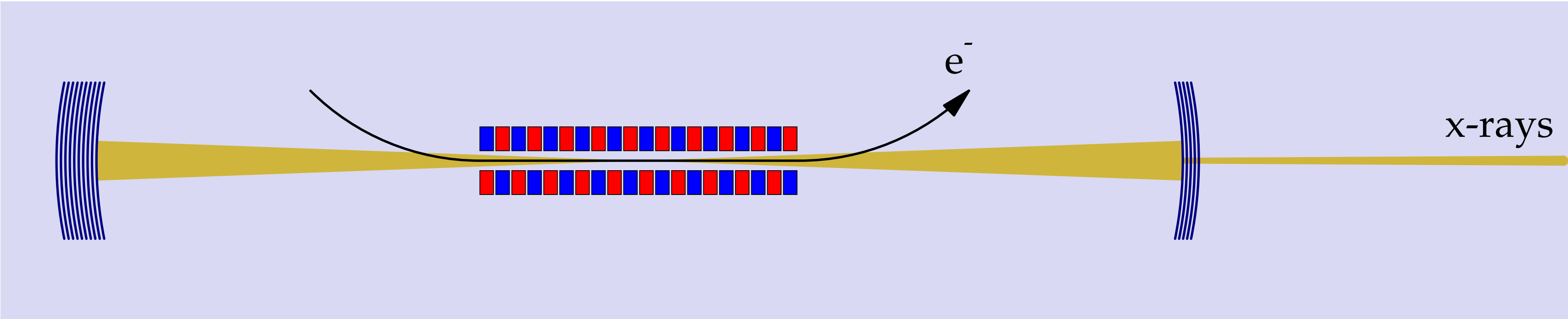
Feasibility of Diamond Cavities for X-Ray Free Electron Laser Oscillator

Yuri Shvyd'ko



In collaboration with

K.-J. Kim, R. Lindberg, S. Stoupin, H. Sinn, A. Cunsolo

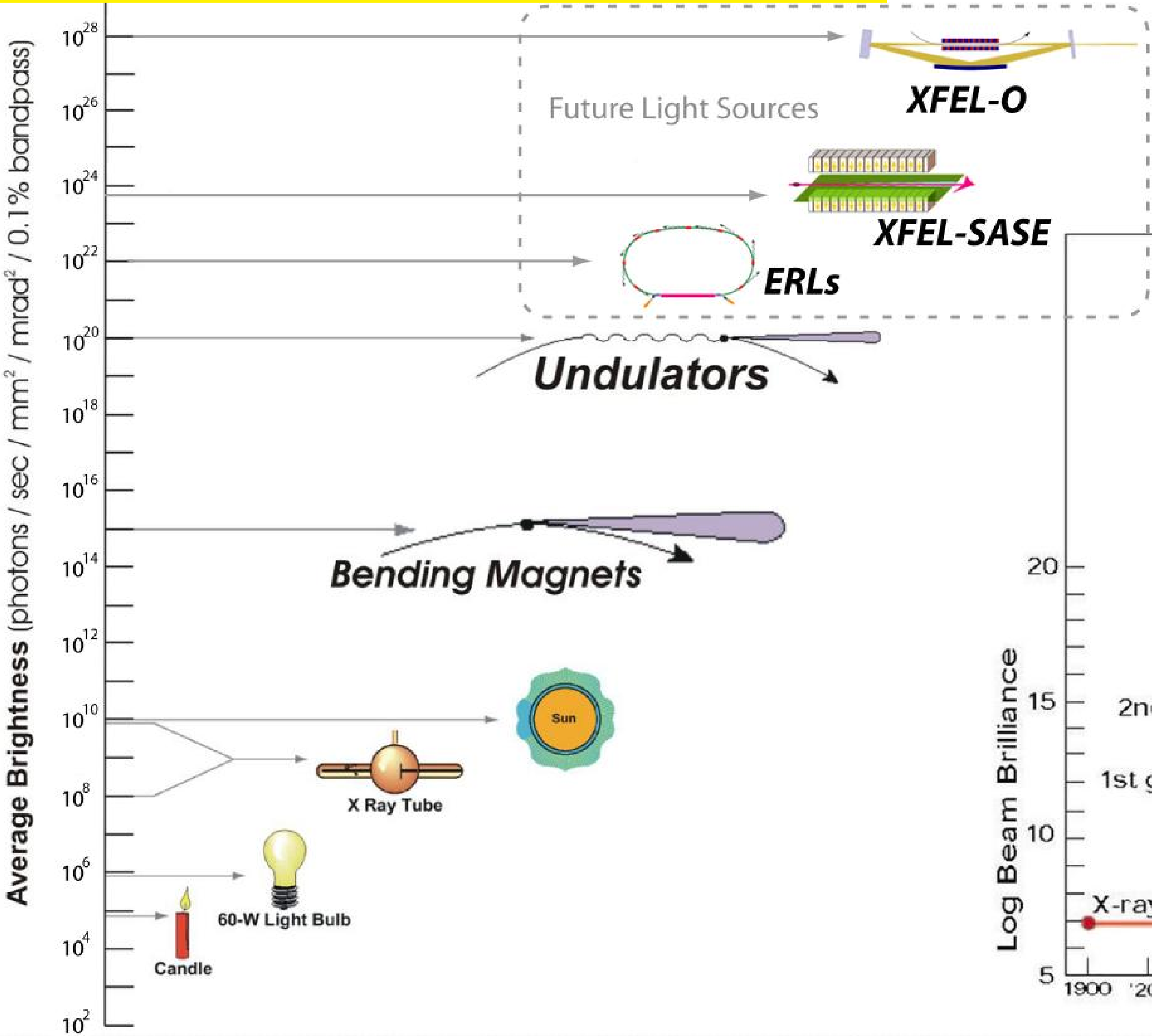
Content

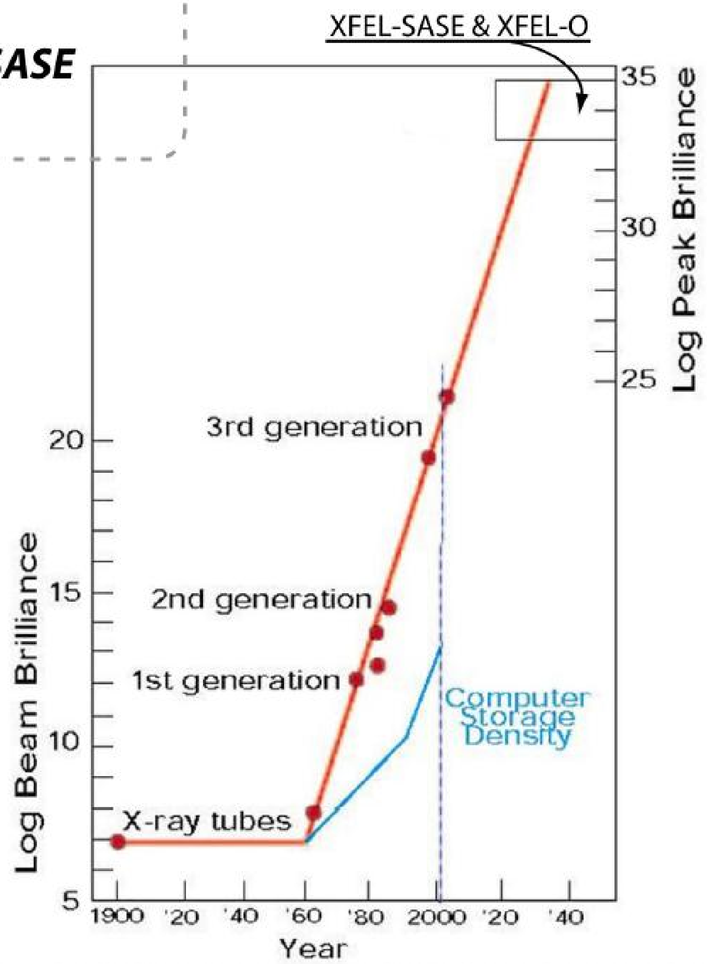
- Coherent x-ray sources
- XFEL-O concept
- X-ray cavities
- Feasibility of the diamond cavities - first experiments:
  - Spectral bandwidth and reflectivity
  - Low temperature thermal expansion
  - Heat load simulation
  - Nanoradian stability
- Conclusions, and Outlook.

Present and Future X-Ray Sources

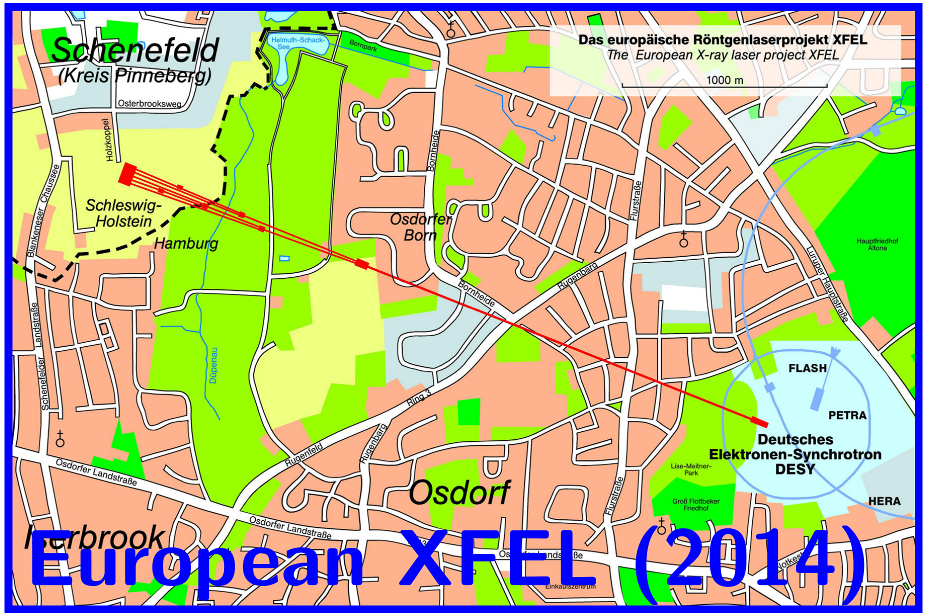
Future: linac-based x-ray sources

Courtesy of K.-J. Kim



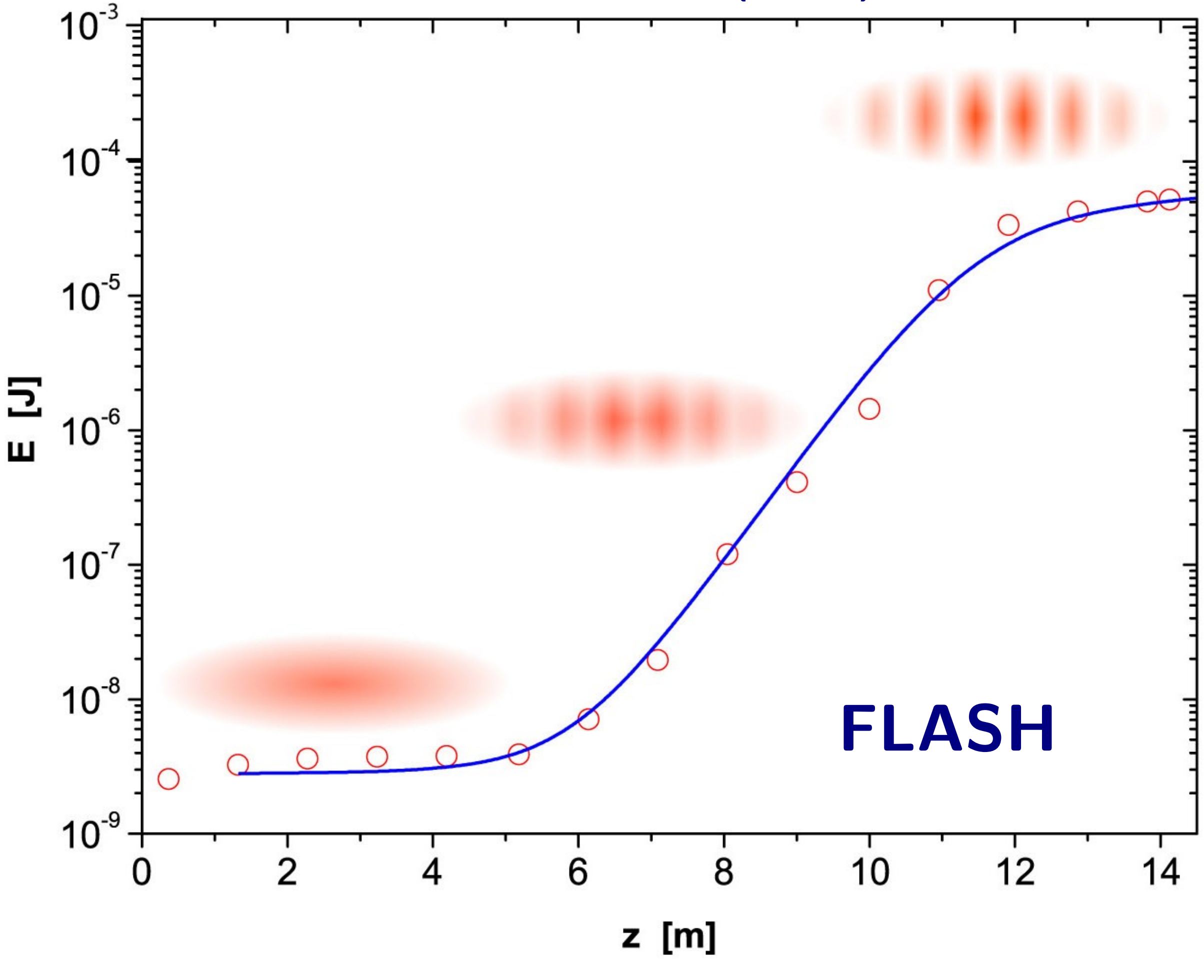


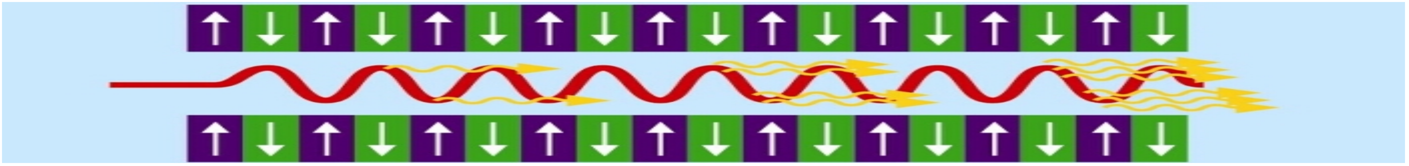
HG-XFEL Facilities



High-Gain SASE XFEL by Microbunching

Kondratenko, Saldin (1979)
Bonifacio, Pellegrini, Narducii (1984)





⇒ In the beginning without micro-bunching all the N electrons can be treated as individually radiating charges, and the resulting spontaneous emission power is proportional to N.

⇒ The shot noise of the electron beam is amplified up to complete micro-bunching.

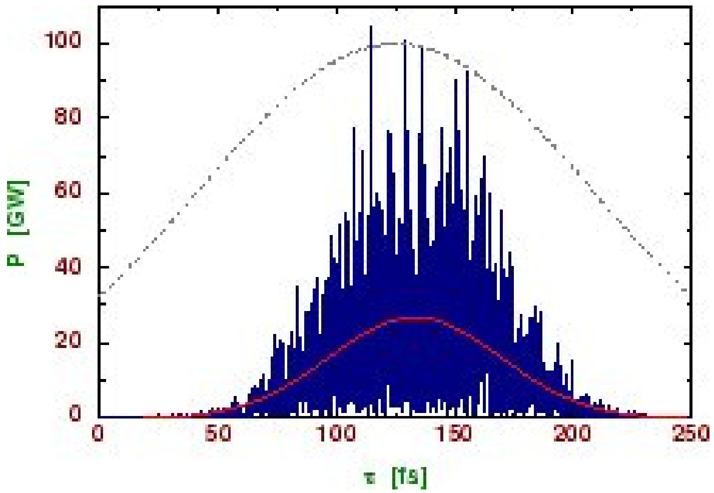
⇒ With complete micro-bunching, all electrons radiate almost in phase. This leads to a radiation power growth as N^2, a processed called self-amplified spontaneous emission (SASE)

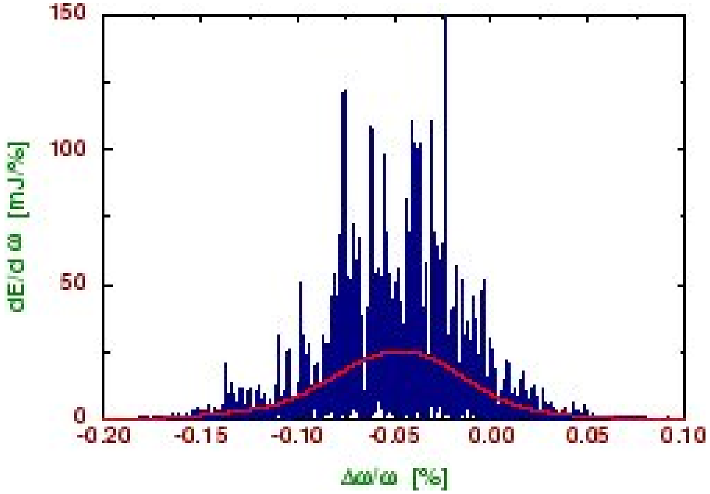
Requires electron beams:
emittance $\varepsilon_{\rm n} \lesssim 10^{-6}$ m rad
energy $E_{\rm e} \simeq 10$ GeV
energy spread $\frac{\sigma_E}{E_{\rm e}} \lesssim 10^{-4}$
peak current $\simeq 10^4$ A
pulse length $\lesssim 100$ fs

Coherent Properties of the HG-XFEL Radiation

- The radiation from a SASE XFEL is fully transversely coherent, nearly Fourier transform limited.

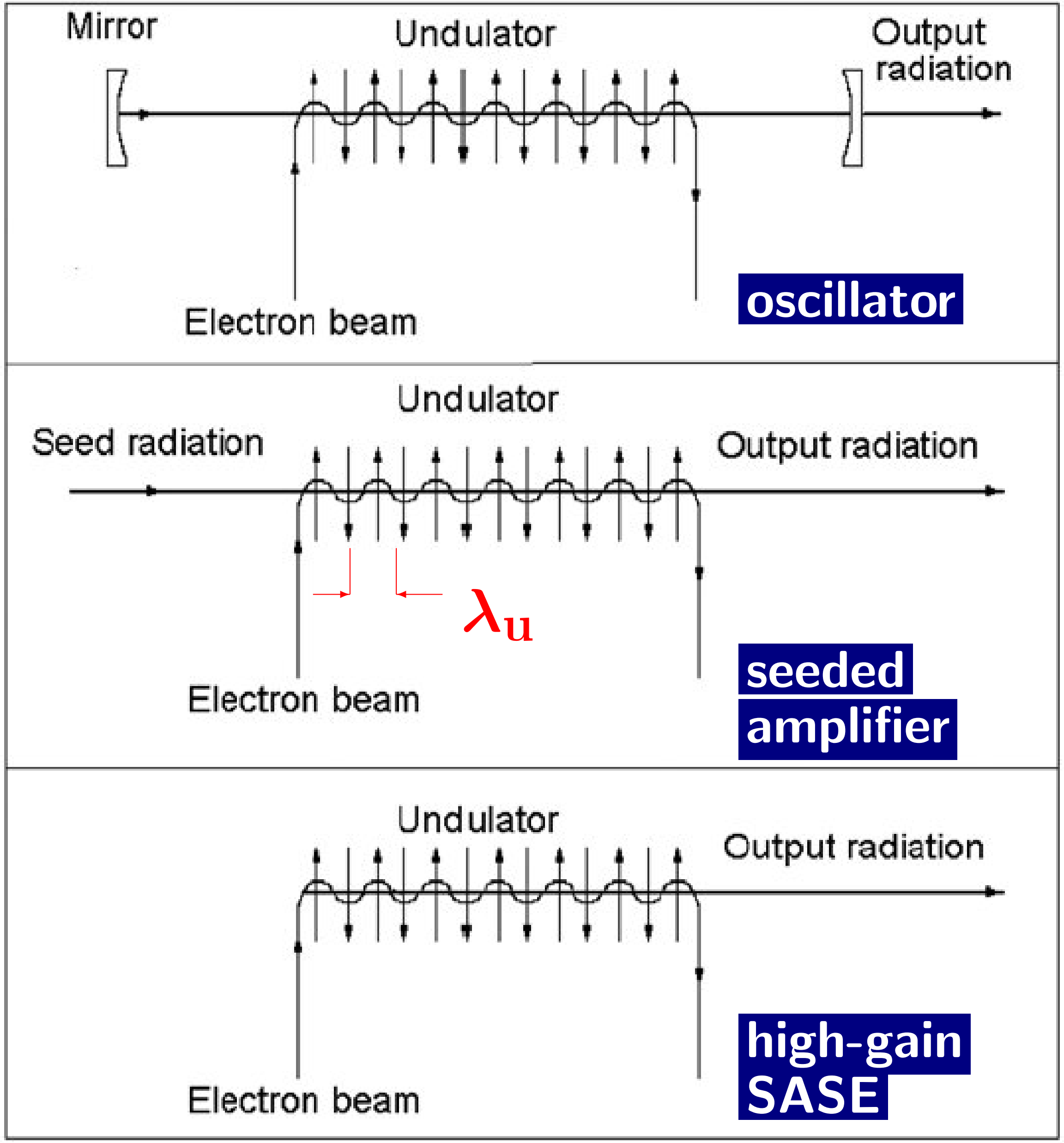
- Temporal coherence is low because of the start-up from noise.





- Seeded FEL amplifier or FEL oscillator would generate radiation with better coherent properties.

FEL configurations



The essential advantage of FEL radiation as compared to undulator radiation is its much higher intensity because a large number N of electrons radiate coherently: $\propto N^2$, producing a clean superradiant pulse.

