PROSPECTS OF AN X-RAY FEL OSCILLATOR

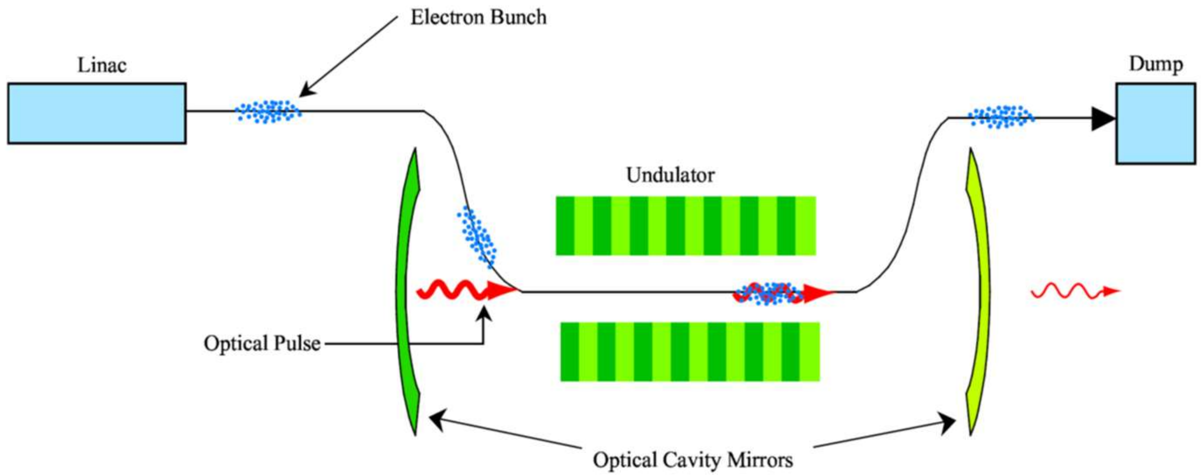
WITH SCRF LINAC OR USR

KWANG-JE KIM

ANL and U. Chicago

March 19, 2018
DESY, Hamburg

FEL OSCILLATOR PRINCIPLE



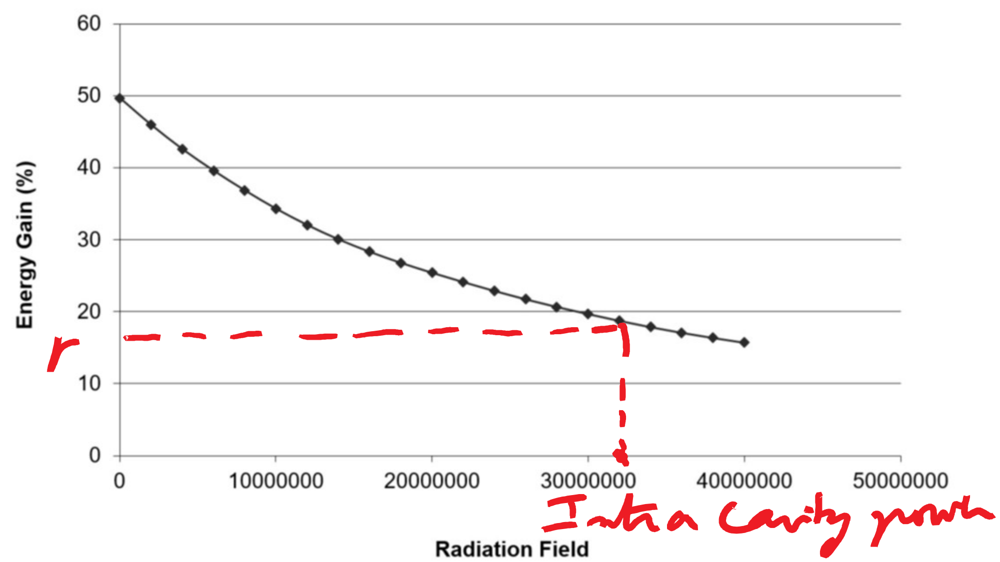
$$P_1 = P_s\,,$$

$$P_n = R_A R_B (1+G) P_{n-1} + P_s \quad \text{for } n > 1$$

$$P_n = \left(\frac{G_T^n - 1}{G_T - 1}\right) P_s\,,\; G_T = R(1+G)$$

~(1−r+g)

- Exponential growth if $G_T > 1$
- Gain drops as the cavity power increases
- Saturation when gain=loss, G_T=1



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No. 118
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No. 4

Free Electron Generation of Extreme Ultraviolet Coherent Radiation

(Brookhaven/OSA, 1983)

Edited by
J. M. J. Madey and C. Pellegrini

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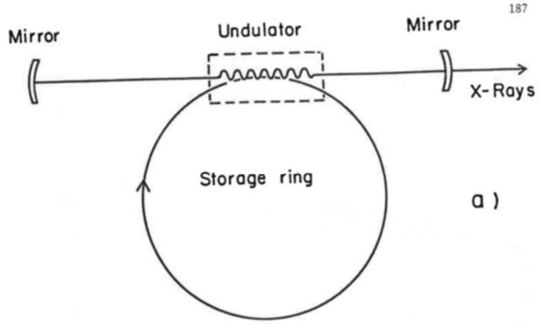
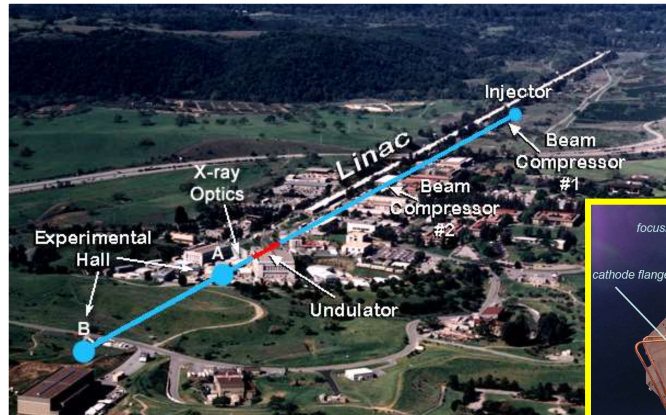
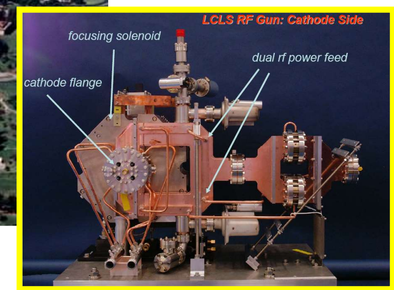


In conclusion, we have demonstrated the feasibility of a free electron laser in the x-ray region, provided that suitable machine parameters can be realized. A realistic machine useable for this project is not probably in existence at the present time, but it is not inconceivable that such a machine may be built in the near future.





