An experimental setup for probing the cryogenic thermal properties of diamond regarding its use in an XFELO*

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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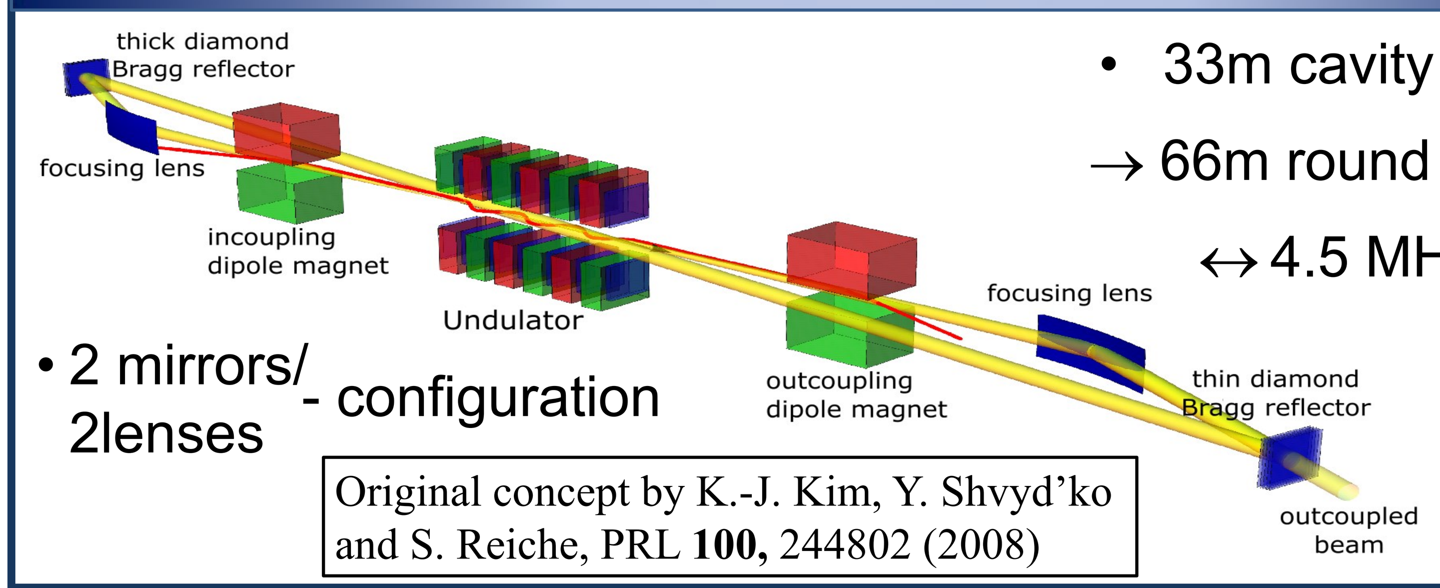
I. Motivation

- XFELO oscillator (XFELO) promises longitudinally coherent hard X-ray pulses
- X-ray cavity based on Bragg reflection
- **Problem**: thermal load on crystals at 4.5 MHz rate
- **Thermal expansion:**
  - – Vibrations and supersonic pulses
  - – Shift of central wavelength satisfying Bragg's law
- material with ideal thermal properties: diamond
- At cryogenic T: Onset of quasi-ballistic processes

