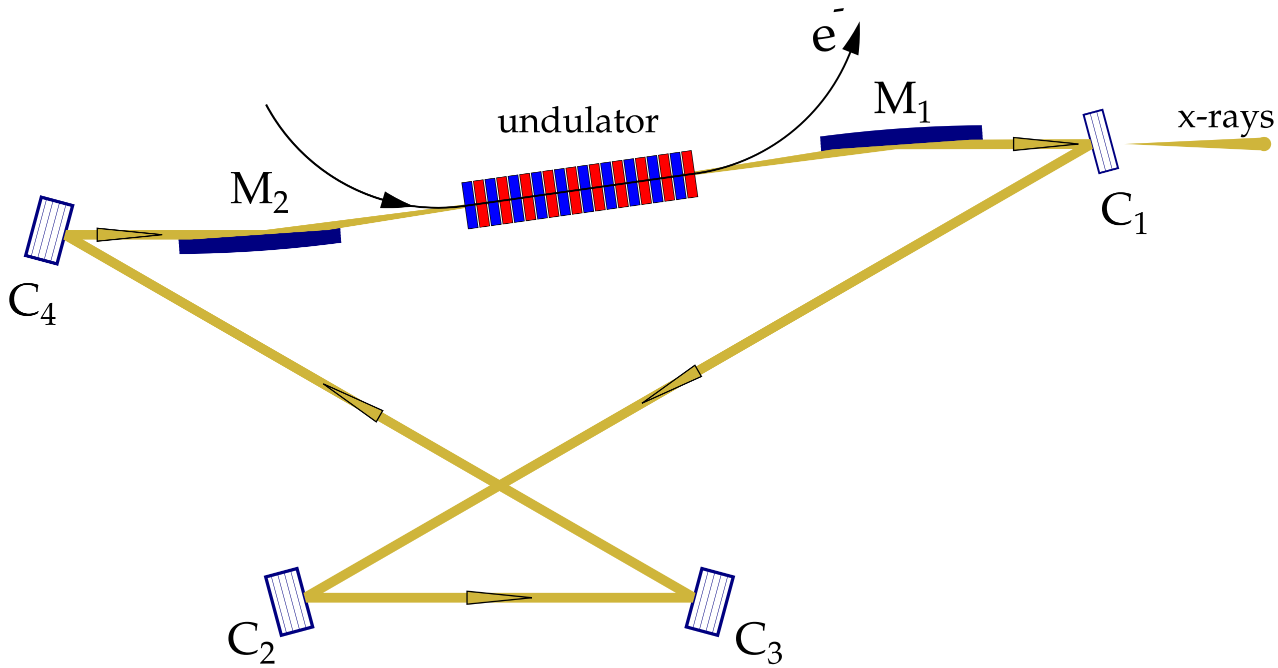
Feasibility of X-ray Cavities for Hard X-ray FEL Oscillators

Yuri Shvyd'ko



32nd International Free Electron Laser Conference FEL 2010
Malmö, Sweden, August 23-27, 2010.

XFELO collaboration:

Kwang-Je Kim (APS)
Stanislav Stoupin (APS)
Ryan Lindberg (APS)
Deming Shu (APS)
Harald Sinn (European XFEL)
Vladimir Blank (TISNCM)

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It is not a machine to produce explosions

with ultra-high number of x-ray photons in ultra-short pulses

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in ultra-short pulses

It is a machine for delicate studies with

high average number of
ultra-high monochromatic hard x-ray photons

XFELO Performance ⟹ Applications

Performance:

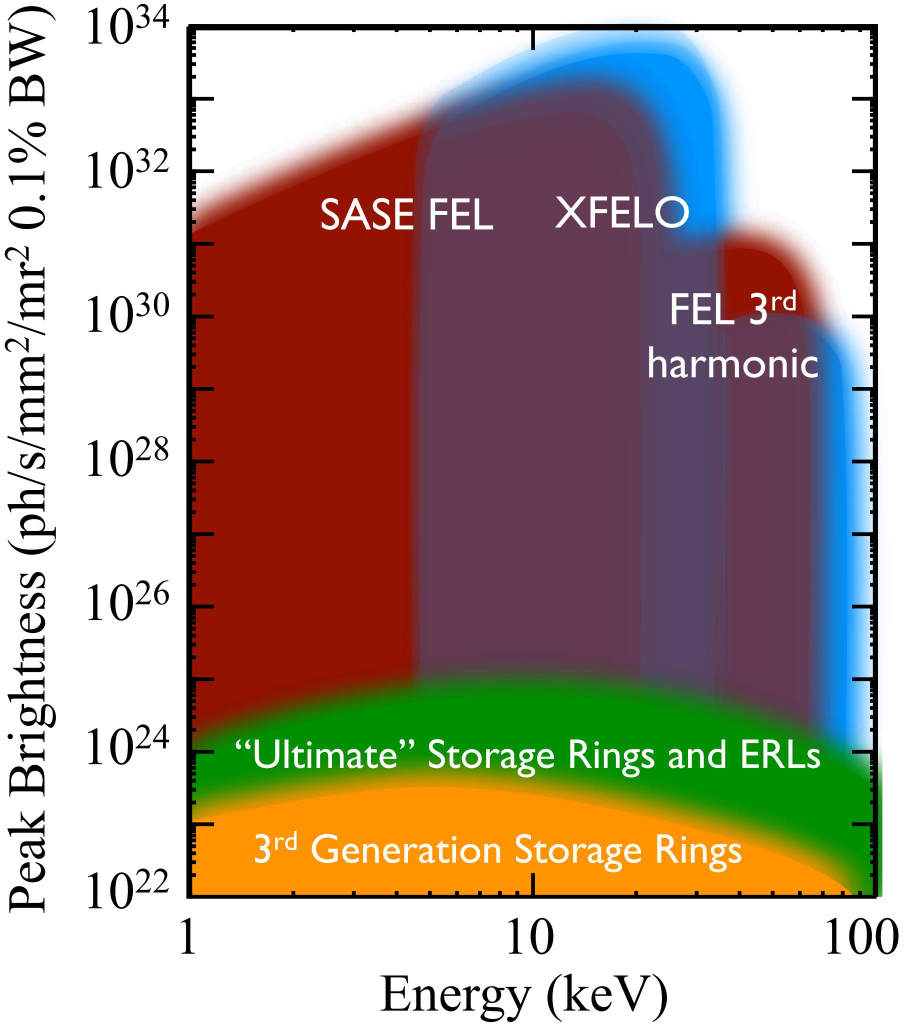
- fully coherent hard x-ray source
- highest average spectral brightness
- meV energy bandwidth
- ps-pulses
- 10^9 photons/pulse
- 1 MHz repetition rate.

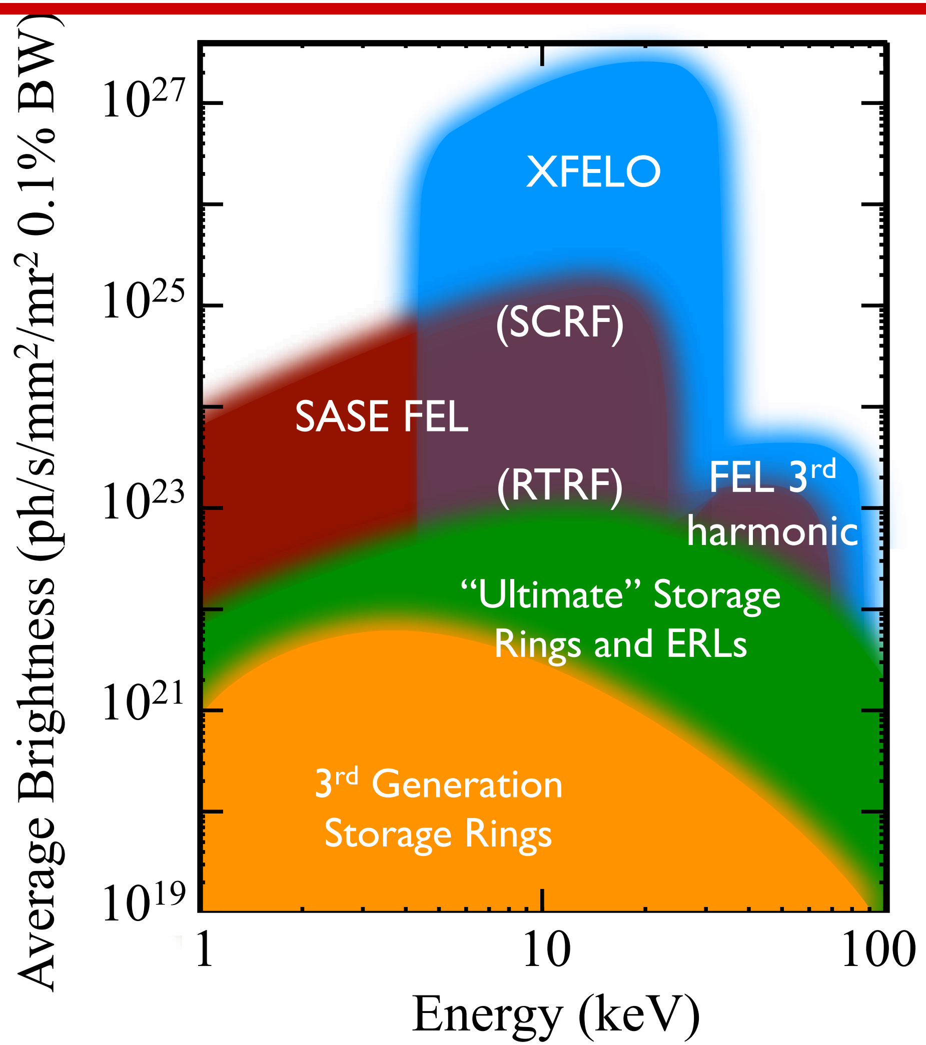
Applications:

- inelastic X-ray scattering (IXS)
- HAXPES
- ps-time measurements
- nuclear resonant spectroscopies
- imaging at near-atomic resolution ($\simeq 1$ nm)
- photon correlation spectroscopy

Science Opportunities with an XFELO Workshop, APS, May 5th, 2010

XFELO vs. SASE XFEL and other sources

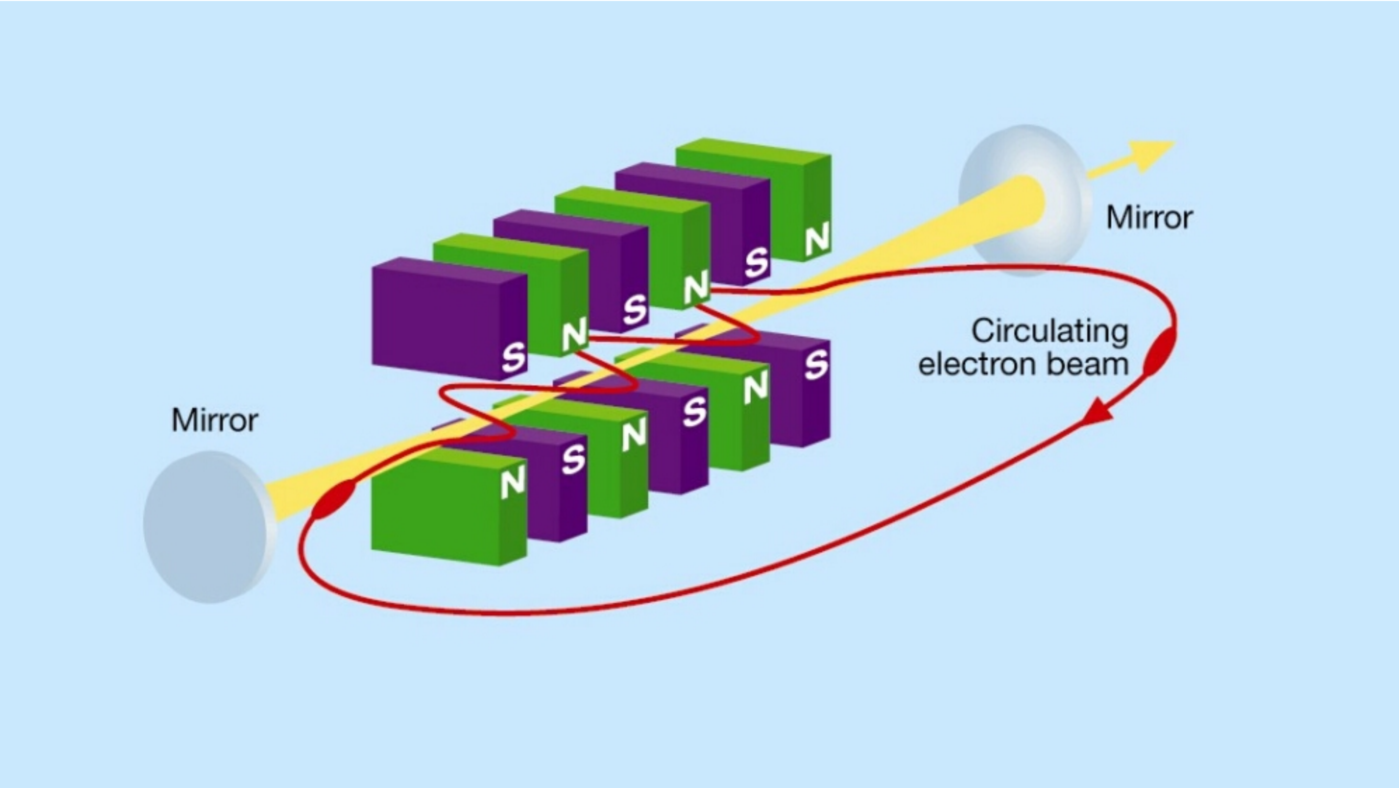




Courtesy of K.-J. Kim & R. Lindberg

XFEL-Oscillator: Is it Feasible?

