# Correlation between microstructure stability and processing parameters in Ti-6Al-4V produced by selective laser melting

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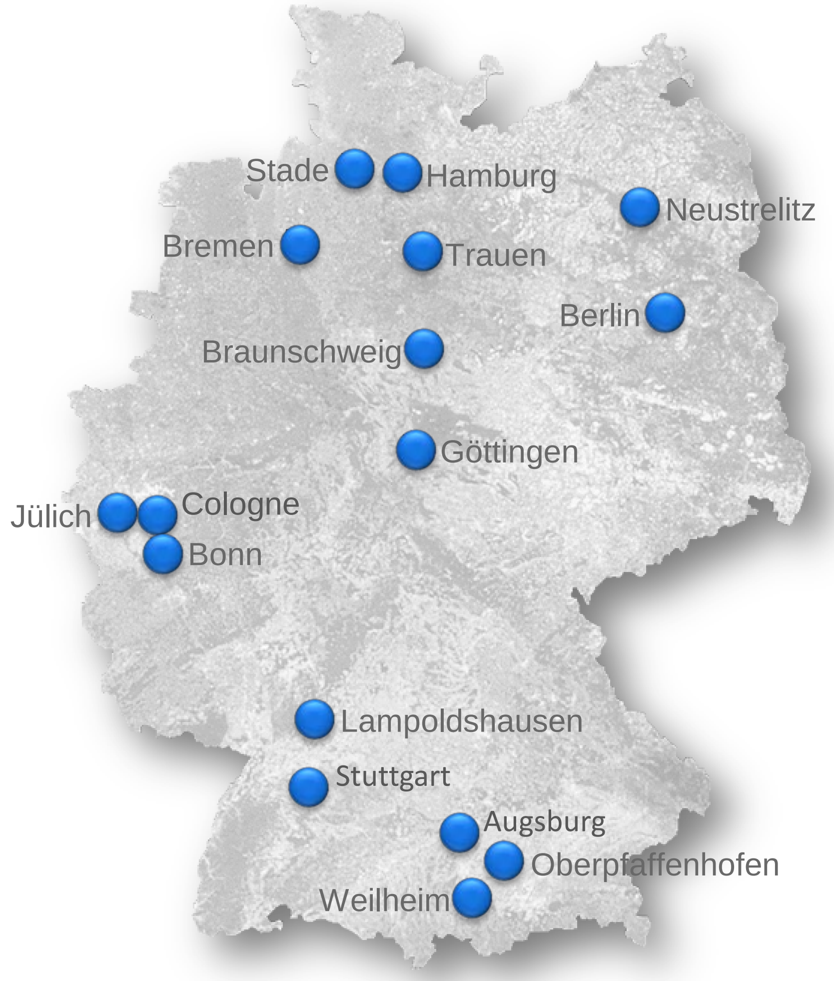
# The German Aerospace Center (DLR)

**Largest aerospace research facility in Europe**

- **~ 8000 employees**
- **32 institutes**
- **16 sites in Germany**
- **Offices in Brussels, Paris, Tokio, Washington**

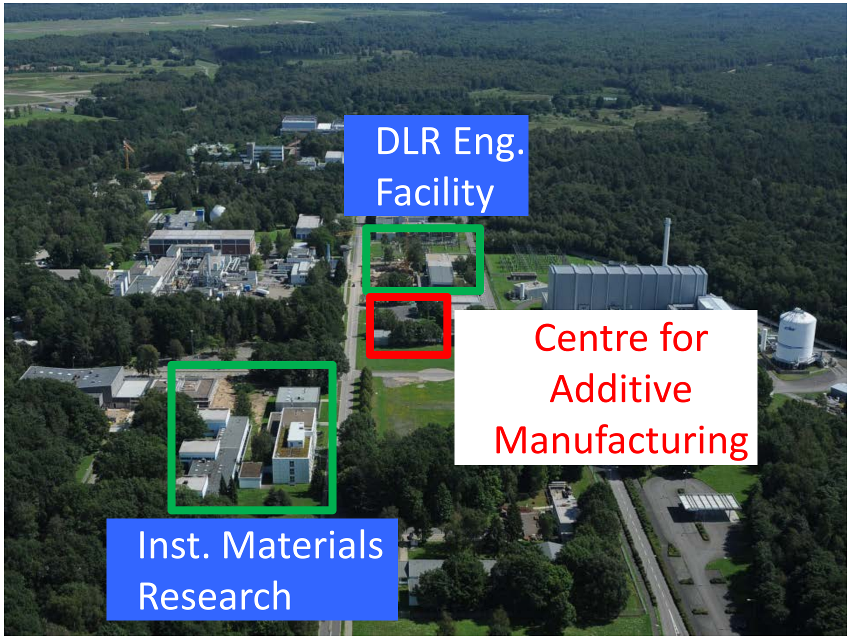
- **Turnover: ~ 1800 M€**

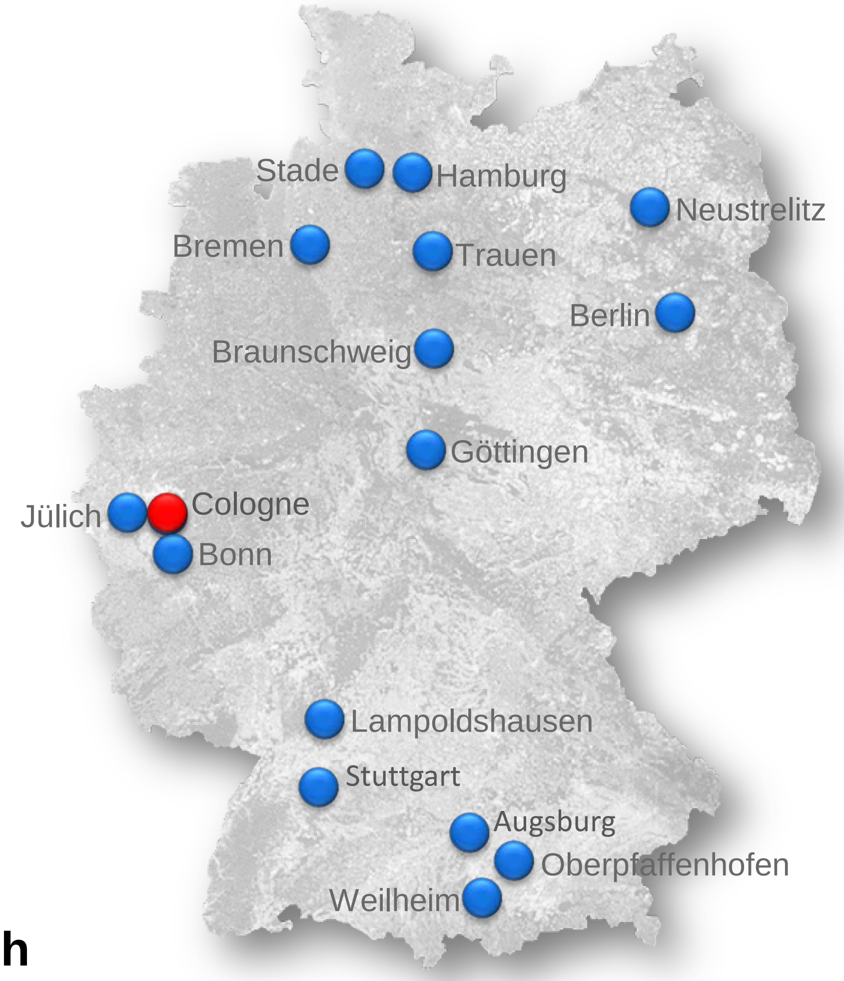
- **Space program 971 M€**
- **Research 798 M€**
  - **Space 50%**
  - **Aeronautics 34%**
  - **Transport 7%**
  - **Energy 9%**



# ALM of metals  at the German Aerospace Center (DLR)

**<u>Today</u>:**
**1 SLM machine for materials research**
**3 SLM machines for production**



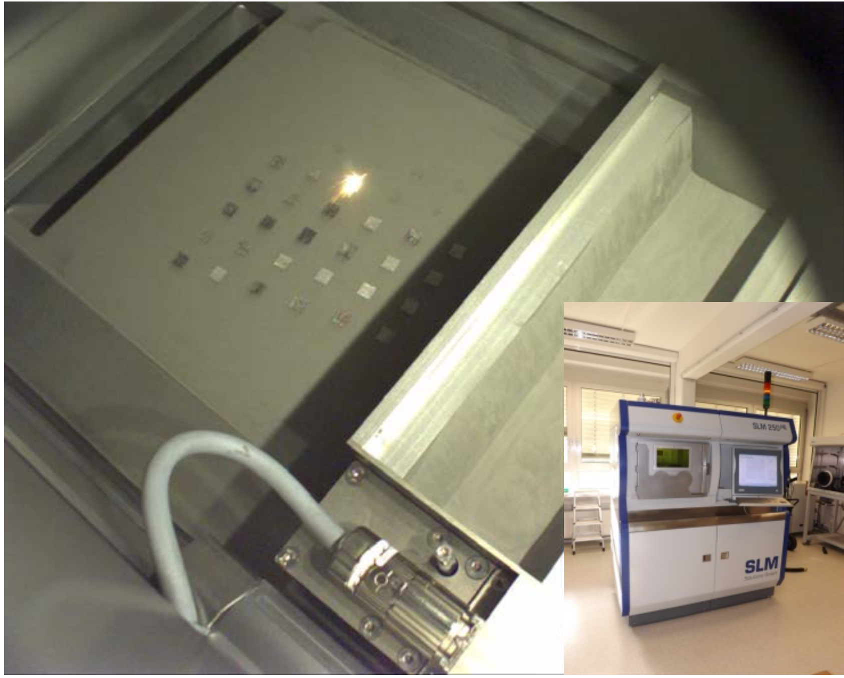



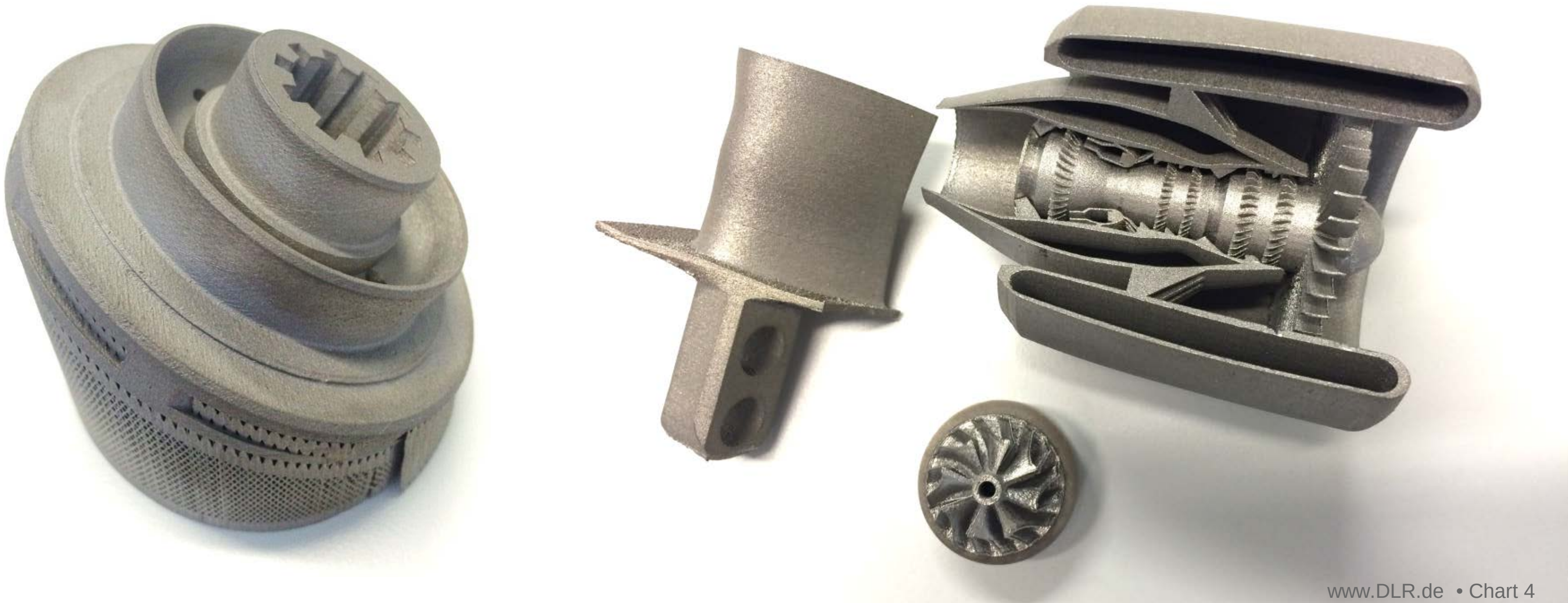

**<u>From 2017?</u>:**
***Centre for Addtive Manufacturing***
**Cologne Site → ALM of Metals**
**1 SLM + 1 LMD machine for materials research**
**4 SLM machines for production incl. large components**
**Diverse characterization and post-treatment facilities**

