Empa
Materials Science and Technology

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Advanced materials processing with intelligent systems

Vision Systems

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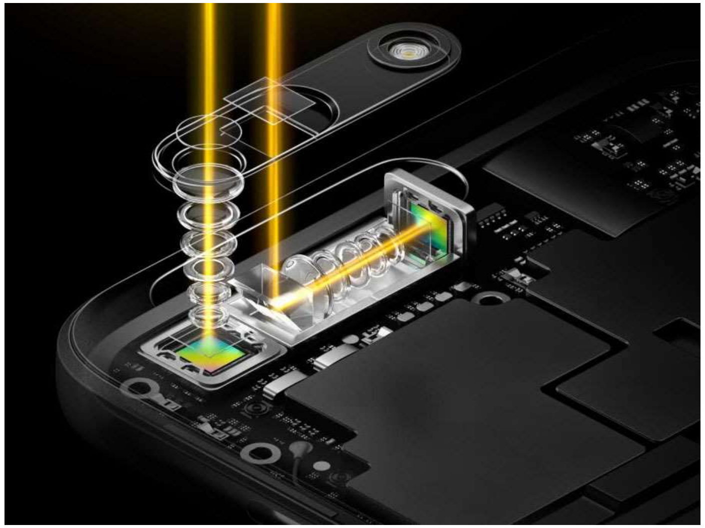
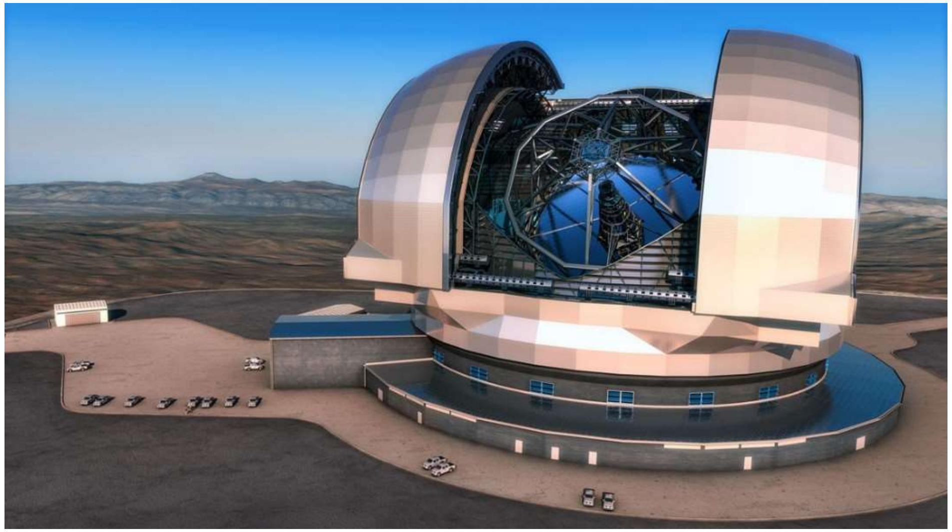
Content

1. Applications of imaging systems
2. Overview of imaging systems
   - Principle
   - Light source
   - Imaging optics
   - Imaging sensor
3. Imaging systems in laser-material processing
   - Laser polishing
   - Laser welding
4. Phase-contrast imaging

1. Applications of vision systems

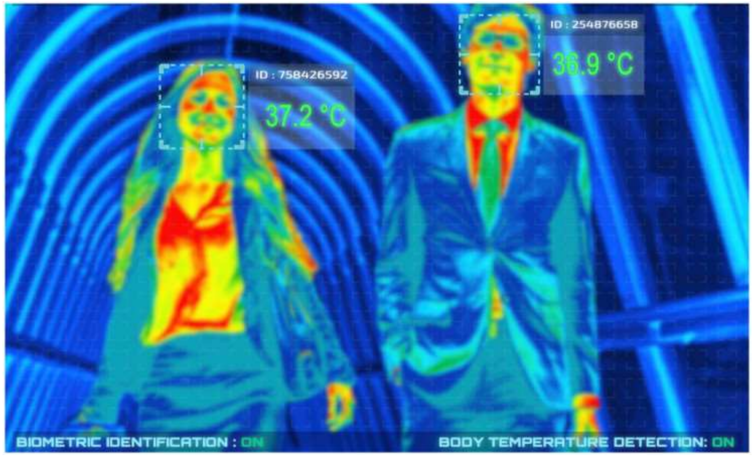
Vision system in daily life



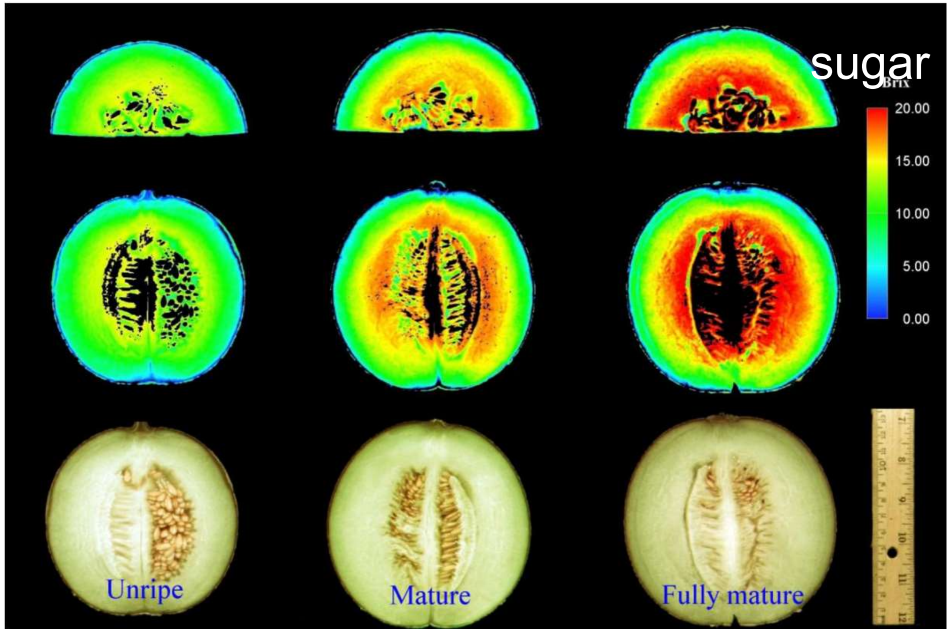


Vision systems exist in all aspects of life

Extracted information



- Geometrical features (conventional cameras)
- Temperature (thermal camera, hyperspectral camera)
- Composition and chemical distribution (hyperspectral camera)



Hyperspectral view of a melon

Limit of vision systems

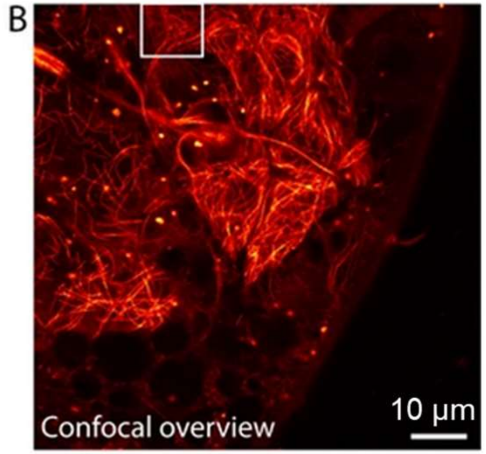
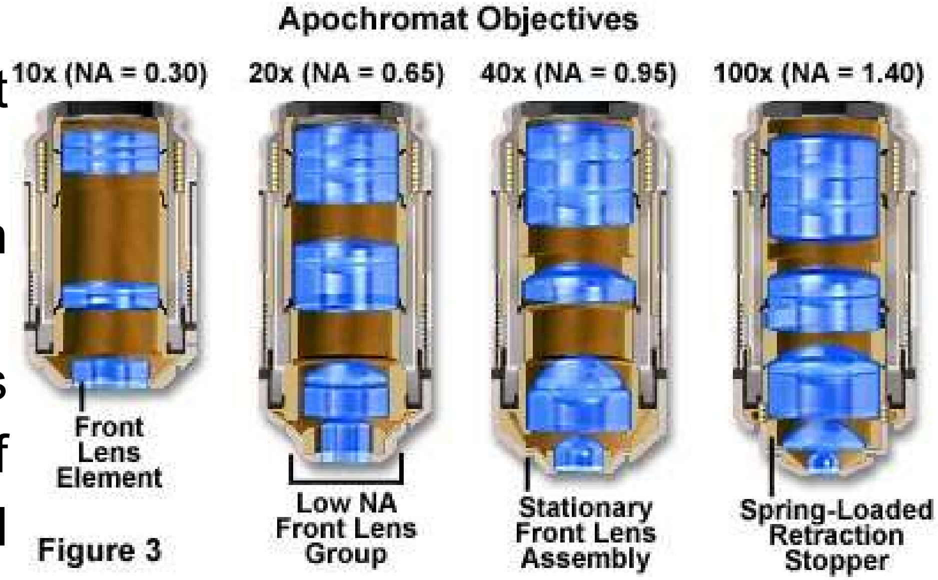


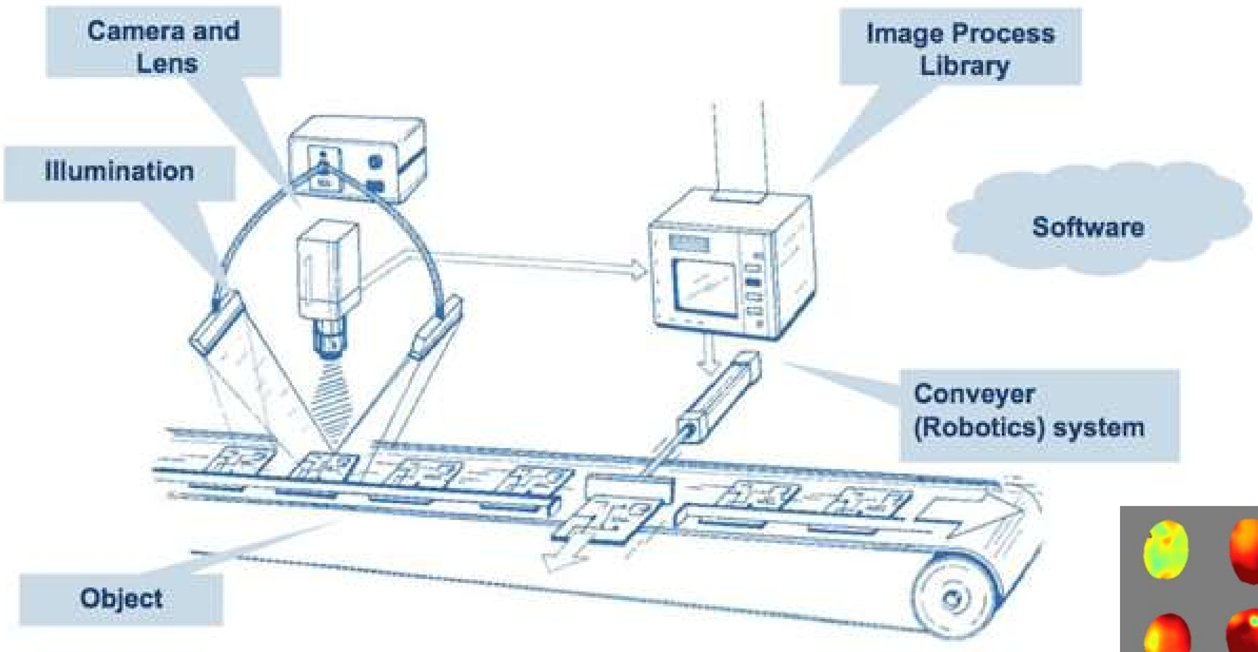
Image of a biological organism

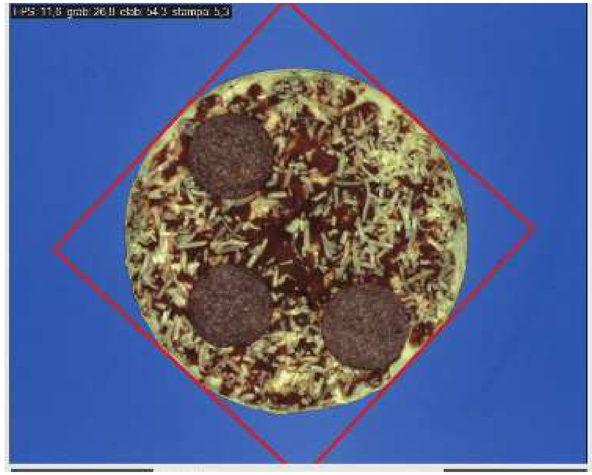


https://www.olympus-lifescience.com/fr/microscope-resource/primer/anatomy/objectives/

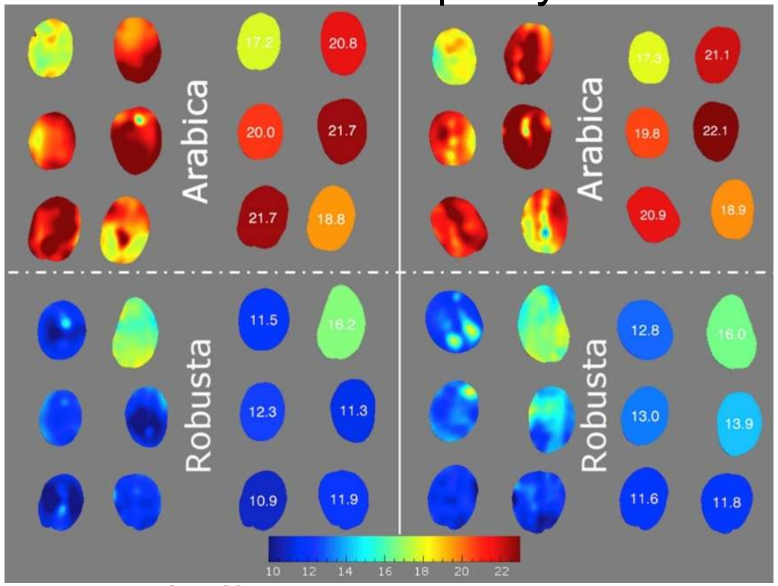
- Field of view up to hundreds of light year
- Spatial resolution down to submicron scale
- Complexity of the system depends heavily on the requirement of imaging resolution and temporal resolution

Machine vision in manufacturing





Pizza quality control



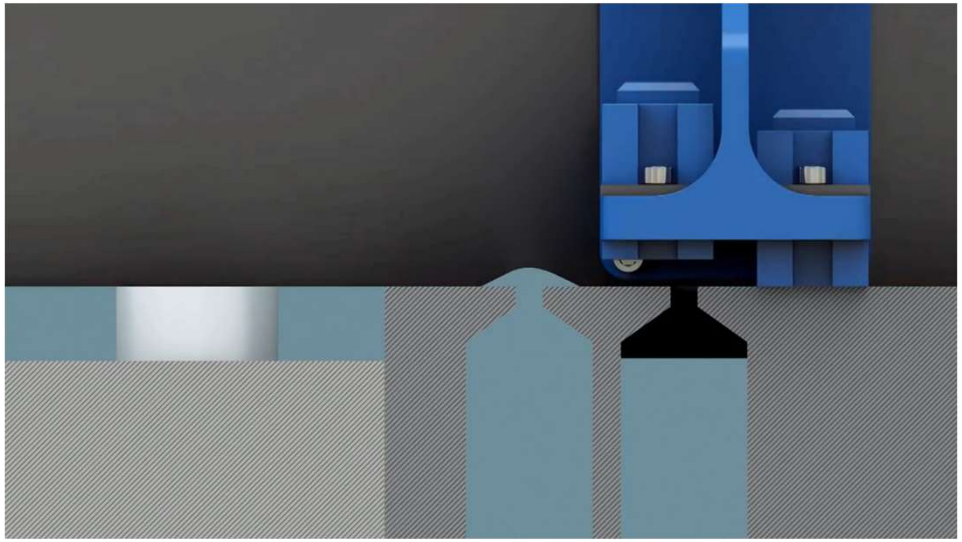
Coffee quality control
(hyperspectral camera)

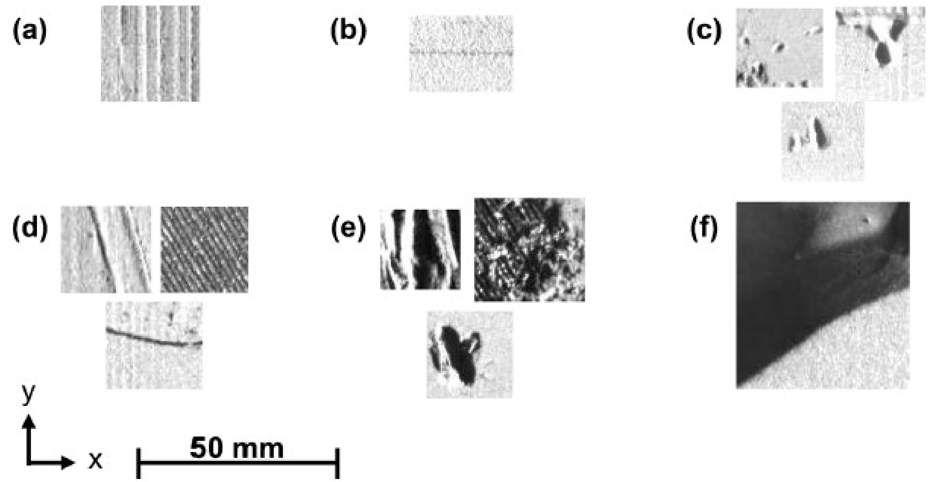
Visualization of specific features in the objects

→ Machine vision for automatic detection of defective objects

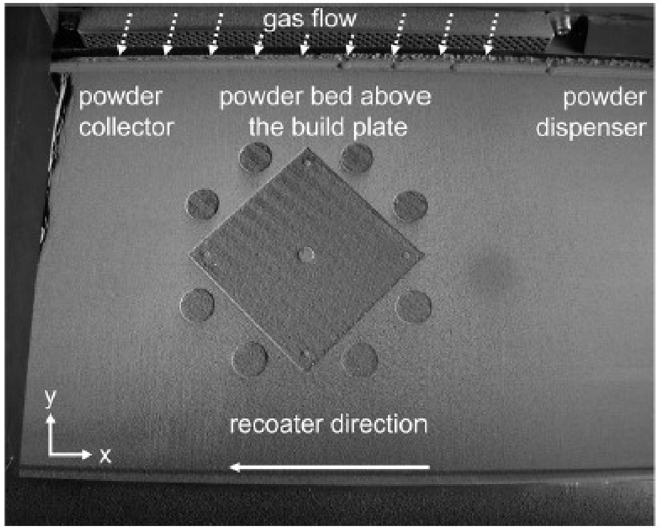
https://doi.org/10.1016/j.jfoodeng.2018.01.009

Machine vision in additive manufacturing





Six different powder bed anomaly (a) *recoater hopping*, (b*) recoater streaking*, (c) *debris*, (d), *super-elevation*, (e) *part damage*, and (f) *incomplete spreading*. https://doi.org/10.1016/j.addma.2017.11.00

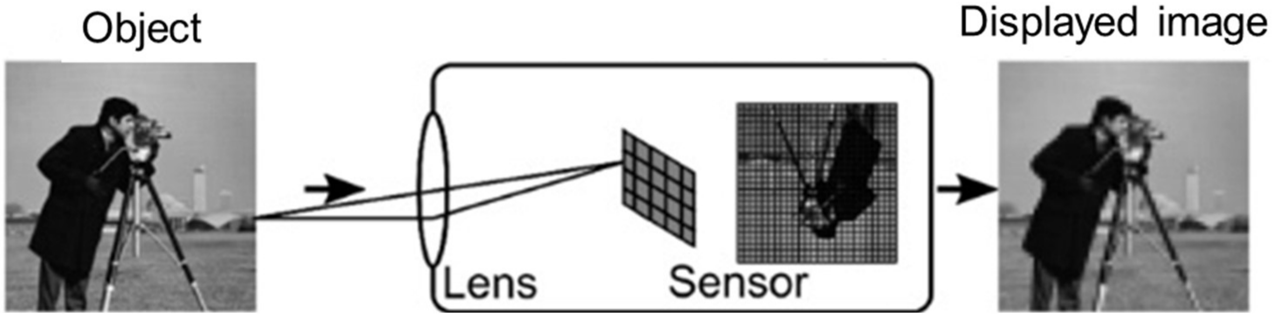


An image taken from inside of the EOS M290 build chamber using the "powder bed camera". It is oriented such that it is looking down at the powder bed.

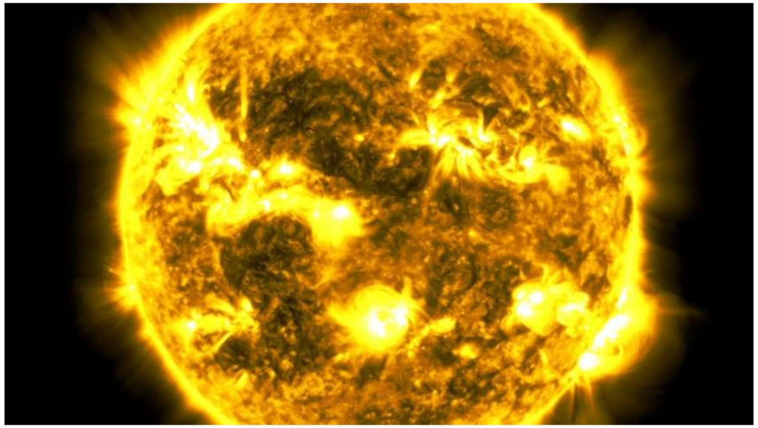
Machine learning / Artificial intelligence

2. Overview of vision system

Imaging principle



Light originated from the object is collected by imaging optics and projected on a 2D array of photosensitive elements.



Self-illumination

Reflection/scattering of light from external illumination source

Fast imaging or high-speed photography

A high-speed camera is a device capable of capturing moving images

- with exposures of **less than 1/1,000** second
- or **frame rates in excess of 250 frames per second**

Football in slow motion

Lightning Strike – real-time and at 2,500 fps

https://www.youtube.com/watch?v=XjwO9InuFJk

https://www.youtube.com/watch?v=WP9_9L20CYM

Fast imaging or high-speed photography

A high-speed camera is a device capable of capturing moving images

- with exposures of **less than 1/1,000** second
- or **frame rates in excess of 250 frames per second**

Avantages:

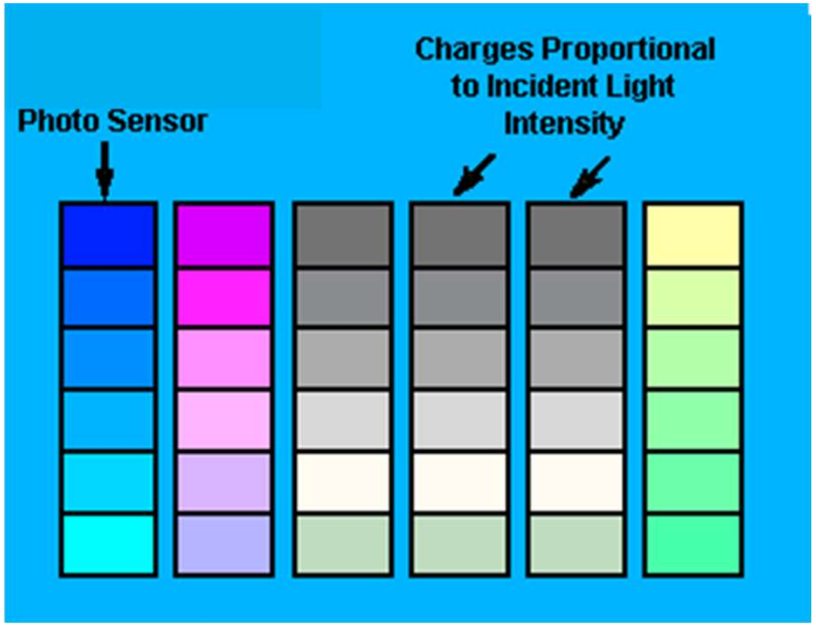
- Visualise events in great detail e.g. melting, solidification, spattering
- Find correlation between sensors signals (e.g. acoustic) and real events
- Confirm hypothesis through visualisation

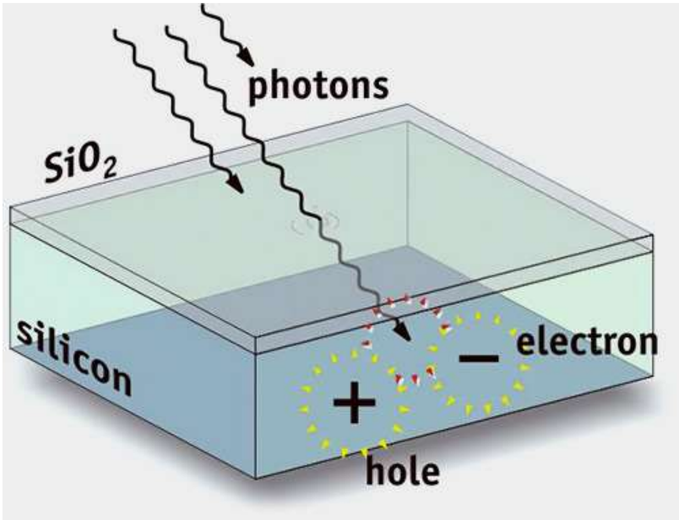
Disadvantages:

- Accessibility of the information / event
- Cost, good high speed camera are above 100 kCHF
  $\rightarrow$ not an wide used industrial solution
- Large amount of data to be treated
- 2D data $\rightarrow$ requires more storage place and time to be treated as compared to 1D e.g. acoustic

Imaging sensors

Imaging sensors



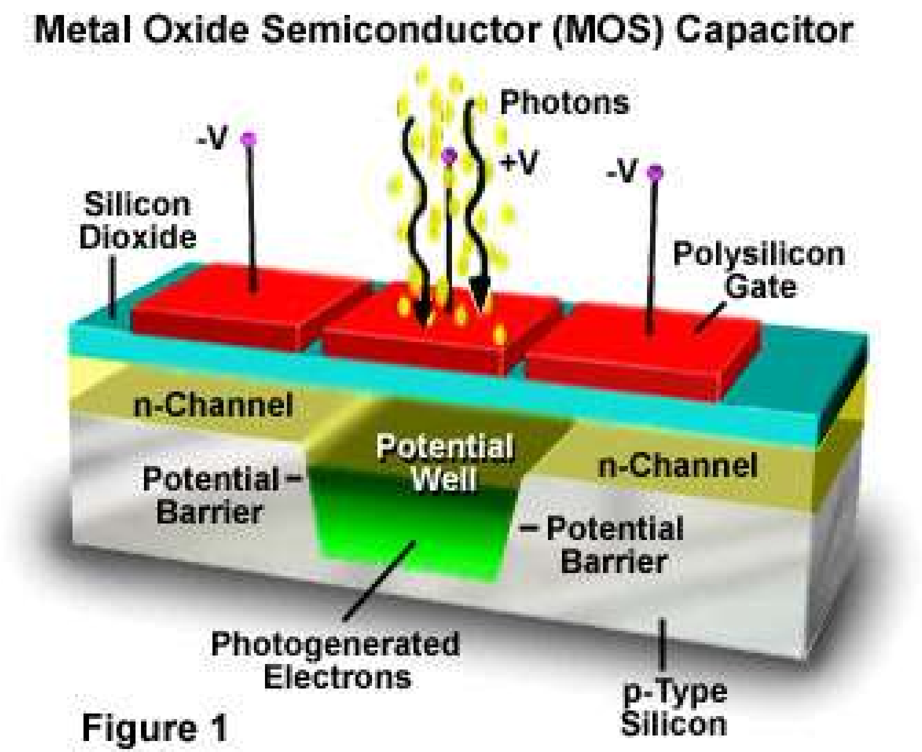


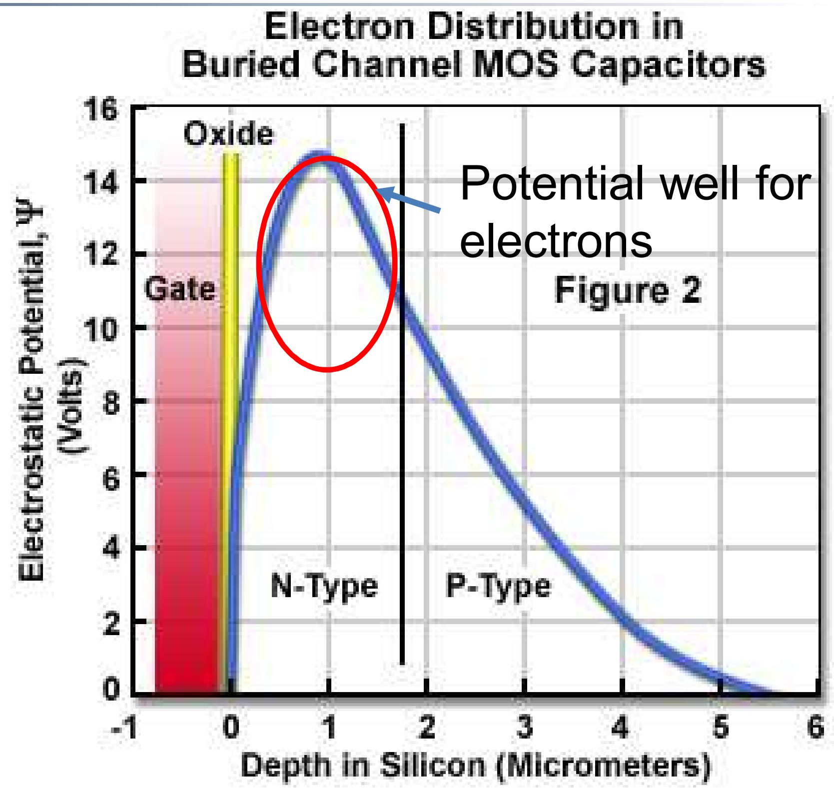
- 2D array of photosensitive elements with output proportional to incident light intensity.
- Two types: Charge-Coupled Device (CCD) and Complementary Metal Oxide Semiconductor (CMOS)
- Light-electricity conversion based on photogeneration of charges in semiconductor

http://members.tripod.com/~Camera_Dave/ccd-history2.htm

https://www.teledynedalsa.com/en/learn/knowledge-center/ccd-vs-cmos/

Metal-Oxide-Semiconductor (MOS)





Potiental well is formed directly below the positively biased *gate*.

