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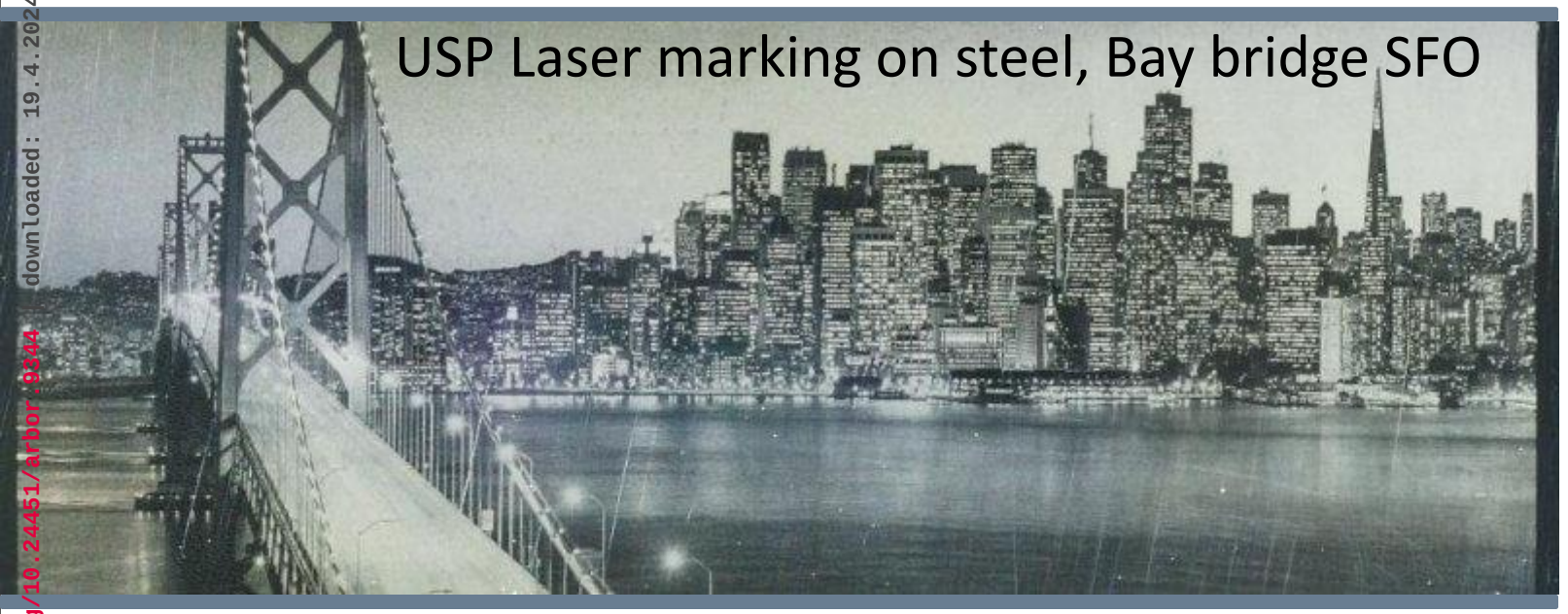

Influence of Pulse Duration in the Pico- and Femtosecond Regime on the Absorptance and Specific Removal Rate

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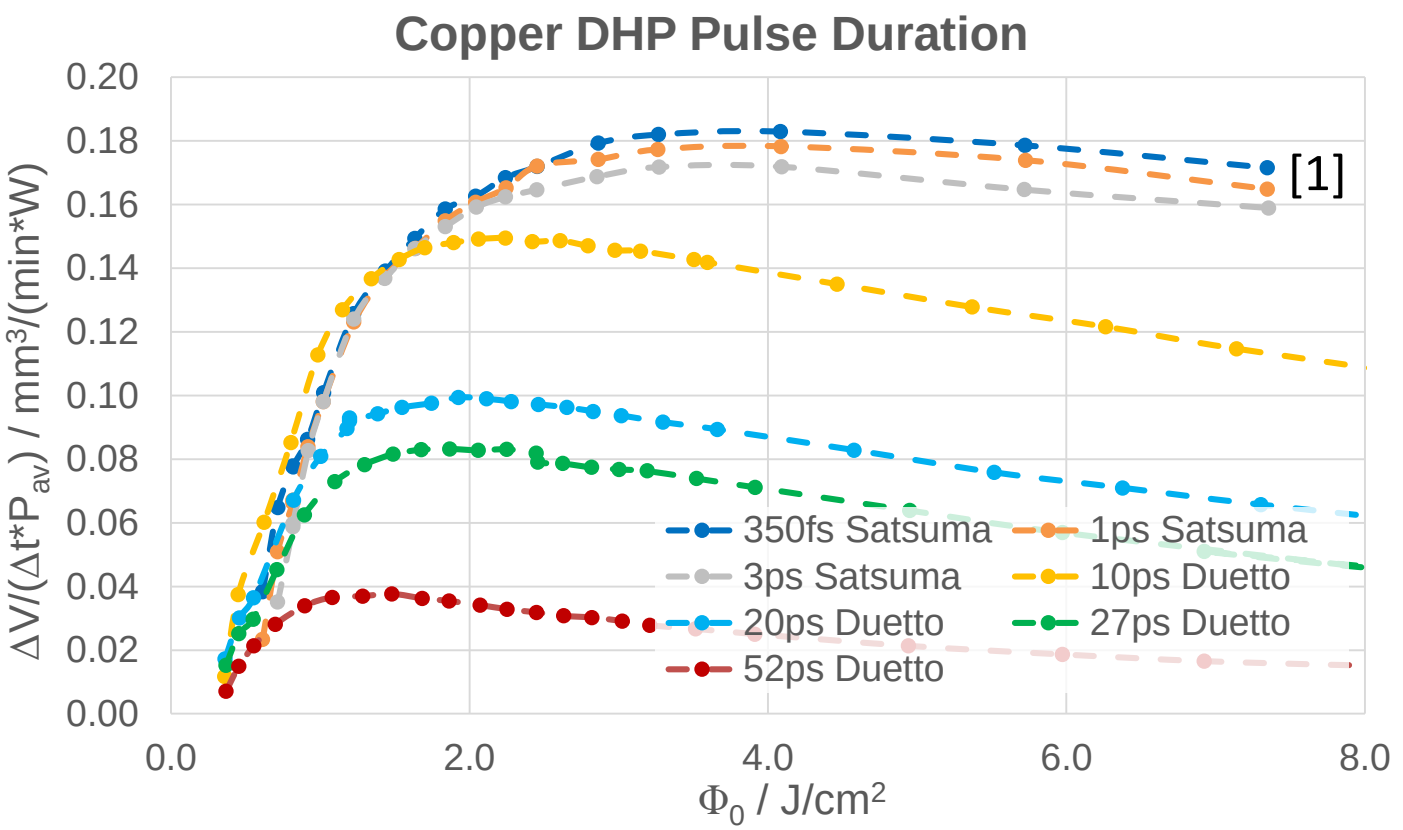
- Motivation
  - Pulse Duration Experiments
  - Double Pulse Experiments
  - Result Comparison and Hypothesis
- Reflectivity Measurement
- Calorimetry
- Conclusion

