EDF EXTENDE

Simulation methodology for worst cases identification during NDE technique qualification

Application on advanced UT method for ISCC detection in safety injection system of nuclear power plant

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EXTENDE Activities

Worldwide CIVA **DISTRIBUTION** and technical **SUPPORT**

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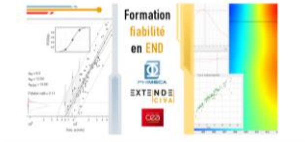

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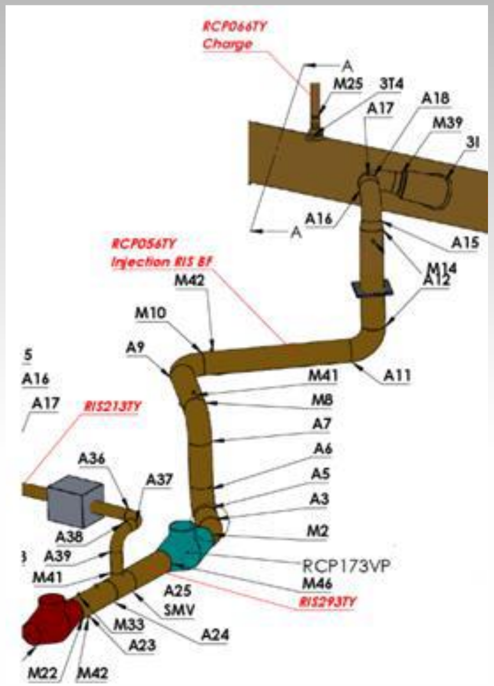
Consulting Study – Context

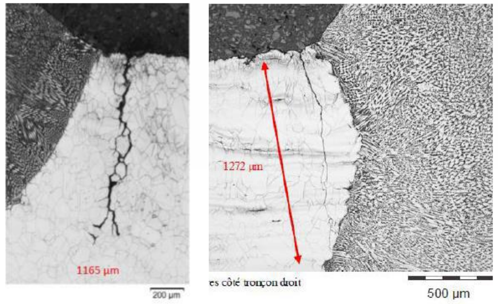


Safety Injection System (SIS)

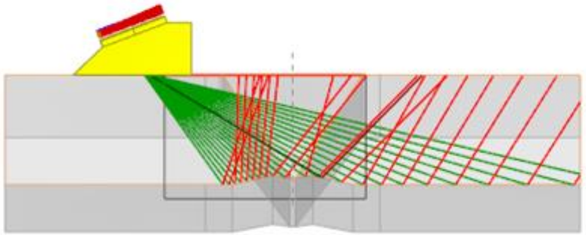
- To inject boron water into the main primary circuit of the nuclear reactor to regulate neutronic activity.
- To maintain enough water level in the reactor core for cooling the combustible.

During regulatory inspection of Civaux unit 1 nuclear facilities (fall 2021), NDE carried out on SIS pipes welds revealed unexpected damages linked to Intergranular Stress Corrosion Cracking phenomenon (ISCC). For precaution, 12 units potentially affected were gradually shut down (for preventive/early maintenance). After investigations, a new NDE design was required to restart these reactors **very quickly** and enable all the nuclear fleet units' inspection

An advanced ultrasonic technique (FMC-PWI-TFM using optimized dual linear probes) was reactively developed and implemented by EDF with the support of its partners to reliably detect and characterize potential cracks. The first NDE system was tested on cut pipes removed from sites for laboratory metallurgical investigations and a good correlation was proven between UT results and ISCC destructive characterizations. The final NDE system was deployed in July 2022 for expertise inspections.



As part of the instruction of the qualification strategy, EDF contacted EXTENDE to determine using CIVA the worst inspection configurations (in terms of specimen and flaw influential parameters) for the detection sensitivity performances of this new NDE technique. Two scenarios were considered by EDF: to determine an impact on performance using CIVA simulation or to create a penalizing mockup for experimental evaluation.