First proposal: Colella and Luccio (1984)



FELs based on the oscillator principle are limited, on the short-wavelength side, 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)

Content

- **XFELO principle and technical challenges**
- **X-ray cavity feasibility studies:**

  ⇒ **reflectivity of diamond crystals**

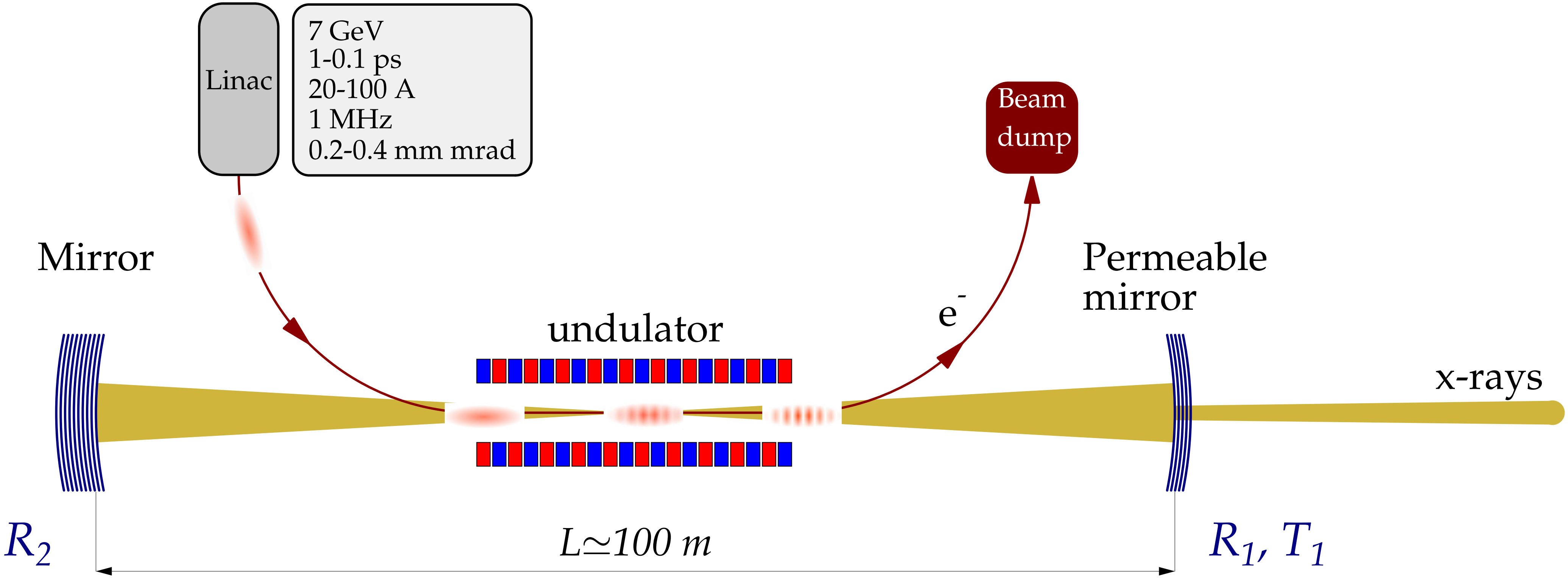
  ⇒ **heat load problem**

  ⇒ **nanoradian angular stabilization**

  ⇒ **radiation damage**

- **Conclusions and Outlook**

XFEL Oscillator Prerequisites

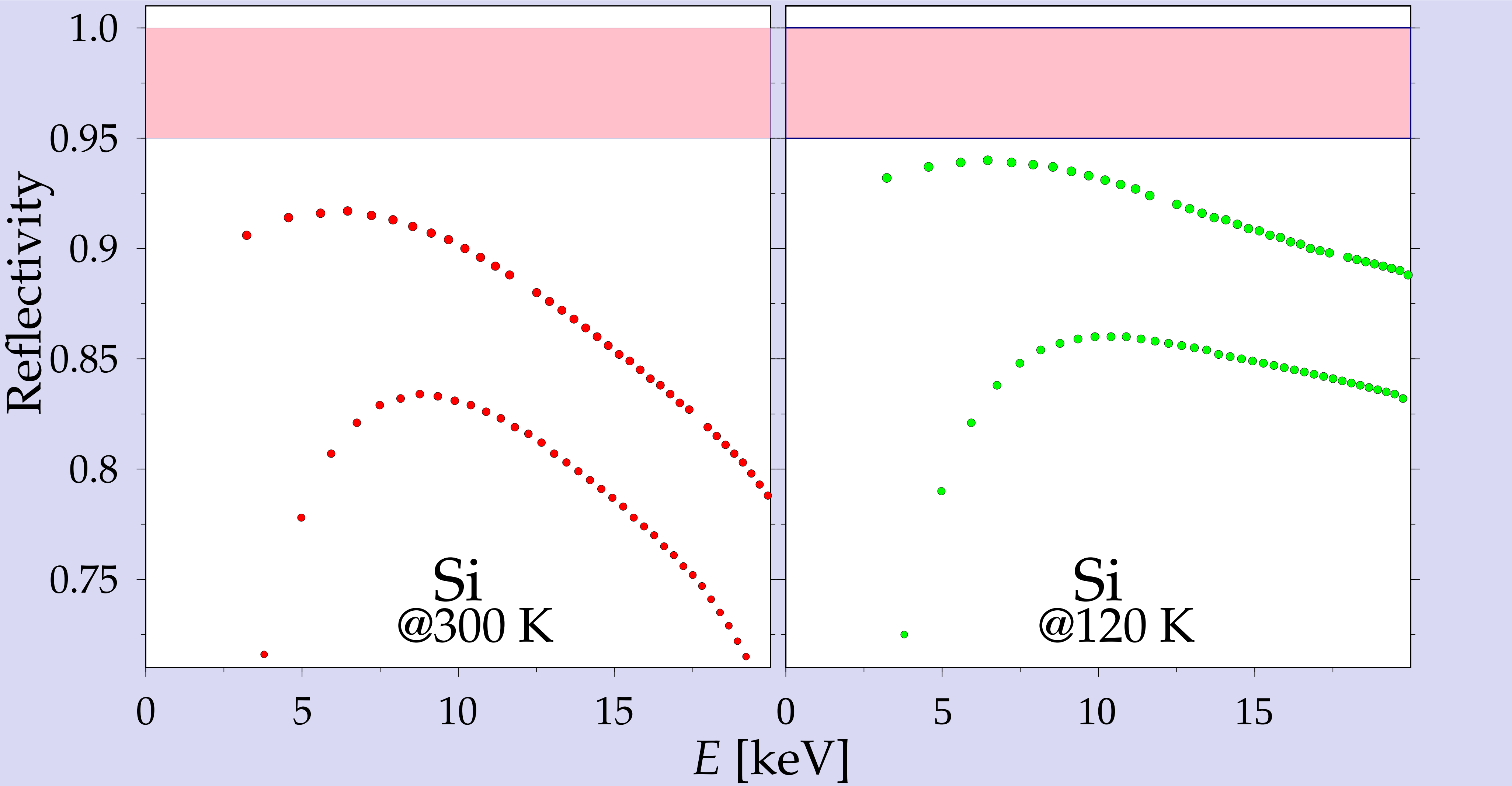


Low gain XFELO requires:

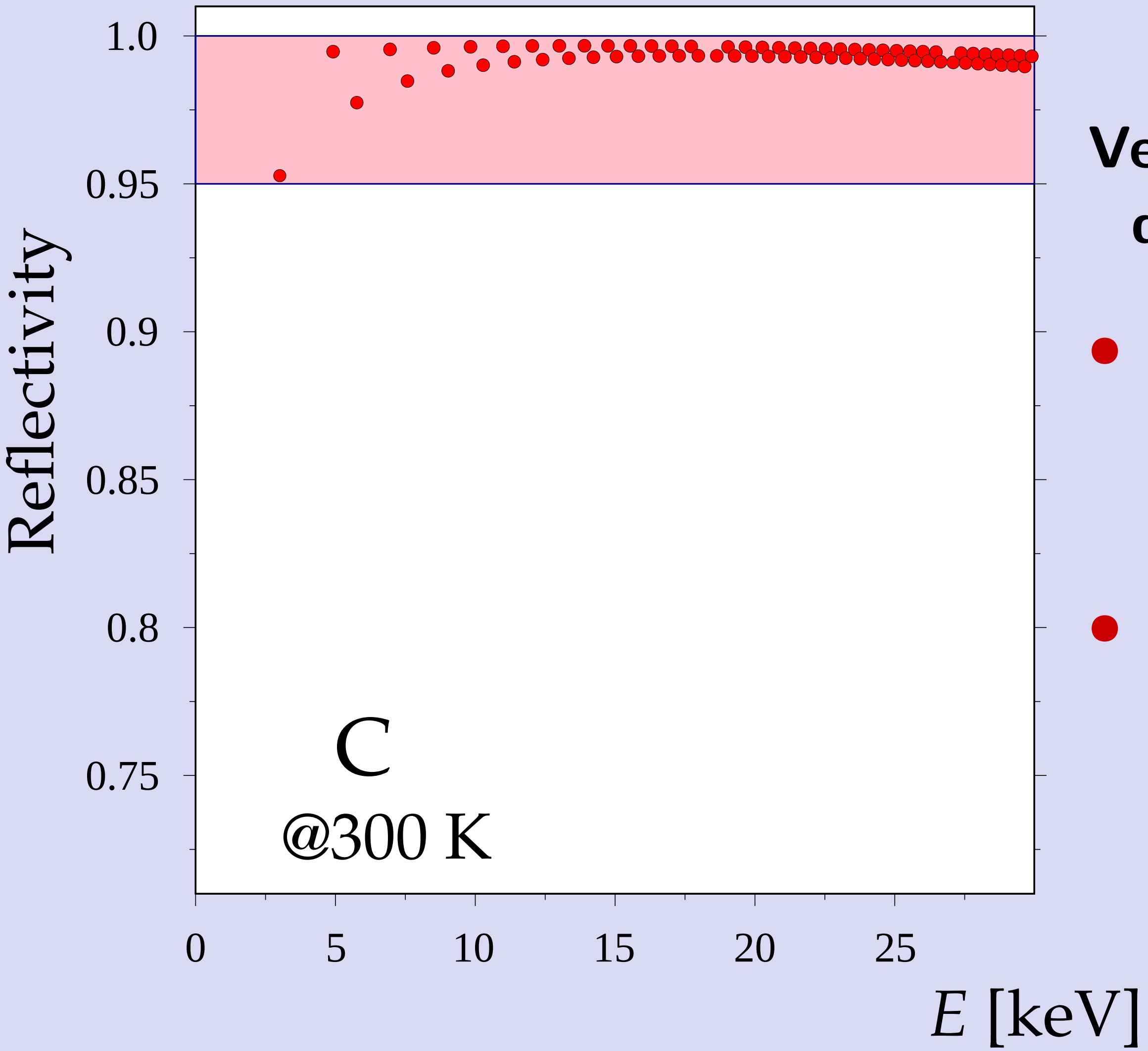
- **ultra-low-emittance ($\varepsilon_n \simeq 0.2 - 0.4$ mm mrad) electron beams,**
- **low-loss x-ray crystal cavity (losses $\simeq 15\%$)** $R_1, R_2 > 95\%, T_1 \simeq 4\%$

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

Reflectivity of Si in Bragg Backscattering



Theory: Highest Bragg Reflectivity from Diamond



Very high reflectivity (in theory) due to:

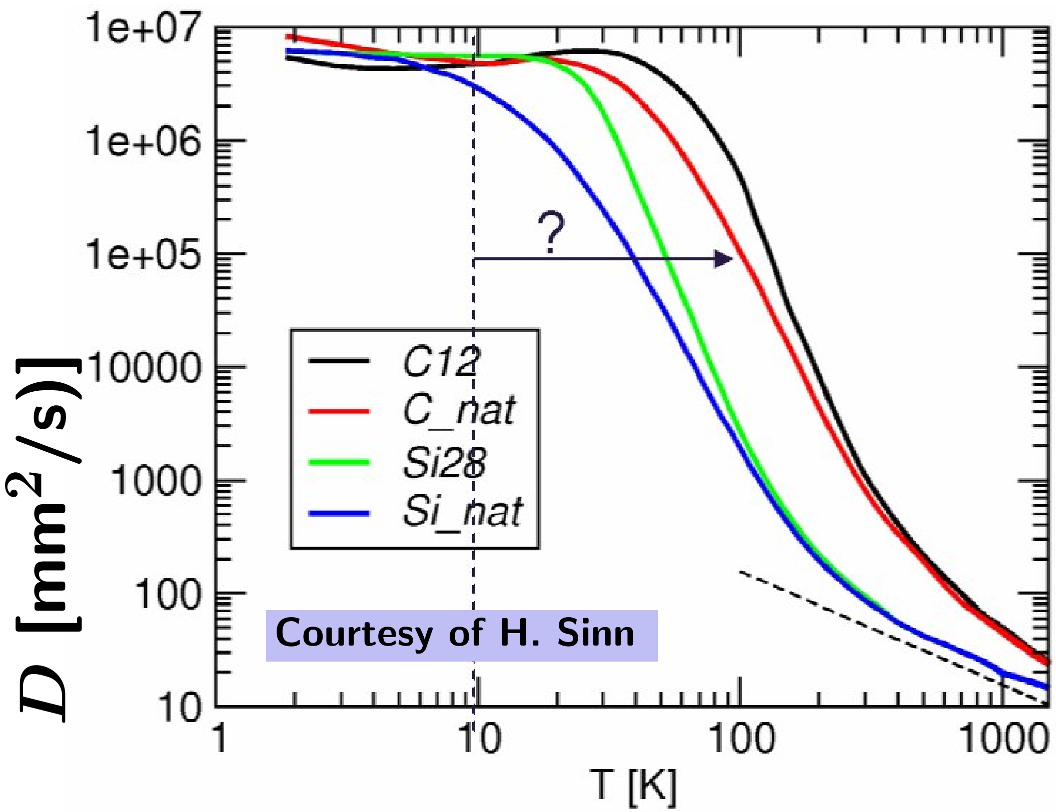
- High Debye Temperature, and thus high Debye-Waller factor
- Low Z, low photo absorption

Superb thermo-mechanical properties of diamond

Ultra-high thermal diffusivity at low temperatures

$$D = \frac{k}{\rho c_p}$$

k - thermal conductivity
ρ - density
c_p - specific heat capacity



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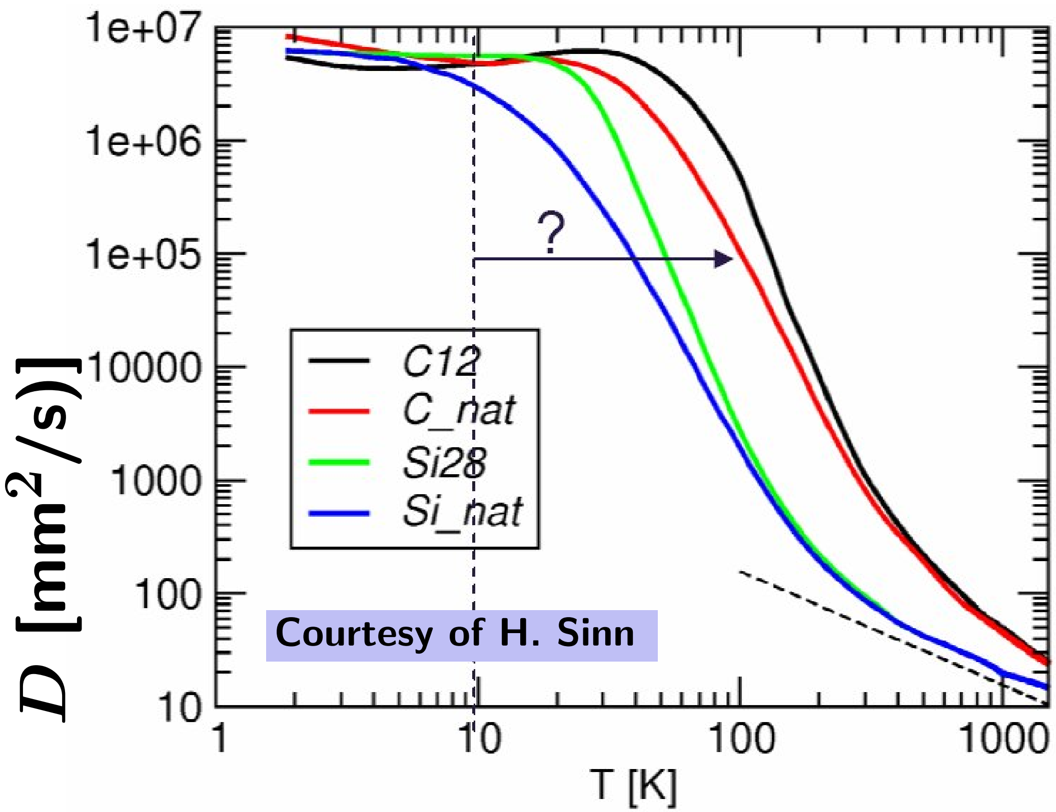
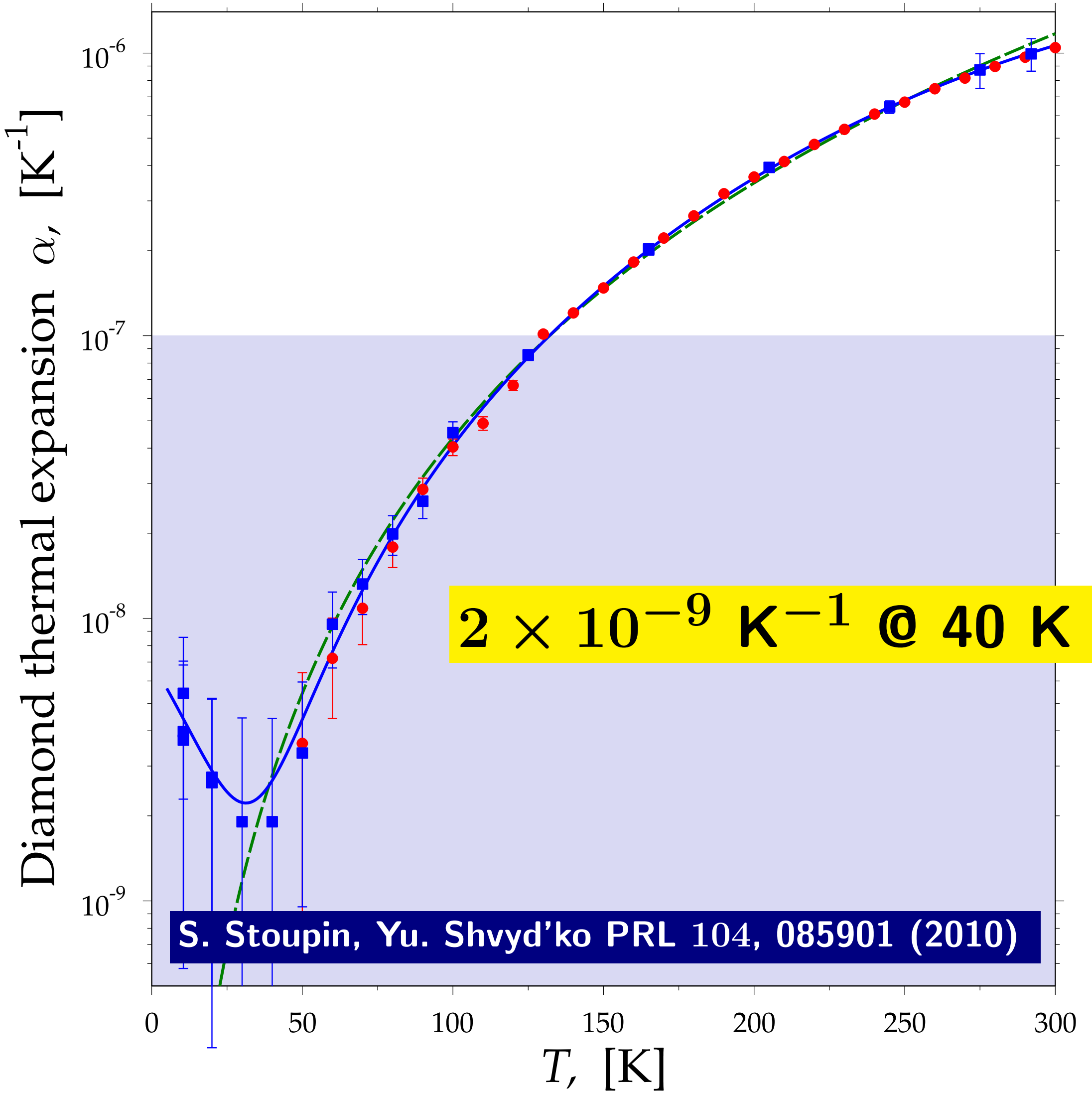
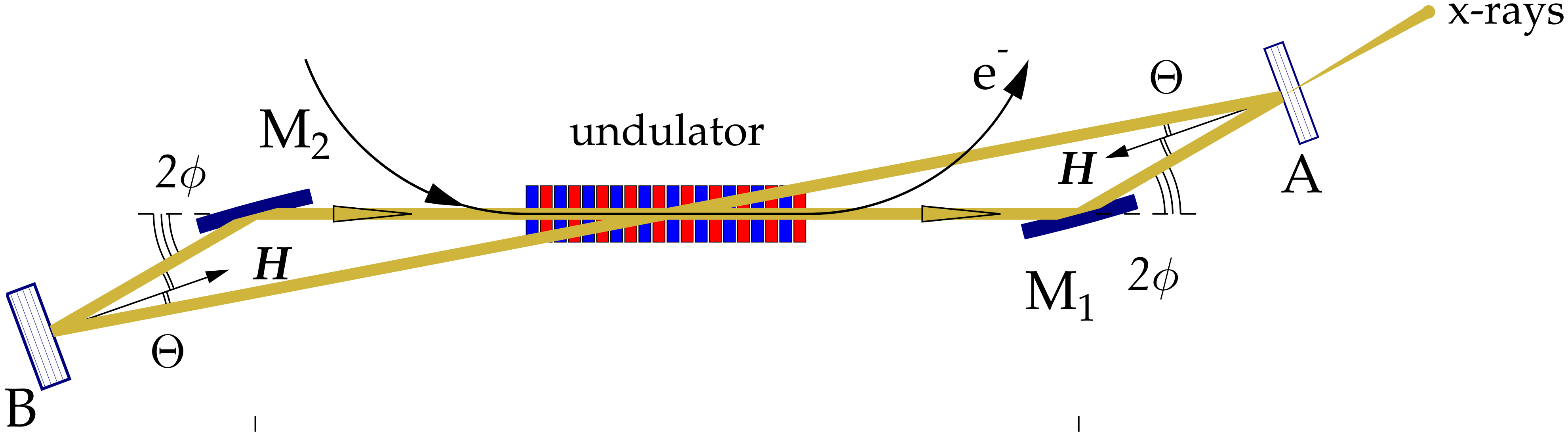