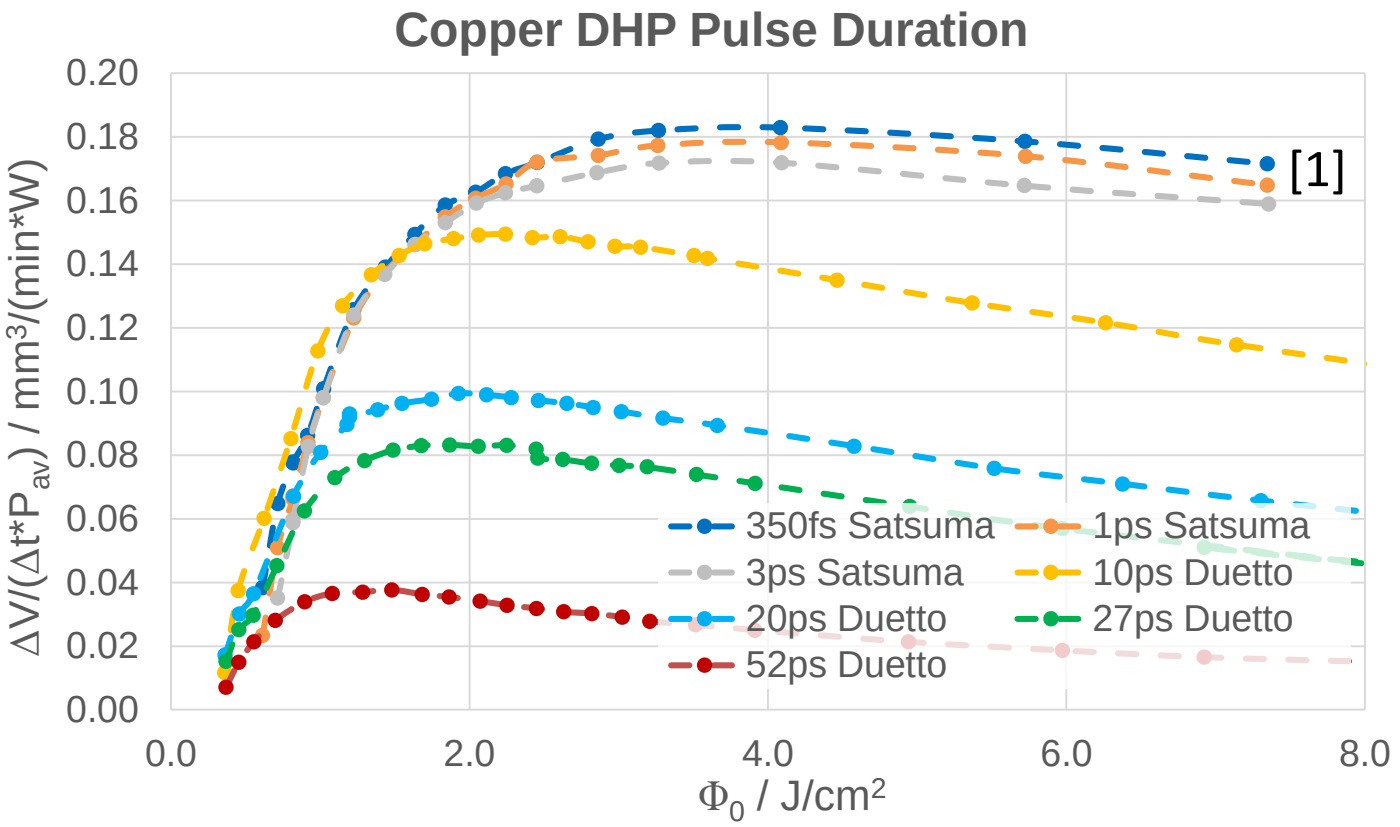
Motivation – Pulse Duration Experiments Copper DHP



- Machined squares
- Used Lasers:
  - 350fs to 3ps:
    - Satsuma HP2, Amplitude
    - λ=1030nm, f_{rep}=505kHz
    - w_0=17.2µm, M^2=1.3
  - 10ps to 52ps:
    - Duetto, Time Bandwidth
    - λ=1064nm, f_{rep}=200kHz
    - w_0=13µm, M^2=1.45

[1] B. Jaeggi, B. Neuenschwander, S. Remund, T. Kramer. 100910J. 10.1117/12.2253696. (2017)

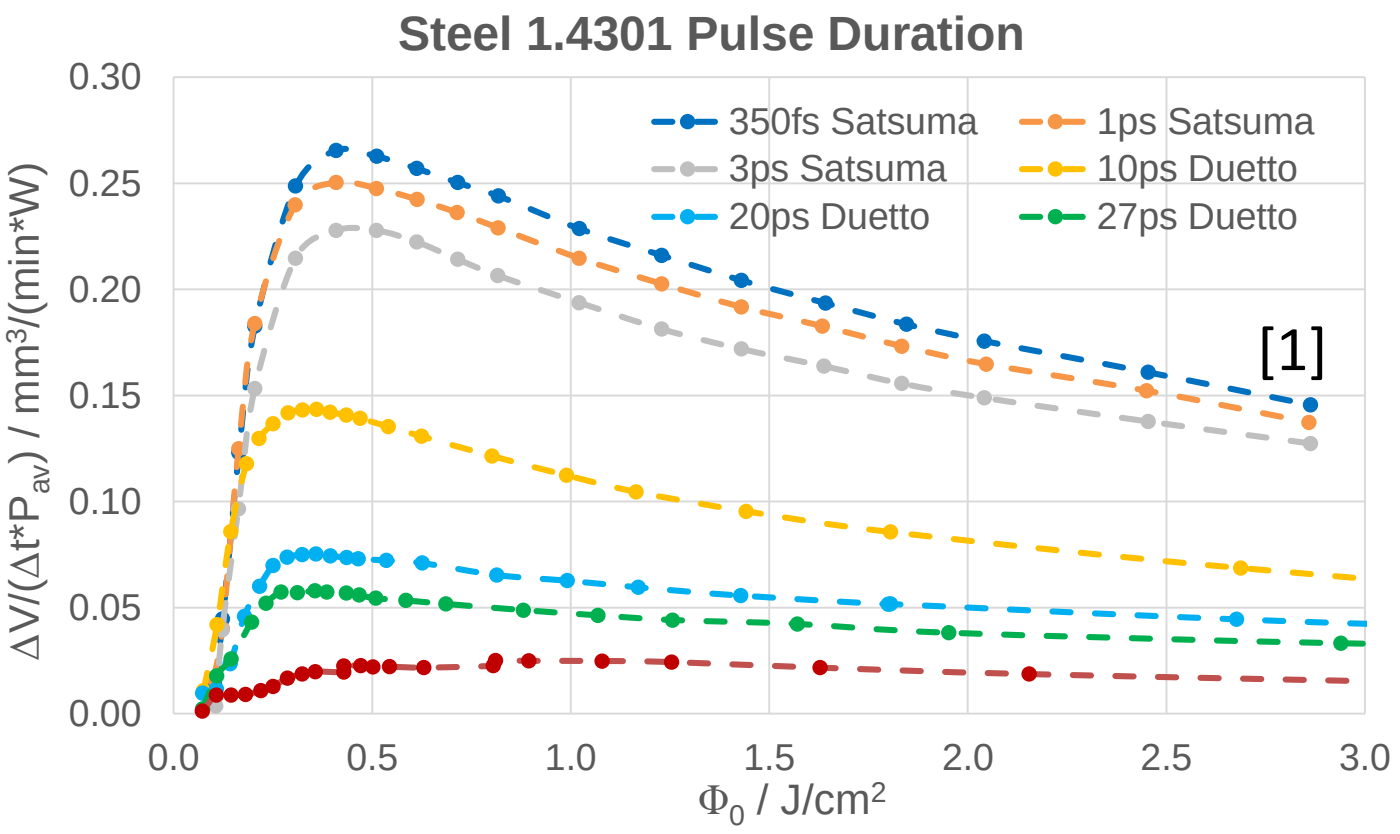
Motivation – Pulse Duration Experiments Copper DHP



- Increasing specific removal rate by decreasing pulse duration
  - 52ps to 3ps nearly 5x
  - 3ps to 350fs around 1.1x

[1] B. Jaeggi, B. Neuenschwander, S. Remund, T. Kramer. 100910J. 10.1117/12.2253696. (2017)

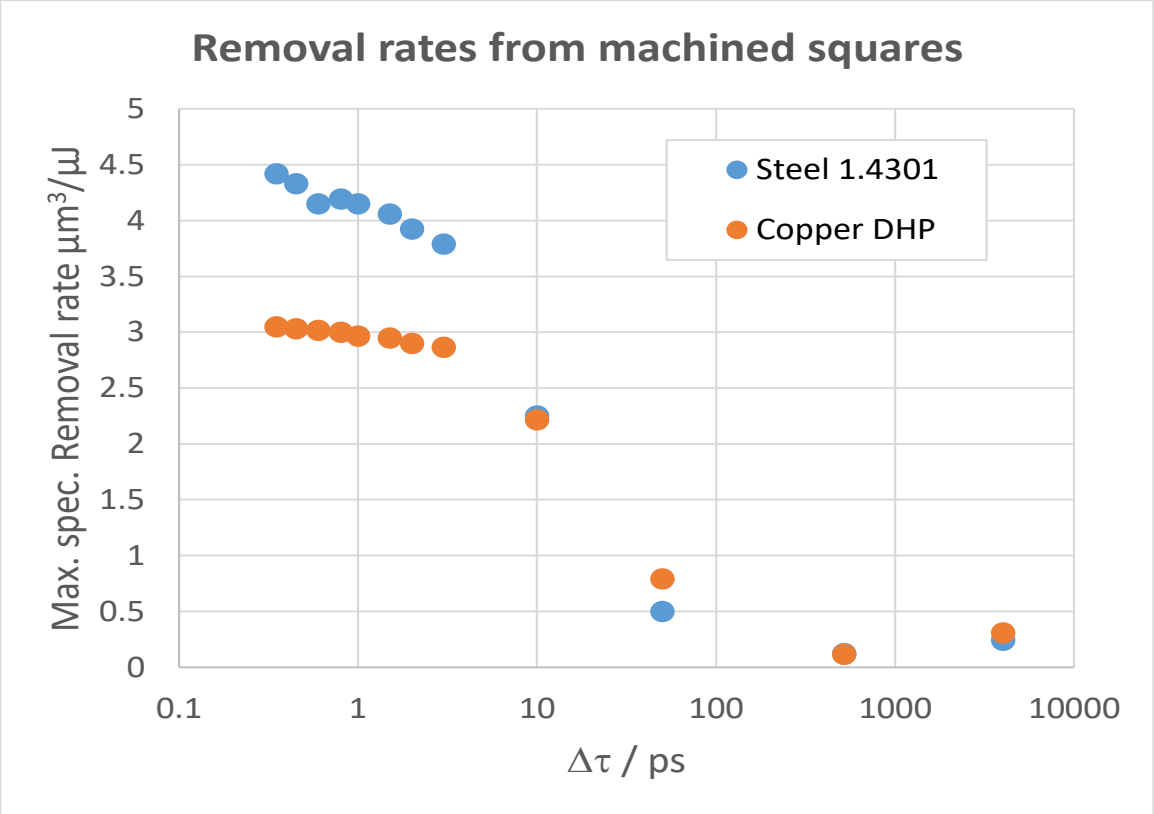
Motivation – Pulse Duration Experiments Steel 1.4301



