Ultrafast melting of colloidal crystals observed in pump-probe experiments at LCLS

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- I. Zaluzhnyy
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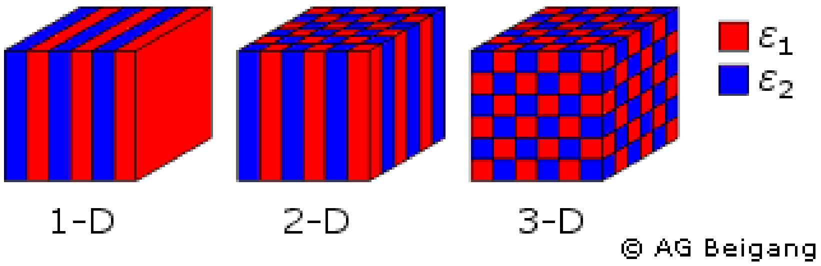
- A. Singer (now@UCSD)
- R. Kurta (now@XFEL)

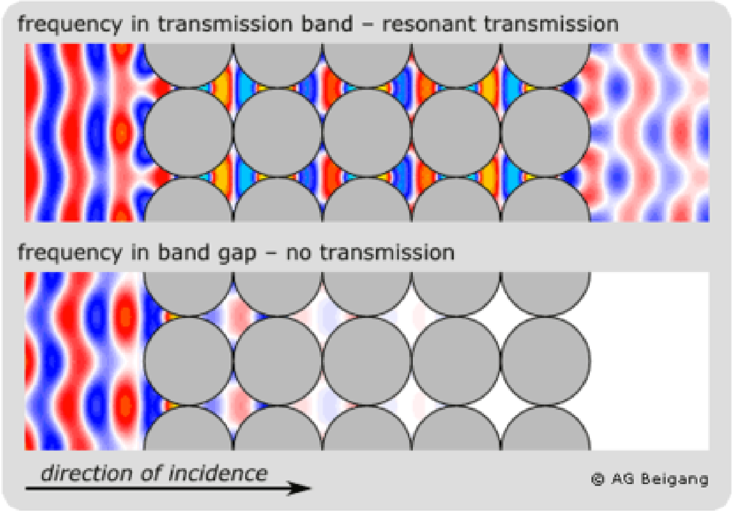
Photonic crystals

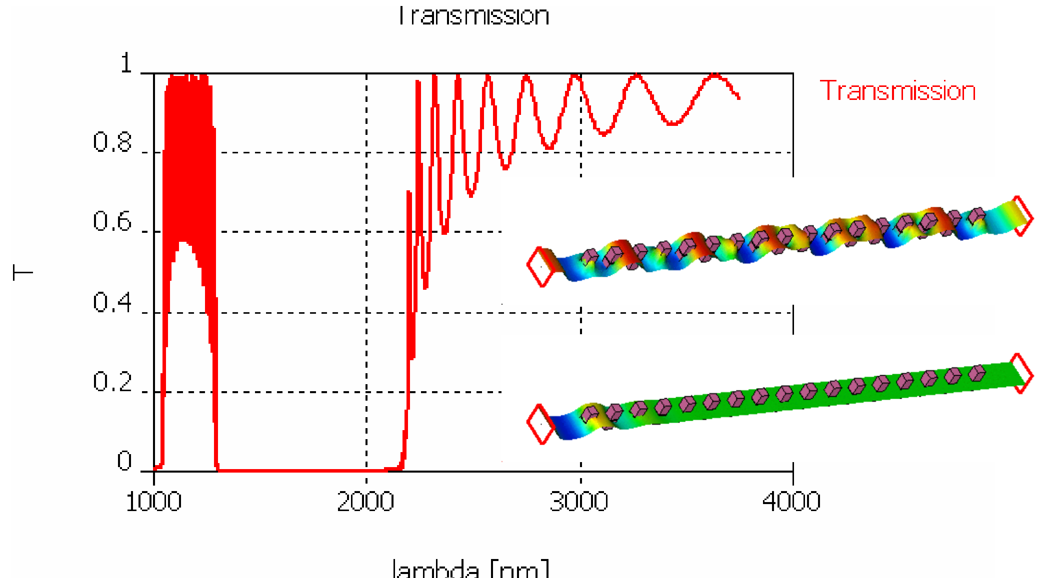
Photonic crystals in nature

Artificial photonic crystals



Photonic band gap materials

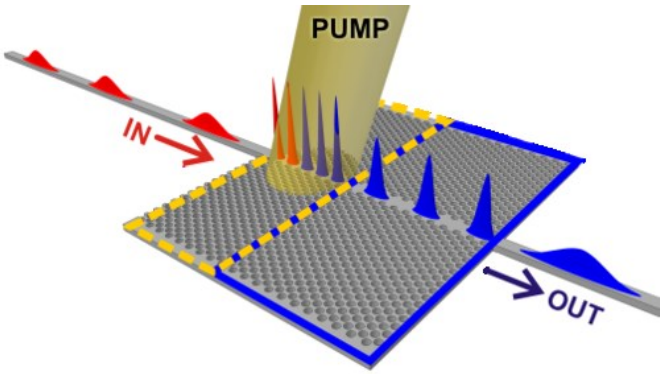


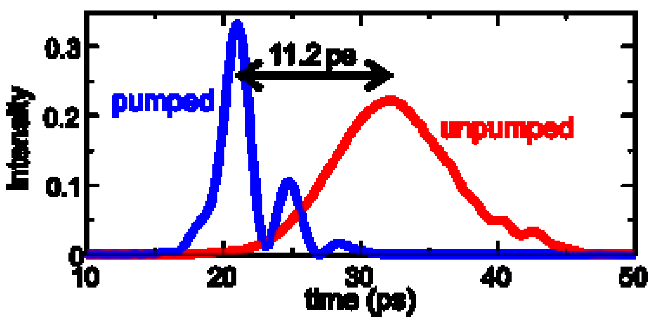


https://www.theochem.kth.se/research/phot_cryst/Photonic_Crystals.html

Tuning of properties by external fields

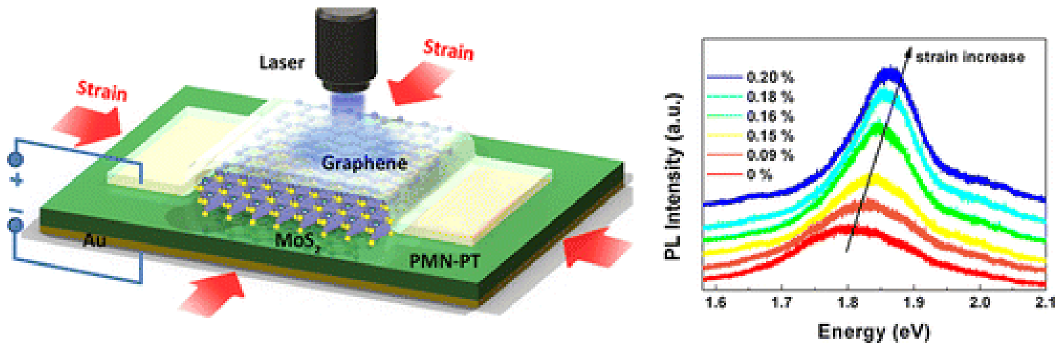
Pumping energy





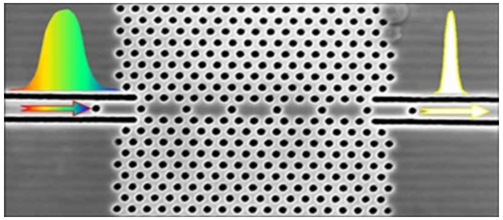
M. Daryl *et al.*, PRL 108, 033902 (2012)

Strain field engineering



Y. Y. Hui et al., ACS Nano 7 (8), 7126 (2013)

Incremental heating



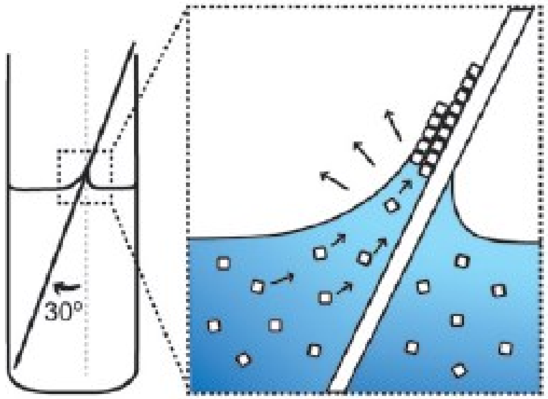
http://www.st-andrews.ac.uk/microphotonics/Gallery.php

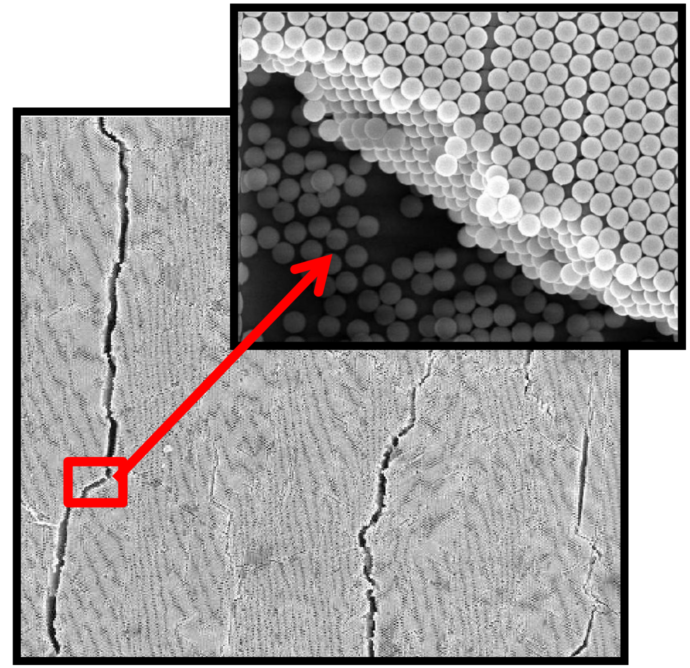
http://www.amolf.nl/research/nanooptics/news/detailpage/artikel/pumped-photonic-crystal-accelerates-slow-light/

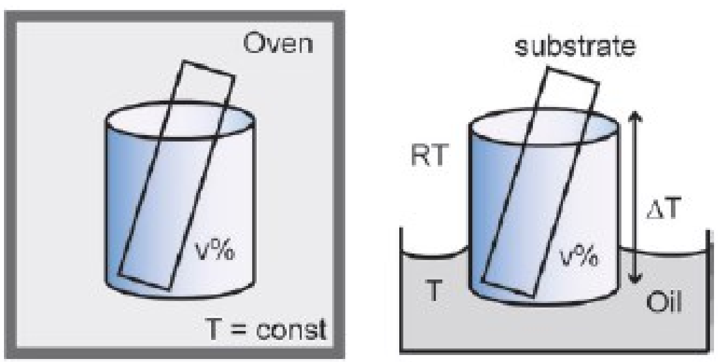
Colloidal crystals grown by self-organization

Growth of the colloidal crystal film

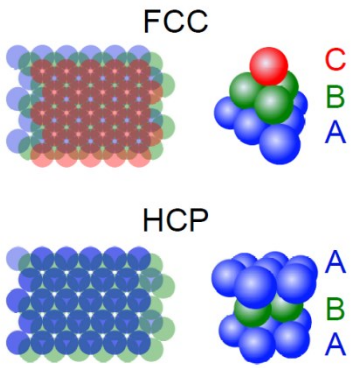
Vertical deposition method







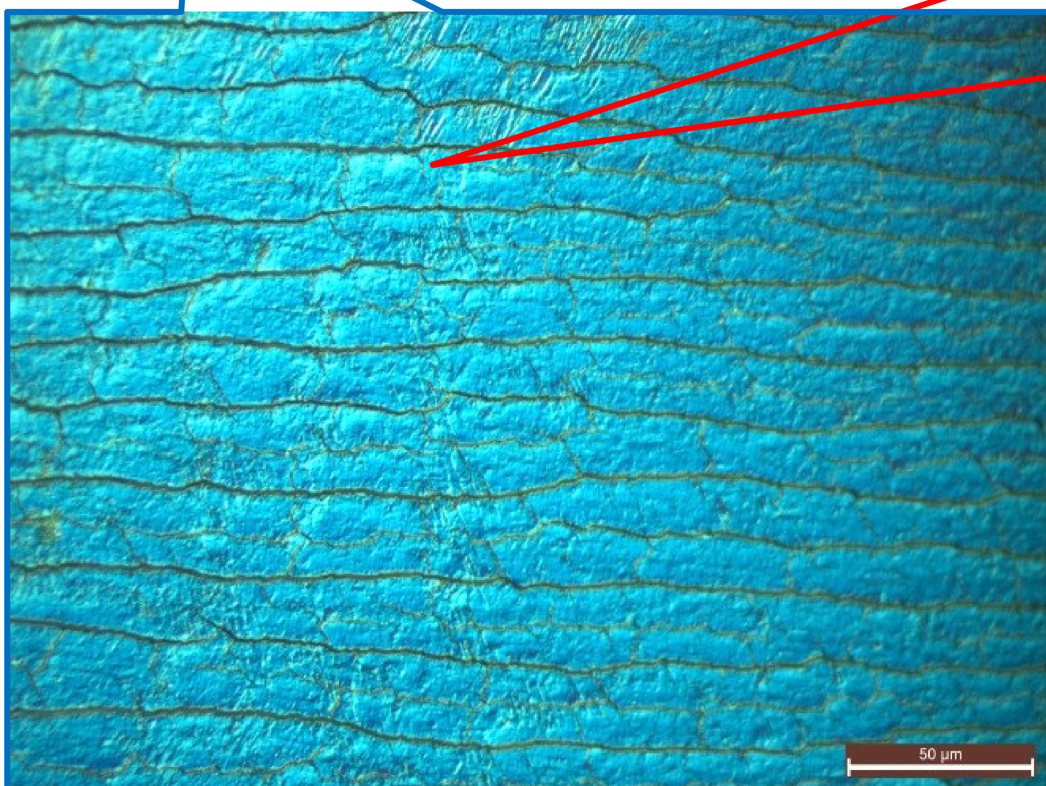
Oven-setup ΔT-setup



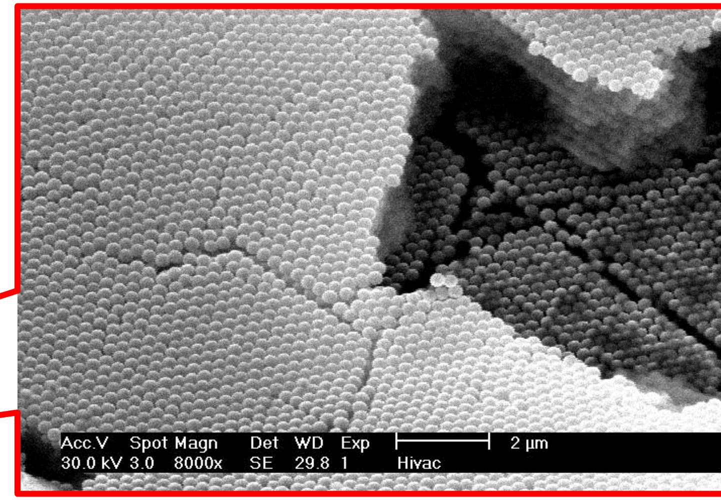
A
B
C = RHCP
A
B

J-M. Meijer, et. al. Langmuir (**2012**), 28, 7631−7638.

