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Examination of laser cutting phenomena by comprehensive steady-state simulations

(Invited)

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Market Overview: Industrial Laser Revenues

Fiber Lasers and Macro Processing Lead in Share and Growth

Table 1. Industrial laser revenues (US$M).

LASER	2013	2014	%	2015	%
CARBON DIOXIDE	863	884	2	877	-1
SOLID-STATE	456	444	-3	431	-3
FIBER	841	960	14	1085	13
OTHER	327	343	5	366	7
TOTAL	2487	2631	6	2759	5

Sources: Strategies Unlimited/Industrial Laser Solutions

34% -> 36% -> 39%

Table 2. All Industrial laser material processing revenues.

REVENUE (US$M)	2013	2014	2015
MARKING	\$335.0	\$347.5	\$370.8
y-to-y		4%	7%
MICRO MATERIALS	\$597.0	\$611.3	\$631.5
y-to-y		2%	3%
MACRO MATERIALS	\$1,554.4	\$1,671.6	\$1,755.6
y-to-y		8%	5%
TOTAL	\$2,486.4	\$2,630.4	\$2,757.9
y-to-y		6%	5%

Sources: Strategies Unlimited

all years ca. 63%

All numbers are from David Belforte‘s great market overview.

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Market Overview: Macroprocessing

Metal Cutting Lasers Dominate with 75% Macro Market Share

(almost 50% of Whole Industrial Laser Market)

Table 6. Lasers used for macroprocessing (1kW or higher).

REVENUE (US$M)	2013	2014	2015
METAL CUTTING	$1,170.5	$1,248.7	$1,293.8
y-to-y		7%	4%
METAL WELDING	$334.2	$366.1	$389.7
y-to-y		10%	6%
OTHER	$49.7	$56.8	$72.0
y-to-y		14%	27%
TOTAL	$1,554.4	$1,671.6	$1,755.6
y-to-y		8%	5%

Sources: Strategies Unlimited

2014:
6000 lasers

…of which more than 30% are fiber lasers
(>50% in 2016)

All numbers are from David Belforte‘s great market overview.

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Market Overview: Macroprocessing
Fiber Lasers Outperform

Table 7. Lasers used for macroprocessing (1kW or higher).

REVENUE (US$M)	2013	2014	2015
CO_2	$696.1	$714.2	$699.9
y-to-y		3%	-2%
FIBER	$512.4	$599.5	$683.4
y-to-y		17%	14%
SOLID STATE	$199.5	$189.5	$181.9
y-to-y		-5%	-4%
DIRECT DIODE/OTHER	$146.5	$168.4	$190.3
y-to-y		15%	13%
TOTAL	$1,554.4	$1,671.6	$1,755.6
y-to-y		8%	5%

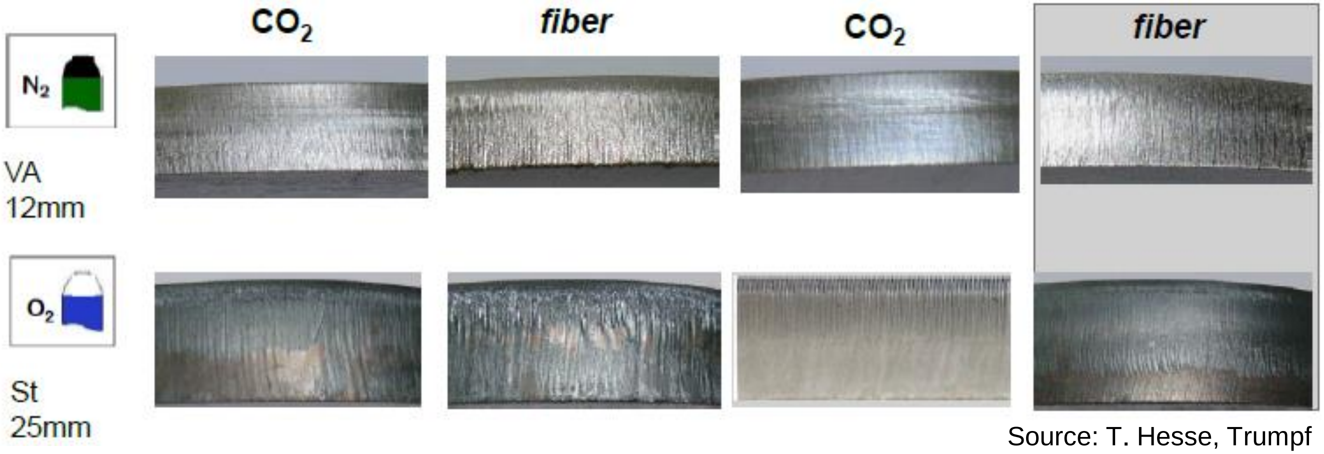
Sources: Strategies Unlimited

33% -> 36% -> 39%

All numbers are from David Belforte‘s great market overview.

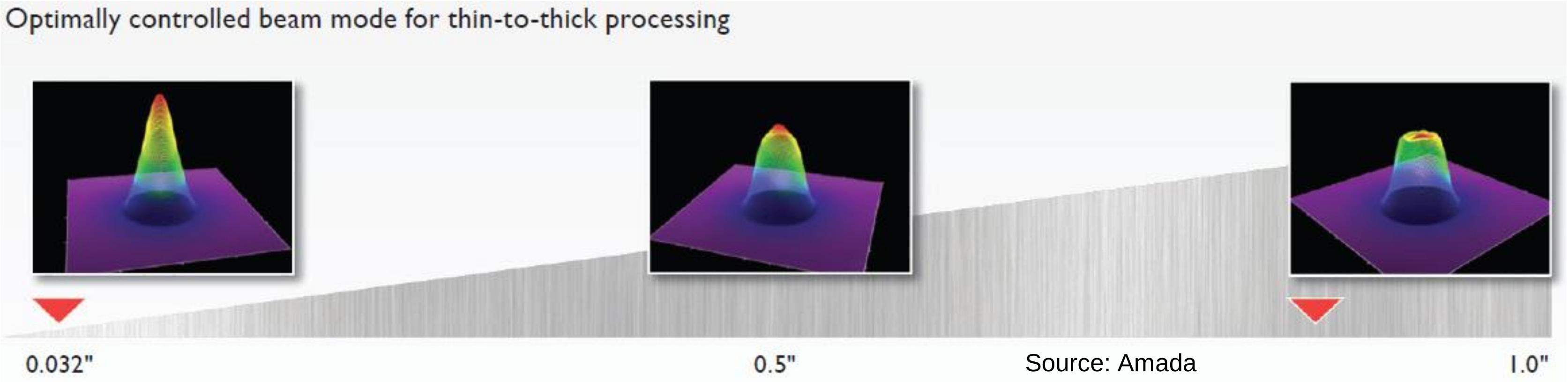
Amada and Trumpf Provide Variable Beam Quality for Versatile Cutting Capabilities

- Trumpf: Standard vs. BrightLine, BrightLine Fiber



Source: T. Hesse, Trumpf

- Amada: ENSIS – Beam shaping principle



Source: Amada

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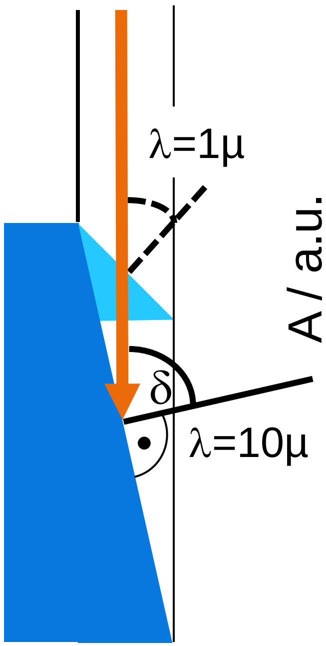
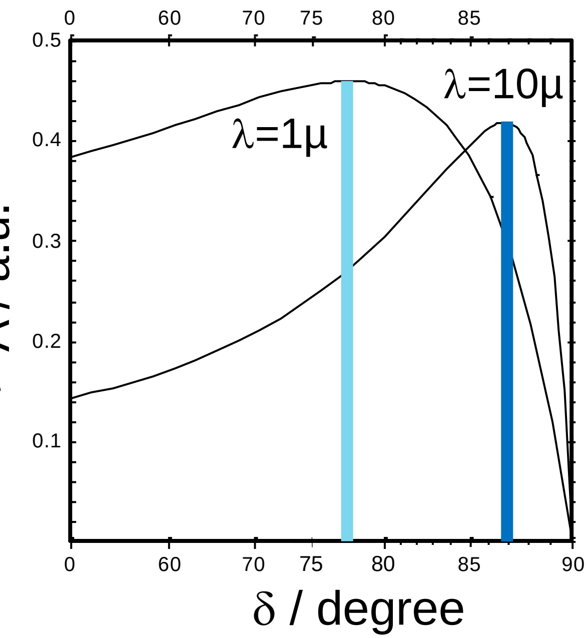
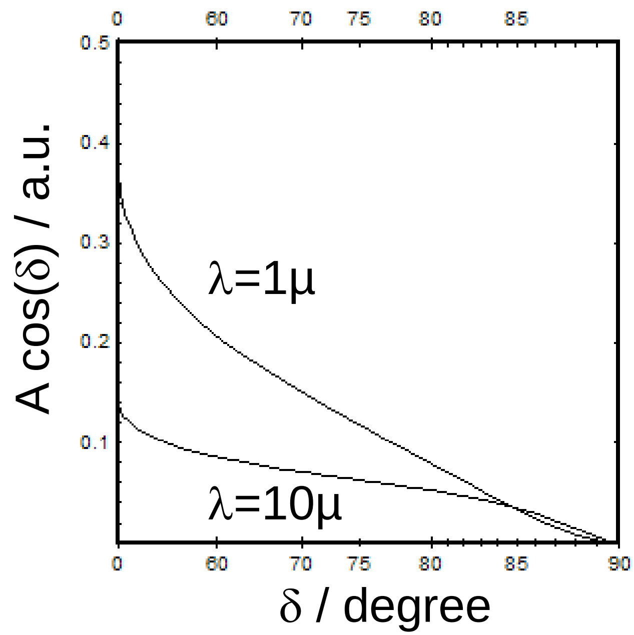
Fresnel Absorption for Steel at 2500 K (Circular / Random Polarisation)*

* Complex refractive index calculated by modified Drude approach (Petring 1994)

- Impact of Wavelength







- A stroke of luck for CO_2 lasers at grazing incidence
- High aspect ratios and grazing incidence are counterproductive at 1µ.

- Higher sensitivity for perturbations at 1µ.