Nuclear Instruments and Methods in Physics Research A318 (1992) 489–494
North-Holland

& METHODS IN PHYSICS RESEARCH
Section A

FEL gain taking into account diffraction and electron beam emittance; generalized Madey's theorem *

Kwang-Je Kim
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

PRL 100, 244802 (2008) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2008

the 1-D
rmula is

A Proposal for an X-Ray Free-Electron Laser Oscillator with an Energy-Recovery Linac

Kwang-Je Kim,[1] Yuri Shvyd'ko,[1] and Sven Reiche[2]

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SMALL SIGNAL GAIN FORMULA

- Start from 3 D Maxwell-Klimontovich equations originally developed for high-gain analysis
- Analytic solution for low gain can be solved in perturbation expansion
- For Gaussian and cylindrically symmetric electron and EM mode shapes, and neglecting focusing:

$$G = \frac{j_{C,h}}{2} \frac{\sigma_x^2}{\Sigma_x^2} \int_{-1/2}^{1/2} ds \int_{-1/2}^{1/2} dz\, e^{-2[2\pi h N_u (z-s)\sigma_\eta]^2} \times \frac{(z-s)\{\sin[2x_0(z-s)] - i\cos[2x_0(z-s)]\}}{1 + zs\frac{L_u^2 \Sigma_\phi^2}{\Sigma_x^2} - i(z-s)\left[kL_u\Sigma_\phi^2 + \frac{L_u}{4k\Sigma_x^2}\right]}.$$

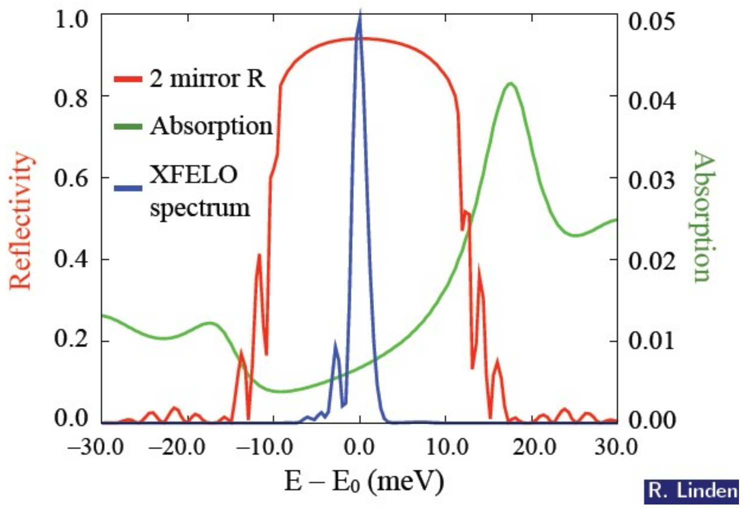
$$\Sigma_x^2 \equiv \sigma_x^2 + \sigma_r^2$$

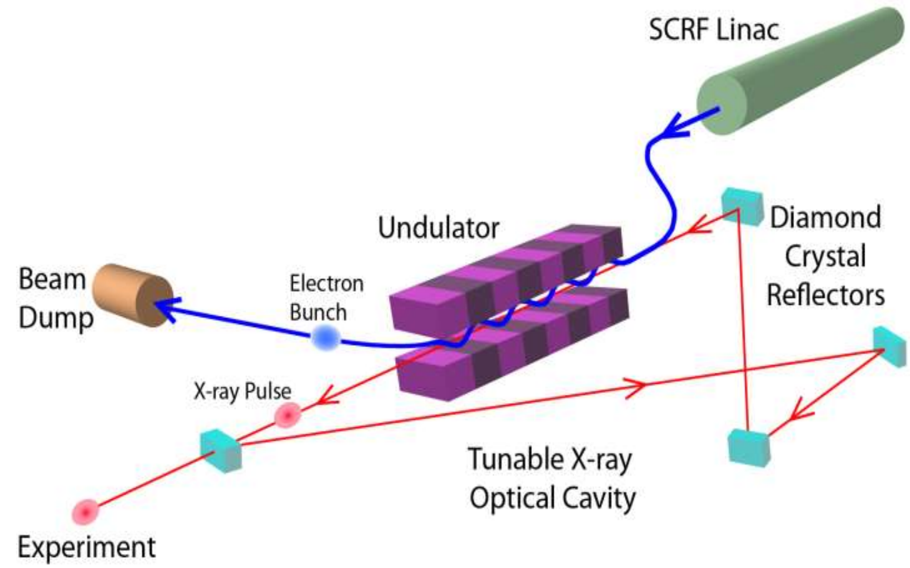
$$\Sigma_\phi^2 \equiv \sigma_p^2 + \sigma_\phi^2$$

$$j_{C,h} = 2h(4\pi\rho N_u)^3 \frac{[\mathrm{JJ}]_h^2}{[\mathrm{JJ}]^2}$$

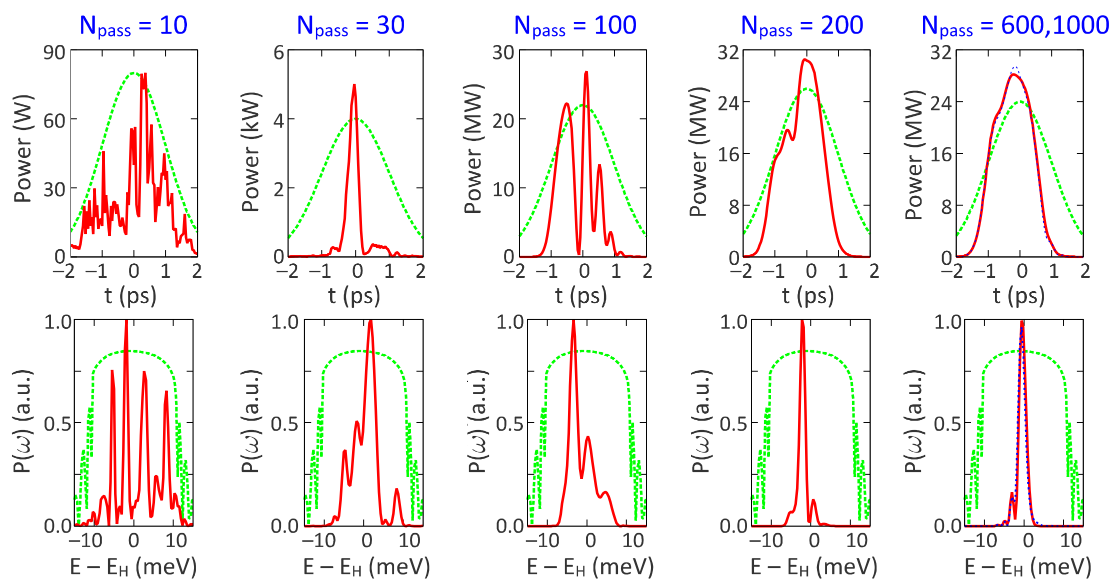
- *The undulator length is limited by the energy spread, thus influencing the gain*
- For pulse evolution, a fast simulation codes are necessary
  - Genesis (took more than one month!)
  - Ginger (much faster)

