AN X-RAY FEL OSCILLATOR FOR NOVEL SCIENCES

KWANG-JE KIM

ANL and U. Chicago

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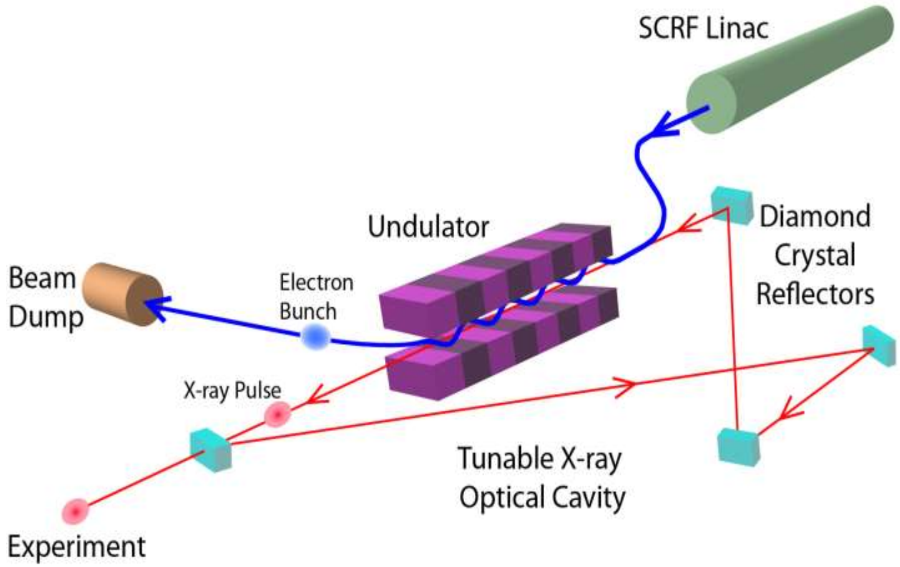
Equatorial Hotel, Shanghai, China

X-RAY FREE-ELECTRON LASER OSCILLATOR (XFELO)



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  - R. Collela and A. Luccio (1983)
- Revived in 2008
  - KJK, Y. Shvyd'ko, S. Reiche
- Much progress in
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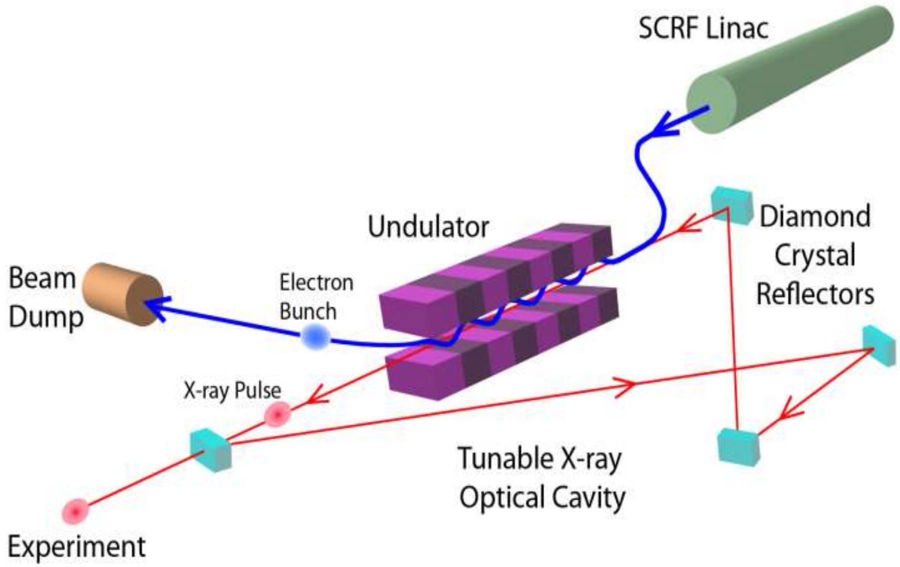

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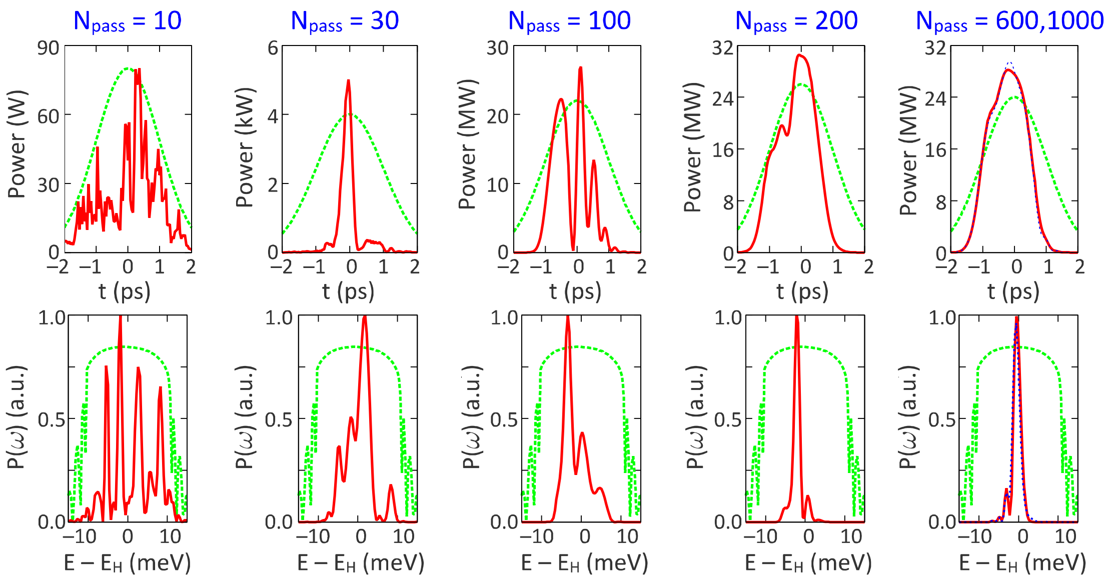

