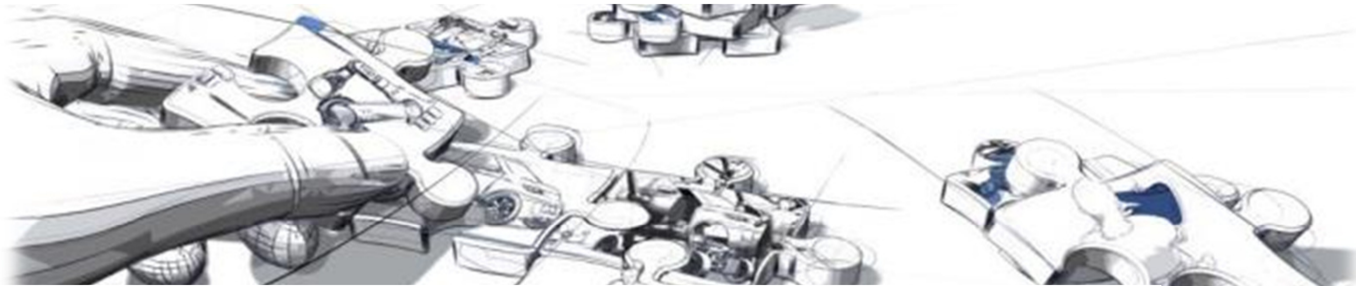
Advanced Manufacturing and Photonics for Production

Driving Innovation by Laser-based Manufacturing to the Regions of Europe



High power Adaptable Laser beams for materials prOcessing HALO

Beam Propagation and Cutting Processes

Organised by LASHARE

LASHARE

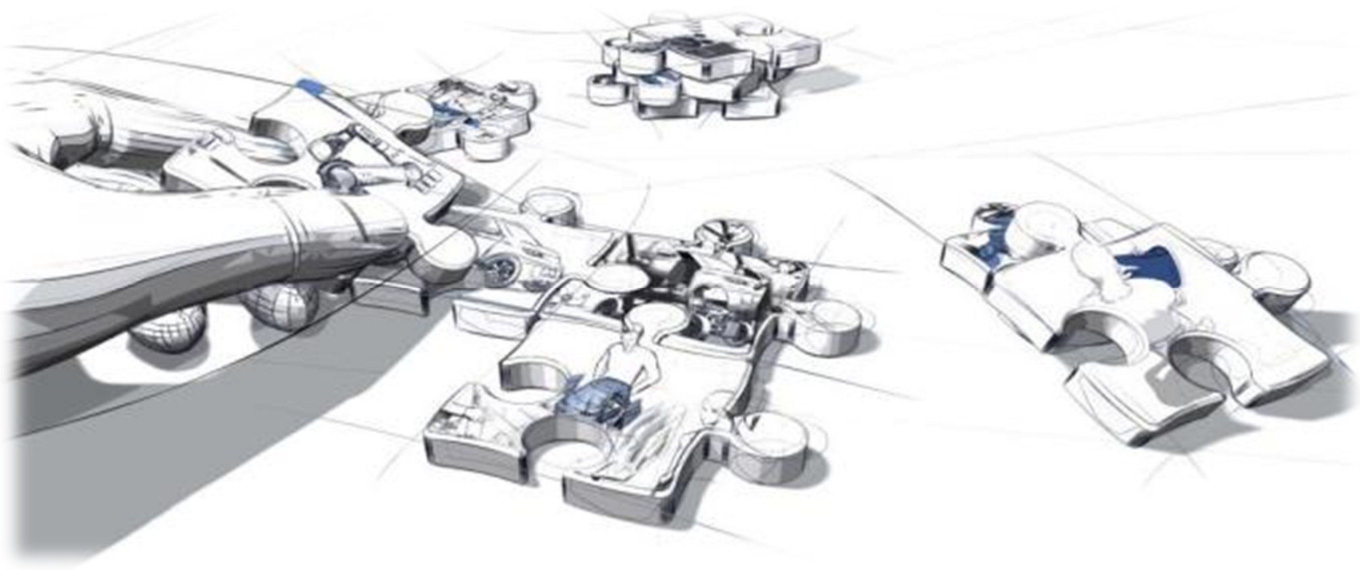
In cooperation and with the support of the European Commission, Photonics21 and Messe München AG

PHOTONICS21

LASER World of PHOTONICS

presentation@toschtec.de

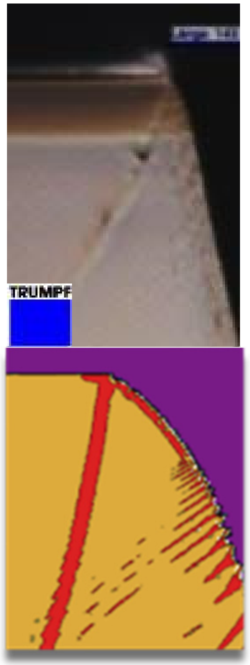
Fraunhofer ILT

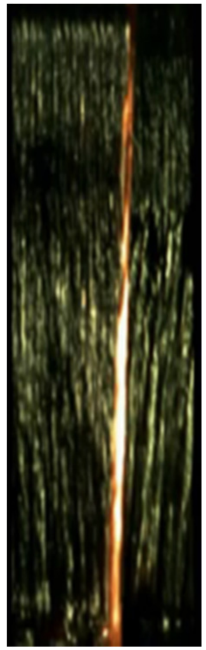


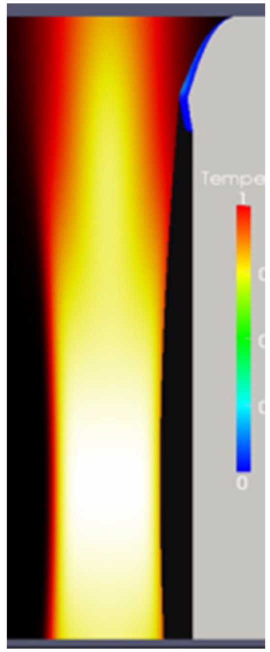
High power Adaptable Laser beams for materials prOcessing
HALO

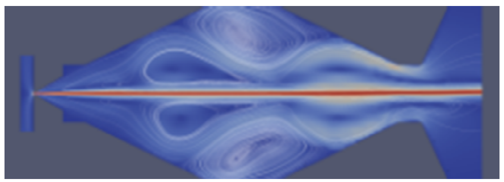
Beam Propagation and Cutting Processes

- **Project Dates**
  - 2012, september until 2016, april
- **9 partners**
  - 1 SME, 4 Industry
  - 4 RTD and Science
- **Budget**
  - $5{,}7 \times 2^6 \times 5^6$ €
- **Demonstrators:**
  - beyond “ablation stop” diffractive optics – glass cutting
  - beyond “shadow instability” beam modification – sheet metal cutting
  - beyond “nozzle damage” beam shaping by water jet – precision cutting







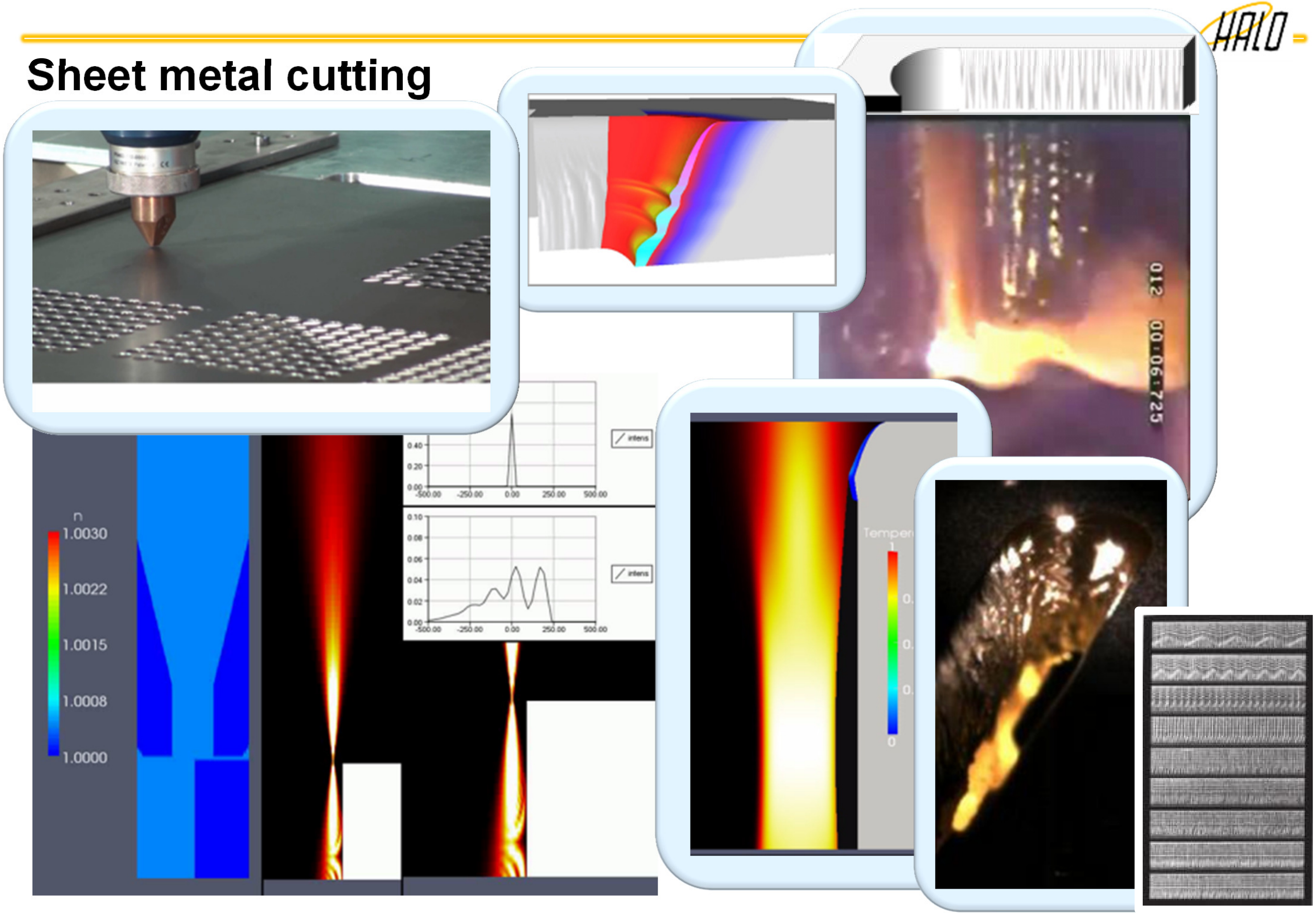


Fraunhofer ILT

The European Perspective

- **Innovations transferred to real world applications**
  beam shaping optics breaking the relevant technical limits
  of leading laser machine markets – now and in future:
  - sheet metal cutting
  - glass cutting
  - water-jet cutting
- **Virtual Production added to Production**
  Meta-Modeling enables to cope with multi-dimensional data :
  - FAST FAst & frugal Simulation Tools by web-application
  - GOT Global Optimization Tools using Morse-Smale Complex/Hyperslices
  - IT IT solutions for development
- **Advances for European Manufacturing**
  beam shaping and modulation is seen to be the key for
  - innovations in laser manufacturing for the next century

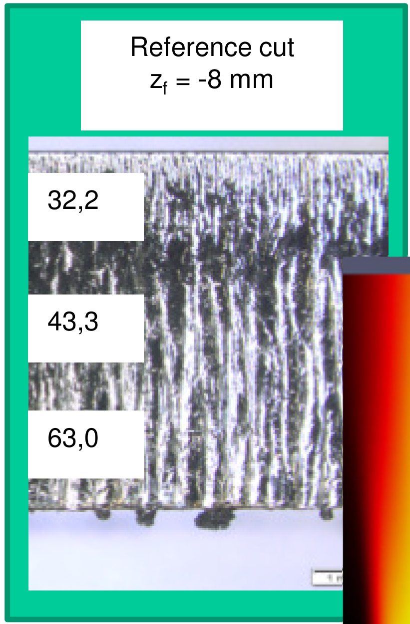
Sheet metal cutting

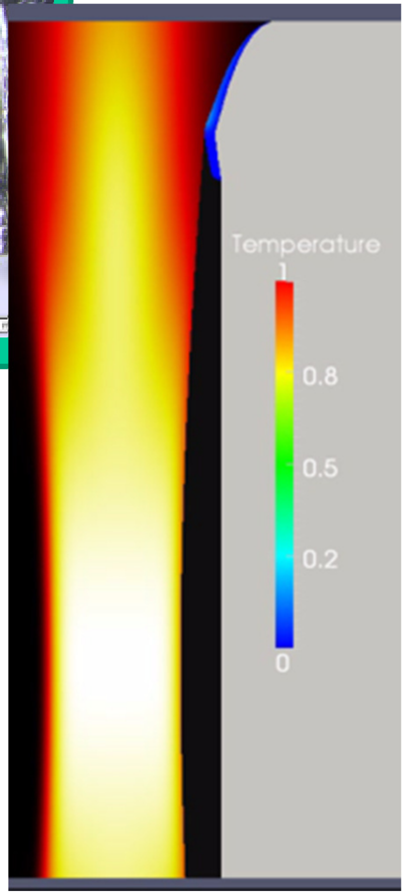


Research Question

1. How to achieve small roughness
   with figer-guided radiation R_z>40 µm @ d=6mm ?

   For sheet metal cutting with mirror guided radiation
   R_z<10µm @ d=12mm is well established!

