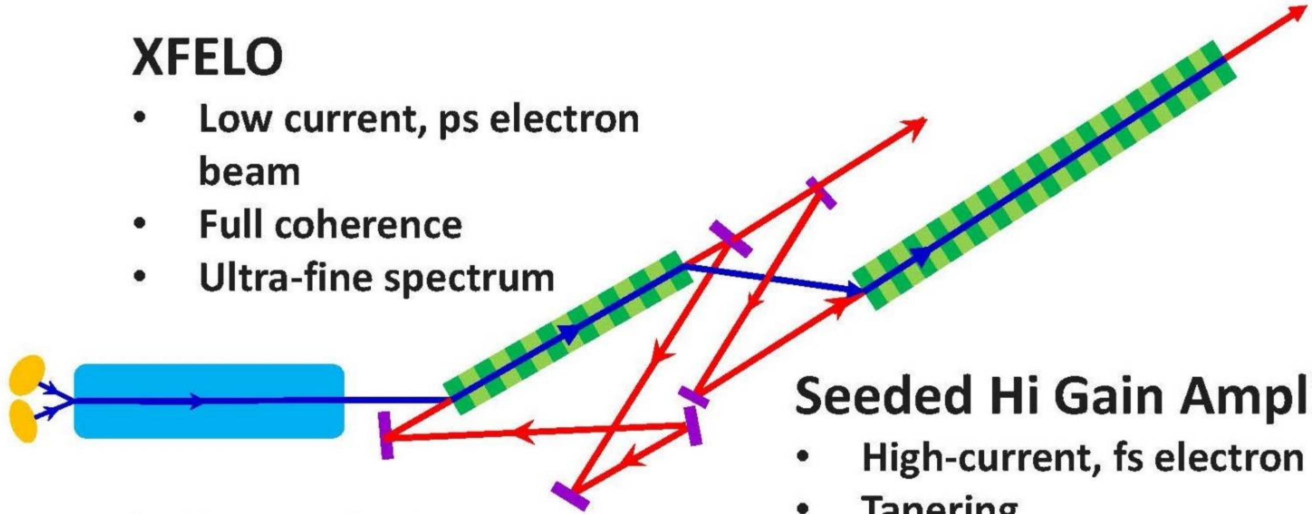
measure resonance of ^{57}Fe sample, adjust cavity length with piezo:





With pico-meter stabilization, XFELO II can produce x-ray spectral comb, opening up experimental quantum x-ray optics

Ultimate X-Ray Facility: X-ray Oscillator-Power Amplifier



XFELO

- Low current, ps electron beam
- Full coherence
- Ultra-fine spectrum

Seeded Hi Gain Amplifier

- High-current, fs electron beam
- Tapering
- Stable, high-power, fs x-ray pulse

- Super conducting accelerator
- Interleaved bunches from two injectors

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