EDF contacted EXTENDE in 2021-2022 to optimize the DLA probe parameters using simulation.

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Simulation methodology for worst cases identification during NDE technique qualification

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- Definition of influential parameters and simulation tool validation
- Monoparametric variations around a nominal inspection configuration
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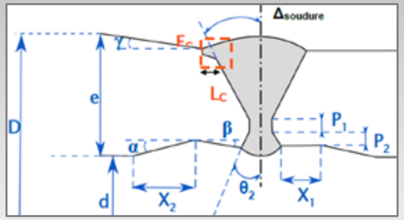
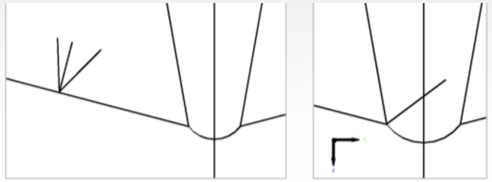


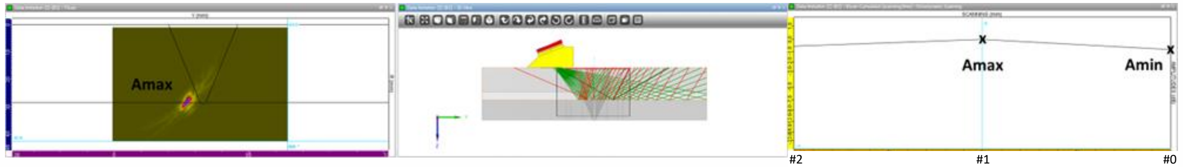
Definition of influential parameters and simulation tool validation

- Define a list of influential parameters (IP) for the studied NDE technique
  - Do not limit the initial number of parameters to avoid missing one
  - Try to reduce this IP number using engineer reasoning, previous results, etc.
  - Be careful with convention definition and variation ranges choices for each IP

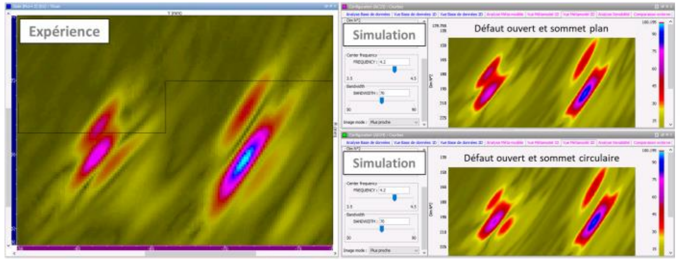
ID	N°	Paramètre	Description	Unité	Valeur min	Valeur max	Valeur nominale	Traitement
0	C21	T	Géométrie Tube / Coude	mm	Data are confidential			Fixe
1	C21	D	Diamètre externe tuyauterie	mm				Fixe
2	C21	Ep	Epaisseur métal de base	mm				Variation
3	C22	α	Angle de délardage côté base	°				Variation
4	C22	β	Angle de délardage côté soudure	°				Variation
5	C24	X1	Largeur de délardage côté soudure	mm				Variation
6	C24	X2	Largeur de délardage côté base	mm				Formule
7	C25	θ_v	Angle soudure chanfrein V	°				Variation
8	C30	cL	Célérité OL métal de base + soudure	m/s				Variation
9	C30	cT	Célérité OT métal de base + soudure	m/s				Variation
10	D1	H	Hauteur du défaut cible	mm				Fixe
13	D3	Tilt	Angle de tilt du défaut cible	°				Variation
15	D5	Pdef	Position axiale du défaut cible	mm				Variation
16	MO	Psonde	Offset face avant sonde / axe soudure	mm				Formule



- Analyze the inspection procedure and the NDE performance criteria
  - Default extracted criteria or customized criteria using script features [Zone coverage, detection sensitivity, characterization/sizing performances? Calibration procedure?]