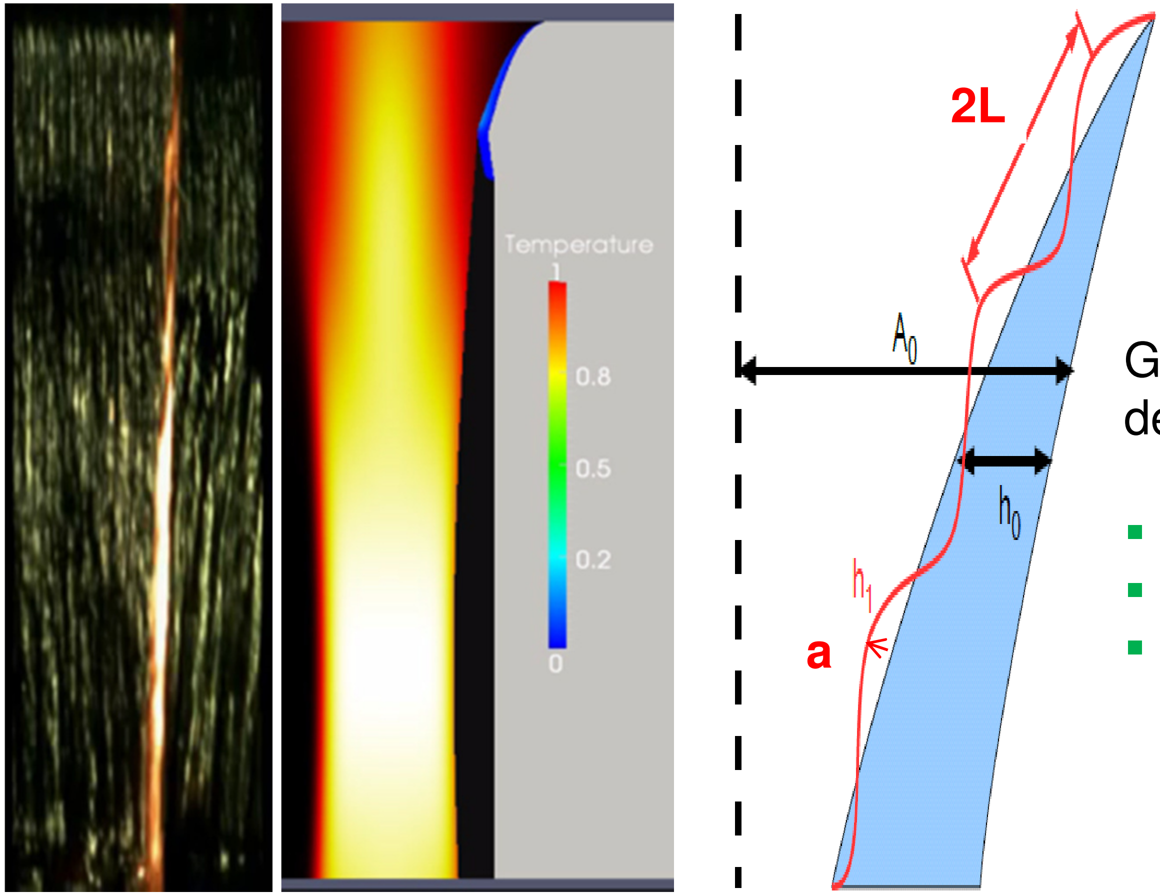




Research **Hypothesis**

1. Avoid shadowing of laser radiation at the cutting front
   → divergent beam shaping! (DE102007024700 FhG ILT)
   → decrease the angle of incidence! (DE10200702470 FhG ILT)

