Thermal Changes in Optical Systems – an Analytical Approach

EPIC Meeting on Ultrafast Laser Processing at the LASER World of PHOTONICS

Dr. Tim Baldsiefen | 230627 – rev2

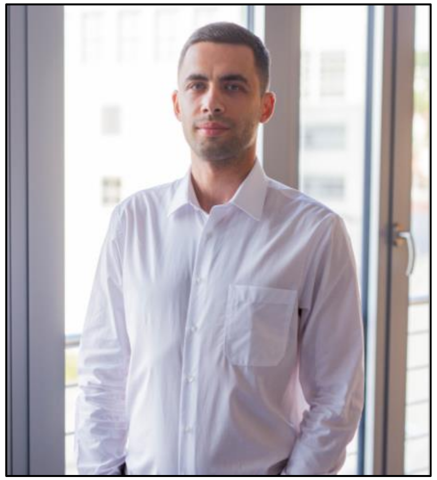
Photonics Precision Engineering GmbH (PPE)
Team in Jena

Dr. Jan Werschnik
15+ years experience

Carolin Münzberg
7+ years experience

Dr. Tim Baldsiefen
10+ years experience

Hans-Jürgen Feige
30+ years experience



Dr. Aleksei Garshin
10+ years experience

Kseniia Zavatskaia
5+ years experience

Thomas Strzeletz
5+ years experience

Dominik Schulz
3+ years experience

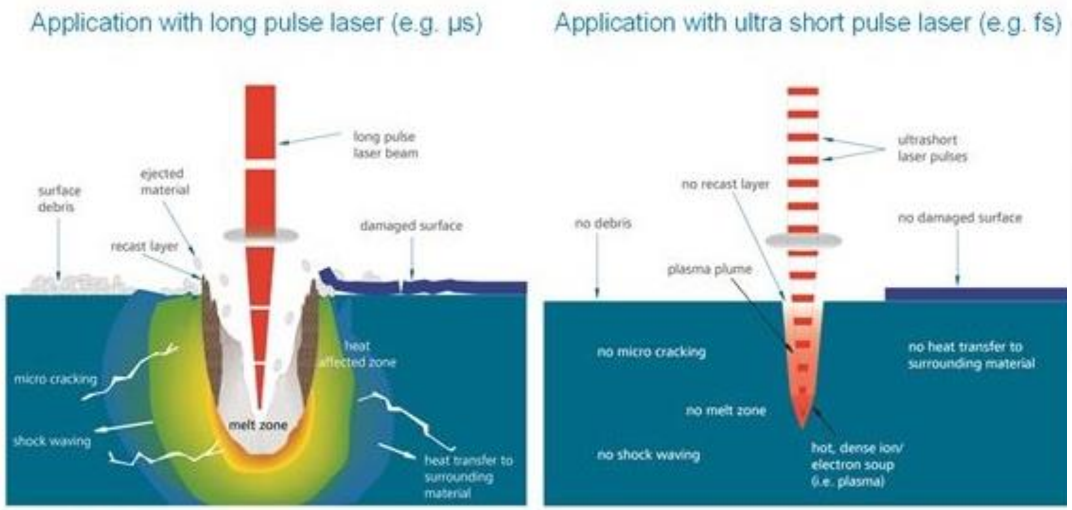
Expertise

- Optical design
- Mechanical design
- Optical metrology
- Optical engineering
- Physics
- Rigorous optical simulations (Maxwell, heat,…)
- Software development
- Data science

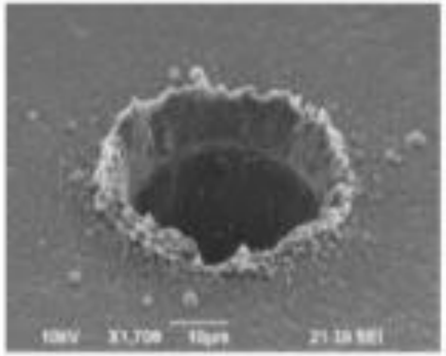
- R&D management
- Project management
- Manufacturing support
- SCM (global)

Ultrafast laser applications
Potential for higher accuracy

- Coulomb explosion compared to melting & evaporation allows higher application accuracy
- Optical system has to provide the required accuracy

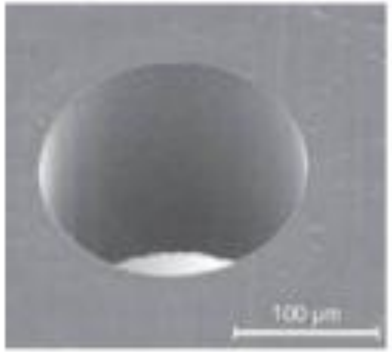


Source: Jenoptik



Nanosecond
HAZ (Heat Affected Zone)
Melt zone adds variability

Picosecond
Less HAZ
Rough surface adds variability



Femtosecond
No HAZ
Low variability

1.) Femtosecond Laser Processing Of Metal And Plastics In The Steven Hypsh; Medical Device Industry
2.) Ultrashort-pulse lasers make near-perfect walls and edges possible Bill Peatman; Industrial Laser Solutionsfor Manufacturing