X-RAY FREE-ELECTRON LASER OSCILLATOR (XFELO)





- Bragg reflectors for hard x-rays
  - R. Collela and A. Luccio (1983)
- Revived in 2008
  - KJK, Y. Shvyd'ko, S. Reiche
- Much progress in
  - Theory/sim: R. Lindberg & W. Fawley
  - X-ray optics exp: S. Stoupin & T. Kolodziej



E-BUNCH FOR ULTRA-FINE BANDWIDTH

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

$$c\Delta\tau \times \frac{\Delta\varepsilon}{\varepsilon} = \frac{\lambda}{2}$$

- **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

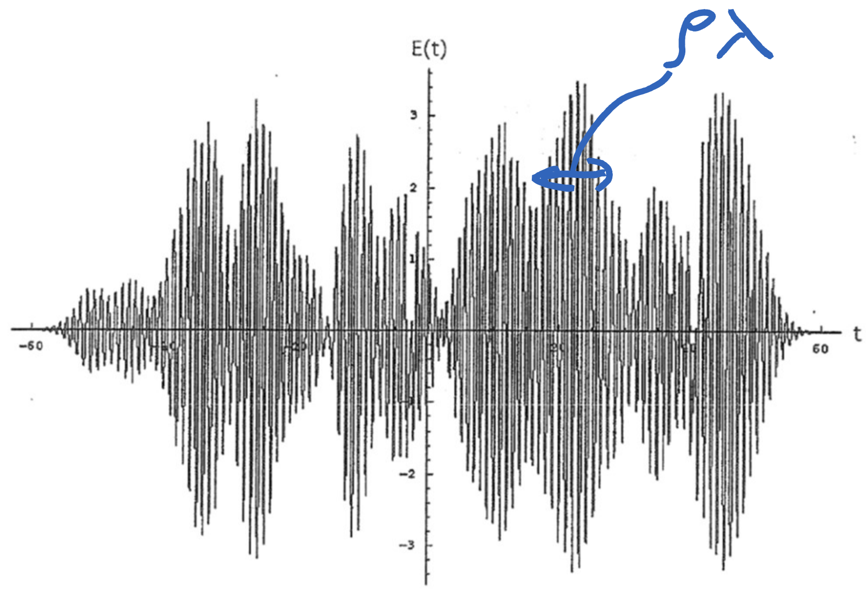
- **If $\Delta\tau$ =600 fs → $\Delta\varepsilon$ ~ 3 meV; $\Delta\varepsilon/\varepsilon$ ~ 2×10^{-7}**

→ Need electron beam with flat energy profile

Flatness of current is less important

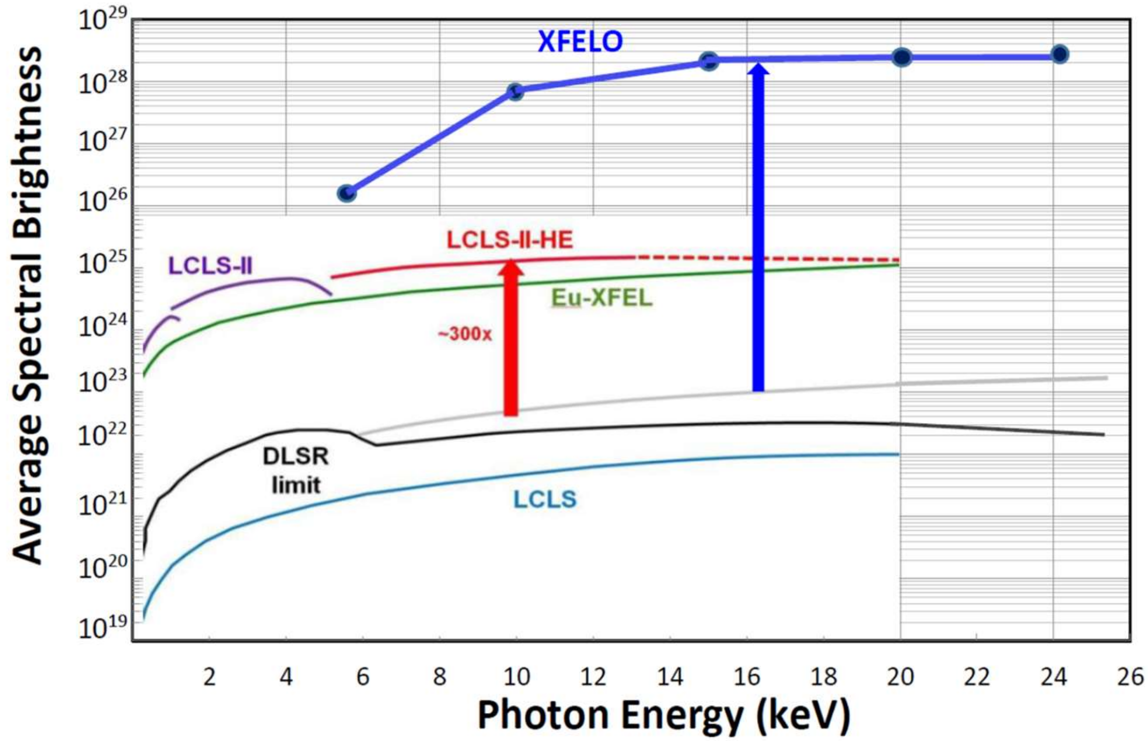
- **Similar requirement in transverse plane→ normalized emittance ~ 0.25 μm**