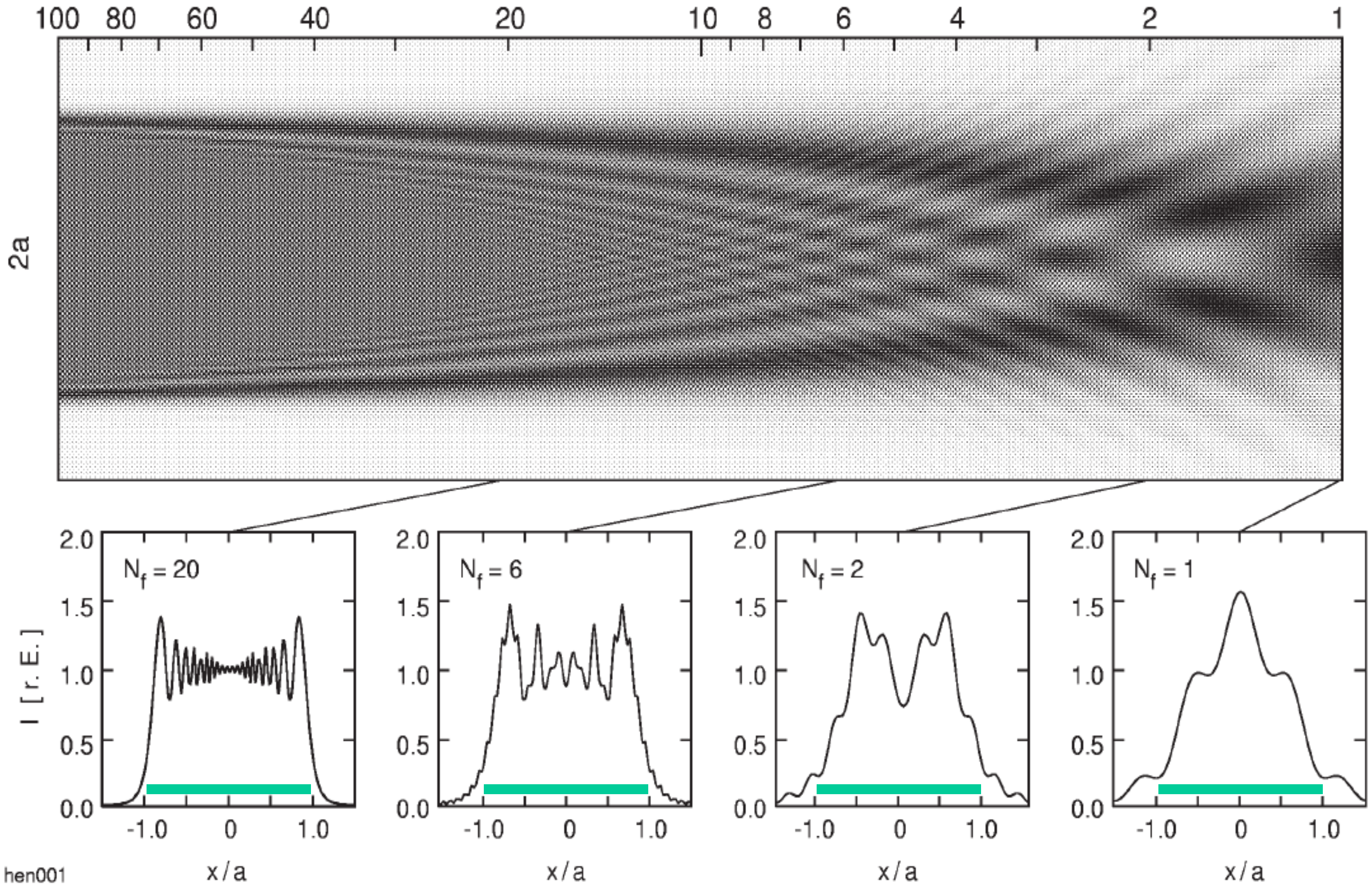
Geometric-optical shadow



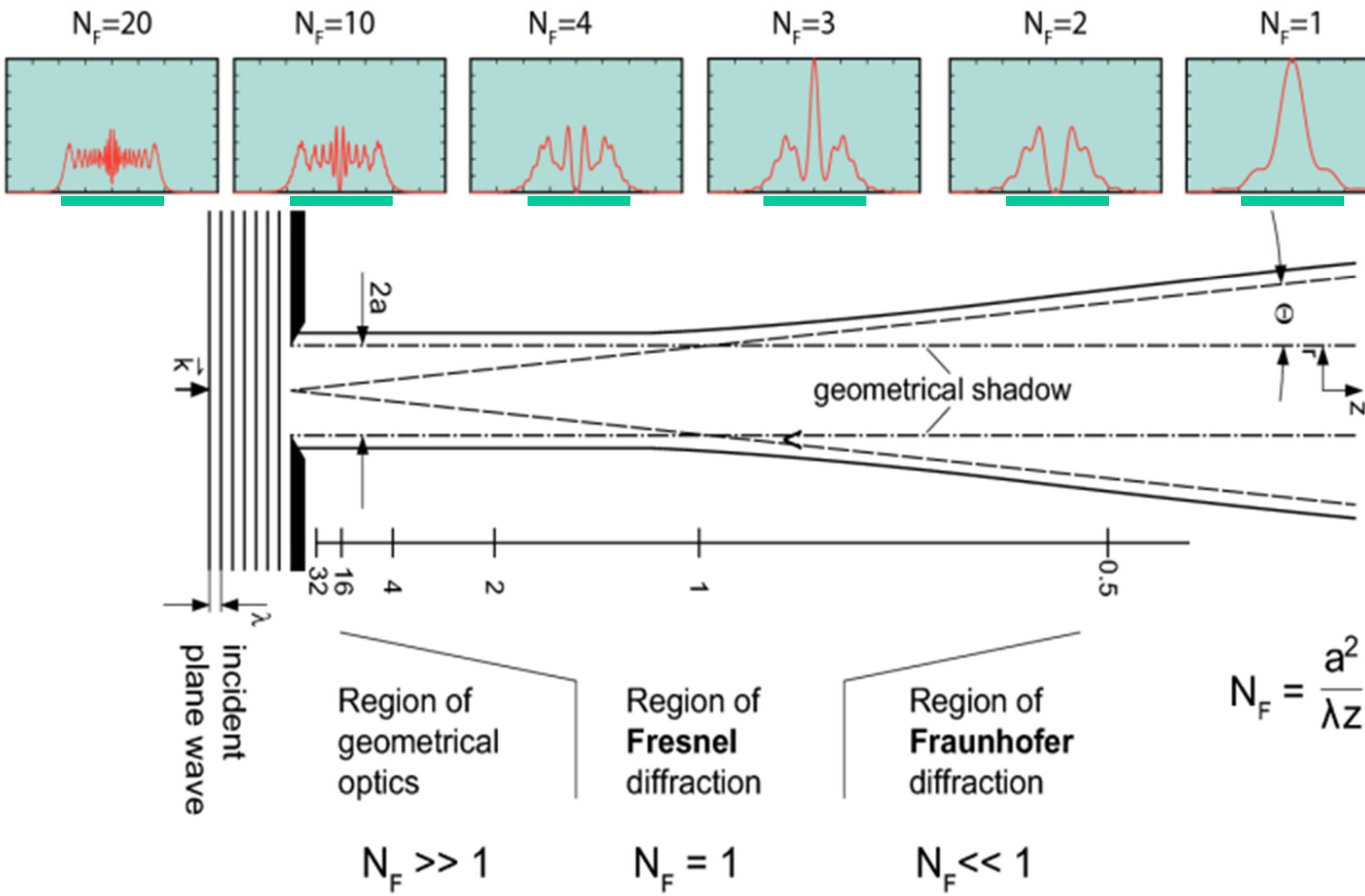
Geometric-optical shadow depending on

- wave amplitude a
- wave length 2L
- angle of inclination

Diffraction at a slit
Fresnel-number $N_f = a^2/(\lambda L)$



Diffraction pattern – Fresnel-number N_F

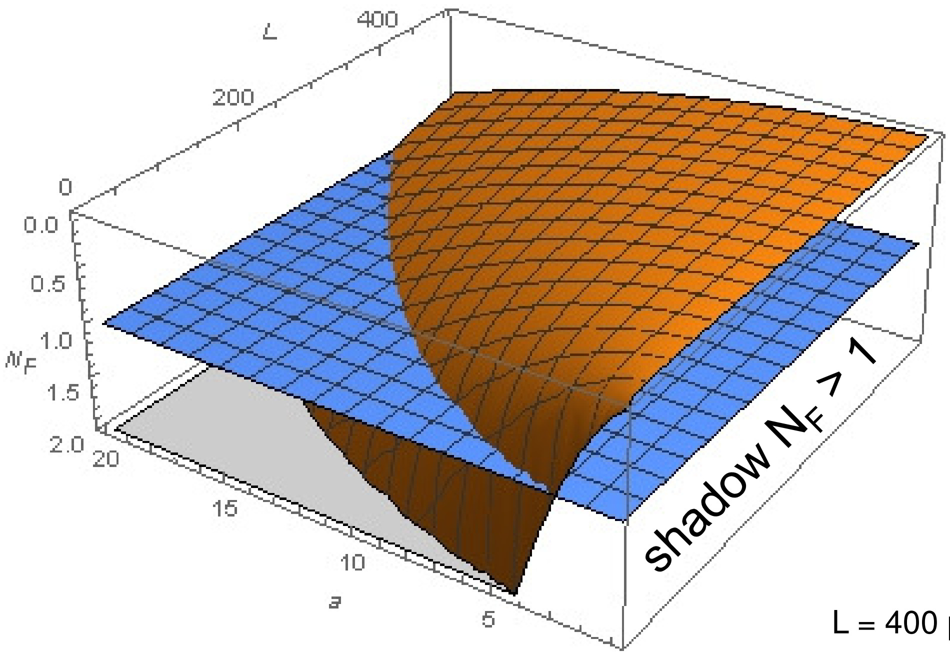


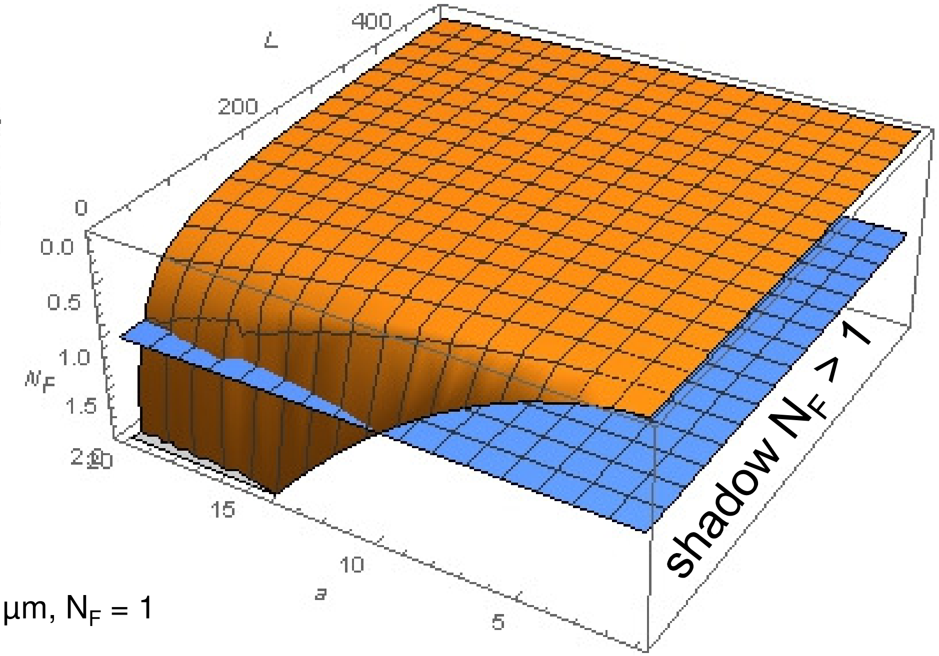
$$N_F = \frac{a^2}{\lambda z}$$

Geometric-optical shadow dominates for Fresnel-number $N_F < 1$

a < 20 µm @ 1µm

a < 60 µm @ 1µm



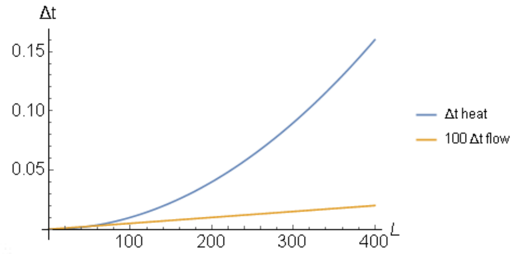


L = 400 µm, N_F = 1

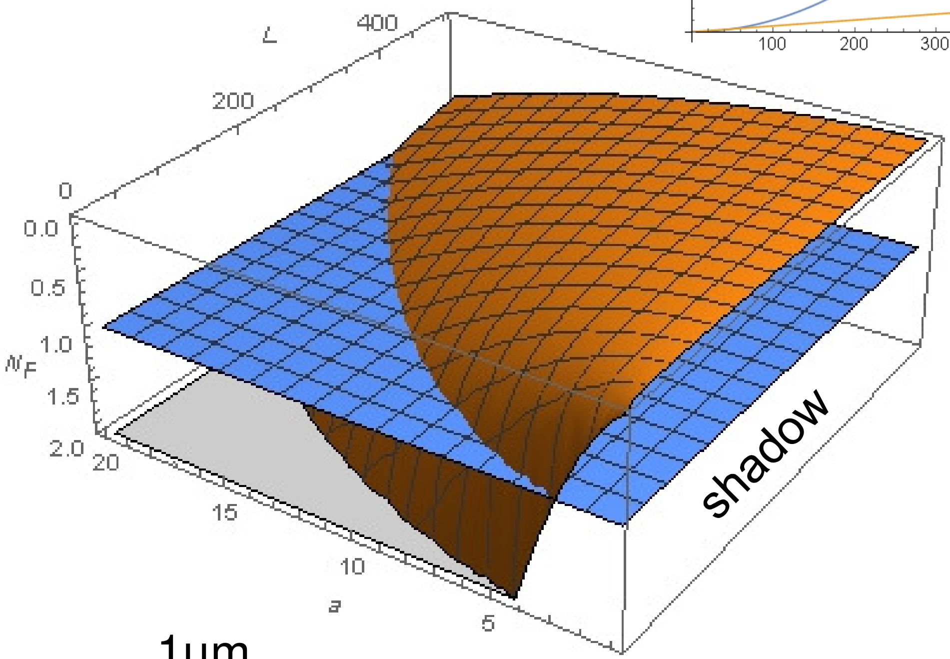
Geometric-optical shadow dominates for Fresnel-number $N_F < 1$