Ultrafast laser applications
Potential for higher accuracy

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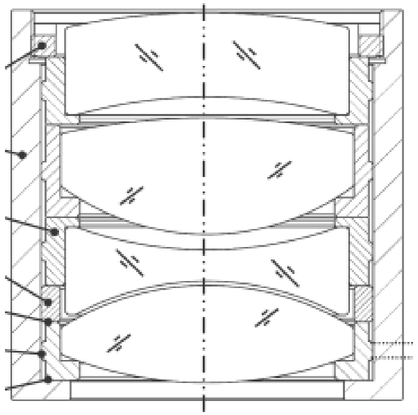
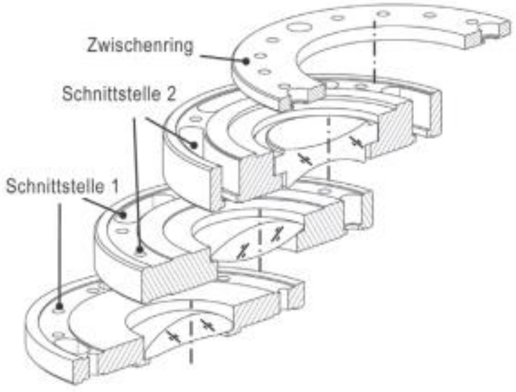
Static accuracy

- better nominal design
- better as-built performance
  - high-accuracy mechanical design
  - high-end assembly and testing

Dynamic accuracy

- performance should not change over application time
- main contributor: thermal changes



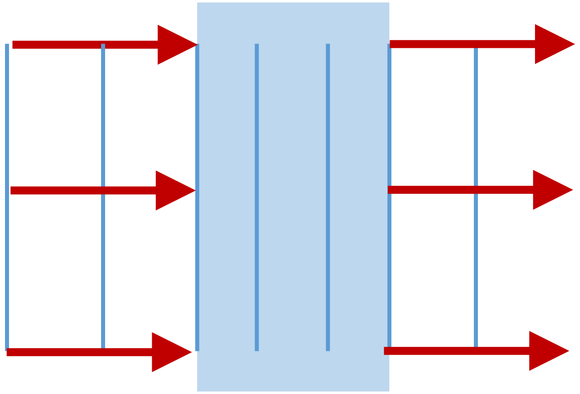


Thermal stability

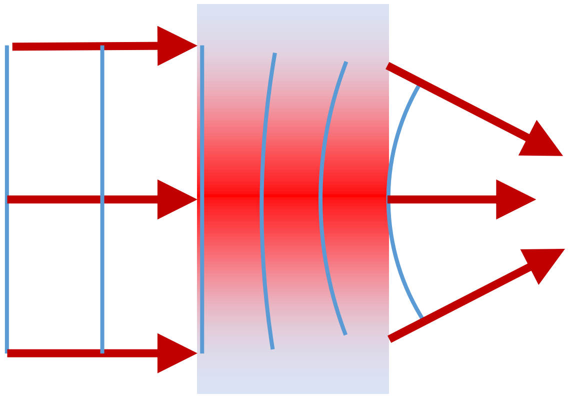
local temperature distribution

- laser power is absorbed, energy flows to edge of lens and is exhanged with surrounding heat bath
- local temperature distribution is formed
    - → index of refraction changes & material geometry
- both effects delay the light
- light at edges of lens is "faster" → focusing effect (this is independent of lens shape)

homogeneous temperature



local temperature



- since most materials show increasing index and expanding size with temperature-increase:
  → there is no compensation by design, only reduction of individual contributions
  → from system perspective one could dynamically refocus, but this requires knowledge about magnitude of focus effect

Estimating focus shift

Classical

- design draft
- give lens geometry to FEM-engineer
- receive temperature distribution
- model focus shift
- reiterate design

- cumbersome
- time-consuming
- does not help much in understanding

Optical-analytical approach (PPE)

- induced phase difference depends linearly on thickness change and index change
- thickness and index, for small temperature changes, change linearly with temperature
- → when passing through material, the induced phase difference is proportional to the **average temperature** seen along the path

Analytics

1. reformulate static heat equation for rotationally symmetric systems for the average temperature along z

$$\overline{T}(\rho)$$

2. Express lens thickness in perturbative expansion

$$\begin{aligned} d(\rho) &= d_0 + \frac{c}{2}\rho^2 \\ c &= \frac{1}{R_2} - \frac{1}{R_1} \end{aligned}$$

3. Solve for specified laser intensity distribution

Example
Gaussian input beam

$$\overline{T}(\rho) \quad = \quad \underbrace{-\frac{P(\alpha d_0 + 2\mu)}{4\pi\lambda d_0}\left(\gamma + \log\left(\frac{\rho^2}{2\sigma^2}\right) - Ei\left(-\frac{\rho^2}{2\sigma^2}\right)\right)}_{\text{solution for plate}} + \underset{\substack{\uparrow \\ \text{1st order corrections in c}}}{\Delta\overline{T}(c;\rho)} + \mathcal{O}(c^2)$$