Require electron beams:

emittance $\varepsilon_n \lesssim 10^{-6}$ **m rad**

energy $E_e \simeq 10$ **GeV**

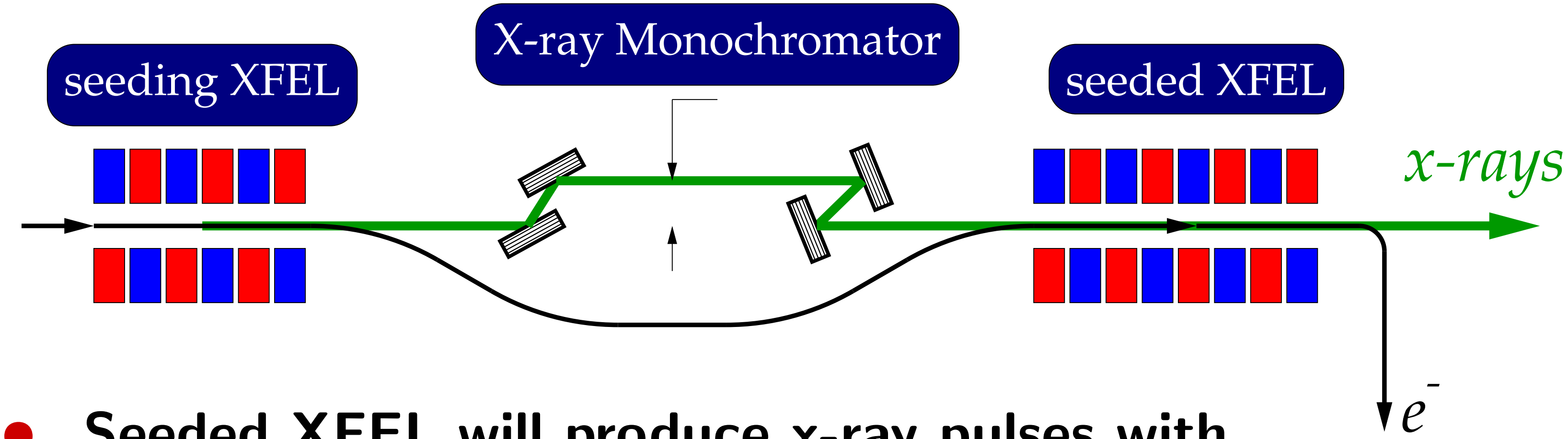
energy spread $\frac{\sigma_E}{E_e} \lesssim 10^{-4}$

peak current $10 - 10^4$ **A**

Resonance condition:

$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + K^2)$$

Seeded (Two-Stage) XFEL



- Seeded XFEL will produce x-ray pulses with
  - $\simeq 9 \times 10^{11}$ photons/pulse (2 mJ/pulse$= 20$ GW)
  - $\simeq 4 \times 10^{16}$ photons/s (100 W)
  - transversly and temporarily coherent
  - $\Delta E \approx 20$ meV (rms) close to the limit given

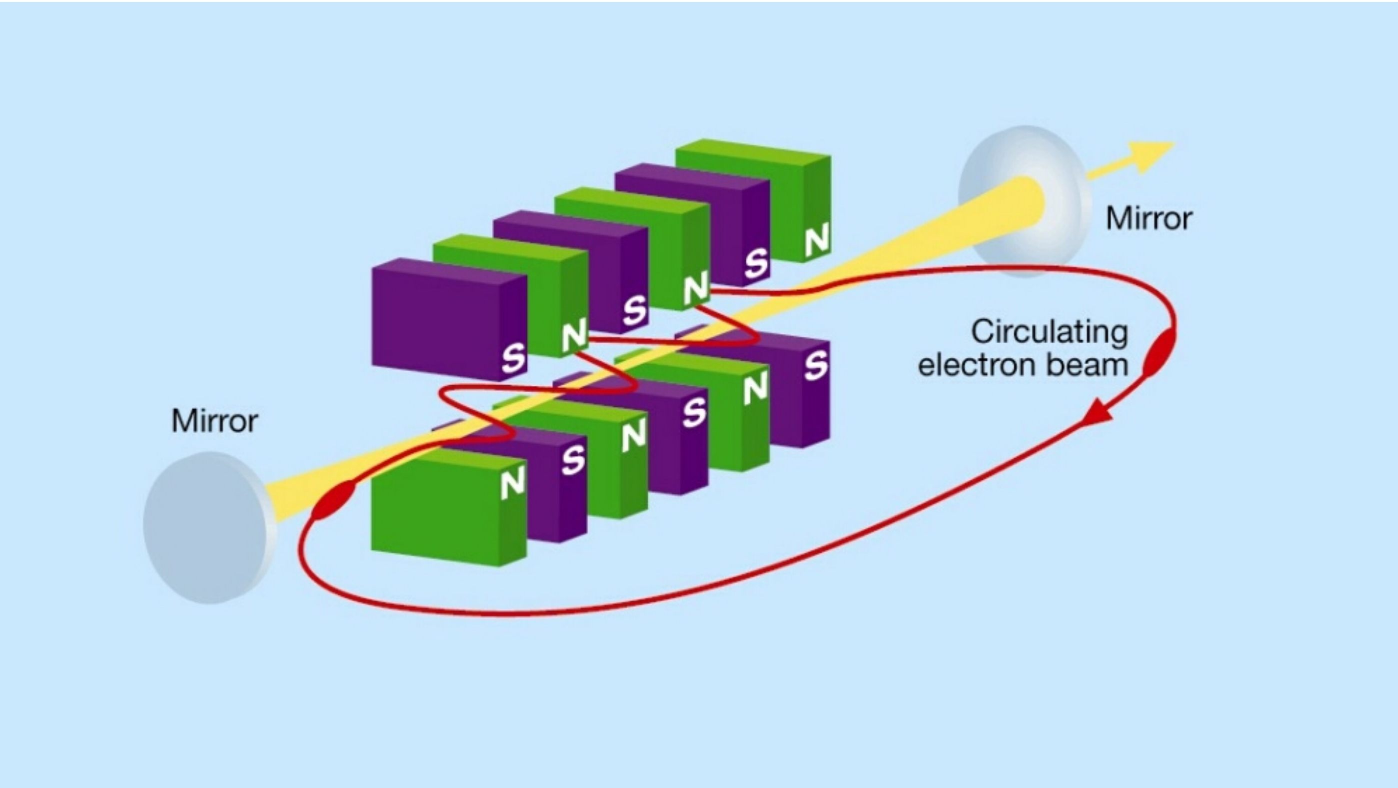
  by the pulse duration $\tau_{\rm e} \approx 0.1$ ps (rms).

- Considered as upgrade of the European XFEL ($>$2014).

- E.L. Saldin, E.A. Schneidmiller, Yu.V. Shvyd'ko, and M.V. Yurkov, "X-ray FEL with a meV bandwidth", NIM, A475 (2001) 357-362.
- The Technical Design Report of the European XFEL, July 2007

Is an XFEL-Oscillator Feasible?

First proposal: Colella and Luccio (1984)



FELs based on the oscillator principle are limited, on the short-wavelength side, to ultraviolet wavelengths, primarily because of **mirror limitations**.

Free-electron lasing at wavelengths shorter than ultraviolet **can be achieved with a single-pass, high-gain FEL amplifier only**.

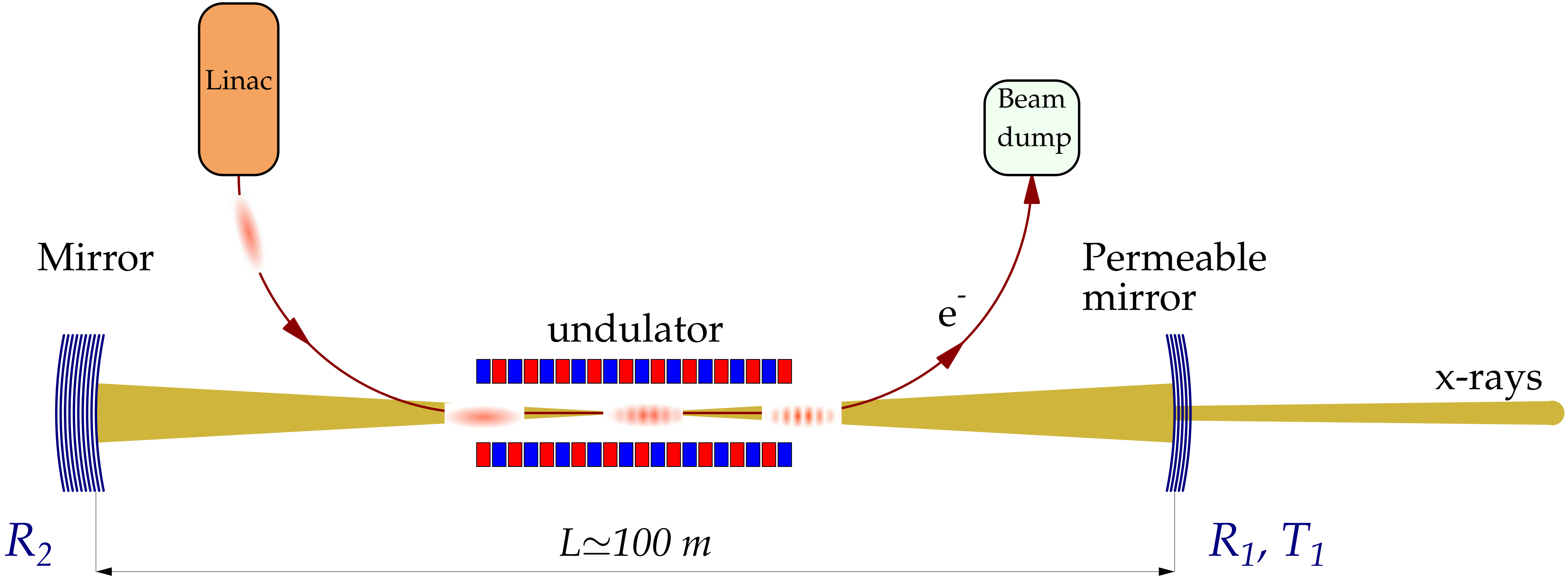
(The Technical Design Report of the European XFEL, July 2007)

XFEL-Oscillator Feasibility

- **Low-gain XFELO is feasible based on:**
  - **low-loss x-ray crystal cavity (losses $\simeq 15\%$),**
  - **ultra-low-emittance ($\varepsilon_{\rm n} \lesssim 10^{-7}$ m rad) electron beams.**

- **K.-J. Kim, Yu. Shvyd'ko, S. Reicher, PRL 100 (2008) 244802.**

X-FEL Oscillator Principles

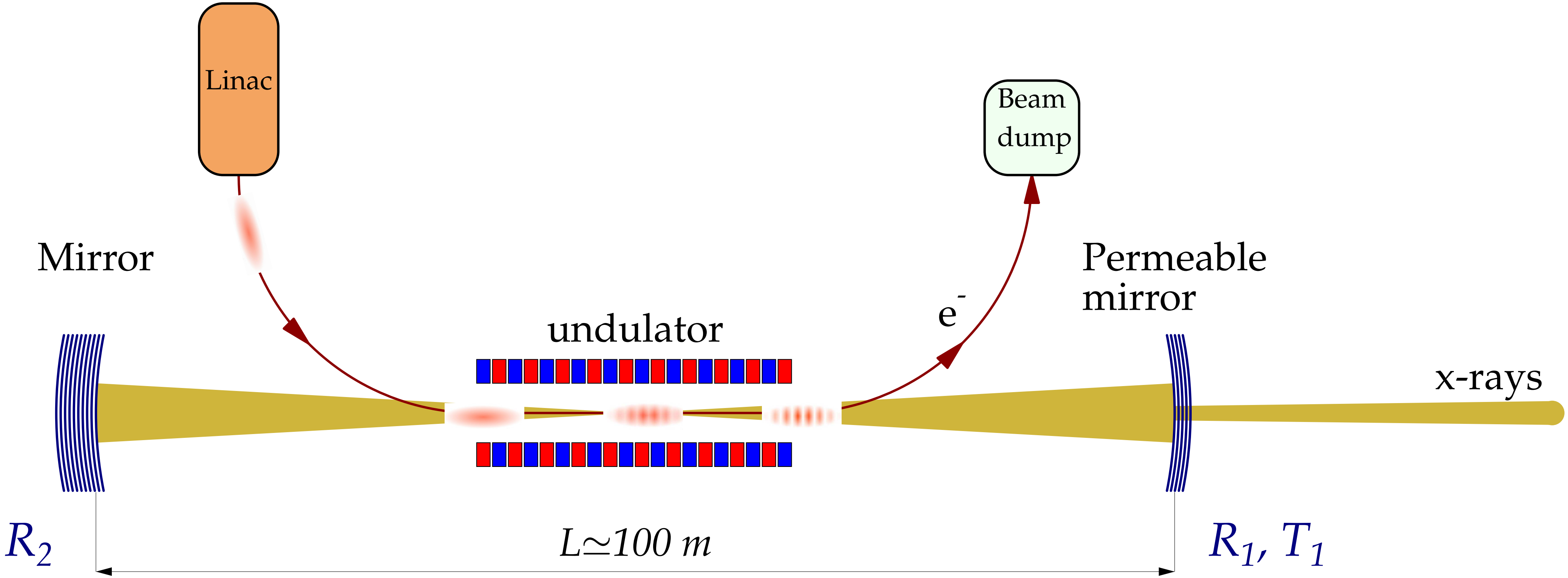


High repetition rate is required: $\nu = c/2L \simeq 1$ MHz.

With $I_\mathrm{p} \simeq 10$ A, $\tau_\mathrm{p} \simeq 1$ ps, $\varepsilon_\mathrm{n} \simeq 10^{-7}$ m rad:

Gain $G > 15$ % is feasible

X-FEL Oscillator Principles



High repetition rate is required: $\nu = c/2L \simeq 1$ MHz.

With $I_p \simeq 10$ A, $\tau_p \simeq 1$ ps, $\varepsilon_n \simeq 10^{-7}$ m rad:

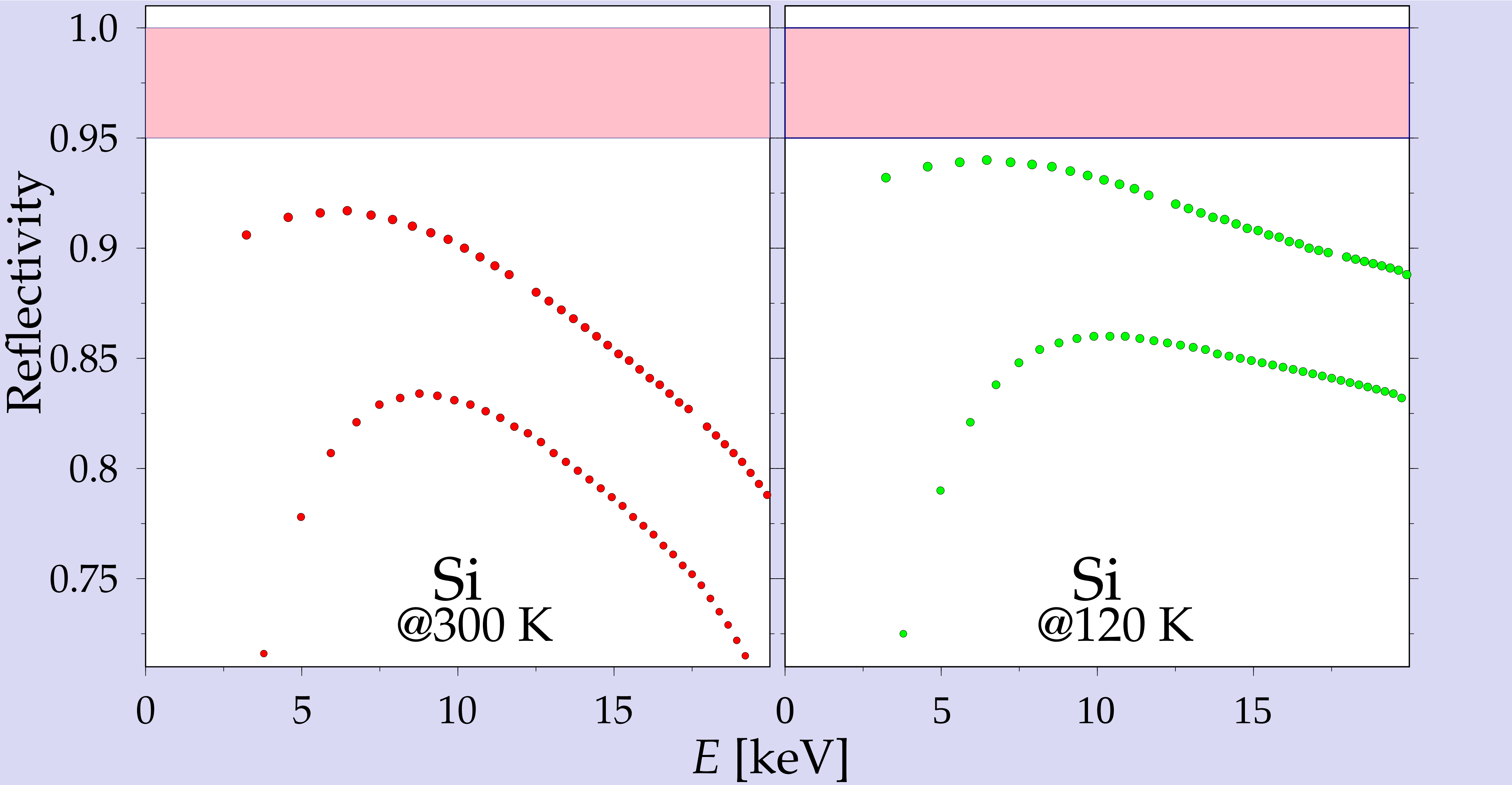
Gain $G > 15$ % is feasible

Small gain requires low-loss optical cavity:

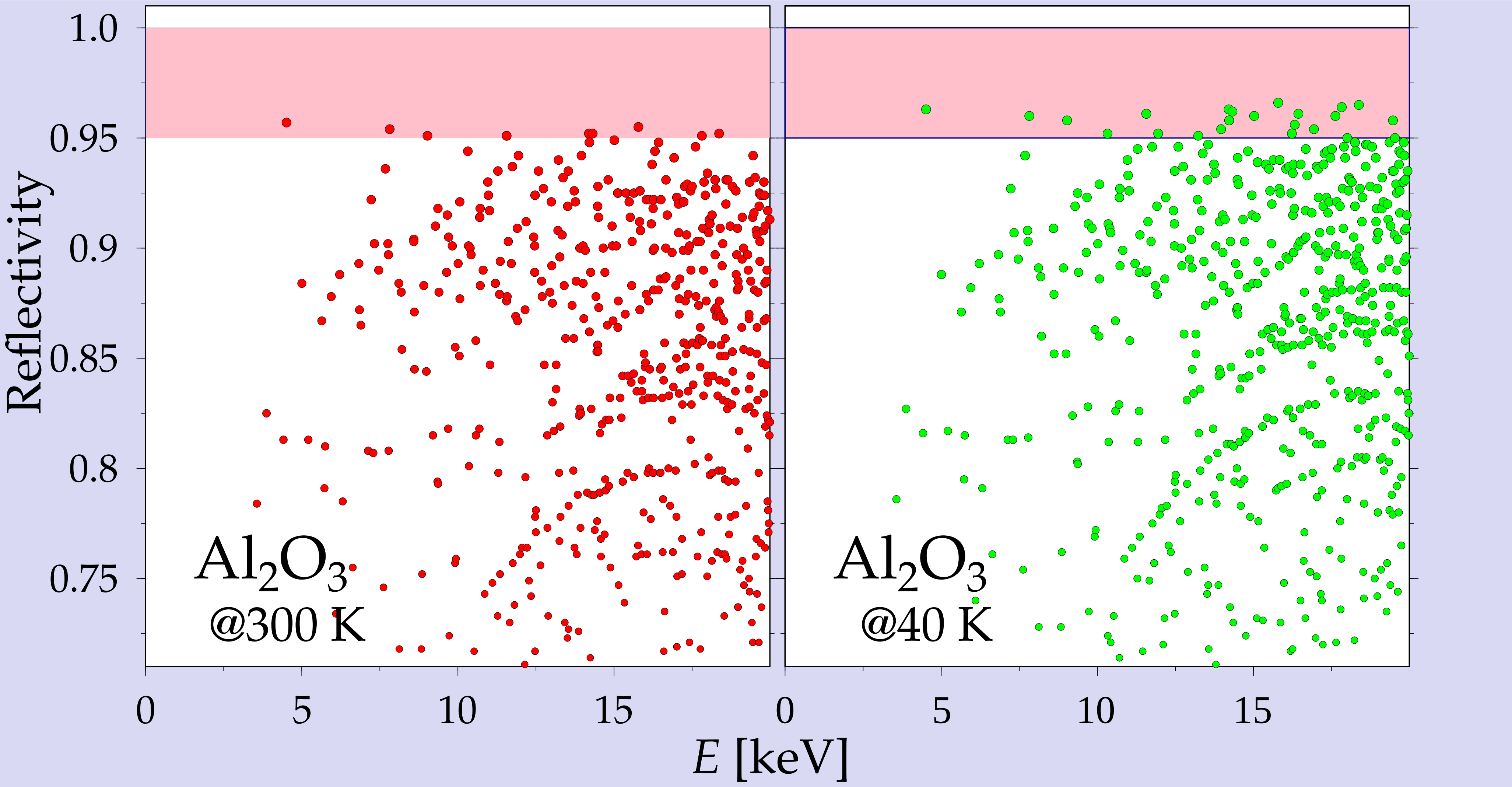
$R_1 \times R_2 > 90\%$

$R_1, R_2 > 95\%$

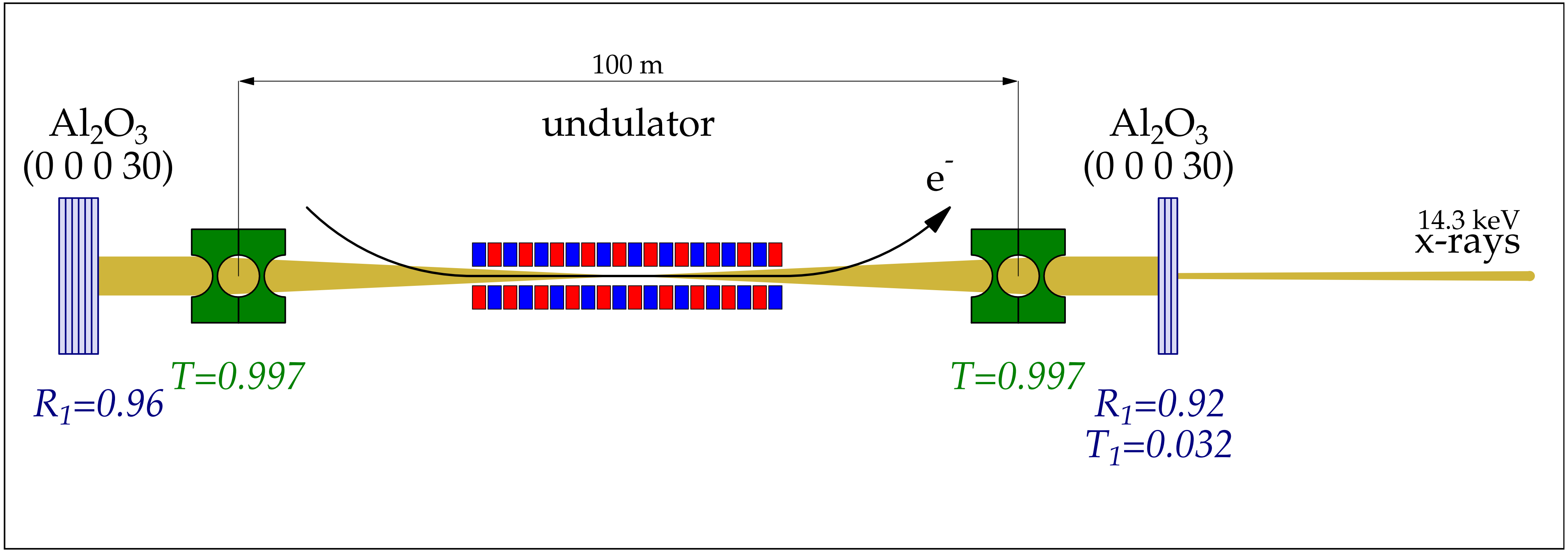
Reflectivity of Si in backscattering



Reflectivity of sapphire in backscattering



Sapphire cavity with CRL



$$R_1 \times R_2 \times T^4 = 0.87$$

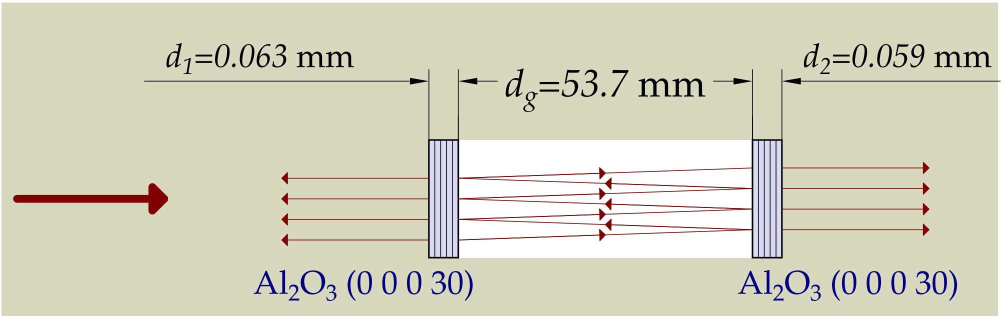
$$T_1 \simeq 0.032$$

CRL: $F = R/2N\delta = 50$ m

$[R = 0.333\ \text{mm};\ N = 2;\ \delta = 1.6 \times 10^{-6}]$

B. Lengeler, C. Schroer, et al, *JSR* **6 (1999) 1153**

Sapphire X-ray resonator demonstrated

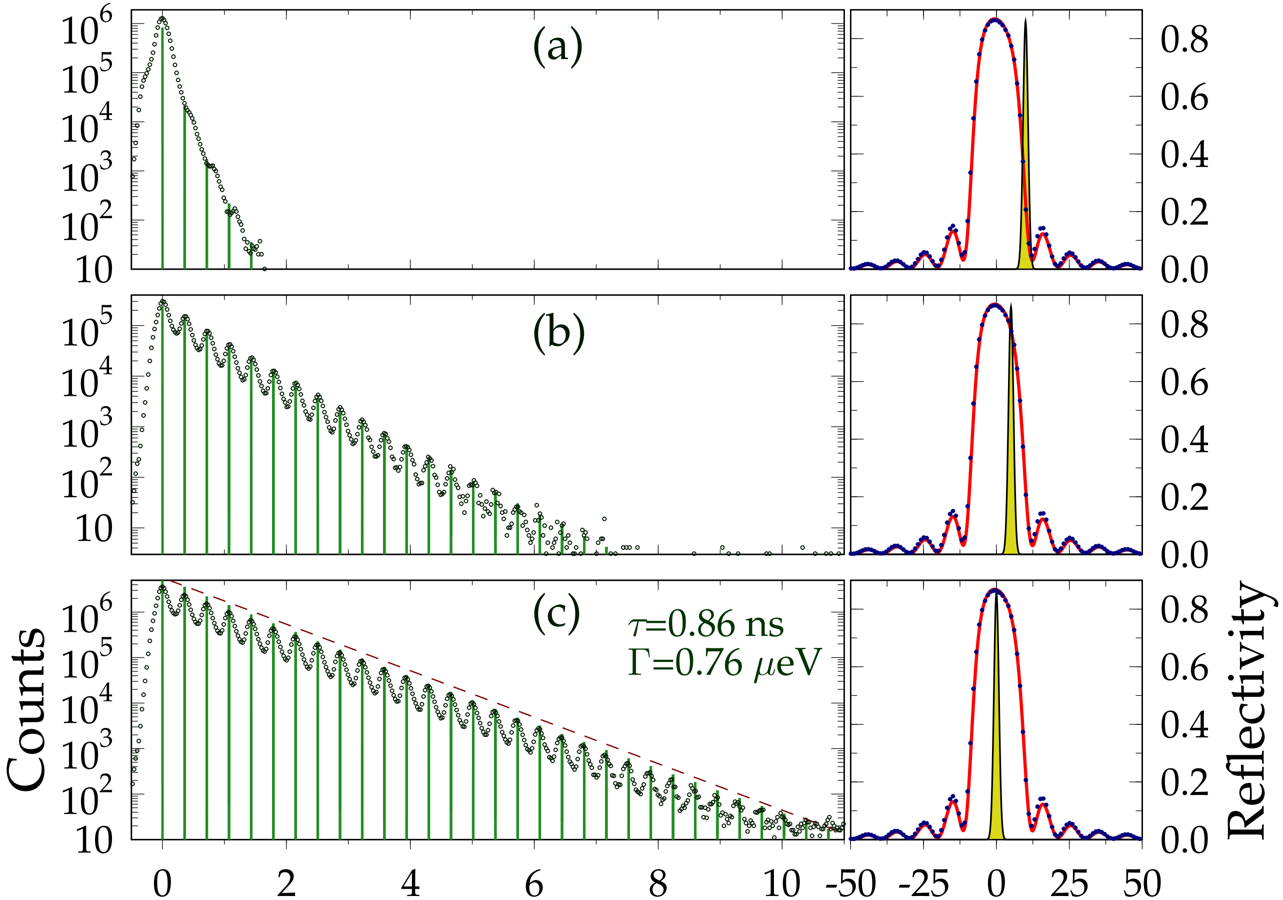


Shvyd'ko, Lerche, Wille et al, *PRL* **90 (2003) 013904**

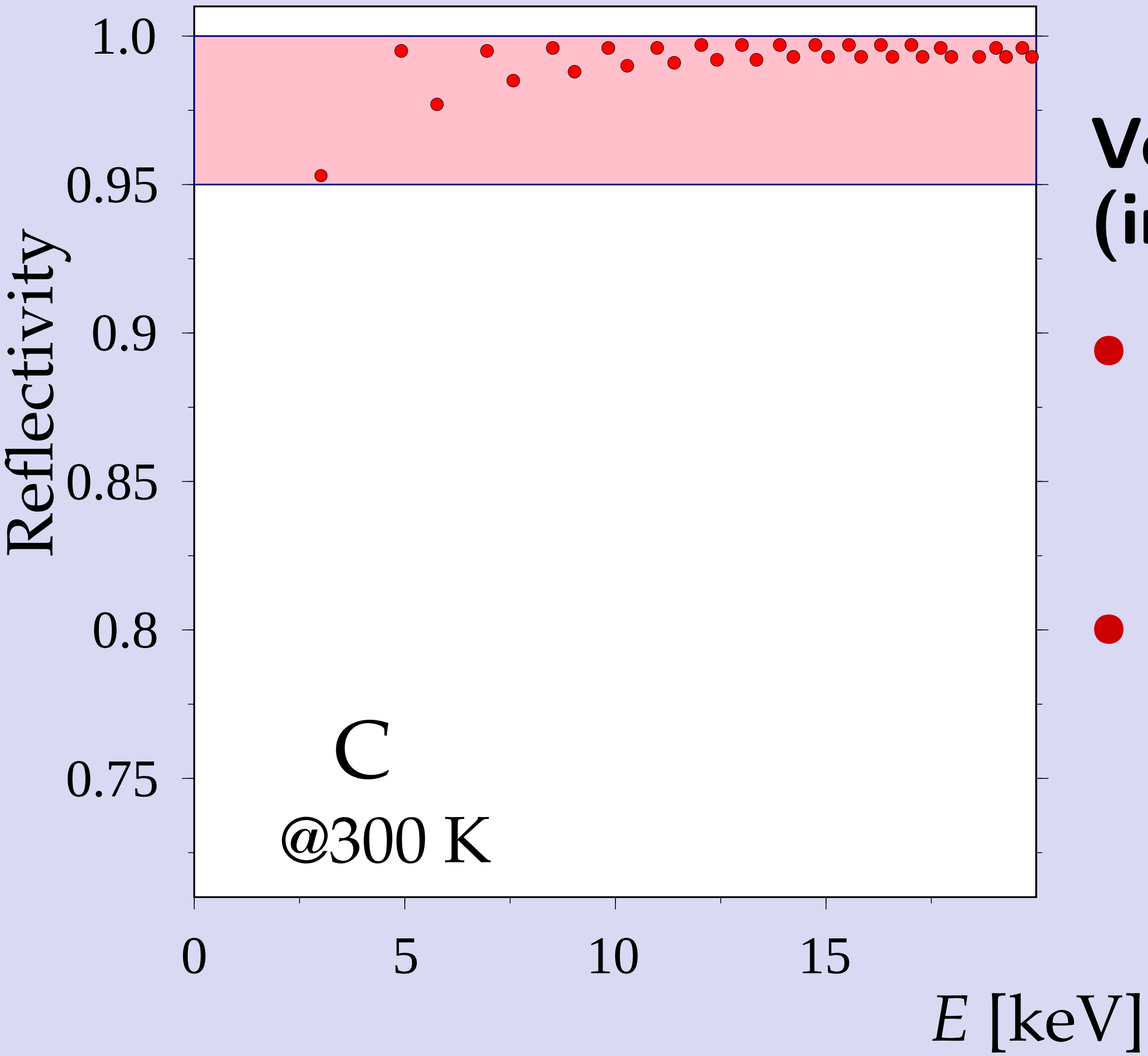
Measured finesse = 15

Measured reflectivyty = 0.82

Expected reflectivyty = 0.86



Reflectivity of diamond in backscattering



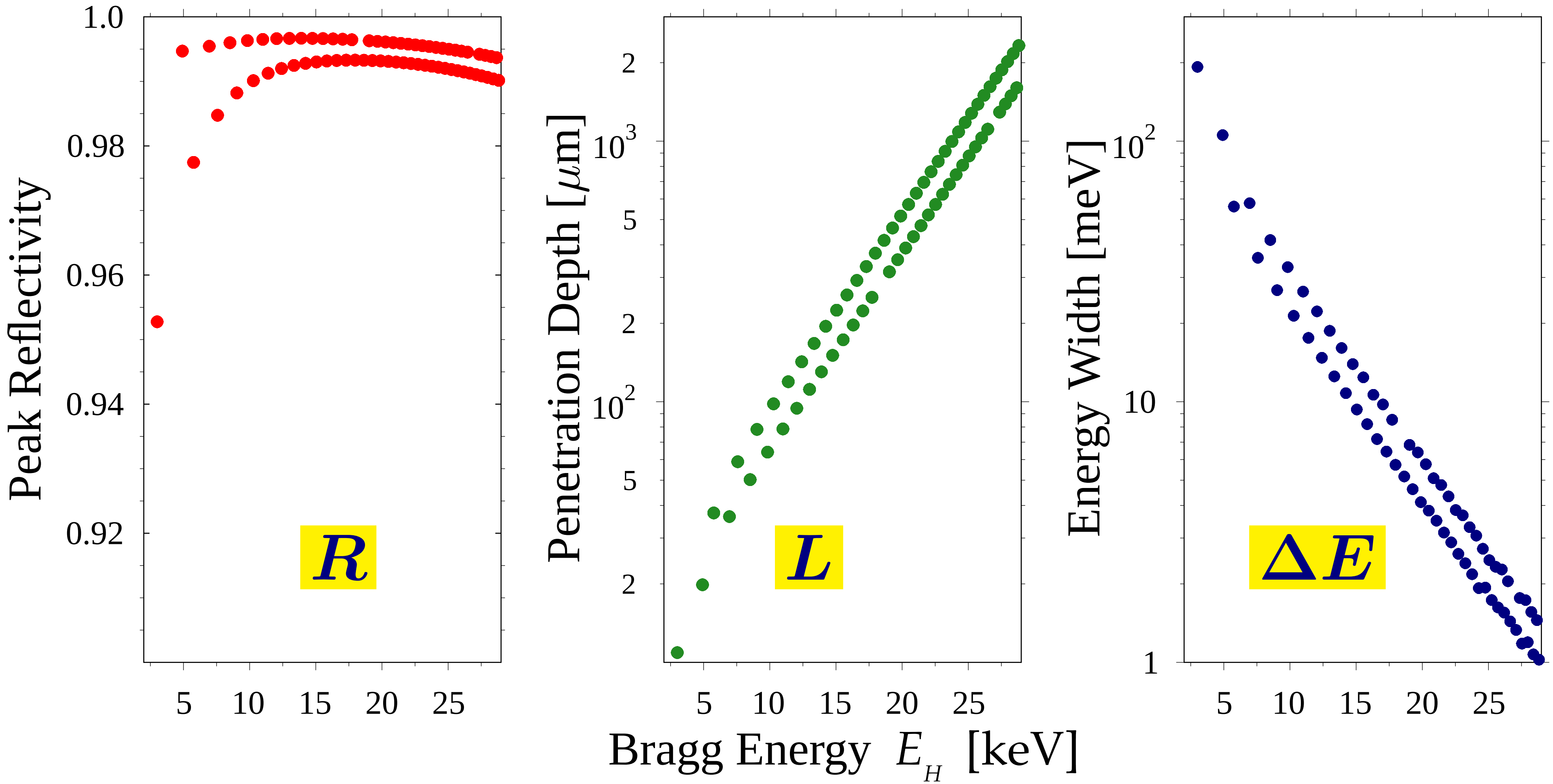
Very high reflectivity (in theory) due to:

- **High Debye Temterature, and thus high Debye-Waller factor**
- **Low Z, low photo absorption**

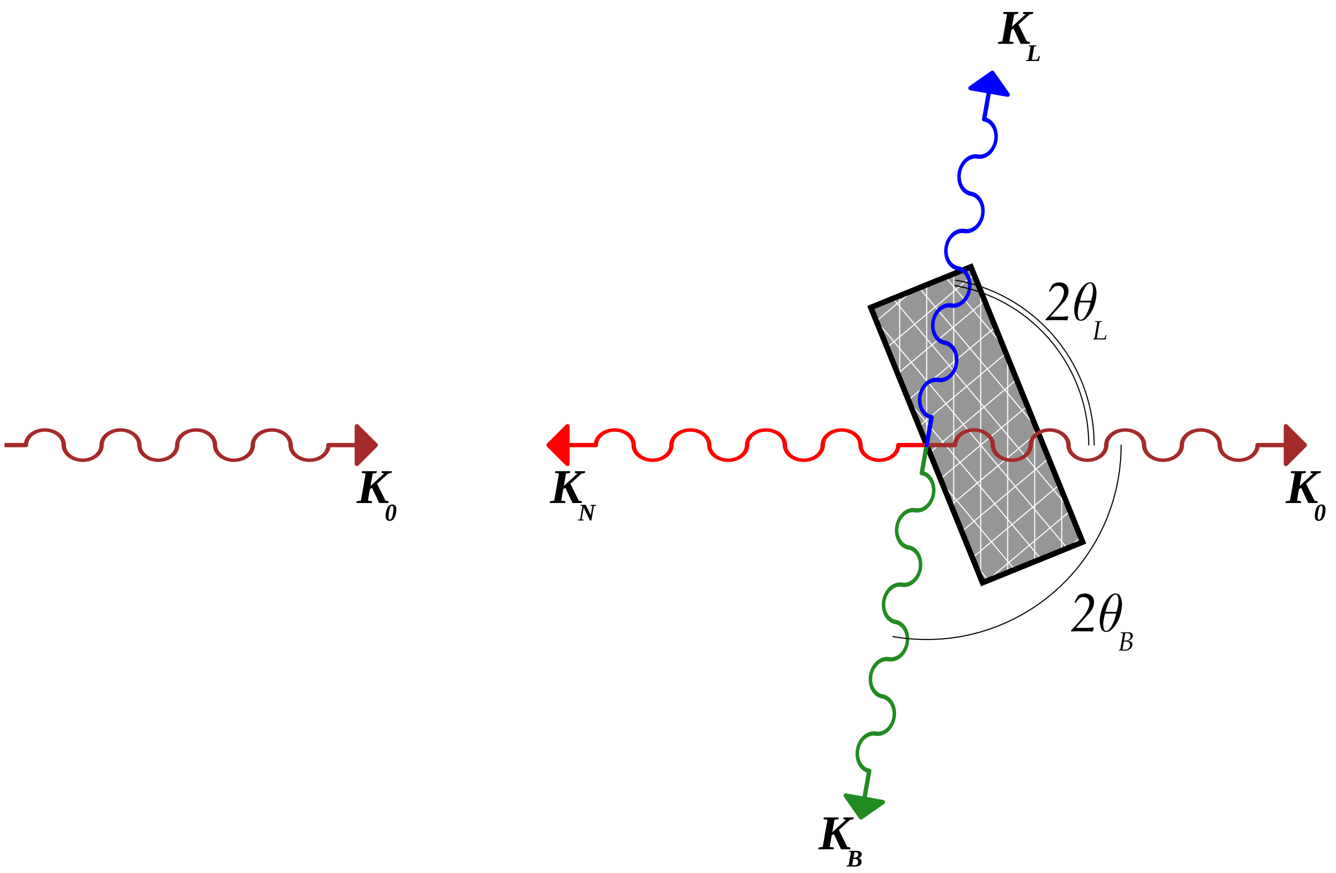
Reflectivity vs. Penetration & Energy Width

R, L, and ΔE are interconnected.

$\Delta E \propto 1/L$



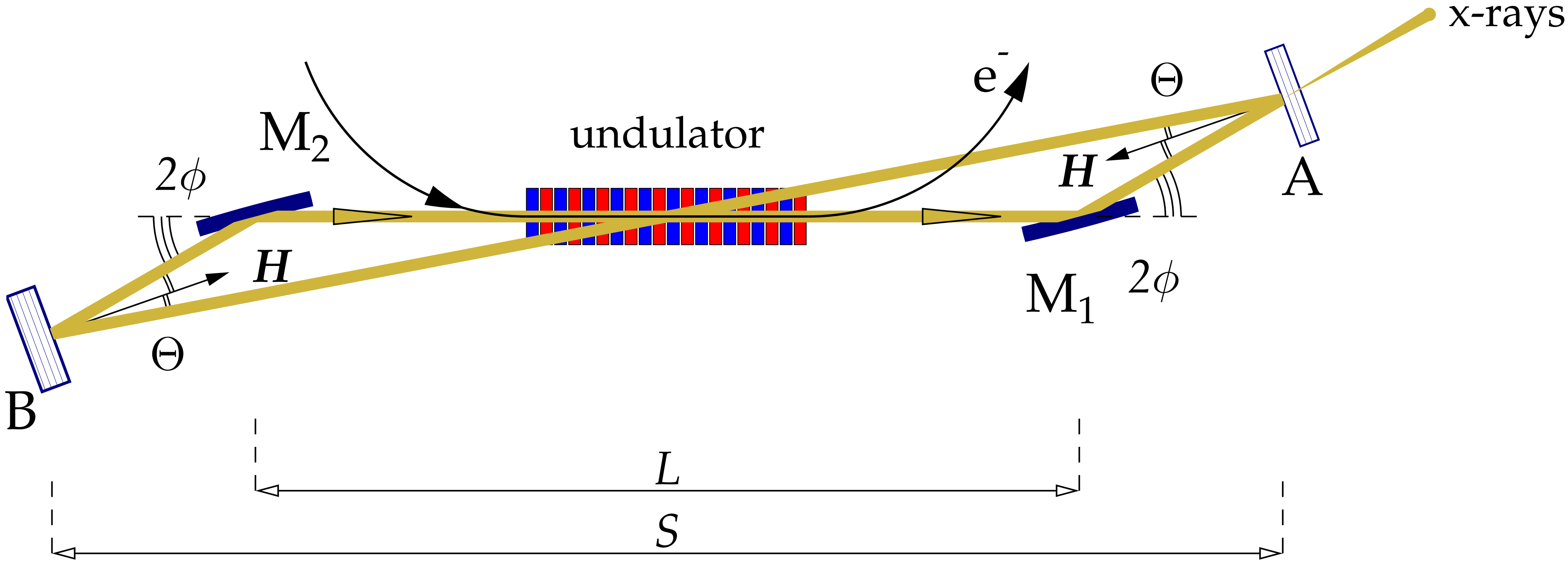
Multiple-beam Bragg Diffraction in Backscattering



Bragg-reflection condition can be fulfilled simultaneously for more than one reflecting atomic plane. In backscattering from Si, C, crystal this happens for all Bragg reflections except (111) and (220).