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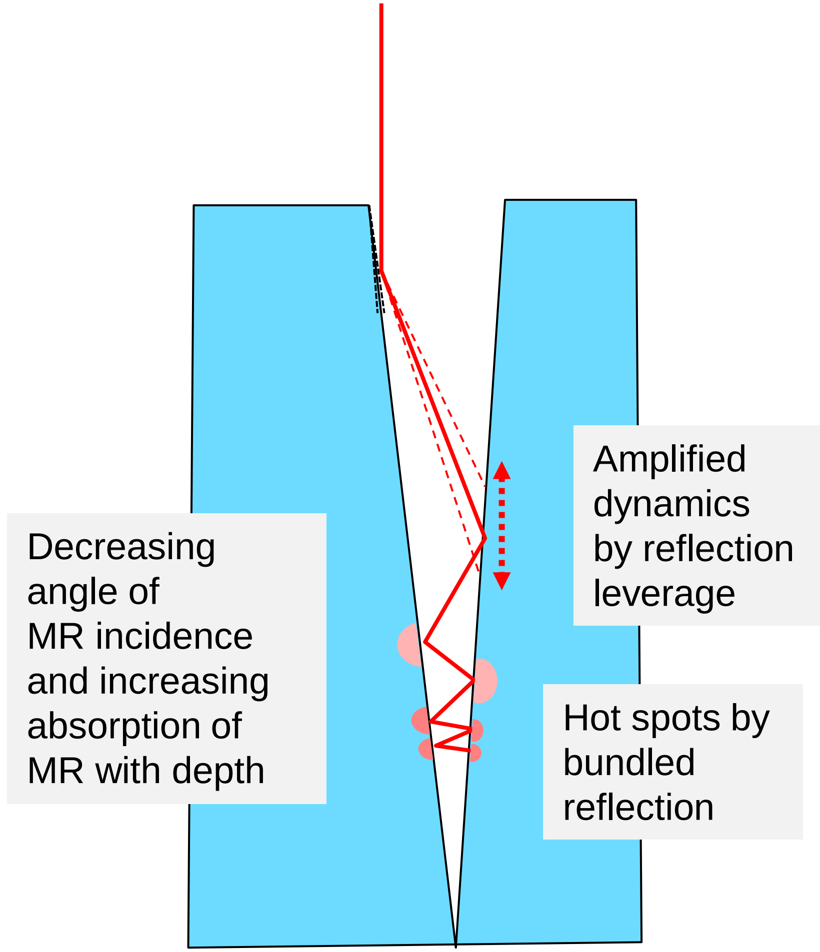
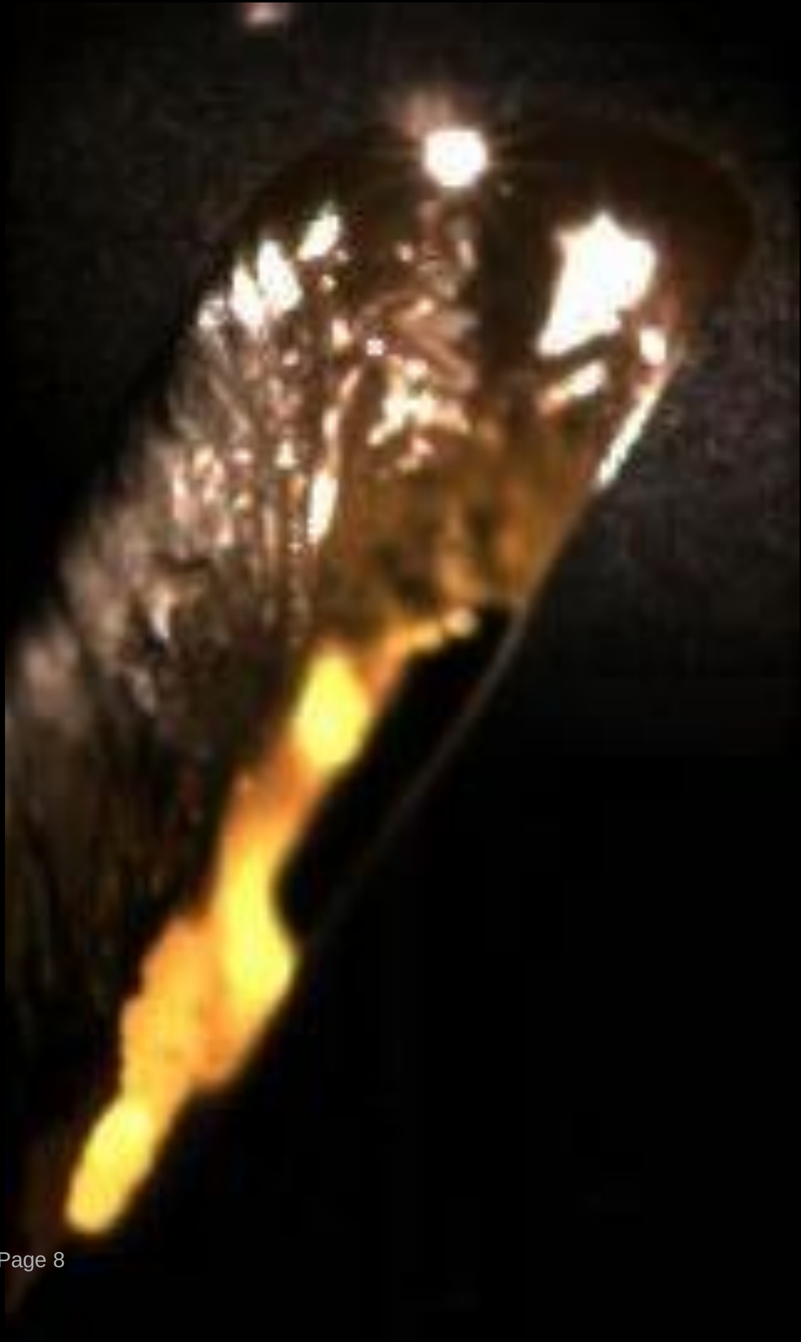
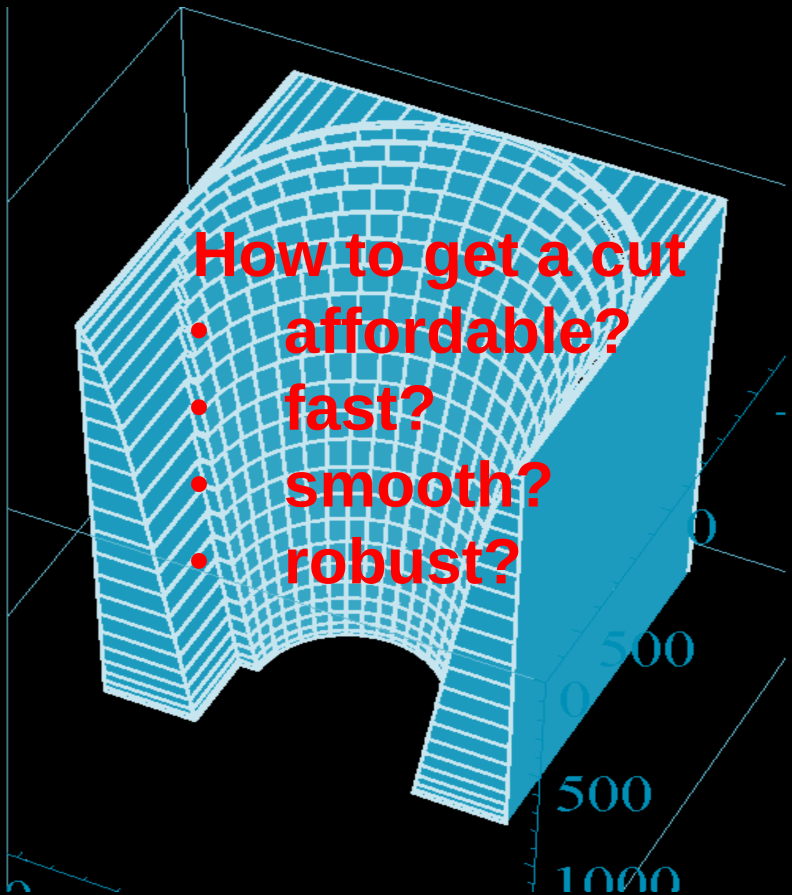
Disclosing the Real Beam Coupling Mechanism in 1µ Laser Cutting

Multiple Reflections Play a Decisive Role

- CALCut MR solution makes explainable:
  - real coupling efficiency (v_{max})
  - wider kerfs
  - amplified dynamics
  - hot spots
  - quality issues
- Countermeasures are evident.







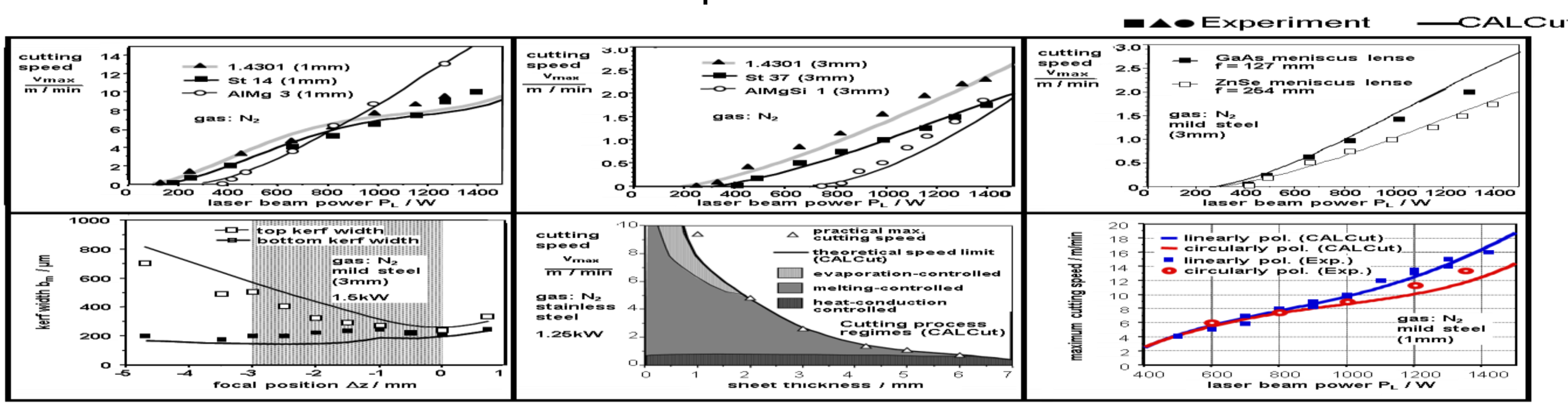
How to get a cut

- affordable?
- fast?
- smooth?
- robust?

Parameter screening: Better to calculate the facts than digging around!

Modelling and Simulation of Laser Beam Cutting

- Experience
  - Analytical equations and reduced models:
    describing singular physical sub-processes in limited dimensions.
  - Fully numerical simulation tools:
    requiring at least several days for the calculation of a short cutting track at one single parameter.
  - The solution is in between:
    Semi-analytical semi-numerical steady-state simulation taking into account all relevant sub-processes in 3-D.