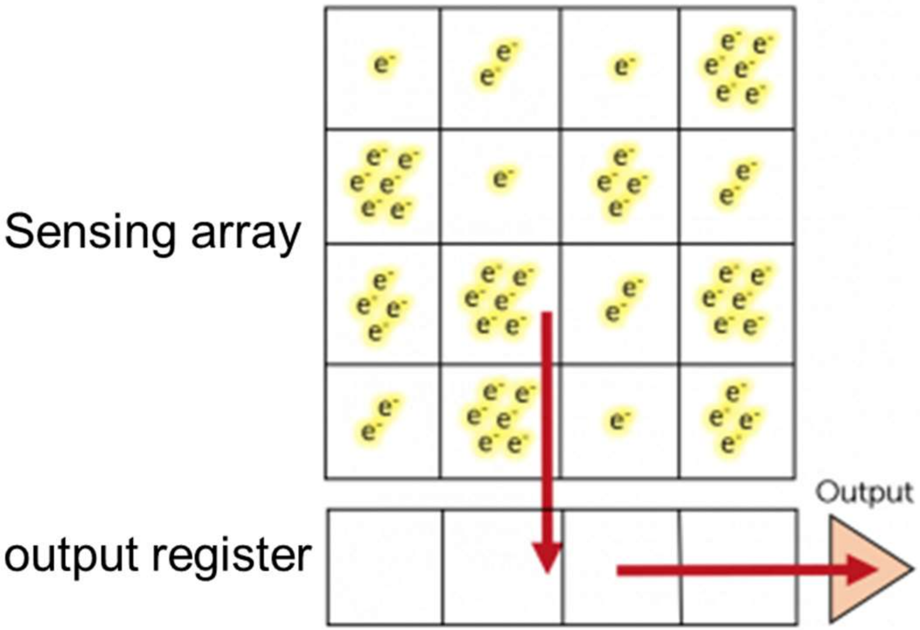
→ The region below each *gate* is one pixel

→ Photogenerated electrons are **accumulated** within the *n*-region, near the *pn* interface

Similar structure for charge generation and accumulation in CCD and CMOS.

https://hamamatsu.magnet.fsu.edu/articles/moscapacitor.html

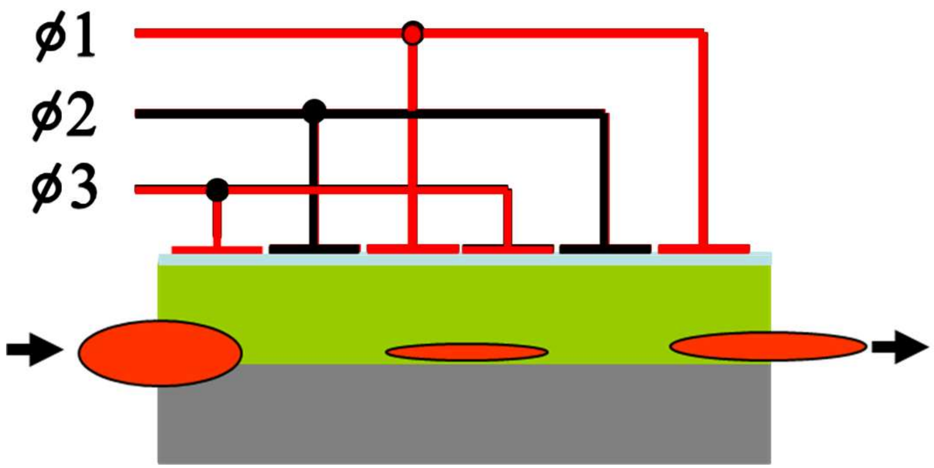
CCD operation principle

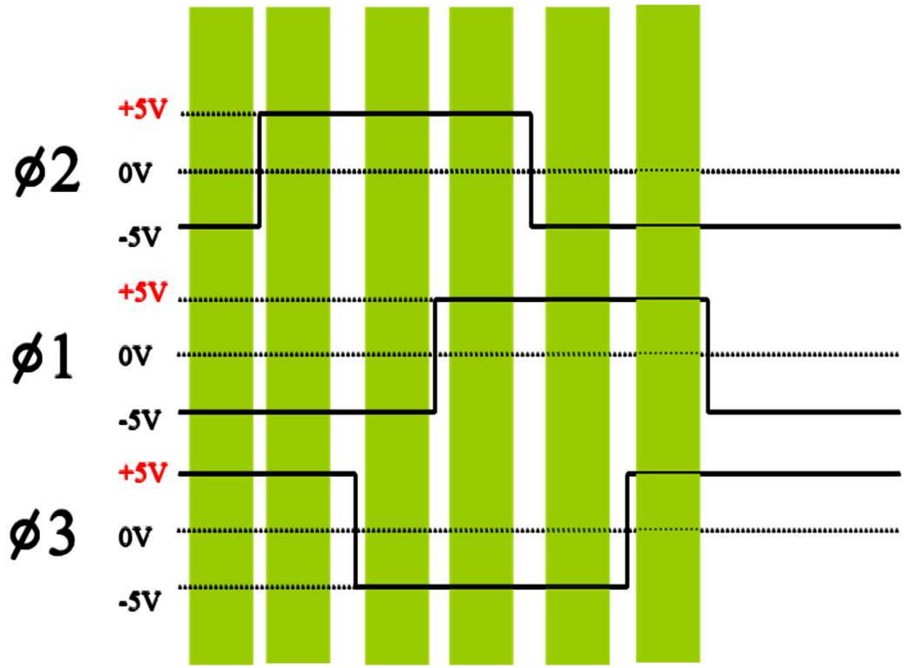


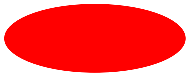
- During charge transfer, sensing array is shielded to avoid additional exposure
  → mechanical shutter
- Accummulated charges are transferred vertically to output register, row by row.
- Pixels in output register are shifted horizontally to read out each pixel.
- Charge transfer process is time consuming.

https://www.princetoninstruments.com/learn/camera-fundamentals/ccd-the-basics

Charge transfer in CCDs



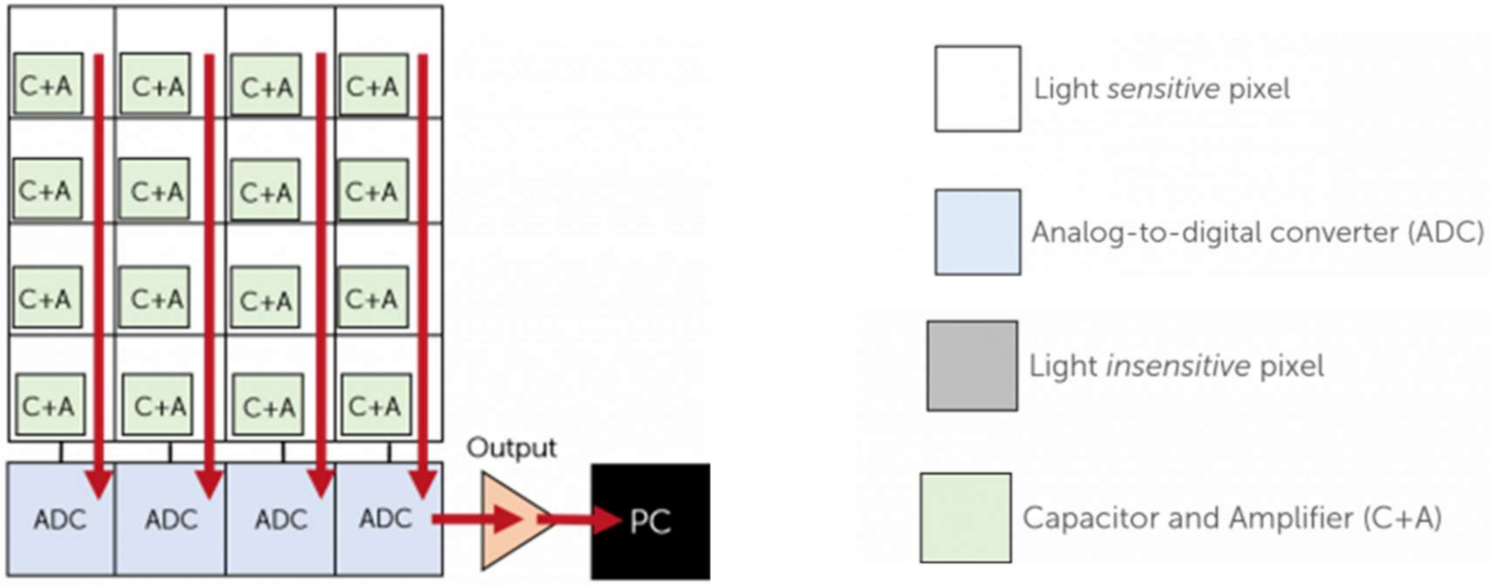




Charge packet accumulated at individual pixel during one exposure to the illumination

Accumulated charges shift from left to right by regulating the applied voltages

CMOS operation principle

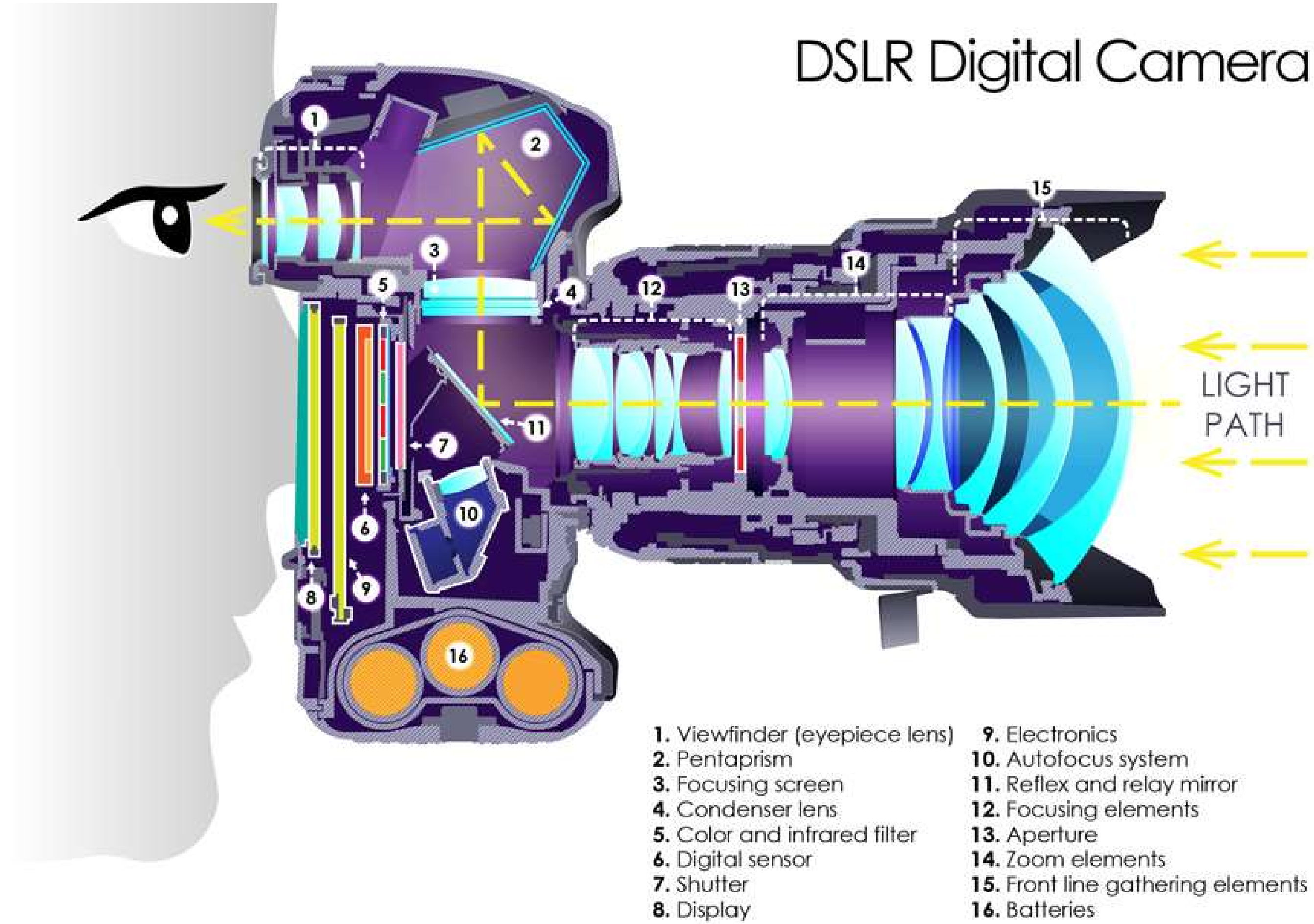


- Pixels include similar MOS structure for photogeneration, together with charge-to-voltage converter, amplifiers, noise-correction, and digitization circuits → smaller area of the photo absorber.
- No physical shifting of charges → faster processing.
- Noises due to the inconsistency in the electronic circuitry in individual pixel.
- Only available for visible imaging

https://www.princetoninstruments.com/learn/camera-fundamentals/scmos-the-basics

Optical system

Complexity of the optical system



Most of the optical components are lenses

Many components → too many interfaces → very complex propagation of the light

https://www.ephotozine.com/article/this-cutaway-diagram-shows-the-inside-of-a-dslr-30546

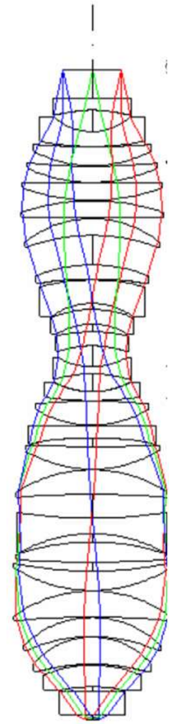
One of the most complex optical system

State-of-the-art microstepper with laser and lens

Wavelength 193 nm

Lens		Field Size	Overlay	Throughput
NA	Resolution	X & Y	16-point Alignment	300 mm Wafers 30 mJ/cm2 (125 shots)
Variable 0.85-1.35	38 nm	26 X 33 mm	2.5 nm*	175 wph

* Single machine overlay including chuck dedication



NA =0.85 y_{imax} = 13.8mm, λ =193nm (ArF) J

A large percentage of high-performance microchips all over the world are now produced using this technology

https://www.zeiss.com/corporate/int/about-zeiss/history/technological-milestones/lithography-optics.html

Geometrical optics

Two regimes of optics

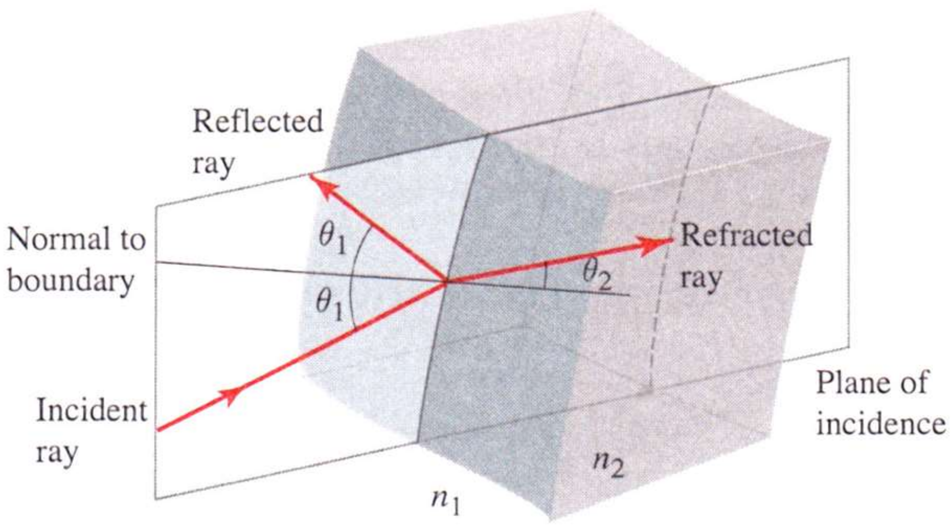
- Wavelength << $D_{objects}$: geometrical optics → Valid for vision systems
- Wavelength > $D_{objects}$: physical optics

Three basic laws:

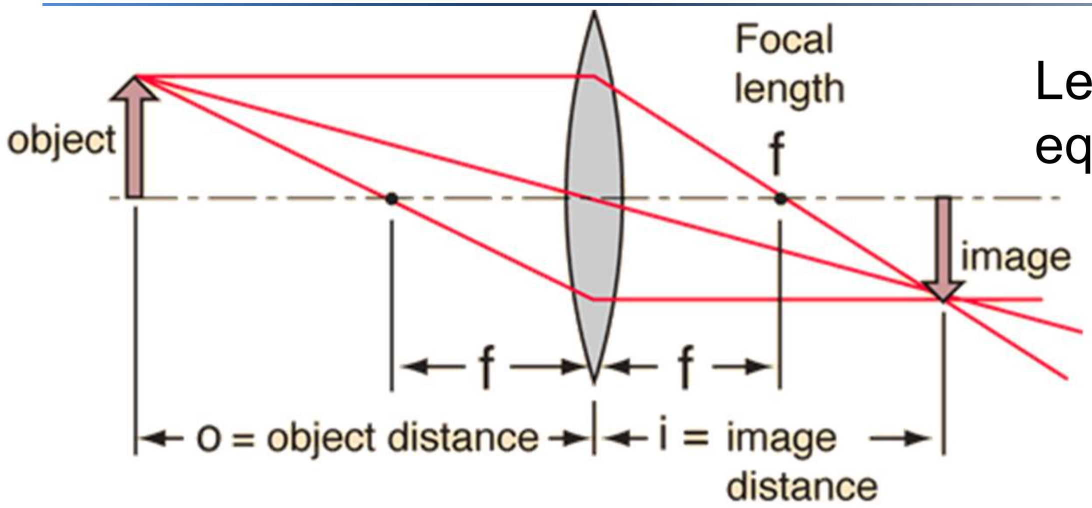
- Rectilinear propagation
- Reflection
- Refraction

Snell's law:

$$n_1 sin\theta_1 = n_2 sin\theta_2$$



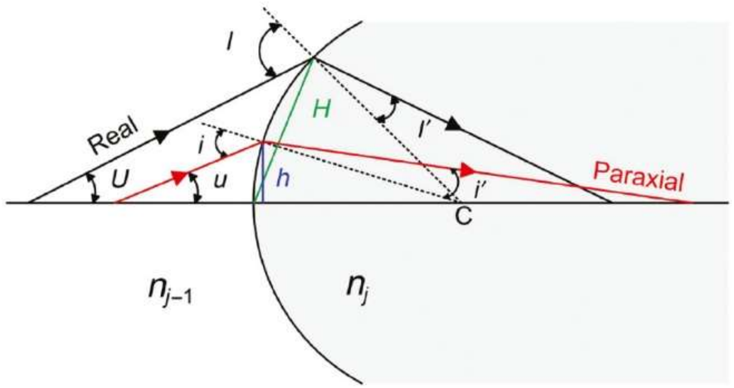
Single lens equation



Lensmaker's equation $\frac{1}{f} \approx (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$

$$\frac{1}{f} = \frac{1}{o} + \frac{1}{i}$$

$$M = \left|\frac{i}{o}\right|$$



f: focal length of the lense

n : index of refraction of the lens

R_1, R_2: radius of curvature on two sides of the lense

o, i: distances lense-object and lense-image

M : magnification of the imaging

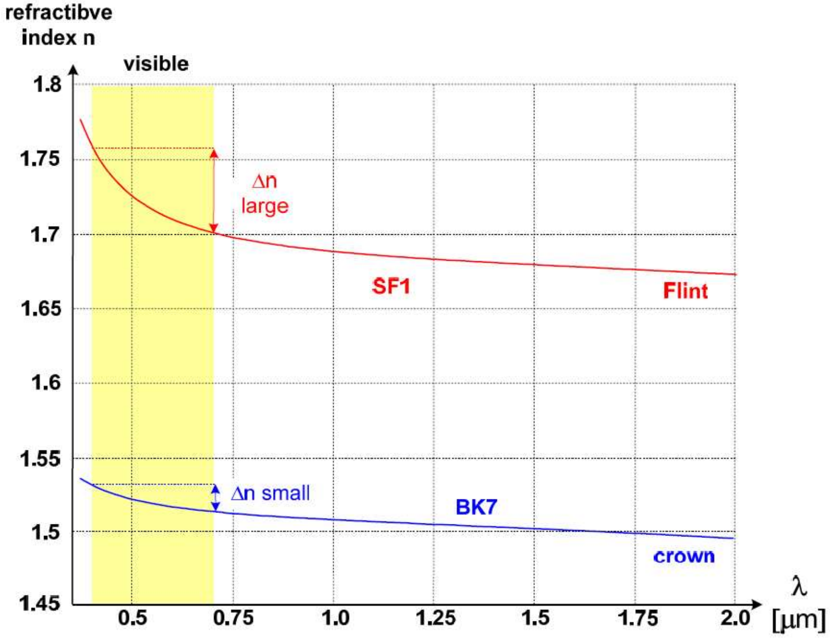
Taylor series approximation

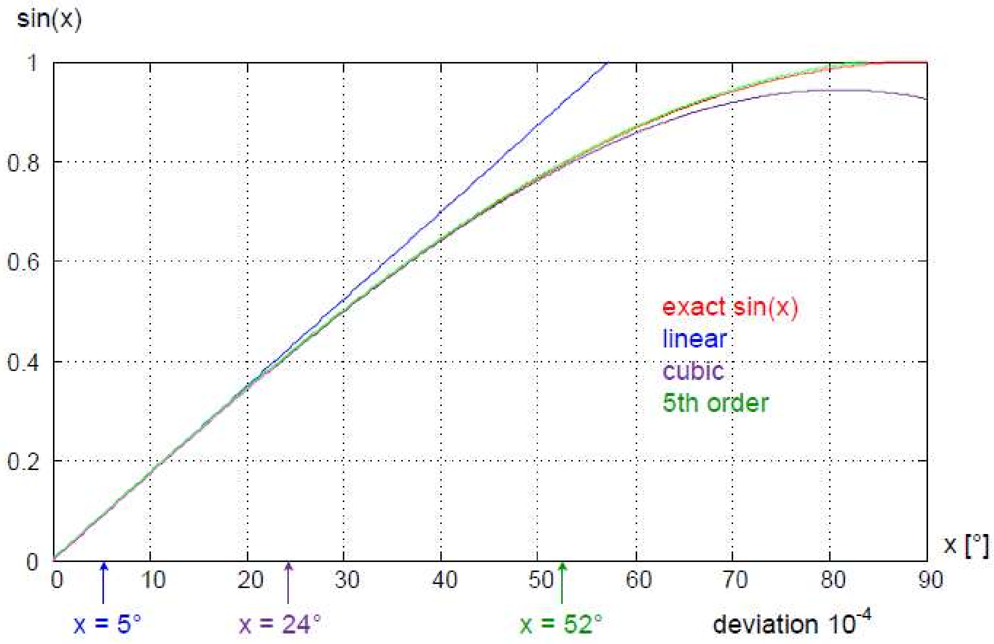
$$\sin(\theta) = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \cdots$$

