Universität Hamburg
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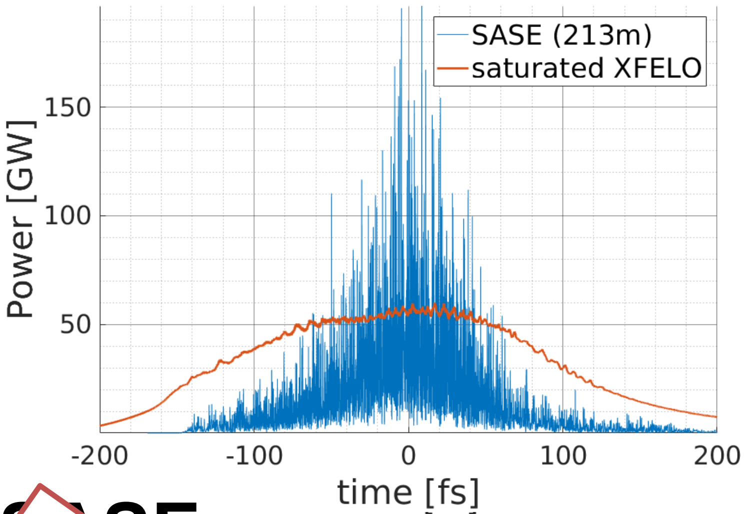
A Hard X-Ray Free-Electron Laser Oscillator at the European XFEL facility

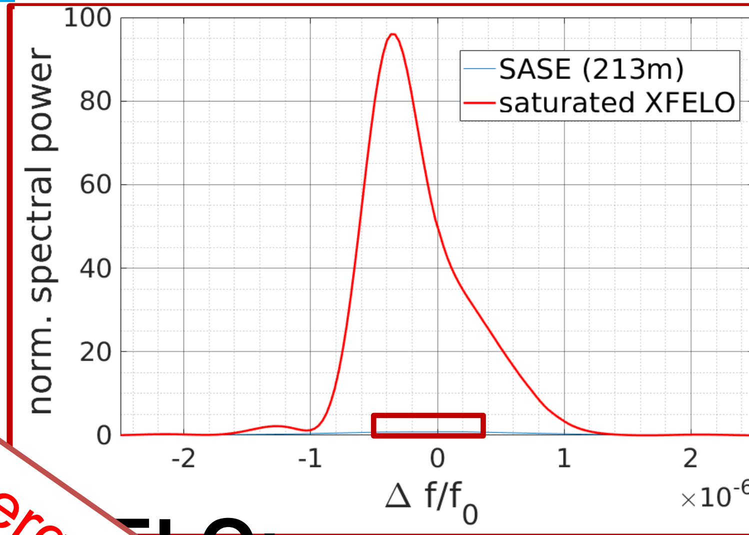
- I.Bahns, W. Decking, P. Rauer, J. Rossbach, H. Sinn -

MT ARD ST3 Annual Meeting 2019

supported by BMBF FKZ 05K16GU4

Why do we need it?





- **SE:**
  - – ... powers
  - – Bandw... $\frac{\Delta\lambda}{} \approx 10^{-3}$
  - – Coherence ... 0.2 fs [1]
  - – Pulse lengths d... ~ 1fs
  - ← Dependent on electr... bunch

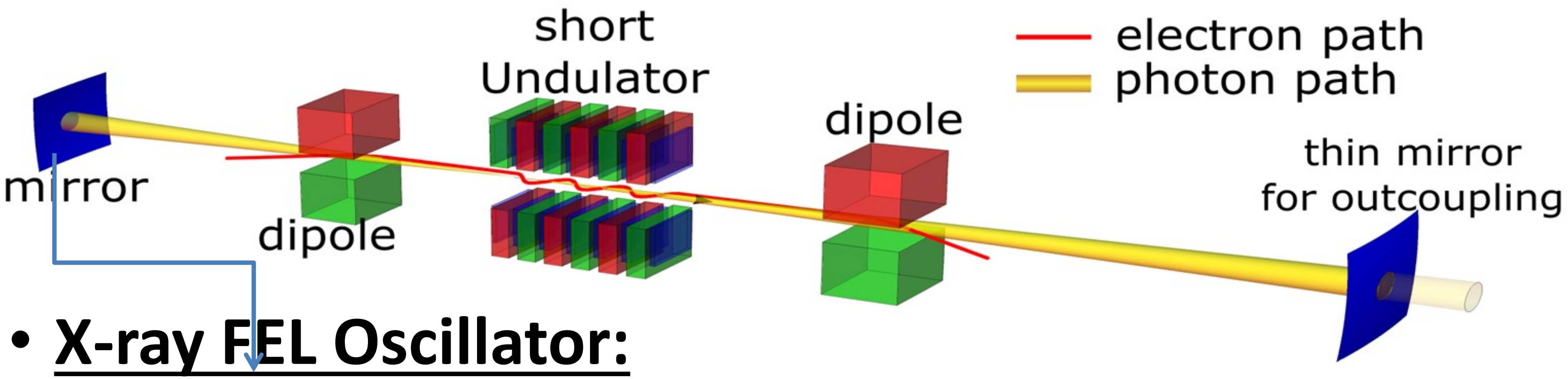
Time resolved measurements!

- **LO:**
  - – ...wers, but < SASE
  - – P...s of ~ 150fs
  - – Bandw... $0^{-6} - 10^{-5}$
  - – Full pulse co...

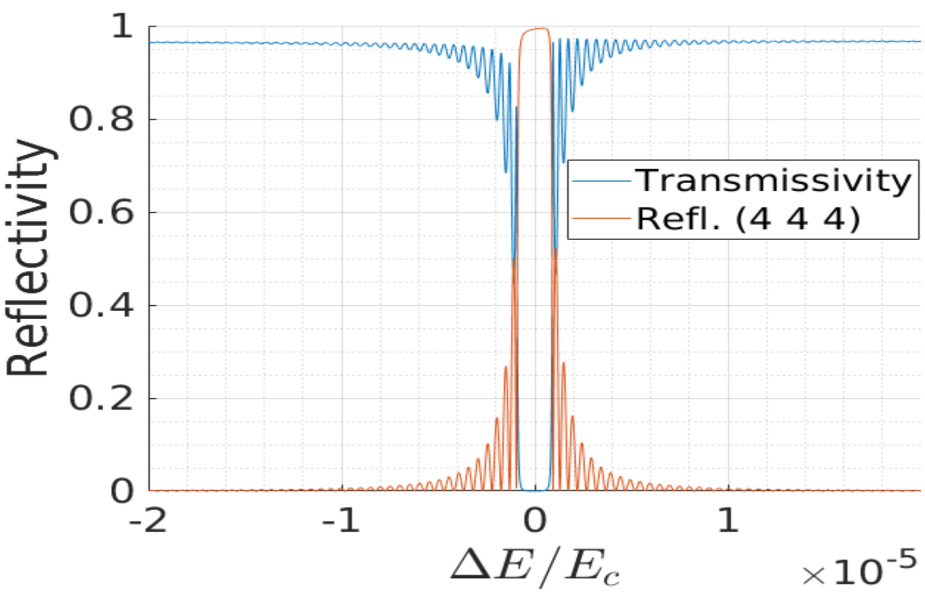
Energy resolved measurements/ measurements requiring coherence!

[1] G. Geloni et al., N. Jour. Phys., 12, 035021 (2010)

XFELO←What‘s that?