$L = 400\ \mu m,\ N_F = 1$

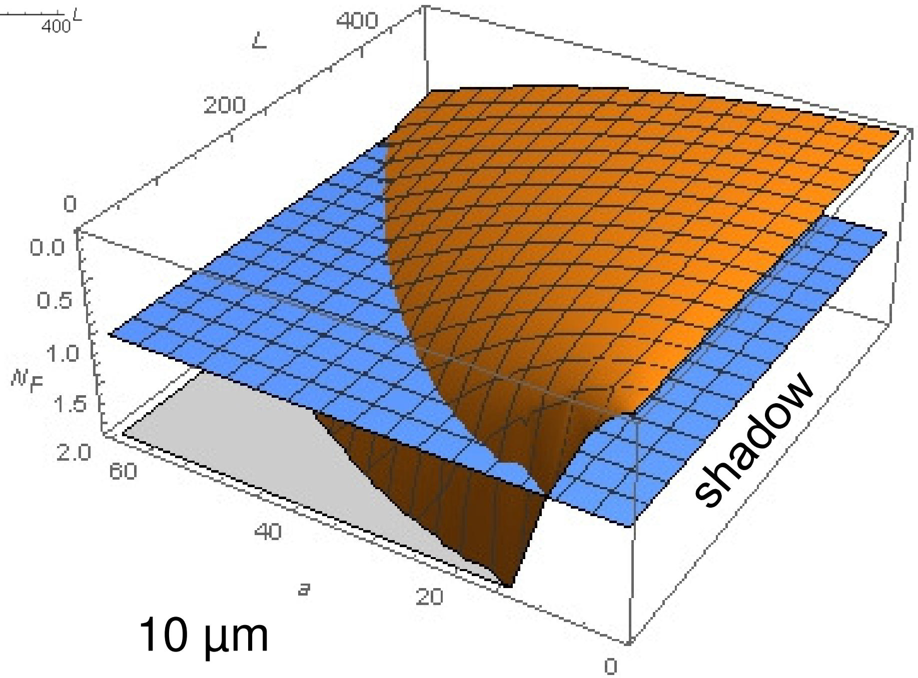
a < 20 µm



a < 60 µm



1µm



10 µm

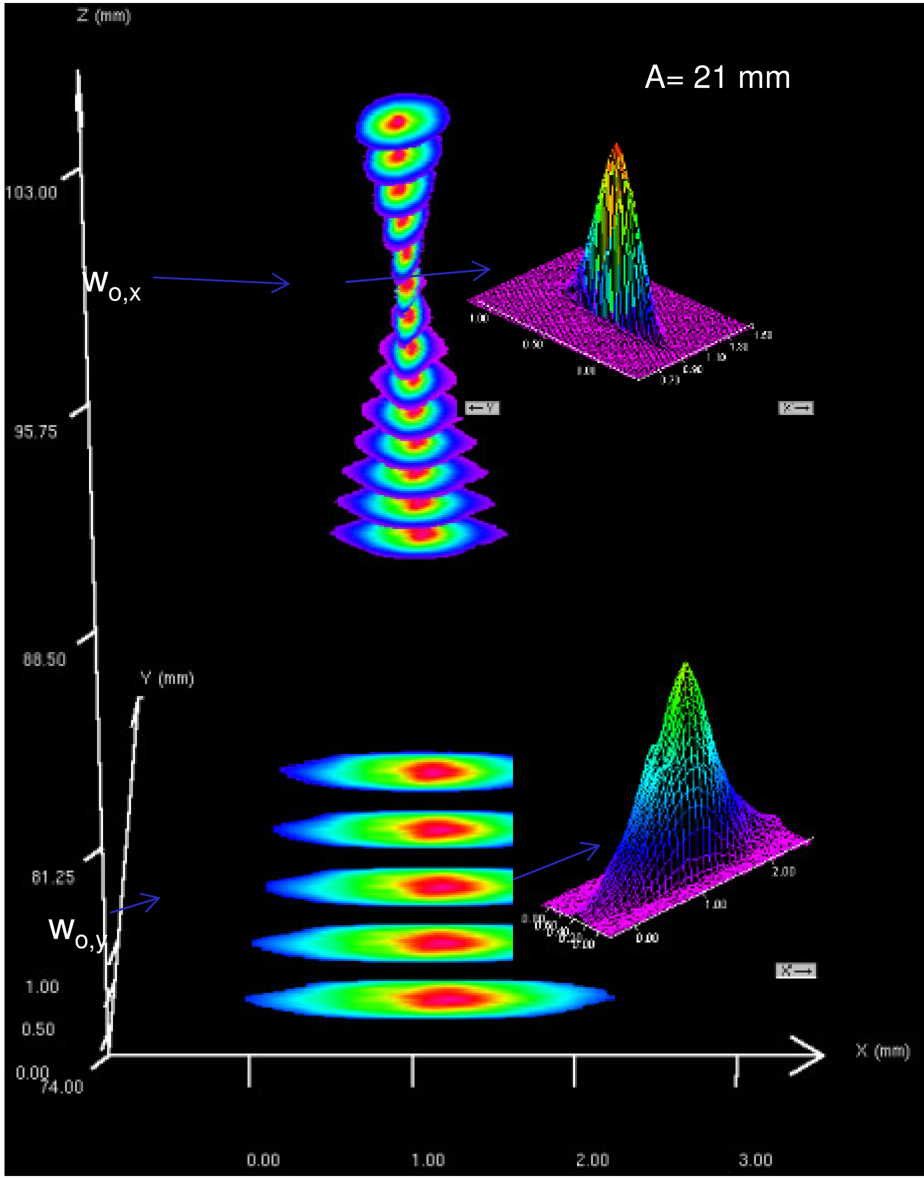
Elliptical beam shape

Research Question

1. How to achieve small roughness with figer-guided radiation?
2. Use of elliptical beam shape
   → decreases angle of inclination?
   → stabilizes melt flow?

Research Hypothesis

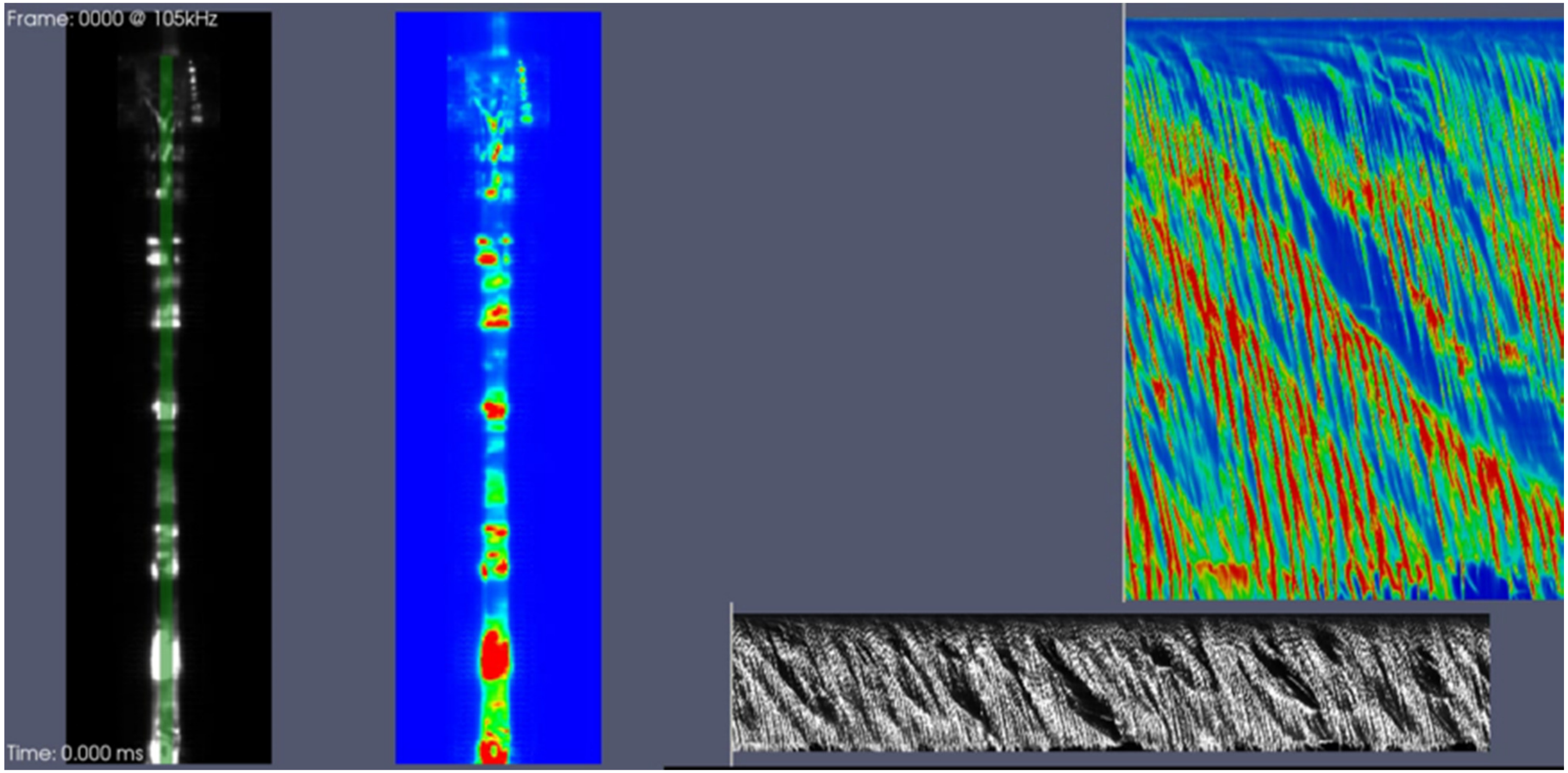
1. Avoid shadowing of laser radiation
   → divergent beam shaping!
   (DE102007024700 FhG ILT)
   → decrease the angle of incidence!
   (DE10200702470 FhG ILT)
2. Stabilized melt flow
   at the apex of the melt front!
   Apex is observable
   by high-speed videography!



Streak analysis – Method I

A = 0 mm
w0 = 120 µm
z_F = -8 mm
d = 8 mm
v_0 = 1.5 m/min

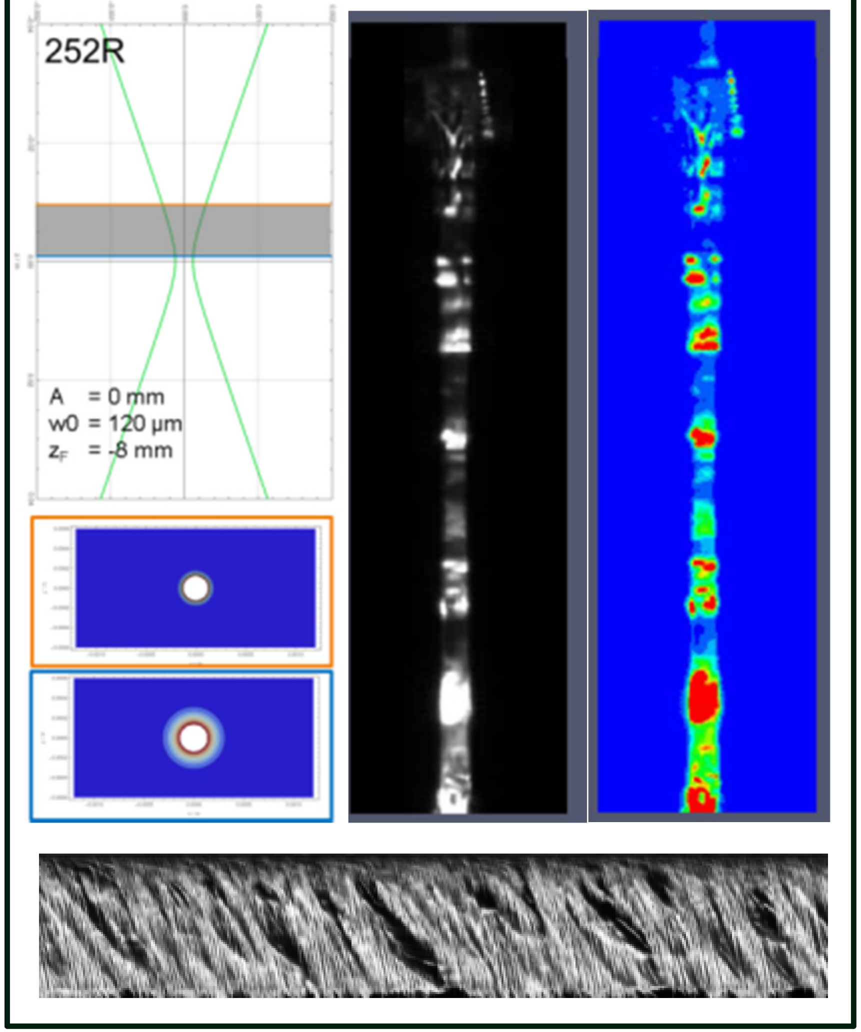
Extraction of one-dimensional time series from high speed videos



