Visualization of engineered residual strain in additive manufacturing materials

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Agenda

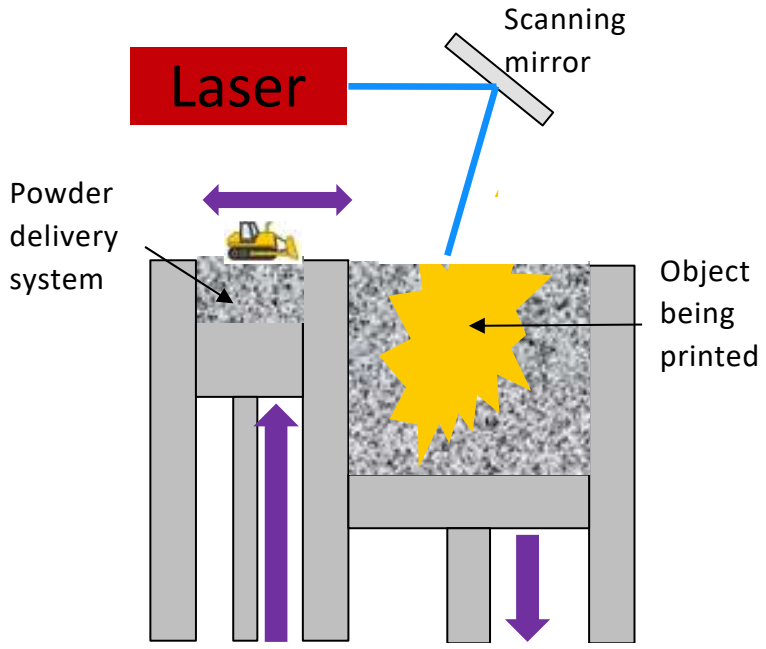
1 Setting the stage: Additive Manufacturing and Neutron Imaging

2 First results: proof of concept

3 Further measurements: new results and outlook

Additive Manufacturing (with metal)

- "Process to build a 3D object from a CAD model by successive addition of material, usually layer by layer" (ex.: Selective Laser Melting)
- PROS: rapid prototyping, complex shapes, lighter parts, fewer moving components, highly customizable
- CONS: slow build rate, no parallelization, many tunable parameters, post processing often required, poor mechanical properties



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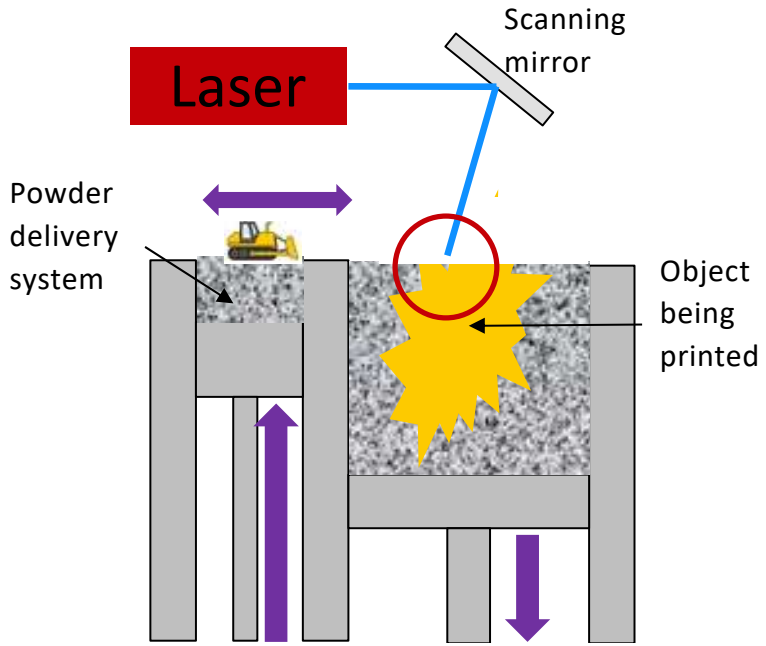

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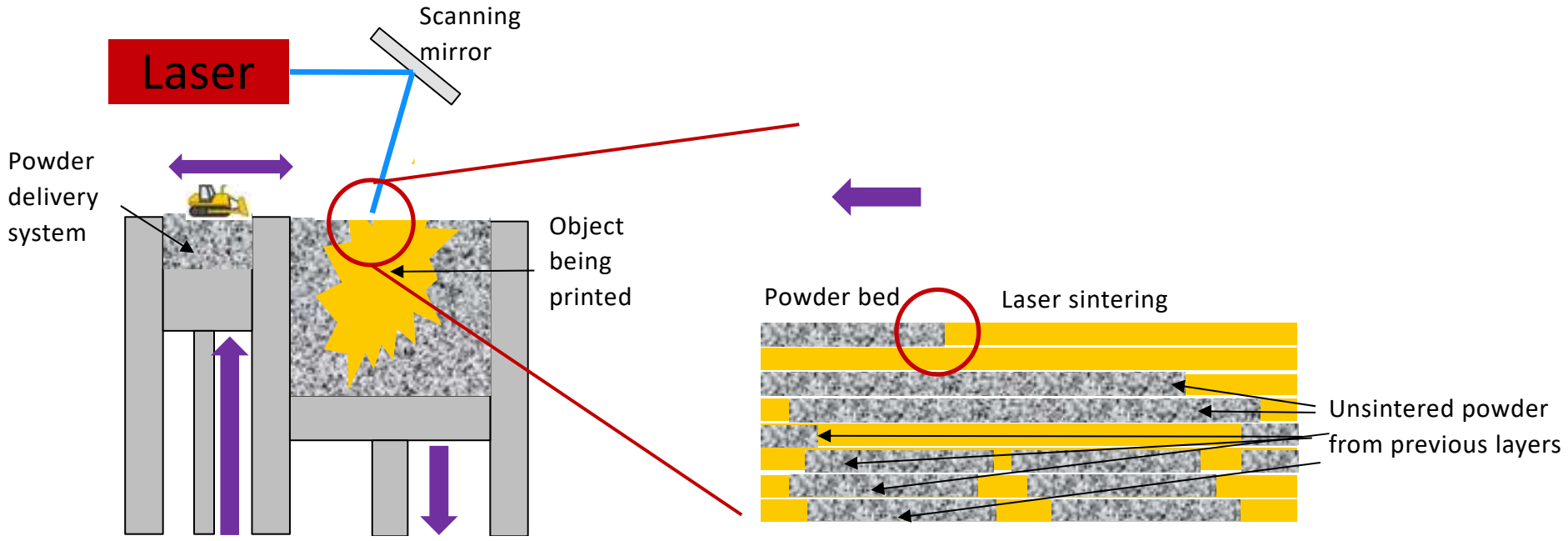
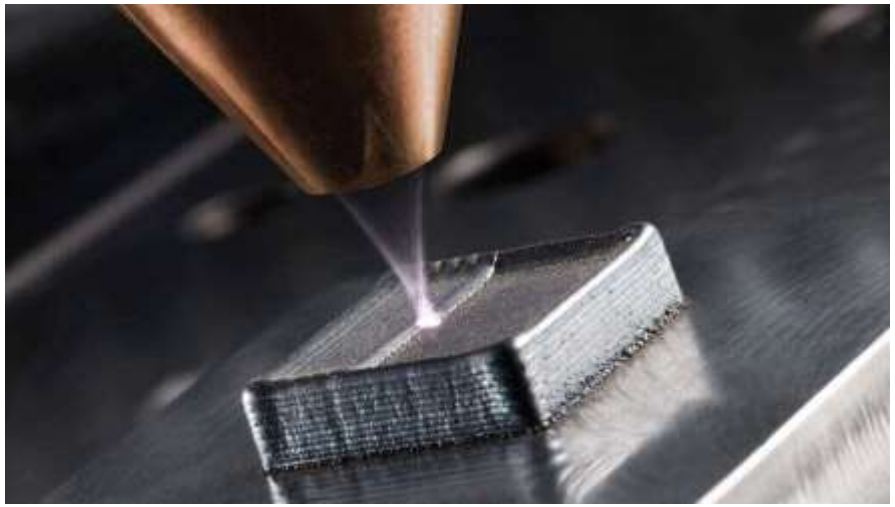
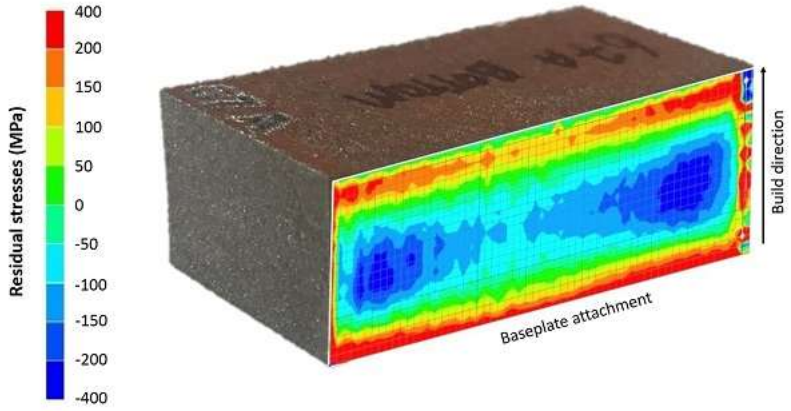