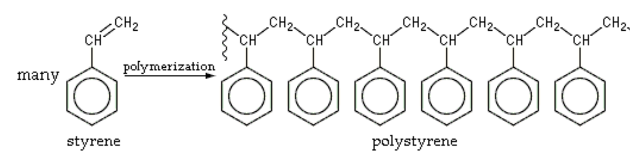
Polystyrene colloidal crystal



Diameter = 160nm

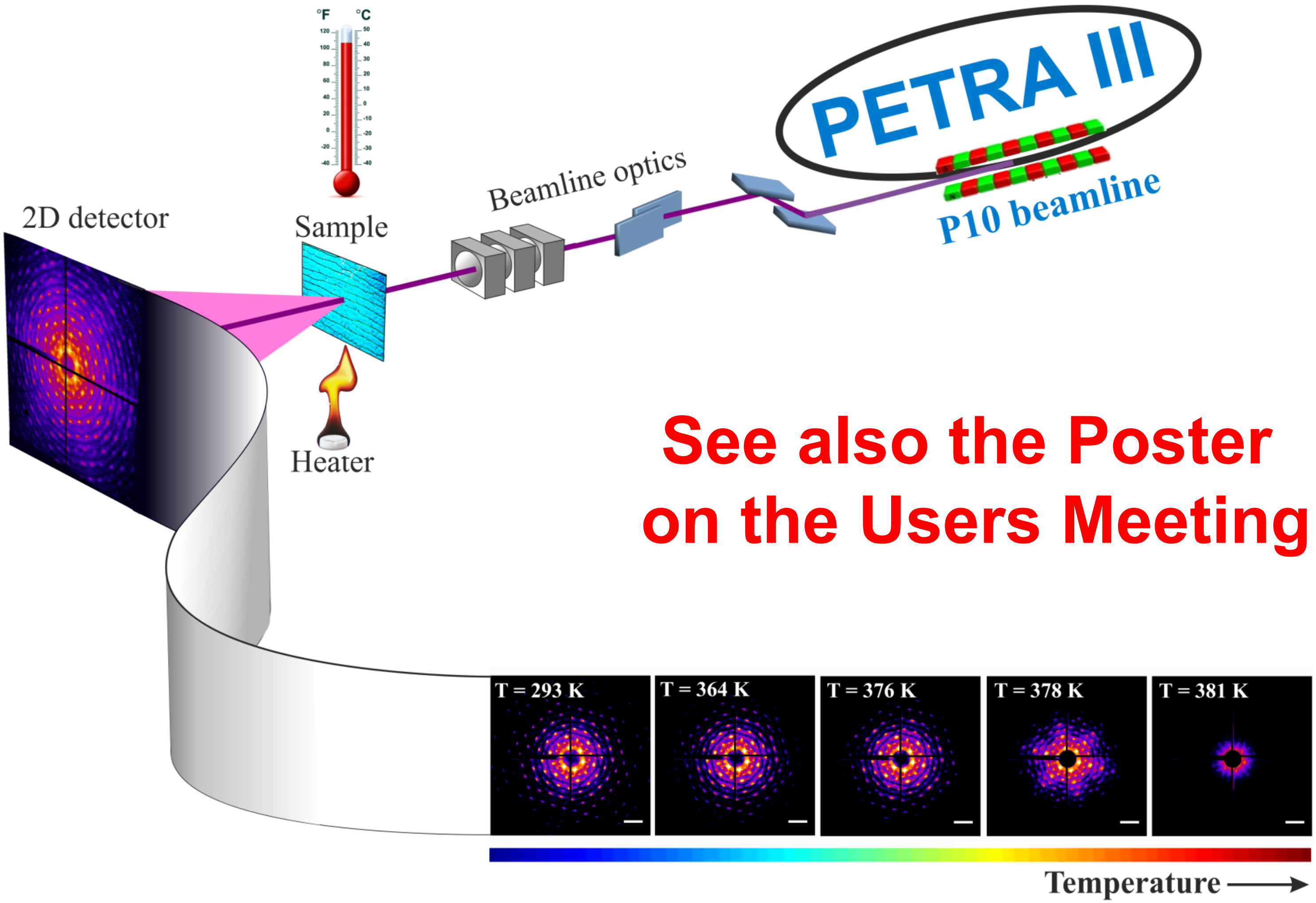


Polystyrene (PS) spheres



Prototype of bio-molecule

Structural evolution of colloidal crystal films in the process of melting

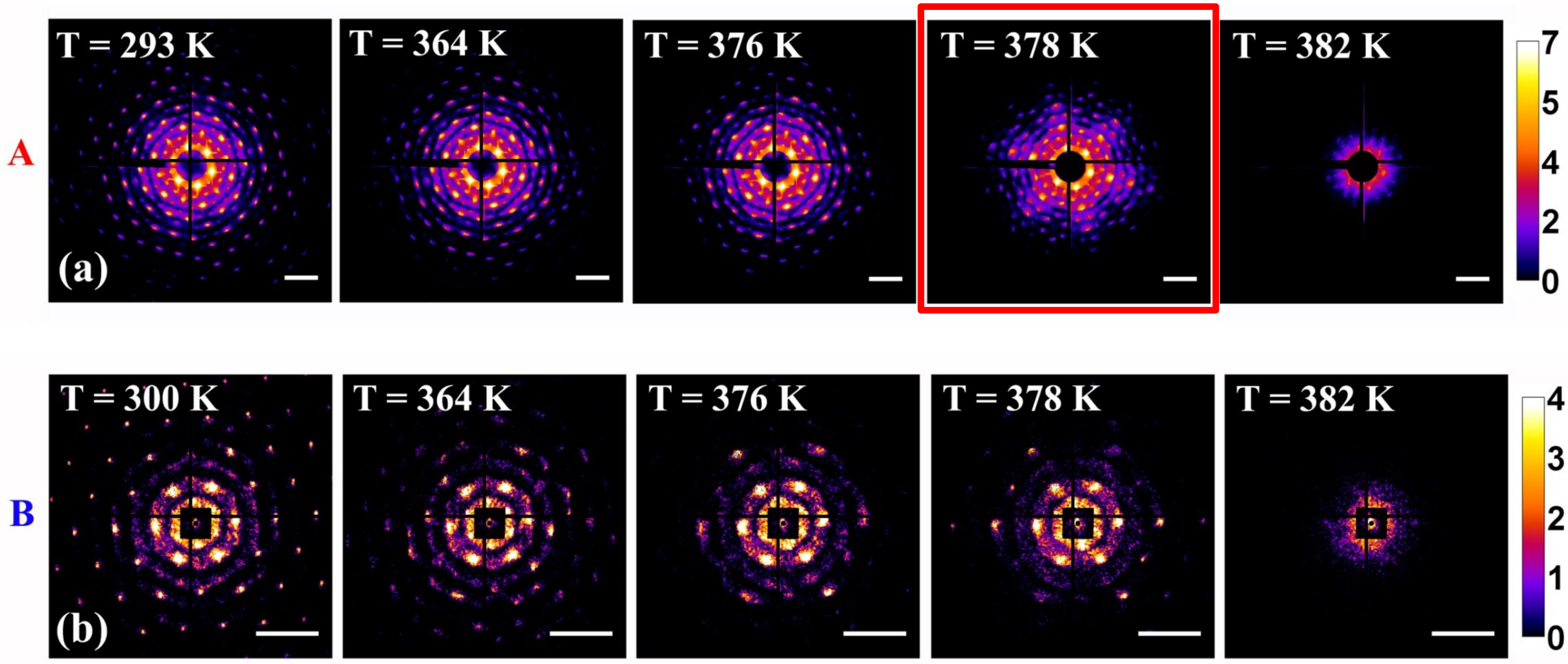


See also the Poster on the Users Meeting

E. Sulyanova et al., Langmuir (2015) (accepted)

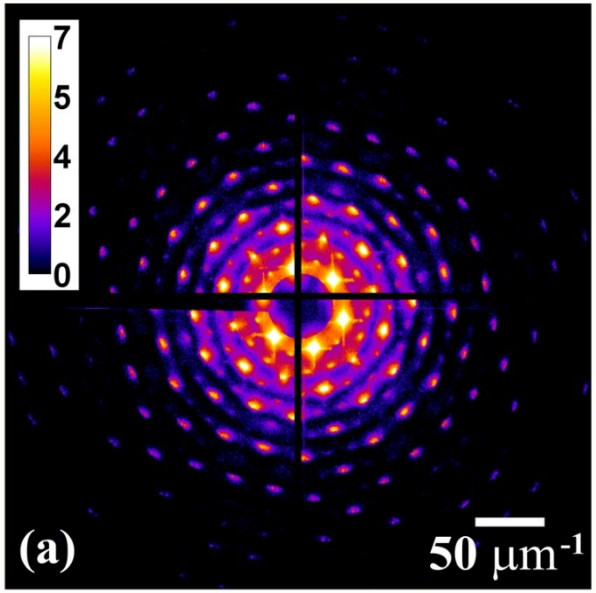
X-ray diffraction patterns measured *in situ* during incremental heating

Experiment A
15 keV, 50 x 50 μm unfocused beam

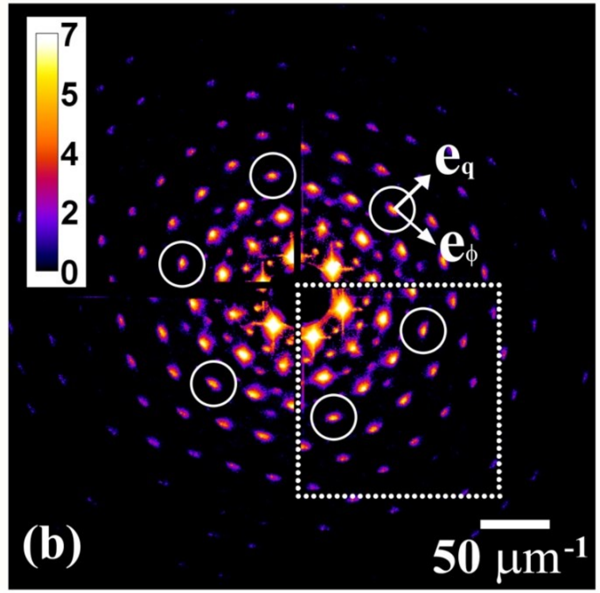


Experiment B
8 keV, 3.5 x 2.8 μm focused beam

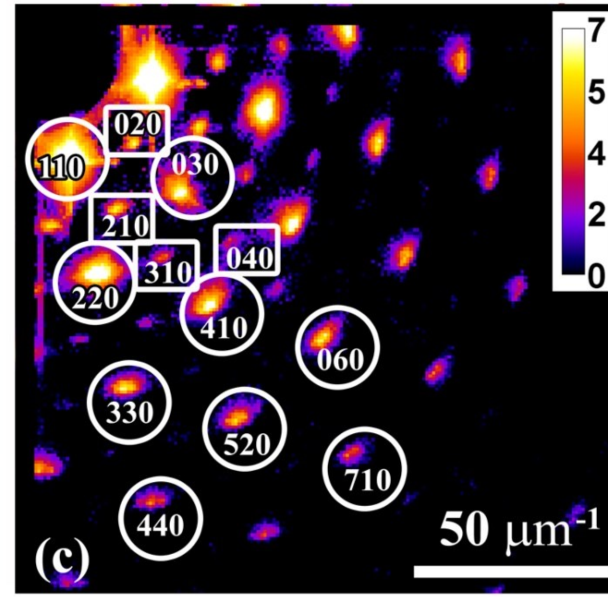
X-ray diffraction pattern of the experiment A measured at room temperature



X-ray diffraction pattern of the experiment A measured at room temperature.



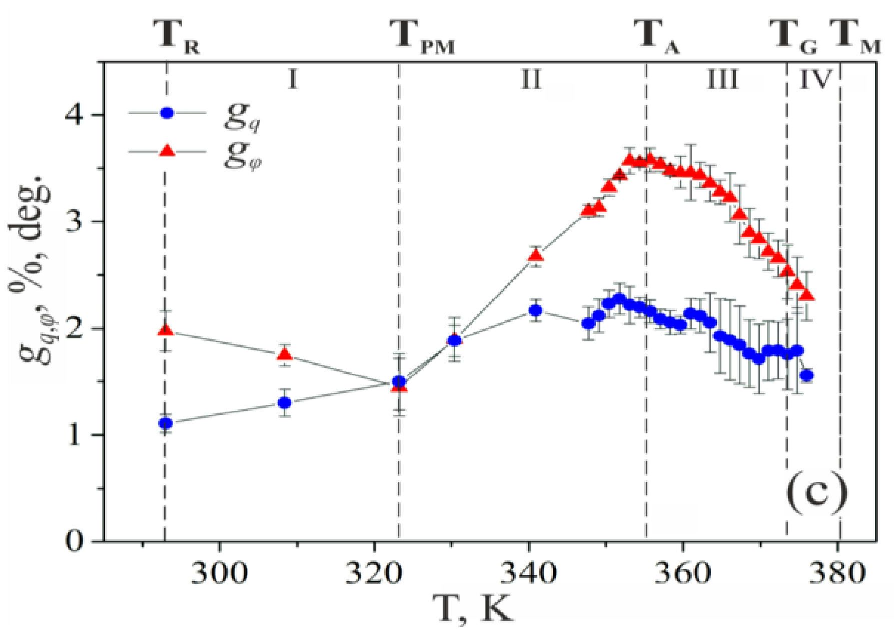
Same pattern with SAXS contribution subtracted.