- **X-ray FEL Oscillator:**

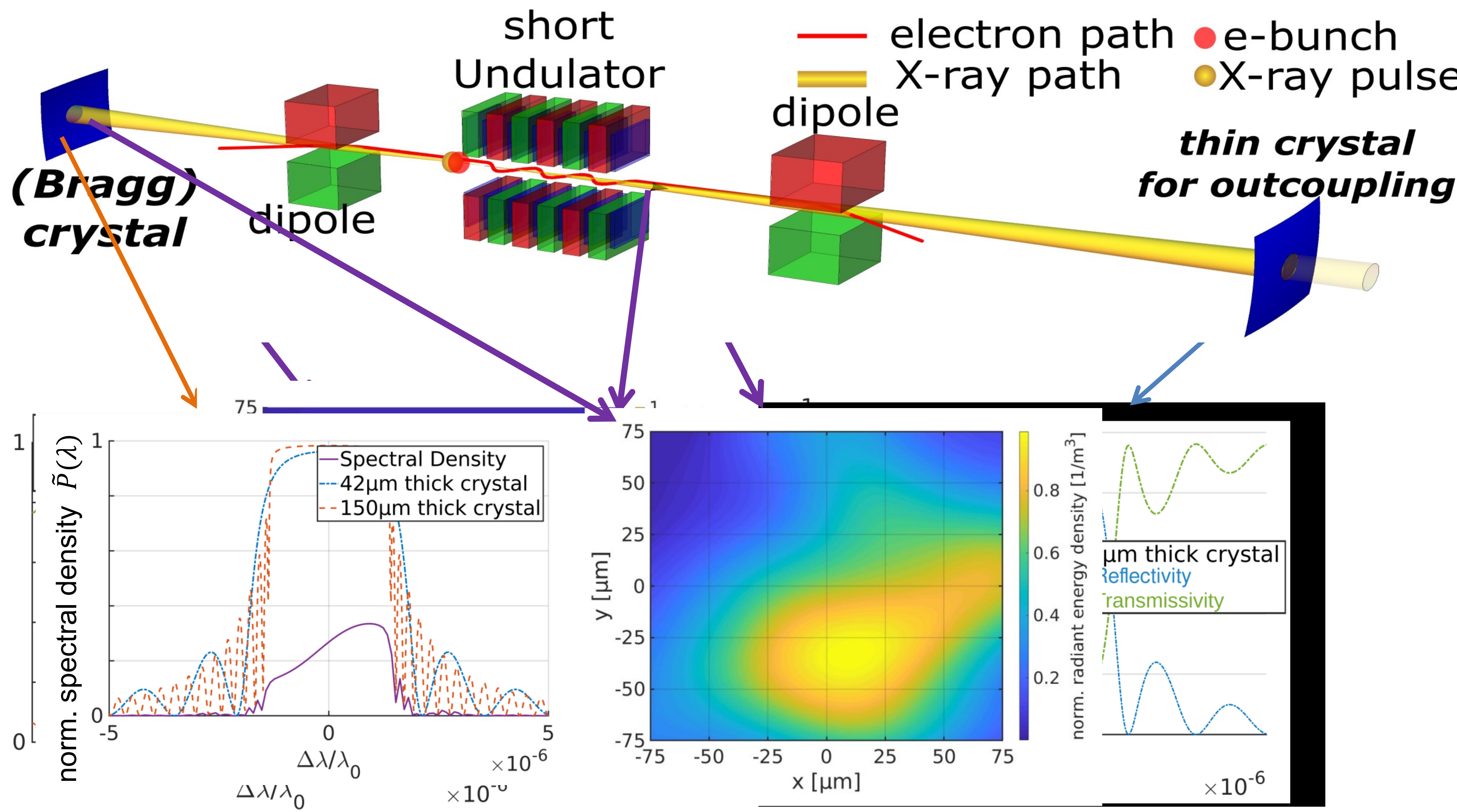


- Replace optical mirrors by Bragg reflection

Bragg‘s law:

$$\boxed{n\lambda = 2d \cdot \sin\theta}$$

The X-ray Free Electron Laser Oscillator (XFELO)



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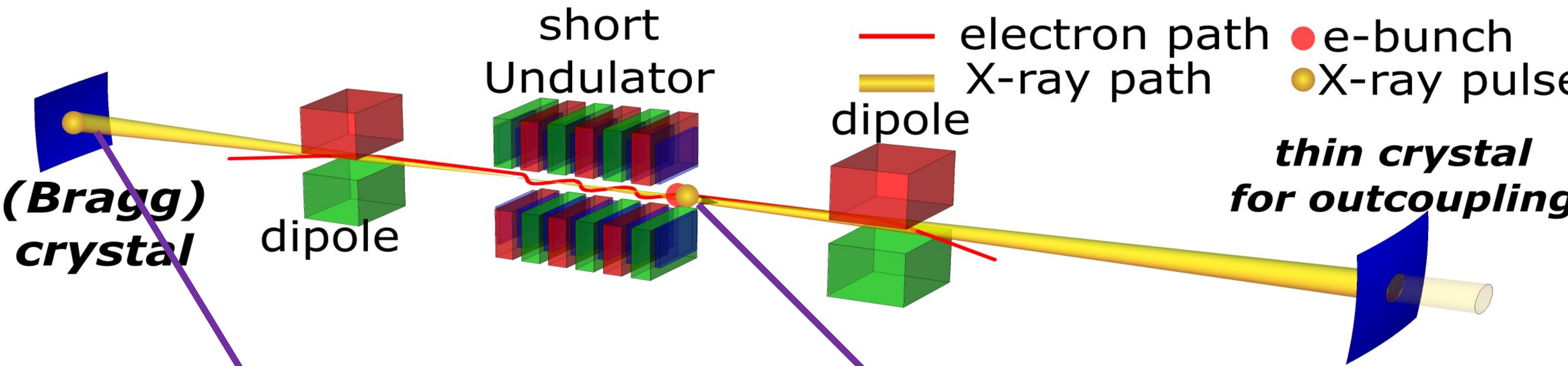
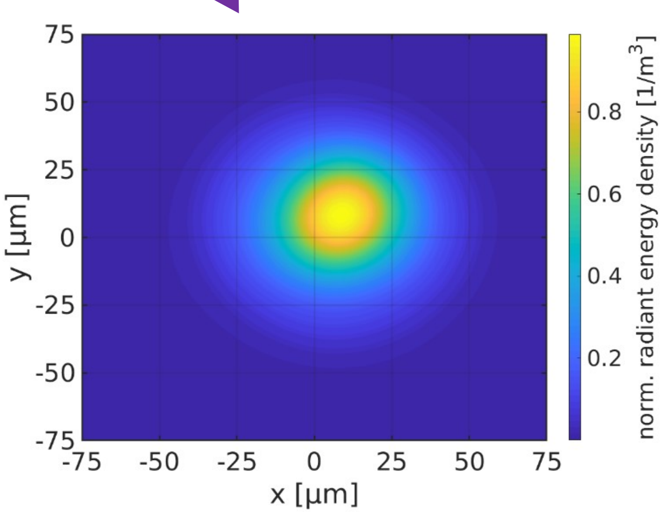
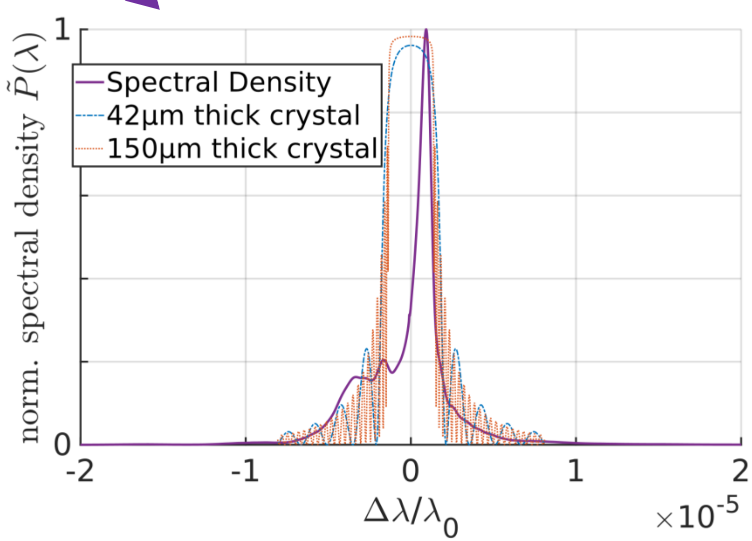
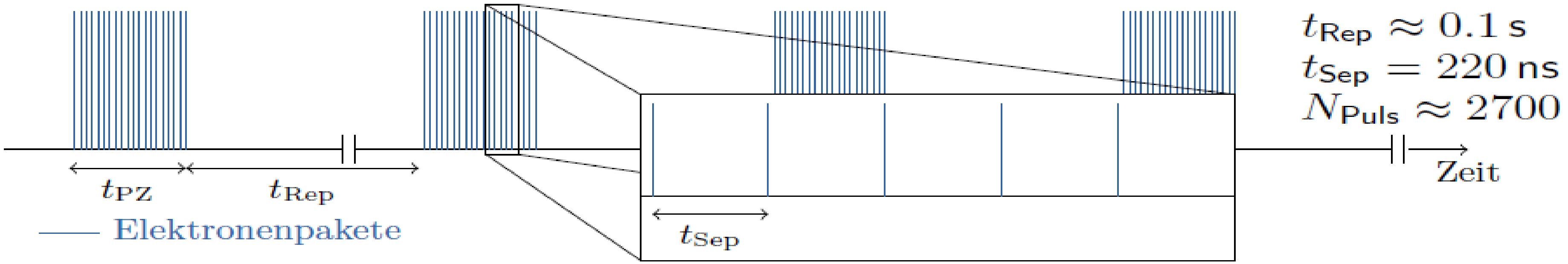






Why Now?



