Progress Towards an X-ray FEL Oscillator

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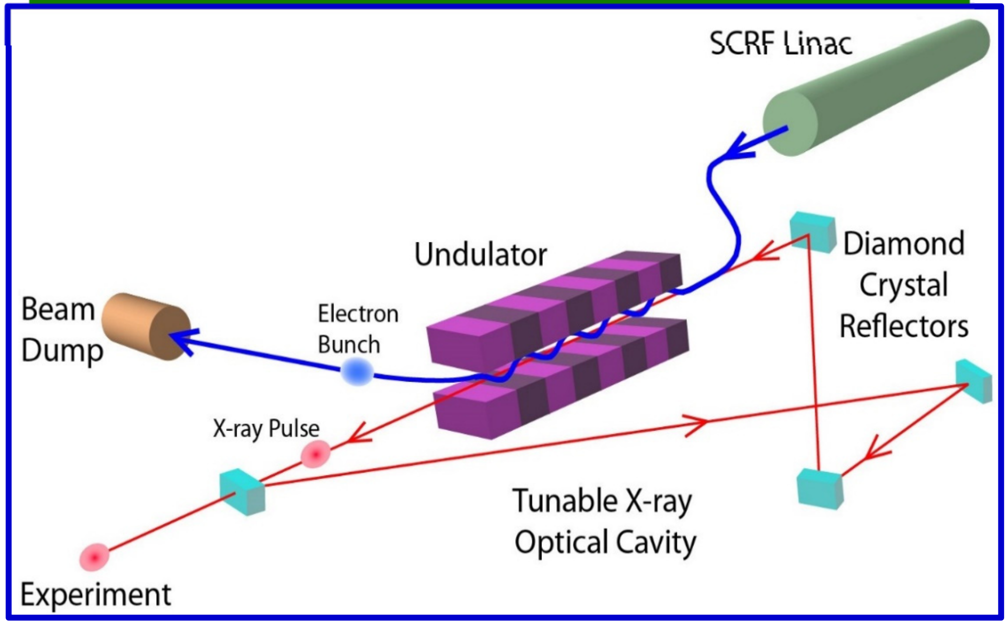
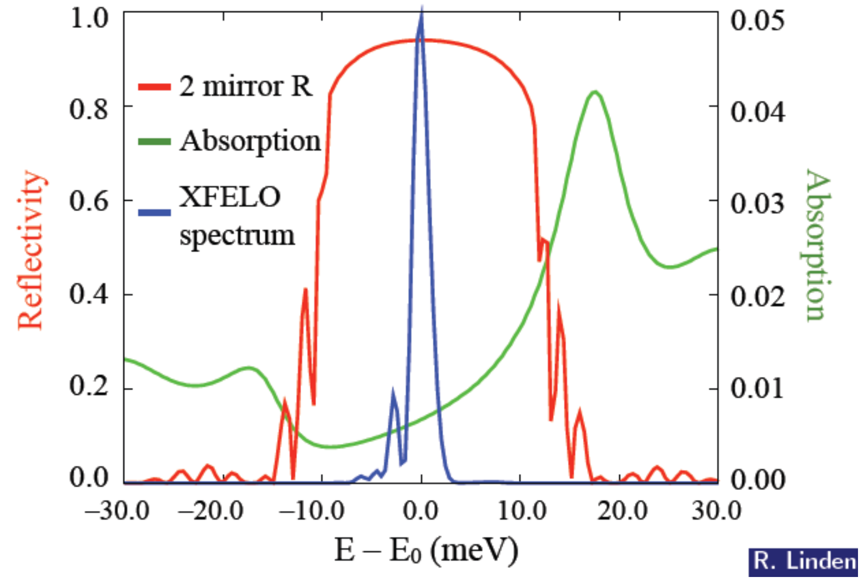
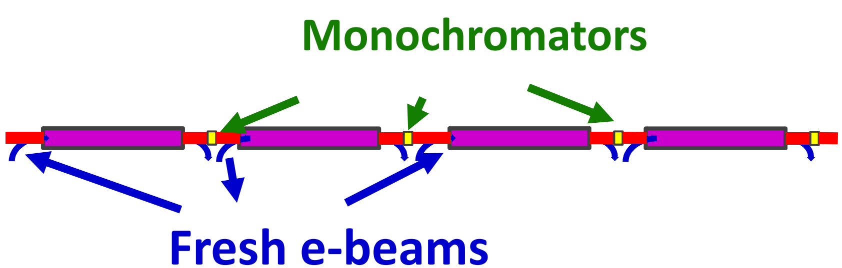
X-Ray FEL Oscillator







