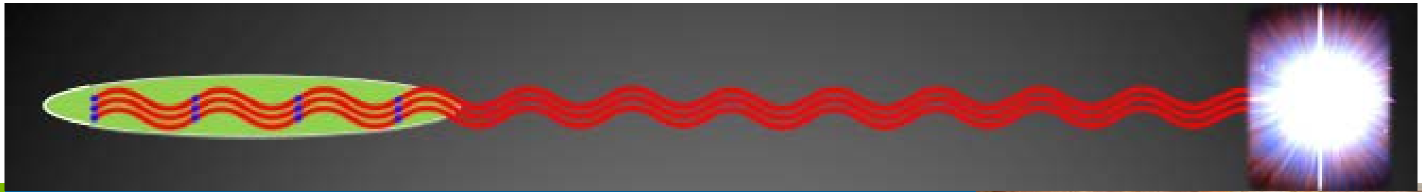


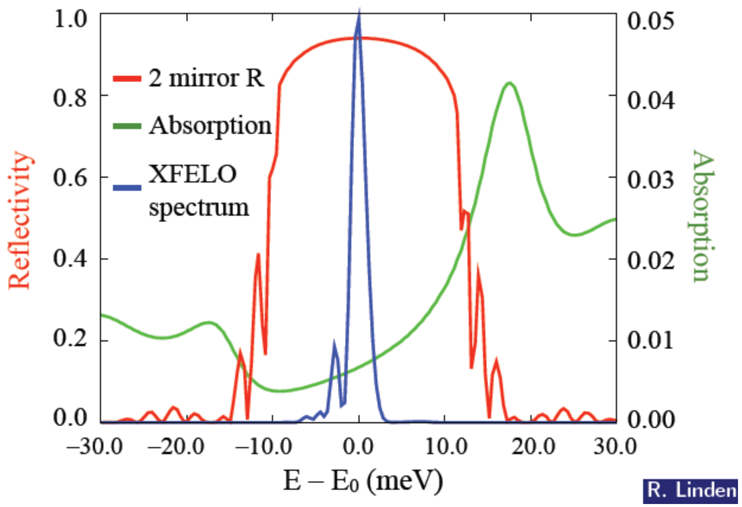
BEAM DYNAMICS PROBLEMS FOR X-RAY FEL OSCILLATOR (XFELO)

KWANG-JE KIM

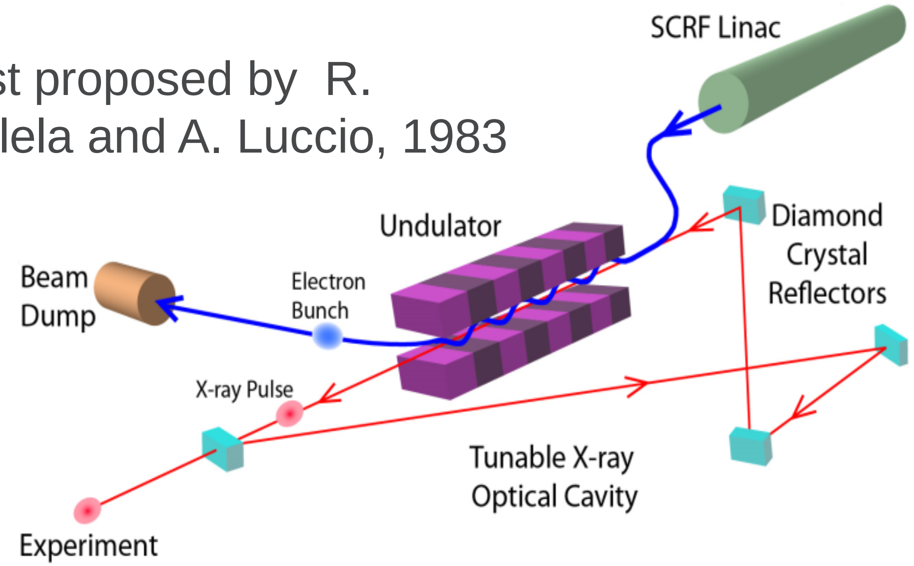
ANL and U. Chicago

September 20, 2017
Arcidosso, Tuscany, Italy

X-RAY FREE-ELECTRON LASER OSCILLATOR (XFELO)