- XFELO necessities:
  - High enough single pass gain to compensate for losses

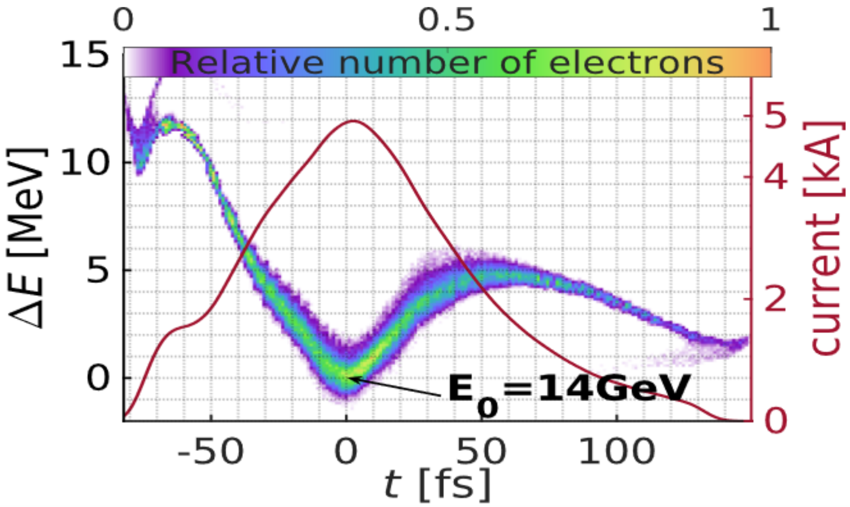
→Brilliant electron beam (Linac)

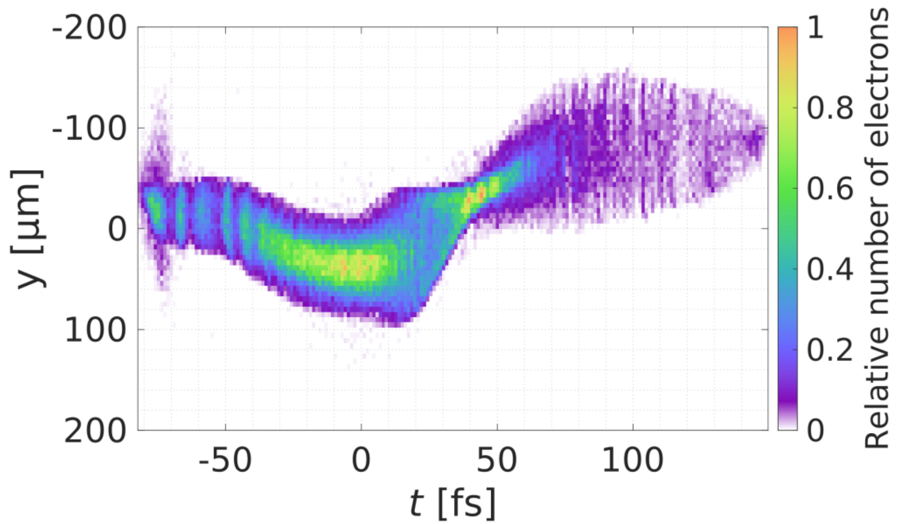
  - Matching between electron bunch repitition and photon pulse circumference rate
    - F.E. LCLS : el. rep-rate = 120 Hz↔2500 **km** optical path length

→ euXFEL: el. rep-rate ~ 4.5 MHz↔66 **m** optical path length!

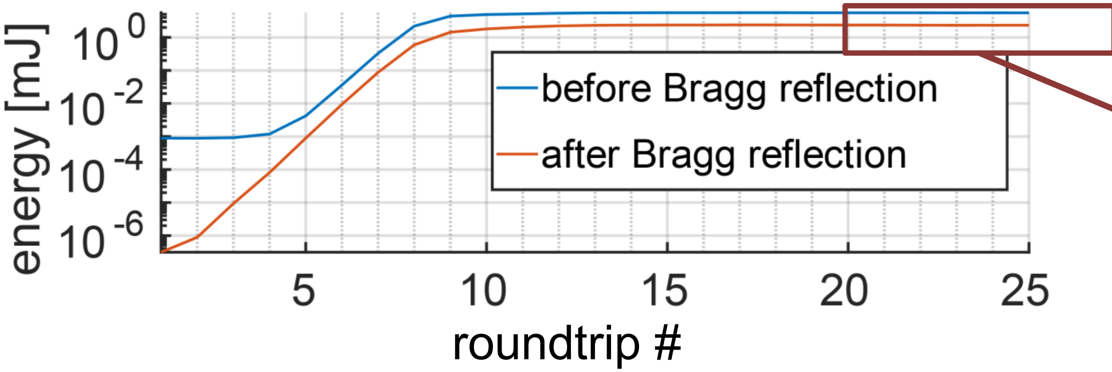
X-RAFEL (non-idealized)

- Issues regarding the realization of an XFELO:
  - High mechanical and optical demands
    - → Time- and positional overlap of el-bunch and X-ray pulse after one circumference
    - → From resonator theory → $\Delta z_{\mathrm{mirror}} \lesssim 10\mu\mathrm{m}; \Delta\theta_{\mathrm{mirror}} \lesssim 12\mathrm{nrad}$
    - → Intermediate Gain Oscillator → $\Delta\theta_{\mathrm{mirror}} \lesssim 100\text{–}200\mathrm{nrad}$ ✓
  - Realistic electron bunch (energy chirp, emissitivies,…)



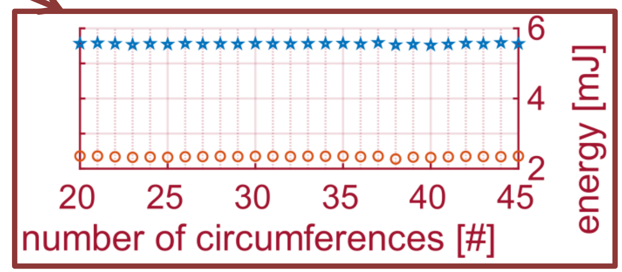


Simulation including mirror tilt and el. jitter

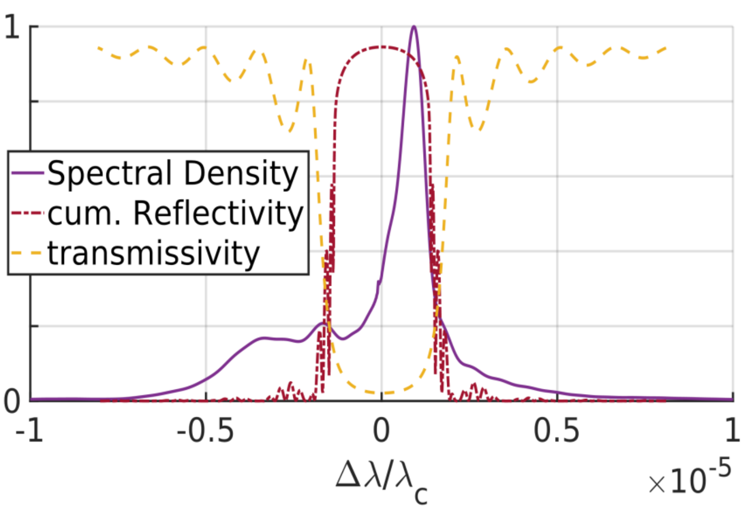


- In Saturation:

$E_{av} \approx 5.56 \pm 0.02$ mJ

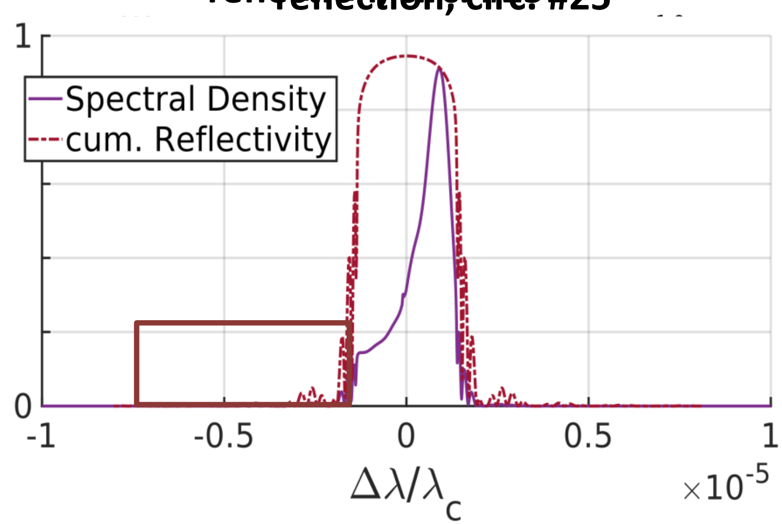


Spectrum before reflection, circ. #25



transv. projection bef. reflection, circ. #25

Spectrum after reflection, circ. #25



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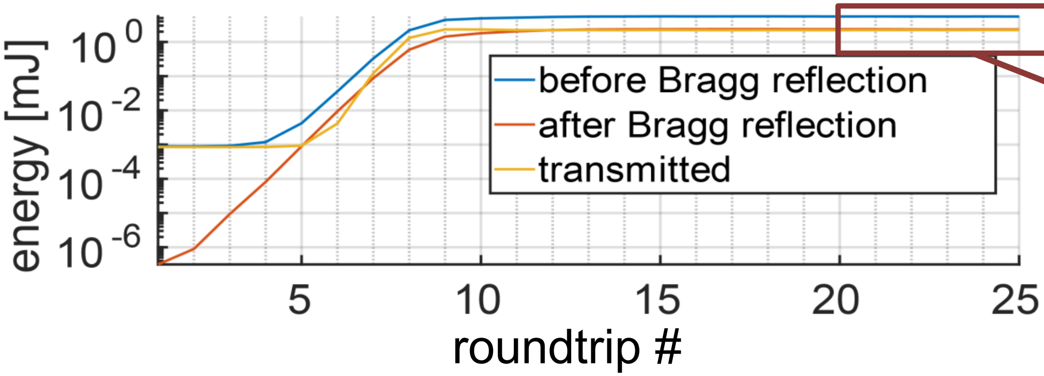