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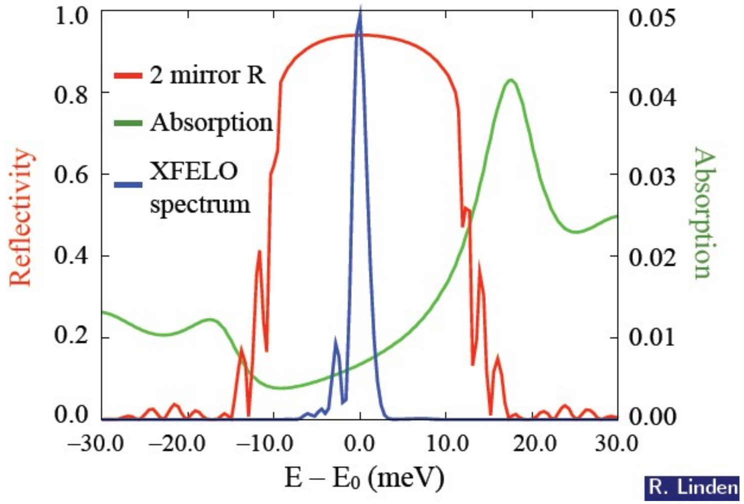

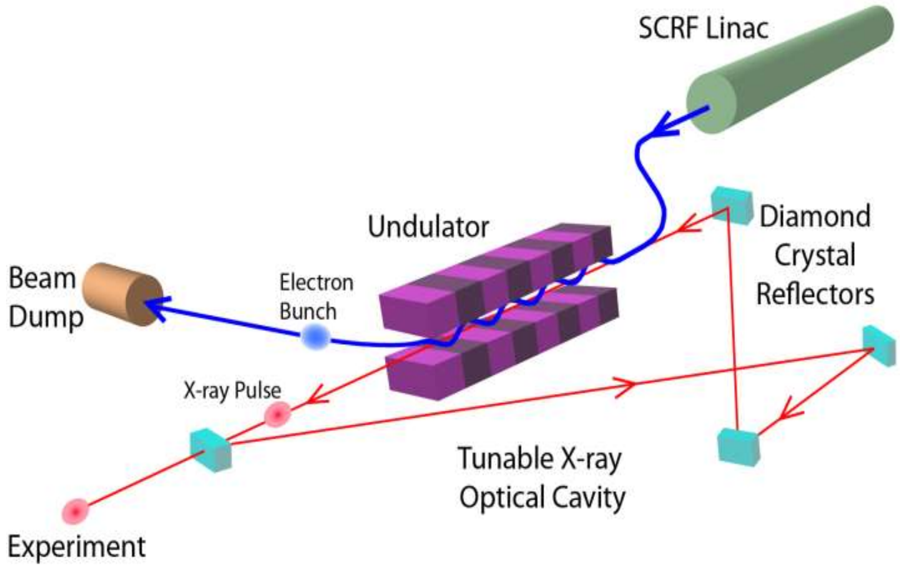

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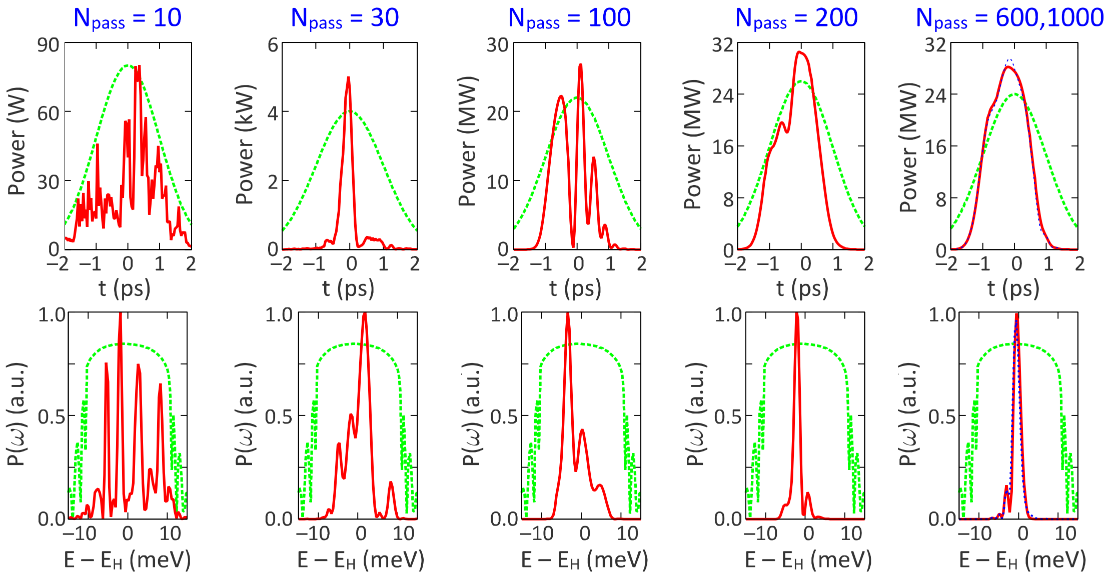
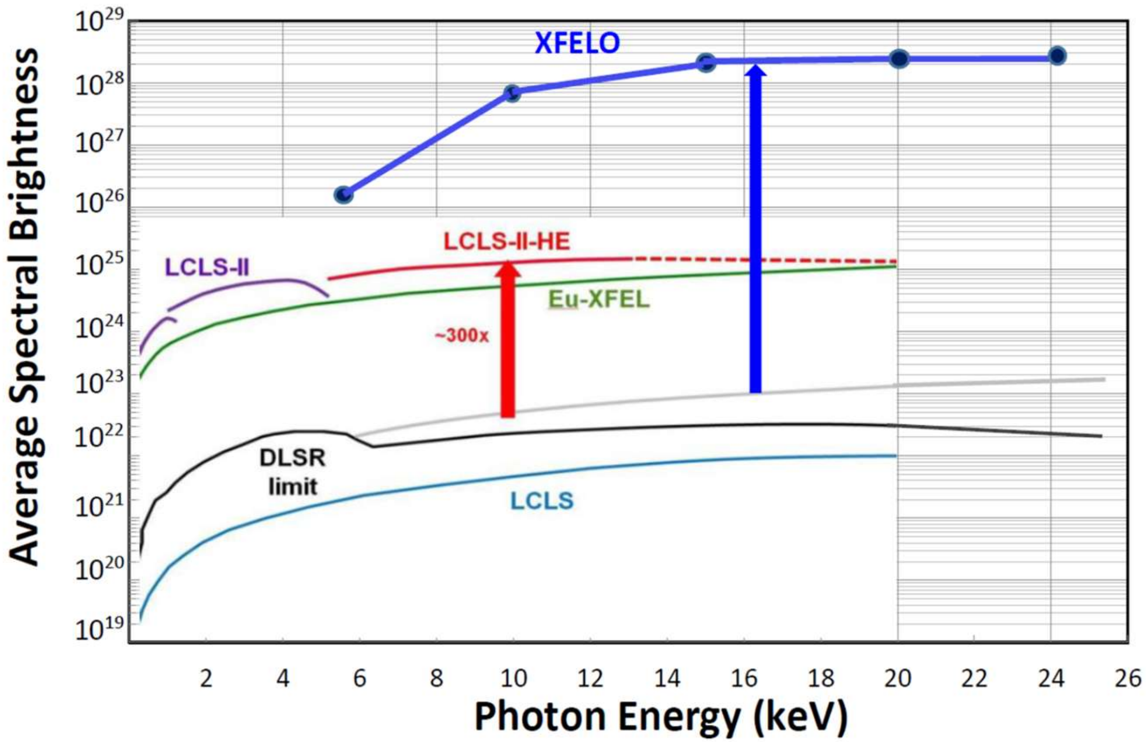


