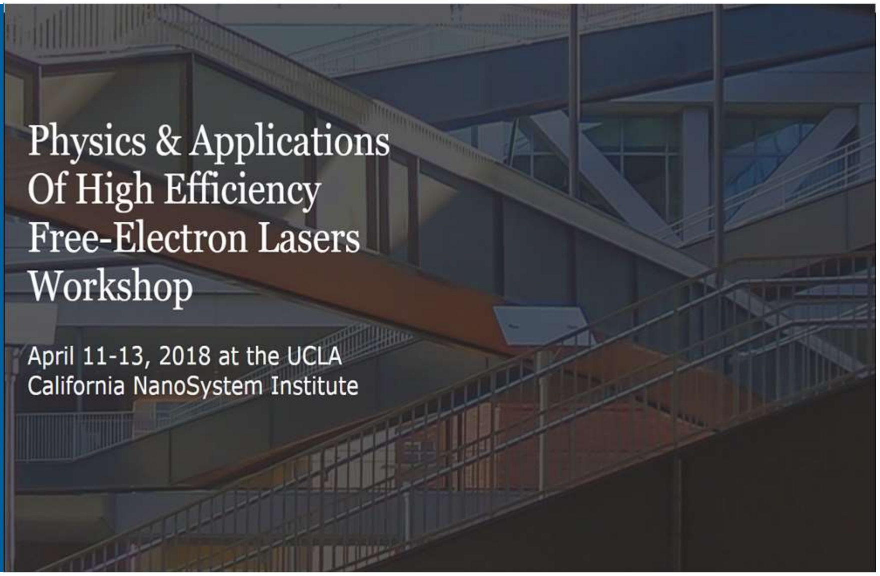
HIGH EFFICIENCY FEL OSCILLATORS


Physics & Applications Of High Efficiency Free-Electron Lasers Workshop

April 11-13, 2018 at the UCLA
California NanoSystem Institute

KWANG-JE KIM

ANL and U. Chicago

April 12, 2018
UCLA

FEL OSCILLATOR PRINCIPLE

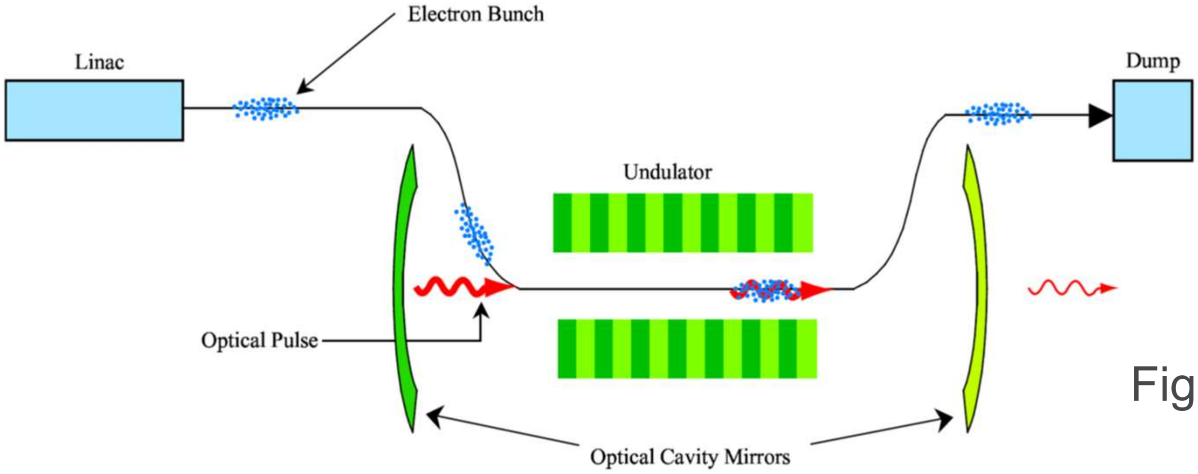


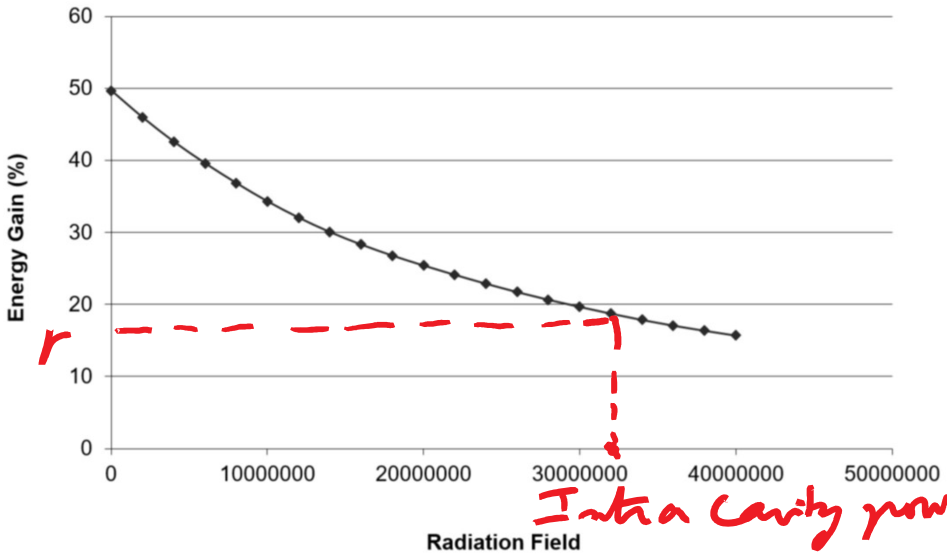
Figure: S. Reiche

$$P_1 = P_s \,,$$

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

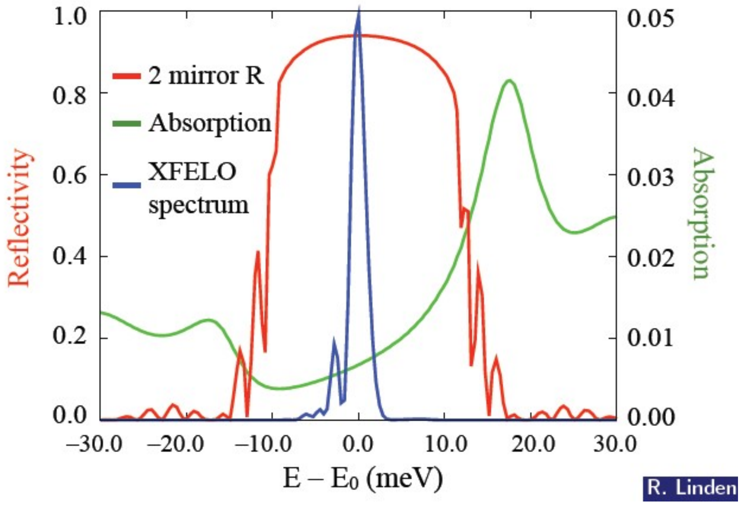
$$P_n = \left(\frac{G_T^n - 1}{G_T - 1} \right) P_s \,, \; G_T = R(1+G) \sim (1 - r + g)$$

