Argonne NATIONAL LABORATORY

ERL 2011

the 50th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

A Review of X-Ray Free Electron Laser Oscillator

ERL 2011

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Argonne National Laboratory

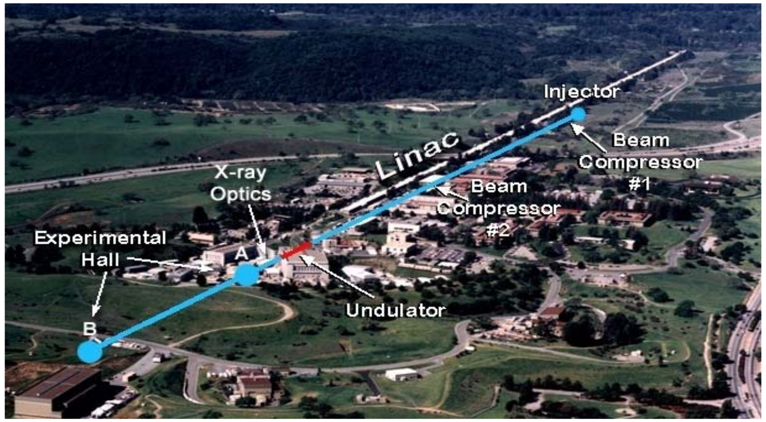
October 16-21, 2011

KEK
Tsukuba

Japan

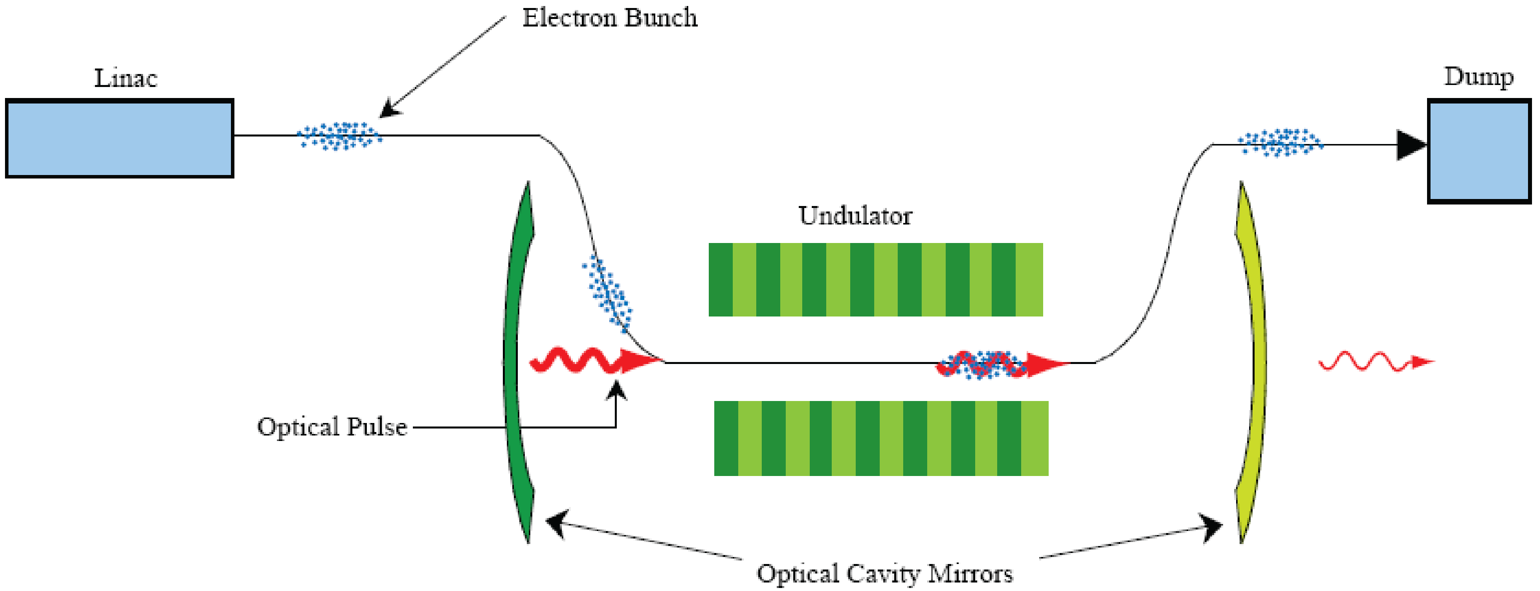
U.S. DEPARTMENT OF ENERGY

FEL Works for Hard X-rays! Self Amplified Spontaneous Emission (SASE)



- **LCLS in 2009, SACLA in 2011**
- **More to come: EuroXFEL (SCRF), PAL XFEL, Swiss XFEL,..**
- **High pulse intensity (10^{12}-10^{13}) photons/sec**
- **Pulse length ~10 - 100 fs**
- **Rep-rate (10^{2} -10^{4} Hz)**
- **Transversely coherent, temporally chaotic $\Delta\omega/\omega = 10^{-3} \rightarrow 10^{-4}$ (with self seeding)**
- **Nanocrystals, single shot imaging, femto-second dynamics,..**

Principles of an FEL Oscillator



- Small signal gain G= $\Delta P_{intra}/P_{intra}$
  - Start-up: $(1+G_0)\, R_1\, R_2 > 1$ (R_1& R_2 : mirror reflectivity)
- Require high reflectivity → oscillator limited to UV and lower energy photons with usual mirror
- X-ray FEL oscillator is feasible by using Bragg mirrors (R. Collela and A. Luccio, 1984; KJK, Y. Shvyd'ko, and S. Reiche, 2008)

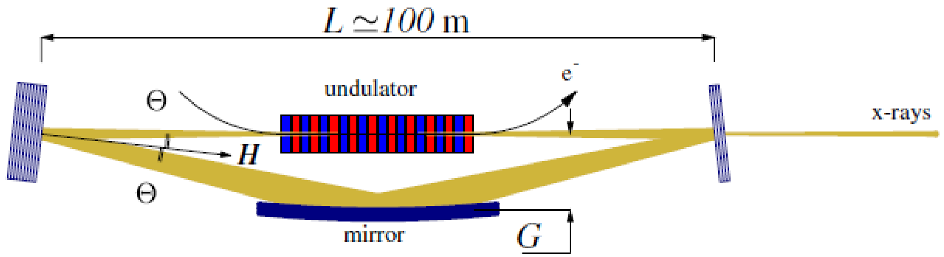
XFELO Cavity Configurations

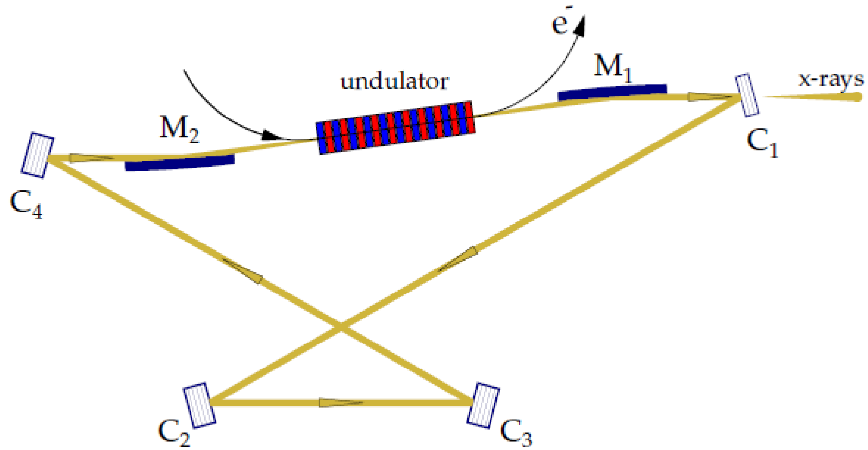
- **Two crystal scheme is not tunable**
- **Tunable with four-crystal scheme**