Si and C are not favorable as X-ray exact-backscattering mirros

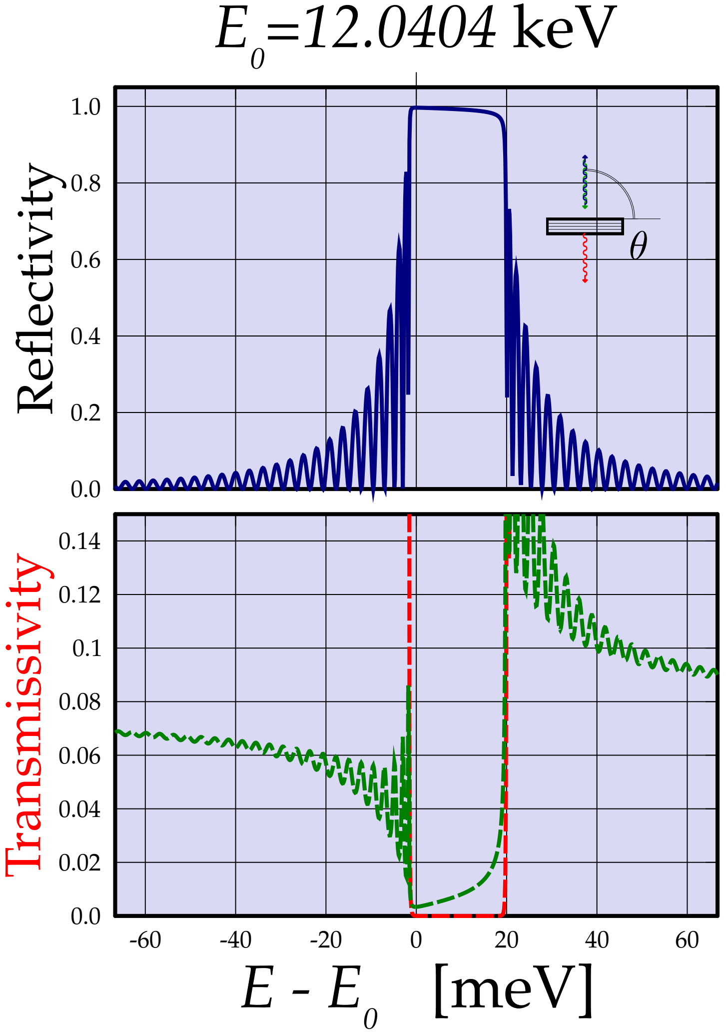
Diamond cavity for the X-FEL Oscillator



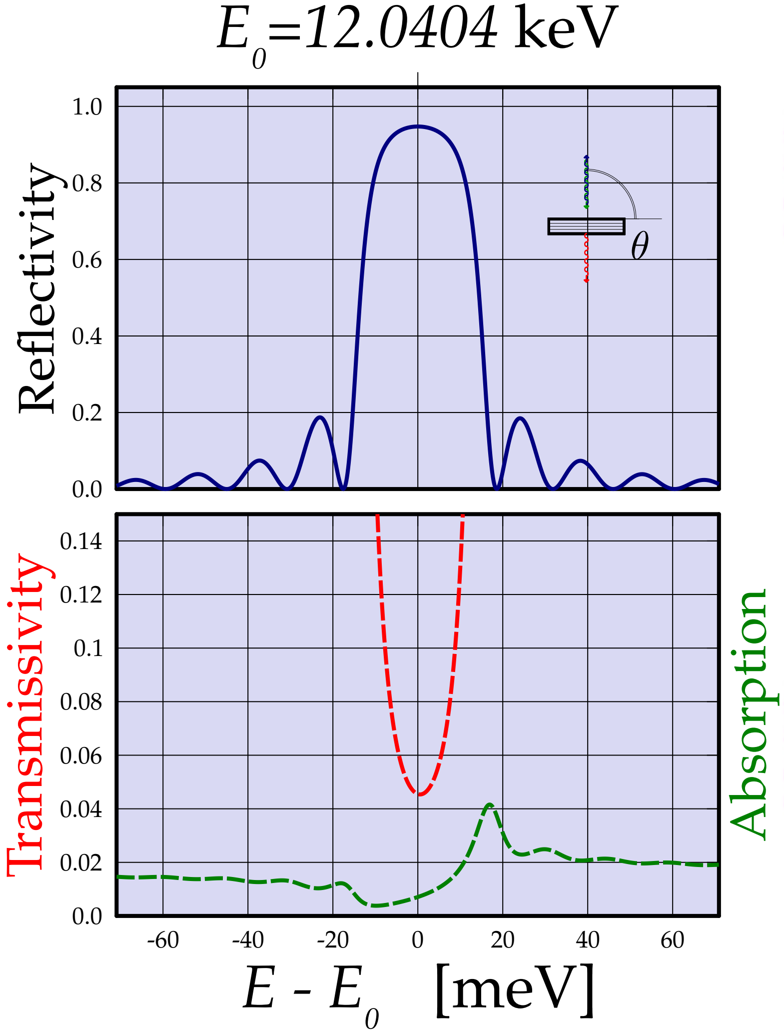
$$R_A \times R_B \times R_{M_1} \times R_{M_2} \simeq 0.9 \qquad T_A \simeq 0.04$$

Diamond crystal and mirror reflectivity @ 12 keV

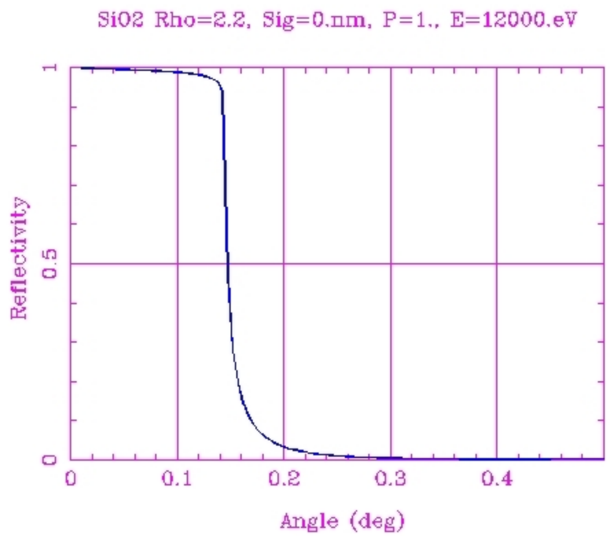
Narrow band mirrors: $\Delta E \approx 10$ meV; $\Delta E \approx \hbar/\tau_p$

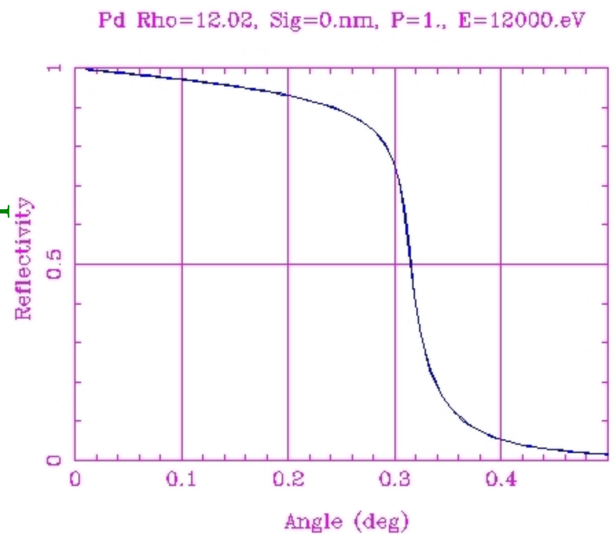


C(4 4 4); L = 0.2 mm; T = 300 K
bradix version: January, 2007



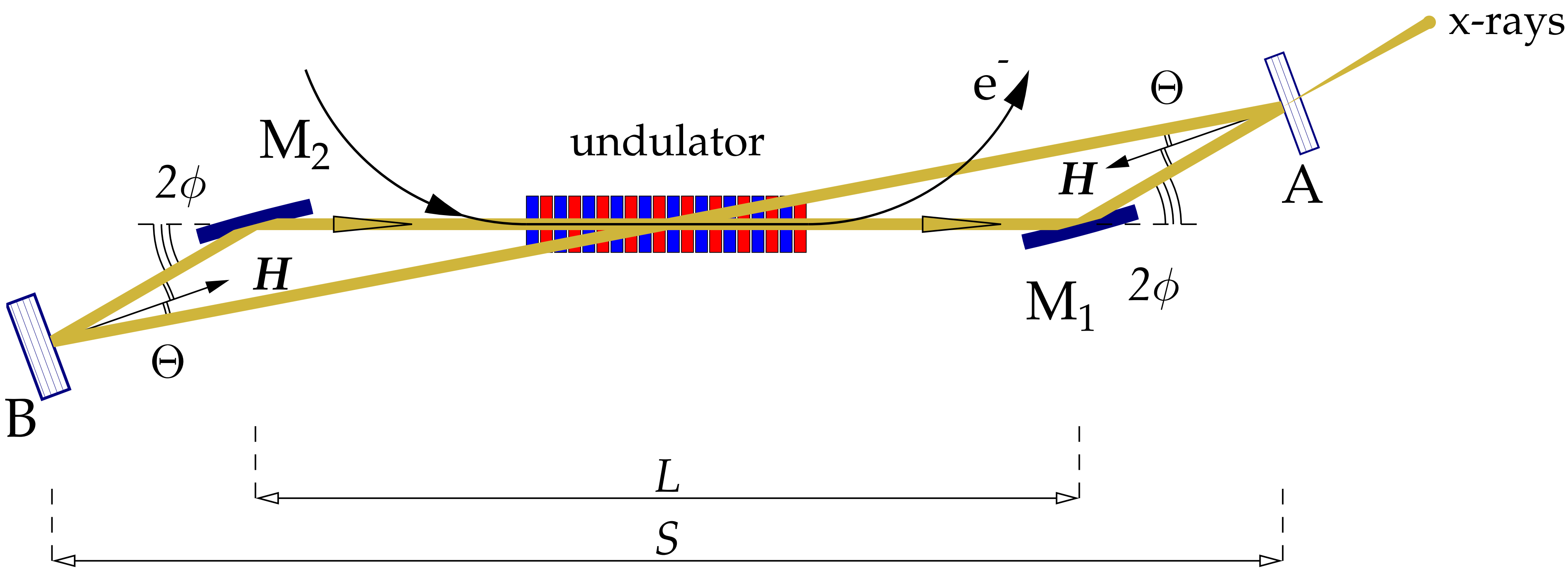
C(4 4 4); L = 0.042 mm; T = 300 K
bradix version: January, 2007





Mirror calculations:
www-cxro.lbl.gov

Two-Crystal Cavity is not Tunable

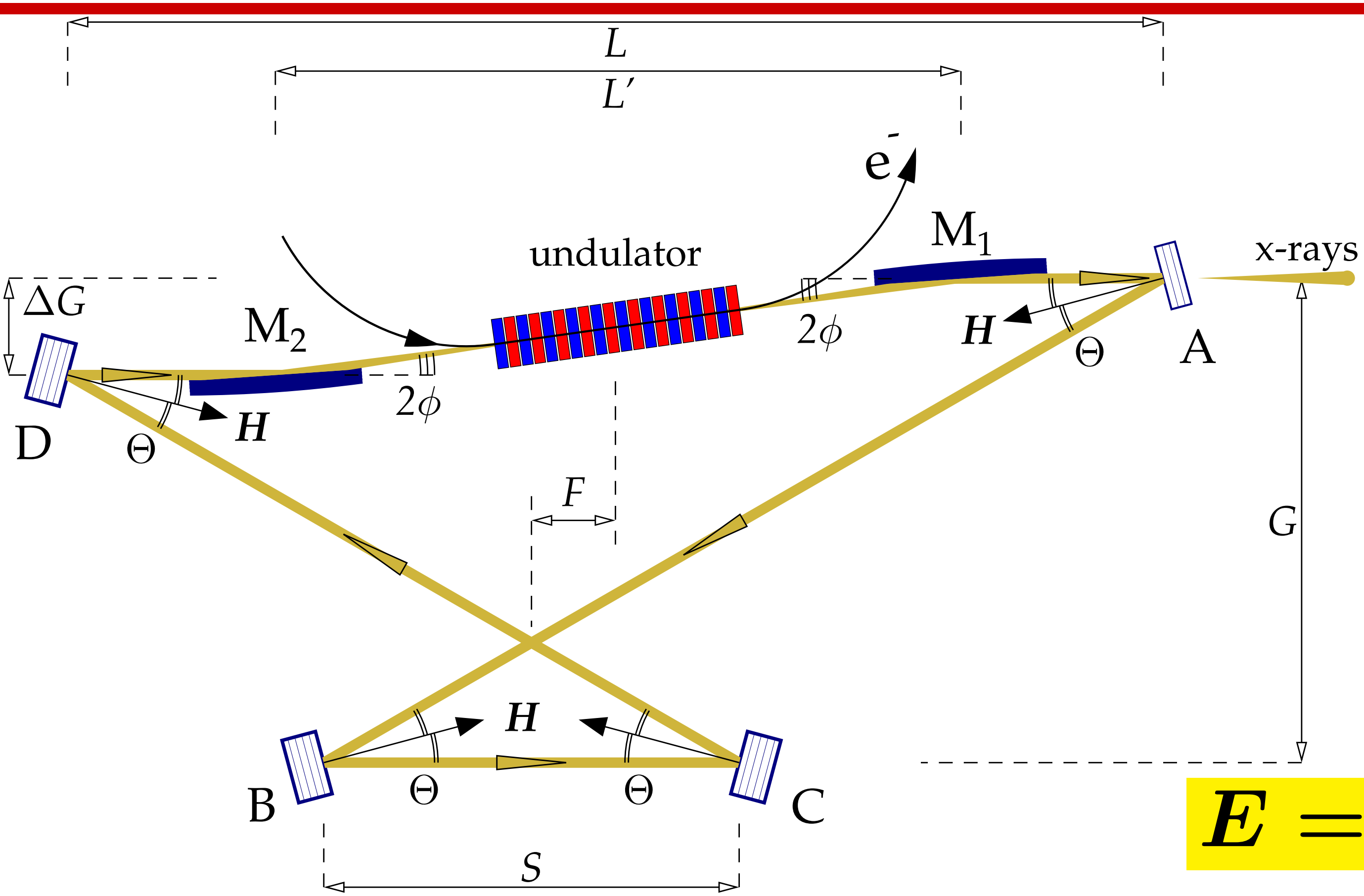


$E = E_H \cos\Theta \quad \Rightarrow$ **Two-crystal scheme is not tunable.**

Because, it is necessary to keep small $\phi \lesssim 2$ mrad

and therefore small $\Theta \lesssim 2$ mrad, for high reflectivity of the mirrors.

Tunable Cavity



$$E = E_H \cos\Theta$$

A four-crystal (A,B,C, and D) x-ray optical cavity allows photon energy E tuning in a broad range by changing the incidence angle Θ.

R.M.J. Cotterill, Appl. Phys. Lett., 12 (1968) 403

K.-J. Kim, and Yu. Shvyd'ko, Phys. Rev. STAB (2009)

XFELO Simulations

R. Linberg, K.-J. Kim, W. Falley, Yu. Shvyd'ko

- **Undulator:**

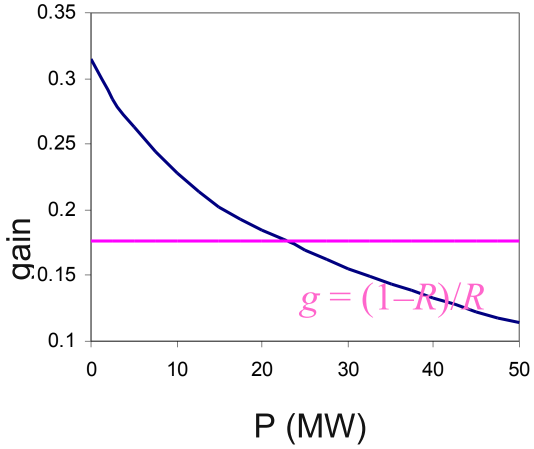
  $\lambda_u = 1.76$ cm K = 1.5

- **Electron beam:**

  $I = 10$A $\varepsilon_x = 2\times10^{-7}$ $\beta_x = 10$ m

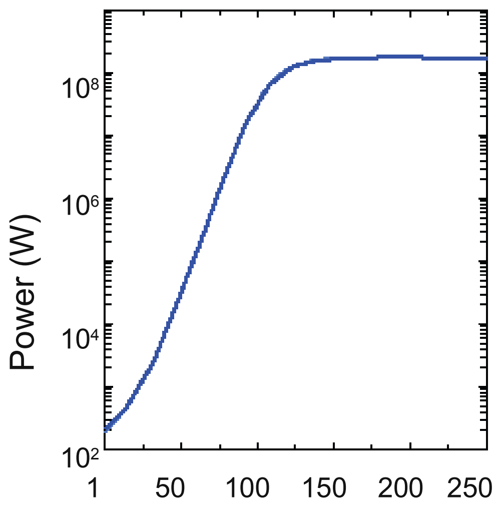
- **Bragg crystal:**

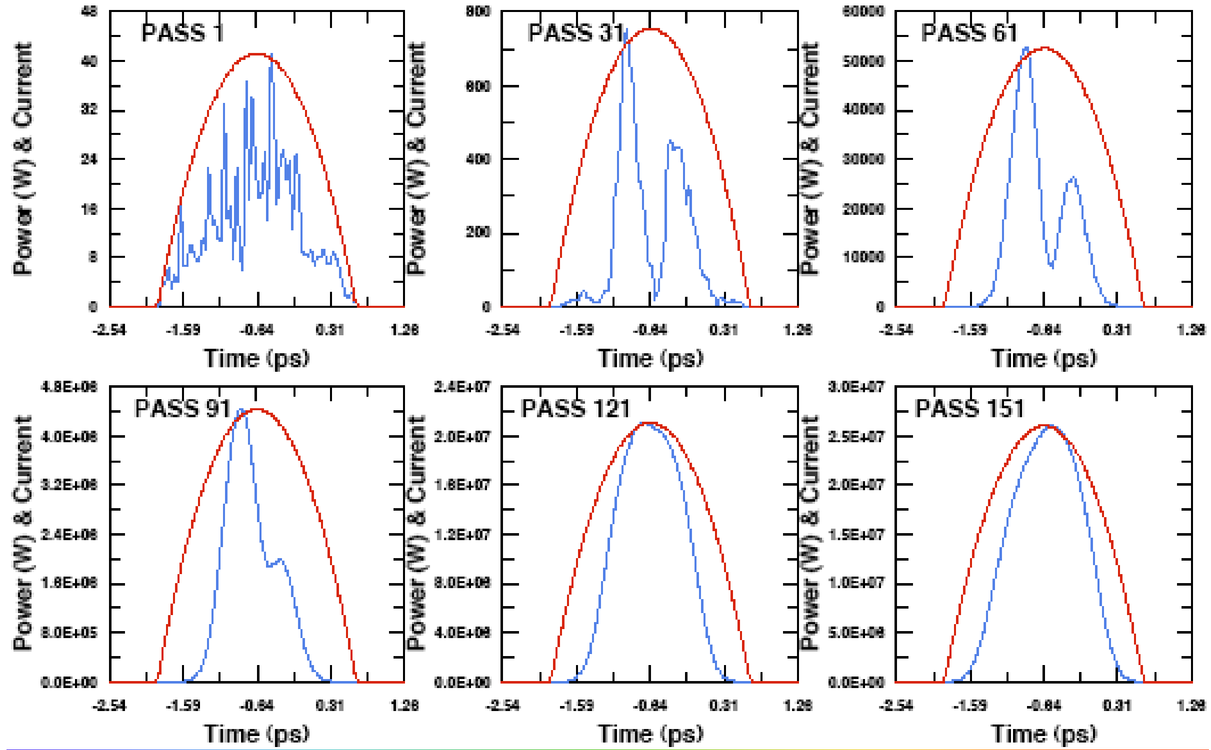
  Diamond, $\tau_M \approx 100$ fs



Single slice gain calculations indicate saturation power ~23 MW for mirror losses = 85%

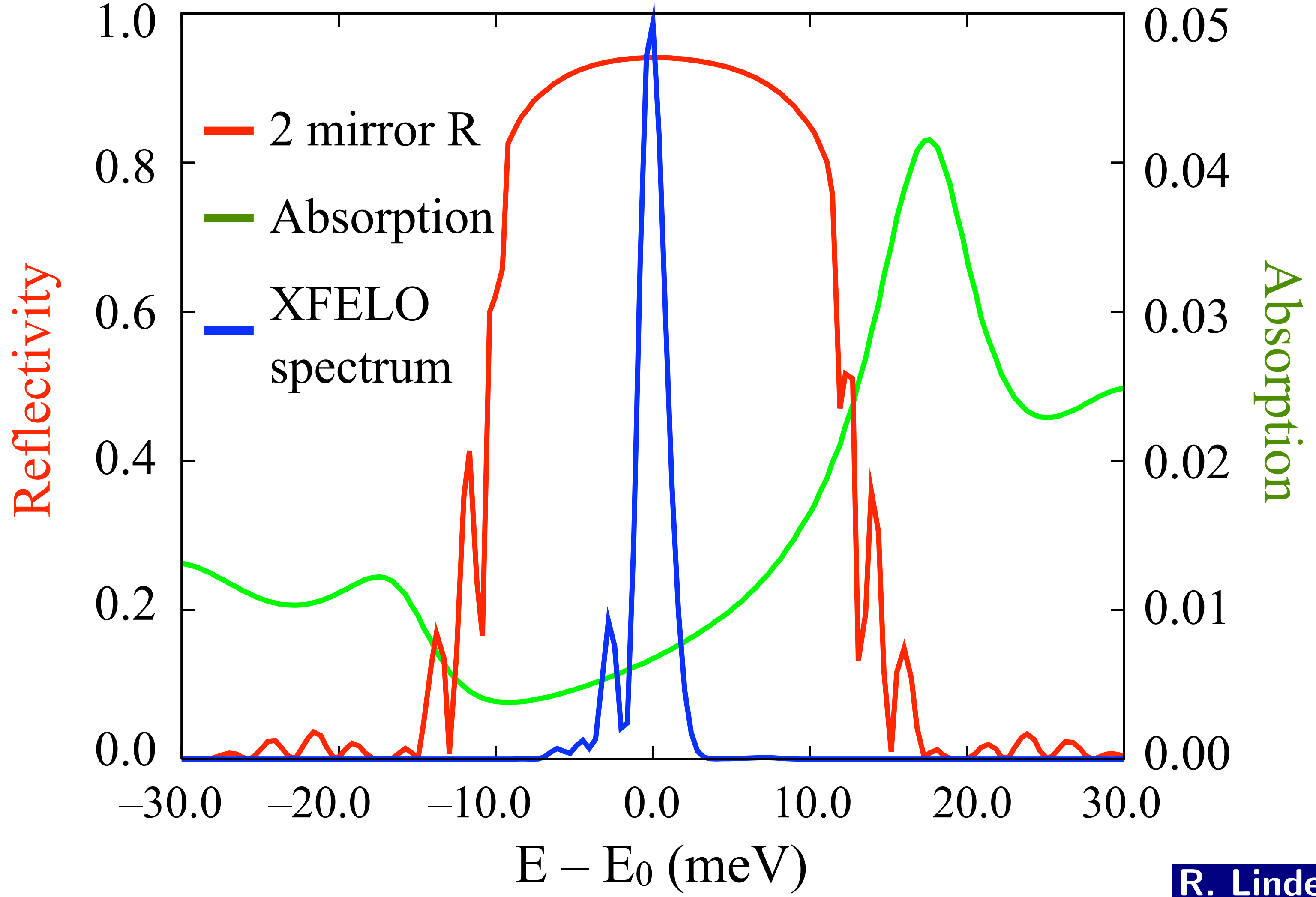
GINGER simulation shows evolution from noise to power levels near those expected





XFELO Spectrum

After 500 passes in 2-crystal diamond cavity:



R. Lindenberg et al.

XFEL-O Performance

- Photon spectral range: $2 \lesssim E \lesssim 25$ keV.
- Full transverse and temporal coherence of ≈ 1 ps (rms) $\Longrightarrow$ $\Delta E \simeq 2$ meV.
- 5×10^8 photons/pulse (1 μJ/pulse)
- Peak spectral brightnes comparable to SASE XFEL.
- Repetition rate $\gtrsim 1.5$ MHz $\Longrightarrow$ (7.5×10^{14} ph/s = 1.7 W) average spectral brightness factor $\simeq 10^5$ larger than SASE XFEL, and comparable to the seeded SASE XFEL.
- Being operated at 14.4 keV, XFEL-O would generate $\approx 10^3$ Mössbauer photons per pulse with a 5 neV spectral width, the natural with of the 14.4 keV nuclear resonance in ^{57}Fe. With a repetition rate of $\gtrsim 10^6$ Hz, the XFEL-O would produce about 10^9 fully coherent 14.4 keV Mossbauer photons per second.
- Tunable.

Science drivers for XFEL-O

Many x-ray spectroscopies and techniques require hard x-rays ($E \gtrsim 2$ keV) with very narrow energy bandwidth $\Delta E \lesssim 1$ meV i.e. temporal coherence $\gtrsim 1$ ps:

- **Inelastic x-ray scattering (IXS).**
- **Nuclear resonant scattering (NRS).**
- **HAXPES (hard-xrays photoemission spectroscopy).**
- **Imaging with hard x-rays at near-atomic resolution ($\simeq 1$ nm).**
- **Time-resolved (ps) measurements (structure, dynamics).**
- **Metrology: Mössbauer wavelength standard for atomic scales.**
- **etc, etc.**

Technical Challenges

Ultra-low emittance injector.

