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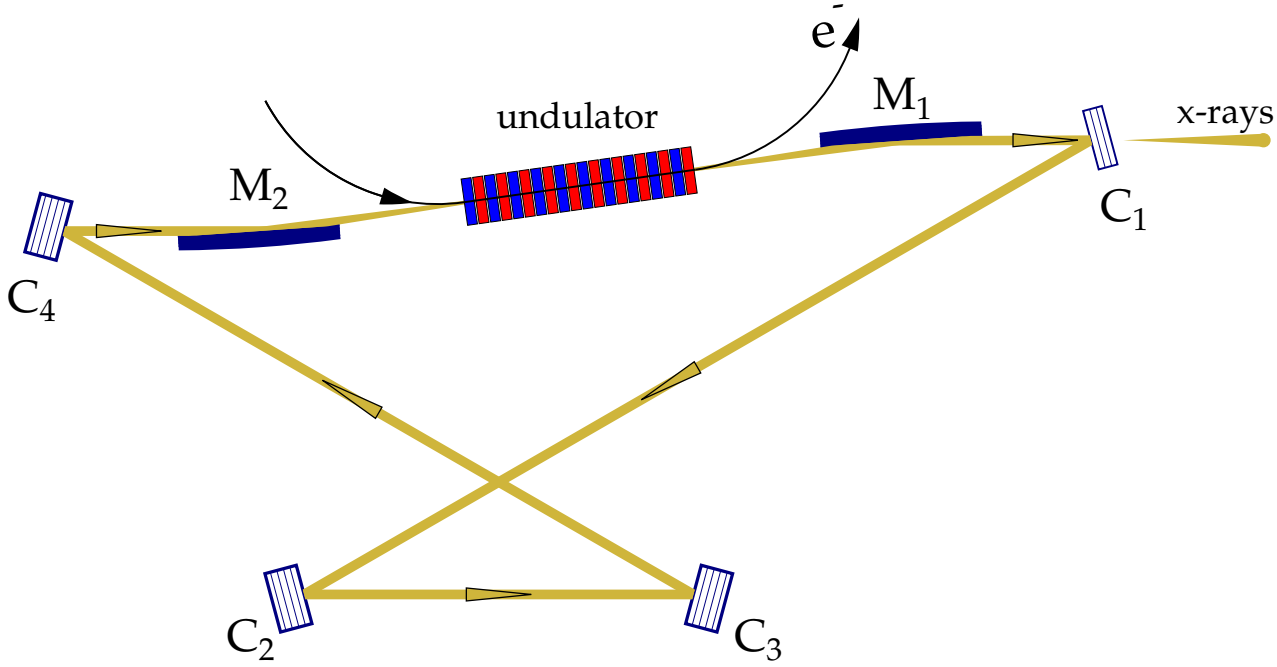
Argonne NATIONAL LABORATORY

... for a brighter future

XFELO X-ray Cavity Feasibility Studies

Yuri Shvyd'ko



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Office of Science U.S. DEPARTMENT OF ENERGY
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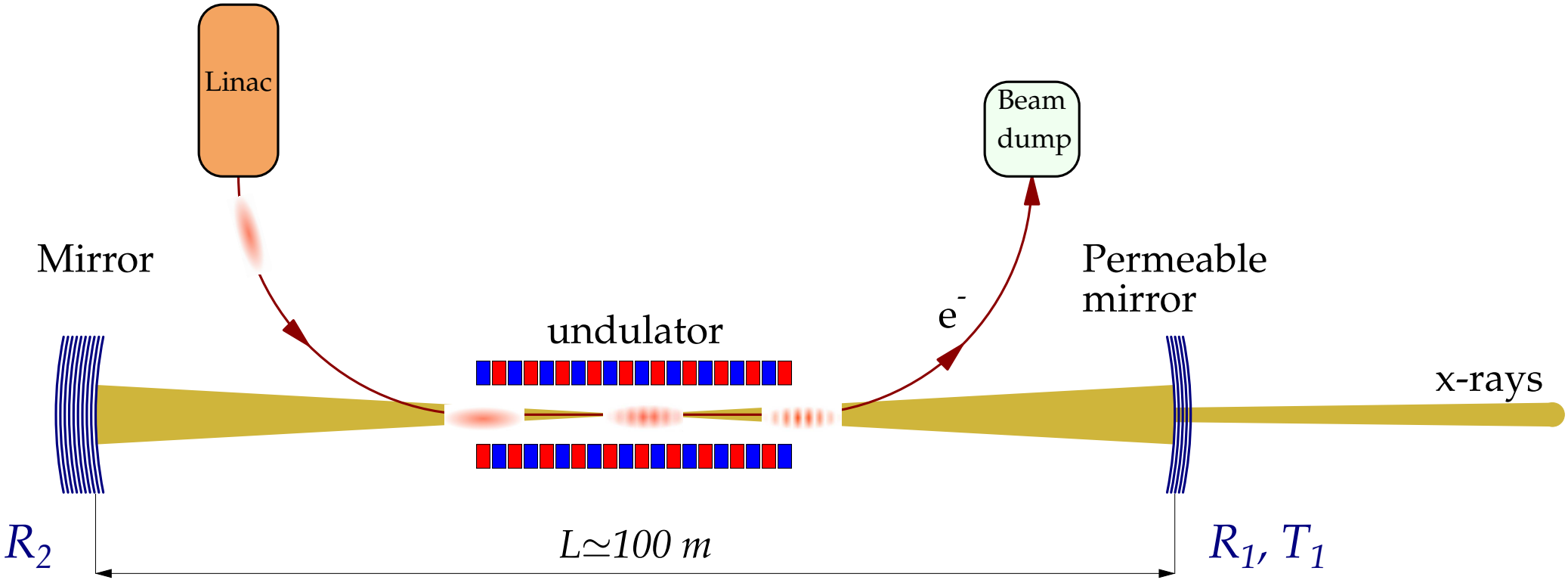
Content

- Technical challenges
- Feasibility studies:
  - $\Rightarrow$ reflectivity of diamond crystals
  - $\Rightarrow$ heat load problem
  - $\Rightarrow$ nanoradian angular stabilization
  - $\Rightarrow$ radiation damage
- Conclusions and Outlook

XFEL Oscillator



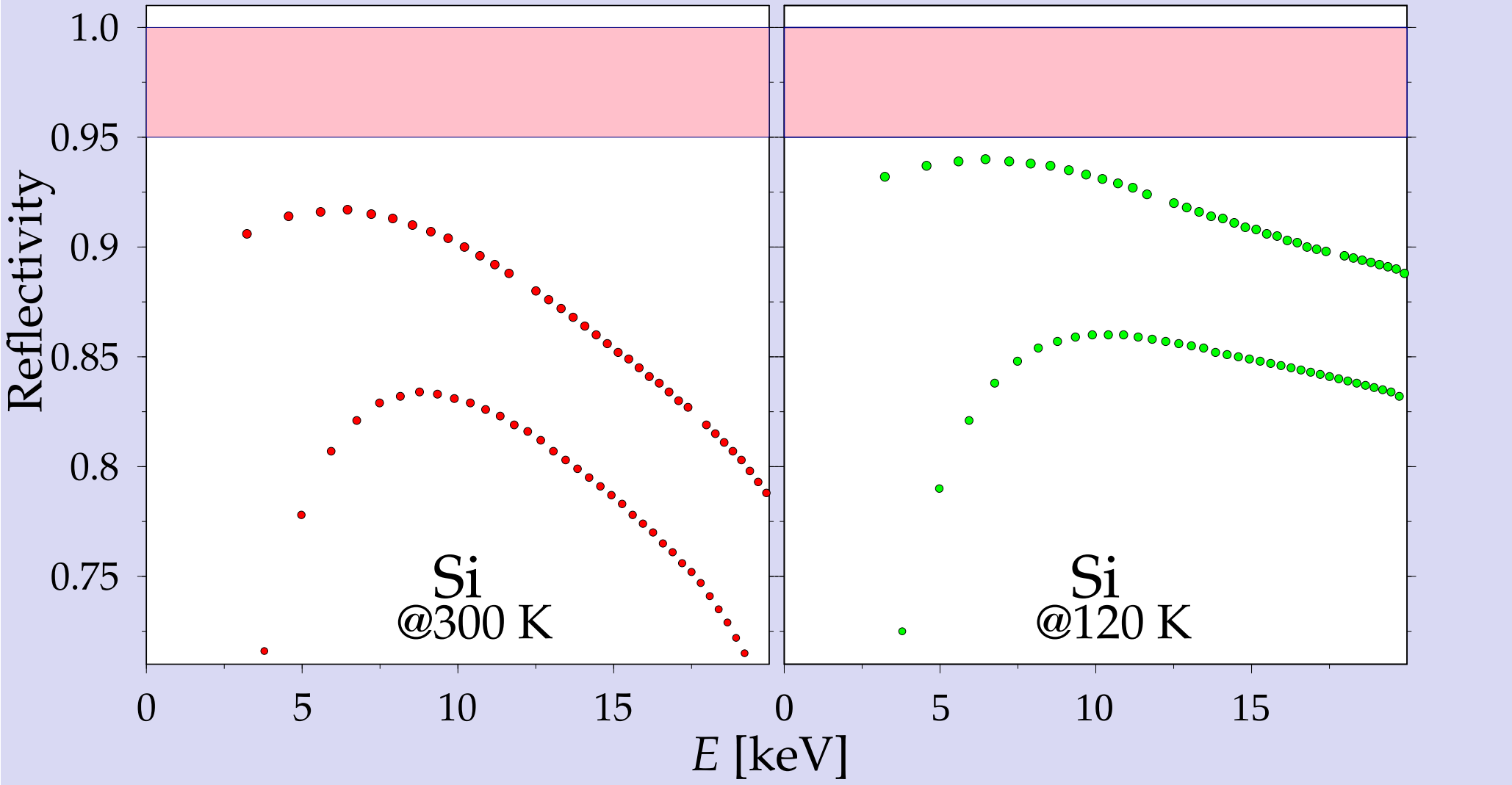
XFELO requires:

- **ultra-low-emittance ($\varepsilon_n \lesssim 10^{-7}$ m rad) electron beams,**
- **low-loss x-ray crystal cavity (losses $\simeq 15\%$)**