Enlarged area of (b) showing Bragg peak indexing.

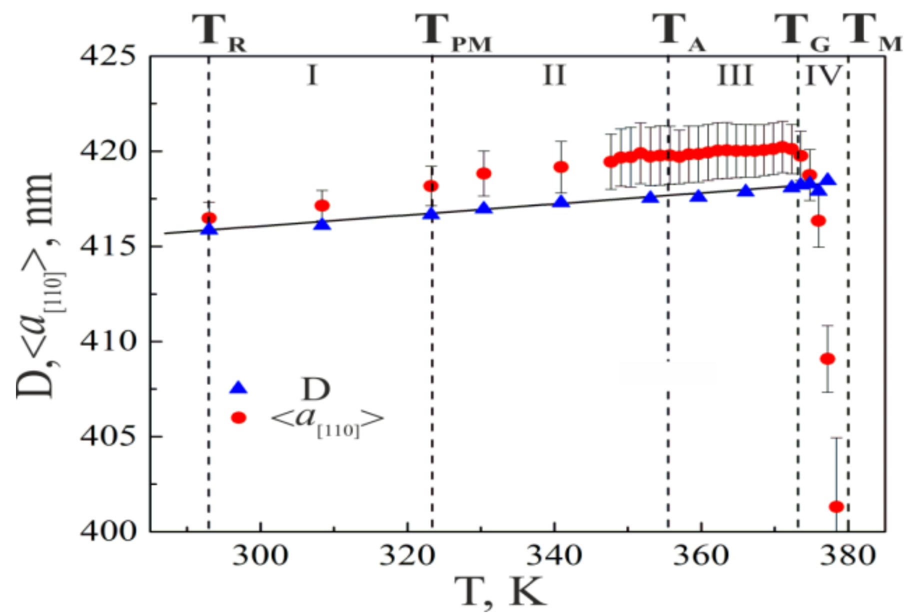
Temperature evolution

Mesoscopic scale



Lattice distortion parameter g_q and domain misorientation parameter g_φ

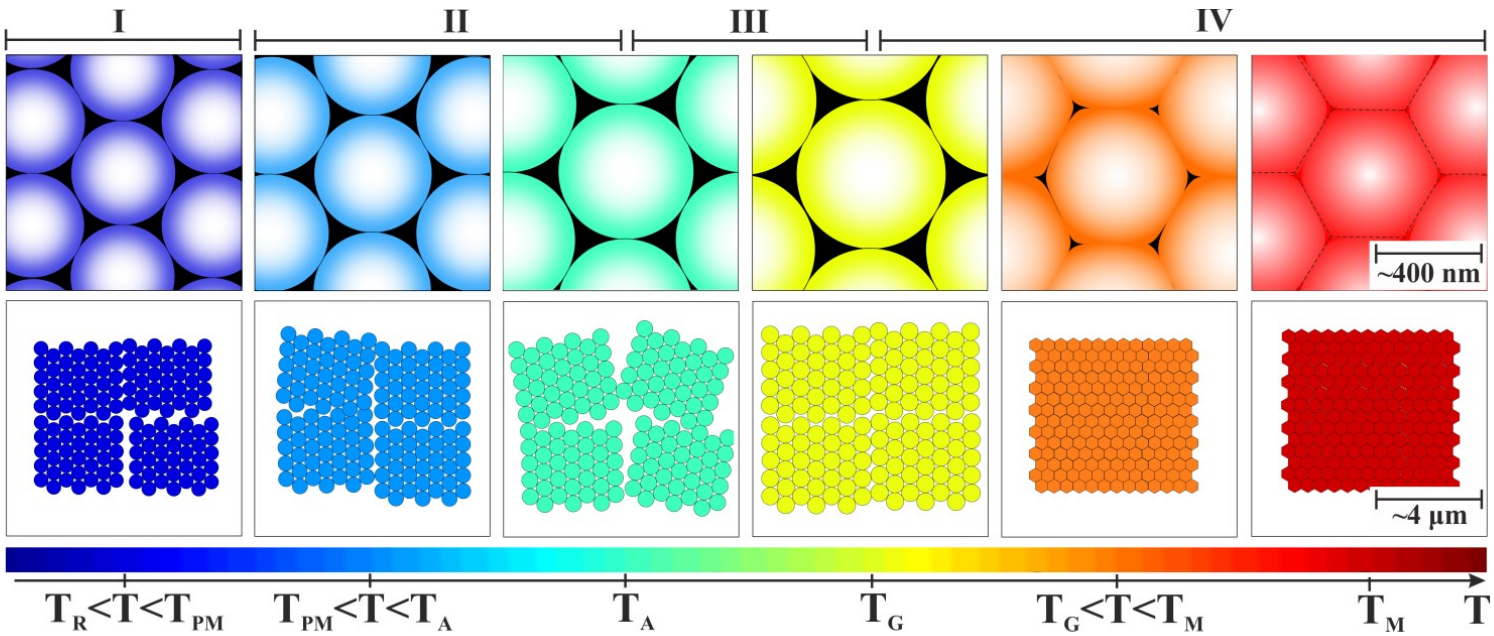
Nano- scale



Polysterene particle diameter D and average lattice parameter $<a_{[110]}>$

The model of colloidal crystal melting process

Nano- scale

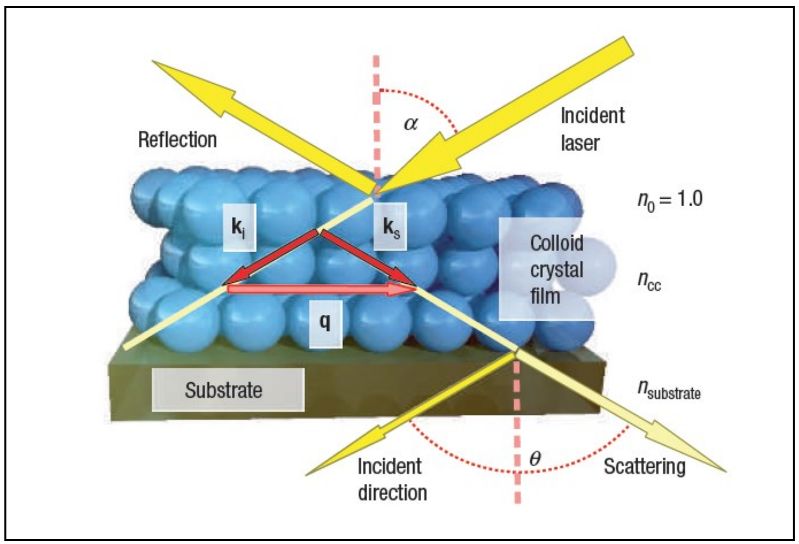


Mesoscopic scale

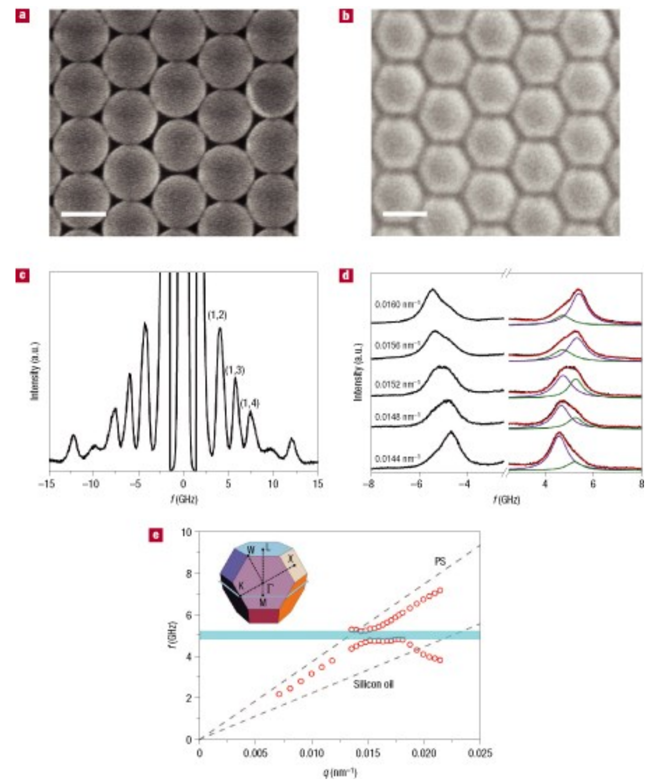
Study of dynamics in colloidal crystals

Observation and tuning of hypersonic bandgaps in colloidal crystals

- Polysterene spheres in air, glycerol, PDMS and silicon oil
- $D = 256\,nm, 307\,nm$
- Brillouin spectroscopy
- No sintering



Supported opal and scattering geometry

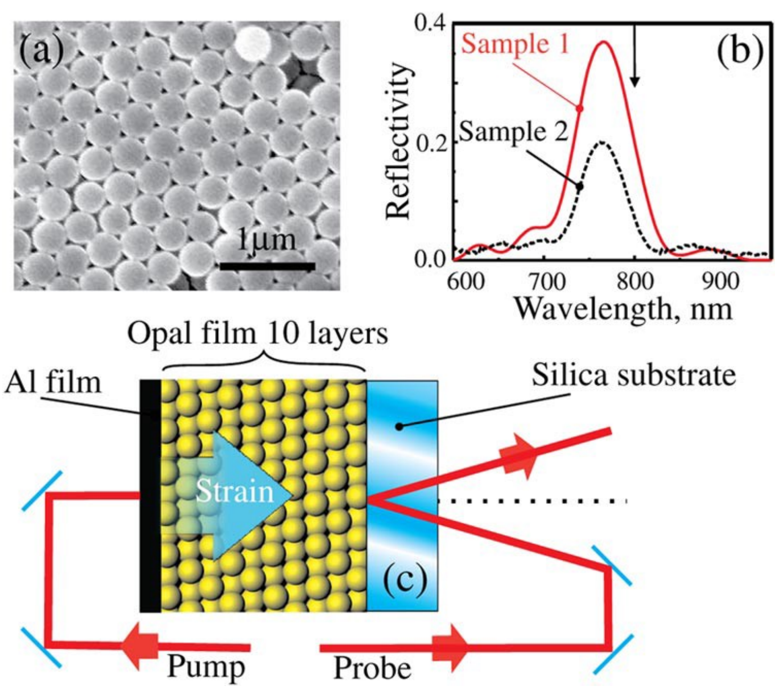


Brillouin light scattering spectra of dry and wet opals and phononic gap

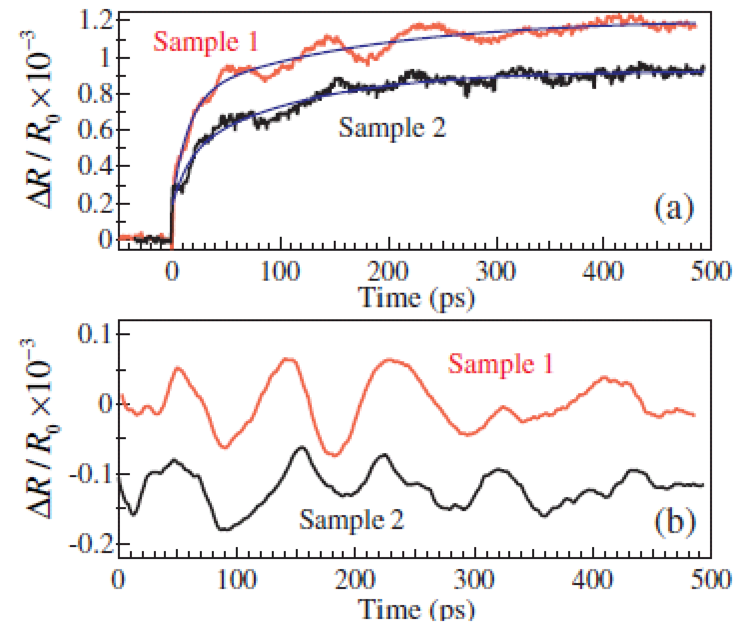
W. Cheng *et al.*, Nature Materials (2006)

Hypersonic modulation of light in three-dimensional photonic and phononic band-gap materials

- Silica spheres, 359 nm diameter, 10-12 layers
- IR energy converted into vibrations with an 100 nm thick Al foil (“hypersonic transducer”)
- Sintered crystal, coupling parameter $\chi = D/2a - 1 = 0.015 \pm 0.005$
- Reflectivity measurements



Set up for pump-probe experiment



Reflectivity measurements

Akimov *et al.*, Phys. Rev. Lett., (2008)