XFELO WITH 8 GEV 8-GEV 1 MHZ SCRF LINAC → $\mathcal{B}$ ~10^{28} #/(MM^2 MR^2 0.1%BW)



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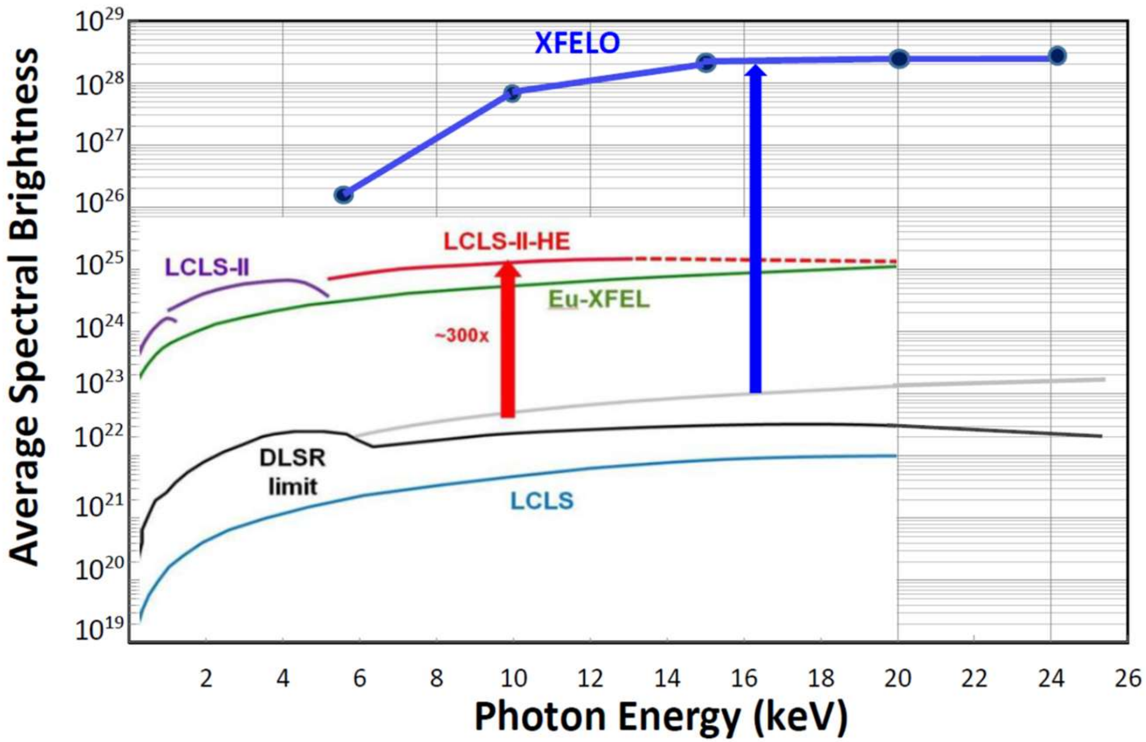

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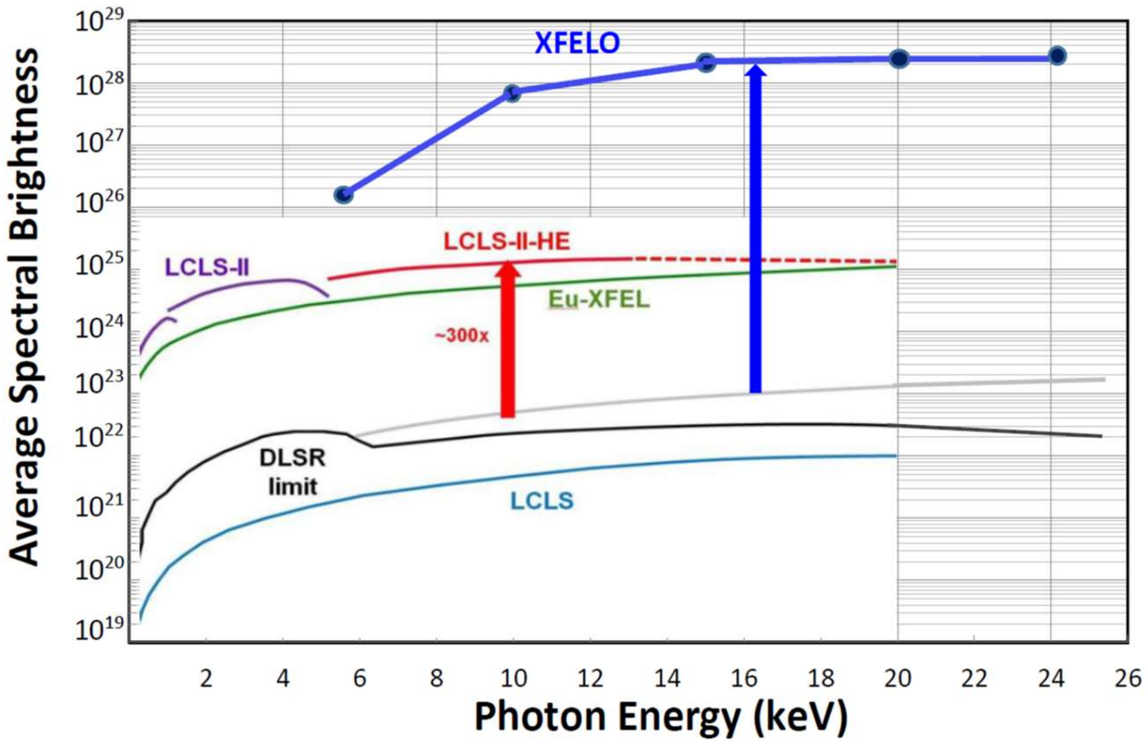
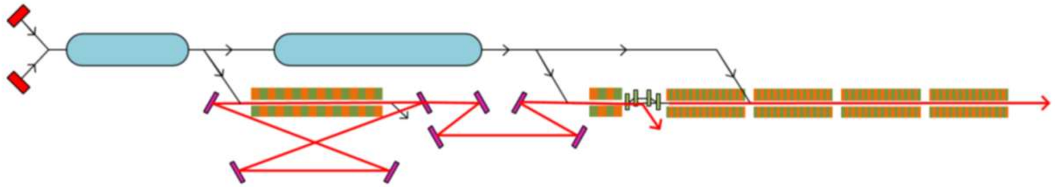