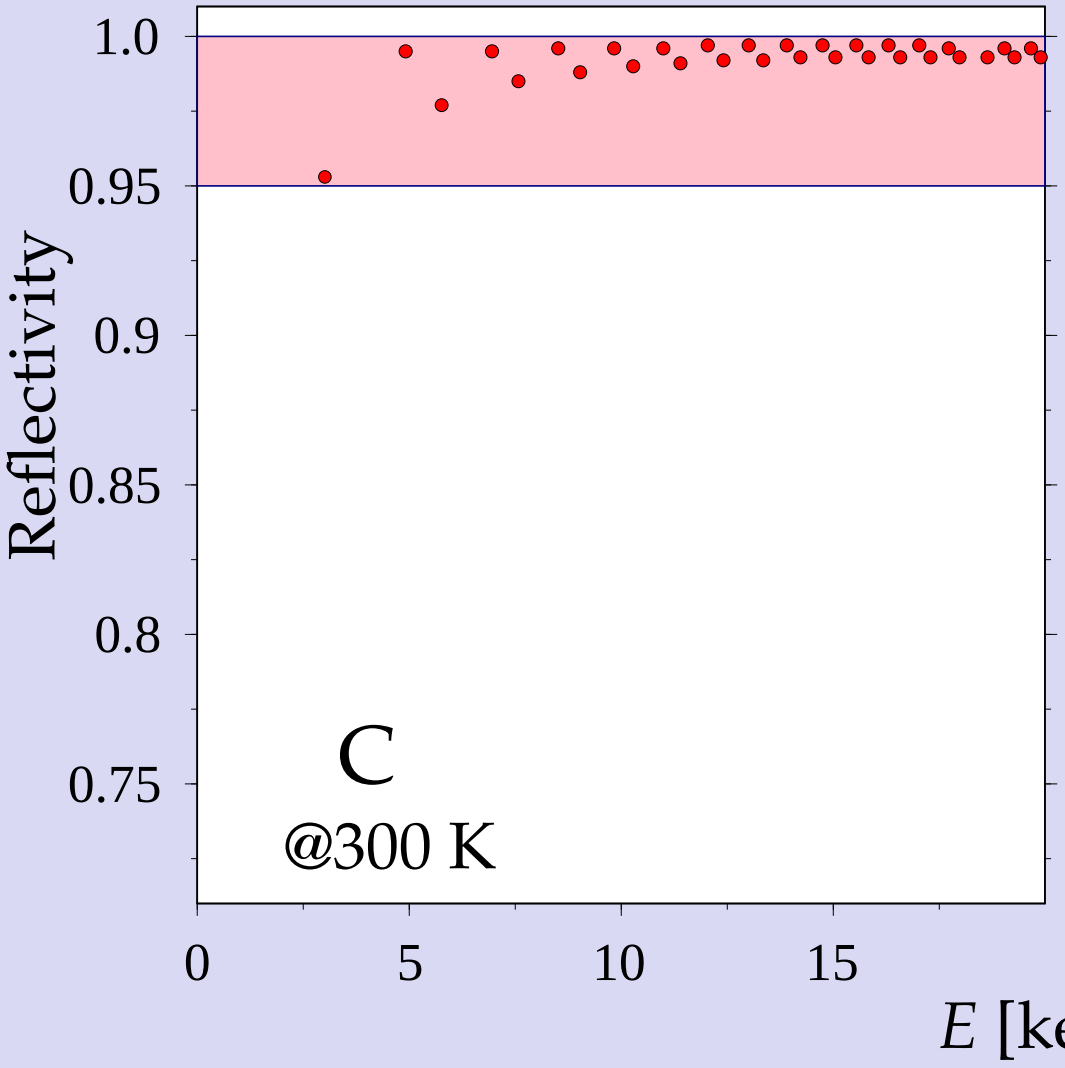
$$R_1, R_2 > 95\%,\ T_1 \simeq 4\%$$

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

Reflectivity of Si in backscattering



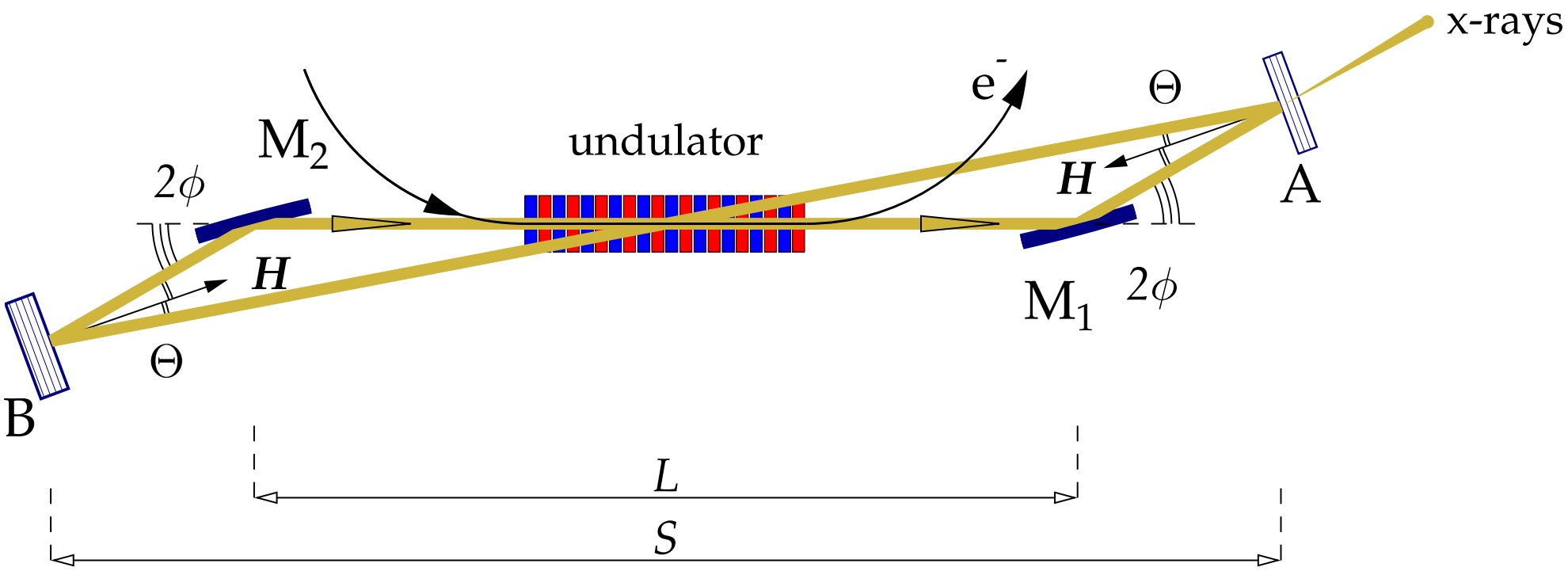
Theory predicts highest reflectivity from diamond



Very high reflectivity (in theory) due to:

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

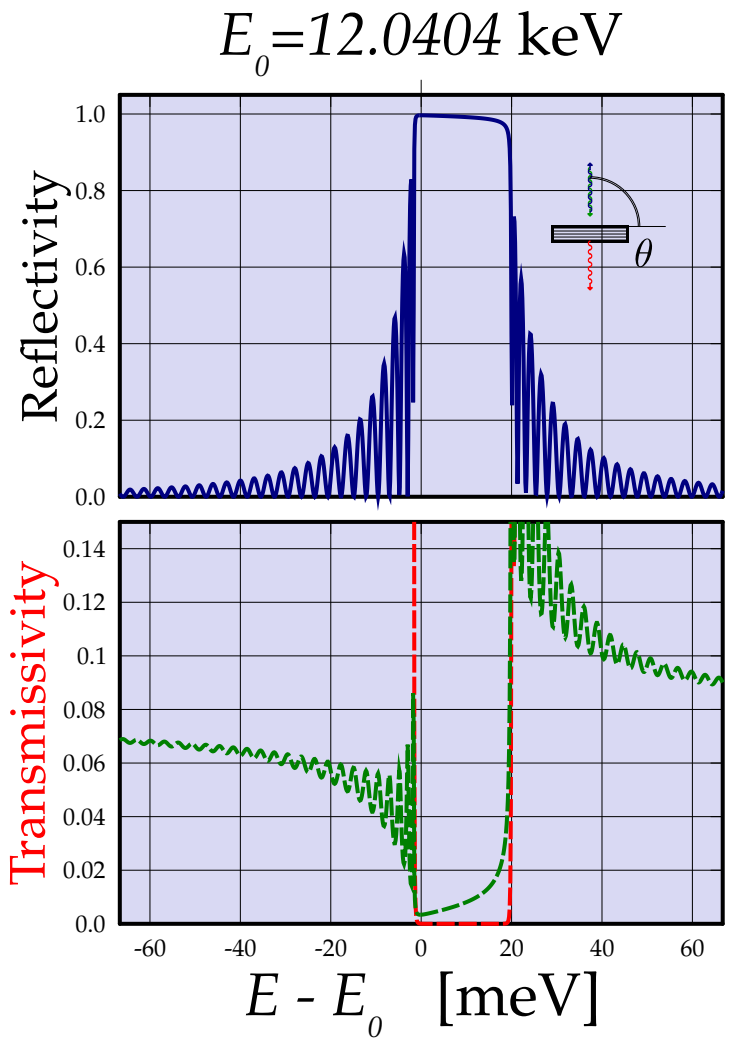
Diamond cavity for the X-FEL Oscillator



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

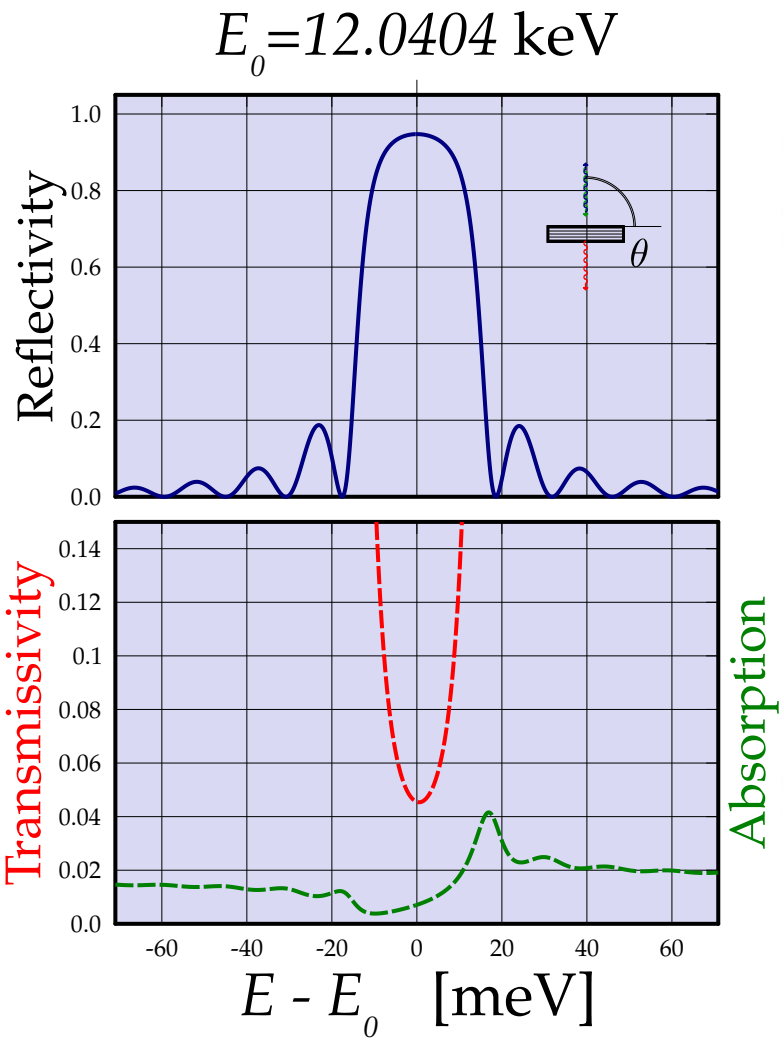
Diamond crystal and mirror reflectivity @ 12 keV