Pump-probe experiment on colloidal crystals at FLASH

Pump probe experiment on colloidal crystal film at FLASH

> **Study of colloidal crystal in the temporal domain**

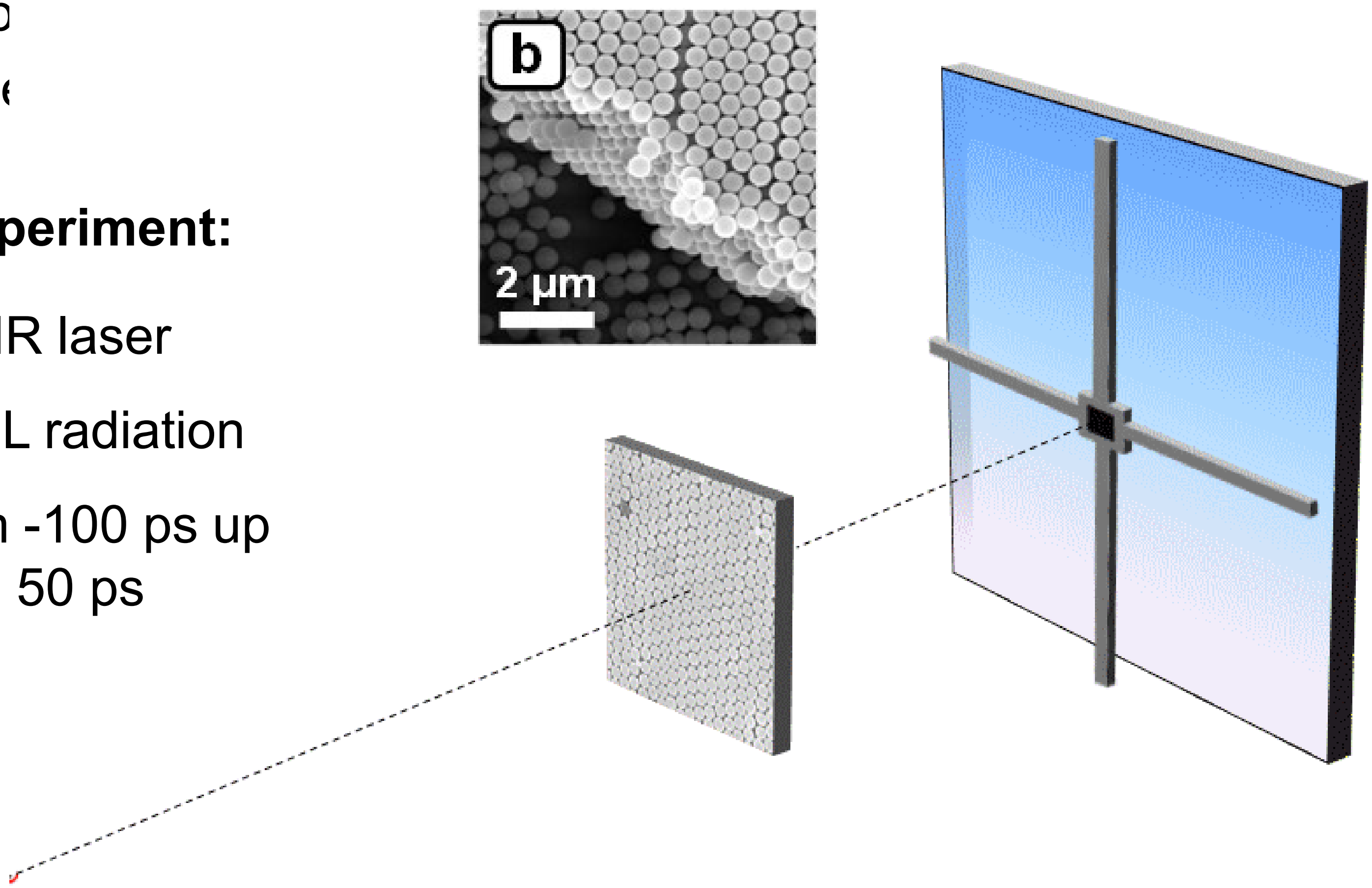
- ✓ Elastic vibration of the spheres (Lamb modes)
- ✓ Collective vib
- ✓ Order-disord

Pump-probe experiment:

> Pump: 800 nm IR laser

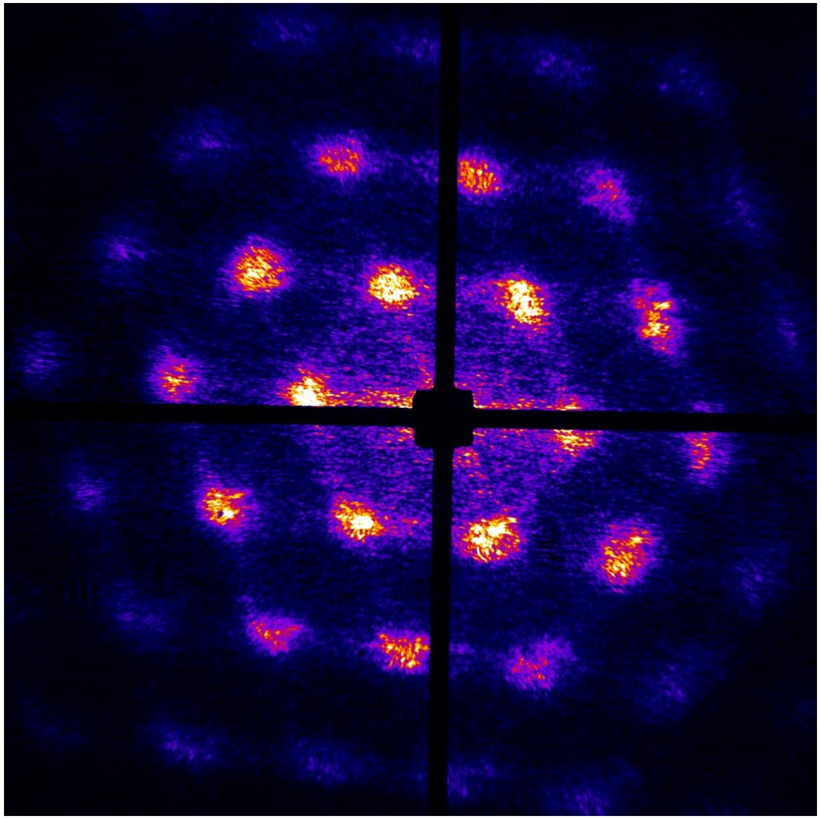
> Probe: 8 nm FEL radiation

> Time delay from -100 ps up to 1000 ps, with 50 ps steps

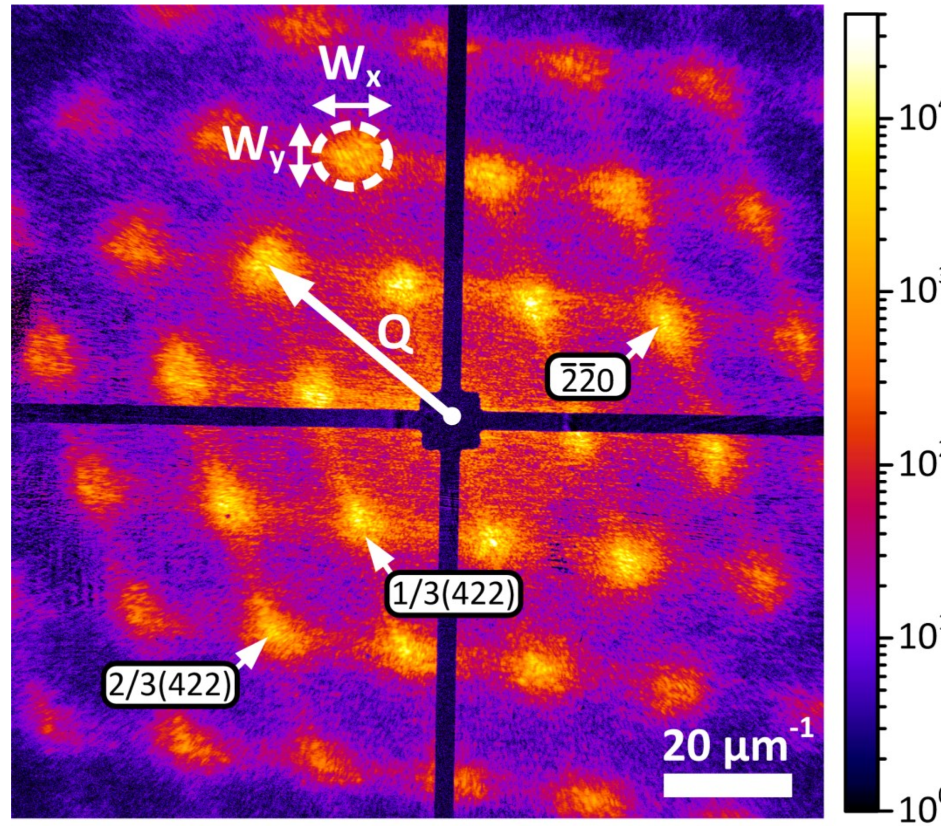


R.Dronyak et. al., Phys Rev B 86 (2012)

Pump-Probe Experiment on Colloidal Crystal Film at FLASH



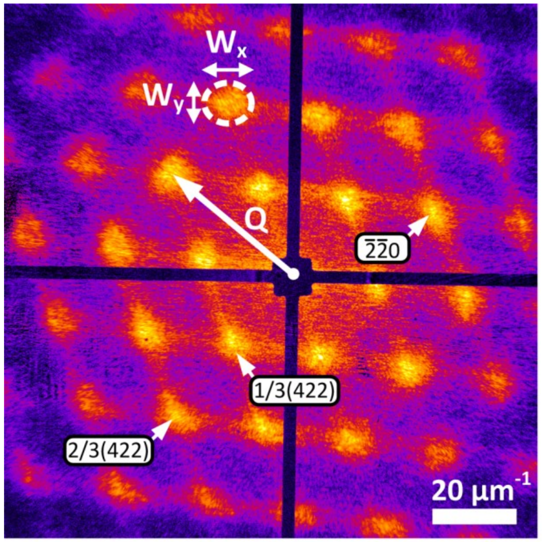
Single-shot diffraction patterns at different time delay

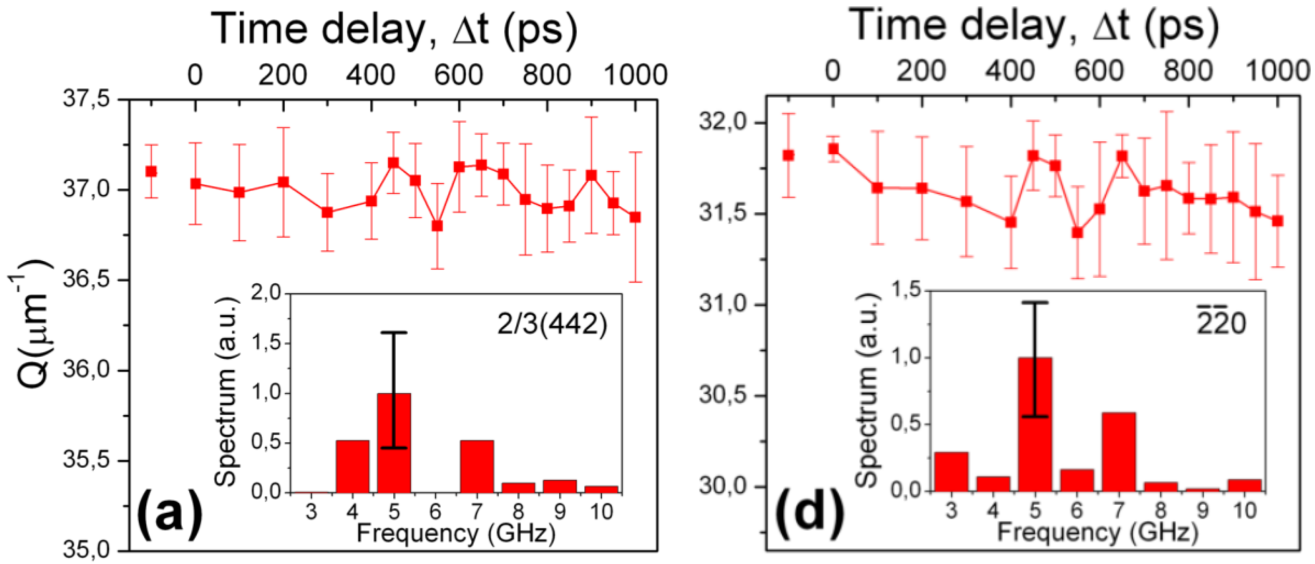


The momentum transfer vector **Q** and the horizontal W_x and vertical W_y size of the peaks were analyzed

R.Dronyak et. al., Phys Rev B 86 (2012)

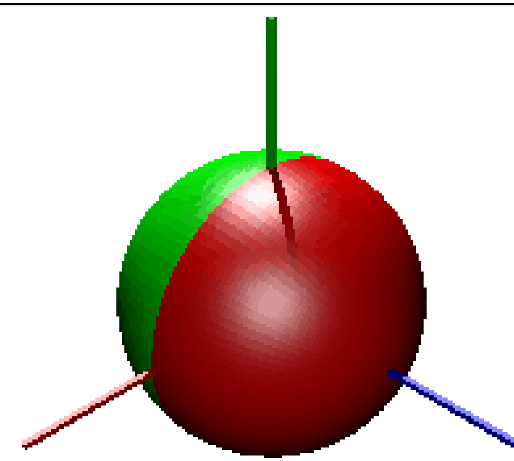
Pump-Probe Experiment on Colloidal Crystal Film at FLASH



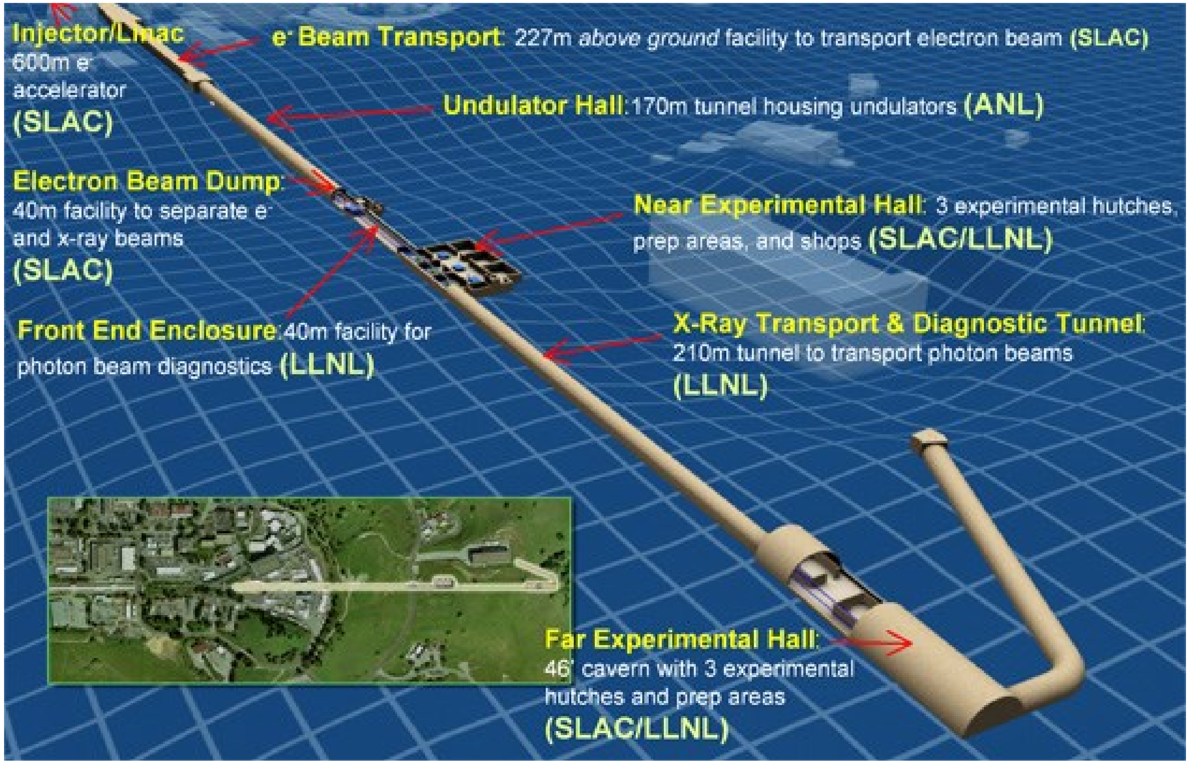


Time dependence and power spectrum of |**Q**| for the selected 2/3(422) and 220 Bragg peaks