Assumptions used:

- Paraxial conditions $\sin(\theta) \approx \theta$
- Constant refractive index $n = n(material)$

Real situation in optical imaging





Curvature of the lense might differ across the lense' surface

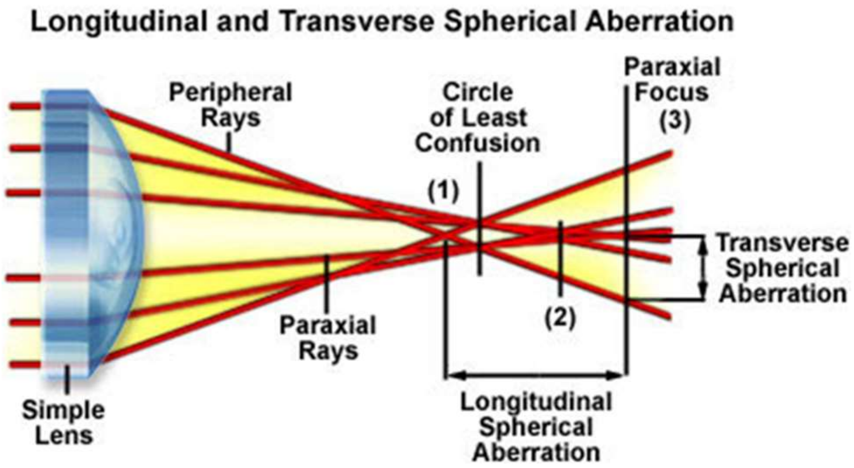
Dependence of refractive index on wavelength

Incoming angles are not always small

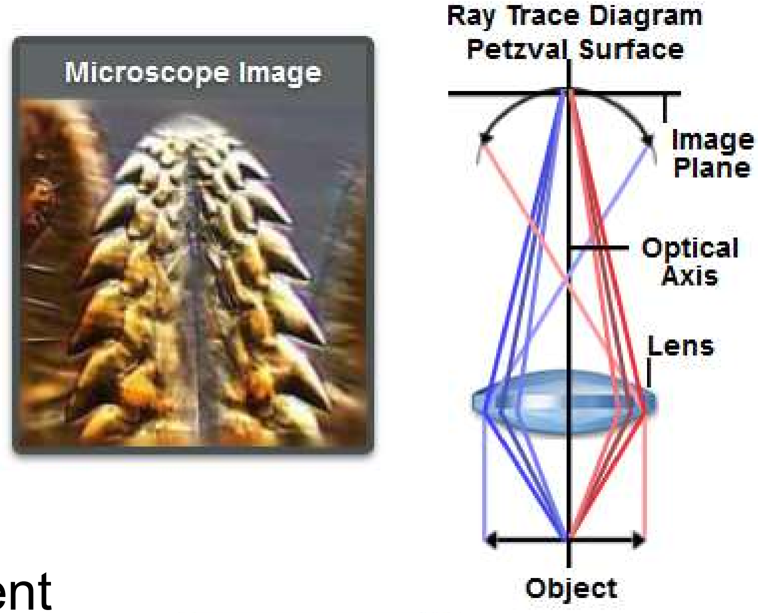
Each light ray experiences different refraction behaviors

Light rays do not converge to a single point at the image plane

Optical aberration - monochromatic



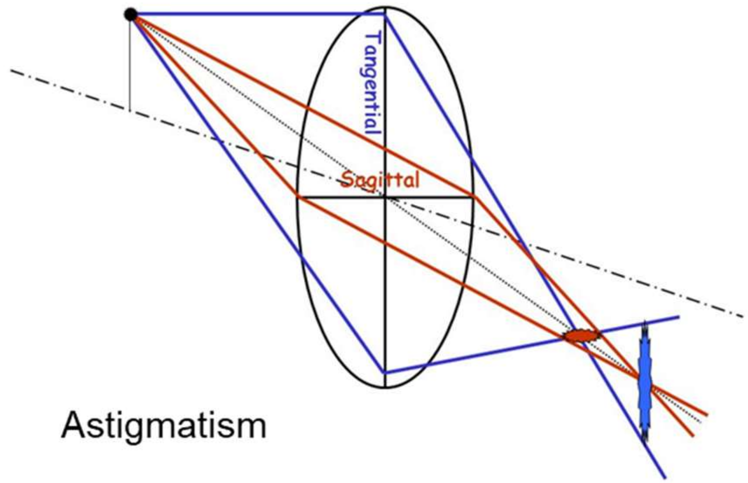
Simple Field Curvature



Example of monochromatic aberrations:

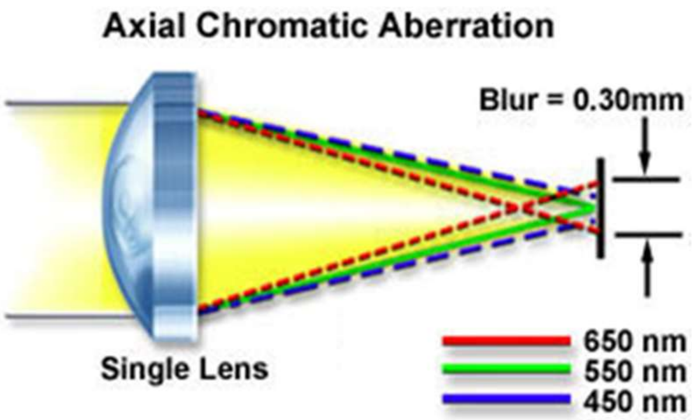
- Spherical aberration: refraction is different between peripheral rays and paraxial rays of collimated incoming beam
- Astigmatism: curvature of the lens is different between tangential plane (vertical) and sagittal plane (horizontal)

    → different focal lengths
- Field curvature, distortion, coma

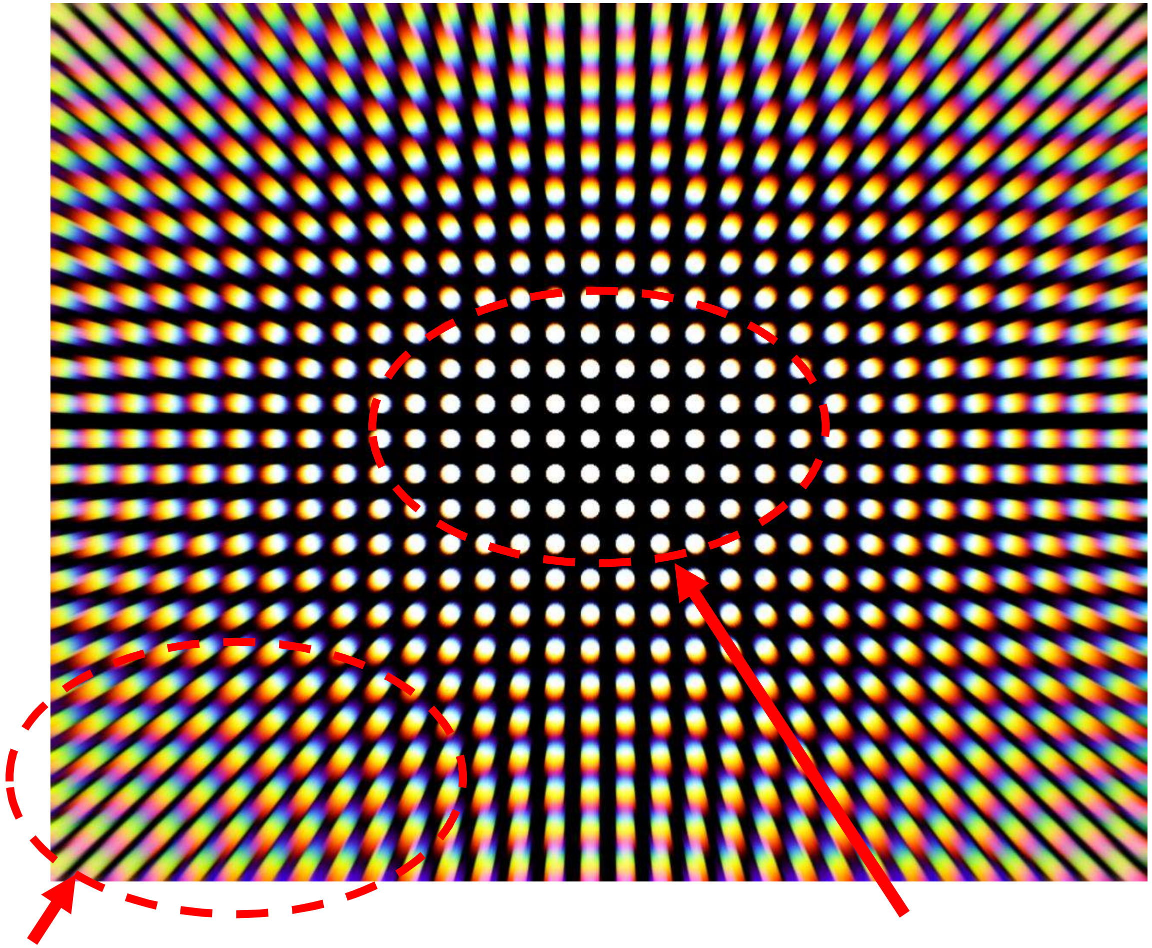


https://micro.magnet.fsu.edu/primer/anatomy/aberrations.html

Chromatic aberration



Chromatic aberration: refraction depends on wavelength of the light

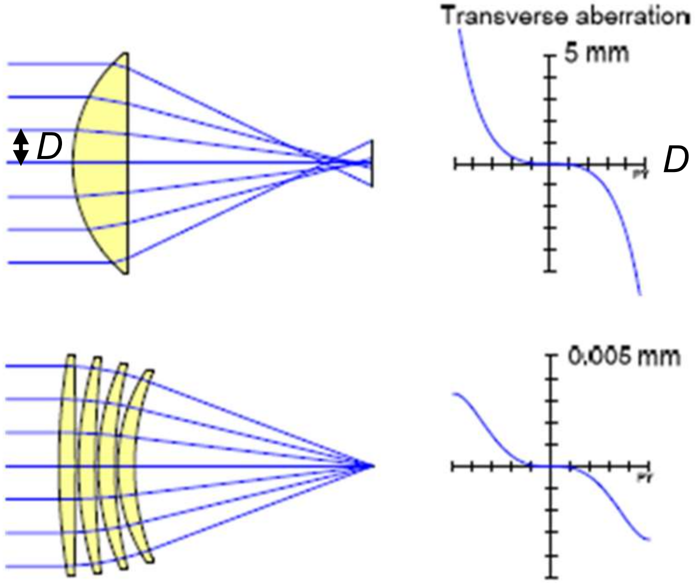


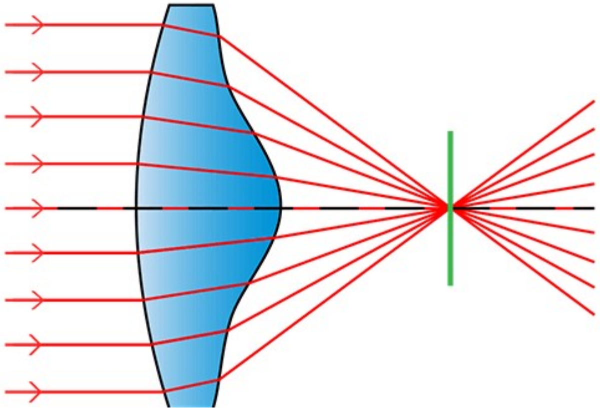
Separation of different wavelengths

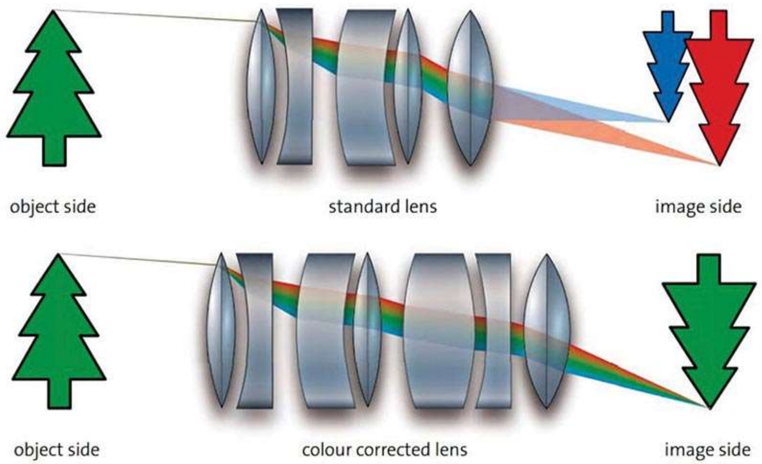
White spost consisting of multiple wavelengths

https://reshade.me/forum/shader-presentation/1083-kingeric1992-s-chromatic-aberration

Corrections of aberrations

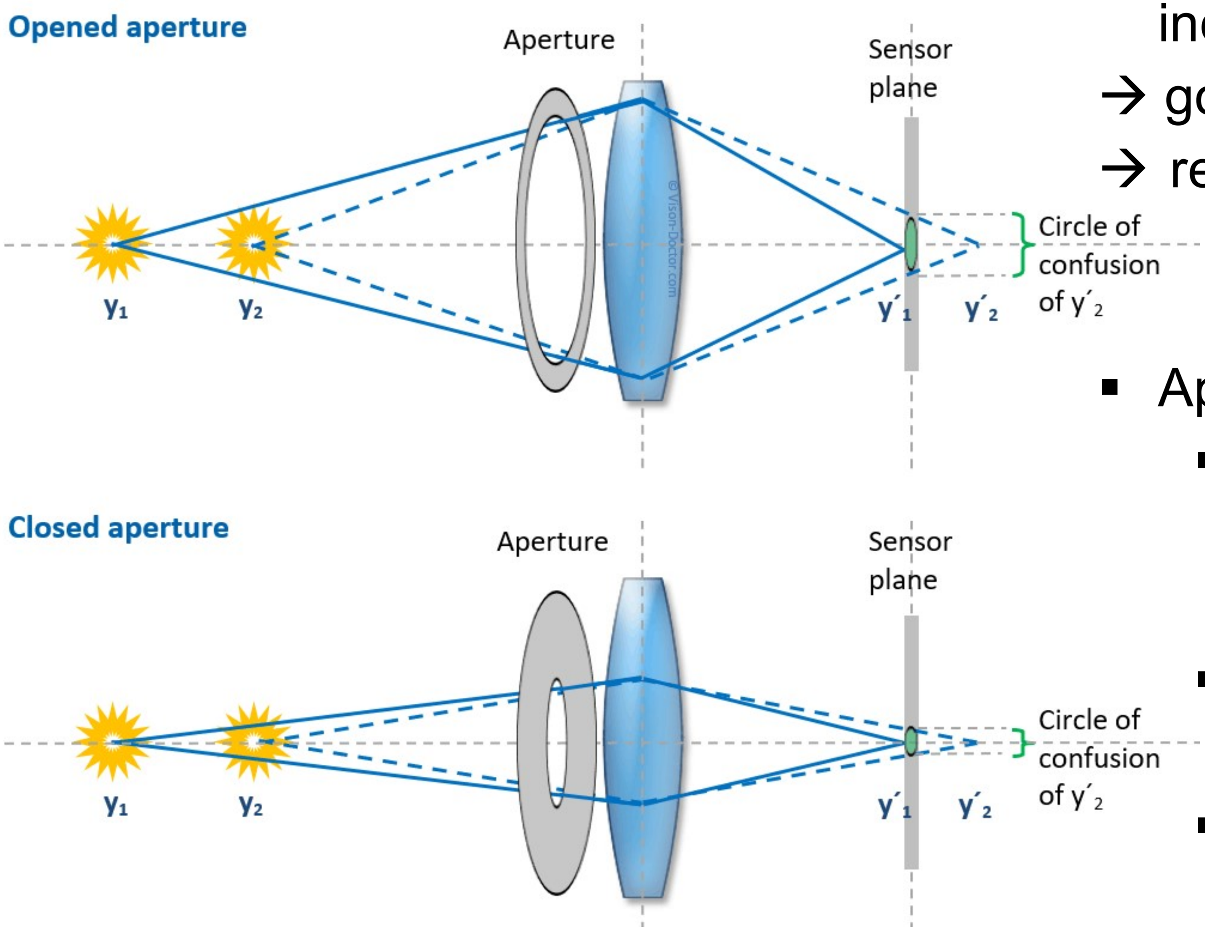






- Customized shape and optical properties of the lenses, this is limited by the thermomechanical properties of the glasses and production methods
- Combination of multiple components to correct the optical abberations.

Aperture in imaging



- Aperture to limit the cone of incoming light

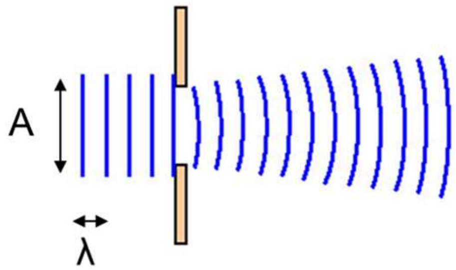
→ go to paraxial conditions

→ reduce optical aberrations

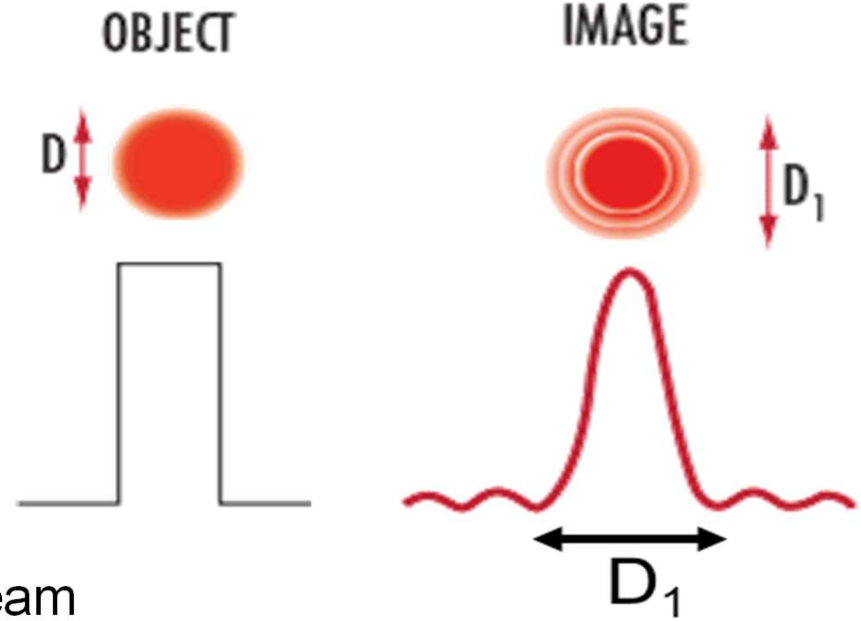
- Aperture also has influence on
  - Depth of field: Large aperture → small depth of field and vice versa
  - Illumination intensity, i.e. exposure time
  - Diffraction limit

https://www.vision-doctor.com/en/optical-basics/depth-of-field.html

Diffraction caused by aperture



A: aperture
λ: wavelength of the light



Intensity distribution

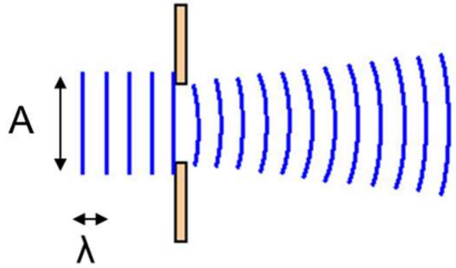
Aperture causes diffraction of the beam
→ Smaller *A* → higher diffraction level
→ Higher *λ* → higher diffraction level
→ Blurring of the image

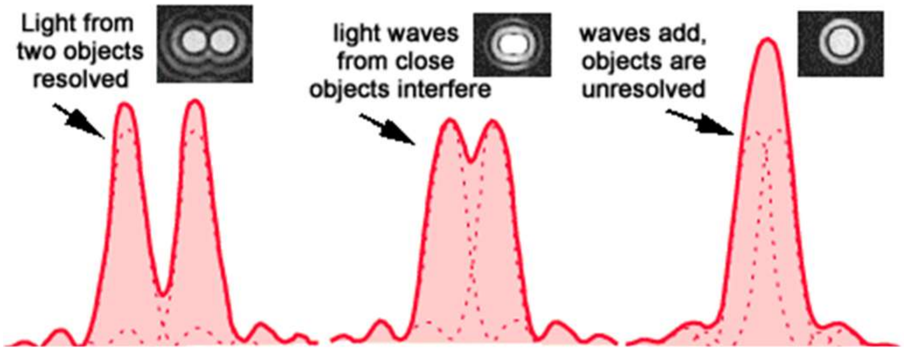
For imaging system, the diameter of the image from a point light source ($D \approx 0$)

$$D_1 = 1.22\,\frac{\lambda \cdot f}{A}$$ *f*: focal length of the system

http://ricecatalyst.org/discoveries/2016/10/3-principles-of-super-lensing-overcoming-the-diffraction-limit

Diffraction caused by aperture





A: aperture
λ: wavelength of the light

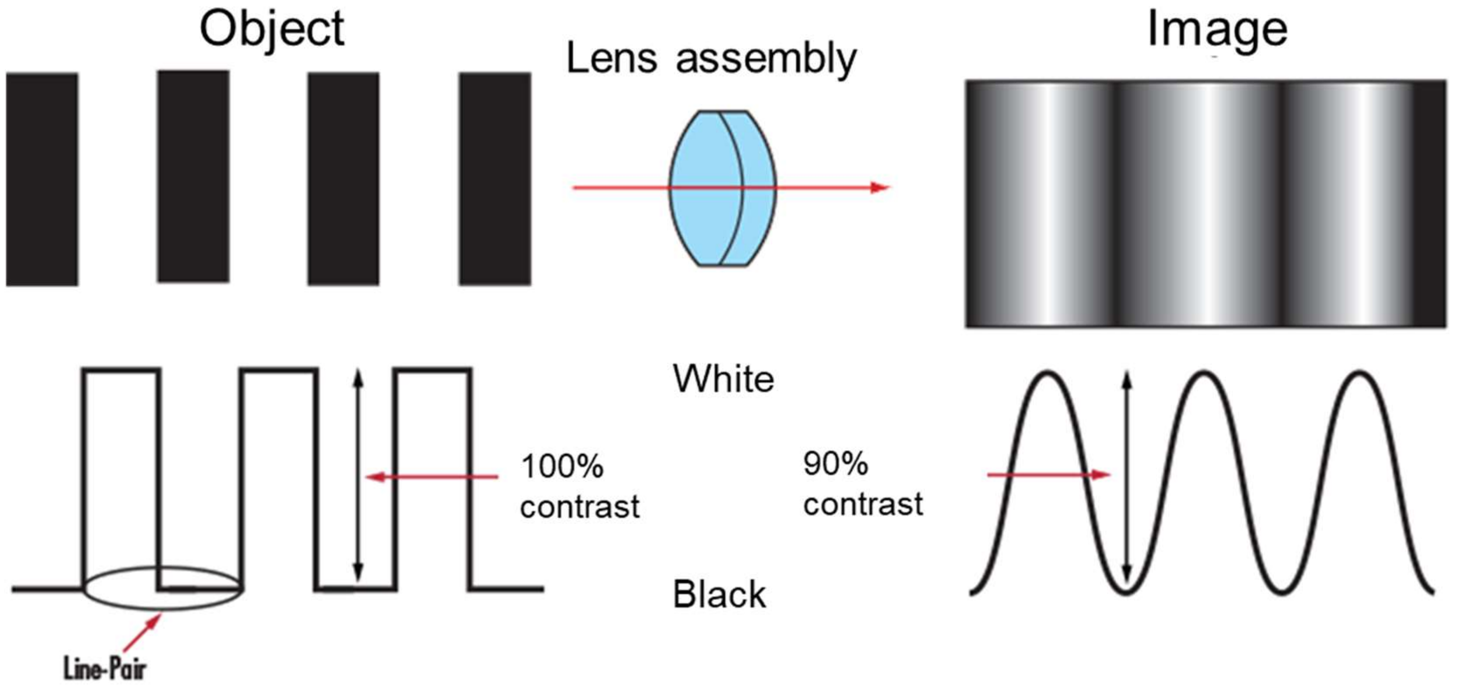
For imaging system, the diameter of the image from a point light source ($D \approx 0$)

$$D_1 = 1.22\frac{\lambda . f}{A}$$ where *f*: focal length of the system

To distinguish 2 objects, the distance of their images' peak has to be larger than $D_1/2 \rightarrow D_{objects} > D_1/2$

http://ricecatalyst.org/discoveries/2016/10/3-principles-of-super-lensing-overcoming-the-diffraction-limit

Imaging resolution

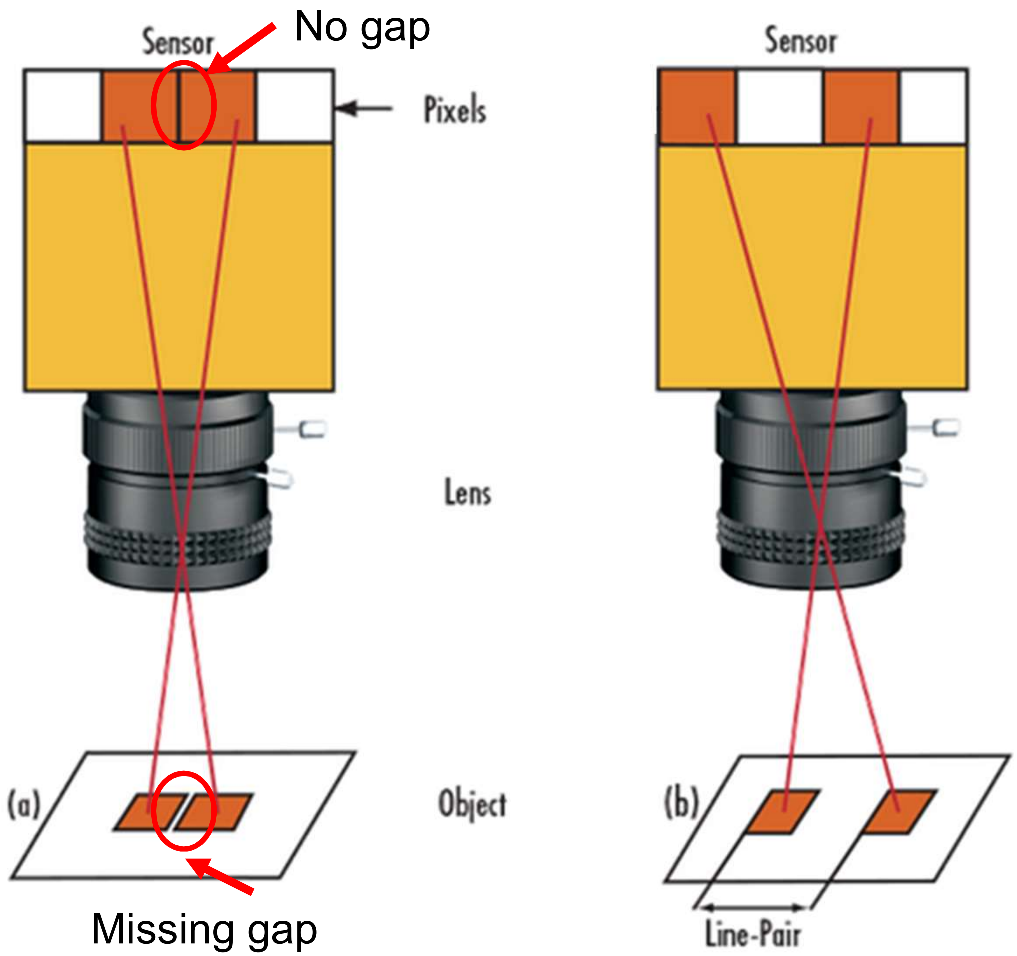


Typical simplification of an object as Line Pairs formed by square waves

Geometrical features not 100% transferred by imaging optics but blurred due to diffraction → overlapping between neighbouring features

https://www.edmundoptics.com/knowledge-center/application-notes/optics/introduction-to-modulation-transfer-function/

Imaging resolution (cont.)