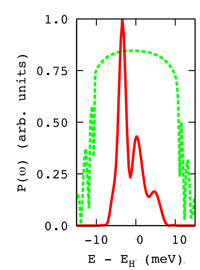


First proposed by R. Collela and A. Luccio, 1983

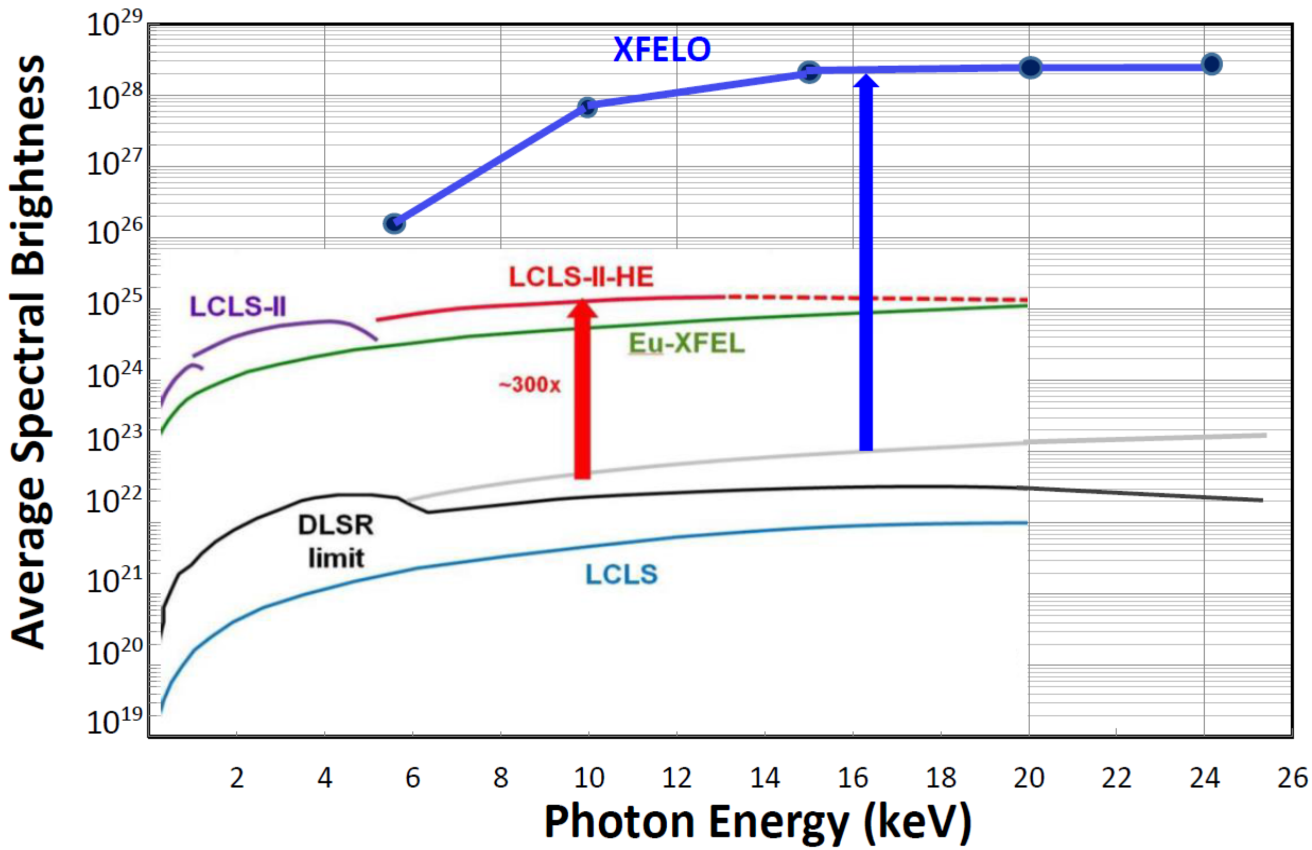


N_{pass} = 10 N_{pass} = 30 N_{pass} = 100 N_{pass} = 200 ,1000

- R. Collela and A. Luccio (1983)
- Revived by KJK, Y. Shvyd'ko, S. Reiche (2008)
- Bragg reflectors for hard x-rays (5 –25 keV)



XFELO WITH 8 GEV 8-GEV 1 MHZ SCRF LINAC → ℬ ~10^{28} #/(MM^2 MR^2 0.1%BW)



- 10^{10} photons/pulse ~ 10^{-2} × SASE
- $\Delta\omega/\omega$ (FWHM)~ 10^{-7} ~ 10^{-4} × SASE
- ℬ = #/$\Delta\omega/\omega$ → ℬ (XFELO)/ ℬ (SASE) ≥ 100 !!

XFELO MAJOR PARAMETERS

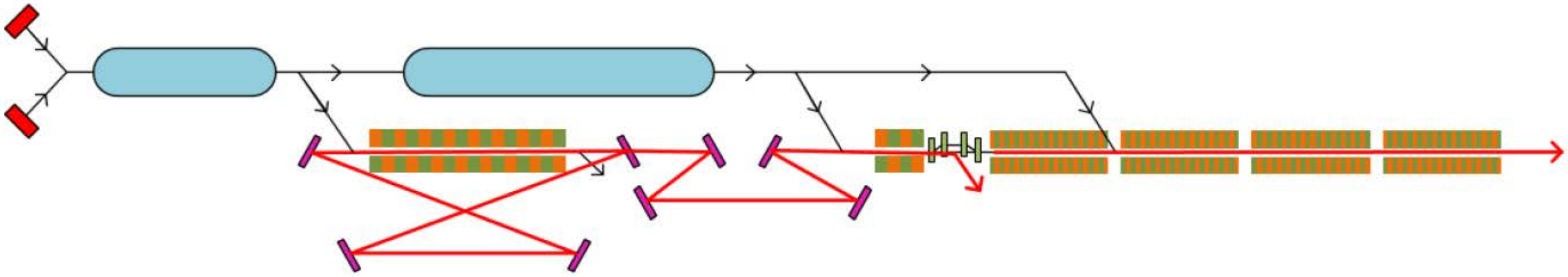
W. Qin, R. Lindberg

Table 1: XFELO simulation parameters and output pulse properties (the repetition rate is assumed to be 1 MHz).

Parameter	**4.9 keV**	**10 keV**	**14.4 keV**	**14.4 keV**	**14.4 keV**	**20 keV**	**24.2 keV**
Electron gun	SCRF	SCRF	NCRF	NCRF	SCRF	SCRF	SCRF
FEL K	3.2128	2.0125	1.4304	1.4837	1.4837	1.0125	1.1539
E_{beam} [GeV]	7.982	7.982	3.994	7.982	7.982	7.982	7.982
ε_n [μm]	0.25	0.25	0.35	0.35	0.25	0.25	0.25
σ_E [keV]	130	130	70	70	130	130	130
λ_u [cm]	2	2	2.6	2	2	2	1.5
N_u	1000	1000	1250	1000	1000	1000	2000
harmonic number	1	1	5	1	1	1	1
Z_R [m]	10	10	10	10	10	10	15
Bragg crystal	C(220)	C(440)	C(733)	C(733)	C(733)	C(880)	C(888)
Output coupling	4%	4%	4%	4%	4%	4%	5%
Pulse energy [μJ]	3.1	21	0.3	7	28	11	4.4
Spectral FWHM [meV]	10.9	5.4	5.8	3.9	3.4	2.7	1.3
Temporal FWHM [fs]	138	530	400	557	693	905	1989
$\sigma_\tau \sigma_\omega$ (FWHM)	2.27	4.37	3.52	3.26	3.58	3.67	4.06
# of Photons/pulse	3.9×10^9	1.3×10^{10}	1.3×10^8	3.1×10^9	1.2×10^{10}	3.4×10^9	1.1×10^9
Spectral flux [ph/s/meV]	3.6×10^{14}	2.4×10^{15}	2.2×10^{13}	7.9×10^{14}	3.6×10^{15}	1.3×10^{15}	8.5×10^{14}

ADVANCED SCHEME I: MOPA WITH FUNDAMENTAL OR HARMONIC GENERATION

KJK, R. Lindberg, & J.H. Wu (MaRie WS, 2016), W. Qin, KJK, RL, JW, FEL 2017)

