

SIMULATION-BASED PERFORMANCES ASSESSMENT OF FMC-TFM ARRAY IMAGING TECHNIQUES

P. Calmon, X. Artusi, R. Miorelli, F. Le Bourdais, S Leberre

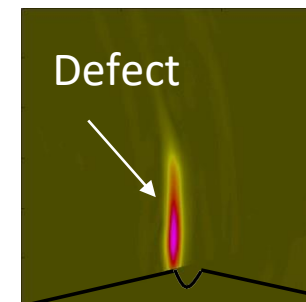
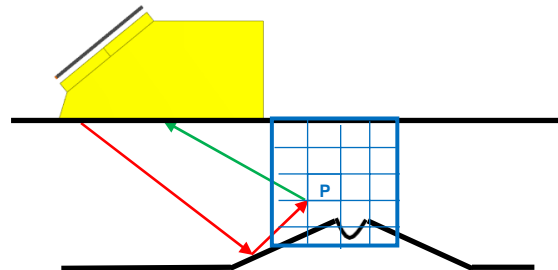
Principle

- **FMC:** Acquisition of the signals for all the pairs of T-R elements
- **TFM:** Processing based on the computation of TOF for all the pixels in the image
- Other acquisition schemes are possible: **SMC, SAFT, PWI, ...**
- **Adaptive TFM:** Surface reconstruction embedded



Multi-modal imaging

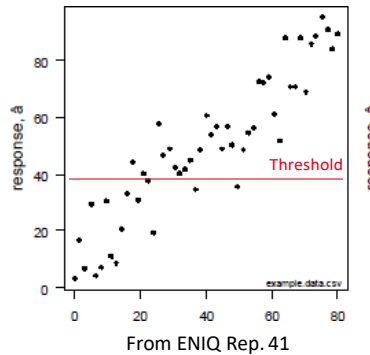
Exploitation of \neq pathes
(or modes) in the part



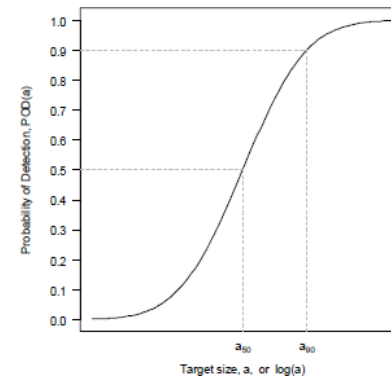
Can provide a
direct image
of the defect

- NDE reliability assesement
 - Important issue when adopting a technique of inspection
 - Deterministic (worst case) vs probabilistic approaches (POD).
 - **Simulation = a powerful tool for performance demonstration in the two contexts**
- POD probabilistic approach

Scattering of the results



Probability of detection



MAPOD: To replace costly experimental trials by numerical simulation.

- Simulation tools
 - Simulation tools for TFM in CIVA
 - Model validation
 - Meta-models

- Reliability assessment applied to TFM
 - Illustration on school case
 - Sensitivity analysis
 - Estimation of POD

- Accuracy assessment (sizing accuracy assessment) ?

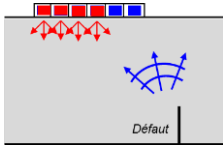
- A few words on statistical estimation of grid spacing influence

- Conclusions

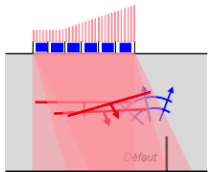
SIMULATION TOOLS FOR TFM

Acquisition schemes

Full Matrix Capture + SMC+...

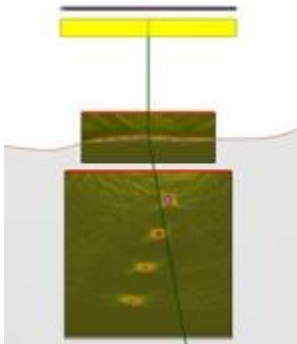


Plane Wave Imaging



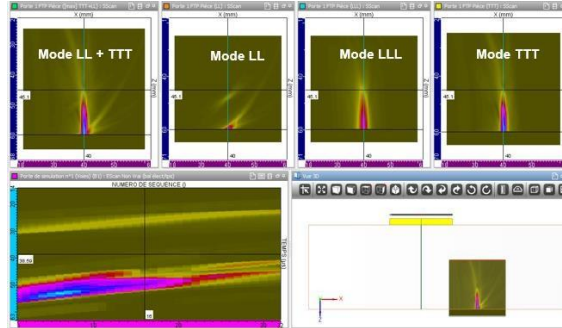
Adaptive TFM

(Embedded Surface reconstruction)

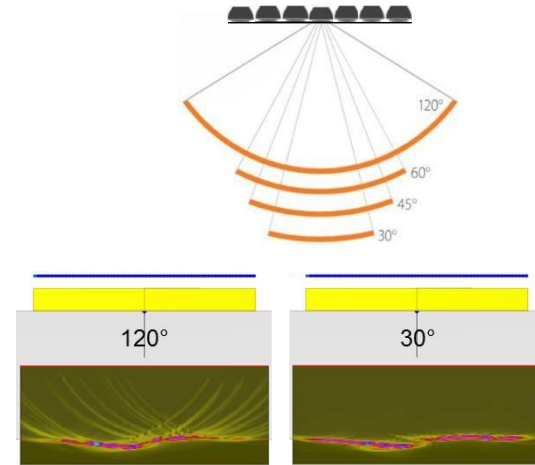


Large set of options and filters

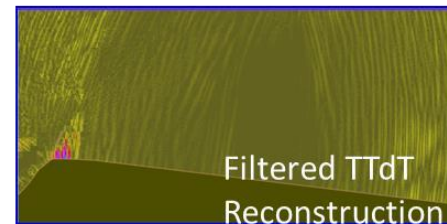
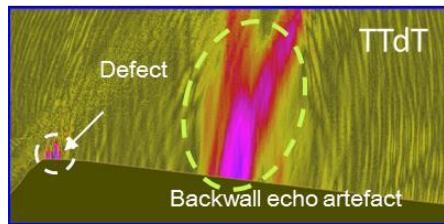
Multimodal



Diffraction cone filtering



Backwall artefact filtering for half-skip modes



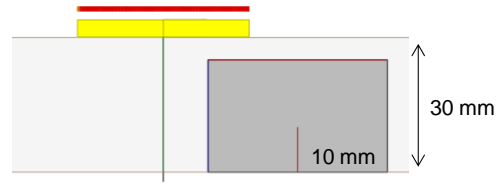
Optimization of FMC
(selection of active elements
Sparse array)