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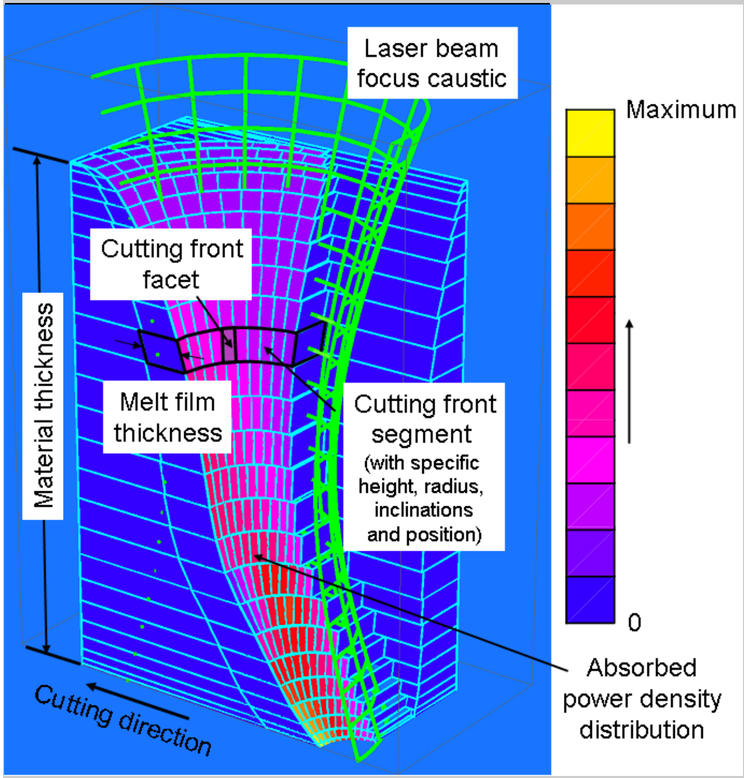
How to apply a simulation successfully

■ Capabilities of CALCut

Input:

- workpiece parameters:
  - ca. 20 material properties
  - thickness
- laser beam parameters:
  - wavelength
  - polarisation
  - intensity distribution
  - beam quality
  - raw beam diameter
  - power
- focussing parameters:
  - type of optical system
  - focal length
  - focal position
- cutting gas parameters:
  - type
  - pressure
- machine parameters:
  - speed



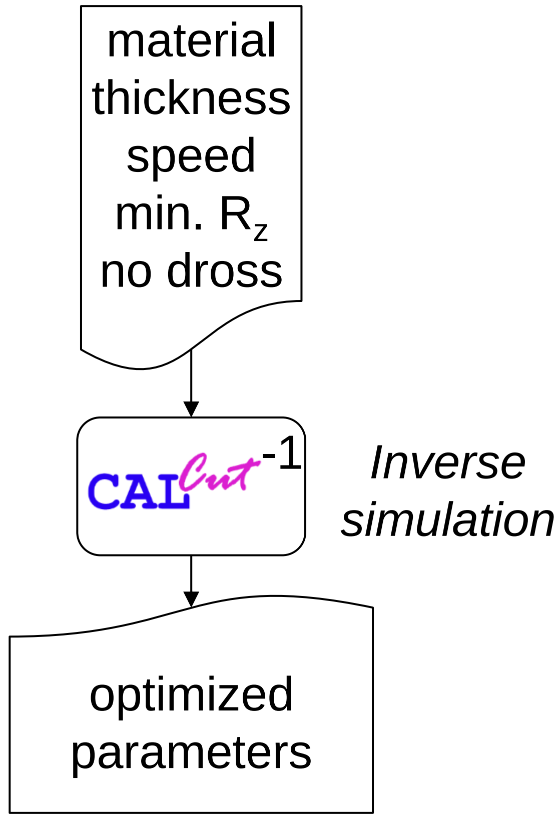
Considered sub-processes and interactions:

- laser beam propagation and focussing
- Fresnel absorption
- multi-reflection (optional)
- heat conduction
- phase transitions and oxidation
- compressible gas flow
- melt flow
- capillary forces
- vapour pressure gradients

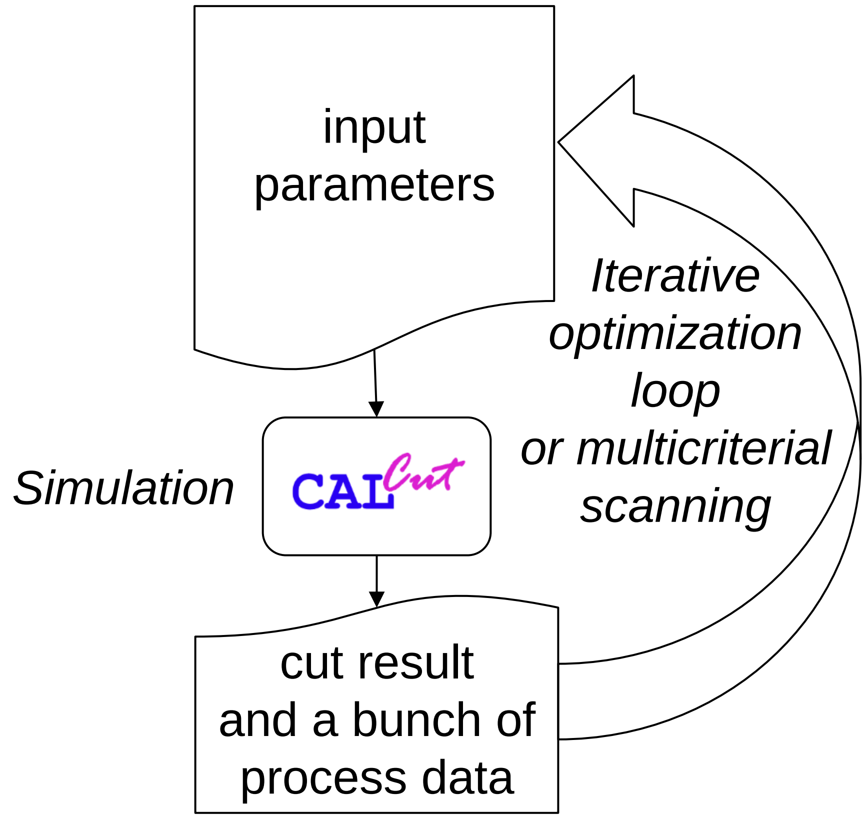
Output:

- max. speed
- kerf geometry
- heat flow distribution
- temperature distribution
- various process variables
- graphical visualization

How to Optimize a Process with a Simulator



This is not how it works!



This is how we have to work with it!

Exercising Simulation-Supported Parameter Screening in EU Project FILCO

- Steps

  - Experience: Parameter dependencies of cutting efficiency and quality are extremely **non-linear**.
  - Goal: **Understand** and optimize the process by simulations.
  - 1st Decision: Define a **base parameter set** based on hitherto knowledge and being suitable for industrial use.
  - Task: Define an **optimization strategy** (beyond any DoE) and use it.
  - Procedure: **Vary optical parameters** over a wide range at the base parameter set and evaluate cutting behavior.

Exercising Simulation-Supported Parameter Screening in EU Project FILCO

- <u>Base Parameter Set</u>
  (with technical, economical and market-relevant arguments)
  - Material: stainless steel 1.4301 *(most common in industry)*
  - Thickness: 6 mm *(in the center of typical application range)*

  - Type of cutting gas: nitrogen (N_2) *(typical type)*
  - Cutting gas pressure: 1.8 MPa *(reasonably high)*

  - Type of laser: fibre-delivered *(evident)*
  - Wavelength: 1 µm *(evident)*
  - Beam quality: 4 mm*mrad (i.e. 100 µm fiber diam.) *(standard)*
  - Polarisation: statistical *(standard)*
  - Beam power: 3 kW *(industrially established; suitable for 6 mm)*

  - Collimation focal length: 100 mm *(compatible with Precitec head)*
    (i.e. collimated beam diameter 15 mm)

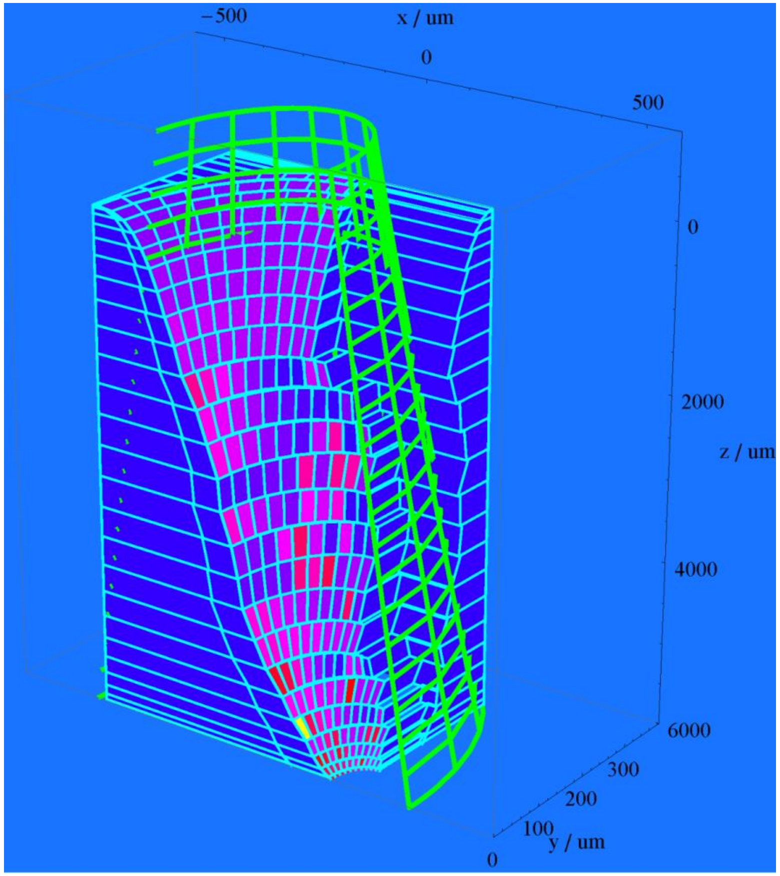
Exercising Simulation-Supported Parameter Screening in EU Project FILCO

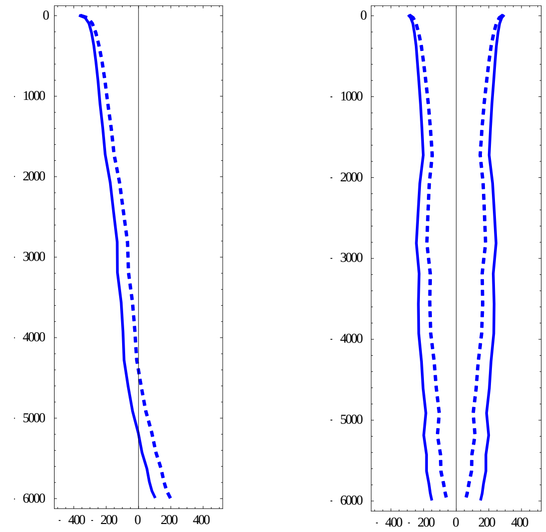
- Optimization Strategy

  - Base parameter set is defined.
  - Optimization target: **max. cutting speed** and **cut quality** (trade-off!)
  - Parameter matrix:
    focusing focal lengths x focal positions
  - CALCut SR-simulations:
    Max. cutting speeds (**efficiency**) and gas jet penetration depths
    (**gas jet effectivity** -> achievable cut quality (burr))
  - CALCut MR-Simulations @ base speed and stepwise increased speeds
  - Further evaluation criteria:
    - Gas jet penetration depth
    - Smoothness of cutting front geometry
    - Regularity of absorbed power density distribution
    - Robustness of cutting front response to incremental speed variations

Exercising Simulation-Supported Parameter Screening in EU Project FILCO

- **Cutting front simulation at optimized parameters**





Cutting front vertex (left) and kerf cross section (right)

CALCut simulation of cutting front with absorbed power density distribution utilizing recommended optical parameters and homogeneous cutting gas flow at reference cutting speed.