X-ray Optics:

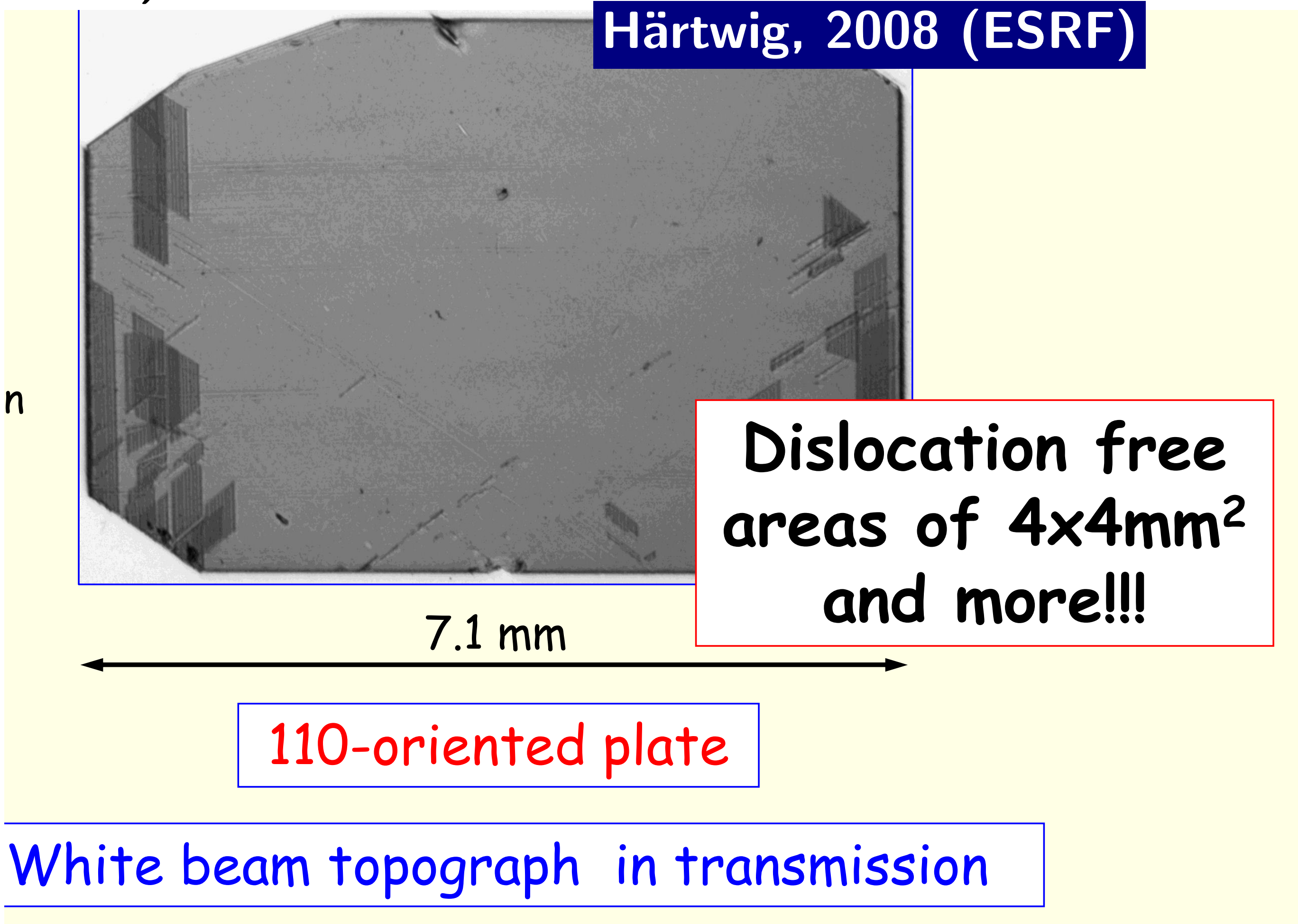
- **Quality of diamond crystals:**
  is the theoretical reflectivity achievable?
- **Heat load problem (reflection region variations $\lesssim 1$ meV).**
- **Angular stability: $\delta\theta \lesssim 10$ nrad**

  Spatial stability: $\delta L \lesssim 3\ \mu$m (rms) $\quad\longrightarrow\quad \delta L/L \lesssim 3\times 10^{-8}$

Quality of Diamond crystals

Required diamond crystals:

- high quality (dislocation free, etc.)
- thin: $\lesssim 200\ \mu m$
- small suffice: $\simeq 1\ mm^2$

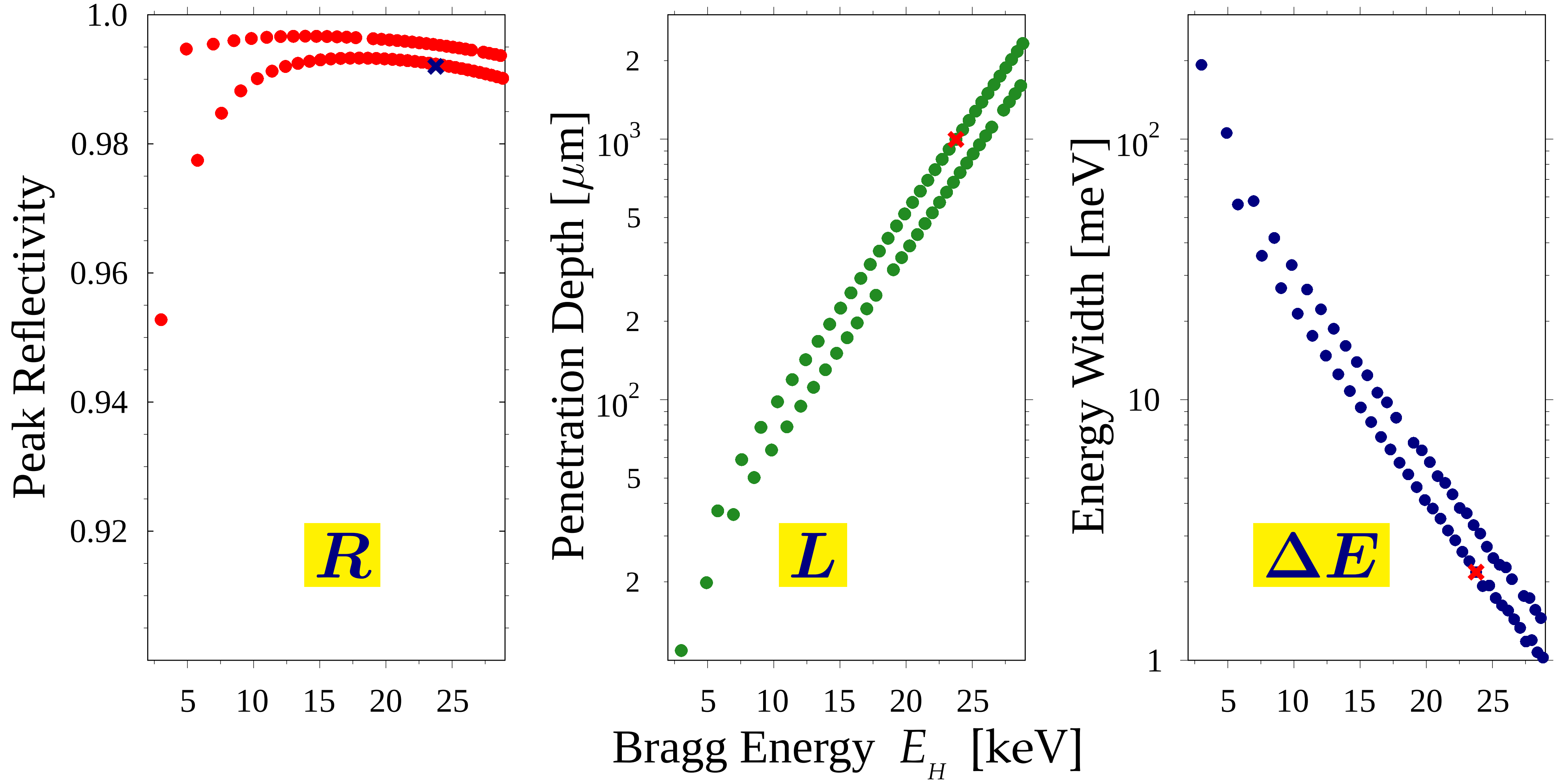


Still open question:
is the theoretical reflectivity achievable?

Reflectivity vs. Penetration & Energy Width

R, L, and ΔE are interconnected.

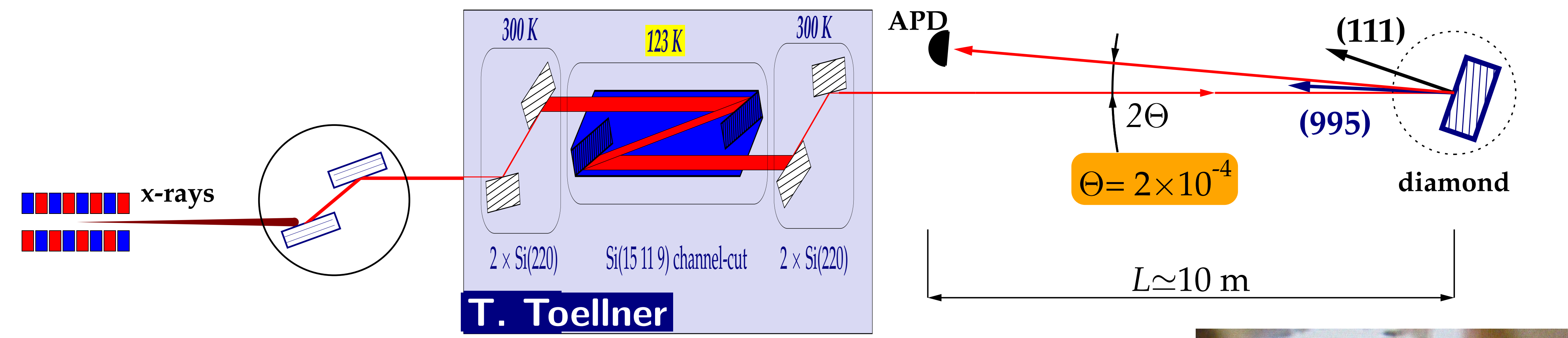
$\Delta E \propto 1/L$



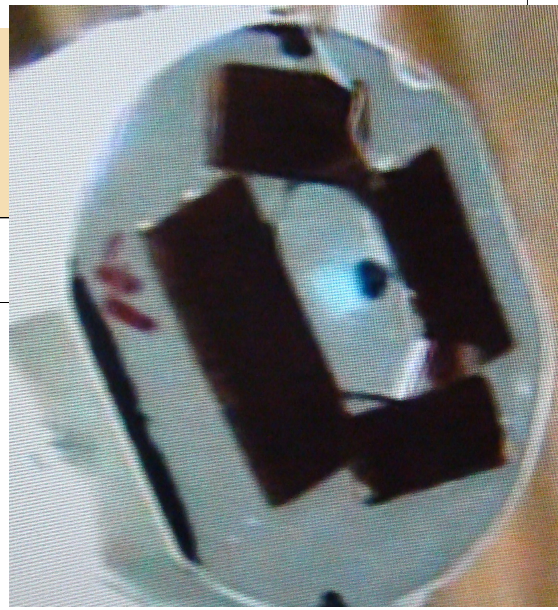
Smallness of ΔE is a hallmark of high quality crystal

Experiment, Sector 30 @ APS, March 2009

S. Stoupin, Yu. Shvyd'ko, A. Cunsolo



undulator	C(111) cooled monochromator	high-resolution monochromator E=23.7 keV
bandwidth $\approx$100 eV	bandwidth $\approx$1.7 eV	bandwidth $\Delta E \approx$ 1 meV



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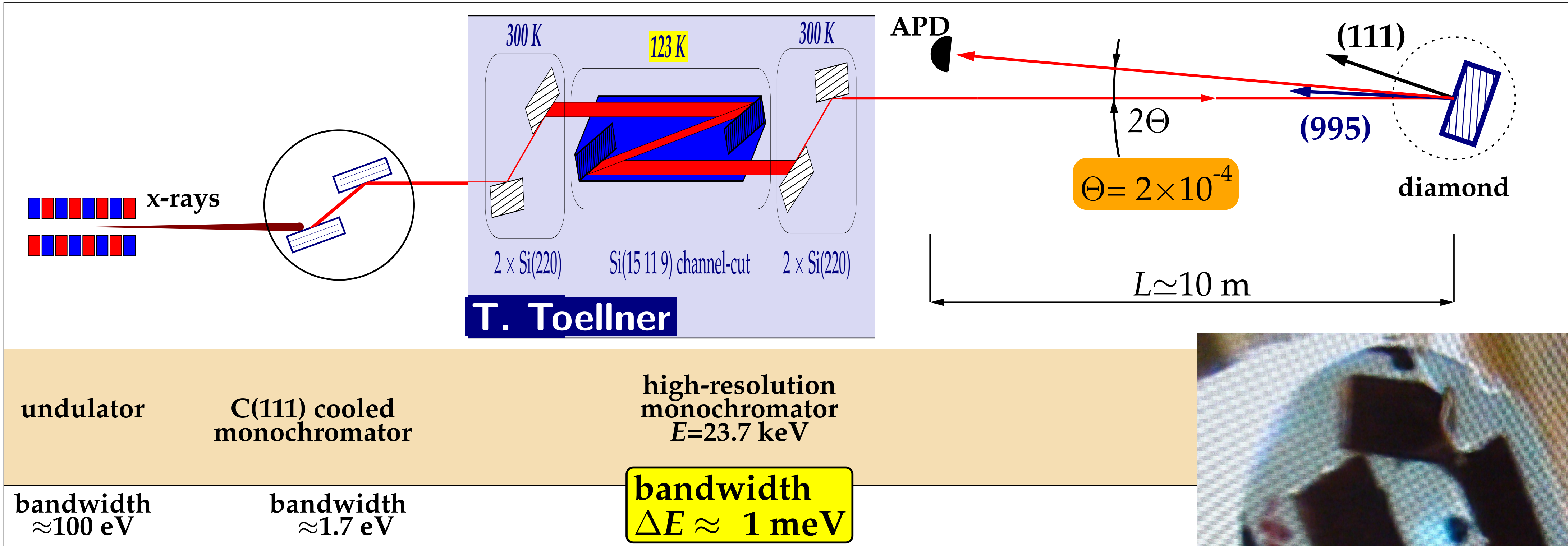
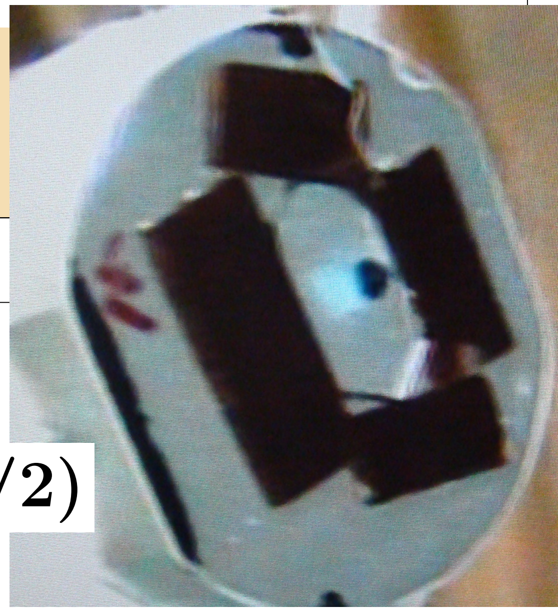




Bragg's law: $\lambda = 2d \sin\theta$

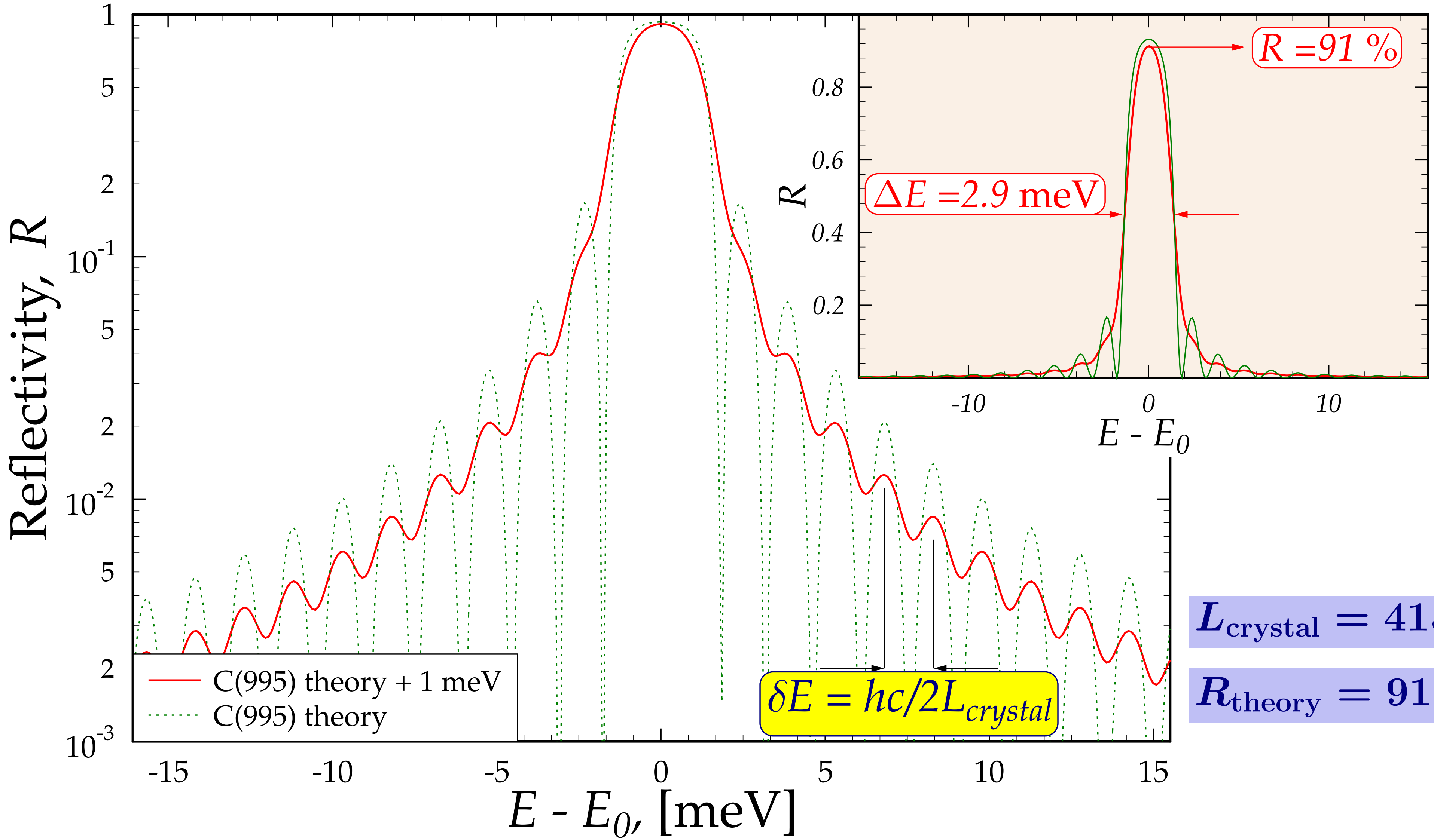
$\theta = \pi/2 - \Theta$ ... **in backscattering:** $\lambda = 2d(1 - \Theta^2/2)$

$E = E_H(1 + \Theta^2/2),\ E_H = hc/2d$

Uncertainty: $\delta E/E_H = \Theta\delta\Theta \ll 10^{-8} \Rightarrow \delta E \ll 0.1$ **meV**