SIMULATION TOOLS FOR TFM: VALIDITY OF THE MODELS

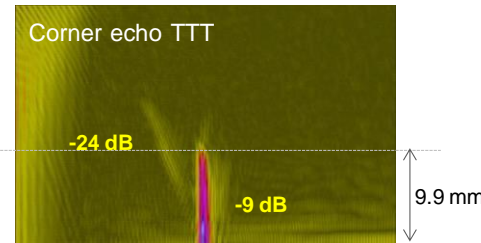
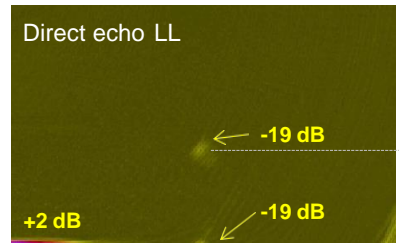
- First requirement : to have well-validated models !
- TFM simulation is based on the standard propagation/interaction CIVA

WFNDEC 2015 Benchmark : Multi-modal TFM (notches in steel blocks)

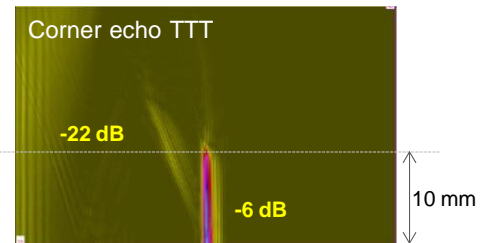
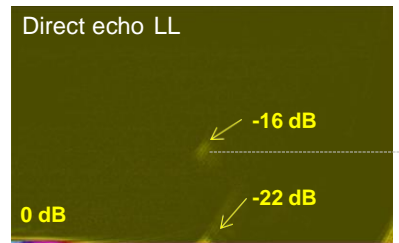


Specimen material : carbon steel 1020
 Density: 7.8 g/cm³
 c_L: 5900 m/s
 c_T: 3230 m/s
 (ref. CEA1105)

Measured

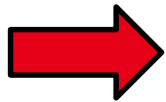
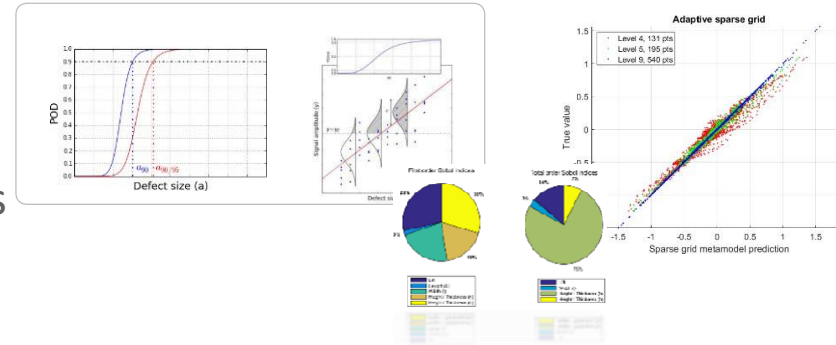


CIVA



Performance demonstration means:

- Multi-parameters studies
- Uncertainty propagation & statistical analysis
- **Intensive computations!**



Development of a simulation strategy based on *metamodels*

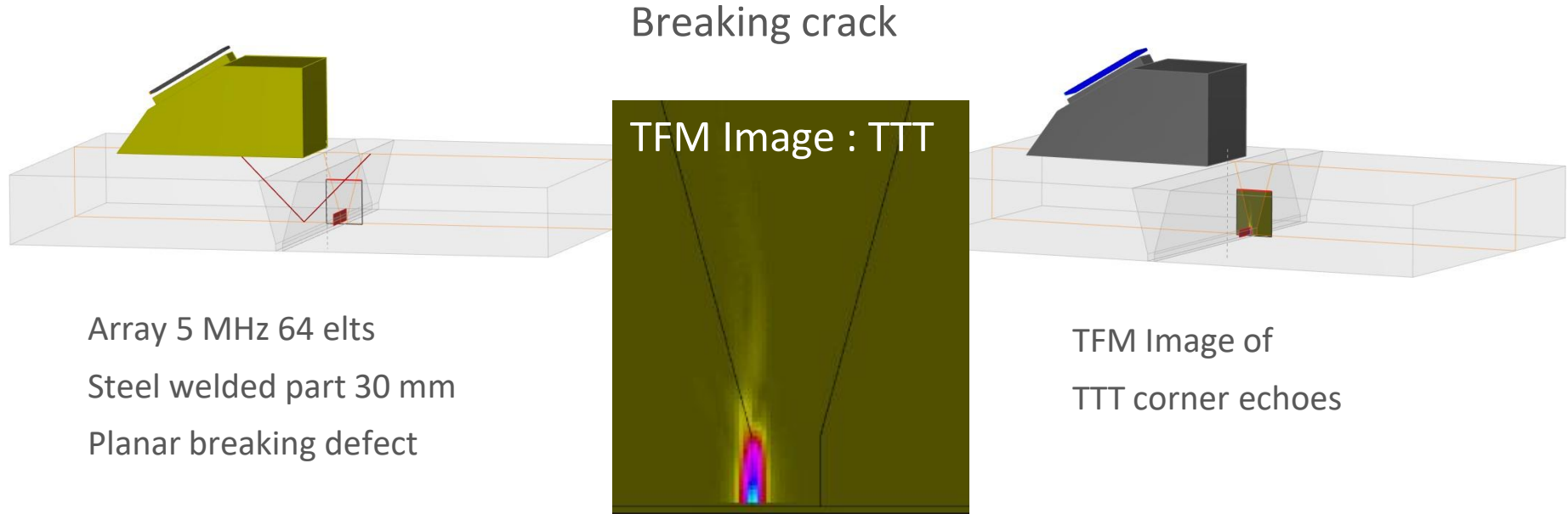
Meta-model: “Smart interpolator” of a numerical data base substituted to a physical model

Two steps:

- Creation of the metamodel:
Implies the generation of a numerical data base (time consuming!)
- Exploitation of the metamodel:
Ultrafast computations

RELIABILITY ASSESSMENT
Sensitivity analysis & POD

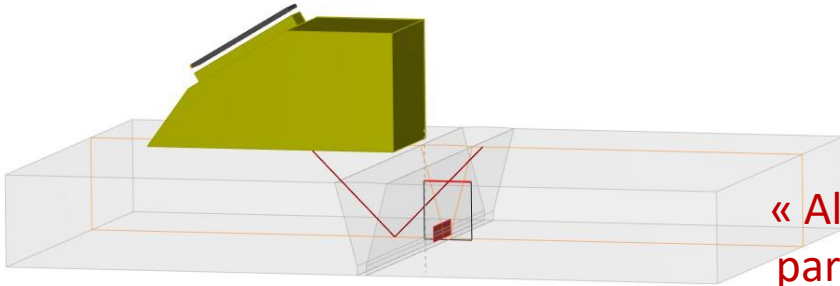
Illustration on one School case: TTT FMC-TFM inspection of a weld



Objective of the study: Estimate the sensitivity of the detection performances to the different parameters and establish a POD.