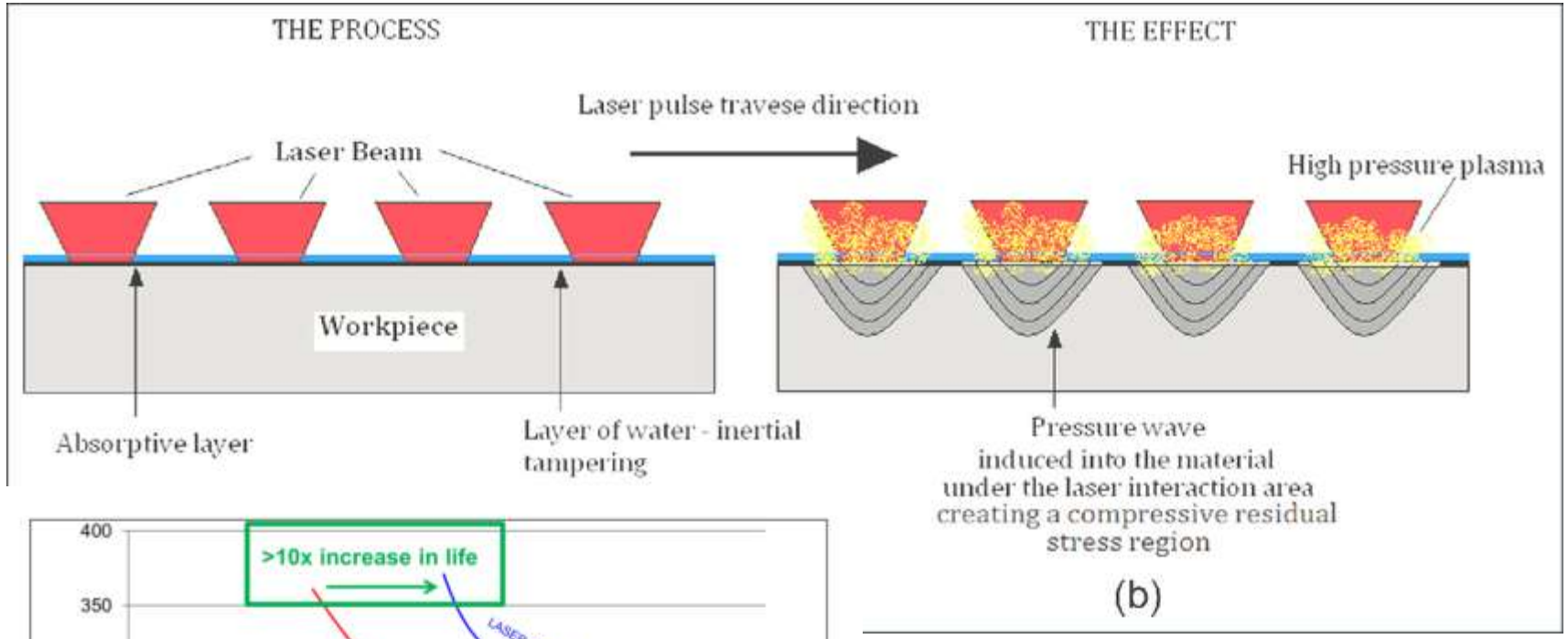
Residual stress on AM samples

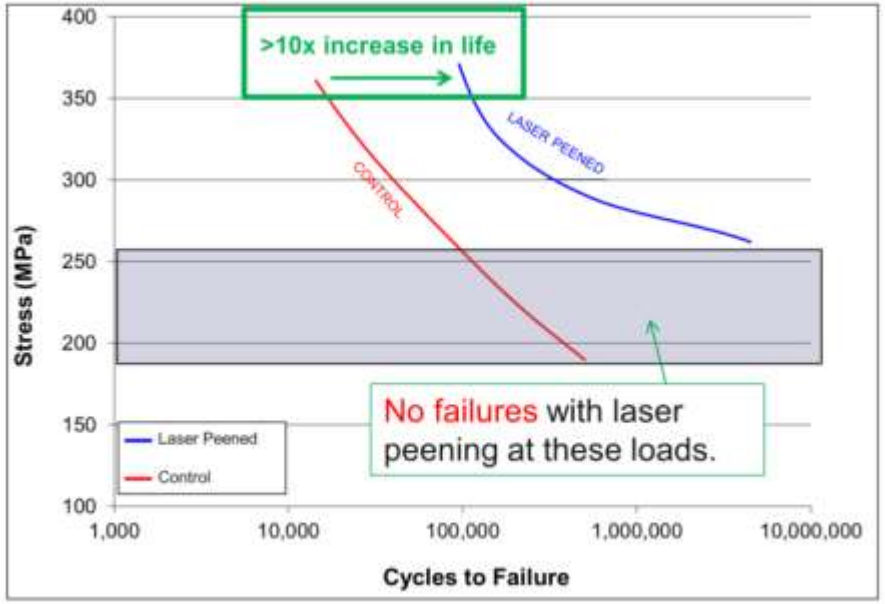
- In Additive Manufacturing, geometry is established at the same time as crystallographic parameters
- Depending on the AM technique, a large number of deposition parameters and post processes can be tuned, resulting in widely different properties of the finished product
- Tensile residual stress is often encountered at the surface, leading to cracking, corrosion and in general poor fatigue resistance