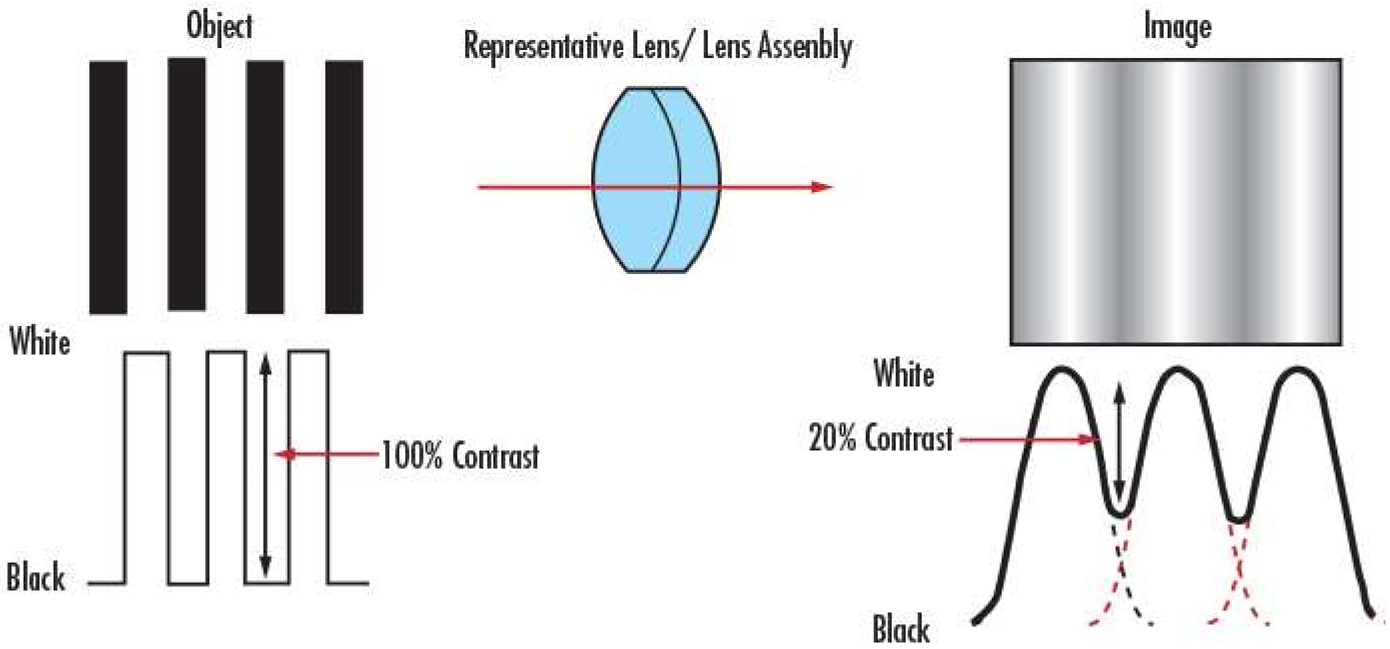
Are the objects resolved?

Objects sucessfully imaged

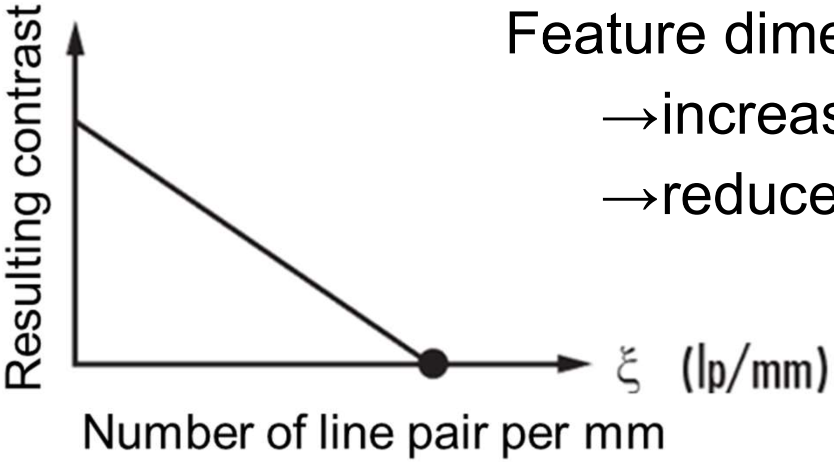
Objects can be resolved if the white and black parts are within two consecutive pixels.

https://www.visiononline.org/userAssets/aiaUploads/file/CVP_Beginning-Optics_Greg-Hollows.pdf

Imaging contrast



$$\% \text{ Contrast} = \left[\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}\right]$$



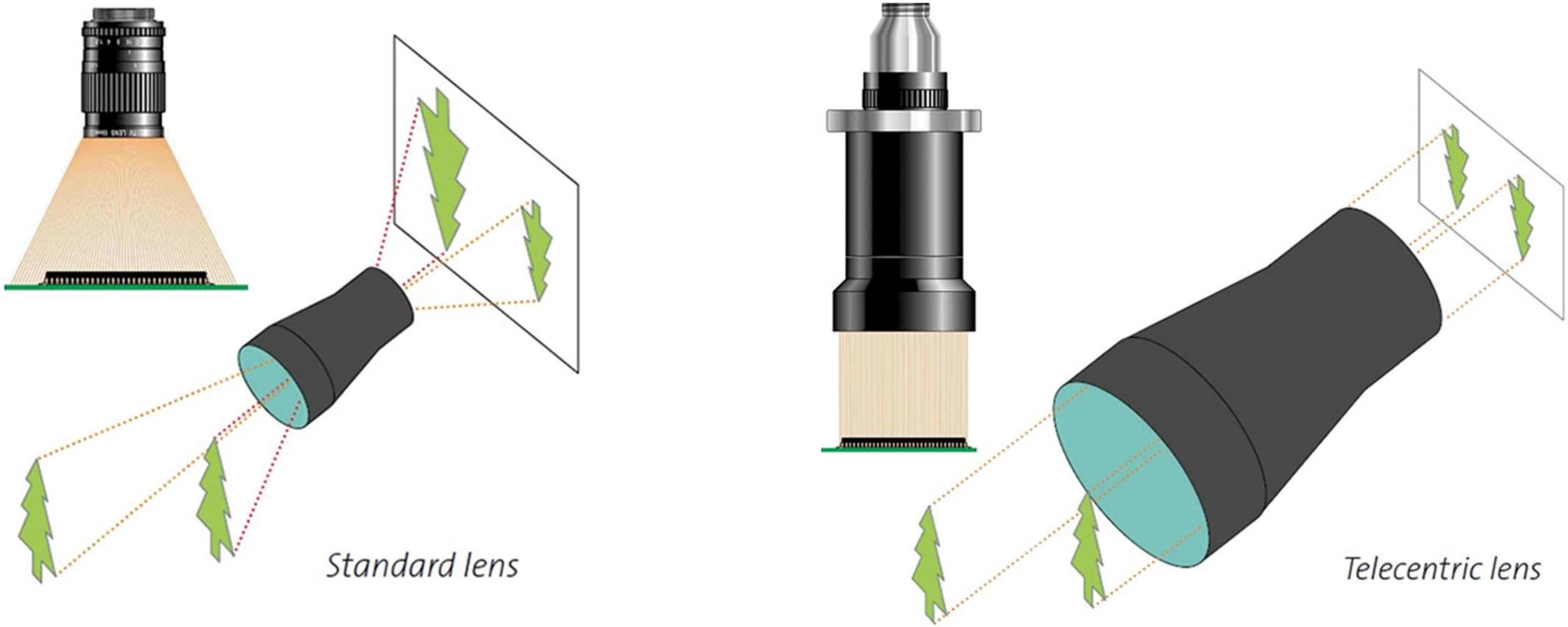
Feature dimension and distances reduce

→increased overlapping of neighbouring features

→reduced imaging contrast

https://www.edmundoptics.com/knowledge-center/application-notes/optics/introduction-to-modulation-transfer-function/

Choice of lenses



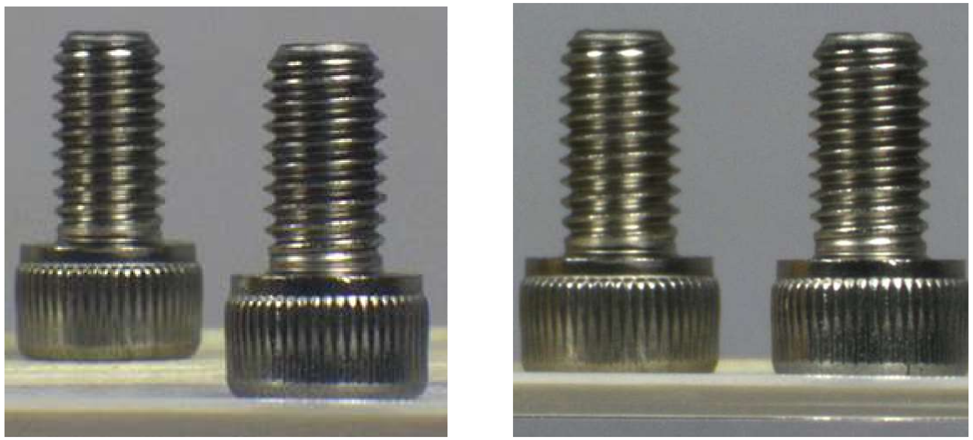
- Standard lenses (wide angle, macro,…) collect light rays within a cone
  → magnification depends on distance to lenses.
- Telecentric lenses collect only collimated light rays
  → all objects in the image have the same magnification irrespective of their distance from the lens

Choice of lense depends on the purpose

https://www.qualitymag.com/articles/94676-optics-for-high-accuracy-machine-vision

Telecentric lens

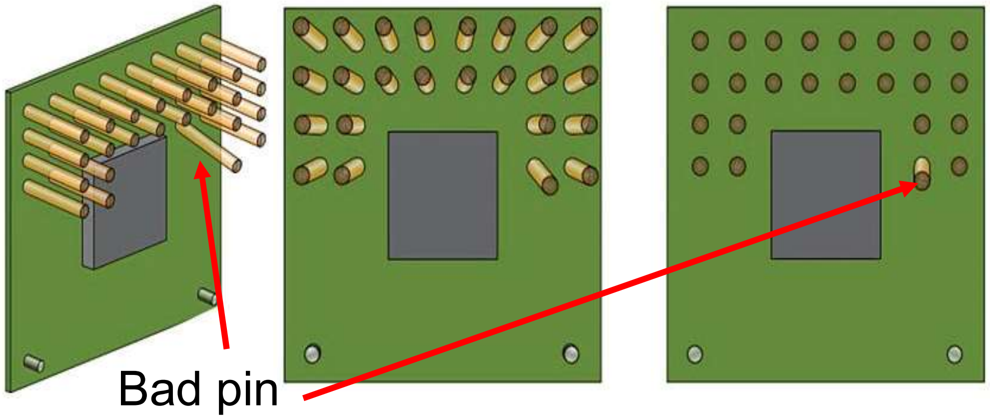
Standard lens | Telecentric lens



Pros:

- Easy to measure sizes of features regardless of the distance.
- Easy to detect geometrical distortion in the object.

Standard lens | Telecentric lens



Cons:

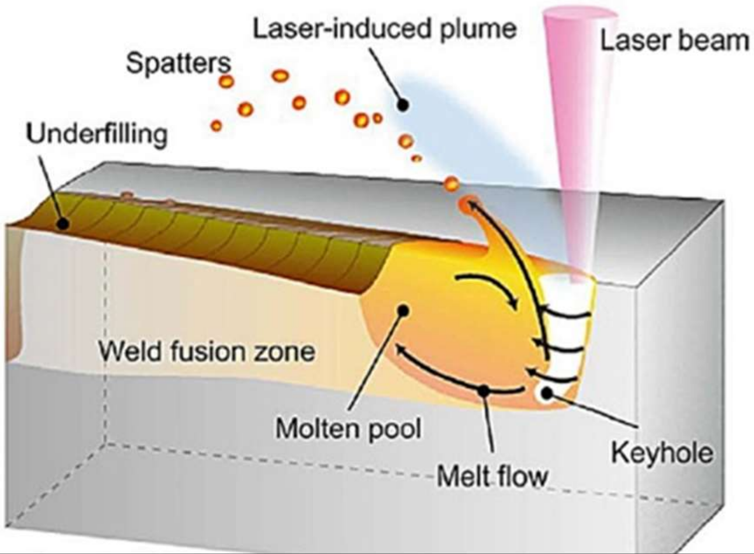
- Limited field of view → limited size of observable objects

3. Vision systems in laser-material processing

Issues to be considered

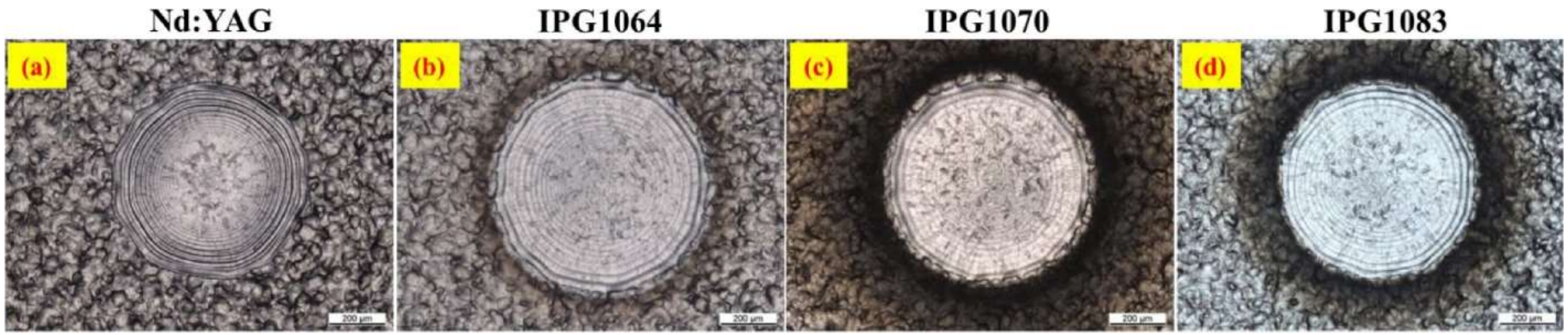
- Object of interest
  - Melt pool
  - Vapor plume
  - Ejected particles

- Properties of the objects
  - Dimension
    - Field of view
    - Type of lens
  - Dynamic behavior
    - Frame rate
    - Exposure time
    - Additional illumination
  - Accesibility
    - Configuration of camera illumination setups.
  - Optical emission/reflection
    - Additional illumination
    - Material for lenses.



Plume observation for process development

Investigation of laser-plume interaction



Application → laser welding of Ti

Approach → move to old Nd:YAG (1064 nm) to new fiber laser

Issue → appearing of **sooth** on the surface of welded titanium when different laser sources are used

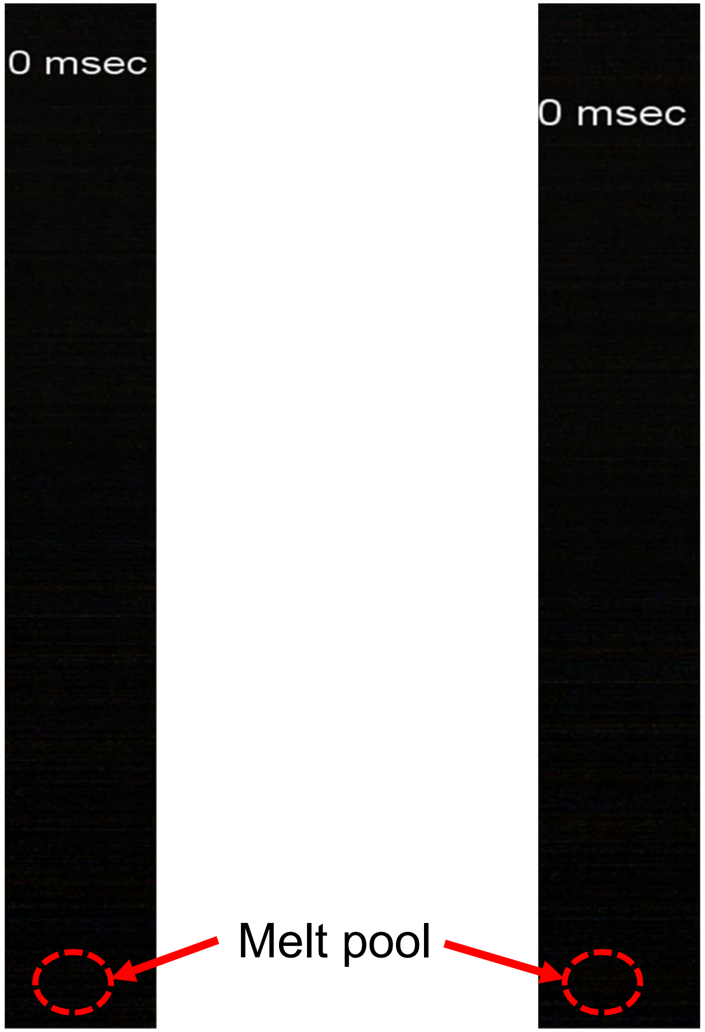
Consequences → laser welding quality is questioned

https://doi.org/10.1016/j.optlaseng.2020.106173

Evolution of vapor plumes

1064 nm, 70 W
3 ms pulse

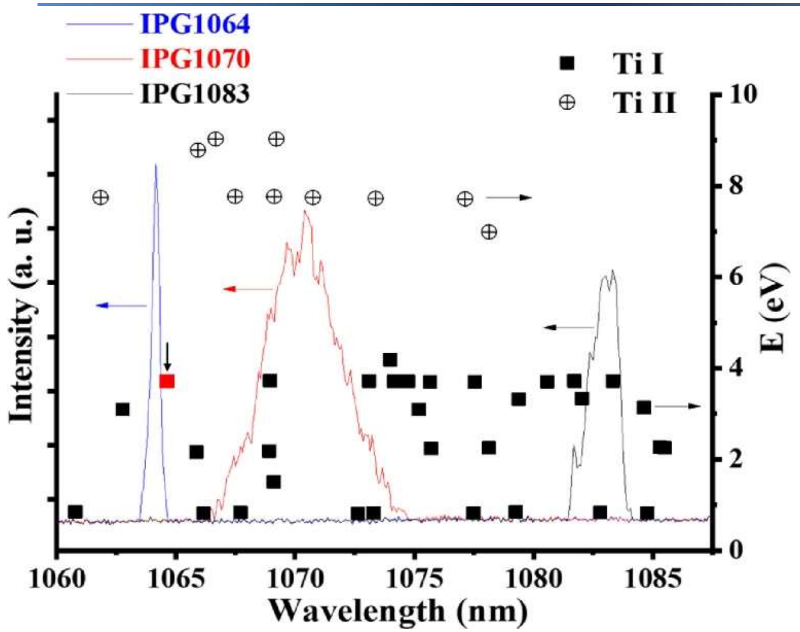
1070 nm, 77 W
3 ms pulse

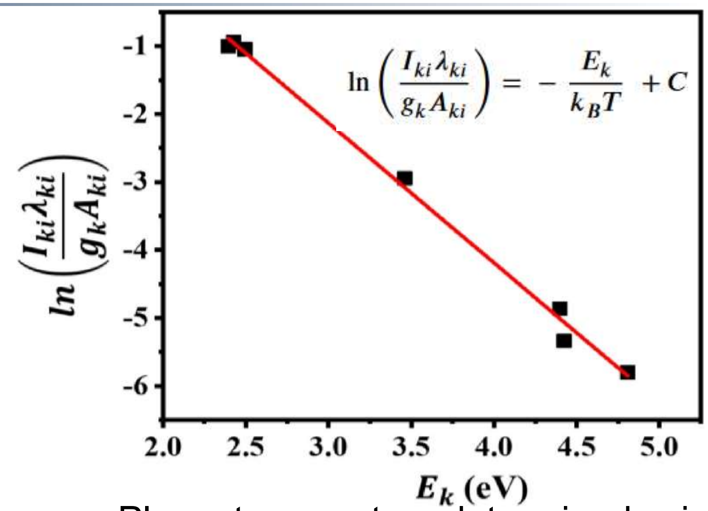


- With 1064 nm laser, the plume could travel a larger distance above the surface.
- The plume appears reddish/yellowish for 1064 nm and white for 1070 nm

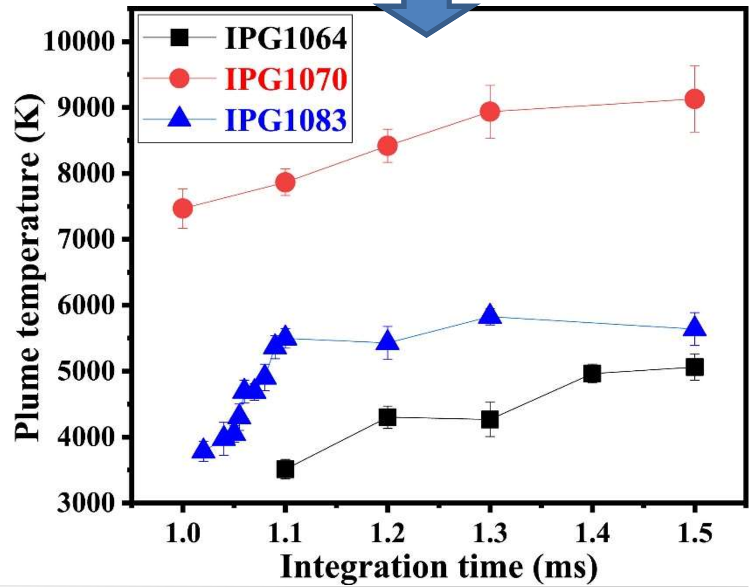
What does it mean regarding the temperature ?