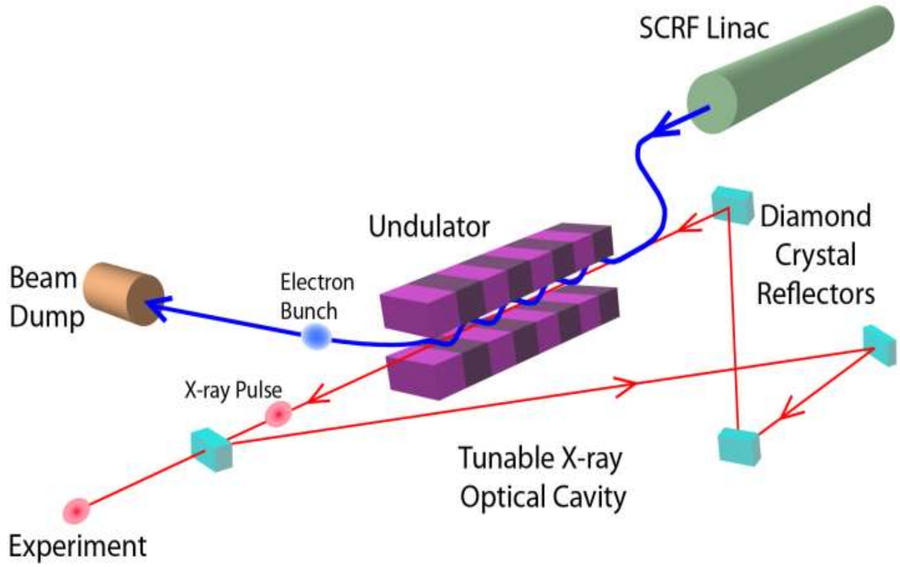
- Exponential growth if $G_T > 1$
- Gain drops as the cavity power increases
- Saturation when gain=loss, G_T=1



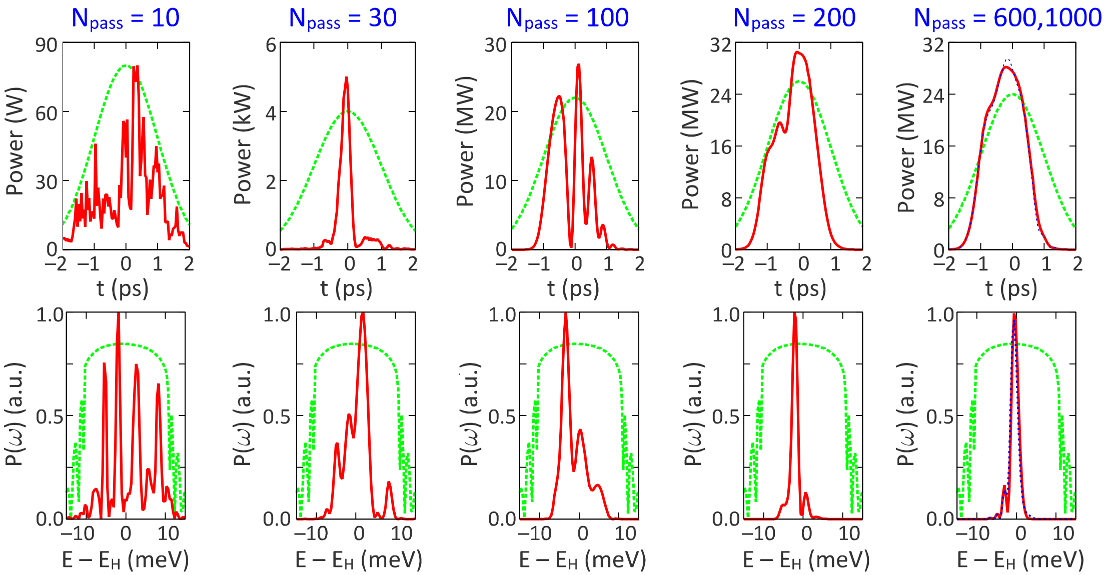
Intra cavity power

X-RAY FREE-ELECTRON LASER OSCILLATOR (XFELO)

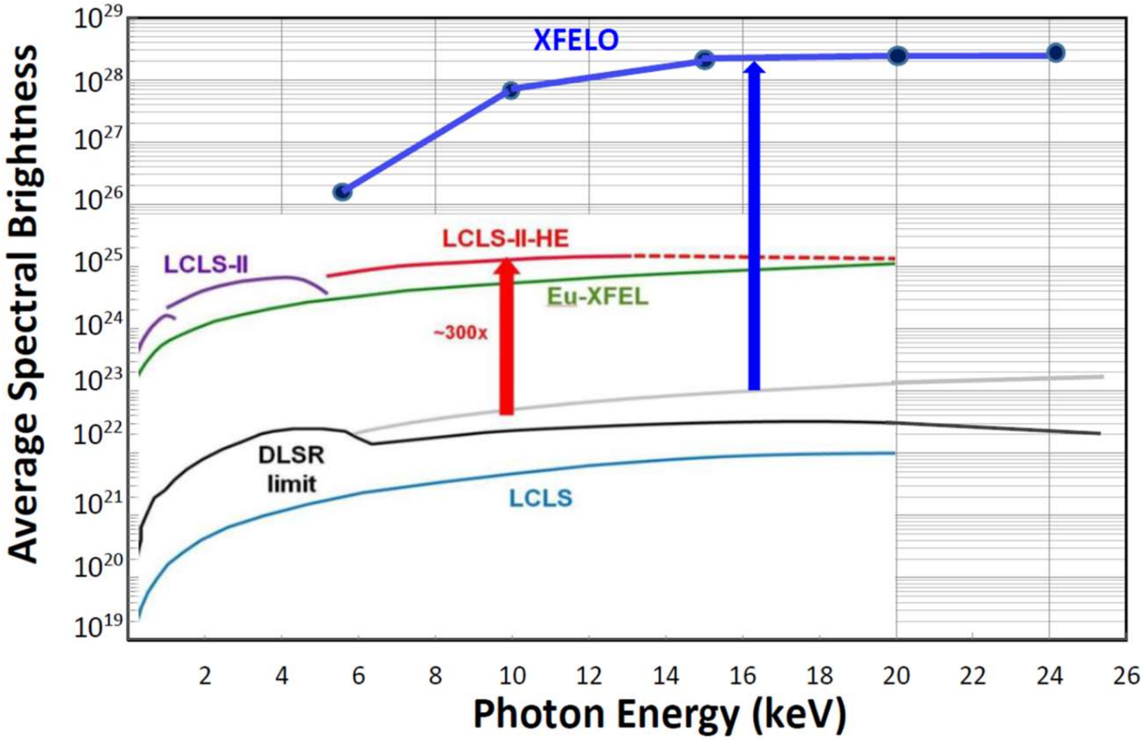




- Bragg reflectors for hard x-rays
  - R. Collela and A. Luccio (1983)
- Revived in 2008
  - KJK, Y. Shvyd’ko, S. Reiche
- Further progresses:
  - Theory/sim: R. Lindberg & W. Fawley, H. Deng,..
  - X-ray optics exp: Y. Shvyd’ko, S. Stoupin & T. Kolodziej…