- Increasing specific removal rate by decreasing pulse duration
  - 52ps to 3ps nearly 10x
  - 3ps to 350fs around 1.2x

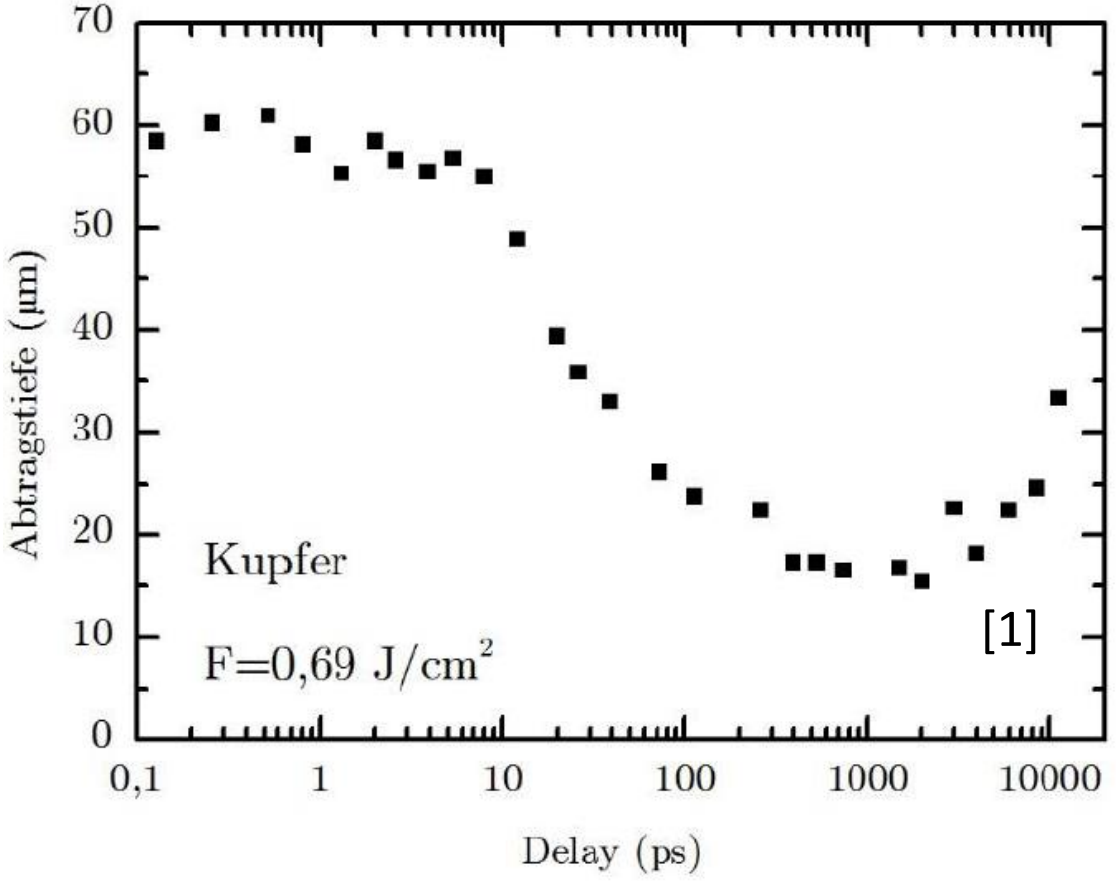
[1] B. Jaeggi, B. Neuenschwander, S. Remund, T. Kramer. 100910J. 10.1117/12.2253696. (2017)

Motivation – Pulse Duration and Removal Rate

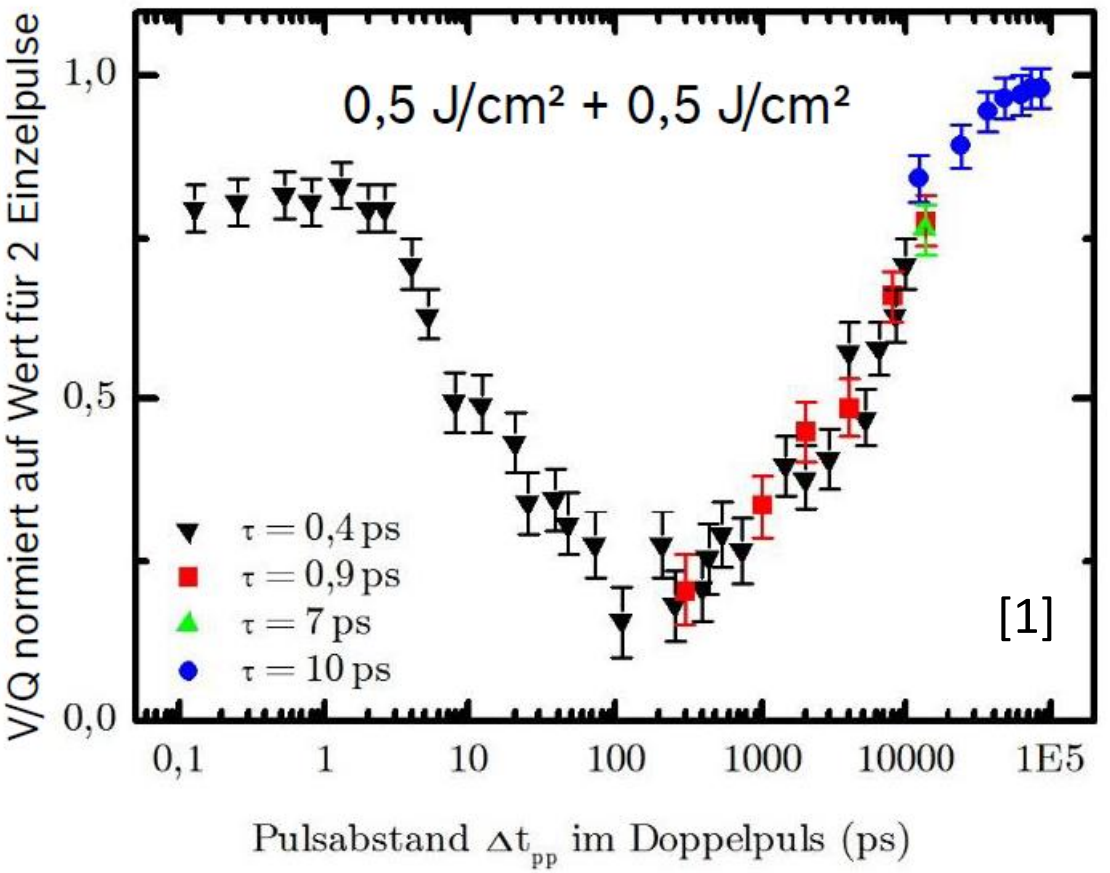


- Shorter pulse durations lead to higher maximal specific removal rates for both materials
  - Cu: Rate for fs nearly constant
  - Steel: Rate increases also for fs