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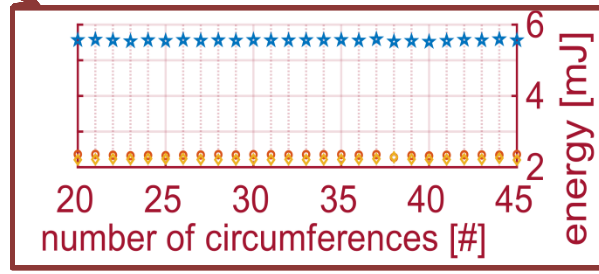

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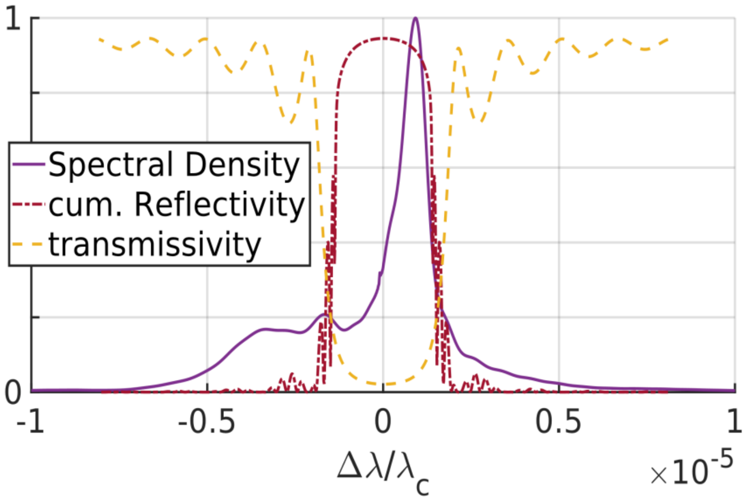
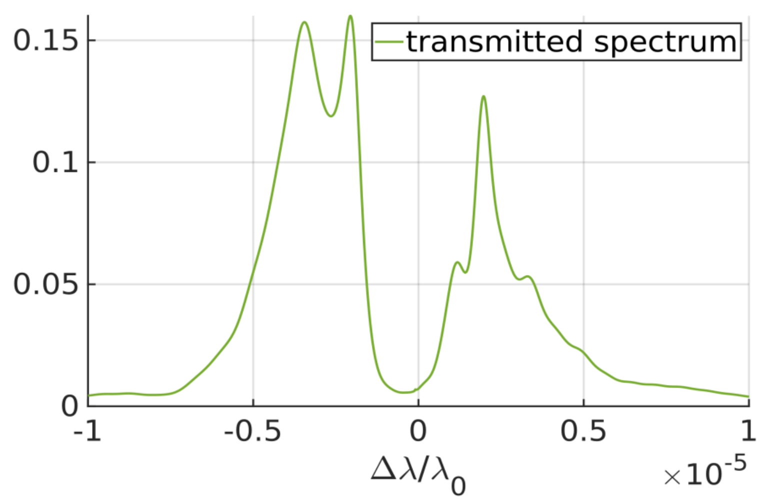


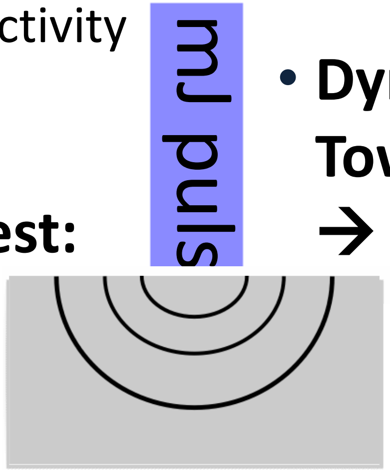


XFELO → Heatload Issues

- Saturated XFELO → 6mJ at >1MHz rep.rate on crystal

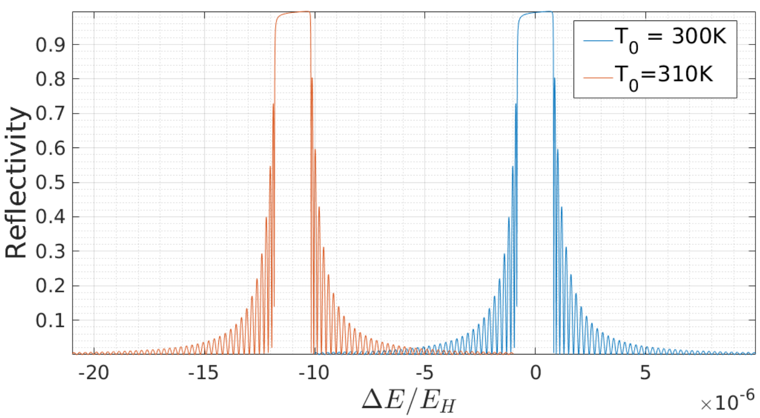
  → Disturbing optical stability ← (long term) vibrations

  → Disturbing crystal spectral reflectivity



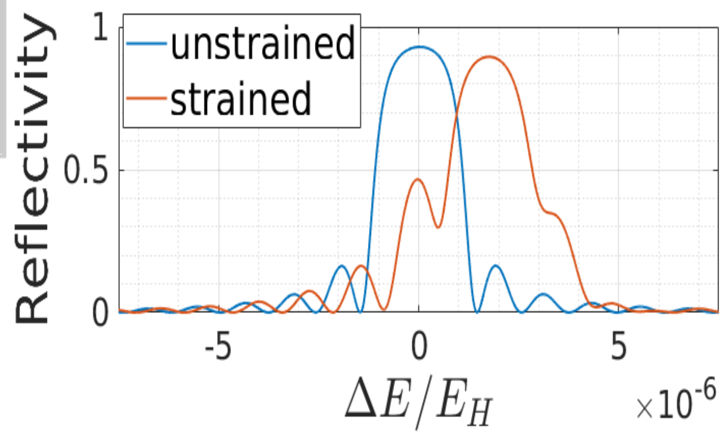
- **Thermal expansion of the lattice in the region of interest:**

$$n\lambda_H = 2d_H(T) \cdot \sin\theta$$



- Implemented in Simulations

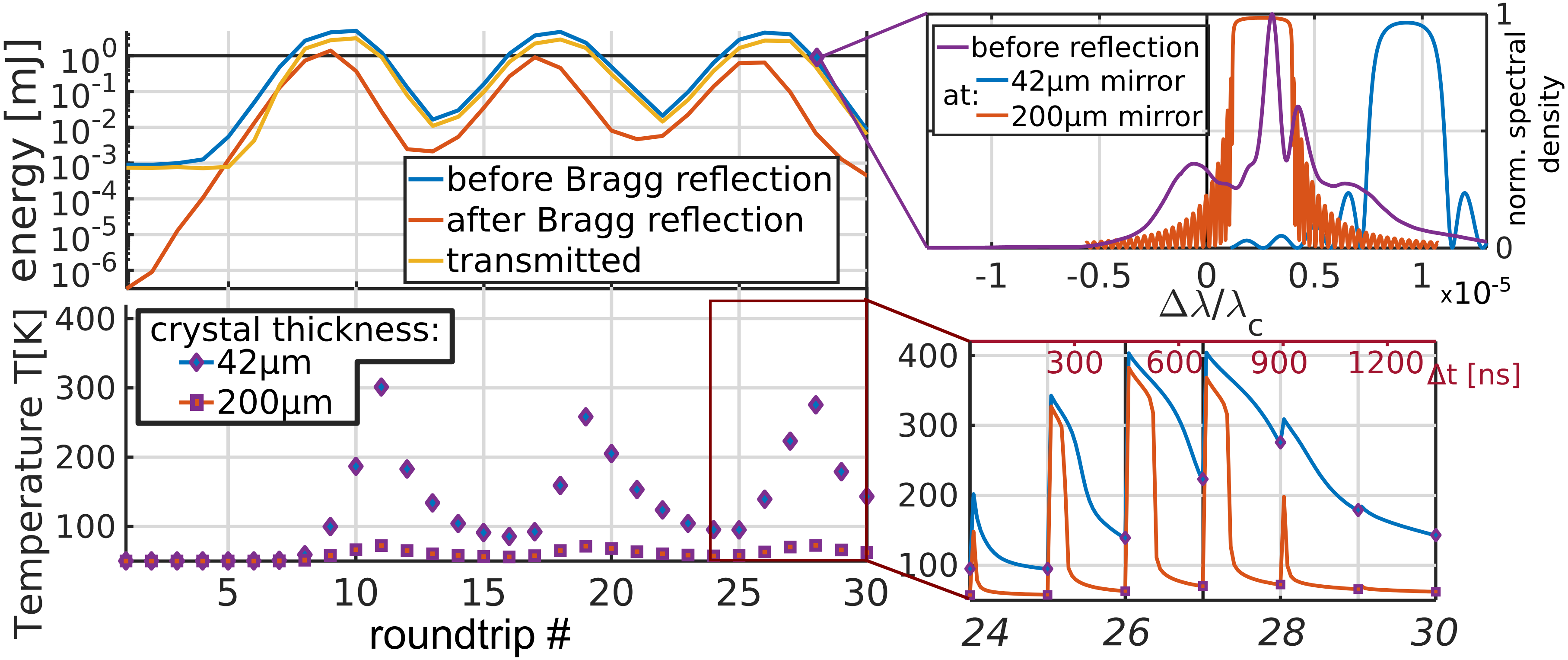
- **Dynamics Answer Of Crystal Towards Rapid Expansion → Strain Waves (Ultrasonics):**