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



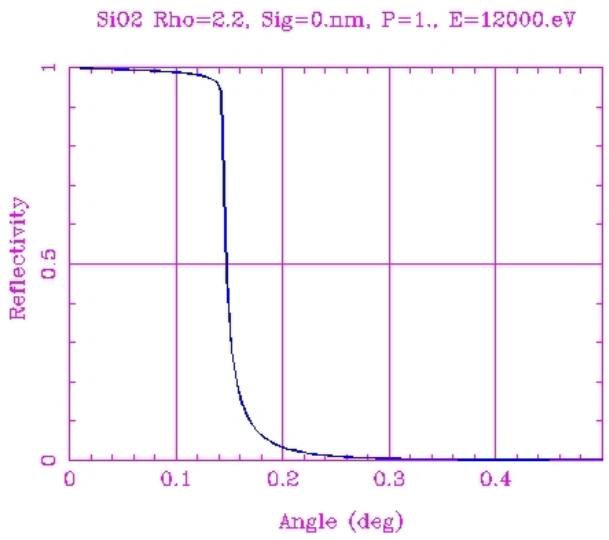
C(4 4 4); L = 0.2 mm; T = 300 K

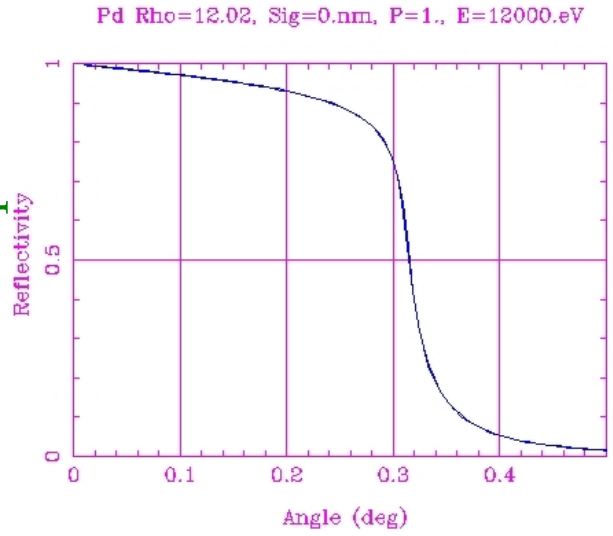
bradix version: January, 2007



C(4 4 4); L = 0.042 mm; T = 300 K

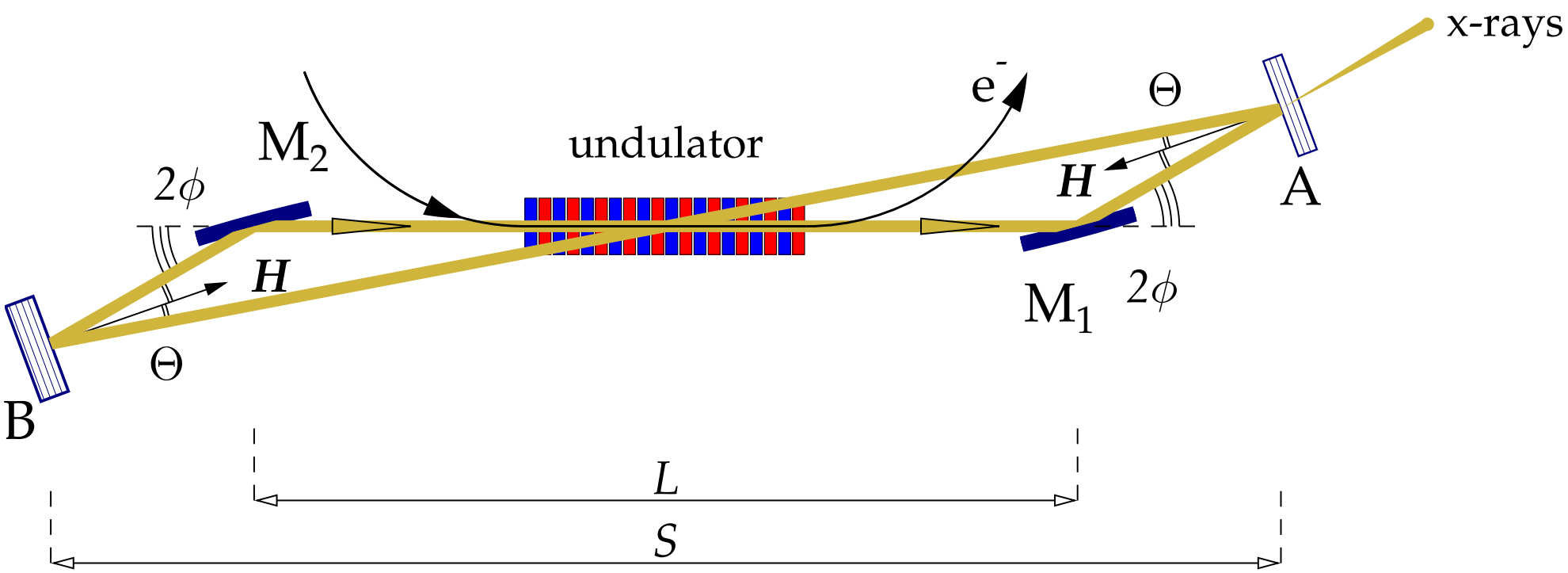
bradix version: January, 2007





Mirror calculations: www-cxro.lbl.gov

Two-Crystal Cavity is not Tunable

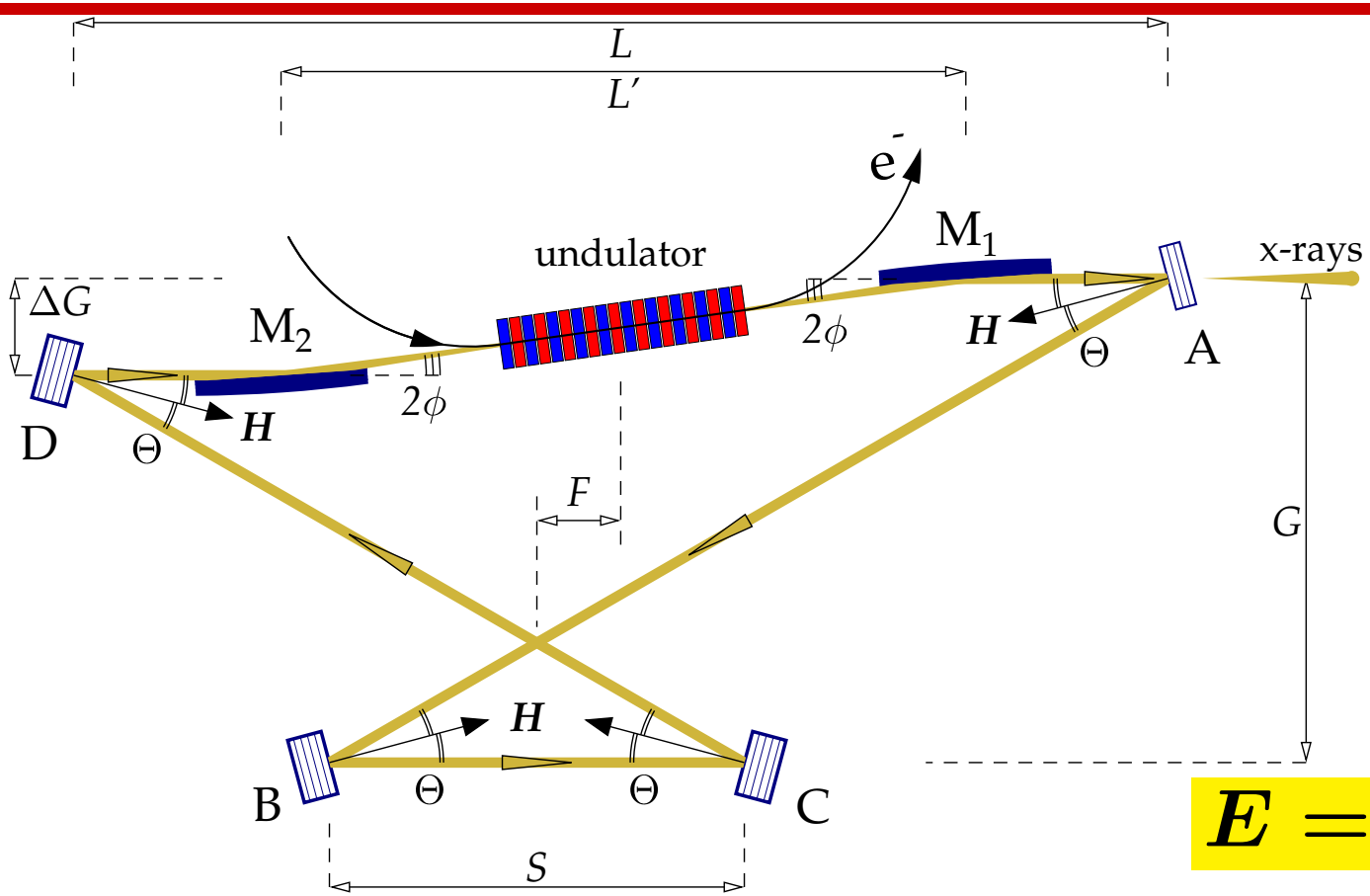


$E = E_H \cos\Theta \quad \Rightarrow \quad$ **Two-crystal scheme is not tunable.**

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



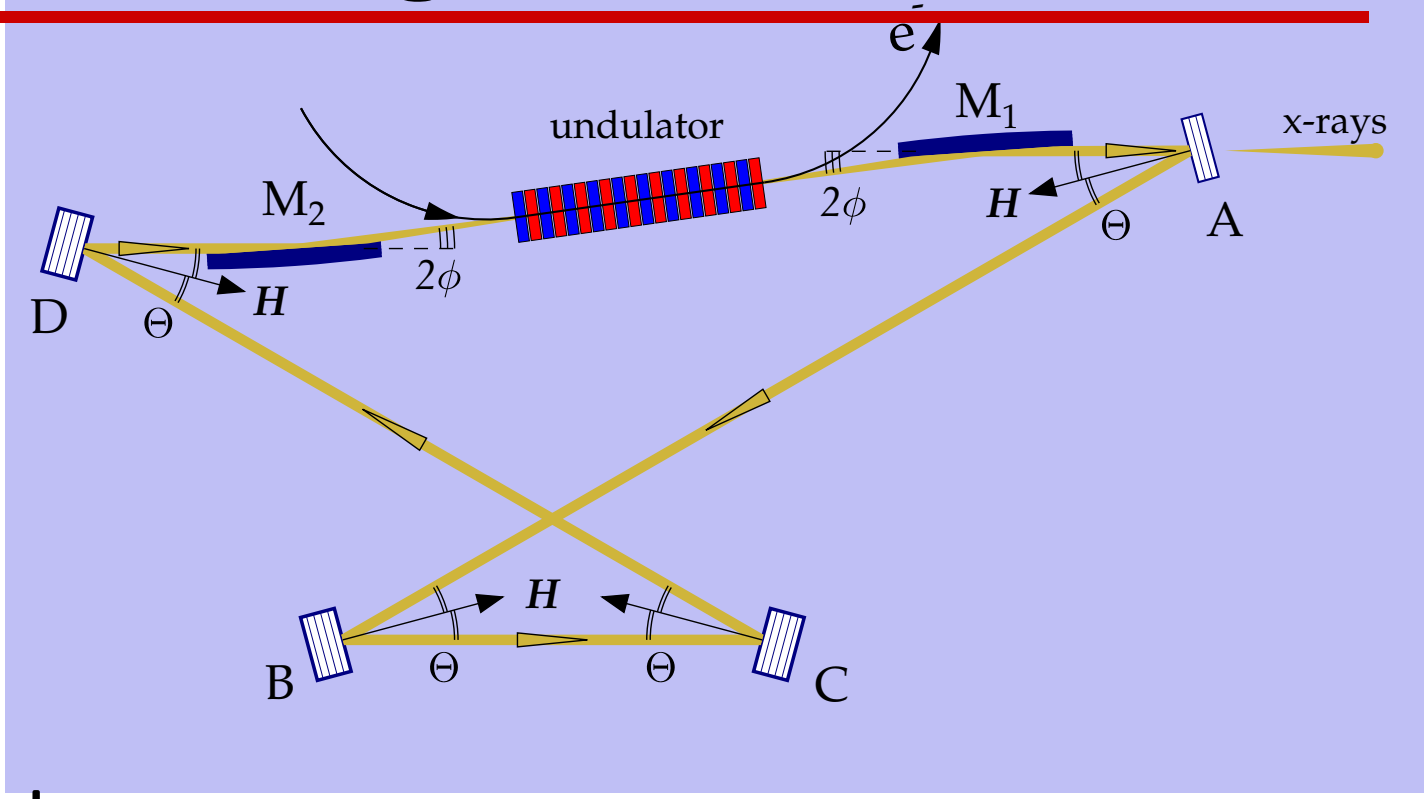
$$E = E_H \cos\Theta$$

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 Technical Challenges



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 (rms)**

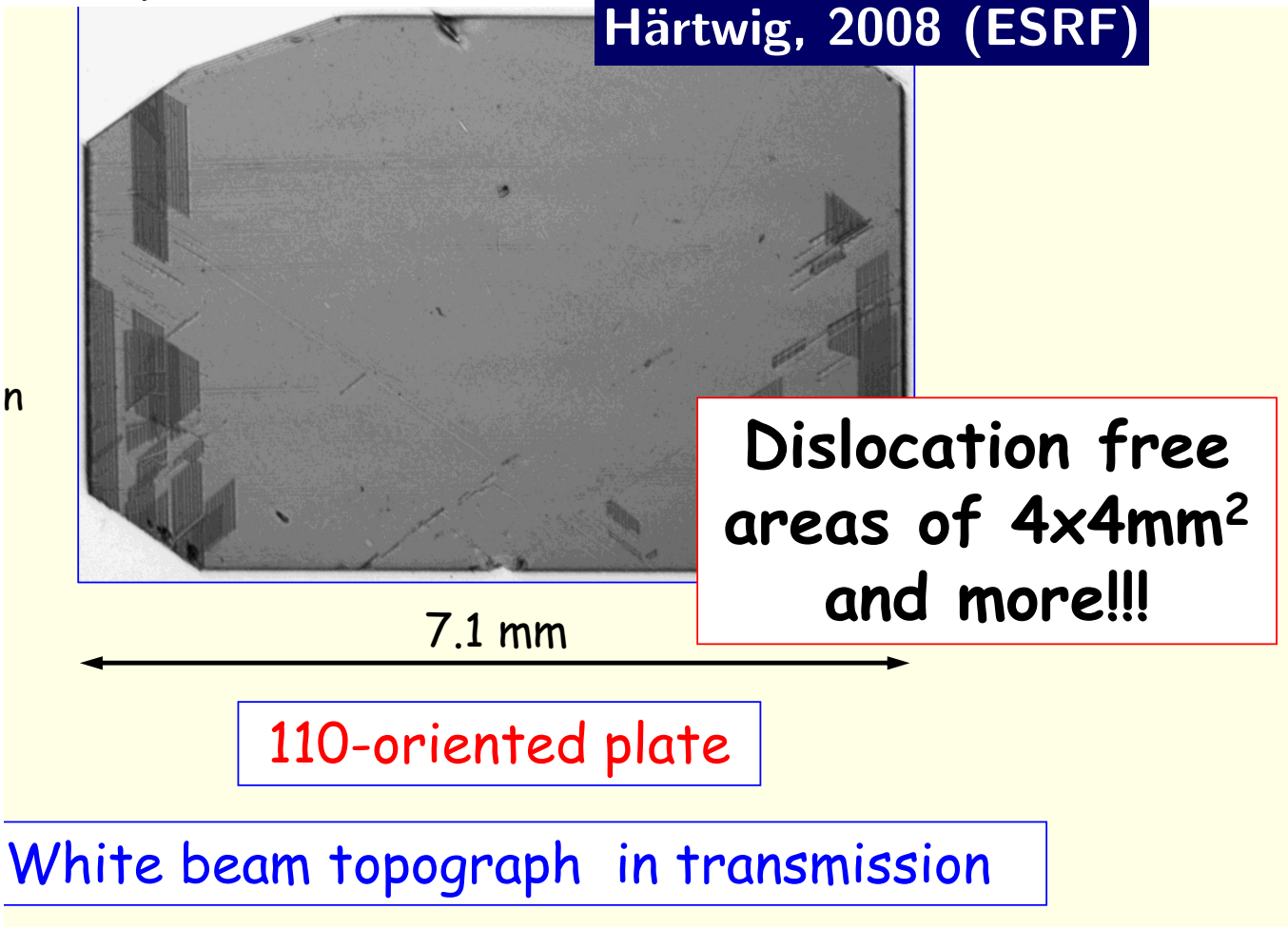
  Spatial stability: $\delta L \lesssim 3$ μm (rms) $\quad\rightarrow\quad \delta L/L \lesssim 3\times 10^{-8}$
- **Radiation damage**

Quality of Diamond crystals

Quality of Diamond crystals

Required diamond crystals:

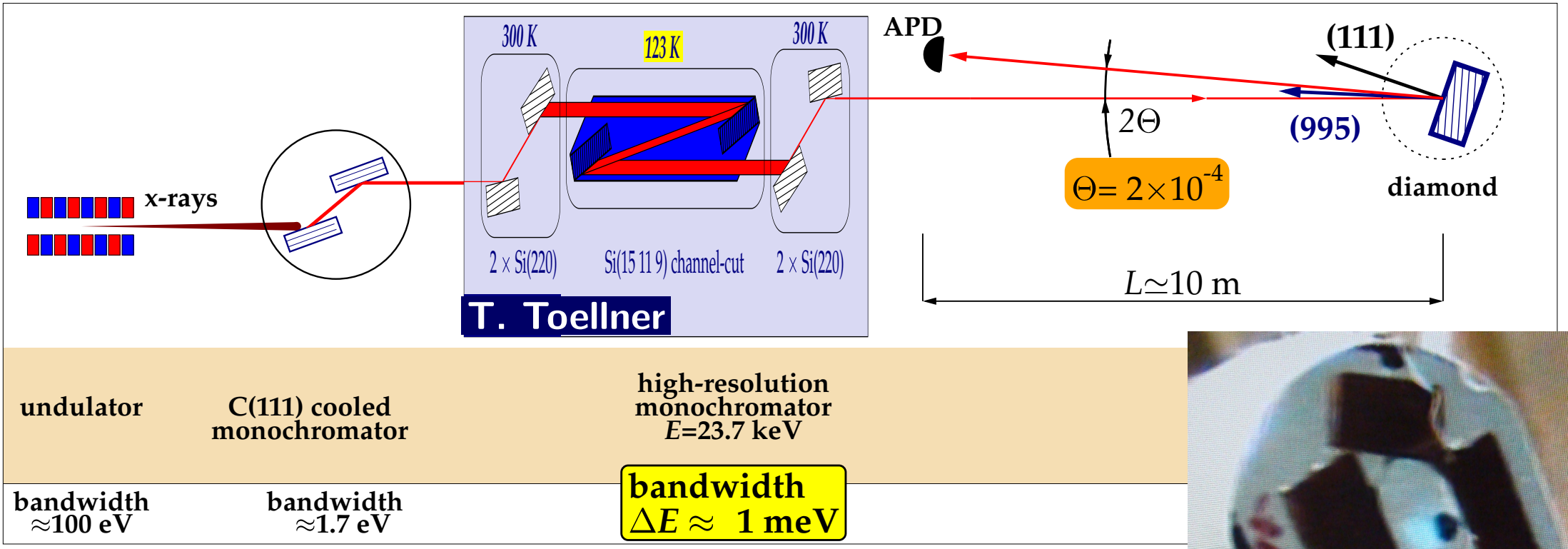
- high quality (dislocation free, etc.)
- thickness: $20 - 2000$ μm
- small suffice: $\simeq 1$ mm^2