# Selective Laser Melting

- **SLM Solutions 280**:
  - High temperature building chamber (≤ 800°C)
  - In situ melt-pool monitoring system

- **<u>Research Focus:</u>**
  - Materials Characterization / Optimization /Development
  - Microstructure vs. Mechanical Properties
  - Manufacturing strategies for different material classes



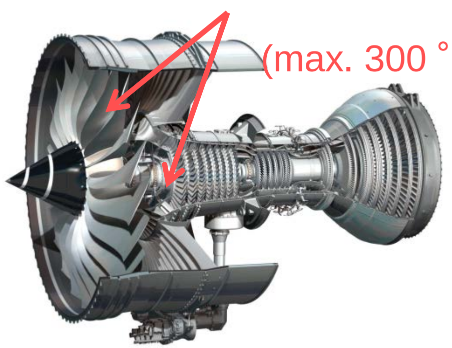



# Selective Laser Melting of Ti-6Al-4V

Additive manufacturing

Selective Laser Melting (SLM)

Ti-6wt%Al-4w%V (TiAl6V4)




## Manufacturing optimization of Ti-6Al-4V

## WHY INSIST ON Ti64?

Most used Ti alloy in space and aeronautics BUT as wrought or cast alloy.

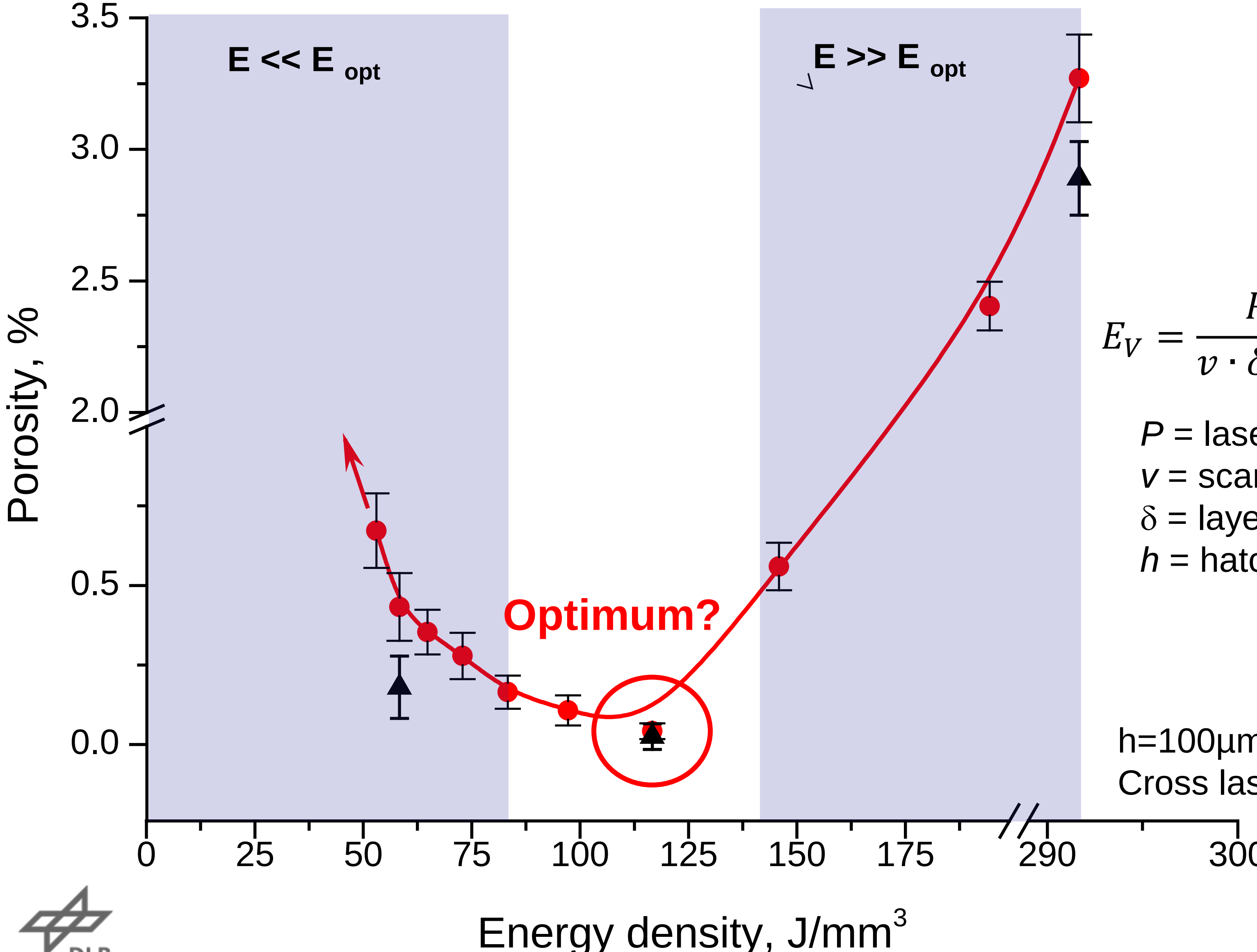
- Industry is pushing the qualification of ALM Ti64 before development of new alloys
- Planned standards for ALM components consider only Ti64 among Ti alloys (e.g. esa)