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

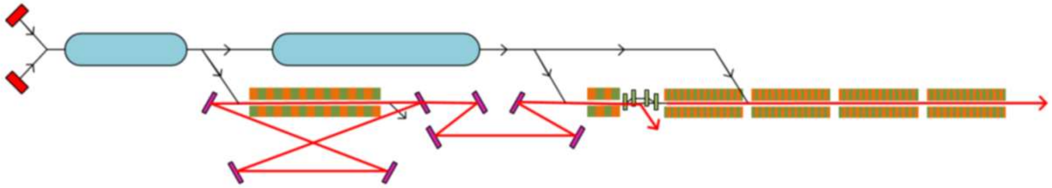


@14.4 keV

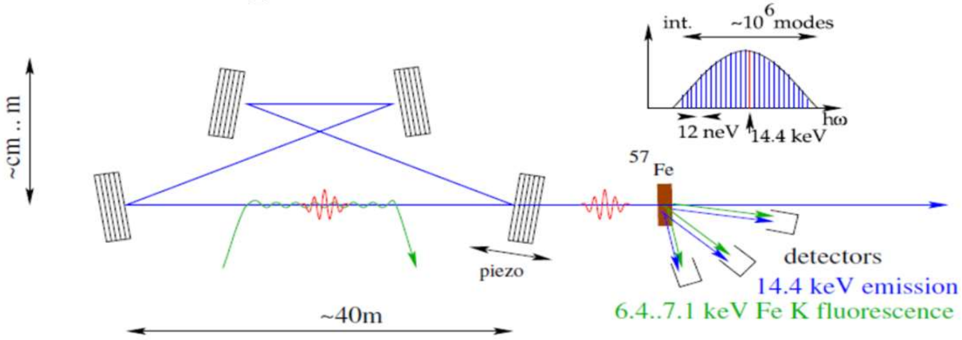
	#/pulse	$\Delta\varepsilon/\varepsilon$	$\Delta\tau$[fs]	B_{ave}	B_{peak}
XFELO	1.2×10^{10}	2.4×10^{-7}	600	2.7×10^{28}	4.0×10^{34}
SASE	5.0×10^{10}	6.0×10^{-4}	30	4.4×10^{25}	1.5×10^{33}

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



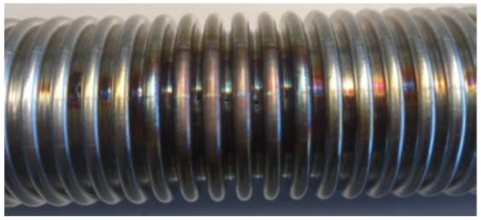
- **X-ray spectral comb generation**

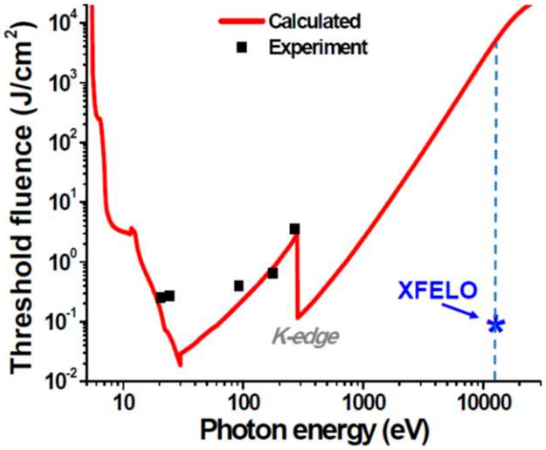


  - Stabilize the roundtrip path length to fraction of wavelength FB referenced to
    - narrow nuclear resonance ^{57}Fe
    - stabilized optical laser (optical comb)
  - ~ 10^6 spectral lines of neV width separated by 12 neV.
  - B. Adams and KJK, PRSTAB (2015)

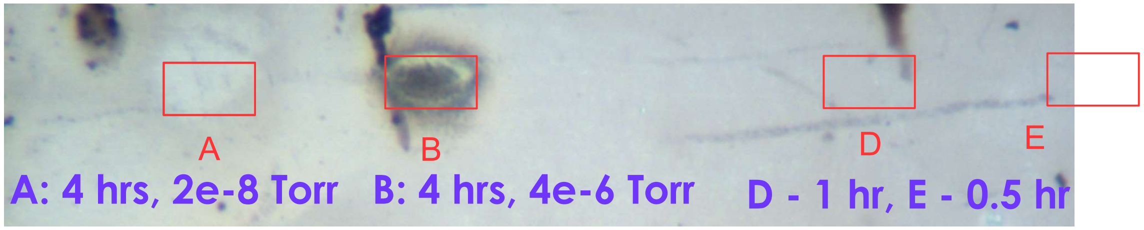
APS TEST FOR DIAMOND ENDURANCE AT 10-20 KW/MM^2 EXPECTED AT X-RAY CAVITY CRYSTALS

- Steel will melt in < milli-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