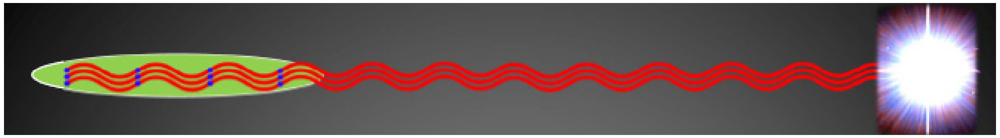
An infinite chain of seeded sections

An X-Ray FEL Oscillator is fully coherent and highly stable

- Full transverse and longitudinal coherence
- Transform limited BW: $\Delta\hbar\omega =$ (3-10) meV for (0.2-1) ps pulse length
- 10^8-10^9 γ's /pulse, or 10^{14}-10^{15} γ's /s
- Complete polarization control with crossed U

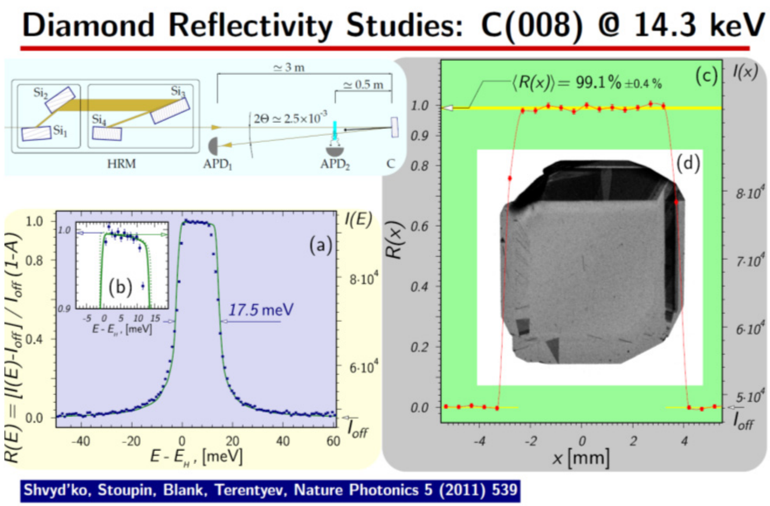
→100-fold higher spectral flux, 10,000-fold higher brightness than MBA-based USR

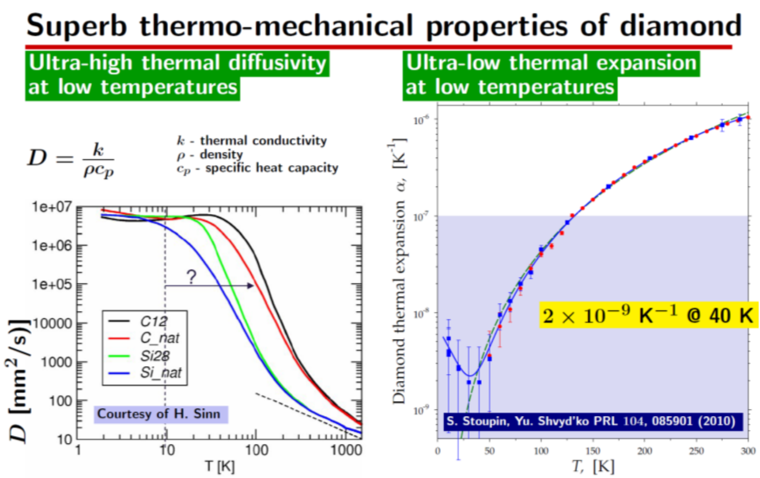
→**Can also serve as a "seed" for high-gain amplifier→ high power & full coherence**

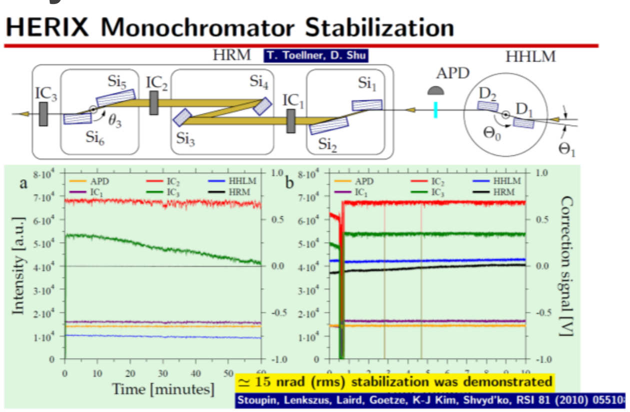


Previous R&D Results

- **XFELO beam dynamics with Bragg reflectors**
  - Low gain theory, simulation code for XFELO evolution taking into account the complex reflectivity of diamond
- **Diamond crystals from TISNCM**
  - Demonstration of high-reflectivity (>99%), High-diffusivity at cryogenic temperature, Simulation of thermal response
- **Null detection feedback**
  - demonstration for 15 n-rad (rms) stability with ~ 1 Hz BW