**1 →** Optimization of process parameters for minimization of voids

**2 →** Microstructure formation and evolution during and after SLM

# Selective Laser Melting of Ti-6Al-4V

## Correlation between Energy density, $E_V$, and total porosity



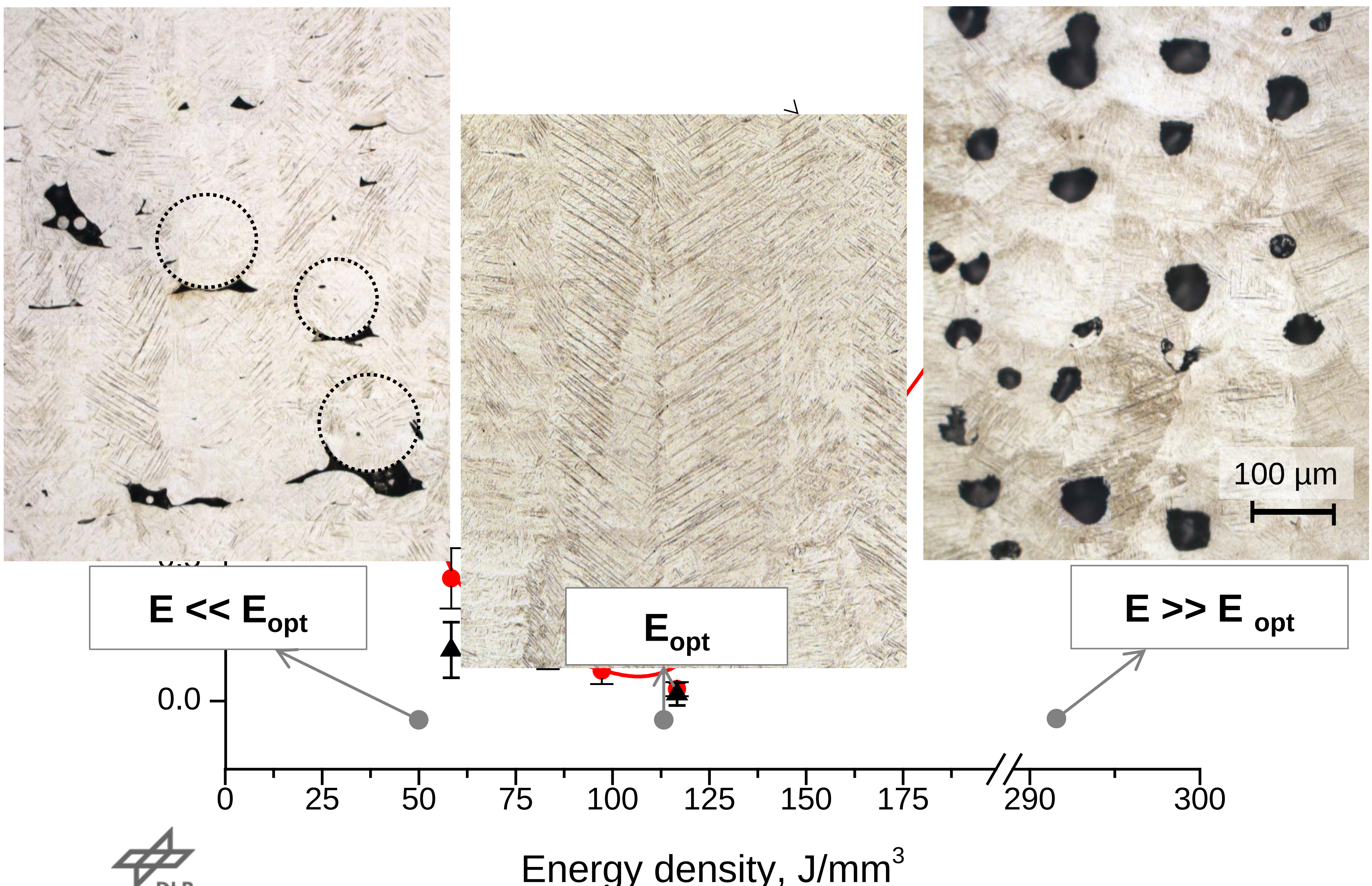

$$E_V = \frac{P}{v \cdot \delta \cdot h} \left[\frac{J}{mm^3}\right]$$

*P* = laser power
*v* = scan velocity
δ = layer thickness
*h* = hatch distance

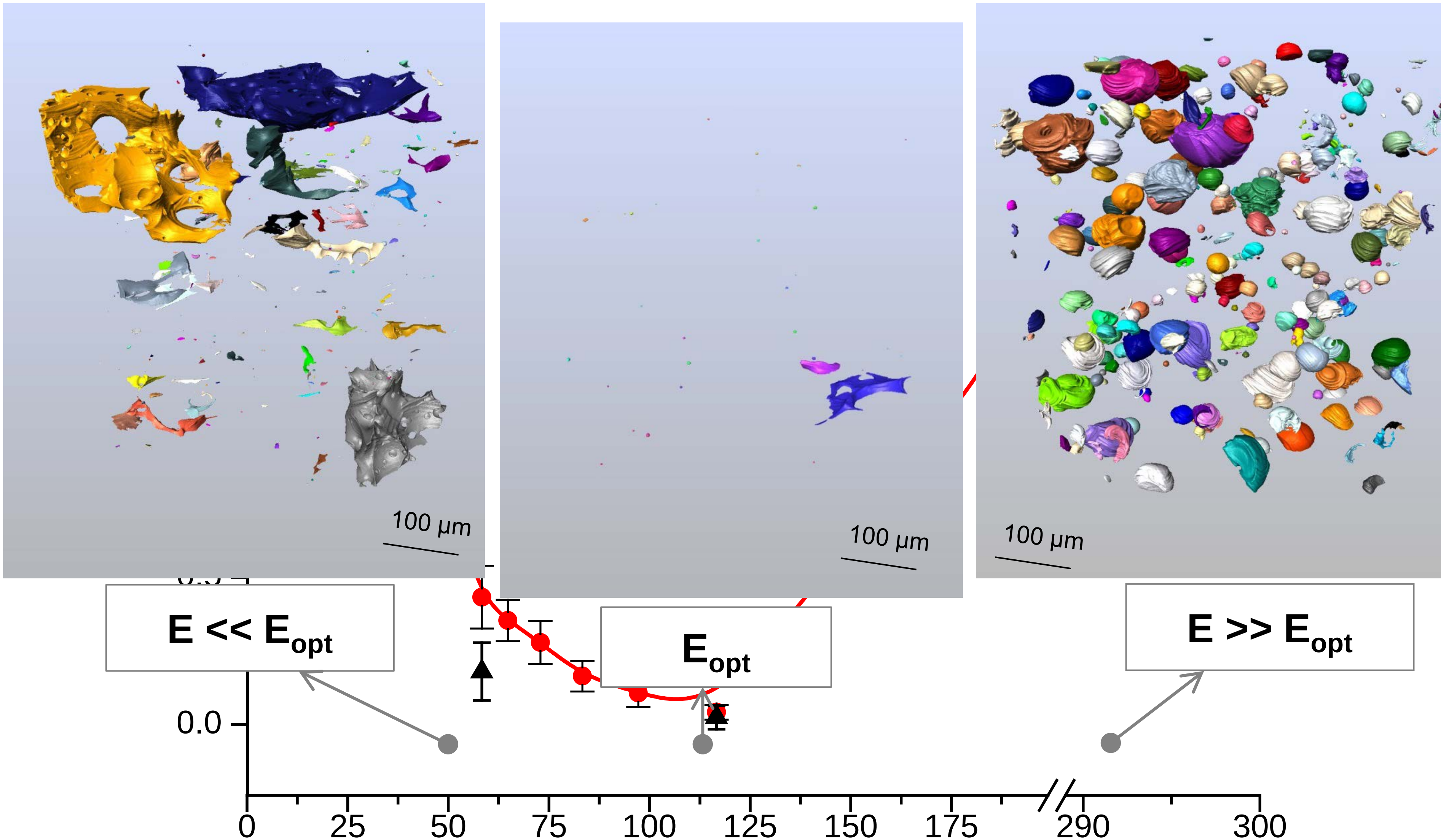
h=100µm, F=2mm
Cross laser strategy

DLR

# Selective Laser Melting of Ti-6Al-4V

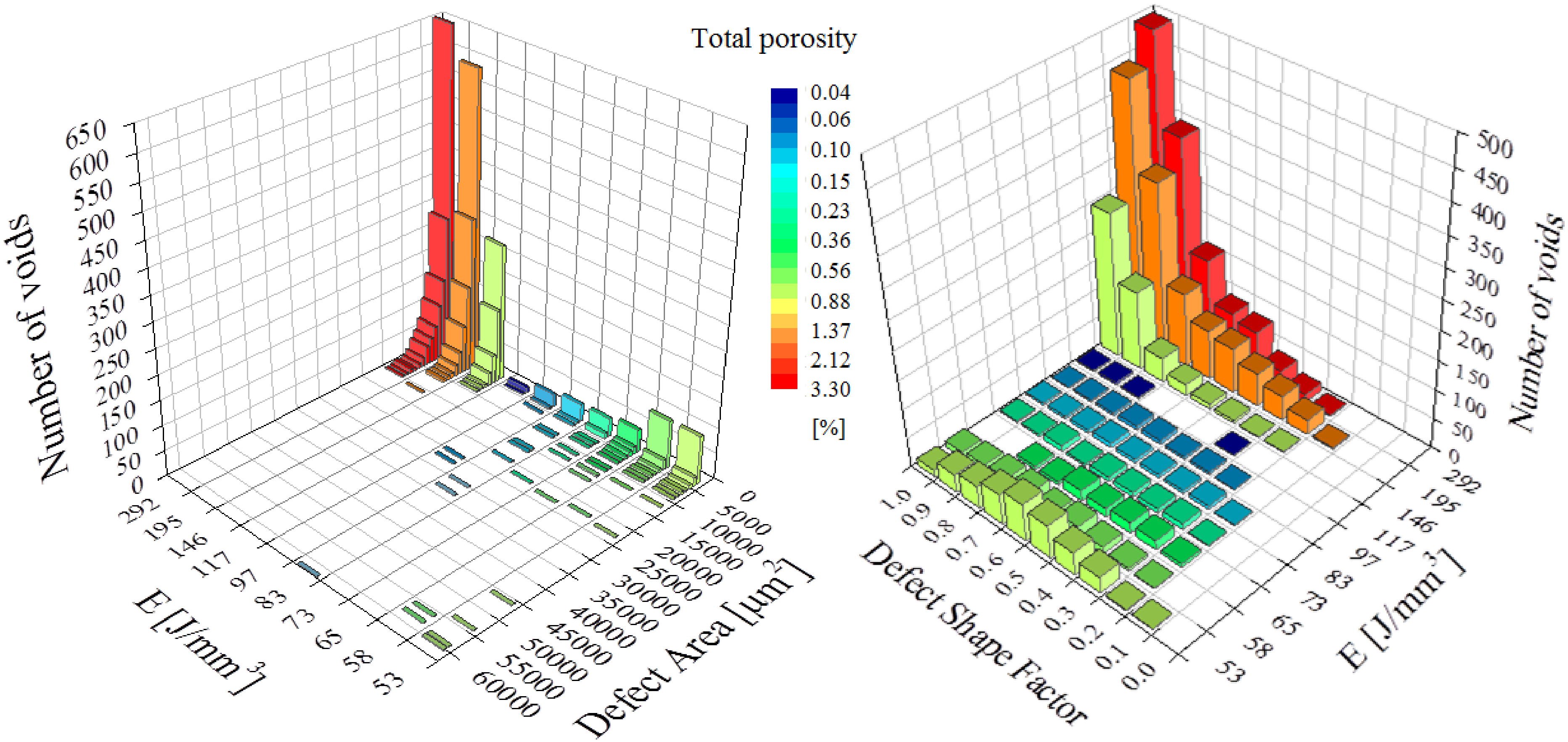


# Selective Laser Melting of Ti-6Al-4V




Kasperovich et al. Materials&Design– (2016)

# Selective Laser Melting of Ti-6Al-4V

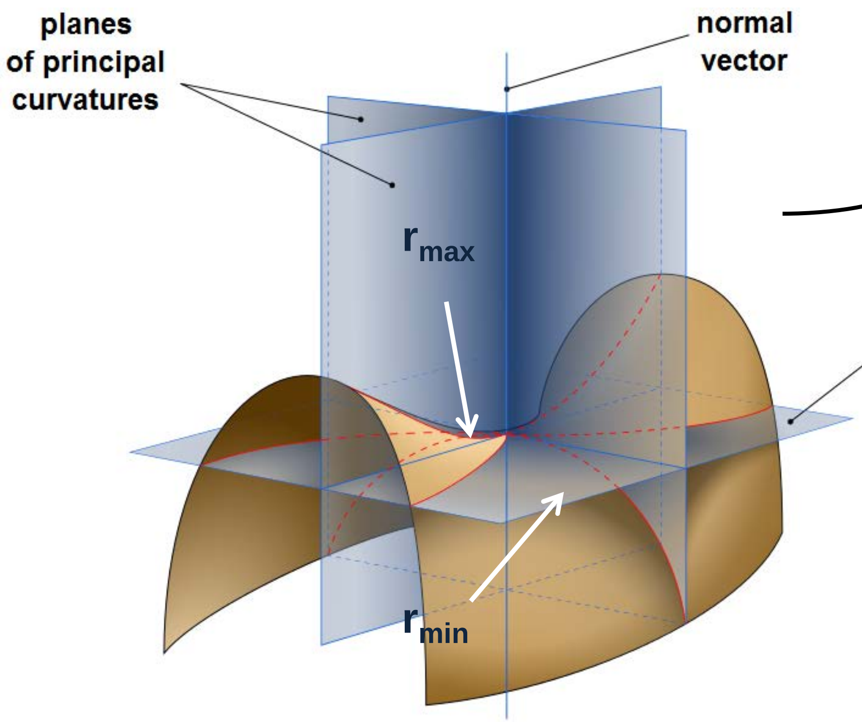


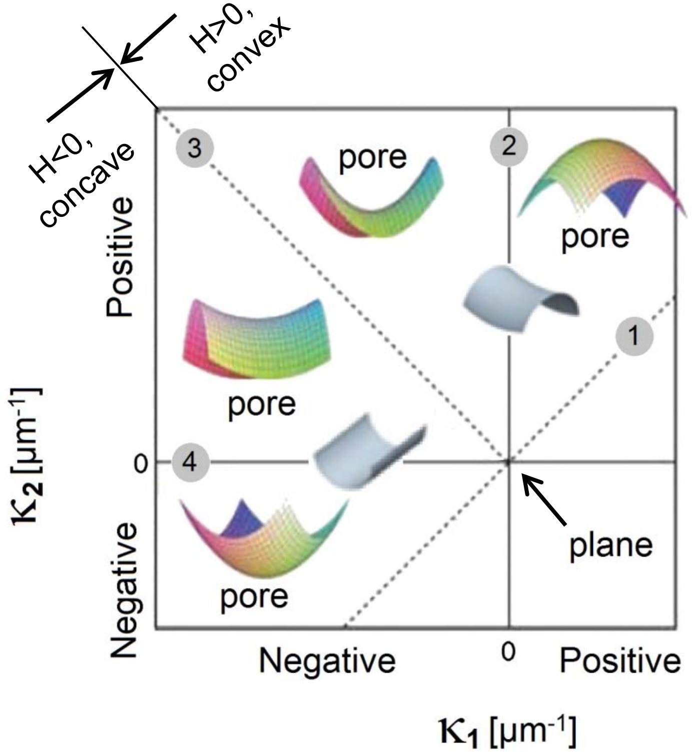



Kasperovich et al. Materials&Design– (2016)

# 3D Analysis of Shape Distribution

## Curvature distribution of pore surfaces




Two principal curvatures: $\kappa_1 = 1/r_{max}$ ; $\kappa_2 = 1/r_{min}$

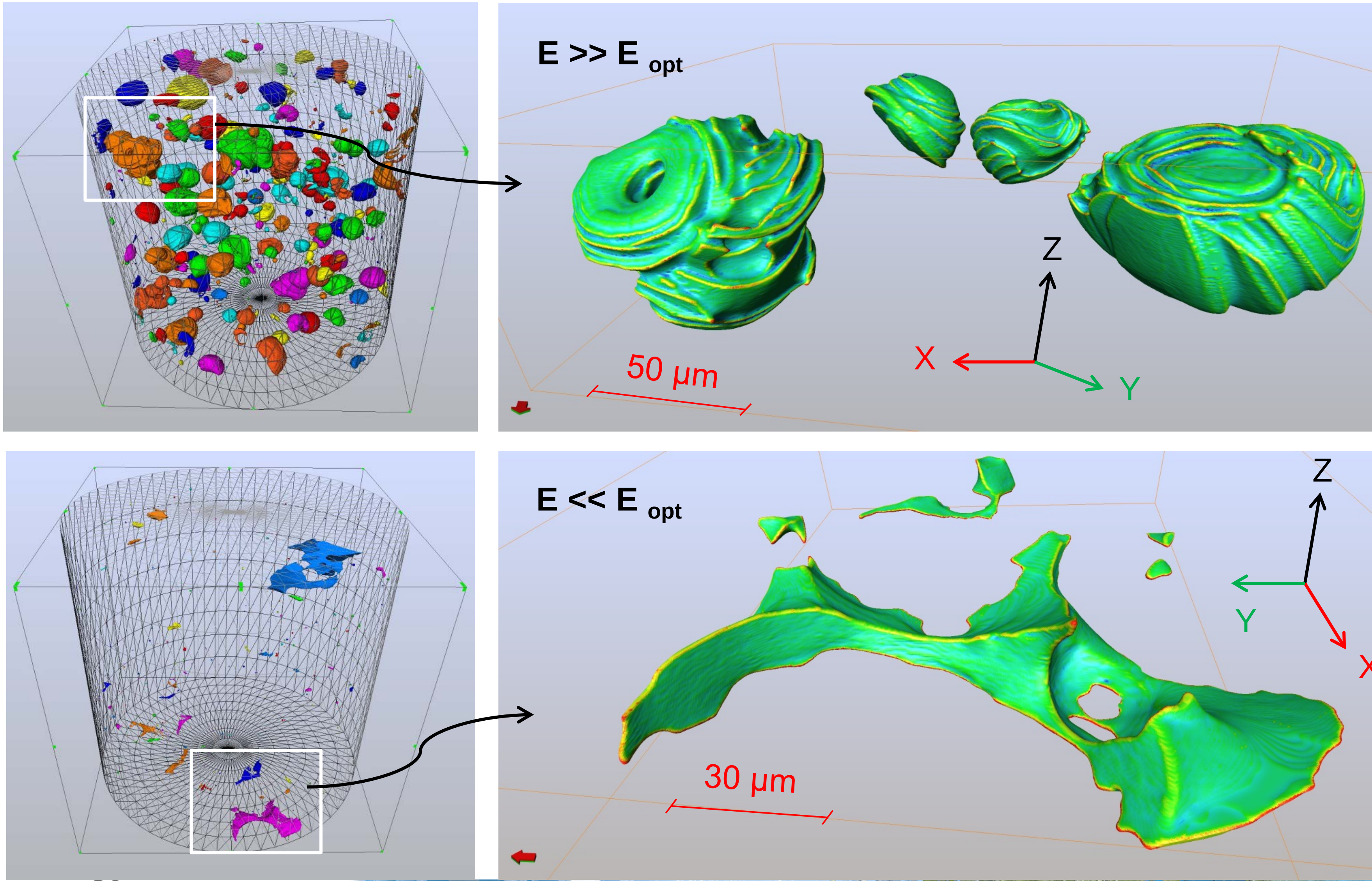
Local mean curvature: $H = (\kappa_1 + \kappa_2)/2$