→Any interesting spectral region can be covered by one chosen crystal material

→Simplify the crystal choice

→Diamond as highest reflectivity & best mechanical and thermal properties



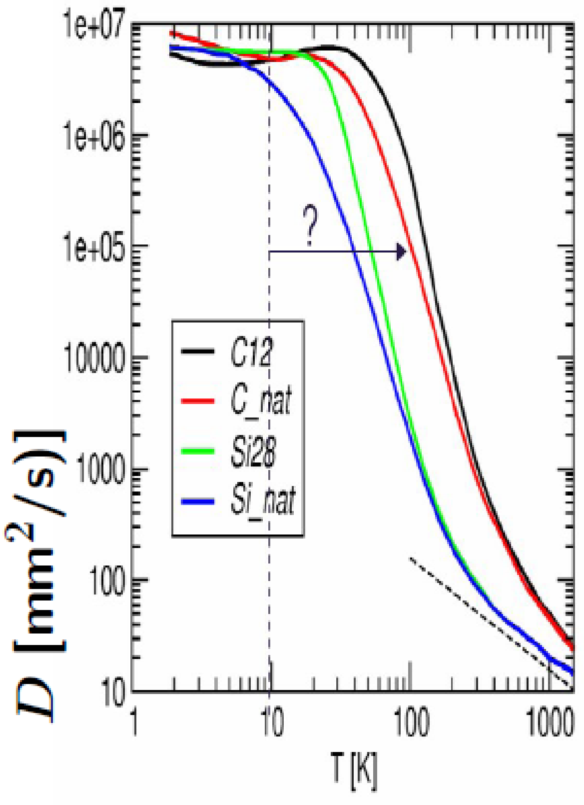


R. M.J.Cotterill, APL, 403,133 (1968)
KJK & Y. Shvyd'ko, PRSTAB (2009)

Diamond: Excellent Physical Properties

Ultra-high thermal diffusivity at low temperatures

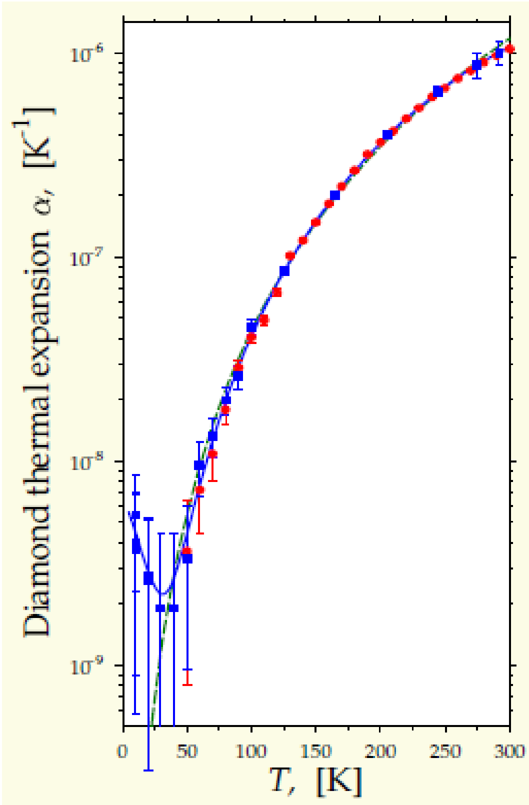
$\simeq 10^5$ mm^{-2}s @ 100 K



Courtesy of H. Sinn

Ultra-low thermal expansion at low temperatures

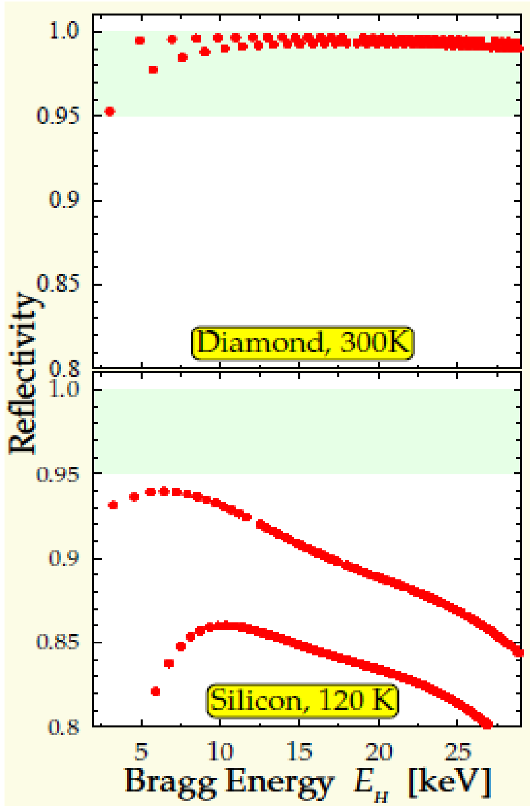
$\simeq 10^{-8}$ K^{-1} @ 100 K



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

Record high reflectivity for hard x-rays

Theory: $> 99\%$



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

Crystal Phase Shift and Cavity Length Detuning

- **Amplitude reflectivity for near normal incidence x-rays**

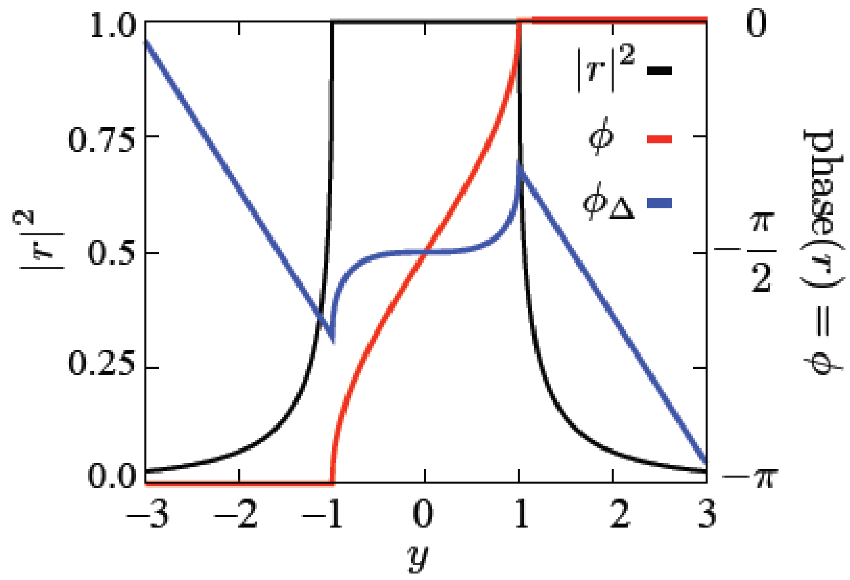
$$r(y) = y - i\sqrt{1-y^2} \approx -ie^{iy}$$