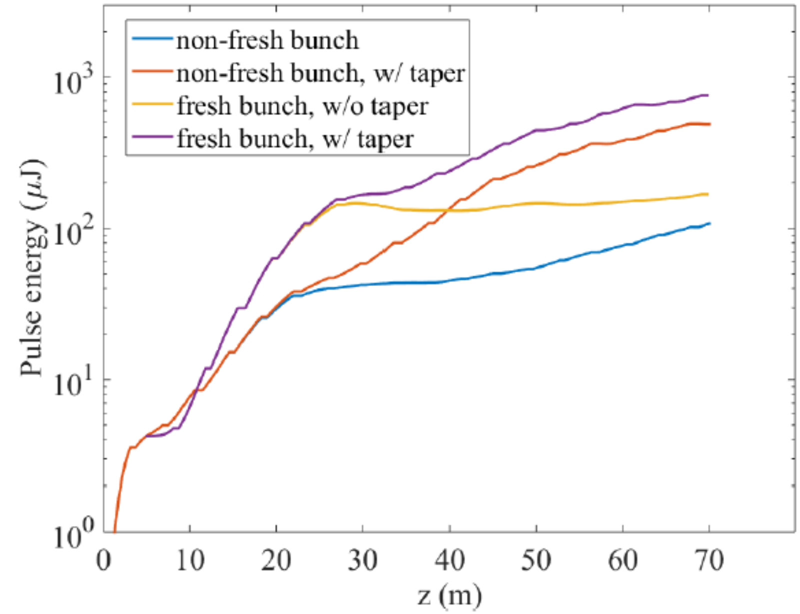


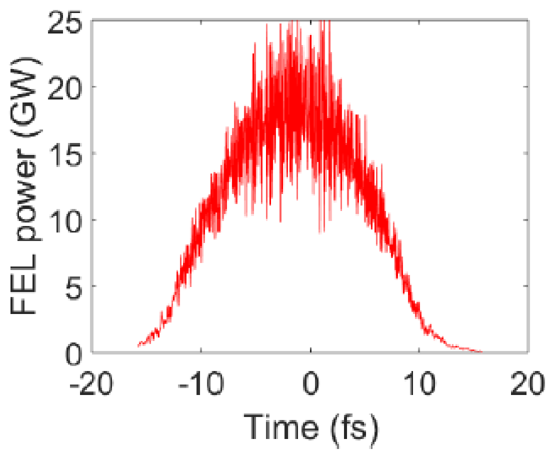
- MOPA: XFELO → HG amplifier with intense, ultrashort e-bunch
  - Ultrashort X-ray pulses, similar to SASE but coherent and stable
- MOHGHG: XFELO→ Harmonics→ HG amplifier
  - Photon energy up to 40-60 keV (MaRIE)

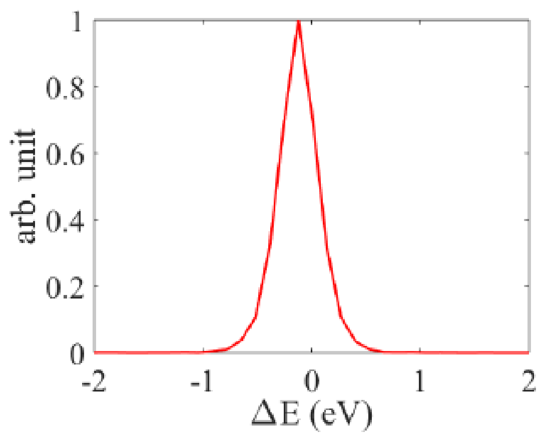
XFELO-HGHG PERFORMANCE

W. Qin, R. Lindberg, J. Wu, KJK

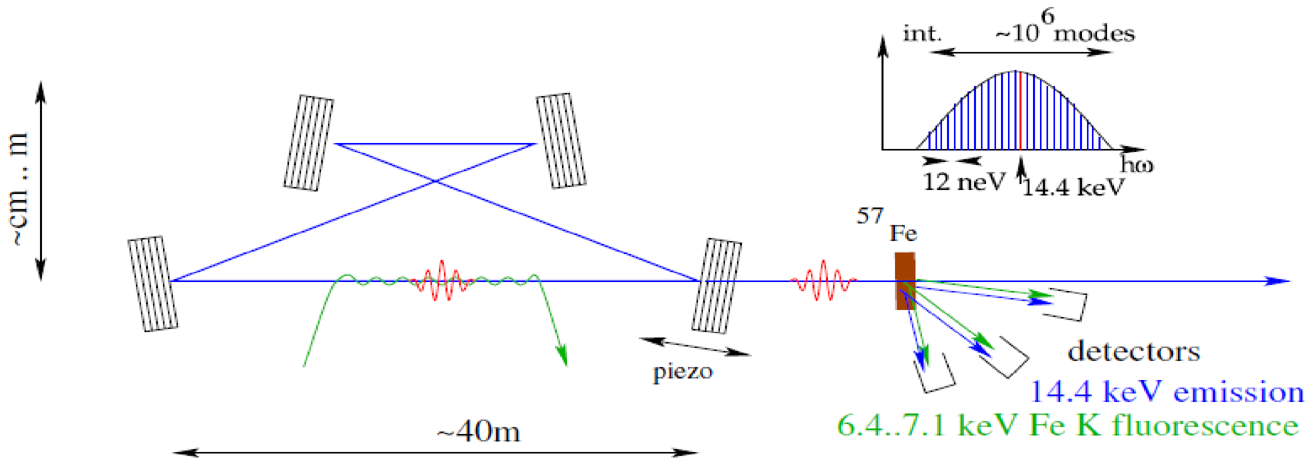
Parameter	XFELO	Mod.	43.2 keV	57.6 keV
FEL K	1.48	2.79	1.44	1.03
E_b [GeV]	8	12	12	12
I_{pk} [A]	120	3400	3400	3400
σ_s [fs]	317	12.5	12.5	12.5
σ_E [MeV]	0.2	1.8	1.8	1.8
λ_u [cm]	2	1.94	1.55	1.55
L_u [m]	20	8	70	70
harmonic	1	1	3	4