Gaussian curvature: $K = (\kappa_1 \times \kappa_2)$

Morphology:
sphere, cylinder, saddle…,
convex (H >0) or concave (H<0)

# Selective Laser Melting of Ti-6Al-4V

## Shape of voids



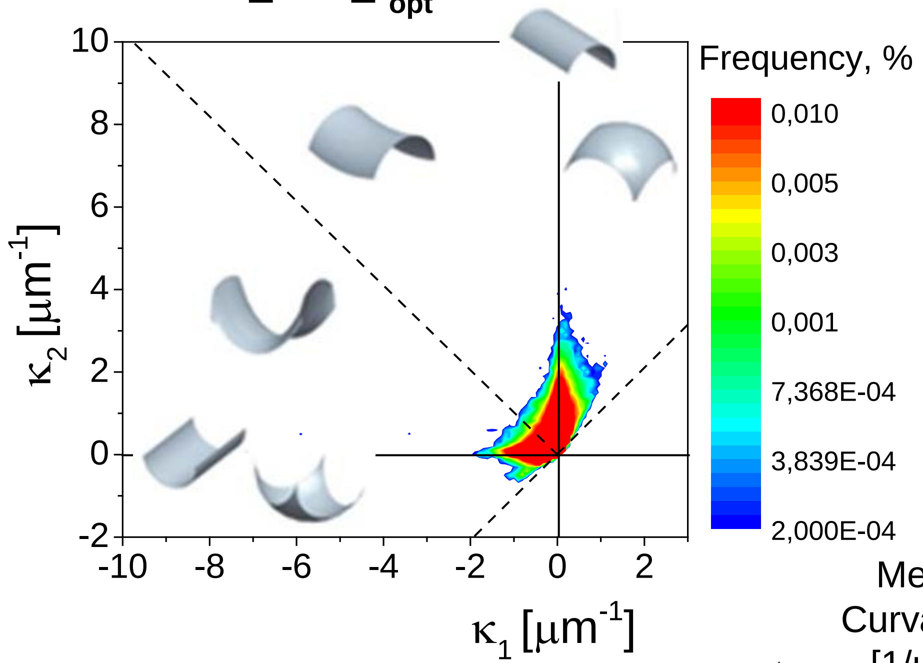

*Bounding cylinders: ø 800 µm h=700 µm*

*Bounding boxes: 350 x 250 x 100 µm³*

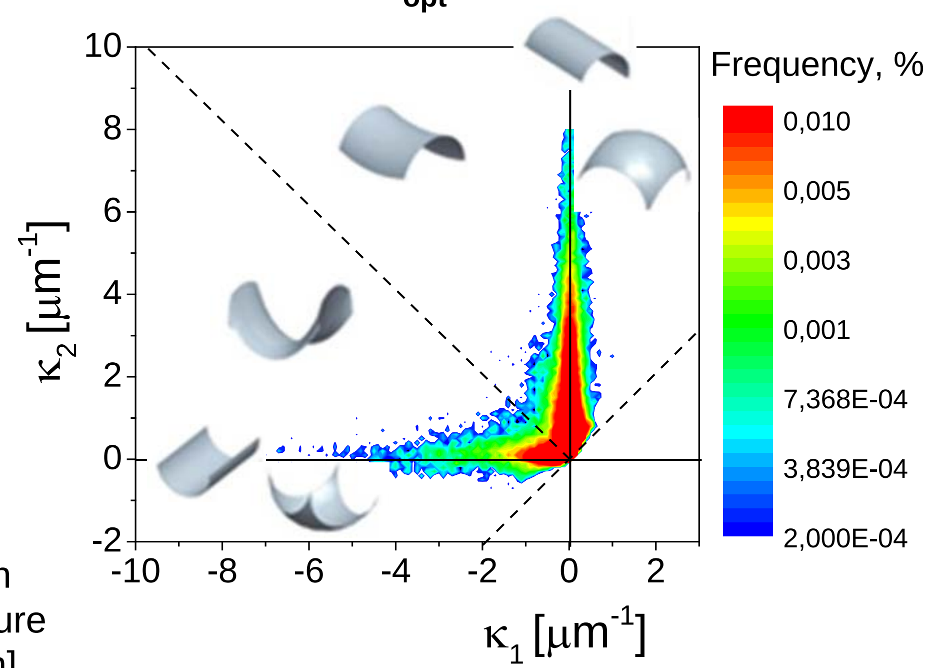
# Selective Laser Melting of Ti-6Al-4V

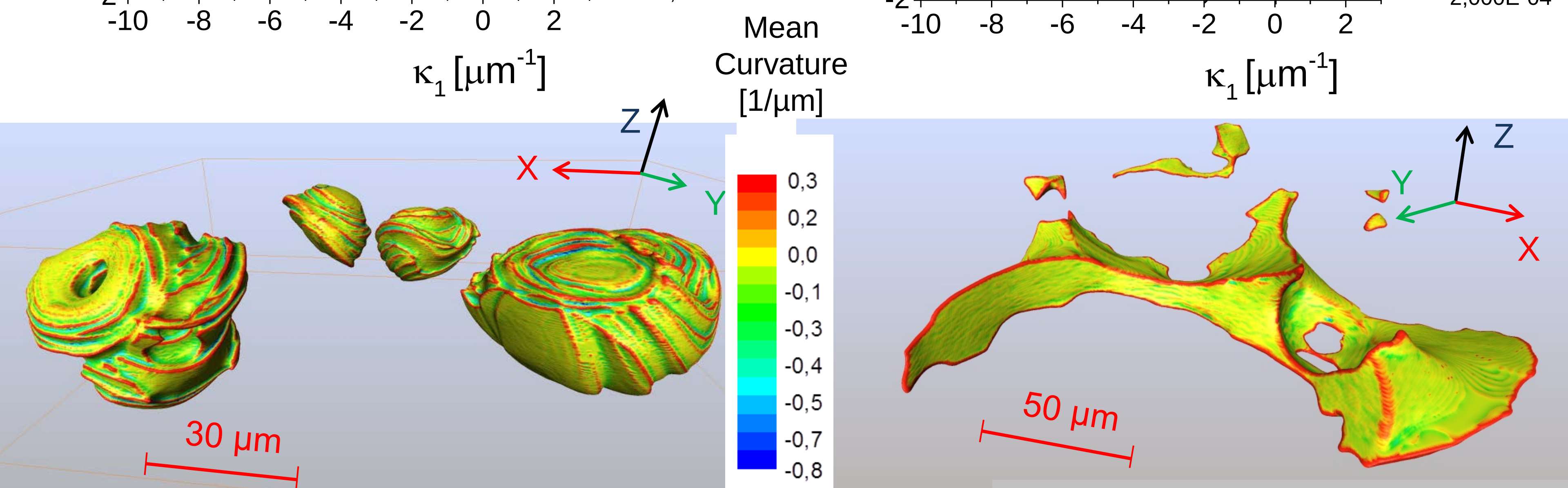
## Shape Distribution of voids

**E >> E opt**




**E << E opt**

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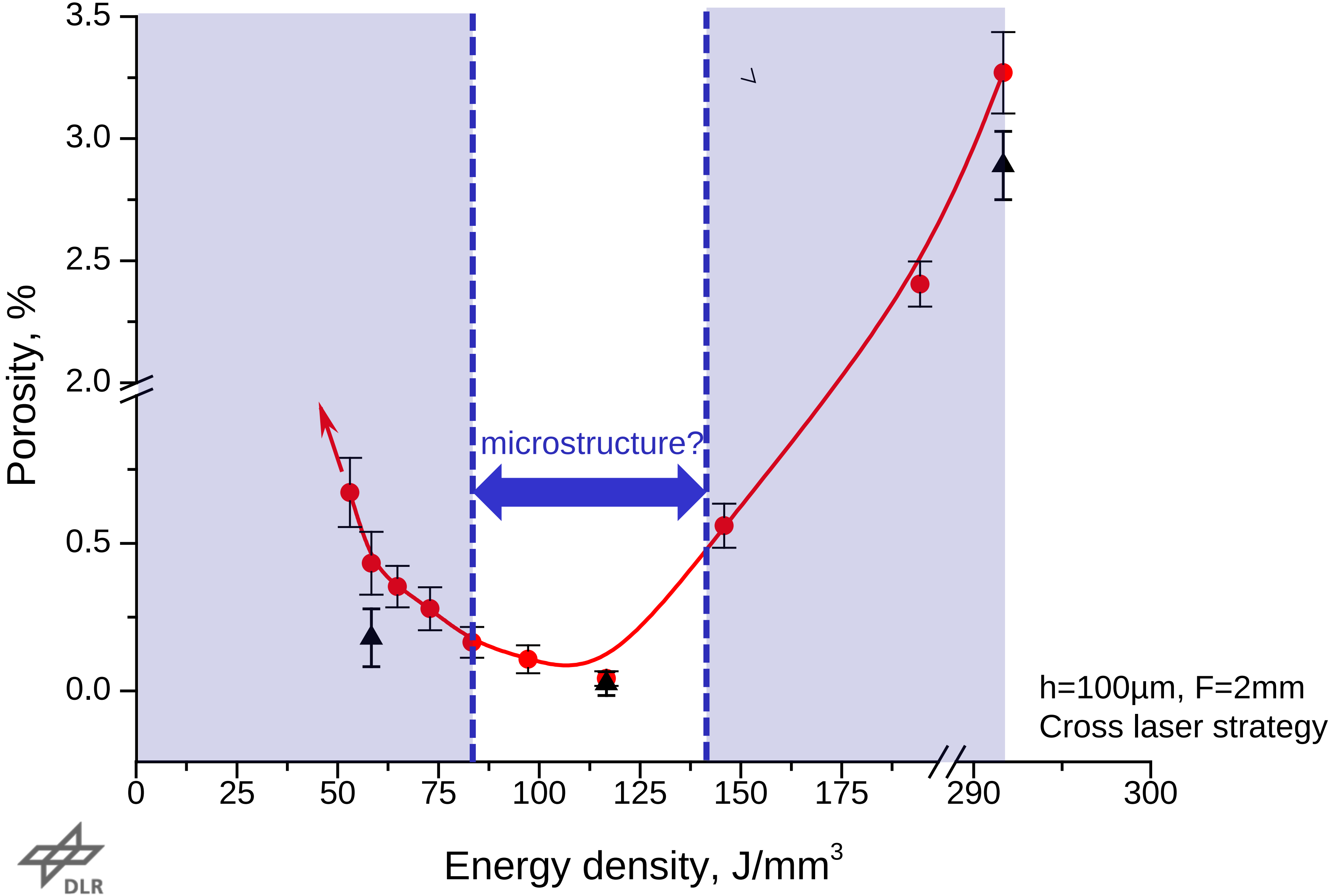
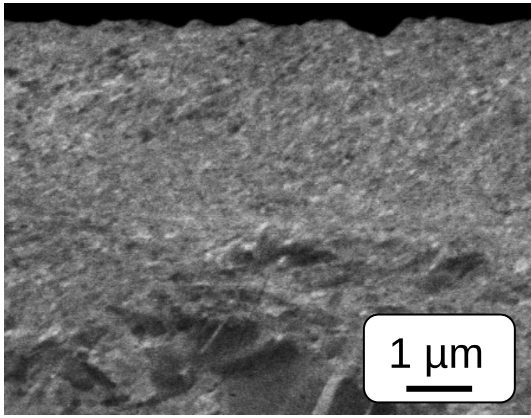
# Selective Laser Melting of Ti-6Al-4V