@14.4 keV

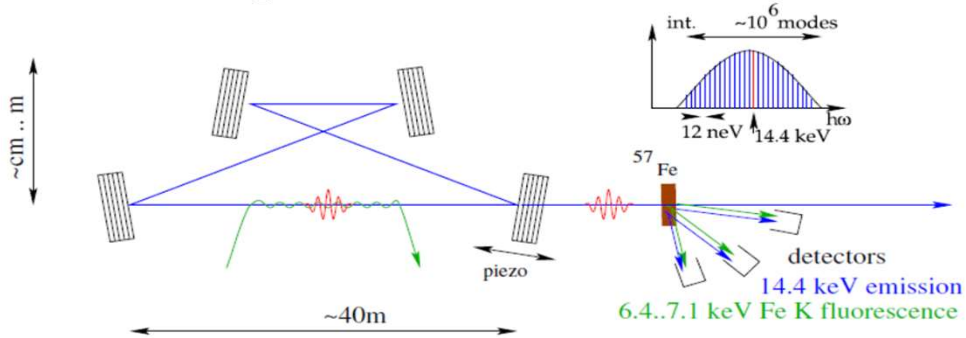
	#/pulse	$\Delta\varepsilon/\varepsilon$	$\Delta\tau$[fs]	B_{ave}	B_{peak}
XFELO	1.2×10^{10}	2.4×10^{-7}	600	2.7×10^{28}	4.0×10^{34}
SASE	5.0×10^{10}	6.0×10^{-3}	30	4.4×10^{25}	1.5×10^{33}

ADVANCED SCHEMES

- **XFELO +(harmonic generation) +high gain amplifier**
  - **Ultrashort X-ray pulses, higher photon energy up t0 60 keV (MaRIE)**
  - KJK, R. Lindberg, J. H. Wu, W. Qin



- **X-ray spectral comb generation**



  - Stabilize the roundtrip path length to fraction of wavelength 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**
  - 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, quantum optics with nuclear states

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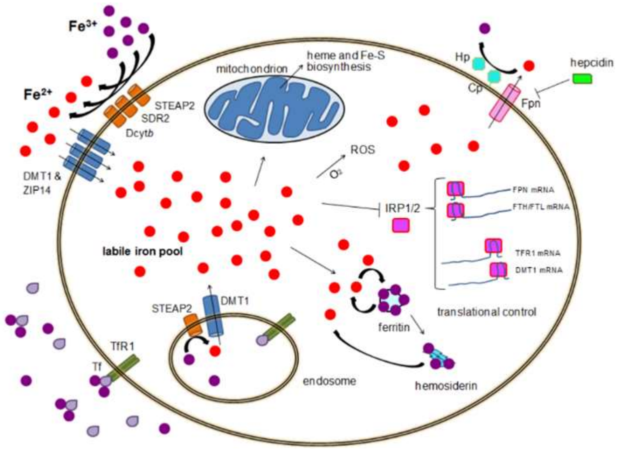

LINAC-BASED XFELO

- Several high-energy CW SCRF linac will be available soon.
  - 8 GeV LCLS-II-HE
  - 8 GeV SCLF
  - Euro-XFEL (17.5 GeV pulsed, or 7 GeV CW retrofit)
- They are for SASE but may have room for an XFELO.

E-BUNCH FOR ULTRA-FINE BANDWIDTH

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- **Temporally coherent X-rays satisfy Fourier condition**:

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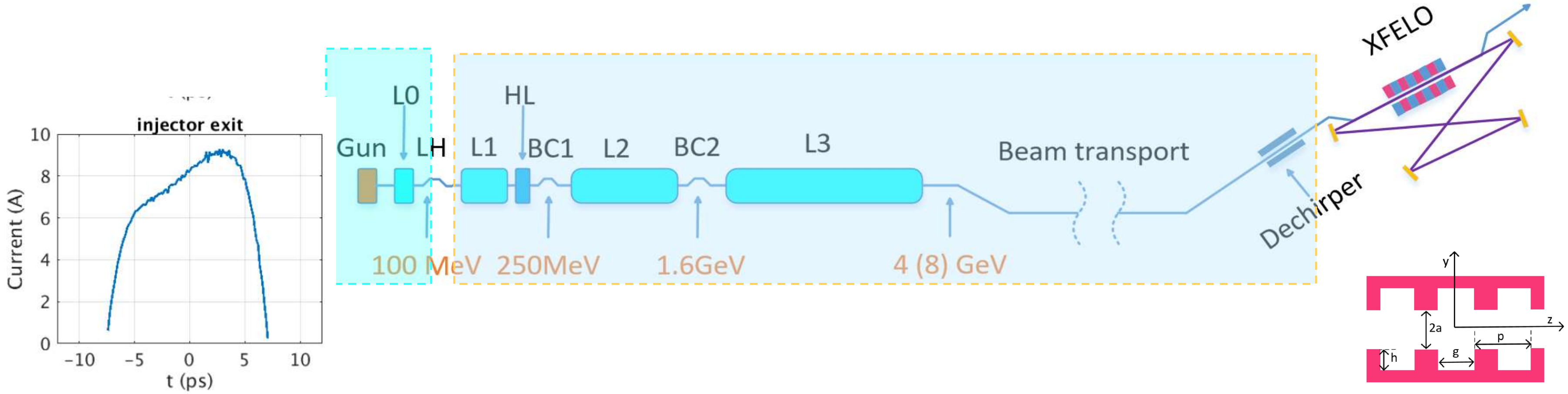
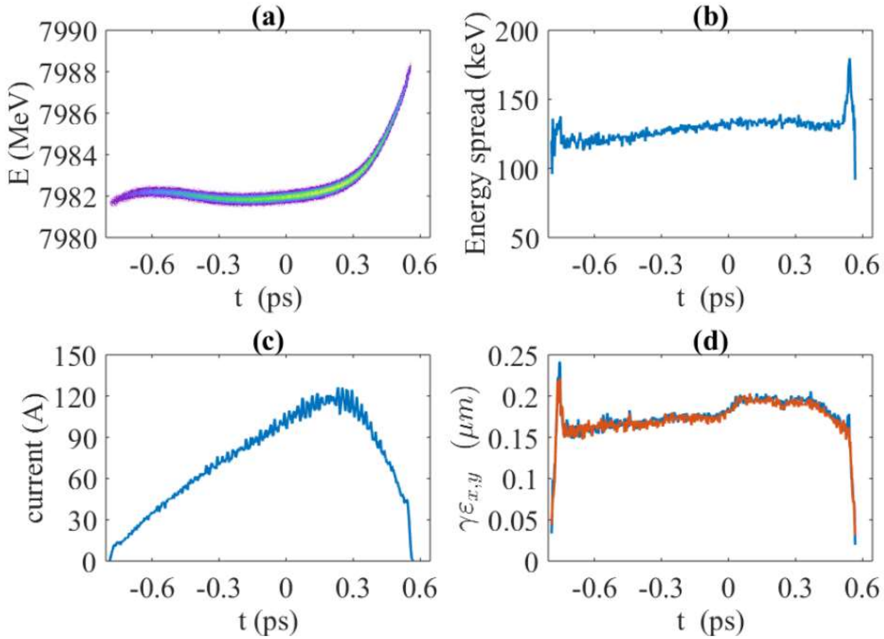
- Diamond crystal BW at hard X-rays ~ 10 meV
  - → For ε=14.4 keV, $\Delta\tau$=200 fs
  - → Electron bunch length should be at least 200 fs
- If $\Delta\tau$ =600 fs → $\Delta\varepsilon$ ~ 3 meV; $\Delta\varepsilon/\varepsilon$ ~ 2×10^{-7}
  - → Need electron beam with flat energy profile
    Flatness of current is less important
- Similar requirement in transverse plane→ normalized emittance ~ 0.25 μm