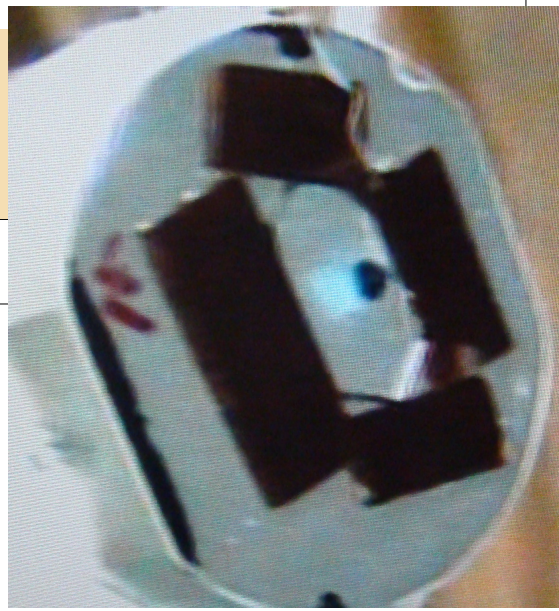
Still open question:

is the theoretical reflectivity achievable?

Experiment, 30-ID @ APS



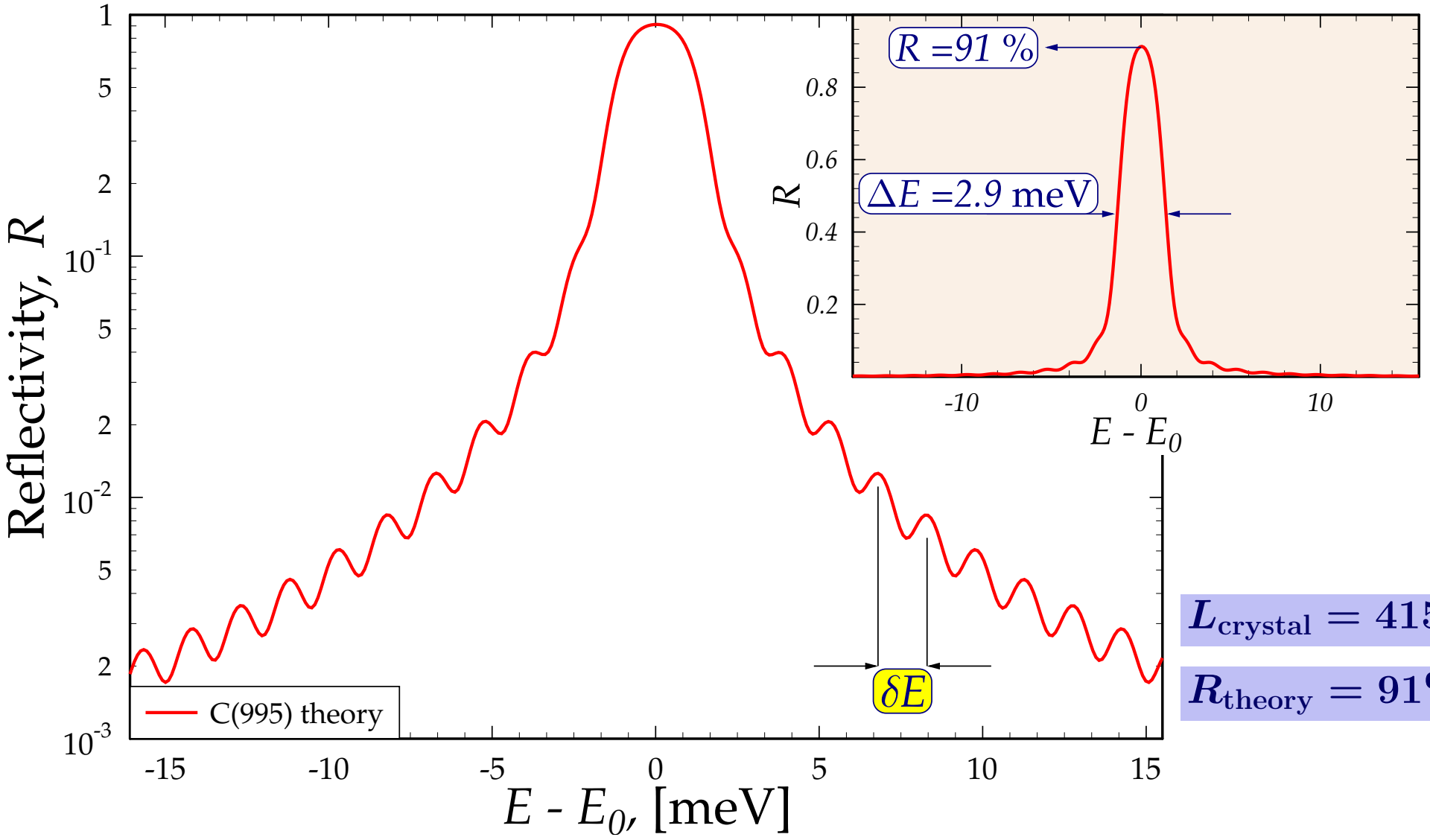
undulator	C(111) cooled monochromator	high-resolution monochromator E=23.7 keV
bandwidth ≈100 eV	bandwidth ≈1.7 eV	bandwidth $\Delta E \approx$ 1 meV



Shvyd'ko, Stoupin, Cunsolo, Said, Huang, Nature Phys. 6, 196 (2010)

Spectral Width and Reflectivity: Theory

C(995), $E_H = 23.765$ keV



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

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

Spectral Width and Reflectivity: Experiment

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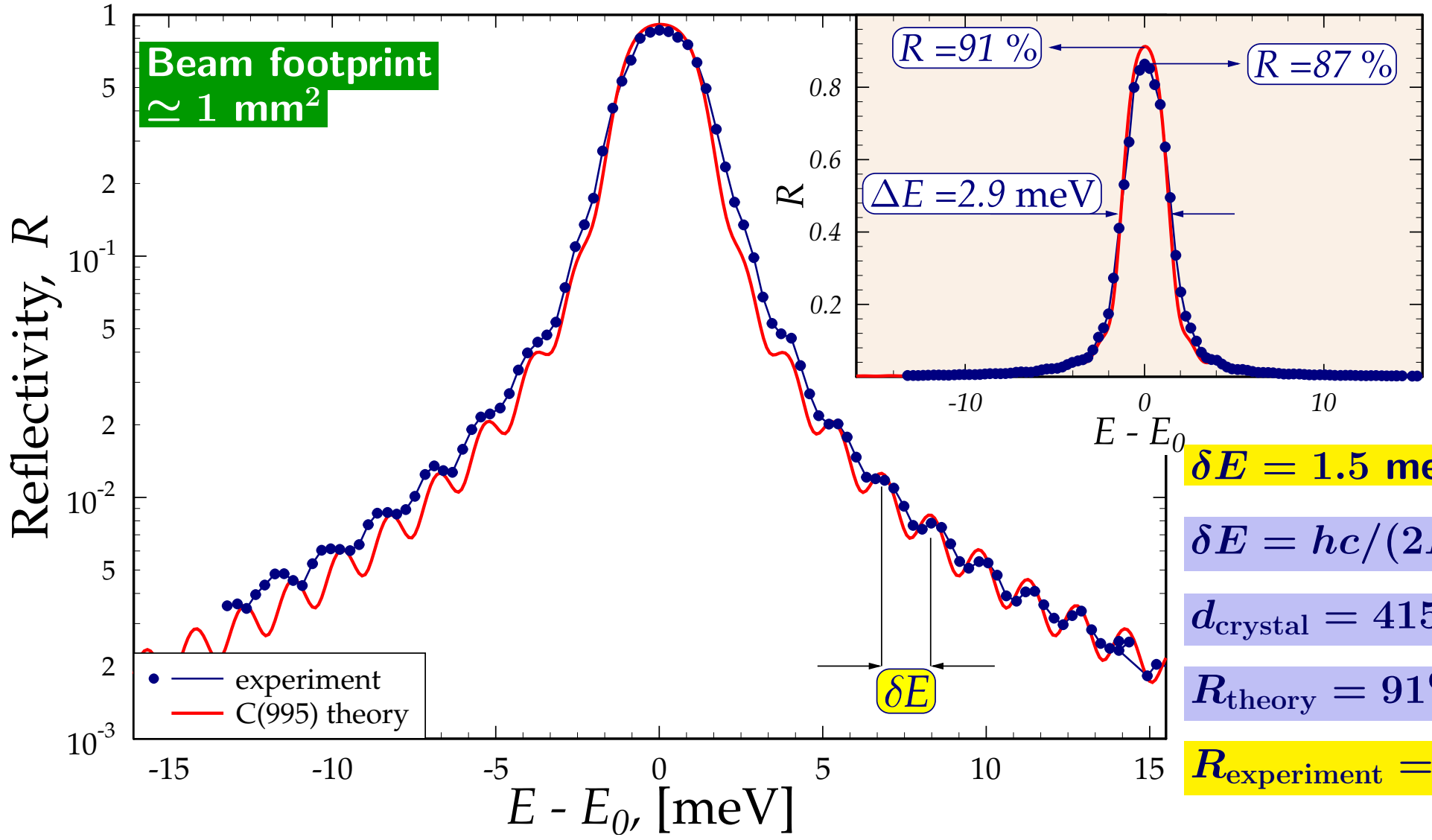
Shvyd'ko, Stoupin, et al, Nature Phys. 6, 196 (2010)



$\delta E = 1.5$ meV

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

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

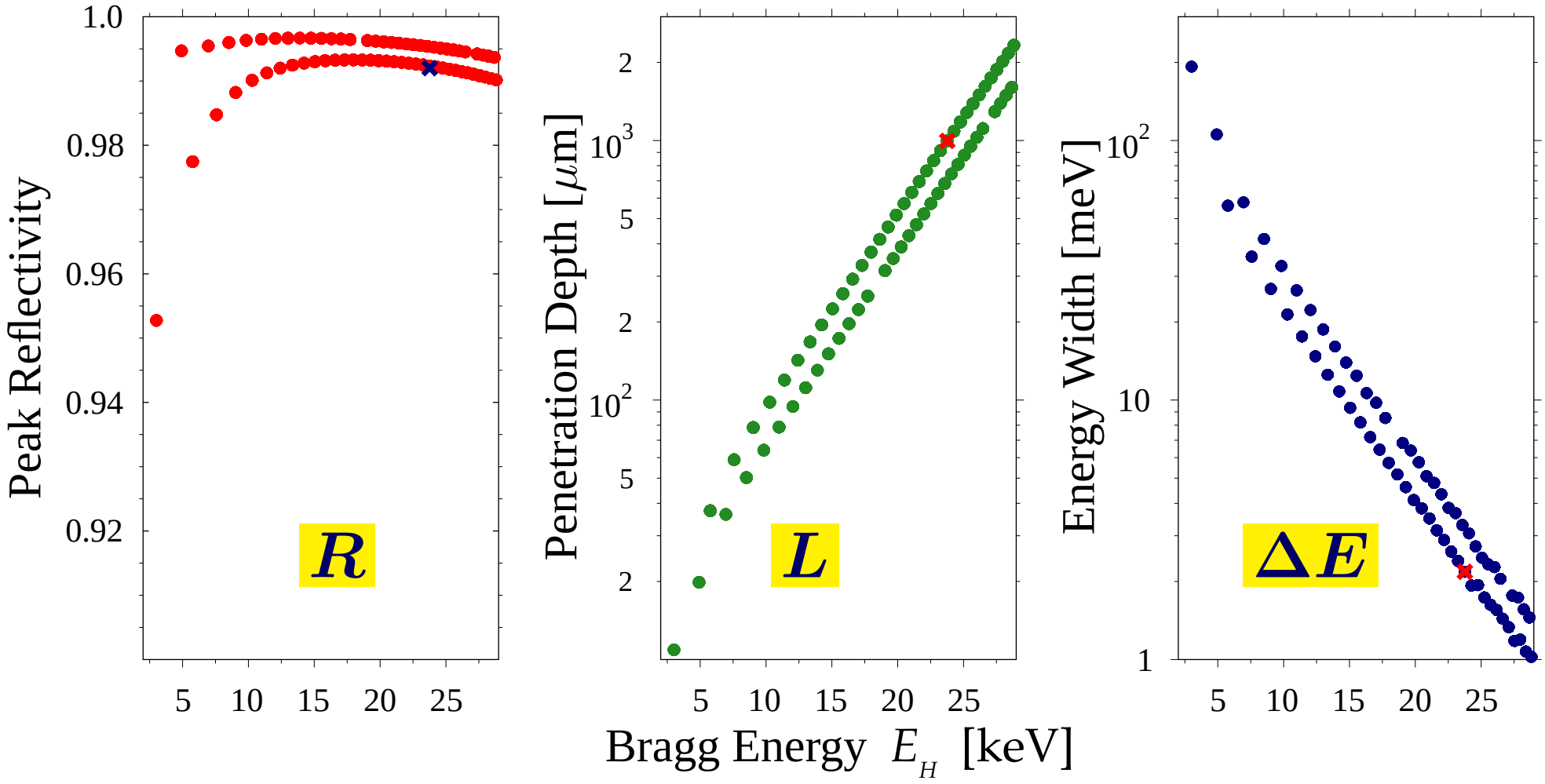
$R_{\text{theory}} = 91\%$

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

Reflectivity vs. Penetration & Energy Width

R, L, and ΔE are interconnected.