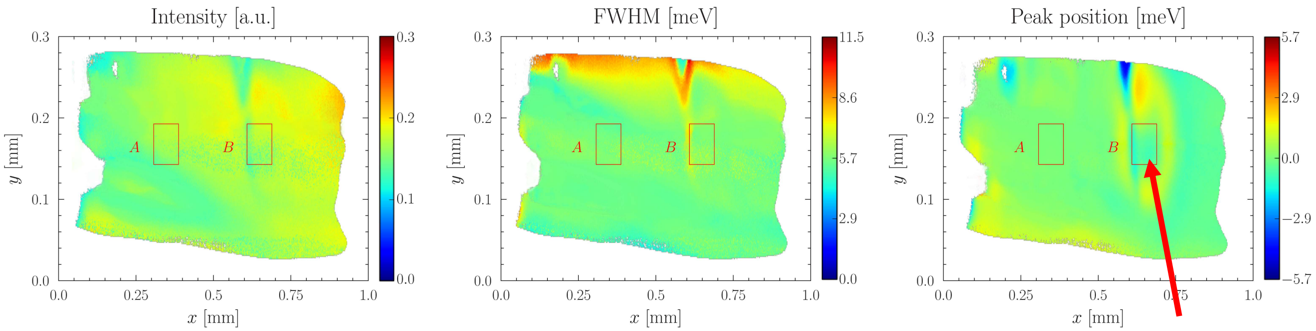


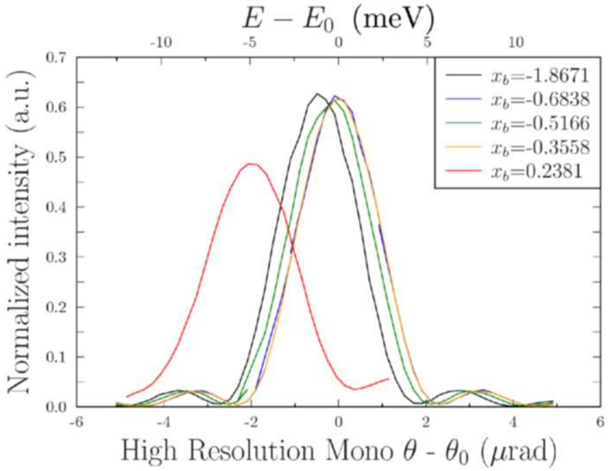


- **UHV (10-8 Torr): No structural damage & no reflectivity change**
- **10-6 Torr: Carbon deposits and shift of Bragg peak by ~ 1 meV**



A: 4 hrs, 2e-8 Torr B: 4 hrs, 4e-6 Torr D - 1 hr, E - 0.5 hr





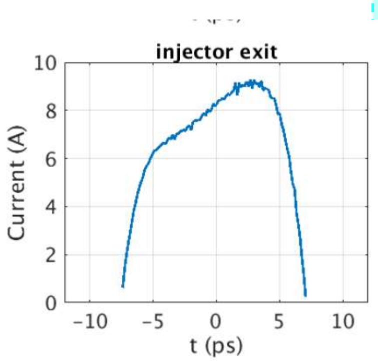
$\delta E/E = \delta d/d = 1.6\text{meV}/24\text{ keV}$

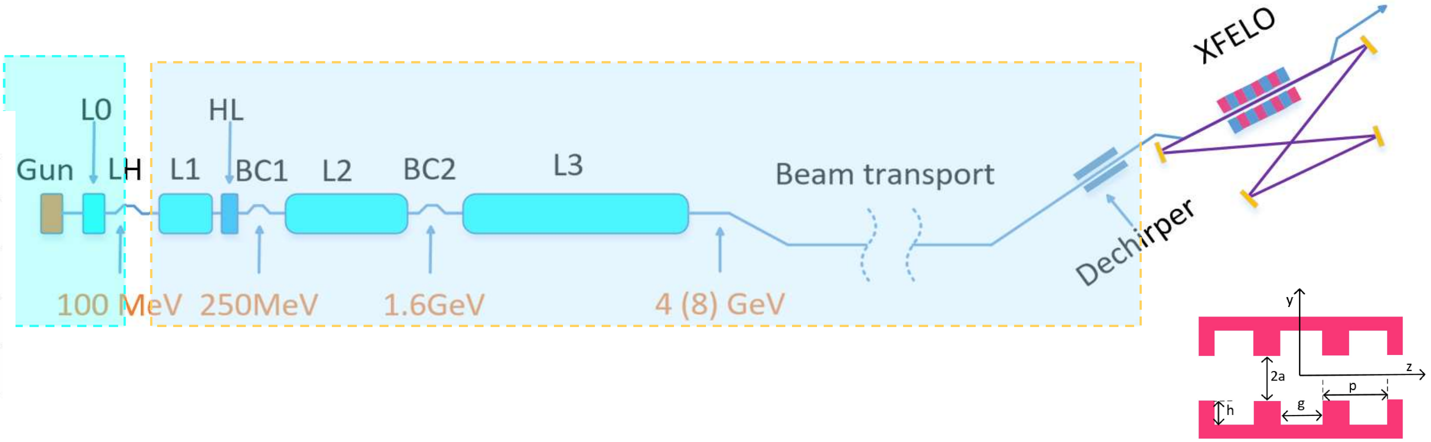
Relative d-spacing change =7 10^{-8}

LINAC-BASED XFELO

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

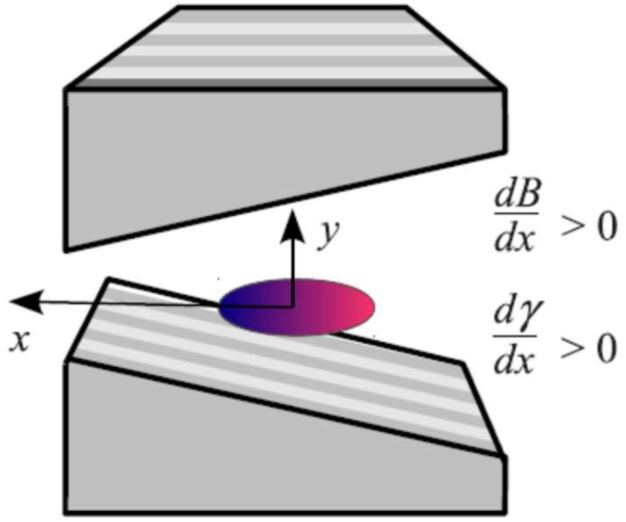
OPTIMIZATION OF INJECTOR-LINAC PARAMETERS





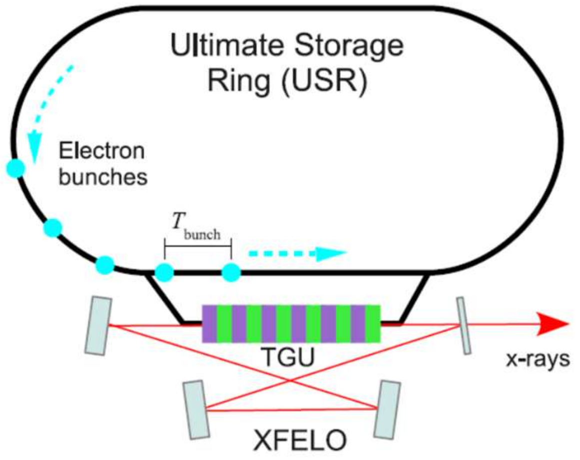
- **The electrons' energy profile (as a function of t) should be flat (within incoherent spread)**
- **Shape the current profile →linear slope in energy versus time→ a de-chirper to remove the slope (K. Bane and G. Stupakov)**
- **Obtain 600 fs of flat energy portion (W. Qin)**