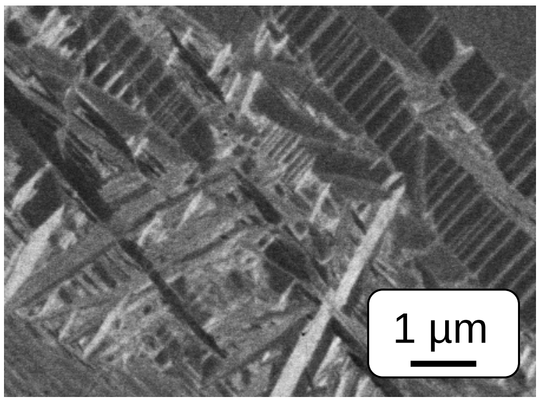
## Microstructure formation within „process window“

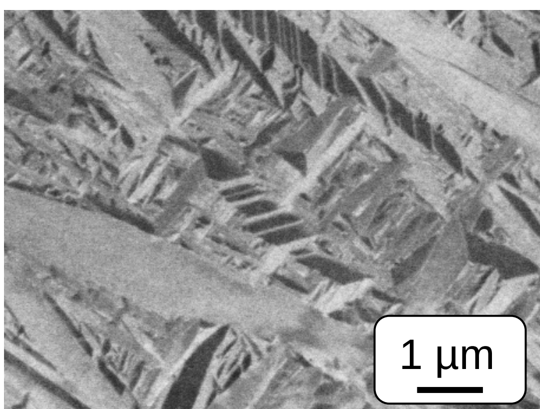


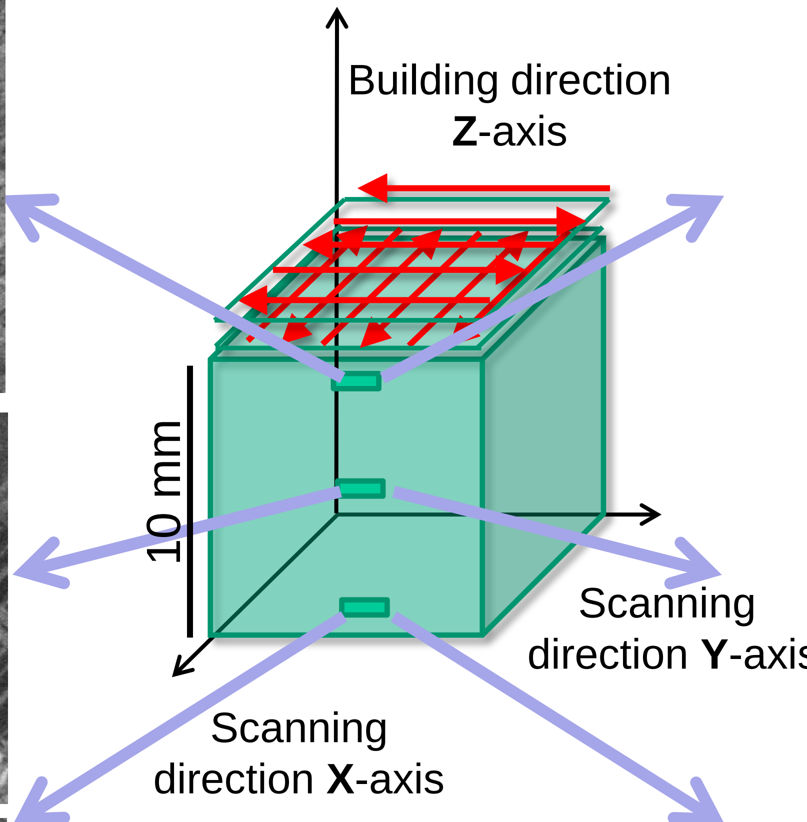
# Selective Laser Melting of Ti-6Al-4V – Microstructure Evolution

**Ti64 ($E_V$=77 J/mm³)**

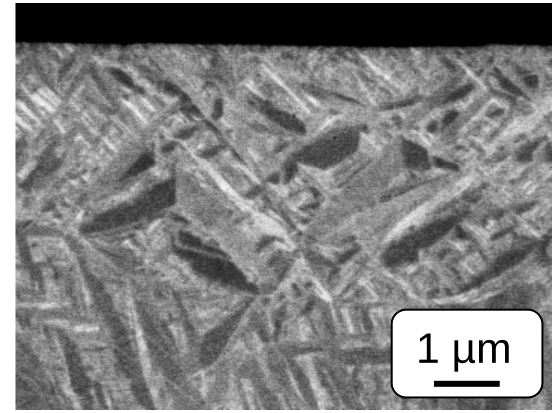


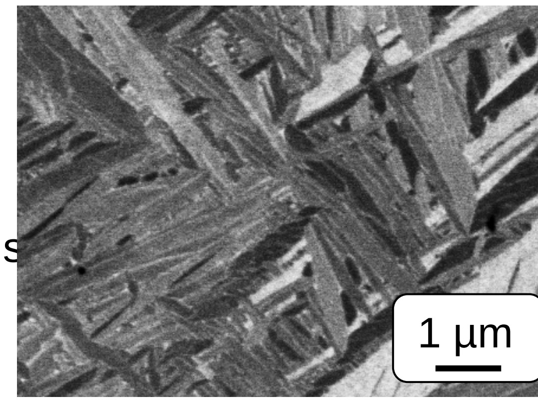



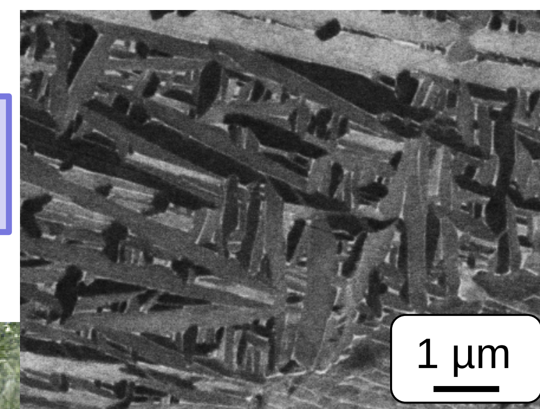




**Ti64 ($E_V$=145 J/mm³)**



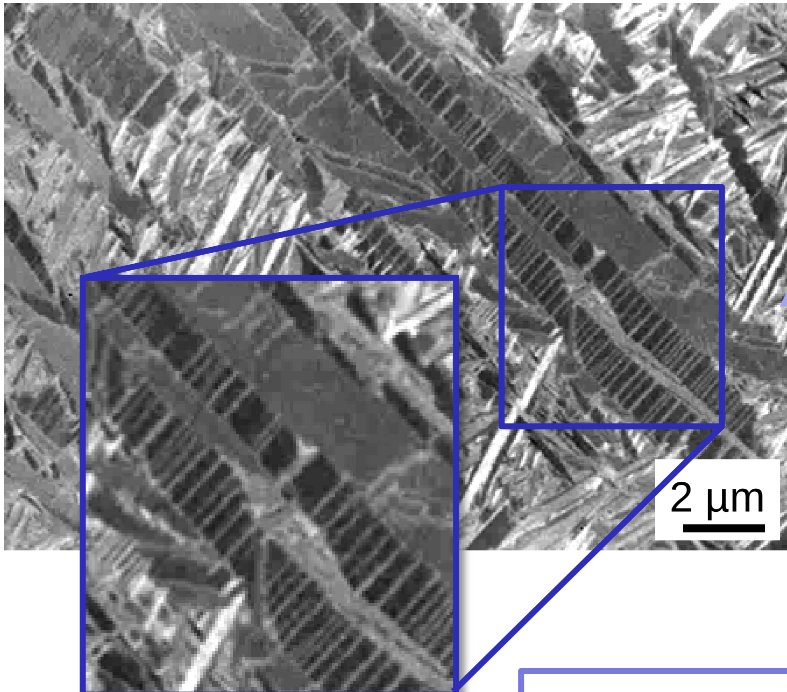



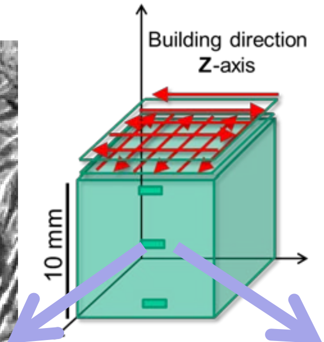




Graded microstructure → function of $E_v$ and building direction

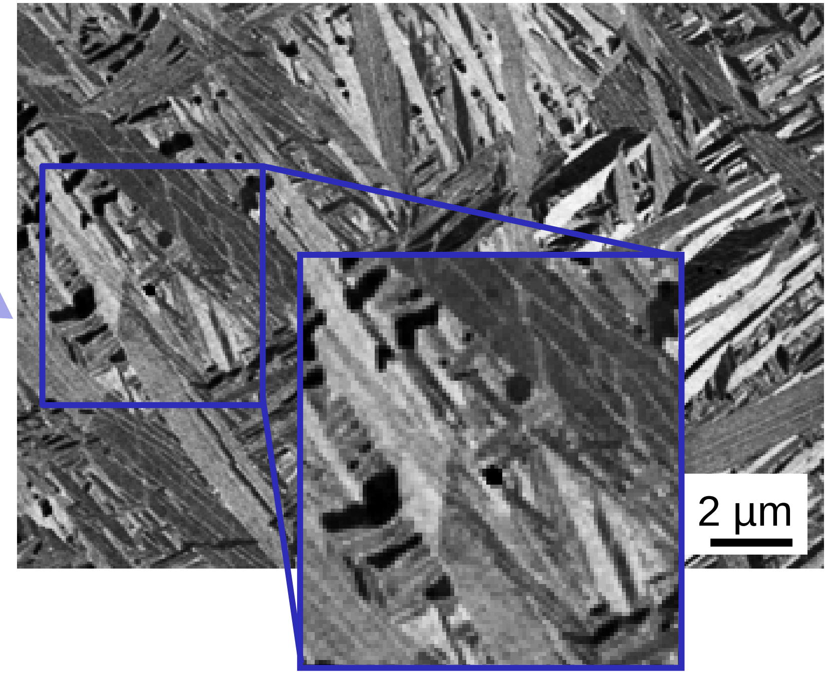
# Selective Laser Melting of Ti-6Al-4V – Microstructure Evolution

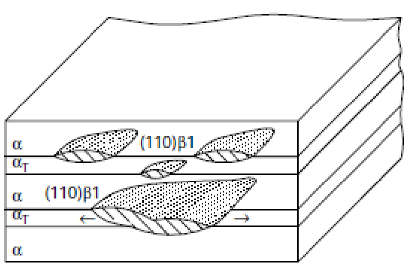
**Ti64 ($E_V$=77 J/mm$^3$)**




**Ti64 ($E_V$=145 J/mm$^3$)**



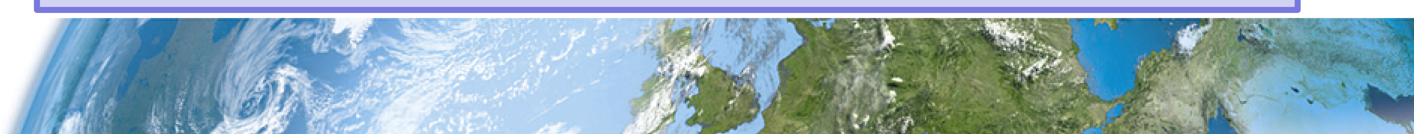

Decomposition of martensite in Zr-2.5Nb at twin boundaries [2]

