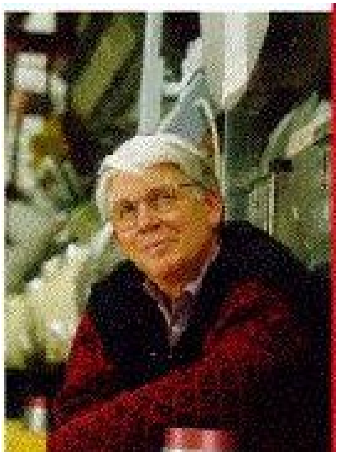


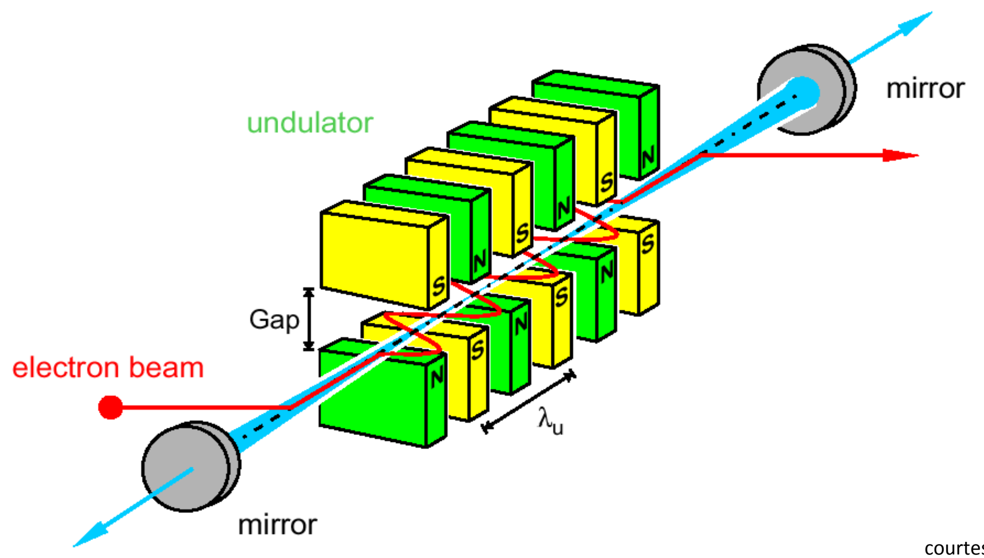
Presentation dedicated to Bjørn H. Wiik

Workshop on shaping the future of the European XFEL: options for the SASE 4/5 tunnels, Dec. 7, 2018

Historic background

FEL oscillator: proposed 1972 by J.M.J. Madey
first experimental proof at Stanford 1976 ($\lambda \approx 3\mu m$)

Main bottleneck: rather small gain per passage
→ needs many round trips of radiation within optical cavity
& synchronized electron bunches → limited to optical wavelengths



courtesy R. Bakker

Way out ①: High gain, single pass FEL (invented by Kondratenko & Saldin 1979)
→ needs kA currents + very long undulator !

Way out ②: Make mirrors from Bragg crystals (proposed by Kim, Shvyd'ko, Reiche 2008)

XFELO benefits

- Fully coherent X-ray pulses with high spectral purity $\frac{\Delta\lambda}{\lambda} \approx 10^{-6}$.
- Excellent stability of pulse energy and spectrum.

- Rather compact/inexpensive set-up (15m undul.).
- Useful as narrow b.w. seeding source for HGHG.
- Rather tolerant on electron beam momentum width
  → May use spent SASE beam.
- Novel techniques can be developed for novel sciences.
- First step for Xray spectral comb (12 neV, Adams & Kim, PRSTAB 2015)

XFELO efforts at Universität Hamburg

2009: JR: Idea to adopt original XFELO (based on cw ERL) for European XFEL parameters

2009 – 2013: J. Zemella: PhD thesis on conceptual XFELO design @ EuXFEL

-- is gain sufficient to reach saturation within few 100 round trips?
-- first simulations of gain until saturation
-- identified major challenges: thermal load on Bragg crystals

2012 – 2018: Chr. Maag: PhD thesis on experimental set-up to test thermal load issues of Bragg crystals under XFELO conditions

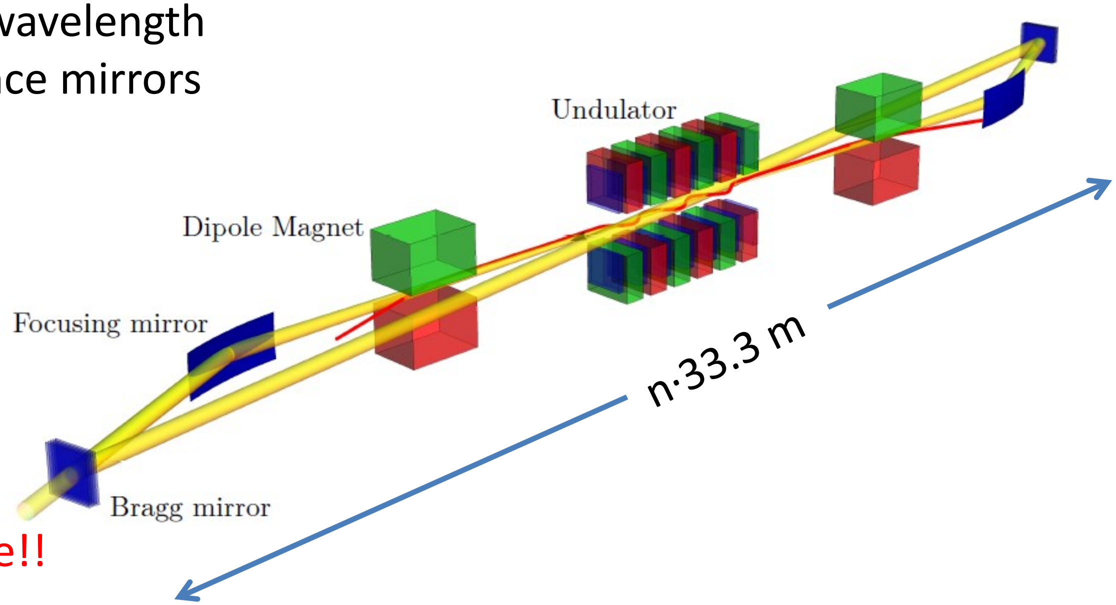
2017 – now: I. Bahns: PhD thesis on experimental investigations of Bragg crystals (ultrasonics, crystal holder, thermal diffusion, …)

P. Thießen: PhD thesis on full scale start-to-end simulation & XFELO implementation at EuXFEL

XFELO basics

Basic scheme :

- Bragg angle fixed for one single wavelength
- X-rays focused by grazing incidence mirrors