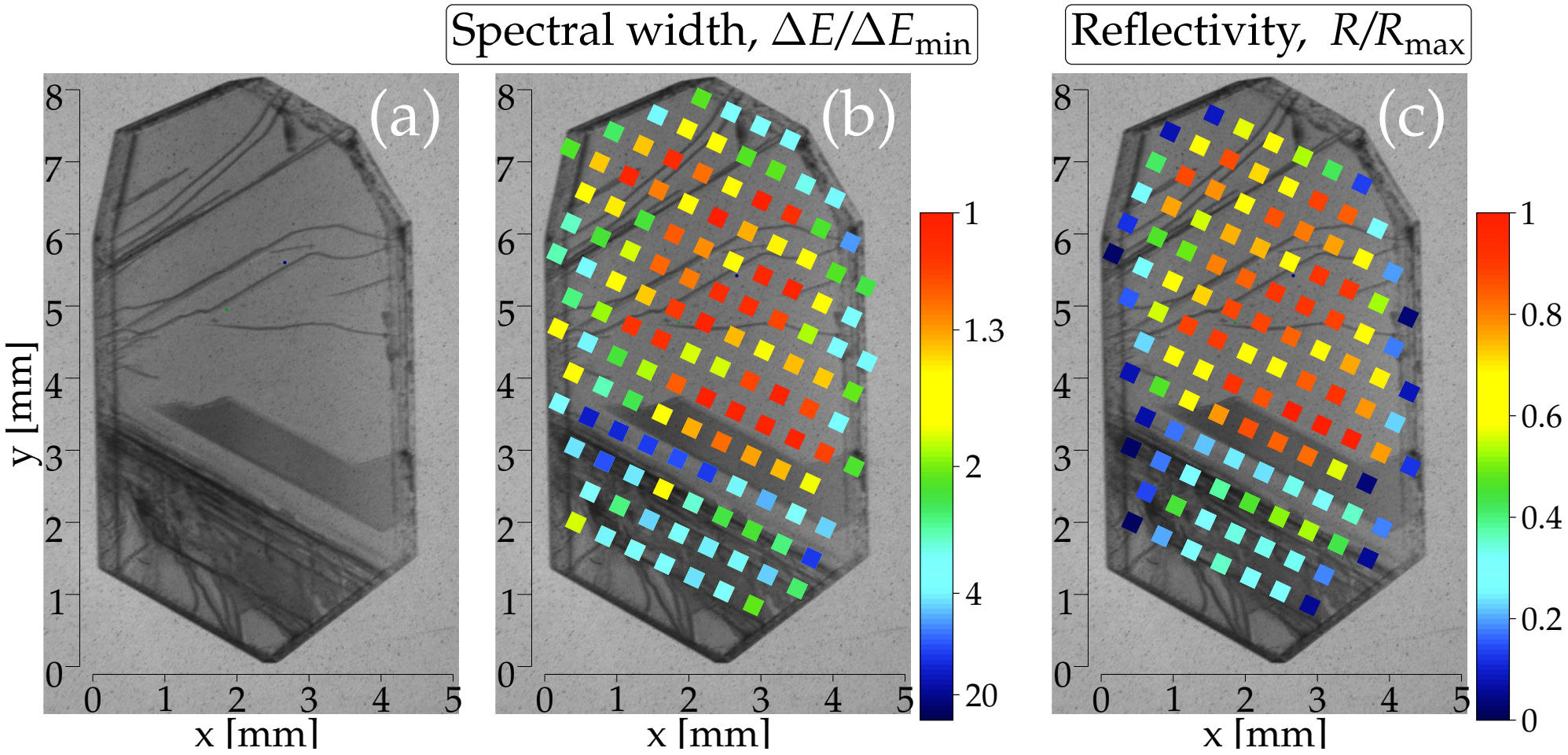
$\Delta E \propto 1/L$



Smallness of ΔE is a hallmark of high quality crystal

Spectral Width and Reflectivity Map

Shvyd'ko, Stoupin, et al, Nature Phys. 6, 196 (2010)



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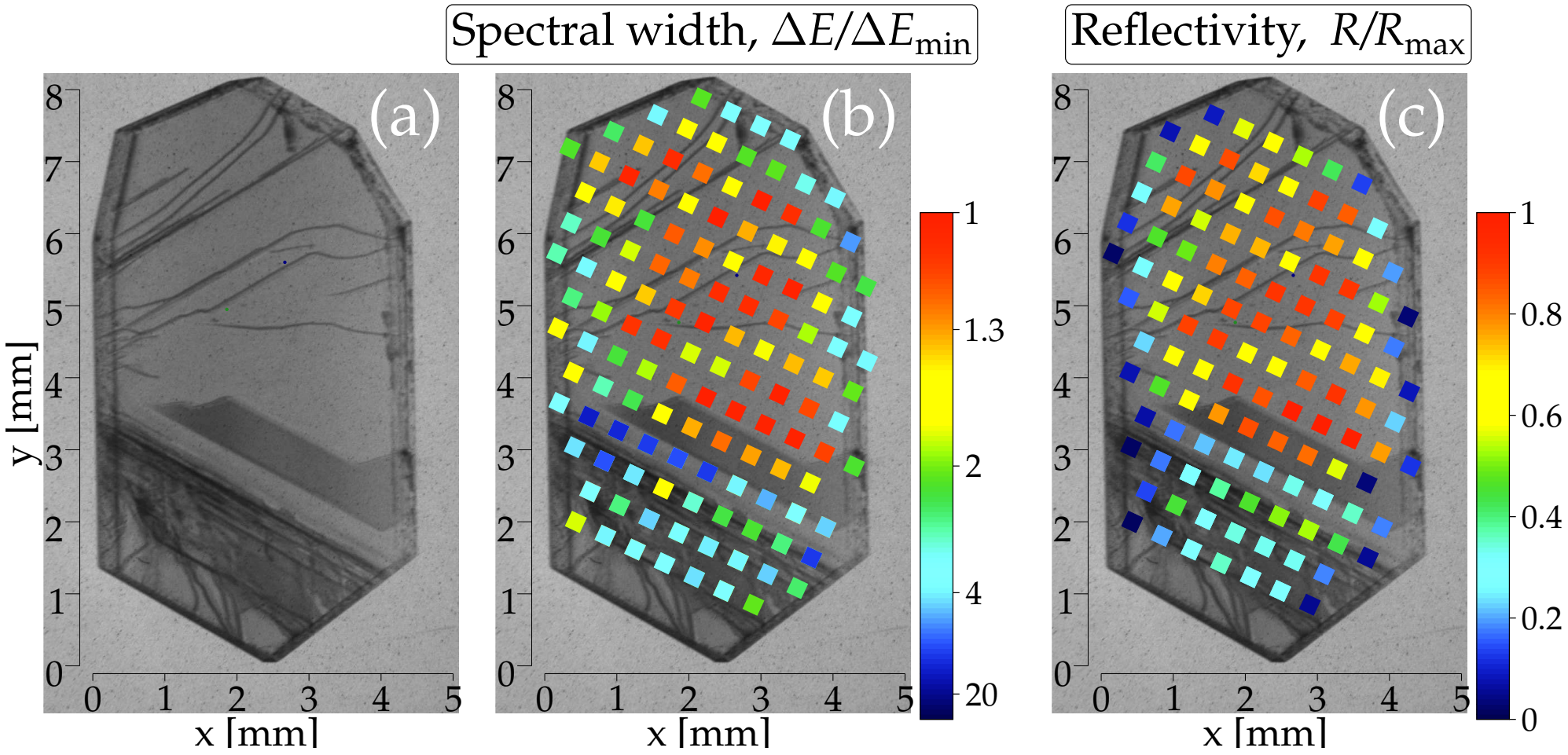

Synthetic diamond crystals are available with theoretically high reflectivity and sufficiently large in size for XFELO cavity applications.

Heat Load 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.

Incident power $\simeq 50$ μJ/pulse.

Absorbed power: $\simeq 1$ μJ/pulse (2%).

Footprint: $\simeq 100 \times 100$ μm^2

Is it a problem?

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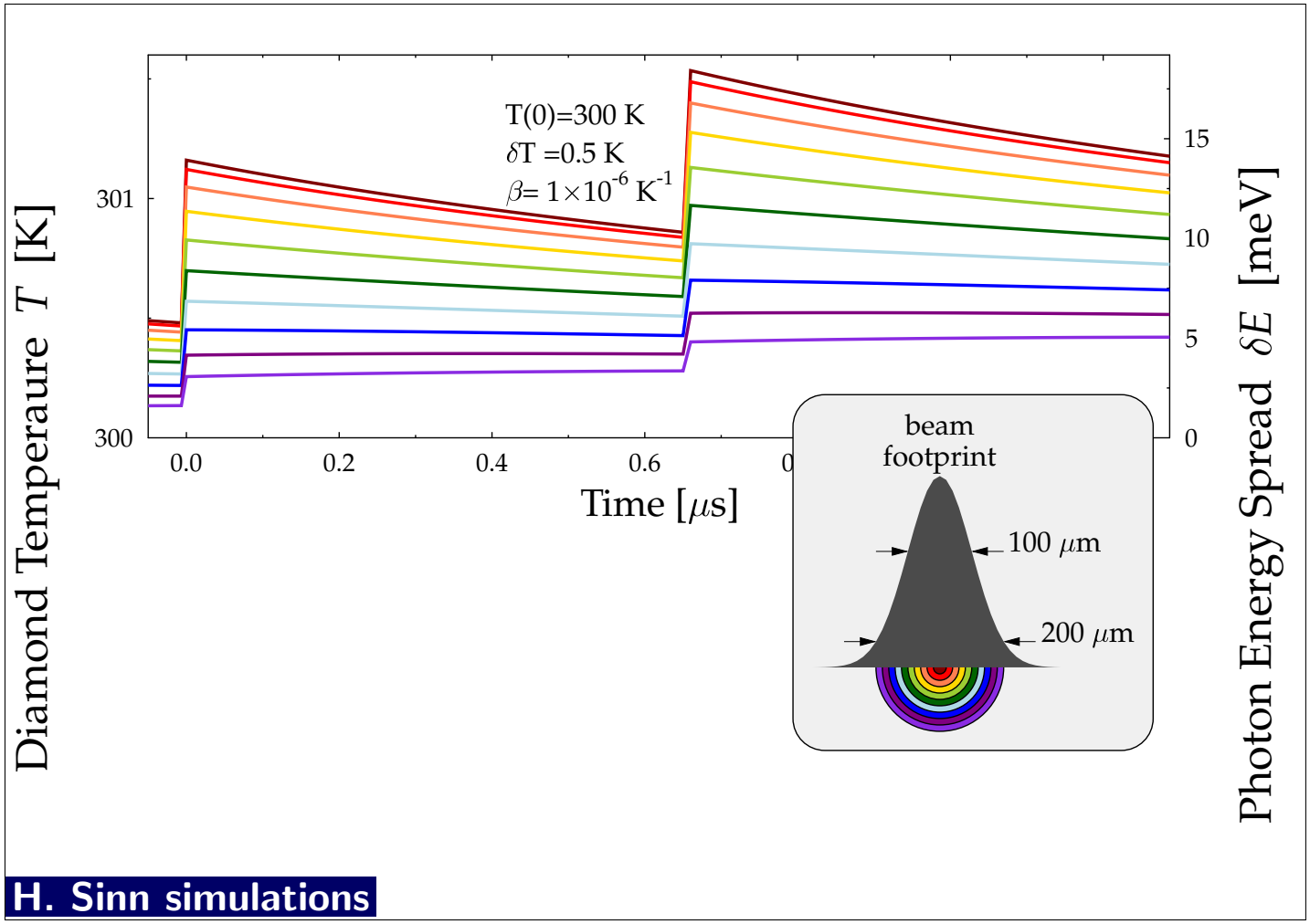

H. Sinn simulations

- **Big temperature jump δT after the x-ray pulse arrival.**
- **T=300K: Big temperature spread by the arrival of**