Difference in laser-plume interaction





Plume temperature determined using Boltzmann plot method

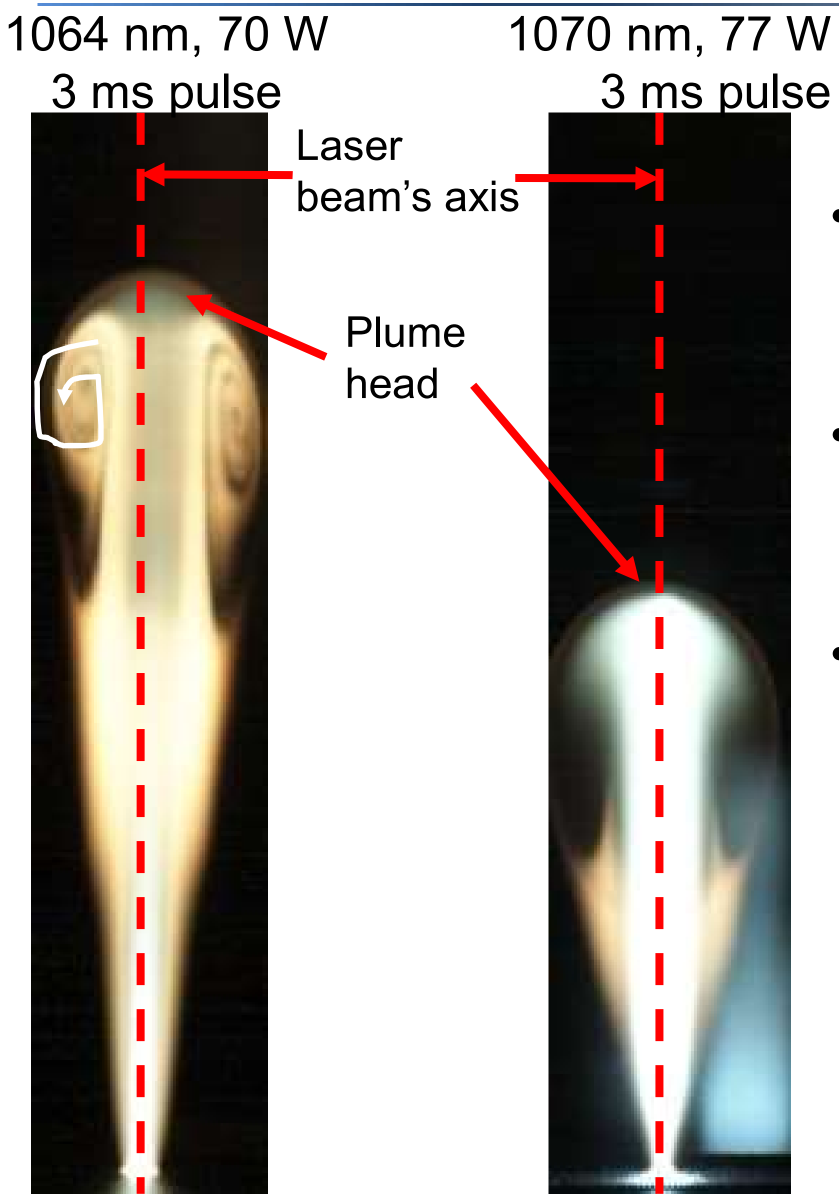


The radiation from IPG1070 and IPG1083 can be easily absorbed by the plume (neutral + single ionized Ti atoms)

→ The resulting plume has higher temperature

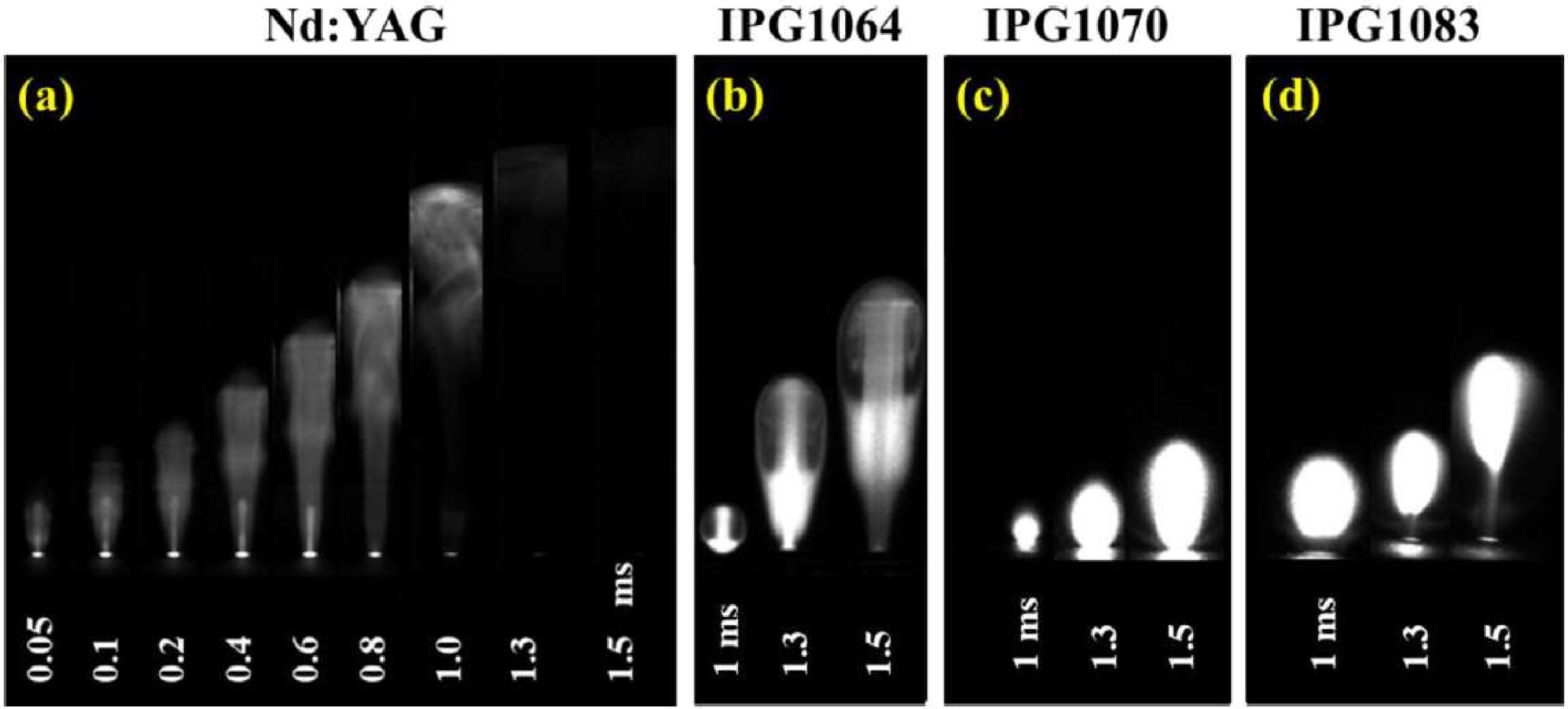
https://doi.org/10.1016/j.optlaseng.2020.106173

Difference in laser-plume interaction



- With 1064 nm laser, plume head has lower temperature due to interaction with cooler atmosphere
- Cooled material in the plume falls down to the side before getting reheated when in contact with the hotter material below
- With 1070 nm, plume head is constantly at high temperature due to the absorption of the incoming laser beam

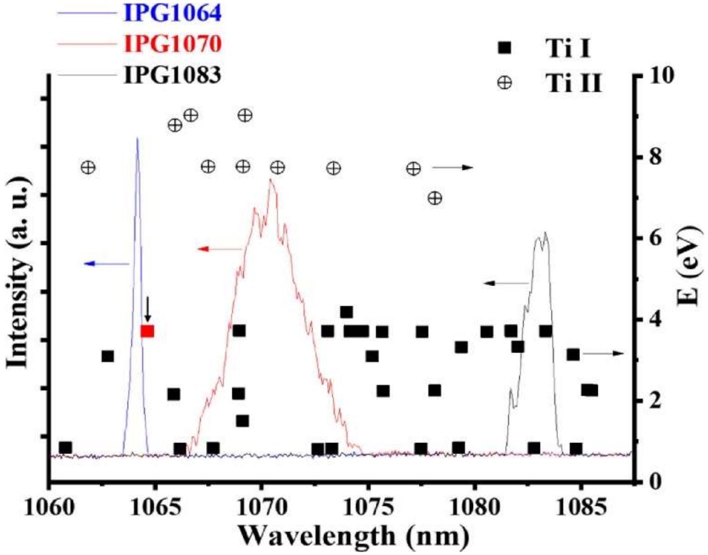
Evolution of vapor plumes



Temporal evolution of the high-speed images of the plume emissions produced by Nd:YAG, IPG1064, IPG1070 and IPG1083 lasers having laser peak power of 1 kW and pulse duration of 1.5 ms from titanium plate

Influence of laser wavelength (cont.)

Initial condition

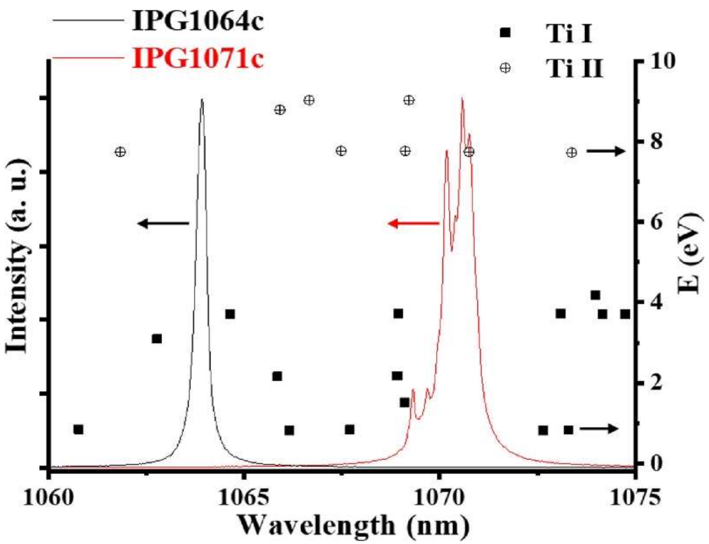


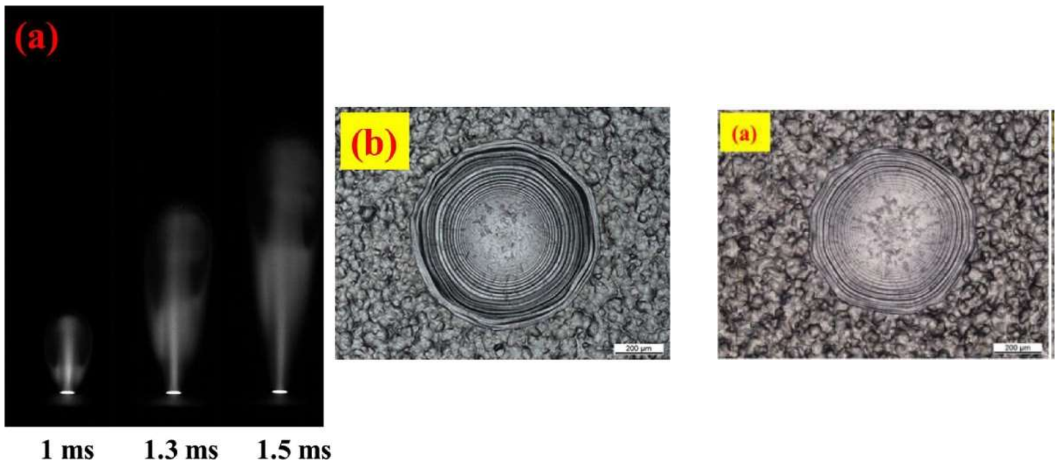
New lasers centered at 1064 nm and 1071 nm with smaller distribution

→ minimal laser absorption by the plume

→ no sooth on the surface.

Customized laser's wavelength

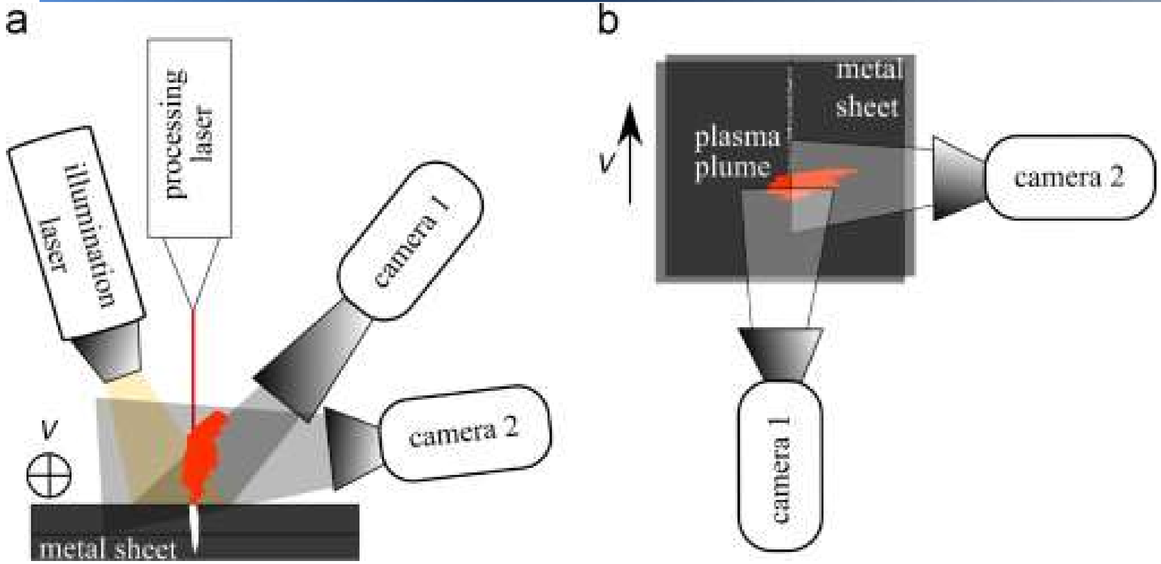




Results of the new 1071 nm and old Nd:YAG

Plume observation for quality monitoring

Imaging setup

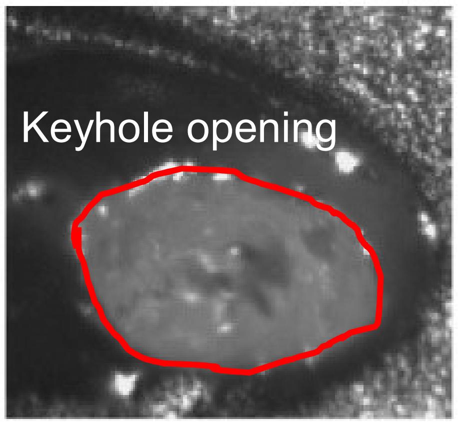


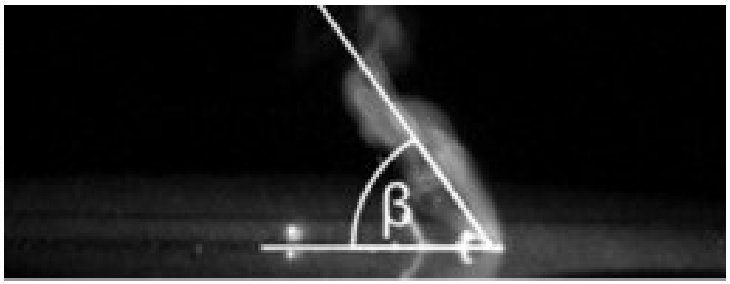
Question:

- Possible to use the plume's visualization to determine process stability?

Features of interest:

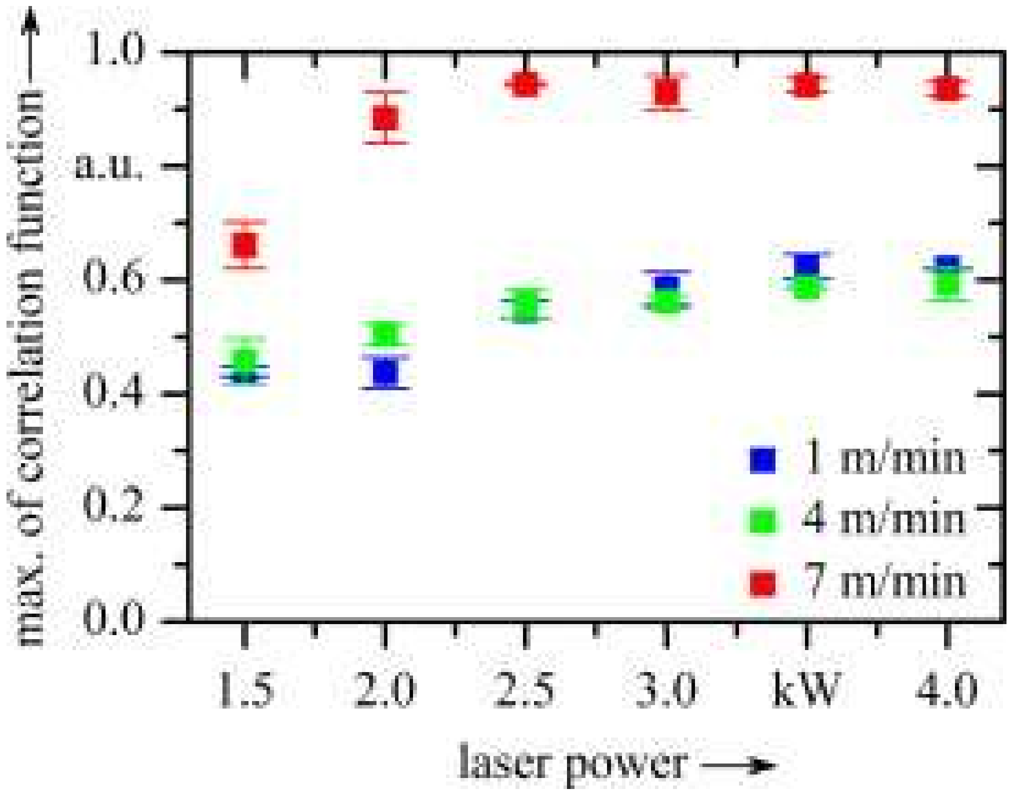
- surface dimension of the keyhole
- inclination angle of the plume





https://doi.org/10.1016/j.optlaseng.2014.07.009

Correlation between features of interest

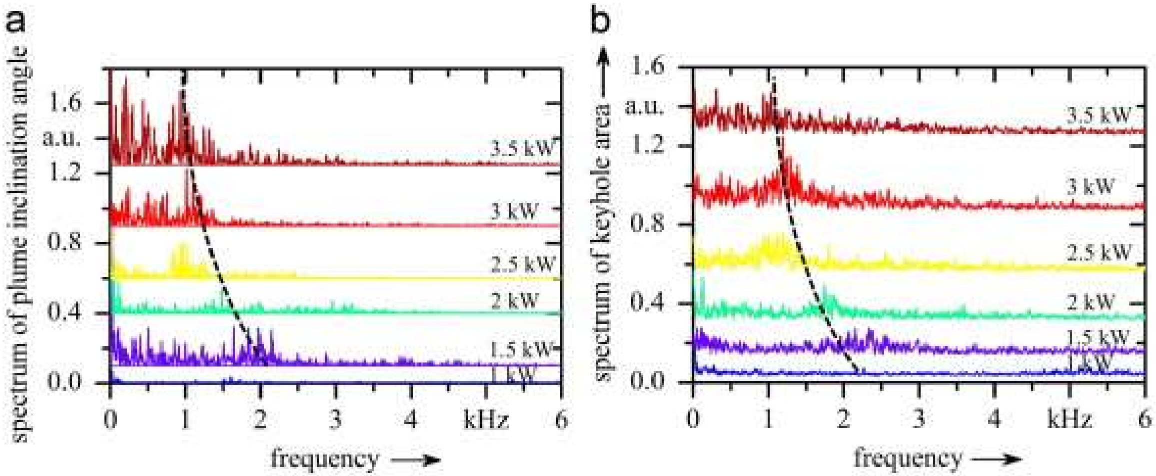


Maximum of the cross-correlation function between the keyhole opening area and the plume inclination angle for 1, 4 and 7 m/min feed rate

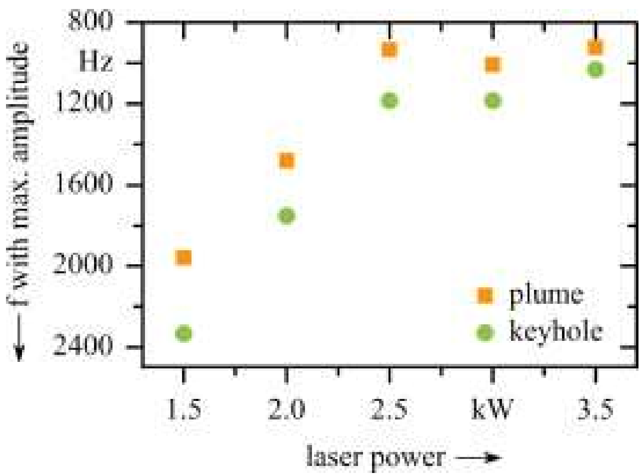
- At 7m/min feed rate, keyhole opening area and plume inclination angle are nicely correlated
- At lower feed rate, keyhole opening area might be also affected by other factors such as flow dynamics of the melt pool

https://doi.org/10.1016/j.optlaseng.2014.07.009

Stability of the process



(a) FFT spectra of the plume inclination angle and (b) the visible keyhole area for a constant feed rate of 7 m/min. The dashed line indicates the trend of the dominating frequencies (no dominating frequency visible for 1 kW).



- Interestingly, the FFT contents of plume inclination angle and keyhole area have similar dependencies on the laser power and fluctuates at similar dominating frequency contents
- It seems that higher laser power leads to lower frequency of the dominant content.

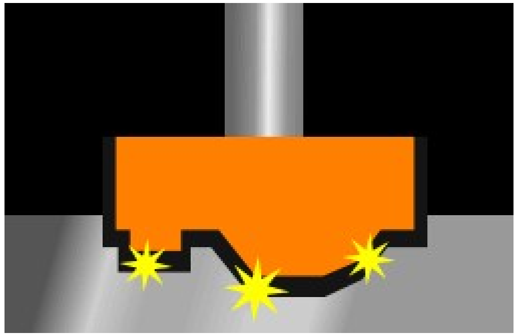
https://doi.org/10.1016/j.optlaseng.2014.07.009

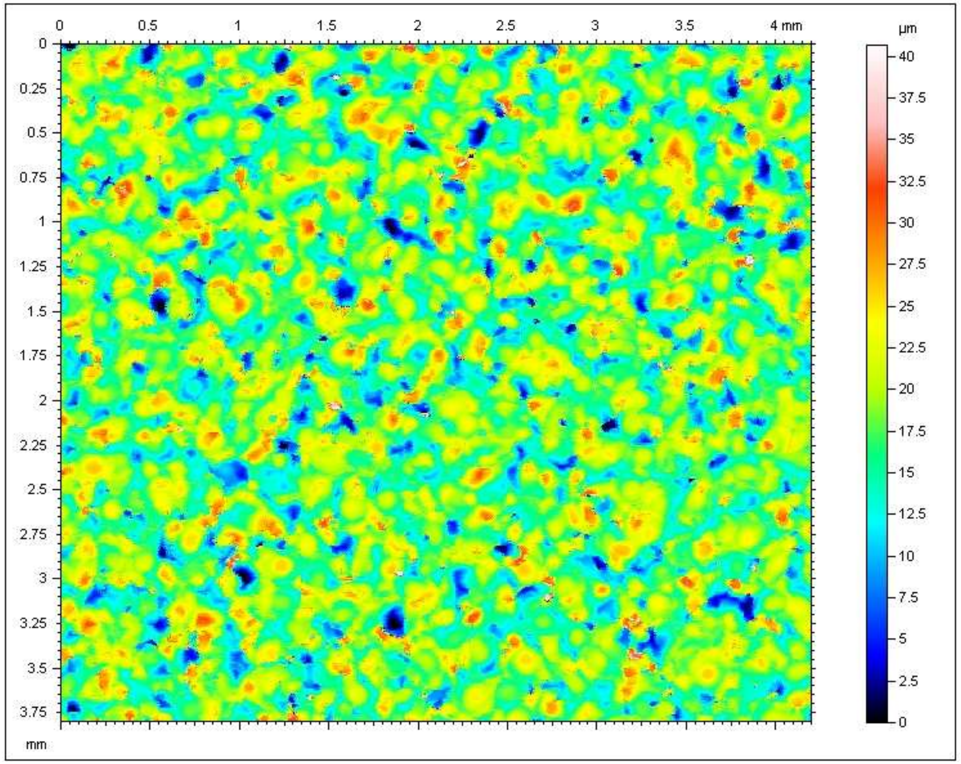
Melt pool observation for process development

Laser polishing of tool steel

Aim: Polishing of hardened tool steel for the mould industry, from electrical discharge machined (EDM) rough surface ($R_a \approx 3.2$ µm) to $R_a \approx 0.3$ µm → a decrease by a factor of 10

Die sink EDM





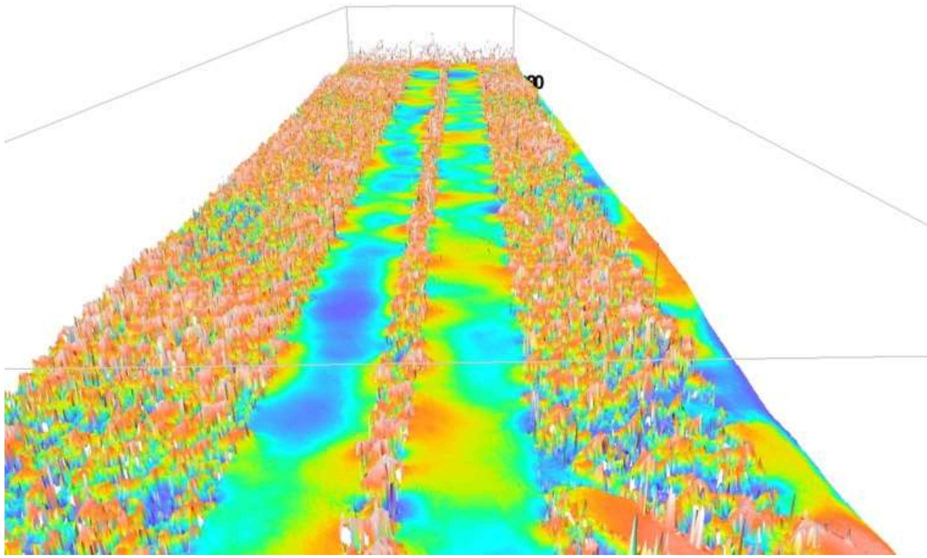
Topographical map of tool steel treated with EDM.

Laser polishing of tool steel

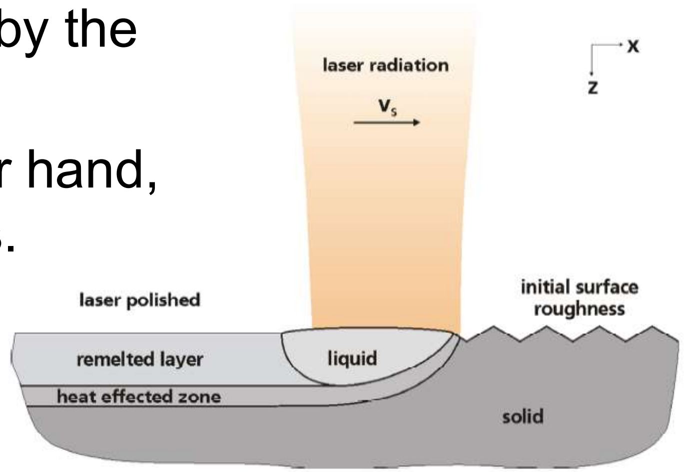
Surface re-melting is a part of the laser polishing process

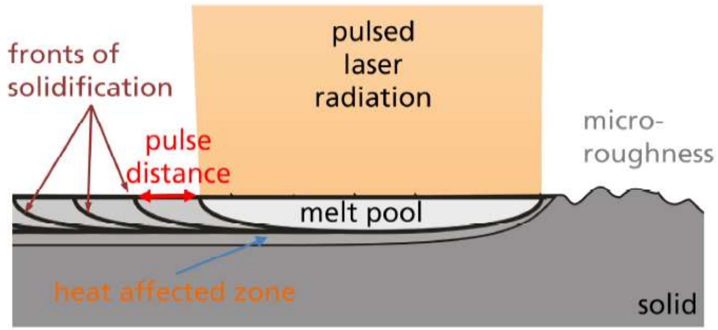
The rough surface of the material is melted by laser radiation. In the liquid state the surface is flatten by the influence of surface tension.

Convective flow or Marangoni effect, on the other hand, can lead to an increase of the surface roughness.