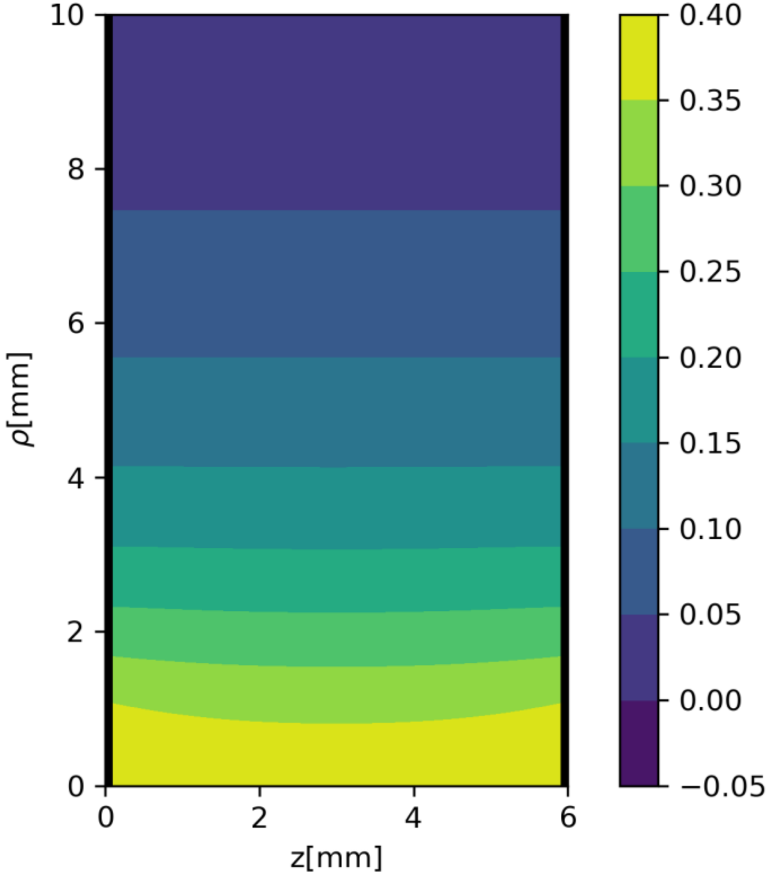
Example

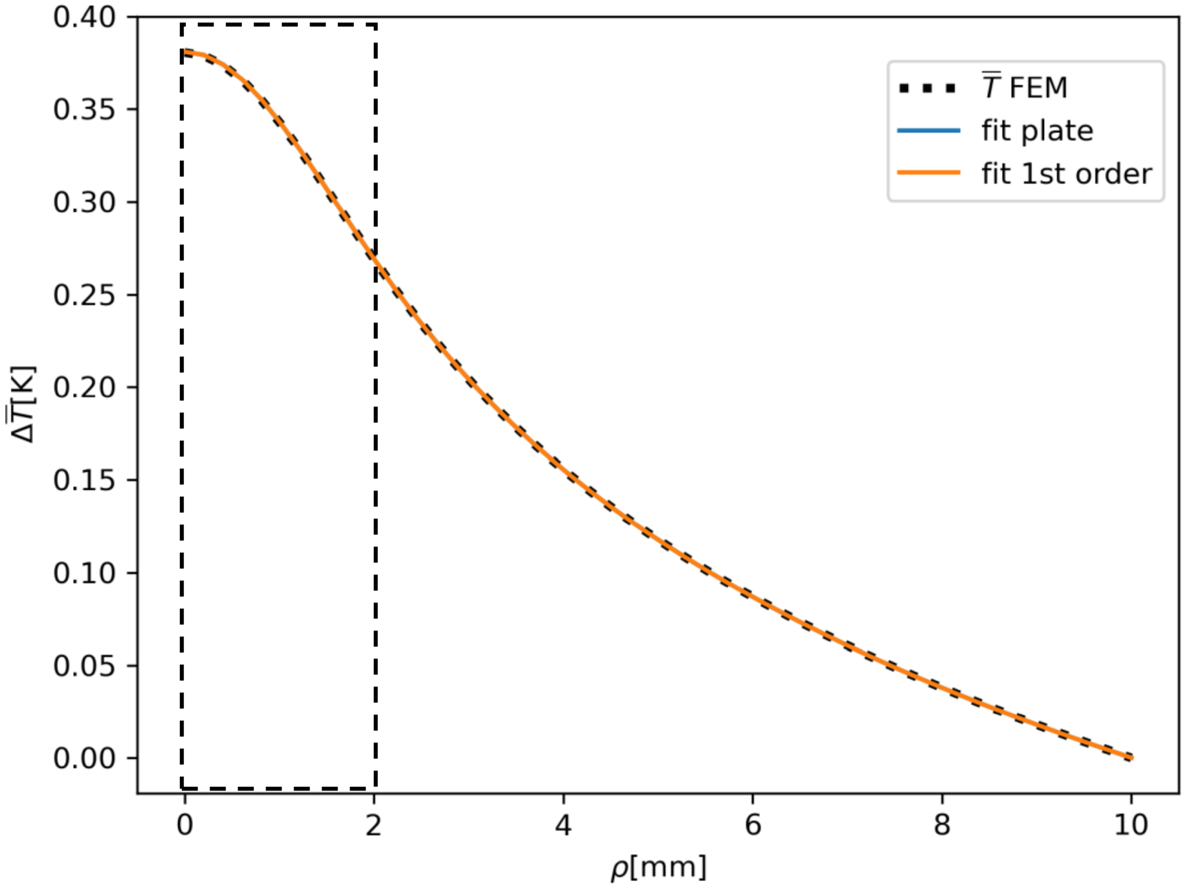
- P: input power → 1W
- λ: heat conductivity → 1W/(m*K)
- α: absorption coefficient material → 1%
- μ: absorption coefficient coating → 200ppm
- σ: beam width (= 1/e2 diameter/4) → 1mm
- d0 = center lens thickness
- c =1/R2-1/R1
- ρ: radial coordinate