→ Fourier's law of classical heat conduction begins to fail

→ **Necessity of measuring thermal properties under XFELO heat load conditions**

II. Draft of an XFELO

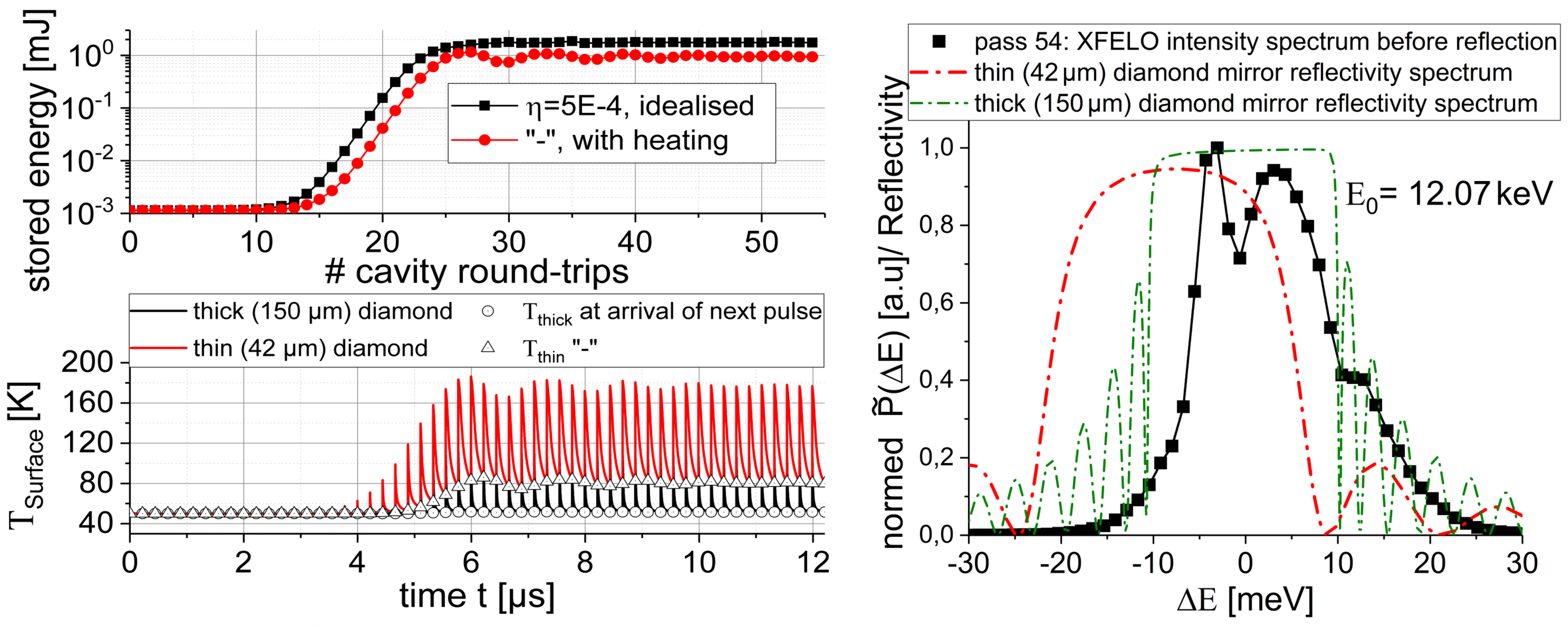


- 33m cavity length
- → 66m round trip length
- ↔ 4.5 MHz rep-rate
- 2 mirrors/ 2lenses - configuration

Original concept by K.-J. Kim, Y. Shvyd'ko and S. Reiche, PRL **100,** 244802 (2008)

III. Sim. XFELO with heating

beam energy E_B [GeV]	slice energy spread σ_E [MeV]	rms bunch length t_B [fs]	peak current I_A[kA]	rms beam size $\sigma_{r,x/y}$ [μm]	radiation wavelength λ_{Bragg} [Å]	undulator parameter K	detuning parameter η [10^{-4}]	undulator length L_U [m]
14.5	1	75.6	4.9	23.23	1.0274	3.0047	5	15