ADVANCED SCHEME II: SPECTRAL COMB FOR HARD X-RAYS

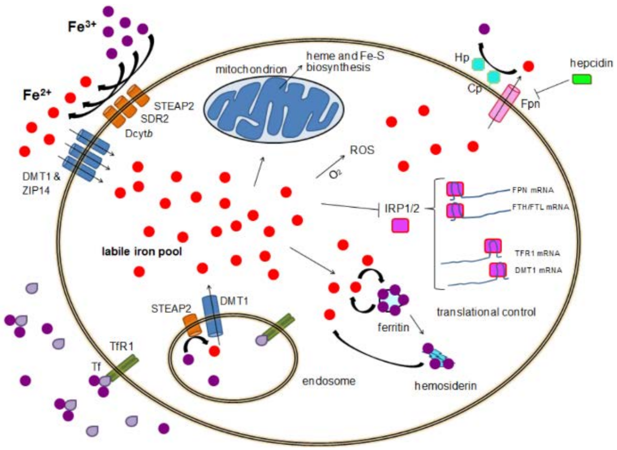


- Stabilize the roundtrip path length to fraction of wavelength with FB referenced to
  - Narrow nuclear resonance ^{57}Fe
  - Stabilized optical laser (optical comb)
- ~ 10^6 spectral lines of neV width separated by 12 neV.
- B. Adams and KJK, PRSTAB (2015)

XFELO SCIENCE RETREAT AT SLAC (6/29-7/1, 2016)

Sciences for high spectral brightness and ultra-fine spectral resolution

- **Enhanced application of techniques developed at 3rd gen and SASE sources**
  - IXS, XPCS, NRS
  - Smaller samples, faster data collection, high resolution..
- **Techniques in infancy at current sources will become practical tools**
  - Medical applications of NRS
  - X-ray NLO, study of red cells without enriching the excited states of Fe
- **Emergence of new areas**
  - X-ray spectral comb→ fundamental sciences with extreme metrology, revolutionizing nuclear physics



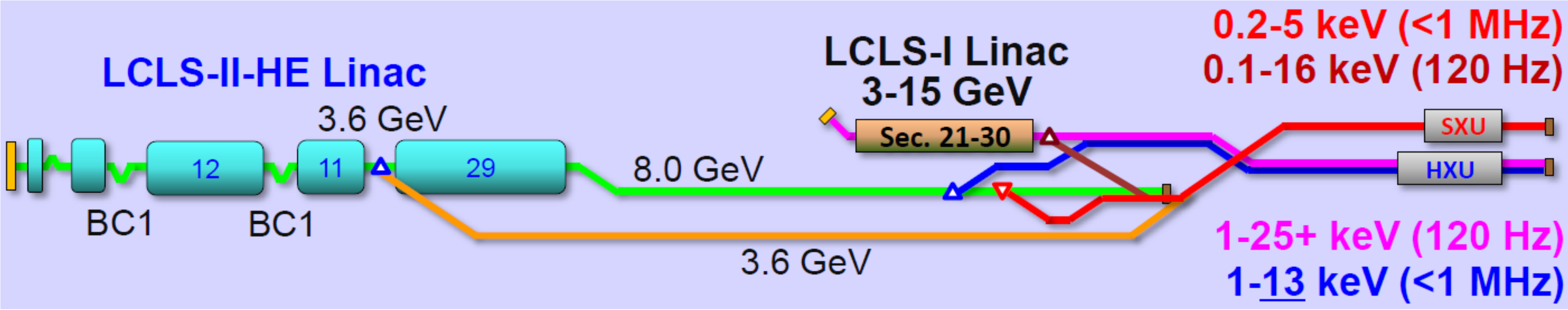
TECHNICAL ISSUES

Much progress has been made during the last ten years

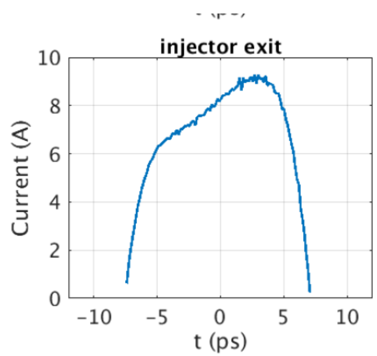
- **Electron accelerator**
  - Electron injector optimization
  - High-energy (~ 8 GeV) SCRF linac: LCLS-II-HE, Shanghai, Retrofitting the EuroFEL linac
- XFELO beam dynamics
  - Use GINGER for amplification and add x-ray propagation and crystal reflection properties. Transvers-temporal coupling is not included yet.
- **X-ray optics**
  - Focusing elements: curved grazing incidence mirrors, CRLs
  - Bragg mirrors: diamond crystals
    - Reflectivity
    - Thermo-mechanical properties
    - Diamond survival/Endurance under intense x-ray environment

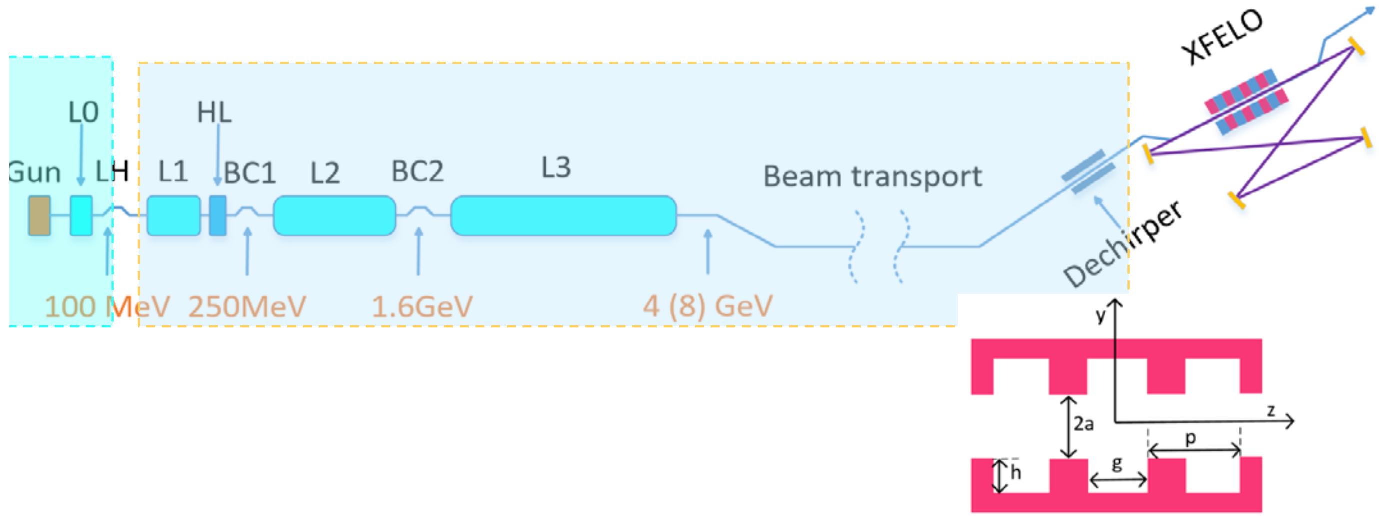
ACCELERATOR CONFIGURATION

- **LCLS-II-HE (8 GeV)**
- **"Advanced photocathode gun" : Wisconsin SCRF gun(40 MeV/m at cathode) or APEX II**