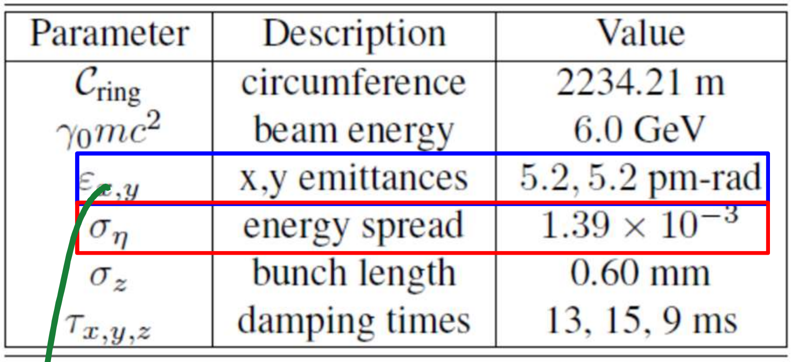
ULTIMATE STORAGE RING BASED XFELO



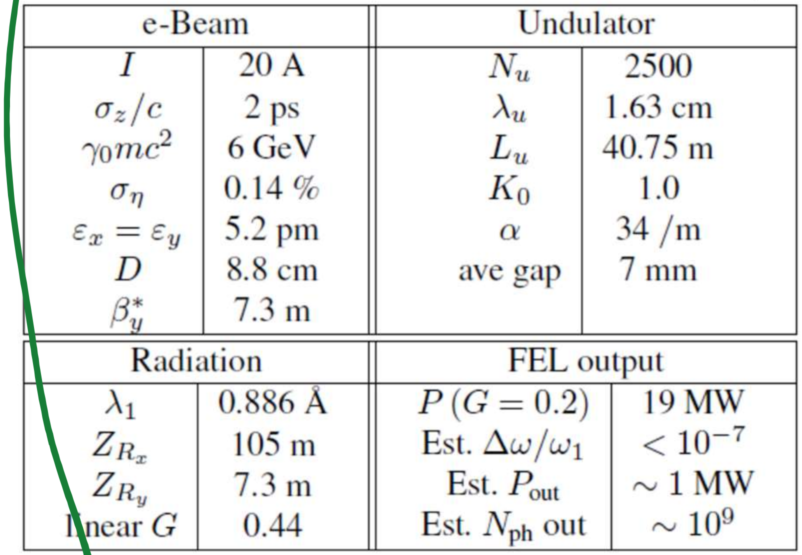
- Electron bunches in USR (large MBA) satisfy transverse emittance condition but spread is too large
- In a transverse gradient undulator (TGU), the x-variation of *K* can be chosen to balance the x-variation in γ from the upstream dispersion to cancel the x-variation of the resonance condition (Todd Smith, et al (1979))
- The performance of a TGU-based XFELO is promising if $D\sigma_\eta >> \sigma_x$ (R. Lindberg, ZRH,KJK, 2013)
- **The energy profile of the storage ring bunch is Gaussian and independent of z→ nicer than in linac.**
- **The bunch length is longer→ larger flux with narrower bandwidth**

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	$\sim 10^9$

(20, 1) pm

- Fill 1117 buckets (every 10th bucket, 6.4 ns spaced), every 93rd bunch kicked into FEL
- TGU gain ~ 40%
- 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 in 0.7 meV→ B_{ave} ~ 10^{26}
- **PETRA-4: 5□more charge in 5□longer bunch.**

XFELO SCIENCES

- **Enhanced application of techniques developed at 3rd gen storage ring (3GSR) sources**
  - IXS (inelastic x-ray scattering), XPCS (X-ray photon correlation spectroscopy), NRS (nuclear resonance scattering),..
  - Smaller samples, faster data collection, higher resolution..
- **Techniques in infancy at current sources (XFEL and 3GSR)**
  - X-ray NLO (non-linear optics)
  - Medical, biological, and industrial applications of application of Mössbauer spectroscopy (e.g., study of red cells without enriching the excited states of Fe, currently takes one week, a few minutes with XFELO)
- **Potential new areas**
  - X-ray coherence control
  - Nuclear quantum optics (analogous to revolution in atomic quantum optics with usual laser)
  - Damage free protein crystallography with entangled state (ghost imaging)
  - Fundamental sciences (corrections to Standard model, etc) with X-ray spectral comb

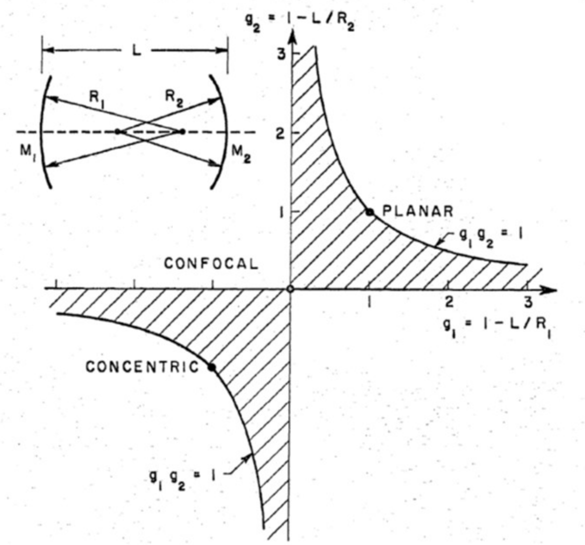
HIGH EFFICIENCY OSCILLATOR

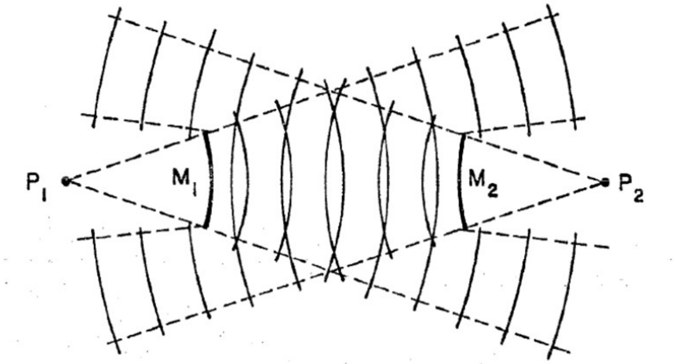
- High efficiency in extracting radiation energy from e-beam and high efficiency in out-coupling
  - Higher power without increasing power on intra-cavity mirrors
- High extraction efficiency
  - TESSA, TESSO, pinched e-beam,
- High out-coupling
  - XFELO: thinner out coupling crystal→ mechanical challenges
  - A few other options follows

PEELING OFF A FRACTION OF X-RAY PHASE SPACE

- Spatial peeling: unstable cavity with diffraction from mirror circumference
- Angular peeling
- spectral peeling

UNSTABLE CAVITIES (A. E. SIEGMAN, 1965)





- “Gaussian” mirror with reflectivity profile: $\exp[-x^2/2{\sigma_x}^2]$

$$\frac{1}{f} \rightarrow \frac{1}{f} + i{\sigma_x}^2/2k$$

→ABCD matrix analysis with complex elements (A. Yariv, 1975)

- Angular peeling: Gaussian angular profile of mirror reflectivity: $\exp[-\varphi^2/2{\sigma_\varphi}^2]$.