Bragg condition:

$$n \cdot \lambda = 2d \cdot \sin\theta_B$$

wavelength

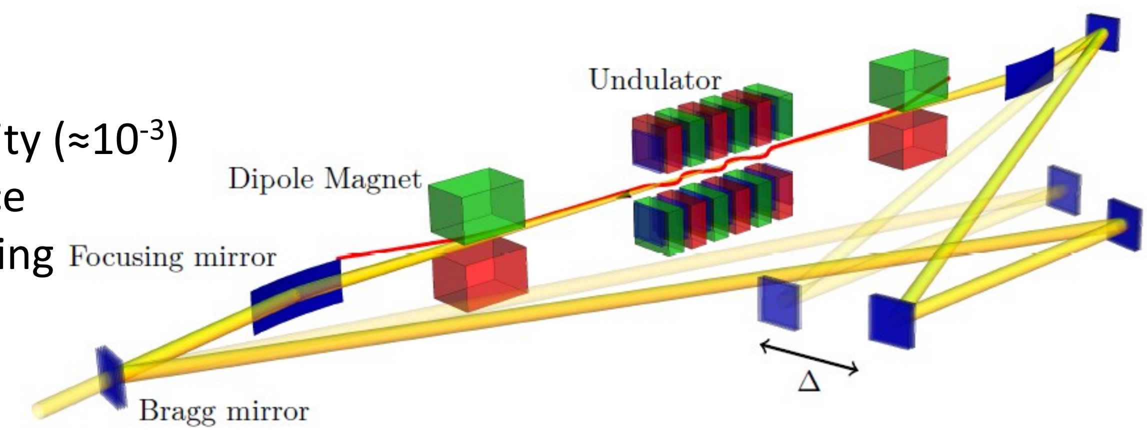
distance between atomic planes

→ depends on temperature!!

Bragg angle

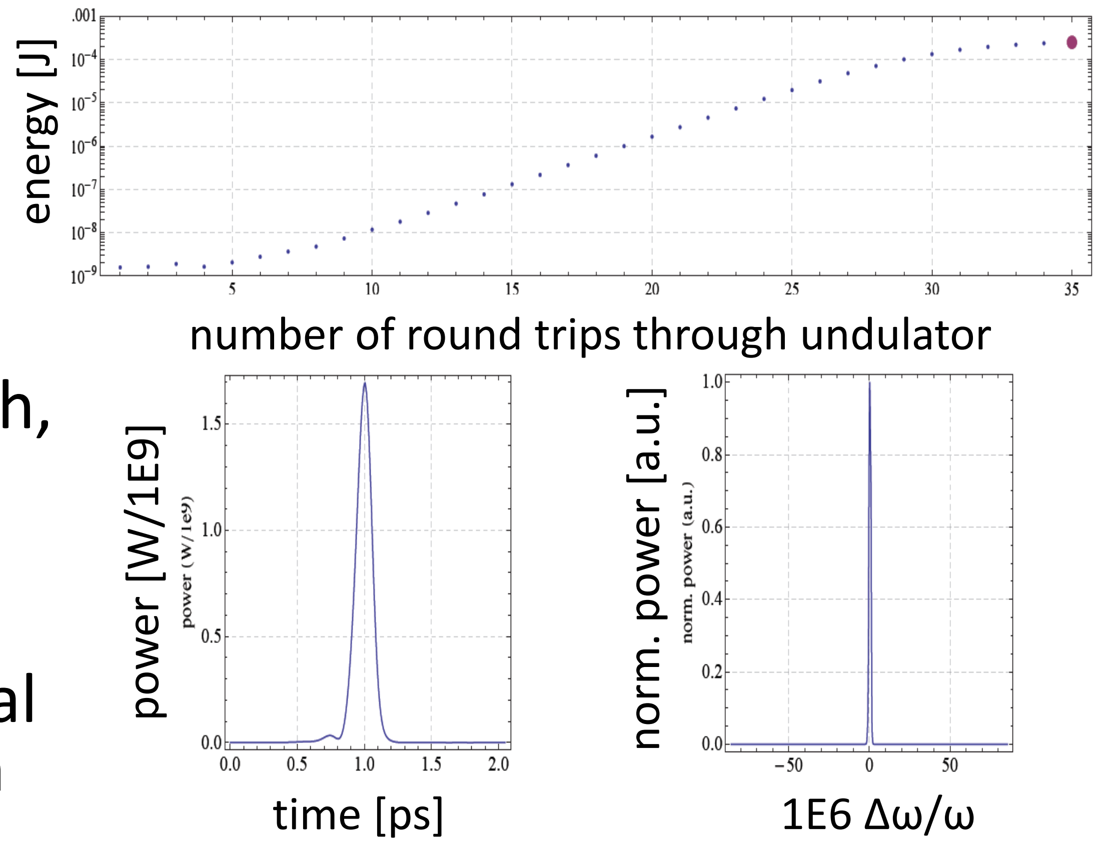
Tunable scheme:

- Bragg angle variable → tunability ($\approx 10^{-3}$)
- determined by transverse space
  Mechanics even more challenging
- Scientific benefit ??



J. Zemella PhD thesis 2010: First simulation of X-ray FEL Oscillator (XFELO)

- From Startup SASE E_{pulse}=1nJ ($\Delta\omega/\omega \approx 10^{-3}$) to fully coherent FEL radiation E_{pulse}=1mJ saturation ($\Delta\omega/\omega \approx 10^{-6}$)
- **Saturation case**: Bandwidth ≈Darwin width, reflectivity >99%, absorptivity <1% Brilliance $\approx 10^{35}$
- Interaction X-ray--material → displacement/strain in the material



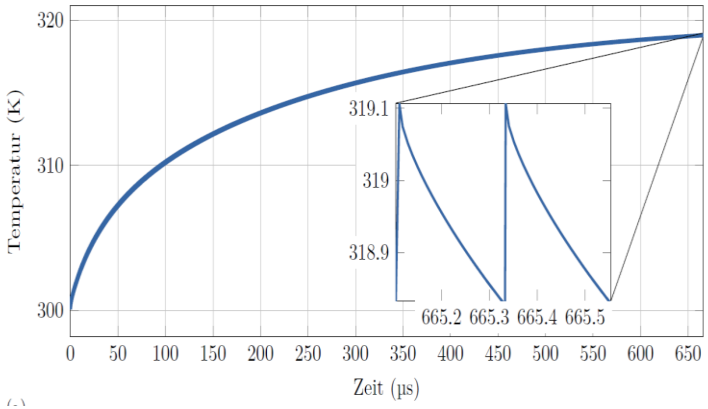
XFELO issues

What do we need to know?

- What happens during pile-up of heating during bunch train?
- Change of Bragg reflectivity after impact of FEL radiation pulse ?
- How does this vary from start-up with SASE to Bragg-filtered radiation pulses?

Pile-up of heating

T_0=300K
E_{Abs}=1.8µJ
σ_r=171µm
d=100µm

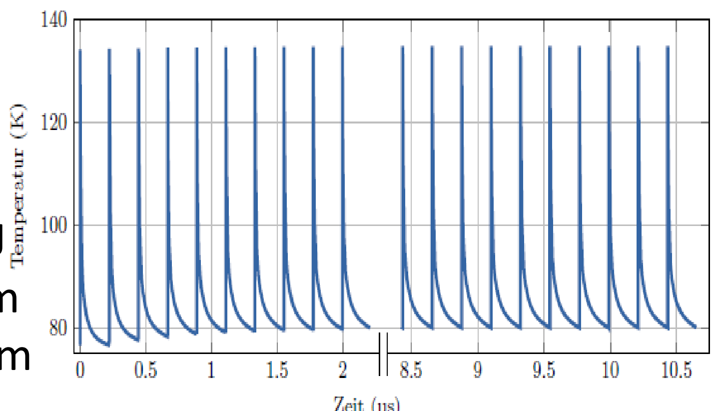


Poor thermal conductivity → Change of the crystal lattice due to thermal expansion