Ultra-low thermal expansion at low temperatures



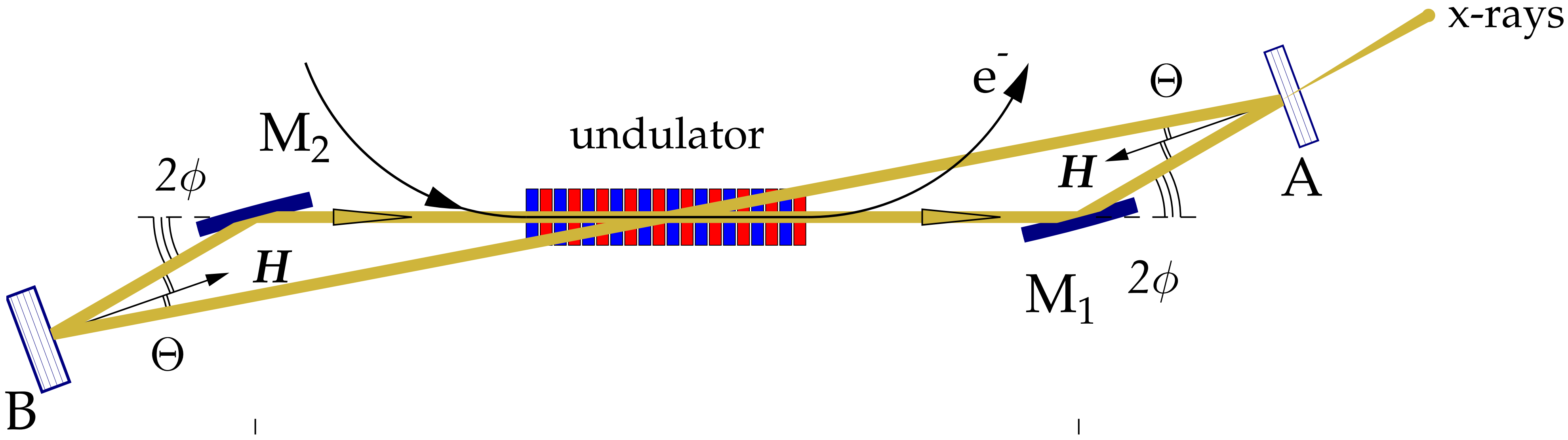
Two-crystal cavity for XFELO



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

$T_A \simeq 0.04$

Two-crystal cavity for XFELO



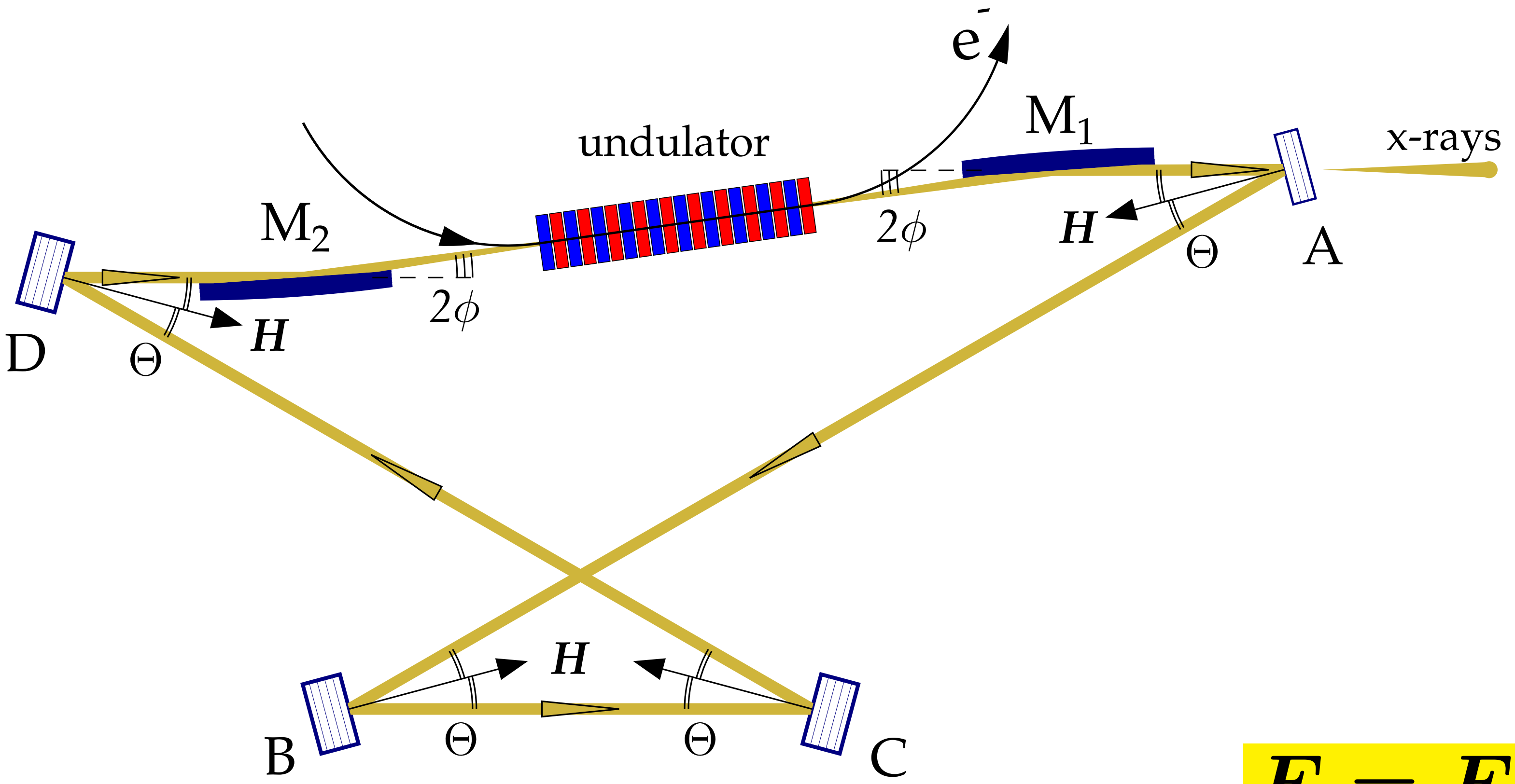
$$R_A \times R_B \times R_{M_1} \times R_{M_2} \simeq 0.9 \qquad T_A \simeq 0.04$$

$E = E_H \cos \Theta \quad \Rightarrow$ **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



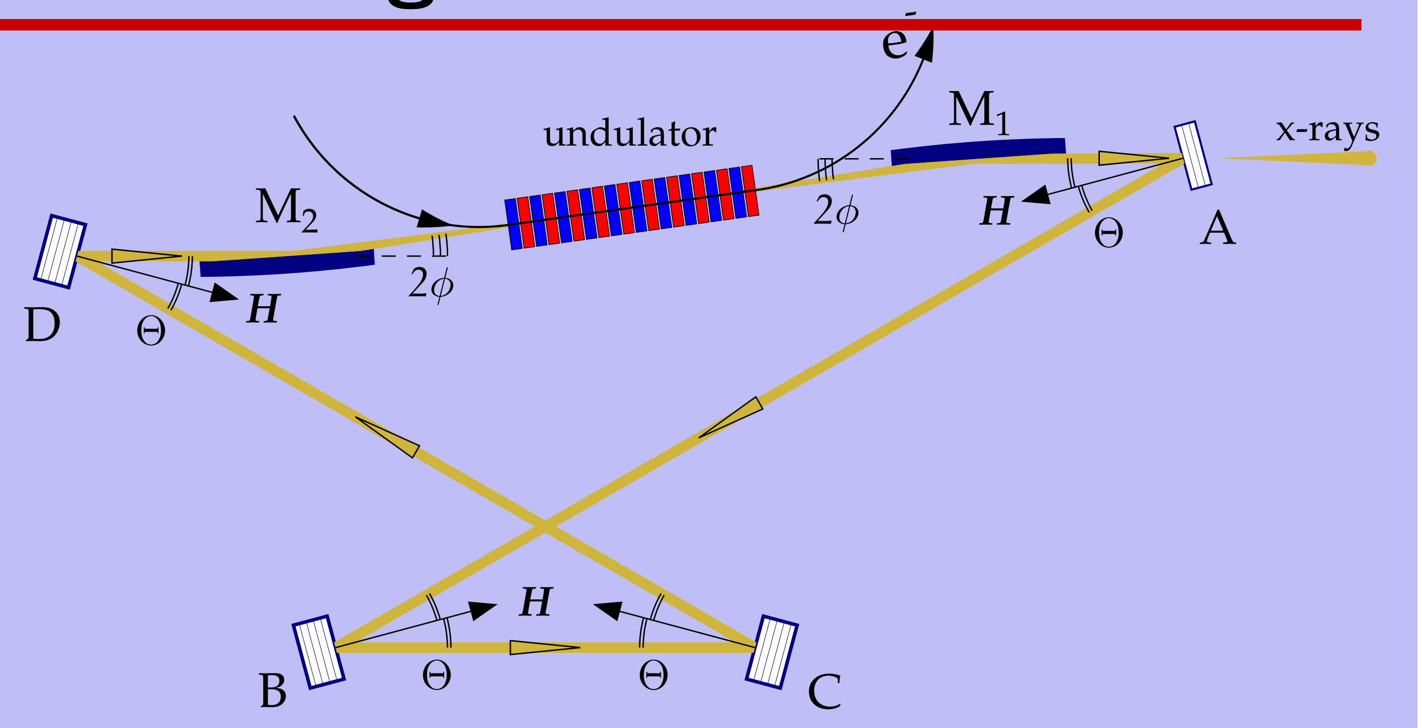
$$E = E_H \cos \Theta$$

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 Technical Challenges



X-ray Optics:

- **Quality of diamond crystals:**
  is the theoretical $\simeq 99\%$ reflectivity achievable?
- **Heat load problem: reflection region variations $\lesssim 1$ meV.**
- **Angular stability: $\delta\theta \lesssim 10$ nrad (rms)**
  Spatial stability: $\delta L \lesssim 3\ \mu$m (rms) $\quad\rightarrow\quad \delta L/L \lesssim 3\times 10^{-8}$
- **Radiation damage**

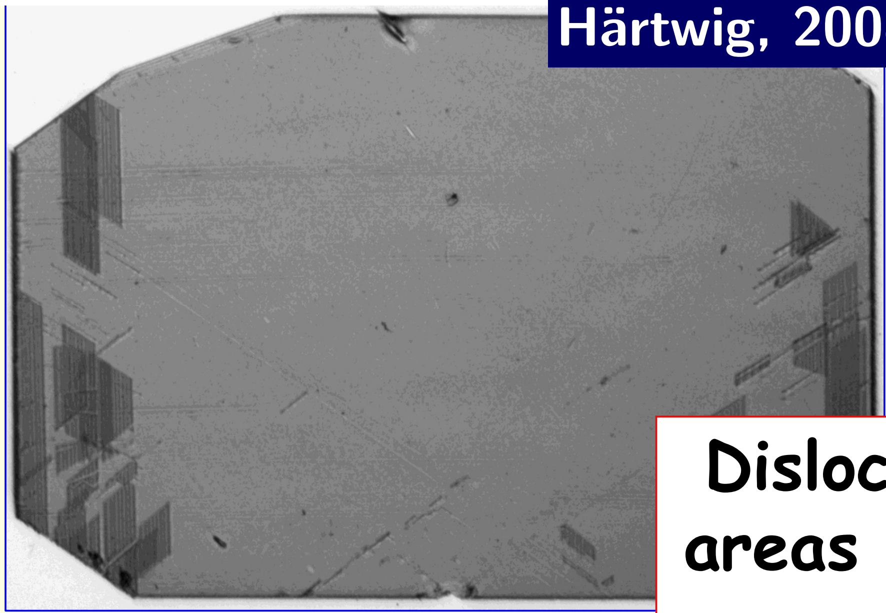
Quality of Diamond crystals

Quality of Diamond crystals

Required diamond crystals:

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

Härtwig, 2008 (ESRF)



n

Dislocation free areas of 4x4mm² and more!!!

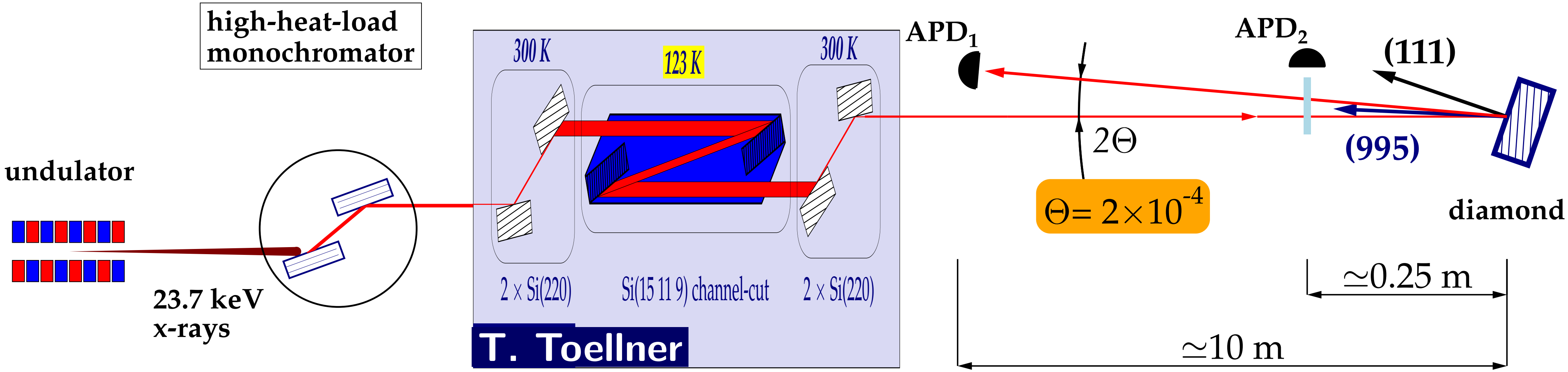
7.1 mm

110-oriented plate

White beam topograph in transmission

Still open question:
is the theoretical 99-98% reflectivity achievable?