Methodology: Metamodels + uncertainty propagation

CREATION OF THE METAMODEL



Array 5 MHz 64 elts

Steel welded part 30 mm

Planar breaking defect

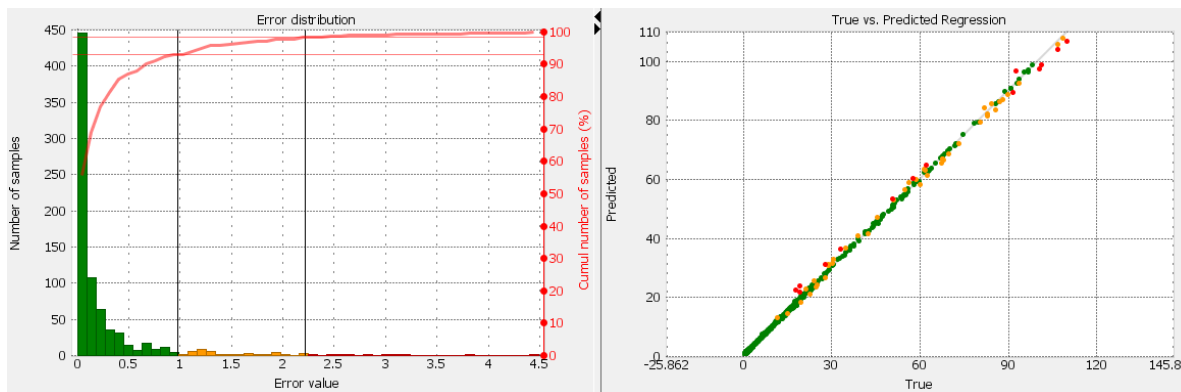
Input: Data base 4 parameters

- Defect Height (0-7 mm)
- Tilt angle (-15°-15°)
- Part thickness: 28-32 mm
- T-waves velocity: 3000-3400

Output: Amplitude Max of TFM-image

Interpolator: Kriging

Cross-Validation

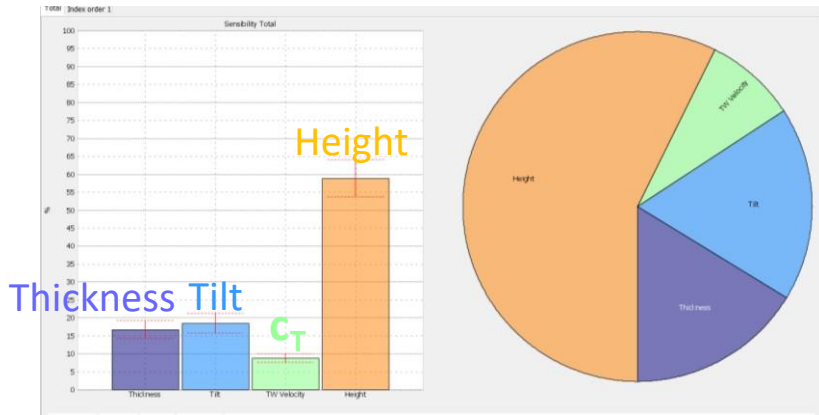


Measure of the discrepancy between CIVA and the meta-model

Sobol Index

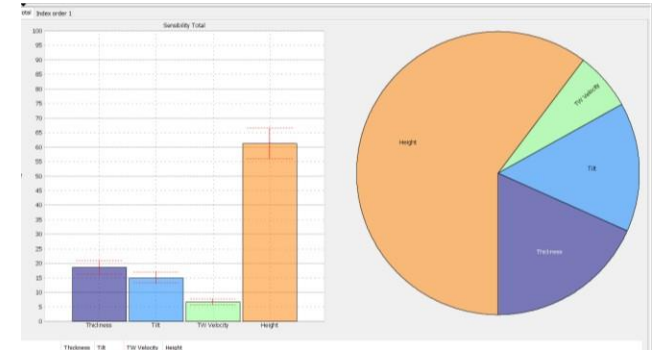
Measure the relative importance of the influential parameters