Theoretical calculations of vibrations of a 400 nm isotropic elastic sphere based on the Lamb theory reveal a 5.07 GHz eigenfrequency of the ground (breathing) mode



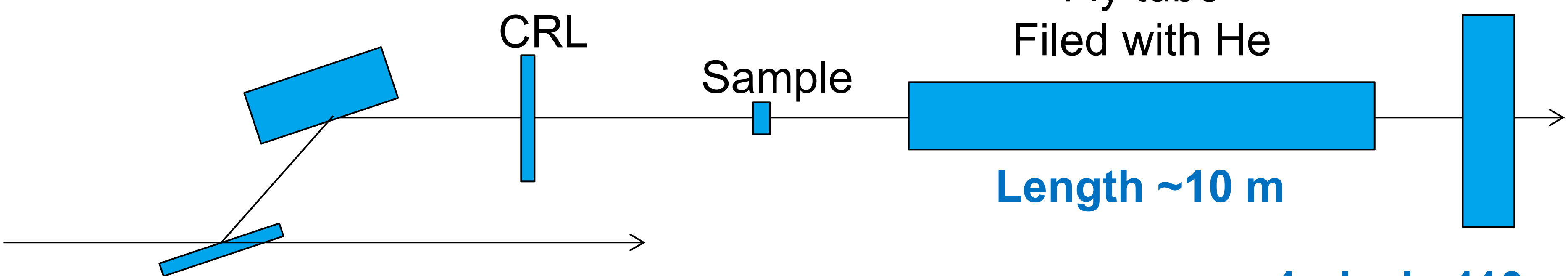
Pump-probe experiment on colloidal crystals at LCLS



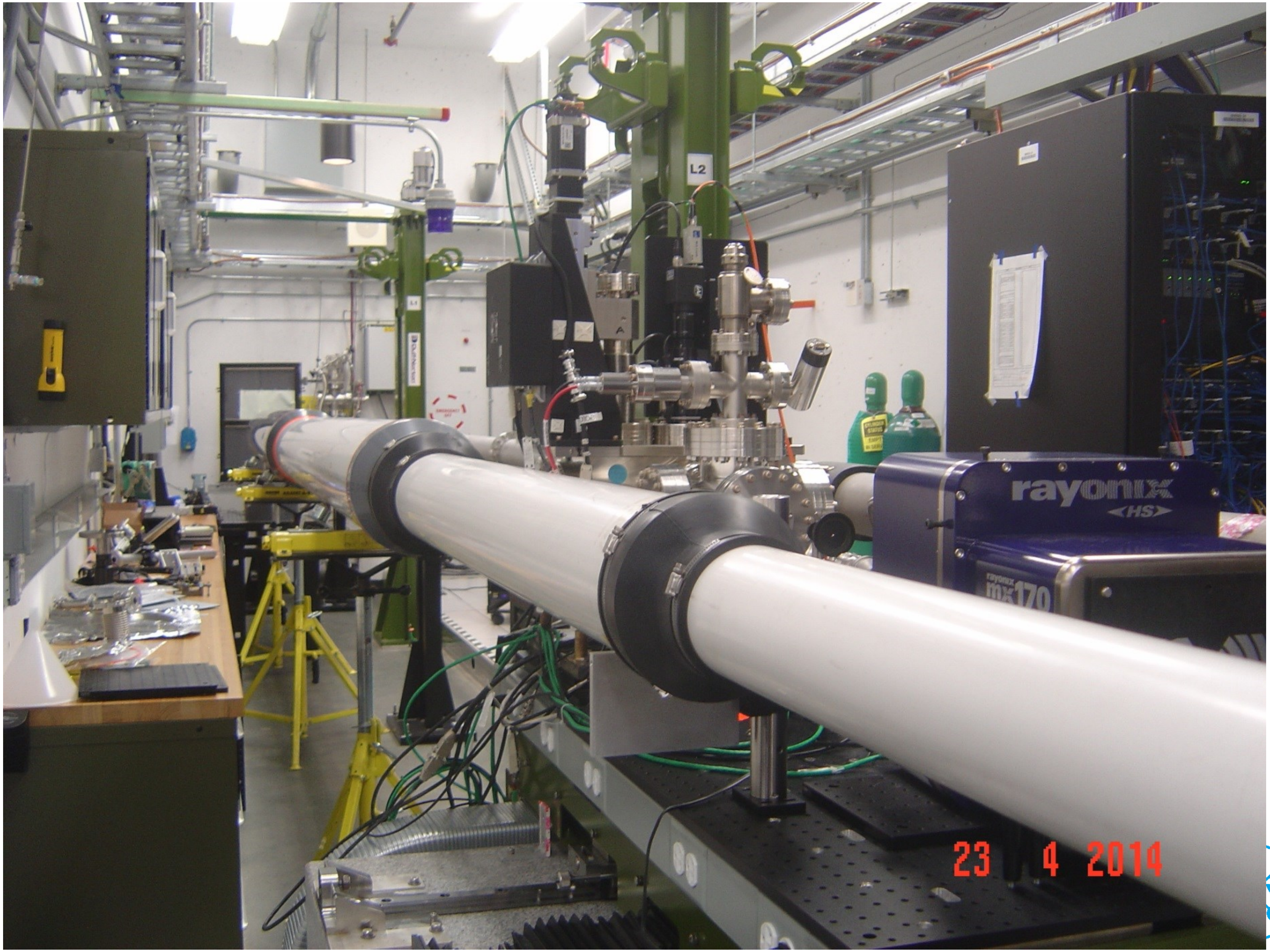
See also the Poster on the Users Meeting

Experimental setup

Experimental setup@XPP



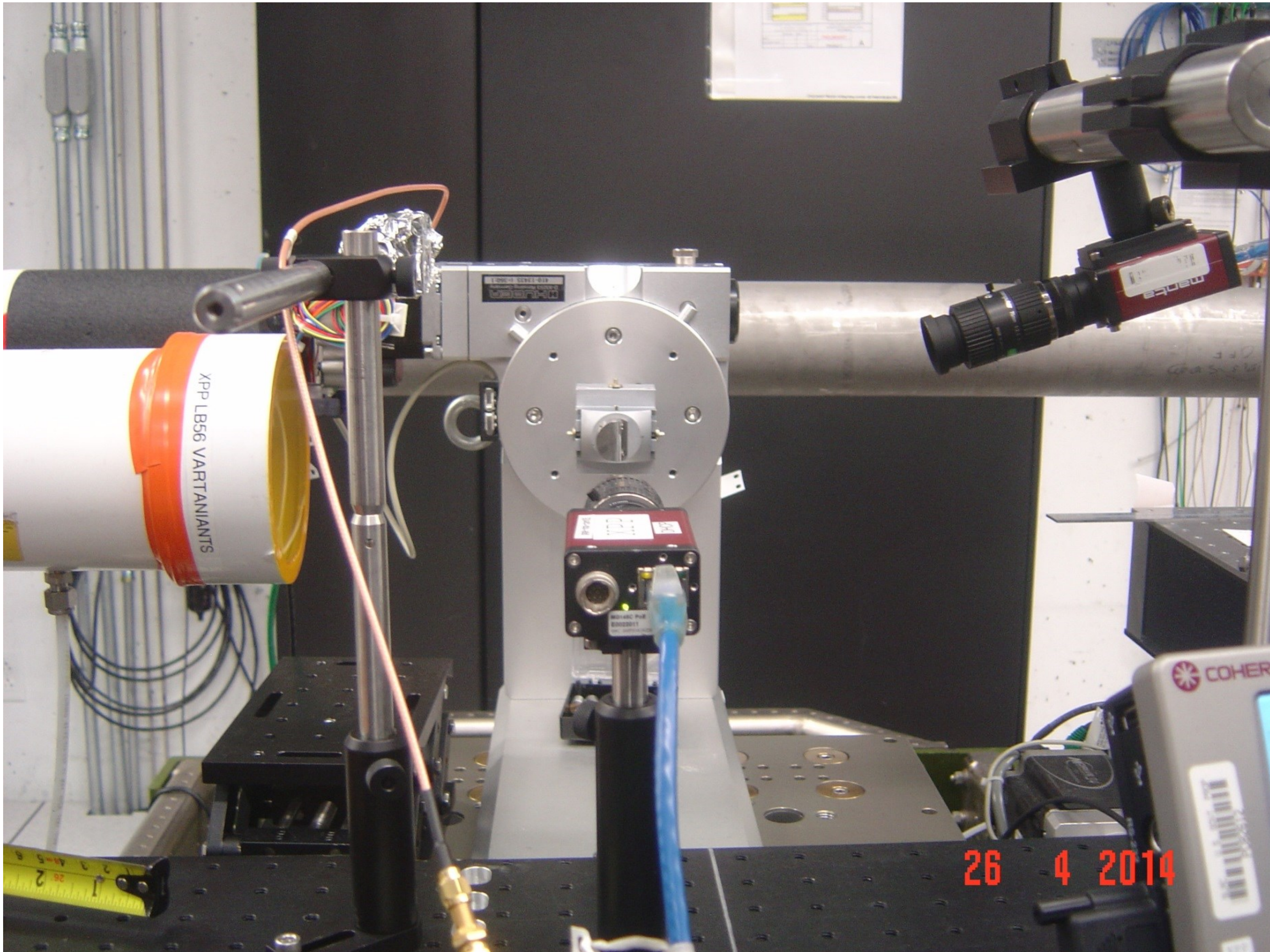
Experimental setup@XPP



Experimental setup@XPP

CSPAD detector

Experimental setup@XPP

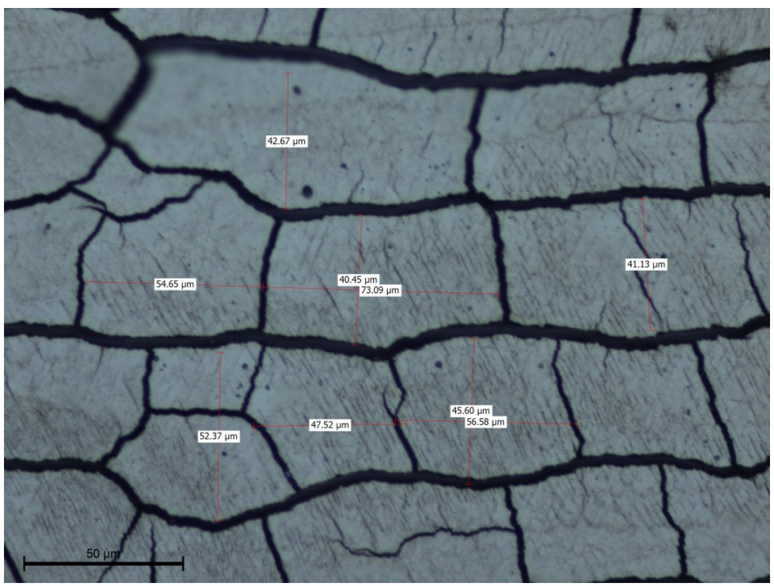


Pump-Probe experiment on colloidal crystals

Samples

PS2_Al_2 (0.1v% D)

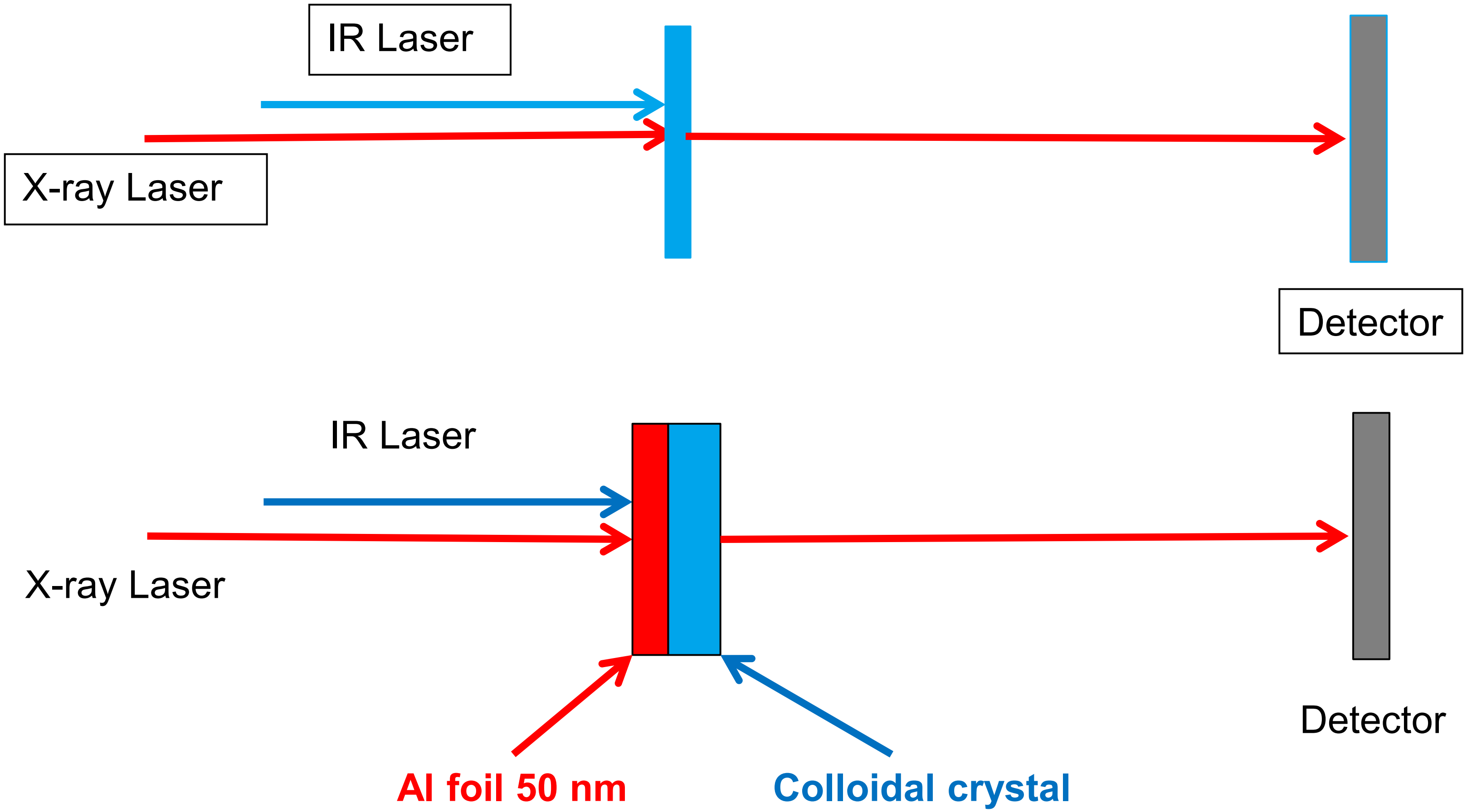
Top to middle of sample. At the top the sample is quite damaged, but the middle region with a lot of layers and larger area’s between the cracks has higher quality.