- Problem: (classical) Fourier heat law fails, because mean free path of phonons ≈ thickness of crystal
- Correction of Fourier Law may work → further theoretical and experimental work necessary
- Solving Boltzmann Heat equation → good approach, but challenging task

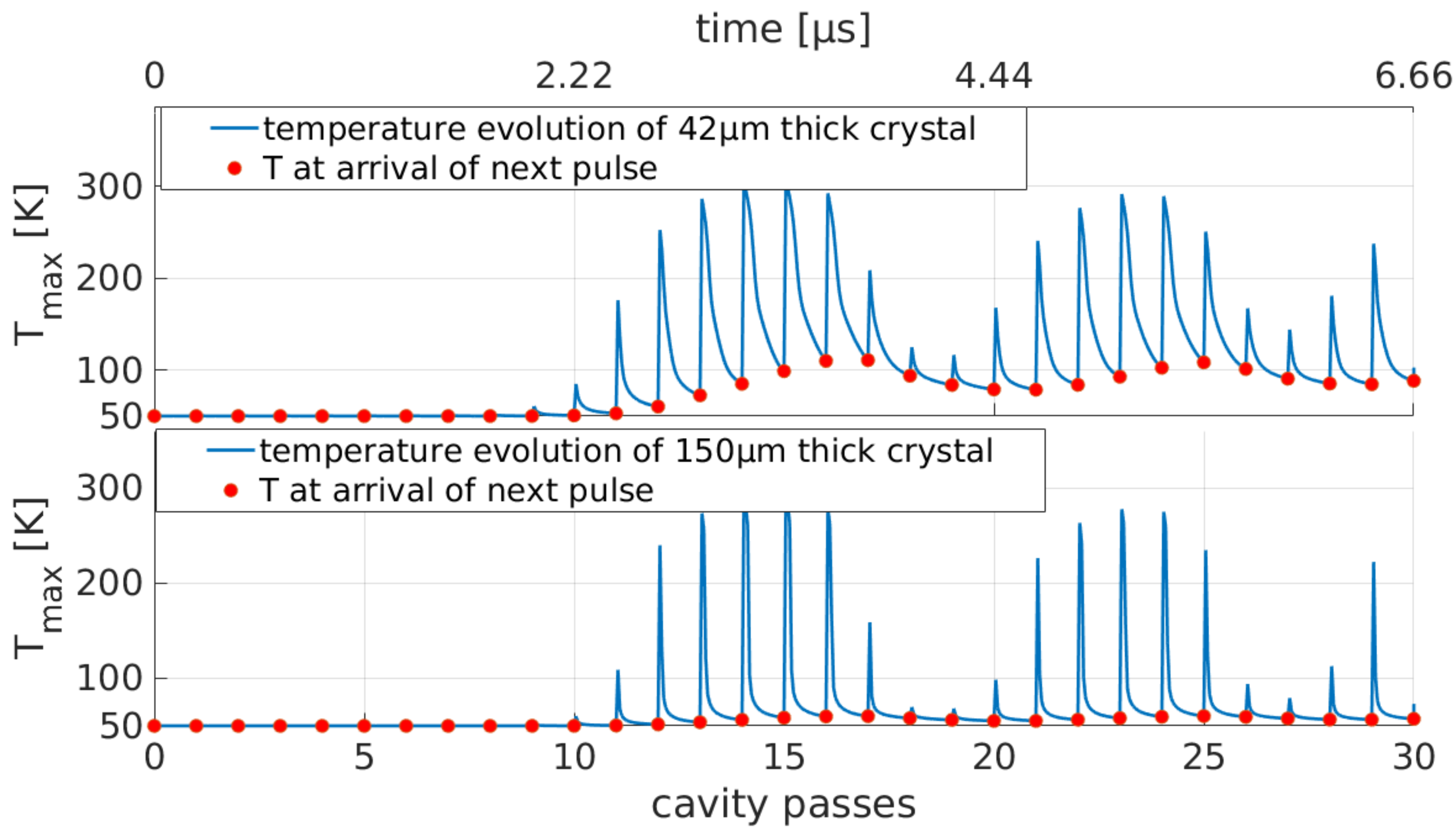
Much better: Cryogenic cooling:
Less heat capacity, but MUCH better thermal conductivity