Full range of defect sizes



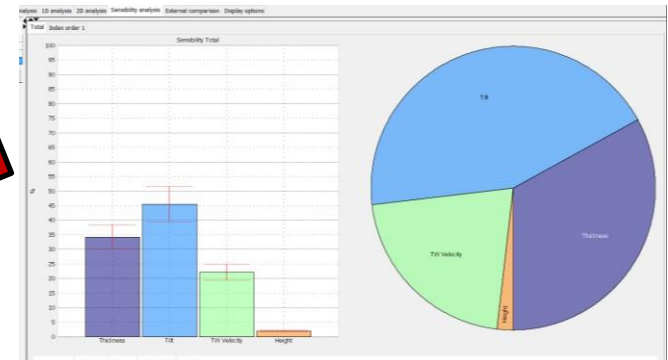
Height 0.5mm – 7mm

Smallest defects



Height 0.5mm – 3mm

Largest defects



Height 3 mm – 7mm



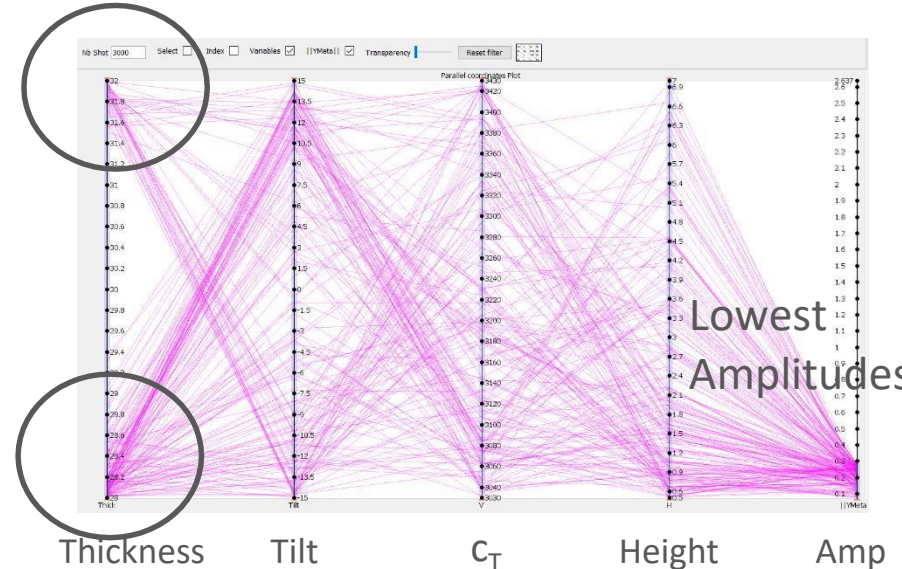
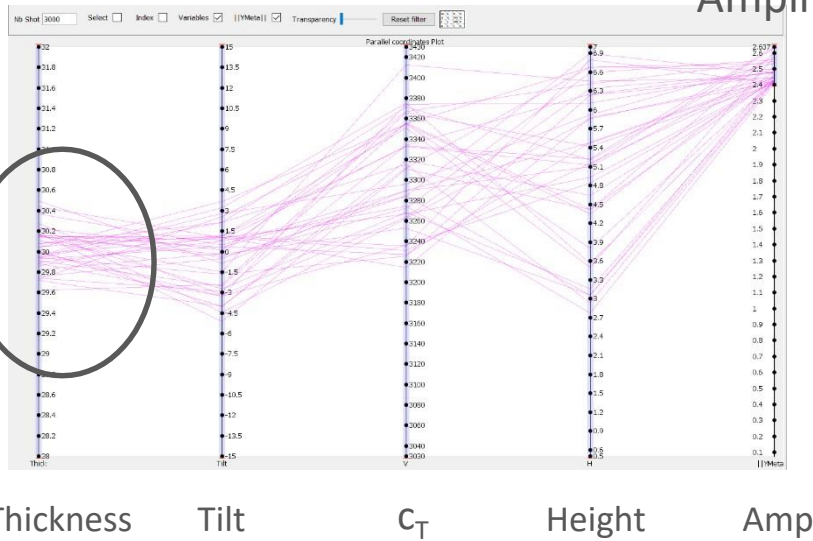
As in conventional UT the amplitude of the corner echo does not vary with Height for large defects (not surprising)

Parallel coordinates plots

Best cases

Highest Amplitude

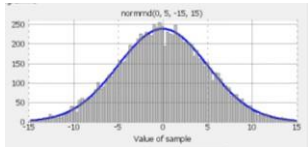
Worst cases



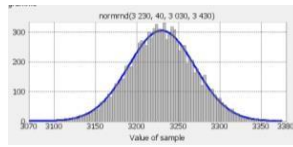
Illustrates the importance of the **tilt** (as in conventional UT)
 And of the knowledge on the real **thickness** (input of the imaging algorithm)

POD ESTIMATION

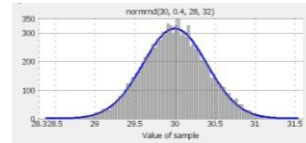
- Distribution of the « aleatory » parameters Tilt, c_T , Thickness:



$$N(0, \sigma_{tilt})$$

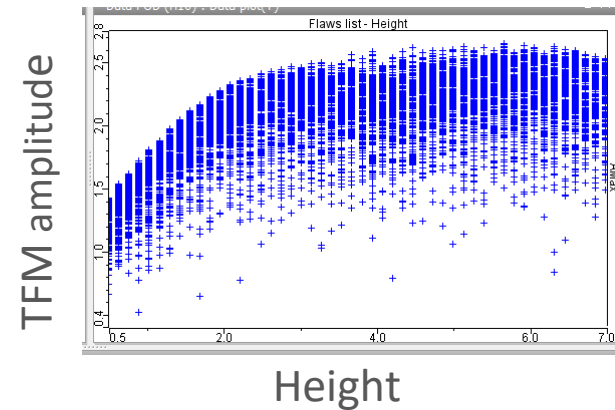


$$N(3230, \sigma_{cT})$$

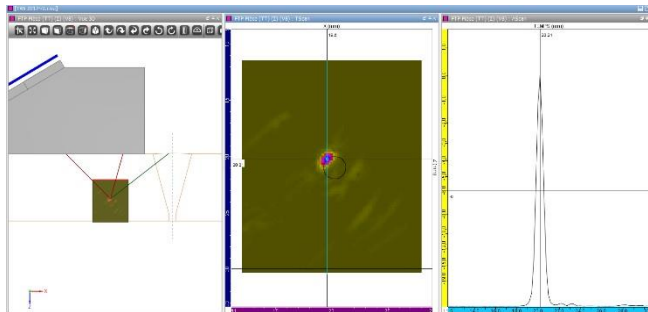


$$N(30, \sigma_{thick})$$

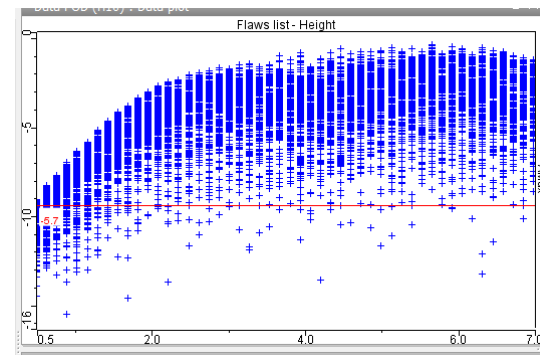
- Meta-model computations (MC sampling):



- Calibration an threshold definition:

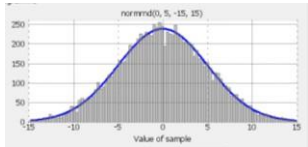


SDH, $\varnothing 2\text{mm}$
Z = 20 mm
Threshold: -6dB

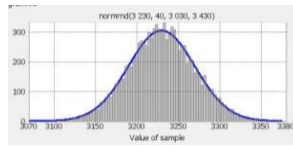


POD ESTIMATION

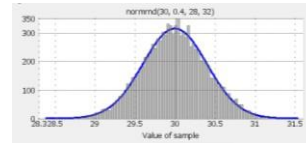
- Distribution of the « aleatory » parameters Tilt, c_T , Thickness:



$$N(0, \sigma_{tilt})$$

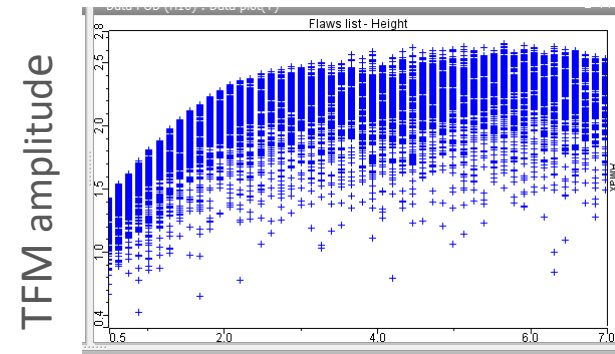


$$N(3230, \sigma_{cT})$$

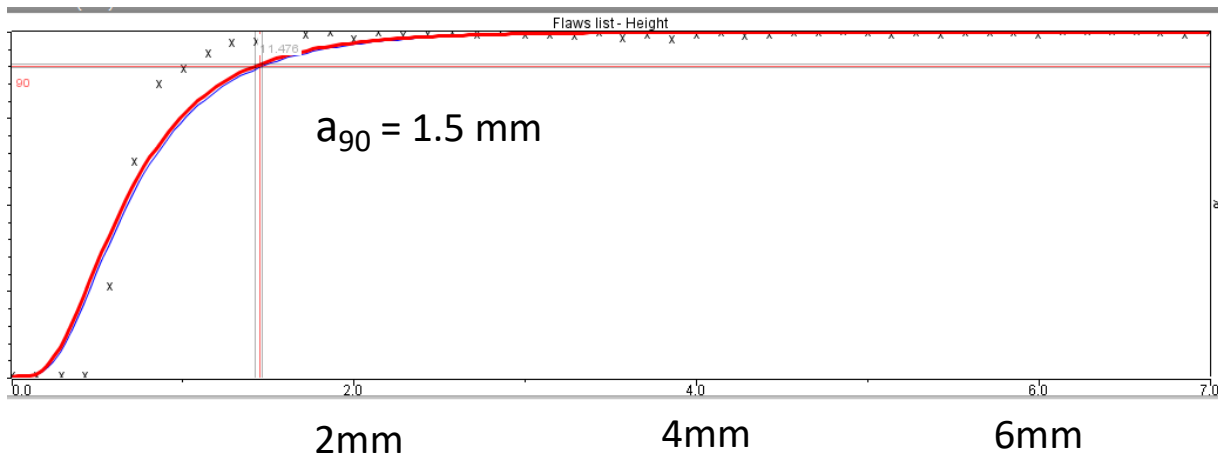


$$N(30, \sigma_{thick})$$

- Meta-model computations (MC sampling):



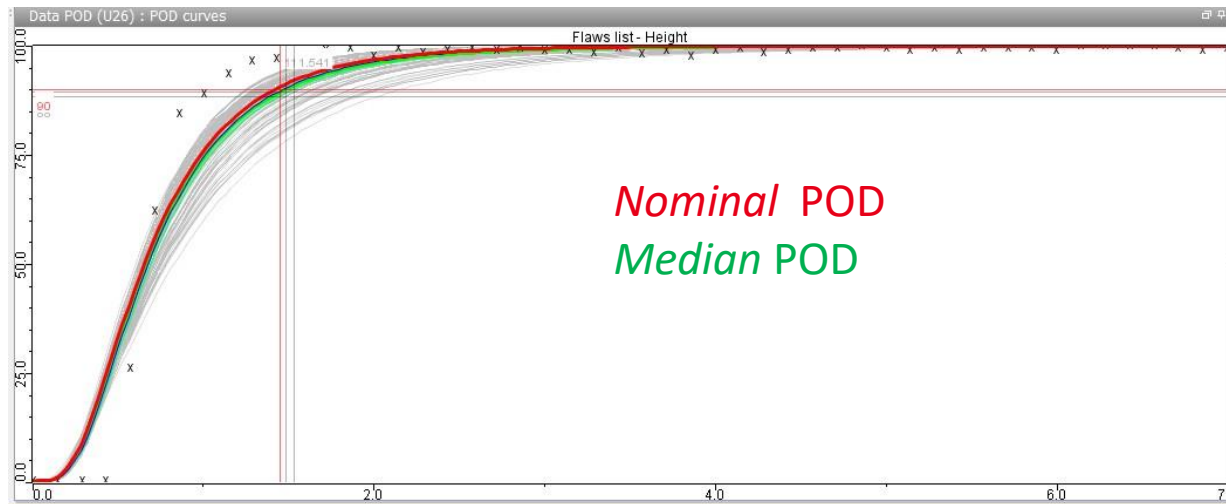
- POD estimation : Hit-miss (logit)



— Logit
x x x x x Hit-miss ratio

POD ESTIMATION

- Validity of one POD curve estimated by simulation: Strongly depends on the variability introduced in the process:



- Possibility to compute « beams » of POD corresponding to different distributions

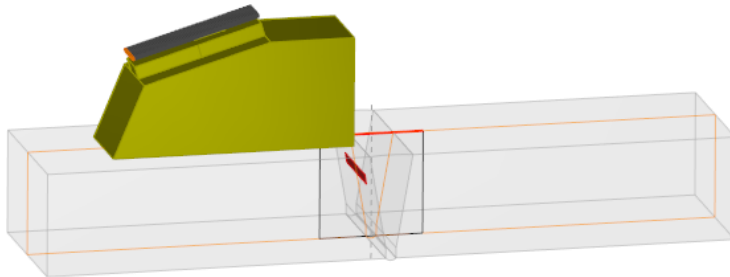
ACCURACY ASSESSMENT

Proof of concept

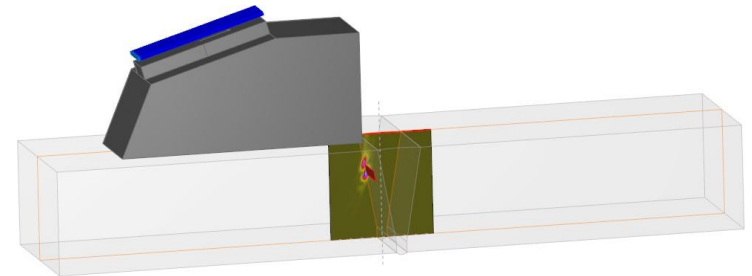
Proof of concept

Illustration on one School case: Sizing accuracy of a FMC/TFM inspection

Defect along the bevel



Array 5 MHz 64 elts
Steel welded part 30 mm



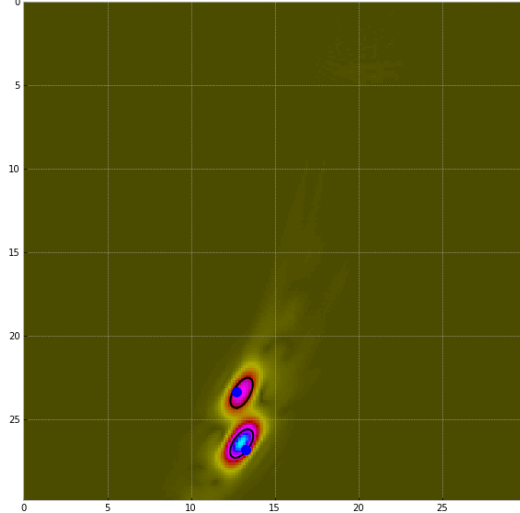
TFM Image of
LL tip diffraction echoes

Proof of concept

Simulation of the sizing procedure :