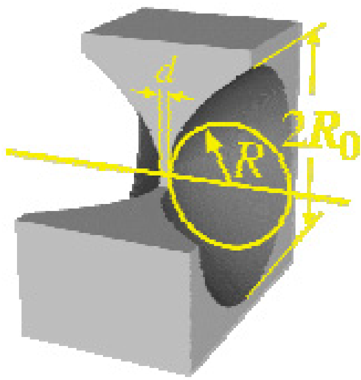


Recent R&D results

- **Be-CRL as a compact, low-loss focusing element**
- **Diamond endurance test under intense x-ray exposure using the APS beamlines**
- **Feasibility a 5^{th} harmonic XFELO using 4 GeV SCRF linac at LCLS II**

Be-CRL as a Compact, Low-loss Focusing Device

- **Jacek Krzywinski emphasized that Be-CRL can be a low-loss (T> 99%) for hard x-rays (> 10 keV) & large focal length (>20m)**

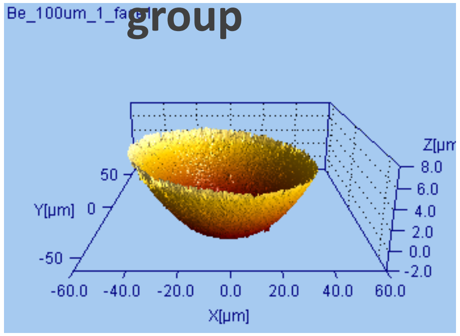


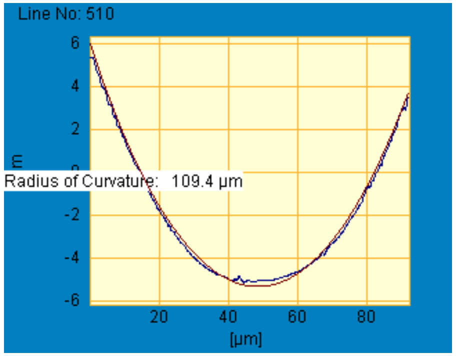
For 14.4 keV, f = 21.1 m, d=30 um σ_r = 28 um,

Crystalline Be, IF 1 grade: Tr = 99.74%
PS20 E grade (atten. length 60% of IF-1): Tr = 99.56%

- **Parabolic profile of Be-CRL from ROPTICS (Lengeler) are acceptable**

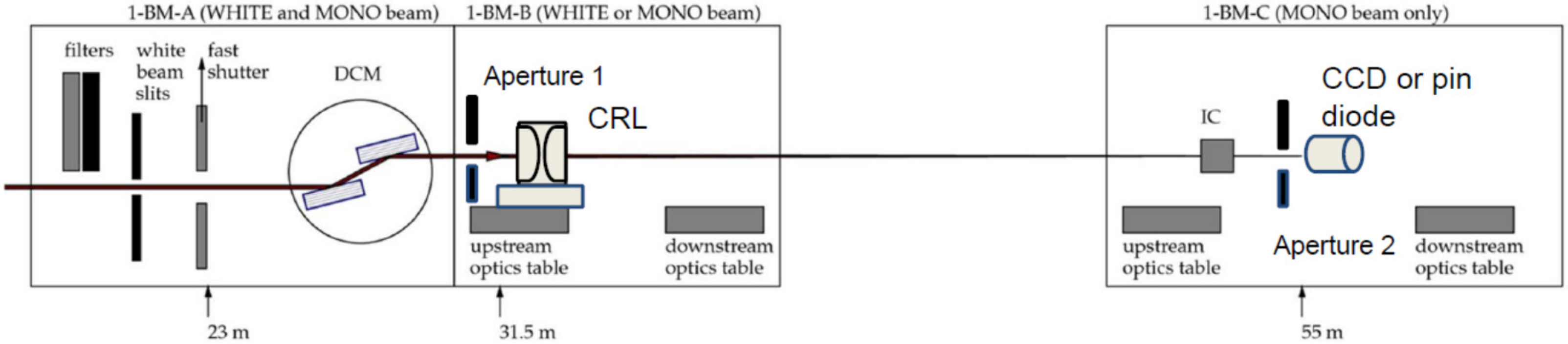
Measurement by the APS metrology group





Be-CRL Test at APS 1 BM-A (July 2015)