$$y = \frac{1}{|\chi_H|}\left[\frac{2(E-E_H)}{E_H} + \chi_0\right]$$

- **XFELO works near y~0. The angular spread effect is small**
- **ω-dependent phase shift**

$$exp(i\omega\tau) \qquad c\tau = \frac{\lambda_H}{2\pi|\chi_H|}$$

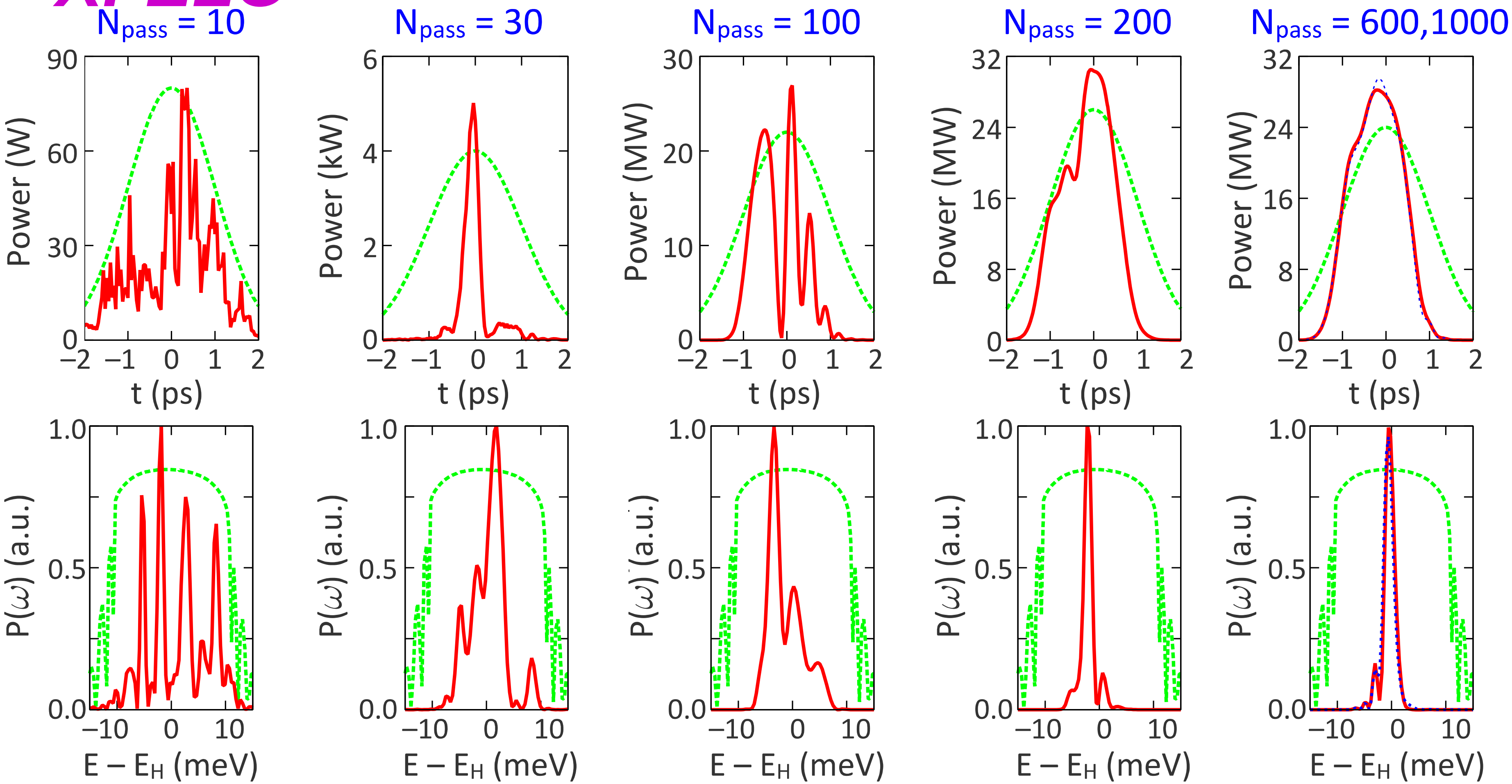
- **can be corrected by cavity length adjustment**



XFELO Modeling

- Analytical
  - Gain calculation taking into account 3D effects, super-mode theory for evolution in optical cavity
- Simulation
  - Genesis (Reiche): (x,y) asymmetric, single wavefront→*Slow:1 month computing from noise to saturation!*
  - Reduced 1-D FEL code (R. Lindberg)
  - GINGER (W. Fawley): (x,y) symmetric→much faster than GENESIS. Implemented a correct crystal response

Temporal and spectral evolution of XFELO



R.R. Lindberg, K.-J. Kim, Yu. Shvyd'ko, and W.M. Fawley, *Phys. Rev. ST-AB.* **14**, 010701 (2011)