Motivation – Two Pulse Burst Experiment



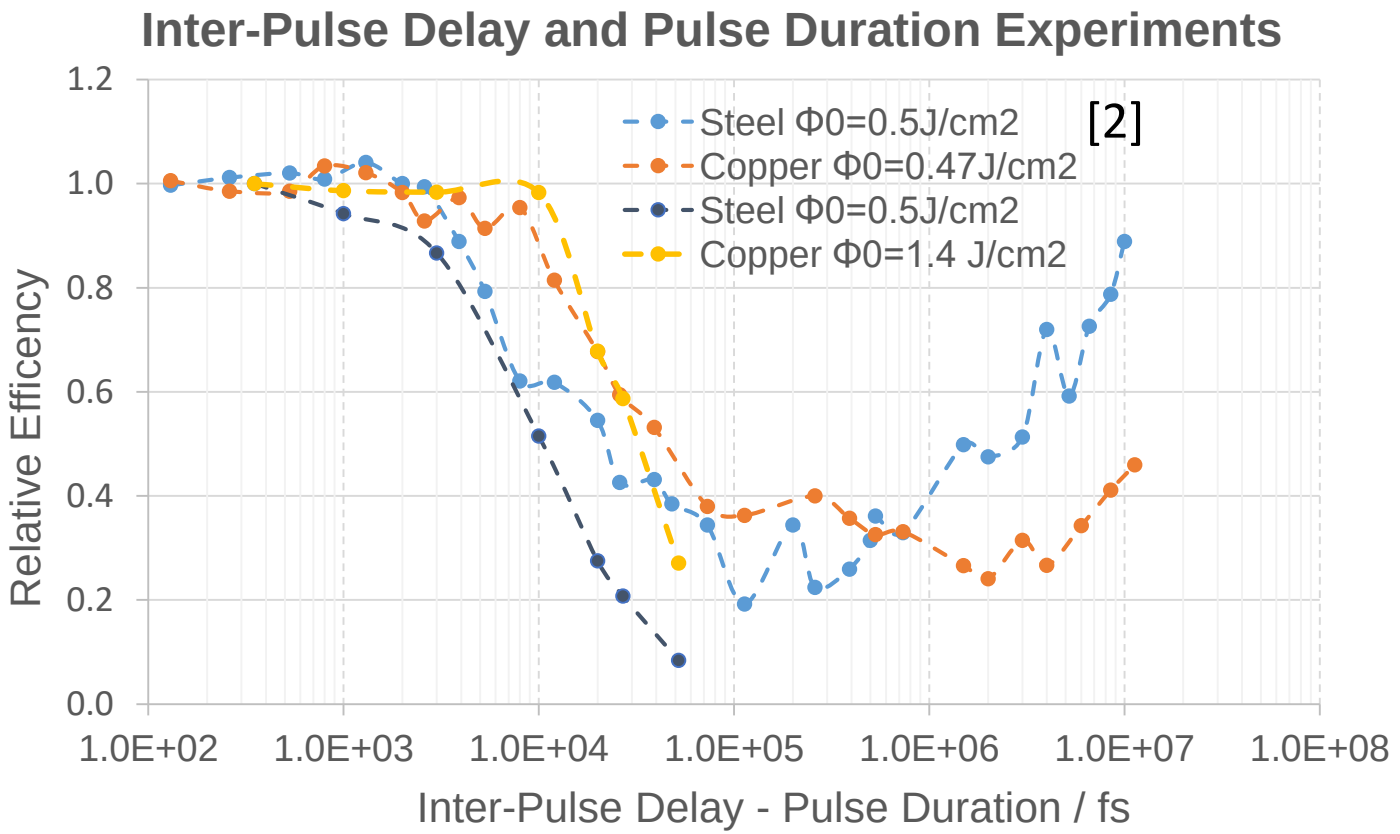
Results for Copper



Results for Steel

[1] A. Michalowski, F. Bauer, T. Bauknecht. (2016). Schwarzwald Workshop IFSW

Motivation – Comparison of Experimental Results



- Inter-pulse delay for double pulse experiment (DP) and pulse duration (tp) show very similar behavior for copper and steel
  - Common cause?

[2] F. Bauer. *Grundlegende Untersuchungen zum Abtragen von Stahl mit ultrakurzen Laserpulsen*. Friedrich-Schiller-Universität Jena, 2018.

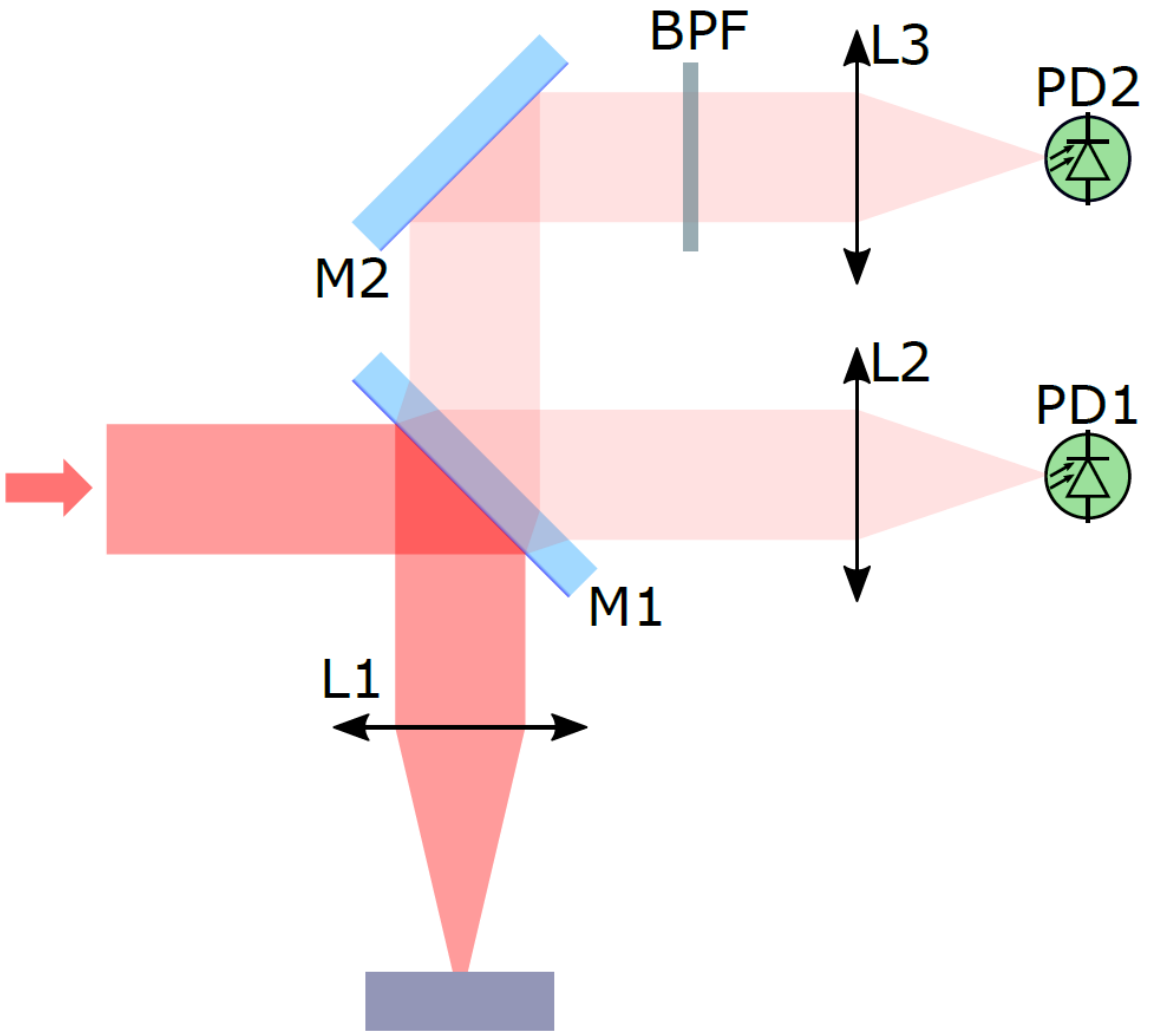
Motivation – Results and Hypothesis

- Hypothesis:
  - Pulse duration dependency: Shielding of pulse by its own processes
  - Double pulse experiments: Shielding of the second by the processes from the first pulse
  - Could both results share the same cause -> Shielding
- Experimental approach:
  - Reflectivity measurements of single pulses for varying pulse durations
  - Calorimetric measurements for varying pulse durations

Reflectivity Measurement – Setup

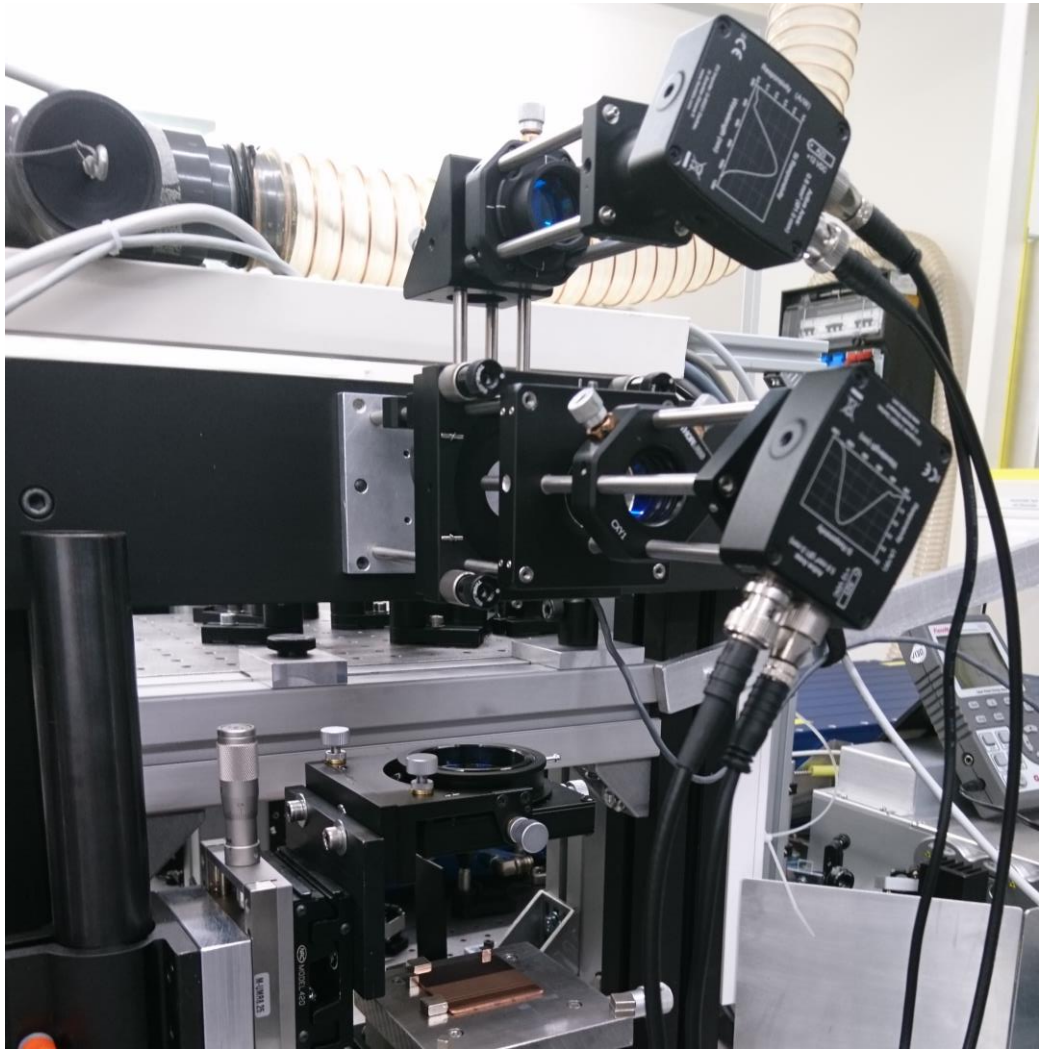
- Laser beam guided by M1 through L1 onto sample
- Transmission of M1 focused by L2 onto PD1
  - **Reference signal**
- Reflection from sample back on M1
- Transmission of back reflection guided by M2 through BPF and L3 onto PD2
  - **Back reflected signal**