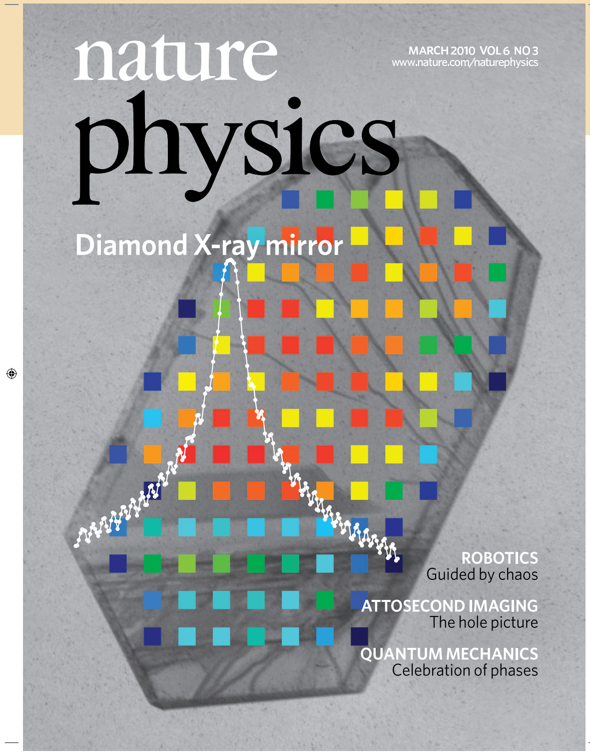
Experiment, 30-ID @ APS



bandwidth ≈100 eV

bandwidth ≈1.7 eV

bandwidth $\Delta E \approx$ 1 meV

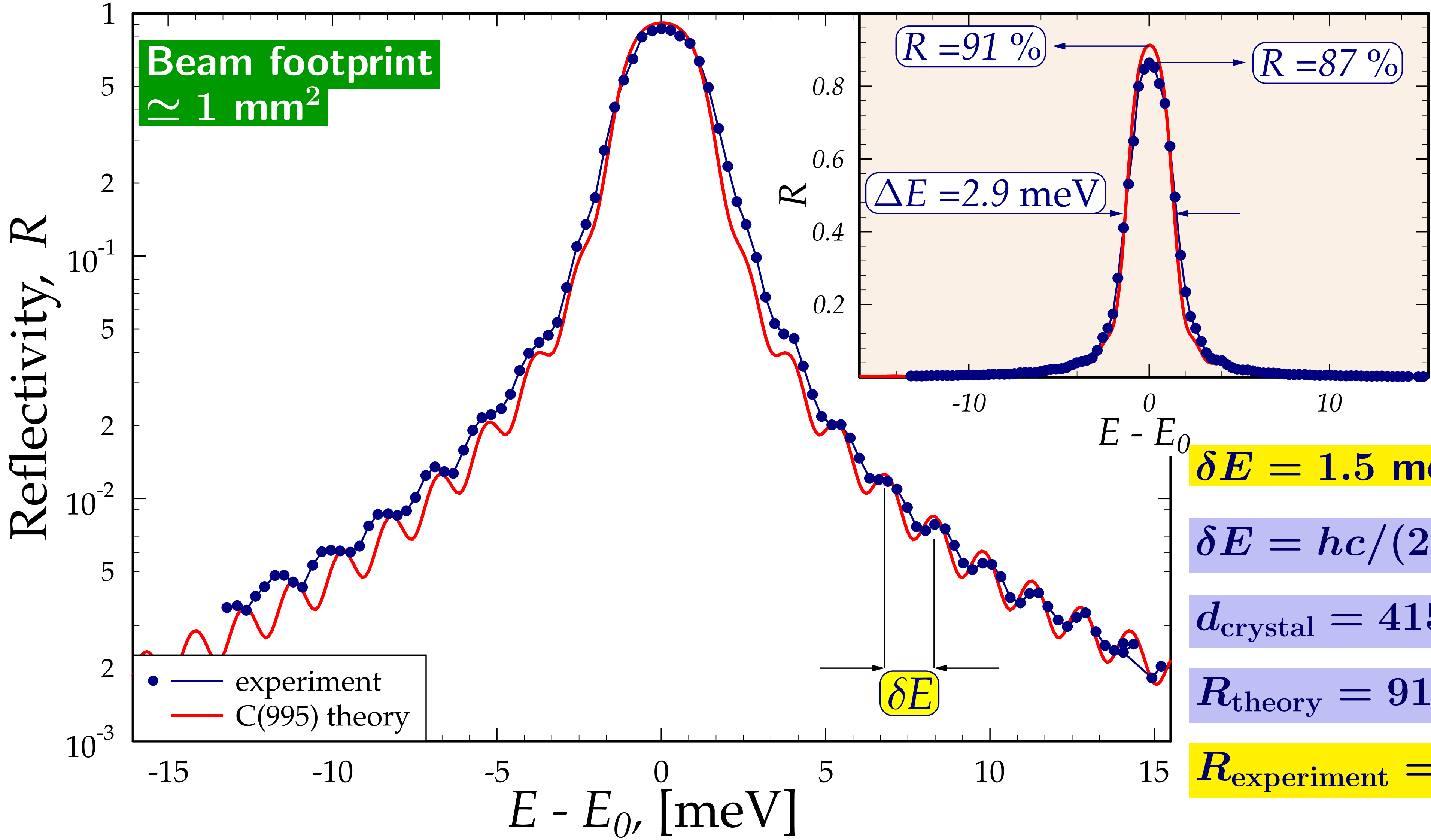


Shvyd'ko, Stoupin, Cunsolo, Said, Huang, Nature Phys. 6, 196 (2010)

Spectral Width and Reflectivity: Experiment

C(995), $E_H = 23.765$ keV

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



$\delta E = 1.5$ meV

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

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

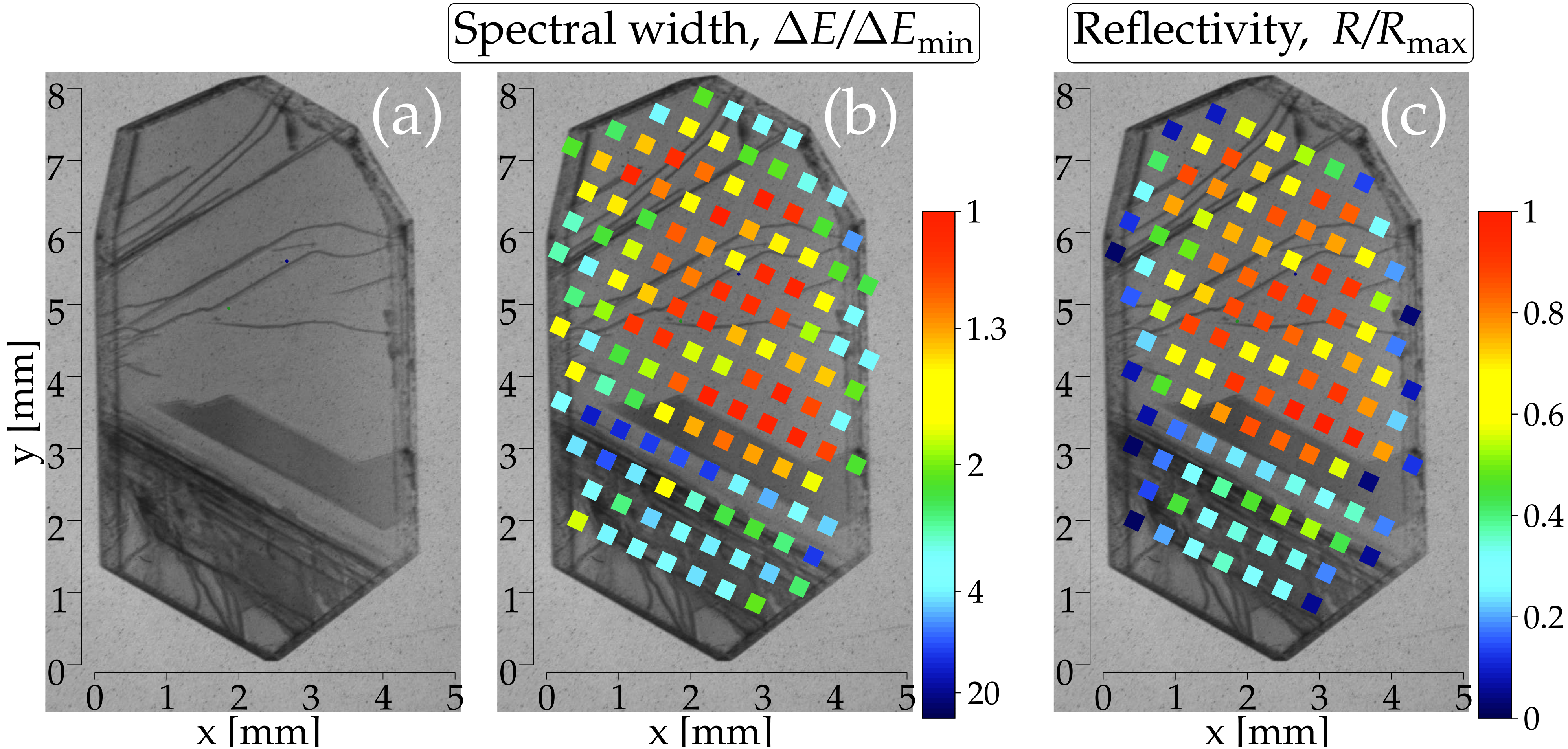
$R_{\rm theory} = 91\%$

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

Spectral Width and Reflectivity Map

IIa Diamond: Sumitomo, Japan

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



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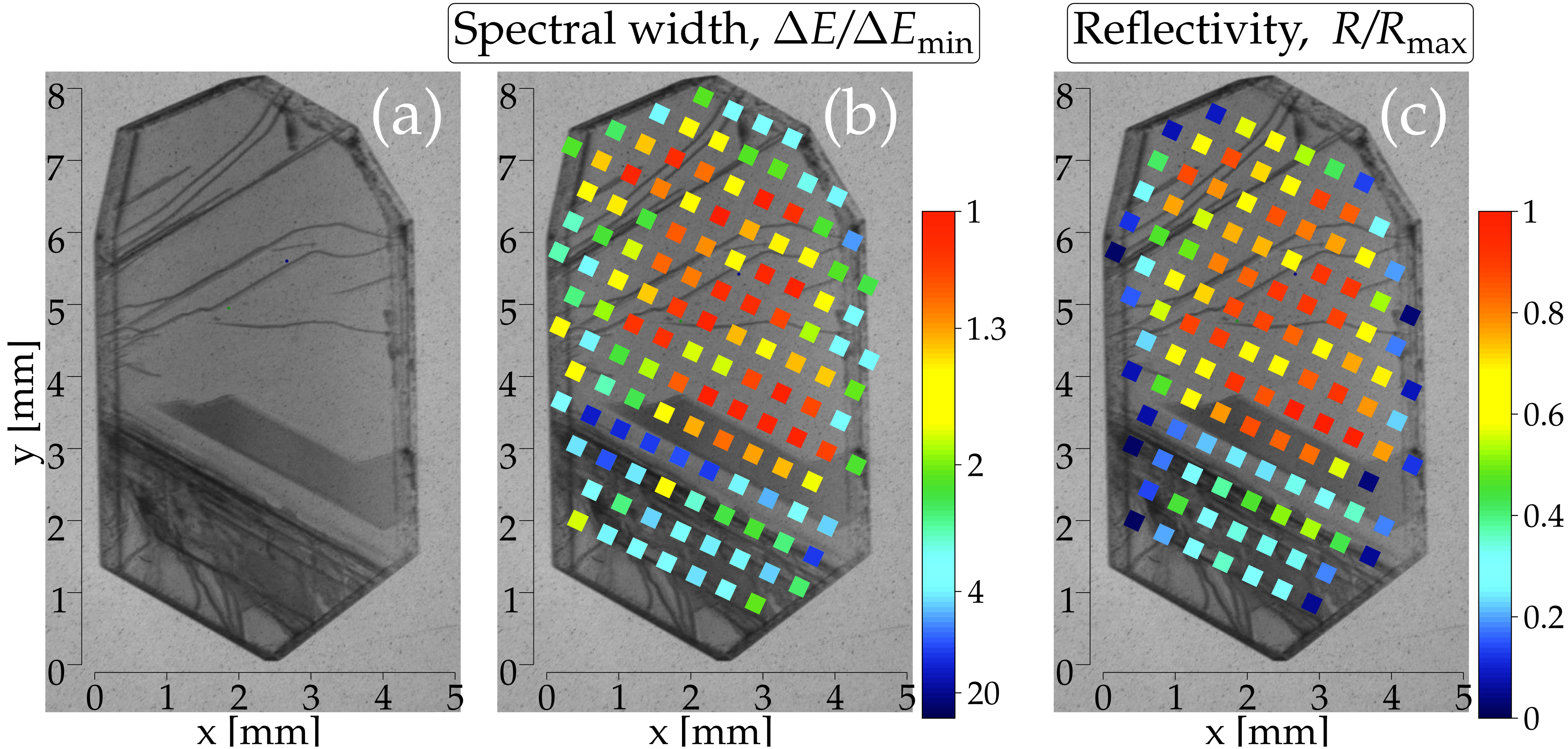

Synthetic diamond crystals are available with theoretically high reflectivity and sufficiently large in size for XFELO cavity applications.

Heat Load Problem

Heat Load Problem

Temperature gradient $\delta T \Rightarrow$ r.c. 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: $\simeq 100 \times 100\ \mu\text{m}^2$

Is it a problem?