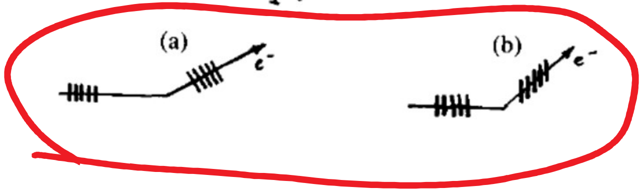
$$\ell \rightarrow \ell + i{\sigma_\varphi}^2/2k.$$

- Spectral peeling with short pulse (XFEL Regen Amplifier, Z. Huang and R. Ruth, 2006)

ISOCHRONOUS BEND EXPERIMENT AT BINP WITH SPONTANEOUS U RAD(IEEE Q.E. VOL 27, 2569 (1991)

Observation of Mutual Coherency of Spontaneous Radiation from Two Undulators Separated by Achromatic Bend

N. G. Gavrilov, G. N. Kulipanov, V. N. Litvinenko, I. V. Pinaev, V. M. Popik, I. G. Silvestrov, A. N. Skrinsky, A. S. Sokolov, N. A. Vinokurov, and P. D. Vobly



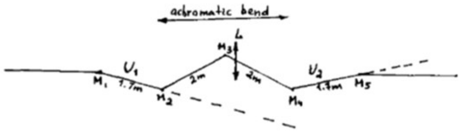
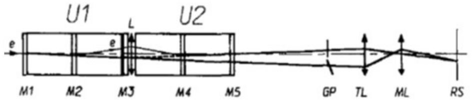
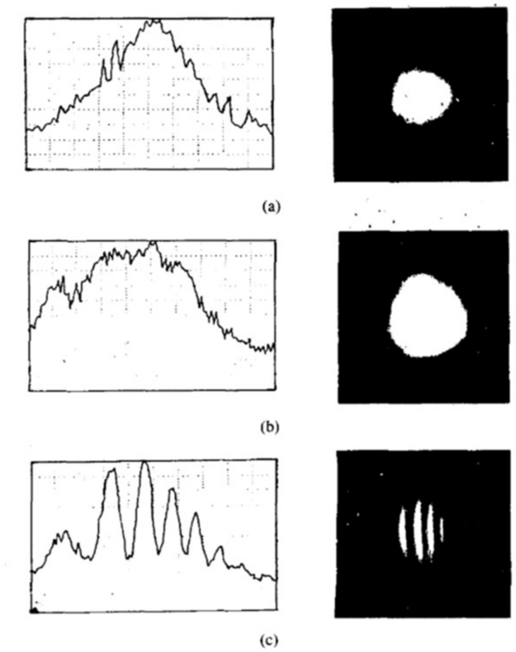
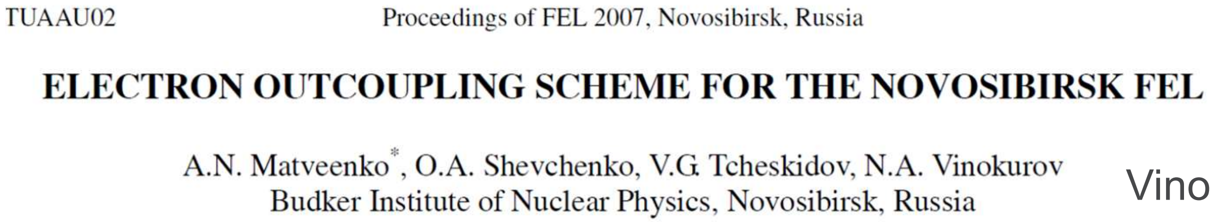


Fig. 2. Schematic of achromatic bend.





- Ee=350 MeV, λ=0.62 μm , $\Delta\theta$=2 mrad
- The e-outcoupling was studied also by W. Fawley (1996), et al but not the bending effect

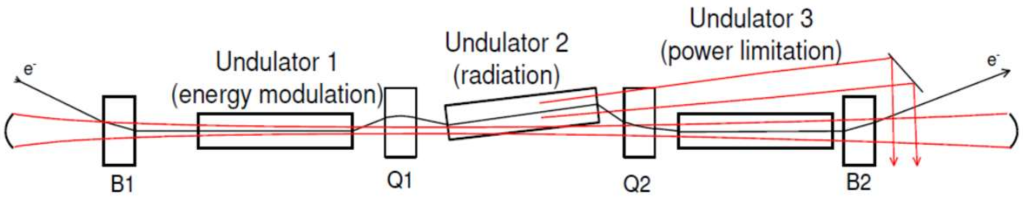


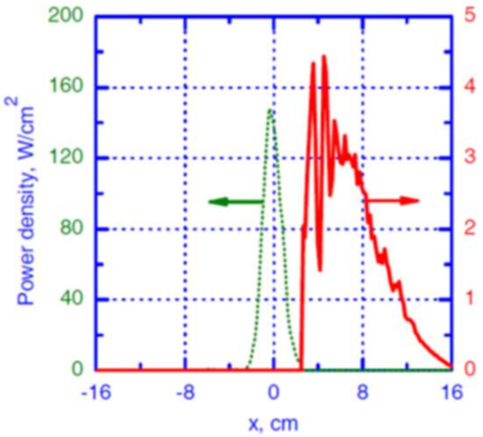
TUAAU02 Proceedings of FEL 2007, Novosibirsk, Russia

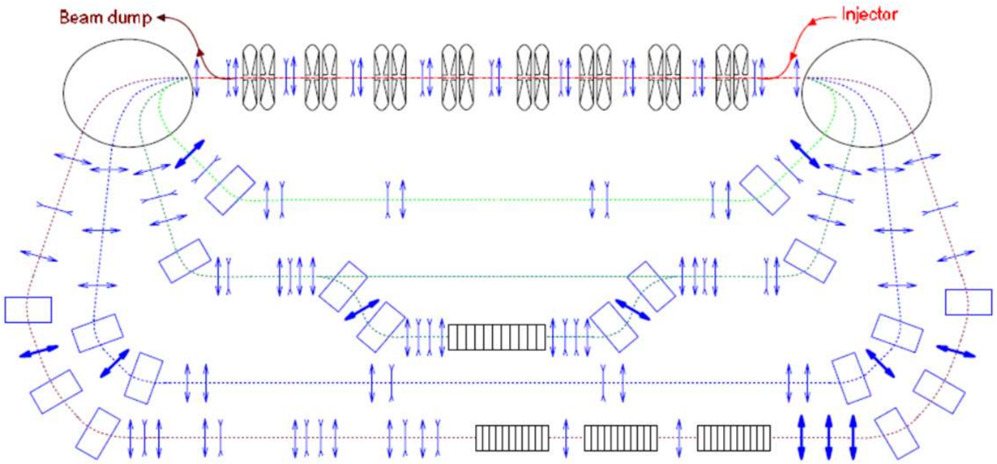
ELECTRON OUTCOUPLING SCHEME FOR THE NOVOSIBIRSK FEL

A.N. Matveenko[*], O.A. Shevchenko, V.G. Tcheskidov, N.A. Vinokurov
Budker Institute of Nuclear Physics, Novosibirsk, Russia