XFELO Main Characteristics

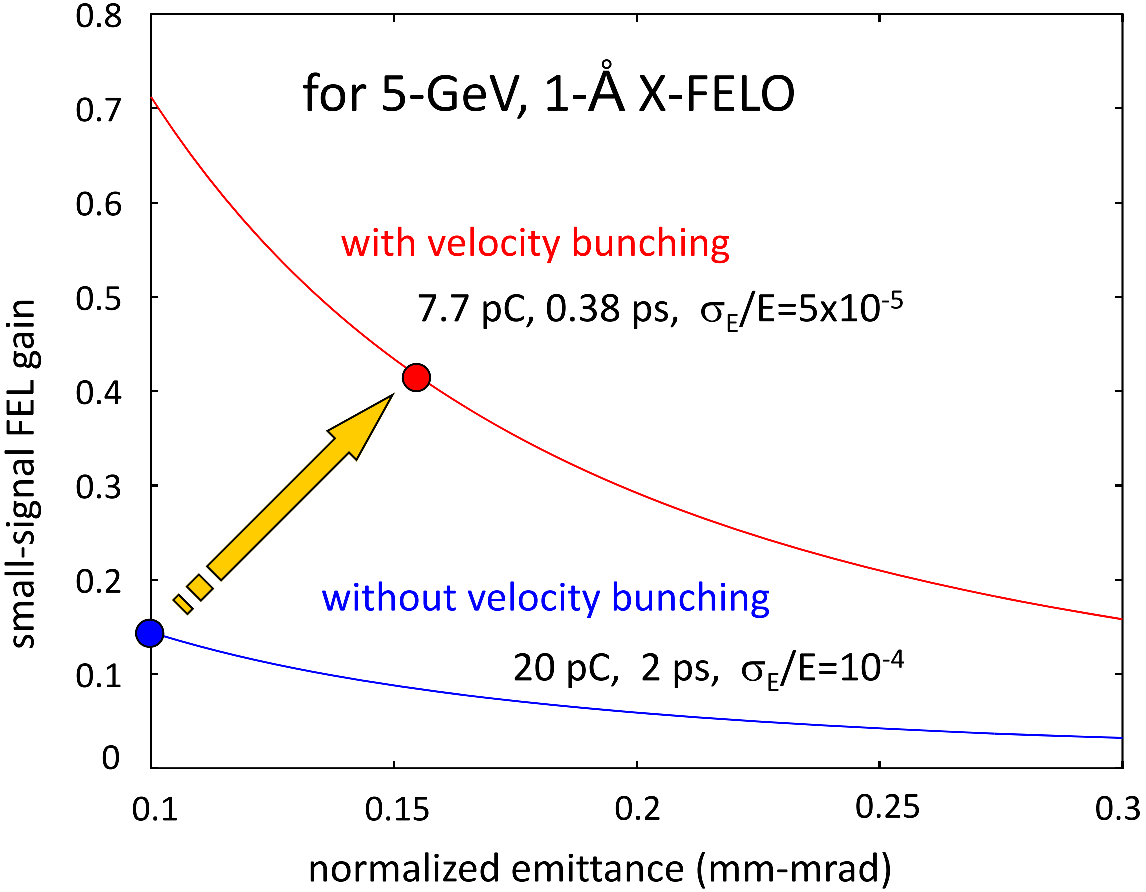
- **Full coherence, transverse & temporal**
- **Ultrafine BW $\Delta\omega/\omega \sim 10^{-7}$, • $\omega \sim 1$ meV**
- **Tunable, typically over 5% photon energy range**
- **Pulse length: 0.1 – 1 ps**
- **High pulse-to-pulse stability**
- **10^9 coherent photons/pulse with 1 MHz rep rate**

Example Parameters based on High Coherence Mode of Cornell ERL

- **Electron beam:**
  - **Energy ~ 7 GeV**
  - **Bunch charge ~ 25-50 pC → *low intensity***
  - **Bunch length (rms) $\le$ 1 (0.1 ps) → Peak current 20 (100) A**
  - **Normalized rms emittance $\le$ 0.2 (0.3) mm-mr, energy spread (rms) ~ 2×10^{-4}**
  - **Constant bunch rep rate @ ~1 MHz**
- **Undulator:**
  - **L_u= 60 (30) m, λ_u ~2.0 cm, K=1.0 – 1.5**
- **Optical cavity:**
  - **2- or 4- diamond crystals and focusing mirrors**
  - **Total round trip reflectivity > 85 (50) %**
- **XFELO output:**
  - **5 keV $\le \hbar\omega \le$ 25 keV**
  - **Bandwidth: $\Delta\omega/\omega$ ~ 1 (5) $\times 10^{-7}$, pulse length (rms) = 500 (80) fs**
  - **# photons/pulse ~ 1×10^{9}**

Blue color in the above indicates short-pulse mode for relaxed tolerances

Enhancement of the FEL gain by velocity bunching (R. Hajima and N. Nishimori, FEL 2009)



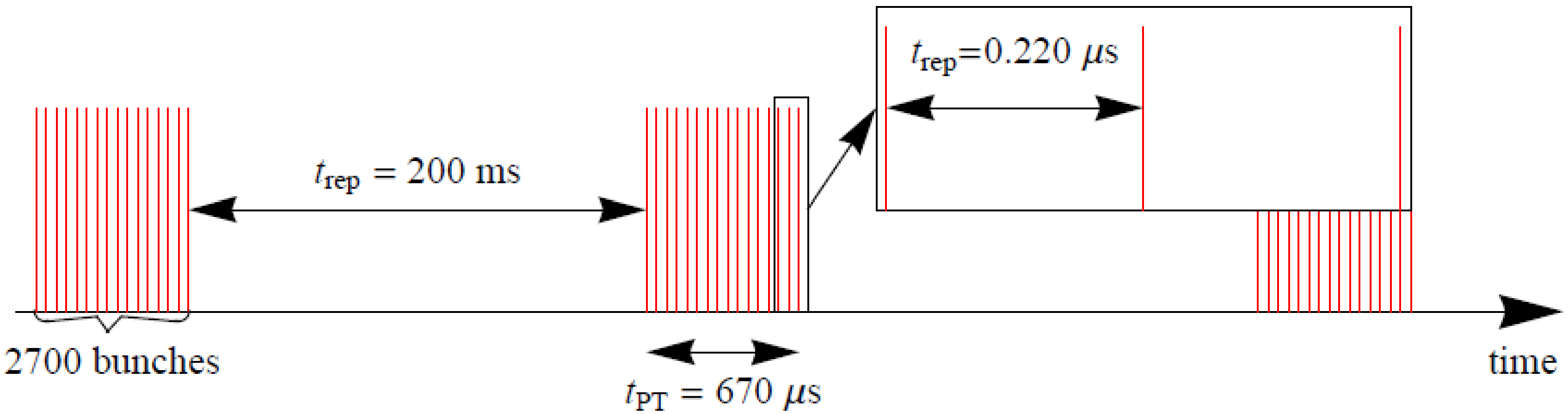
Gain~40% is possible even with emittance growth during the bunching.

Accelerator Technology for an XFELO can take advantage of ERL development

- **The gun/injector technology "exists"**
  - **XFELO can use the guns for Cornell & KEK-JAEA ERLs at a reduced rep rate**
  - **The LCLS low charge mode demonstrated the required bunch characteristics**
  - **The LBNL gun design (187 MHz gun cavity) can be operated to meet the XFELO requirements**
- **The main accelerator can use an ERL design. However, energy recovery is not necessary since the beam current is low (~ 50 μA)**

A Pulsed XFELO can be installed at EuroXFEL (J. Zemella and J. Rossbach)

- **Sufficient number of bunches in one macropulse**
- **Bunch separation is reasonable**