T_0=75K
E_{Abs}=5µJ
σ_r=86µm
d=100µm

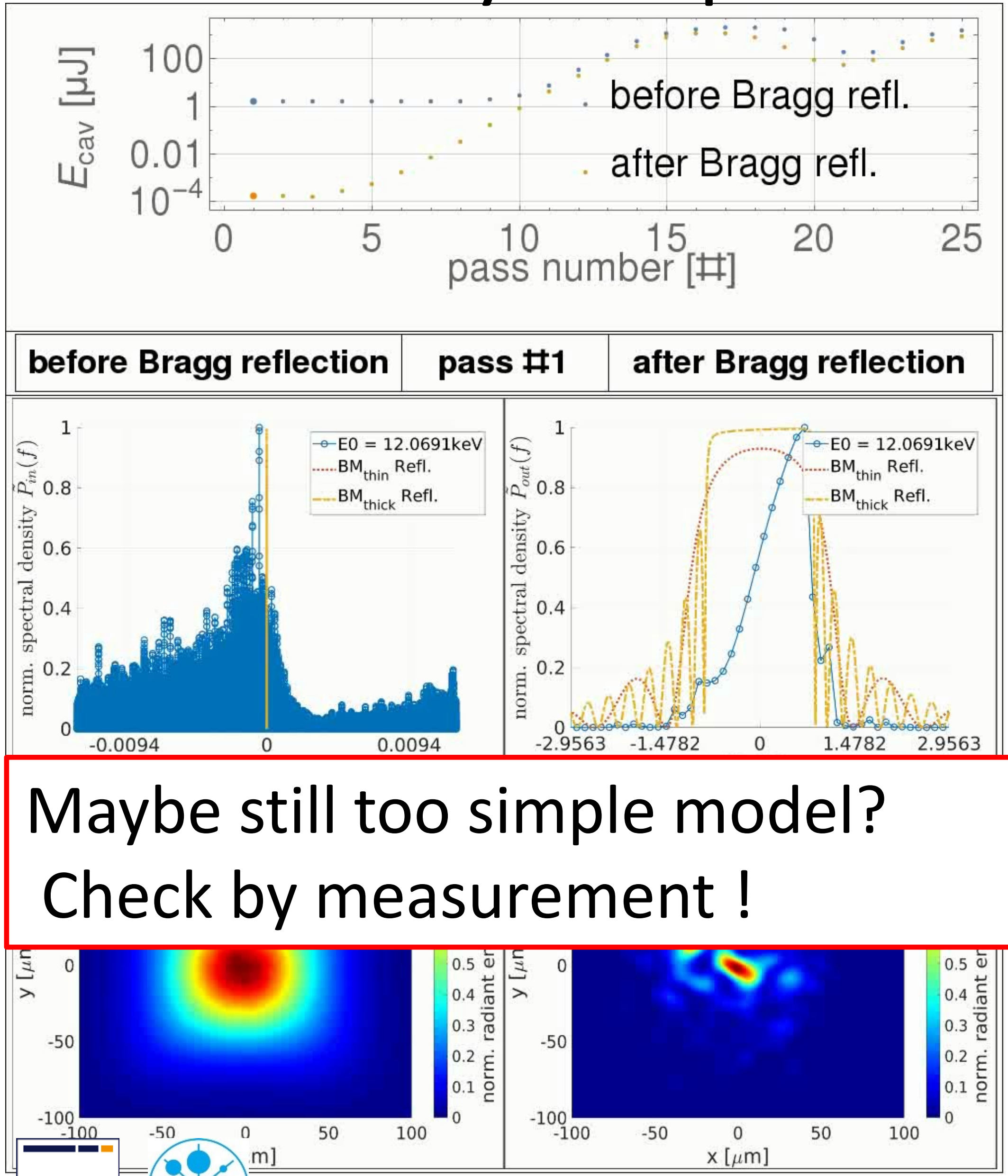


Pile-up of heating

P. Thiessen: 1D→2D in simulation, improve heat conductivity model



Cavity fill-up

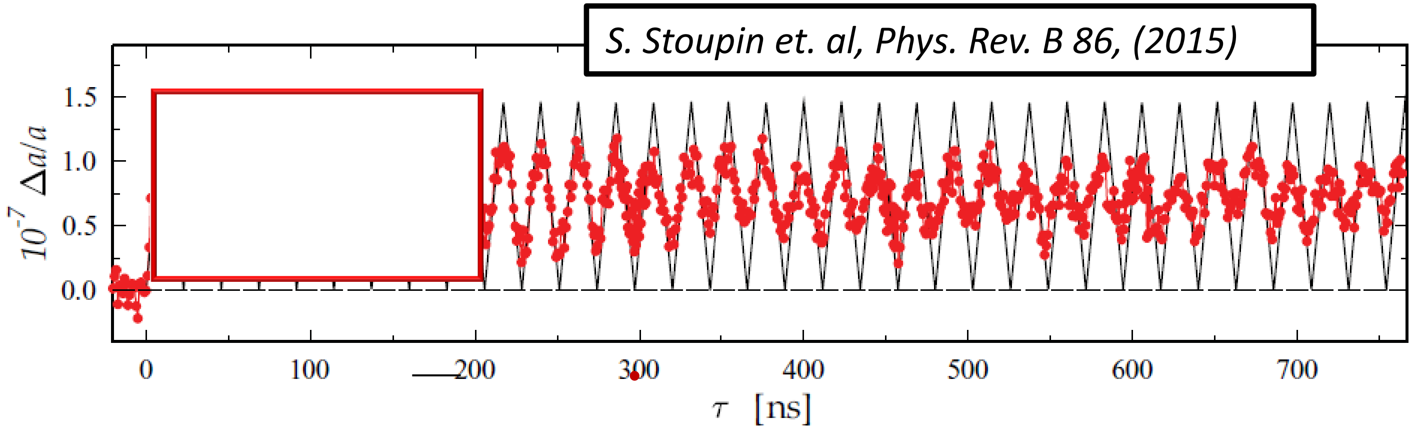


Maybe still too simple model?
Check by measurement !

XFELO relevant measurements - elsewhere

Important measurement at ANL:

Reflectivity of spontaneous undulator radiation from nitrogen-doped diamond after excitation with laser pulse λ=400nm tp=100ps



strain at surface: theo. measure

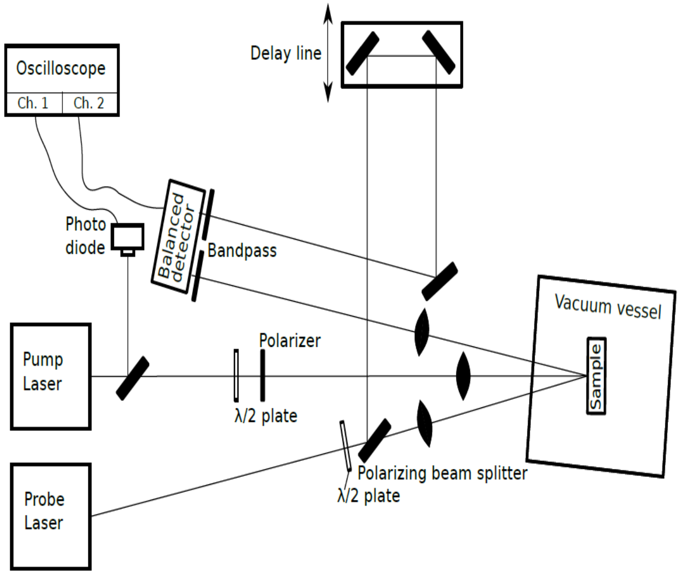
- **Room temperature**
- **Spontaneous radiation → large depth of penetration** ($L_{abs} >> d_{crystal}$)
- **Broad spot on crystal → 1 D problem**

XFELO relevant measurements @ Univ. HH

What we can measure is the change of optical reflectivity of the surface. If this changes, it is plausible that it is due to change of temperature.

BUT: By how much does the temperature change in fact?
And by how much do the Bragg properties change?

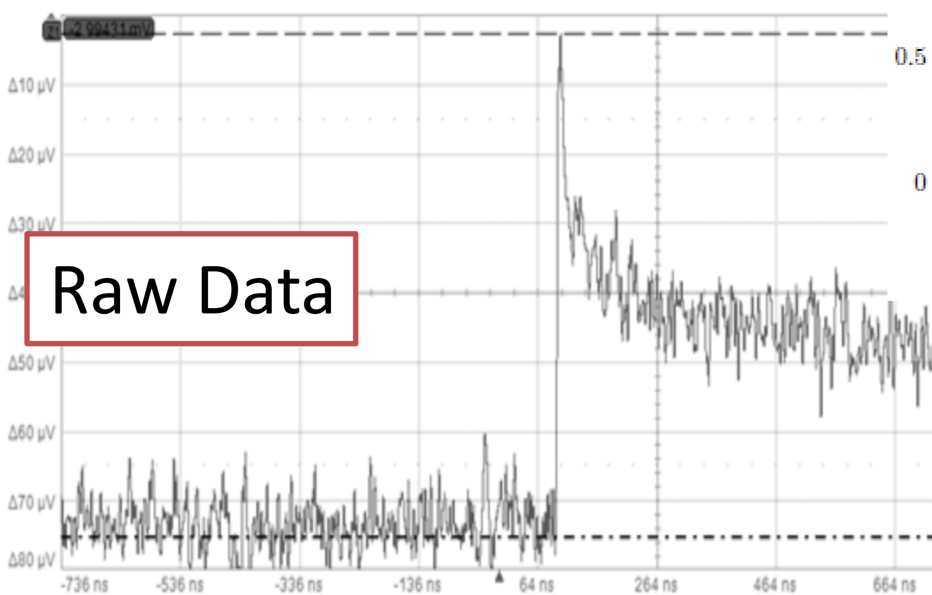
Experimental Setup for Thermoreflectivity (Maag Diss. 2018)