TEMPORAL-SPECTRAL PROPERTIES OF SASE



- Coherence length ~ $\rho\lambda$
- Bandwidth $\Delta\varepsilon/\varepsilon \sim \rho$
- $\Delta\varepsilon \sim$ 10 eV for hard X-ray (14.4 keV)
- A pulse of length Dt has several coherent spikes
- The temporal phase space $\Delta\tau \times \Delta\varepsilon/\varepsilon$ are two orders of magnitudes larger than XFELO

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

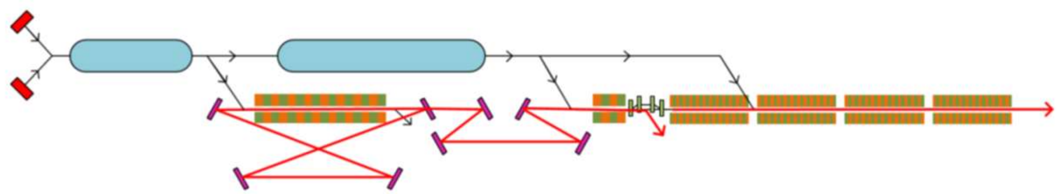


@14.4 keV

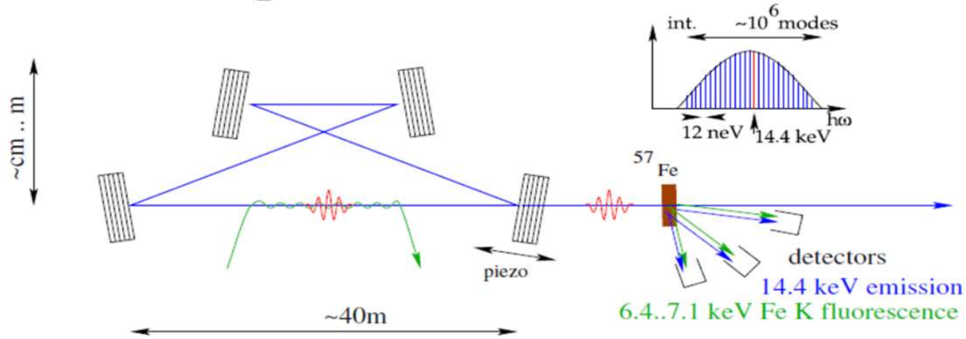
	#/pulse	$\Delta\varepsilon/\varepsilon$	$\Delta\tau$[fs]	B_{ave}	B_{peak}
XFELO	1.2×10^{10}	2.4×10^{-7}	600	2.7×10^{28}	4.0×10^{34}
SASE	5.0×10^{10}	6.0×10^{-4}	30	4.4×10^{25}	1.5×10^{33}

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**

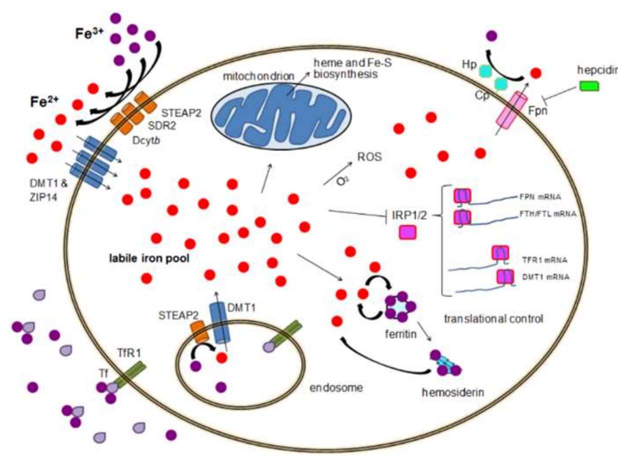


  - Stabilize the roundtrip path length to fraction of wavelength FB referenced to
    - narrow nuclear resonance ^{57}Fe
    - stabilized optical laser (optical comb)
  - ~ 10^6 spectral lines of neV width separated by 12 neV.
  - B. Adams and KJK, PRSTAB (2015)

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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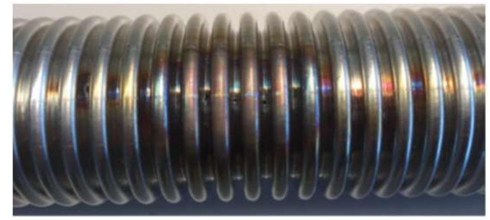
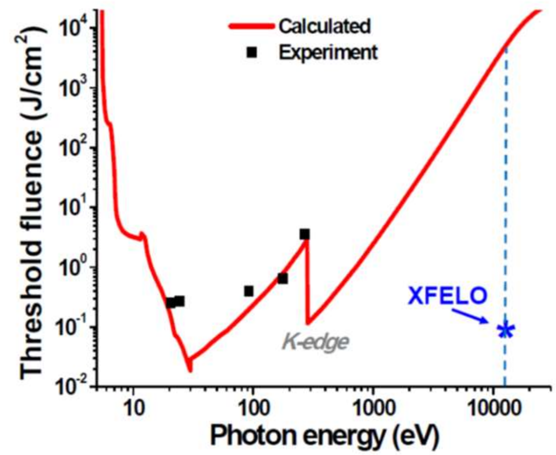
DIAMOND CRYSTAL FOR XFELO MIRROR

- 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)