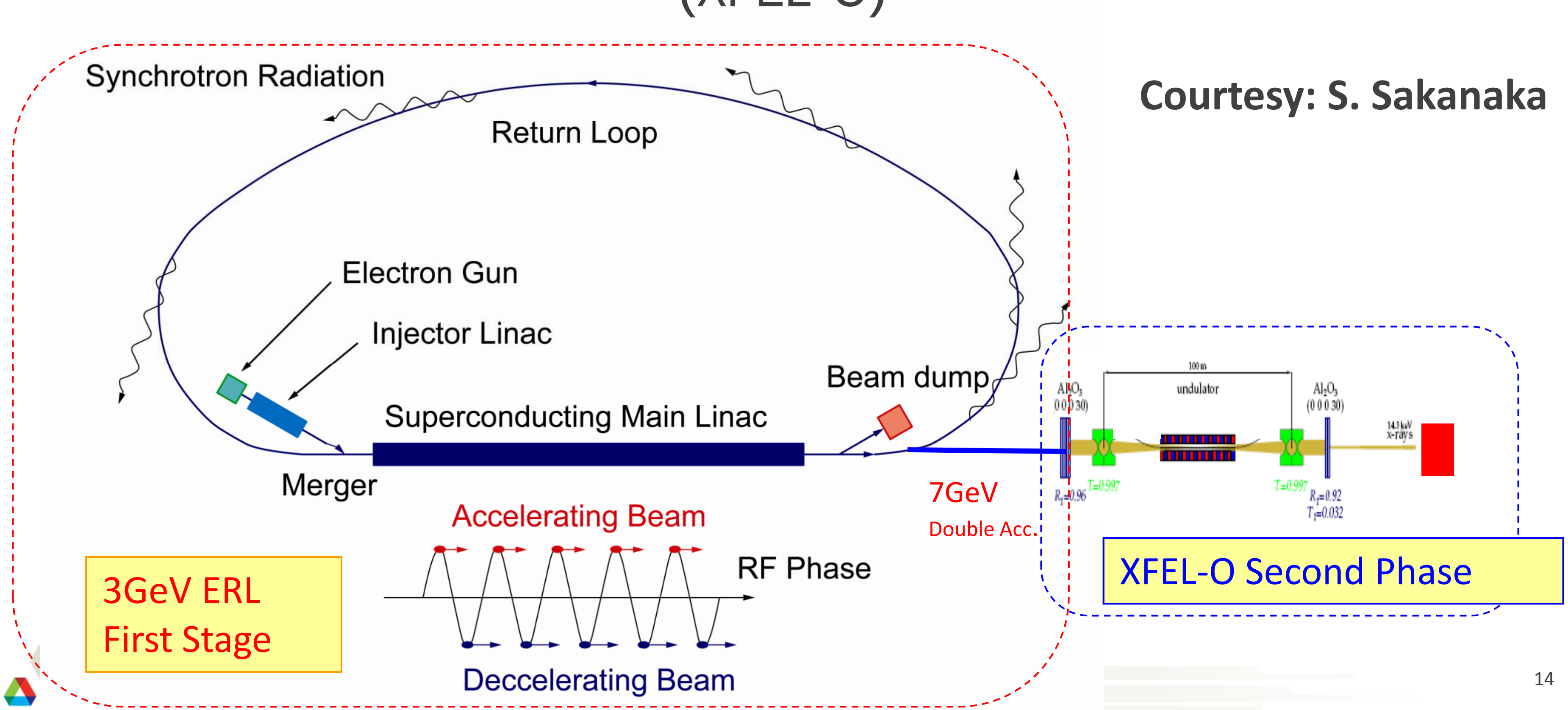


Future light source of the Photon Factory

User's demands : Cutting edge and Work house
To realize a sustainable society.
Ultra-fast phenomena, Nano-meter scale,
Nondestructive measurement, Soft and hard X-ray

→ 3GeV ERL

3 GeV Energy Recovery Linac (ERL) and Resonant type of XFEL (XFEL-O)



Courtesy: S. Sakanaka

XFELO applications

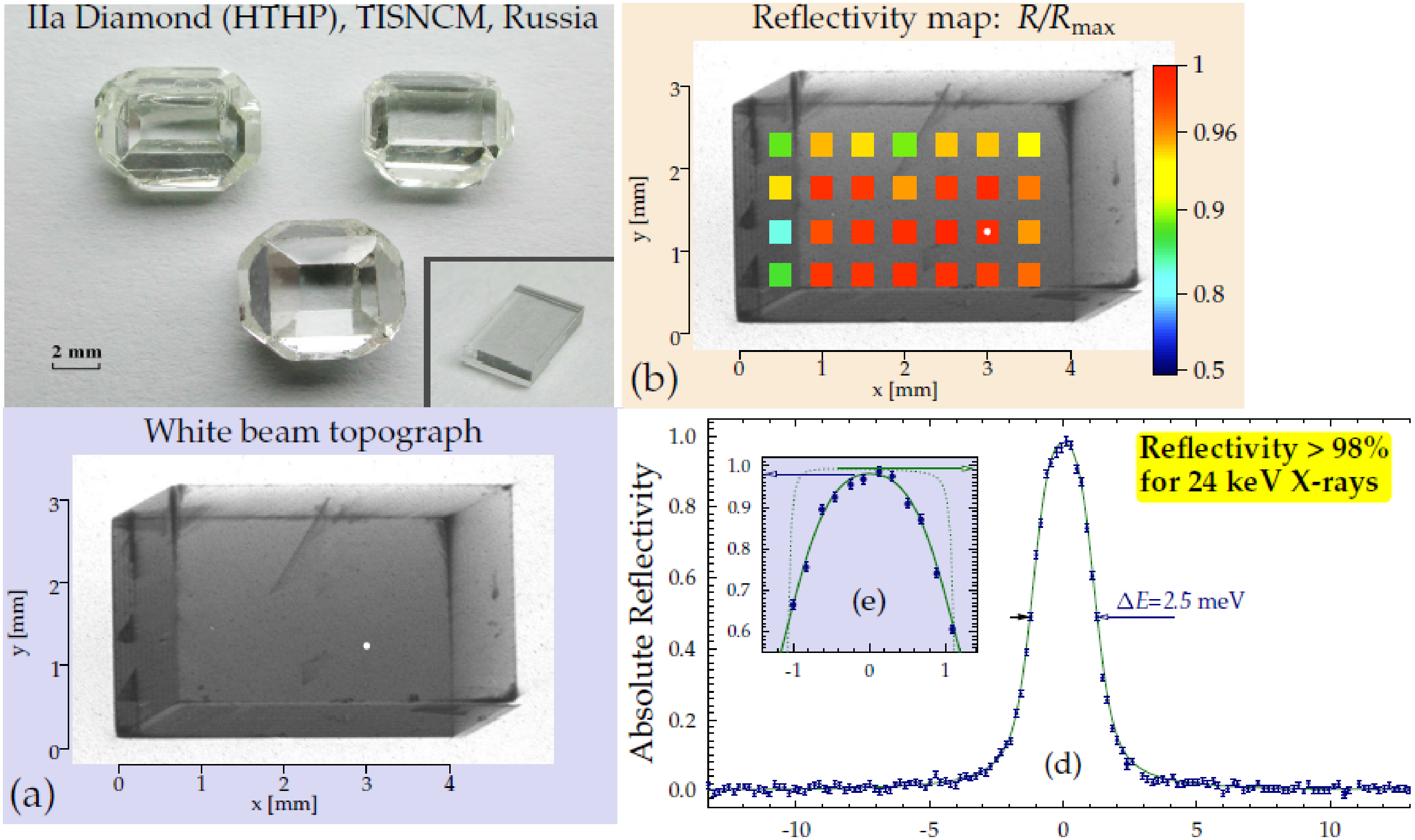
- **High resolution spectroscopy**
  - **Inelastic x-ray scattering**
- **Mössbauer spectroscopy**
  - **10^3/pulse, 10^9/sec Moessbauer γs (14.4 keV, 5 neV BW)**
- **X-ray photoemission spectroscopy**
  - **Bulk-sensitive Fermi surface study with HX-TR-AR PES**
- **X-ray imaging with near atomic resolution (~1 nm)**
  - **Smaller focal spot with the absence of chromatic aberration**
- ***….and new applications***