- Influence unknown todate → checked by simulation as well as by experiment [I.Bahns]

→ Not yet implemented

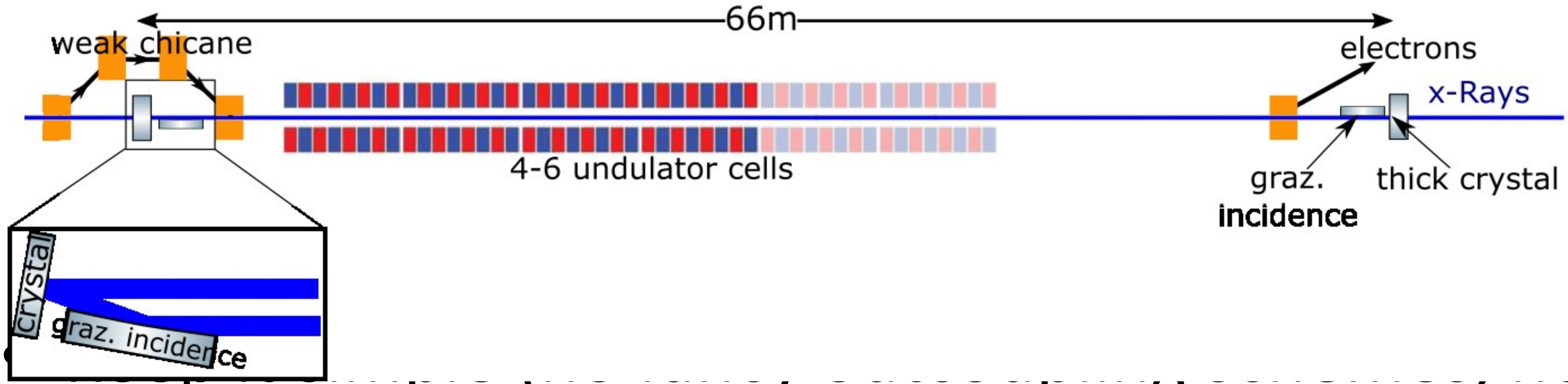
Heatload → Pile-up of heating



- Heatload leads to strong temperature rise in crystal
- Beat in crystal temperature
- Beat also apparent in XFELO-energy
- Different heating of crystals → Shift of res. wavelength with respect to each other

Future Plans at EuXFEL

- Implement a proof-of-principle XFELO at the end of the SASE1 tunnel (last 4-6 Undulators)



- … tunability, two(four) thick mirrors, compliant with standard operation)

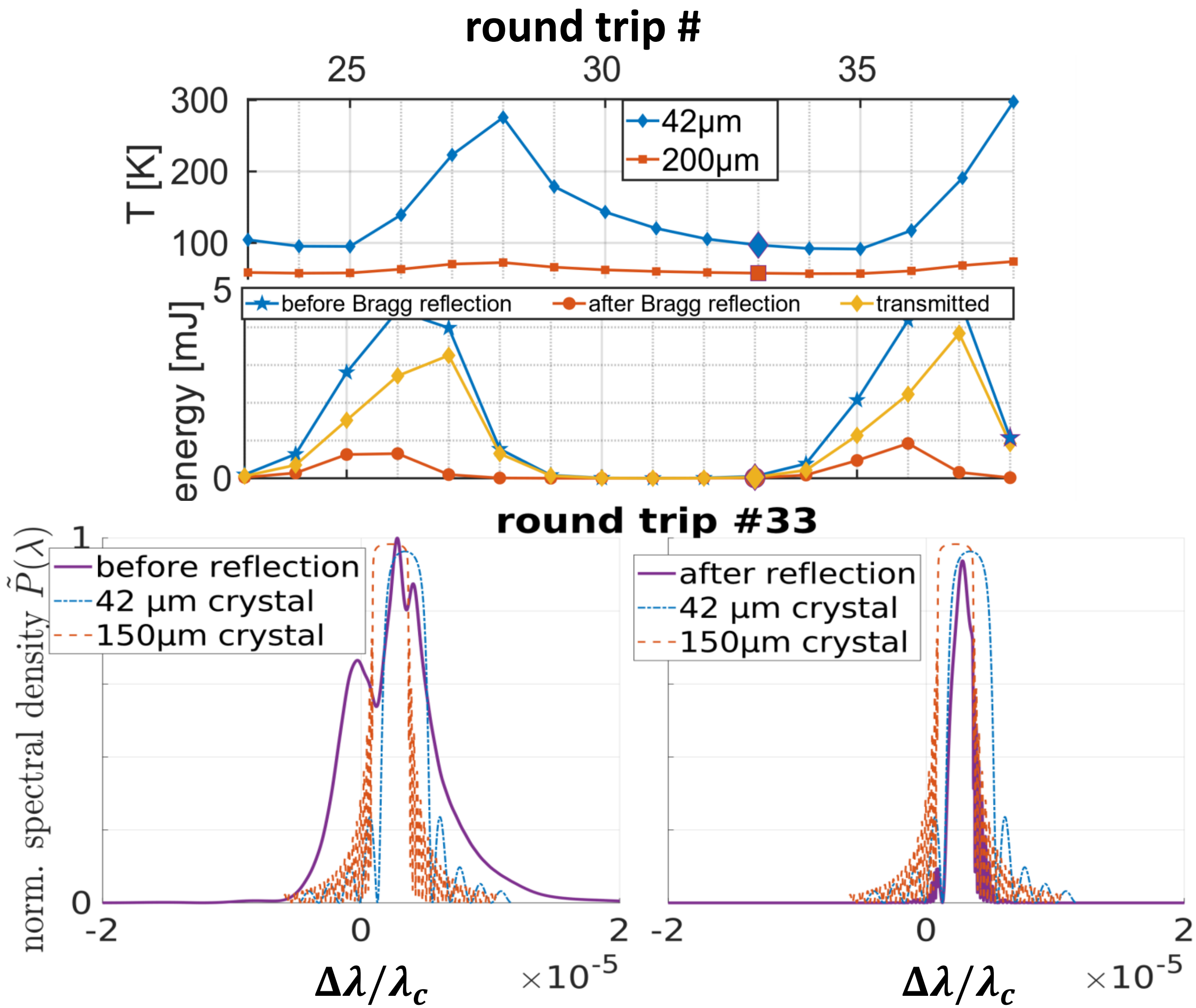
NOT AN APPROVED PROJECT

Conclusion

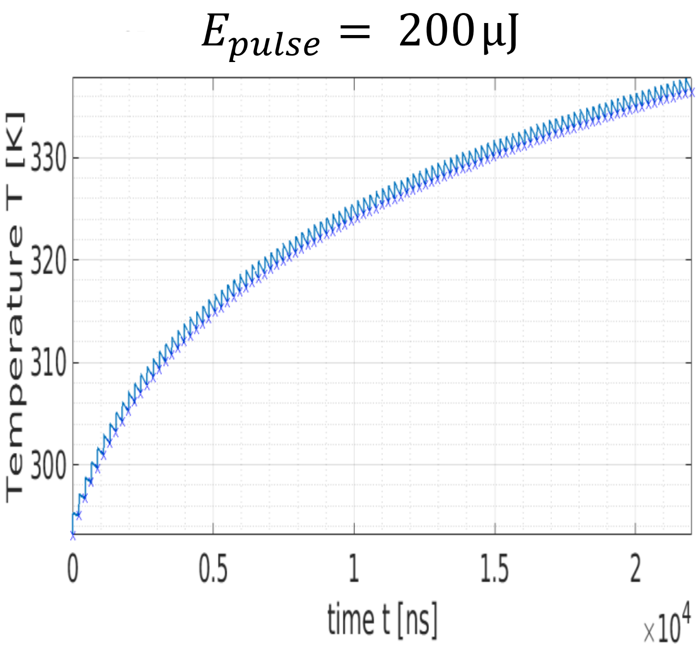
- European XFEL ideal source for implementing an XFELO
- Mechanical tolerances are state of art
- Problems:
  - Outcoupling (keeping longitudinal coherence)
  - Heatload ← Stability at saturation
- Need to try it out → Proof of principle experiment