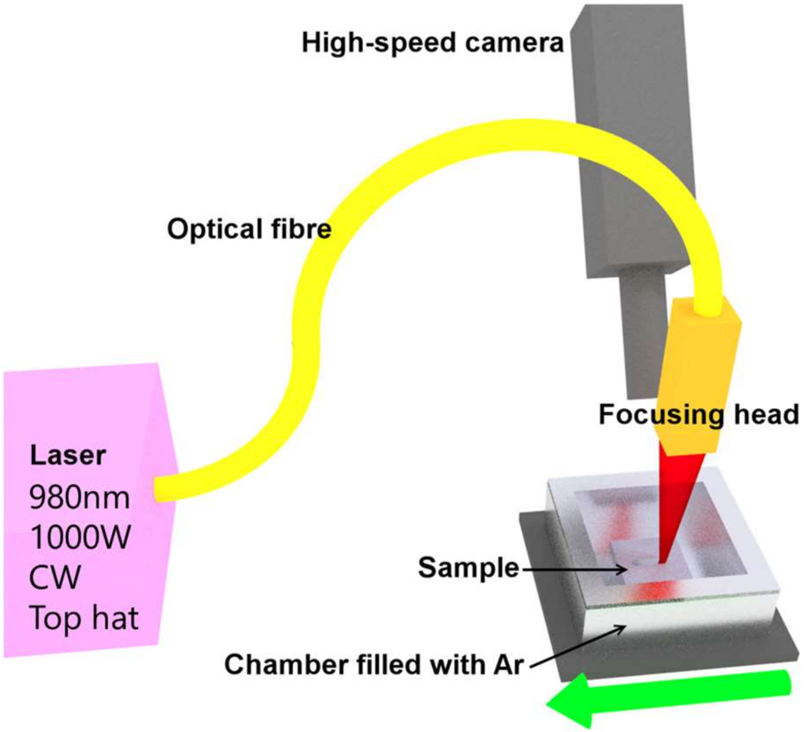
Surface topography with 2 re-melted lines, in the center





Temmler A, Willenborg E, Wissenbach K. Laser polishing [10.1117/12.906001](10.1117/12.906001)

Experimental setup

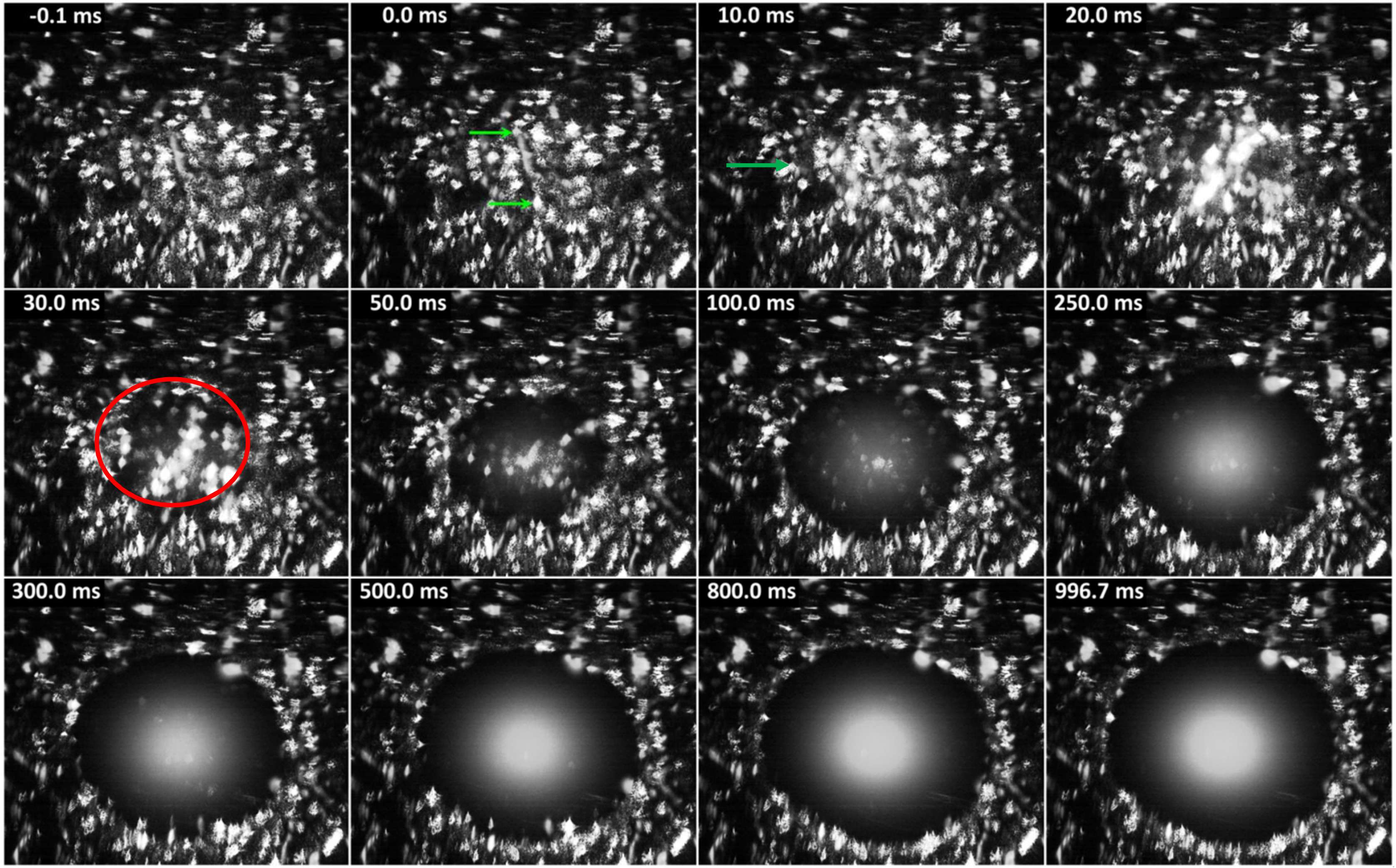


- Observation:
  - High speed camera at 10 kHz
  - A telecentric objective Moritex ML-Z07545 used at 4.5x magnification
  - Low pass filter at 800 nm to cut laser light
  - External illumination by a 532 nm laser

Evolution of the melt pool for a fixed illumination

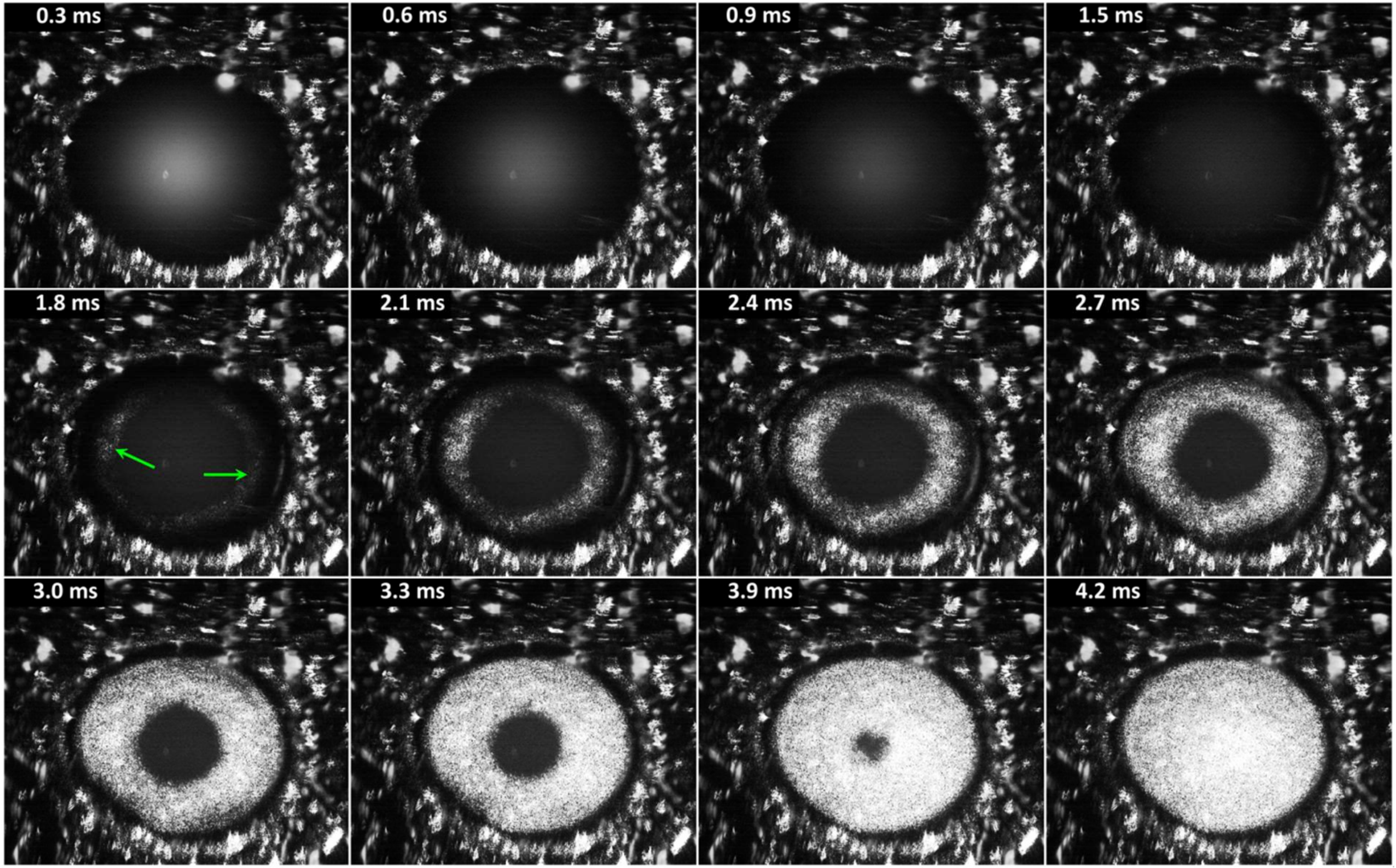
- Laser conditions :
  - Wavelength NIR
  - Spot size ≈ 1 mm
  - Power ≈ 300 W
  - Velocity 0 mm/s
  - Illumination ≈ 1 s.
- Observation:
  - High speed camera at 10 kHz
  - With a telecentric objective Moritex ML-Z07545 0.75-4.5x used at the highest magnification (4,5x)
  - Low pass filter at 800 nm to cut laser light
  - External illumination by a 532 nm laser

Evolution of the melt pool for a fixed illumination



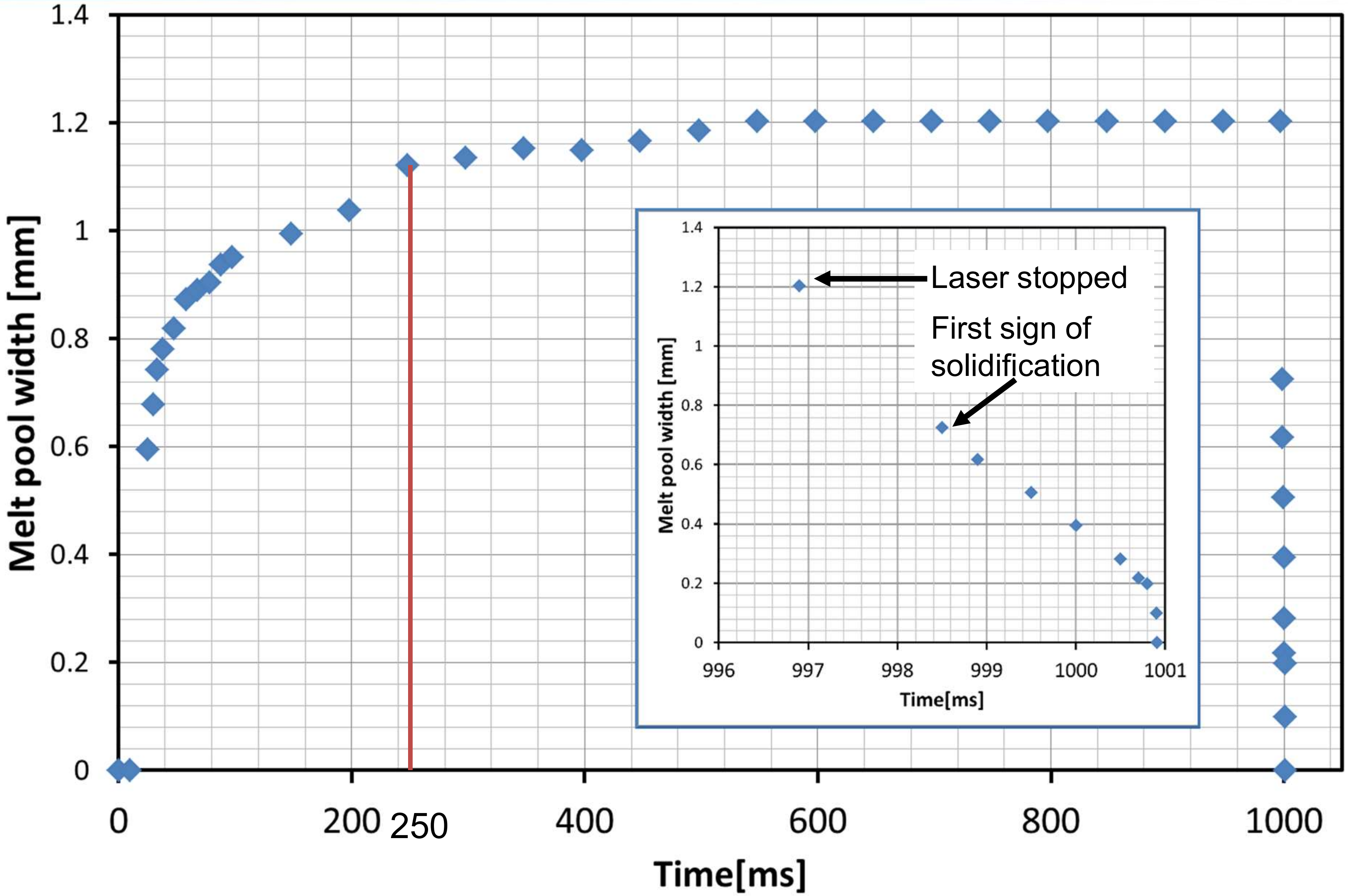
Evolution of the melt pool during a static experiment, with a power of 317 W for a duration of 997 ms.

Evolution of the melt pool for a fixed illumination



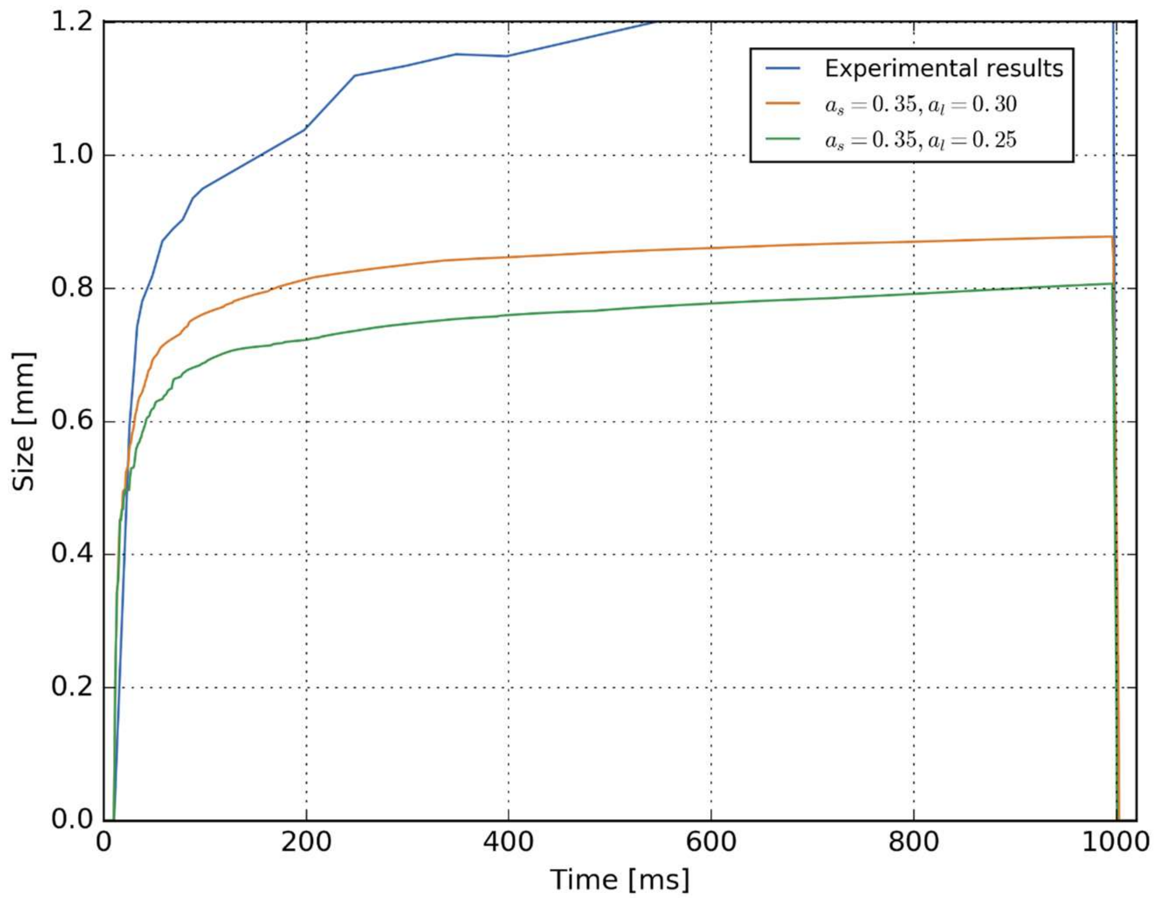
Solidification sequence for the same experiment as in the previous slide. Time stamps are from the end of laser illumination.

Evolution of the melt pool for a fixed illumination



Evolution of the melt pool with time. Bleu diamonds are the measured data from the high speed images. The inset shows the detail of the solidification.

Evolution of the melt pool for a fixed illumination simulation vs experiment



Time evolution of the melt pool width. The inset shows the detail of the solidification. a_s and a_l are the absorption coefficients in solid and liquid, respectively

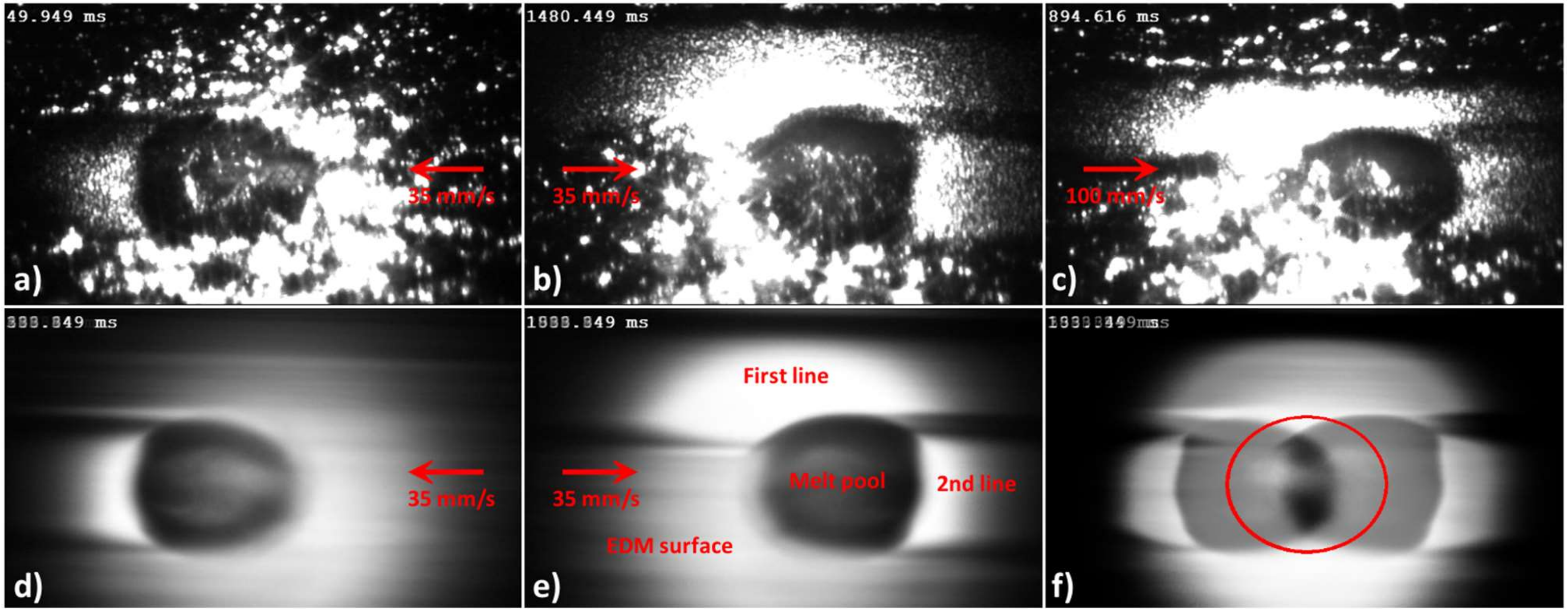
Evolution of the melt pool for a moving sample

- Laser conditions :
  - Wavelength NIR
  - Spot size ≈ 1 mm
  - Power ≈ 450 W
  - Velocity 50 mm/s
  - Illumination ≈ 1 s.
- Observation:
  - High speed camera at 10 kHz
  - With a telecentric objective Moritex ML-Z07545 0.75-4.5x used at the highest magnification (4,5x)
  - Red filter (0.3% pass in NIR)

Evolution of the melt pool for a moving sample – return with 90% overlap

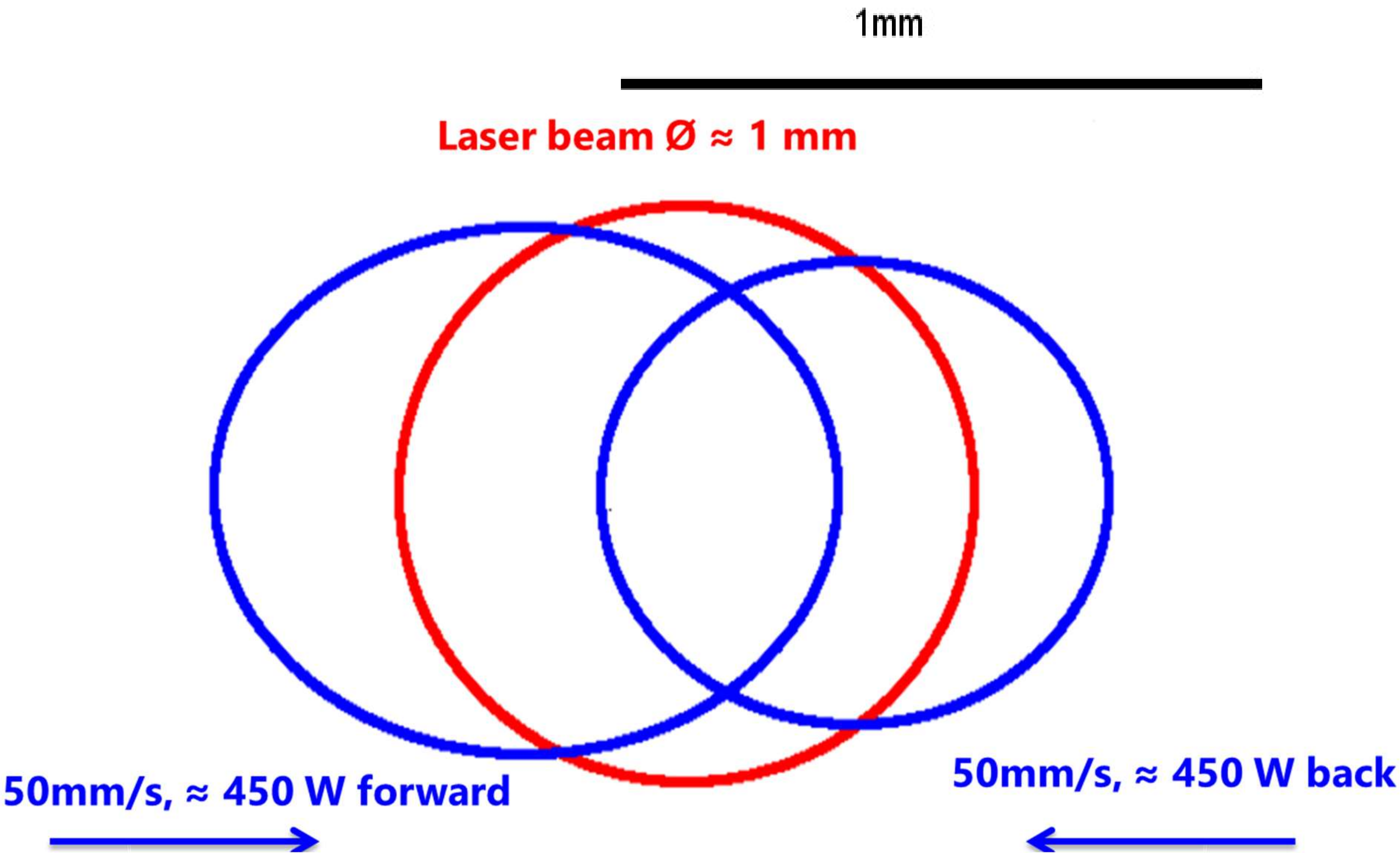
- Laser conditions :
  - Wavelength NIR
  - Spot size ≈ 1 mm
  - Power ≈ 450 W
  - Velocity 50 mm/s
  - Illumination ≈ 1 s.
- Observation:
  - High speed camera at 10 kHz
  - With a telecentric objective Moritex ML-Z07545 0.75-4.5x used at the highest magnification (4,5x)
  - Red filter (0.3% pass in NIR)

Evolution of the melt pool for a moving sample

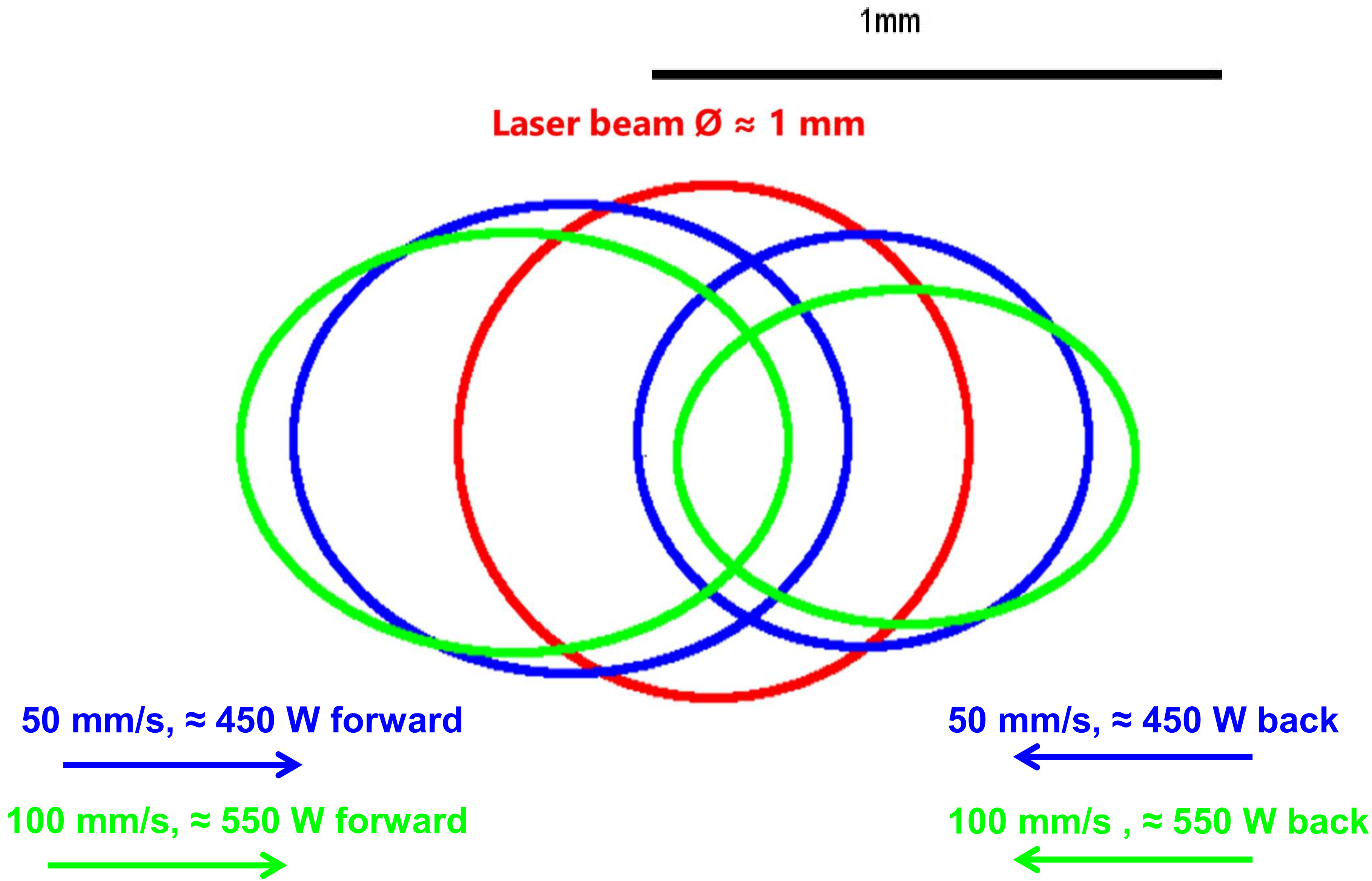


a) First line at 35 mm/s and 415 W. b) Second line with an overlap of 30% also at 35 mm/s and 415 W. c) Second line at 100 mm/s and 561 W. d) Average of the light intensity of all image for the first line at 35 mm/s and 415 W. e) Average of the light intensity of all image for the second line at 35 mm/s and 415 W. f) Combination of 50% d) and 50% e). For a scale indication, the ellipses in *f* represent the spot diameter of 0.9 mm and so main axes gives the scale in *x* and *y*-directions. All images have the same scale.