Spectral Width and Reflectivity: Theory

C(995), $E_H = 23.765$ keV



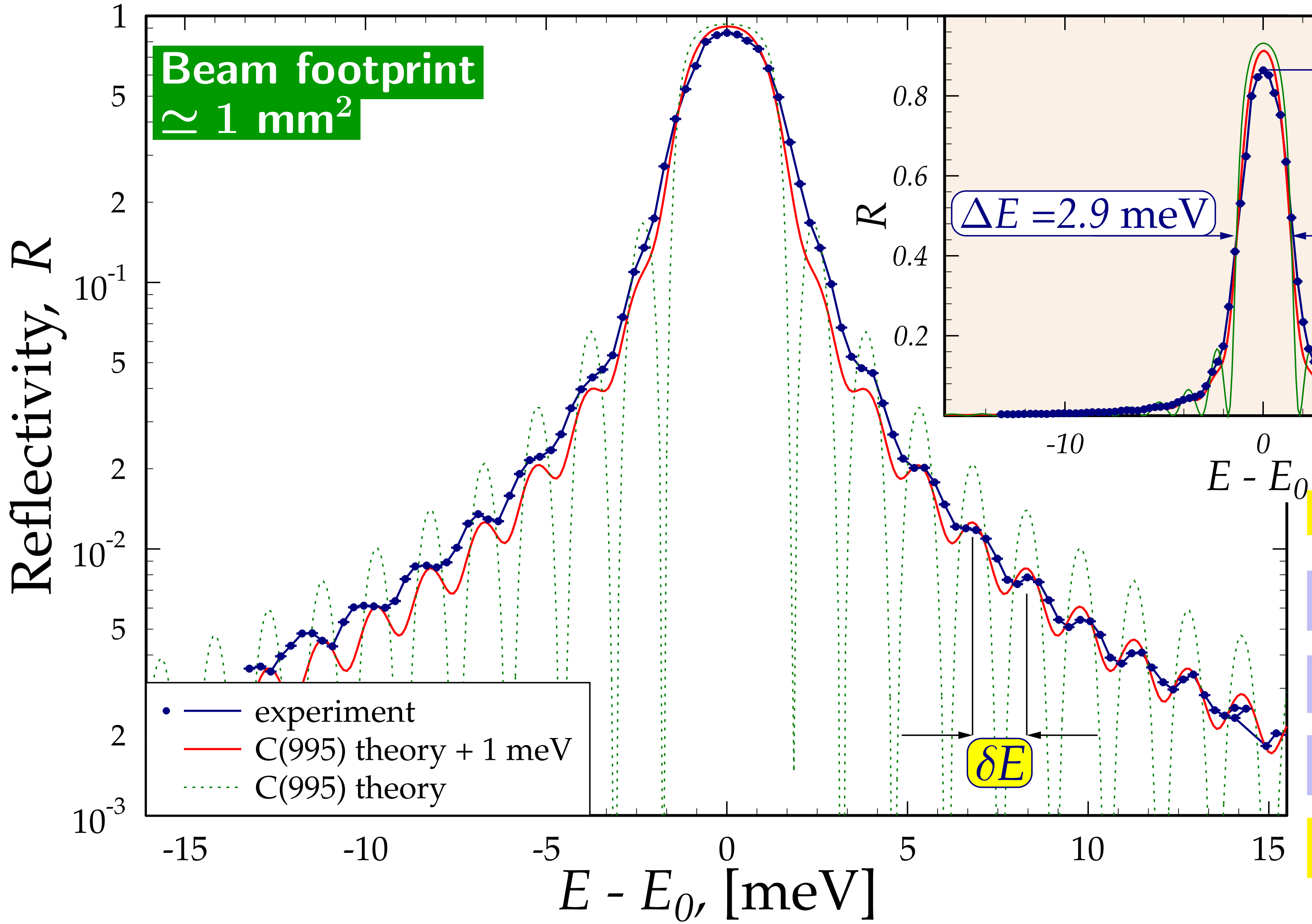
$L_{\text{crystal}} = 415 \mu m$

$R_{\text{theory}} = 91\%$

Spectral Width and Reflectivity: Experiment

C(995), $E_H = 23.765$ keV

Yu. Shvyd'ko, S. Stoupin, A. Cunsolo



$\delta E = 1.5$ meV

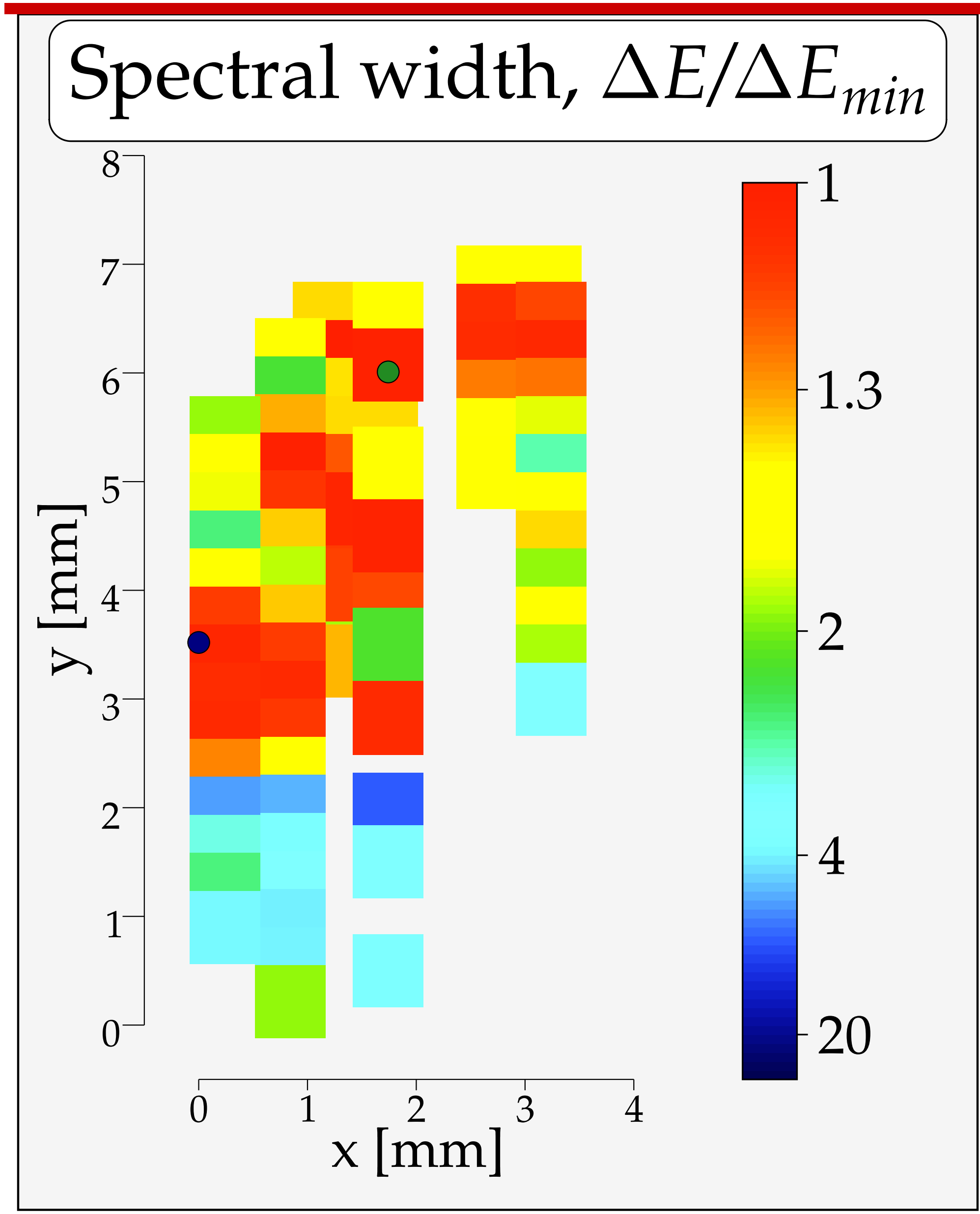
$\delta E = hc/(2L_{\rm crystal})$

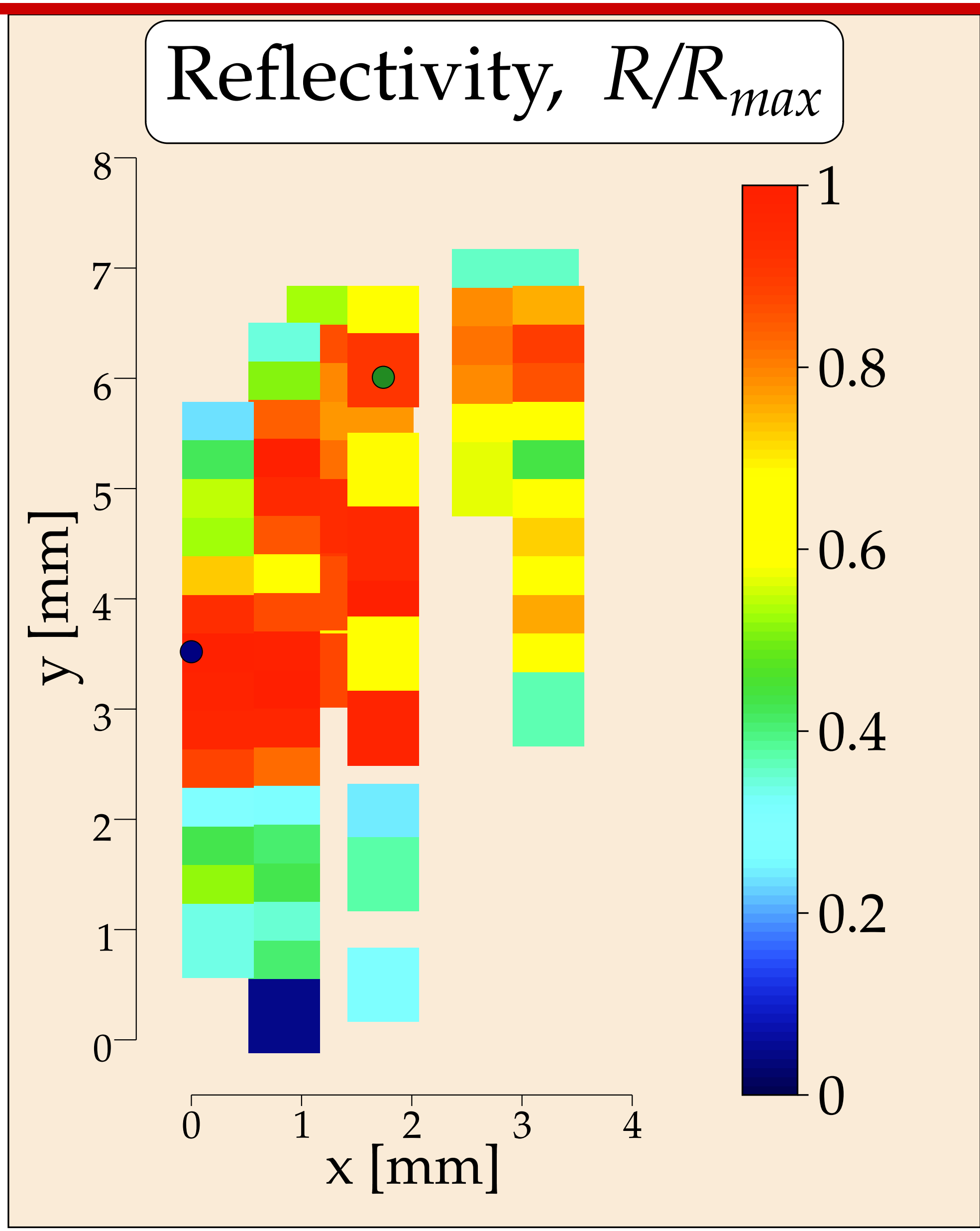
$d_{\rm crystal} = 415 \pm 5 \mu m$

$R_{\rm theory} = 91\%$

$R_{\rm experiment} = 87\%$

Spectral Width and Reflectivity Measurements





Heat Load Problem

Temperature gradient $\delta T \Rightarrow$ energy spread $\delta E/E = \beta\delta T$.
Requirement: $\delta E \lesssim 1$ meV, when the next pulse arrives.

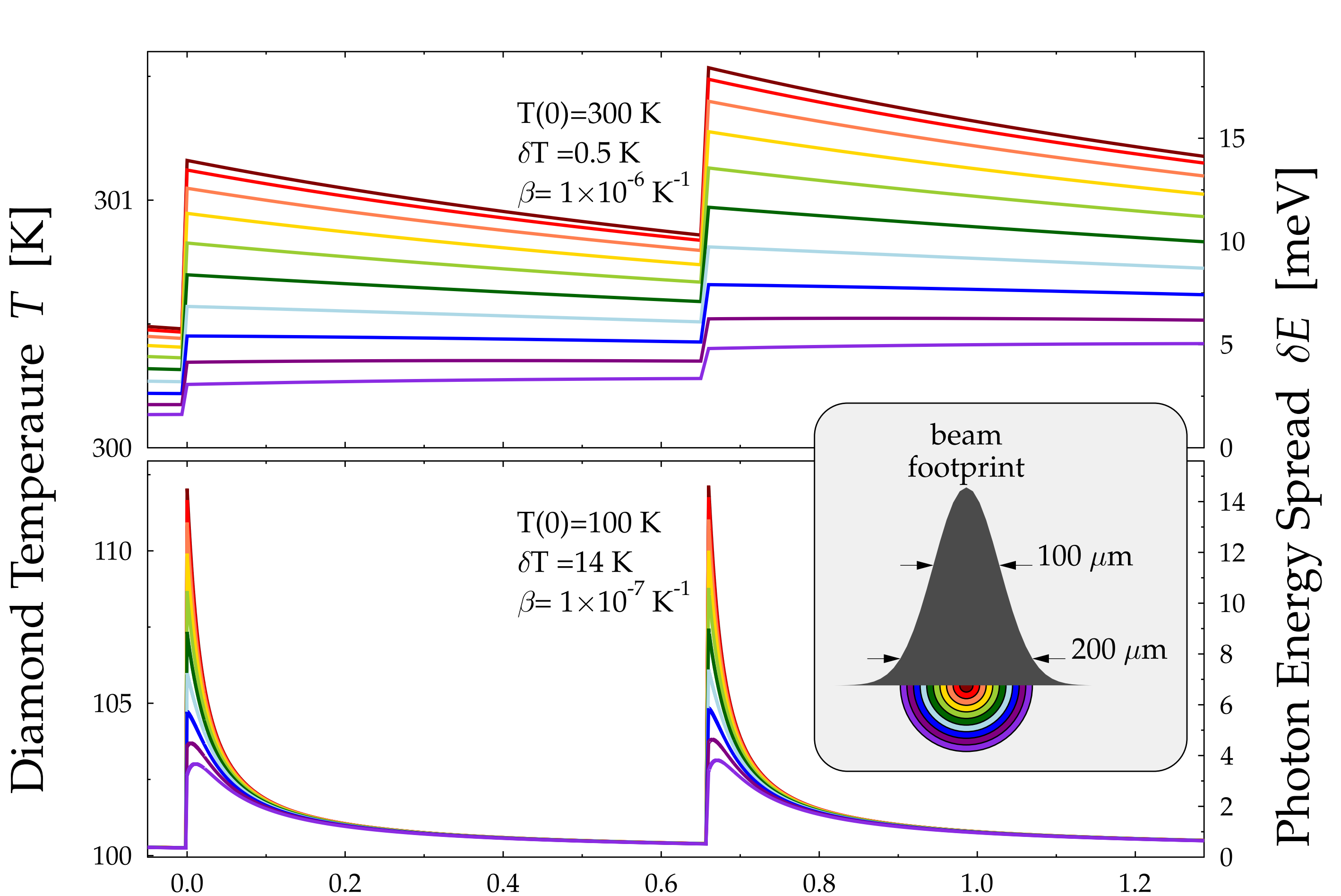
Incident power $\simeq 50\ \mu$J/pulse.
Absorbed power: $\simeq 1\ \mu$J/pulse (2%).
Footprint: $\simeq 100 \times 100\ \mu$m^2

Is it a problem?

Heat Load Problem

Temperature gradient $\delta T \Rightarrow$ energy spread $\delta E/E = \beta \delta T$.

Requirement: $\delta E \lesssim 1$ meV, when the next pulse arrives.



H. Sinn simulations

- **Big temperature jump δT after the x-ray pulse arrival.**
- **T=300K: Big temperature spread by the arrival of the next x-ray pulse.**
- **T=100K: Negligible temperature spread by the arrival of the next x-ray pulse.**
- **Reasons:**
  1. **High temperature diffusivity $\mathcal{D}$**
  2. **Low temperature expansion β**

Solution: Maintain diamond at $T < 100$ K!

Thermal Expansion in Diamond < 2009

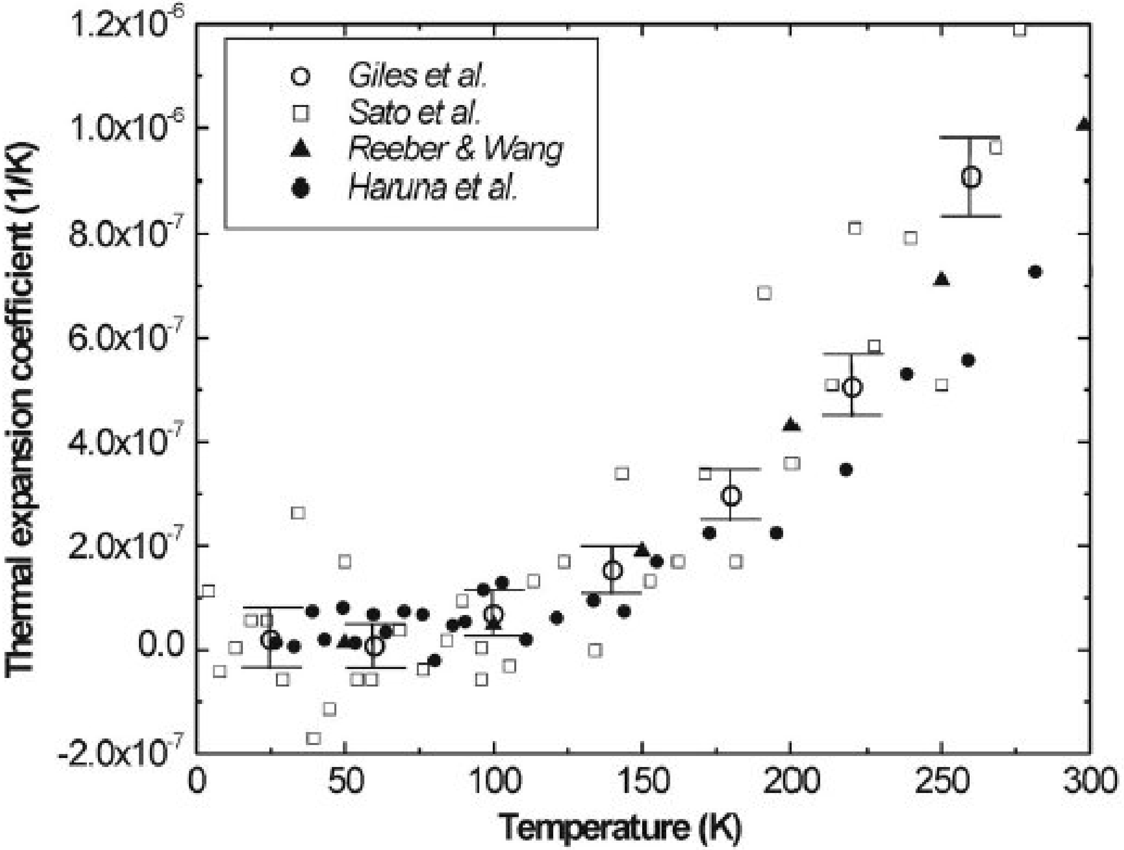
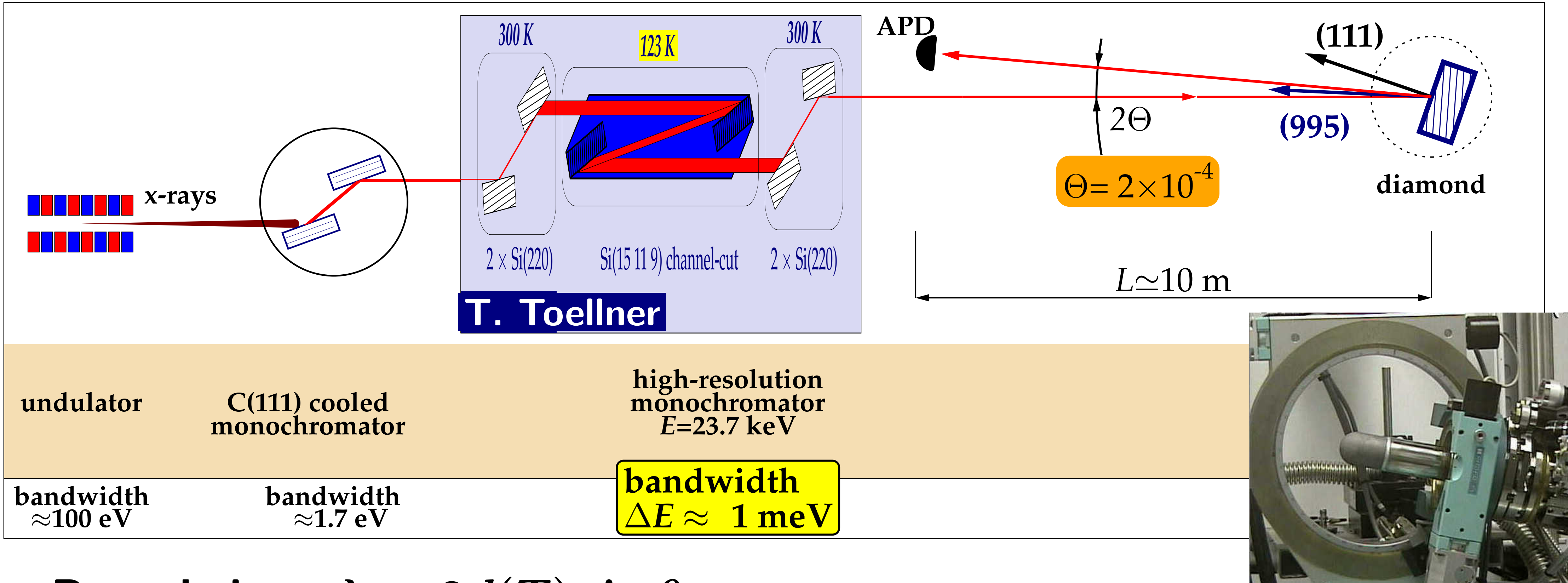


Figure 5
Linear thermal expansion coefficient (α) obtained in the present work compared with other results found in the recent literature. Values for α between 30 K and 90 K are of the order of 1×10^{-7}, compatible with published results.

C. Giles et al, J. Synchrotron Rad. (2005). 12, 349

Diamond Thermal Expansion: Sector 30 @ APS



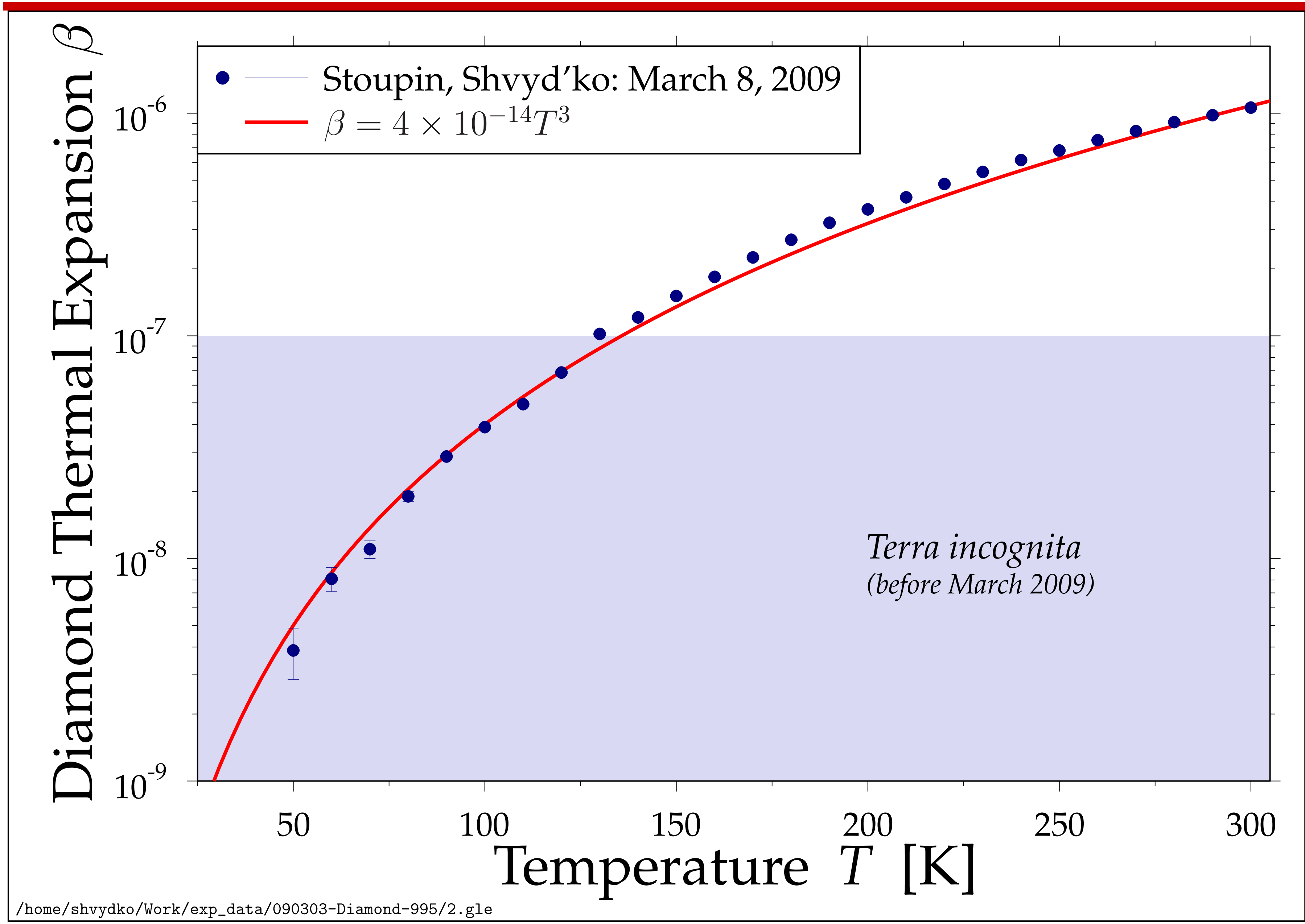
Bragg's law: $\lambda = 2d(T)\sin\theta$

$\theta = \pi/2 - \Theta$ ... **in backscattering:** $\lambda = 2d(1 - \Theta^2/2)$

$E = E_H(T)(1 + \Theta^2/2),\ E_H(T) = hc/2d(T)$

Uncertainty: $\delta E/E_H = \Theta\delta\Theta \ll 10^{-8} \Rightarrow \delta E \ll 0.1$ **meV**

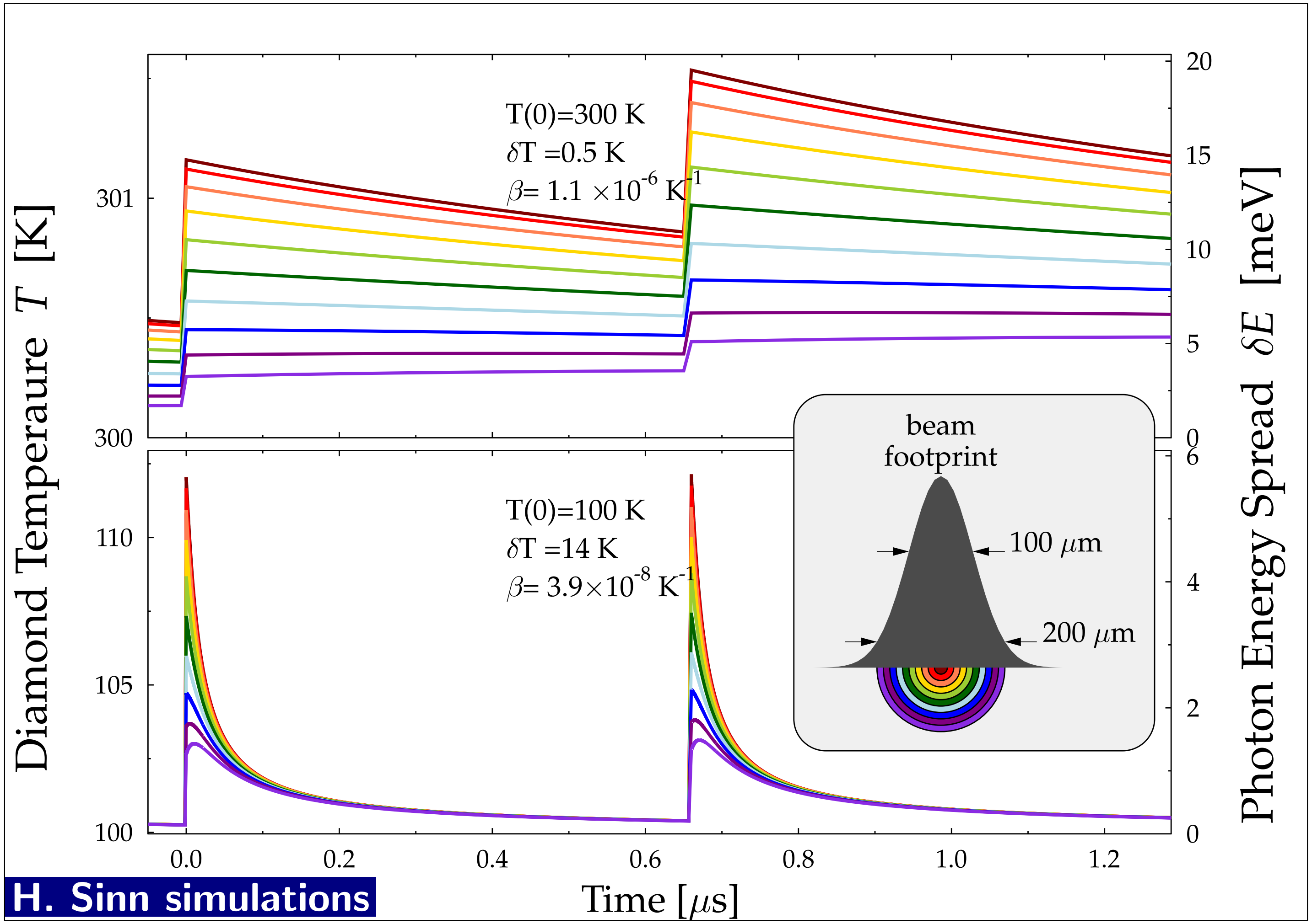
Diamond Thermal Expansion: APS Sector 30



Heat Load Problem

Temperature gradient $\delta T \Rightarrow$ energy spread $\delta E/E = \beta\delta T$.