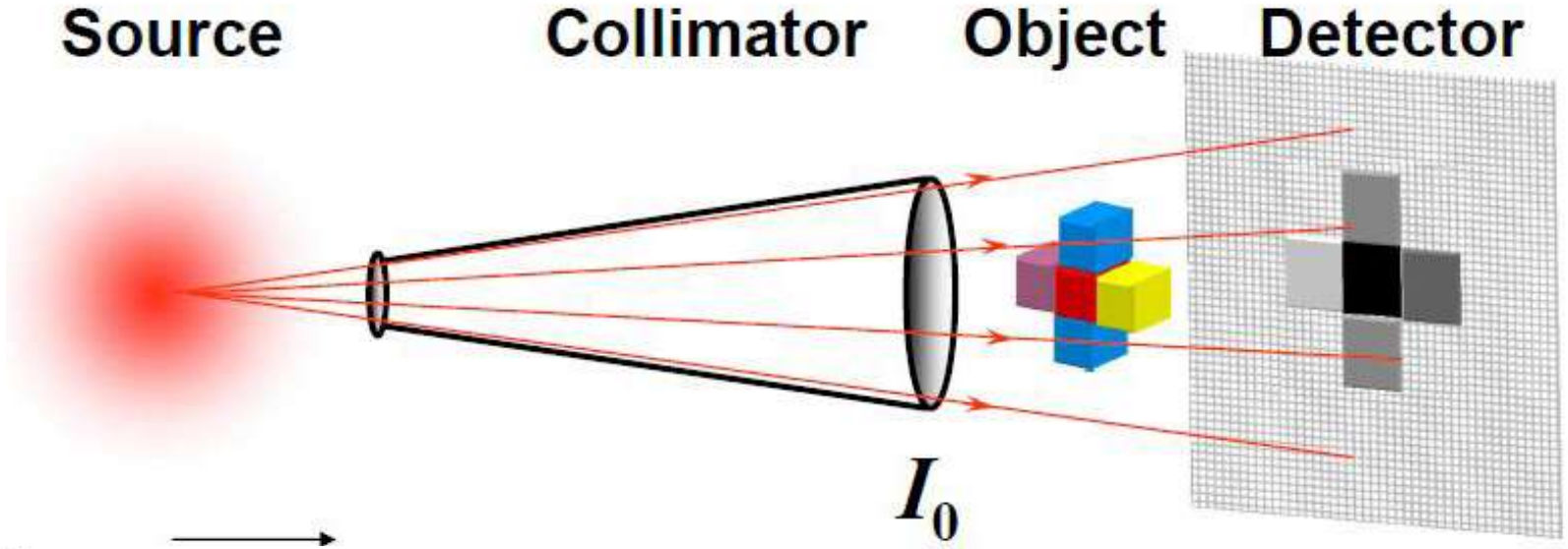
Laser Shock Peening

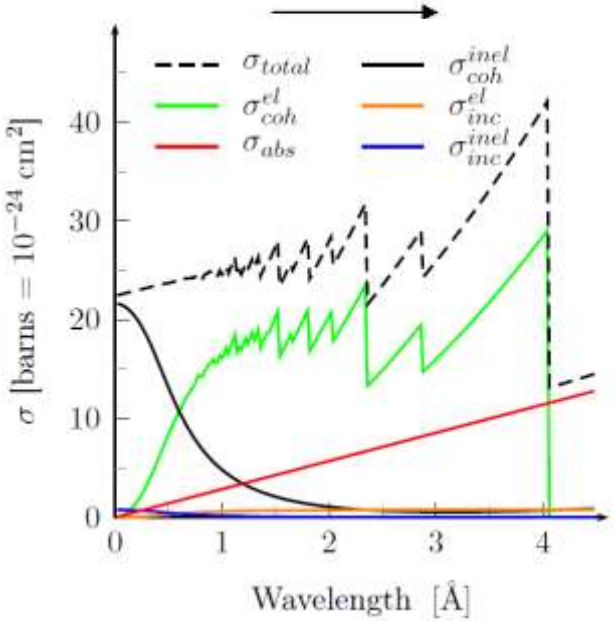




Ti-6Al-4V : Fretting Fatigue Resistance

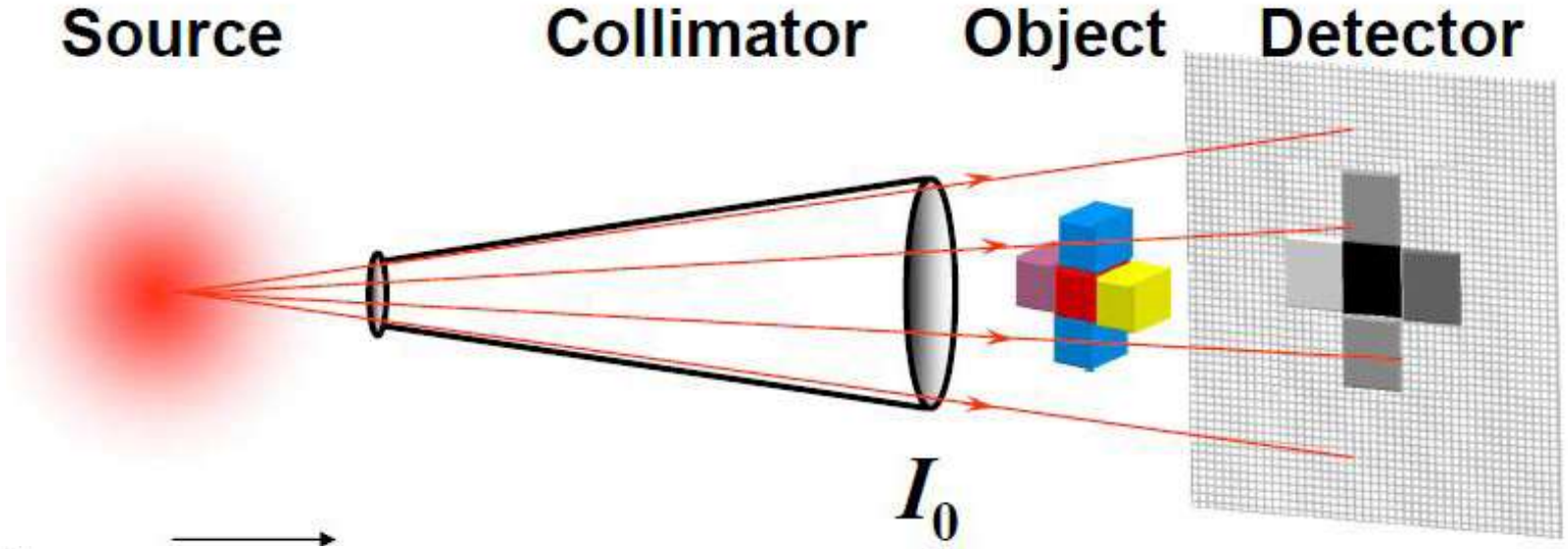
Neutron imaging with energy resolution

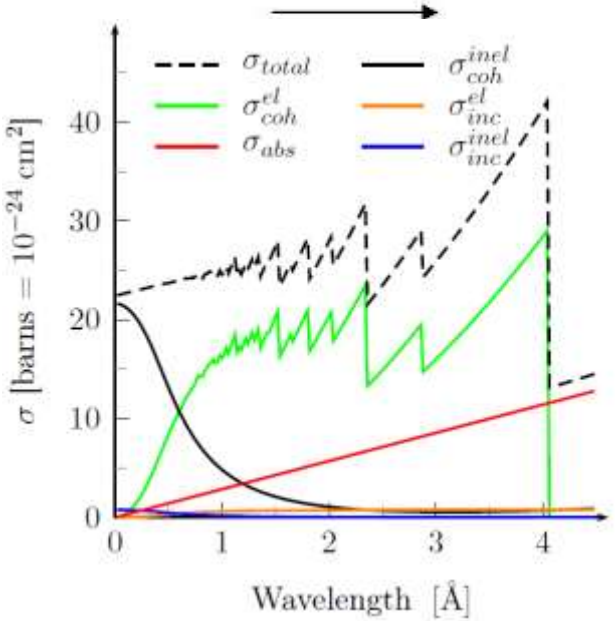




$$\sigma_{total} = \sigma_{coh}^{inel} + \sigma_{incoh}^{inel} + \sigma_{coh}^{el} + \sigma_{incoh}^{el} + \sigma_{abs}$$

Neutron imaging with energy resolution





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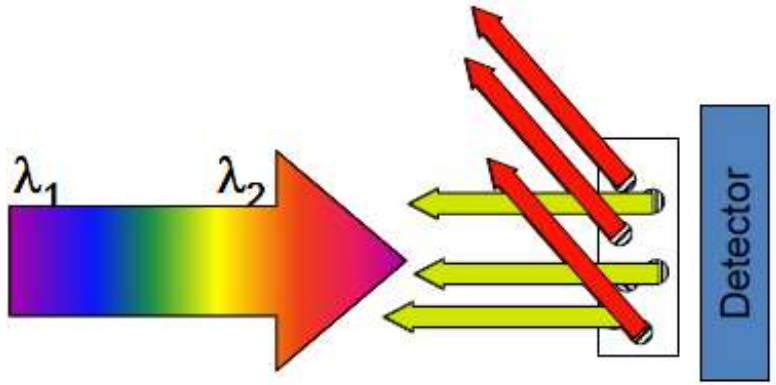
Bragg Edges

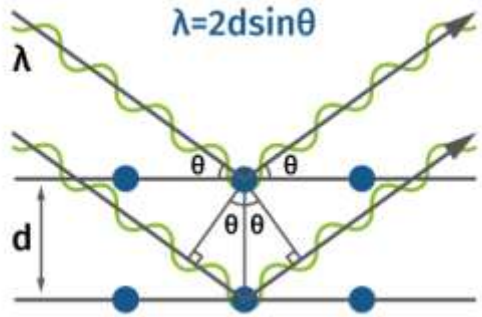


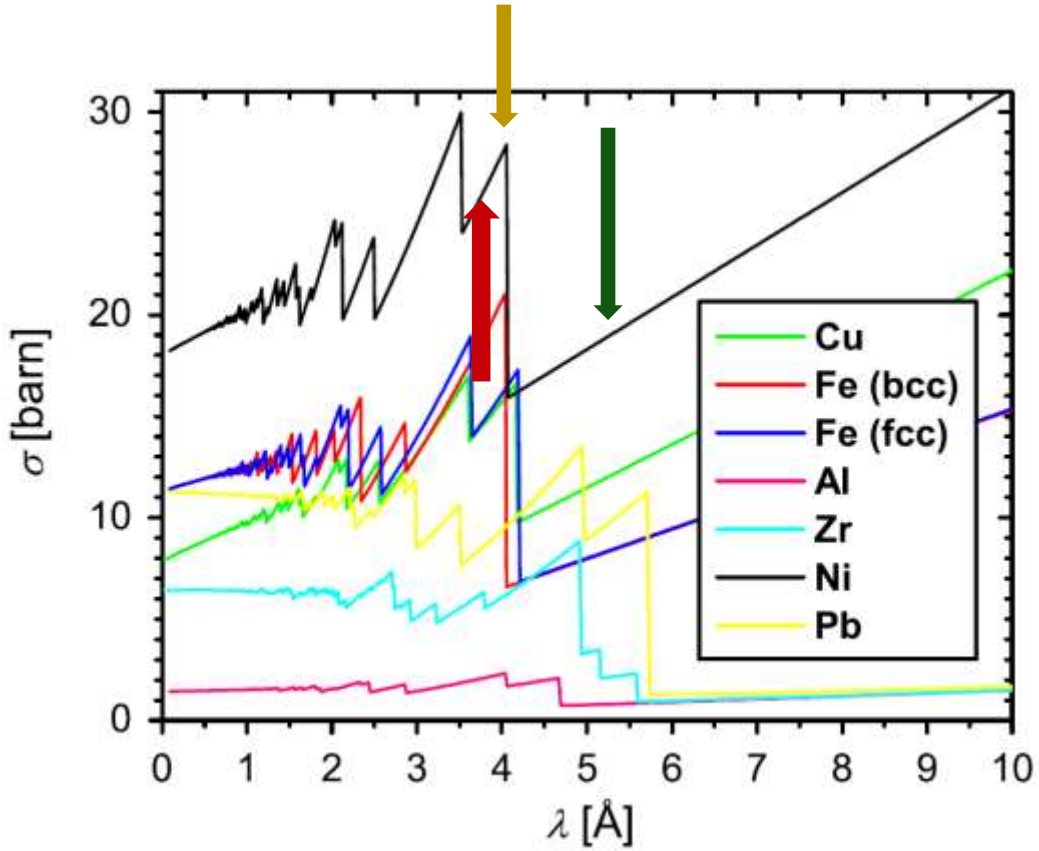
$2d_{hkl}\sin\theta=\lambda$

$2d_{hkl}\sin 90^\circ=\lambda$

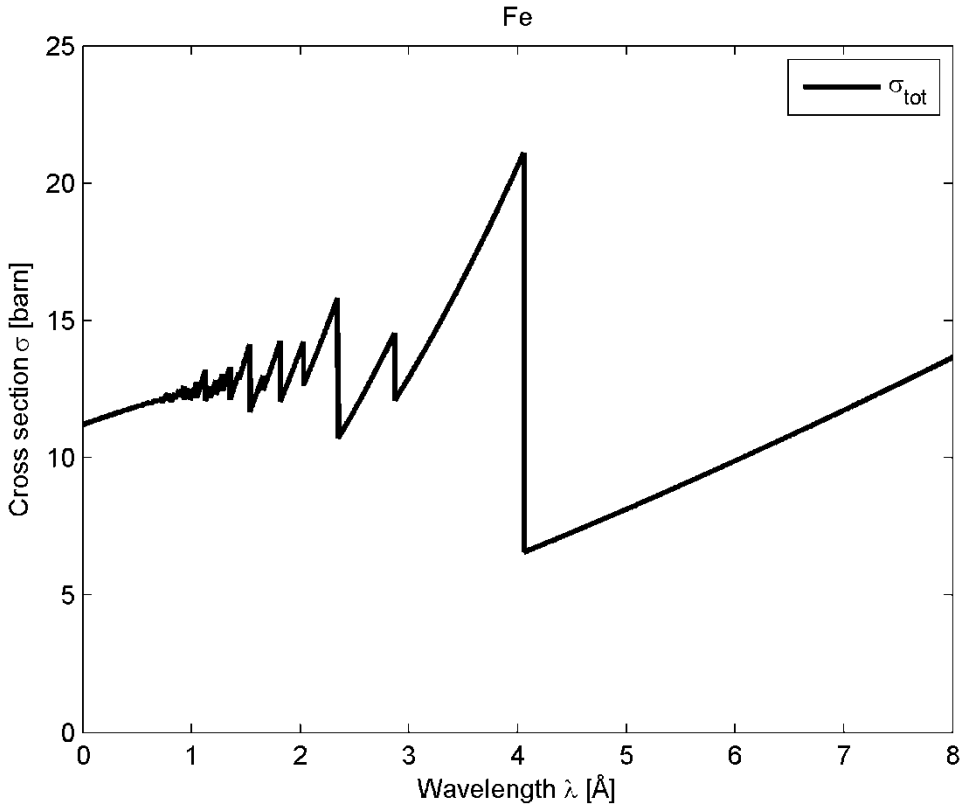
$2d_{hkl}\sin\theta<\lambda$

Bragg's law:





Energy-selective Imaging: Bragg edge analysis



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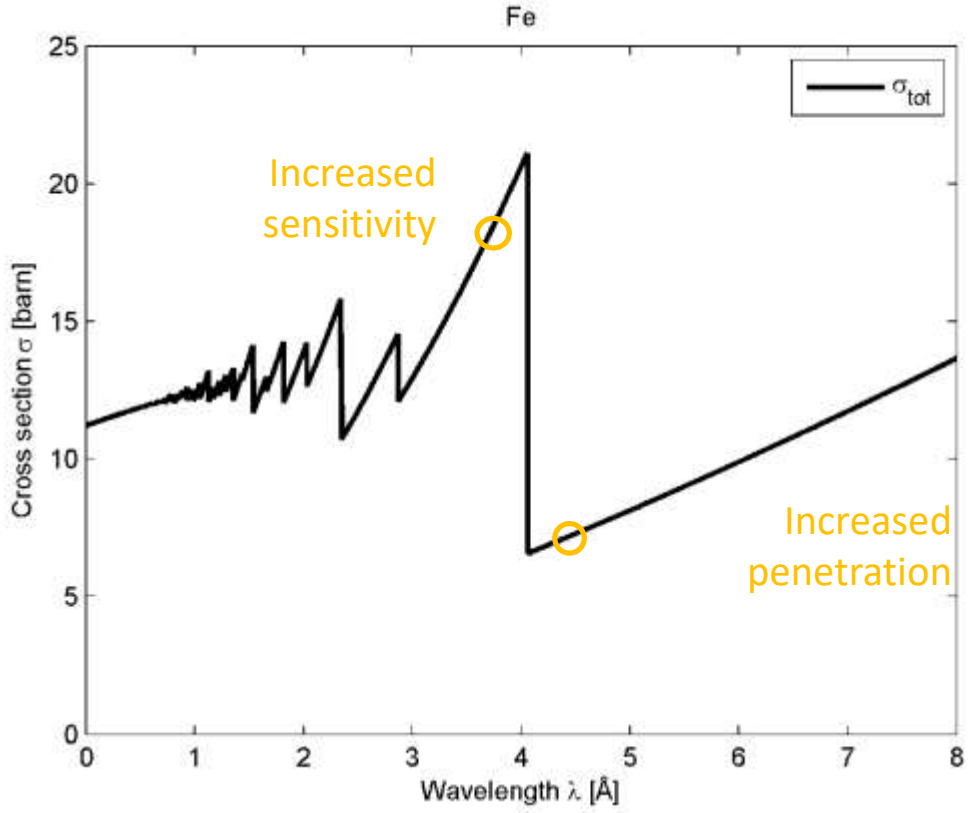

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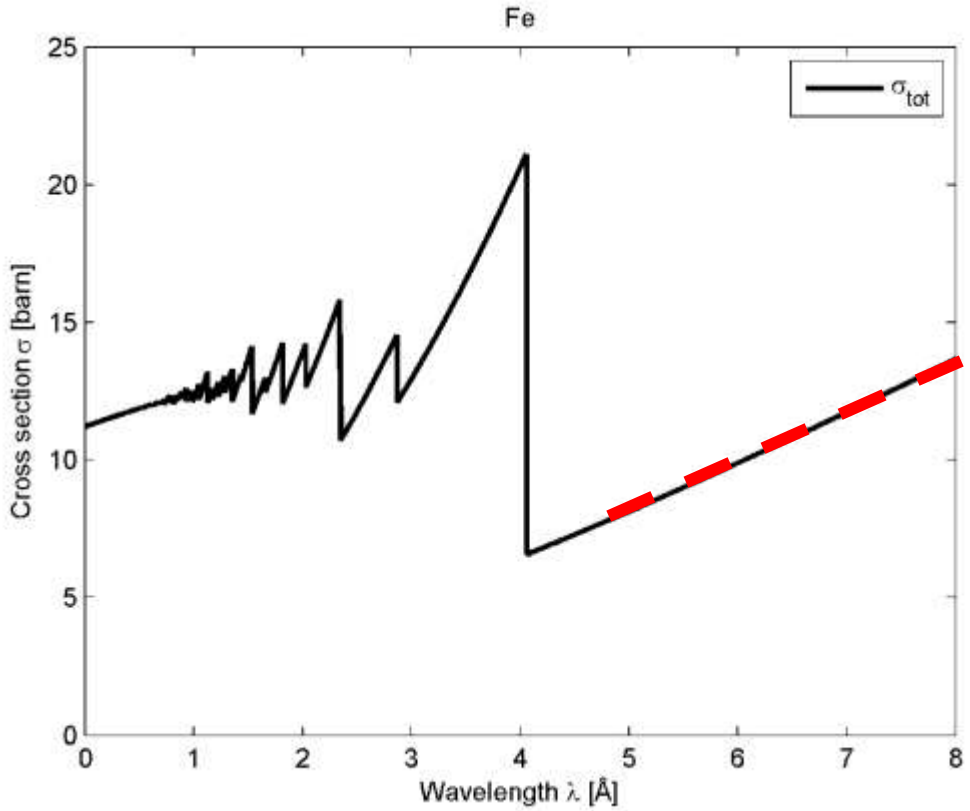
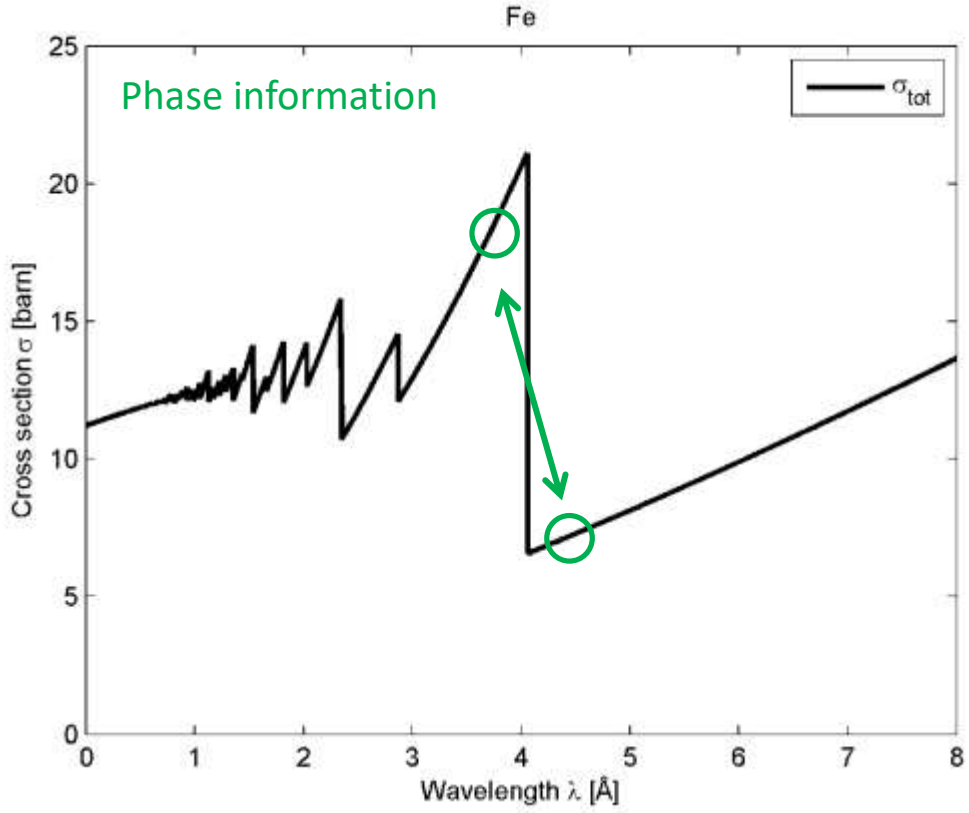


Absorption range

Energy-selective Imaging: Bragg edge analysis



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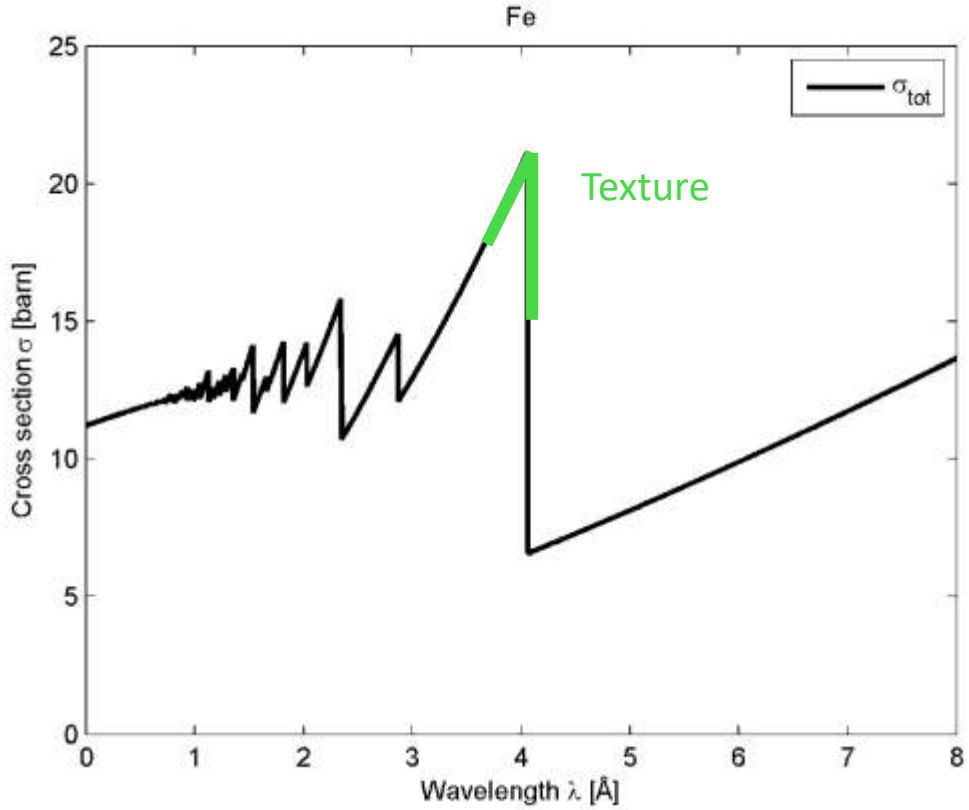