Vinokurov, 1985, 1991

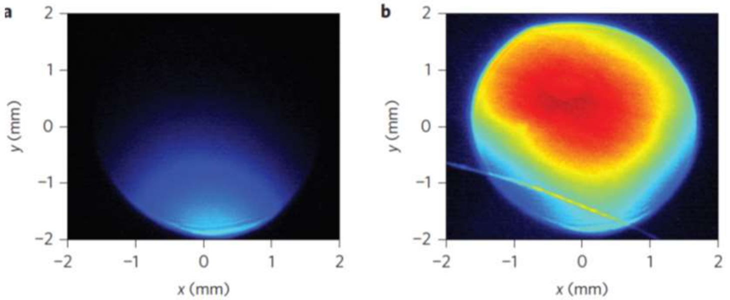


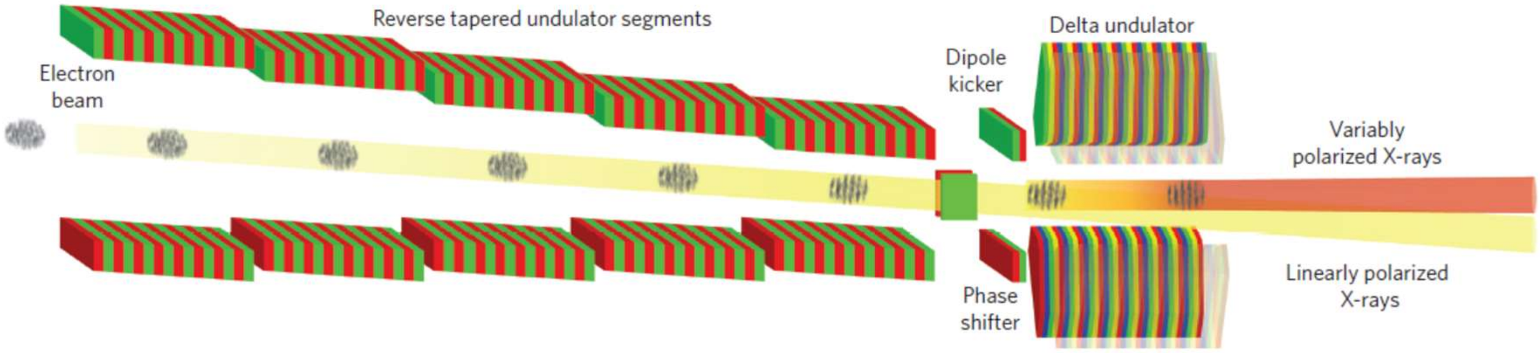




- Ee= 40 MeV, λ=15 μm , $\Delta\theta$=3 mrad
- FEL optimization for maximum bunching at U2
- Challenges: Isochronous kick at < 1 Å ?

DELTA AFTER-BURNER AT LCLS (2016)





- A. A. Lutman, et al., Nature photonics, 2016
- Ee= 4 GeV, λ=17.5 Å, $\Delta\theta$ ~ 54 μrad
- The radiation direction was observed to rotate by a comparable amount

BEND+ DEFOCUSING QUAD GIVES RISE TO WAVE-FRONT ROTATION IN THE CORRECT DIRECTION

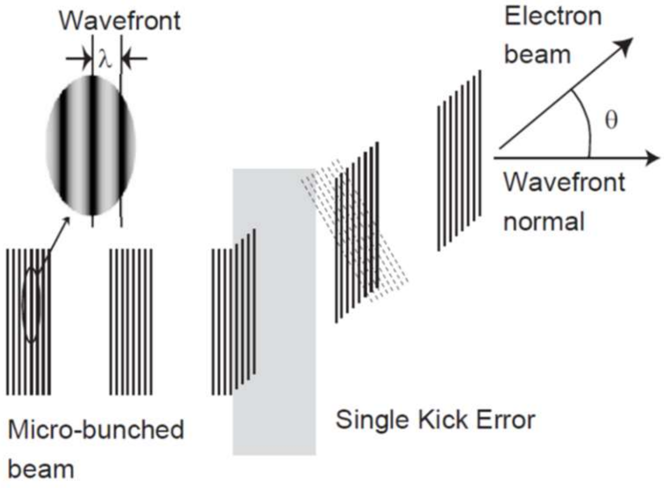
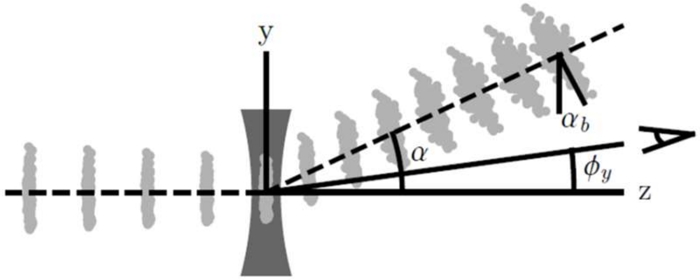
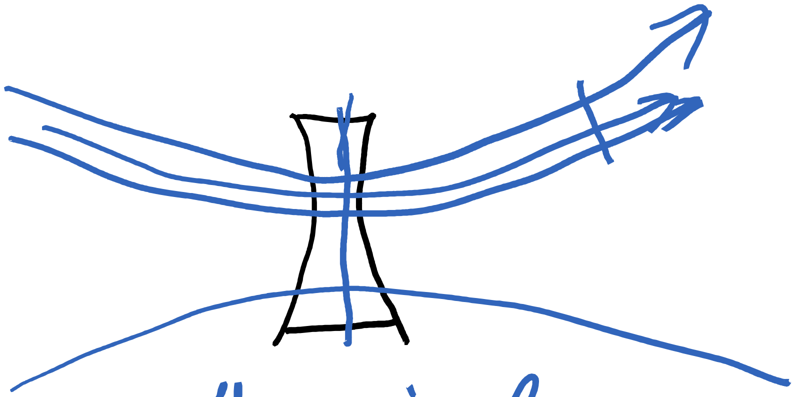