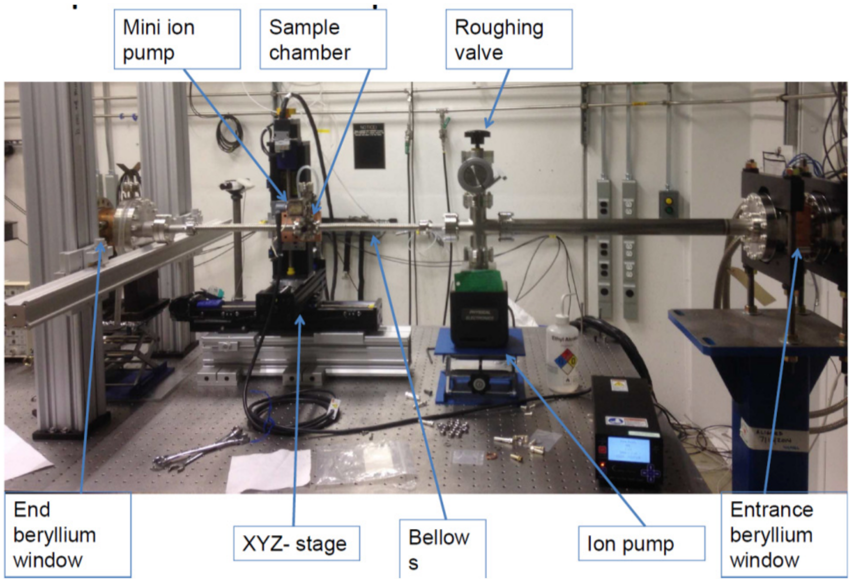
(S. Stoupin, J. Kryziwinski, K. Kolodziej, Y. Shvyd'ko, D. Shu, X.Shi,..)

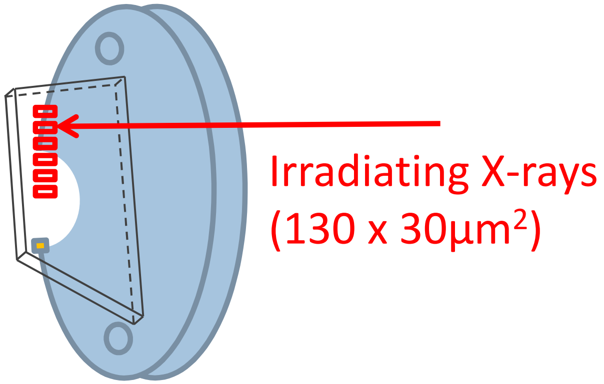


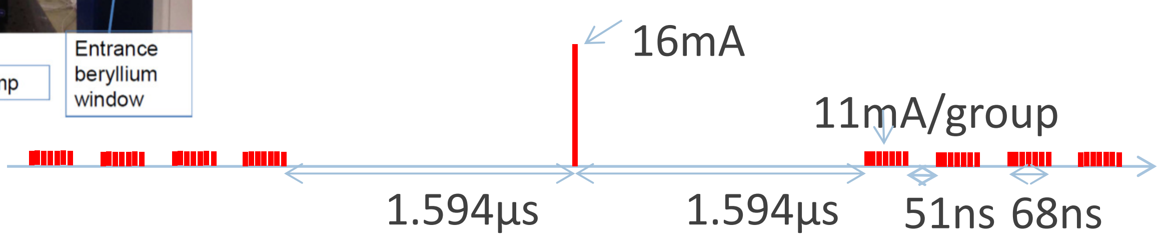
- **Transmission of a Be-CRL of f=50 m (from Lengeler) was tested to be close to 99%**
- **Wavefront measurement data is being processed**
- **Be-CRL endurance under intense x-ray exposure was demonstrated as a by-product of the diamond endurance test.**

Diamond irradiation experiment at APS,
(March-July, 2015, T. Kolodziej, Y. Shvyd'ko, S. Stoupin, D. Shu,..)

- **34 ID-E: 4 kW/mm^2 in 0.5x0.5 μm^2**
- **35 ID-B: 8 kW/mm^2 in 120x30 μm^2 spot (~XFELO)**
- **Raman characterization (of surface contamination)**
- **Double crystal topography at 1BM-B**