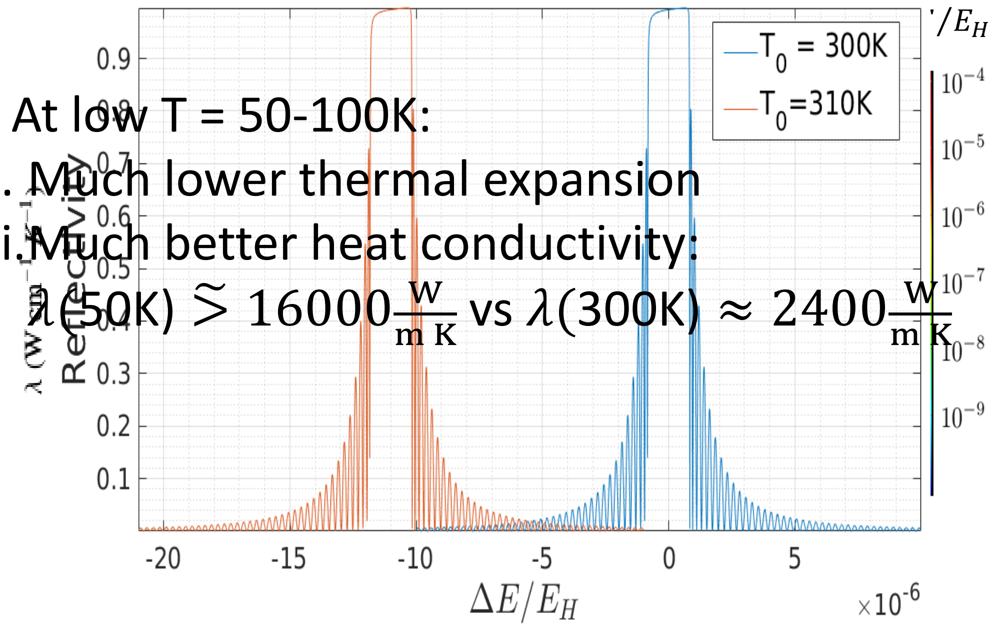
Thank you for listening

Heatload → Pile-up of heating



Laser-crystal interaction in detail





- At low T = 50-100K:
  i. Much lower thermal expansion
  ii. Much better heat conductivity:
  $\lambda(50\mathrm{K}) \gtrsim 16000\frac{\mathrm{W}}{\mathrm{m\,K}}$ vs $\lambda(300\mathrm{K}) \approx 2400\frac{\mathrm{W}}{\mathrm{m\,K}}$

- Pulsed Laser irradiation of diamond crystals lead to a stacking temperature increase → thermal expansion → shift of Bragg conditions

→ importance of cooling

→ necessity of considering nanoscale effects (like boundary scattering)

← Included in model by reduced anisotropic thermal conductivity

Nanoscale heat transport

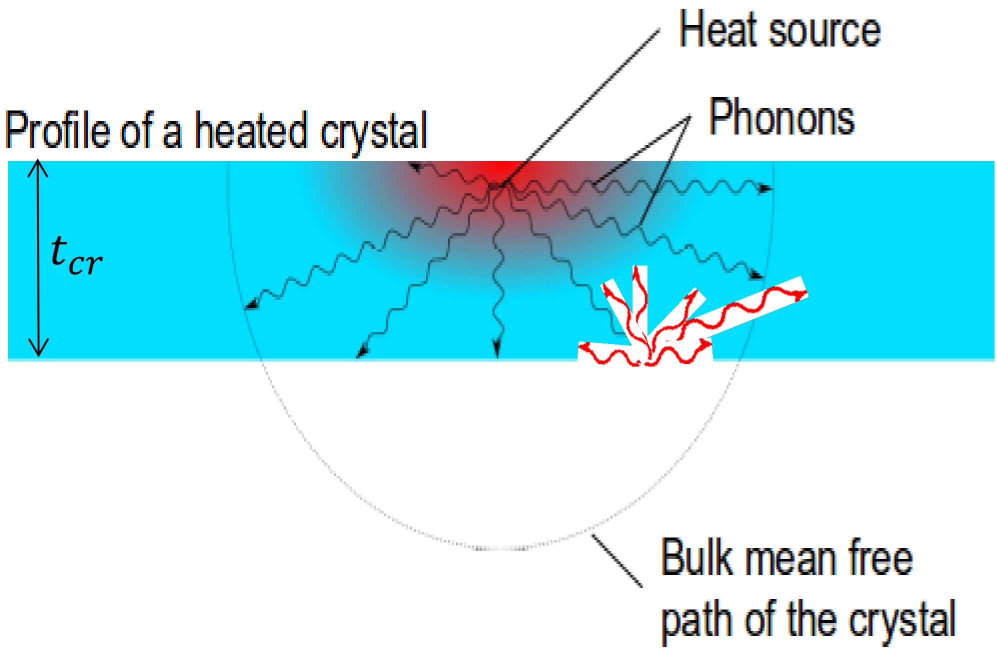
- Boundary scattering -

- At low temperatures the mean free path of the heat carriers increases

→ Phonons can reach the crystal boundaries without scattering

→ At boundaries can be reflected specularly (no influence on direction parallel to surface), diffusively (boundaries act like point defects), or inelastic

→ Conditions generally unknown: **Necessity of experimental measurement!**



- Currently evaluation based on work of A. Majumdar (1993) assuming diffusive boundaries:

$$\boxed{\lambda_{eff}(T) = \lambda(T) \cdot \left(\frac{4}{3}\frac{l_{mfp}}{t_{cr}}+1\right)^{-1}}$$

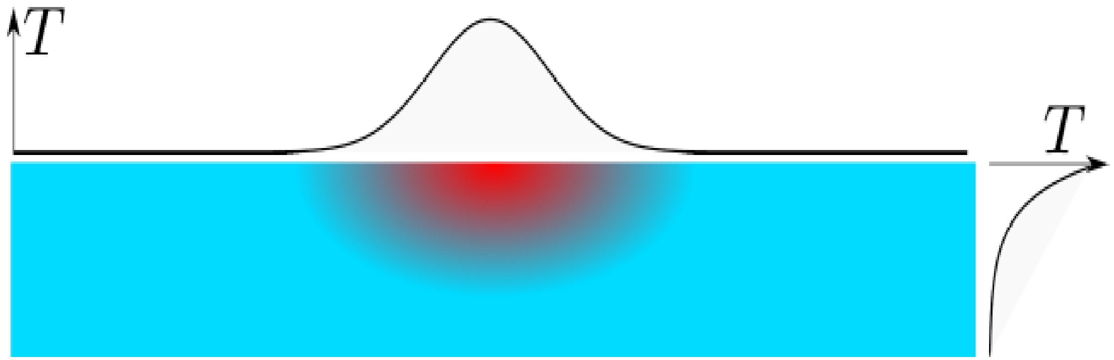
Nanoscale heat transport
- Gradient effect -

- Heat source (temperature curvature) on same scale as l_{mfp} of carriers:

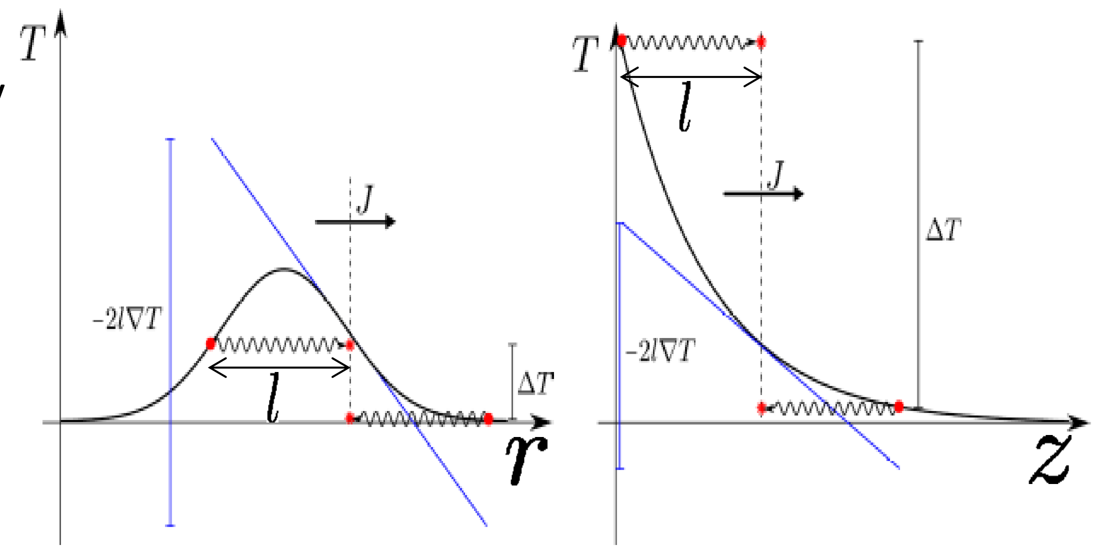
→ **Work by** *Maassen, Lundstrom* **and** *Kaiser* (2015-2017) → In 1D: $\Delta T(r\,/\,z) = -2\,l_{mfp}\,\nabla T(r\,/\,z)$
ΔT: Temperature difference between phonons with mean free path traveling in pos. and neg. directions