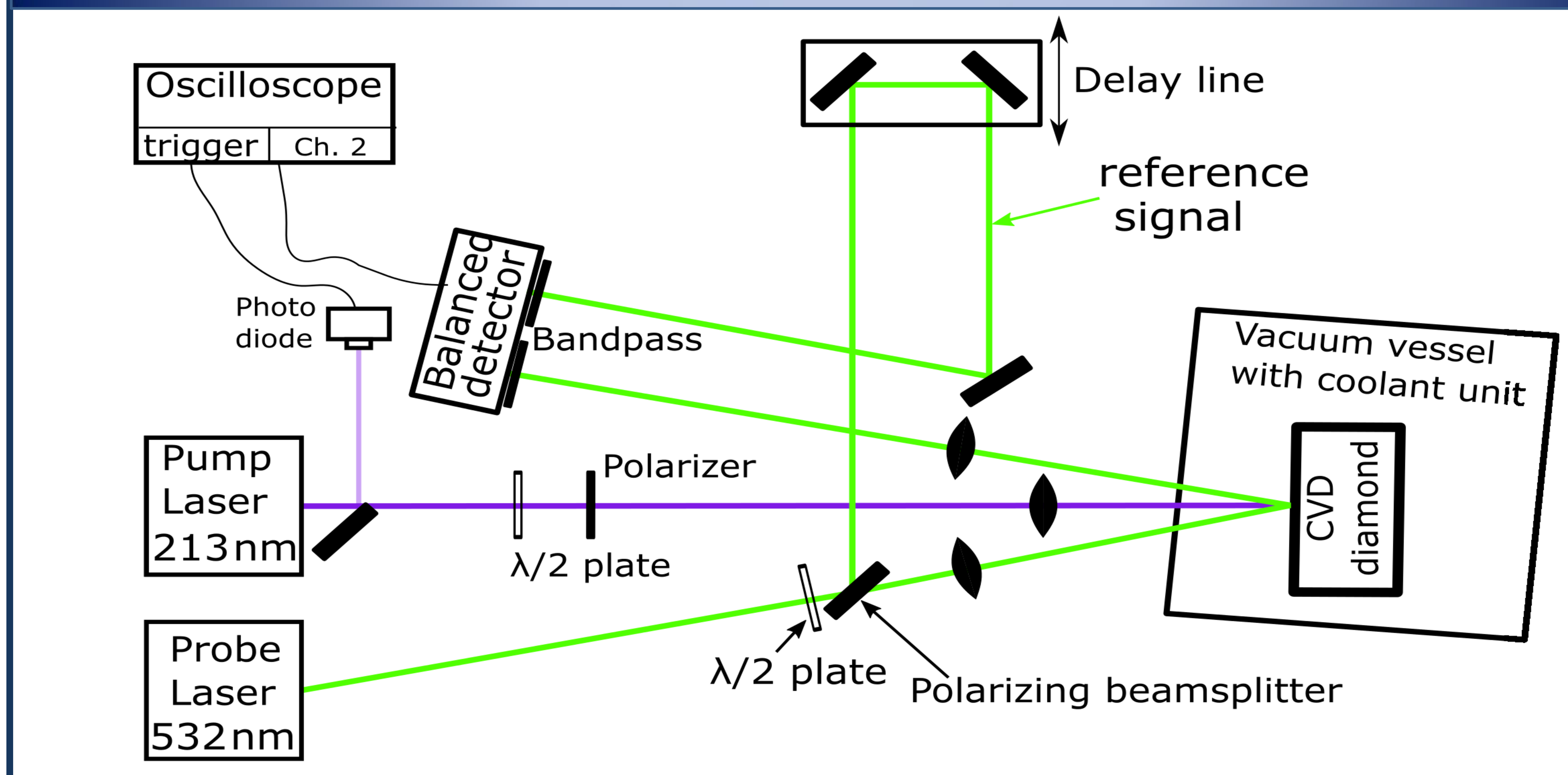
- Heating → Reduction of E_{sat} and bad spectral coherence
- But: simulations based on Fourier's law → not accurate

IV. Quasi-ballistic processes

1. Gradient effect:
   - – Thermal gradient ∇T varies on length scale ($\sim l_{\text{opt}}$) comparable to mean free path l_{mfp}
   - – Fourier's law based on local thermal equilibrium and $t \gg \tau$ → becomes erroneous
   - – Deviation from fit to Fourier's law is good measure for influence of ballistic processes
2. Boundary scattering: $l_{mfp}^{(bulk)} \gg d_{thickness.}$
   - – Boundary conditions depend on energy ε dependent $l_{\text{mfp}}(\varepsilon)$

→ *very hard to predict*

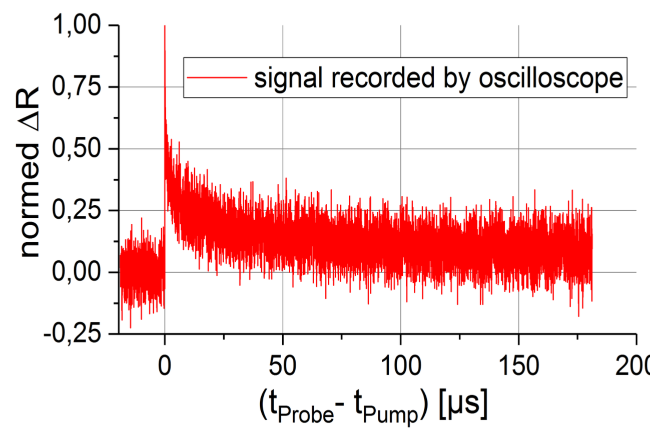
V. Experimental setup



- Nanosecond 213 nm UV pump laser:
  - – deposits ~ same pulse energy as an XFELO pulse (~ 2.5 μJ) with same penetration depth → **perfect for mimicking XFELO heat load**
  - – causes heating in diamond sample