FILCO Beam Forming Unit and Cutting Head: Next Steps after Parameter Optimization

- Estimate F-number range for the aspired application range.
- Minimize number of optical components (cost efficiency, robustness).
- Choose standard lens diameters (cost efficiency).
- Ensure sufficient system aperture for high power laser beams.
- Design sufficient lens edge thickness for mechanical robustness.
- Design adequate optical imaging quality – nearly diffraction limited but not exaggerating (not for SM-fibers)

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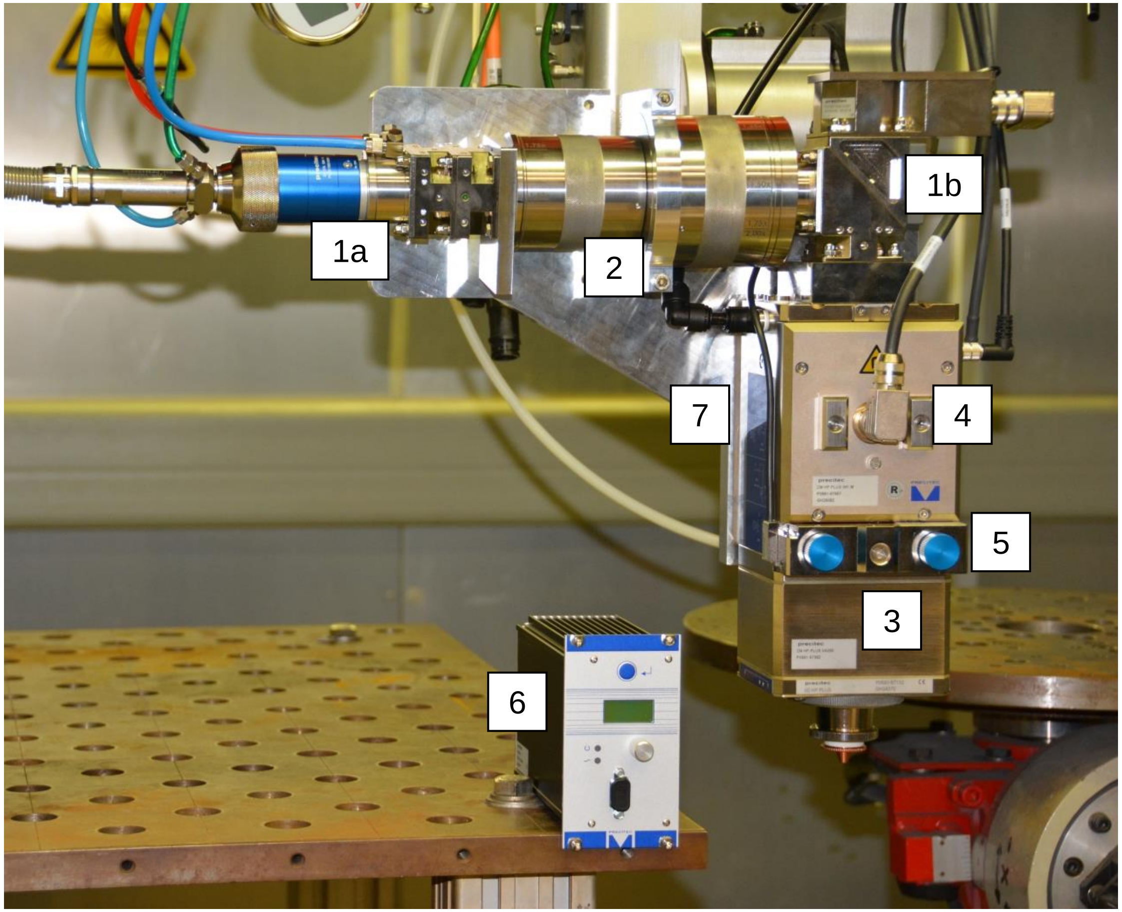
FILCO Beam Forming Unit and Cutting Head: The FILCO Cutting Head Prototype



- 1a. Fiber connector with collimator optics
- 1b. 90° beam bending
- 2. FILCO beam forming unit (variable zoom beam expander)
- 3. Head module with extension
- 4. Motorized focusing
- 5. Monitored protection window
- 6. Height control
- 7. Mounting plate

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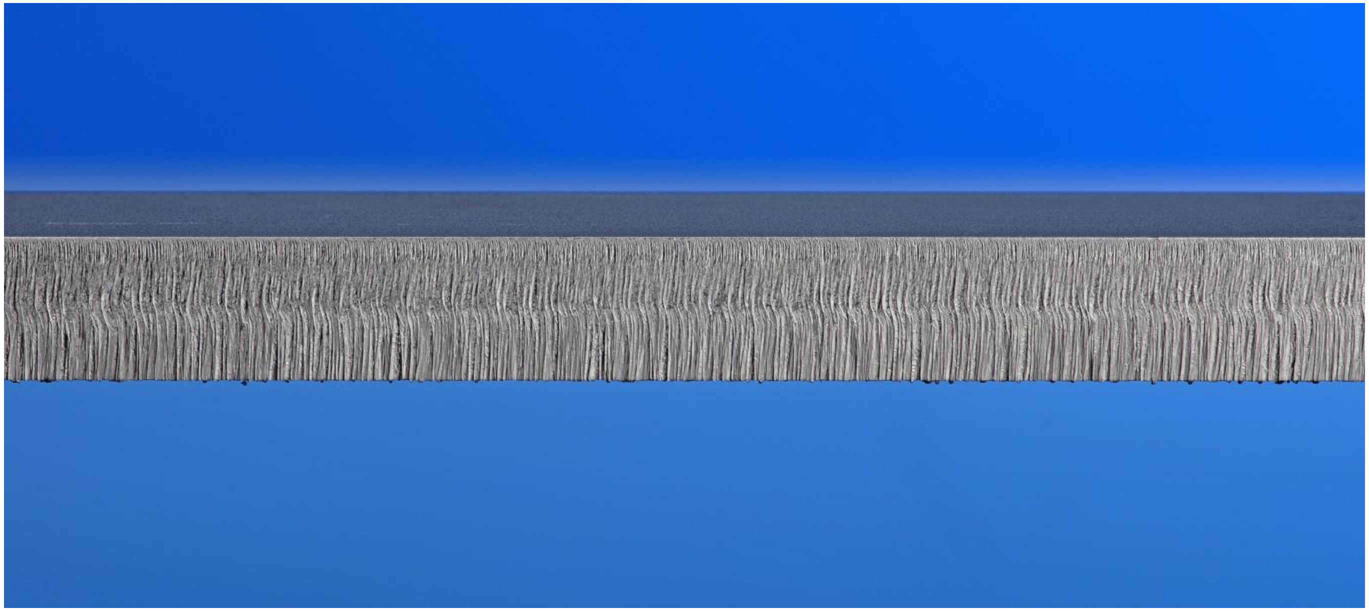
FILCO Beam Forming Unit and Cutting Head: Improved Cutting Result



Reference material 6 mm stainless steel
Fiber laser, fiber diameter 100µm, 3kW beam power, cutting speed 2.4 m/min.
Collimated beam diameter 17 mm, focal length 250 mm
Maximum roughness R_z=30.5µm, maximum dross length 0.12mm.

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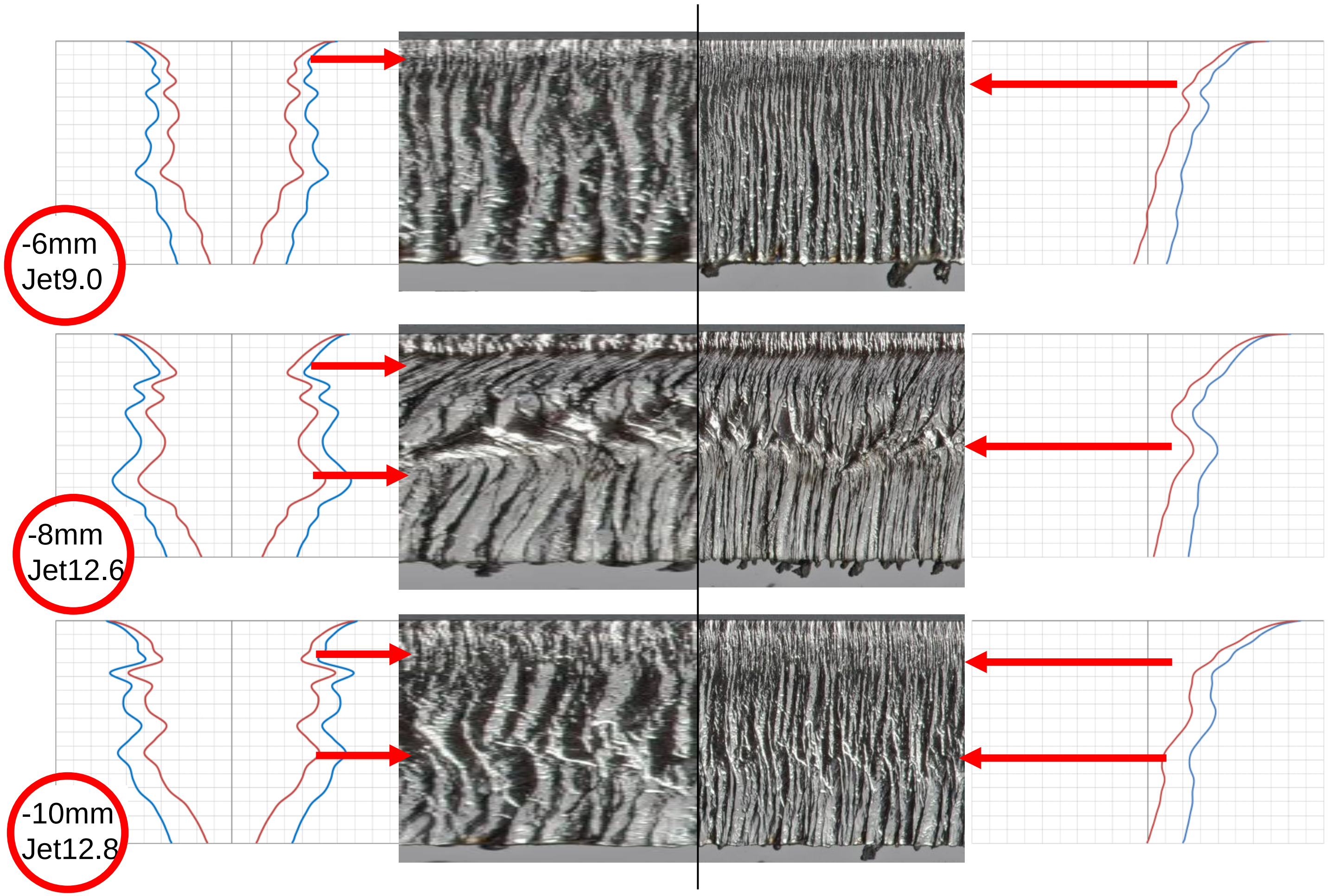
Further Verification of FILCO's CALCut Simulations in Experiments of EU-Project HALO

- 8mm stainless steel
- Fiber laser 3.75kW, fiber diameter 100µm
- Beam quality K=0.104
- Zoom case 1x
- Nitrogen 20bar, 3mm nozzle, distance 0.7mm
- Cutting speed 1.8m/min
- Focal position varied from -10mm to +10mm

