



# Améliorer la résolution angulaire en EBSD

## Pourquoi ? Comment ?

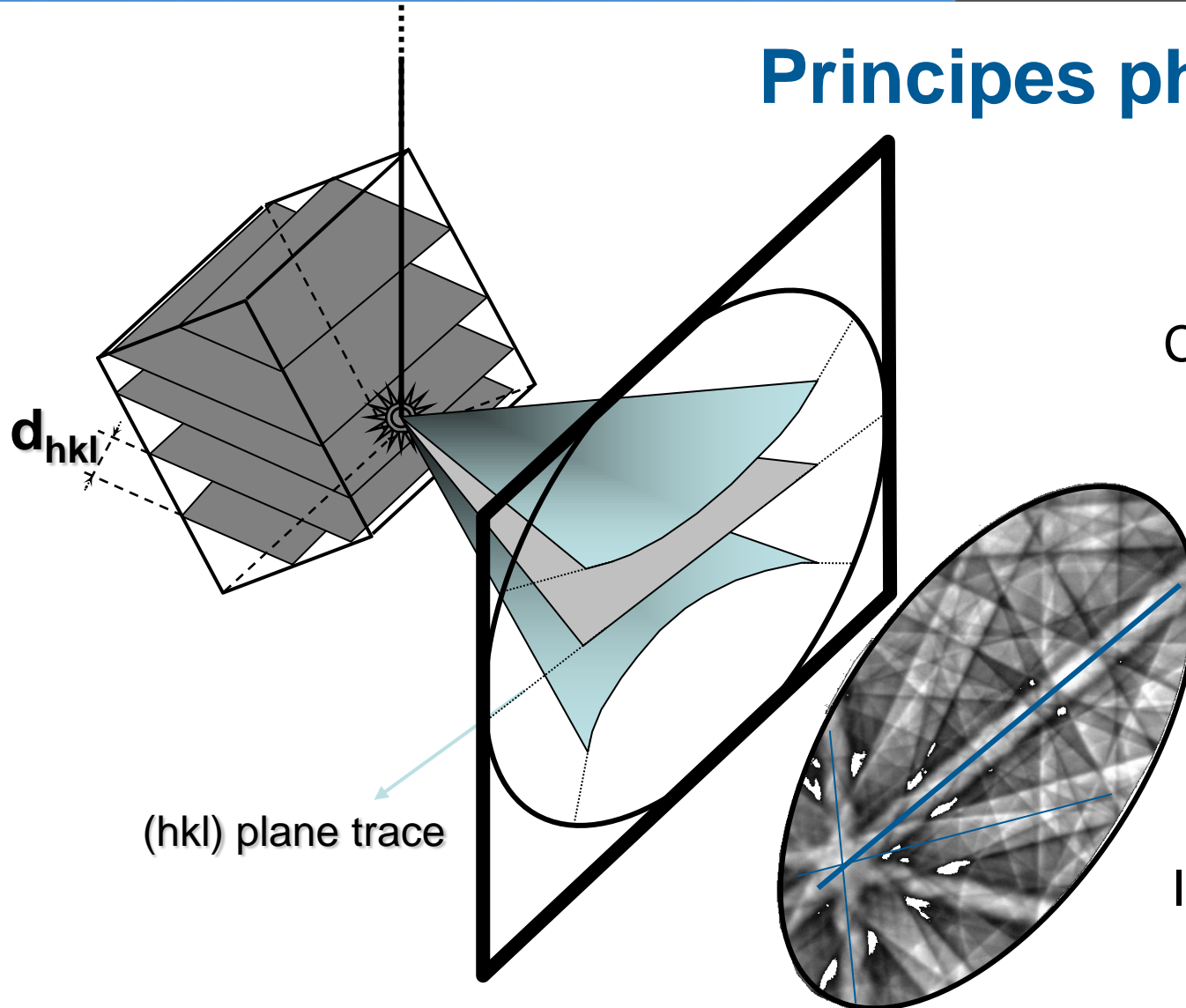
*Claire MAURICE*

*Laboratoire Georges Friedel – UMR CNRS 5307*





# Principes physiques de l'EBSD



## Projection gnomonique

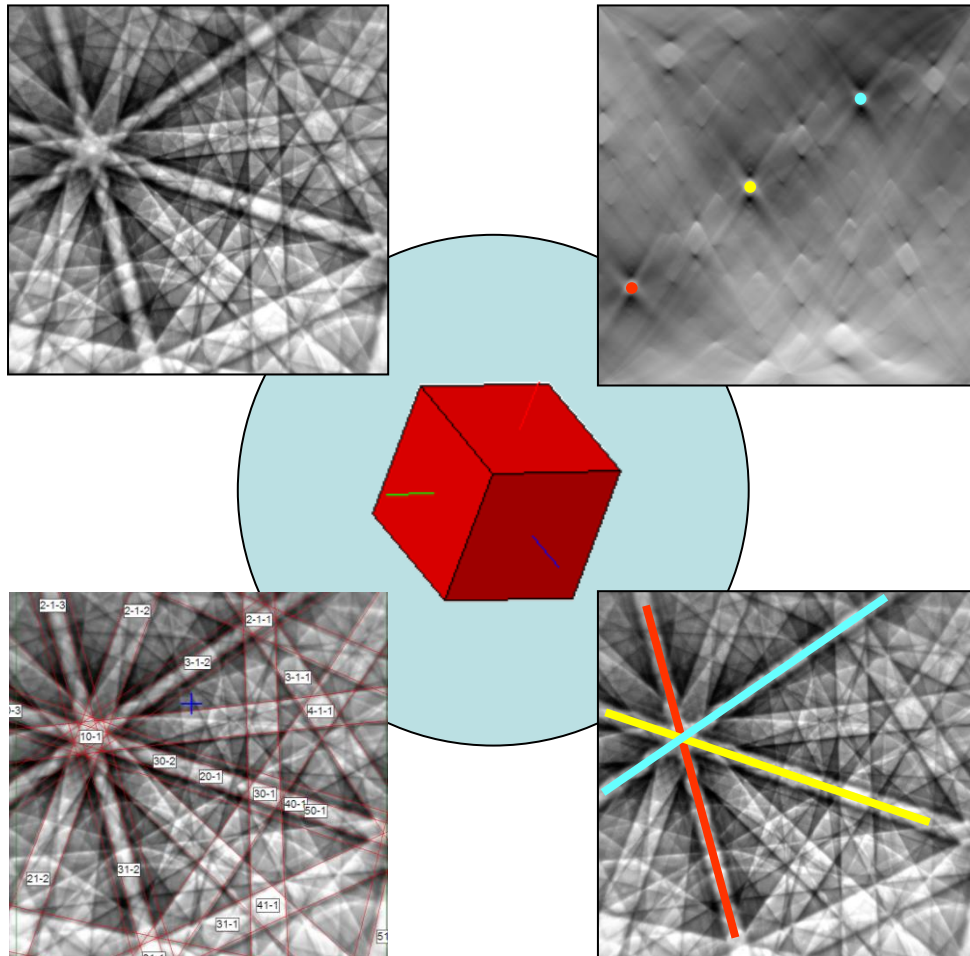
Cônes de Kossel -> Hyperboles

1 Bande de Kikuchi  
= 1 famille de plans cristallo.

Intersections  
= Axes de Zone



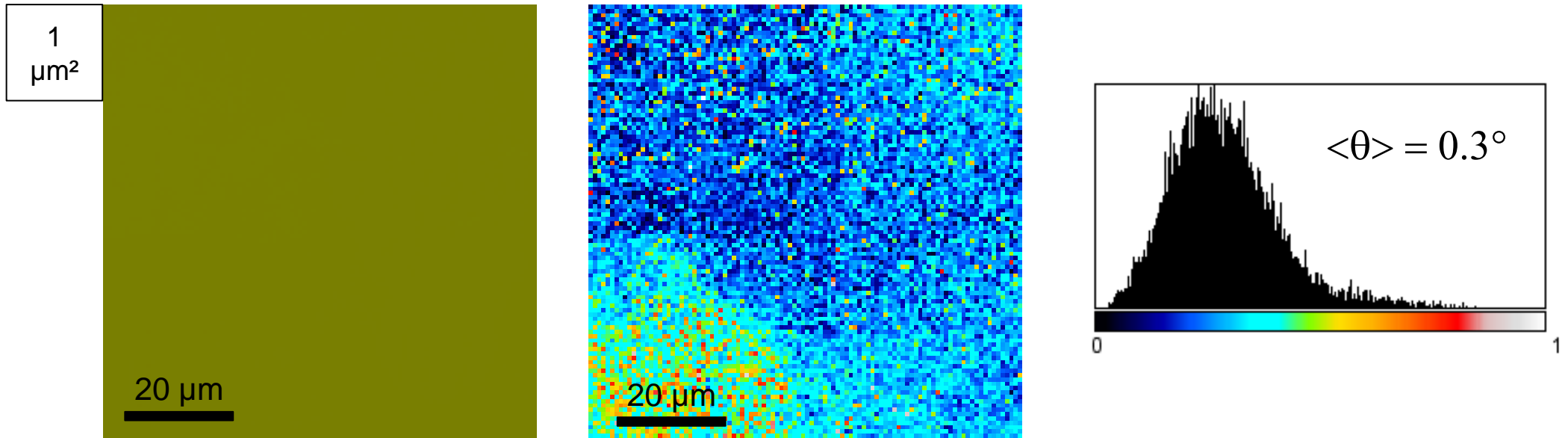
# Indexation Standard



## Performances

Angulaire ( <i>relatif</i> )	0,1° - 0,5°	
Spatiale	W	FEG
Latérale ( <i>//</i> axe de tilt)	0,5 $\mu\text{m}$	20 nm
Longitudinale	x 3	
Profondeur	qqs 10 nm	

## Nickel superalloy – Single Crystal

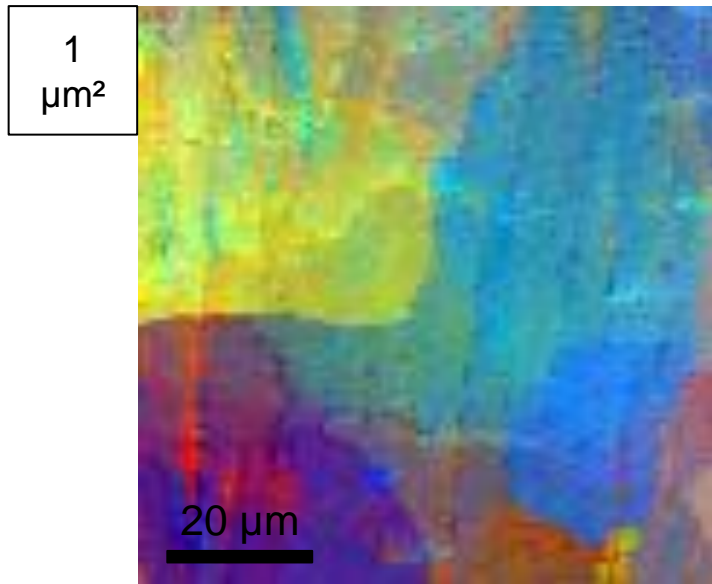


Euler angles

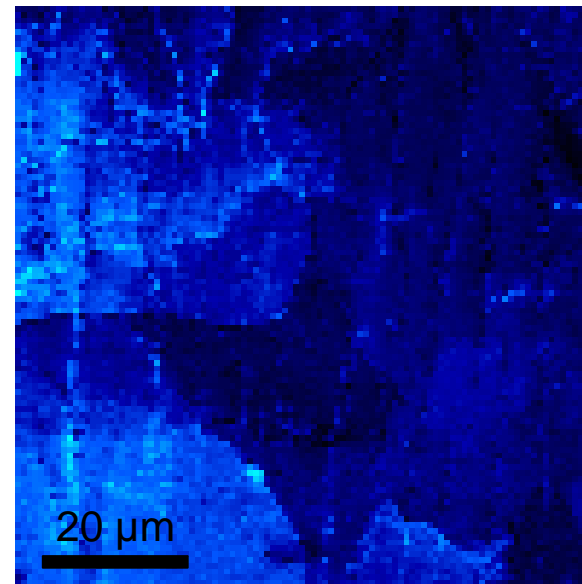
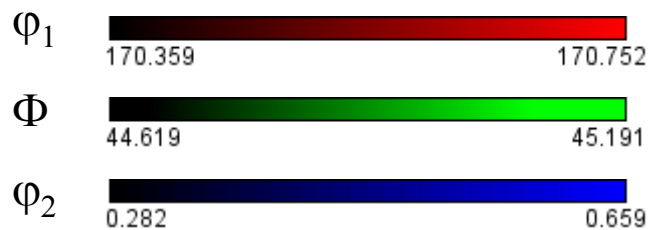
Deviation from  
mean orientation

**Not much to look at, except for the usual noise !**

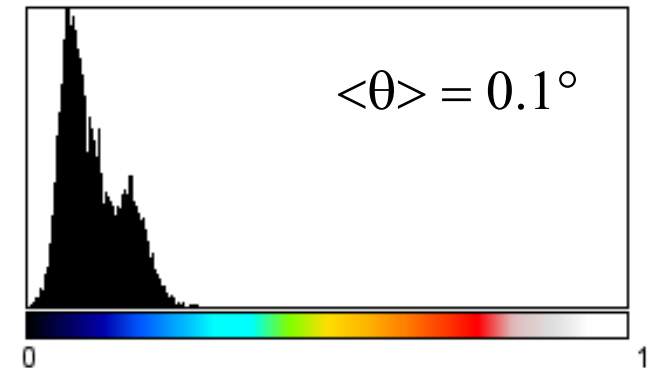
## With HAR-EBSD



Enhanced Euler angles

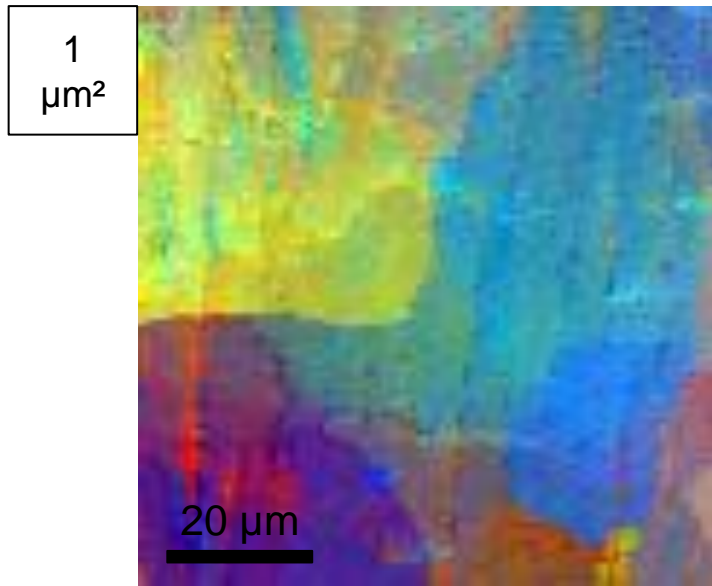


Deviation from mean orientation

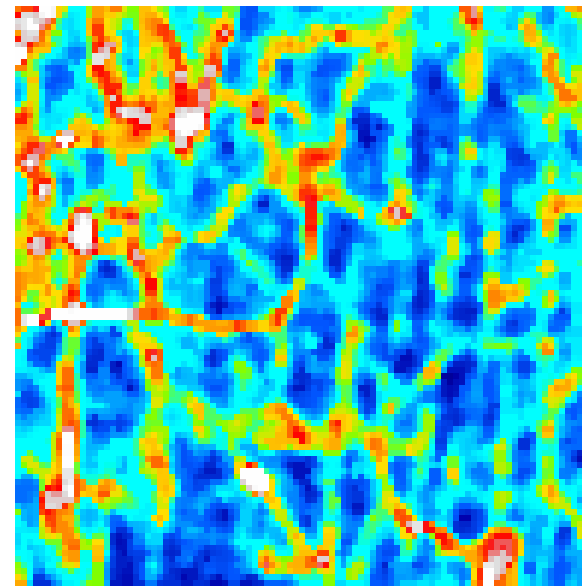
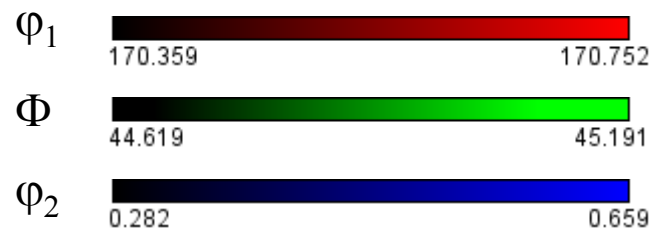