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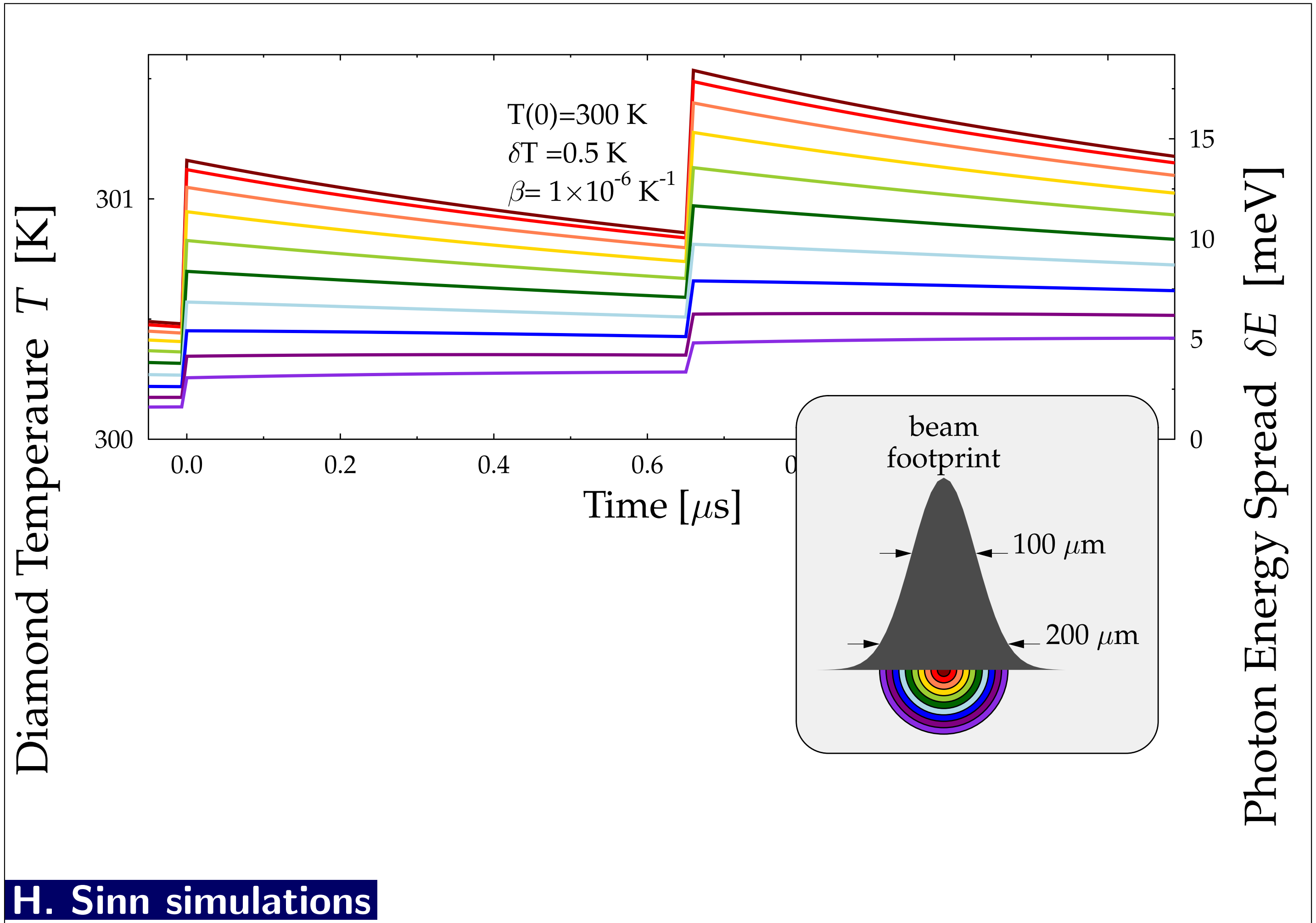

- **Big temperature jump δT after the x-ray pulse arrival.**
- **T=300K: Big temperature spread by the arrival of**

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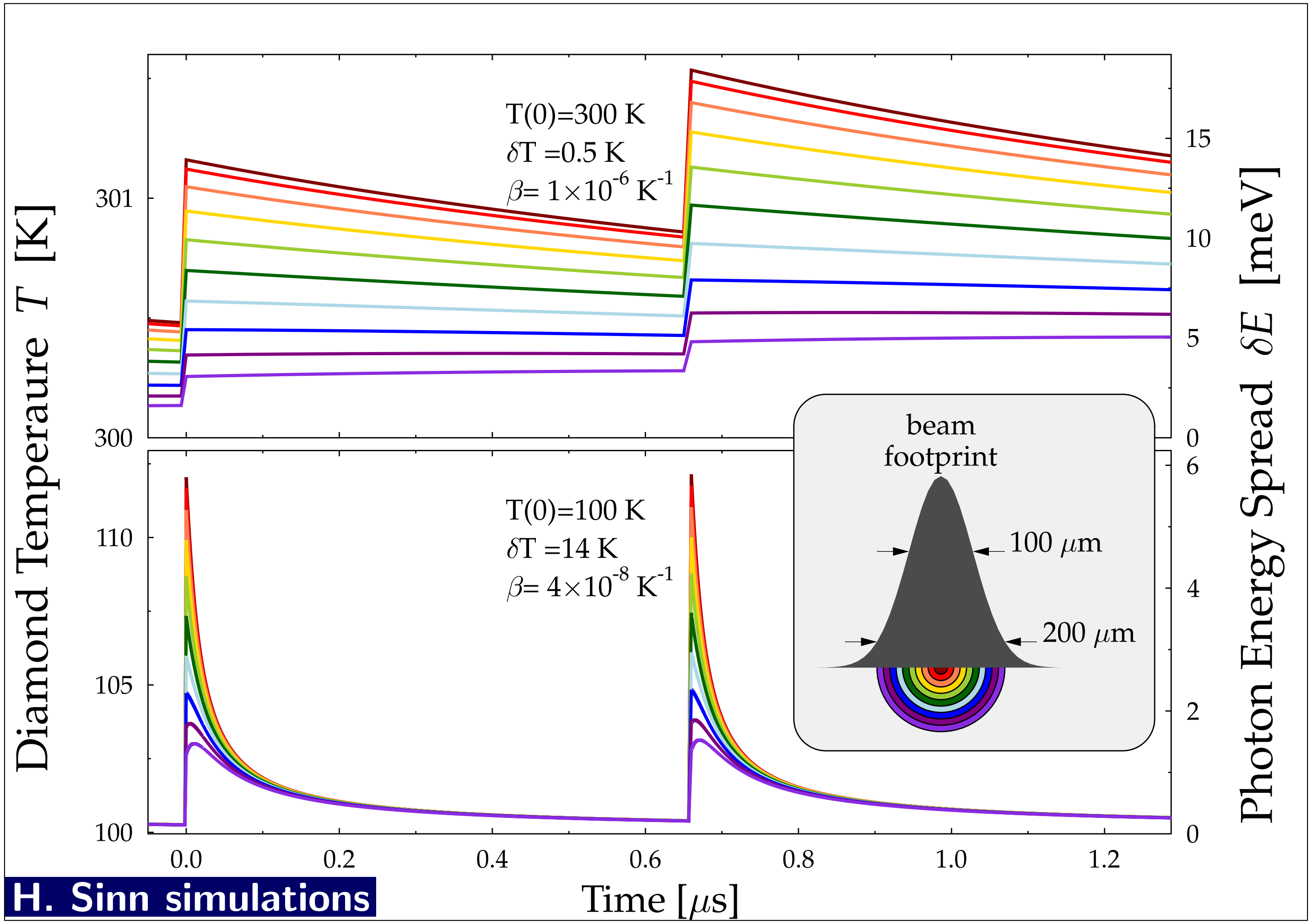

- **Big temperature jump δT after the x-ray pulse arrival.**
- **T=300K: Big temperature spread by the arrival of the next x-ray pulse.**
- **T=100K: Negligible temperature spread by the arrival of the next x-ray pulse.**

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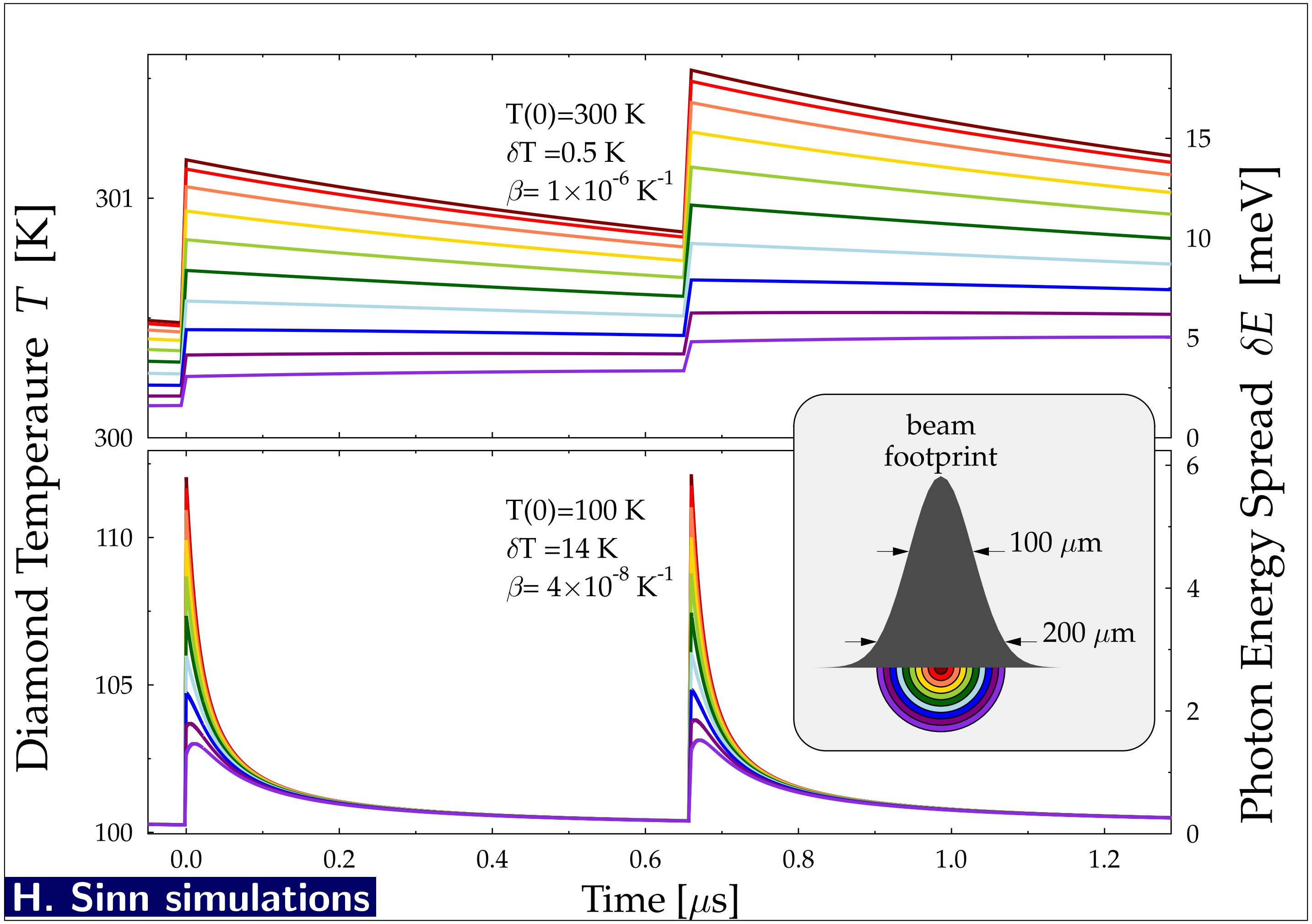

- **Big temperature jump δT after the x-ray pulse arrival.**
- **T=300K: Big temperature spread by the arrival of the next x-ray pulse.**
- **T=100K: Negligible temperature spread by the arrival of the next x-ray pulse.**
- **Reasons:**
  1. **High temperature diffusivity $\mathcal{D}$**
  2. **Low temperature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

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

Angular & Spatial Stability

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

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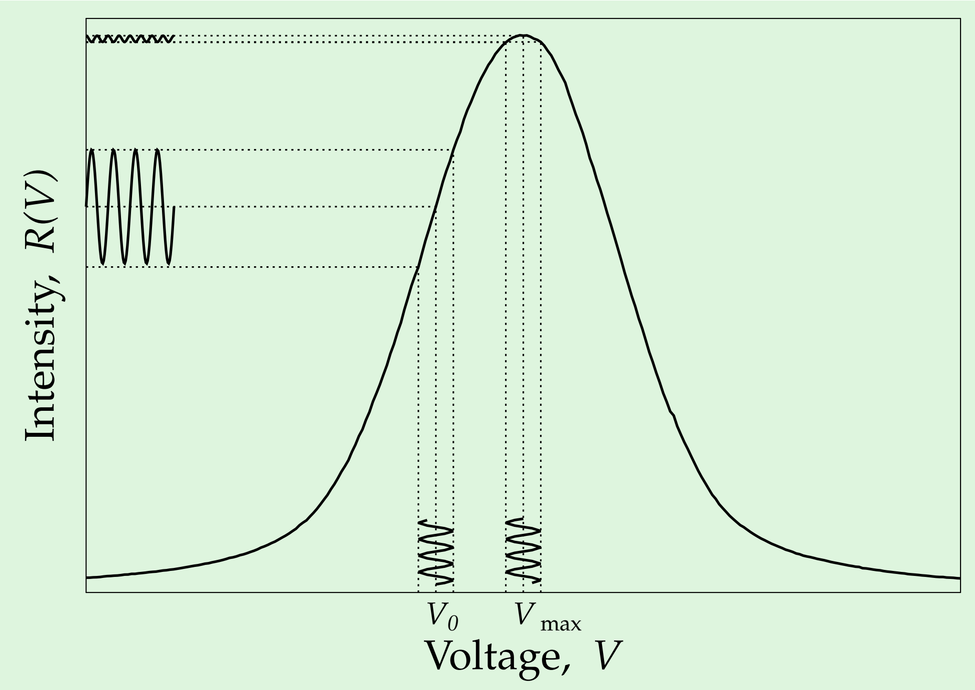
Solution: Null-detection hardware feedback. (LIGO prototype)