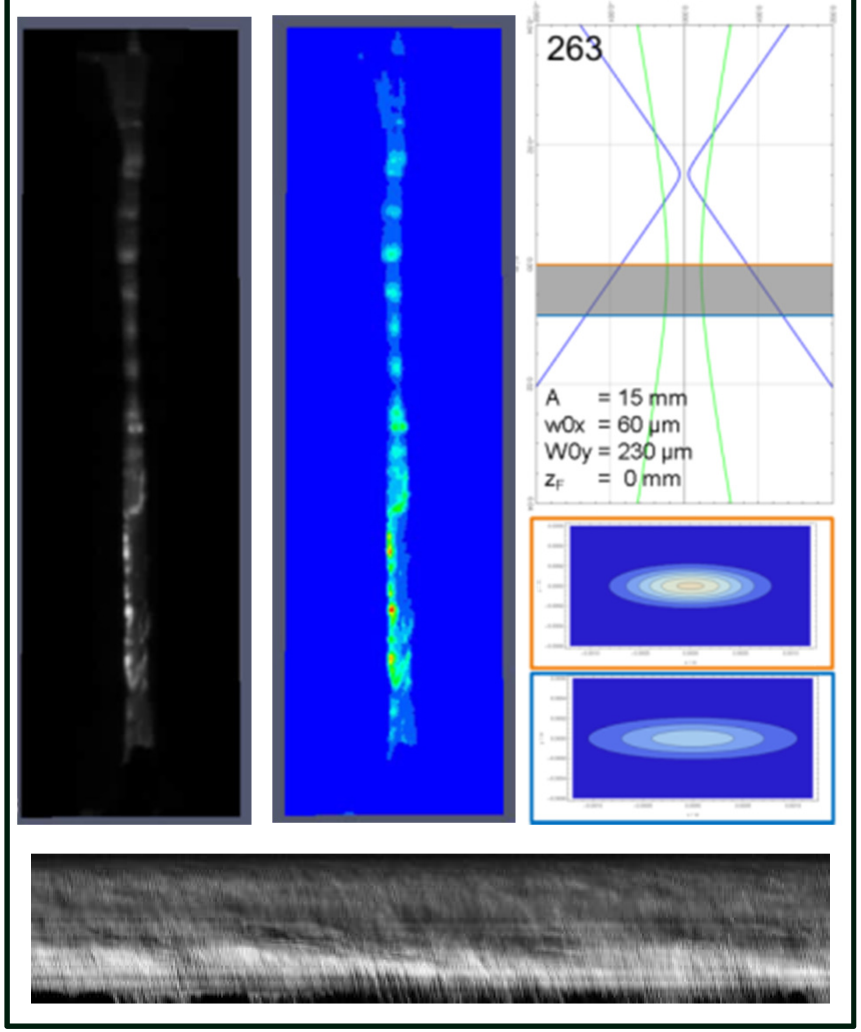
time

High speed videography → streak imaging

Reference cut

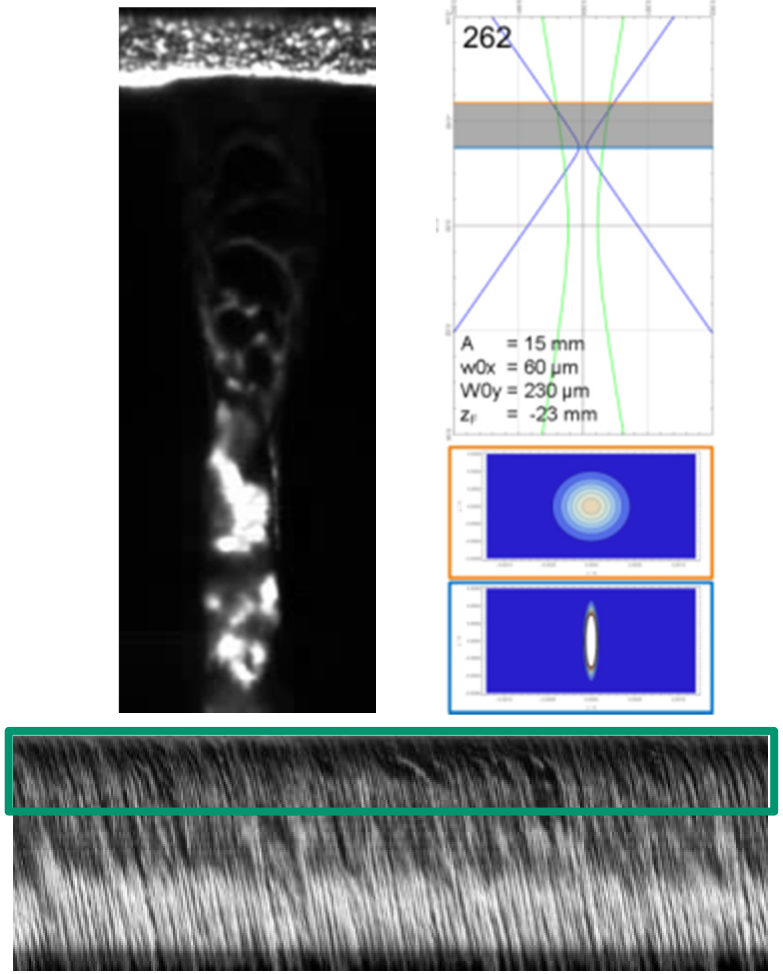


Stabilzed melt flow

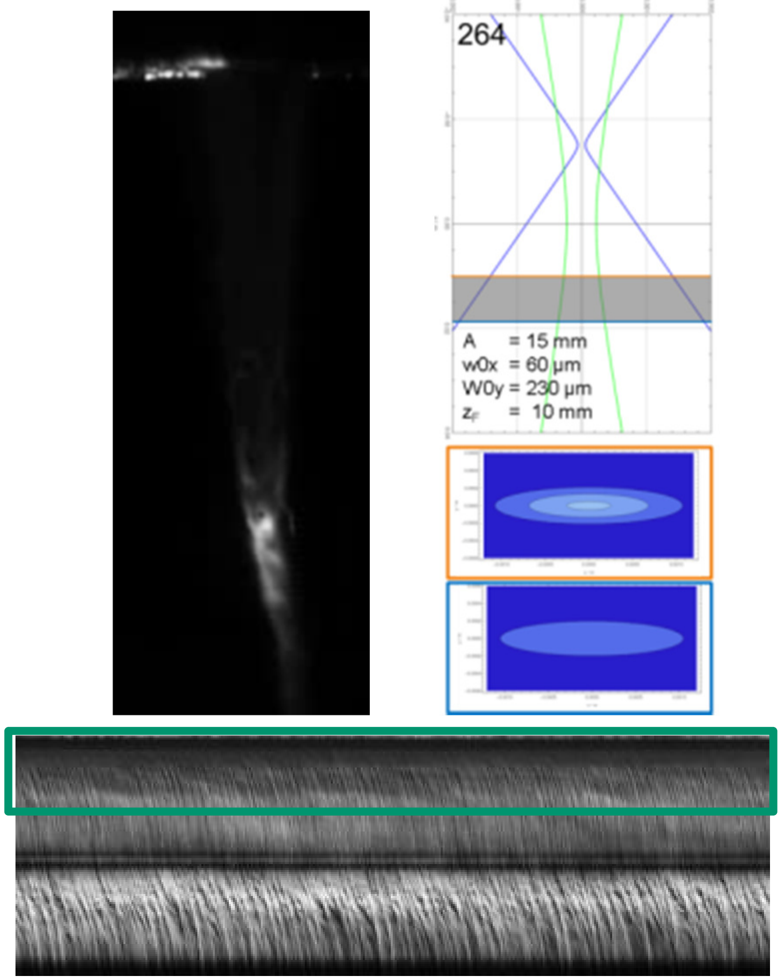


High speed videography of entrance edge

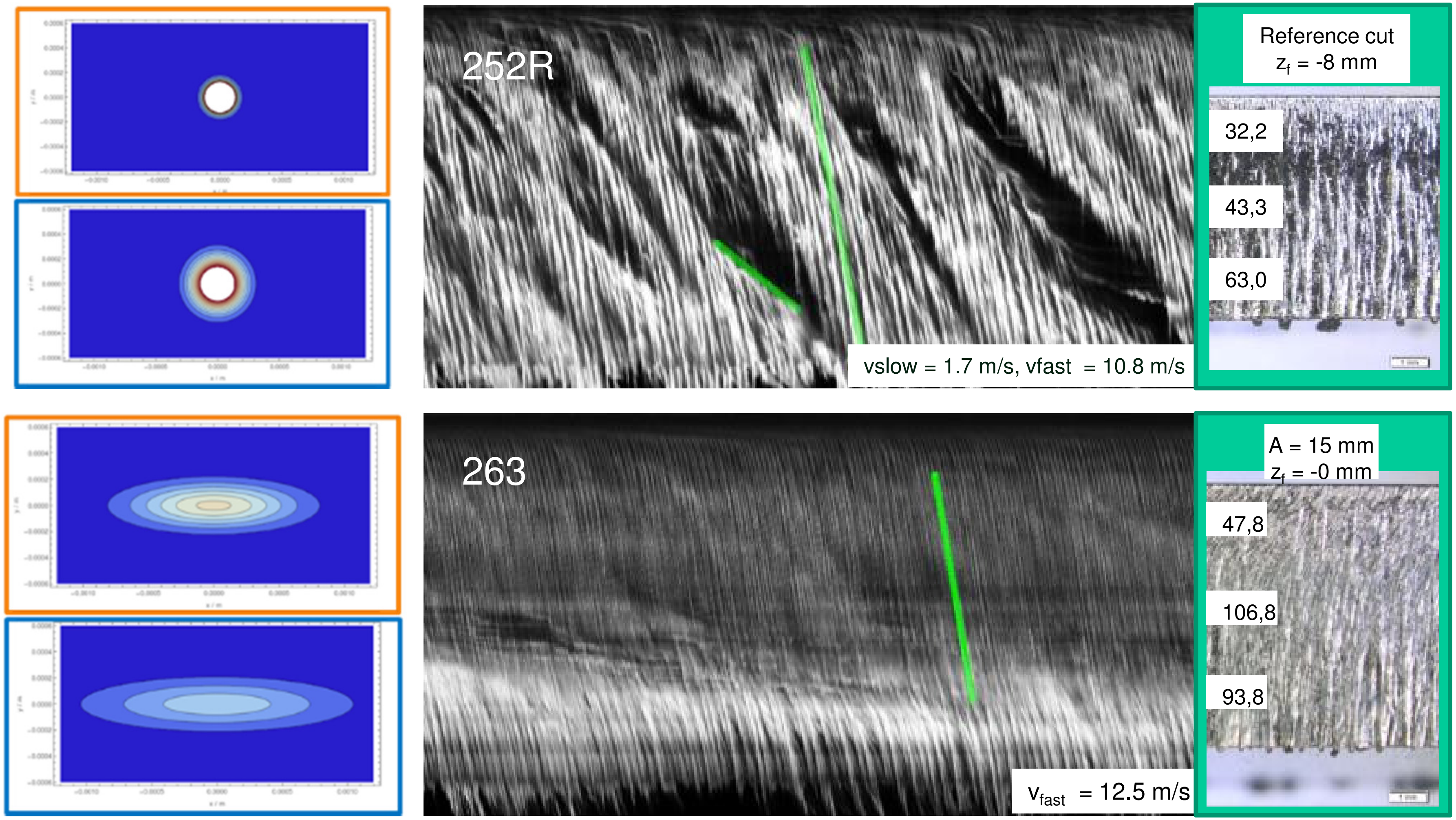
High standard deviation 262



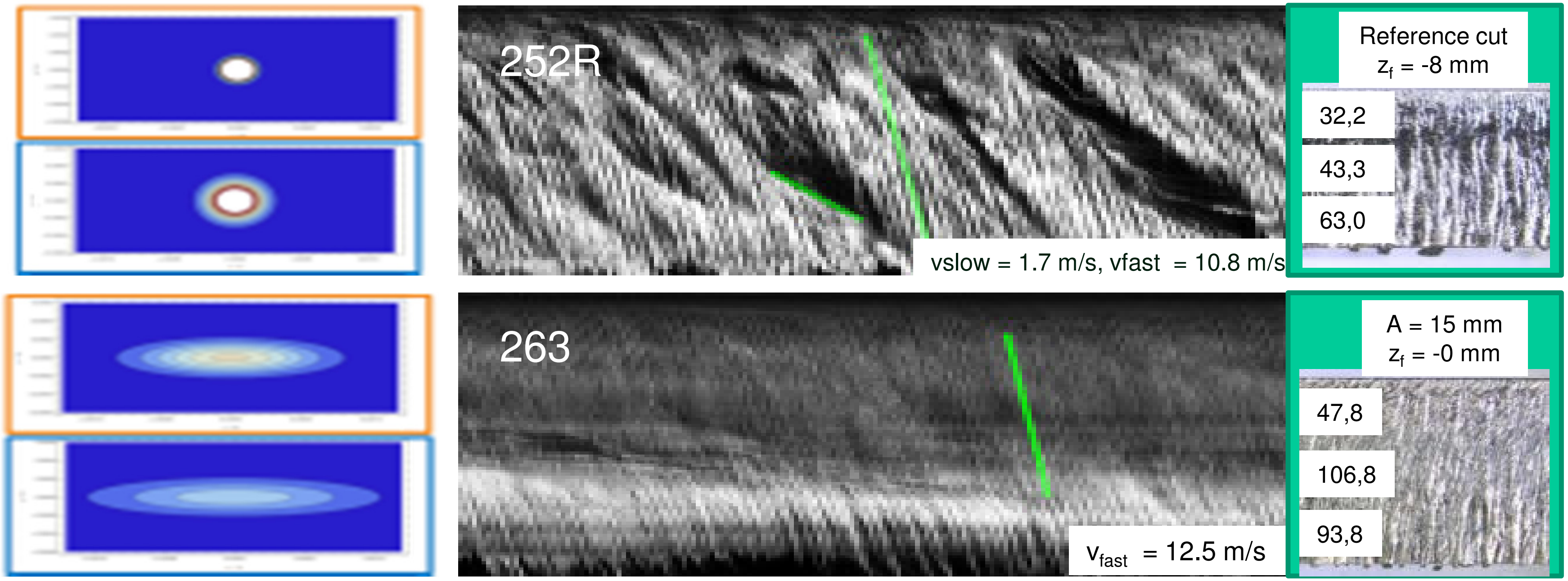
Stabilzed melt flow 264



Streak Front Imaging – melt flow stabilty / roughness



Streak Front Imaging – apex melt flow stabilty / roughness



apex melt flow stabilty and **cut edge roughness:**

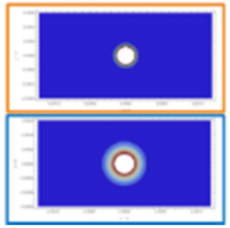
- in general are not in a one-to-one (monoton) relation