**HAR-EBSD reveals slightly misoriented domains**

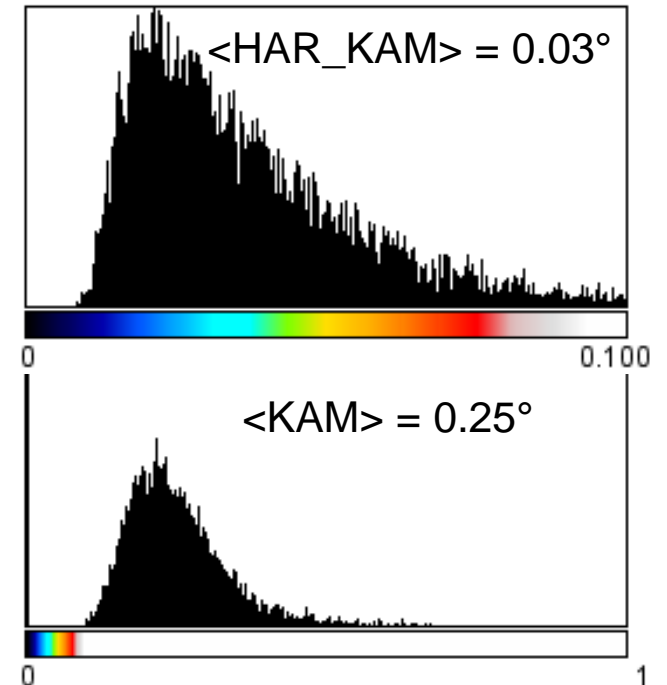
## With HAR-EBSD



Enhanced Euler angles



Kernel Average Mis.



**HAR-EBSD detects misorientations below  $0.1^\circ$  & improves rotation axis determination**

## 1 – The principles of HAR-EBSD

## 2 – A few selected examples

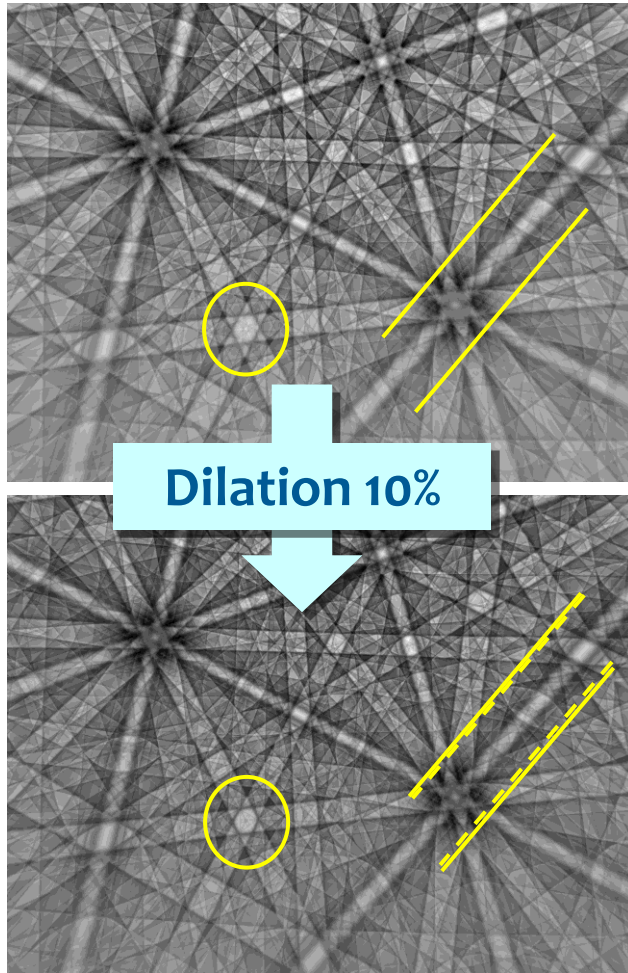
*elasticity – lattice defects – elasto-plastic polyX*

## 3 – Current Limitations : why not try 3D Hough ?

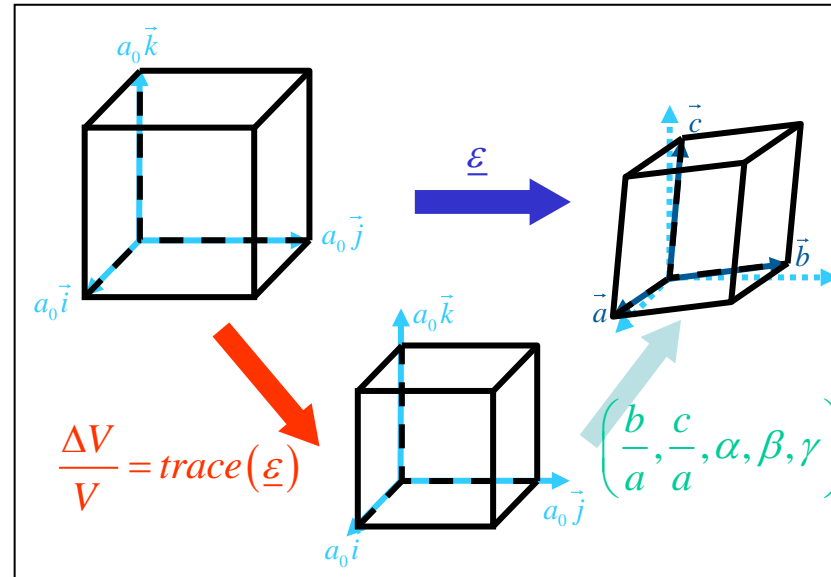
## 4 – Source Point and Elastic Strain

*How to kill two birds with one stone ?*

## 5 – Conclusions



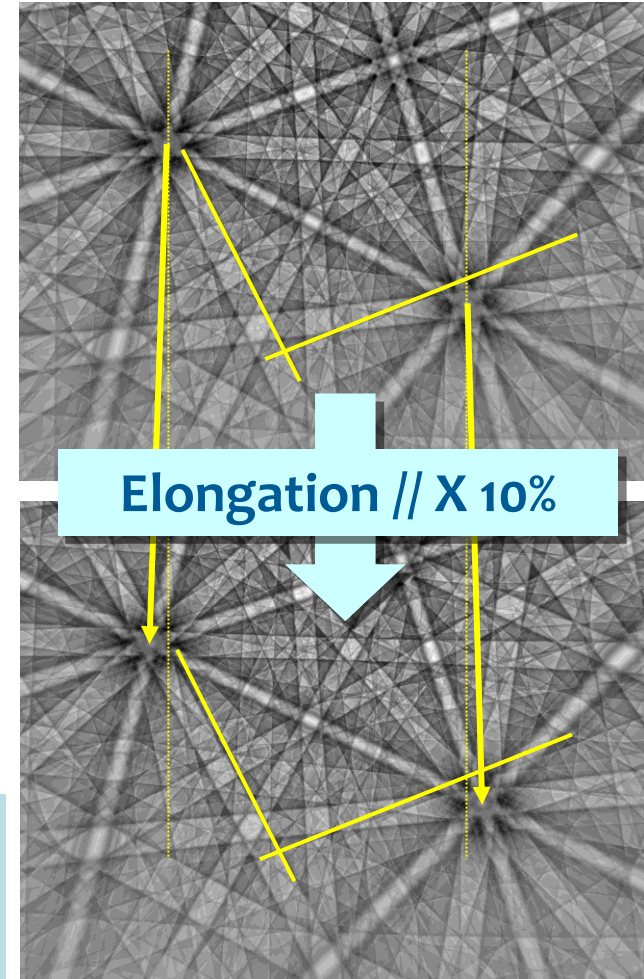
**Dilation 10%**



**Band width change**

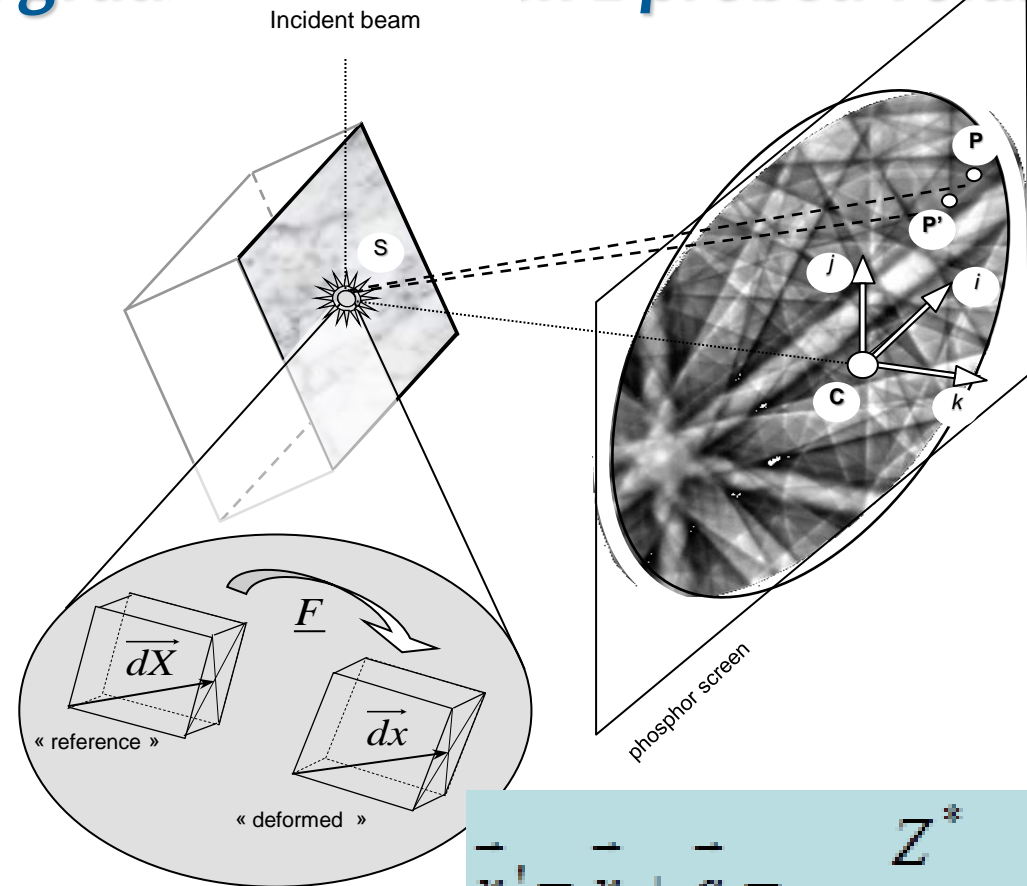
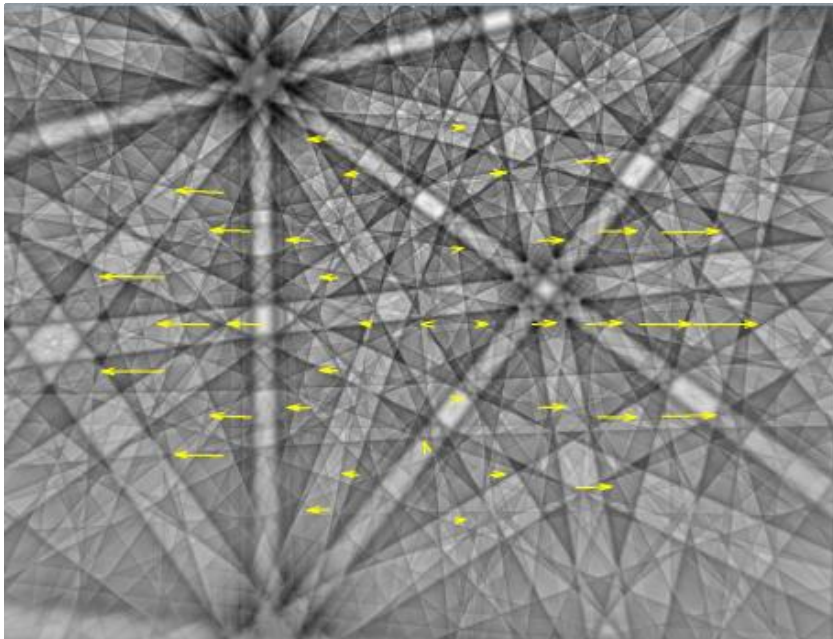
**Zone axes move**

**Interplanar angles change**



**Elongation // X 10%**

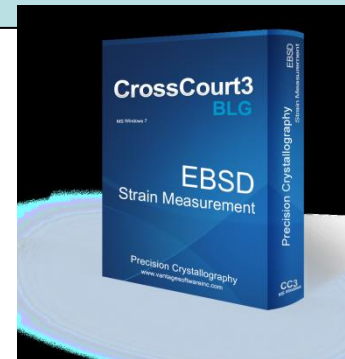
## Link the displacement field between 2 EBSPs to the material deformation gradient between 2 probed volumes



DIC used to measure shifts between 2 EBSPs

$$\bar{r}' = \bar{r} + \bar{q} = \frac{Z^*}{(\underline{F} \cdot \bar{r}) \cdot \bar{k}} \underline{F} \cdot \bar{r}$$

1993	Troost et al.	Microscale Elastic-Strain Determination by Backscatter Kikuchi Diffraction in the Scanning Electron-Microscope
1996	Wilkinson	Measurement of elastic strains and small lattice rotations using electron back scatter diffraction
<b>2004</b>	<b>Villert et al.</b>	<b>Début de thèse à Saint-Etienne (CEA – ST Micro)</b>
2006	Wilkinson et al.	High-resolution elastic strain measurement from electron backscatter diffraction patterns: New levels of sensitivity.
2007	Winkelmann et al.	Many-beam dynamical simulation of electron backscatter diffraction patterns.
2009	Villert et al.	Accuracy assessment of elastic strain measurement by EBSD.