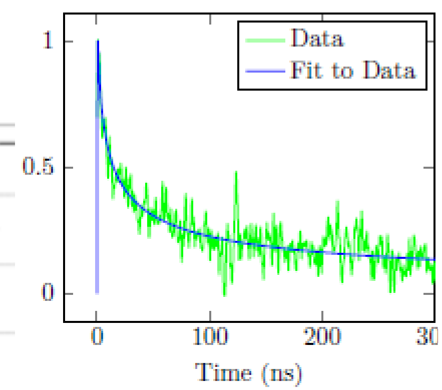


Pump UV Laser E_p=1µJ; t_p=1ns; penetration depth = 3µm

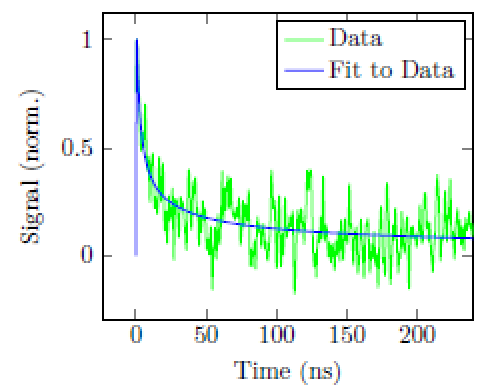
Pump laser → temporal change refractive index → Temporal change in reflectivity → heat propagation

Refl. change ↔ Temp. change: assumed to be linear





Measurement at 297K

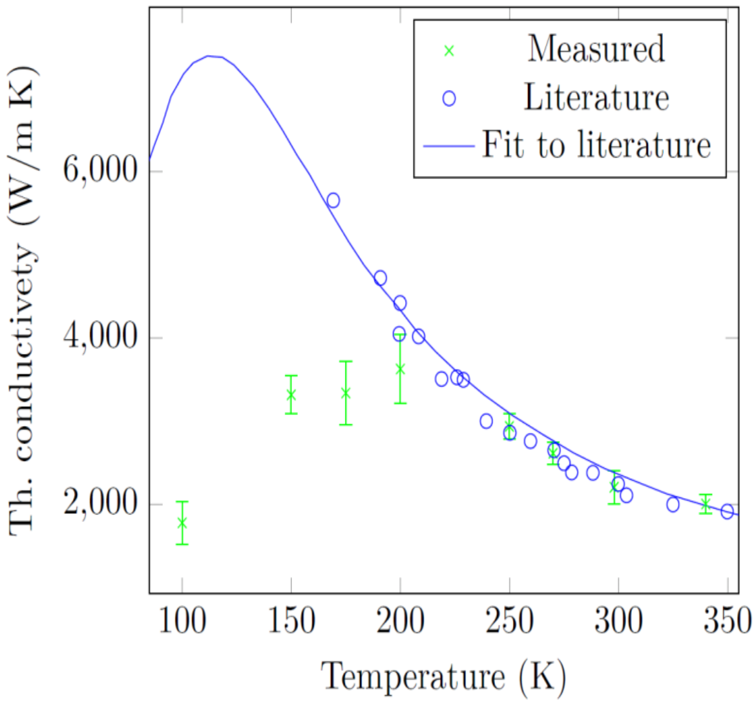


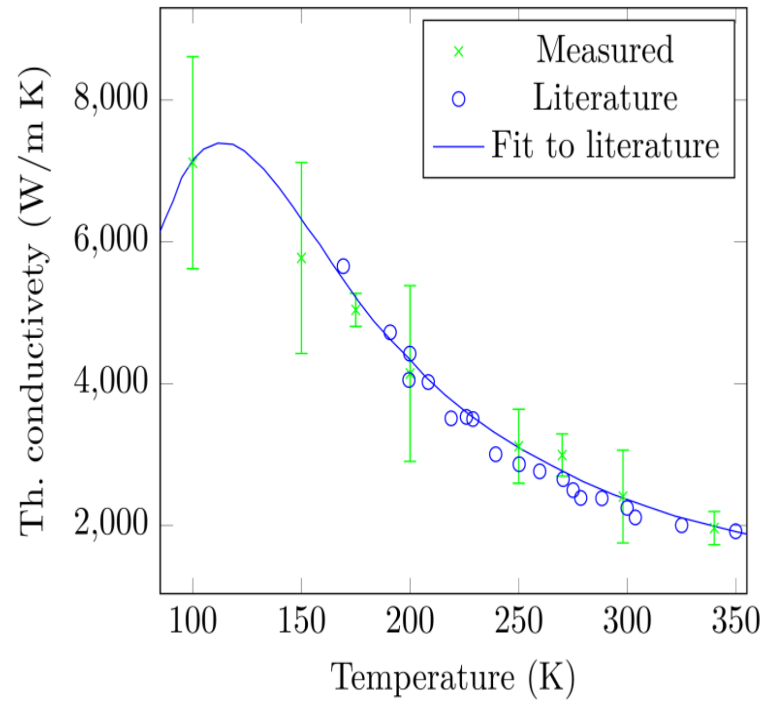
Measurement at 150K

Long term signal fit:

$$U_{\mathrm{el}}(t) = U_{\mathrm{el}}^{(0)} + U_{\mathrm{el}}^{(1)} \cdot \exp\left(\frac{t}{\tau_{\mathrm{el}}}\right)$$

Thermoreflectivity of Bragg crystals:





Failure of classical heat conductivity (Fourier model) at T <220K
Mfp length of phonons comparable with crystal dimensions

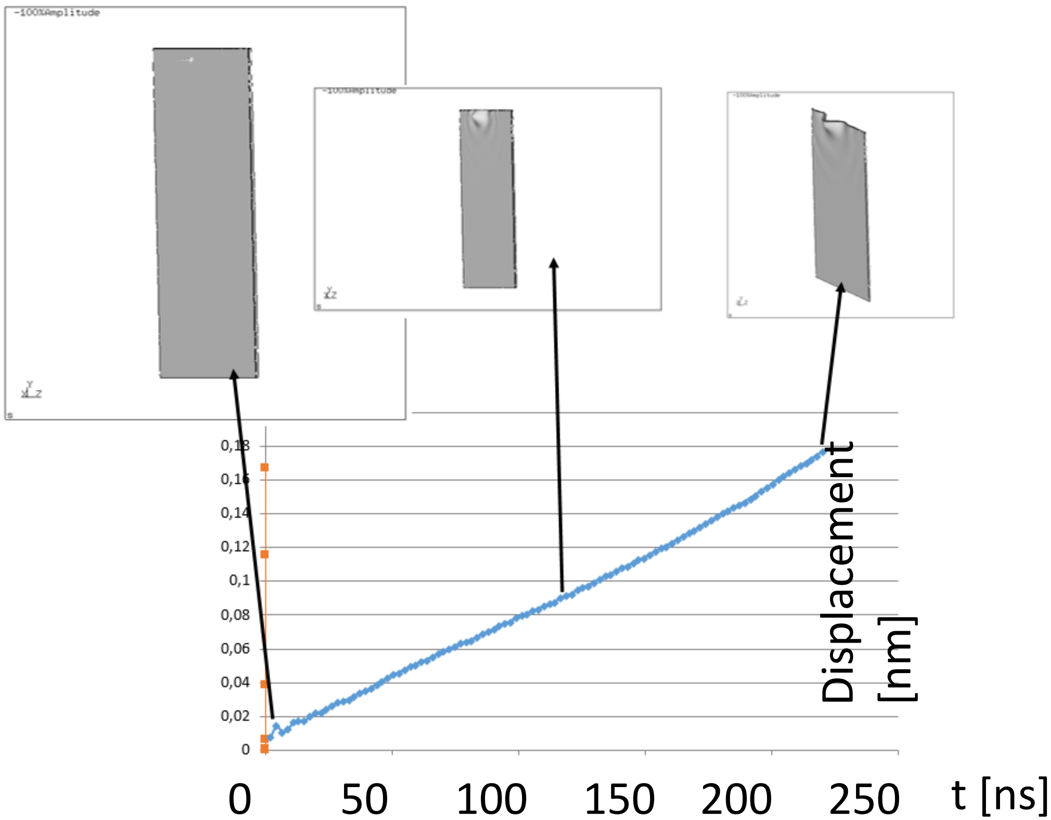
Hyperbolic heat equation suitable for modeling the 1D heat conduction at T>100K