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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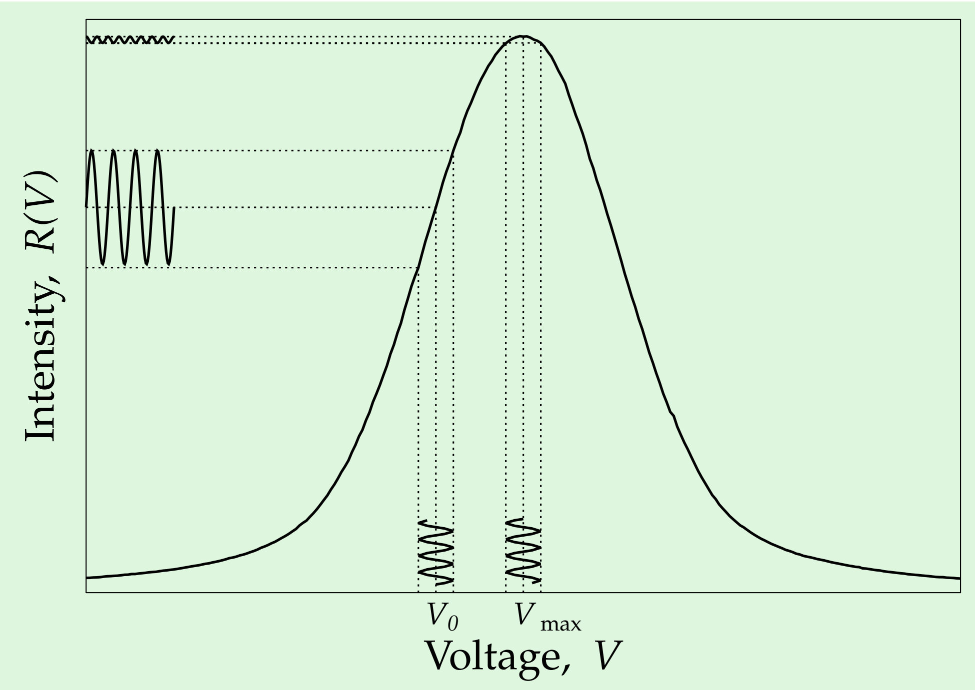
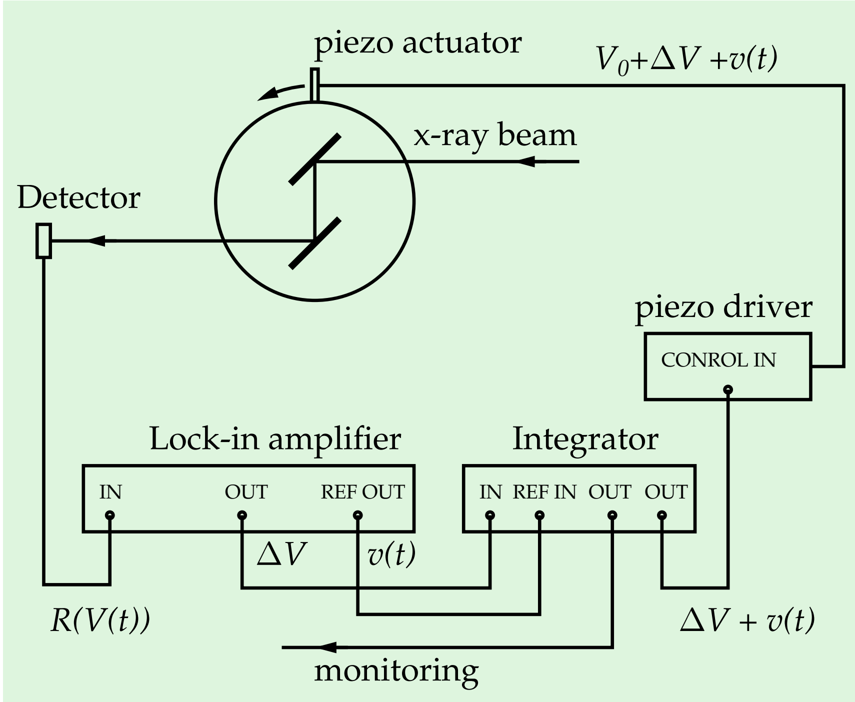
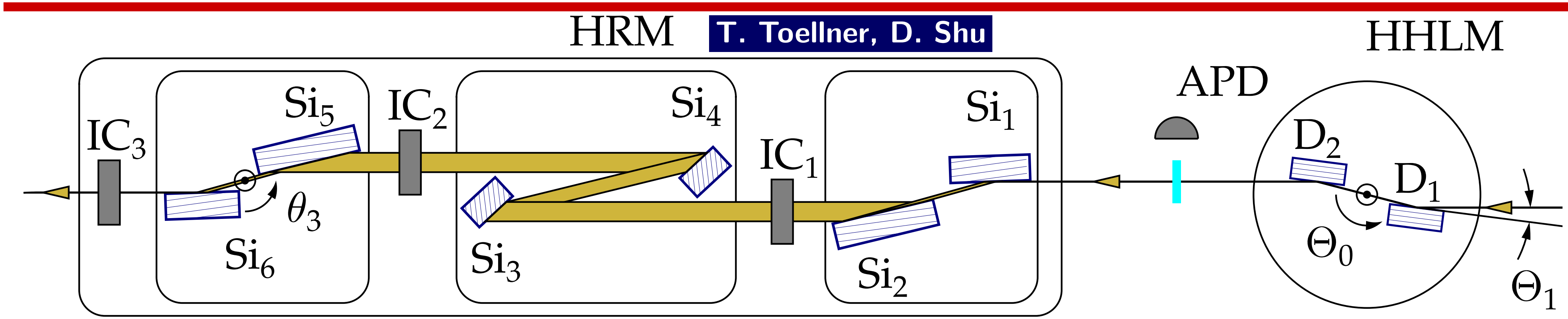


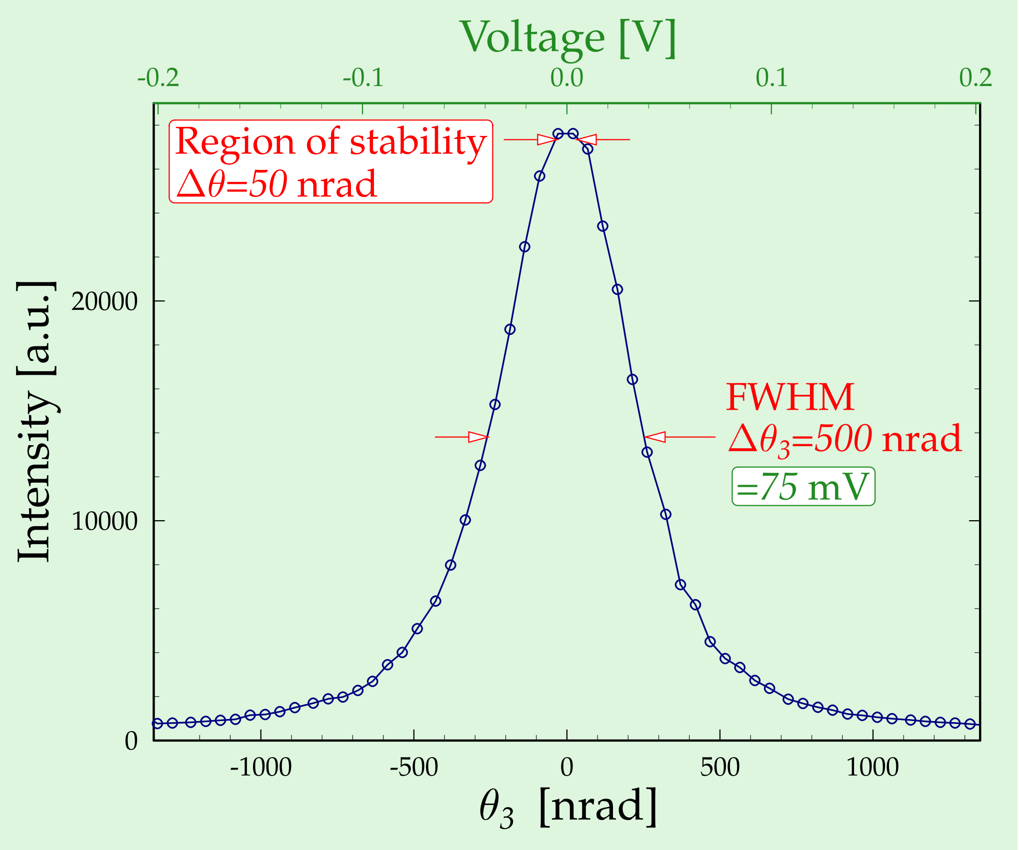


X-ray intensity: linear response to small angular oscillations is proportional to angular deviation from the maximum of the rocking curve.

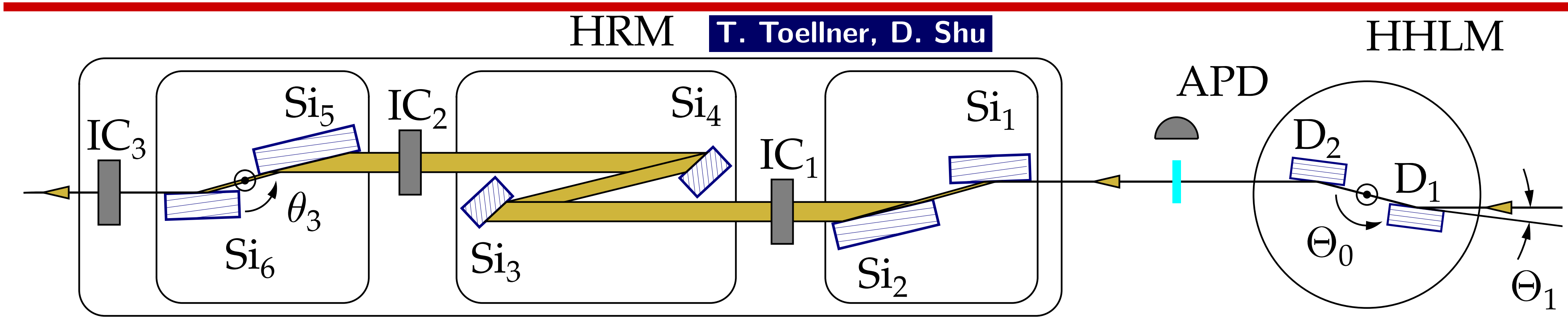
Feedback: correction signal is extracted using lock-in amplification.