Practical Verification of CALCut Simulations

Irregular Striation Pattern



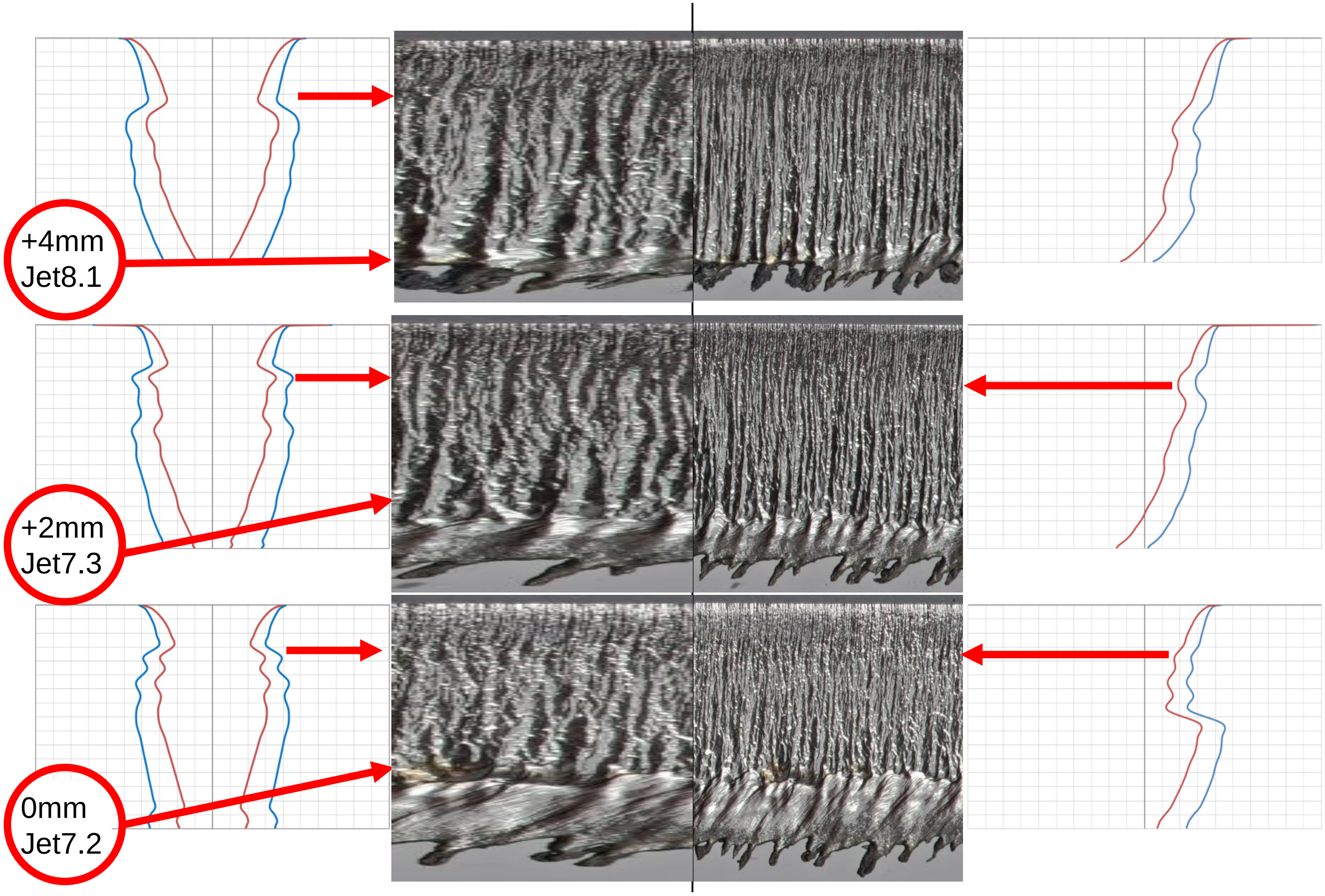
Trisection of striation pattern

Trisection of striation pattern

Kinked CALCut contours correspond to strong irregularities in striation pattern.

Practical Verification of CALCut Simulations

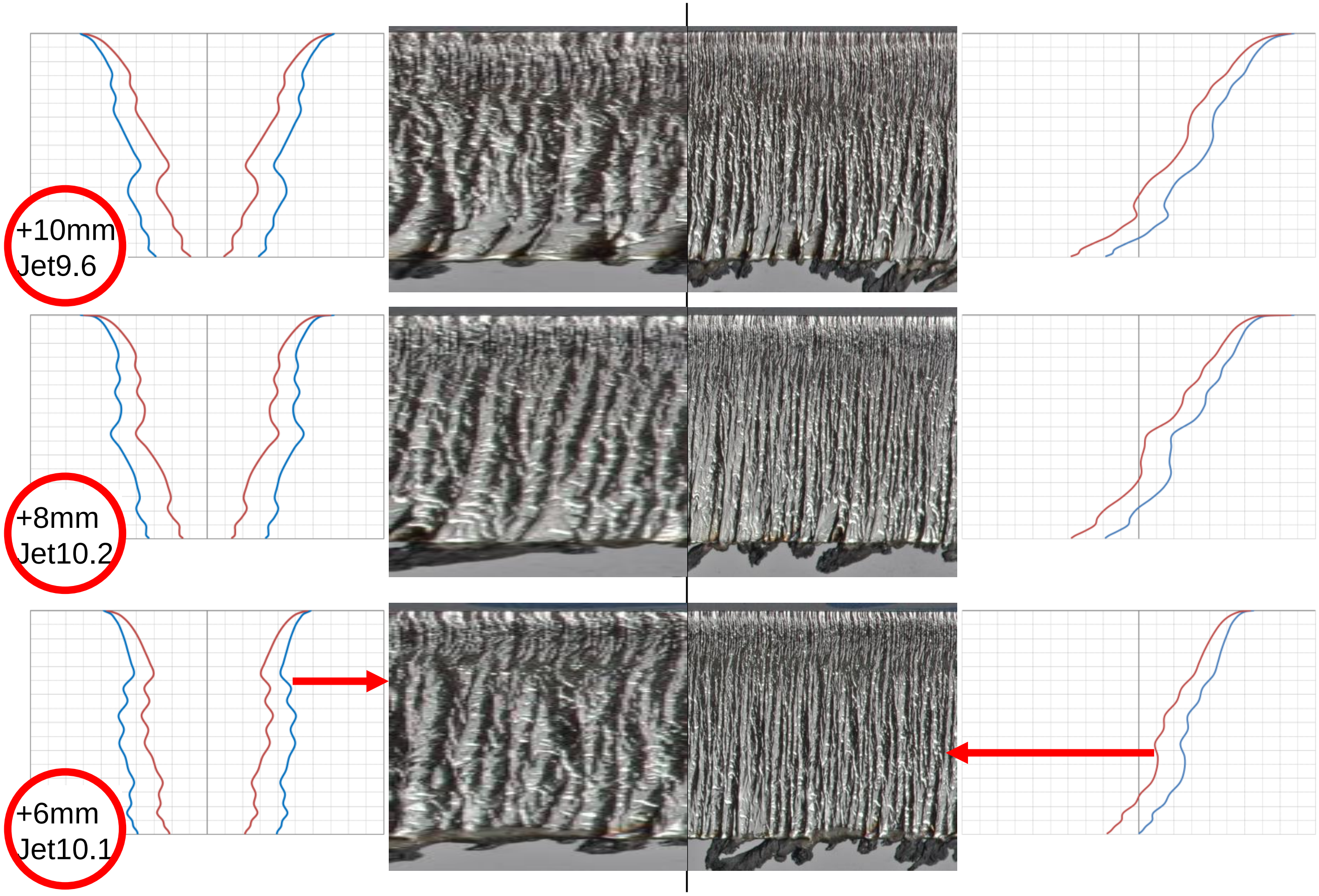
Striation Drag Level



CALCut's jet penetration corresponds to striation drag level.

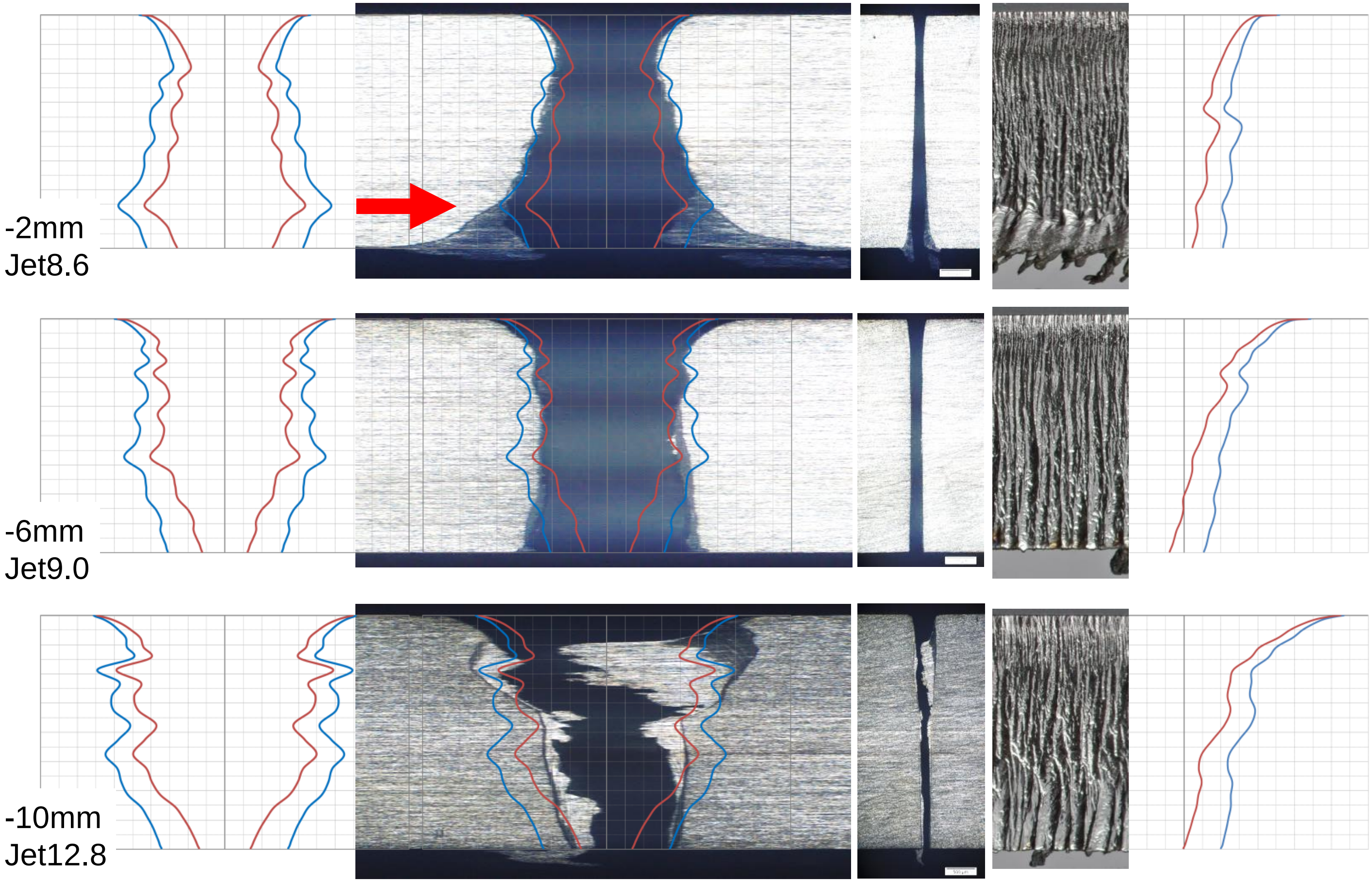
Practical Verification of CALCut Simulations

Regular Striation Pattern



Smooth CALCut contours correspond to straight striations.