Requirement: $\delta E \lesssim 1$ meV, when the next pulse arrives.



- **Big temperature jump δT after the x-ray pulse arrival.**
- **T=300K: Big temperature spread by the arrival of the next x-ray pulse.**
- **T=100K: Negligible temperature spread by the arrival of the next x-ray pulse.**
- **Reasons:**
  1. **High temperature diffusivity $\mathcal{D}$**
  2. **Low temperature expansion β**

Solution: Maintain diamond at $T < 100$ K!

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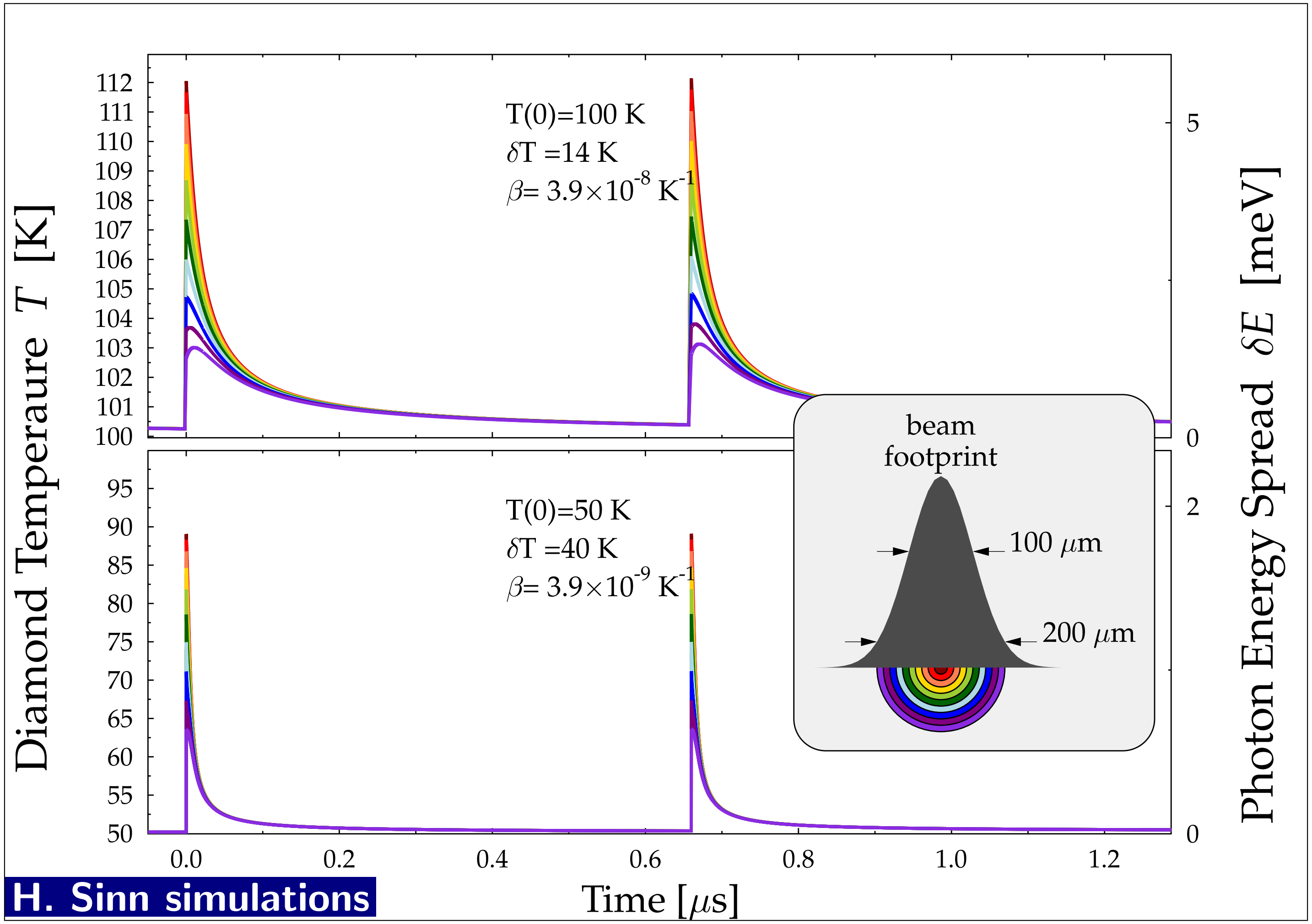

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Solution: Maintain diamond at $T < 100$ K!

Best Temperature for Diamond

$\delta E/E \propto \beta(T)\delta T$

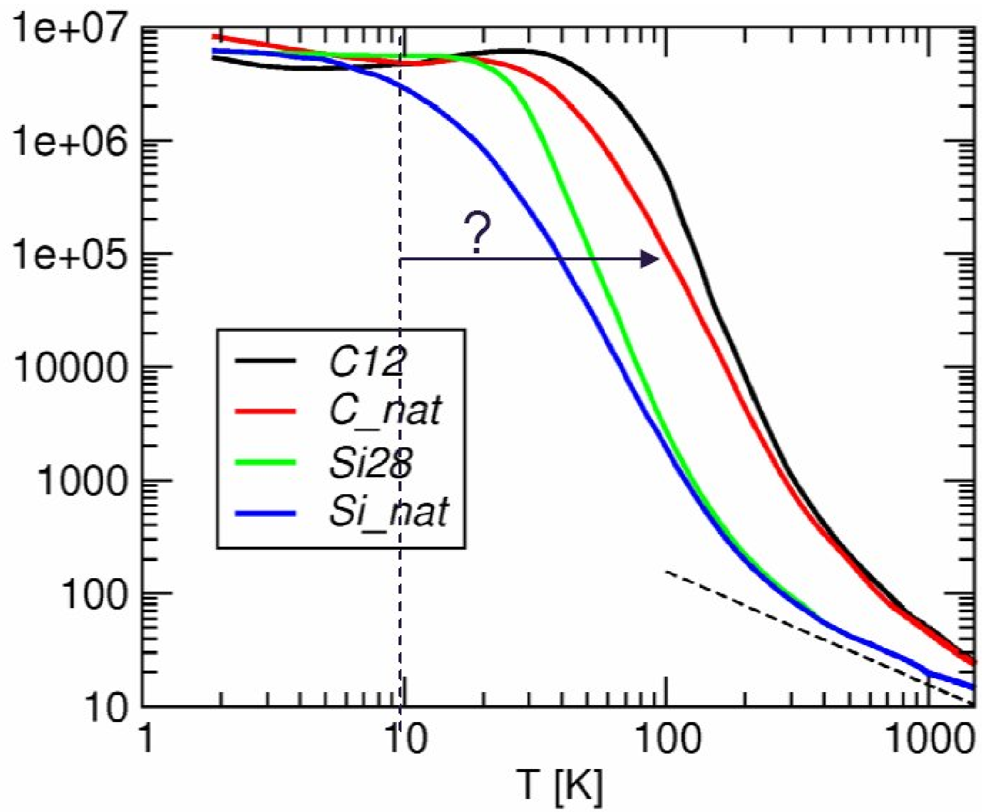
$\delta T \propto 1/C_v(T) \propto T^{-3}$

$\beta \propto C_v \propto T^3$

$\delta E/E \simeq$ const

Best temperature is defined by

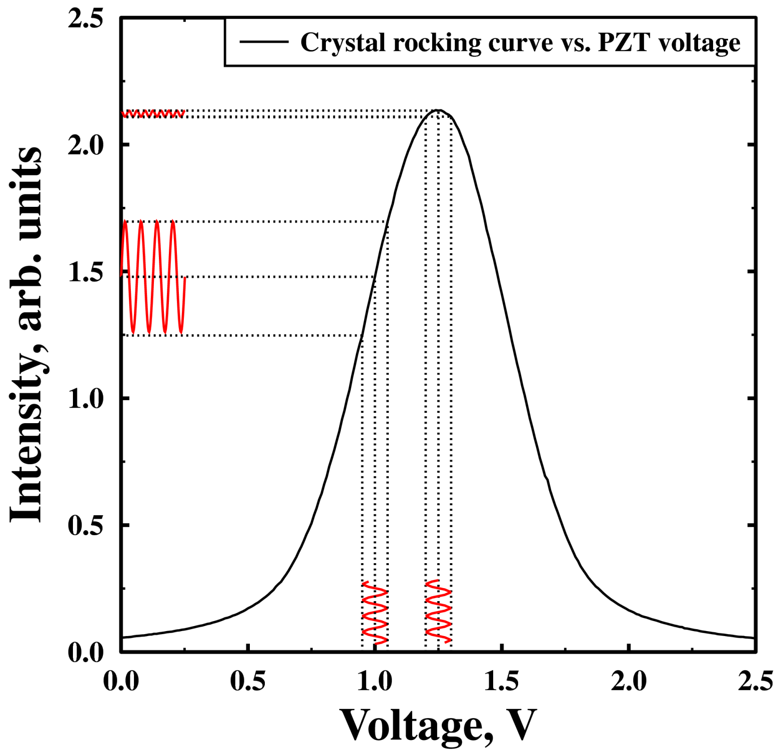
maximum thermal diffusivity

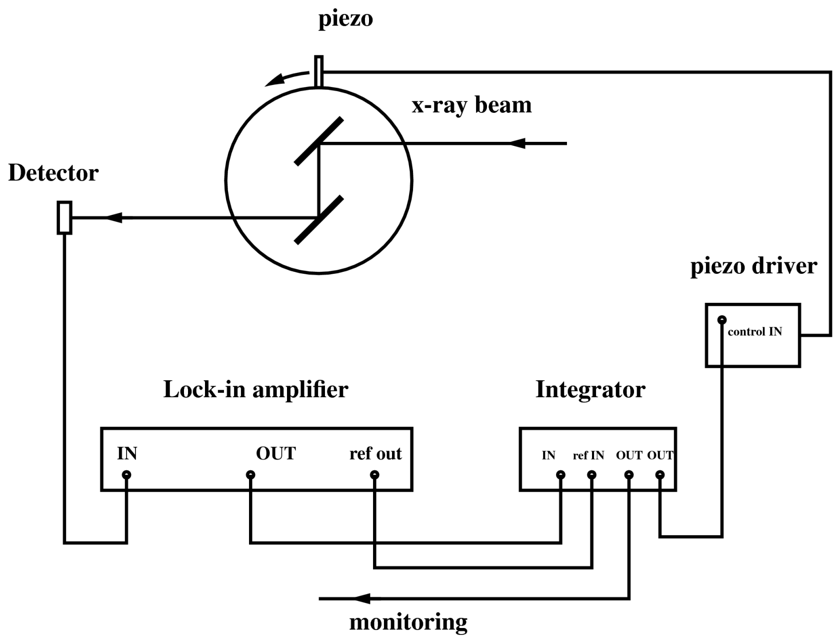


Angular & Spatial Stability

Required angular stability: $\delta\theta \lesssim 10$ nrad
Required spatial stability: $\delta L \lesssim 3\ \mu$m (rms) $\Rightarrow \delta L/L \simeq 3 \times 10^{-8}$ ($L = 100$ m)

Solution: Null-detection harware feedback. (LIGO prototype)



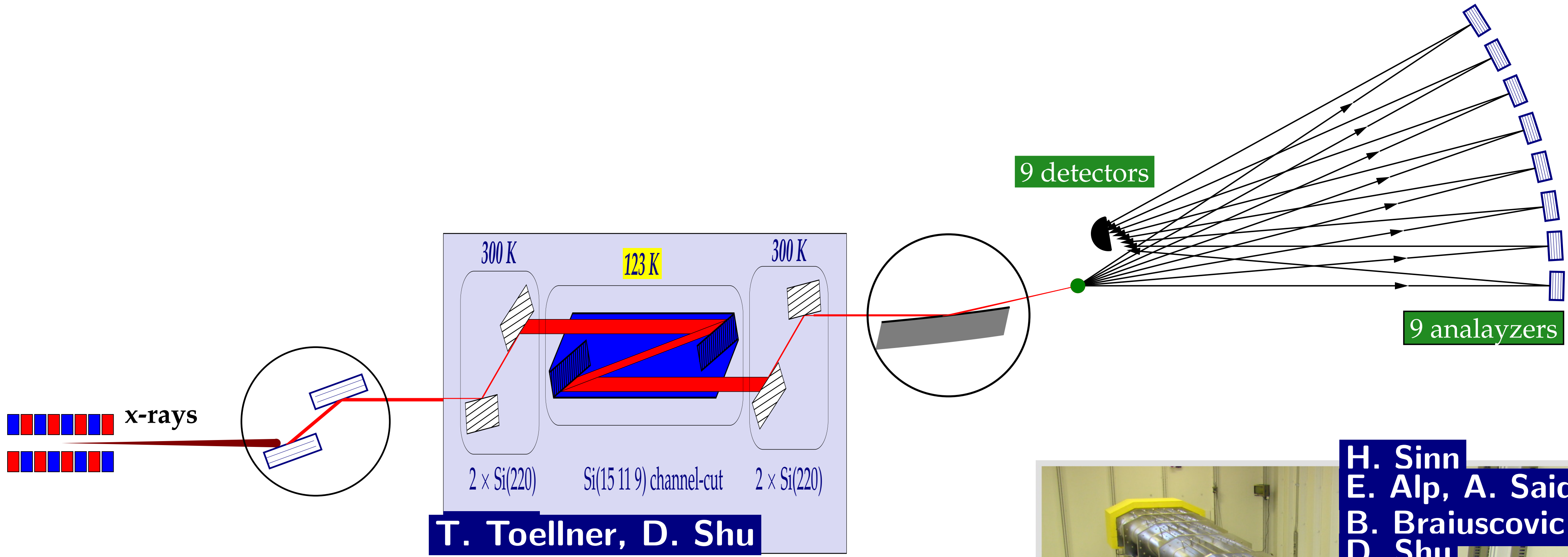


$\simeq$ 50 nrad stability was demonstrated at Sector 30

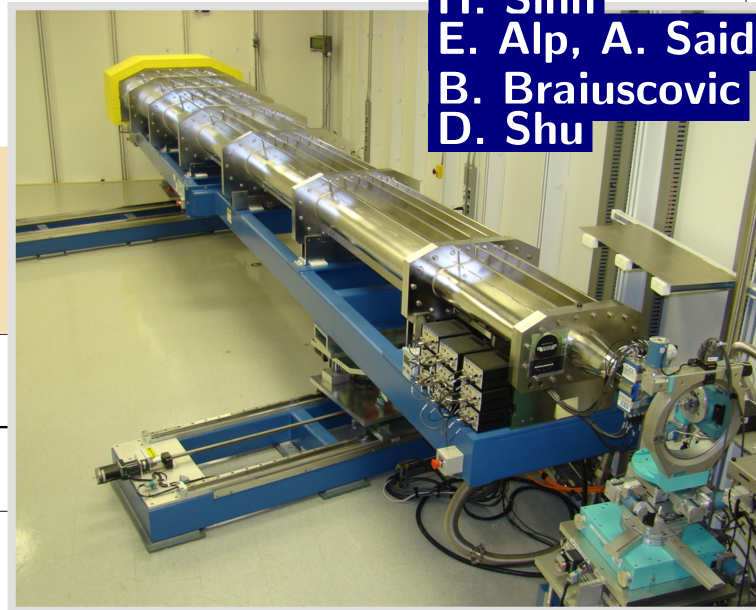
S. Stoupin, F. Lenkszus, R. Laird, K.-J. Kim, Yu. Shvyd'ko

- Transmitted x-ray intensity: the linear response to a small oscillating signal is proportional to angular deviation from the maximum of the rocking curve
- Feedback/correction signal is extracted using lock-in amplification

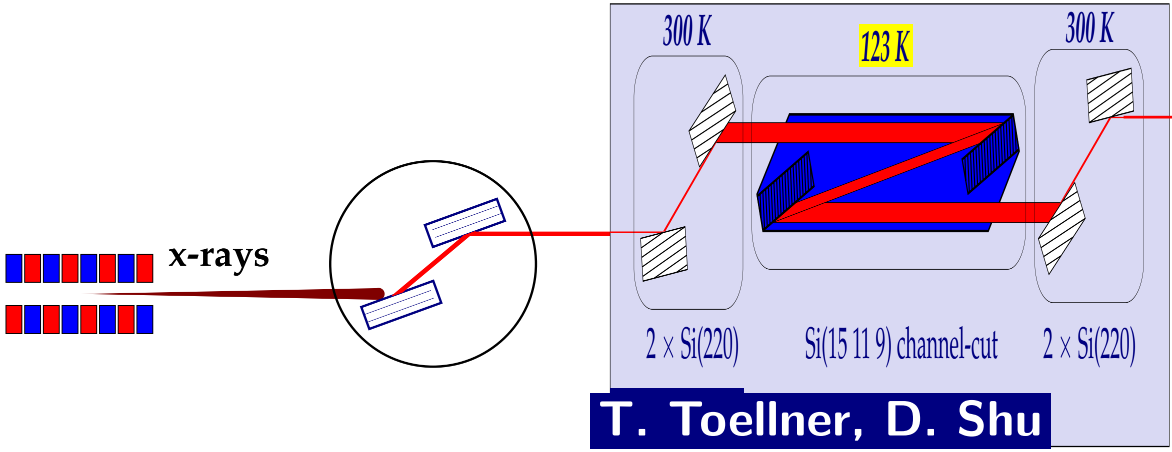
HERIX Instrument - Sector 30 @ APS

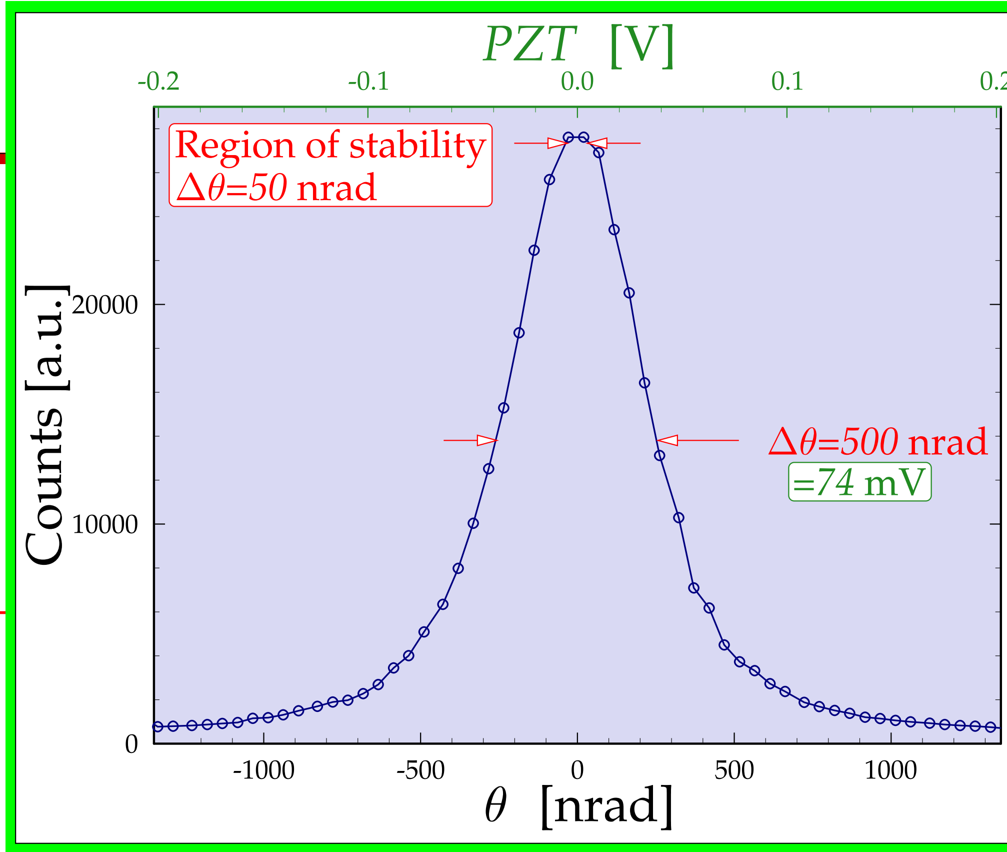


undulator	C(111) cooled monochromator	high-resolution monochromator 23.74 keV	KB focusing mirror
bandwidth ≈100 eV	bandwidth ≈1.7 eV	bandwidth ≈ 0.9 meV	focus 5 μm $\times$40 μm
1×10^{13} Hz @ 23.74 keV			2×10^{9} Hz