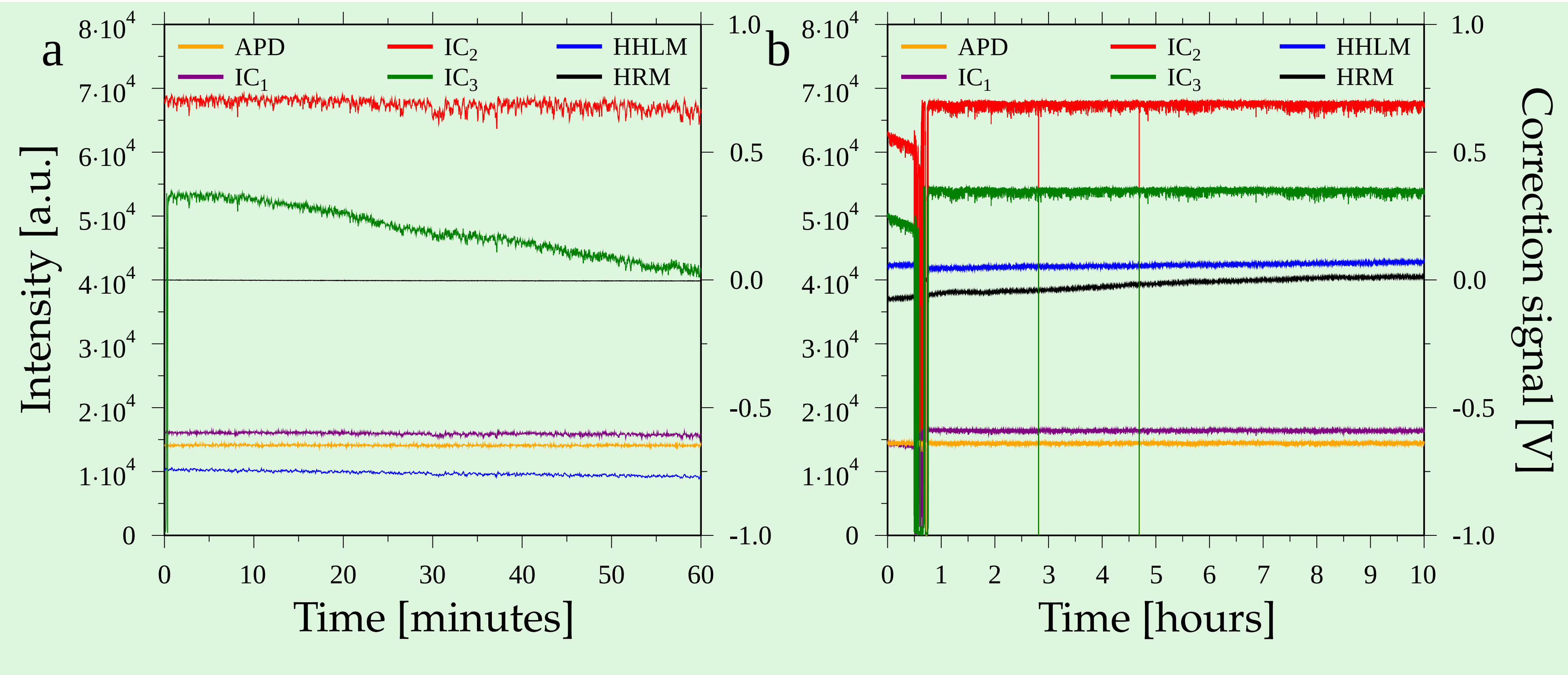
HERIX Monochromator Stability Region





HERIX Monochromator Stabilization





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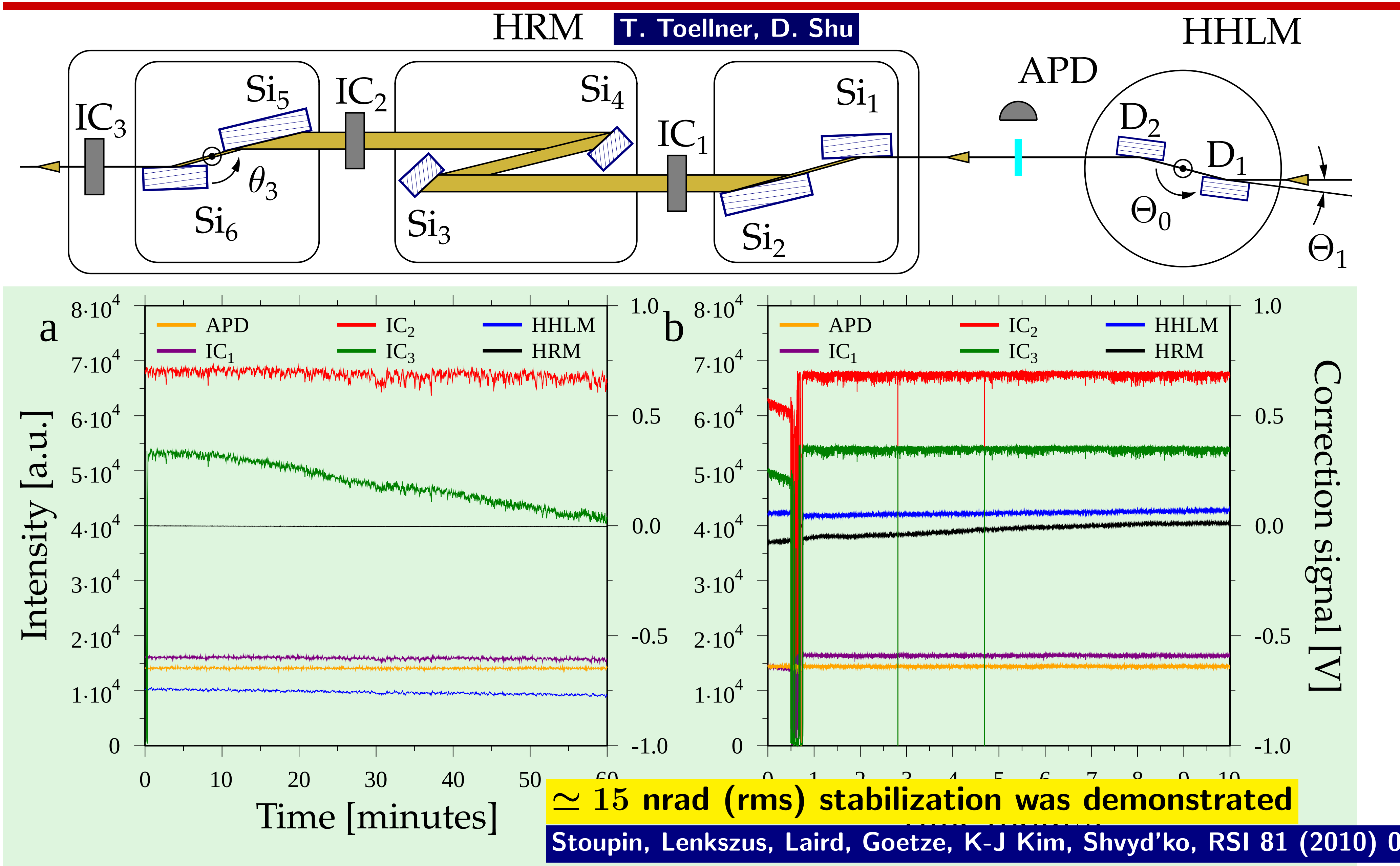

$\simeq$ 15 nrad (rms) stabilization was demonstrated

Stoupin, Lenkszus, Laird, Goetze, K-J Kim, Shvyd'ko, RSI 81 (2010) 05510

Radiation damage in diamond

Radiation damage in diamond

XFELO generates:

50μJ/pulse @ 12 keV with $\simeq 1$ MHz rep. rate
Footprint: $A = 1.6 \times 10^{-2}$ mm^2 (rms)
Flux $\simeq 2 \times 10^{18}$ ph/s/mm^2 $\simeq 4$ kW/mm^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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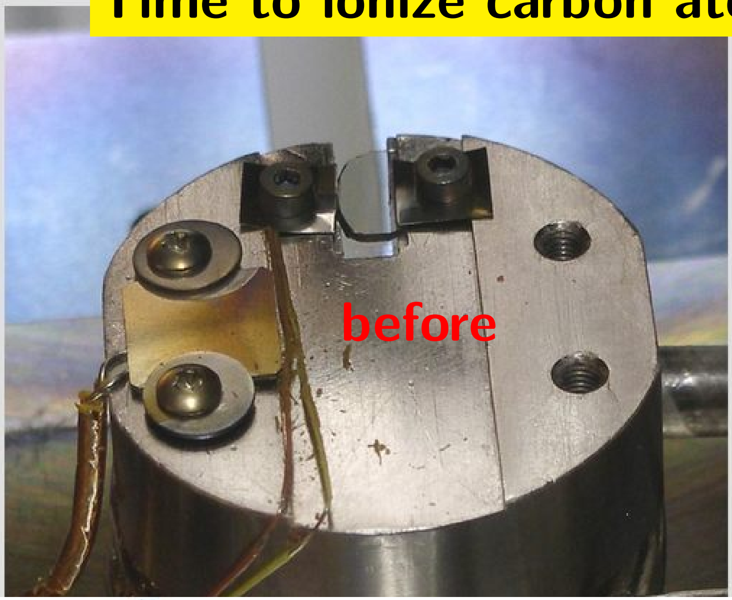
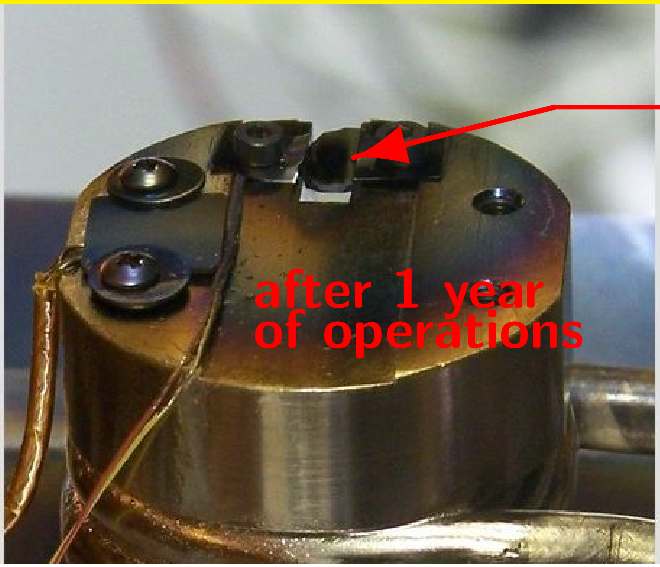
APS undulators generate:

Flux $\simeq 5 \times 10^{15}$ ph/s/mm^2 $\simeq 0.15$ kW/mm^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.

Diamond under 3.5 kW/mm^2 load survives

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

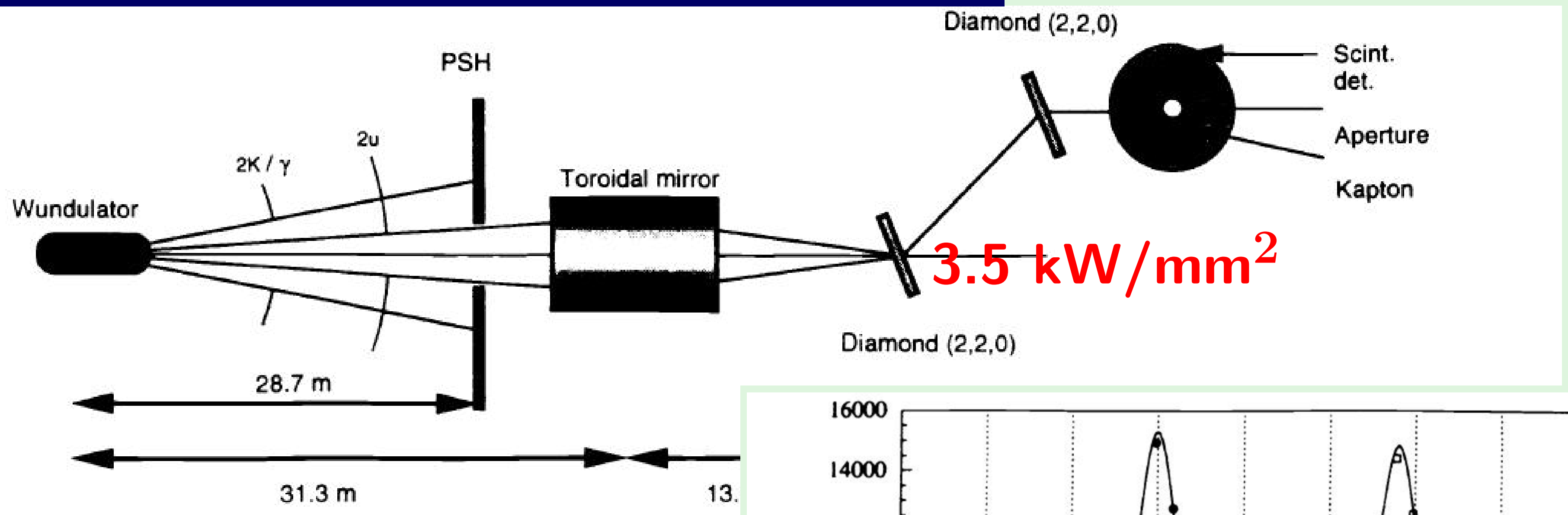


Fig. 2 Schematic diagram of the experimental setup

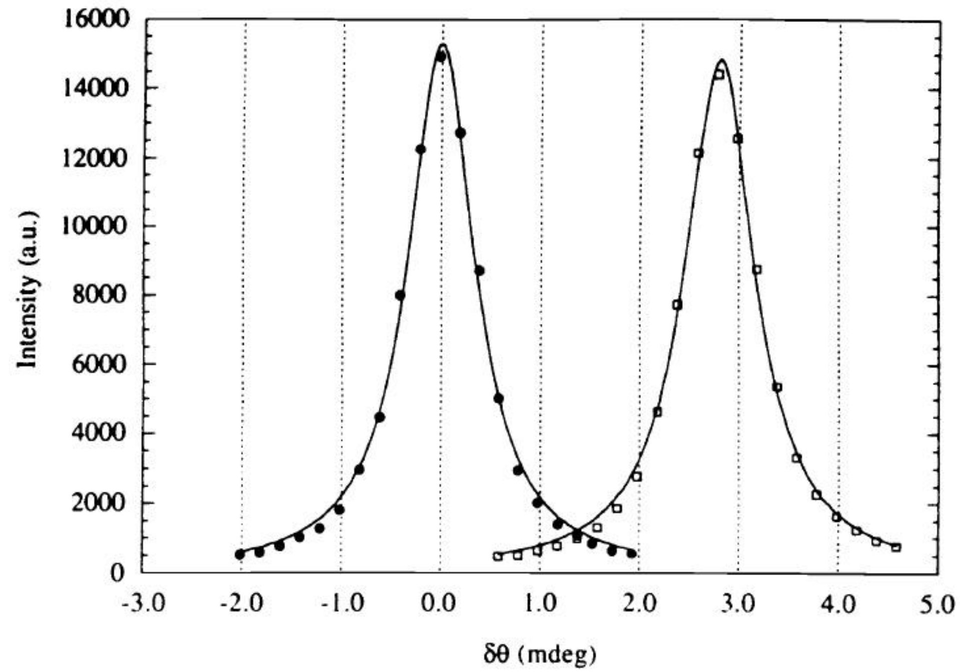


Fig. 3 Rocking curves of the analyzer at low and high power levels. The full lines are least squares fitted Lorentzians.[26]

Conclusions and Outlook

Yet no show stoppers for XFELO cavities are detected:

- Quality of diamond crystals: ✓
  theoretical $> 98\%$ reflectivity is achievable.
- Heat load problem: ✓
  simulations indicate that Bragg reflection region variations can be $\lesssim 1$ meV.
- Angular stability: ✓
  $\delta\theta \simeq 10$ nrad (rms) can be achieved
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radiation damage, diamond reflectivity, focusing mirrors, nanoradian positioning, multi-axis feedback stabilization, whisper quiet crystal cryogenic cooling, test cavity, etc.

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Thank you for your attention