## Digital Image Correlation

**StrainCorrelator**

Mode Project Calibration Tools Help

**Lens Distorsion**

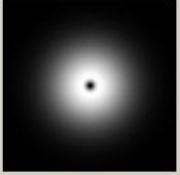
Correct Lens Distorsions

**Band Pass Filter Settings**

Ideal     Gaussian  
 Smoothed     Butterworth

LowFreq cutoff=5    HighFreq cutoff=40

Modified Hamming Window



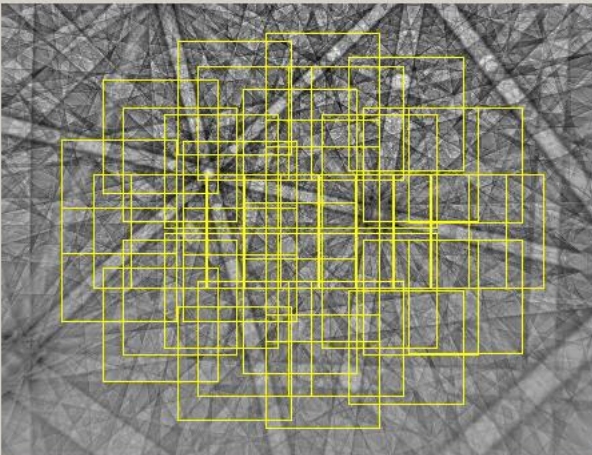
**ROIs Settings**

ROI size: 256 pixels

Nb of ROIs: 39

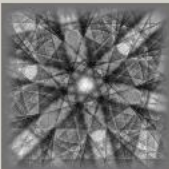
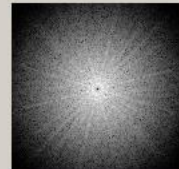

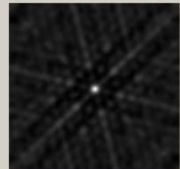
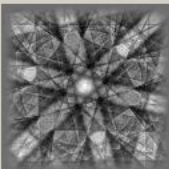
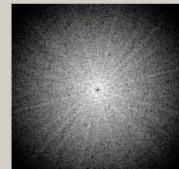

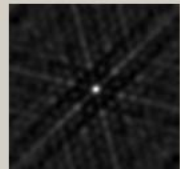
- ROI#0 at (544,384)
- ROI#1 at (460,385)
- ROI#2 at (628,386)
- ROI#3 at (409,309)
- ROI#4 at (595,263)
- ROI#5 at (712,384)
- ROI#6 at (595,505)
- ROI#7 at (409,459)
- ROI#8 at (796,384)
- ROI#9 at (722,519)
- ROI#10 at (544,576)

Save ROIs    Load ROIs



340  
260

**Iterative sub-pixel cross correlation**

			
<b>Ref ROI</b>	<b>Ref FFT</b>	<b>Band pass filtered + Hamming</b>	<b>Auto correl.</b>
			
<b>Def ROI</b>	<b>Def FFT</b>	<b>Cross correl.</b>	

**StrainCorrelator**
Interactive mode

Mode Project Calibration Tools Help

Image source  
 Simulation  Experiment

Image files  
 Reference Pattern  
 ...  
 Deformed Pattern  
 ...

Source displacement compensation  
 use orientations to rotate EBSP

Cross Correlation

Linear system  F=I+eps+om  F=Rx(I+eps)

Use 1 in 1 ROI in optimization

Fit F tensor

Locate Pattern Center

Results summary

Shift informations

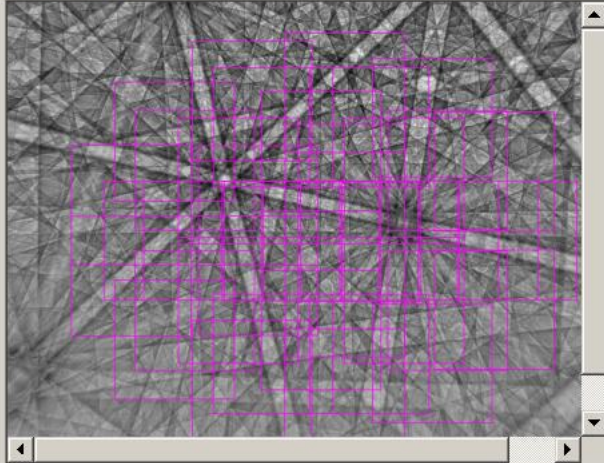
Min	<input type="text" value="1.18"/>
Max	<input type="text" value="4.57"/>
Mean	<input type="text" value="2.46"/>
Correlation error	<input type="text" value="0.814"/>
XCF mean	<input type="text" value="0.9565"/>

Measured Displacement Gradient

<input type="text" value="-25.391"/>	<input type="text" value="-13.705"/>	<input type="text" value="-44.327"/>
<input type="text" value="28.692"/>	<input type="text" value="22.052"/>	<input type="text" value="9.953"/>
<input type="text" value="28.395"/>	<input type="text" value="1.583"/>	<input type="text" value="3.256"/>
Mean Ang. Error (10e-4 rad)	<input type="text" value="6.141"/>	
Measurement error	<input type="text" value="3.263"/>	

Interactif Project Settings

Reference Image



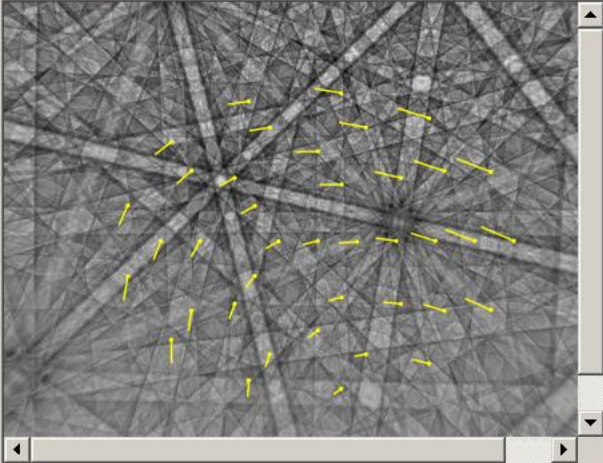
Reference Pattern Information

Projection

Imposed displacement gradient

Euler

Deformed Image



Deformed Pattern Information

Finite Rotation

Projection

Imposed displacement gradient

Euler

	ROI X pos	ROI Y pos	Measured X shift	Measured Y shift	XCF	Simulated X shift	Simulated Y shift	XCF error	Use	Calculate X shift	Calculate Y shift
1	672	512	-1.424	0.3651	0.9578	-1.416	0.4056	0.6113	<input checked="" type="checkbox"/>	-0.2083	0.5489
2	588	513	-1.19	0.6691	0.9563	-1.169	0.7651	1.461	<input checked="" type="checkbox"/>	0.1232	0.8739
3	756	514	-1.677	0.1045	0.9574	-1.692	0.05086	0.8135	<input checked="" type="checkbox"/>	-0.5251	0.224

## Project mode

StrainCorrelator
Mode Project Calibration Tools Help

Channel5 Project

Current Project  
Ramin\_16\_L7\_GB1

in\_16\_L7/Ramin\_16\_L7\_GB1/Ramin\_16\_L7\_GB1Images

Use Corrected Data

---

Projection Parameters

0,4536 0,7726 0,5171

---

Map Information

Step Size: 0.5x0.5 microns

Map Size: 100x120

---

Reference Points

(82 66) Clear All

---

Solve options

Source Displacement Compensation

Use Orientations to Rotate EBSP

Compute Stress Tensor (s33=0)

Use RANSAC algorithm

Linear system  F=I+eps+om  F=(I+eps)\*R

---

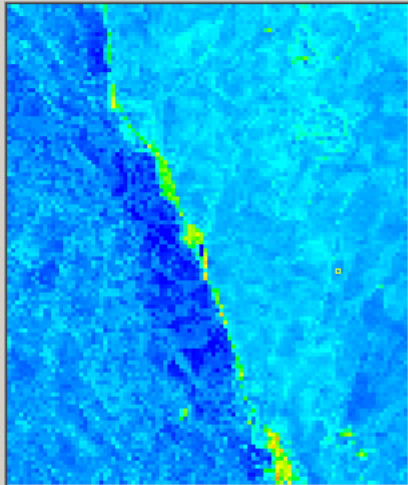
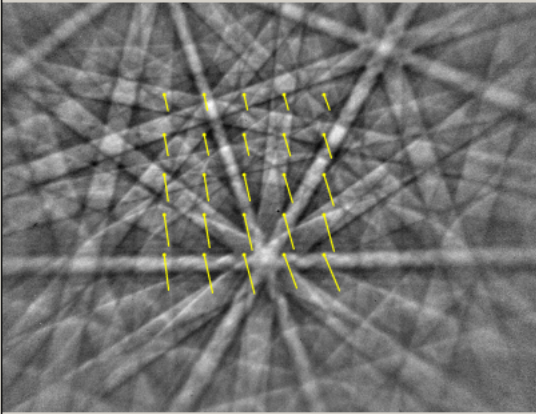
Cycle Control

Strain Identification

Undo Shift Measurement

Accept Discard

Interactif
Project
Settings

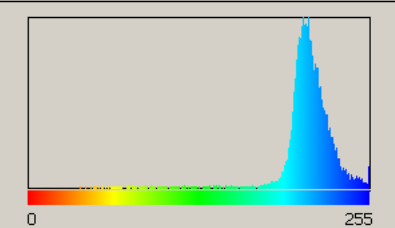



Map : Band Contrast      Zoom : 8

---

Map Contrast

Min = 39,0000      Max = 255,0000



Count : 12000      Min : 39

Mean : 210.49      Max : 255

StdDev : 18.3044      Mode : 210

---

Pixel X=39 Y=68      BC = 255      BS = 140

                         Euler = (62.315 30.648 7.36415)

---

'Grain' identification parameters

                         XCF value = 0.117115      reference pixel = 0

---

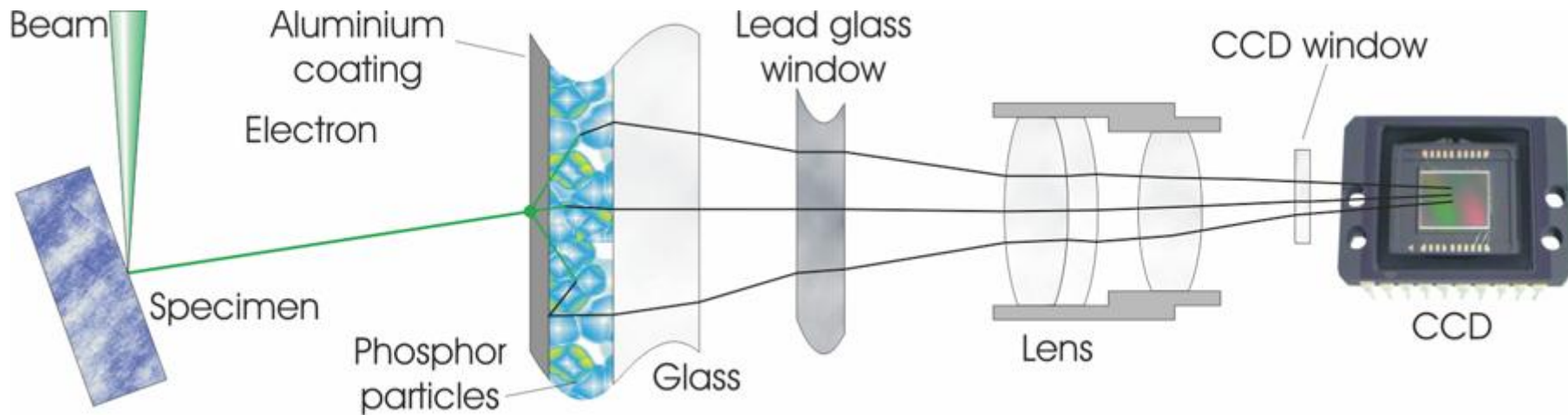
Shift stats

minShift = 4.31      maxShift = 11.3      meanShift = 7.81

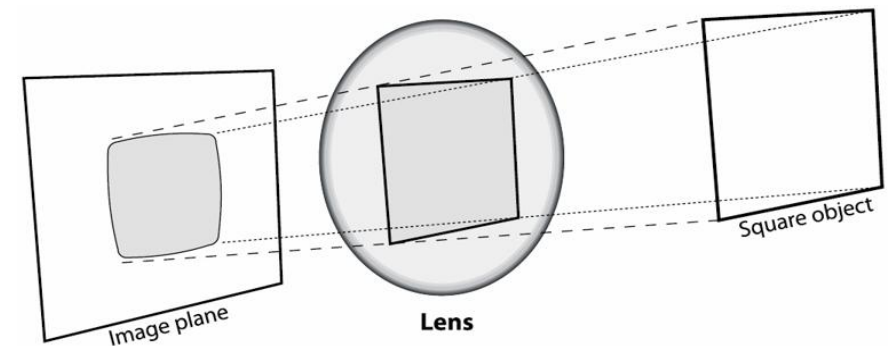
minXCF = 1      maxXCF = 1      meanXCF = 1