OPTIMIZATION OF INJECTOR-LINAC PARAMETERS





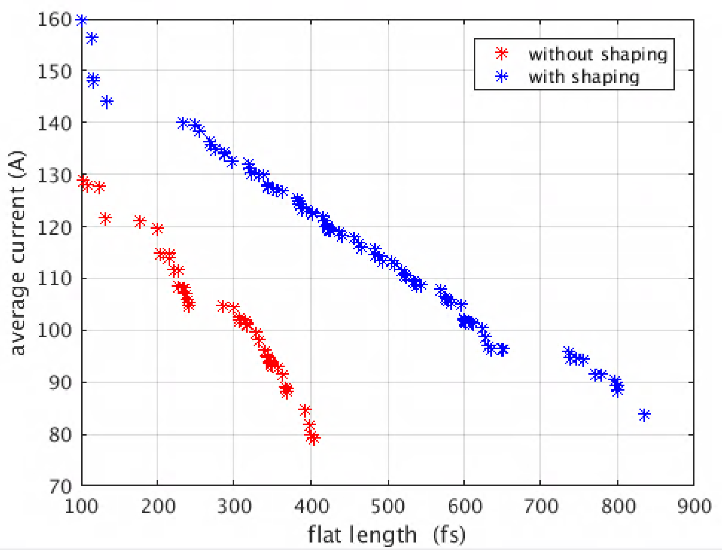
- X-ray pulse: $\Delta\tau \times \Delta\omega/\omega = \lambda/(2c)$ (FWHM): For 10 - 20 keV → $\Delta\tau \sim$ ps

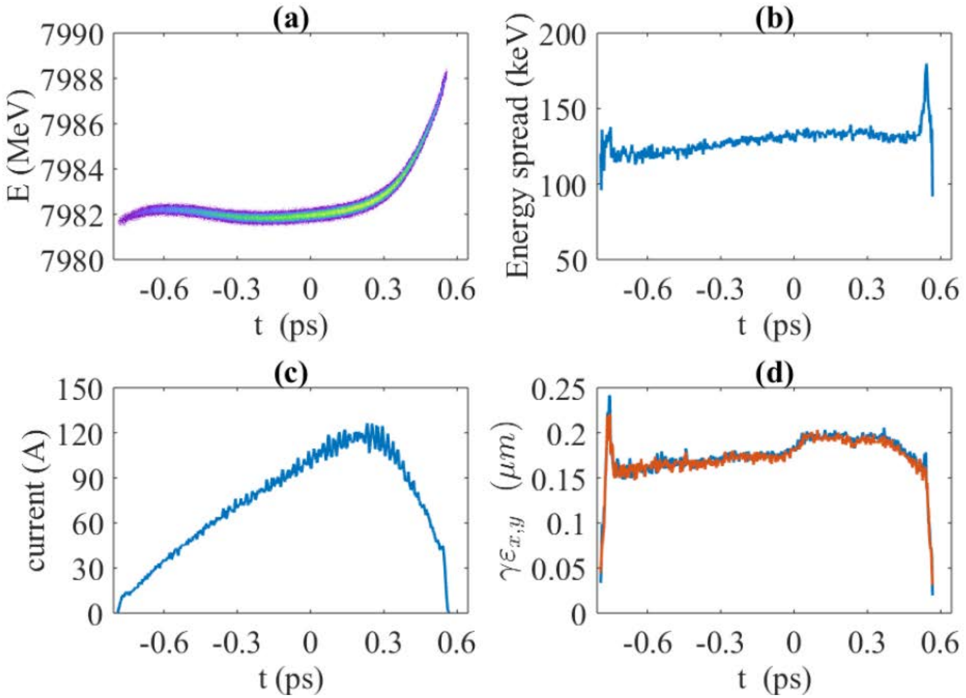
→The electrons' energy profile should be flat (within incoherent spread) over ~ ps

- Shape the current profile at the cathode to linearize the wake-induced energy loss & use a de-chirper to remove the slope (K. Bane, W. Qin)
- RF phase, beam current, bunch compressor and WF talk to each other
- S2E simulation: Injector (ASTRA), linac (LiTrack), XFELO (GINGER)

OPTIMIZATION : APEX II & LCLS-II-HE

- With shaping & and higher gradient gun
  - about twice useful charge in the flat part
  - better emittance
  - Higher energy spread (injector current lower than APEX)