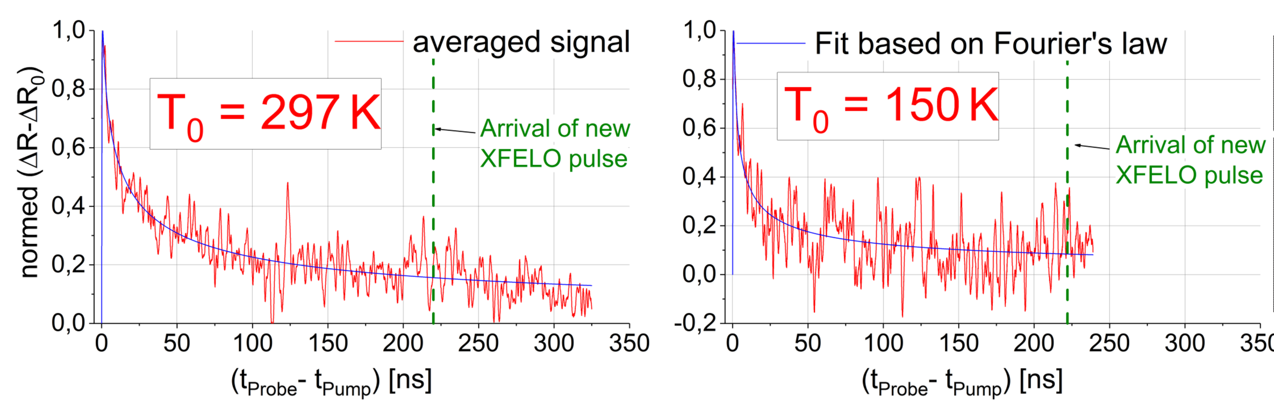
→ measured by green cw laser through shift in reflectivity → ${}^{\Delta R}/_{R} \propto k_T \Delta T$

VI. Measurements



- Measured „raw" signal at $T_0 = 297$ K:
  - – Slow μs – ms long decline back to initial state
  - ○ Too slow for thermal process (on ns scale)
  - → Excitation of long living electronic states: change in refractive index $\tilde{\eta}$→ change in R

→On ns-scale apparent as constant offset ΔR_0



T [K]	$\lambda^{(\text{app})}$ [W/(m · K)]	$\lambda^{(\text{Lit.})}$ [W/(m · K)]	l_{mfp}/l_{opt}
297	2130 ± 170	2300	0.025
250	3000 ± 230	3030	0.05
200	3500 ± 600	4100	0.175
150	3300 ± 700	7000	0.8

- Decline of ΔR on the ns-scale → reliable fit by Fourier's law
  - – λ at $T_0 = 297$ K and $T_0 = 250$ K agrees well with literature

  →expected, as $l_{mfp} \ll l_{opt}$ (no ballistic processes) → **proof of principle**
  - – At $T_0 = 150$ K strong deviation from literature
    ← $l_{mfp} \approx l_{opt}$ ← **ballistic processes**
- $T_0 = 297$ K: At 220 ns (green line) thermal processes not fully declined

  →Pile up of heat in diamond at 4.5 MHz repetition rate (XFELO)
- $T_0 = 150$ K: At 220 ns ΔR stronger declined → **Importance of cooling!**

Conclusion & Outlook

- Optical Experiment for measuring the thermal properties of diamond under XFELO conditions without necessity of valuable beamtime
- Measurements for the first time reveal significant influence of ballistic processes due to the gradient effect in diamond at low temperatures
- **Outlook:**– Refine current low T_0 measurements → information on pile up
  - – additional measurements at lower temperatures to include effect of boundary scattering and on various differing crystals
  - – Use setup for probing additional information such as ultrasonic pulses (*Bahns et al., paper TUC02, this conference*)

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