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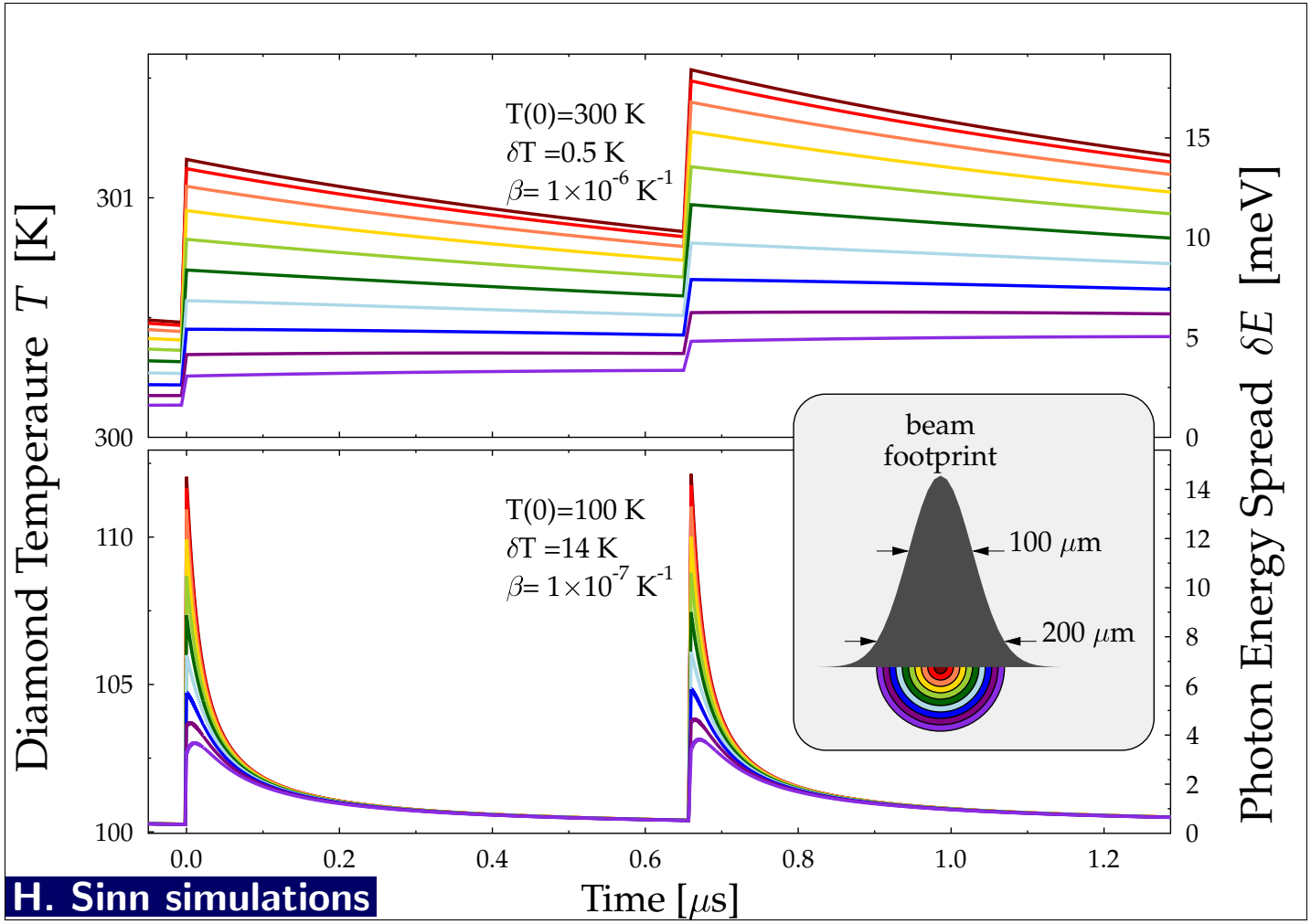

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- **Big temperature jump δT after the x-ray pulse arrival.**
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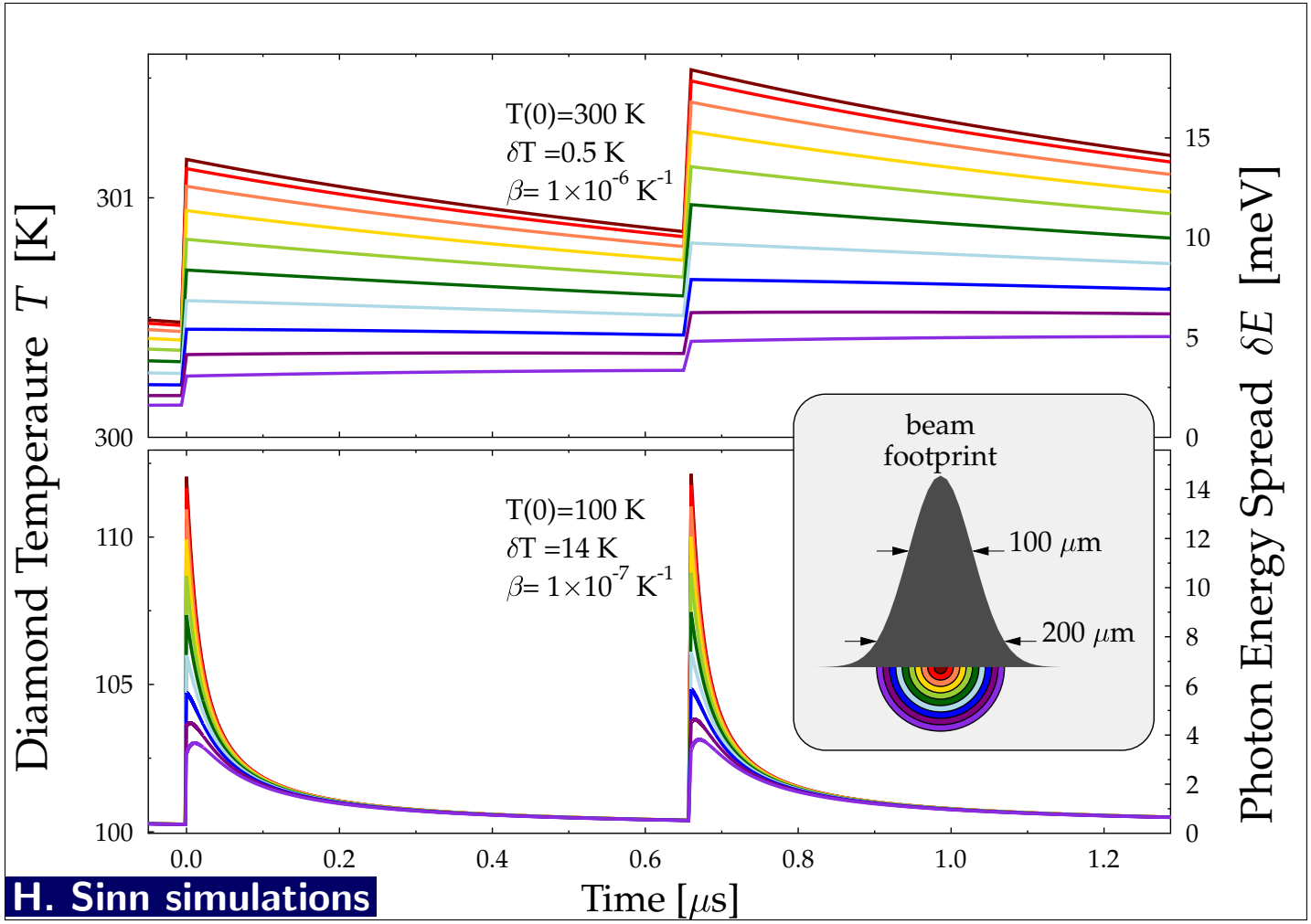
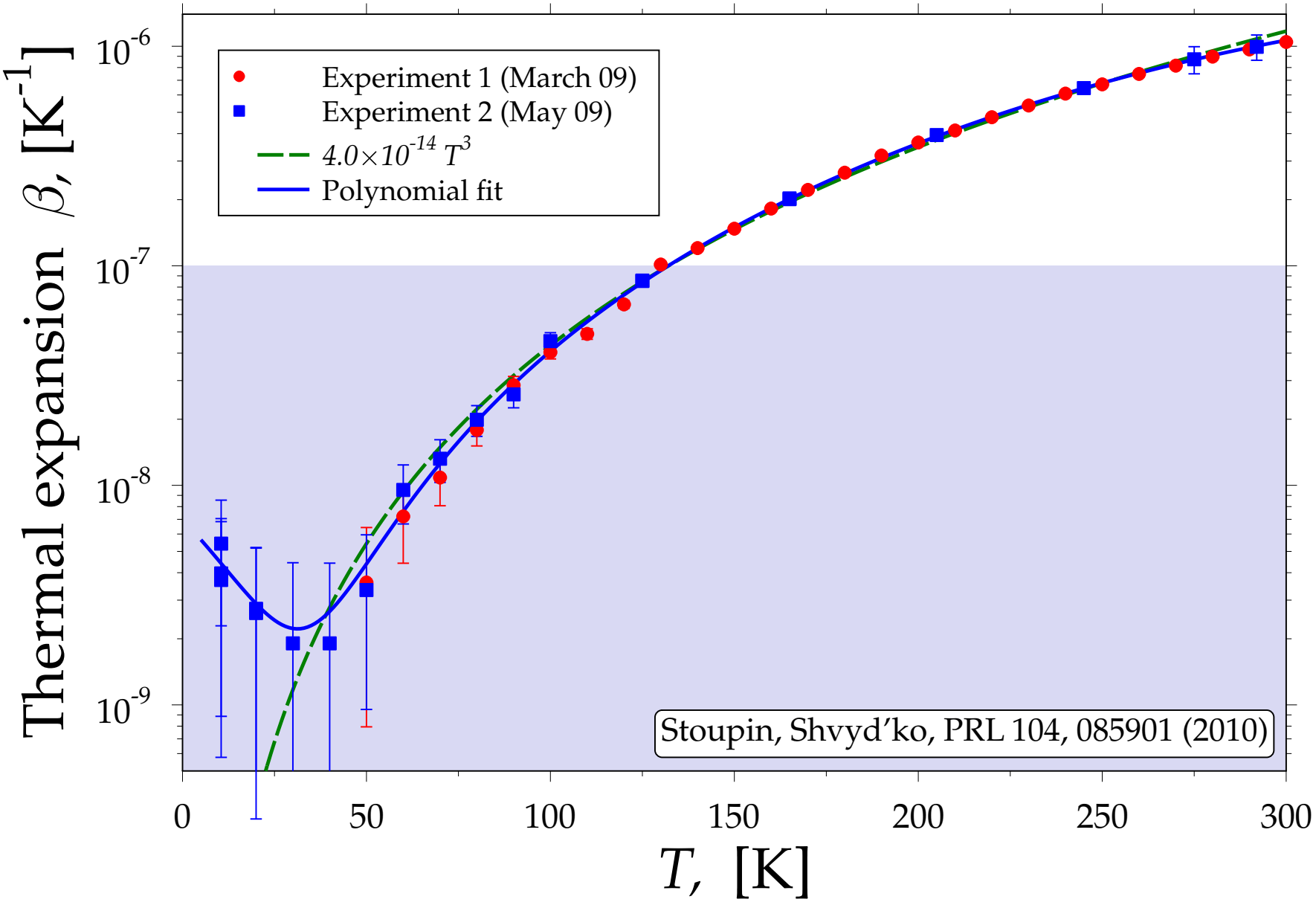


H. Sinn simulations

- **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!**

Diamond Thermal Expansion



Heat Load Problem

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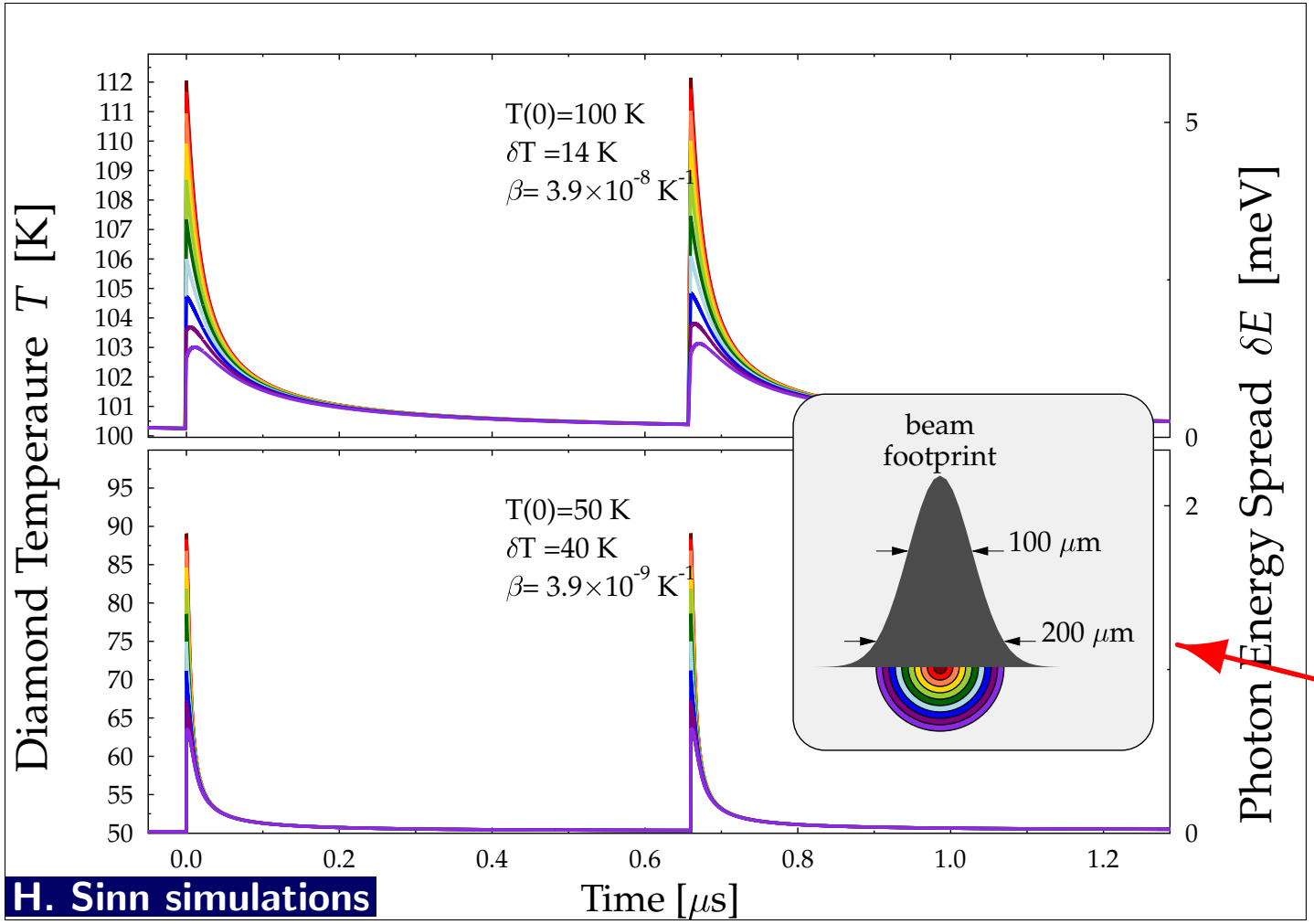
Requirement: $\delta E \lesssim 1$ **meV, when the next pulse arrives.**