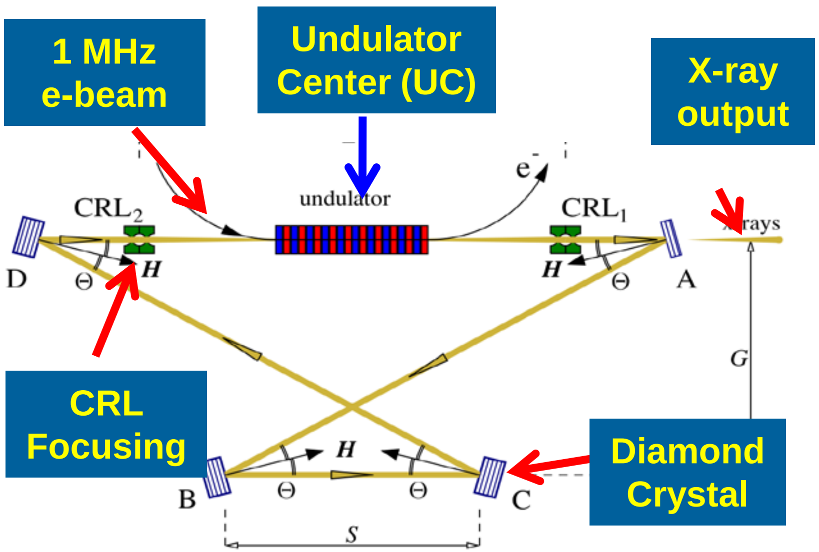


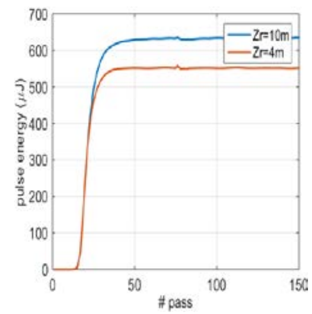


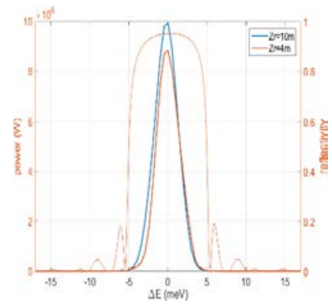
@ undulator entrance

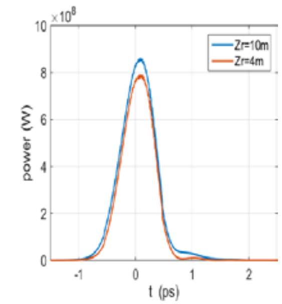
- Over 600 fs flat part, 120 A peak current
- Low slice emittance and slice energy spread
- Projected energy spread 0.02%

X-RAY CAVITY AND UNDULATOR





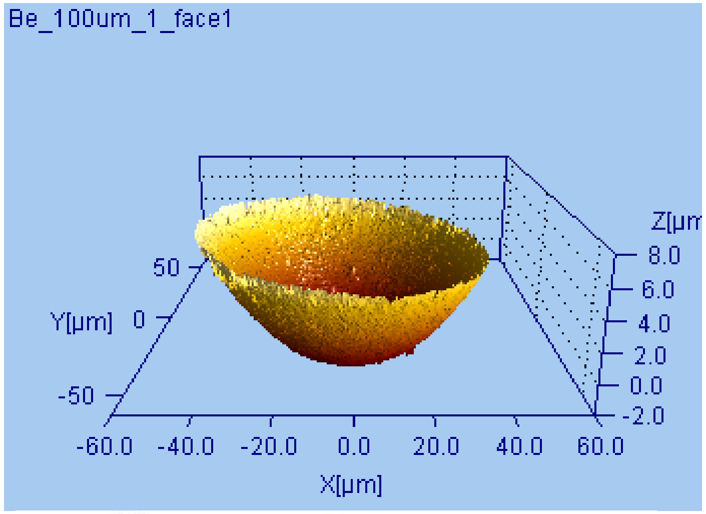


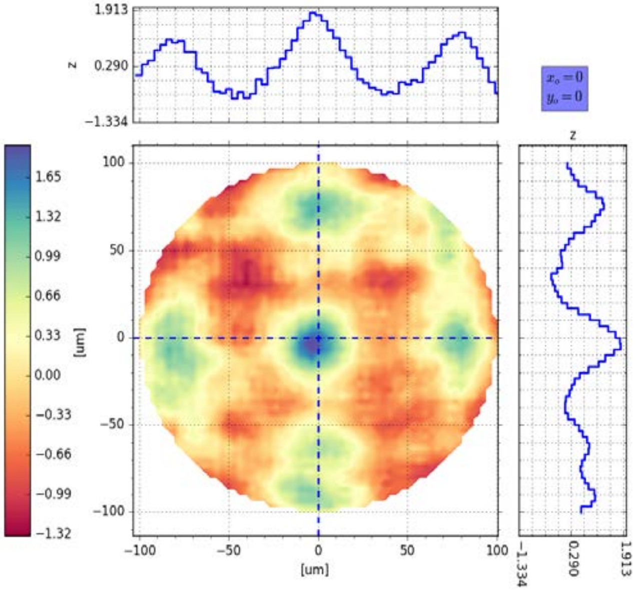


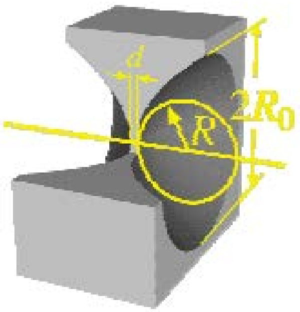
- **Works best where Bragg scat. has high R and not-to-narrow BW--- 5-25 keV**
- **For 14.4 keV λ_U=2 cm, *K*=1.49 → SC NbTi : *K*max=3.1→ 5.2 keV**

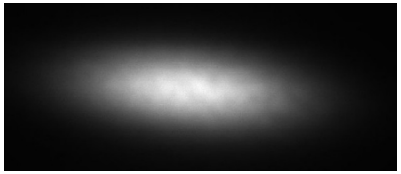
BERYLLIUM CRL AS A COMPACT, LOW-LOSS FOCUSING ELEMENT

- CRL normally used with many-lens set for tight focusing→ high loss
- For XFELO, f ~ 100 m→ at most two-face unit
- Test Be-CRL, R=100 μm at APS
  - T > 98% @ 14.4 keV
  - Metrology & Talbot interferometry → deviation from parabolic surface < 1 μm
  - Excellent imaging quality
  - Can withstand the intense intra-cavity x-ray power (10-20 kW/mm²)