OPTIMIZATION OF INJECTOR-LINAC PARAMETERS



- The electrons' energy profile (as a function of t) should be flat (within incoherent spread)
- Shape the current profile →linear slope in energy versus time→ a de-chirper to remove the slope (K. Bane and G. Stupakov)
- Obtain 600 fs of flat energy portion (W. Qin)

OPTIMIZATION : APEX-II & LCLS-II-HE (W. QIN)

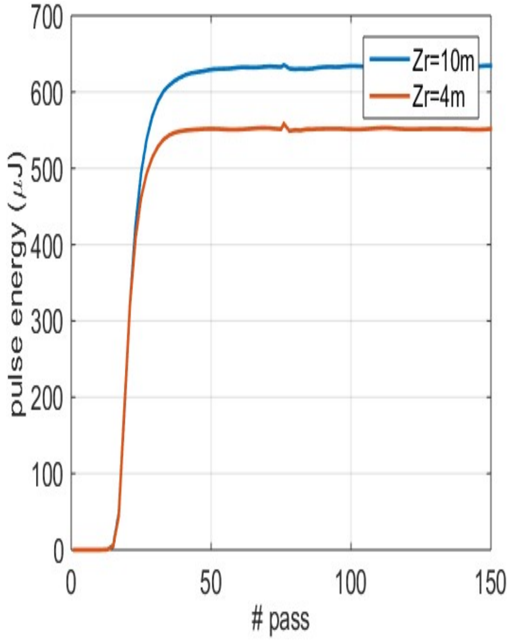


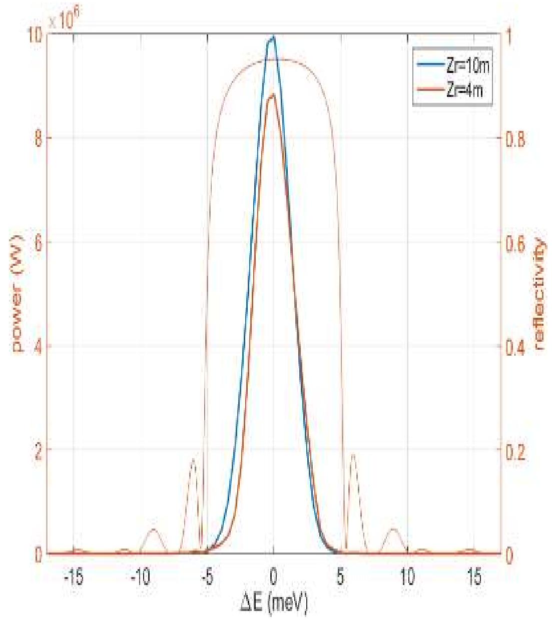
@ undulator entrance

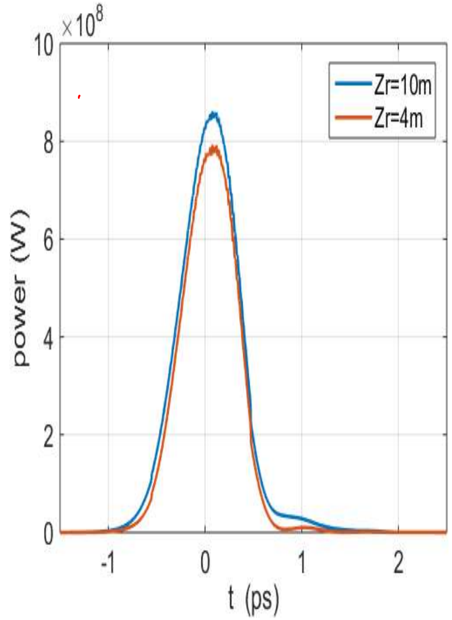
- **Over 600 fs flat part, 120 A peak current**
- **Low slice emittance and slice energy spread**
- **Projected energy spread 0.02%**

XFELO MODELING

- The first GENESIS run took > 1 month
- Faster with GINGER (add x-ray propagation and crystal reflection)
- Transverse-temporal coupling is not included yet.