- Ratio indicates **relative reflectivity**

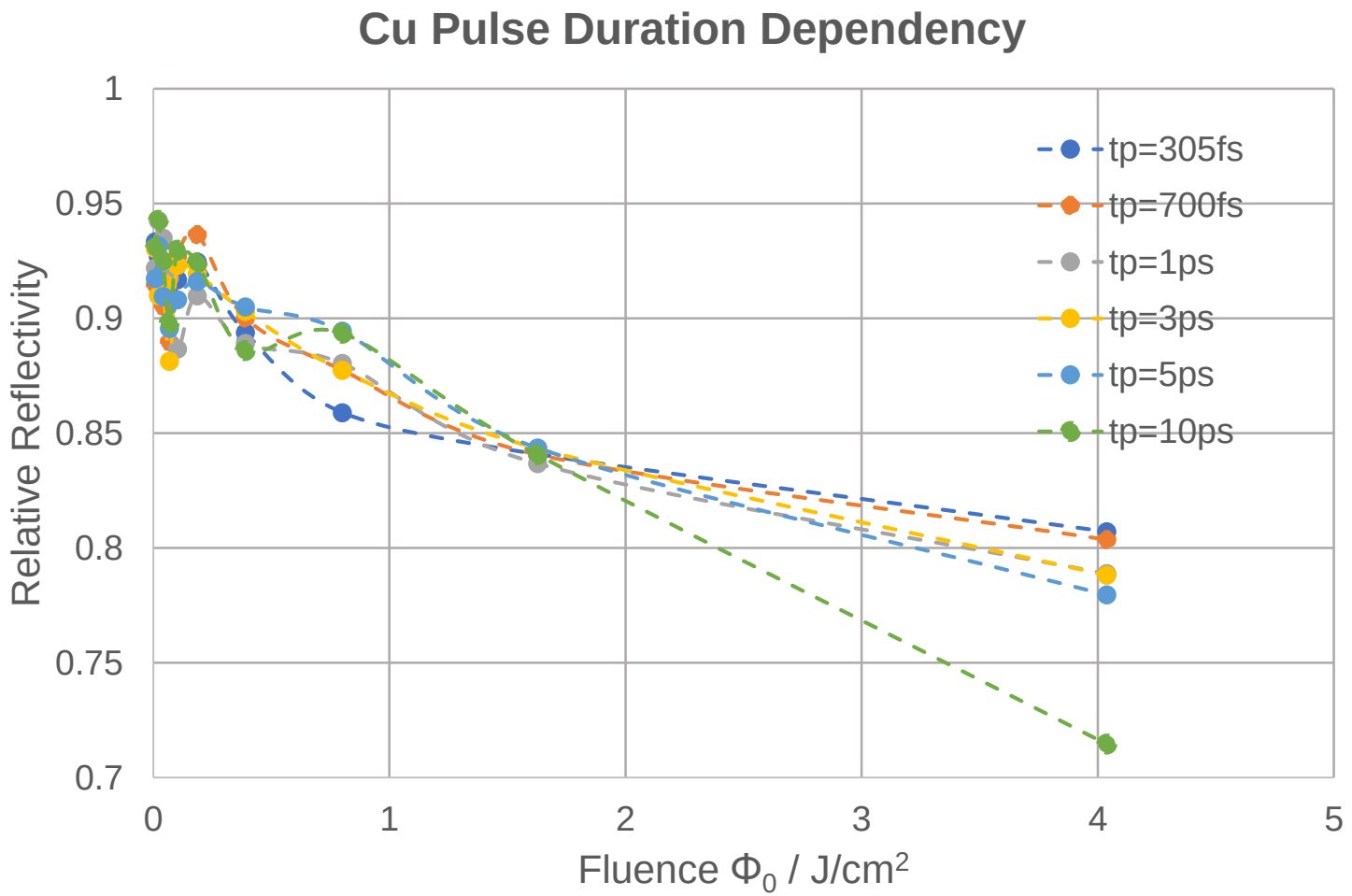


Reflectivity Measurement – Setup

- Laser: Satsuma HP2, Amplitude Systèmes, λ= 1030nm, f_{L1}=100mm -> w_0=13µm, M^2=1.6
- M1&M2: HR1030/45 PW1025C, Laser Components GmbH
- PD1&PD2: DET10A2, Thorlabs GmbH, Si detector, 200-1100nm, 1ns rise time
- BPF: Hard coated OD 4, 1025nm CWL, 50nm bandpass filter, Edmund Optics
- Oscilloscope: LeCroy waveRunner 104MXi, 1GHz, 10GS/s
- Signal integrated (Simpson method)