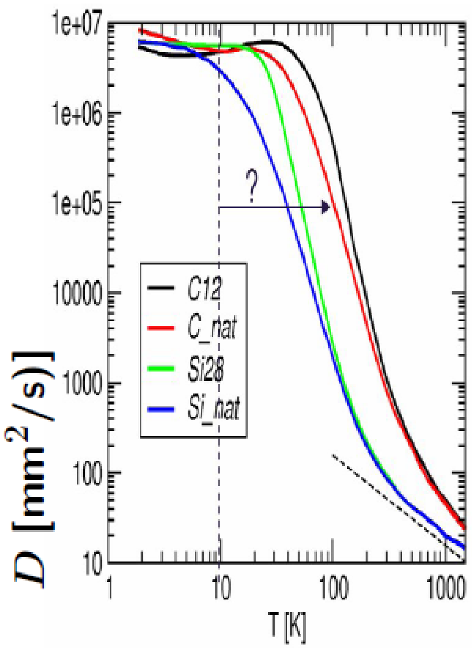




DIAMOND AS BRAGG REFLECTOR: EXCELLENT THERMO-MECHANICAL PROPERTIES

Ultra-high thermal diffusivity at low temperatures

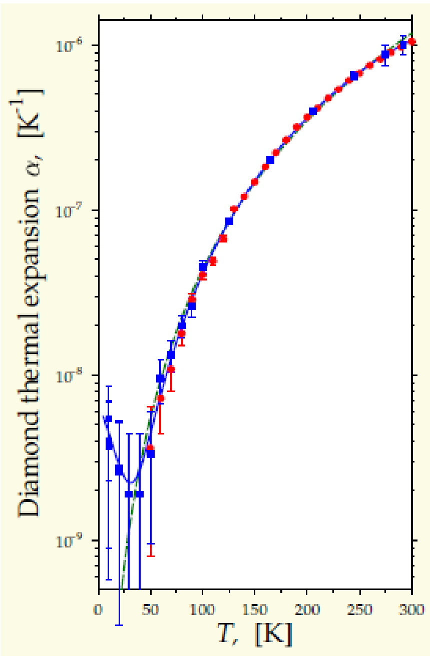
$\simeq 10^5$ mm^{-2}s @ 100 K



Courtesy of H. Sinn

Ultra-low thermal expansion at low temperatures

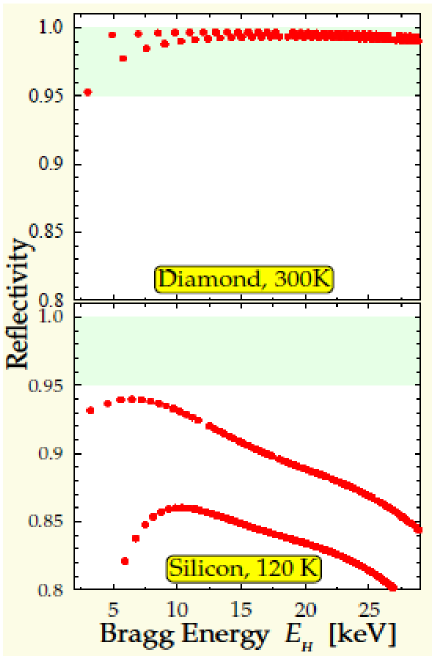
$\simeq 10^{-8}$ K^{-1} @ 100 K



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

Record high reflectivity for hard x-rays

Theory: $> 99\%$

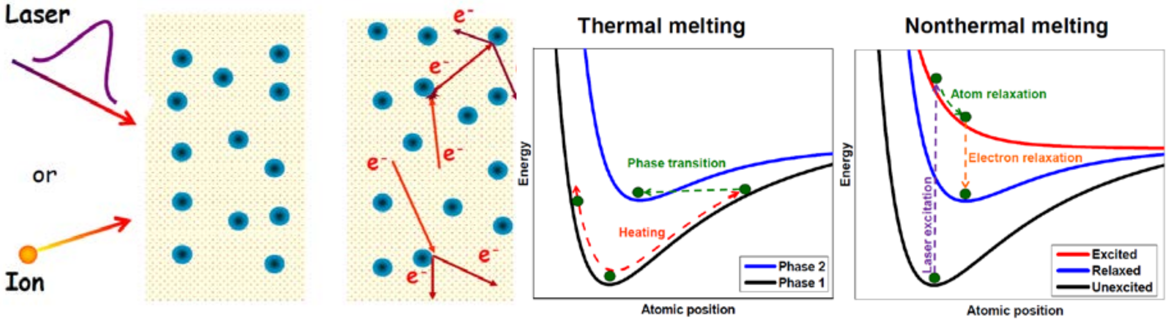


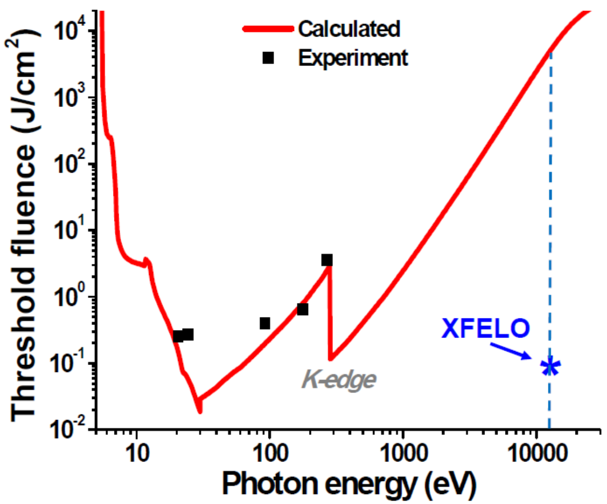
Yu. Shvyd'ko et al Nature Phys. (2010)

- Y. Shvyd'ko, V. Blank, and S. Terentyev, MRS Bul., 42, 437 (2017)

THEORY: XFELO INTENSITY IS WELL BELOW THE DAMAGE THRESHOLD OF DIAMOND

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

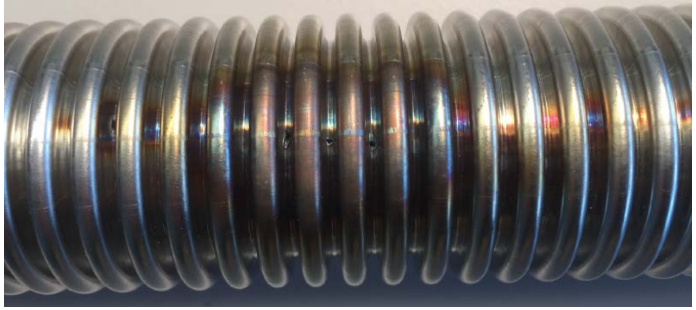
Multishot effects:

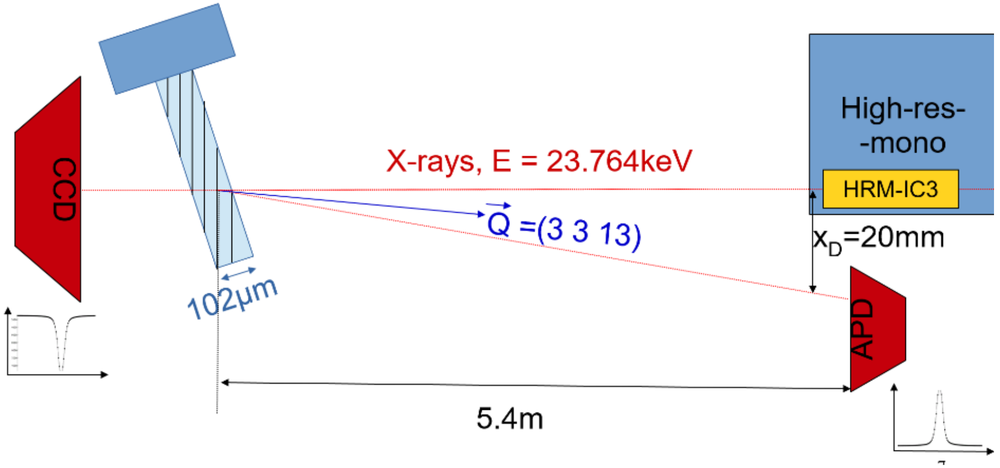
- ✗ 1) Melting, stresses, fatigue (require heating)
- ✗ 2) Electrons recombine: fluorescence <1 ns
- ✗ 3) Point defects are not produced
- ✓ 4) Surface effects may play a role ~1 µm