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Angular & Spatial Stability

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

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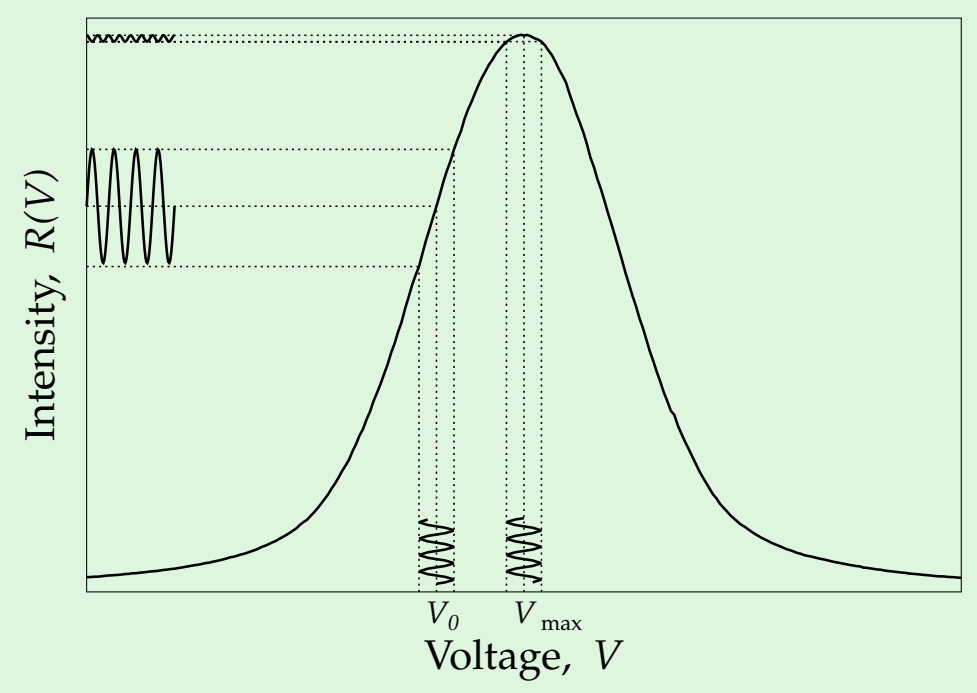

X-ray intensity: linear response to small angular oscillations is proportional to angular deviation from the maximum of the rocking curve.

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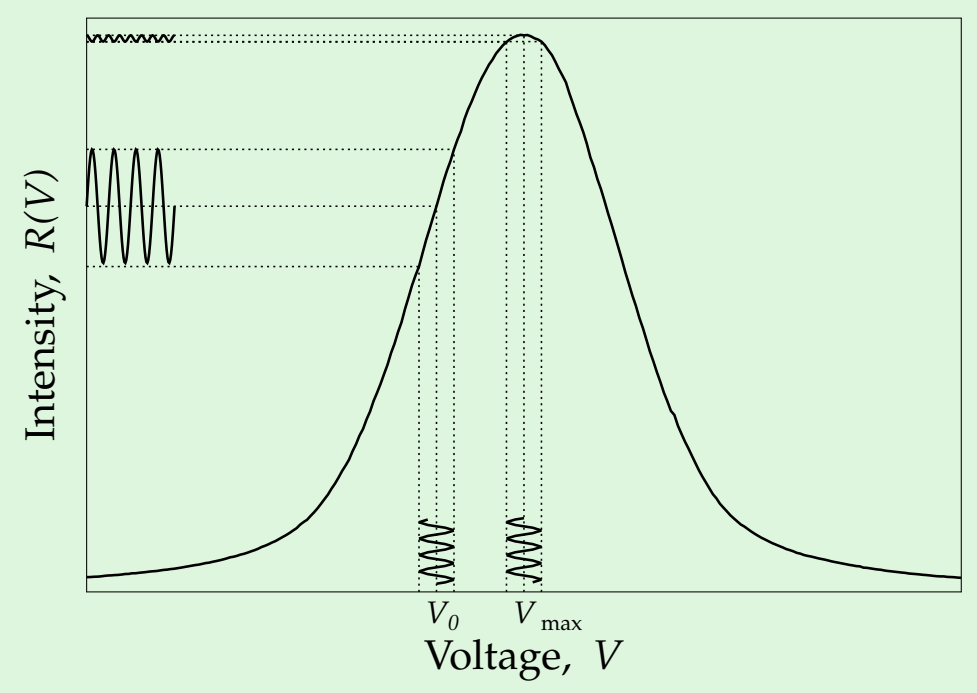
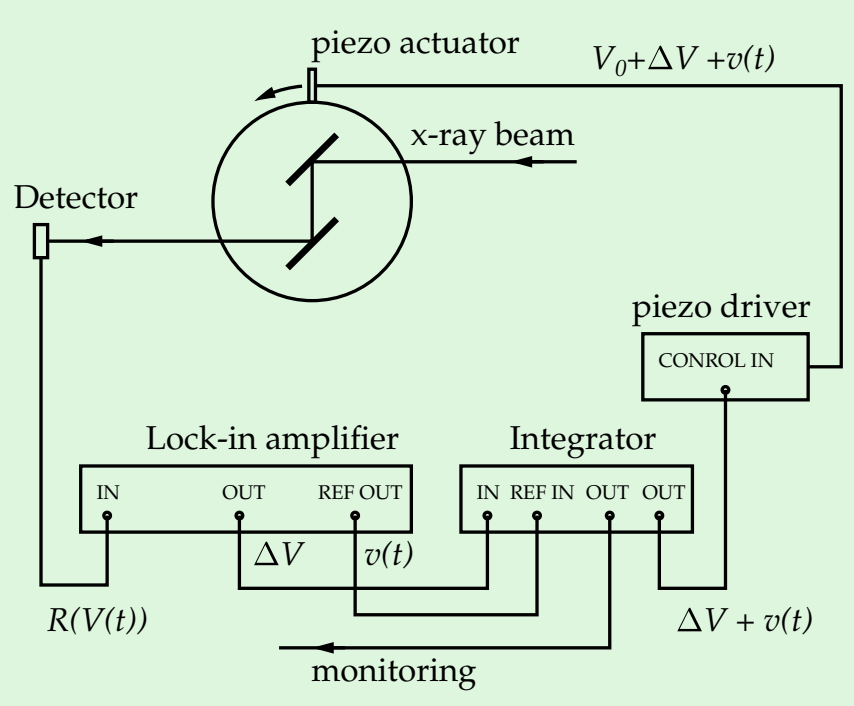
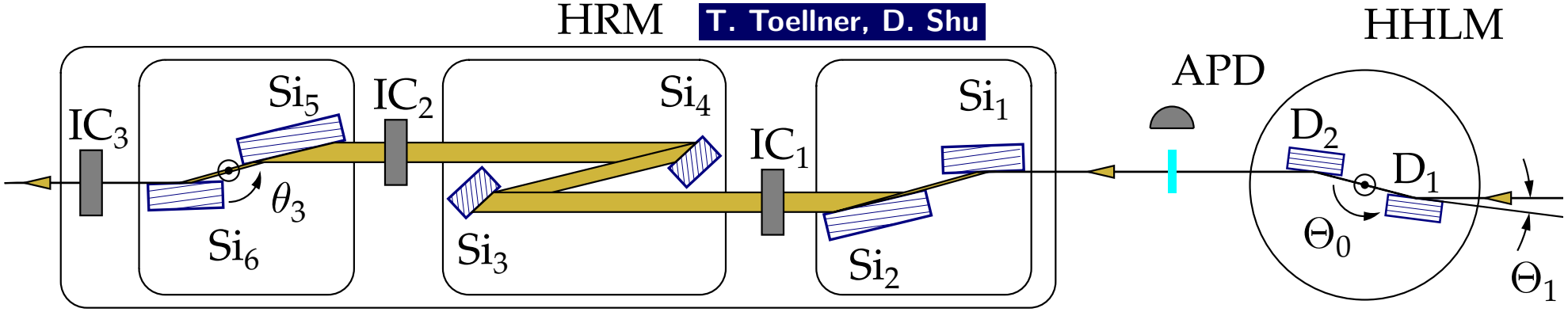


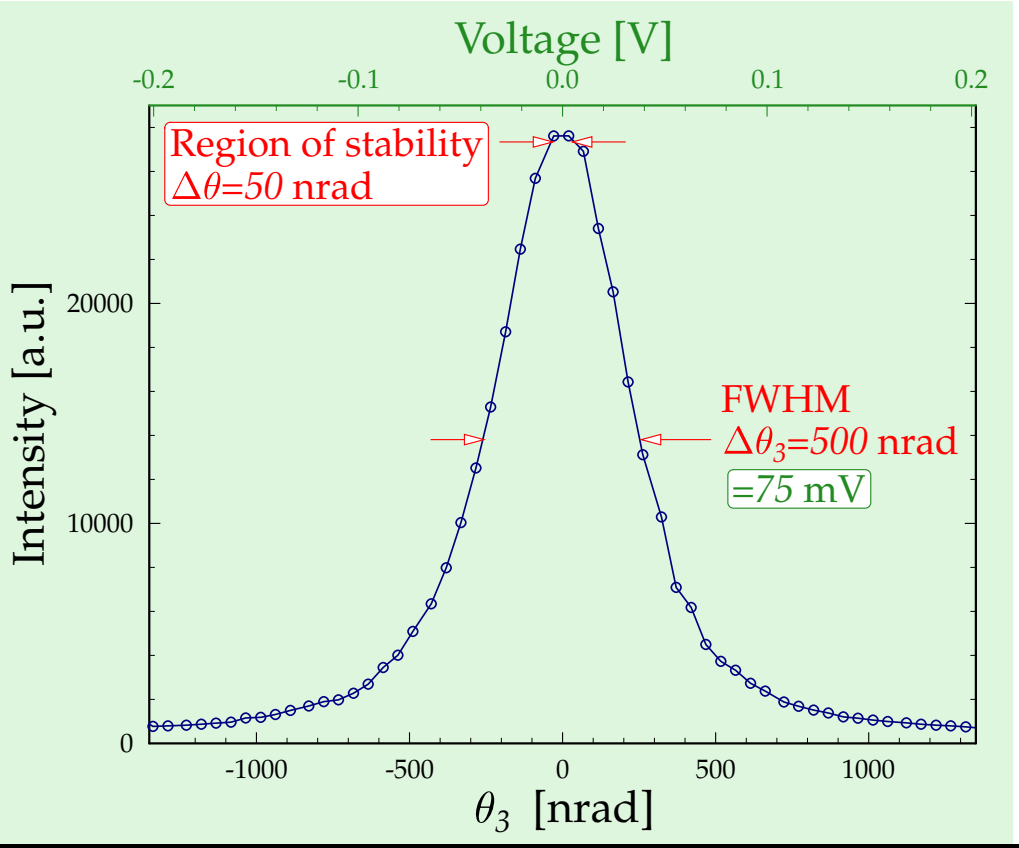


X-ray intensity: **linear response to small angular oscillations is proportional to angular deviation from the maximum of the rocking curve.**

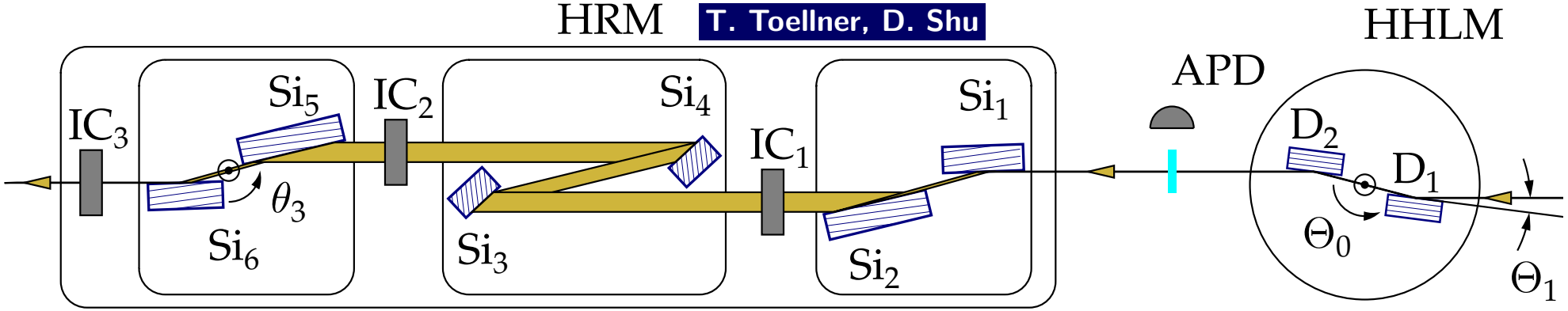
Feedback: **correction signal is extracted using lock-in amplification.**