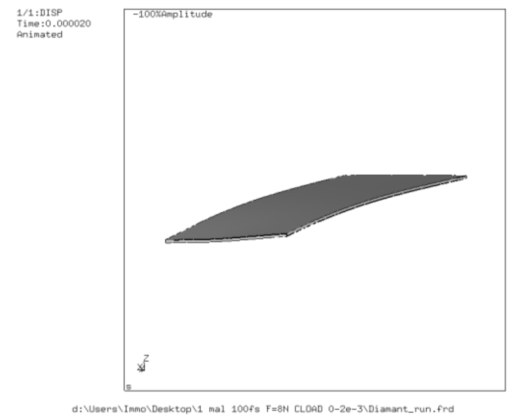
What else will happen?

Vibration! → Thermoelastic strain waves

due to dynamic thermal expansion and radiation pressure

Low damping rate of ultrasonic in single crystalline diamond !



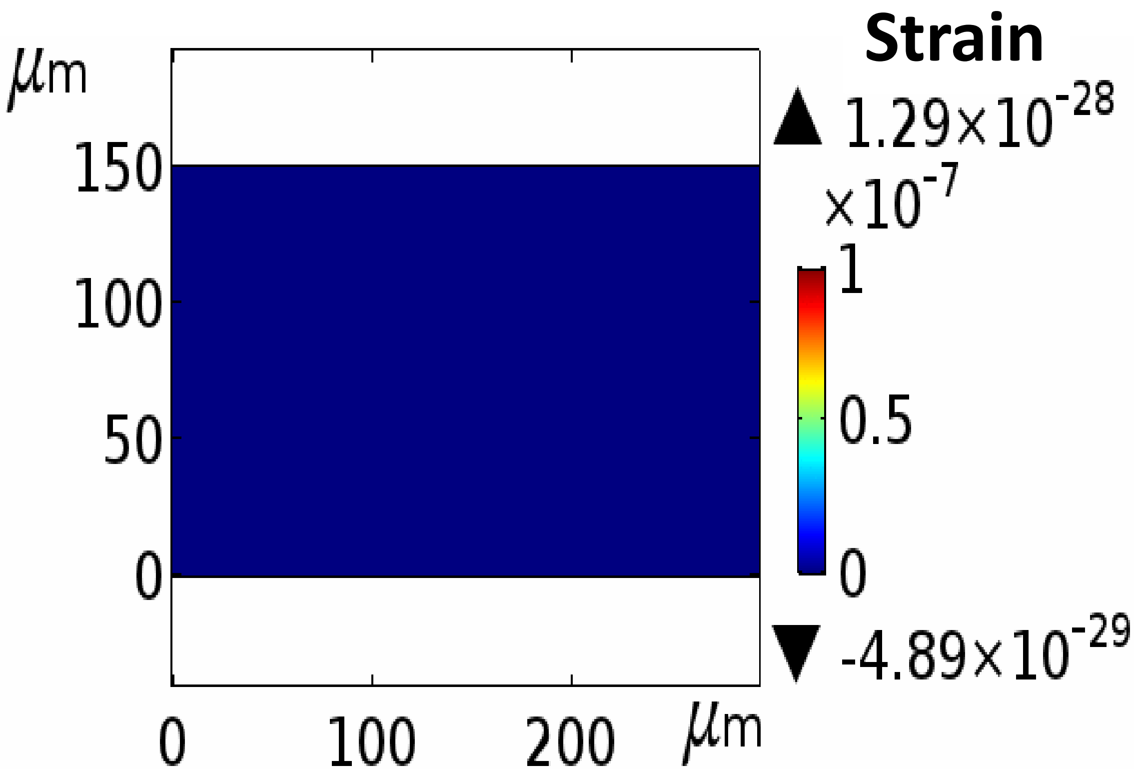


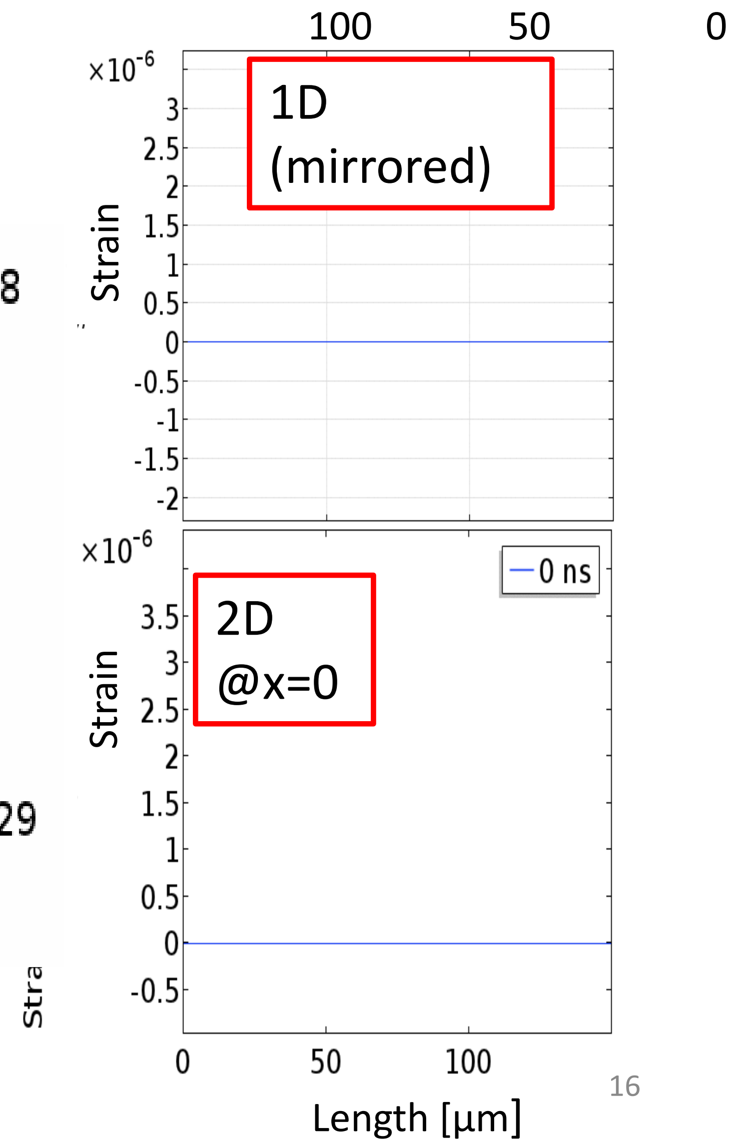
→ Ultrasonics will induce local density changes inside crystal

Note: Angular tolerance for Bragg reflection ≈ 100 nrad !