Challenges for X-ray Optical Elements

- Quality of diamond crystals
- Heat load dynamics: Can ΔE< 1 meV maintained?
- Radiation damage issues
- Stability
  - Angular <10 nr & position< 3 μm @ 1 kHz BW
- Surface qualities
  - Reflectivity and wavefront distortion

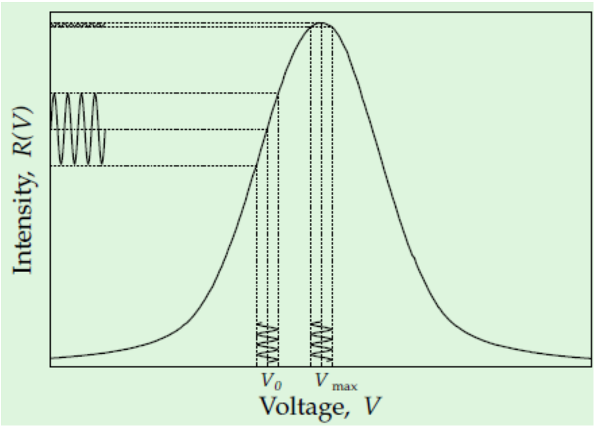
Reflectivity of TISNCM Diamond was measured to be >98% at the APS*

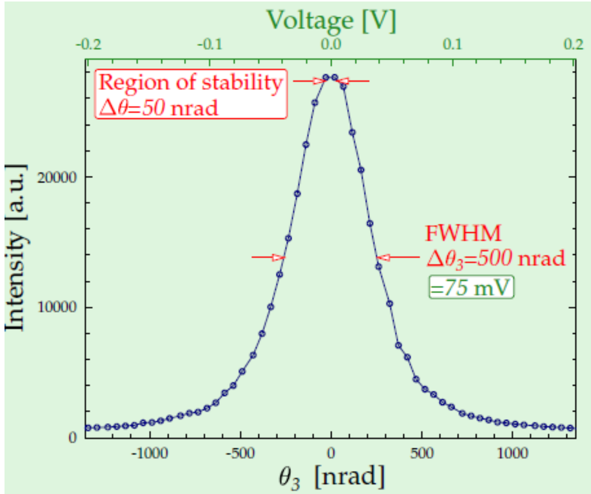
***Technological Institute for Superhard Novel Carbon Materials, Russia**

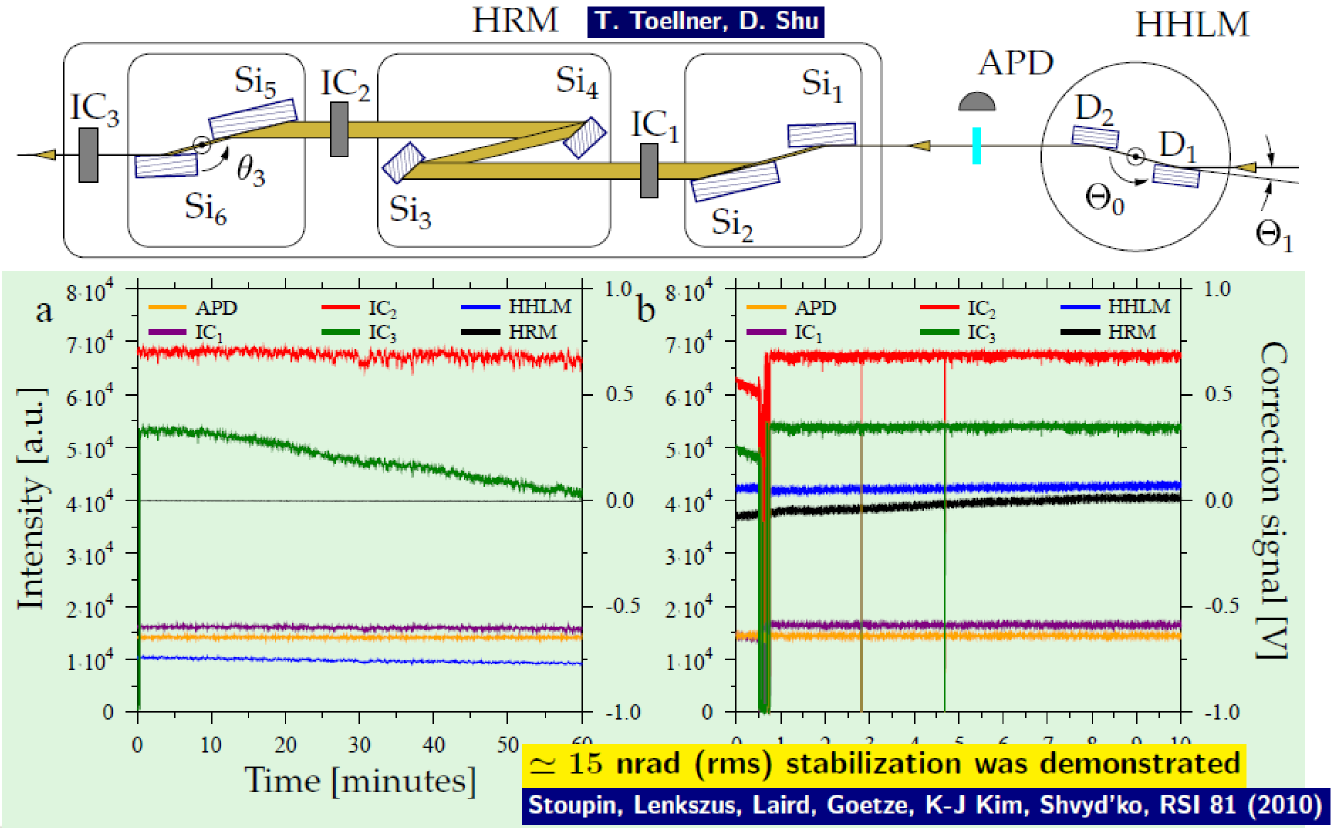


Shvyd'ko, Stoupin, Blank, Terentyev (2011) tbp

Angular Stability: APS S-30 Monochromator Stabilization via Null Feedback (LIGO) achieved 15 nrad stability close to requirement 10 nrad, but need higher BW (~1Hz→1kHz)