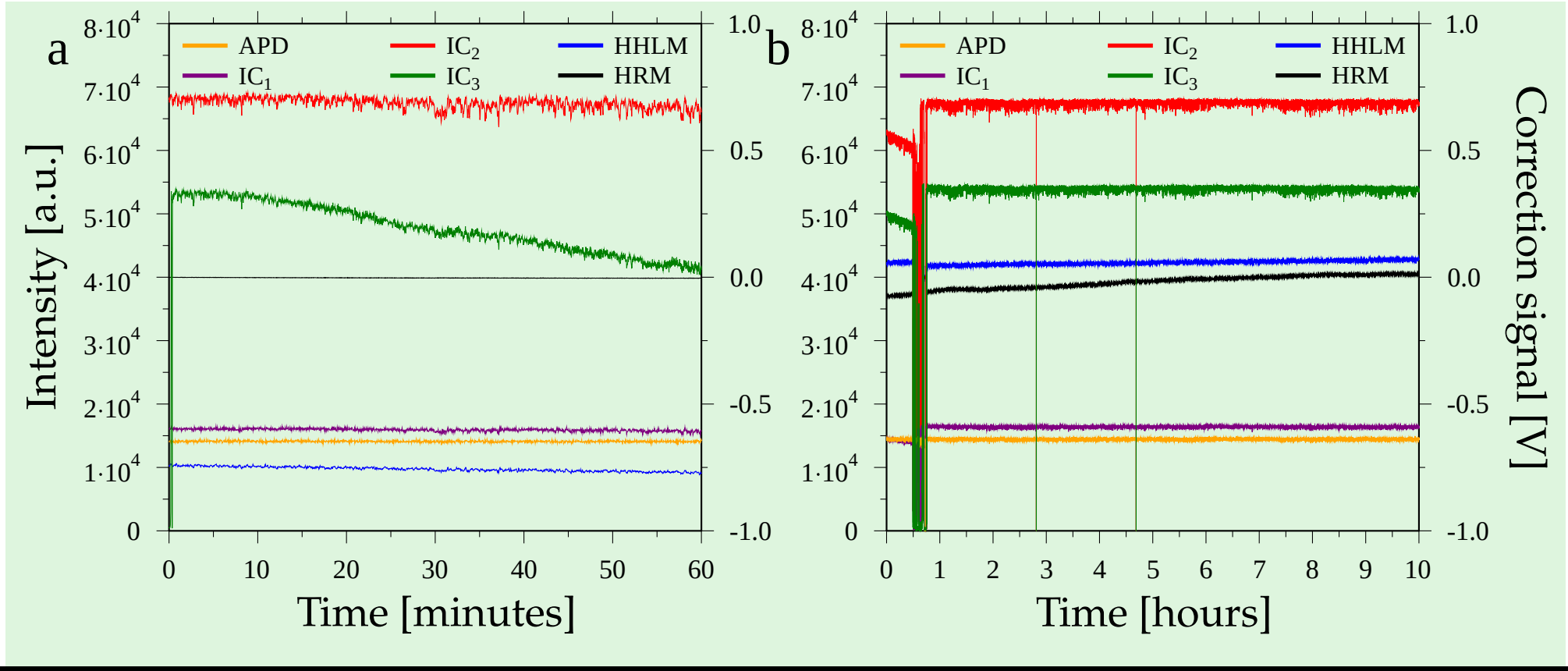
HERIX Monochromator Stability Region





HERIX Monochromator Stabilization





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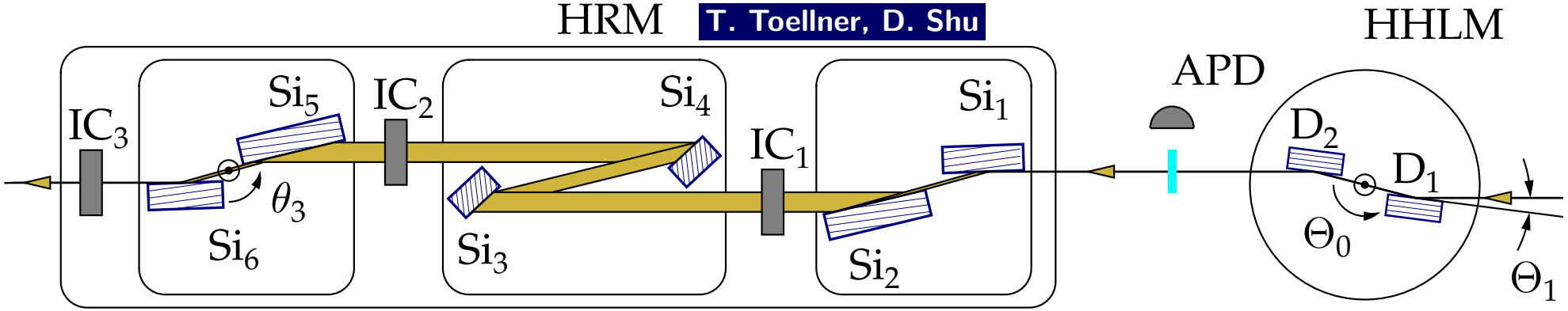

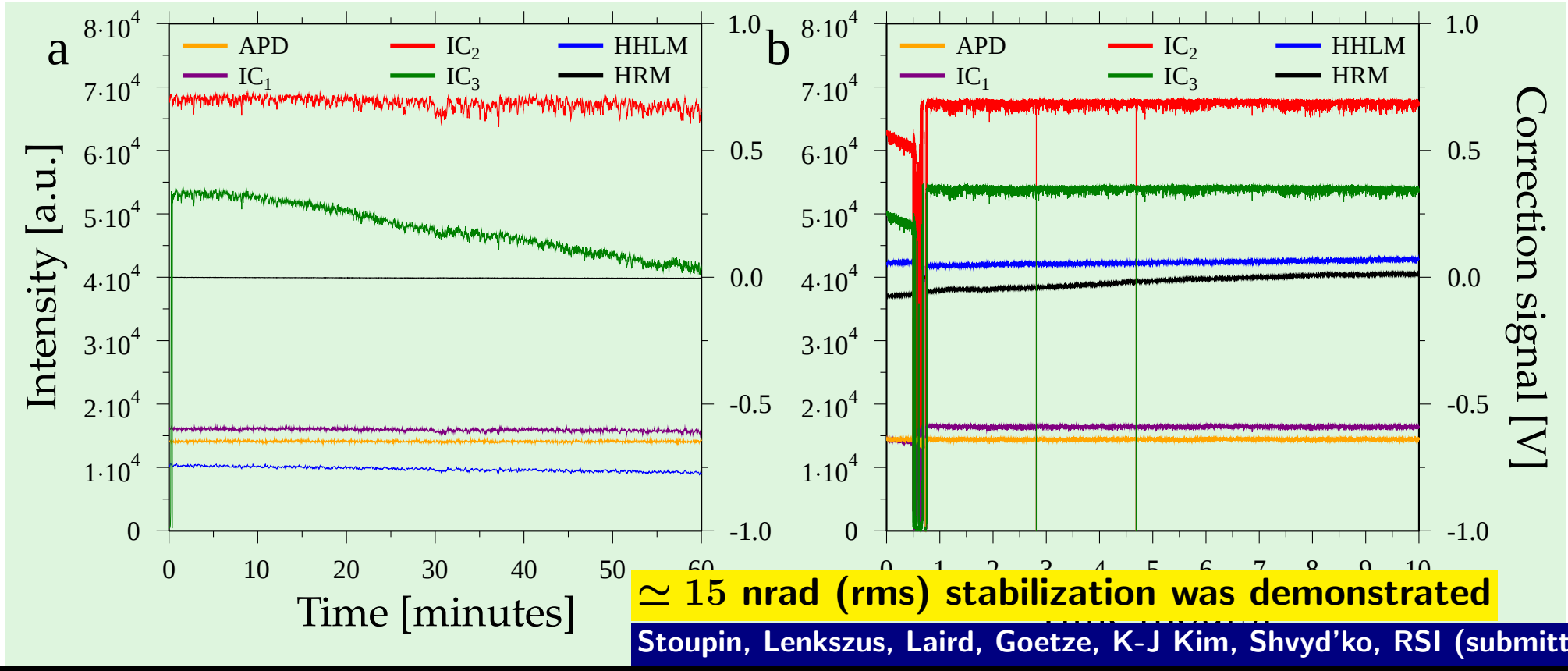

≃ 15 nrad (rms) stabilization was demonstrated

Stoupin, Lenkszus, Laird, Goetze, K-J Kim, Shvyd'ko, RSI (submitted)

Radiation damage in diamond

Radiation damage in diamond

XFELO generates:

50μJ/pulse @ 12 keV with $\simeq 1$ MHz rep. rate
Footprint: $A = 1.6 \times 10^{-4}$ cm^2 (rms)
Flux $\simeq 2 \times 10^{20}$ ph/s/cm^2

Time to ionize carbon atom with 100% probability: $T \simeq 250$ s Robin Santra

Can this produce irreversible changes in the perfect crystal lattice structure?

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APS undulators generate:

Flux $\simeq 5 \times 10^{17}$ ph/s/cm^2

Time to ionize carbon atom with 100% probability: $T' \simeq 10^5$ s $\simeq 1$ day

Graphitization of the surface layer of the diamond crystal is observed after several days of operations. Though, no significant degradation in the performance of the high-heat-load monochromator is observed after a year of operations.

How to mitigate radiation damage in diamond?

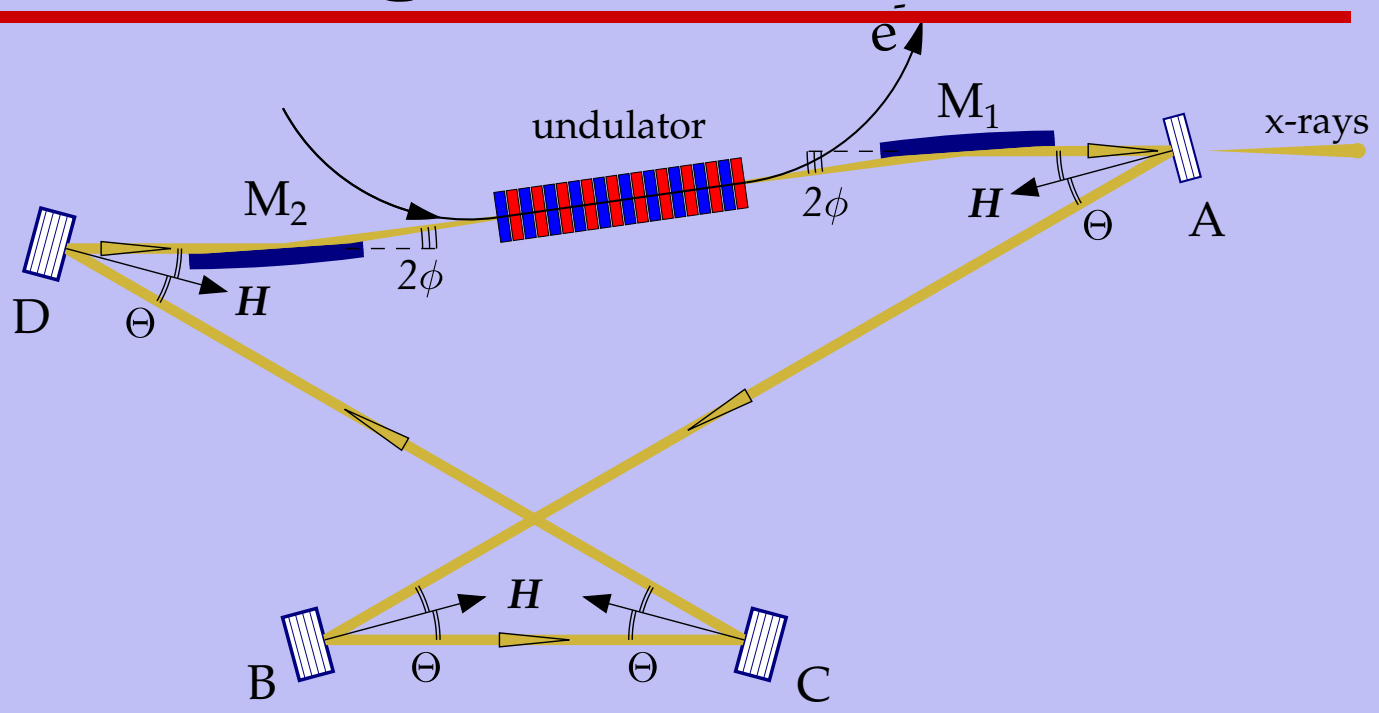
⇒ Operate diamond at cryogenic temperatures.

⇒ Use isotopically pure ^{12}C crystals.
Laser damage threshold is more than order of magnitude higher for isotopically pure diamond.
Anthony et al, PRB, 42 1104 (1990)

⇒ Apply electric fields to keep the electrons in diamond (K-J. Kim)

⇒ ....

XFELO Technical Challenges



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  Spatial stability: $\delta L \lesssim 3$ μm (rms) $\rightarrow$ $\delta L/L \lesssim 3 \times 10^{-8}$
- **Radiation damage** ?

Acknowledgments

XFELO collaboration:

Kwang-Je Kim (APS)

Stanislav Stoupin (APS)
Ryan Lindberg (APS)
Sven Reiche (SLS)
Bill Fawley, (LBNL)
Frank Lenkszus (APS)
Deming Shu (APS)
Harald Sinn (European XFEL)

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Robert Laird (APS)
Stan Whitcomb (LIGO)
Al Macrander (APS)
Tim Roberts (APS)
Kurt Goetze (APS)
Emil Trakhtenberg (APS)
Ayman Said (APS)
Alessandro Cunsolo (APS)
Tom Toellner (APS)
Lahsen Assoufid (APS)