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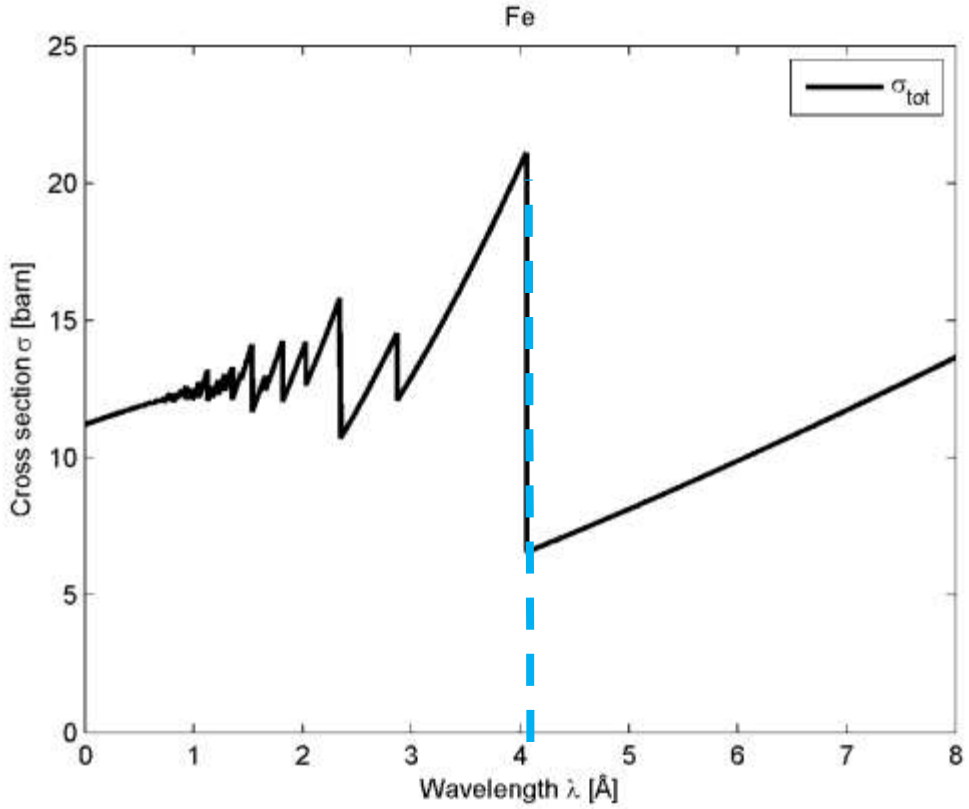
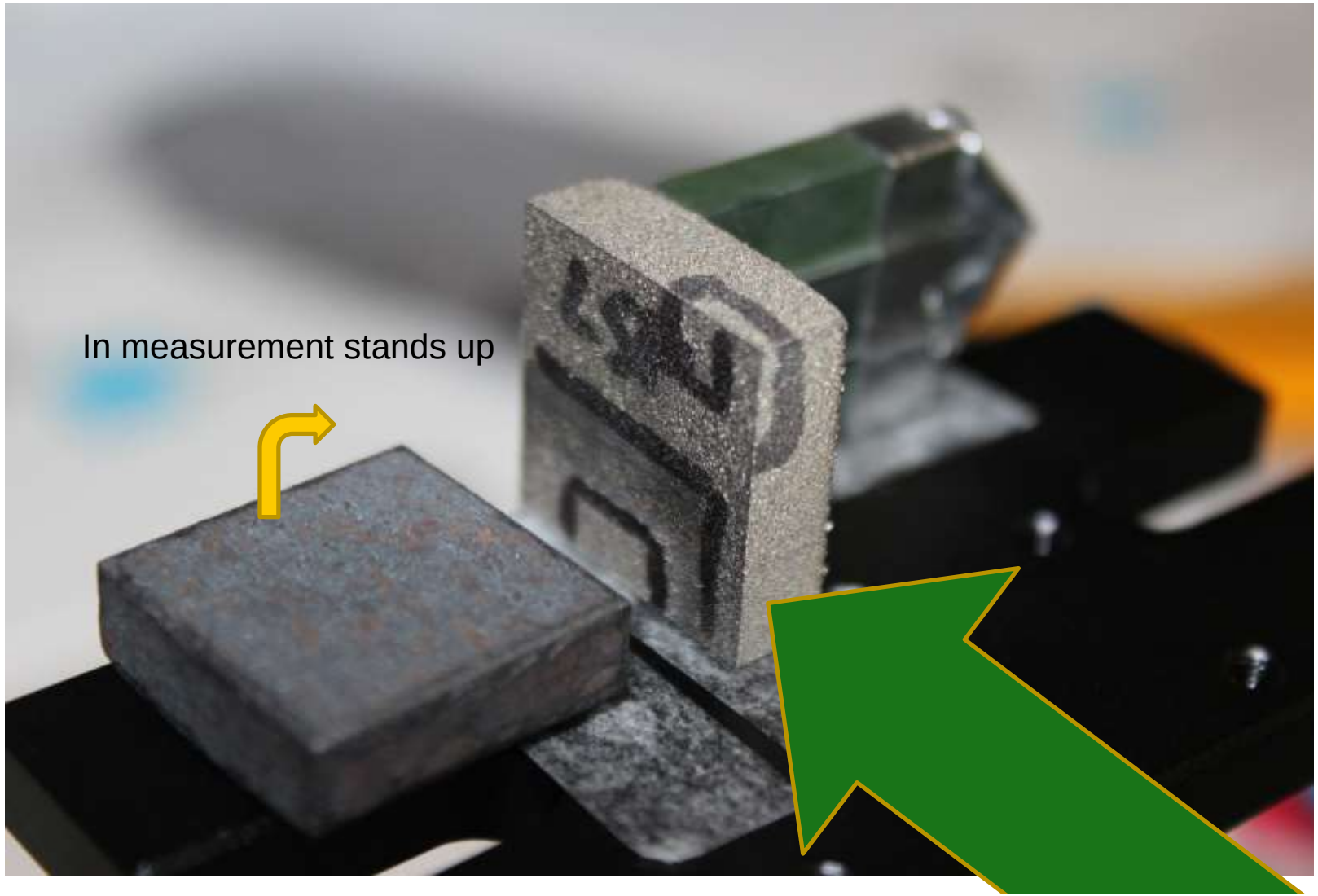


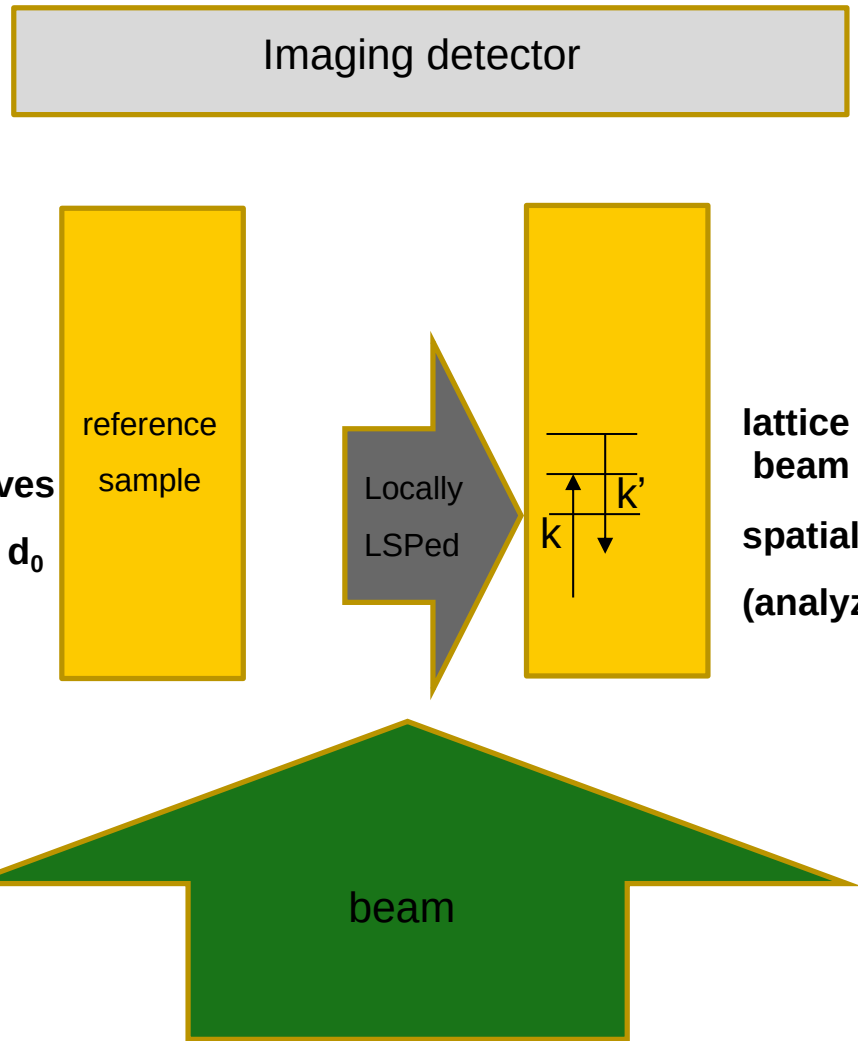
Strain Imaging

First experiments (RADEN @JPARC)

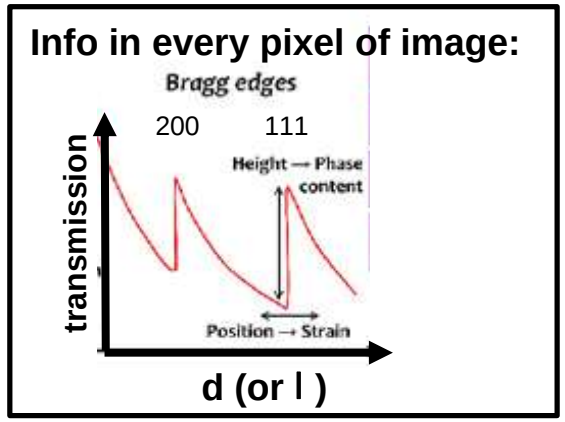


Experiment schematics

View from the top:



Reference serves as measure of d_0

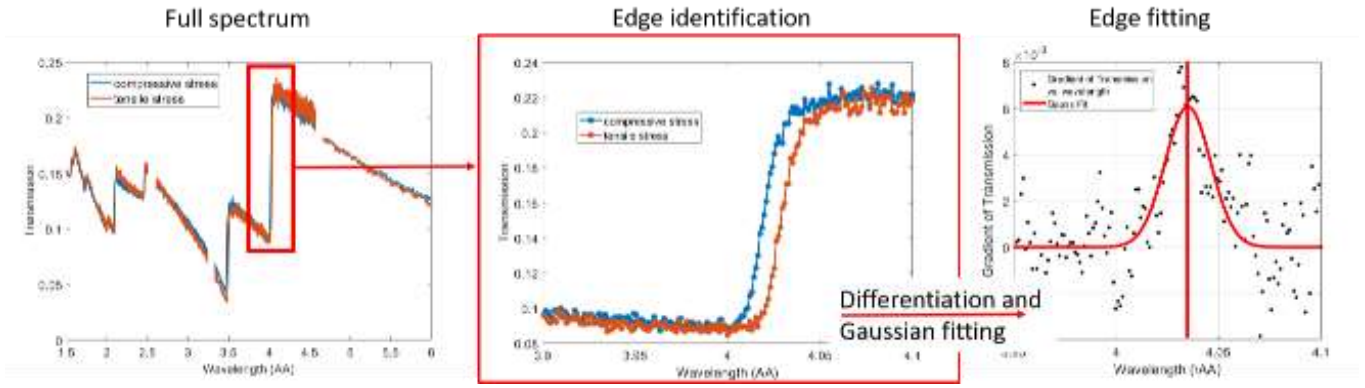


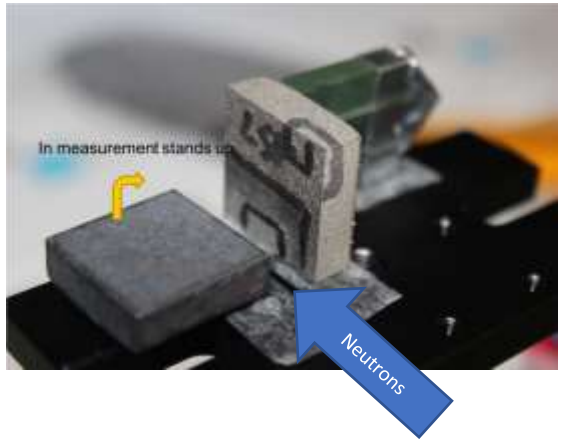
lattice distance d (strain Dd/d_0) measured in beam direction, and integrating over thickness

spatially resolved over cross section

(analyzed for 111 peak of fcc Fe)

Spectra analysis (pixel-wise)





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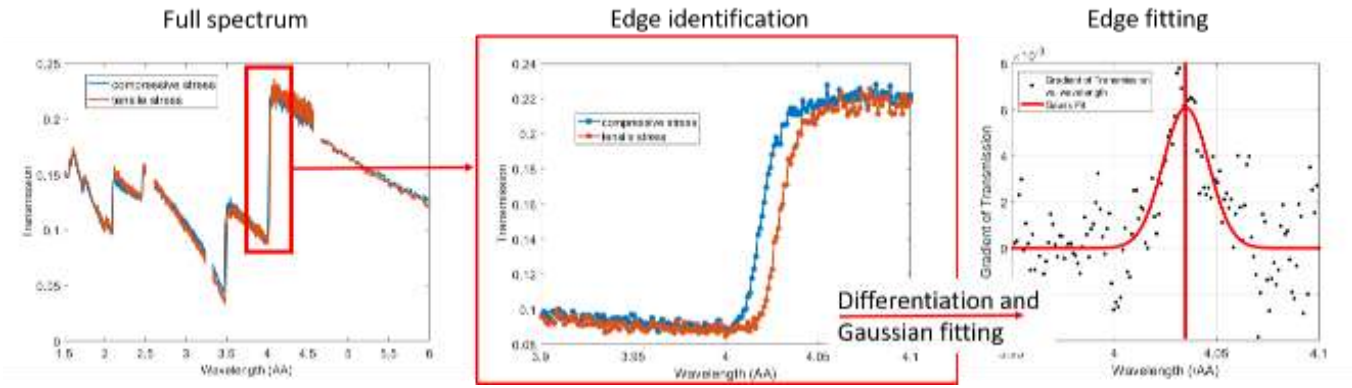
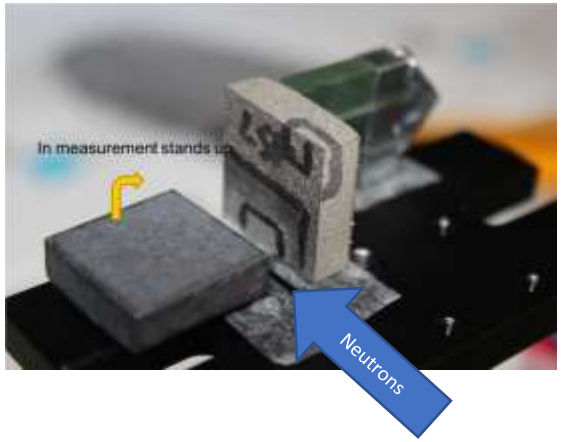
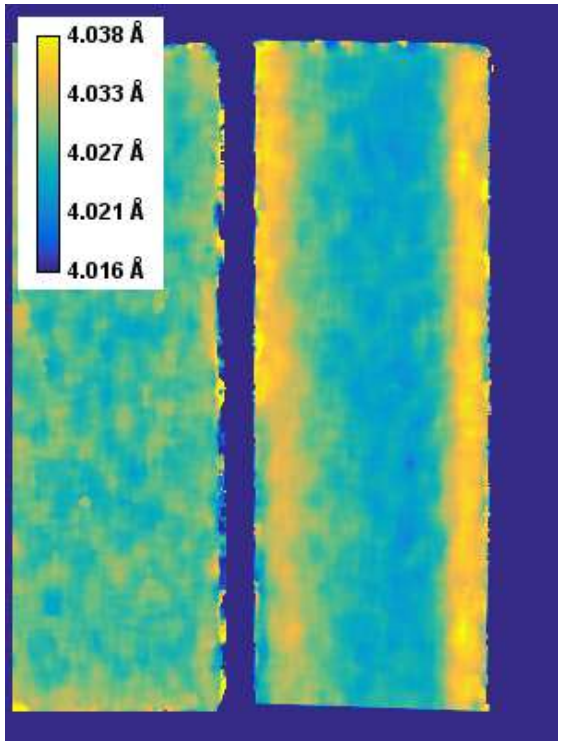
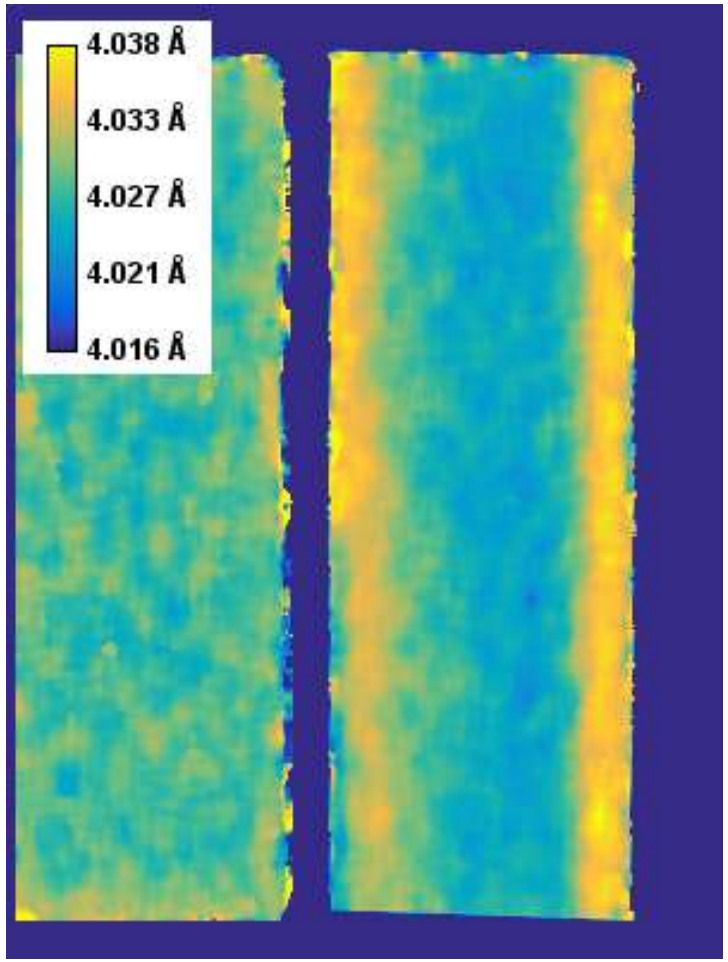






Strain map



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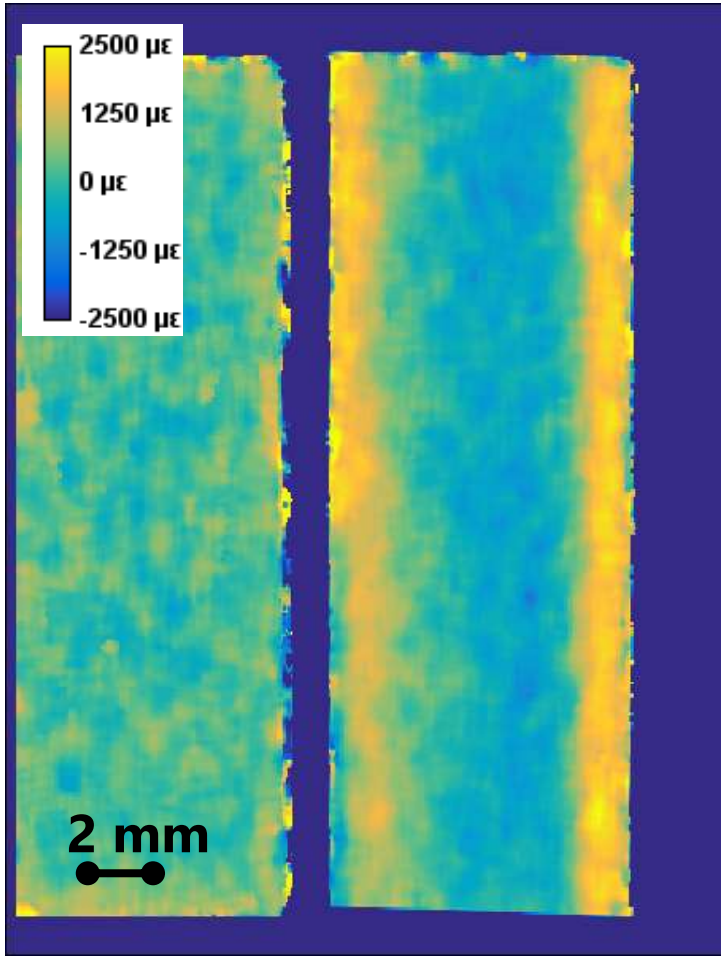