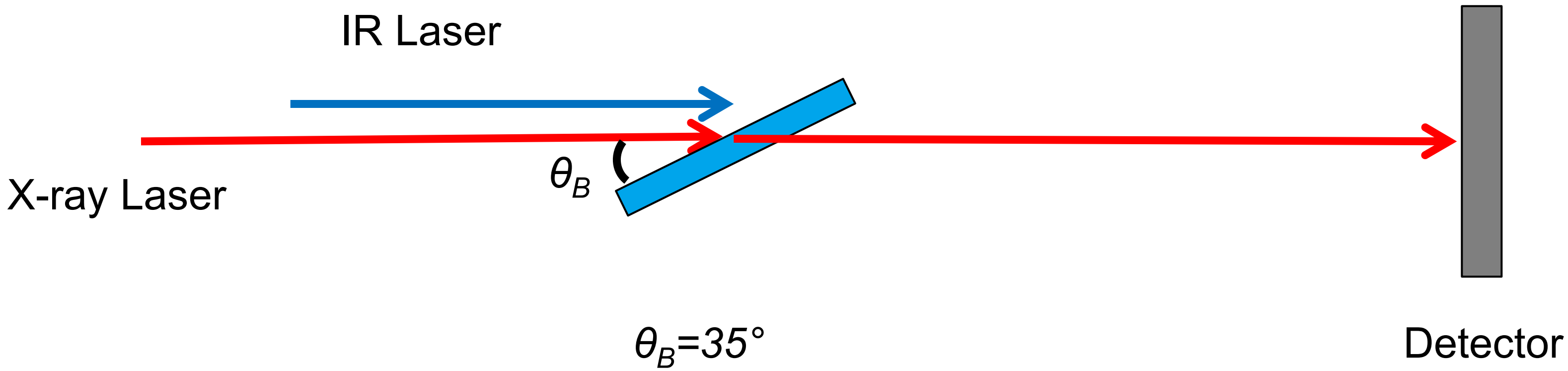
Distance between cracks around 50 µm

In the film parts lines typical for stacking defects can be seen. These indicate that even at this thick region the film is still ordered.

1-st experimental geometry



2-nd experimental geometry



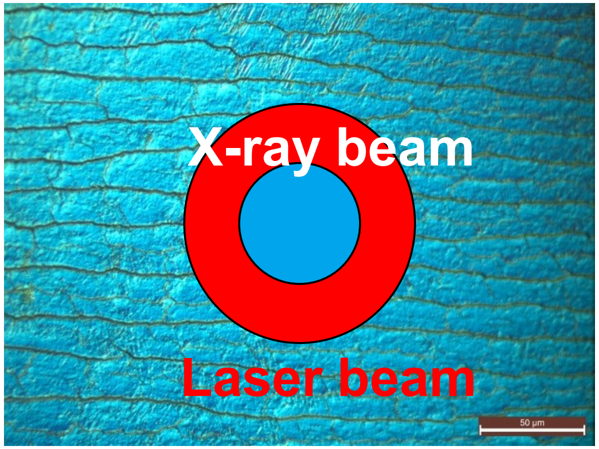
Parameters of X-ray and IR laser beams

1. X-ray beam

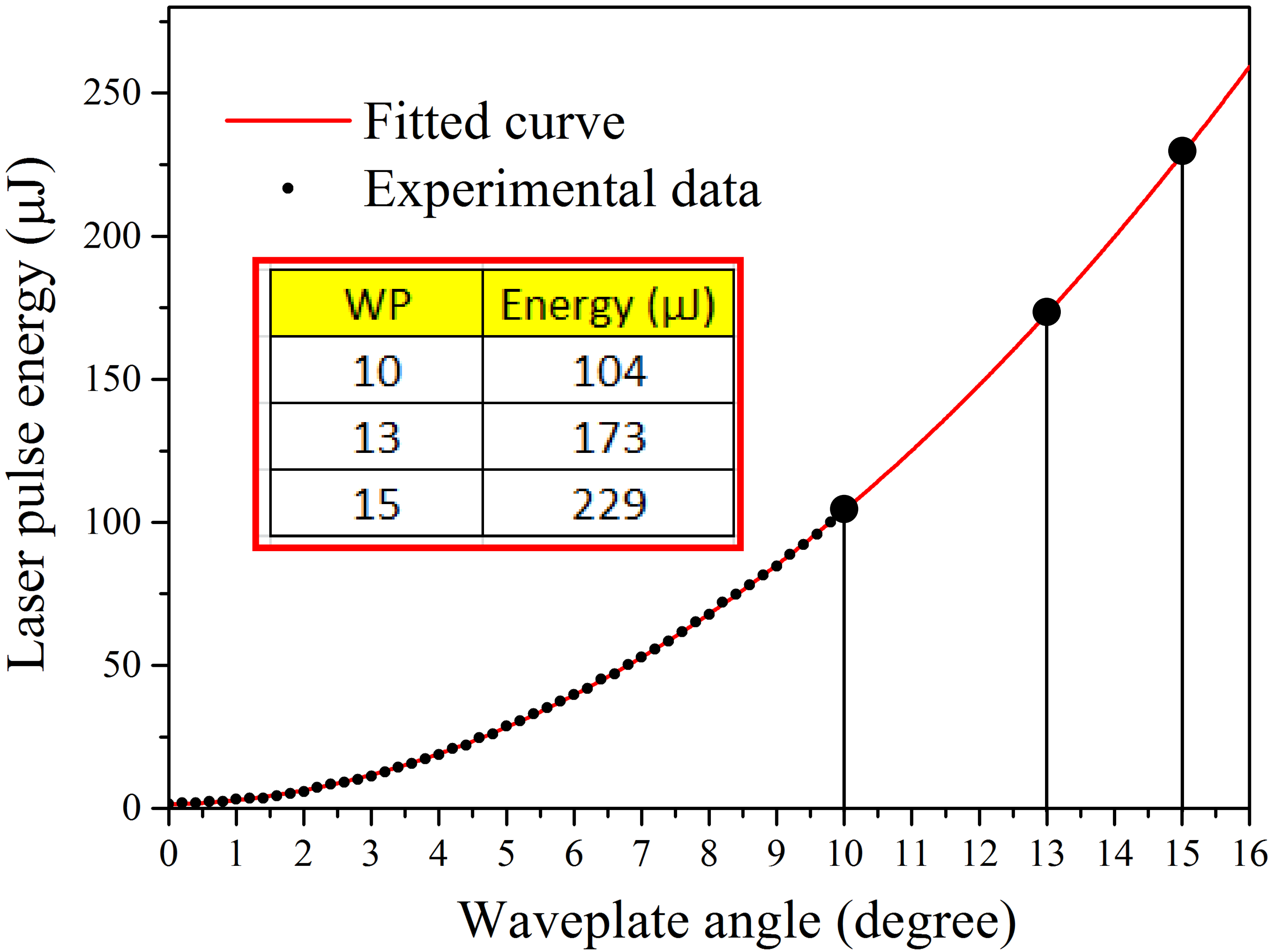
- E=8 keV
- Pulse duration: ≤ 50 fs
- $Flux_{sample}$ ~10^9 ph/pulse
- Focus ~ 50 µm
- Energy bandwidth ~10^{-4}

2. Laser beam

- λ_{las} = 800 nm
- Pulse duration: ≤ 50 fs
- E ~ 2 mJ
- Power: P ~ $4 \cdot 10^{10}$ W
- Focus ~ 100 µm