Figure by T. Tanaka





off-axis beam

ANALYSIS OF B+Q KICK (J. MACARTHER, ZRH, 2018)

- Analysis of simple kick based on Maxwell-Klimontovich equations (J. MacArthur) agree with experiment and GENESIS
- Second order isochronous bend for 7 GeV looks OK for 1 Å without ICS and CSR

$$\mathcal{F}(\theta,\eta,\mathbf{x},\mathbf{x}';z) = \tfrac{k_1}{I/ec}\sum_{j=1}^{N_e}\delta(\theta-\theta_j)\delta(\eta-\eta_j)\times \delta(\mathbf{x}-\mathbf{x}_j)\delta(\mathbf{x}'-\mathbf{x}'_j),$$

$$\left[\frac{\partial}{\partial z}+i\Delta\nu k_u+\frac{ik}{2}\boldsymbol{\phi}^2\right]\tilde{E}_\nu = -\kappa_1 n_e\int d\mathbf{x}'d\eta\tilde{F}_\nu$$

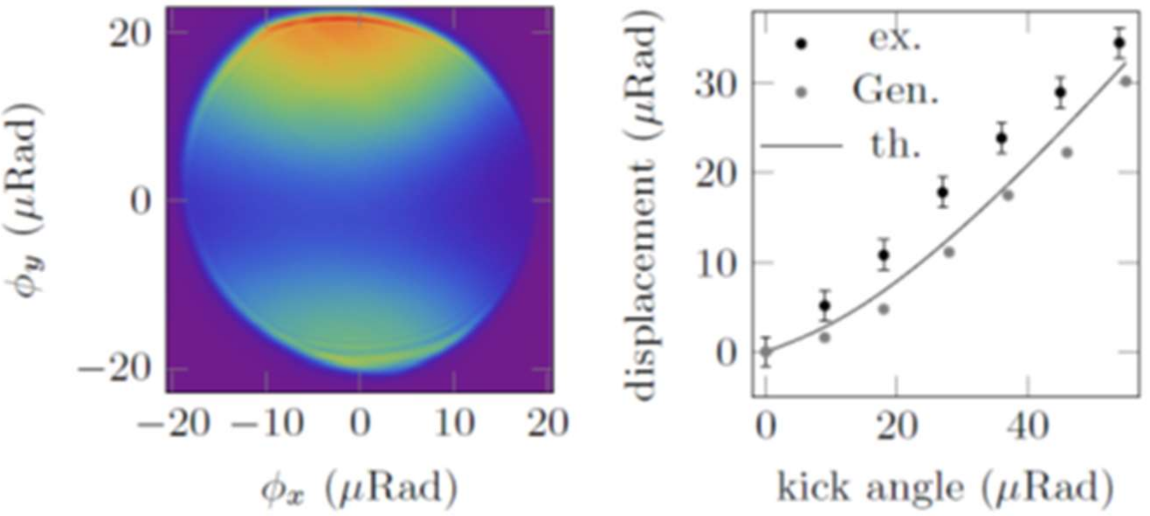
$$\left[\frac{d}{dz}+i\left(2\nu\eta k_u-\frac{k}{2}\mathbf{x}'^2\right)\right]F_\nu = -\chi_1 E_\nu\frac{\partial\bar{F}}{\partial\eta},$$

$$\tilde{E}_\nu(\boldsymbol{\phi};z) = \tfrac{1}{\lambda^2}\int d\mathbf{x}E_\nu(\mathbf{x};z)e^{-ik\mathbf{x}\cdot\boldsymbol{\phi}},$$

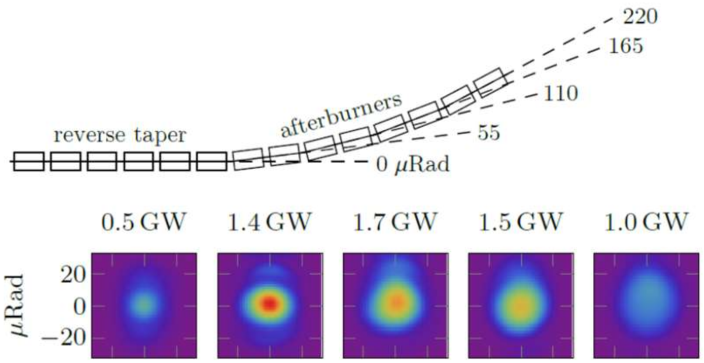
$$\tilde{F}(\phi,\boldsymbol{x}',\eta;z) = \tfrac{1}{\lambda^2}\int d\mathbf{x}F_\nu(\mathbf{x},\boldsymbol{x}',\eta;z)e^{-ik\mathbf{x}\cdot\boldsymbol{\phi}}$$

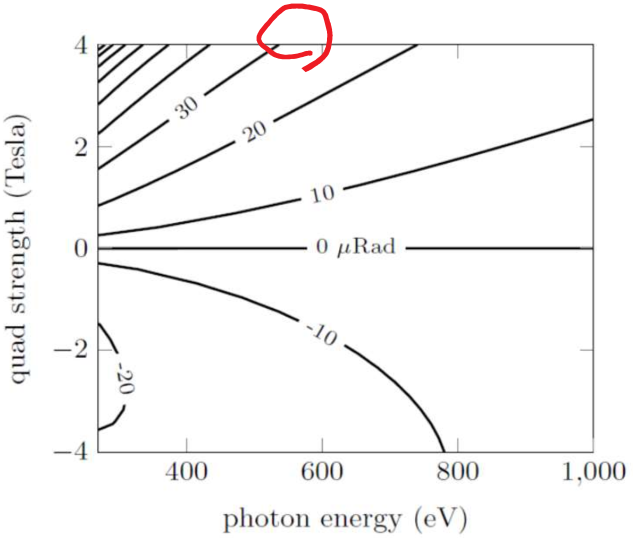
$$x(z) = x_0+(x'_0+R_{21}x_0)\,z$$

$$y(z) = y_0+(y'_0+R_{43}y_0+\alpha)\,z$$



ISOCHROUS KICK AT 1 Å?





- Simple kick (B with Q) (J. MacArther)
  - With reasonable quad strength, single kick ~ 30 µrad for 530 keV
  - Multiple kick up to 220 µrad
  - For >10 keV, 5 kick→ multiple kick to 50 µrad ?
- DBA lattice optimization (Y. Sun)
  - Emittance< 0.3 mm-mrad, energy spread < 3 10-4
  - gives 200-400 50 µrad (Y. Sun)
  - IBS and collective effects need to be studied

SUMMARY

- An XFELO is feasible from beam dynamics and X-ray optics
- 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 $\mathcal{B}_{av}$ $>10^{26}$
- Some options for higher out-coupling efficiency have been explored