## EBSP distortion



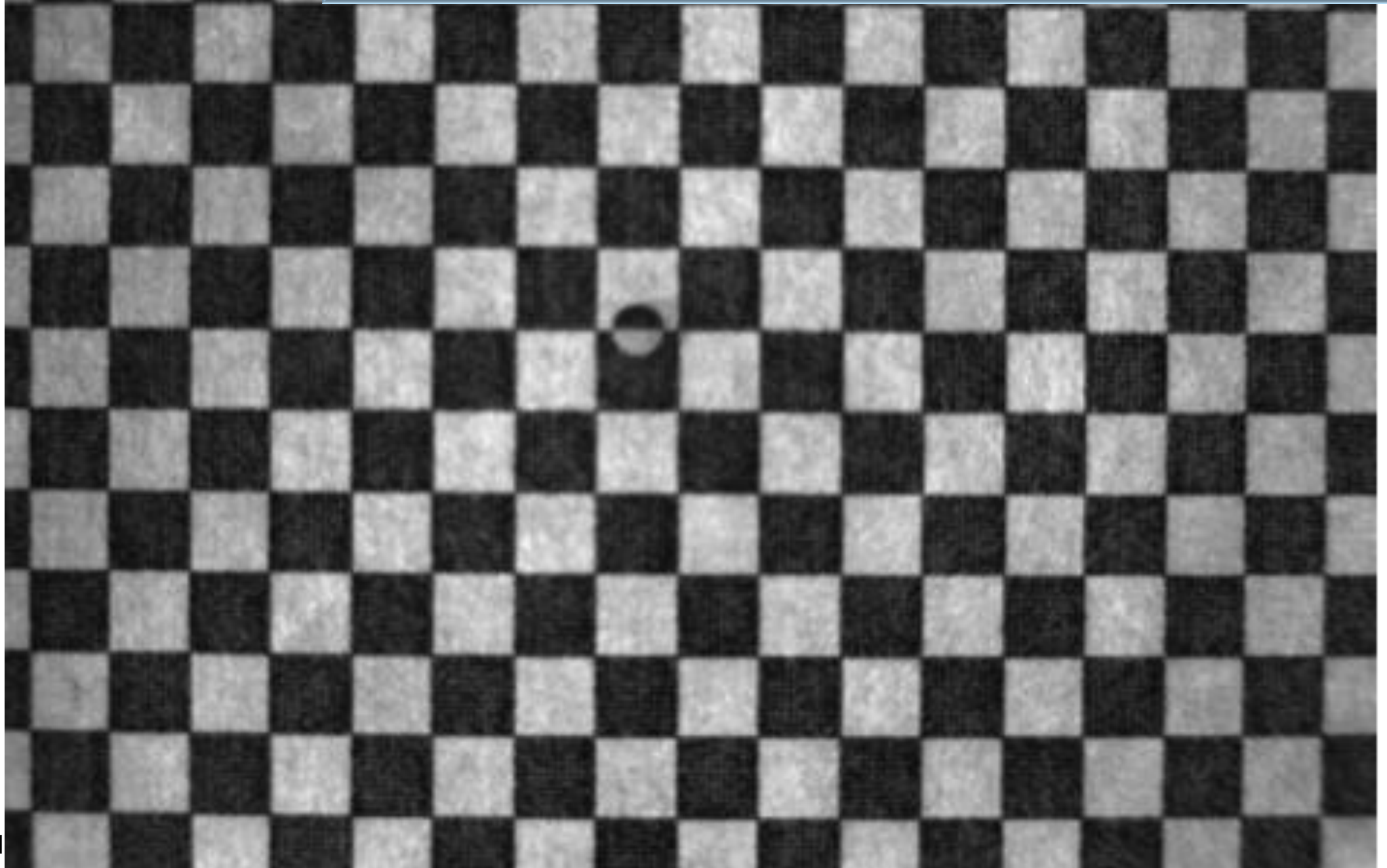
- Lens = Distortion
- CCD + Lens + Phosphor = Misalignment
- Present in all detectors
- Usually not seen by indexing



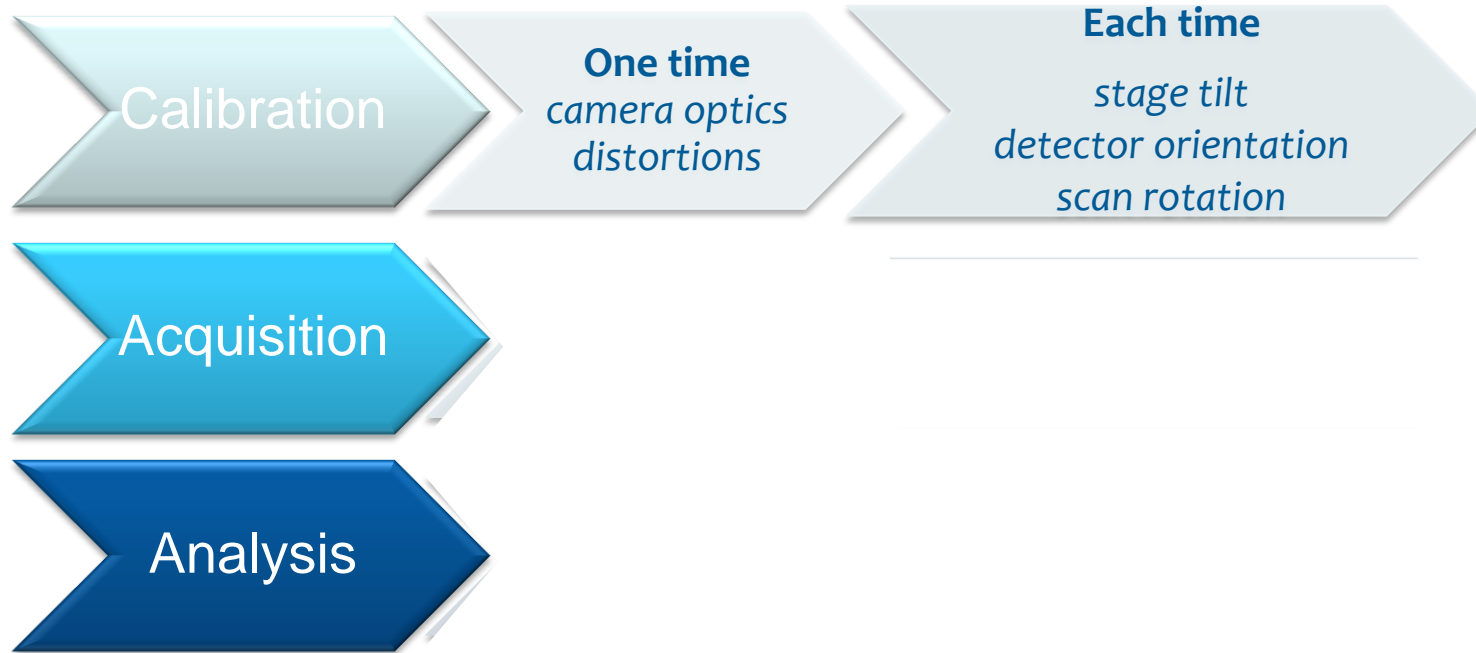
Square grid in front of camera nose (phosphor destroyed)



**Square grid in front of camera nose (phosphor destroyed)  
as seen by the CCD !!!**

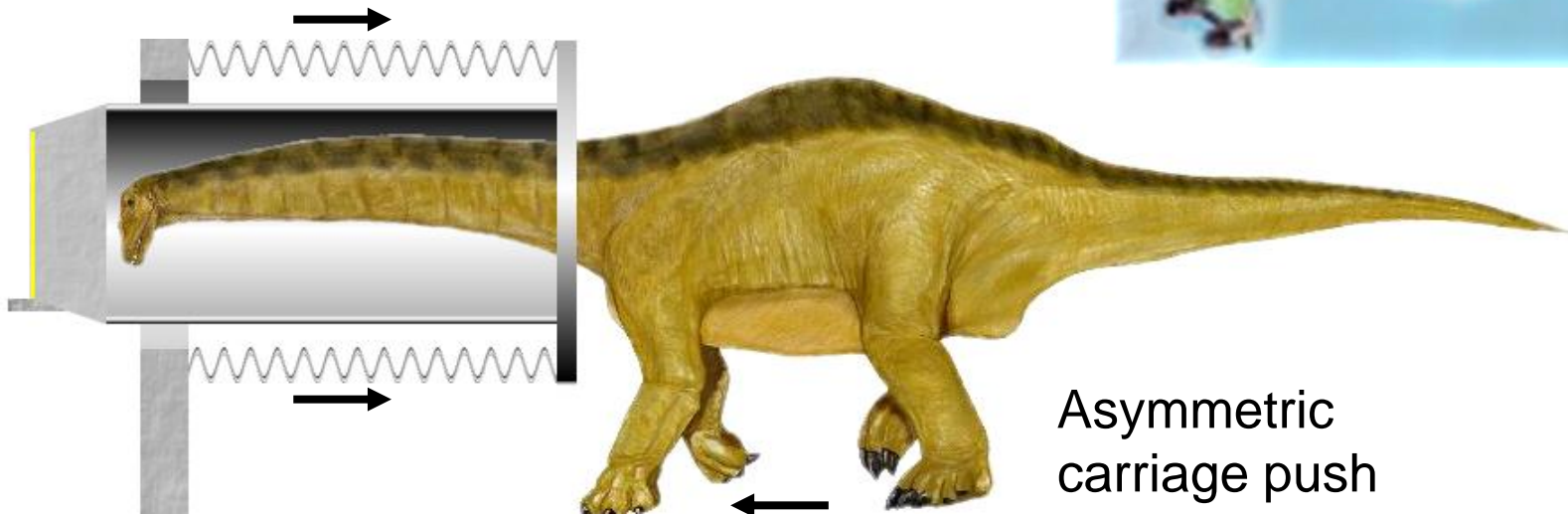
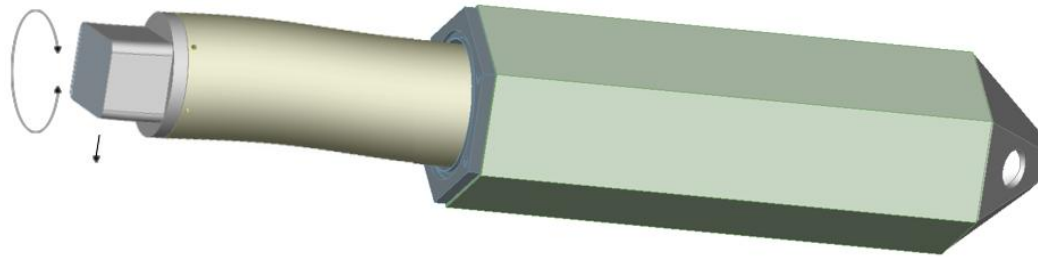


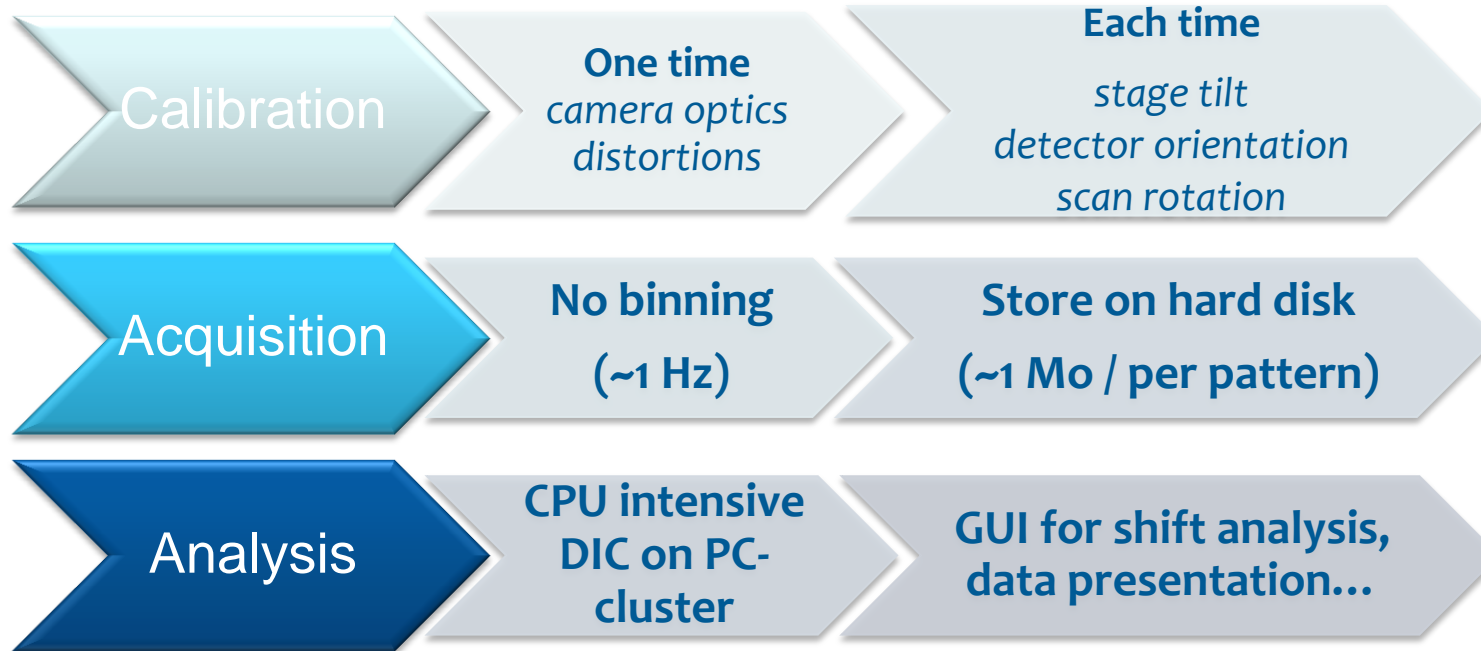
The good news : can be calibrated and corrected for...