- Automatic localization of the maxima of the two tip diffraction reconstructed echoes on the TFM image.
- + Random process to account for noise/measurement accuracy

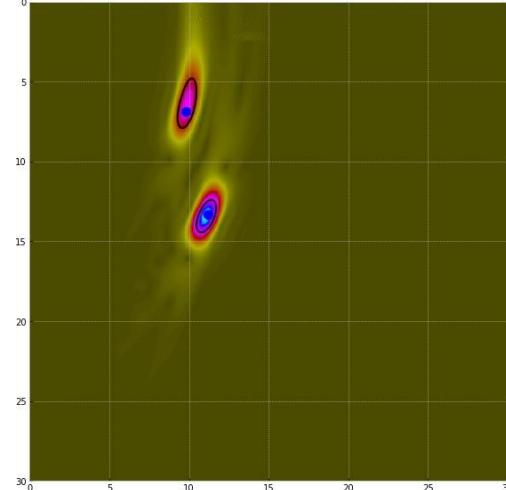
defect height : 3.0 mm, pixel resolution : 0.15 mm, tilt : 10.0°, depth : 25.0 mm



True defect size : 3.00 mm
Estimated defect size : 3.50 mm

Edge localization:
Random value
within 2dB spots

defect height : 7.0 mm, pixel resolution : 0.05 mm, tilt : 0.0°, depth : 10.0 mm



True defect size : 7.00 mm
Estimated defect size : 6.59 mm

Proof of concept

- Introduction of the variability + uncertainty propagation:

➔ Same as for a POD study

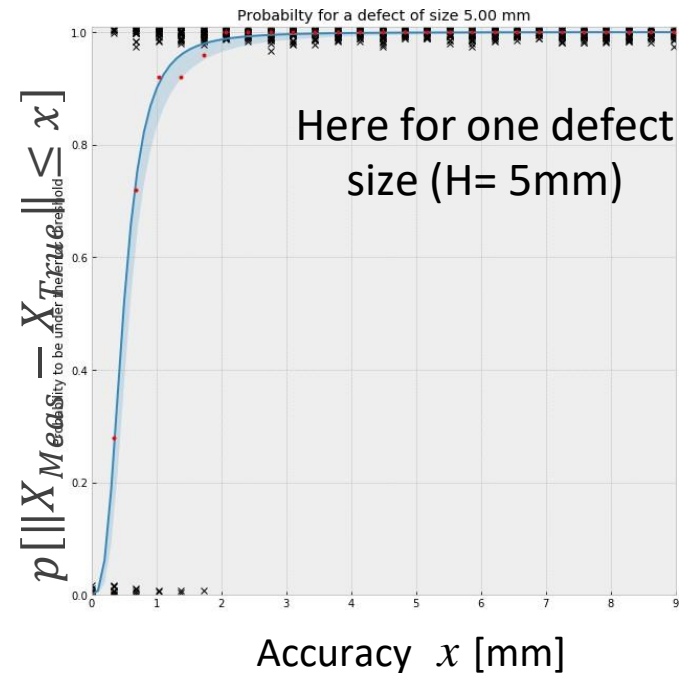
In this example:

- Variability :
 - Defect height: : 1-10mm (Uniform)
 - Defect tilt: -10°,10° (Normal)
 - Depth along the bevel: 10-25mm (Uniform)
- Use of CIVA metamodel

- Definition of a metric:

$$\text{Probability of accuracy}(x) = p[\|X_{Meas} - X_{True}\| \leq x]$$

$$x \in [0, \dots mm]$$



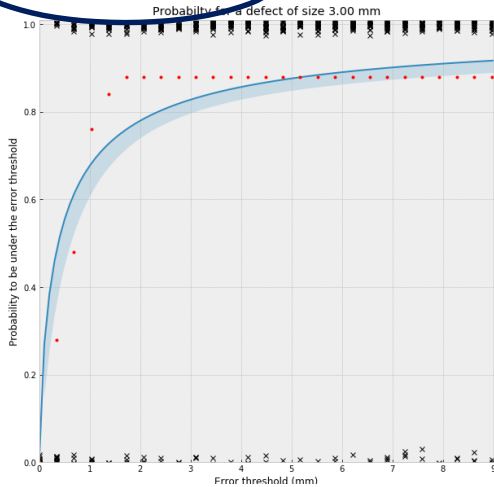
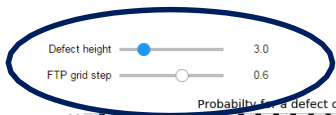
Example of representation

Proof of concept

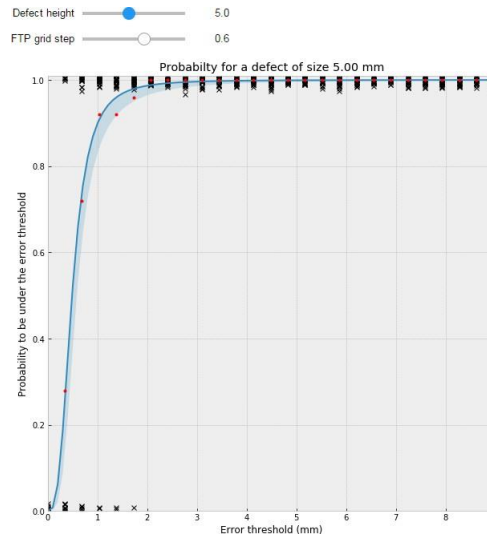
- Illustration of the potential of the analysis (here school case):