→ Fourier's law $q = -\lambda\nabla T$ based on (false) linear approximation: low order diffusion equations (first order Fourier for steady state and second order Cattaneo $\tau\frac{\delta \boldsymbol{q}}{\delta t} + \boldsymbol{q} = -\lambda\nabla\boldsymbol{T}$ for transient) also account for ballistic effects when using correct boundary conditions

→ First experiments by C.Maag confirm assumptions in 1D



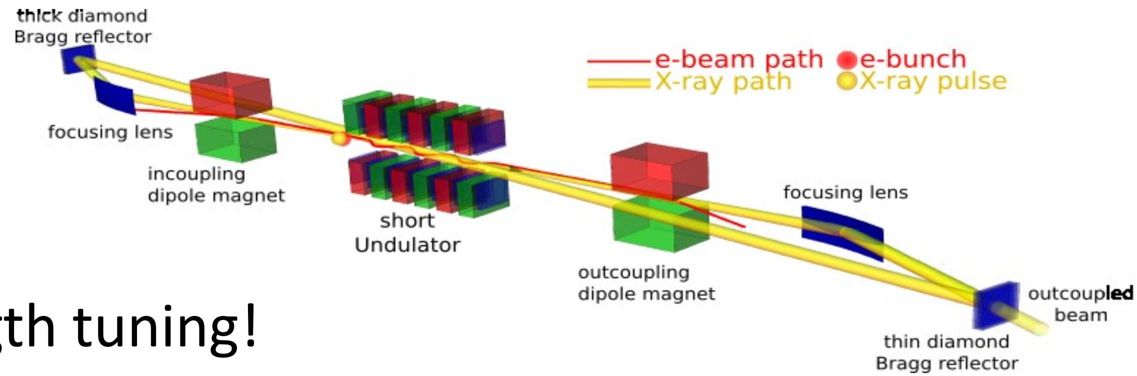
Profile of a heated crystal



XFELO – configurations

- Two Bragg-mirrors, two focussing elements

- Bragg‘s Law: $n \cdot \lambda = 2 * d_H \sin \Theta$



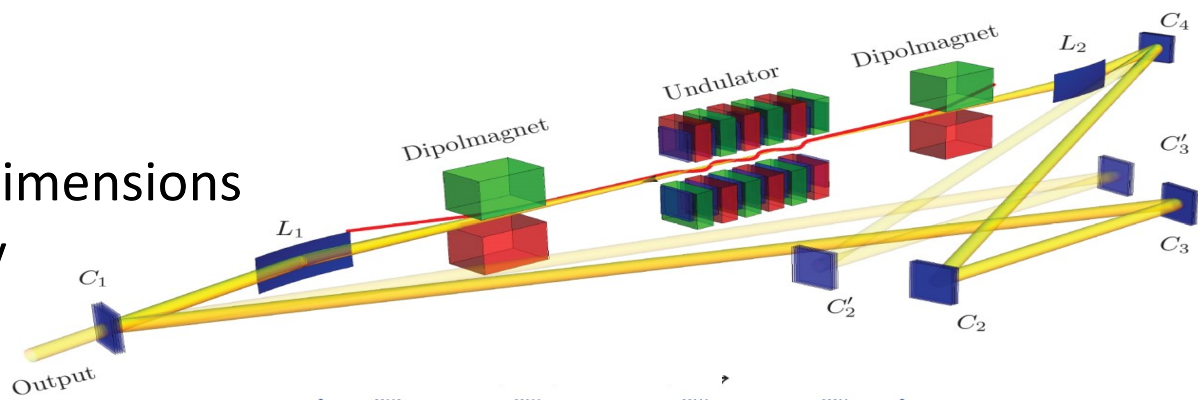
→ No continuous wavelength tuning!

- Four Bragg-mirrors, one focussing element

- Angle Θ adjustable

→ Tunability of wavelength λ
  - Limited by transverse dimensions
- At cost of more complexity

  → Optical Losses



Some Symantics: XFELO vs. RAFEL

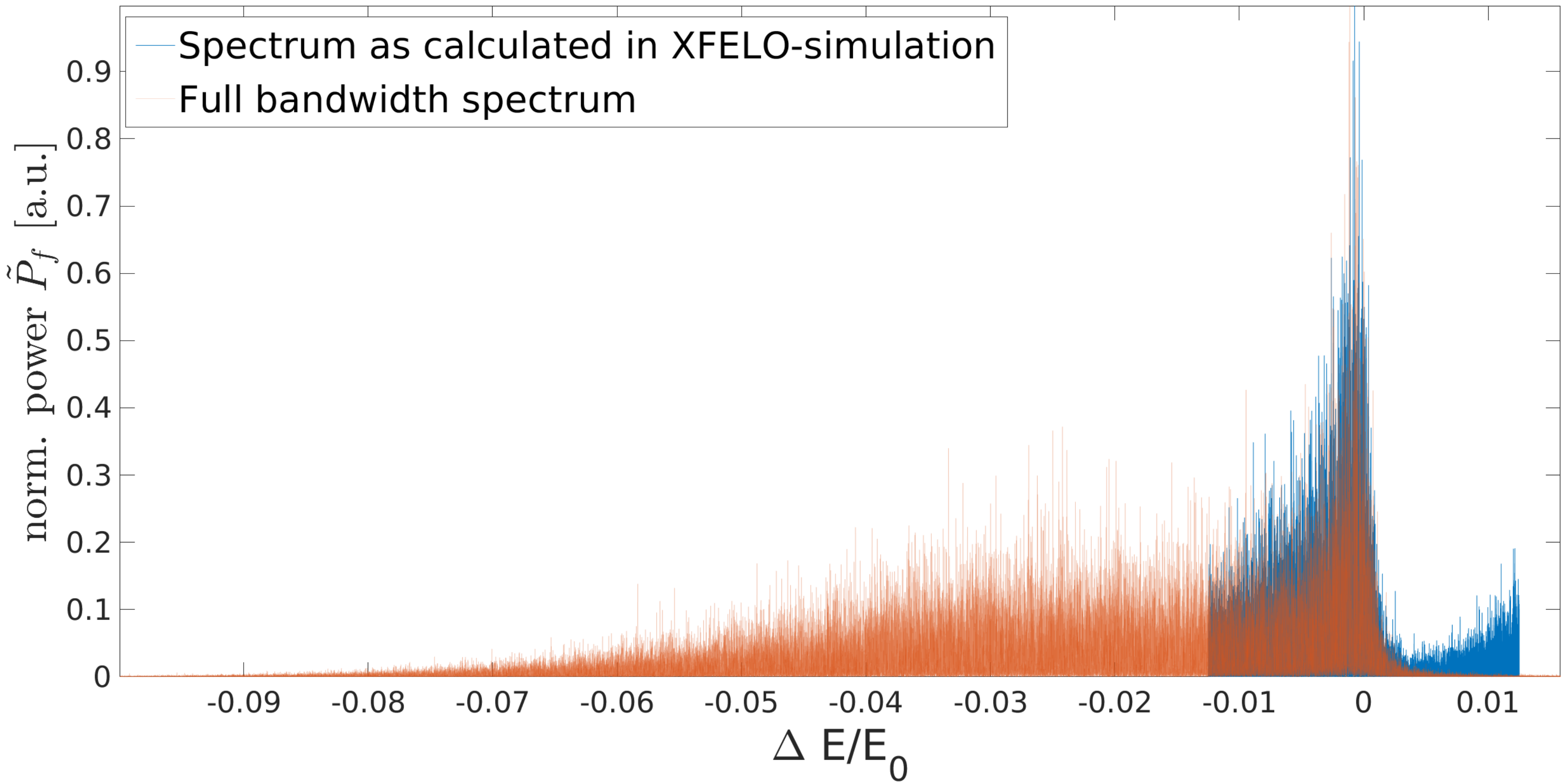
XFELO

- Low gain device ($\mathcal{G} \ll 1$)
- Saturation after some hundreds of roundtrips
  → Very stable output
- Principally upgradable to phase locked resonator
- Low gain ← Very sensitive to all forms of distortions

(X-)RAFEL

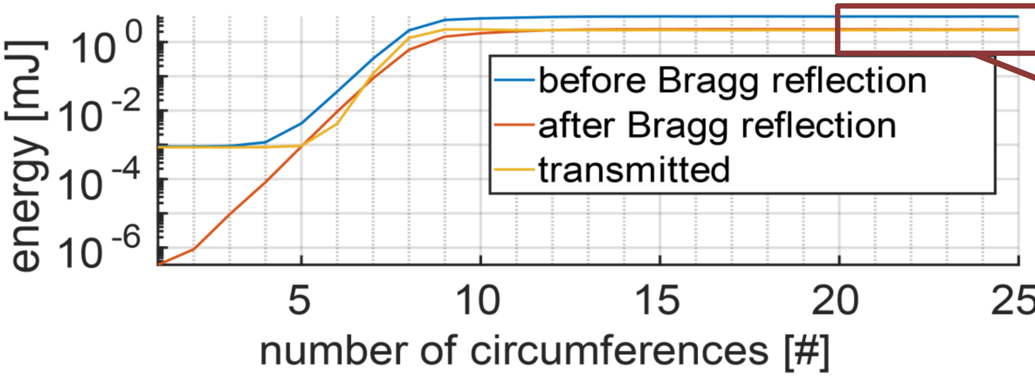
- Intermediate to high gain device ($\boxed{\mathcal{G} \geq 1}$ to $\mathcal{G} \gg 1$)
- Saturation after from 5 to some tens of roundtrips
- Less sensitive to distortions than XFELO
- Output more dependent on electron beam properties + fluctuations
- Much more stable than SASE due to powerful seed