Practical Verification of CALCut Simulations
Kerf Characteristics



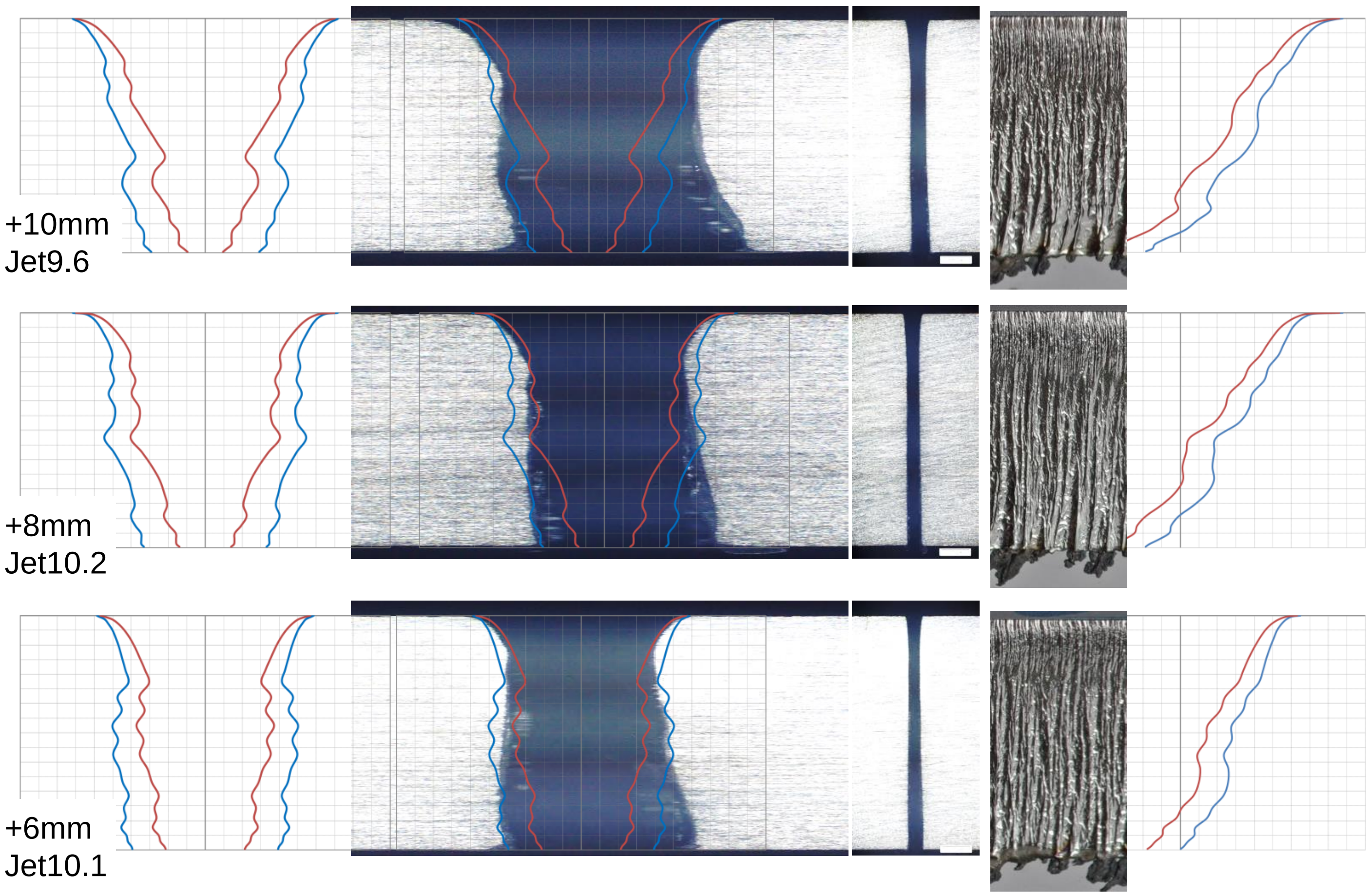
Expanding kerf followed by kerf choking.

Good case: Confirmed by CALCut

Bad case: Confirmed by CALCut

CALCut kerfs (incl. entrance & exit) correspond with reality.

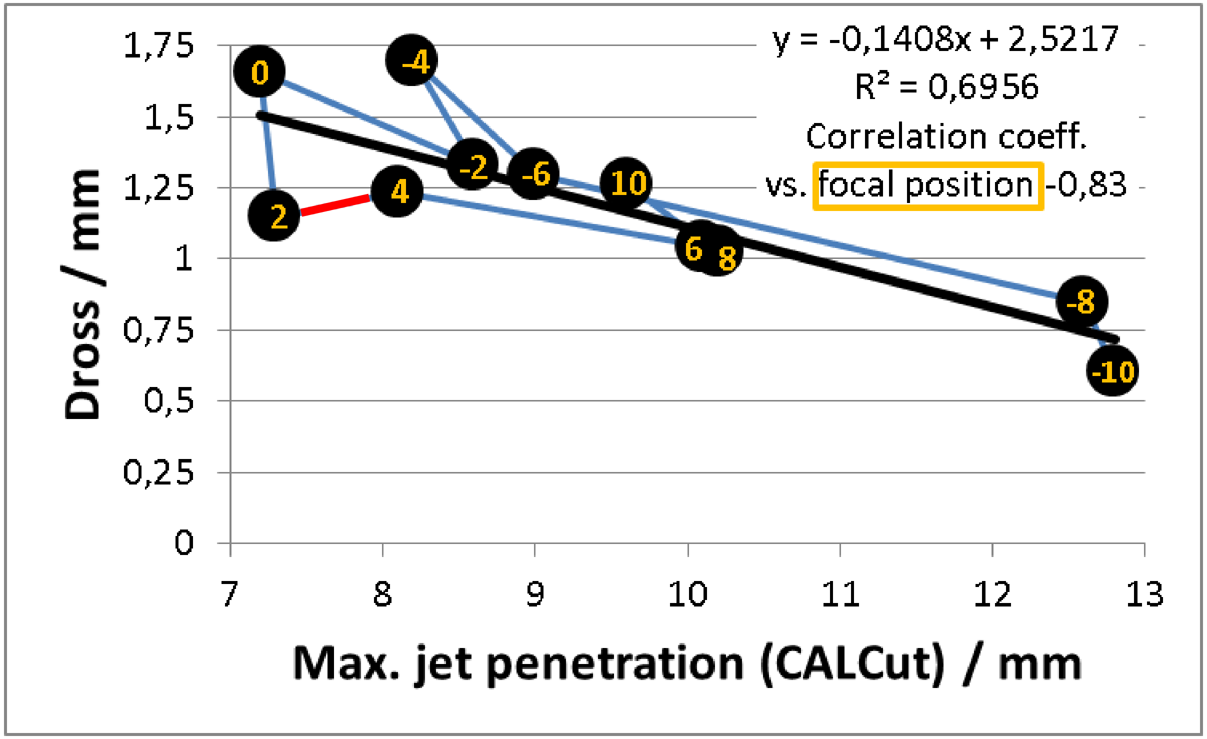
Practical Verification of CALCut Simulations
Asymmetry of Cross Sections



Good case:
Confirmed
by CALCut

CALCut kerf cross sections deviate less from experiment than left edge from right.

Practical Verification of CALCut Simulations
CALCut's Jet Penetration Index Correlates with Dross Length



Global and local trends of dross vs. focal position are correctly described by CALCut with only 1 exception out of 12.

Correlation coefficient = -0.83

(<u>Absolute</u> dross height can be reduced by improved nozzle parameters.)

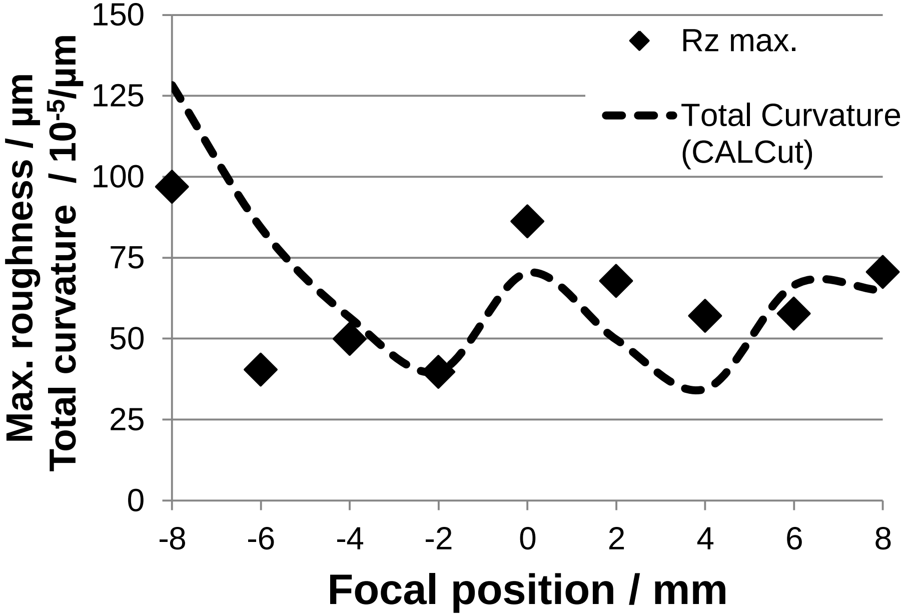
Practical Verification of CALCut Simulations

CALCut's Total Curvature Describes the Irregularity of the Cutting Front and Correlates with Edge Roughness