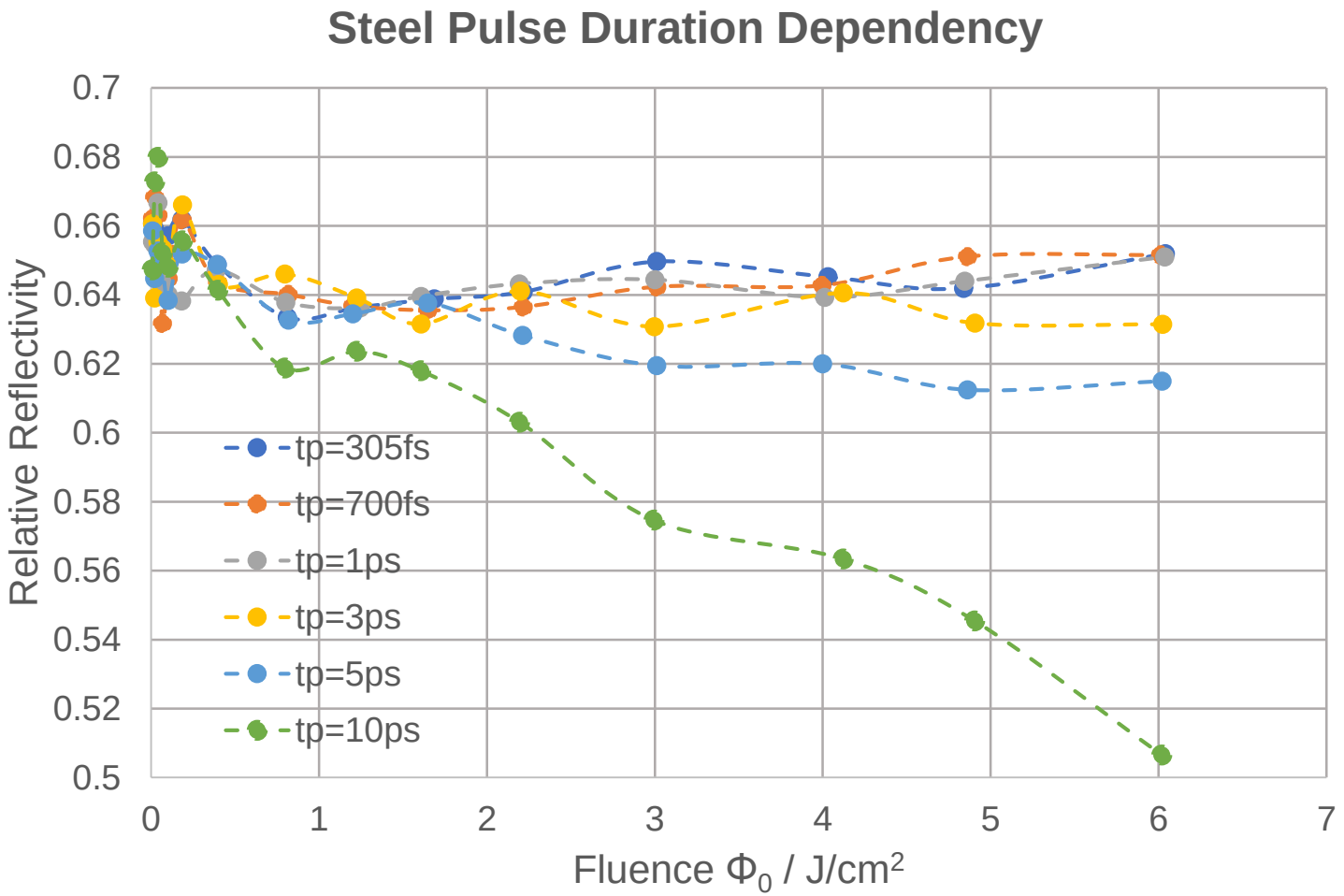


Reflectivity Measurement – Results Copper DHP



- Decreasing reflectivity by increasing fluence
- At Φ_0=4 J/cm² small separation for 305fs to 5ps
  - 10ps nearly 10% reduced reflectivity
  - Pulse duration dependent reflection indicated for 10ps
- Higher threshold fluence due to single pulse (incubation)

Reflectivity Measurement – Results Steel 1.4301

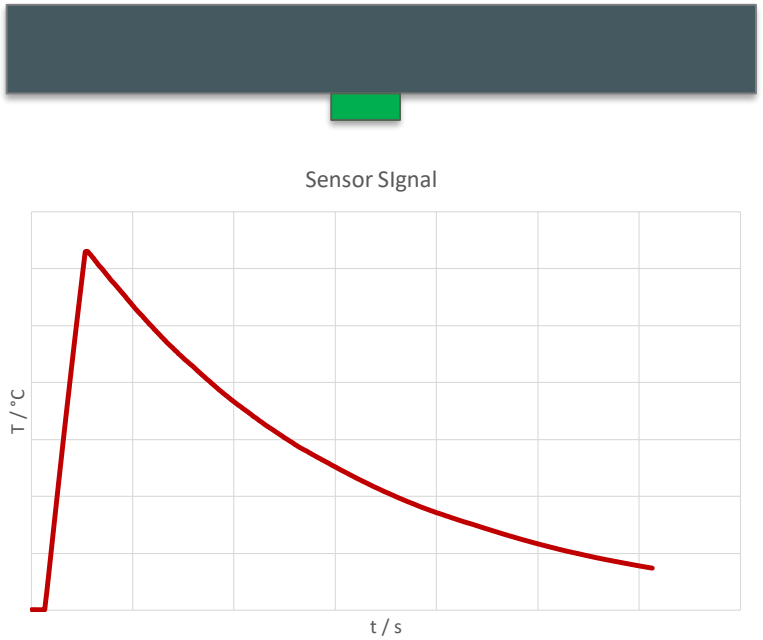


- For 305fs to 1ps similar values
- 3ps decreasing reflectivity after Φ_0=3 J/cm²
- 5ps decreasing reflectivity after Φ_0=2 J/cm²
- 10ps decreasing reflectivity already after Φ_0=1 J/cm²
  - Pulse duration dependency indicated from 3ps to 10ps

Calorimetry

- A part of the incoming energy is always converted to heat
- Sample is heated up, T measured with a PT1000
- Cooling after irradiation

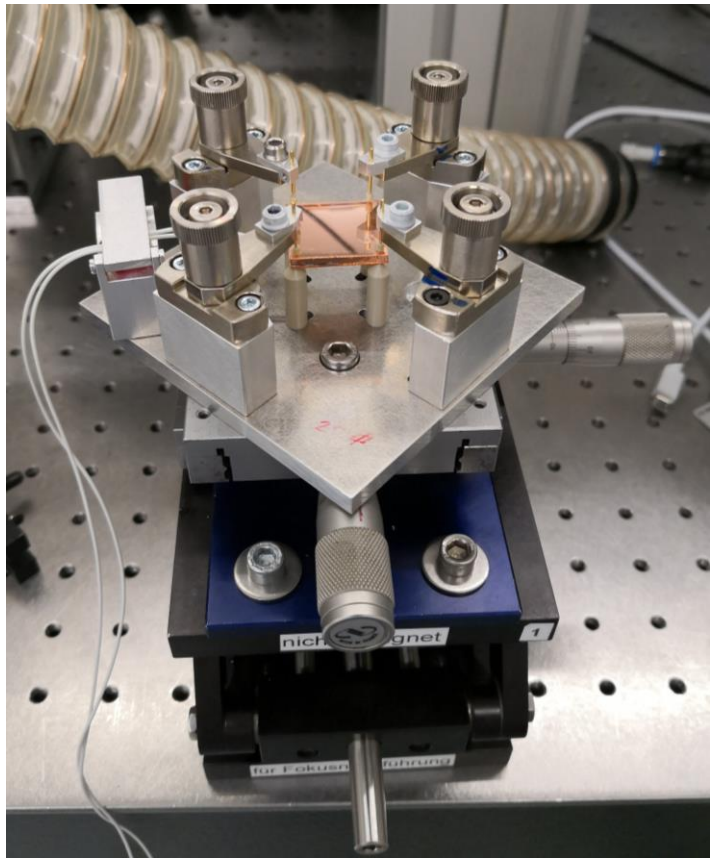
Calorimetry



- A part of the incoming energy is always converted to heat
- Sample is heated up, T measured with a PT1000
- Cooling after irradiation
- From this curve the residual energy in the sample can be calculated [4]

[4]: F. Bauer, A. Michalowski, Th. Kiedrowski, S. Nolte, Opt. Expr. 23, 1035 – 1043, (2015)

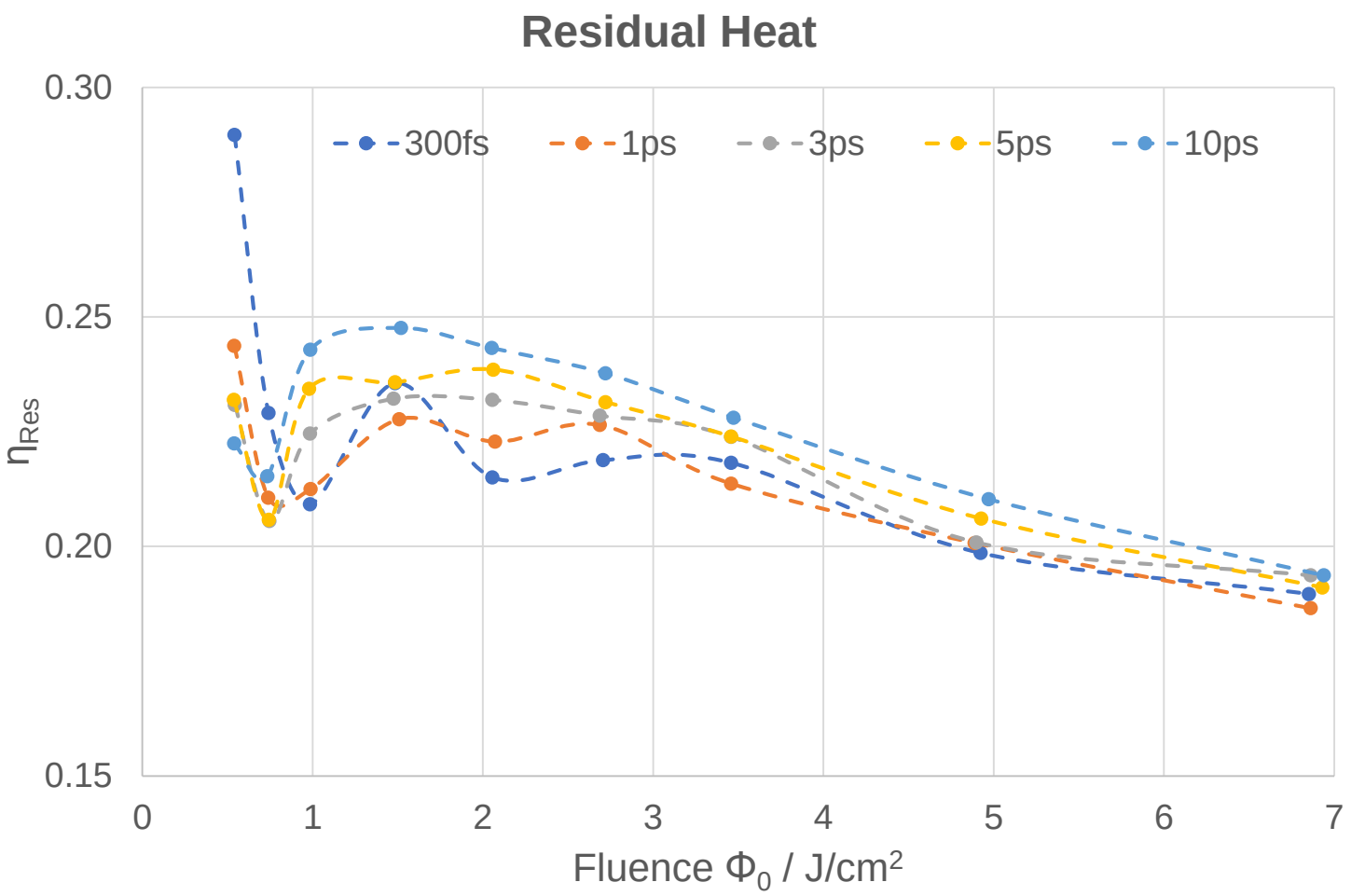
Calorimetry – Setup



- A part of the incoming energy is always converted to heat
- Sample is heated up, T measured with a PT1000
- Cooling after irradiation
- From this curve the residual energy in the sample can be calculated [4]
- E_{Heat} respectively $\eta_{Heat} = E_{Heat}/E_{in}$ is measured