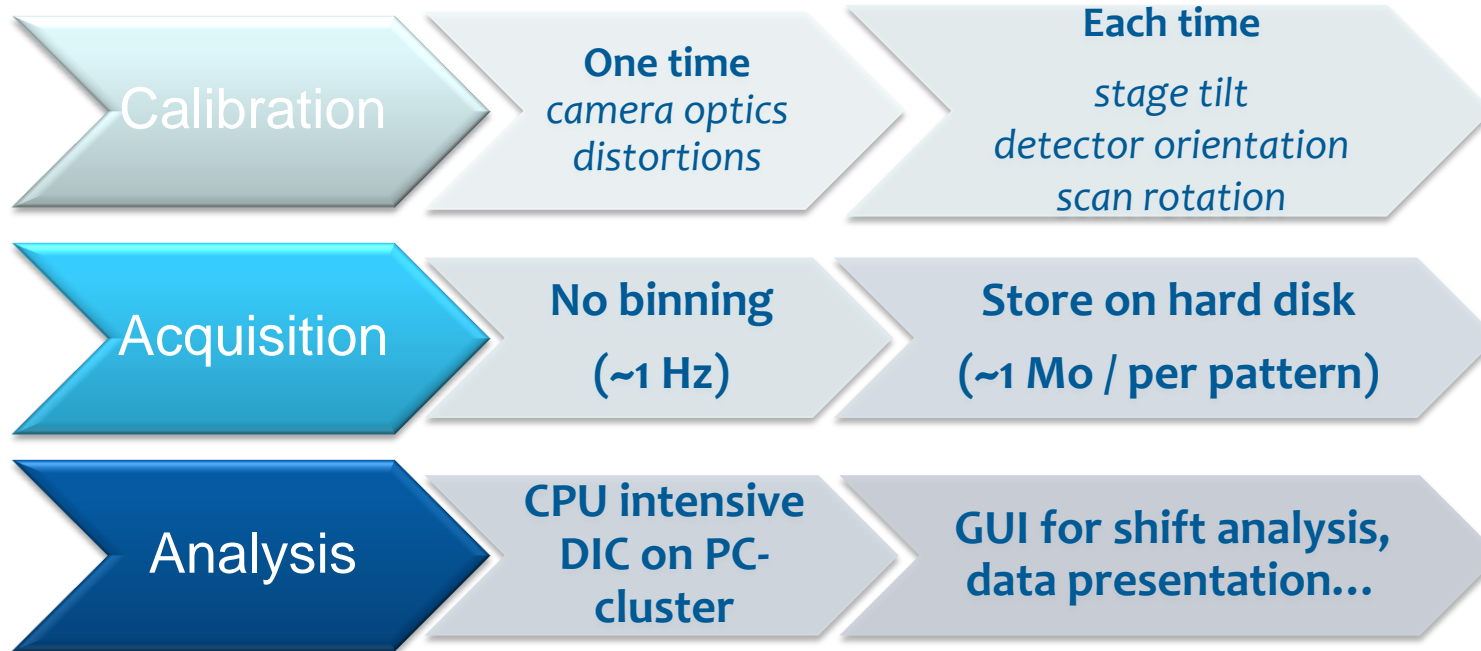


## Mechanical issues (courtesy A.P. Day)

- Camera rotation & shift
- Droop, twist, boing & bounce



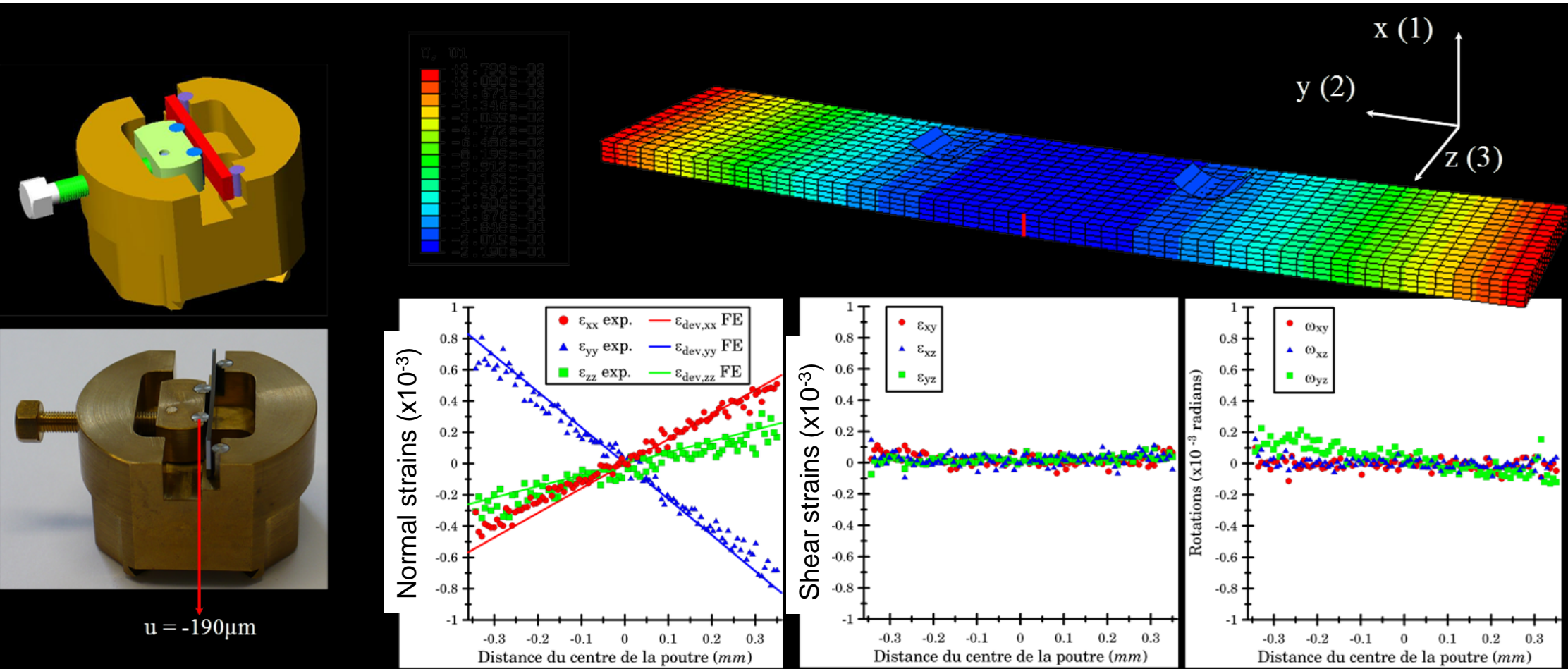




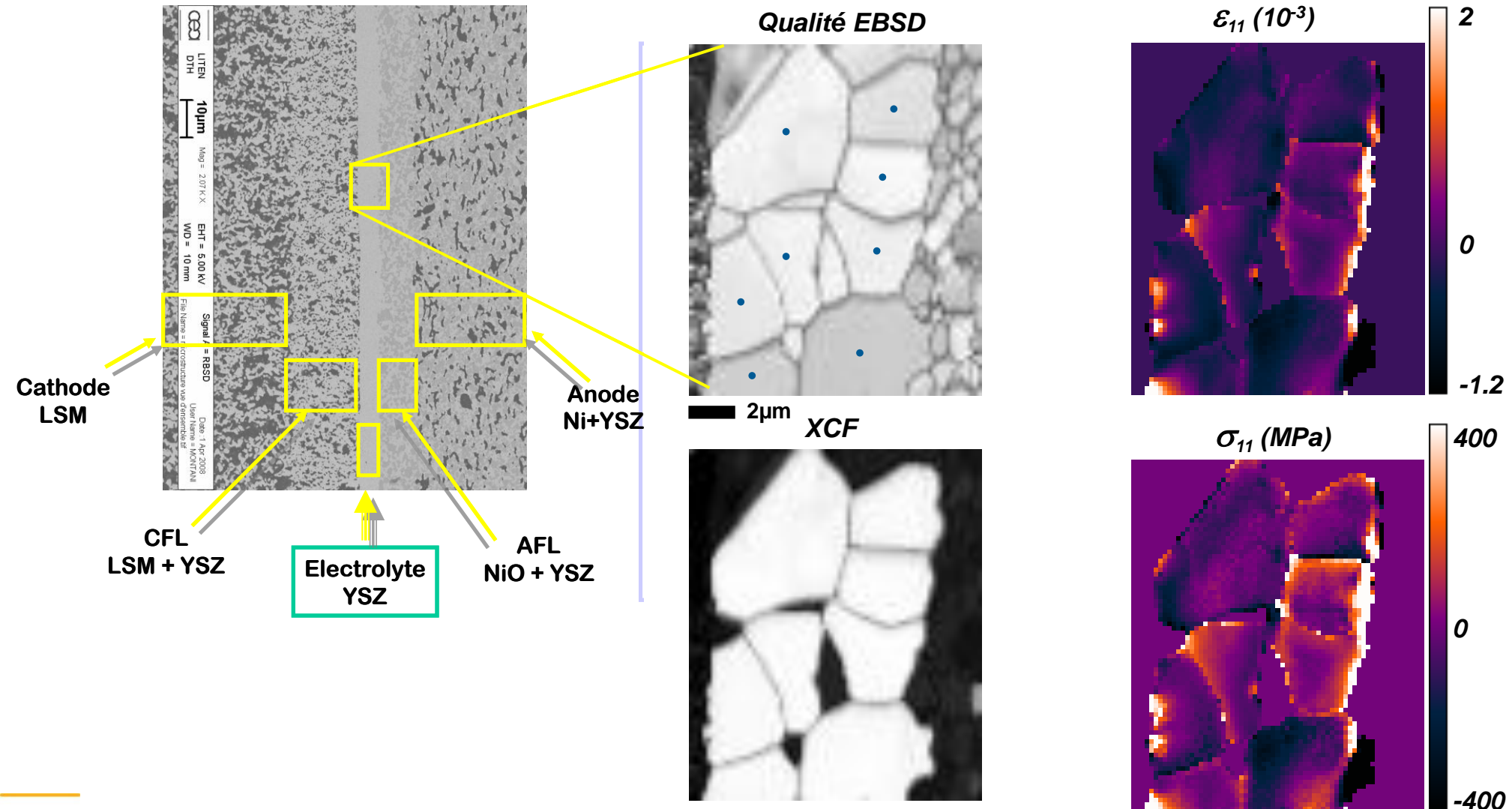
Relatively small maps : 200x200 points = 50 Go !!!

More time required for data transfer than for (acquisition + analysis)

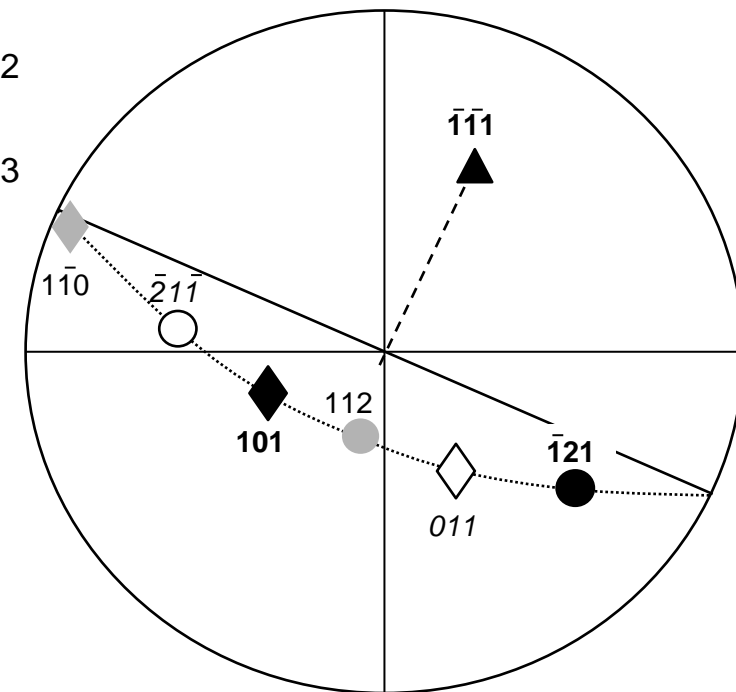
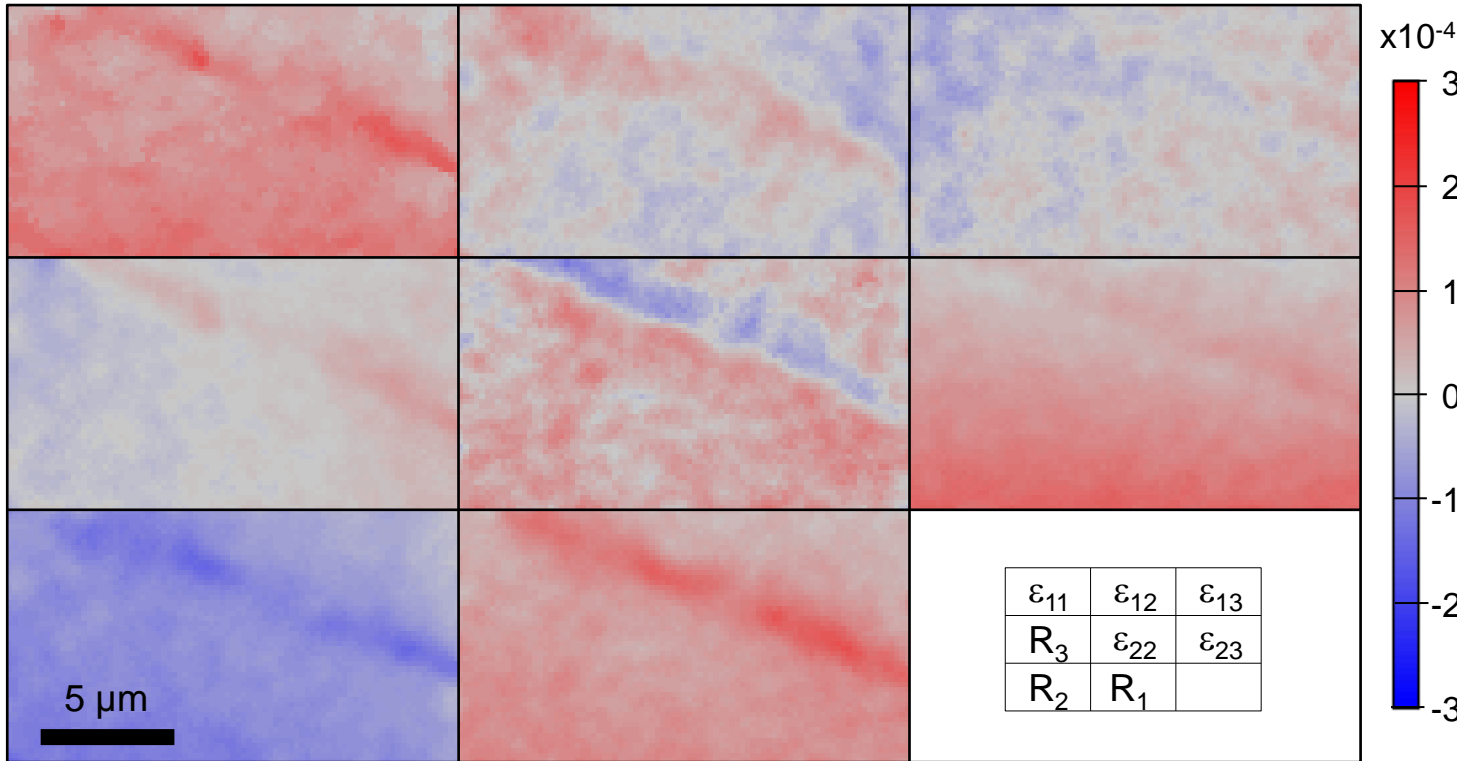
## 4 point bending of a Si single crystal