- γ: Euler-Mascheroni constant (0.577…)
- Ei(): exponential integral function

Example
Plate

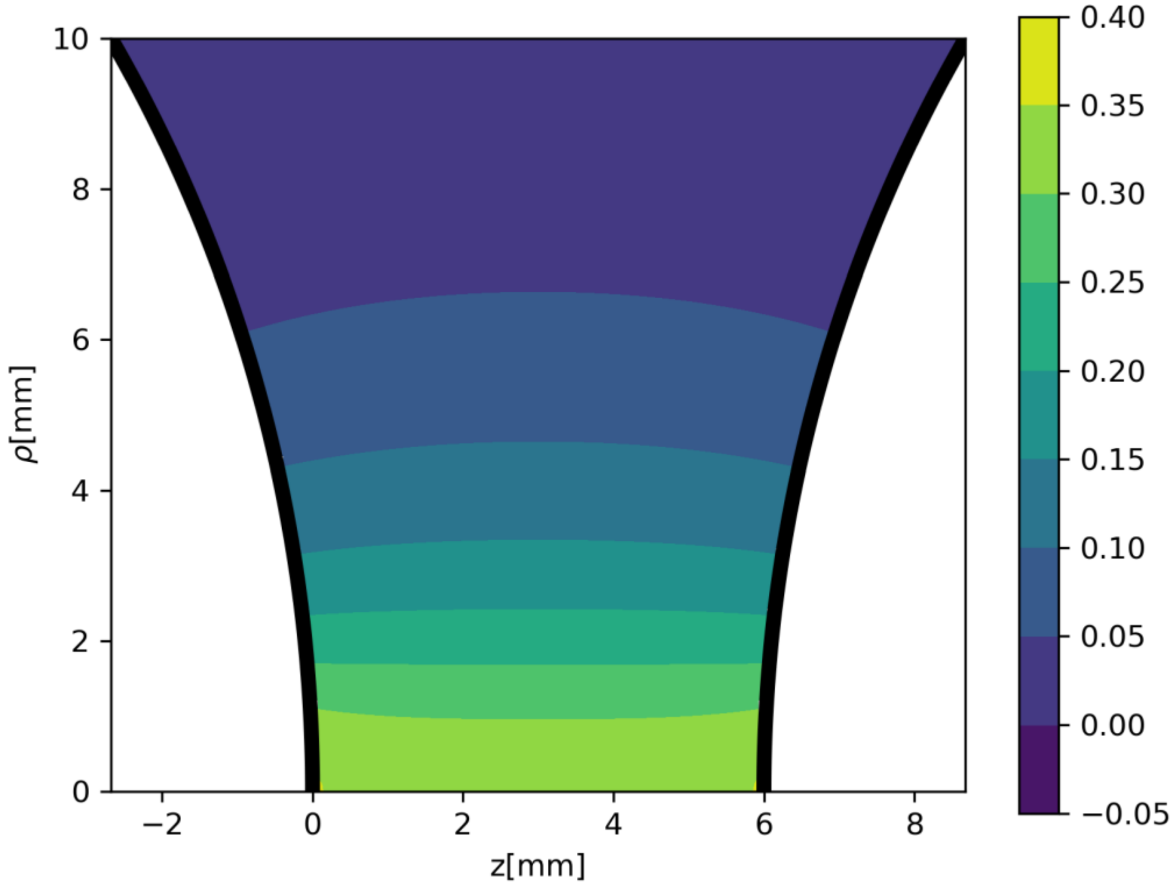
- lens diameter = 10mm; d0 = 6mm

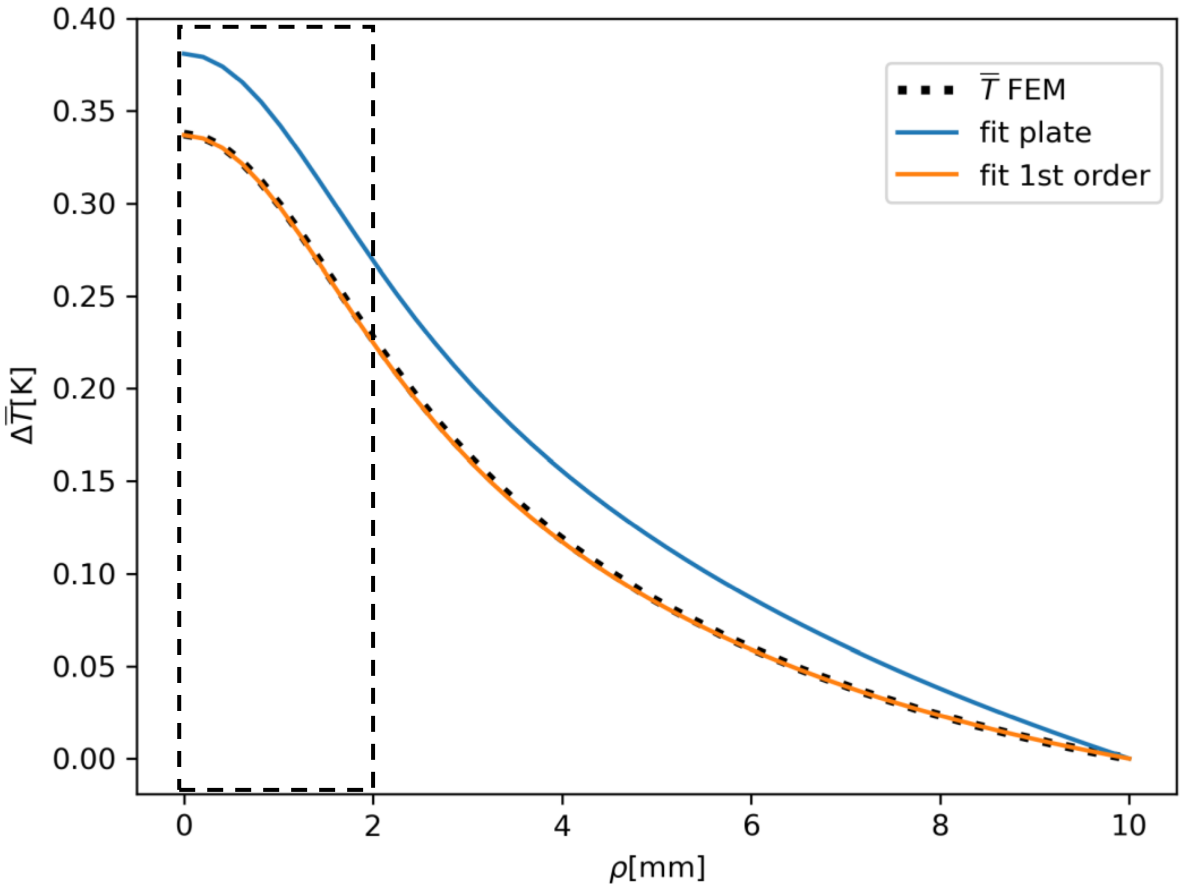