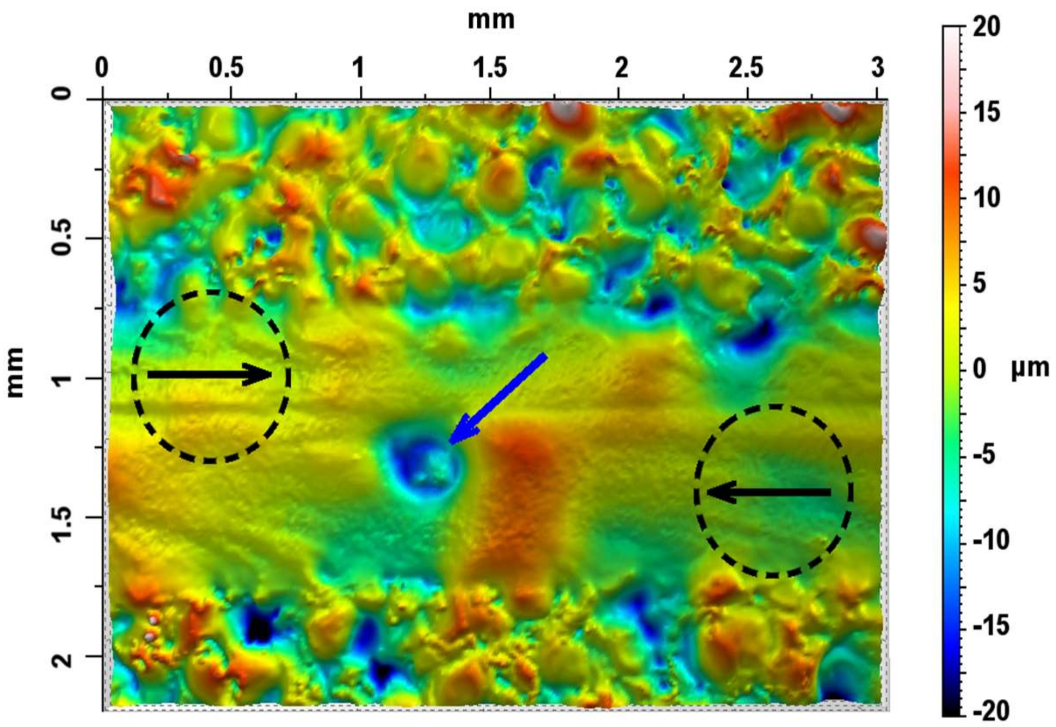
Evolution of the melt pool for a moving sample



Evolution of the melt pool for a moving sample



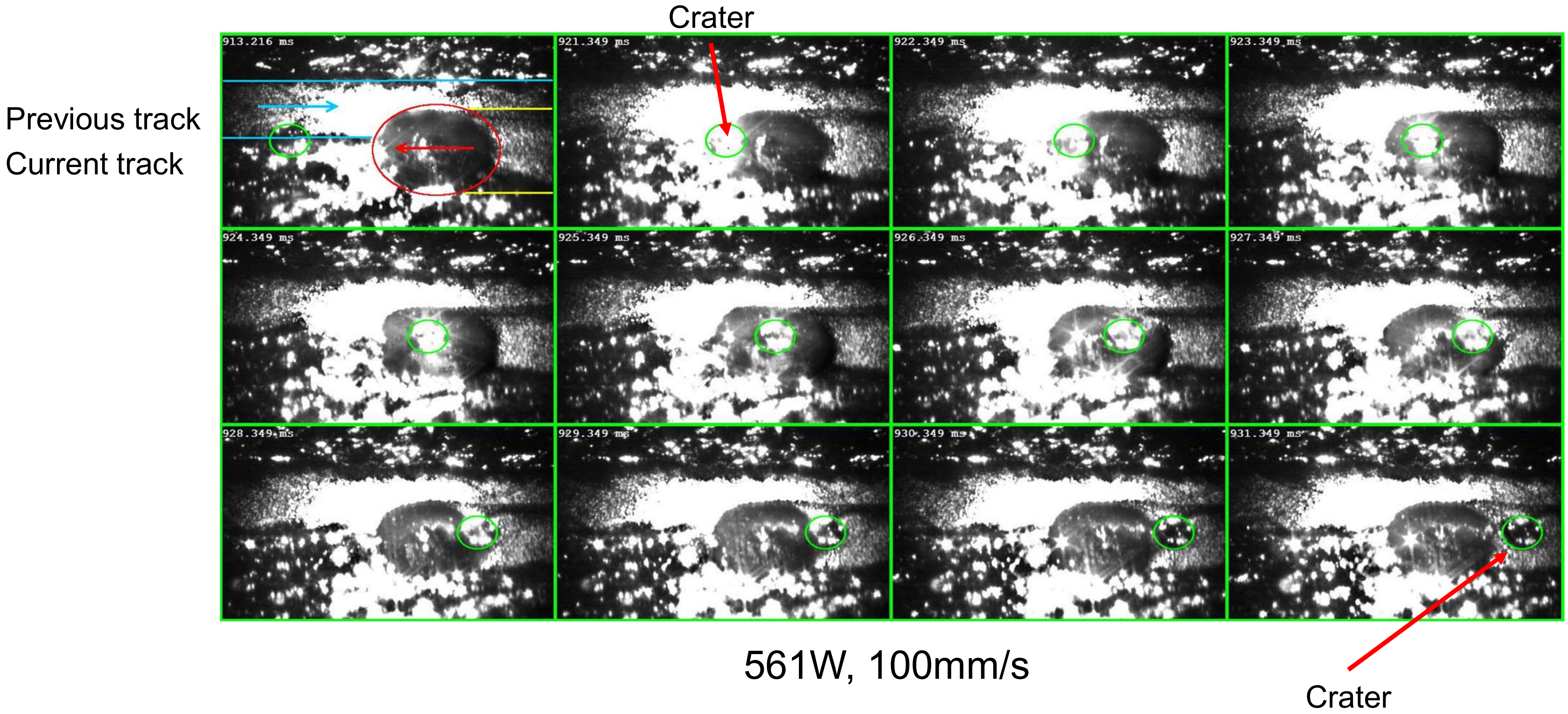
Issues with laser polishing of EDM surfaces



Topographical map of a crater (indicated by blue arrow) observed on sample treated at a speed of 100 mm/s and laser power of 561W. The melt track was made by two consecutive laser scans, whose directions are indicated by the arrows. The dashed circles approximate the dimension of the melt pool.

- Presence of craters on the laser polished surface
- The craters cannot be removed by the melting process

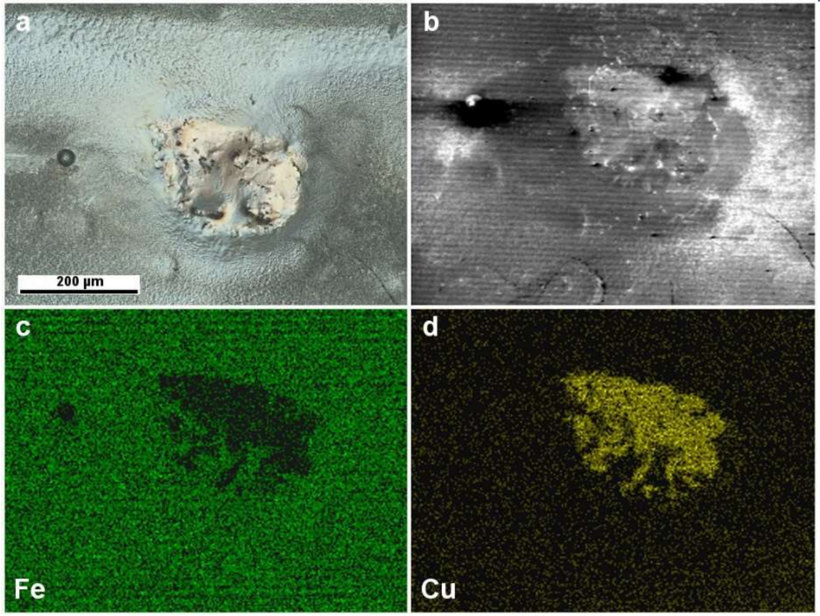
Interaction between the crater and the melt pool



561W, 100mm/s

- The crater seems not melted during the interaction with the melt pool.
- The crater shows high optical reflectance.
- Size of the melt pool slightly decreased when the crater is within the melt pool.

Origin of the crater

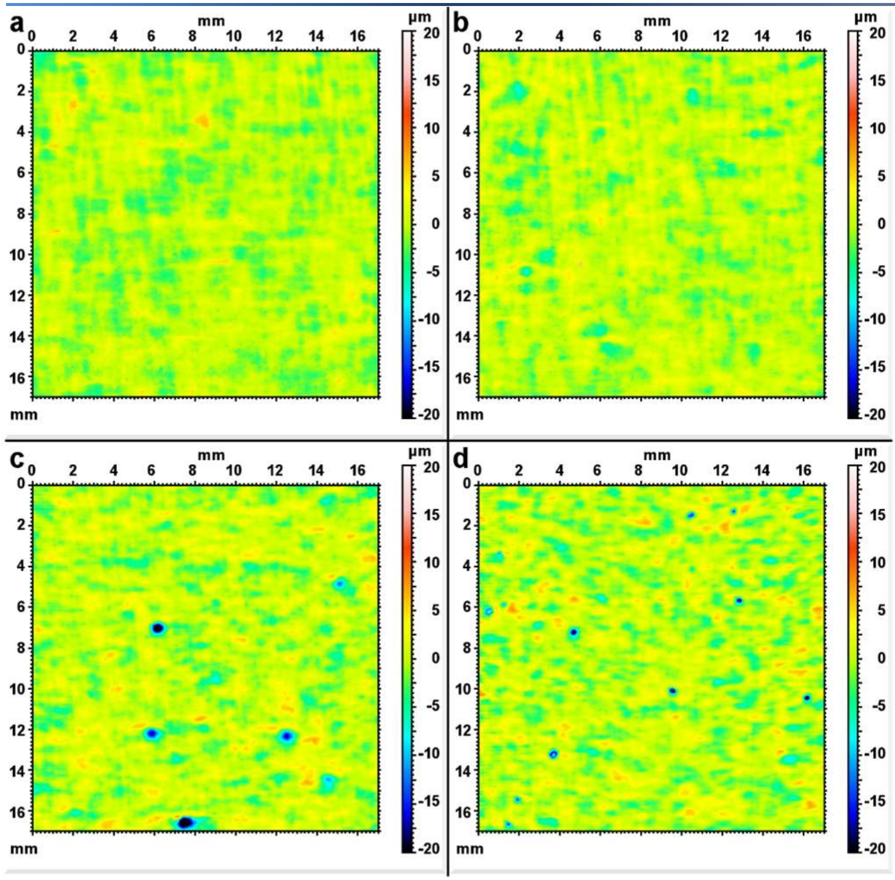


(a) Light microscope, (b) SEM,
(c) and (d) SEM+EDX

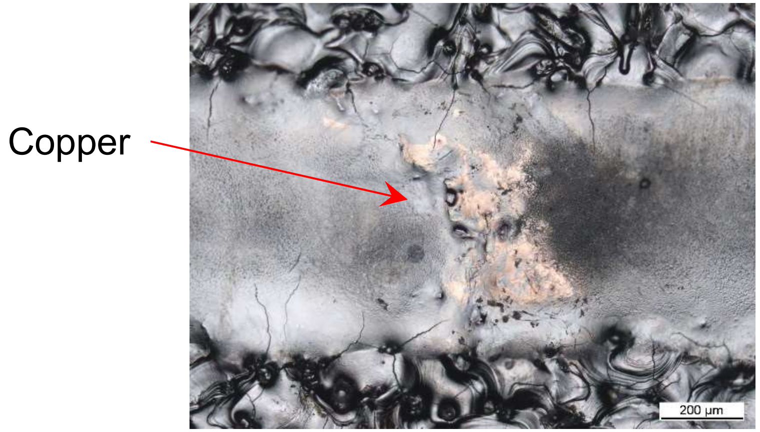
- Copper (Cu) detected at the craters.
- Cu likely came from the electrodes used in the EDM process.
- Cu has very high reflectance (> 90%) →
  - Likely to be melted by heat transfer from the molten stainless steel.
  - Can reduce the total absorbed laser energy → reduce melt pool temperature and size.

Surface treatment	C (at.%)	Si (at.%)	Mn (at.%)	Cr (at.%)	Mo (at.%)	Ni (at.%)	Cu (at.%)	Fe (at.%)
EDM	**1.680**	**0.901**	**0.273**	**4.847**	**1.274**	**0.206**	**1.440**	**88.630**
Mechanical	**0.417**	**0.849**	**0.333**	**5.007**	**1.253**	**0.227**	**0.066**	**91.150**

Influence of scanning velocity



Topographical maps of 17x17mm^2 realized on the same sample for (a) 415 W, 35 mm/s, (b) 454 W, 50 mm/s, (c) 561 W, 100 mm/s and (d) 651 W, 150 mm/s with a spacing between the lines of 90 µm.



454 W, 50mm/s

How to remove the crater?

- Use very high laser power → ?
- Change laser => green laser → ?
- Change scanning velocity → ?

- At low velocity, no crater was observed and the copper trace seems to be melted
- At velocity above 50 mm/s
  → increased amount of craters

Challenges in imaging of melt pool

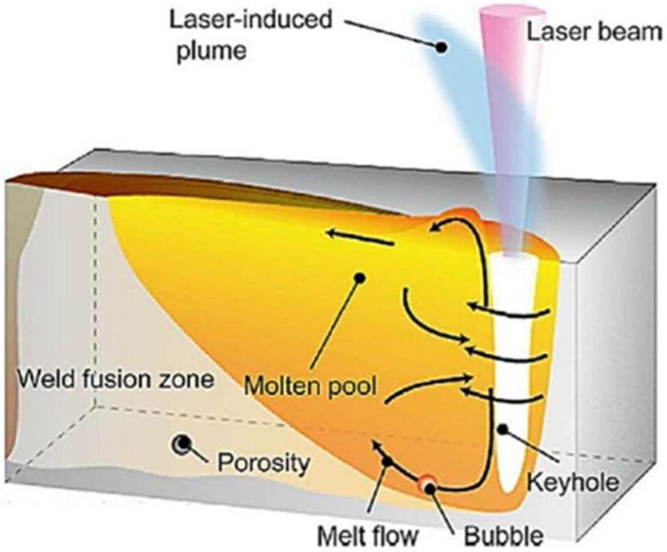
Speckles Melting start Melt pool

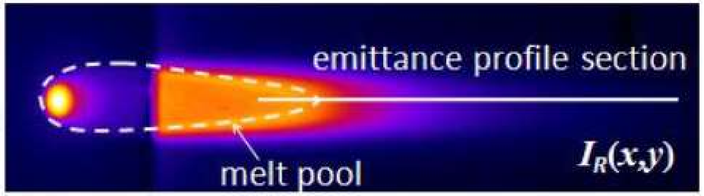
High-speed images during laser melting; 532 nm laser as illumination source
Melt pool > 1 mm in diameter

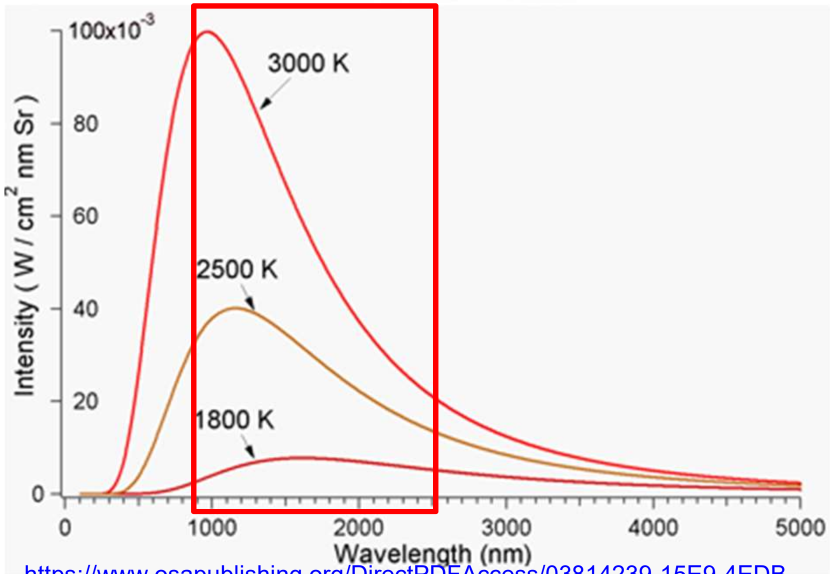
- Speckle pattern within the illuminated spot
- Speckle due to the interference on the image plane of the laser light scattered/reflected from the surface
- Speckle pattern depends on illumination wavelength, viewing angle, roughness of the surface….

Speckle is significant when observing small melt pool, i.e. 30–100 μm

Challenges in imaging of melt pool







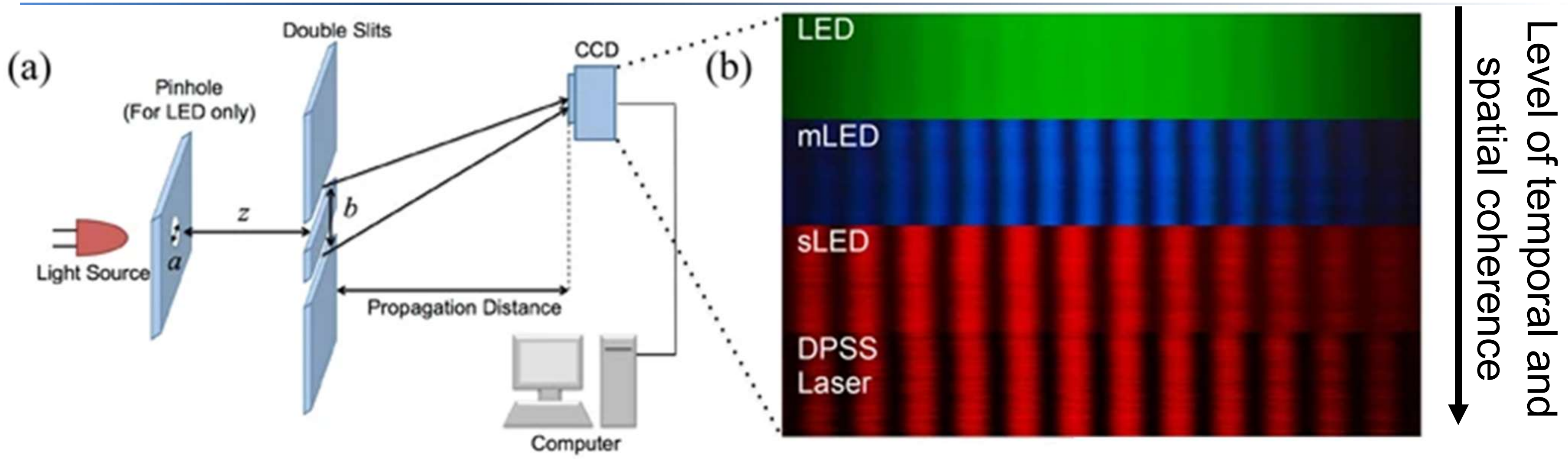
https://www.osapublishing.org/DirectPDFAccess/03814239-15E9-4EDB-BA9FB0FE86FF90DA_367322/oe-25-12-13539.pdf?da=1&id=367322&seq=0&mobile=no

Black-body radiation as light source:

- Limited only to the hottest part of the melt pool
- Possible optical chromatic aberration due to the broad spectral range of emission
- Low imaging resolution if only NIR wavelength is used (thermal camera)
- Visual accessbility affected by the irradiating plume

Powerful external illumination source

Choice of illumination source

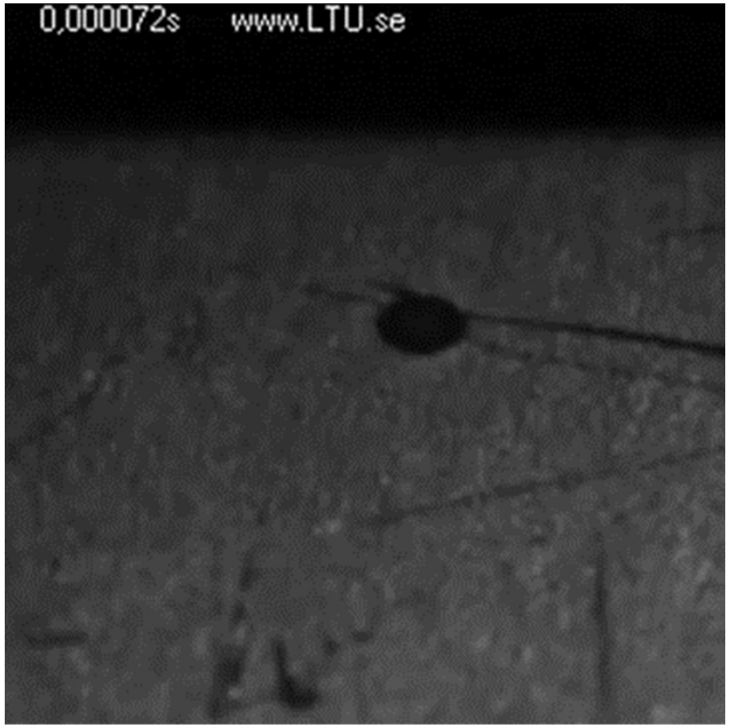


Interference is more significant with increasing level of coherence in light source.

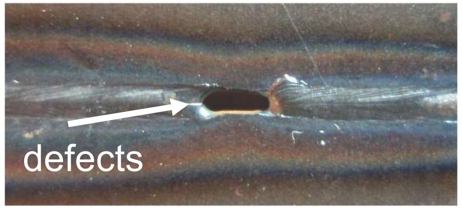
Use of incohrent light source

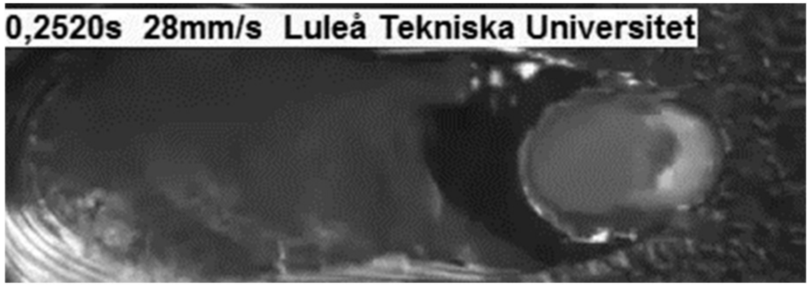
https://doi.org/10.1038/s41598-017-06215-x

High speed imaging of melt pool



Keyhole observation





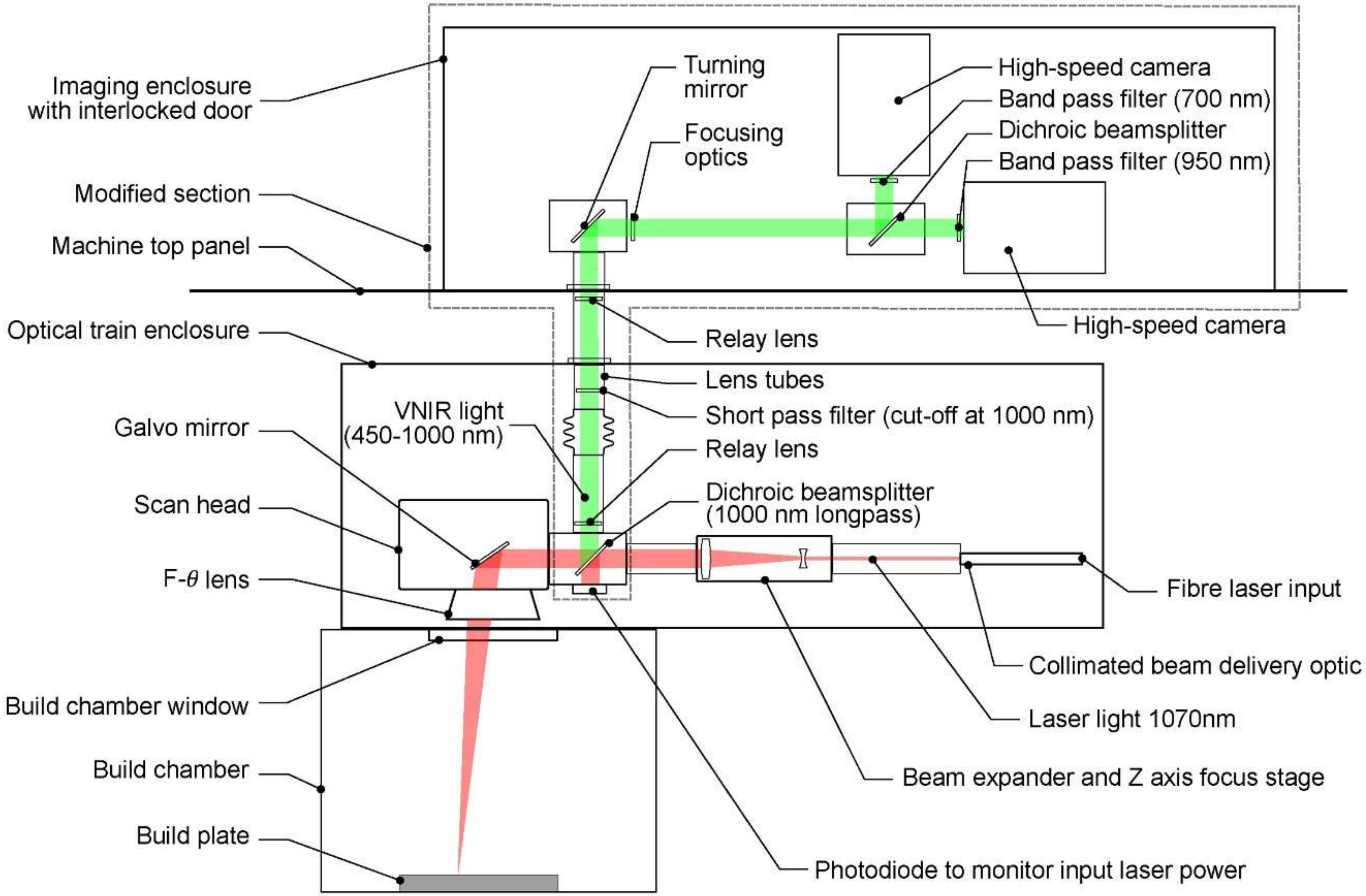
Defect formation in laser welding

280 – 500 W
640 nm or 810 nm

Visualization at much higher frame rate and better spatial resolution thanks to the powerful incoherent illumination source.