## Residual strains in SOFC



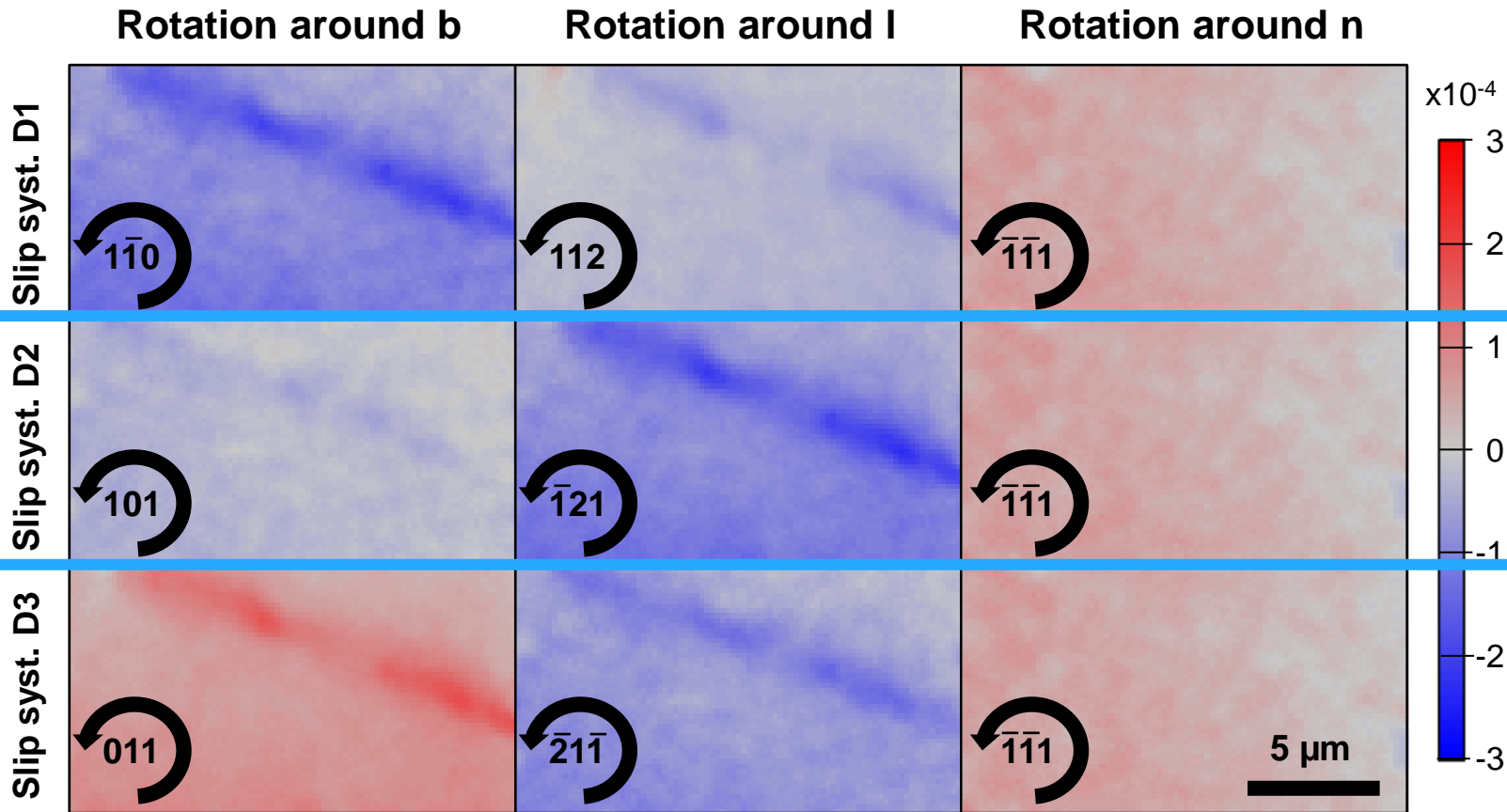
## 316L Single Crystal



**Strain and rotation tensor in Sample reference frame**

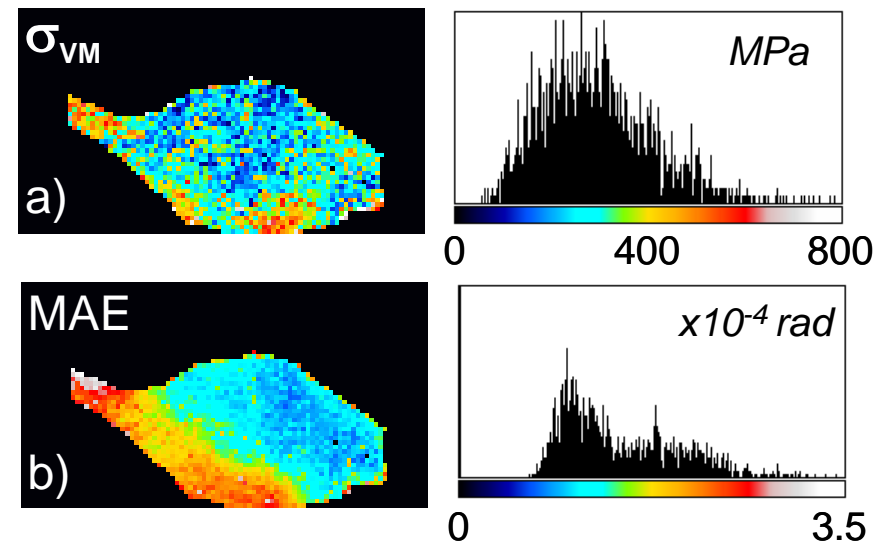
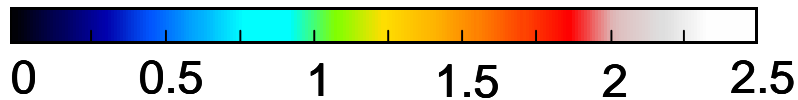
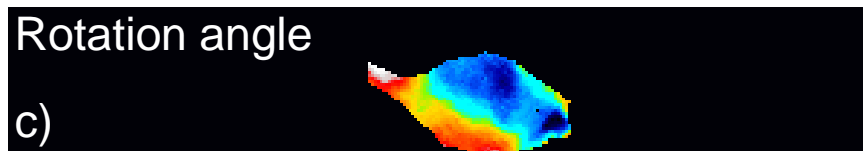
**Linear features // to (-1-11) plane trace**

## Rotation tensor projected onto the 3 possible (-1-11) slip systems



Consistent with edge dislocations on D2

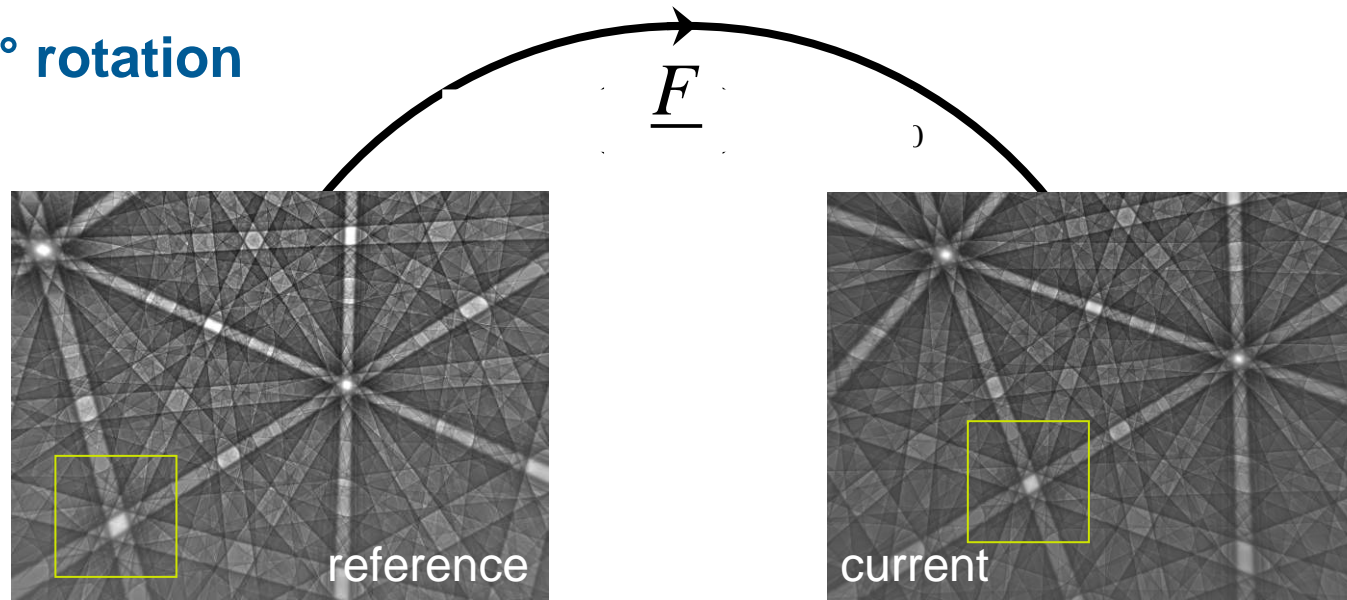
## IF steel deformed 2.5% in traction



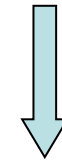
Anomalous strains and stresses are found in regions rotated by more than 1° from the reference point

Sample provided by ENSAM-Metz  
ANR-SAKE collaboration

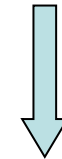
15° rotation



**ROI patterns are stretched and rotated**

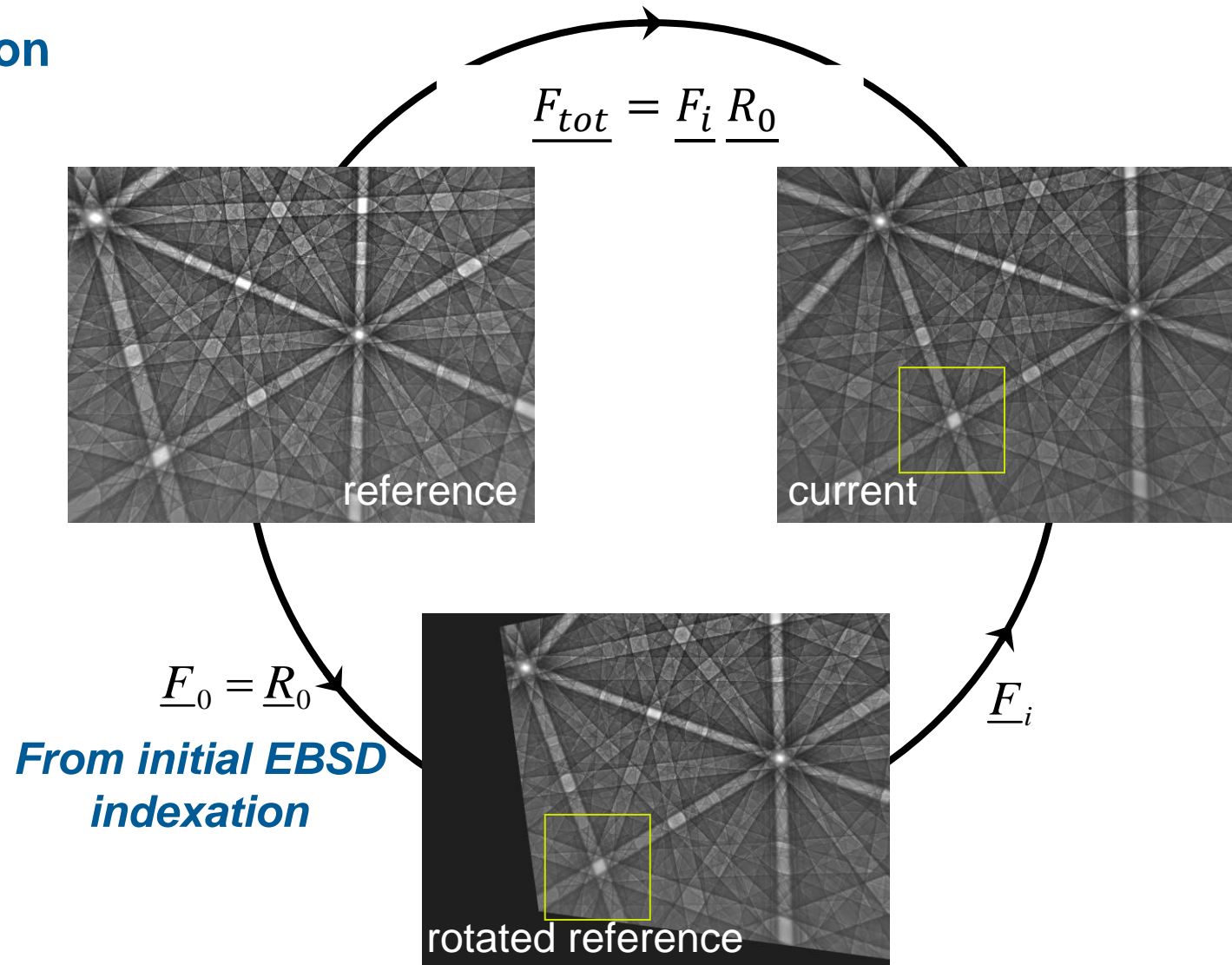


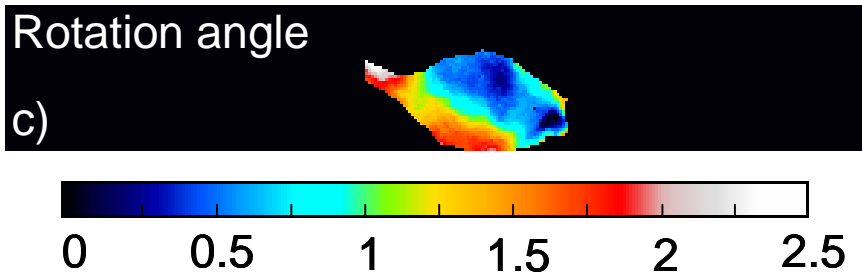
***Displacement field is poorly approximated by ROI shifts***



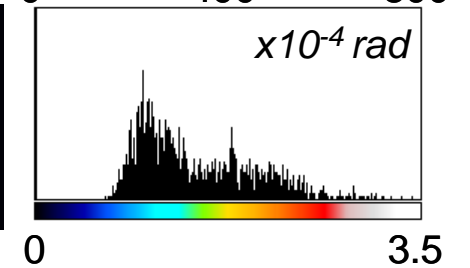
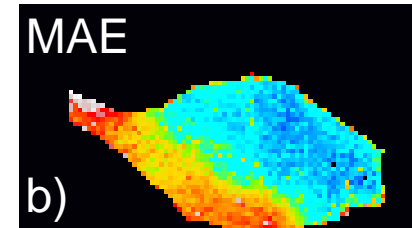
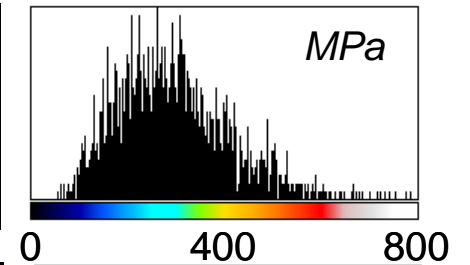
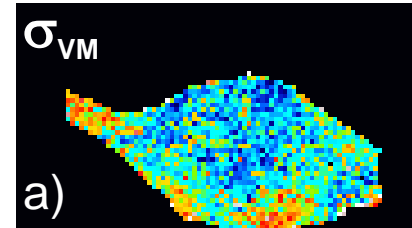
***Phantom strains and rotations***

## 15° rotation

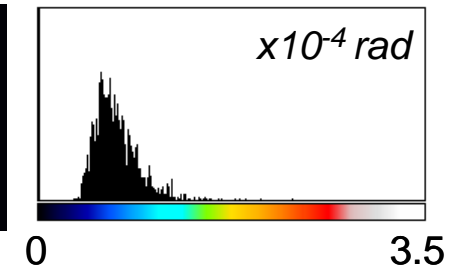
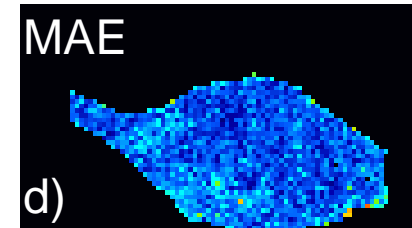
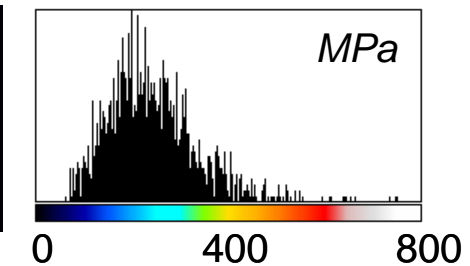
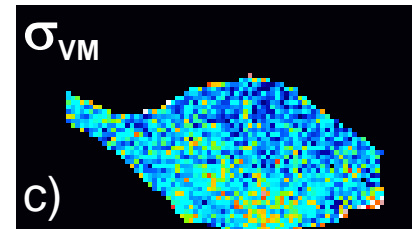