Assessment of the sizing accuracy vs the size of the defect

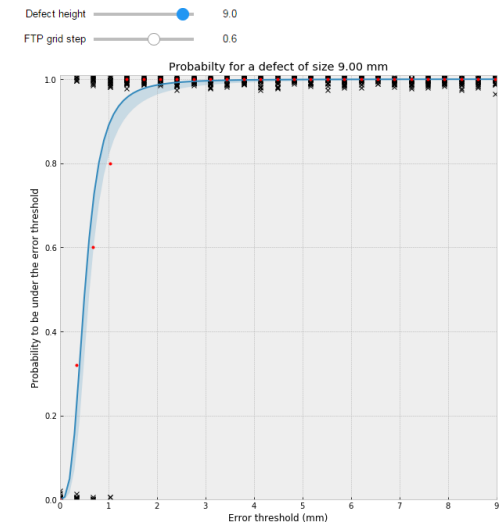
Interactive variation



H = 3mm



H = 5mm



H = 9mm

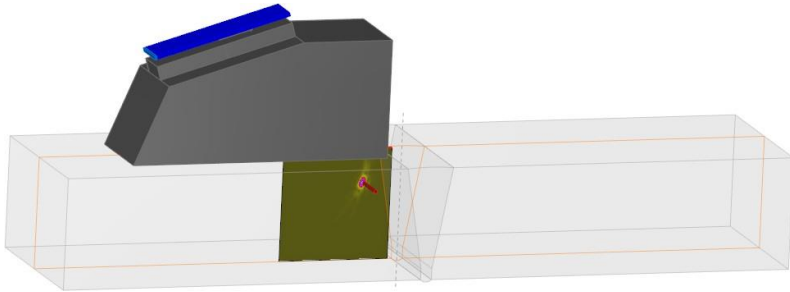
More difficult to size small defects

ADDITIONAL EXAMPLE

Influence of the grid « resolution »

Estimation of the influence of the grid spacing on TFM images

Configuration similar to the previous ones



Array 5 MHz 64 elts

Steel welded part 30 mm

SDH Φ 2mm

Methodology:

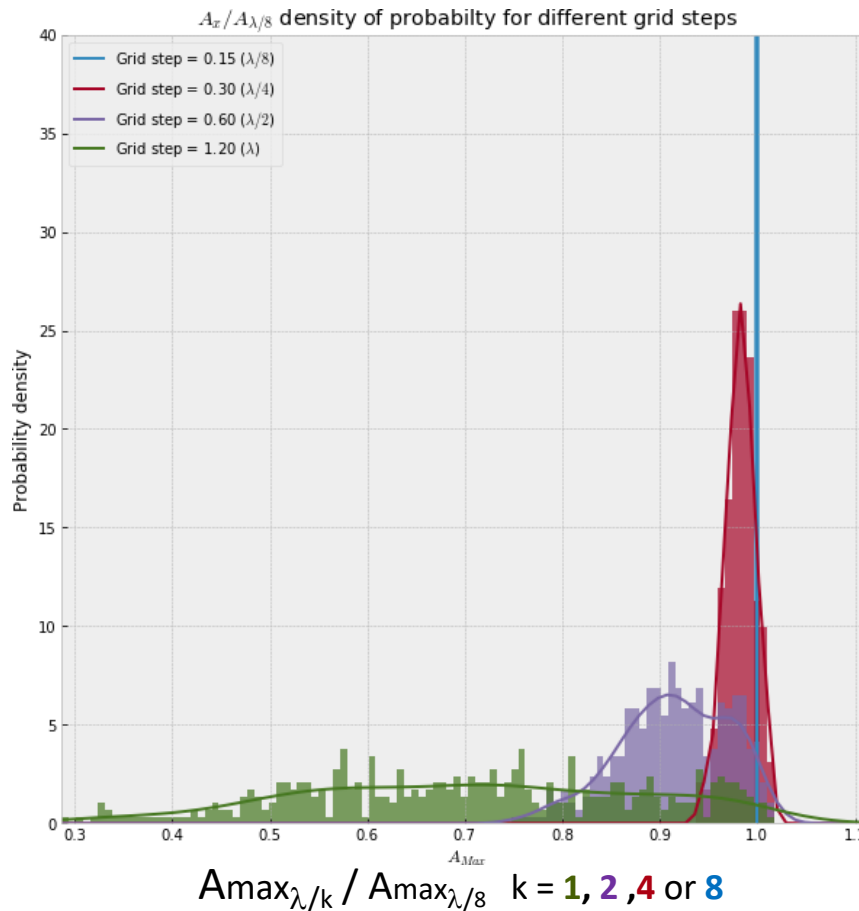
- Statistical estimation of the amplitude loss on the TFM image of a SDH Φ 2mm with increased grid spacing.
- 4 grid spacing: $\lambda/8$, $\lambda/4$, $\lambda/2$, λ . $\lambda/8$ considered as the reference.
- Statistical sampling of 400 defects aleatory located in the ROI..
- Simulation of the 4 x400 TFM images and (automatic) extraction of the amplitude max.
- Histogram representation of the amplitudes for the 4 grid spacing.

SIMULATION- BASED RELIABILITY ASSESSMENT

Estimation of the influence of the grid spacing on TFM images

Result

Statistical distributions



Rough conclusions

- At $\lambda/4$ the loss is < 1 dB
- At $\lambda/2$ the loss is < 2 dB
- At λ the loss > 6 dB

- Simulation tools can be used to optimize or assess the performances of TFM as others UT techniques.
- In particular, we have illustrated the possibility to carry out sensitivity analysis and POD study on a Multi-modal TFM technique (detection criteria = amplitude threshold).
- The influence of parameters specific to TFM can be quantitatively estimated on a case by case basis.
- We have also shown how the accuracy of a sizing can also be estimated by using simulation.
- We have not discussed automatic diagnostic on TFM inspection (attend **R. Fernandez 's talk Tuesday 16h** Session: Energy Generation)
- We have not discussed adaptive imaging (attend **F. Cartier 's talk Wed 16h** Session: PAUT-Signal processing)