X-ray Free Electron Laser Oscillator (idealized)



Simulation including mirror tilt and el. jitter

- Additionally including: - mirror tilt of $\Delta\theta \cong 100$ nrad - arr. time jitter of 30fs



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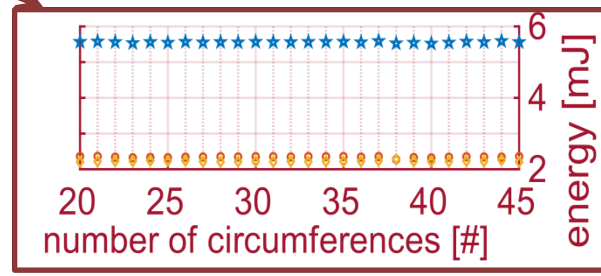

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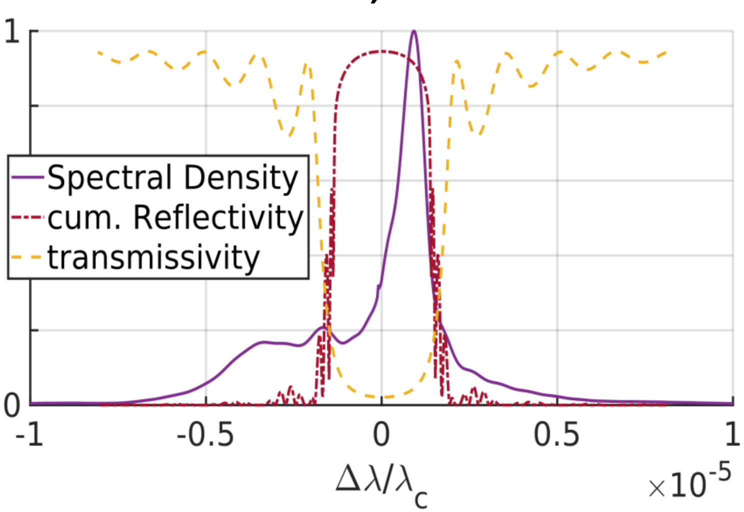
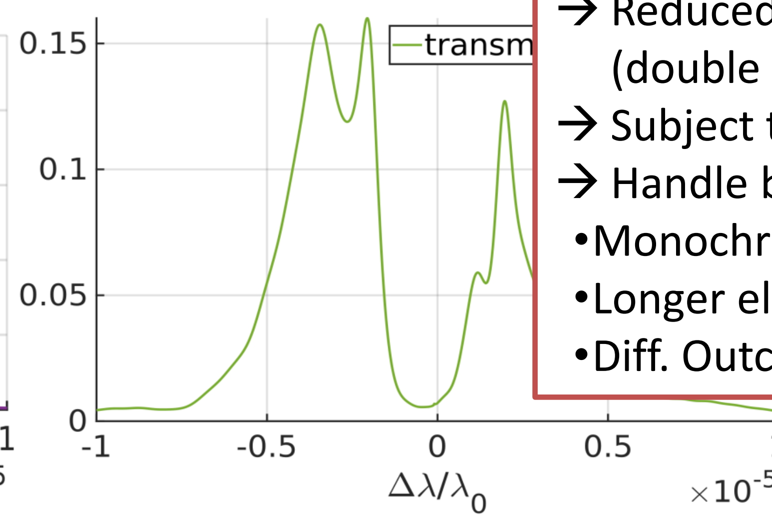
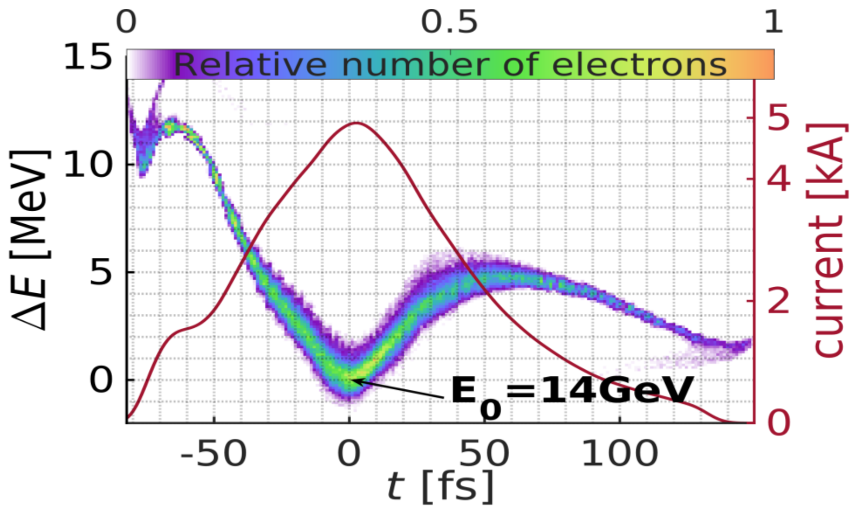




→ Reduced long. Coherence (double pulse structure)
→ Subject to electron jitter
→ Handle by:
- Monochromatization
- Longer electron bunches
- Diff. Outcoupling schemes

XFELO width realistic e-bunch

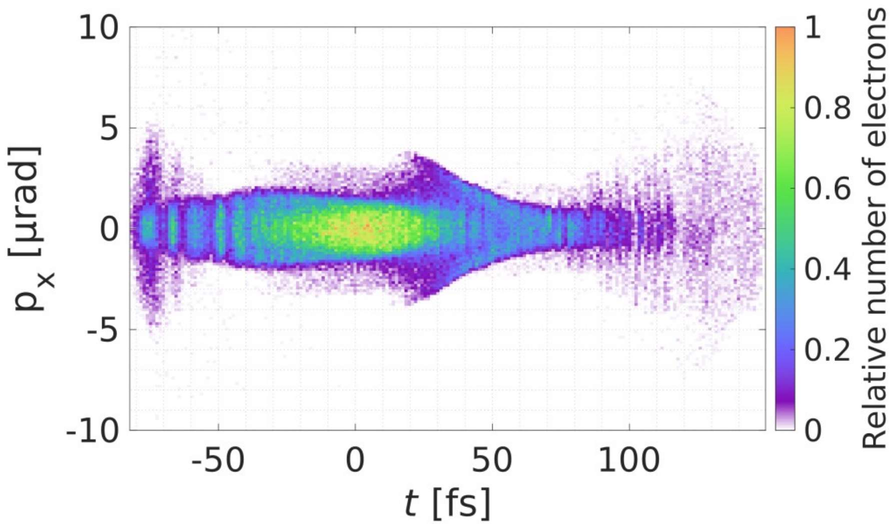
- Electron distribution from start to end simulations [1]

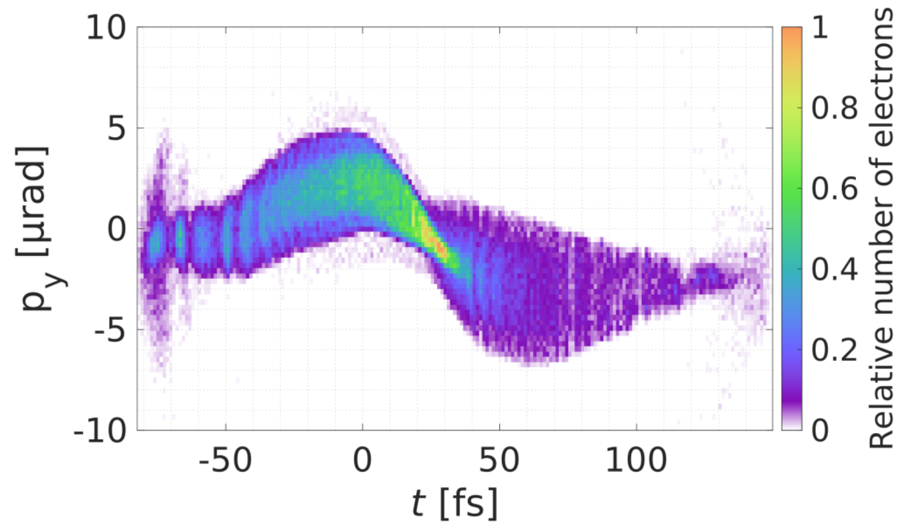


- Electron distribution (500pC) at beginning of SASE1 Undulator
  – Pronounced energy chirp

  → May be problematic for XFELO due to very small *seeding* bandwidth

[1] Igor Zagorodnov, *http://www.desy.de/fel-beam/s2e/xfel/Nominal/nom500pC.html*





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