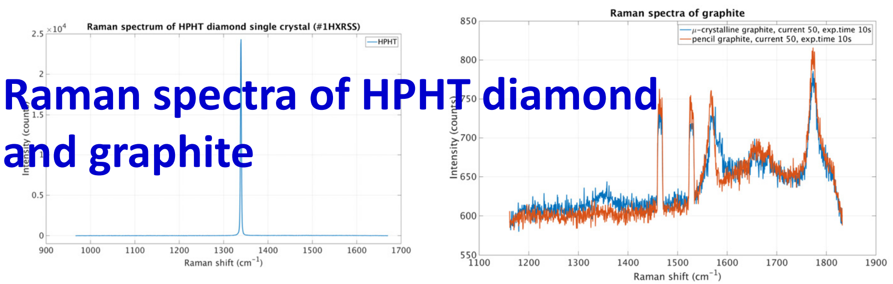




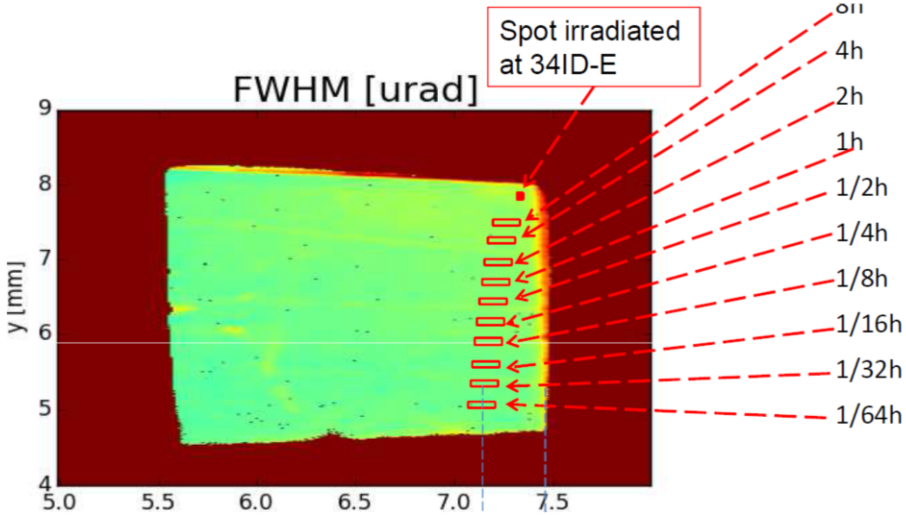


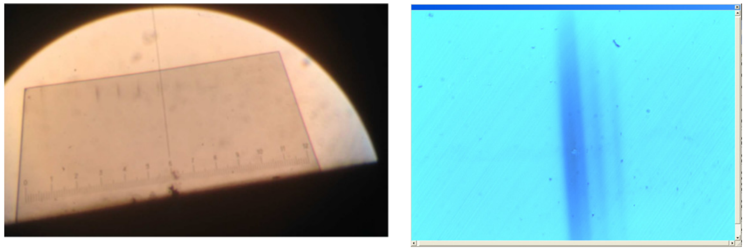
E-beam pulse format at APS

No evidence of graphite formation from double crystal Raman topography



Raman spectra of HPHT diamond and graphite



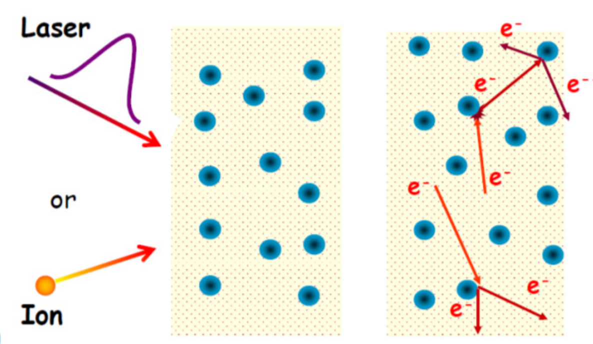


Optical microscope images

- **High-resolution reflectivity measurement, the ultimate test, will be done when beamtime becomes available**
- **We will also look at the surface with an AFM**

Simulation/Estimates to Predict Damages

- **Phay Ho and Chris Knight (APS): Atomistic modelling**
- **N. Medvedev (CFEL): Simulation & estimates**

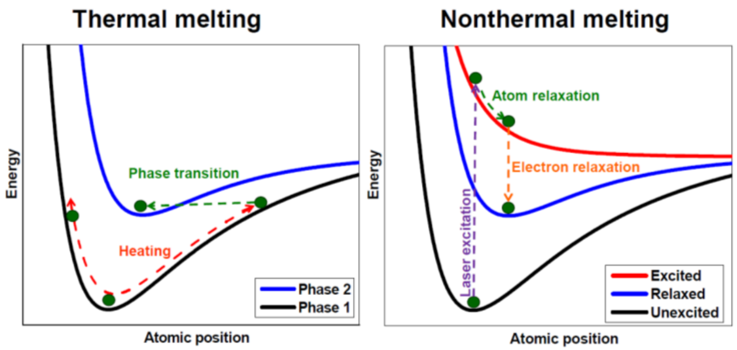


Single shot effects:

✗ 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



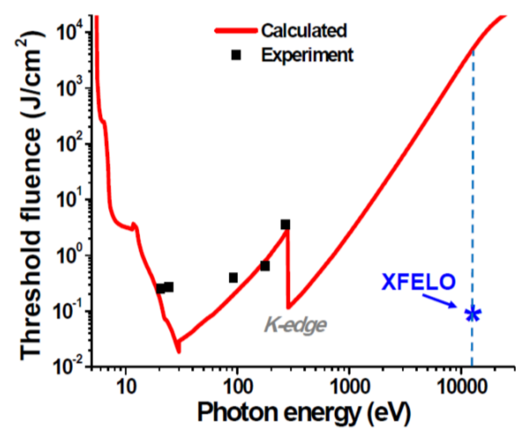
Multishot effects:

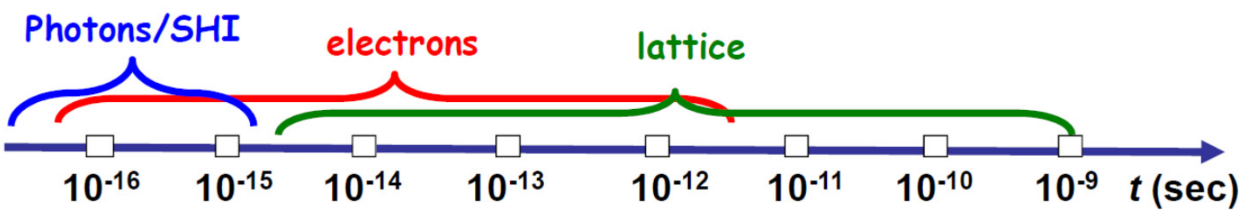
✗ 1) Melting, stresses, fatigue (require heating)

✗ 2) Electrons recombine: fluorescence <1 ns

✗ 3) Point defects are not produced

✓ 4) Surface effects may play a role ~1 μm





A Multi-GeV SCRF Linac with Few MHz Rep Rate (CW): The main Cost Driver

- The 17.5 GeV European XFEL linac can run a pulsed XFELO, or CW at 7 GeV (J. Sekutowicz)
- 4 GeV LCLS II linac can drive a hard x-ray XFELO by operating at 5^{th} harmonic

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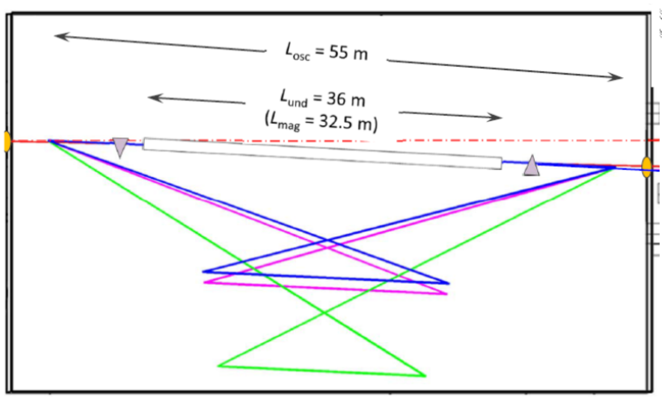
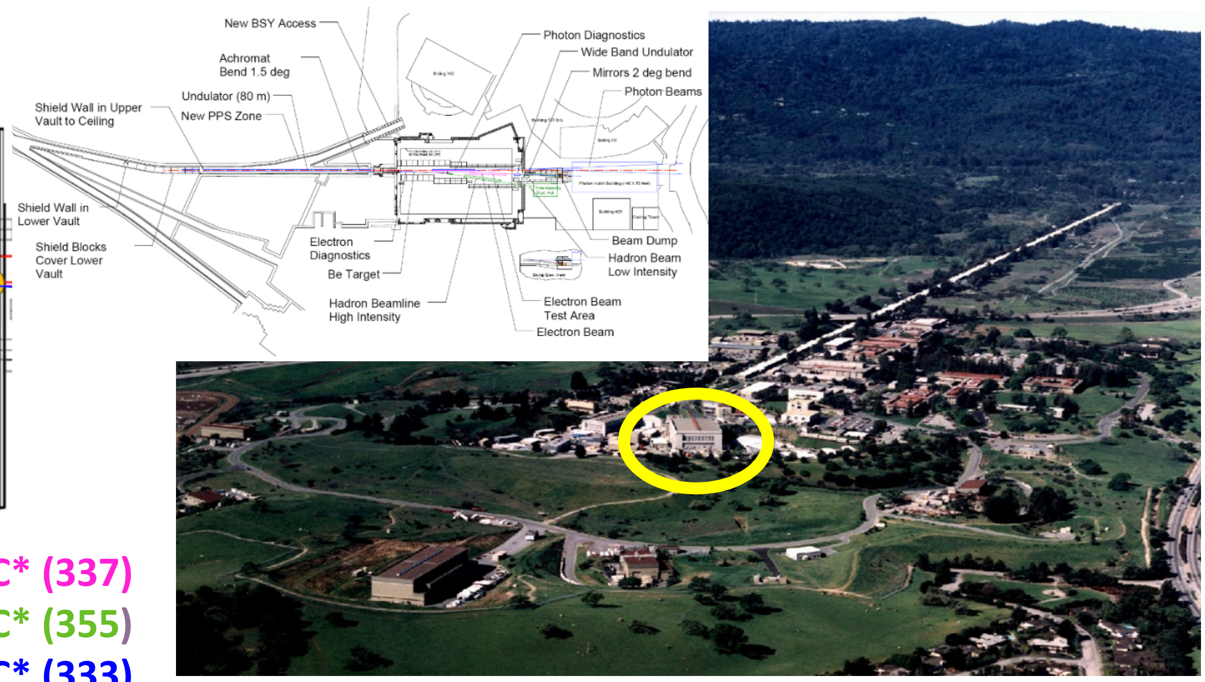