Without RRT

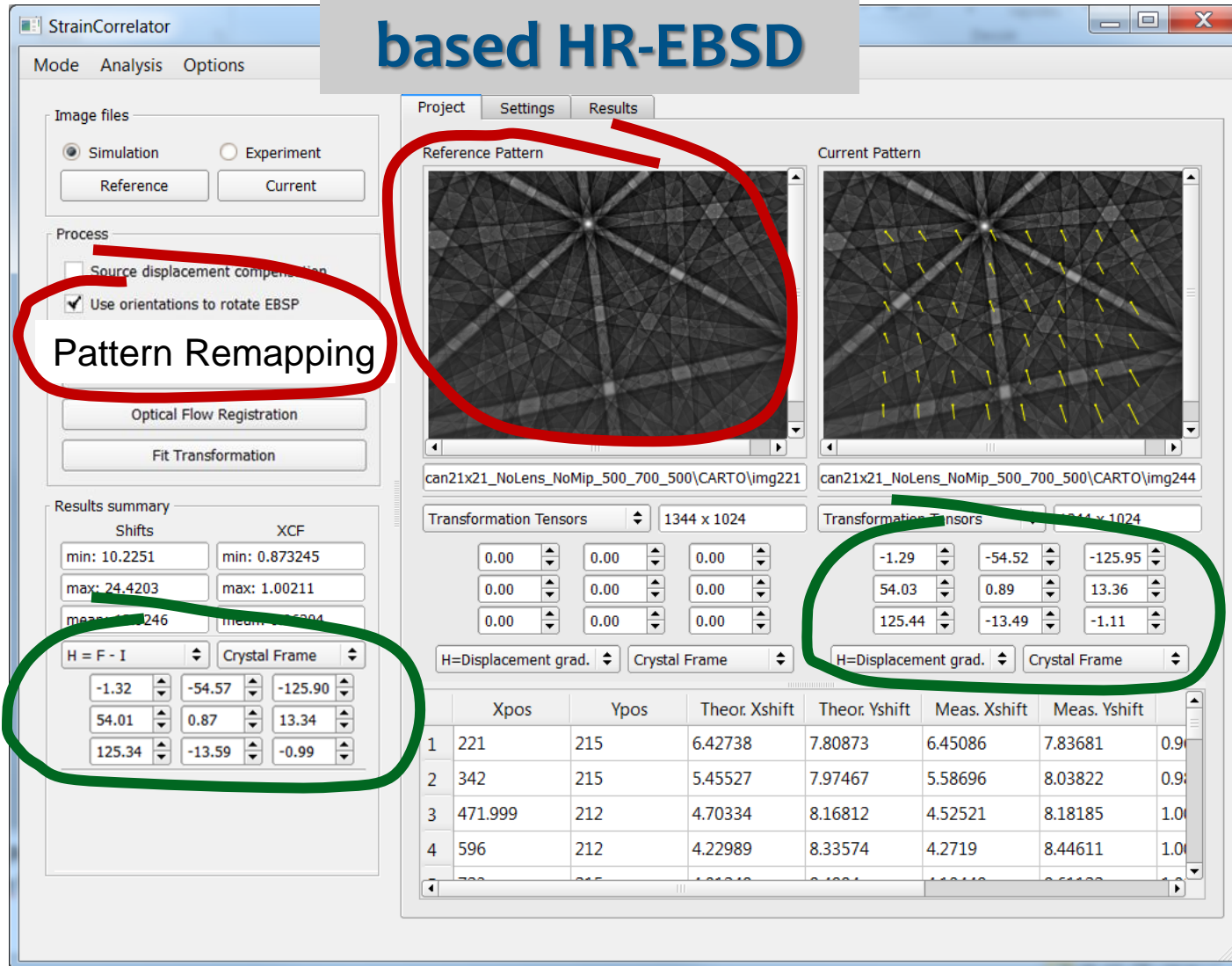


With RRT



Remapping of one of the pattern solves the problem.

## Cross-correlation based HR-EBSD



The screenshot shows the StrainCorrelator software interface. The 'Process' section has 'Use orientations to rotate EBSD' checked, and 'Pattern Remapping' is highlighted with a red circle. The 'Results summary' section shows 'Shifts' and 'XCF' values, with the 'H = F - I' section highlighted in green. The 'Reference Pattern' and 'Current Pattern' are shown side-by-side, with the 'Current Pattern' having yellow arrows indicating shifts. The 'Transformation Tensors' section shows a 1344 x 1024 matrix, with the 'Current Pattern' section highlighted in green. The 'Results' section shows a table of Xpos, Ypos, Theor. Xshift, Theor. Yshift, Meas. Xshift, and Meas. Yshift.

	Xpos	Ypos	Theor. Xshift	Theor. Yshift	Meas. Xshift	Meas. Yshift
1	221	215	6.42738	7.80873	6.45086	7.83681
2	342	215	5.45527	7.97467	5.58696	8.03822
3	471.999	212	4.70334	8.16812	4.52521	8.18185
4	596	212	4.22989	8.33574	4.2719	8.44611

### Some success

Good agreement  
« imposed / measured »  
Max error  $\sim 0.1 \times 10^{-4}$

### But a few limitations

- Unknown mechanical state  
*Intragranular variations  
i.e. Type III Res.Stress only*
- Unknown source position  
*Possible artefacts when  
remapping*

## A few ideas to overcome the reference pattern problem

### Use a simulated pattern as reference

Attractive idea ....

... but many issues as shown by Britton et al. – Ultramicroscopy 2010

*“Factors affecting the accuracy of high resolution electron backscatter diffraction when using simulated patterns”*

### Combine Kossel microdiffraction (mean strain) and EBSD (local gradient)

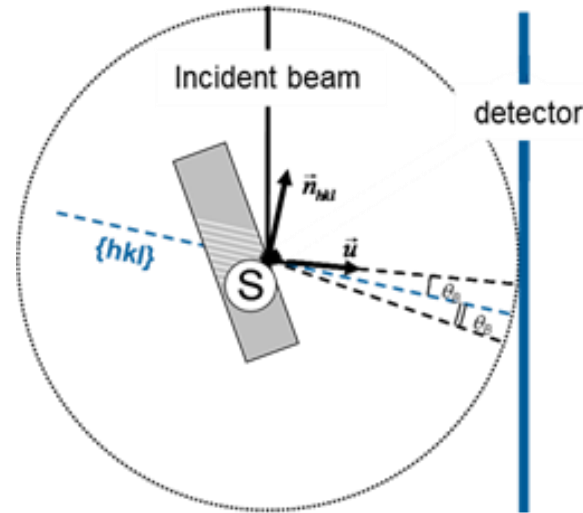
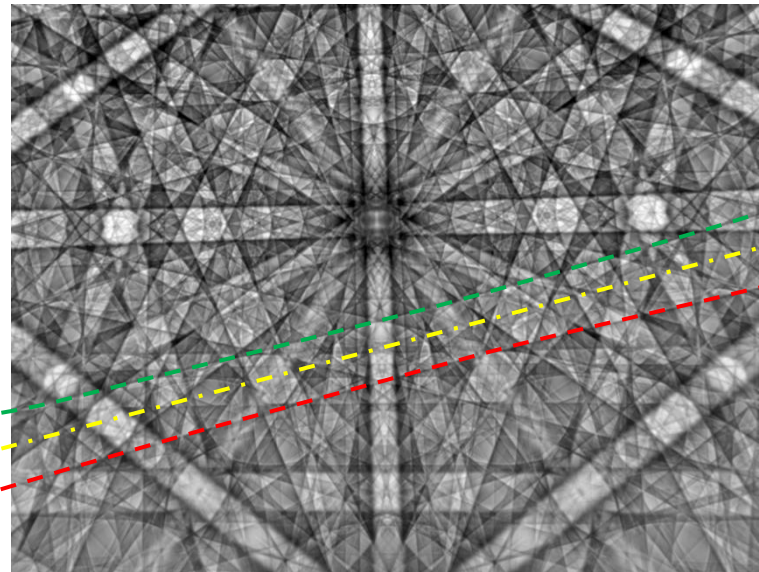
ANR Project SAKE : Strain Analysis by Kossel and EBSD

(ENSAM Metz – Mines Saint-Etienne – STMicronics)

### Enhance the angular resolution of direct pattern analysis

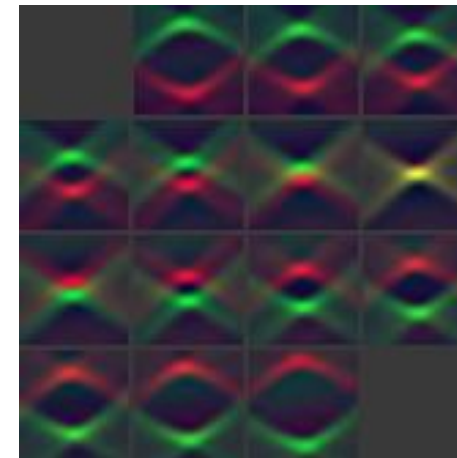
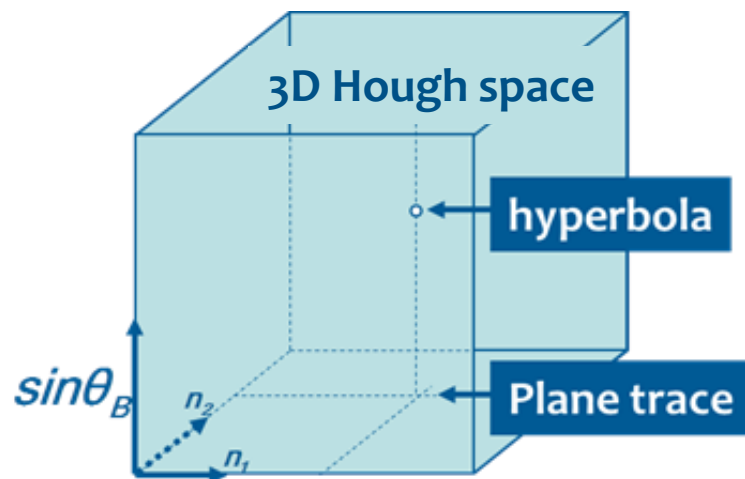
Based on accurate edge localisation by 3D Hough transform

## High Angular Accuracy EBSD



Plausible Kossel Lines

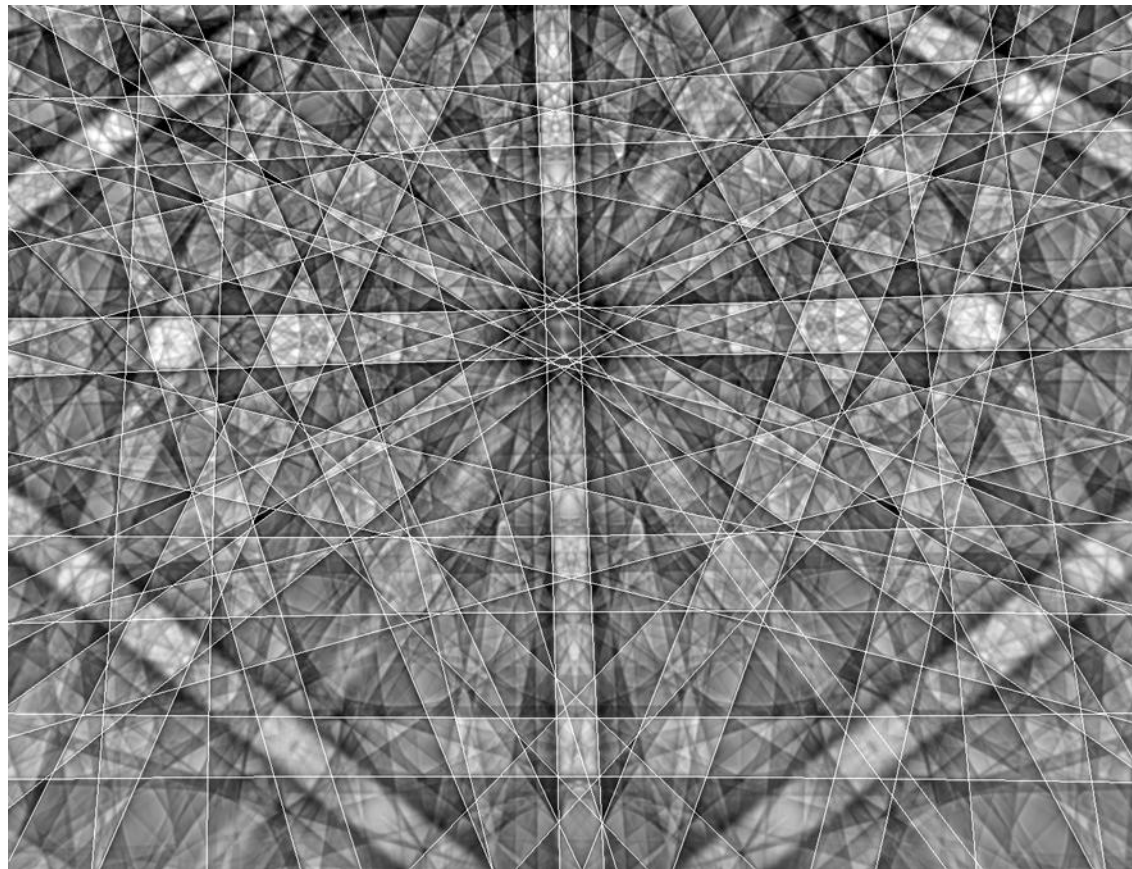
$$\vec{u} \cdot \vec{n} = \sin\theta_B$$