APS TEST FOR DIAMOND ENDURANCE AT X-RAY POWER DENSITY 10-20 KW/MM^2

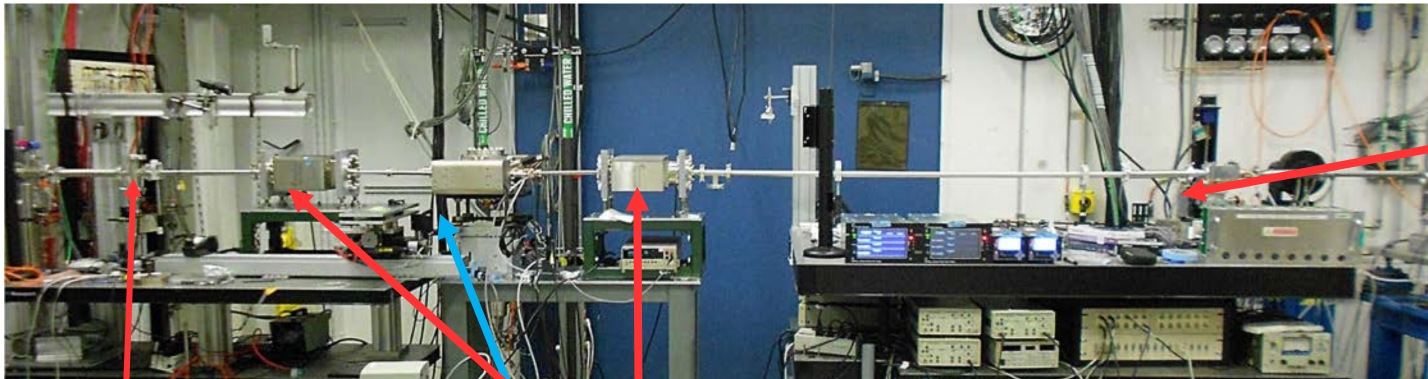
- Irradiation
  - **9 kW/mm^2** in 30x120 μm^2 spots (K-B mirror focusing) under medium vacuum
  - **12.5 kW/mm^2** in 30x40 μm^2 spots (Be-CRL focusing) under UHV (~10^{-8})
- Analysis: high-resolution (meV) topography
- T. Kolodziej, et al

Unfocussed X-ray beam burns stainless steel in few minutes





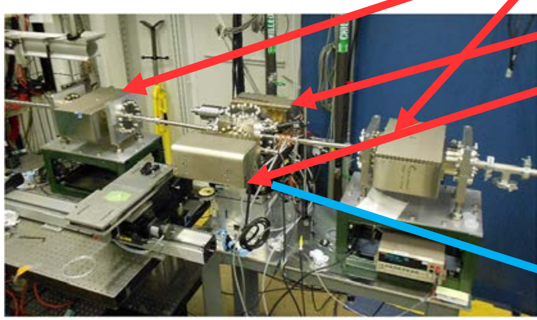
Irradiation 12.5 kW/mm^2 at APS 7-ID-B



Be-CRL

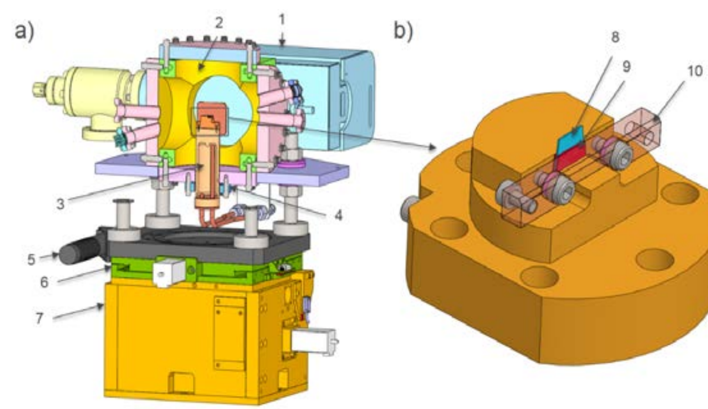
Scattering detector

Differential ion pumps



Side ion pumps

UHV irradiation Chamber (gold-coated)



See S. Kearney, et al, MOP056

TOPOGRAPH AFTER IRRADIATION INDICATES NO STRUCTURAL DAMAGE BUT BRAGG PEAK SHIFTS BY ~ 1 MEV OF THE ROCKING CURVES NEAR THE CARBON DEPOSITS

$\delta E/E = \delta d/d = 1.6 meV/24\ keV$

Relative d-spacing change $= 7\ 10^{-8}$

CONCLUSIONS

- An XFELO is feasible from beam dynamics and X-ray optics
- Several projects for construction of ~8 GeV SCRF linac exist
  - LCLS-II-HE, Shanghai, EuroXFEL,..
- An XFELO with an optimized injector will producing fully coherent x-rays with $\mathcal{B}_{av} \sim 10^{28}$
  - $>10^5$ than DLSR
  - For < 13 keV, XFELO >100 than SASE
  - For >13 keV, SASE is supressed
- Strong scientific cases exist for narrow BW, coherent X-rays
  - An XFELO will drive the techniques already developed to a new level of capabilities
  - Novel techniques can be developed for novel sciences

THANKS TO:

- ANL: W. Grizolli, S. Kearney, R. Lindberg, T. Kolodziej , X. Shi, D. Shu, Y. Shvyd'ko
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- Peking U./SLAC (student): W. Qin
- DESY: J. Zemella
- Cornell U.: S. Stoupin
- TISNCM: V. Blank, S. Terentyev
- CAS: N. Medvedev