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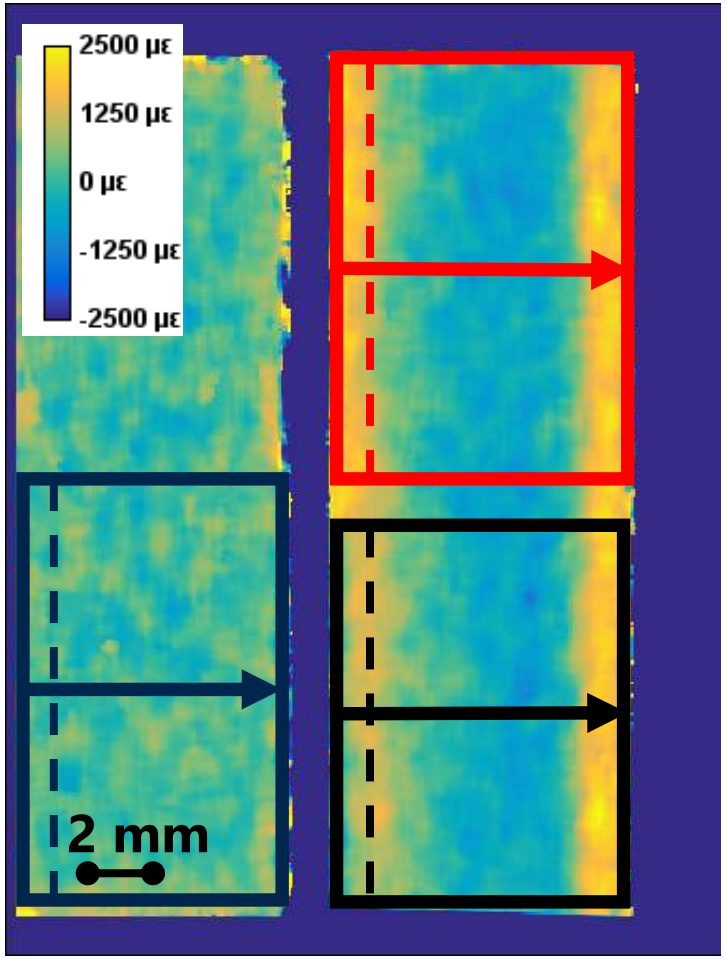
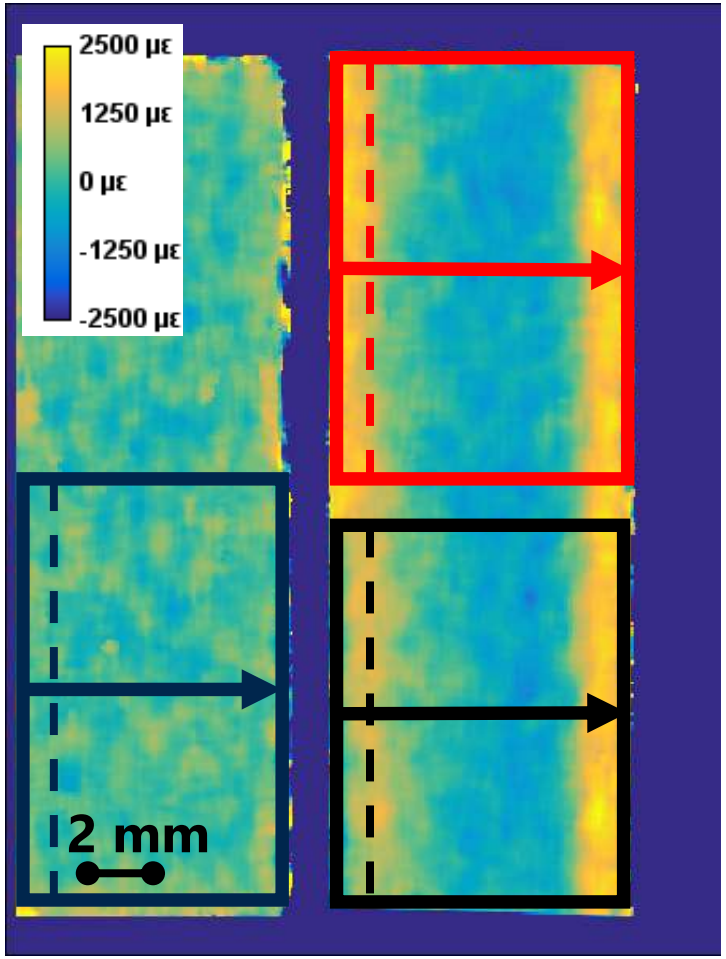
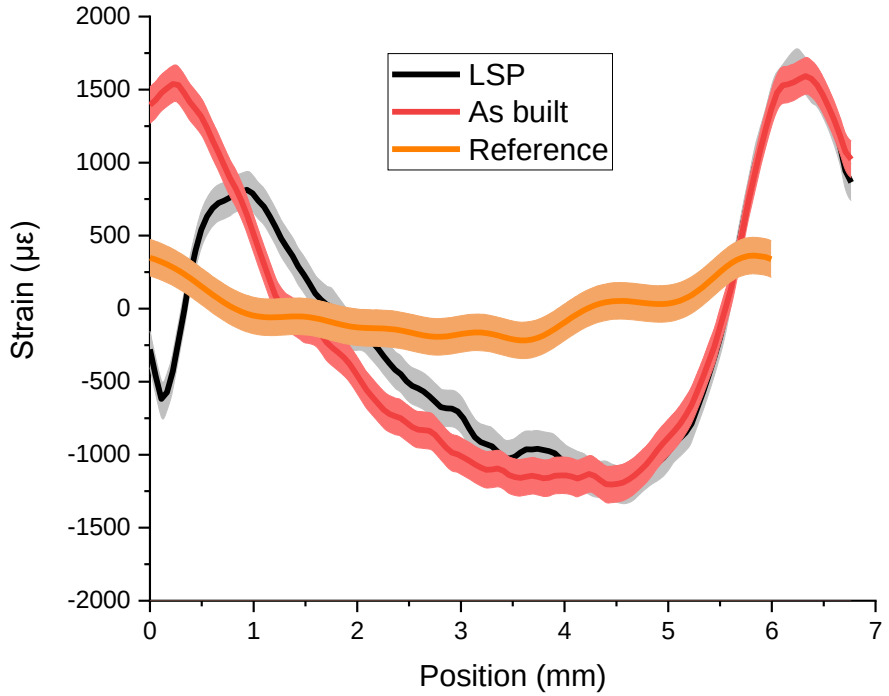
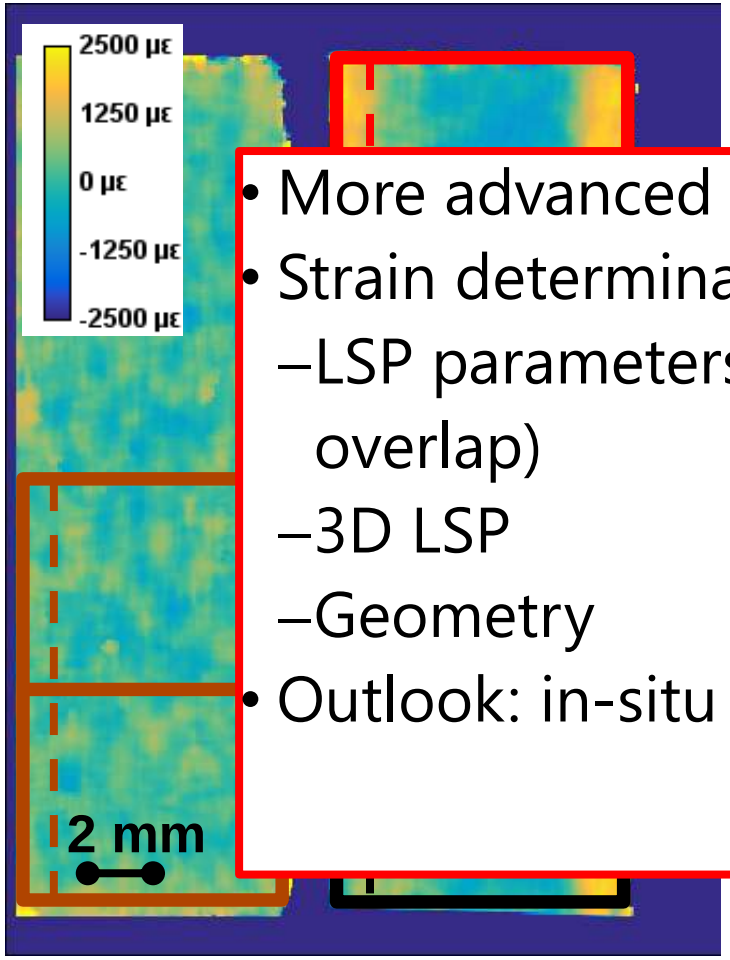


Strain map


2500 με
1250 με
0 με
-1250 με
-2500 με
2 mm


LSP
As built
Reference
Strain (με)
Position (mm)
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1
2
3
4
5
6
7