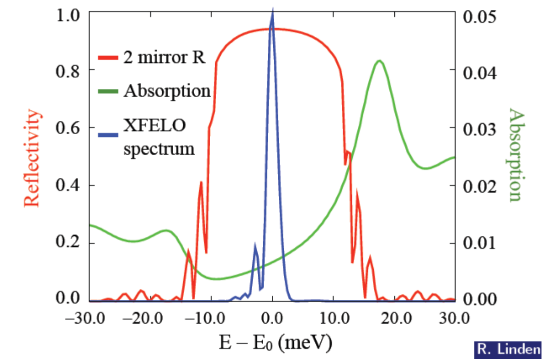
E_{ph} = 14.4 keV, $2\vartheta_r$ = 18.4º, C* (337)
E_{ph} = 13.8 keV, $2\vartheta_r$ = 29.3º, C* (355)
E_{ph} = 9.13 keV, $2\vartheta_r$ = 17.0º, C* (333)

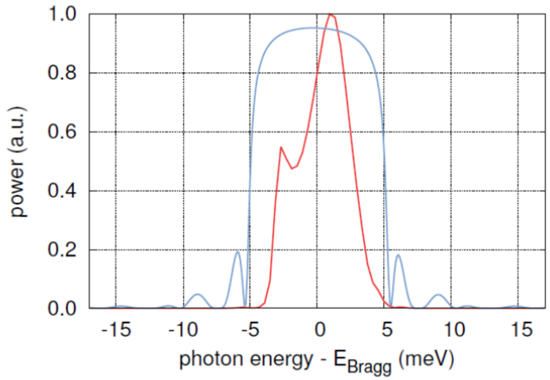


Harmonic XFELO (H.X. Deng & Z. M. Dai)

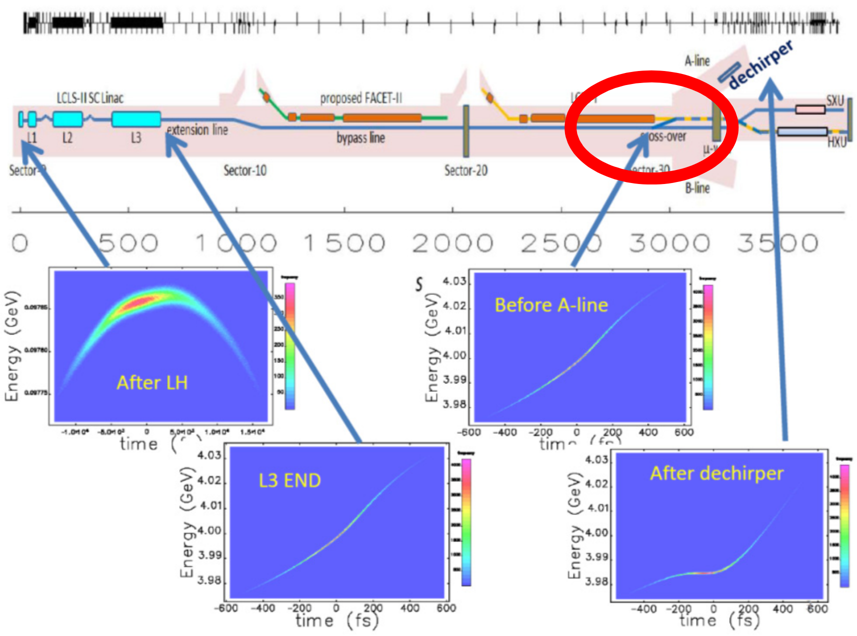
- If $\Delta\gamma/\gamma$ is small, the gain at harmonic can be high (Madey's theorem.)
- Full simulation via extended GINGER (W. Fawley) & a new code by R. Lindberg (J. Zemella, et al., TUP030)
- The tolerance of e-beam correlated energy spread may limit the bunch length → FEL gain decreases and spectral BW ~10 meV larger than 1 meV

Parameter	Value	Units
e^--beam energy	4.0	GeV
Peak current	120.0	A
Bunch charge	50.0	pC
Bunch length (rms)	166.7	fs
Energy spread	200.0	keV
Norm. emittance	0.3	μm
Photon energy at 5^{th} harmonic	14.4	keV
Undulator period	26.0	mm
Number of undulator periods	1250	
Undulator parameter K	1.433	
loss per round-trip	15.0	%
Rayleigh length	12.0	m
Distance rad. waist-undulator center	-1.0	m