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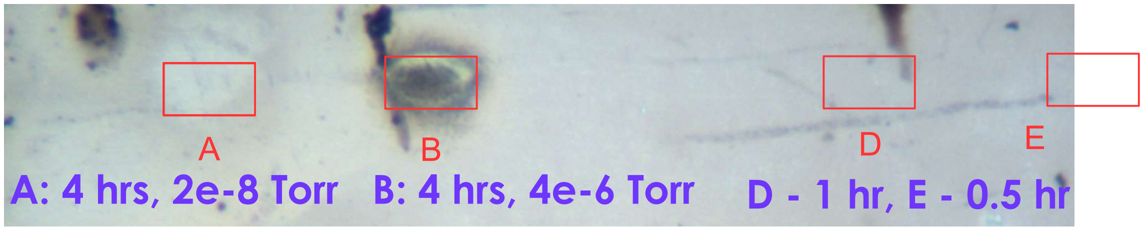
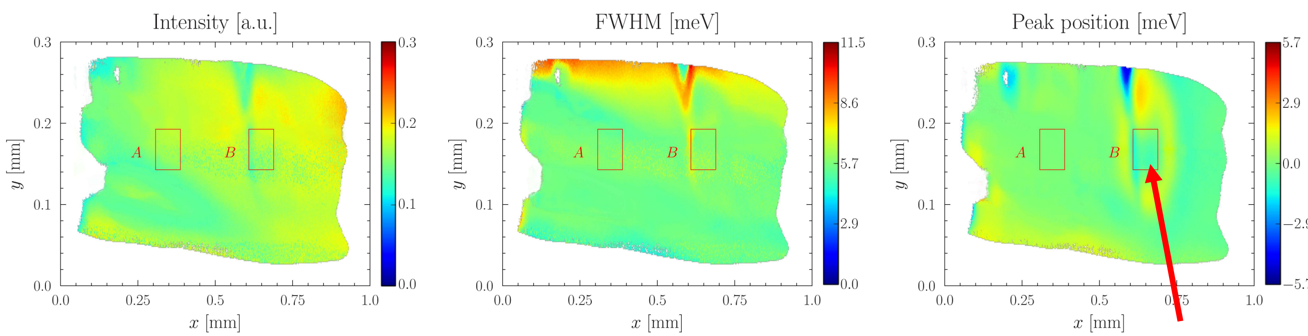
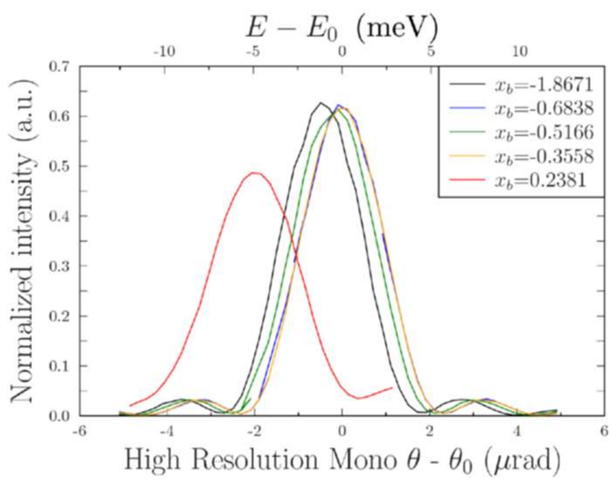
- **UHV (10-8 Torr): No structural damage & no reflectivity change**
- **10-6 Torr: Carbon deposits and shift of Bragg peak by ~ 1 meV**



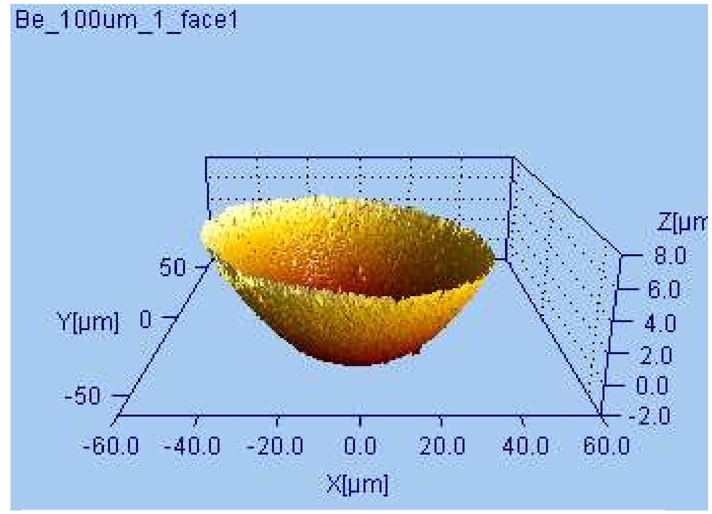


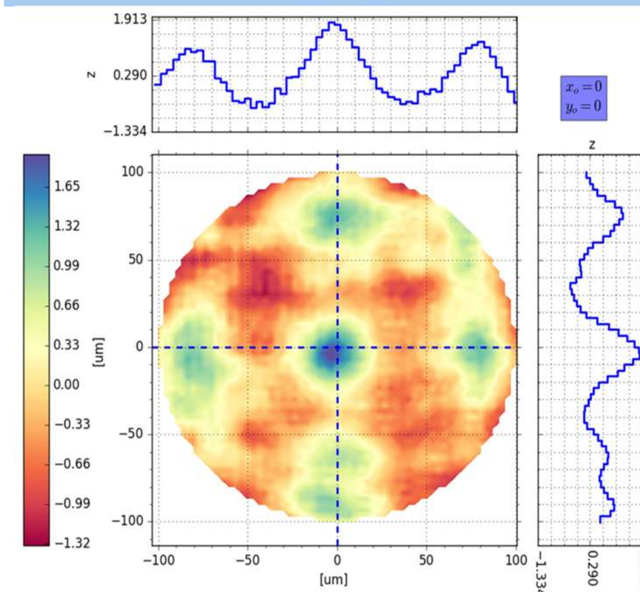


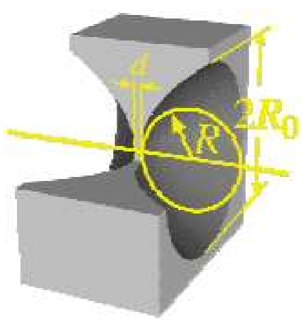
$\delta E/E = \delta d/d = 1.6$ meV/24 keV
Relative d-spacing change =7 10^{-8}