Example
bi-concave

- lens diameter = 10mm; d0 = 6mm; radius left = -20mm; radius right = 20mm





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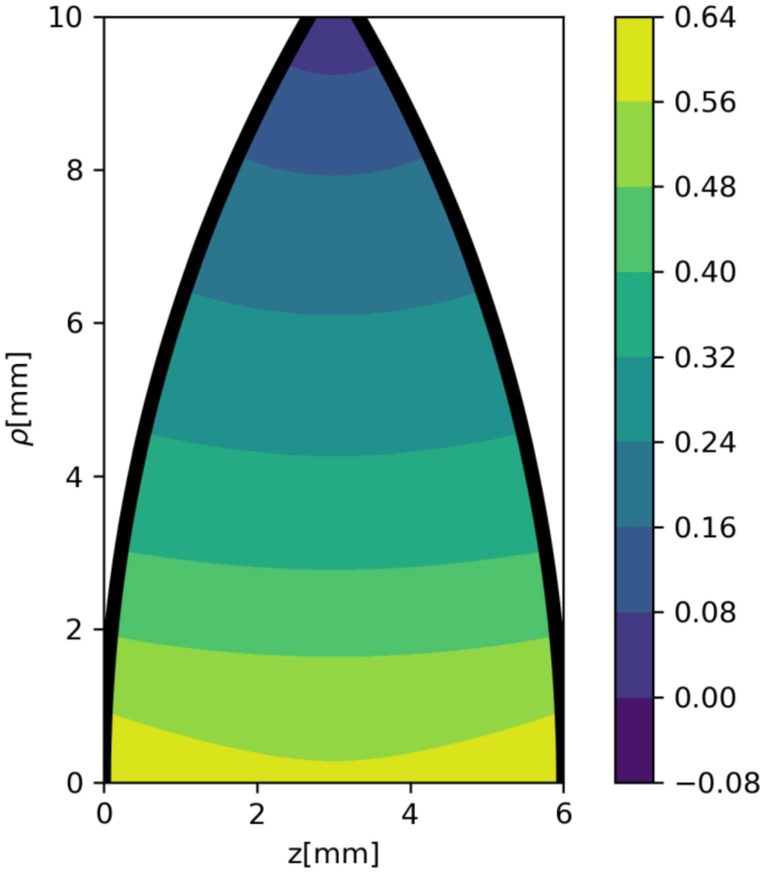