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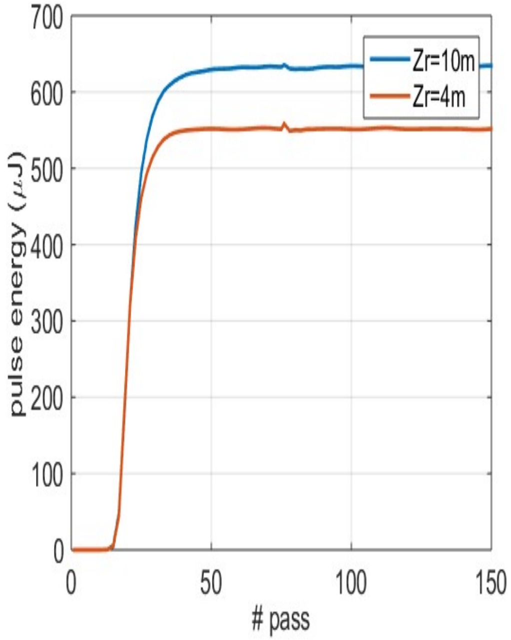

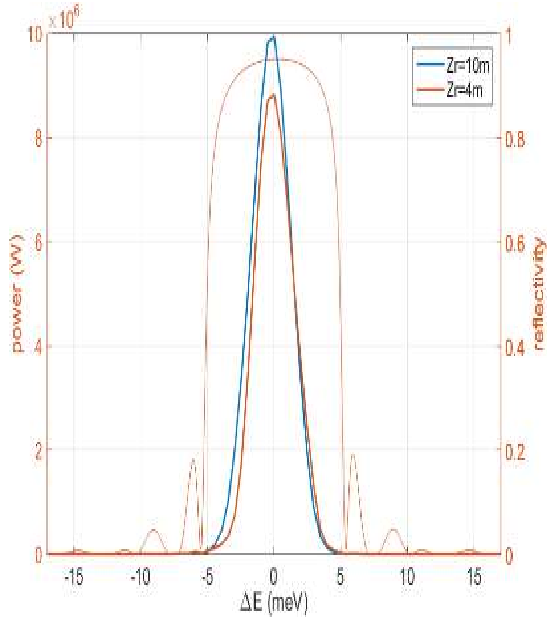

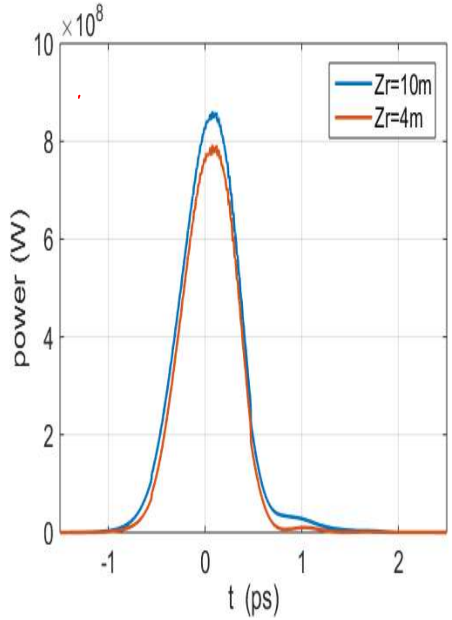

- **For 14.4 keV λ_U=2 cm, *K*=1.49 → SC NbTi : *K*max=3.1→ 5.2 keV**

TGU-ENABLED, USR-BASED XFELO (PEP-X)

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Parameter	Description	Value
$\mathcal{C}_{\text{ring}}$	circumference	2234.21 m
$\gamma_0 mc^2$	beam energy	6.0 GeV
$\varepsilon_{x,y}$	x,y emittances	5.2, 5.2 pm-rad
σ_η	energy spread	1.39×10^{-3}
σ_z	bunch length	0.60 mm
$\tau_{x,y,z}$	damping times	13, 15, 9 ms

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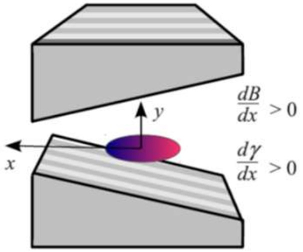

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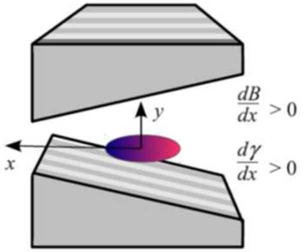

T. Smith, et al.

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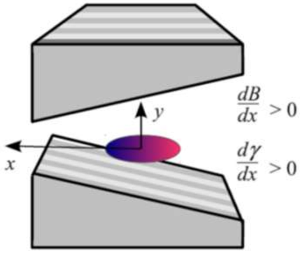

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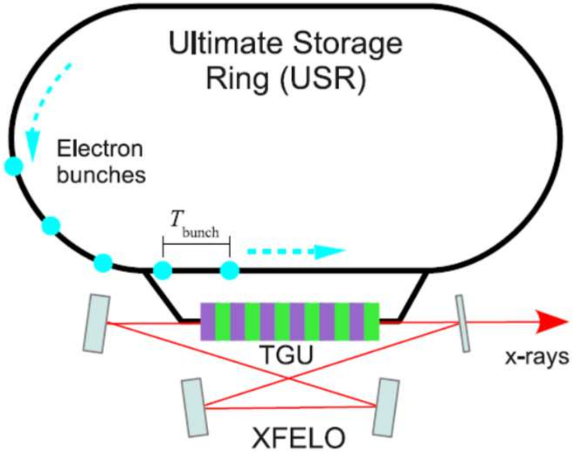

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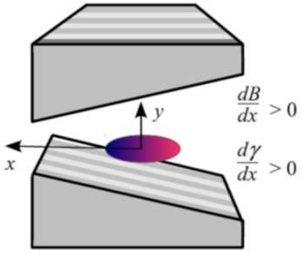

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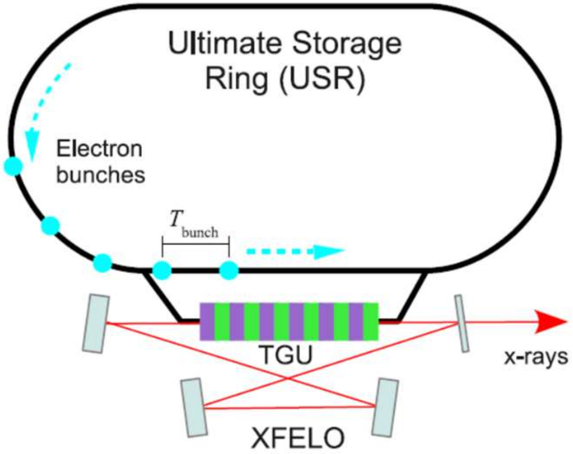

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- Fill 1117 buckets (every 10th bucket, 6.4 ns spaced)
- Every 93rd bunch kicked into FEL (0.65 μs)
- All bunches are used after 0.69 ms
- Cool for 3 damping time (45 ms) → ~ 1% duty factor
- ~10^9 photons/pulse, but BW 0.7 meV !!