With the low peak current (100 A), the emittance and slice energy spread can be preserved during the transport to, and large bend at BSY *(Y. Ding, K. Bane)*

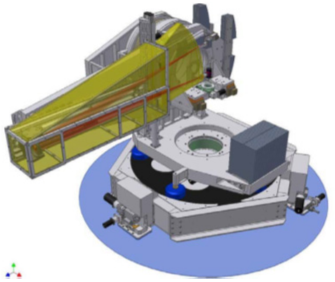


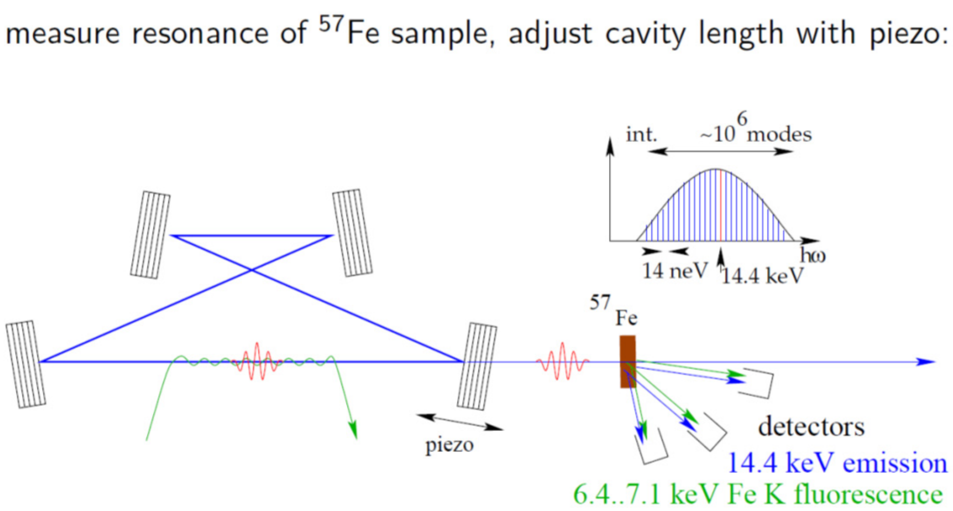
- **The *E-t* chirp generated during compression can be corrected by a passive dechirper**
- **The wakefield limits the slope correction to ~150 fs**

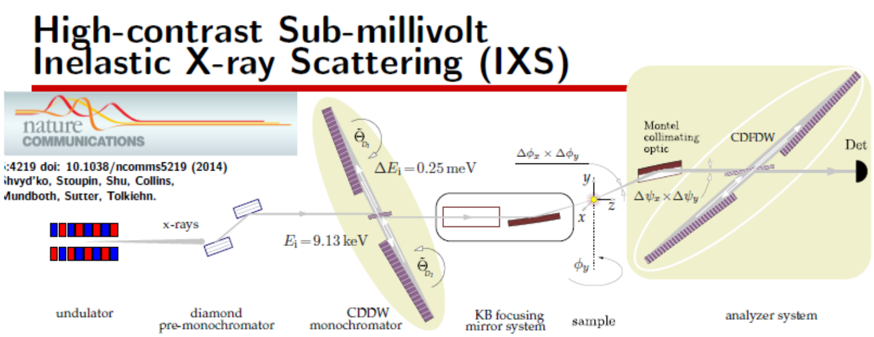
Methods for longer flat beam are being investigated (backtracking,..)

Science with an XFELO

- Enhanced IXS for elucidating the emergent phenomena of strongly correlated system
  - High Tc Superconductivity,..
- Moessbauer, XPCS,…
- Provide MHz, hard x-rays for LCLS II
- Can serve as a seed for high-gain amplifier→ A perfect XFEL facility







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

Concluding remarks

- An XFELO will enhance the capability of X-ray FEL as a scientific instrument
- A “perfect” facility with HGXFEL& XFELO, together or separately
- 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
- An XFELO can be implemented at European XFEL (pulsed or CW) and LCLS II (CW)

XFELO Collaboration
SLAC, ANL/APS, (Chem, MCS) C-FEL

- General: Z. Huang, J. Hastings, J. Frisch, T. Maxwell, Y. Shvyd'ko, KJK
- FEL physics/simulation: R. Lindberg, W. Fawley, Y. Ding, G. Marcus, T. Maxwell, J. Zemella (DESY)
- Diamond crytal: Yuri, T. Kolodziej
- MCMD simulation: Ph. Ho, Ch. Knight, N. Medvedev
- CRL lens: J. Krzywinski, S. Stoupin, L. Assoufid, X. Shi
- Optical cavity mechanical design: D. Shu
- Electron beam: Y. Ding, K. Bane, P. Emma, T. Raubenheimer, D. Walz
- Sciences: J. Hastings, Y. Shvyd'ko, J. Arthur,..