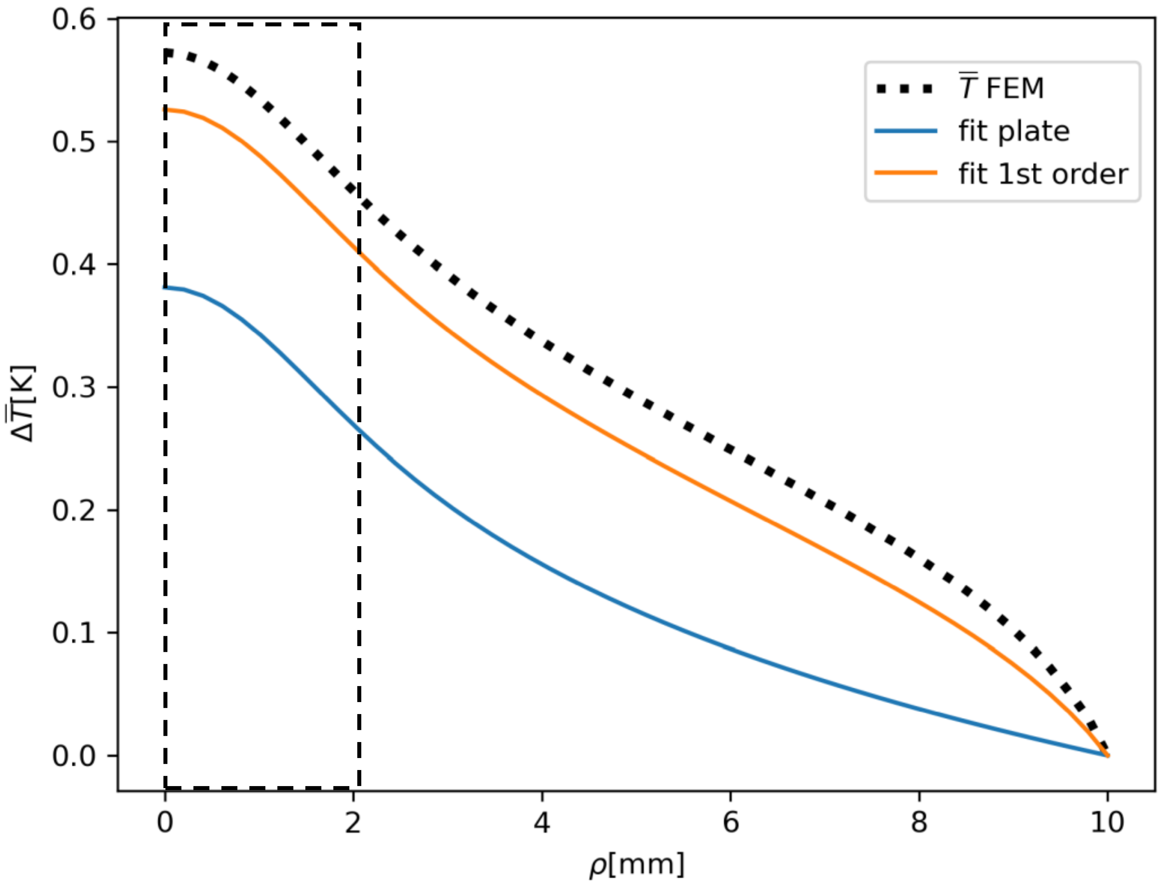

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