Next steps



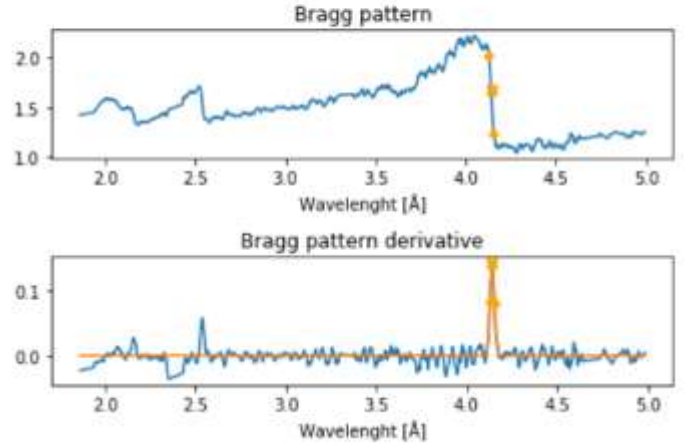
- More advanced fitting routines
- Strain determination as a function of:
  - LSP parameters (scanning strategy, laser power, laser spot overlap)
  - 3D LSP
  - Geometry
- Outlook: in-situ strain measurement

More advanced fitting

Advanced Bragg edge Fitting:

$$\mathrm{Tr}(\lambda) = \exp\left[-(a_0 + b_0\lambda)\right] \times \left(\exp\left[-(a_{hkl} + b_{hkl}\lambda)\right] + \left\{1 - \exp\left[-(a_{hkl} + b_{hkl}\lambda)\right]\right\}\right) \times \frac{1}{2}\left[\mathrm{erfc}\left(-\frac{\lambda - \lambda_{hkl}}{2^{1/2}\sigma}\right) - \exp\left(-\frac{\lambda - \lambda_{hkl}}{\tau} + \frac{\sigma^2}{2\tau^2}\right) \times \mathrm{erfc}\left(-\frac{\lambda - \lambda_{hkl}}{2^{1/2}\sigma} + \frac{\sigma}{\tau}\right)\right],$$

```
Edge position =  4.140657306309953
Edge height =  0.6986338585953783
Edge width =  0.012508366080305222
idx_low =  476 idx_high =  482
```



Gaussian Bragg edge Fitting:

Fit the transmission derivative with a Gaussian

https://github.com/neutronimaging/ToFImaging

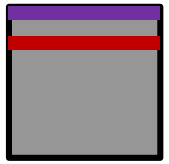
Parametric study of LBPF and 3D-LSP

Additive Manufactoring samples:

- Stainless Steel 316L

Different Laser Shock Peening (LSP):

- 2D LSP
- Buried (B)
- 3D LSP (2D + B)
- As Built (AB)



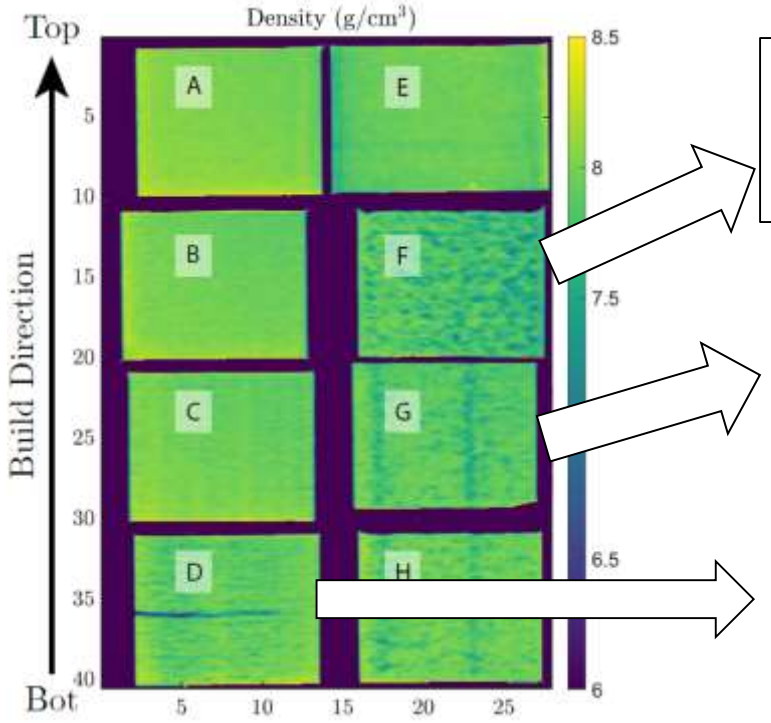
AM Parameters: Strategy (Parallel/Chess), Density (Low/High), Supports (No/Yes)

LSP Parameters: Strategy (AB/B/2D/3D), Energy(1.0/1.5), Overlap(0.4%/0.8%)

Scanned with Bragg Edge Imaging at RADEN (J-PARC, JAPAN)

AM parameters

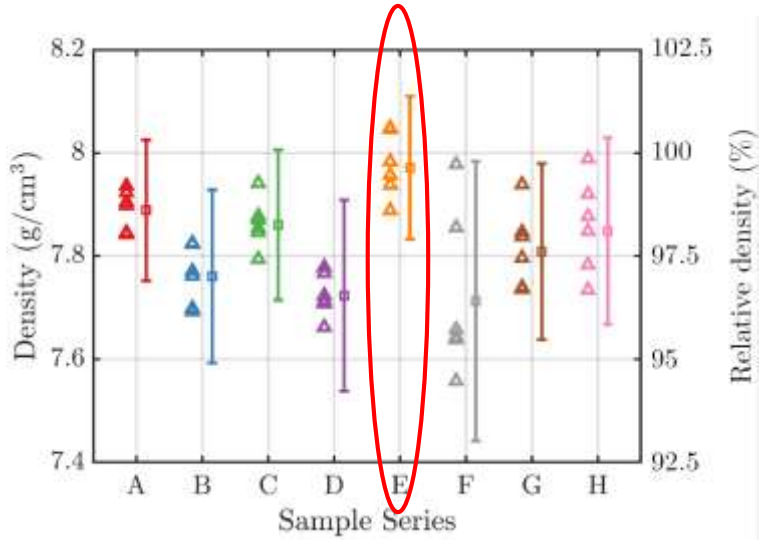
LPBF Parameters: Strategy (Parallel/Chess), Density (Low/High), Supports (No/Yes)



Porosity defects in the bulk sample

Issues with the powder coating blade

Detection of delamination defects



One set of parameters carried out the best and most consistent results of bulk density

Busi, M., et al. *Additive Manufacturing* (2020)

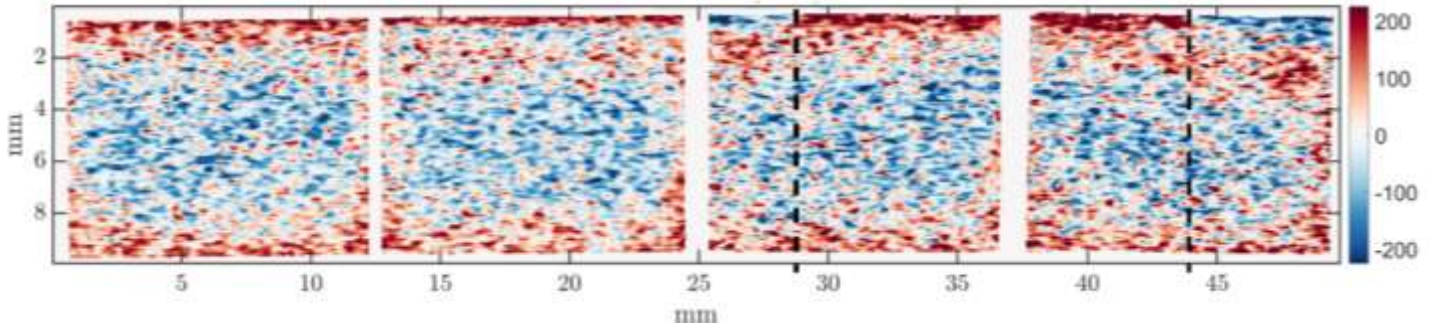
LSP parameters

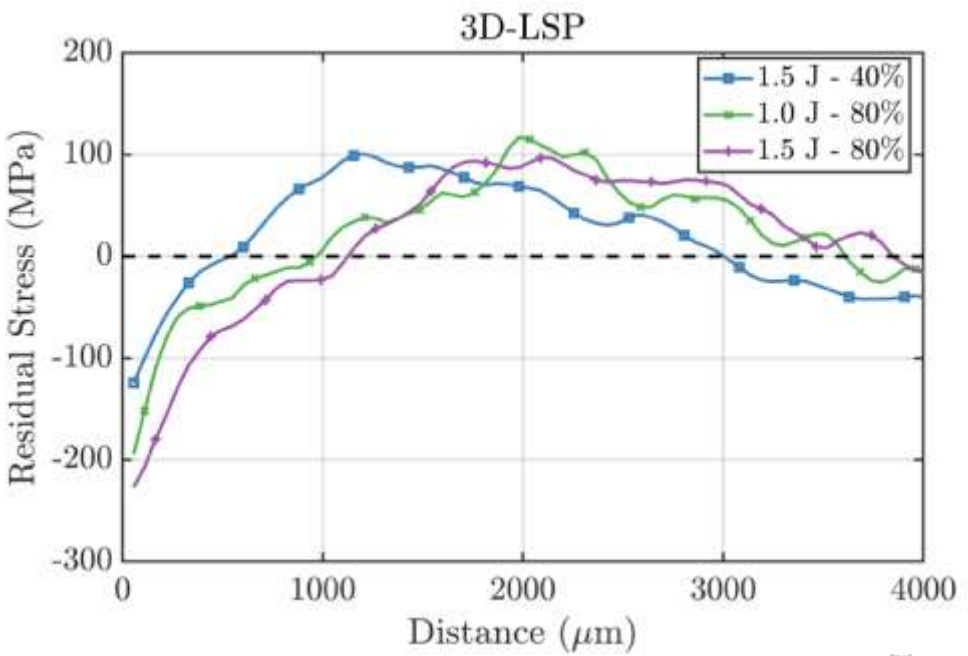
Main findings:

I. 3D-LSP, is able to push the CRS deeper into the sample compared to 2D-LSP

II. The best results are found for 1.5 J and 80% overlap

III. The overlap has higher influence than the laser energy





Questions?