I. Bahns: 2D simulation of ultrasonic propagation

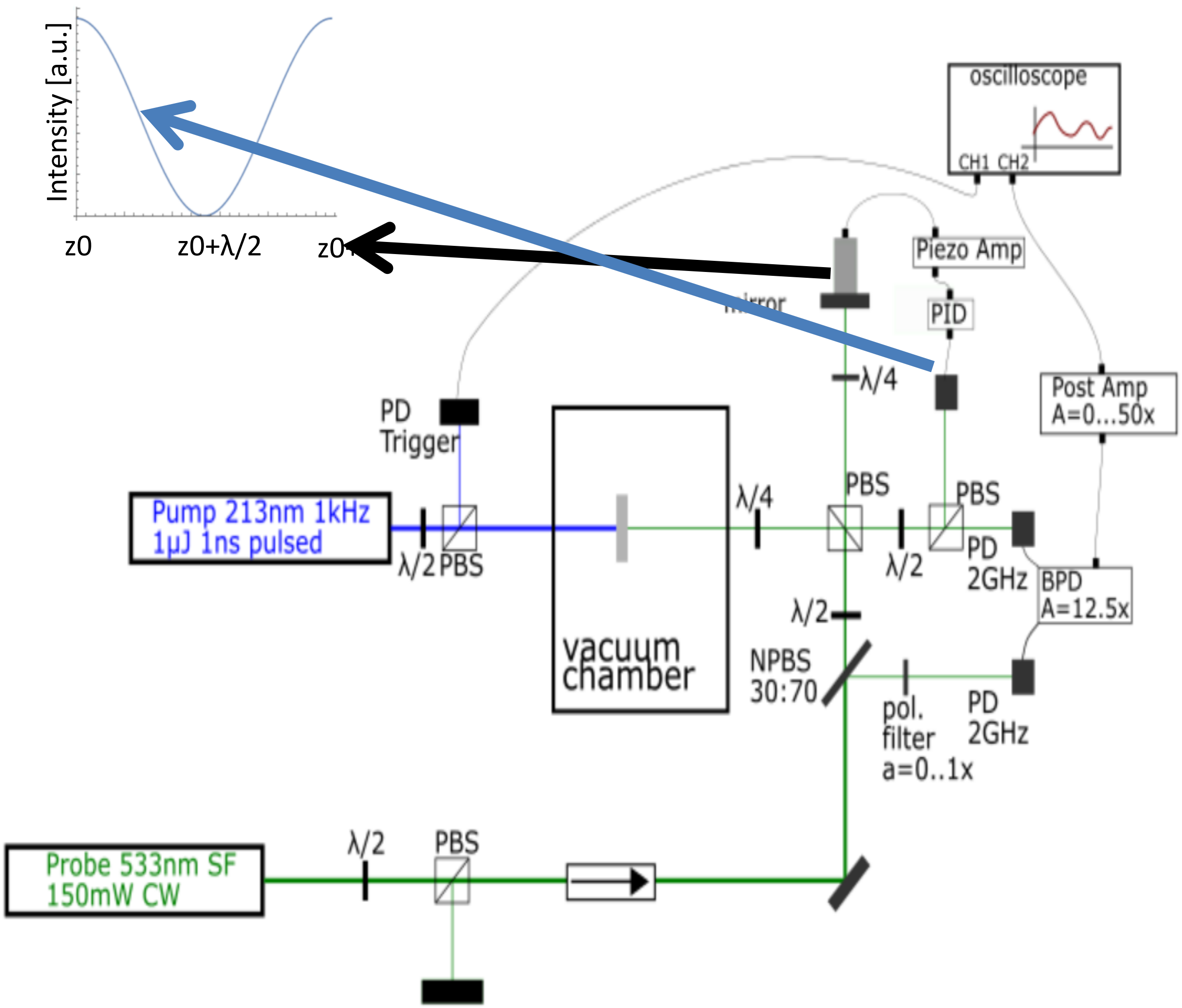
first 5ns after absorption of 1 µJ X-ray pulse
150µm thick diamond crystal (444)
penetration depth=20µm





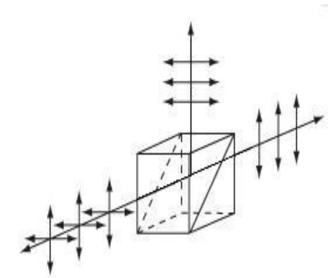
Not yet implemented in XFELO S2E simulation

I. Bahns : generate ultrasonic wave by pump laser pulse and measure displacement on back side of crystal by interferometry