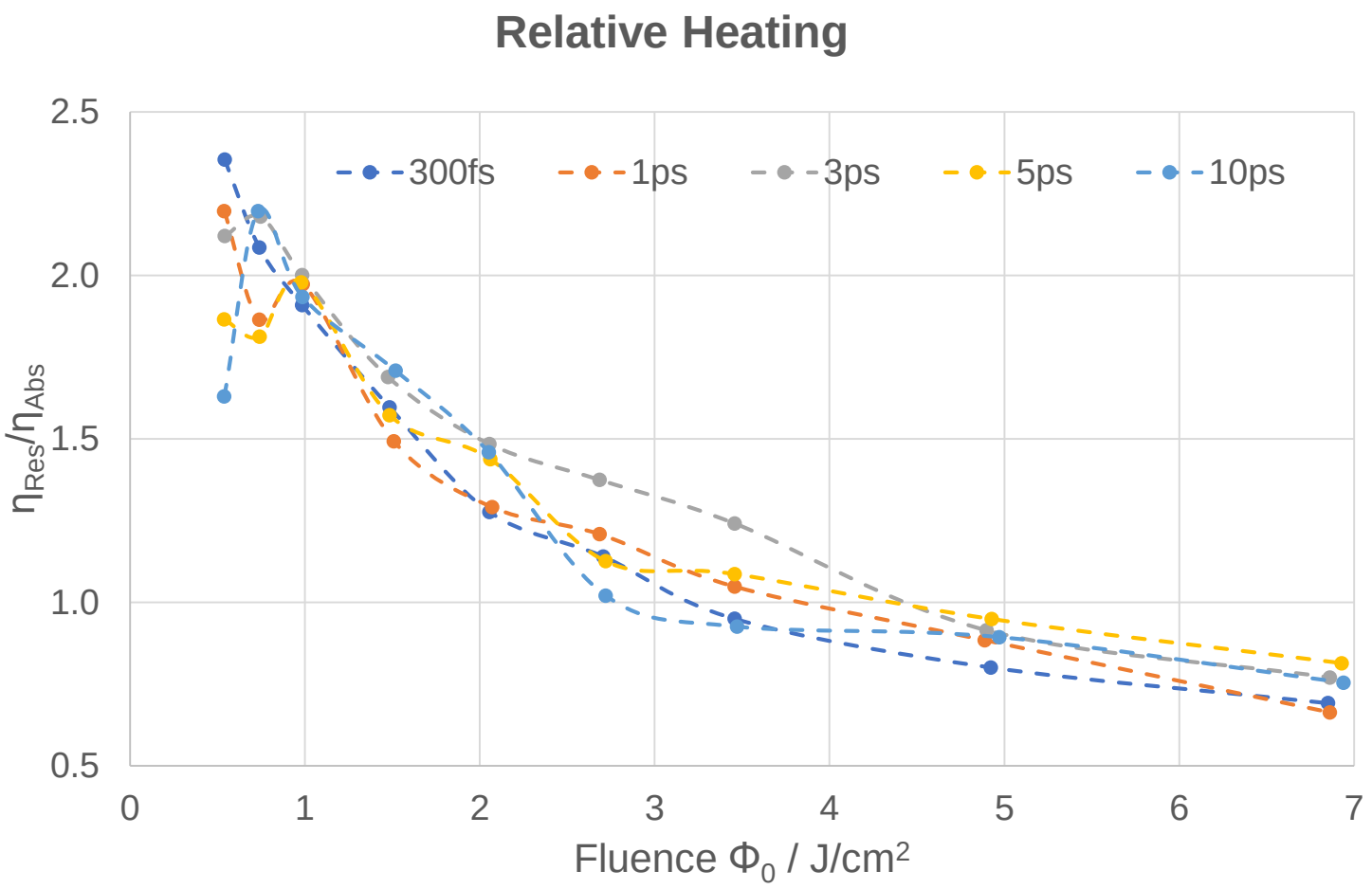
[4]: F. Bauer, A. Michalowski, Th. Kiedrowski, S. Nolte, Opt. Expr. 23, 1035 – 1043, (2015)

Calorimetry – Results Copper DHP



- Similar and nearly constant residual heat for all pulse durations
- High reflectivity of copper indicated