The total curvature of a function F(z) is a measure for its "roughness":

$$\int_{z1}^{z2} \left[\frac{F''(z)}{(1+F'^2)^{3/2}}\right]^2 dz$$

V. Blobel and E. Lohrmann: Statistische und numerische Methoden der Datenanalyse, G. Teubner 1998



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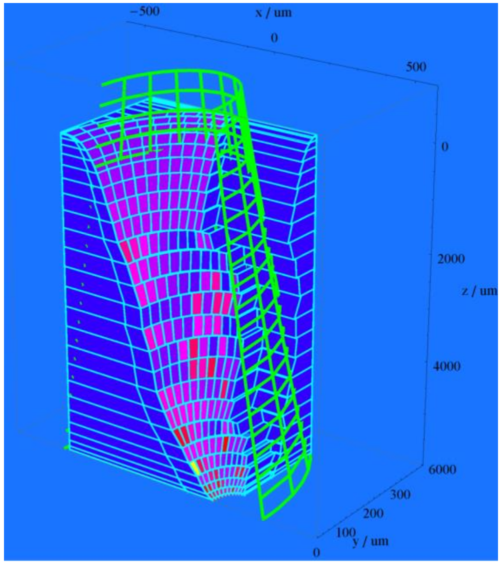
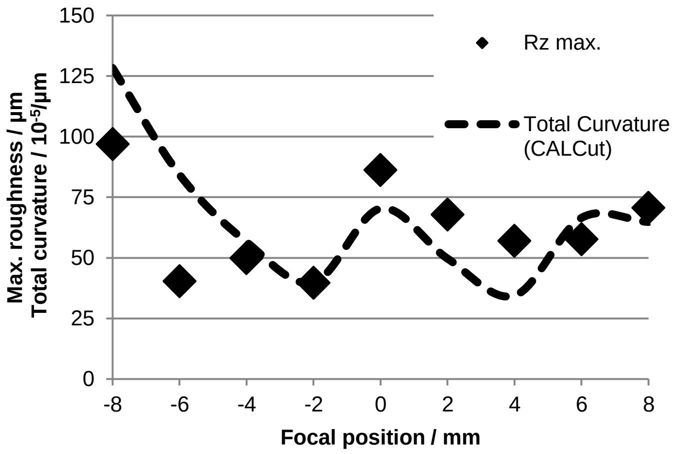
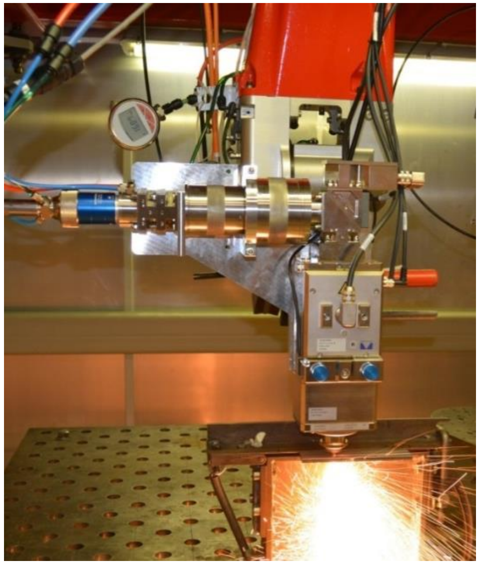
Results from EU Projects FILCO and HALO

- Optimization procedure with CALCut developed and demonstrated
- Well correlating CALCut criteria identified for dross and roughness
- FILCO beam forming unit designed, manufactured, installed and put into operation as a variable zoom beam expander







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Add-on:
Simulations reveal effects of wavelength, beam quality and power density distribution on “front irregularity“

- Preselected parameter set:
  - Stainless steel 12 mm
  - Laser beam power 5 kW
  - Cutting speed 0.8 m/min
  - Nitrogen 2 MPa
  - Focal position -10 mm

- Varied parameters:
  - Wavelength: CO_2 or fiber
  - Beam quality: K(CO_2)=0.4, fiber: K=0.09 (100µ) or K=0.03 (300µ)
  - Power density distribution: gauss, ring or bull‘s eye shaped

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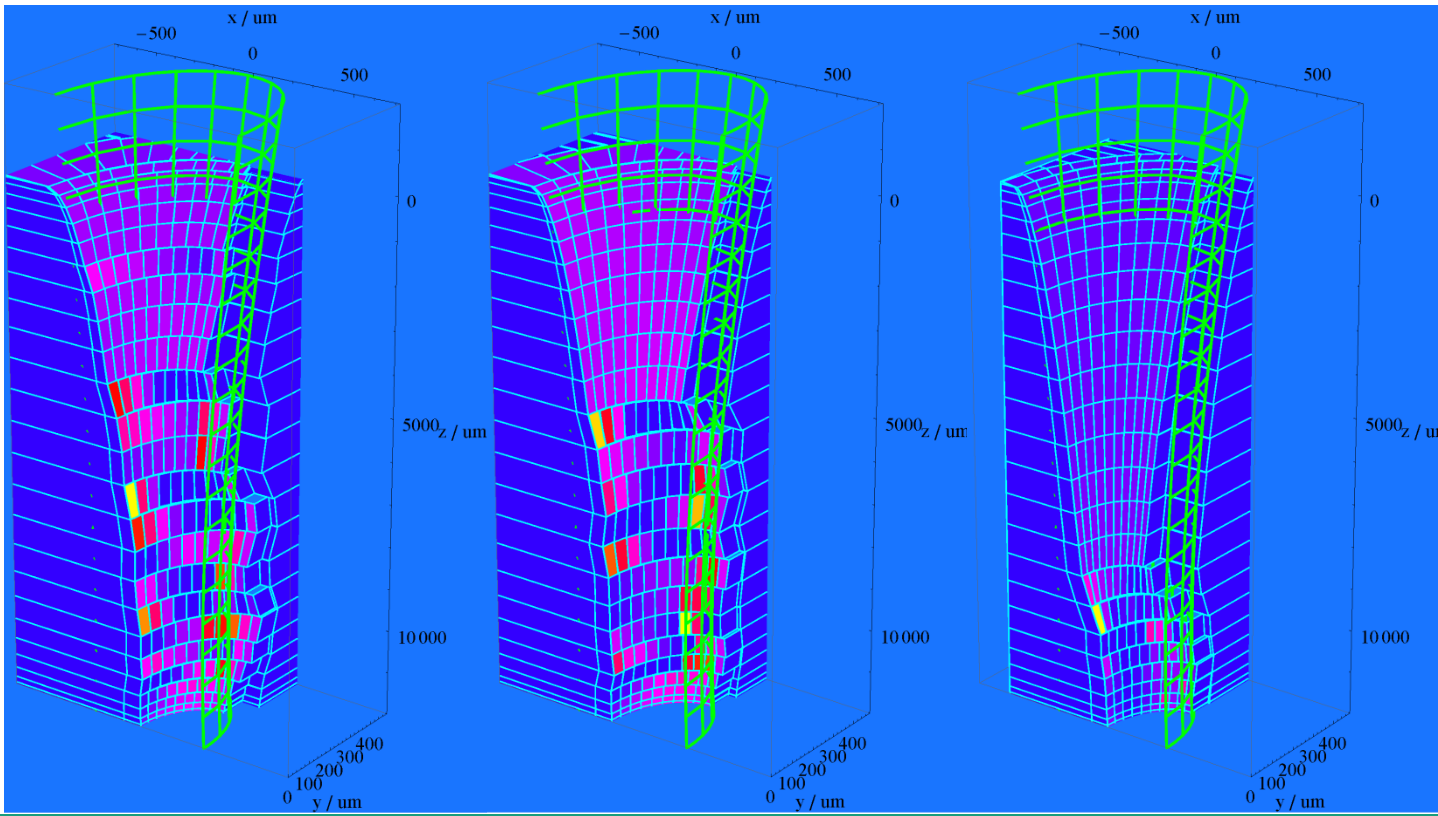
Simulations reveal effects of wavelength, beam quality and power density distribution on “front irregularity“
(@ preselected base parameter set as specified above!)

- **CO_2 laser (10µ, K=0.4)**

Distribution	**gauss**	**ring**	**bull‘s eye**	
Irregularity	51	28	10	[10^{-5}/µm]

- In thick sections some MR effects even @10µ



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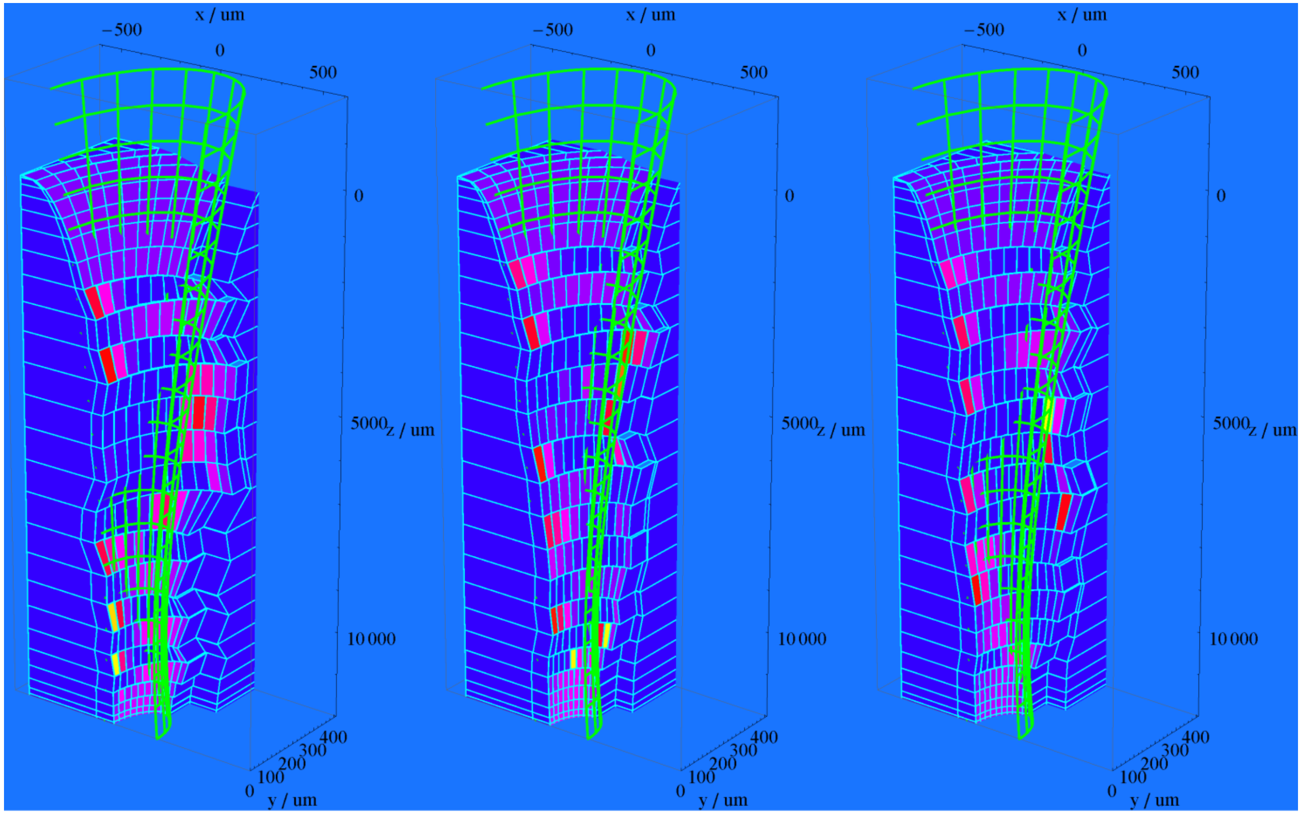
Simulations reveal effects of wavelength, beam quality and power density distribution on “front irregularity“ (@ preselected base parameter set as specified above!)