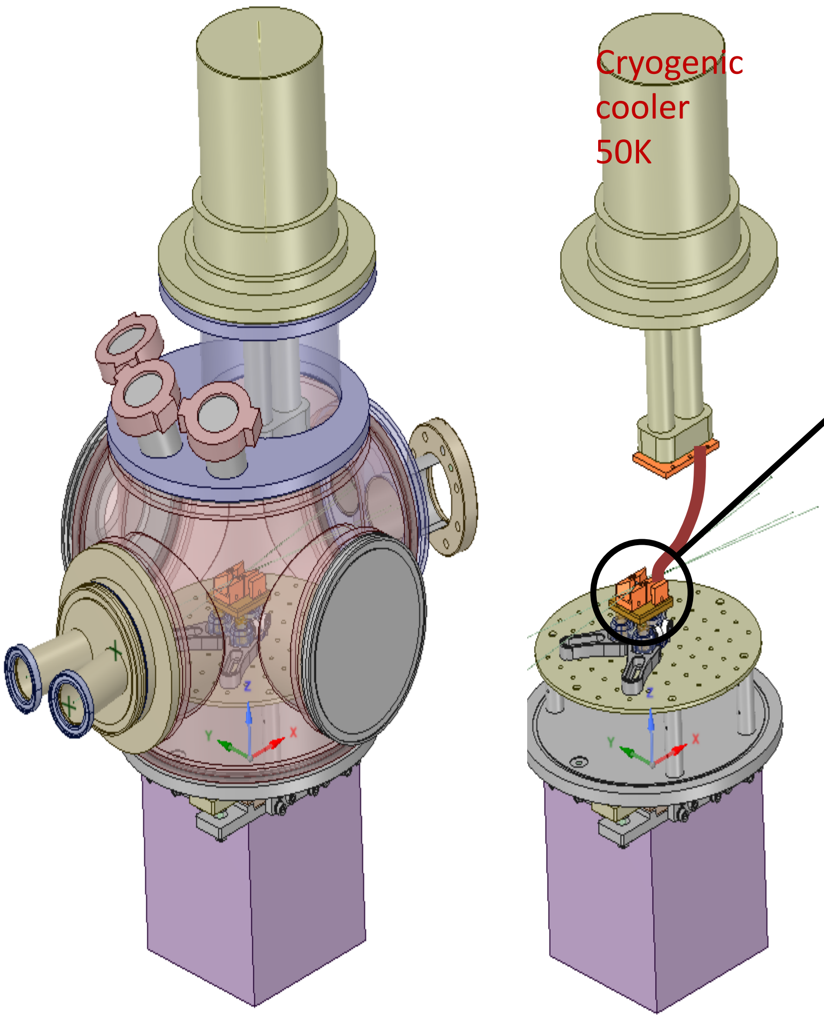


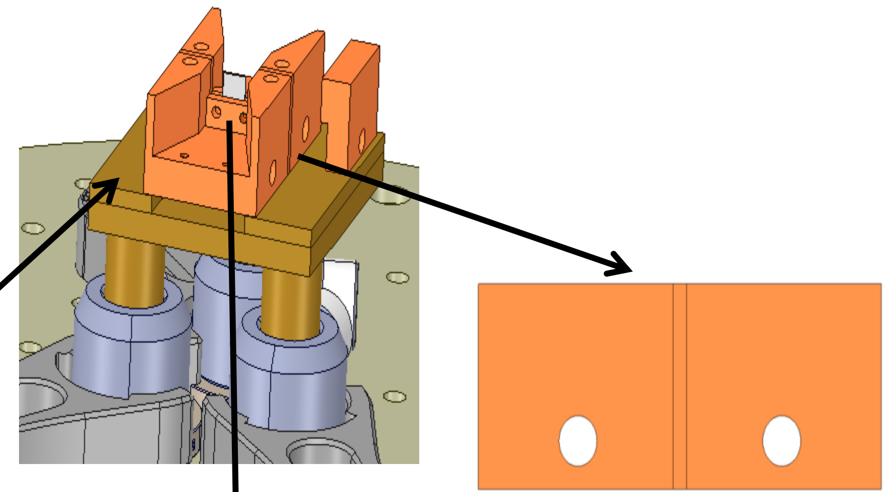
Pump UV Laser E_p=1μJ

t_p=1ns

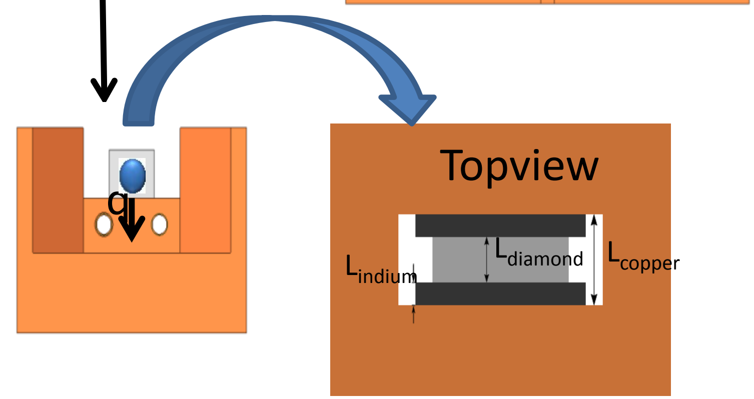


Experimental Setup for Sample Holder





Heat transfer coefficient:
$h=q/\Delta T$ → thermal contact



Matched geometry/material expansion for low strain at low temperature

Attention:

What we did so far is nice theory,

or we mimic the XFEL pulse by a pump laser pulse.

→ We need a critical experiment :

HXRSS-setup for first XFELO-experiments

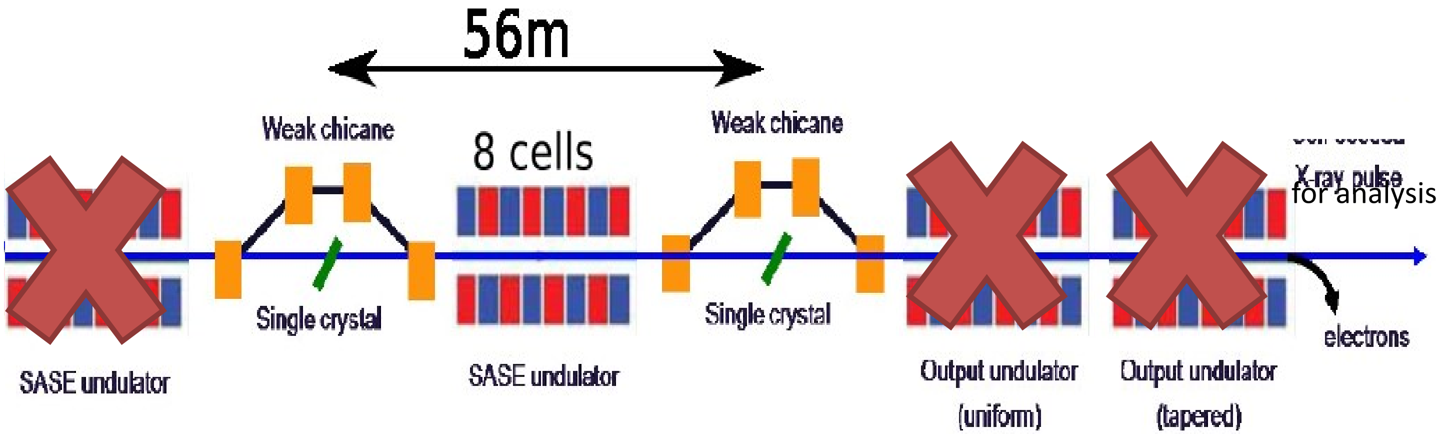


Fig.1. Schematic layout of the two-stage setup HXRSS system.

- First experiments with not-matched pass-to-pass will test reflectivity of circulating x-ray pulse.
  - Minimum results: testing alignment
  - Better:Testing diffraction calculations by probing intensity of reflected waves
  - Best: Probing the diffraction altered by the heating of the crystal

Conclusion & Outlook

1. XFEL oscillator would turn the EuXFEL into a REAL laser
2. Main issue: X-ray radiation load on Bragg crystal
3. Rather advanced understanding of physics and S2E modelling
4. Pump-probe lab for ns-scale investigation of thermal load and ultrasonics – first results
5. Critical experiment at Self-Seeding set-up will validate models

Next:

1. Investigate outcoupling issue
2. Investigate crystal holder options & mechanical tolerances
3. Consolidate S2E simulation tools --- what determines saturation?
4. Work out proposal, including X-ray seeding and spent beam option

NOW it's not too early and (hopefully) not too late to be the first !

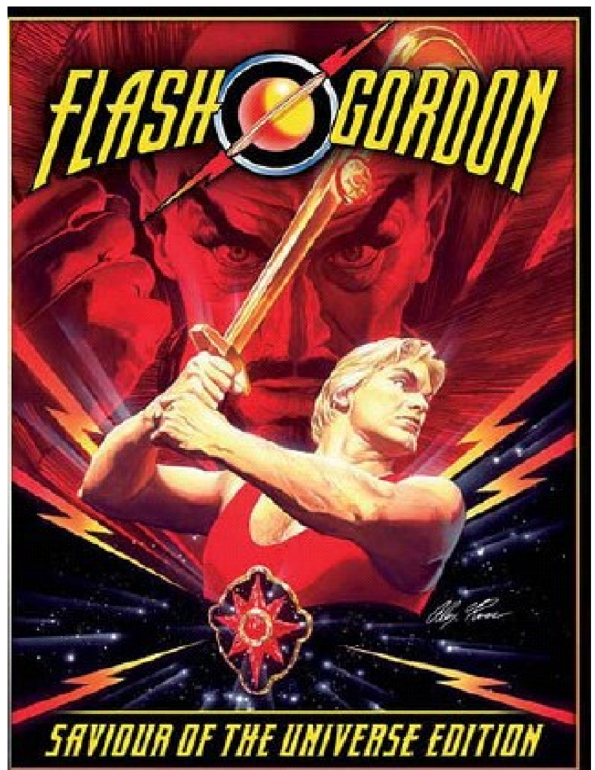
Present team: I. Bahns, W. Decking, W. Hillert, J. Rossbach, H. Sinn, P. Thiessen

Different FEL generations already visible

Different FELs have complementary characteristics and applications !

XFELO

FLASH & EuXFEL



FEL 1