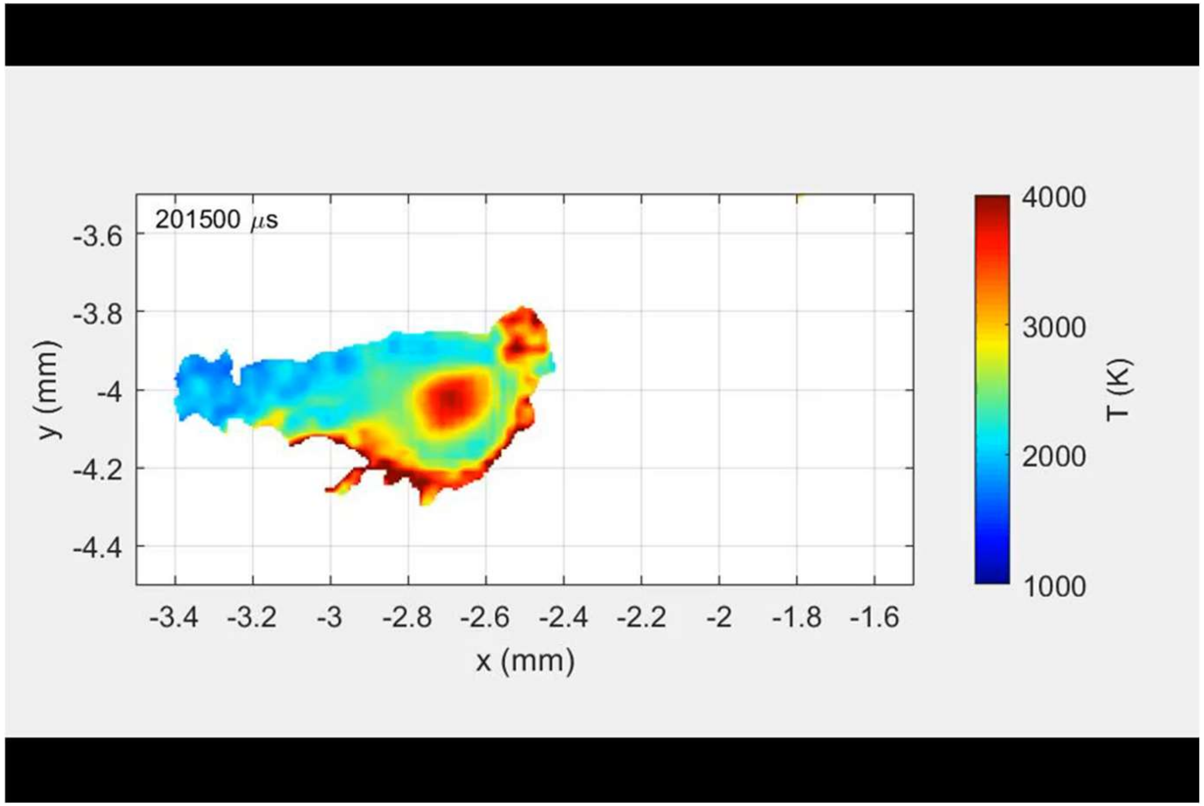
Thermal imaging for process development and monitoring

Thermal imaging setup for powder bed fusion



https://www.sciencedirect.com/science/article/pii/S221486041830188X

Thermal imaging of the process zone

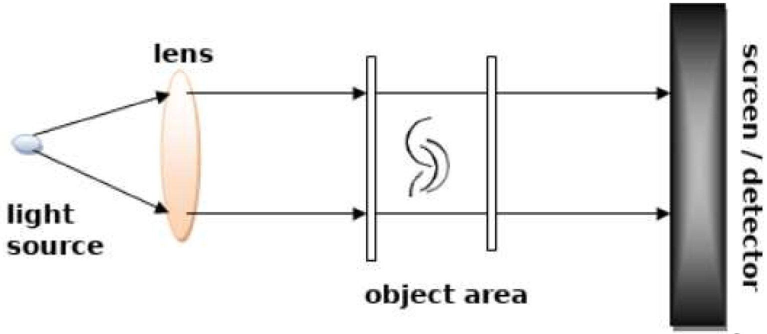


- Obtained information: temperature distribution in the melt pool, profile of the melt pool, cooling rate, spatters, ejections
- Limitations: uncertainty in emissivity value, possibility of vapor plume and spatters hindering the observation of the melt pool.

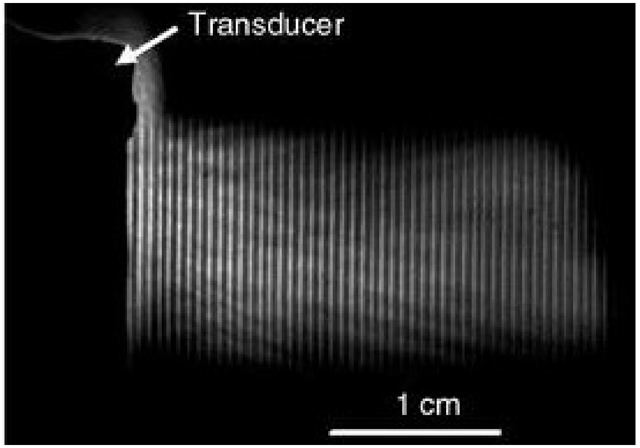
https://www.sciencedirect.com/science/article/pii/S221486041830188X

4. Phase-contrast imaging

Phase-contrast imaging



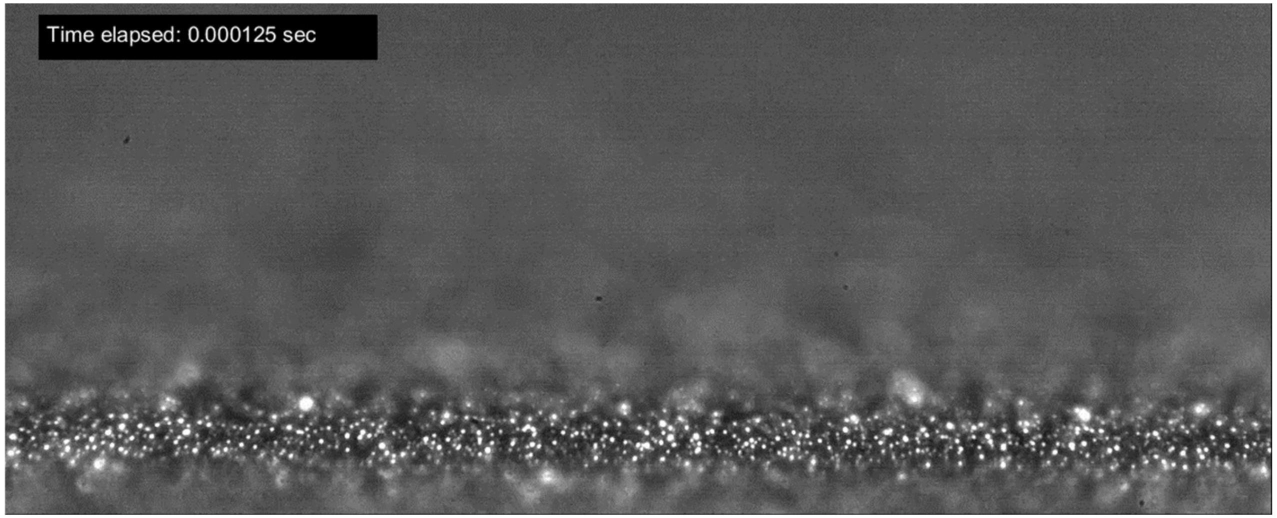
- Based on the differences in optical properties of the object as compared to the surrounding.
- Objects: vapor plume, processed zone, ejected materials and airborne shockwave.
- Information about the volumetric behaviors.



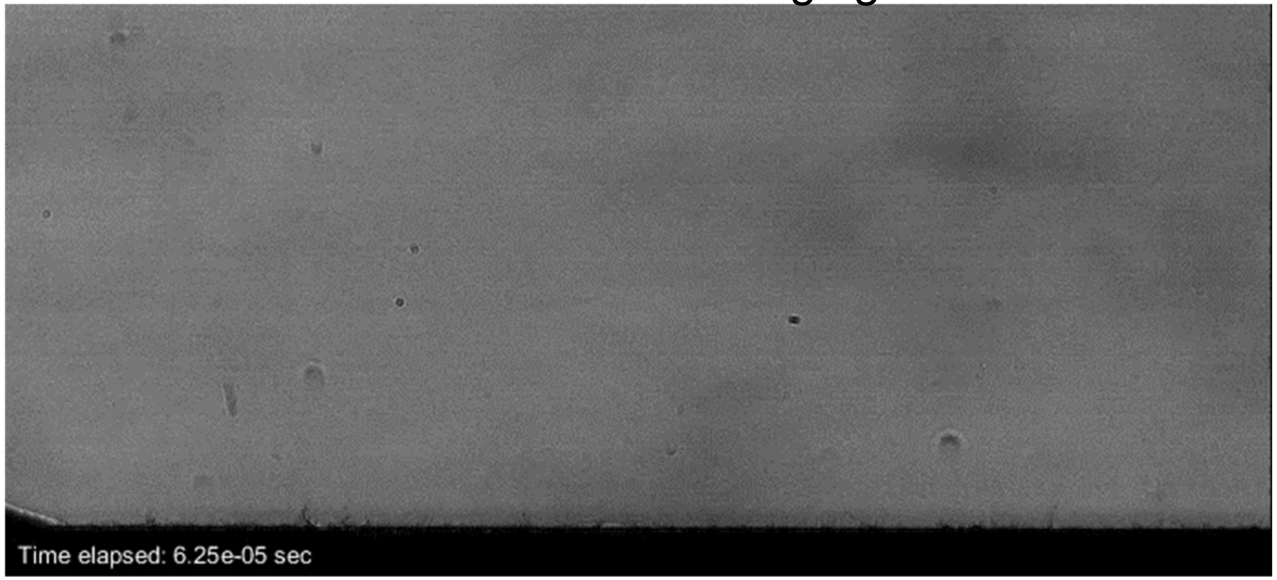
https://ecap.nat.fau.de/wp-content/uploads/2019/02/2019_Akstaller_MA.pdf

https://gfycat.com/discover/schlieren-gifs

Conventional vs phase-contrast imaging



Conventional imaging

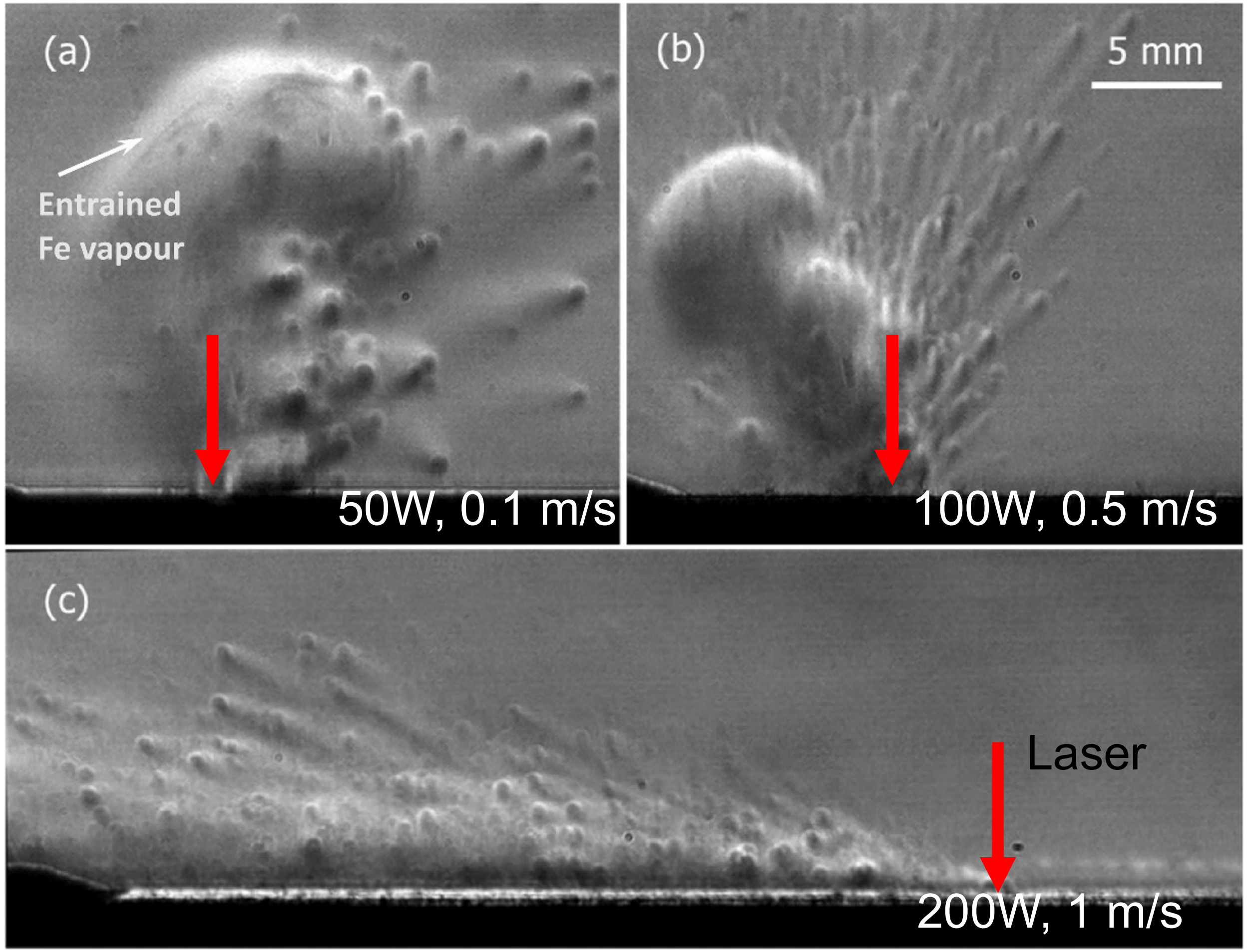


Phase-contrast imaging

- Phase-constrast imaging provides better visualization of the atmospheric regions with changes in refractive index.

https://doi.org/10.1016/j.actamat.2017.09.051

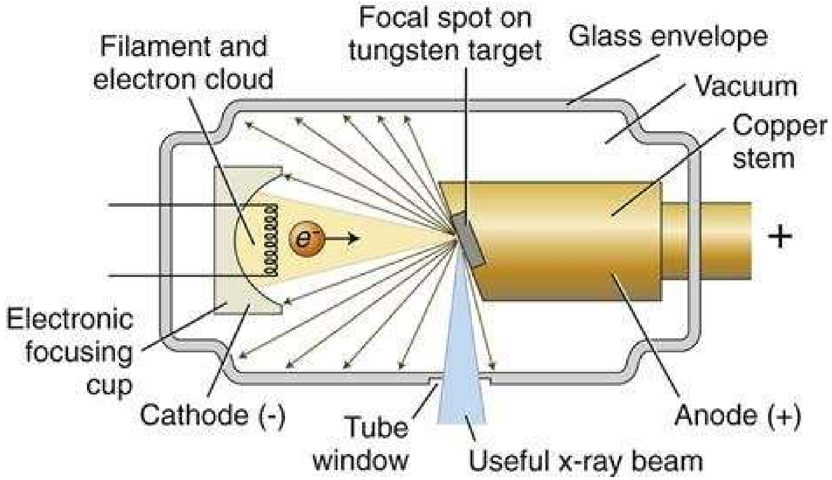
Influence of process conditions on gas flow



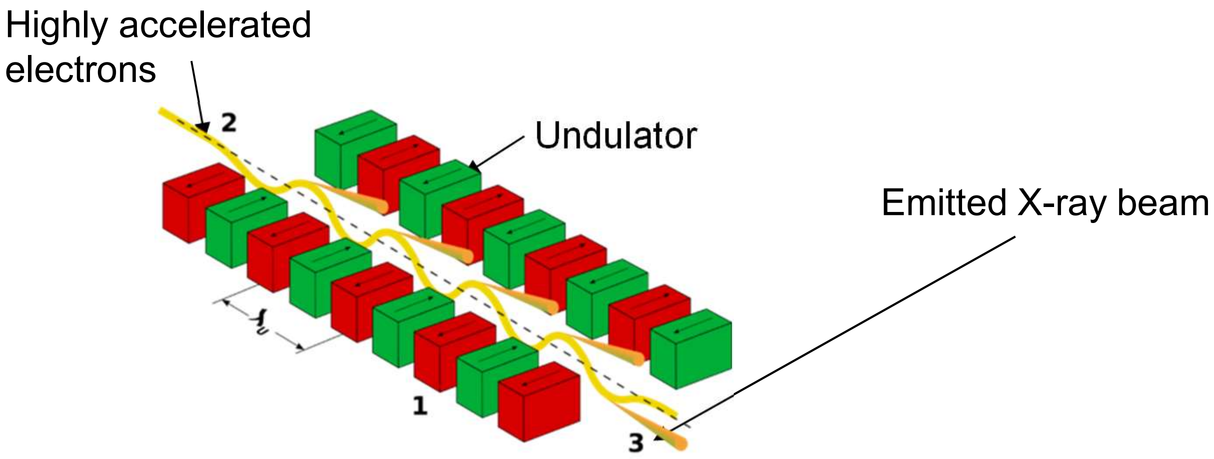
- With the same energy density, high scanning speed is preferable to reduce the influence from the vapor plume and the hot gas zones.

Phase-constrast X-ray imaging

Object of interest: a very wide range due to the good penetration of X-ray

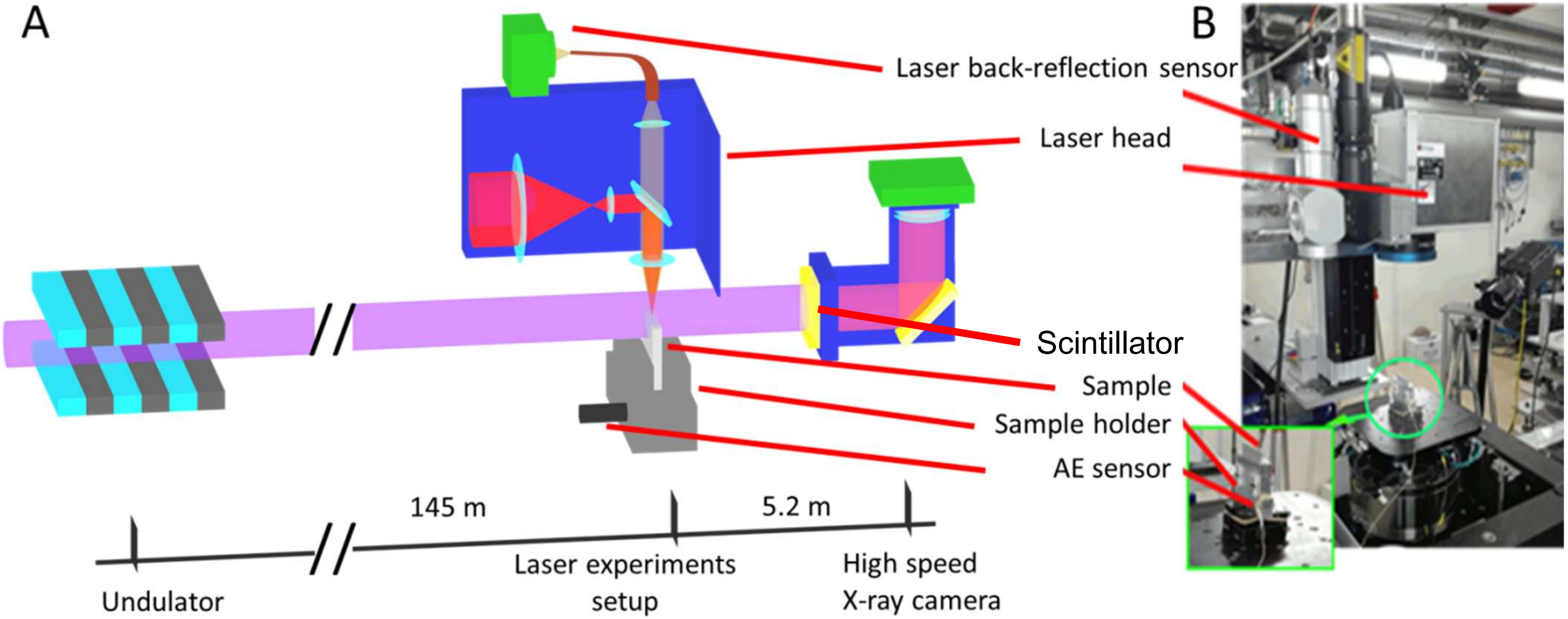


X-ray tube



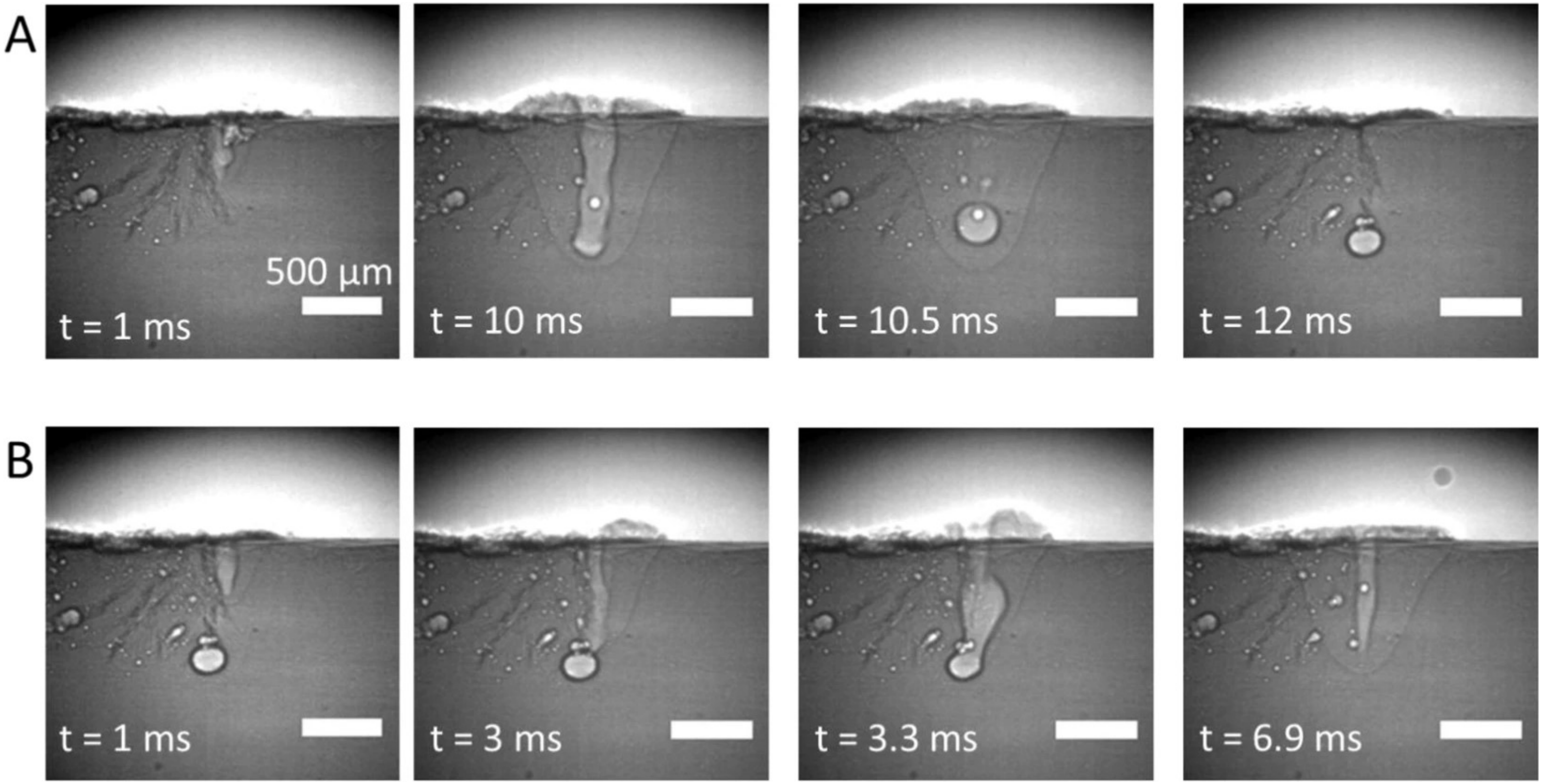
Synchrotron source

Process dynamic visualization



(A) Schematic of the experimental setup for in-situ X-ray radiography of the laser welds. The bar below defines the key nodes of the setup and their mutual positions; (B) Picture of the welding experimental station.

Process dynamic visualization



Visualization of sub-surface events, e.g. the removal of pores during laser welding.

Summary

- Visualization can provide significantly more information about the process.
- Main limitations: temporal and spatial resolutions, cost of implementation.

Thank you for your attention