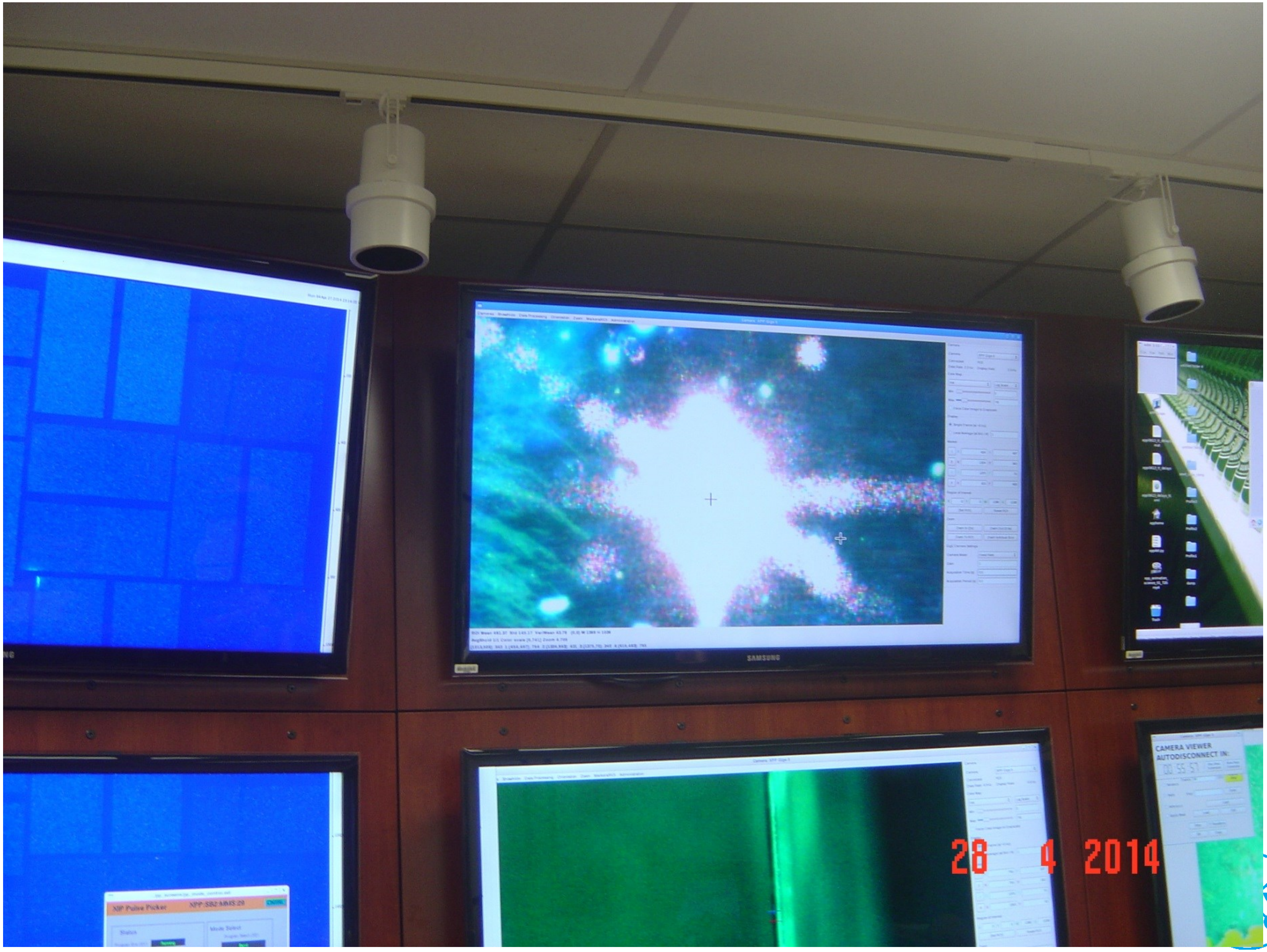


Energy of infrared laser

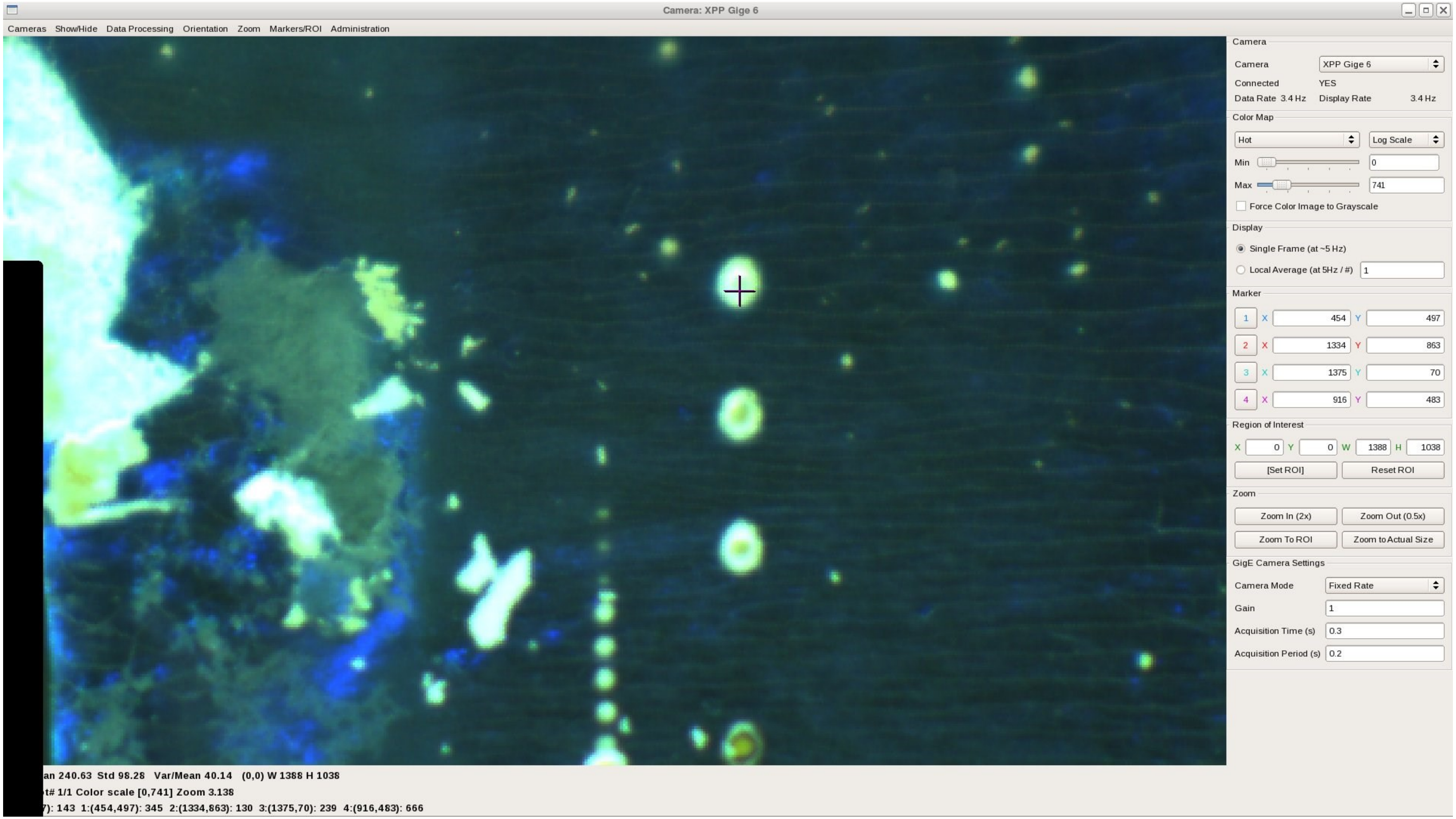


WP	Energy (μJ)
10	104
13	173
15	229

Pump-Probe experiment on colloidal crystals



Pump-Probe on Colloidal Crystals

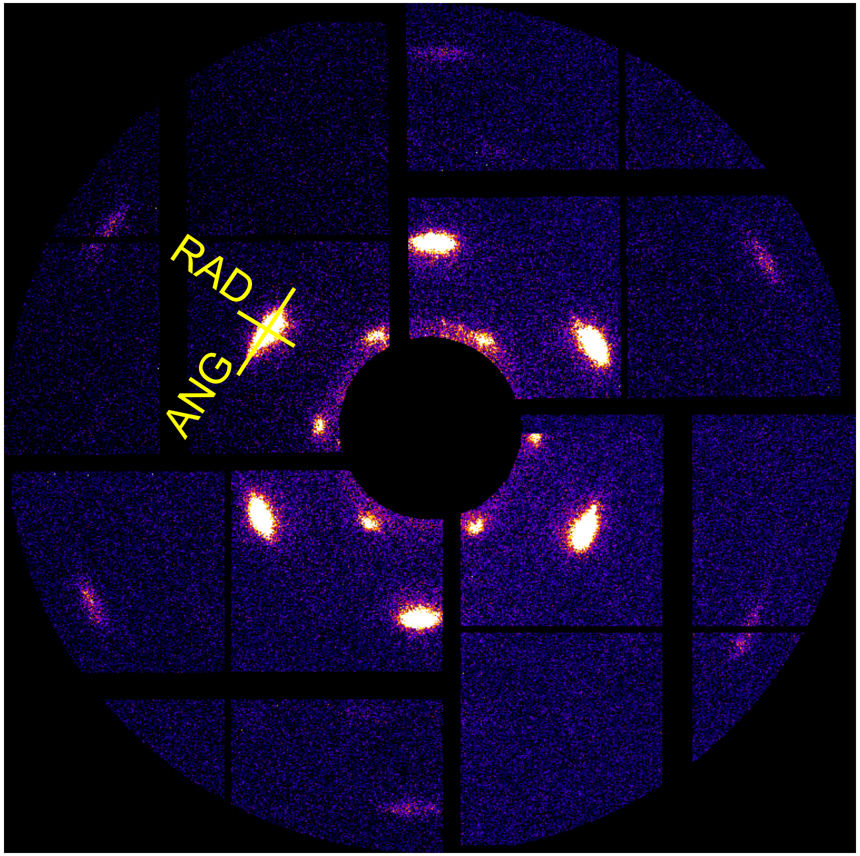


Damage produced by laser power 7° wave plate angle (~50 μJ)

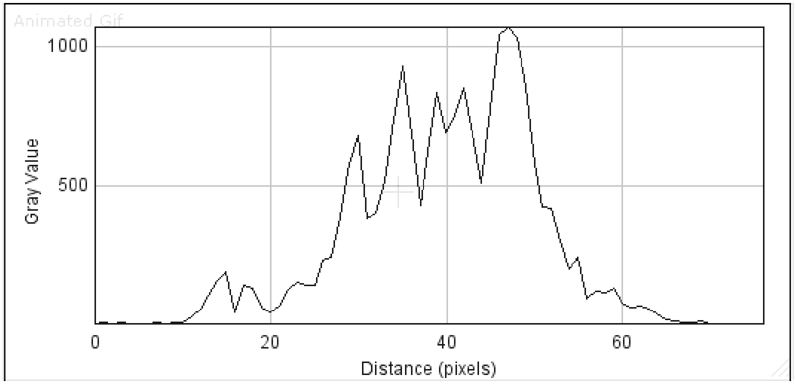
Study of ultrafast melting of colloidal crystals

Run 187 first 100 frames at one position X-rays only

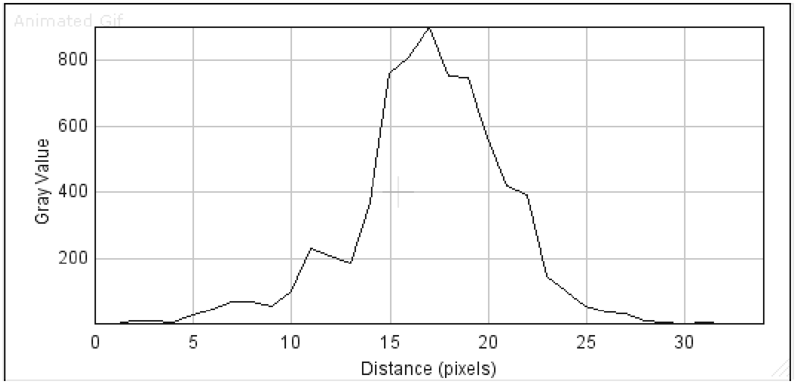
Detector frame in linear scale



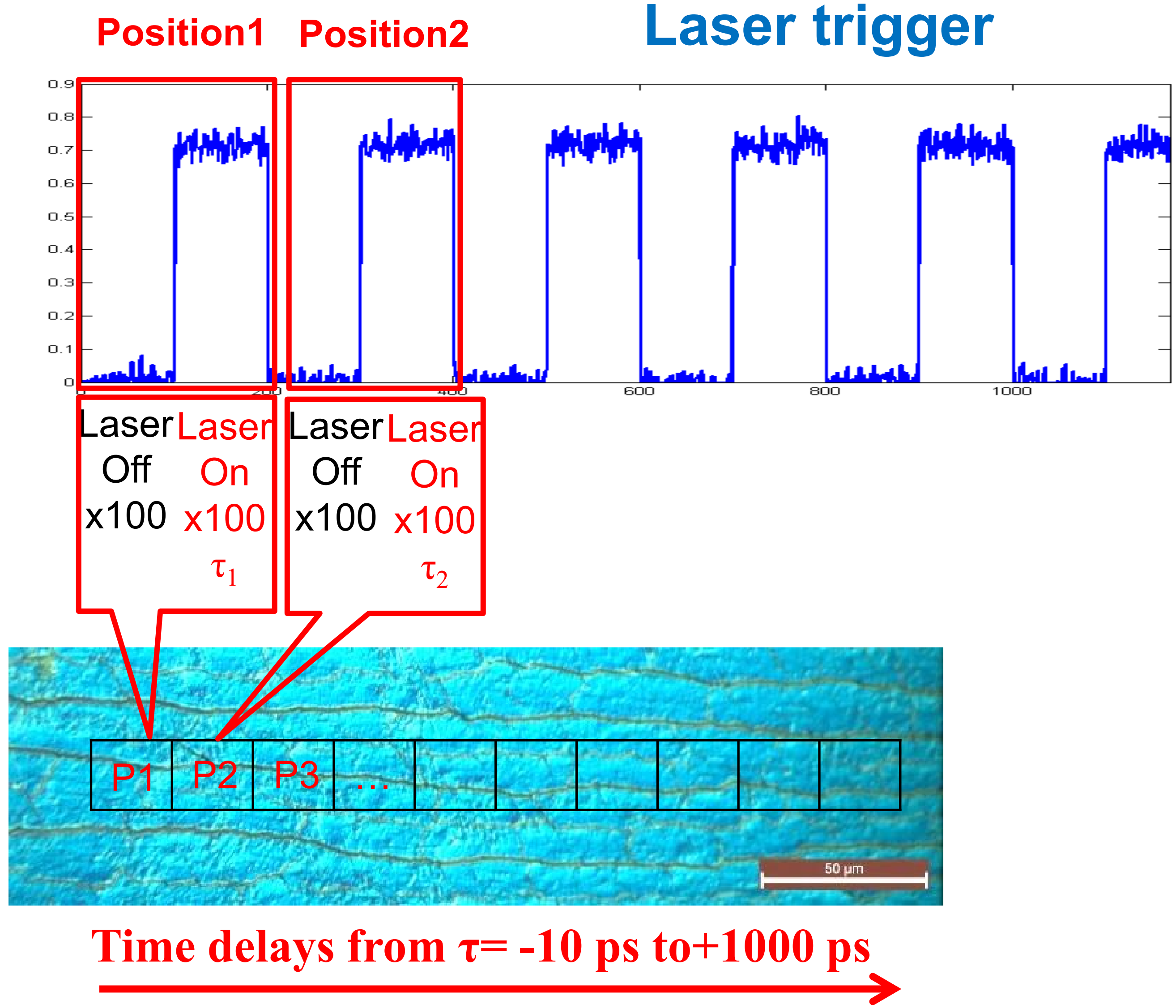
Intensity distribution along angular direction (ANG)



Intensity distribution along radial direction (RAD)