HERIX Monochromator





undulator	C(111) cooled monochromator	high-resolution monochromator 23.74 keV	KB focusing mirror
bandwidth $\approx$100 eV	bandwidth $\approx$1.7 eV	bandwidth $\approx$ 0.9 meV	focus 5 μm $\times$40 μm
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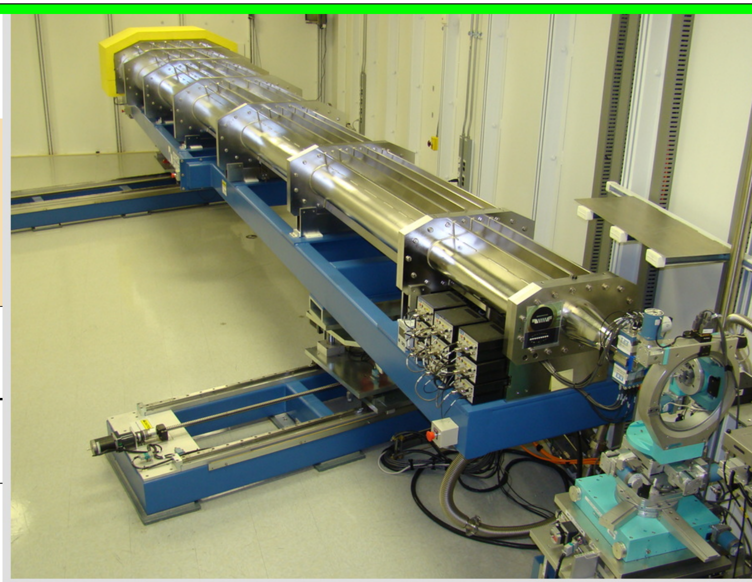
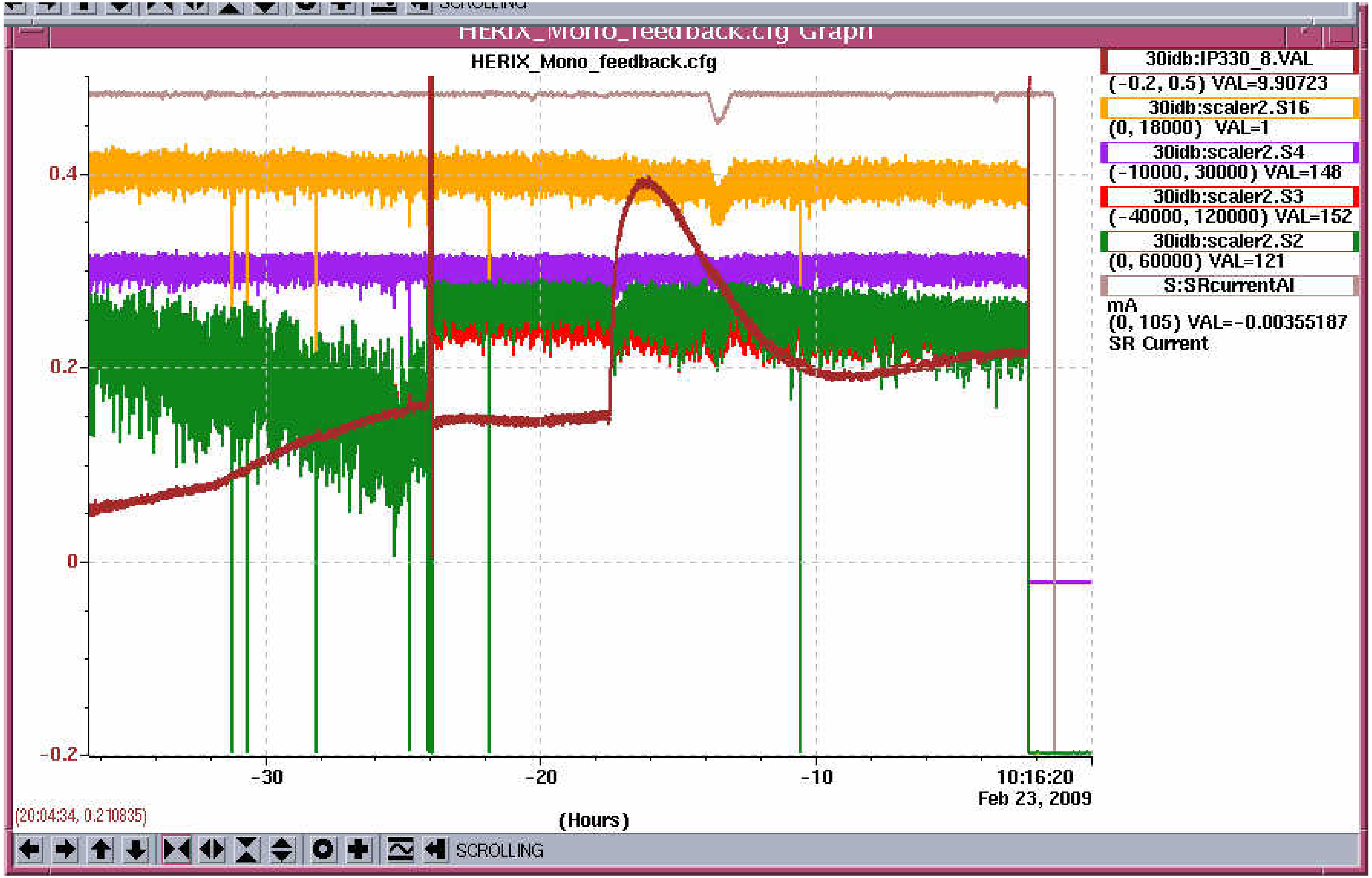
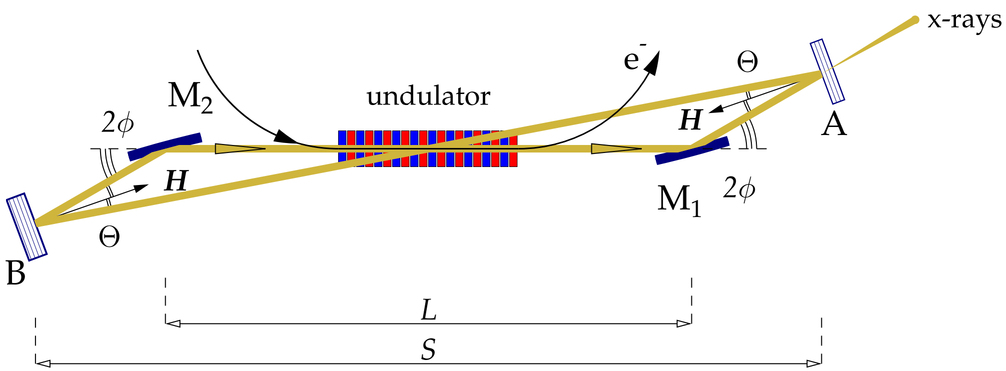
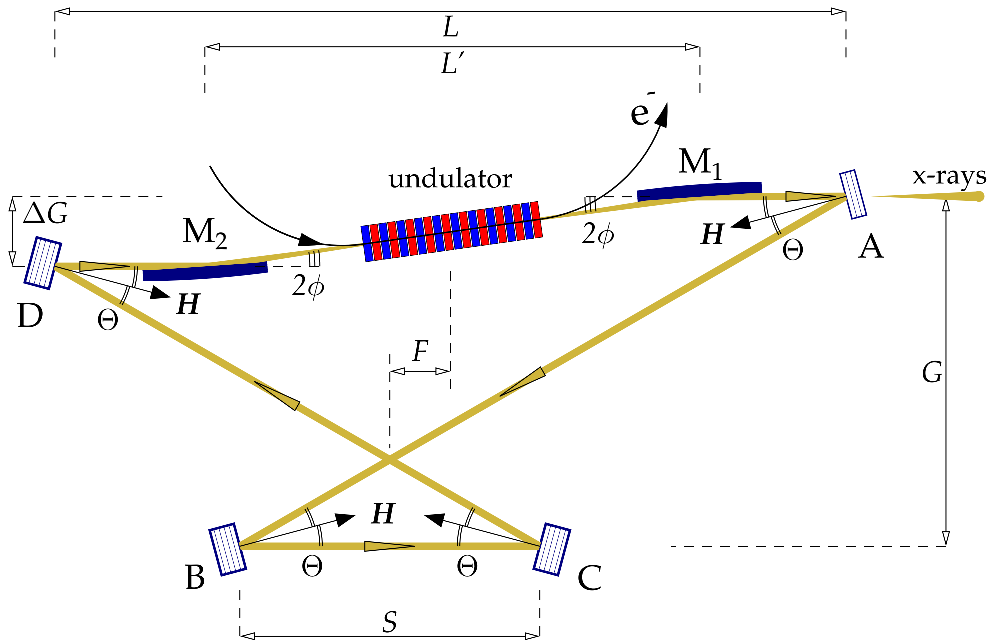


HERIX Monochromator Stability



XFELO Technical Challenges





X-ray Optics:

- **Quality of diamond crystals: is the theoretical reflectivity achievable?** **m. p. yes**
- **Heat load problem (reflection region variations $\lesssim 1$ meV).** **m. p. yes**
- **Angular stability: $\delta\theta \lesssim 10$ nrad** **m. p. yes**

  Spatial stability: $\delta L \lesssim 3\ \mu$m (rms) $\quad \longrightarrow \quad \delta L/L \lesssim 3 \times 10^{-8}$

Summary & Outlook

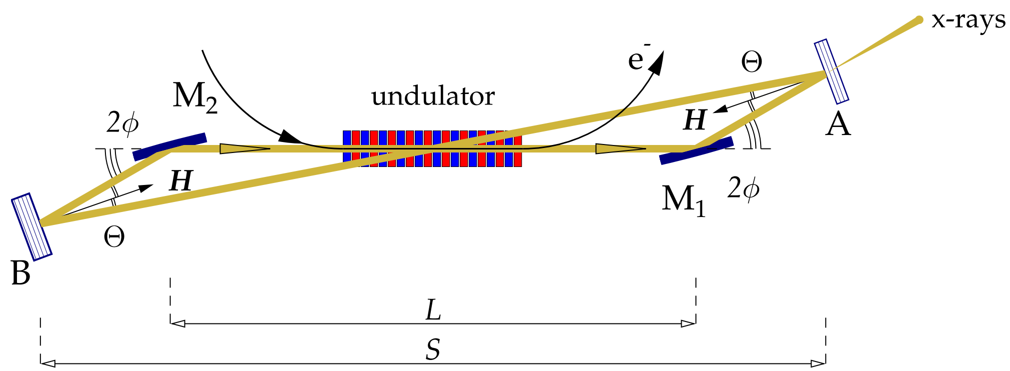
XFEL-O:

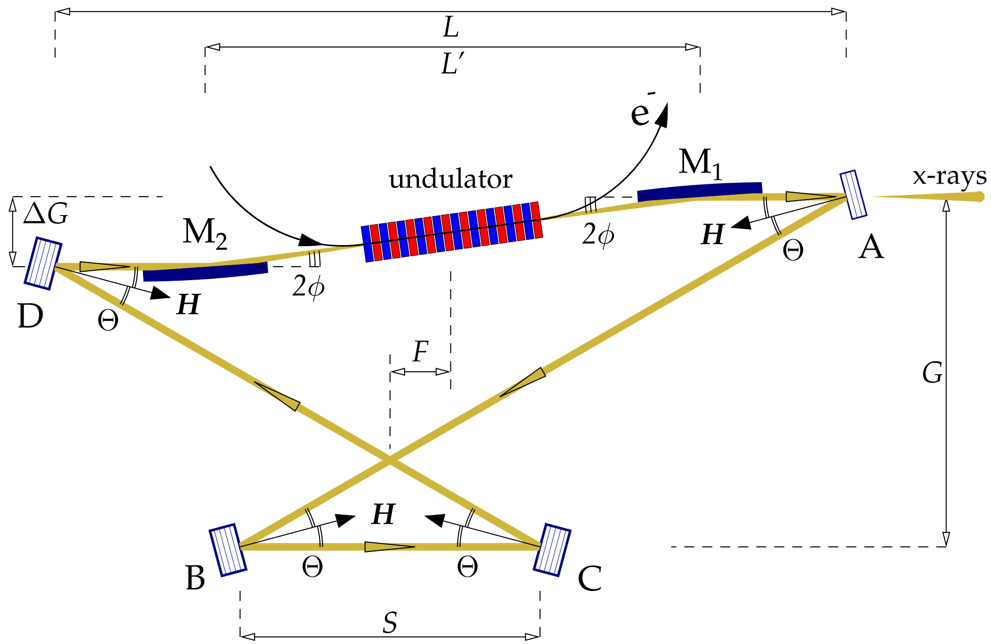
- Highset spectral brightness.
- Small energy bandwidth.
- Full coherence. • ps-pulses.

Applications:

- Nuclear resonant spectroscopies.
- Inelastic X-ray scattering.
- HAXPES. • ps-Time measurements.
- Imaging at near-atomic resolution ($\simeq 1$ nm).

Low loss x-ray cavities are feasible! X-ray cavities of different types for the XFEL-O under consideration, including tunable ones.



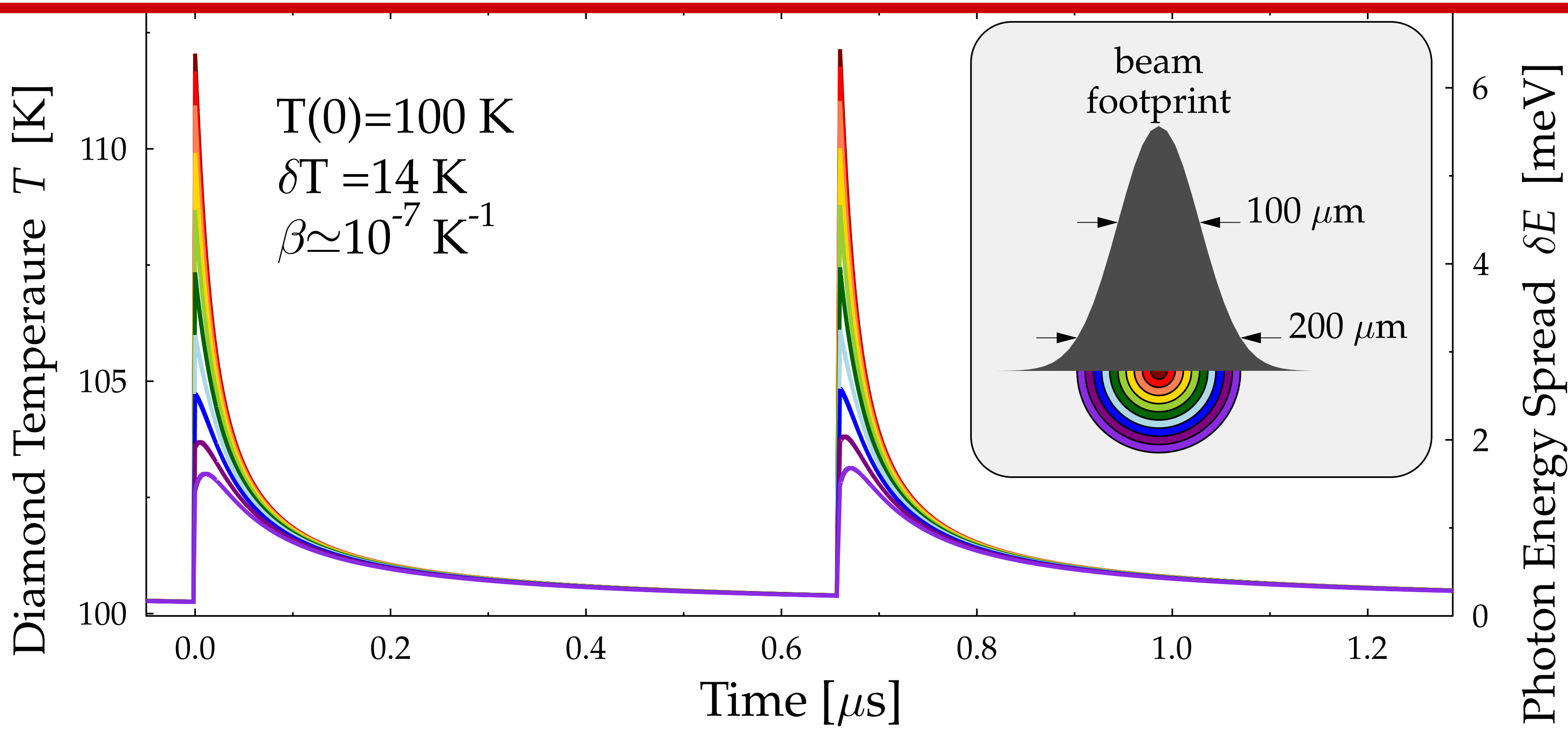


XFEL-O R+D project is in progress at the APS.

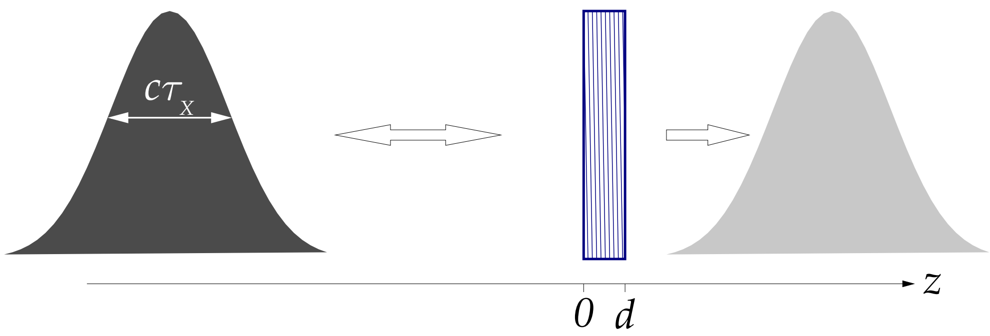
Acknowledgments

Robert Winarski (APS)
Tim Graber (APS)
Frank Lenkszus (APS)
Robert Laird (APS)
Stan Whitcomb (LIGO)
Harald Sinn (European XFEL)
Al Macrander (APS)
Lahsen Assoufid (APS)
Tom Toellner (APS)
Deming Shu (APS)
Sven Reiche (UCLA)
W. Falley (BLNL)
Ay man Said (APS)
Tim Roberts (APS)
Emil Trakhtenberg (APS)

Heat Shock Waves



How fast the temperature jump δT results in thermal expansion and in energy variation δE?

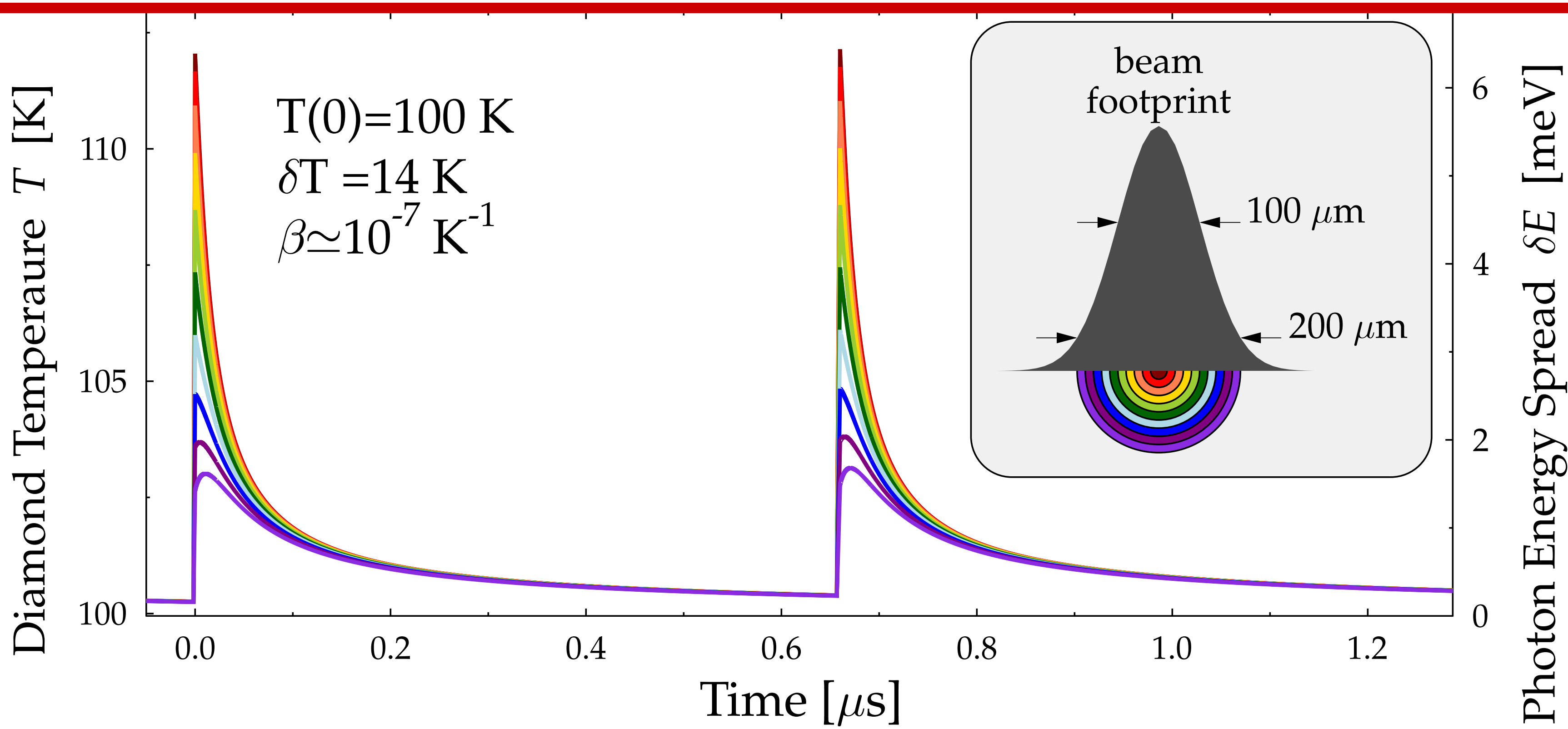


$\tau_x = 1$ ps (rms) $\Rightarrow c\tau_x = 300\ \mu$m

$d \simeq 50\ \mu$m

Interaction time: $\tau_x = 1$ ps (rms)

Heat Shock Waves



How fast the temperature jump δT results in thermal expansion <u>and</u> in energy variation δE?

Pedestrian: $\tau_{\mathrm{D}} = \frac{d}{c_\ell} \simeq 2$ **ns** [**sound velocity** $c_\ell = 1.8 \times 10^4$ **km/s**]

Y.C.Lee: $\tau_{\mathrm{D}}^{*} = \tau_{\mathrm{D}} \frac{1}{\beta \Delta T} \simeq 1$ **ms** [J. Phys.: Cond. Matter: 20 (2008) 055202]

Thermal expansion is yet negligible while the pulse is on $\tau_{\mathrm{x}} << \tau_{\mathrm{D}} << \tau_{\mathrm{D}}^{*}$ **!!!!**