- **100µ fiber (1µ, K=0.09)**

Distribution	**gauss**	**ring**	**bull‘s eye**	
Irregularity	145	46	63	[10^{-5}/µm]

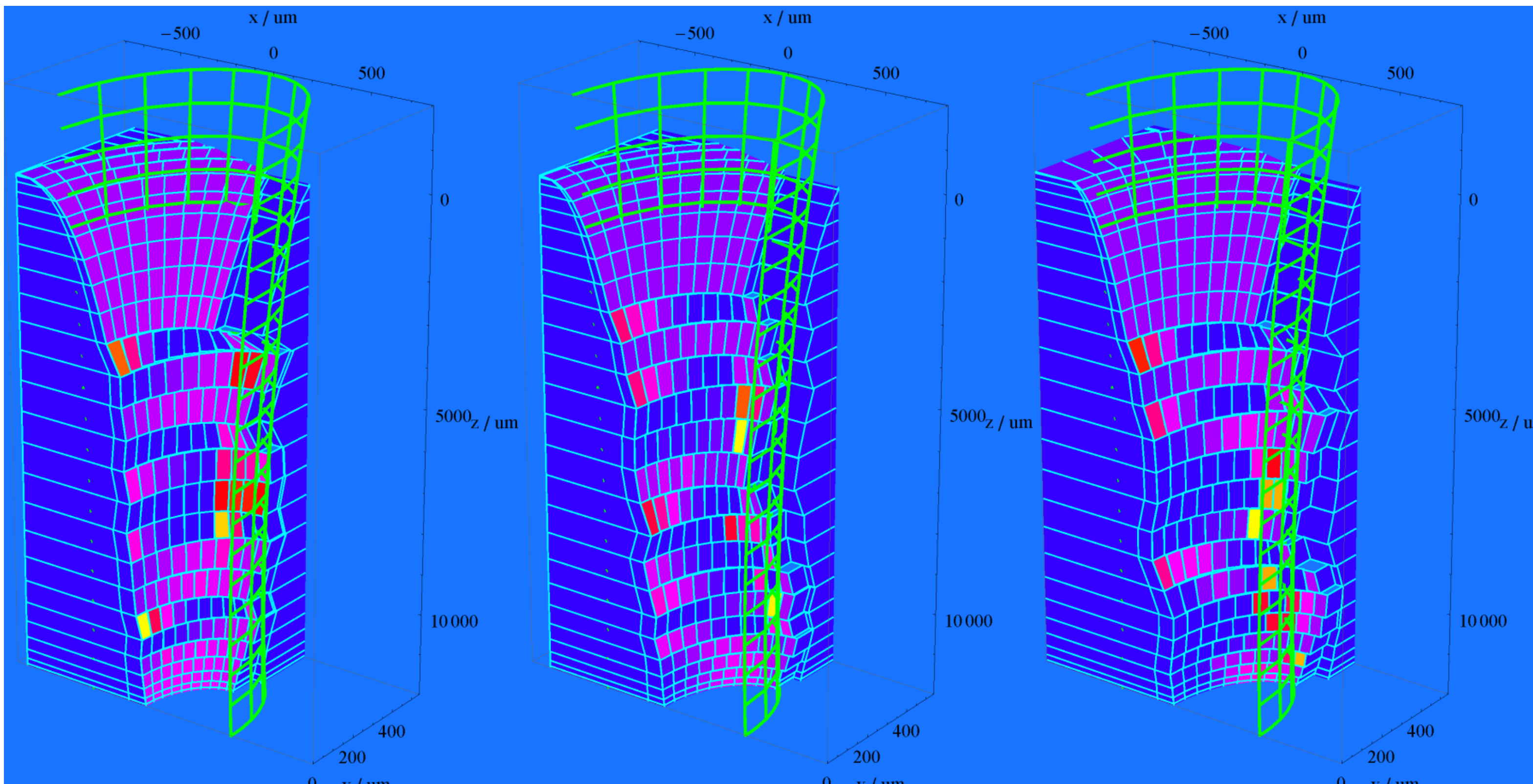
- Worst case for thick sections: High beam quality and gaussian beam distribution @1µ wavelength



Simulations reveal effects of wavelength, beam quality and power density distribution on “front irregularity“
(@ preselected base parameter set as specified above!)

- **300µ fiber (1µ, K=0.03)**

Distribution	**gauss**	**ring**	**bull‘s eye**	
Irregularity	105	88	75	[10^{-5}/µm]



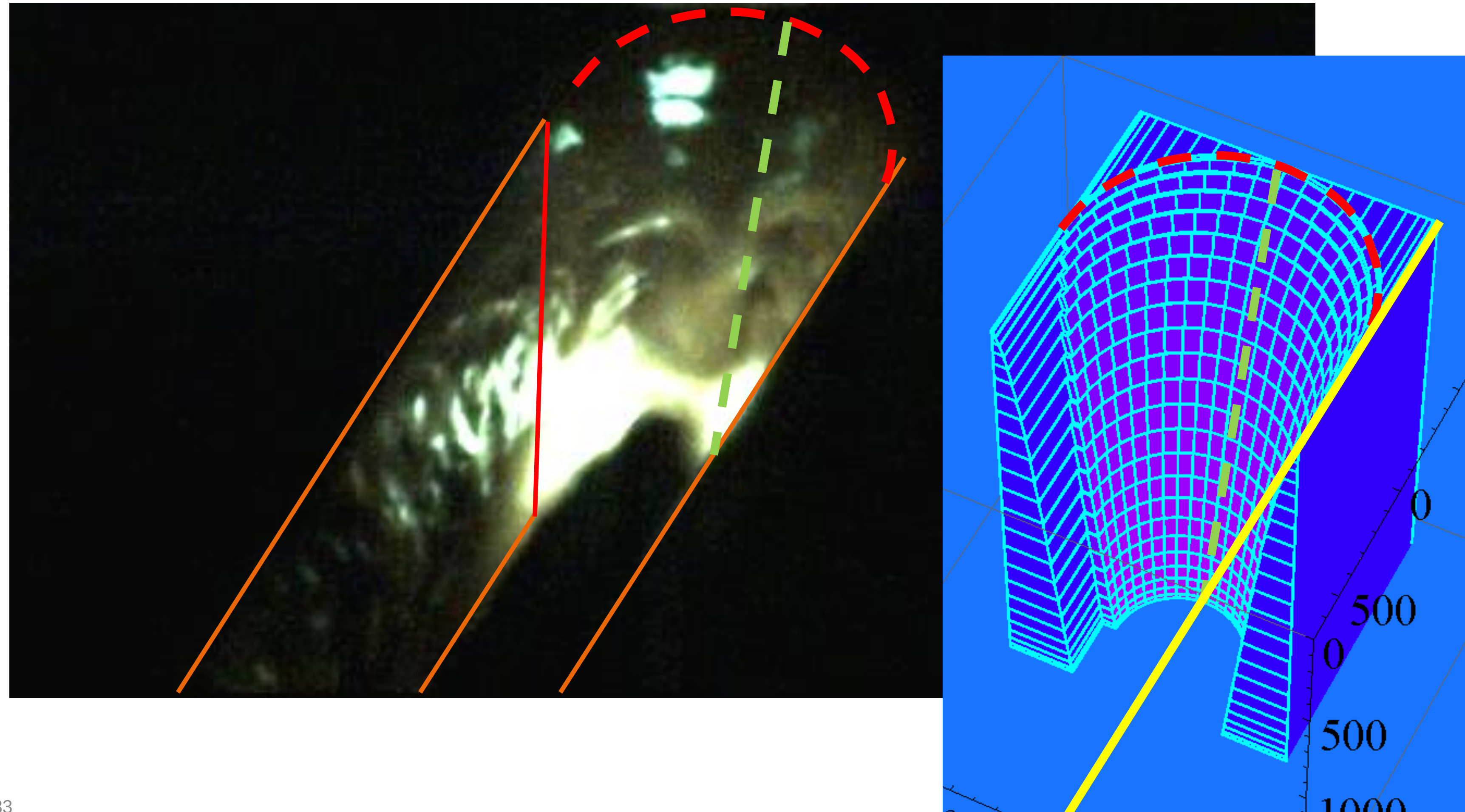
Summary

- Take-away messages from CALCut results:
  - Advantage of 10µ wavelength for smooth cuts (low irregularity) quantifiable by CALCut.
  - For thick sections, according to CALCut ring and bull‘s-eye shaped power density distributions more suitable then gaussian.
  - For thick sections lower beam quality can be beneficial, depending on beam distribution.
  - In a high-dimensional parameter space calculations enable identification of optimum parameter regimes.

- And:
  - First technical solutions for variable beam quality are industrially implemented.
  - Still much space for further improvements.

Practically Visualized and Theoretically Simulated View of a Cutting Front

- The cutting front geometry and many other of its properties can be calculated.



Examination of laser cutting phenomena by comprehensive steady-state simulations (Abstract I/II)

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The debate about the capabilities of CO_2 laser and fiber laser cutting systems goes on. Beside experimental work, process diagnostics and theoretical considerations gain attention. The latter vary from analytical equations generally describing singular physical sub-processes [1)] to fully numerical simulation tools requiring at least several days for the calculation of a short cutting track for one single parameter [2)].

Fundamental questions remain: What are the mechanisms of melting bump formation? How do horizontal and vertical melting strings arise? Which melting film surface temperatures occur? How far does vaporization as well as multiple reflections contribute to the process? The experts have hardly come to a consolidated understanding of these phenomena or of parameter dependencies at all - mainly because most parameter dependencies show highly nonlinear behaviour. [3)]

Systematic simulation calculations based on an established steady-state cutting model [4)] shall support parameter screening and reveal new insights. The calculation of the steady-state process by a combination of semi-analytical and semi-numerical algorithms is demonstrated to be an effective way to improve process understanding. Based on well-defined criteria process regimes for optimized cutting efficiency and cut quality are identified. The simulation-supported parameter screening is believed to take on a key role in future laser cutting process development.

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Examination of laser cutting phenomena by comprehensive steady-state simulations (Abstract II/II)

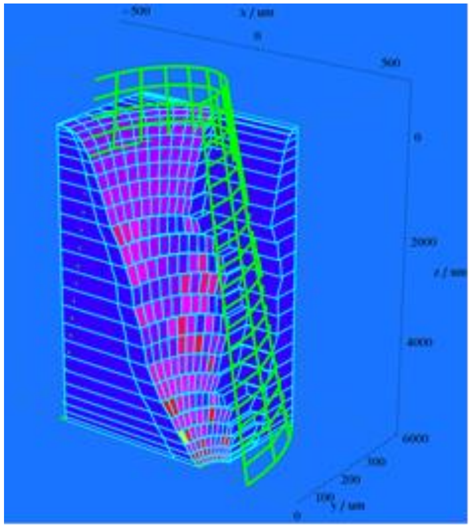

Figure 1: Typical representation of a steady-state cutting front simulated with CALCut

1) K. Hirano, R. Fabbro, Experimental investigation of hydrodynamics of melt layer during laser cutting of steel, J. Phys. D: Appl. Phys. **44** (2011).

2) A. Otto, H. Koch, K.-H. Leitz, M. Schmidt, Numerical Simulations - A Versatile Approach for Better Understanding Dynamics in Laser Material Processing, , Physics Procedia **12**, 11-20 (2011).

3) D. Petring, T. Molitor, F. Schneider, N. Wolf, Diagnostics, modeling and simulation: Three keys towards mastering the cutting process with fiber, disk and diode lasers, Physics Procedia **39**, 186–196 (2012).

4) D. Petring, Computer simulation of laser cutting for the limiting-value-oriented development of robust processes, Welding and Cutting **4** No. 1, 37-42 (2005)

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