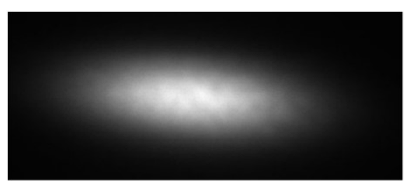
BERYLLIUM CRL AS A COMPACT, LOW-LOSS FOCUSING ELEMENT

- 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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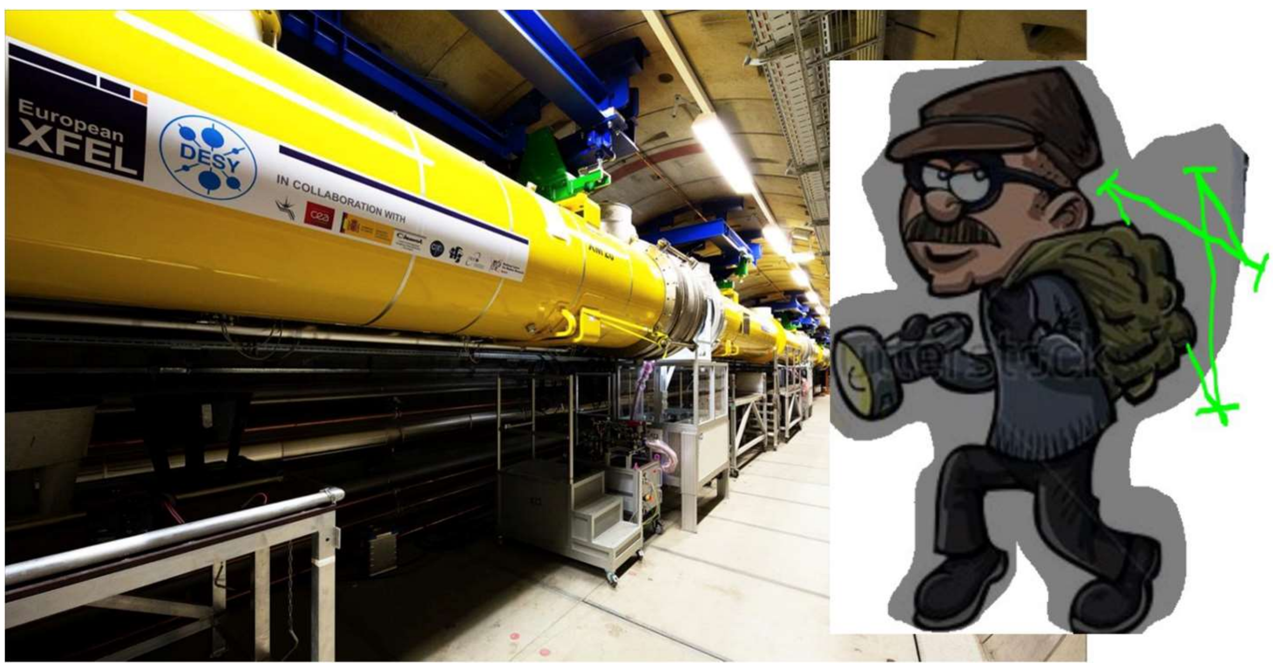
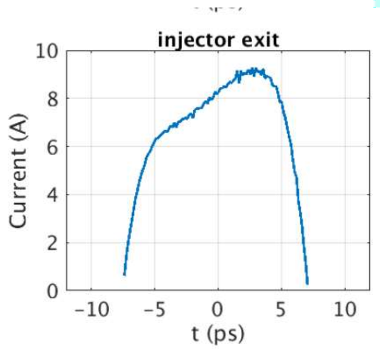
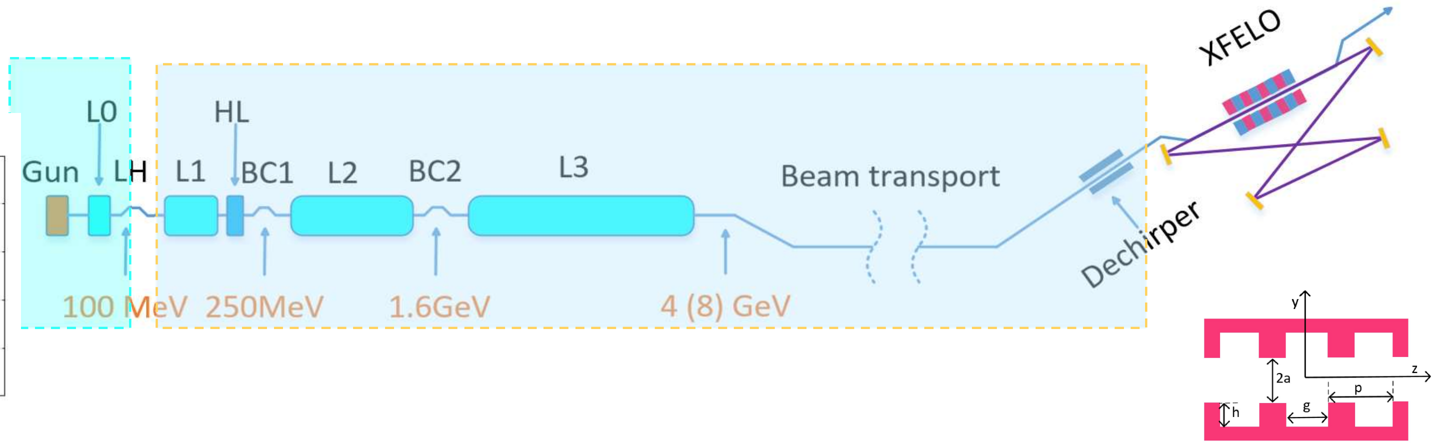
LINAC-BASED XFELO

- Several high-energy CW SCRF linac could be available near future.
  - 8 GeV LCLS-II-HE (Hopefully)
  - 8 GeV SCLF
  - Euro-XFEL (17.5 GeV pulsed, or 7 GeV CW retrofit?)
- These are all for SASE but may have room for an XFELO.



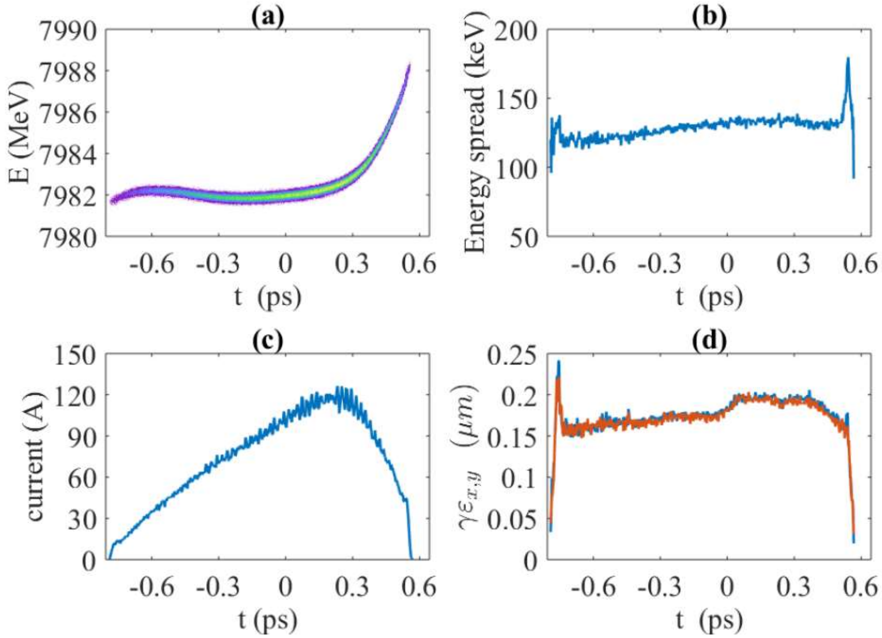
OPTIMIZATION OF INJECTOR-LINAC PARAMETERS