→B_{ave} ~ 10^{26}

- We are looking into the PETRA IV case

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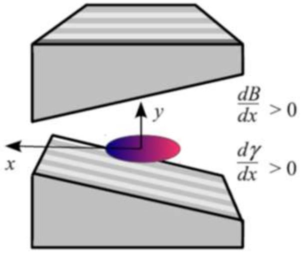

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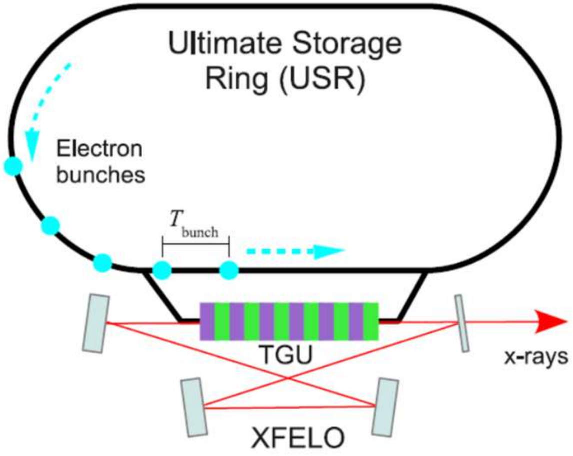

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e-Beam		Undulator	
I	20 A	N_u	2500
σ_z/c	2 ps	λ_u	1.63 cm
$\gamma_0 mc^2$	6 GeV	L_u	40.75 m
σ_η	0.14 %	K_0	1.0
$\varepsilon_x = \varepsilon_y$	5.2 pm	α	34 /m
D	8.8 cm	ave gap	7 mm
β_y^*	7.3 m		

Radiation		FEL output	
λ_1	0.886 Å	$P\,(G=0.2)$	19 MW
Z_{R_x}	105 m	Est. $\Delta\omega/\omega_1$	$< 10^{-7}$
Z_{R_y}	7.3 m	Est. P_{out}	~ 1 MW
linear G	0.44	Est. N_{ph} out	$\sim 10^9$

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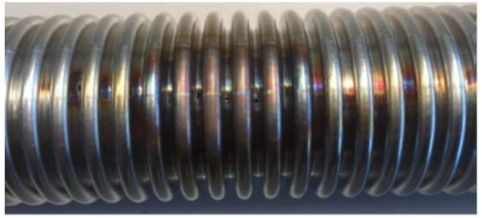
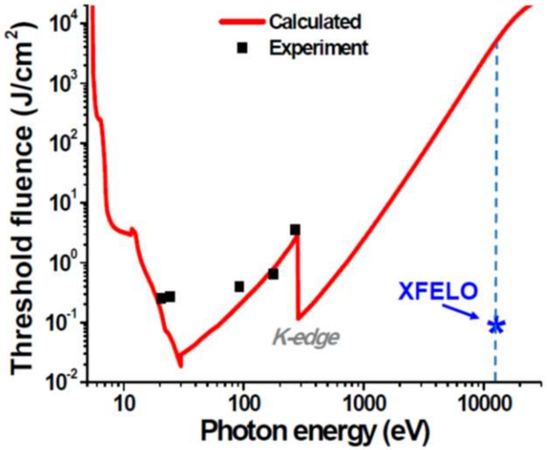
DIAMOND CRYSTAL FOR XFELO MIRROR

- With the zig-zag configuration, diamond can cover all wavelengths
- High-reflectivity (>99%) with synthetic diamond demonstrated (Y. Shvyd'ko, et al.)
- High diffusivity and small expansion coefficient at <100 K
  - Uneven heating of the surface does not lead to XFELO degradation
- Stability in the crystal orientation
  - Null-position FB at APS demonstrated 15 nrad stability at ~ 1 Hz BW
    - Need to improve < 10 nrad and 1 kHz BW