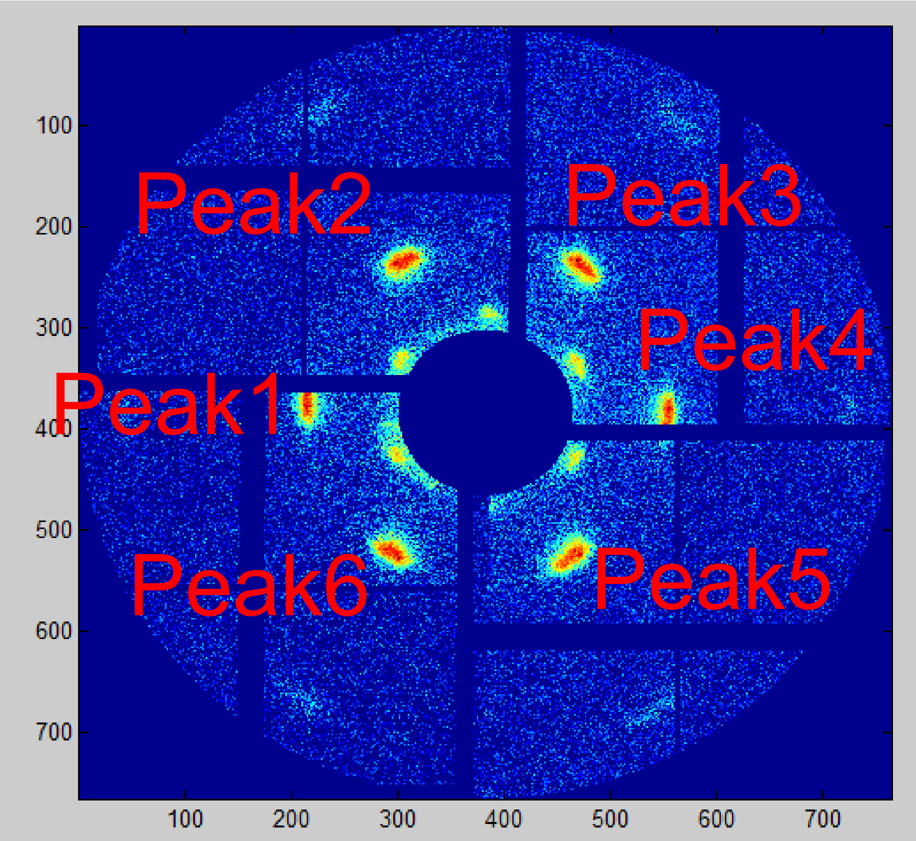


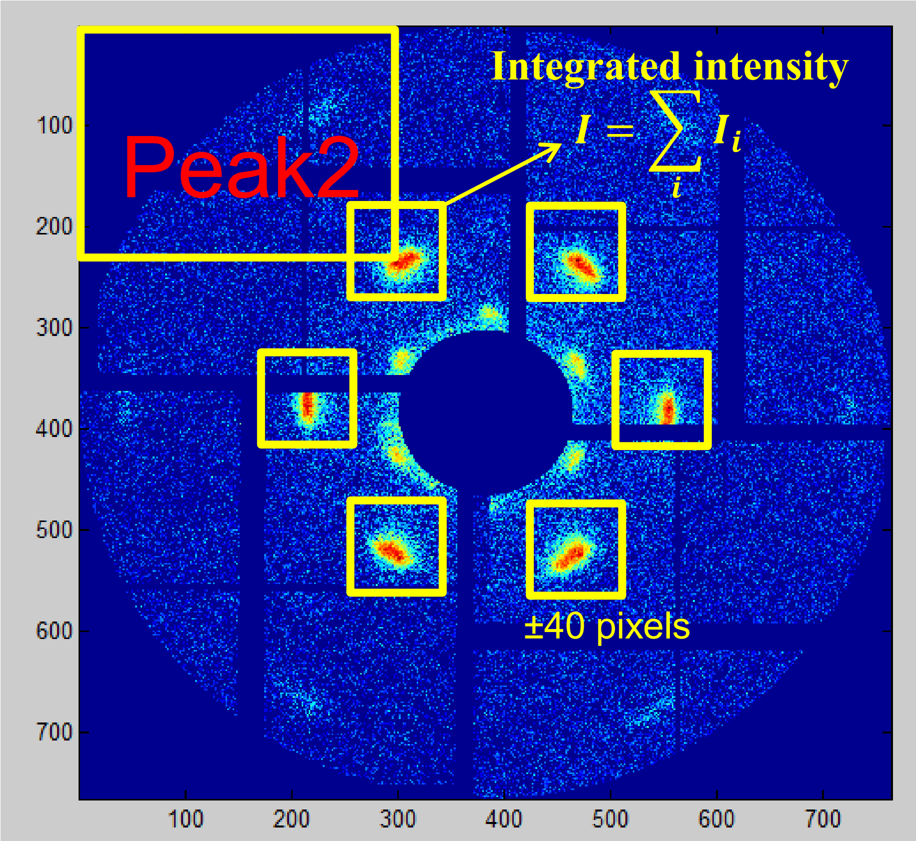
Pump-probe experiment



Decay of integrated intensity

Decay of integrated intensity of the peaks



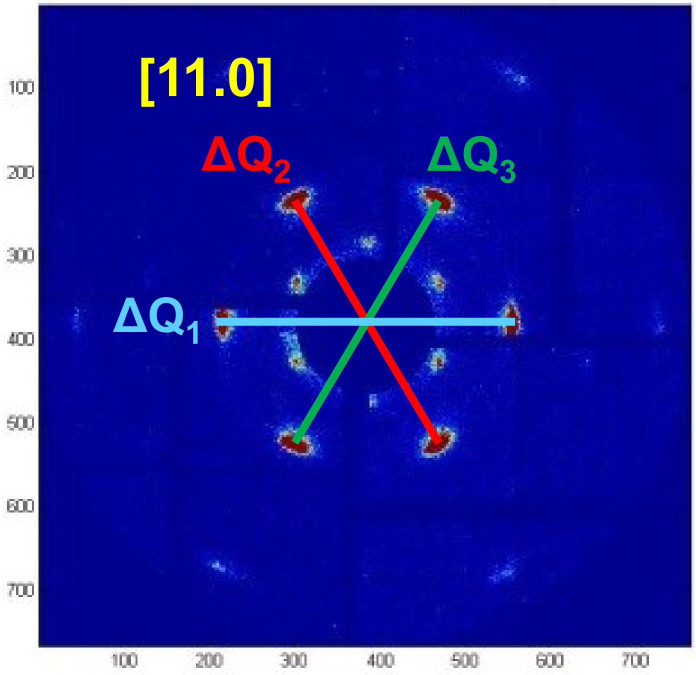


$$\boxed{\frac{\Delta I(\tau)}{\langle I \rangle} = \frac{I_1^{on}(\tau) - \langle I^{off} \rangle}{\langle I^{off} \rangle}}$$

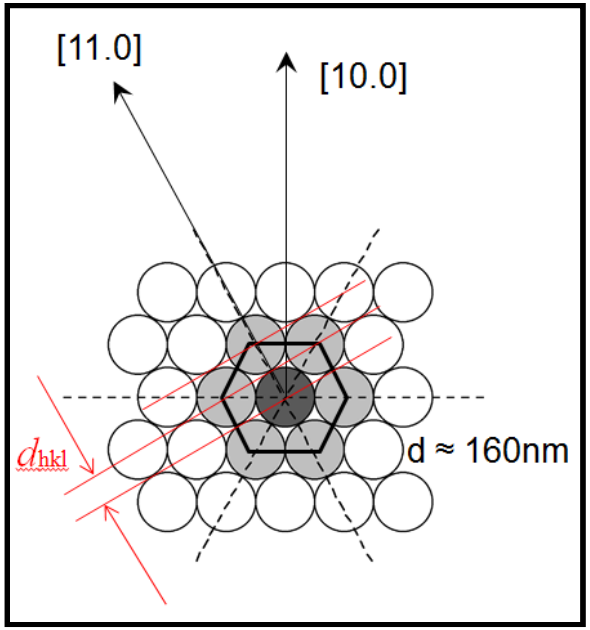
- τ is time delay between laser and X-ray pulses

Decay of the interplaner distance

Decay of the interplanar distance



Experimental diffraction pattern



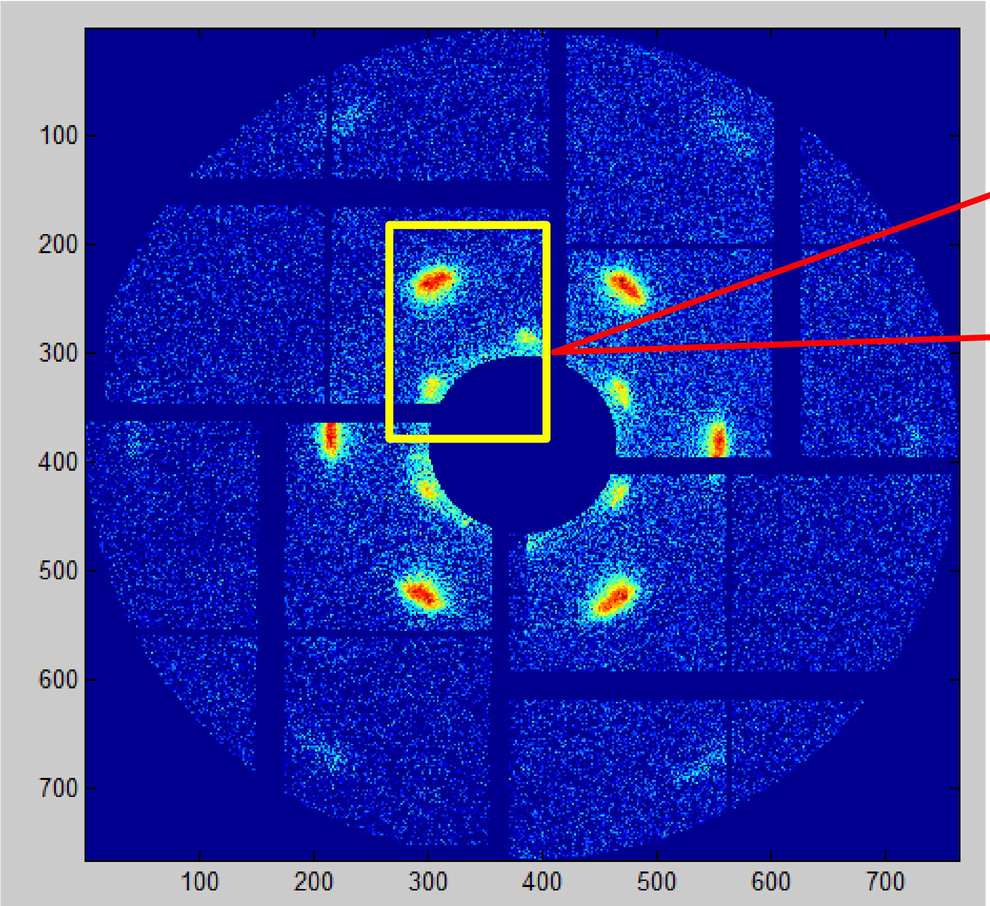
Crystallographic directions in colloidal crystal

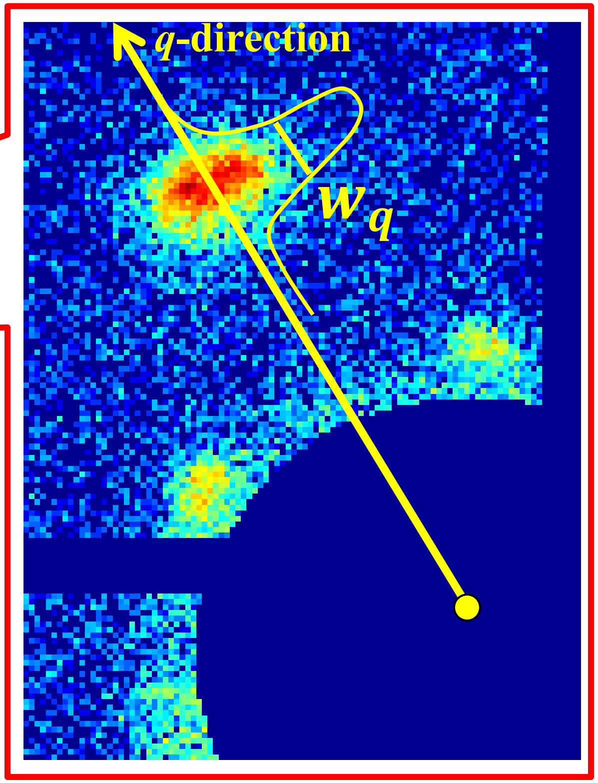
$$\boxed{\frac{\Delta Q(\tau)}{\langle Q\rangle} = \frac{Q_1^{on}(\tau) - \langle Q^{off}\rangle}{\langle Q^{off}\rangle}}$$

- **τ is time delay between laser and X-ray pulses**

Bragg peak’s broadening in q-direction

Bragg peak's broadening in *q*-direction





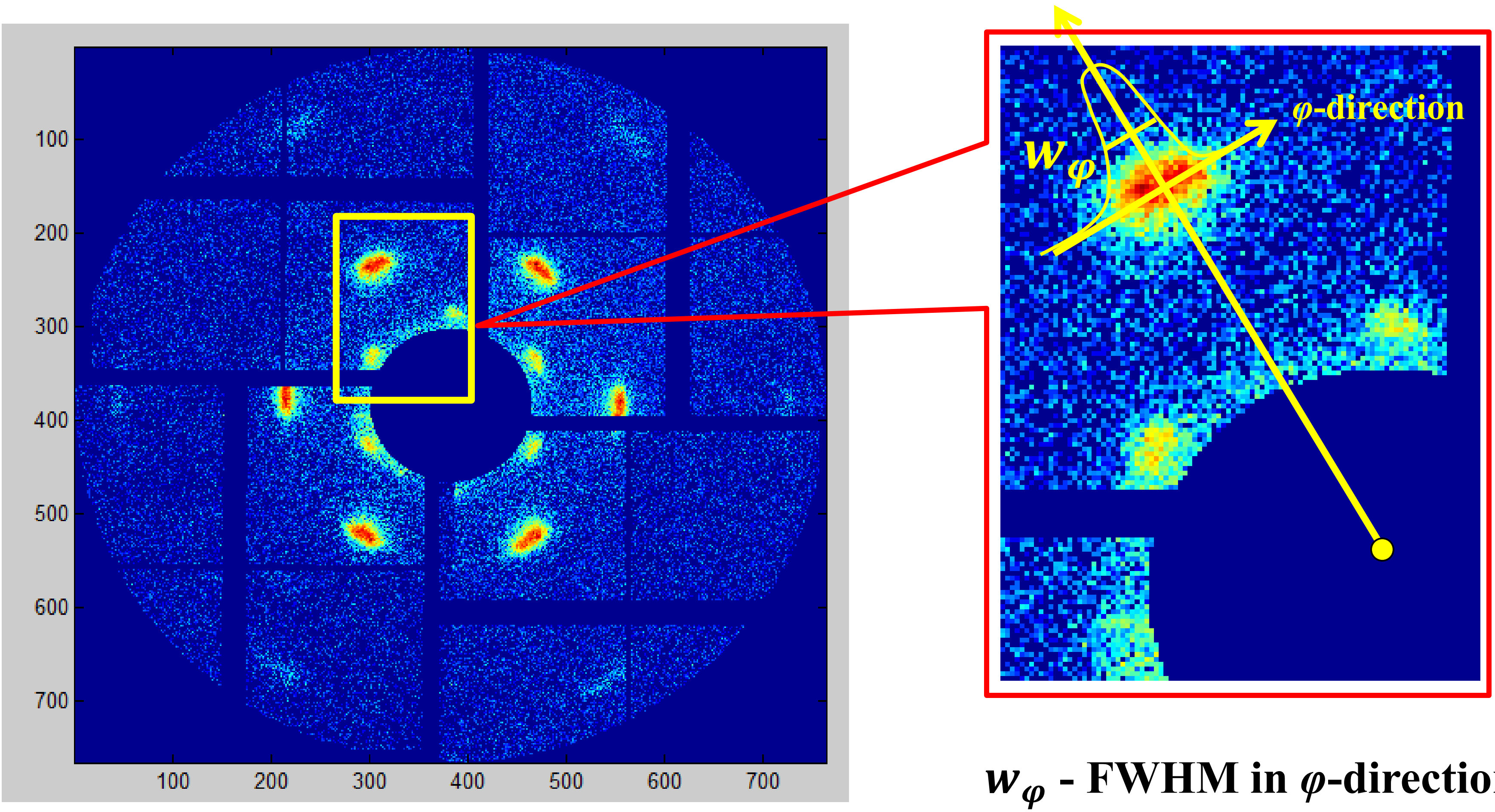
w_q - FWHM in *q*-direction

$$\frac{\Delta w_q(\tau)}{\langle w_q \rangle} = \frac{{w_q}_1^{on}(\tau) - \langle {w_q}^{off} \rangle}{\langle {w_q}^{off} \rangle}$$

- τ is time delay between laser and X-ray pulses

Bragg peak's broadening in φ-direction

Bragg peak's broadening in φ-direction



w_φ - FWHM in φ-direction

$$\frac{\Delta w_\varphi(\tau)}{\langle w_\varphi \rangle} = \frac{{w_\varphi}_1^{on}(\tau) - \langle {w_\varphi}^{off} \rangle}{\langle {w_\varphi}^{off} \rangle}$$

- τ is time delay between laser and X-ray pulses

Model of ultrafast melting of colloidal crystal

1. Energy transfer from IR laser to colloidal crystal

2. Response of colloidal crystal lattice

Energy transfer from IR laser to colloidal crystal

- IR wavelength: 800 nm
- Energy: 1.5 eV

- Energy of chemical bonds: (C-C, C-H) ~3-4 eV

- Absorption coefficient of 800 nm radiation in polystyrene: 10^{-4}

- Temperature raise: one-two degrees

Members of the team

On site

1. I. Vartaniants (DESY, Germany) (spokesmen)
2. M. Chollet (LCLS, USA) (LCLS beamline responsible)
3. J.M. Meijer (University of Utrecht, Nederlands)
4. R. Kurta (DESY, Germany)
5. D. Dzhigaev (DESY, Germany)
6. O. Gorobtsov (DESY, Germany)
7. A. Singer (UCSD, USA)
8. S. Boutet (LCLS, USA)
9. G. Williams (LCLS, USA)
10. D. Zhu (LCLS, USA)
11. O. Magnussen (University of Kiel, Germany) (observer)

Off site

1. A. Petukhov (University of Utrecht, Nederlands)
2. S. Lazarev (DESY, Germany)
3. A. Shabalin (DESY, Germany)
4. O. Yefanov (CFEL, Germany)
5. E. Sulyanova (IC RAS, Russia)

Experiment is over!!!

Thank you for your attention