- **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)**

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

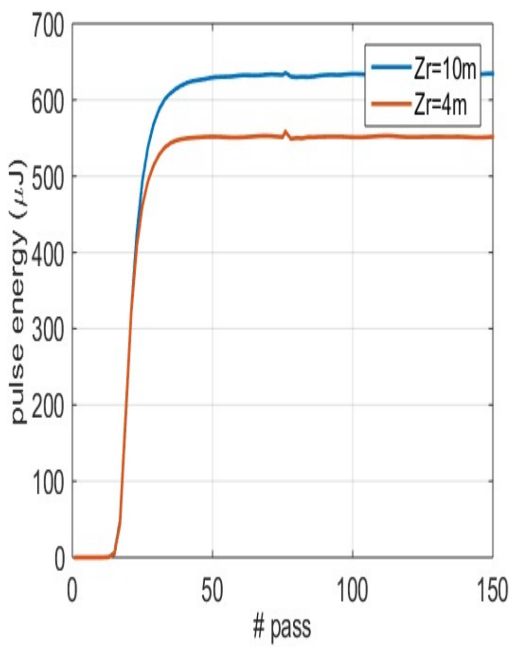


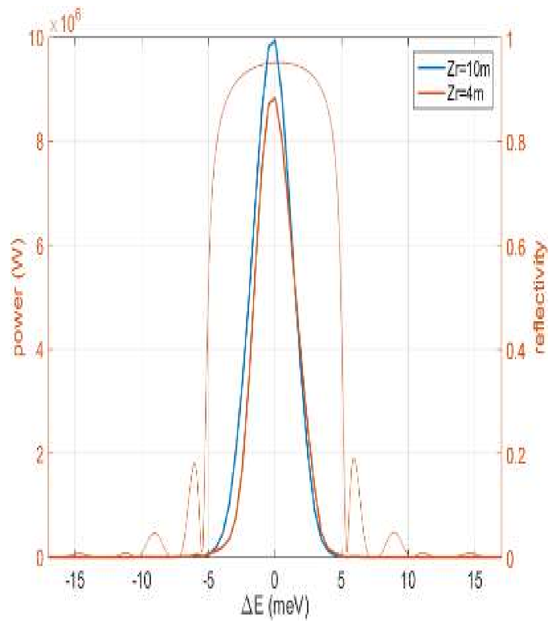
@ undulator entrance

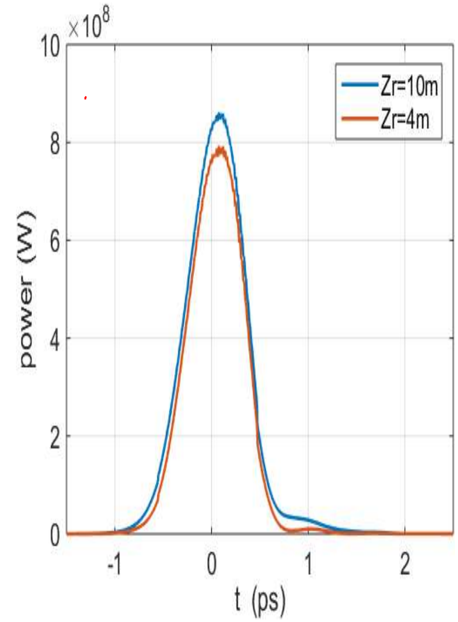
- Over 600 fs flat part, 120 A peak current
  - Low slice emittance and slice energy spread
- Projected energy spread 0.02%

MODELING OF LINAC BASED XFELO

- Electron beam input from linac simulation code
- Use GINGER and add x-ray propagation and crystal reflection
- Transverse-temporal coupling is not included yet.







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

ULTIMATE STORAGE RING BASED XFELO

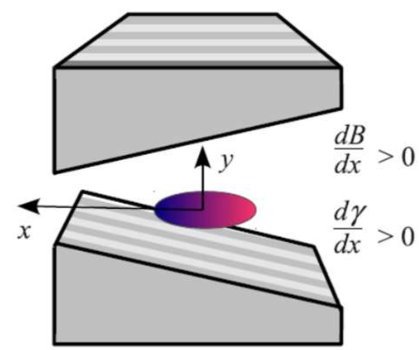
- USR can produce electron beams transversely matched to hard X-ray beams
- However the energy spread is more than one orders of magnitudes
- Todd Smith, et al (1979) proposed to spread the beam transversely by a dispersion and using a transverse gradient undulator so that *K* is a function of energy, which is cancelled by the variation in the γ factor in the resonance condition:

$$\lambda = \lambda_u \frac{1+K^2(x_j)/2}{2\gamma_j^2} \equiv \lambda_u \frac{1+K^2(x_j)/2}{2\gamma_0^2(1+\eta_j)^2} \qquad x_j = D\eta_j + x_{\beta_j}$$

$$\lambda = \lambda_u \frac{1+K^2(D\eta_j + x_{\beta_j})/2}{2\gamma_0^2(1+\eta_j)^2} \approx \lambda_u \frac{1+K_0^2/2}{2\gamma_0^2}\left[1 + \frac{K_0^2\alpha(D\eta_j + x_{\beta_j})}{1+K_0^2/2} - 2\eta_j\right]$$

$$\alpha D = \frac{2+K_0^2}{K_0^2} \qquad \lambda = \lambda_1\left(1 - 2\frac{x_{\beta j}}{D}\right)$$

- Thus $\sigma_\eta \to \dfrac{\sigma_x}{D}$
- TGU XFELO will work only if $D\sigma_\eta >> \sigma_x$