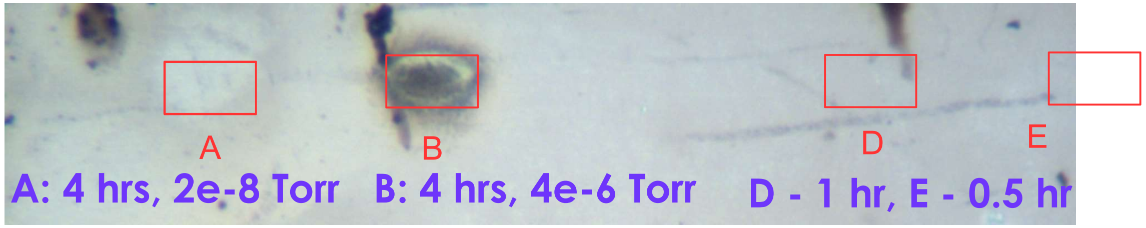
APS TEST FOR DIAMOND ENDURANCE AT X-RAY POWER DENSITY 10-20 KW/MM^2

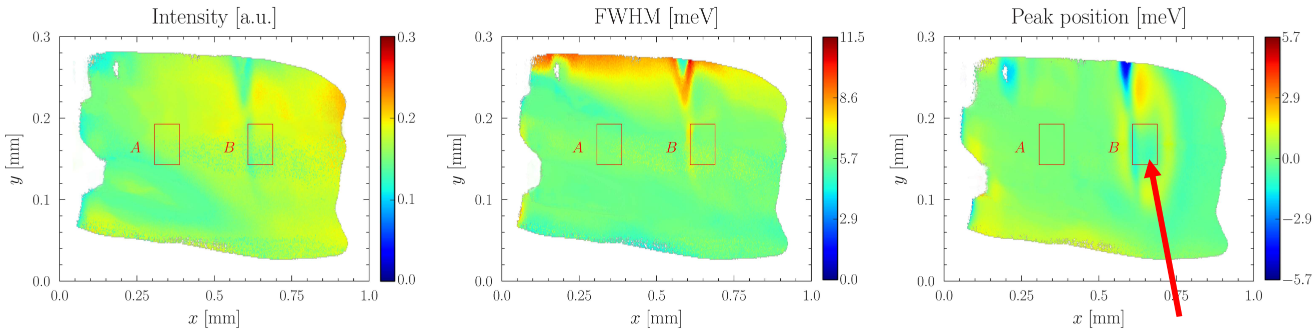


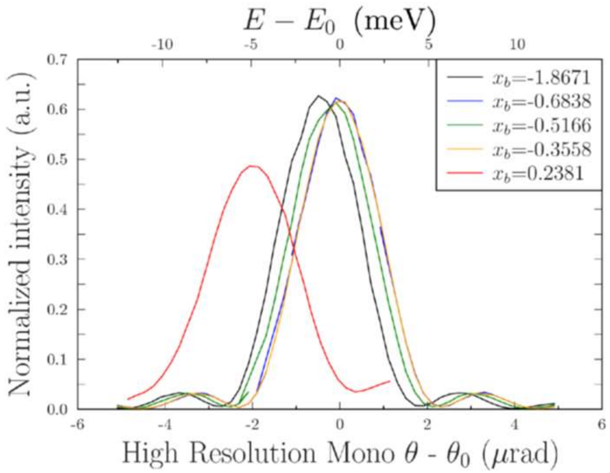
- Steel will melt in < mili-seconds
- But far below theoretical estimates of damage fluence (N. Medvedev)
- Irradiation up to 4 hours at APS
  – **9 kW/mm^2** in 30x120 μm^2 spots (K-B mirror focusing) under medium vacuum
  – **12.5 kW/mm^2** in 30x40 μm^2 spots (Be-CRL focusing) under UHV (~10^{-8})
- High-resolution (meV) topography
- T. Kolodziej, et al (submitted for pub)



- **UHV (10-8 Torr): No structural damage & no reflectivity change**
- **10-6 Torr: Carbon deposits and shift of Bragg peak by ~ 1 meV**







δE/E=δd/d=1.6meV/24 keV

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

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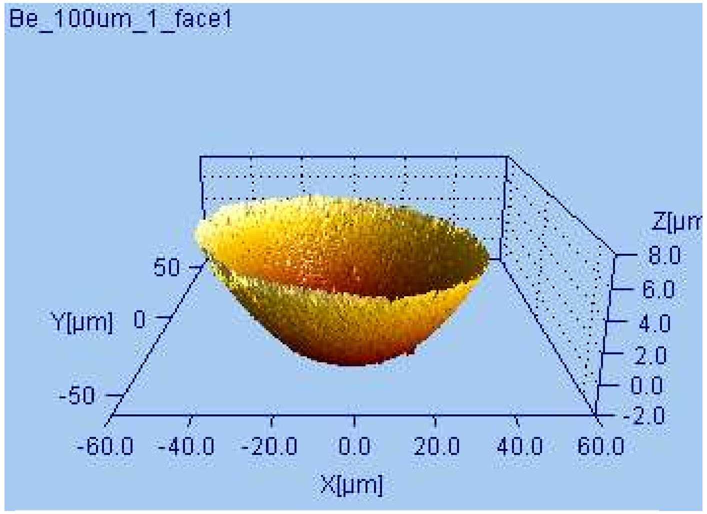
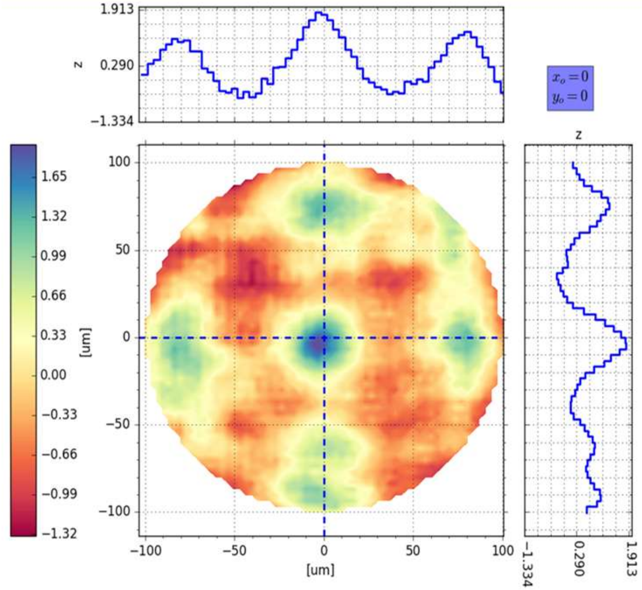
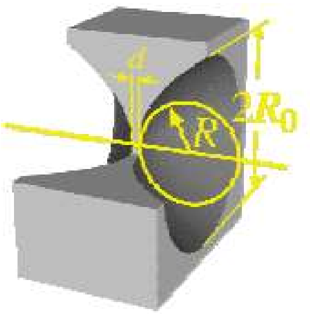
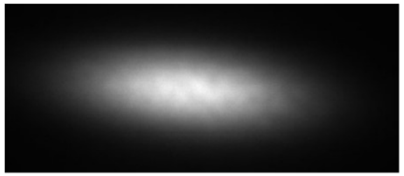
BERYLLIUM CRL AS A COMPACT, LOW-LOSS FOCUSING ELEMENT

- CRL normally used with many-lens set for tight focusing→ high loss
- For XFELO, f ~ 50 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/mm^2)









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CONCLUSIONS

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- An XFELO is feasible from beam dynamics and X-ray optics
- Several projects for construction of ~8 GeV SCRF linac exist
  - LCLS-II-HE, SCLF, EuroXFEL,..
- Linac-based XFELO with an optimized injector will producing fully coherent x-rays with $\mathcal{B}_{av}$ ~ 10^{28}
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CONCLUSIONS

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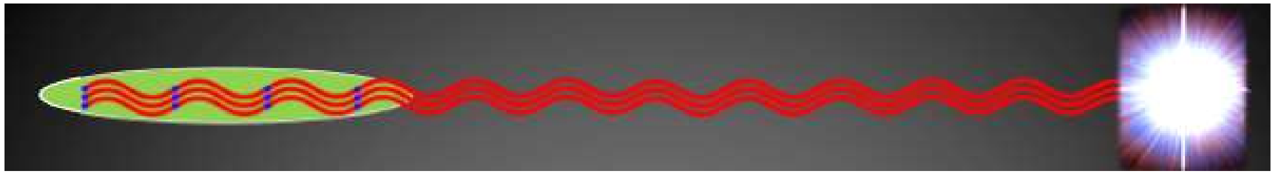

孔子西遊於衛
顏淵問師金
以夫子之行為奚如？
師金曰
惜乎，而夫子其窮哉！

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