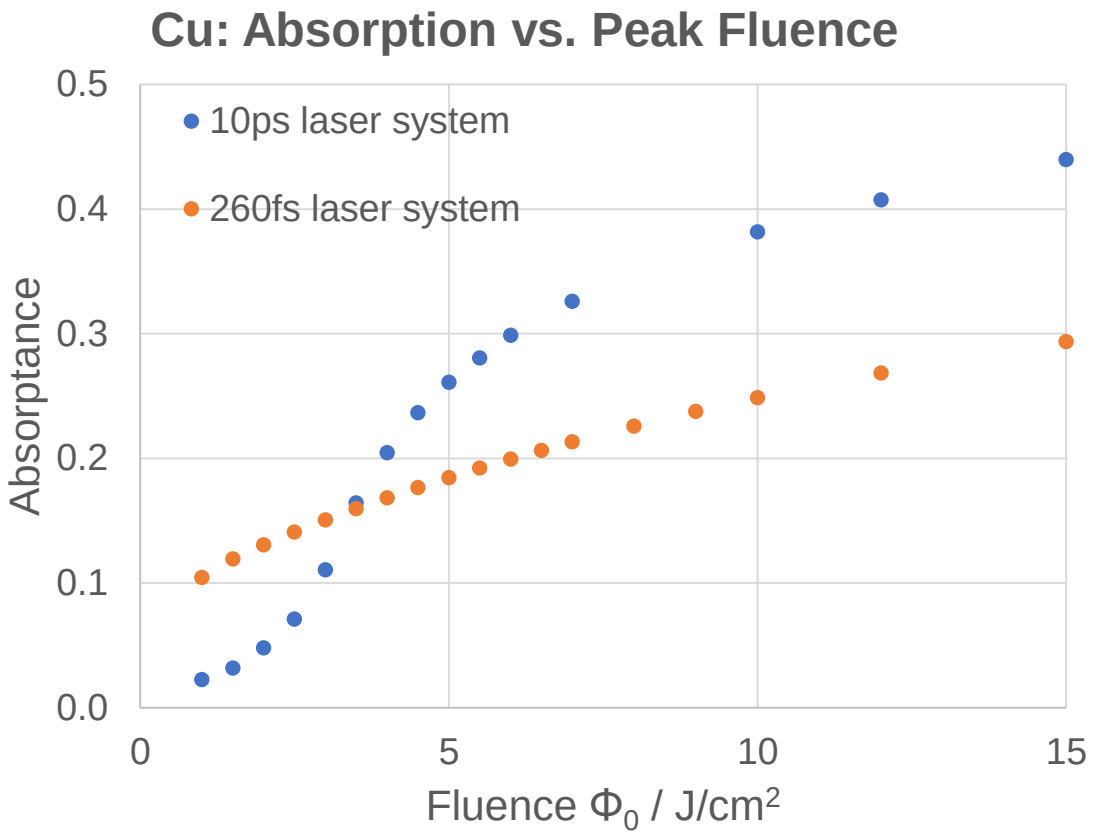
Calorimetry – Results Copper DHP



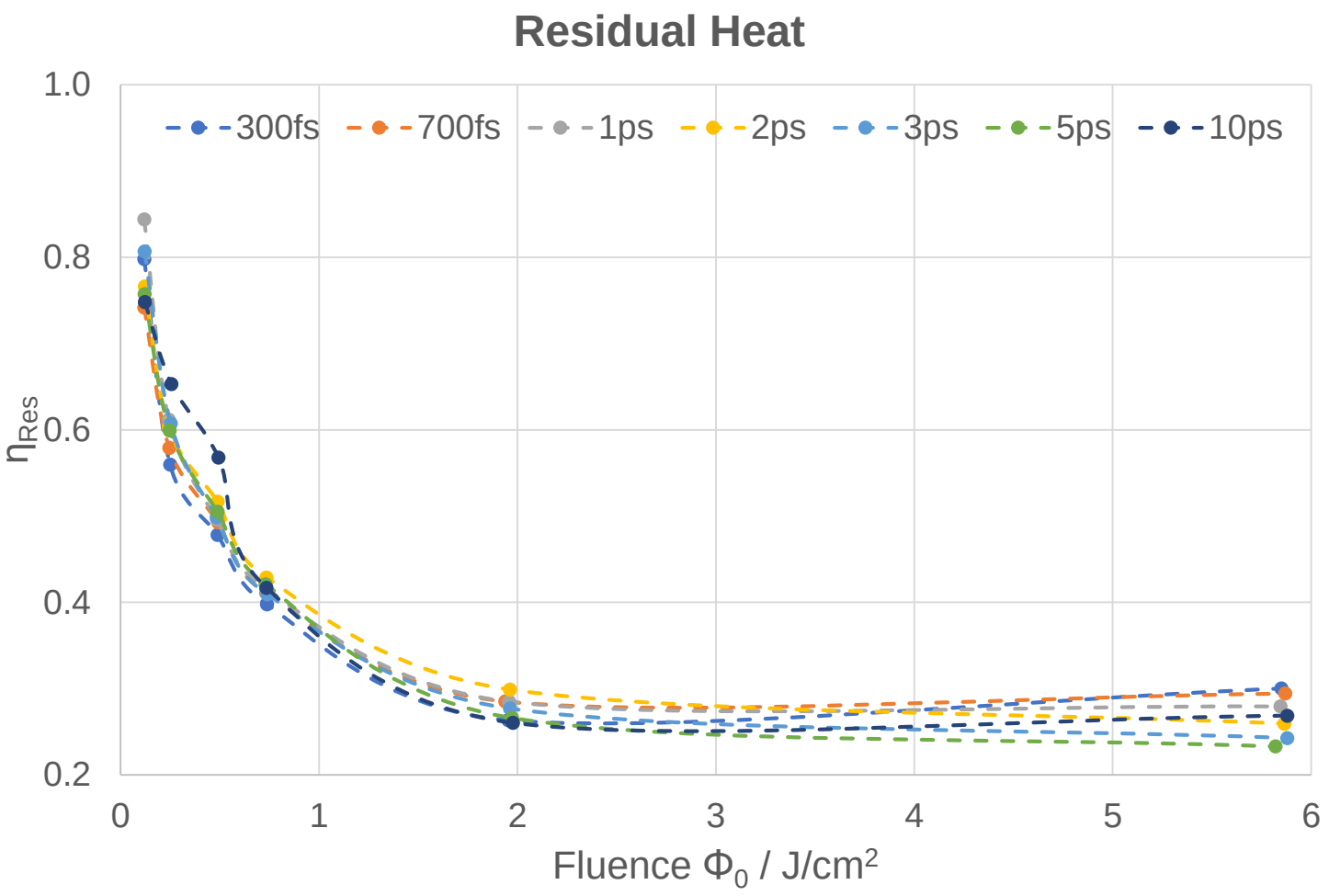
- No evidence for major impact by pulse duration
- Exceptional high relative heating meaning residual heat much higher than absorptance
  - H1: Plasma causes higher absorption -> additional energy transfer
  - H2: Fluence dependent absorption

Calorimetry – Two Temperature Model

- Two phase change models for melting and evaporation under superheating
- Calculated for a temporal gaussian shaped pulse, rotation symmetric model -> Yiming Zhang
- TTM based on:
  - S.Y. Wang, Y. Ren, C.W. Cheng, J.K. Chen, D.Y. Tzou. Applied Surface Science,Volume 265, (2013)
  - Y. Ren, J. K. Chena, Y. Zhang. Journal of Applied Physics 110, 113102 (2011)

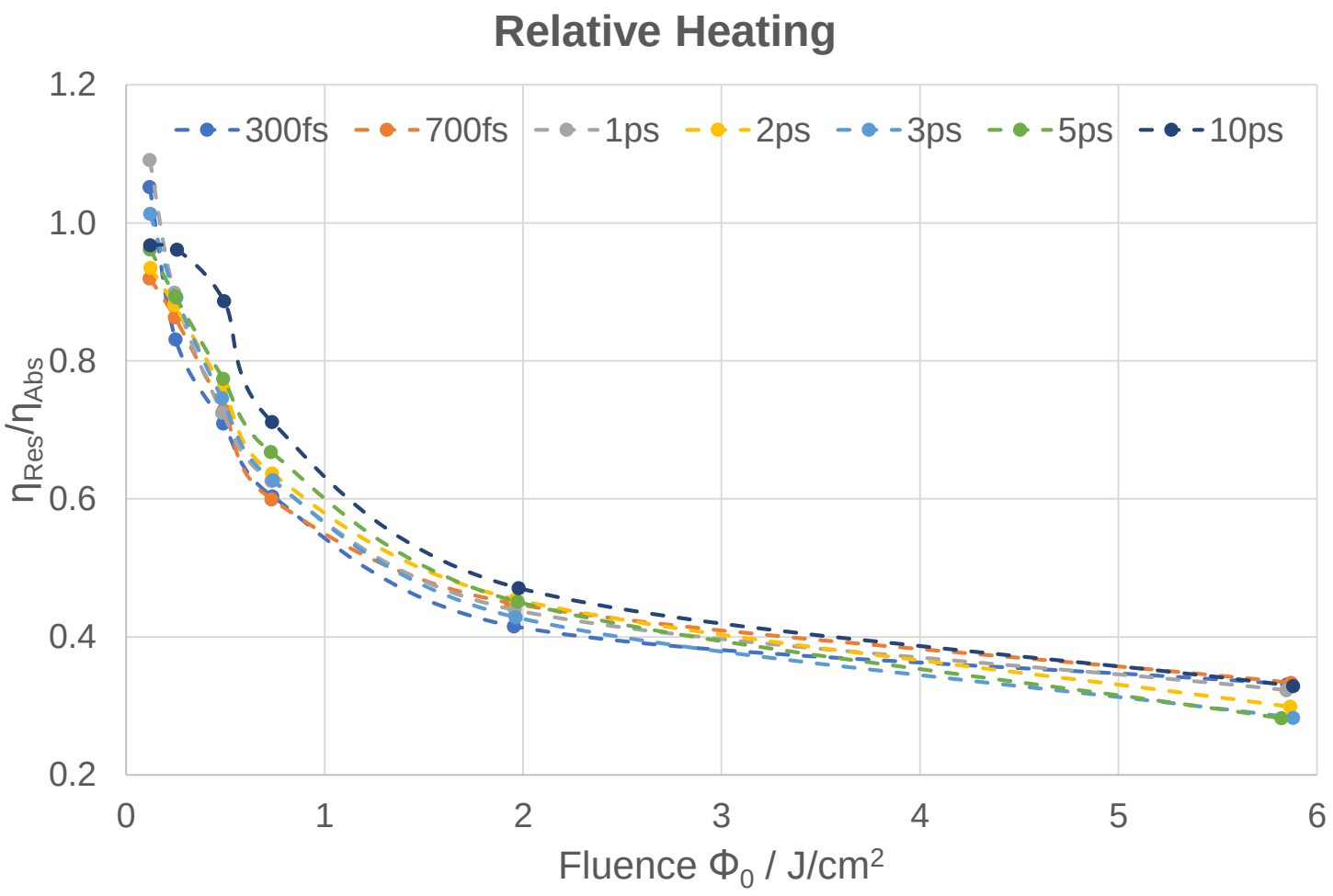


Calorimetry – Results Steel 1.4301



- Residual heat on steel for low fluences unusually high
- Fast decreasing toward 30%
- No evidence for impact by pulse duration

Calorimetry – Results Steel 1.4301



- Relative heating >1 at low fluences caused by high residual heat
- Trend follows curves from residual heat

Conclusion

- Reflectivity measurement supports shielding hypothesis
  - Pulse duration dependent intra-pulse shielding for steel
  - For copper only reasonable difference with 10ps pulses
    - Both comparable with pulse duration and double pulse experiments
- Decreasing reflectivity of copper with increasing peak fluence compatible with TTM simulation
  - However, reflectivity experiment cannot determine reason for decreasing reflectivity by increasing fluence

Conclusion

- No major evidence of pulse duration dependency indicated by calorimetry
  - Evidence was not necessarily assumed
- Two unusual results from calorimetry
  - Cu: residual heat higher than absorptance
    - 1. Hypothesis: Plasma from ablation causes higher absorption -> additional insert of energy
    - 2. Hypothesis: Fluence dependent absorption -> TTM simulation
      - Pulse duration dependency compatible with simulation
      - No such behavior for steel or at least only for 10ps
  - Steel: high residual heat for low fluences
    - No TTM simulation found for steel

Thank You for Your Attention