TGU PERFORMANCE

- TGU performance for the case when electrons execute many betatron oscillation inside the undulator (N. Kroll, 1983)
  – In order for TGU reduce the acceptable energy spread by a factor R, the beam emittance should be reduced by the same factor R
  – Not realistic since R ~10
- When the betatron focusing is negligible, then another theory applies (R. Lindberg, et al.,)
  – Similar to asymmetric beam but $\sigma_\eta \to \frac{\sigma_x}{D}$

$$\Sigma_x \equiv \sqrt{\sigma_x^2 + \sigma_{r_x}^2 + D^2\sigma_\eta^2} \quad \Sigma_{\phi_x} \equiv \sqrt{\sigma_{p_x}^2 + \sigma_{\phi_x}^2}$$

$$\Sigma_y \equiv \sqrt{\sigma_y^2 + \sigma_{r_y}^2} \quad \Sigma_{\phi_y} \equiv \sqrt{\sigma_{p_y}^2 + \sigma_{\phi_y}^2}$$

THE GAIN EXPRESSION FOR TGU XFELO WITH ASYMMETRIC ELECTRON AND PHOTON BEAMS (R. LINDBERG, ET AL. FEL 2013)

$$G = -\frac{2\pi^2}{\gamma}\frac{I}{I_A}\frac{K_0^2[\mathrm{JJ}]^2}{1+K_0^2/2}\frac{N_u^3\lambda_1^2}{2\pi\Sigma_x\Sigma_y}\int_{-1/2}^{1/2} dz ds \ \exp\left\{-\frac{2[2\pi N_u(z-s)\sigma_\eta\sigma_x]^2}{\sigma_x^2+D^2\sigma_\eta^2}\right\}$$

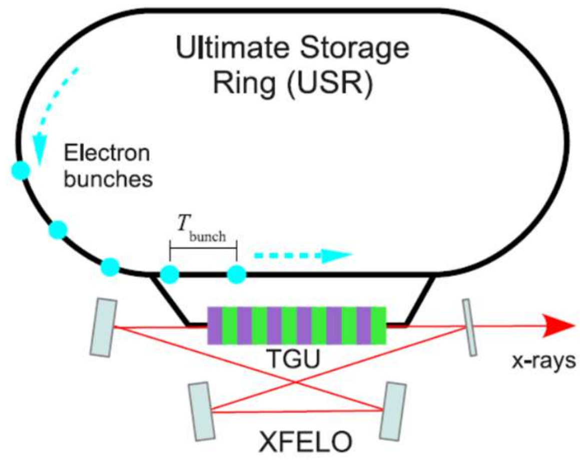
$$\times \frac{(z-s)\exp[2\pi i N_u\Delta\nu(z-s)]}{i\sqrt{\mathcal{D}_x\mathcal{D}_y}} \ \exp\left\{-\frac{[2\pi N_u L_u(z^2-s^2)D\sigma_{px}\sigma_\eta^2]^2}{2(\sigma_x^2+D^2\sigma_\eta^2)^2}\right\}$$

$$\mathcal{D}_{x,y} \equiv 1 + zs\frac{L_u^2\Sigma_{\phi_{x,y}}^2}{\Sigma_{x,y}^2} - i\left[(z-s)k_1 L_u\Sigma_{\phi_{x,y}}^2 + \frac{(z-s)L_u}{4k_1\Sigma_{x,y}^2}\right]$$

$$\Sigma_x \equiv \sqrt{\sigma_x^2+\sigma_{r_x}^2+D^2\sigma_\eta^2} \quad \Sigma_{\phi_x} \equiv \sqrt{\sigma_{p_x}^2+\sigma_{\phi_x}^2}$$

$$\Sigma_y \equiv \sqrt{\sigma_y^2+\sigma_{r_y}^2} \quad \Sigma_{\phi_y} \equiv \sqrt{\sigma_{p_y}^2+\sigma_{\phi_y}^2}$$

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



Parameter	Description	Value
C_{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

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	$\sim 10^9$

- Fill 1117 buckets (every 10th bucket, 6.4 ns spaced),
- TGU gain ~ 40%
- Every 93rd bunch kicked into FEL (0.65 μs)
- All bunches are used after 0.69 ms
- Cool for 3 damping time (3 τ_y=45 ms)
  → ~ 1% duty factor
- ~10^9 photons/pulse, but BW 0.7 meV !!

→B_{ave} ~ 10^{26}

PRELIMINARY BUT CORRECTED BEAM PARAMETERS (M. BORLAND)

- M. Borland: PEP-X lattice with damping wiggler: With1.5 GHz and V=80MV for the rf, lattice , at 4.5 GeV, emittance is 5pm x 5pm at 4.5 GeV. At 6 GeV, the emittance goes to 10pm x 10pm. The zero-current rms bunch length of 0.82 mm becomes 0.97 mm rms at 100 pC/bunch. I=16 A (Haissinski with 0.5 Ohm broad band impedance.)
- Emittance (1, 19) pm→ (1.2, 23) due to IBS, I=16 A.
- (βx, βy) = (50, 7.5) m
- Hybrid undulator with 5 mm gap.
- The gain is 36%--OK.
- Note x-direction is the dispersing direction. The undulator is vertical
- Can we operate PETRA V in a similar parameter regime but with a less extreme RF?

- **The energy profile of the storage ring bunch is Gaussian and independent of z→ much nicer than in linac.**
- **The bunch length is longer→ narrower bandwidth**

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, SCLF, EuroXFEL,..
- Linac-based XFELO with an optimized injector will producing fully coherent x-rays with $\mathcal{B}_{av}$ ~ 10^{28}
- USR-based pulsed XFELO might be feasible with $\mathcal{B}_{av}$ ~10^{26}
- Scientific cases exist for narrow BW, coherent X-rays
  - An XFELO will drive the techniques already developed to a new level of capabilities (IXS, XPCS..)
  - Novel techniques can be developed for novel sciences
    - Quantum optics with nuclear states,..

An XFELO is a real laser!

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!

COLLABORATORS:

- ANL: W. Grizolli, S. Kearney, R. Lindberg, T. Kolodziej , X. Shi, D. Shu, Y. Shvyd'ko
- SLAC: K. Bane, Z. Huang, Y. Ding, P. Emma, W. Fawley, J. Hastings, J. Krzywinski, G. Marcus, T. Maxwell
- Peking U./SLAC (student): W. Qin
- DESY: J. Zemella
- Cornell U.: S. Stoupin
- TISNCM: V. Blank, S. Terentyev
- CAS: N. Medvedev

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