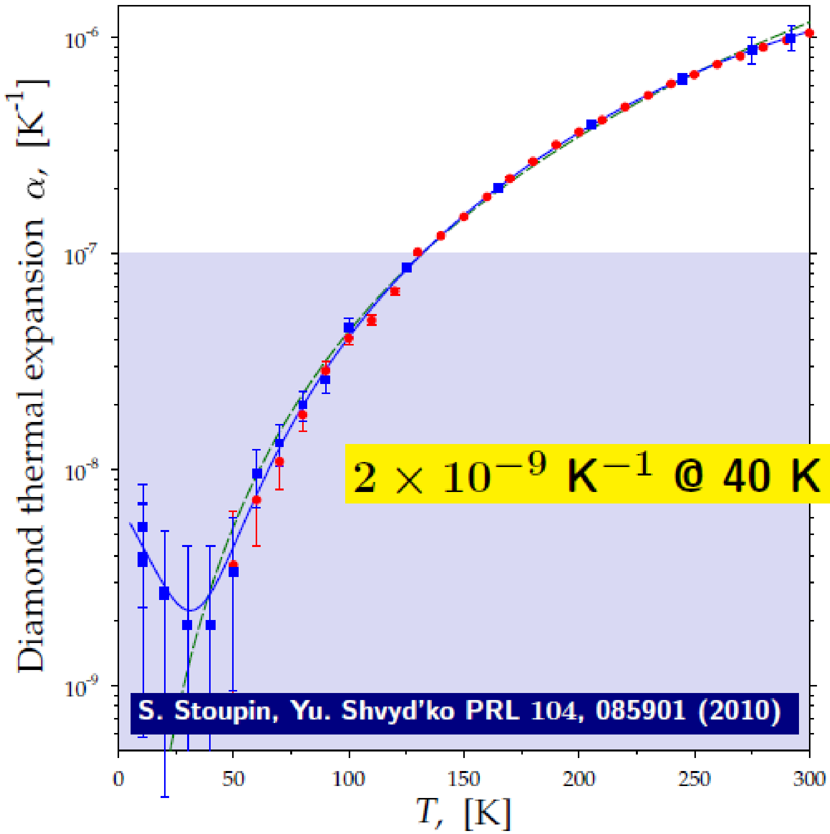


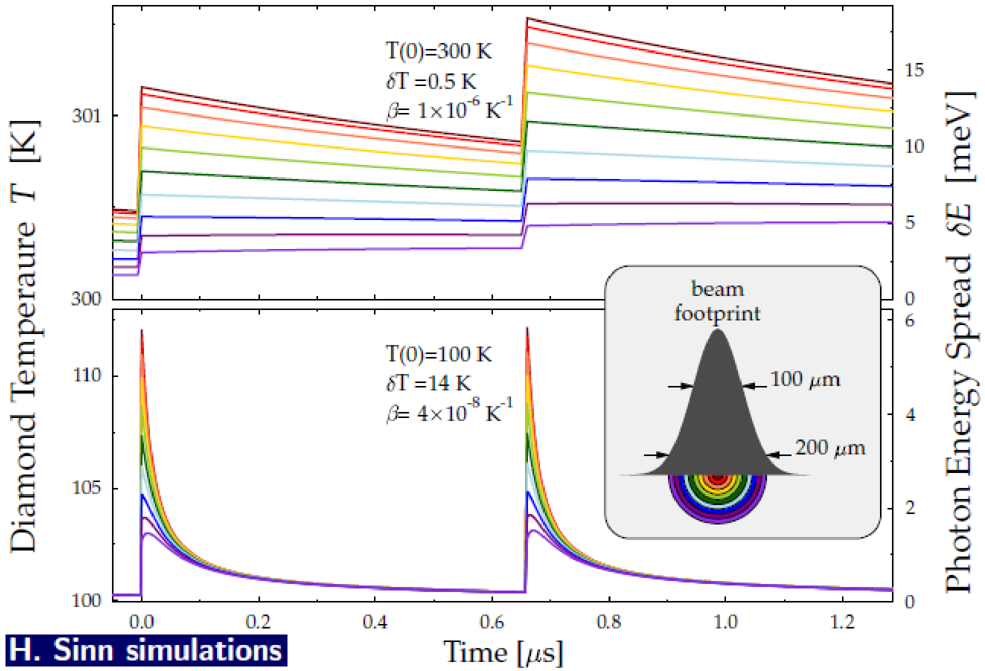




Heat Load Dynamics

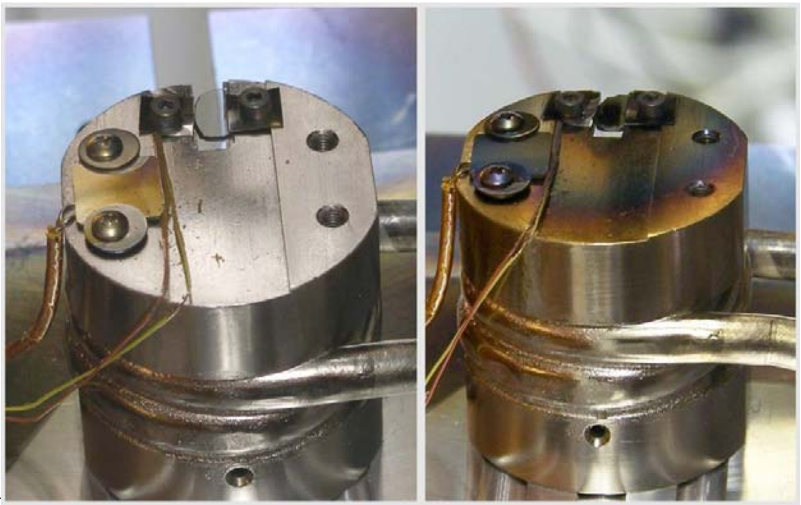
- **As an intracavity x-ray pulse hit crystals, r-dependent temperature rise δT → crystal expansion → $\delta E/E = \beta\ \delta T$ ($\delta L/L=\beta\ \delta T$).** **Is this $<10^{-7}$?**
- **Yes, if cooled to a cryogenic temperature:T< 100K**
  - **Inter-pulse $\delta E/E$ $<10^{-7}$ due to high thermal-diffusivity**
  - **Intra-pulse $\delta E/E$ $<10^{-7}$ due to β $<10^{-7}$**
- **Experimental study under way using laser heating and x-ray probe**





Radiation damage issues

- Power density on crystals is about 4 kW/mm^2 ($2 \cdot 10^{18}$ photons/s/mm^2 @ 12.4 keV) ~ 30 times that of the APS undulators
- All atoms will be ionized in 250s (Robin Santra)
- Recombination processes may prevent an irreversible damage
- Charge build-up from lost photoelectrons at the surface may lead to structural change at the surface
- Possible remedies
  – Isotopically pure ^{12}C crystals, cryogenic temperature
  – Attaching a thin conducting layer, e.g. graphene



Graphitization of a diamond crystal at an APS HHLM at the APS. The surface became darkened, but without apparent performance degradation after 1 year of exposure.