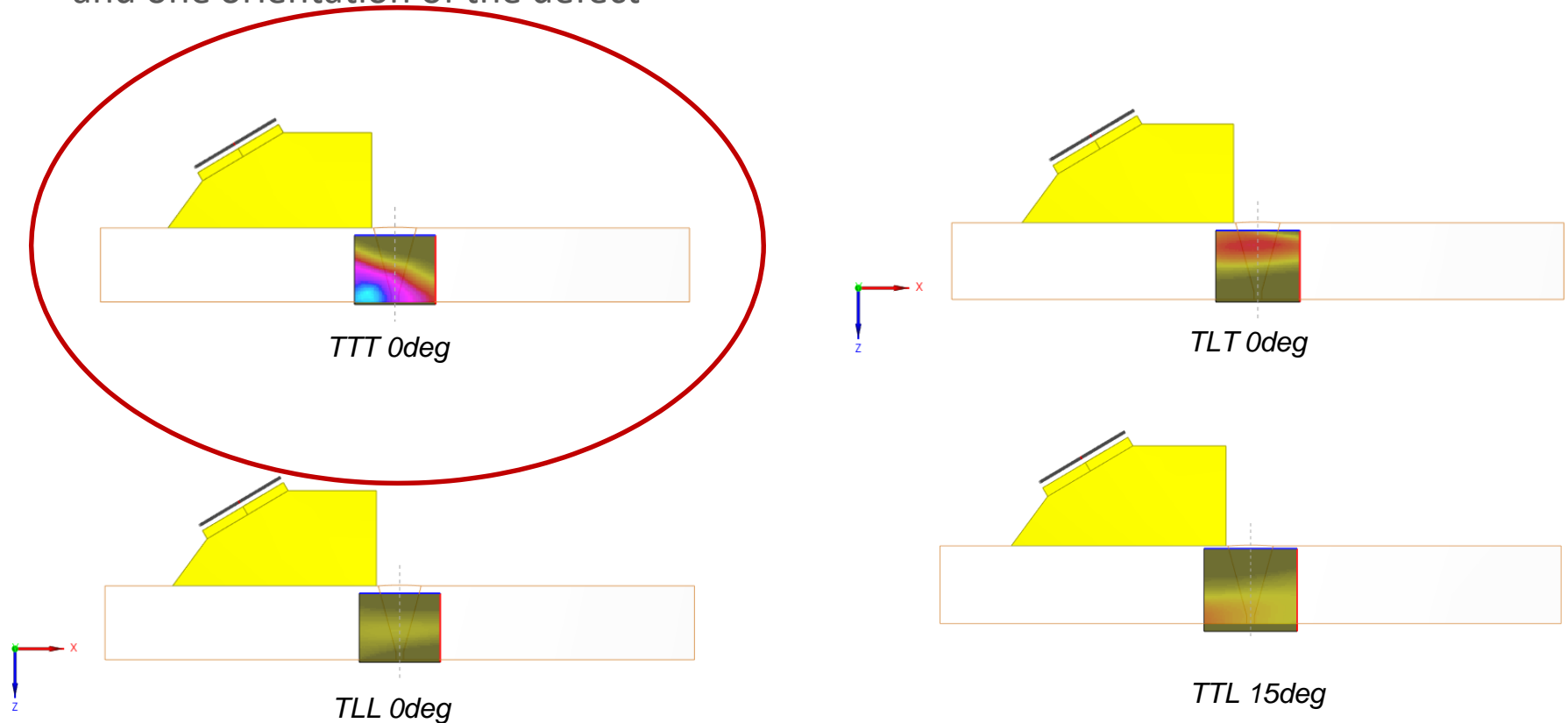
Thank you for your attention

Commissariat à l'énergie atomique et aux énergies alternatives
Institut List | CEA SACLAY NANO-INNOV | BAT. 861 – PC142
91191 Gif-sur-Yvette Cedex - FRANCE
www-list.cea.fr

Établissement public à caractère industriel et commercial | RCS Paris B 775 685 019

A PRIORI ESTIMATION OF RELEVANT MODES

Key idea: Exploitation of a **Sensitivity maps** (operator « SEE ») defined for one mode and one orientation of the defect



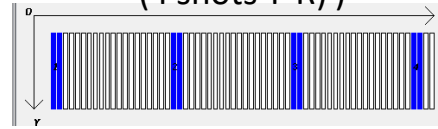
SEE: Estimation of the weighed number of T-R pairs in condition of specular reflexion

SIMULATION vs EXPERIMENT FOR ≠ ACQUISITIONS SCHEMES

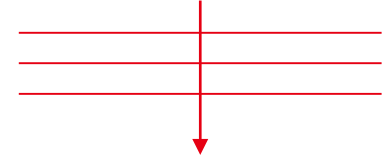
Array 64 elts
Steel 2MHz
SDH, Ø2mm
Z = 45 mm

FMC-TFM

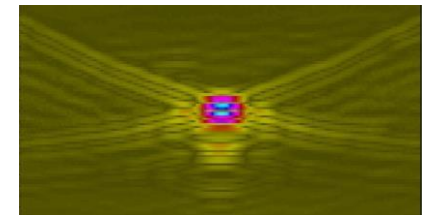
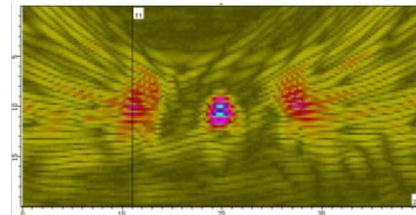
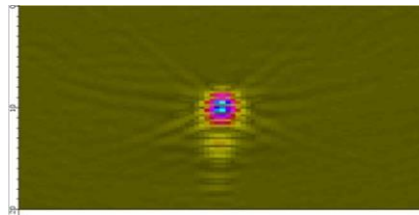
SMC-TFM
(4 shots T-R)



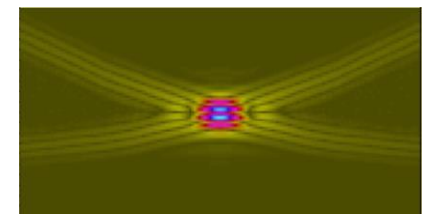
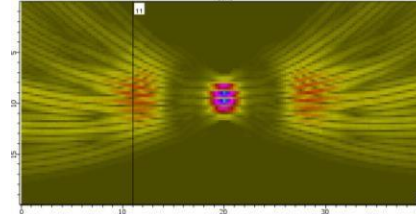
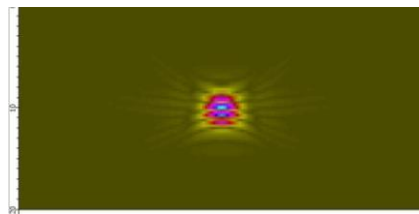
PWI LO°-TFM
(1 shot-all R)



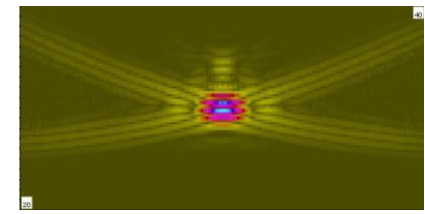
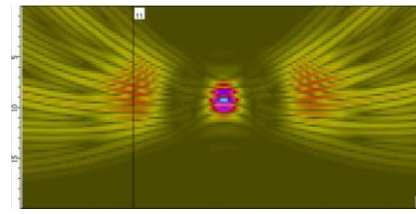
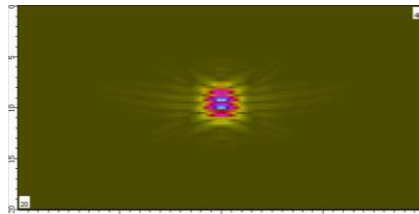
Experiment



Simulation



Snapshots of
the T-R field



Quite good agreement + interesting (basic) information