β can nucleate at α‘ twin boundaries and at dislocations within α‘ during ageing

[1] Ljutering 40

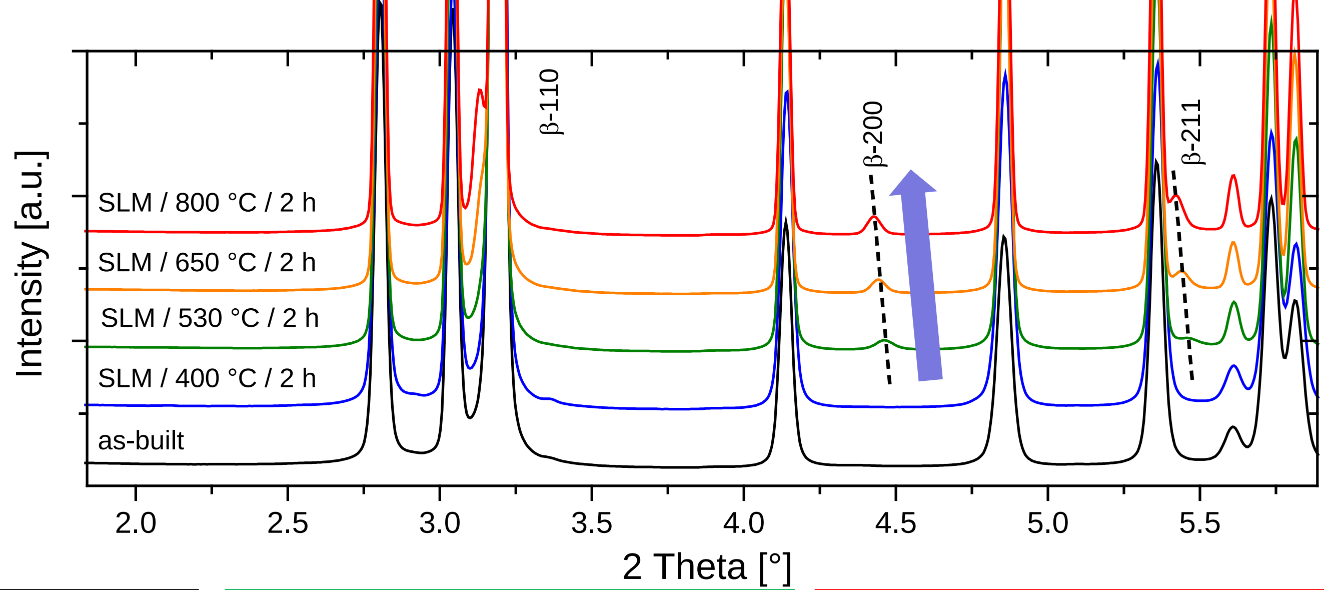
[2] S. Banerjee, P. Mukhopadhyay, Phase Transformations 2007, p 614-615

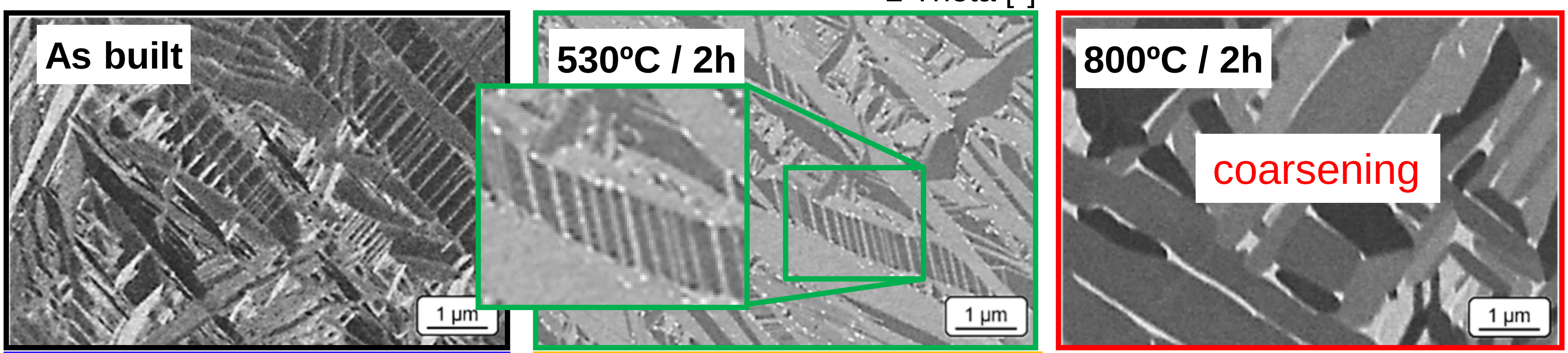
**Is it possible to obtain a fine α+β microstructure by ageing the SLM as-built condition?**

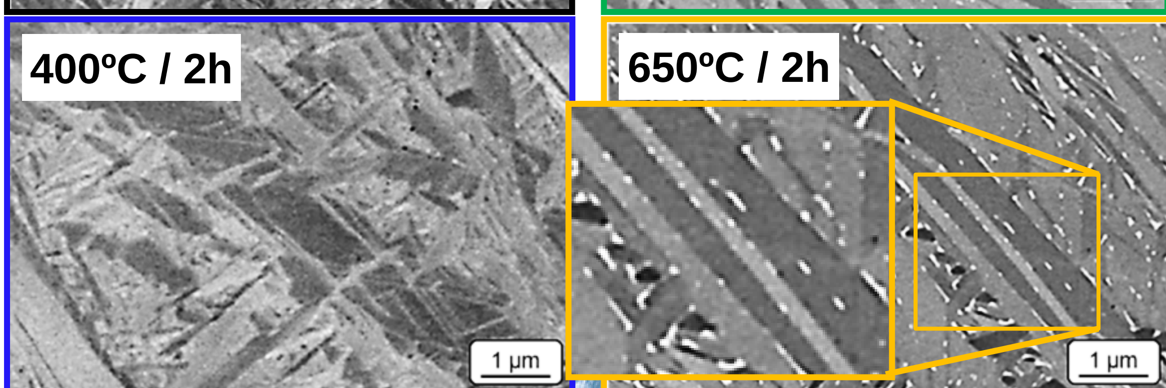


# Selective Laser Melting of Ti-6Al-4V – Microstructure Evolution

**$E_V$=77 J/mm³**



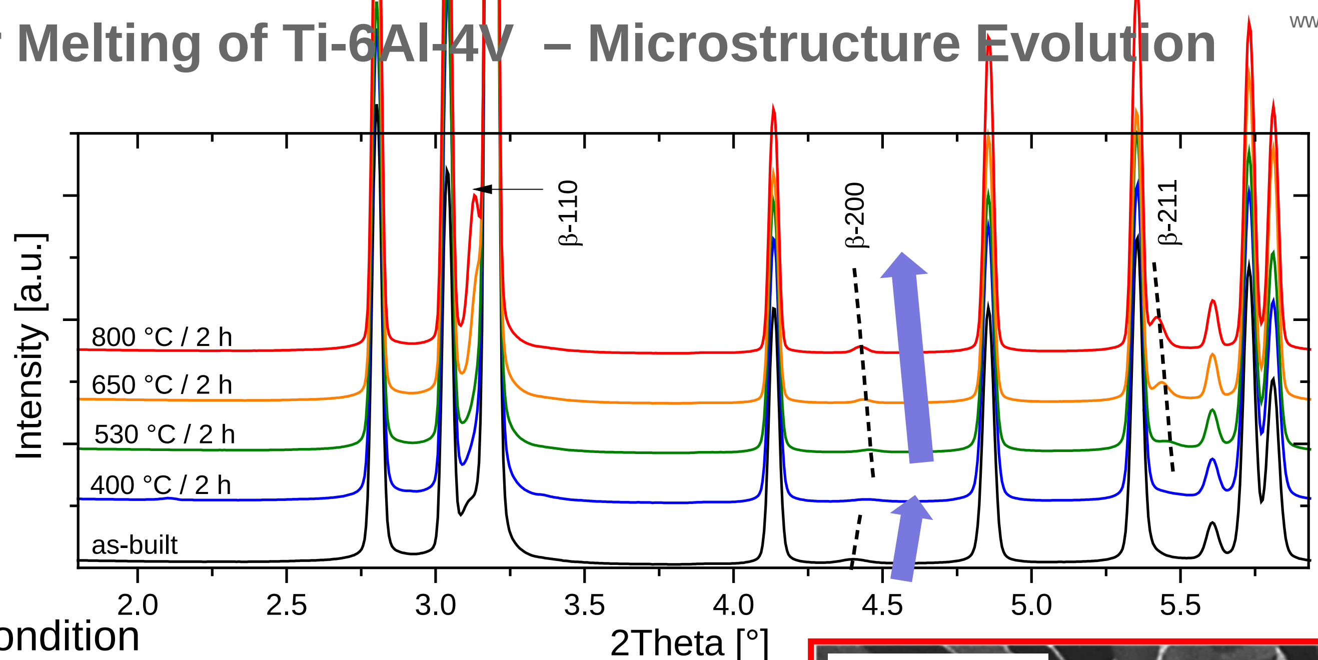



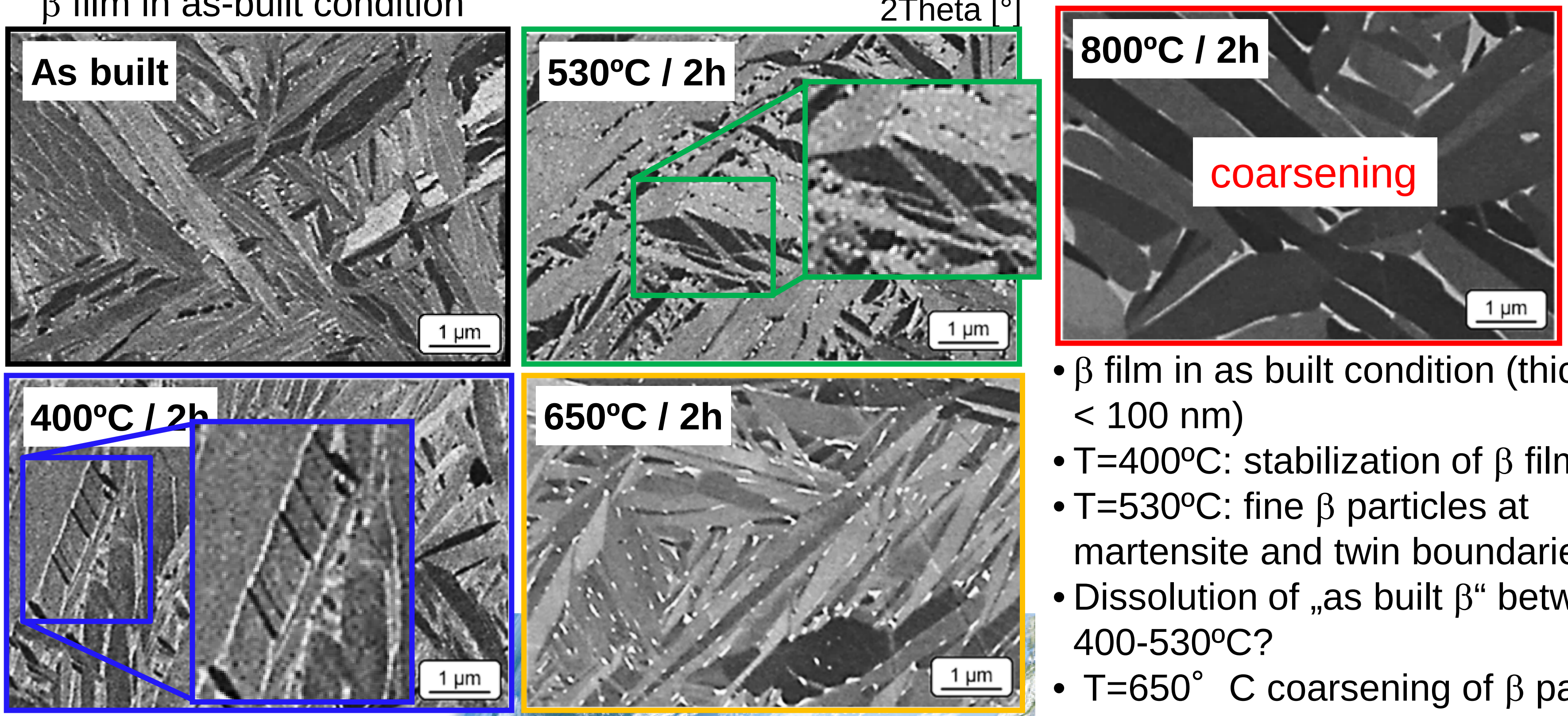

- <u>T=530ºC</u>: formation of fine β particles (< 100nm) at martensite and twin boundaries.
- <u>T=650ºC</u>: coarsening of β
- <u>T=800ºC</u>: significant coarsening of α+β microstructure