Hypothesis: the dependency becomes one-to-one (monotone)

- for restricted parameter ranges
- in particular, for large circular beam radius @ large power

Streak analysis – Method II

Analysis of one-dimensional time series from high speed videos



- Maximum

$$X_{max_{i\in[1,n]}} = max\{X_i\}$$

- Average

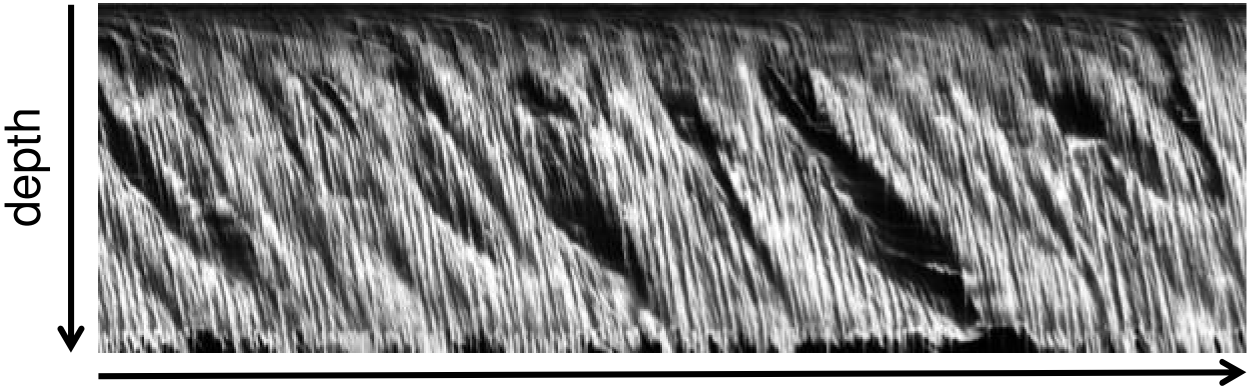
$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$$

- Standard deviation

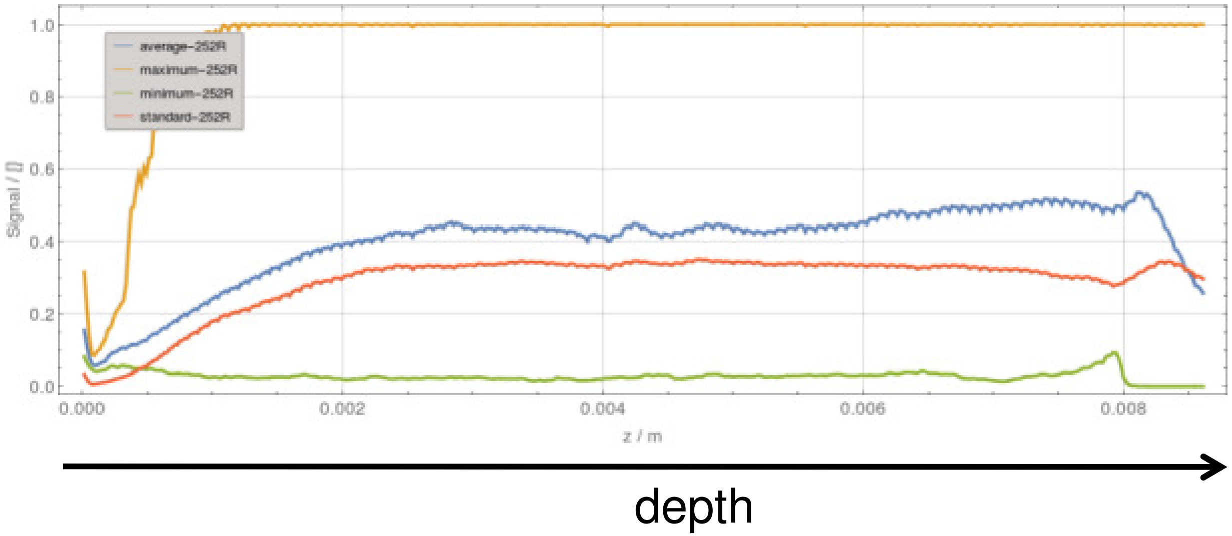
$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2}$$

- Minimum

$$X_{min_{i\in[1,n]}} = min\{X_i\}$$

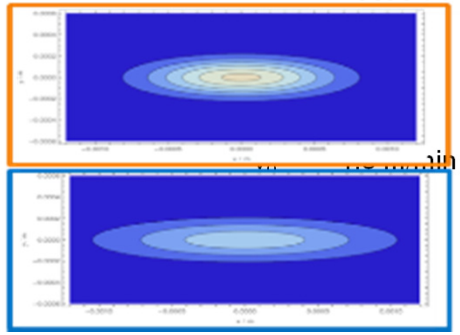


A = 0 mm w0 = 120 µm
z_F = -8 mm d = 8 mm v_0 = 1.5 m/min



Streak analysis – Method II

Low standard deviation
→ stabilzed melt flow



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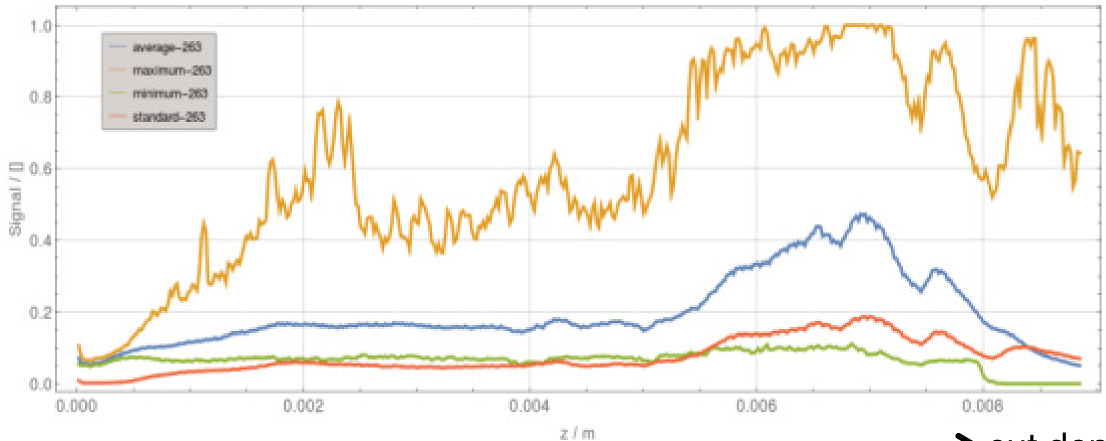
- Minimum

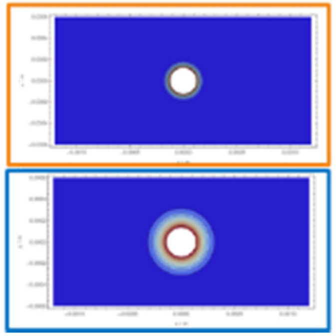
$$X_{min_{i\in[1,n]}} = min\{X_i\}$$

time

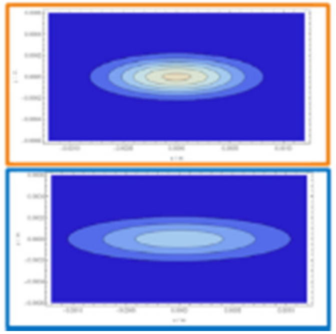


cut depth

High standard deviation
→ instable melt flow

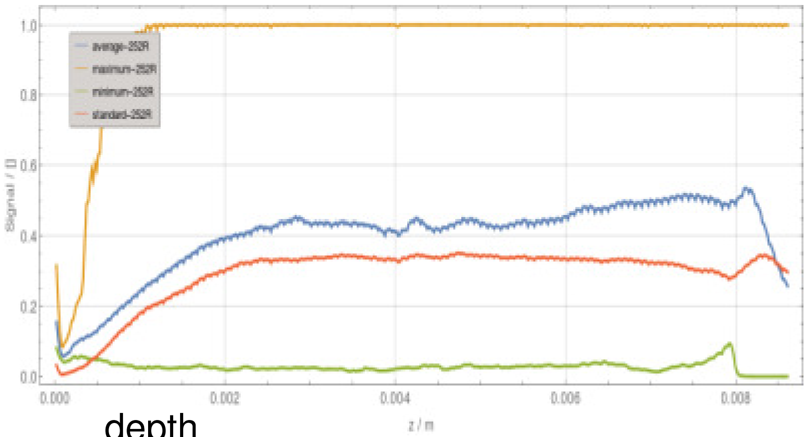


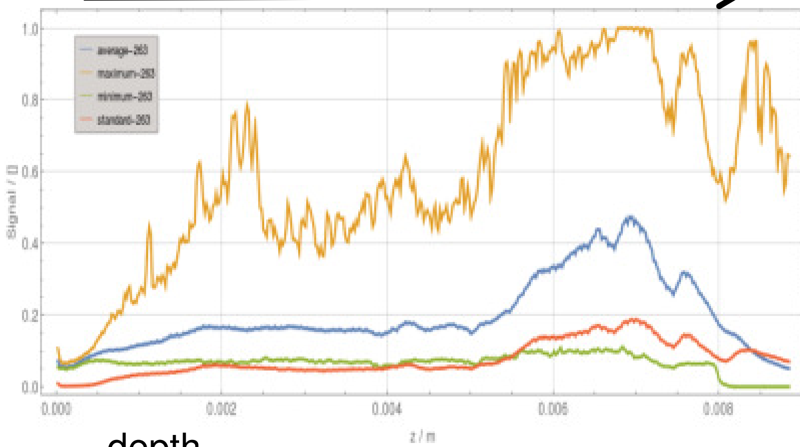
Low standard deviation
→ stabilzed melt flow



time

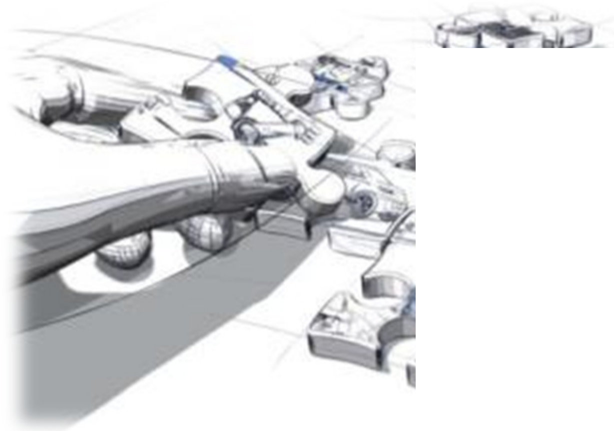
time





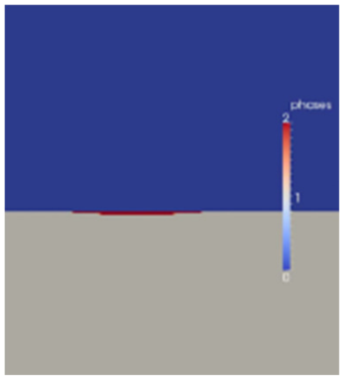
depth

depth



Modelling and Simulation
Virtual Production

numerical
simulation



process maps
visual design

model reduction

enabling value

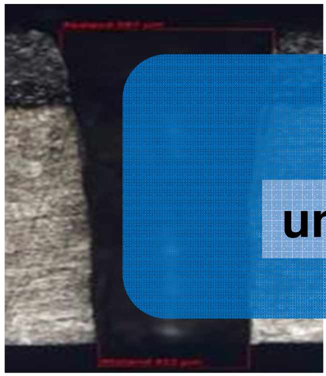
- **Developer Know-How**
- **Quality of Product**
- **maximum Productivity**