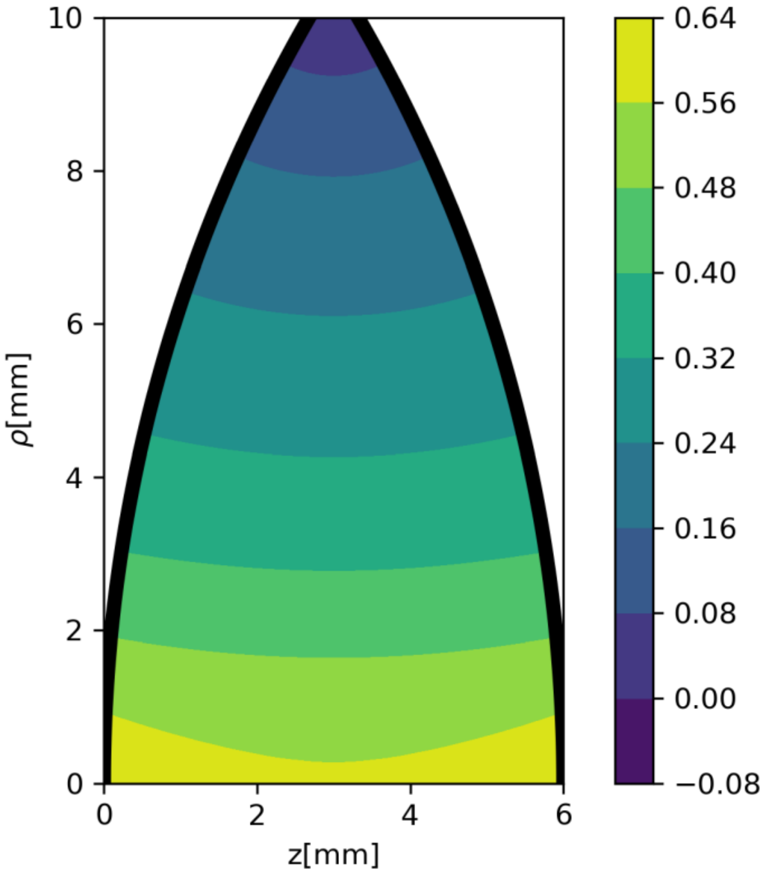
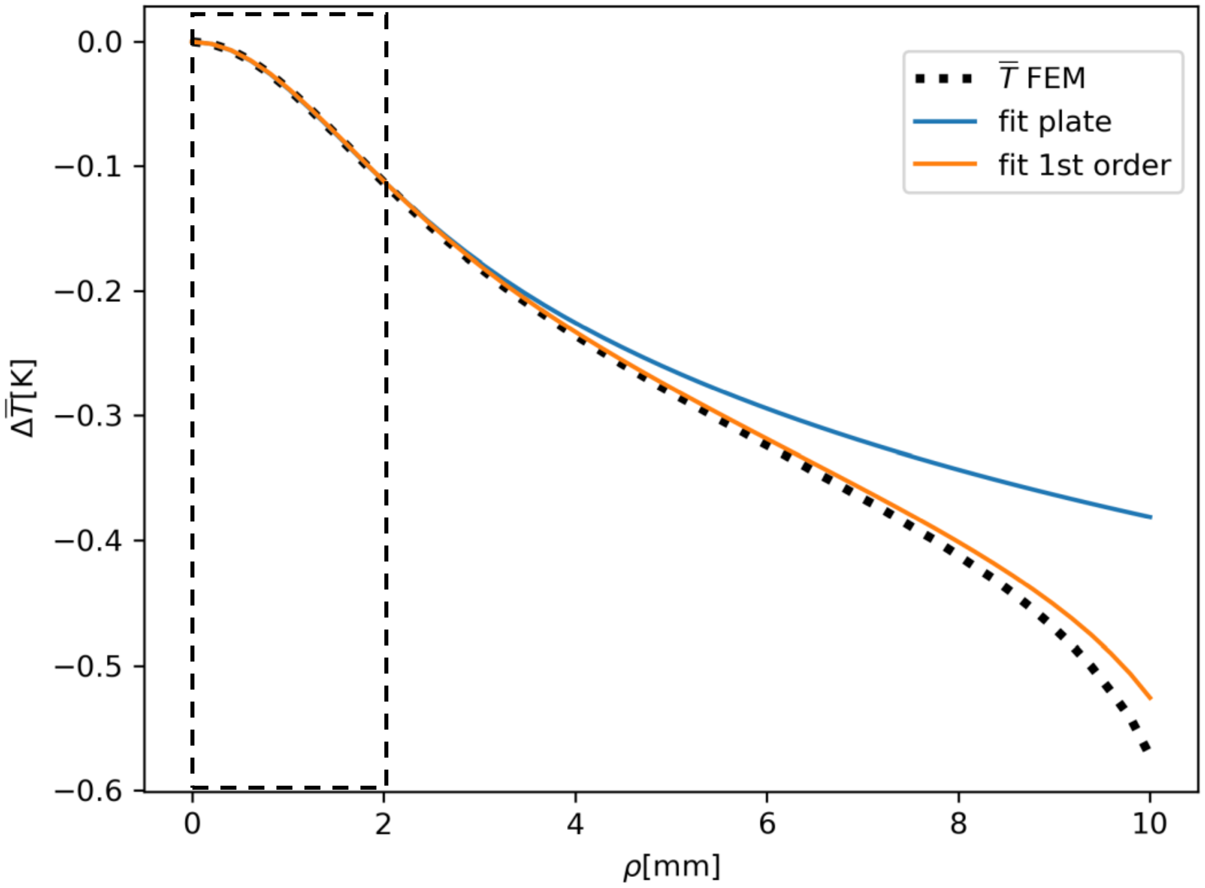