# Selective Laser Melting of Ti-6Al-4V – Microstructure Evolution

**$E_V$=145 J/mm³**

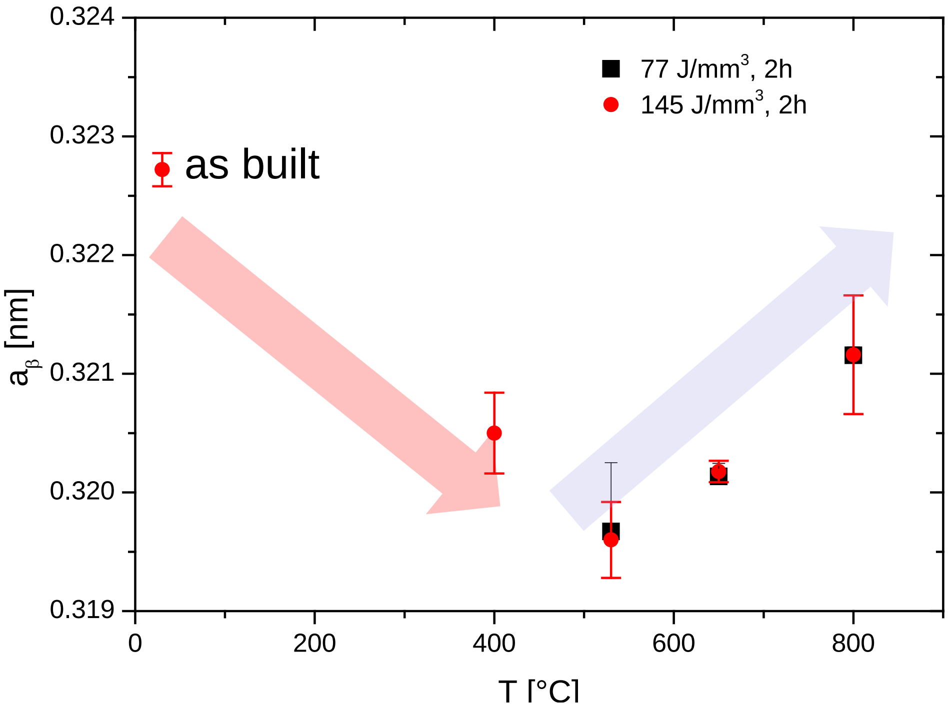


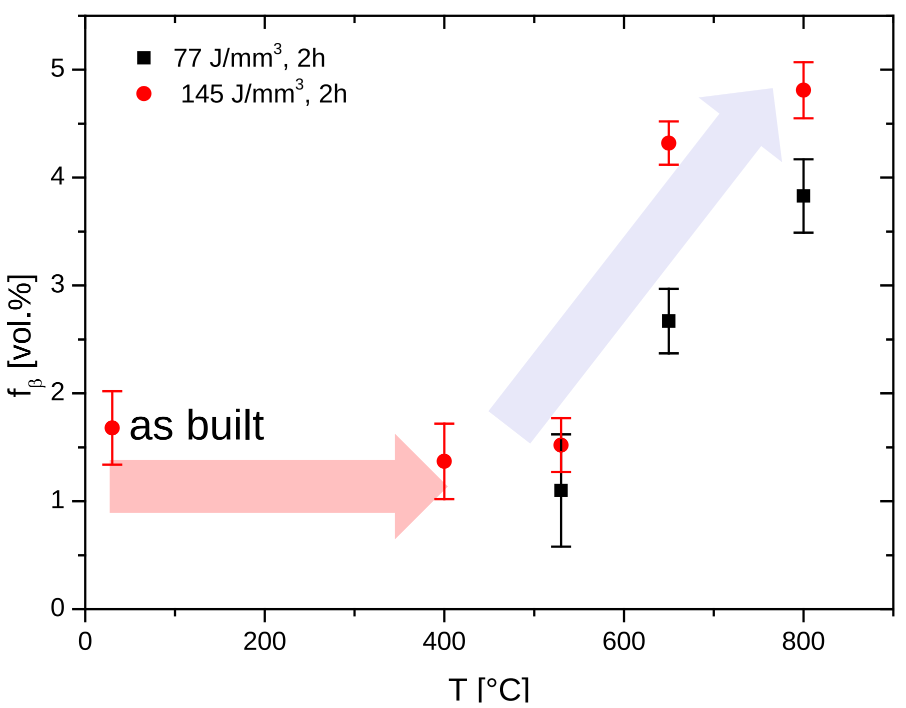

β film in as-built condition




- β film in as built condition (thickness < 100 nm)
- T=400ºC: stabilization of β film
- T=530ºC: fine β particles at martensite and twin boundaries
- Dissolution of „as built β“ between 400-530ºC?
- T=650° C coarsening of β particles

# Selective Laser Melting of Ti64 – Isothermal ageing




145 J/mm³

- As built to 400ºC/2h → Chemical stabilization of β film → increase of V content at constant volume fraction

77 and 145 J/mm³

- T > 530ºC: precipitation of β → increase of volume fraction with corresponding decrease in V content

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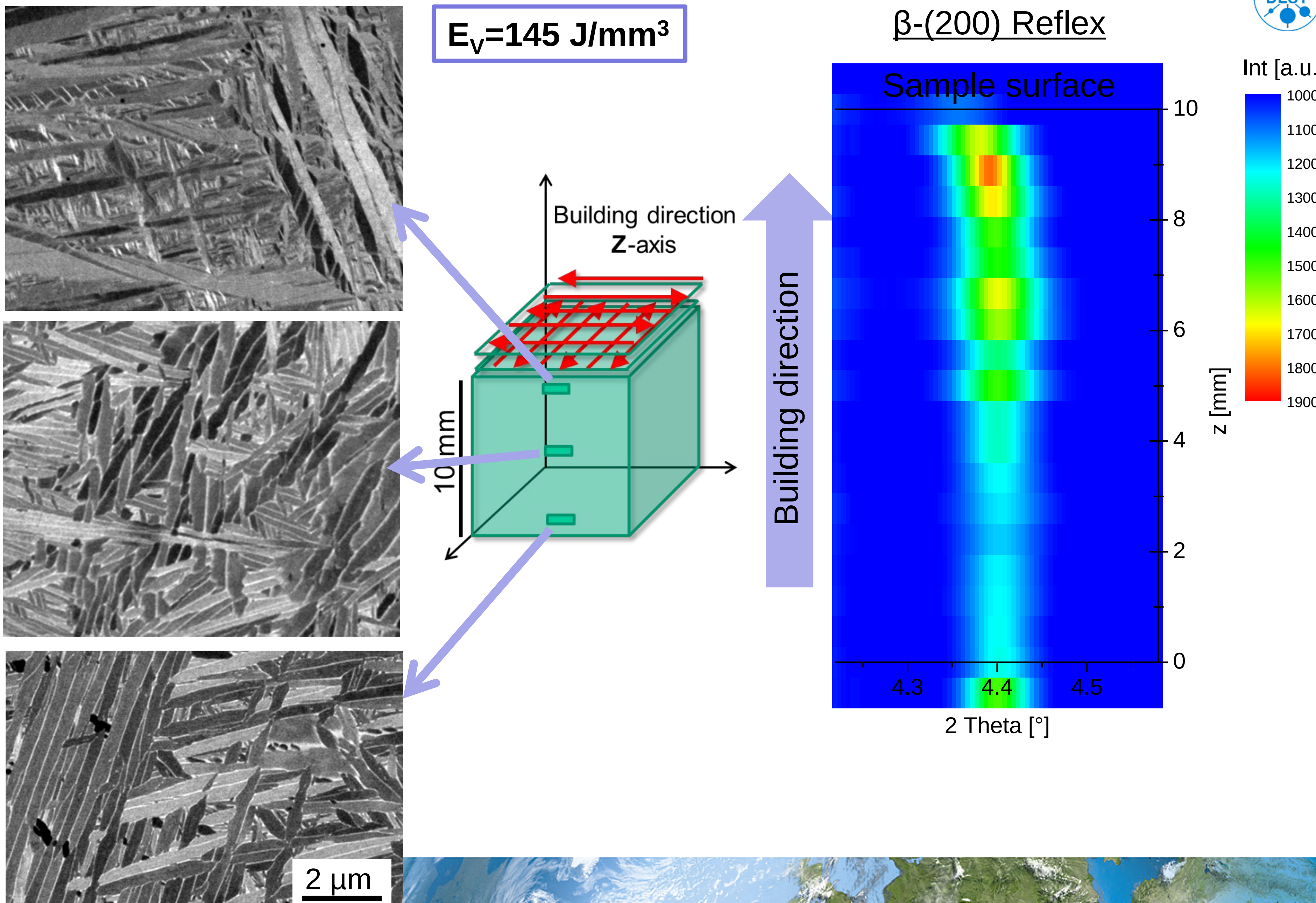
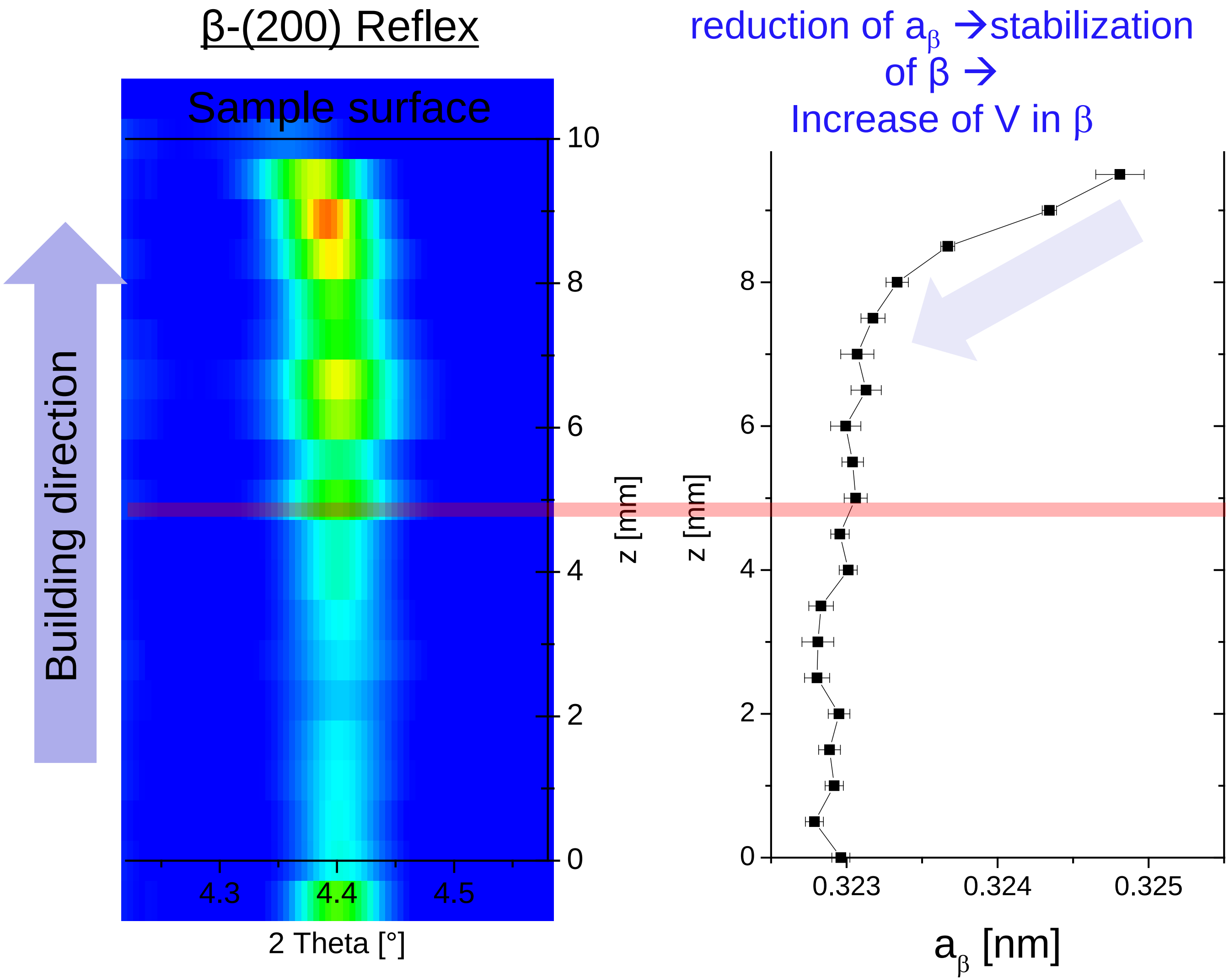
# Selective Laser Melting – Intrinsic heat treatment during SLM