Constant  $\sin\theta_B$  sections

## Known EBSD Geometry

### On unstrained germanium (simulation)



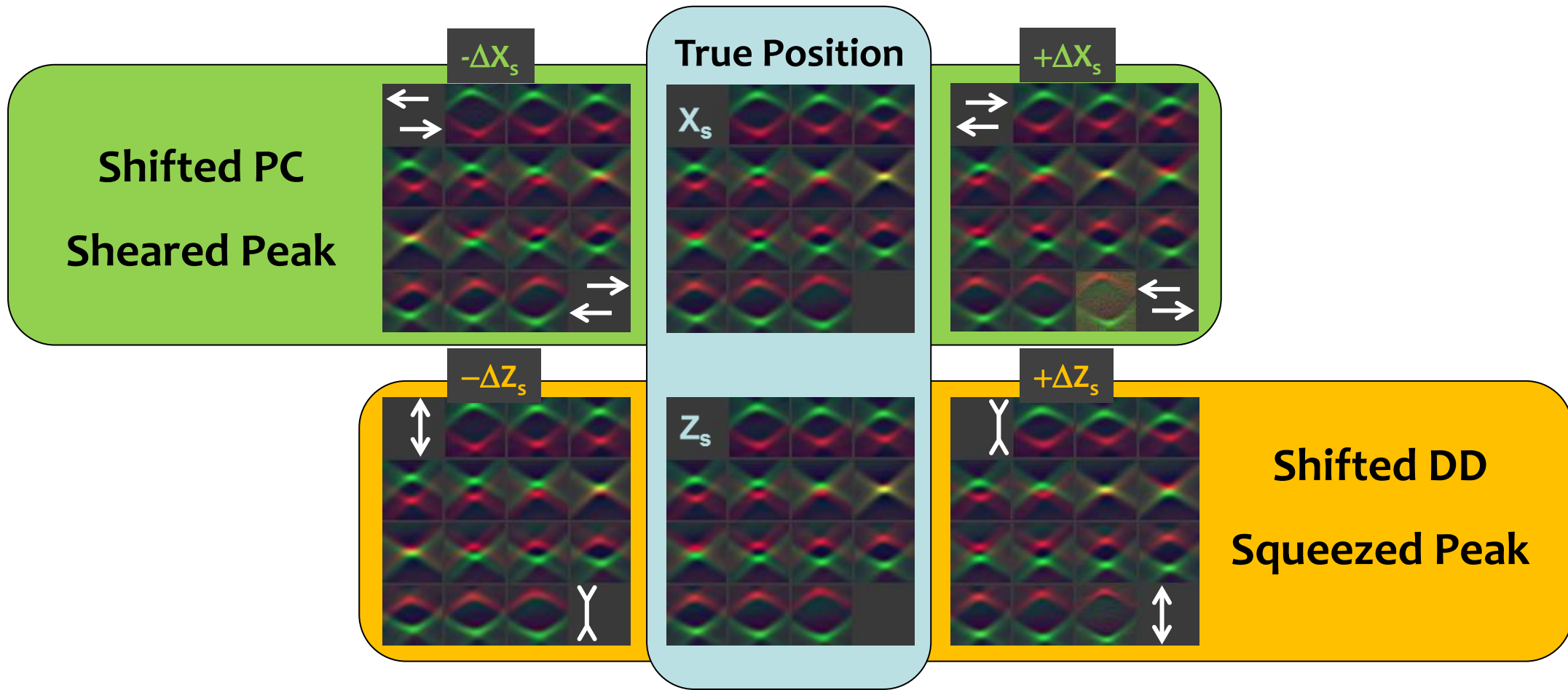
25 reflectors are detected

From these reflectors :

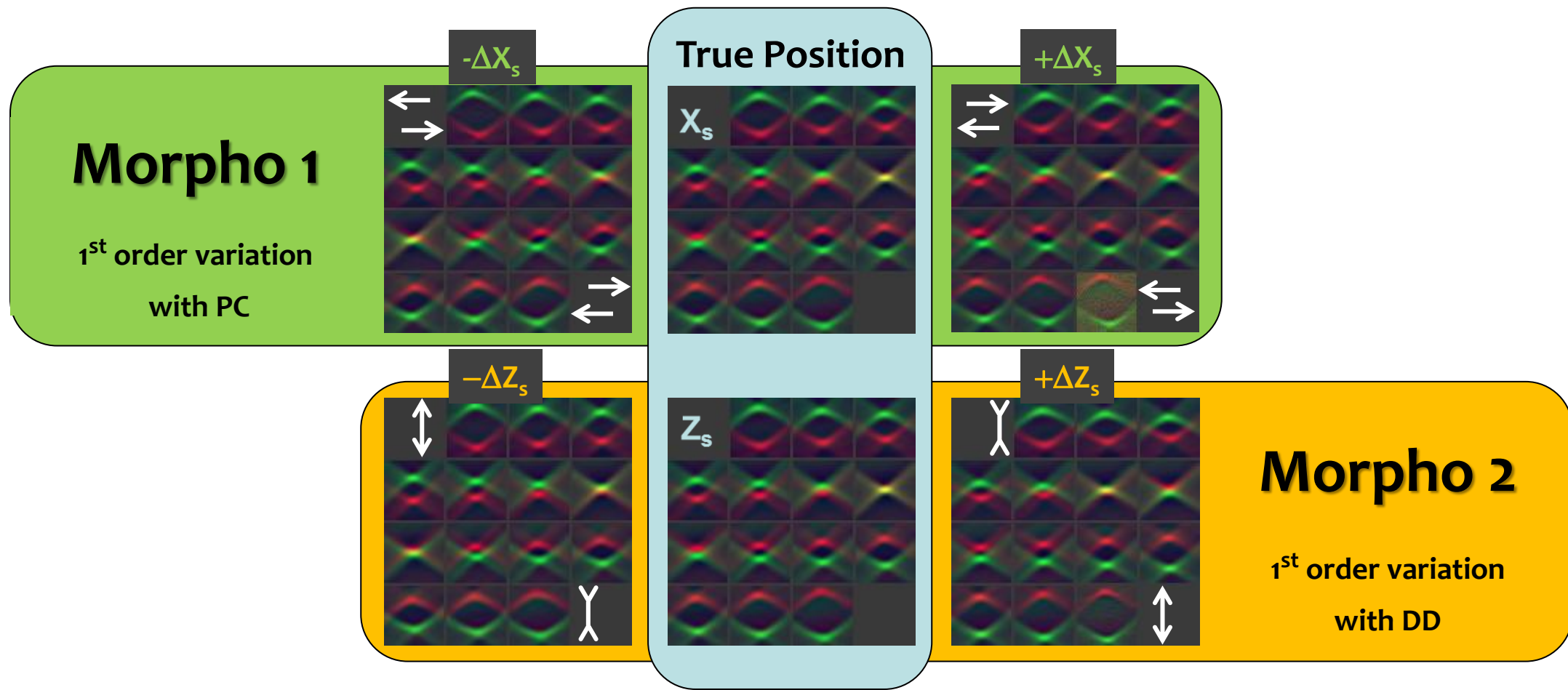
- Refine the lattice parameters
- Refine the orientation
- Compute strains and stresses

$$\underline{\sigma} = \begin{pmatrix} 5.4 & 6.7 & -5.8 \\ & 8.9 & 3.4 \\ & & 0.1 \end{pmatrix} \text{MPa}$$

## Not so well-known EBSD Geometry

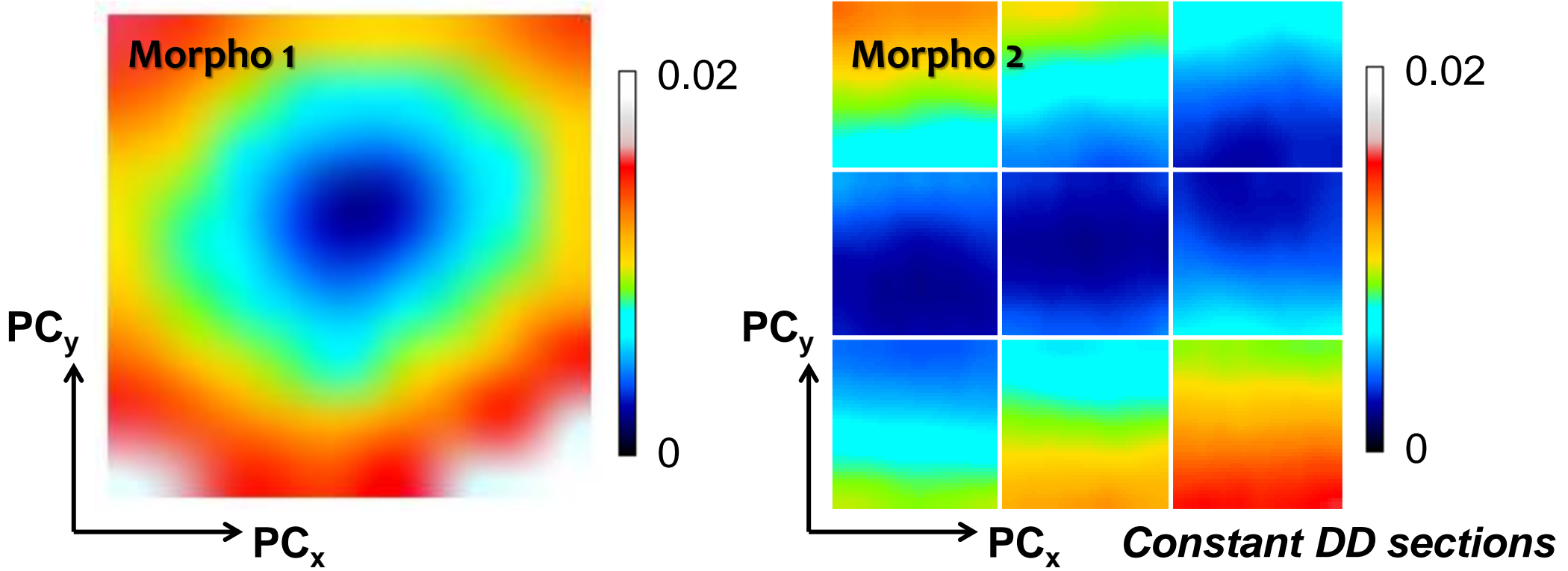


## Two Morphological Descriptors to quantify the parallax error

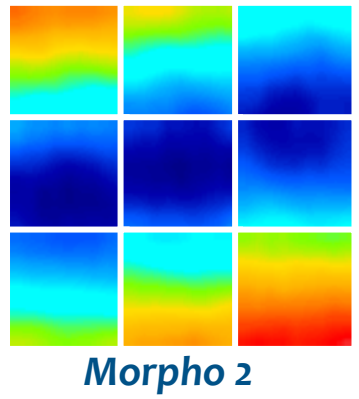
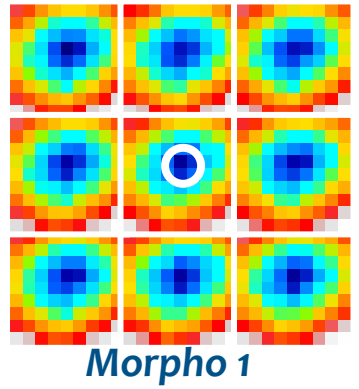


## Scanning the Source Point space

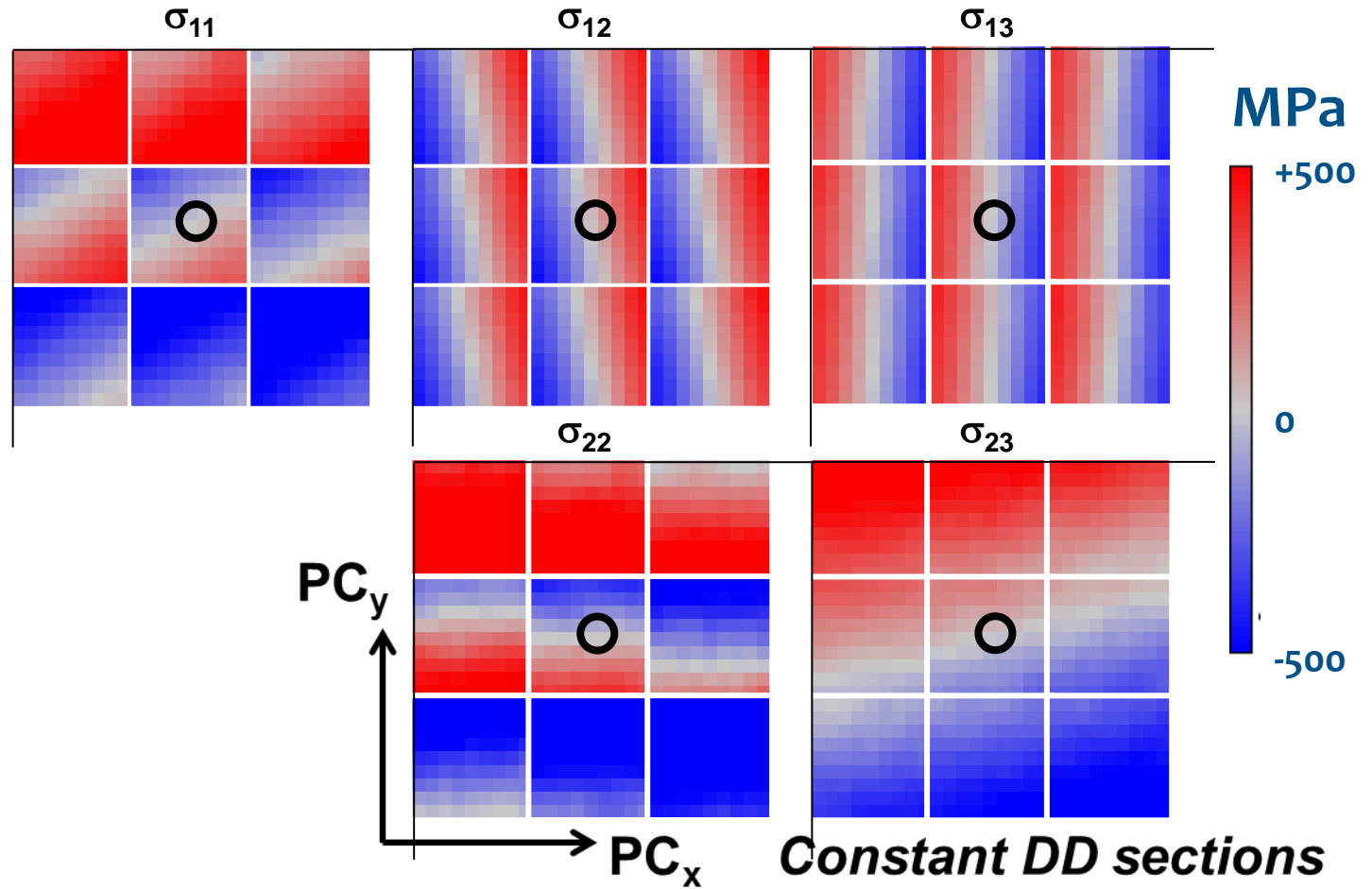
Variation of the Morphological Descriptors for PC variation of  $\pm 4$  pixels around true position



## Scanning the Source Point space



### Mechanical state : Stress Tensor



## Relative HR-EBSD by cross-correlation



**geometric principles** well established  
effectively measures **low misorientations  $< 0.1^\circ$  (check with TEM)**  
**remapping** helps in case of orientation gradients

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## « Absolute » HR-EBSD



**3D Hough** can yield both **Source Point position** and **Strain**

*This work is receiving financial support from the french ANR*



SAKE ANR-07-NANO-029  
AMOS ANR-10-NANO-015  
MICROSTRESS



**Co-workers :** Roland FORTUNIER, Sébastien VILLERT, Krzysytof DZIECIOL,  
Emeric PLANCHER (thèse EDF)

**Thank you for your attention**