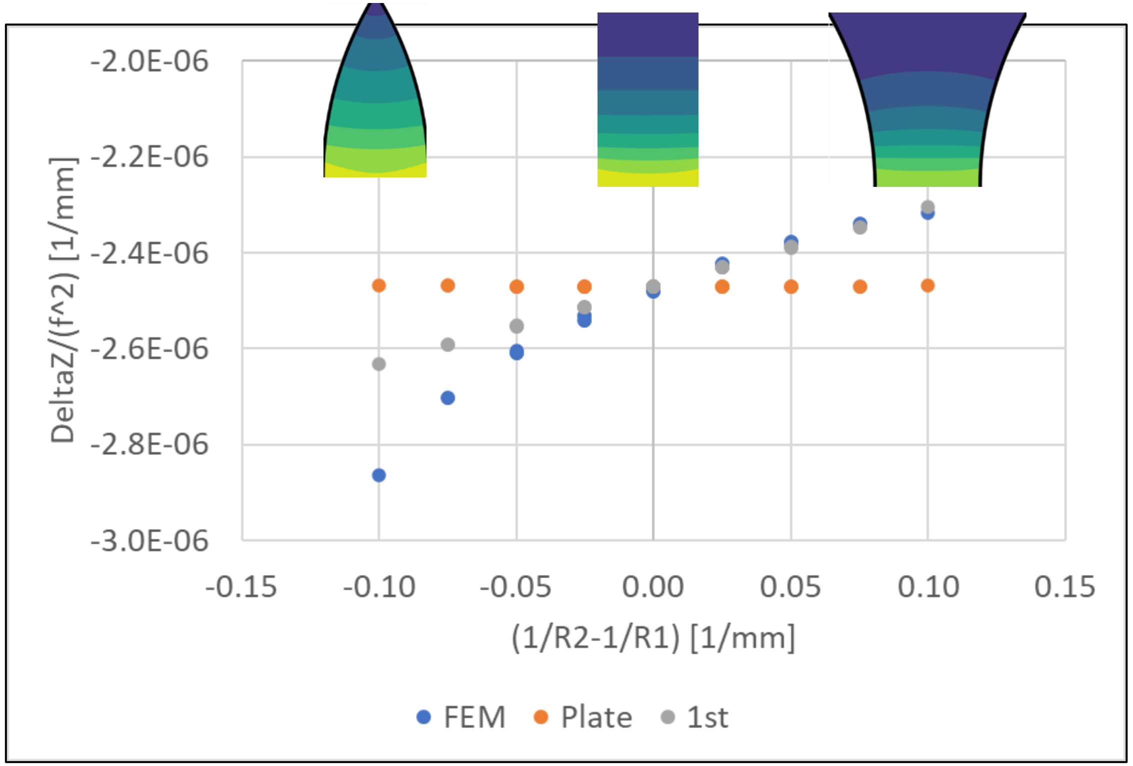


- very good agreement in regions of large intensity

Thermal focus shift

- from analytical expressions for thermal distribution, one can now derive approximations for the thermal focus shift in the image plane

$$\Delta z \quad = -\left(\frac{\partial n}{\partial T} + (n-1)\kappa\right)\frac{P_0(\alpha d_0 + 2\mu)}{4\pi\lambda}\left(\left(\frac{f^2}{\sigma^2} - 1\right)\ln(2) - 1\right) + \Delta z(c) + \mathcal{O}(c^2)$$



- κ: thermal expansion coefficient
- the 1st order correction to the focus shift already improves the estimate, especially for lenses with increasing edge thickness (1/R2-1/R1) > 0
- for lenses with strongly decreasing edge thickness, one would need to use higher order fits to the focus shift approximation

Summary

- to realize the accuracy provided by utrafast application processed, the optical system needs to conserve this accuracy
- absorbed laser light in optical system leads to formation of local temperature distribution and therefore focus shift
- this effect (almost) always moves the focus towards the optical system → compensation by design not possible
- we were able to derive simple analytical expressions to estimate the thermal distributions and the resulting focus shift
- the expressions for Gaussian input beam were compared to full FEM results and the high accuracy of the expressions was shown
  - solutions to topHat intensity distributions were also derived

- these approximations
  - → are very fast and numerically stable
  - → give insight into the interplay of physical parameters leading to the focus shift
  - → can be used in dynamic refocusing routines

- we are happy to adjust these procedures to your situation and support your application

core formulas

$$\overline{T}(\rho) \quad = \quad -\frac{P(\alpha d_0 + 2\mu)}{4\pi\lambda d_0}\left(\gamma + \log\left(\frac{\rho^2}{2\sigma^2}\right) - Ei\left(-\frac{\rho^2}{2\sigma^2}\right)\right) + \Delta\overline{T}(c;\rho) + \mathcal{O}(c^2)$$

$$\Delta z \quad = -\left(\tfrac{\partial n}{\partial T} + (n-1)\kappa\right)\tfrac{P_0(\alpha d_0 + 2\mu)}{4\pi\lambda}\left(\left(\tfrac{f^2}{\sigma^2} - 1\right)\ln(2) - 1\right) + \Delta z(c) + \mathcal{O}(c^2)$$