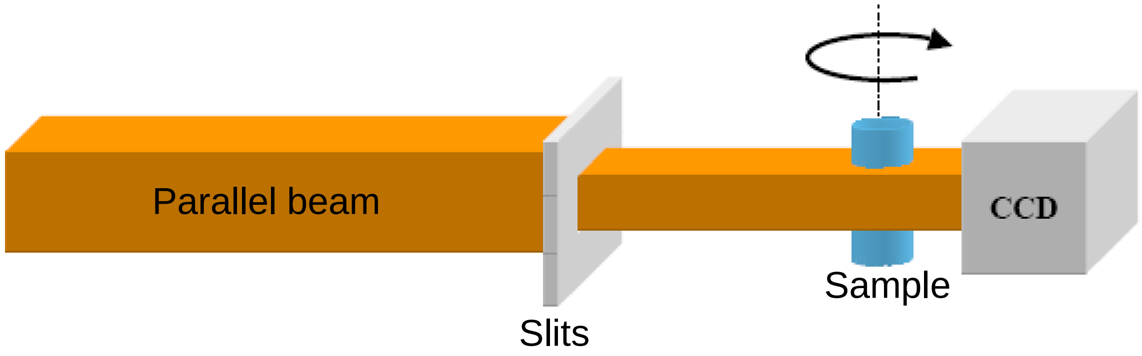
# Selective Laser Melting – Intrinsic heat treatment during SLM



# Synchrotron Tomography
# Increasing spatial resolution

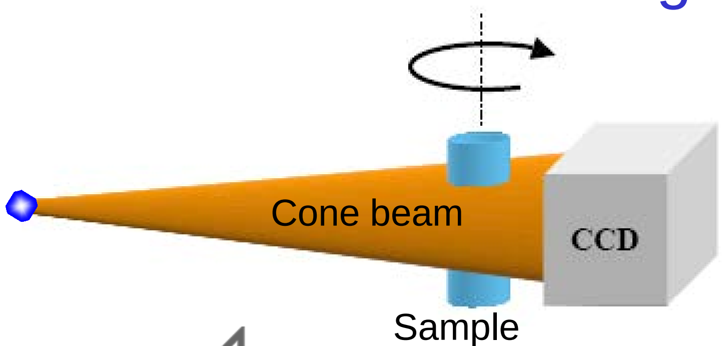
## Experimental setups

### Parallel beam tomography (default technique)



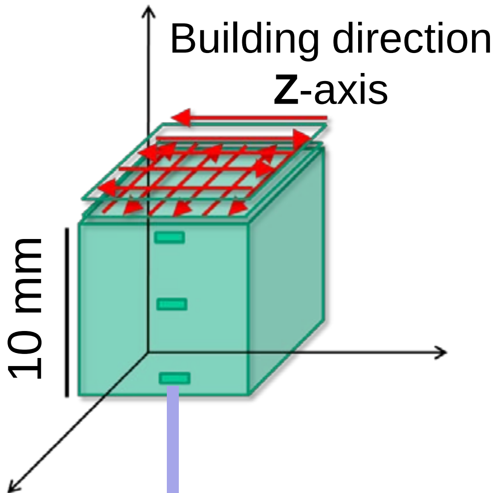

- No magnification (resolution limited by detector system)
- 180° scan
- Simple setup

### Cone beam tomography (focusing optics are necessary)




- Focusing optics are necessary (complex setup)
- Magnification → higher resolution than parallel beam
- 360° scan

# Selective Laser Melting – Intrinsic heat treatment during SLM

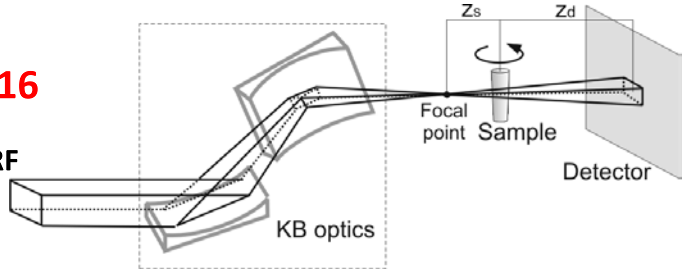



**Holotomography ESRF - ID16NI**

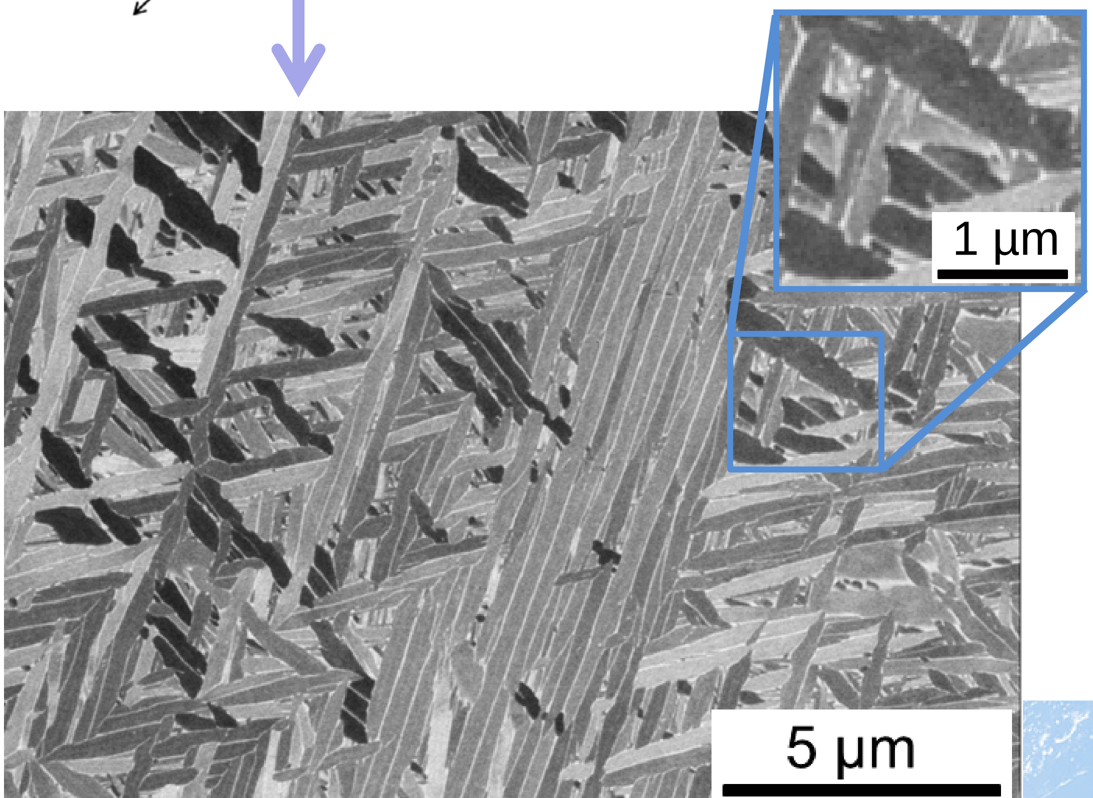
**Energy = 33.6 keV**

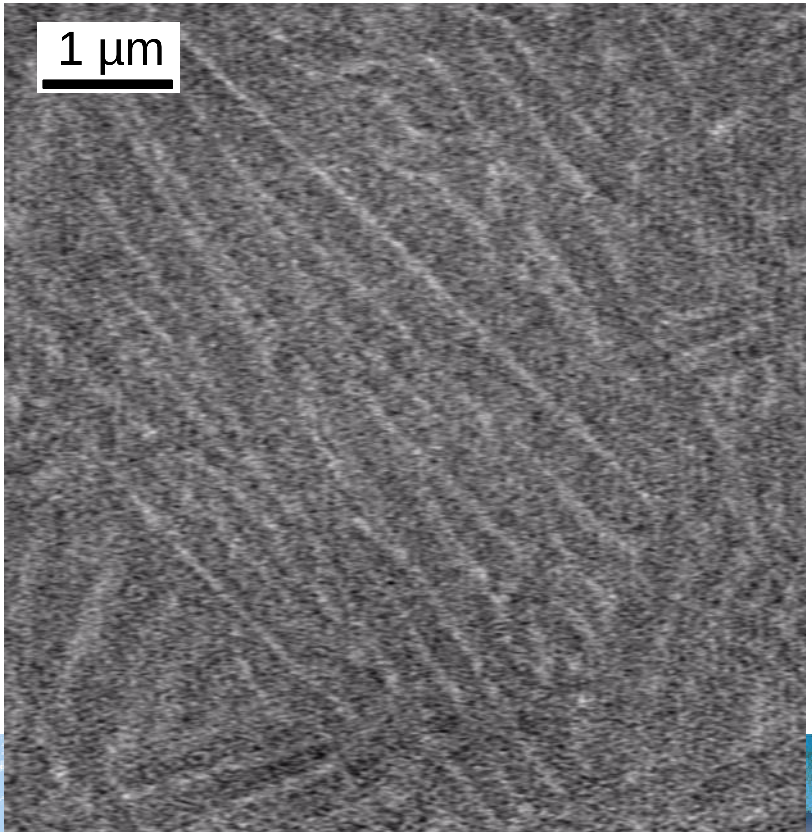
**Experiments April 2016**

**Cooperation with**
**J. Da Silva / P. Cloetens - ESRF**




**Voxel size = (10 nm)³ / Res > 50nm?**



# Conclusions

**Correlation between porosity and energy density of SLM process:**

- Type of voids depends on process energy density → excessive $E_v$ results in „round“ voids, while narrow crack-like voids are found for insufficient $E_v$
- Processing porosity can be significantly reduced (< 0.05vol%) → presence of scarce elongated crack-like voids for the condition with minimum volume fraction of voids → Compromise between volume fraction and morphology should be considered

**Evolution of SLM microstructure by post heat treatments:**

- Ev= 77 J/mm³ → presence of significant fraction of twins in $\alpha$‘ for the as-built condition → T=530° C/2h formation of $\beta$ particles < 100nm at $\alpha$‘ and twin boundaries
- Ev=145 J/mm³ → $\beta$ film with thickness < 100nm in as built condition (present up to 400° C)
  → T=530° C/2h formation of $\beta$ particles < 100nm at $\alpha$‘ and twin boundaries

**Microstructure gradient due to intrinsic heat treatment:**

(For high Ev) → stabilization of the microstructure by intrinsic heat treatment at about 5 mm from the surface.

$\beta$ film seems to have a large interconnectivity → effect on ductility?

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# Special Issue "Metals for Additive Manufacturing"

**Quicklinks**

- Special Issue Editors
- Special Issue Information
- Keywords
- Published Papers

materials

**Impact Factor= 2.728**
**Open Access**

A special issue of *Materials* (ISSN 1996-1944).

Deadline for manuscript submissions: **30 November 2016**

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*Guest Editor*
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Linder Höhe, 51147 Köln,
Website: http://www.dlr.de
**Interests:** metallic structu

# THANK YOU!

## Special Issue Information

Dear Colleagues,

Additive manufacturing is … ex geometries, highly customized parts, small p … under which materials are processed … f microstructures and, consequently, materials p … ocus research and development activities on … the whole production chain, *i.e.*, from powder p … ssue is dedicated to disseminate these scienti …

It is my pleasure to invite … of new alloys for additive manufacturing, e.g., microstructure formation and evolution, effects of defects, processing strategies, alloys' composition, and alloys' performance.

Prof. Dr. Guillermo Requena
*Guest Editor*