Diamond under 3.5 kW/mm2 heatload survived

J. Als-Niesen, A. K. Freund, et al, NIM, B94, 348-350 (1994).

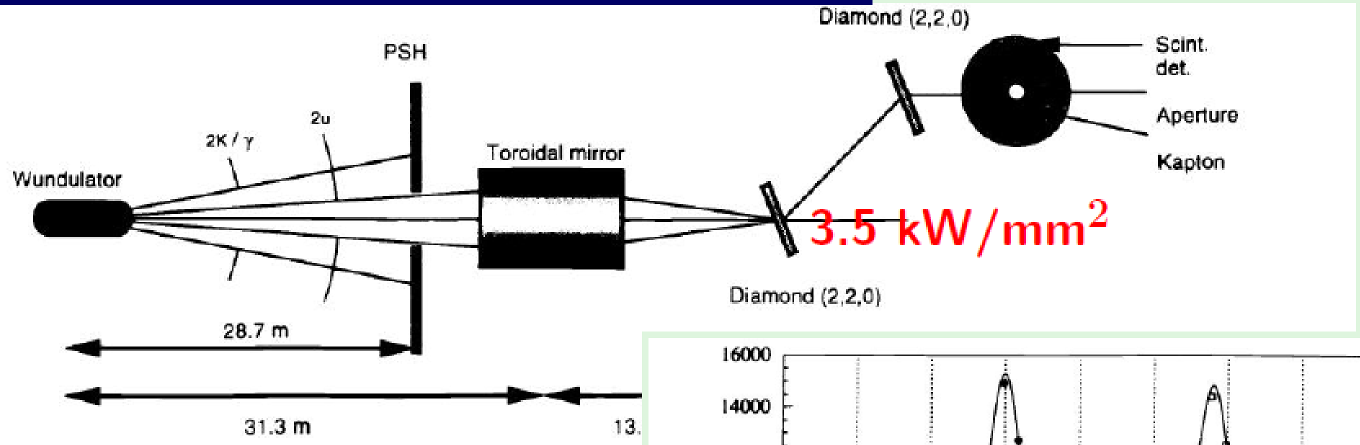


Fig. 2 Schematic diagram of the experimental setup

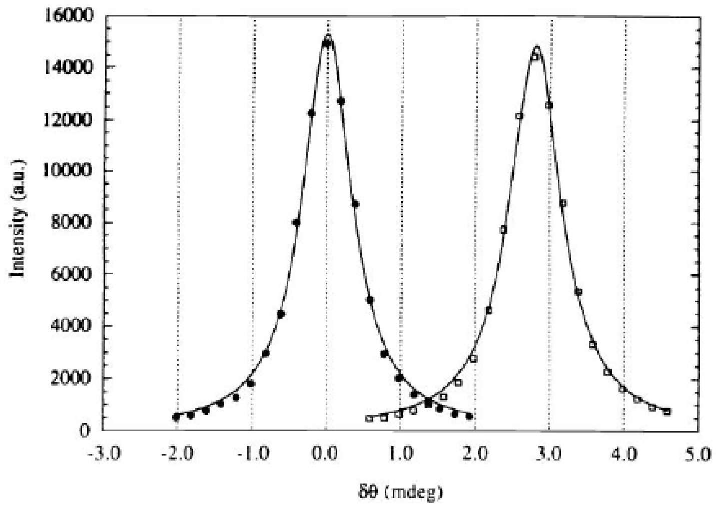
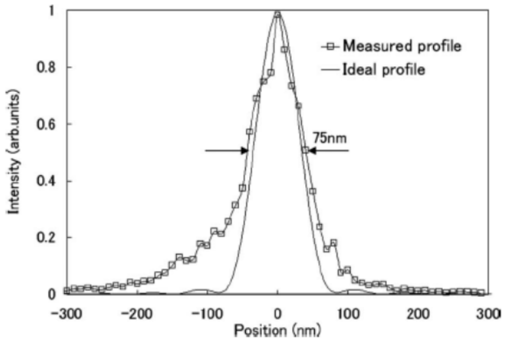
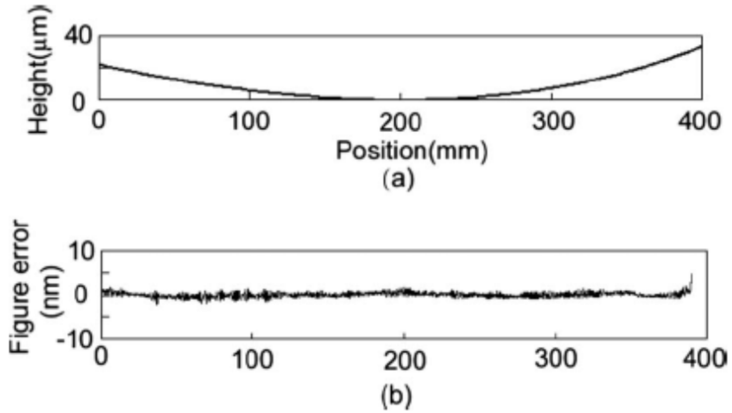


Fig. 3 Rocking curves of the analyzer at low and high power levels. The full lines are least squares fitted Lorentzians.[26]

Grazing Incidence, Curved Mirror





H. Mimura, et. al.

RSI 79, 083104, 2008

- **JTEC**
  - **Developing a technique combining elastic emission machining (EEM, slow) and electrolytic in-process dressing (ELID, fast) to fabricate a smooth surface to <nm height error and 0.25 mrad figure error**
  - **Issue: large ration in the sagital and meridional depths**
  - **Such mirrors are sought after by “every body” in SR business**
- **Other ways of focusing**
  - **Curved crystal surface, CRL,..**

Mitigating Factors for Surface Roughness Tolerance of Optical Elements in Hard X-Ray FEL Oscillator

- **The height error *h* in grazing incidence curved mirror:**
  - **$h \ll \lambda/4\pi\theta$, θ=angle of incidence ~ 0.001**

- **The error on crystal surface finish Δz:**
  - **$\Delta z\,(1-n) \ll \lambda$, n= index of refraction~ $1-10^{-6}$**

Conclusions

- An XFELO will be a “true” x-ray laser
- Challenges for XFELO accelerator system are being addressed by ERL R&D
- X-ray optics for XFELO may be feasible
  - Quality of diamond crystals: Near theoretical reflectivity (> 98%) has been measured
  - Heat loading: Temporal and spatial variation in Bragg reflection energy can be < 1 meV
  - The radiation damage issue: need further study but encouraging indirect evidence
  - Angular stability of ~10 nrad can be achieved
  - The surface roughness requirements: consistent with the state-of-the-art technology