economic value

- **Skilled machine operator**

Modelling and Simulation
Virtual Production

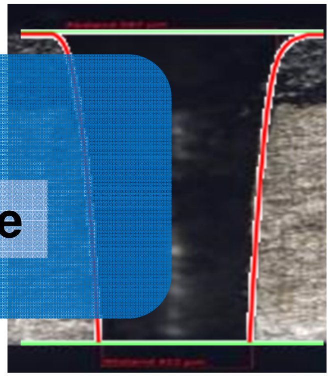
experimental evidence



numerical simulation

Urs Eppelt

reduced model

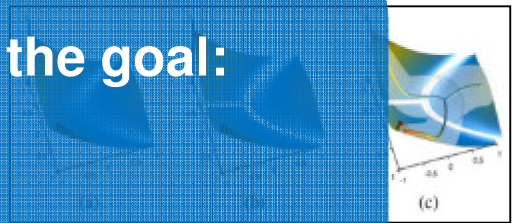


the tools:

understand – reduce

enabling value

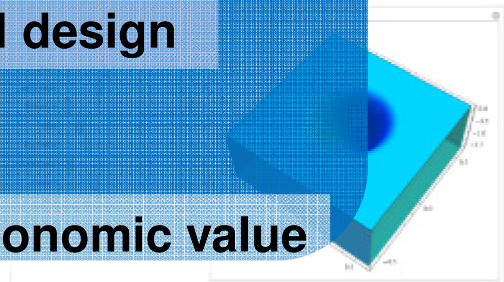
the goal:



Source: Gerber

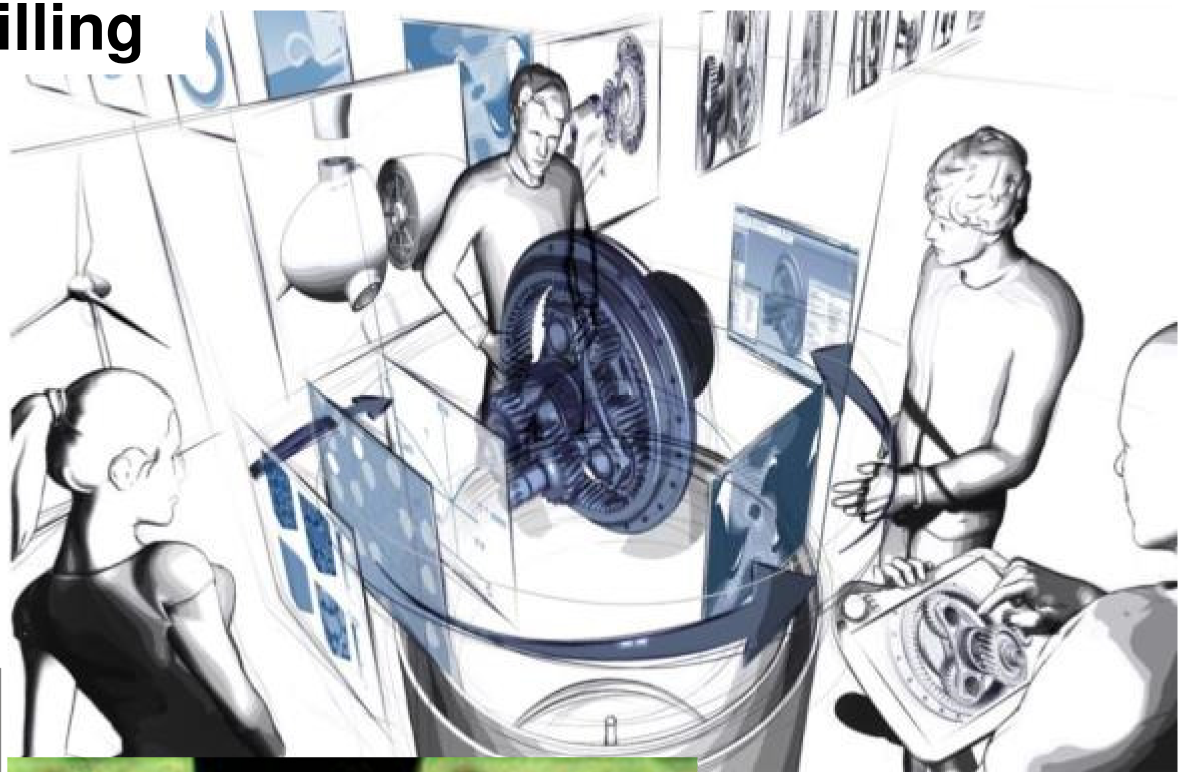
process maps

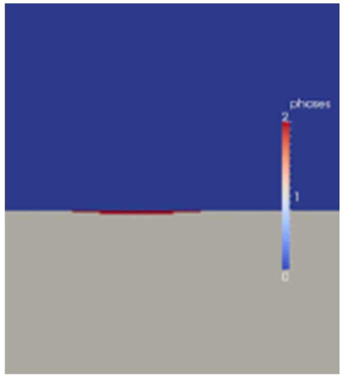
visual design

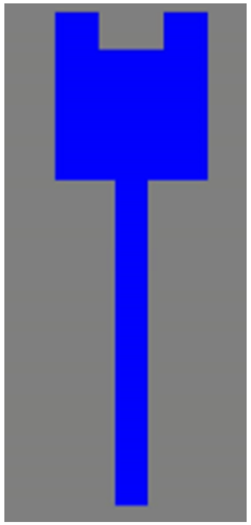


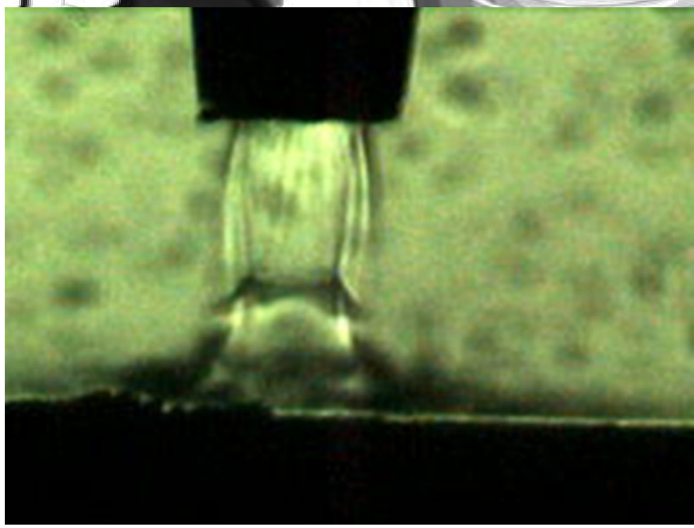
economic value

Turbine blade laser drilling









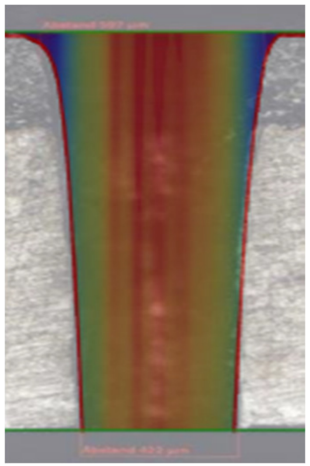
Fraunhofer ILT

Meta-Modelling

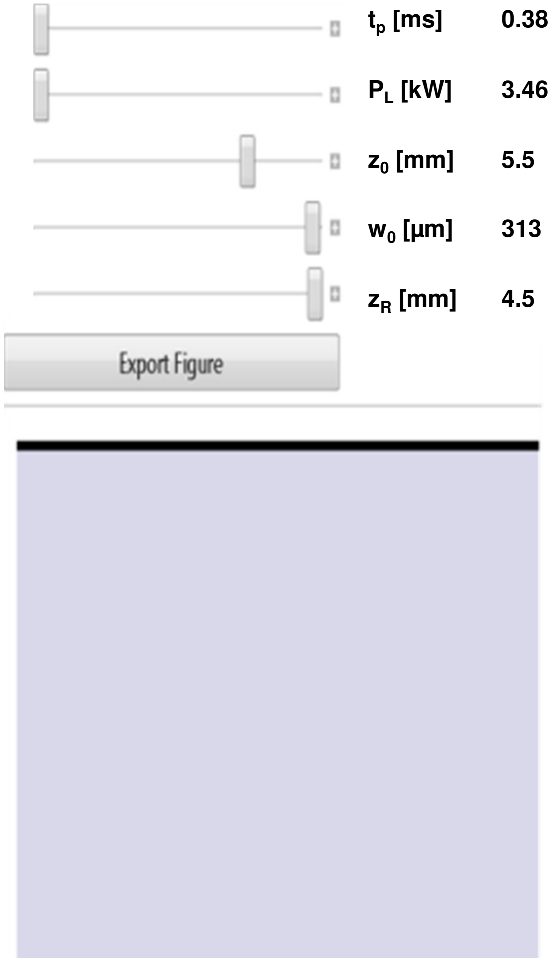
Morse-Smale Complex

multi-dimensional data visualization

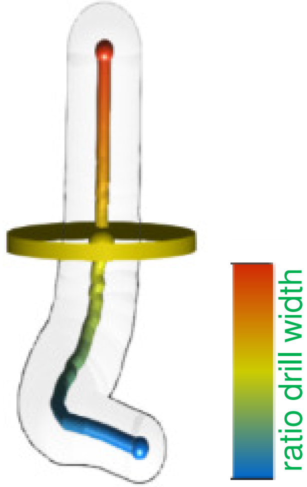
Application example:
„turbine blade laser drilling“

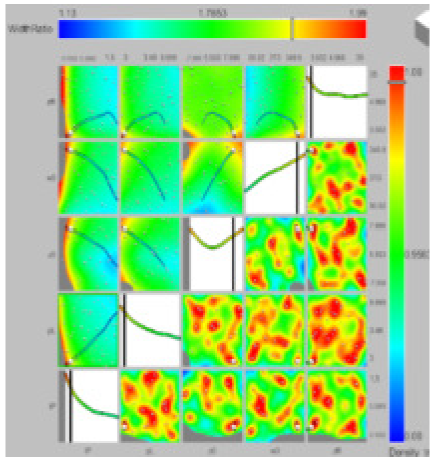


web-application:
Fast & Frugal Simulation



optimization tool:
Morse-Smale Complex
Hyperslices



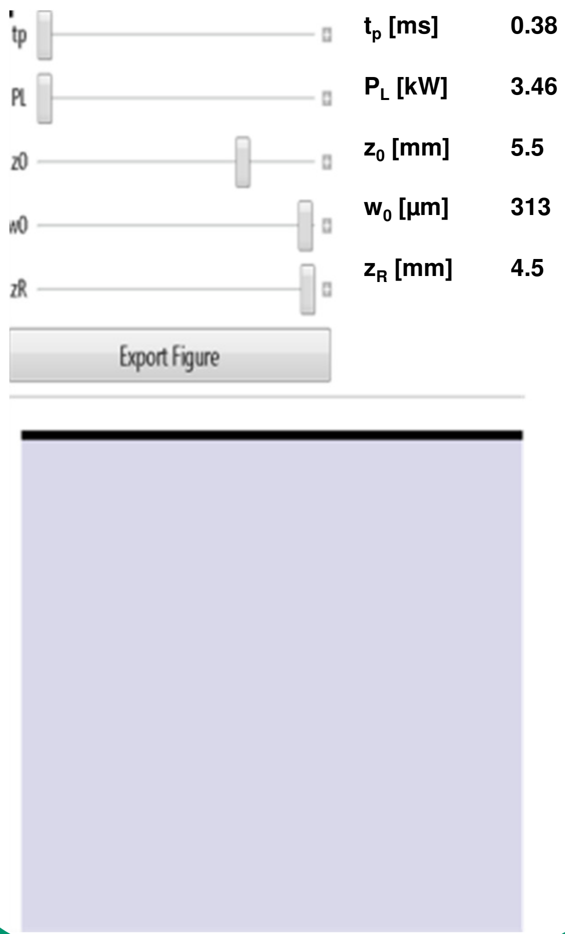


Fraunhofer ILT

Reduced Modelling: Asymptotic Drilling

Ablation occurs when the incident fluence $\mathbf{F}\cos\theta$ reaches the threshold fluence $\mathbf{F_{th}}$ of the material:

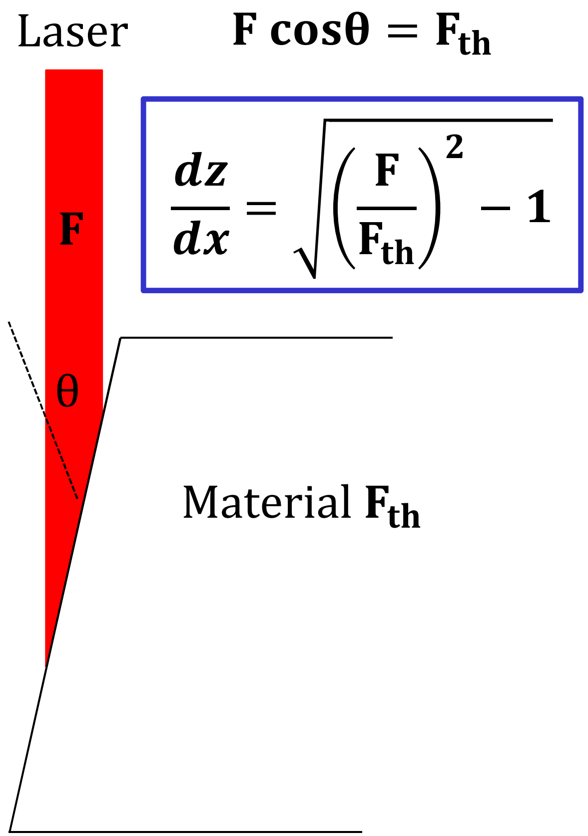
web-application:
Fast & Frugal Simulation



Simulation Know-How:
reduced model

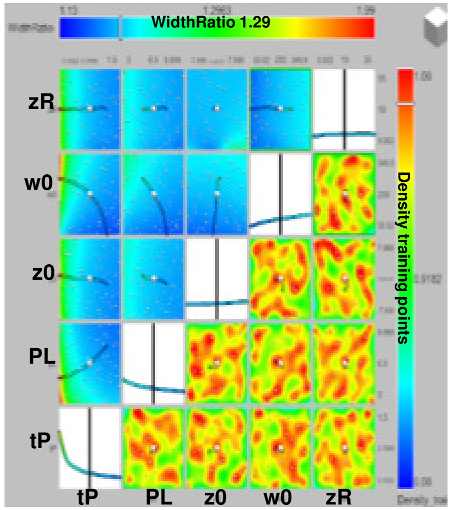
$$\mathbf{F}\cos\theta = \mathbf{F_{th}}$$

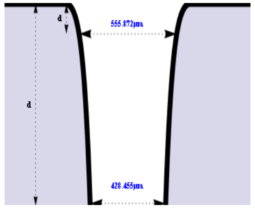
$$\frac{dz}{dx} = \sqrt{\left(\frac{\mathbf{F}}{\mathbf{F_{th}}}\right)^2 - 1}$$



Metamodeling-I: Hyperslice Representation

Fast online Optimization through Process Map





tP	0.79
PL	6.5
z0	-0.001
w0	200
zR	19

Approach

Sampling

↓

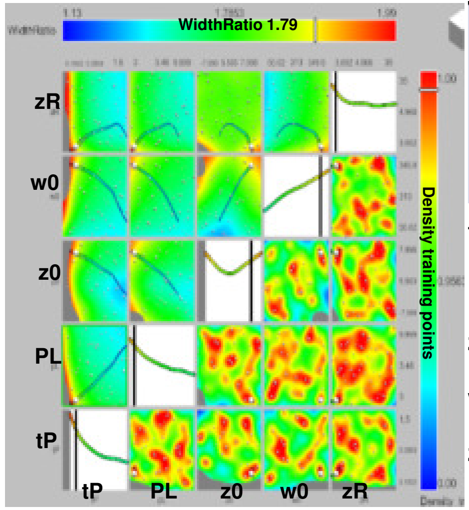
Simulation

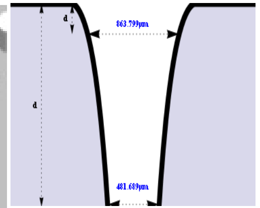
↓

Interpolation

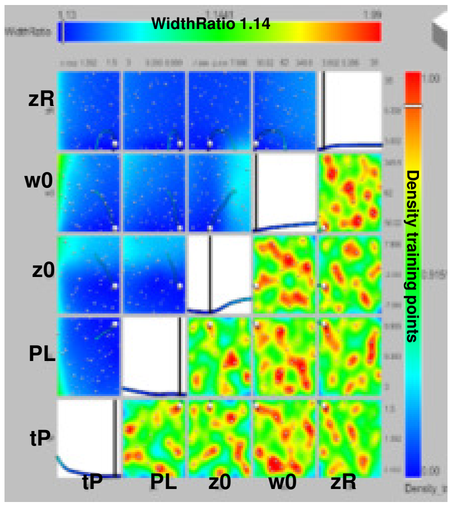
↓

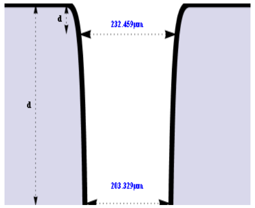
Visualization



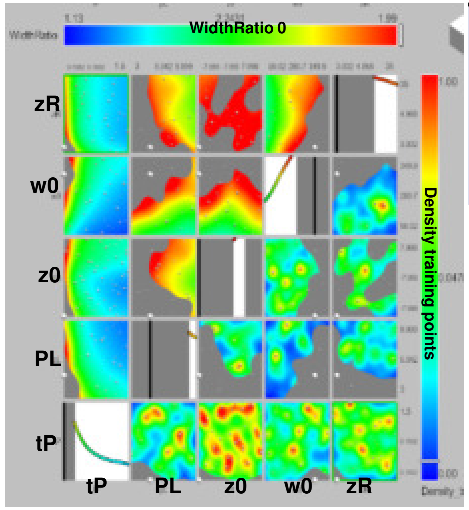


tP	0.38
PL	3.46
z0	5.5
w0	313
zR	4.5





tP	1.39
PL	9.3
z0	-2.4
w0	62
zR	5.39

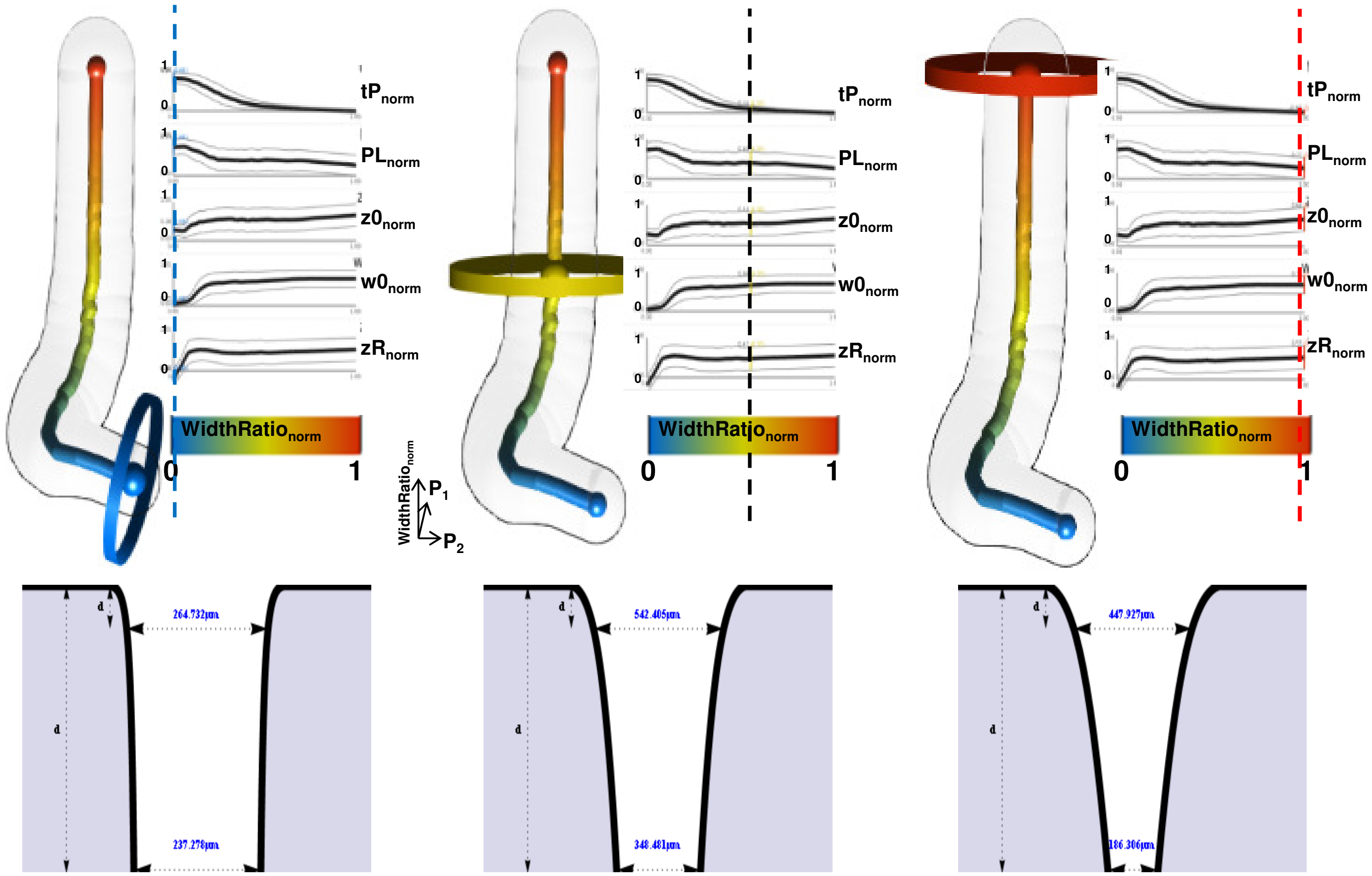


No Drill

tP	1.39
PL	9.3
z0	-2.4
w0	62
zR	5.39

Metamodeling-II: Morse Smale Complex

Visualization and Exploration
of multi-dimensional criteria-parameter representation



Project the extremal points and the regression curves onto its first two principal components P_1 & P_2

Approach

Morse Smale Domain Decomposition

↓

Geometric crystals (Regression)

↓

Dimension Reduction (PCA*)

*PCA Principal Component Analysis

Summary

- **ADAPTABLE LASER BEAMS**
  - SHEET METAL CUTTING – ELLIPTICAL BEAMS
- **VIRTUAL PRODUCTION:**
  DESIGN THINKING FOR MACHINE DESIGN
  - META-MODELLING ENABLES DESIGN THINKING
  - MODEL REDUCTION ENABLES META-MODELLING
- **TAILORED CUSTOMER SOFTWARE**
  - **WEB-APPLICATION:**
    FAST FRUGAL SIMULATION
  - **OPTIMIZATION TOOL:**
    MORSE-SMALE COMPLEX
    HYPERSLICES
  - SIMULATION KNOW-HOW:
    REDUCED MODEL