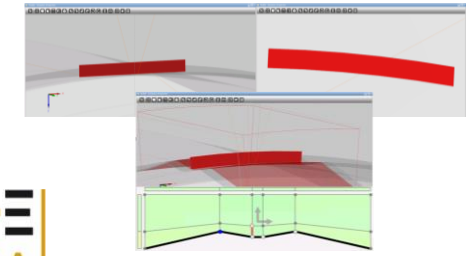


- Investigate the relevance of the software (CIVA) to simulate the NDE technique performances to qualify over all the IP variation ranges
  - Compare simulation and experimental results
  - Test and justify the best simulation options and strategy for all the IP variation ranges



- **This first phase is of paramount importance to validate the simulation tool and define an appropriate strategy (best computation time / results accuracy tradeoff) to generate relevant databases with all possible IP combinations for sensitivity analysis study.**

- Warning: All modifications in terms of IP and their variation ranges must be carefully addressed since it may require to relaunch all the simulations to ensure the relevance of the simulation tool under such new conditions.



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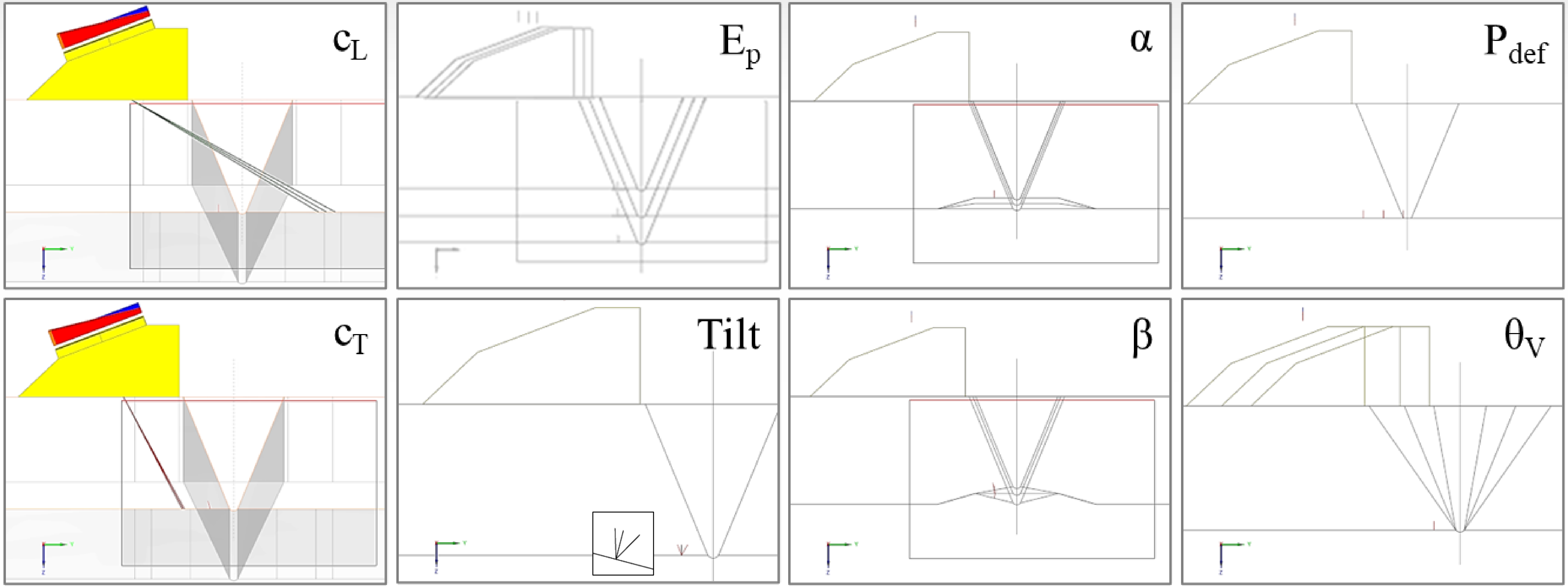

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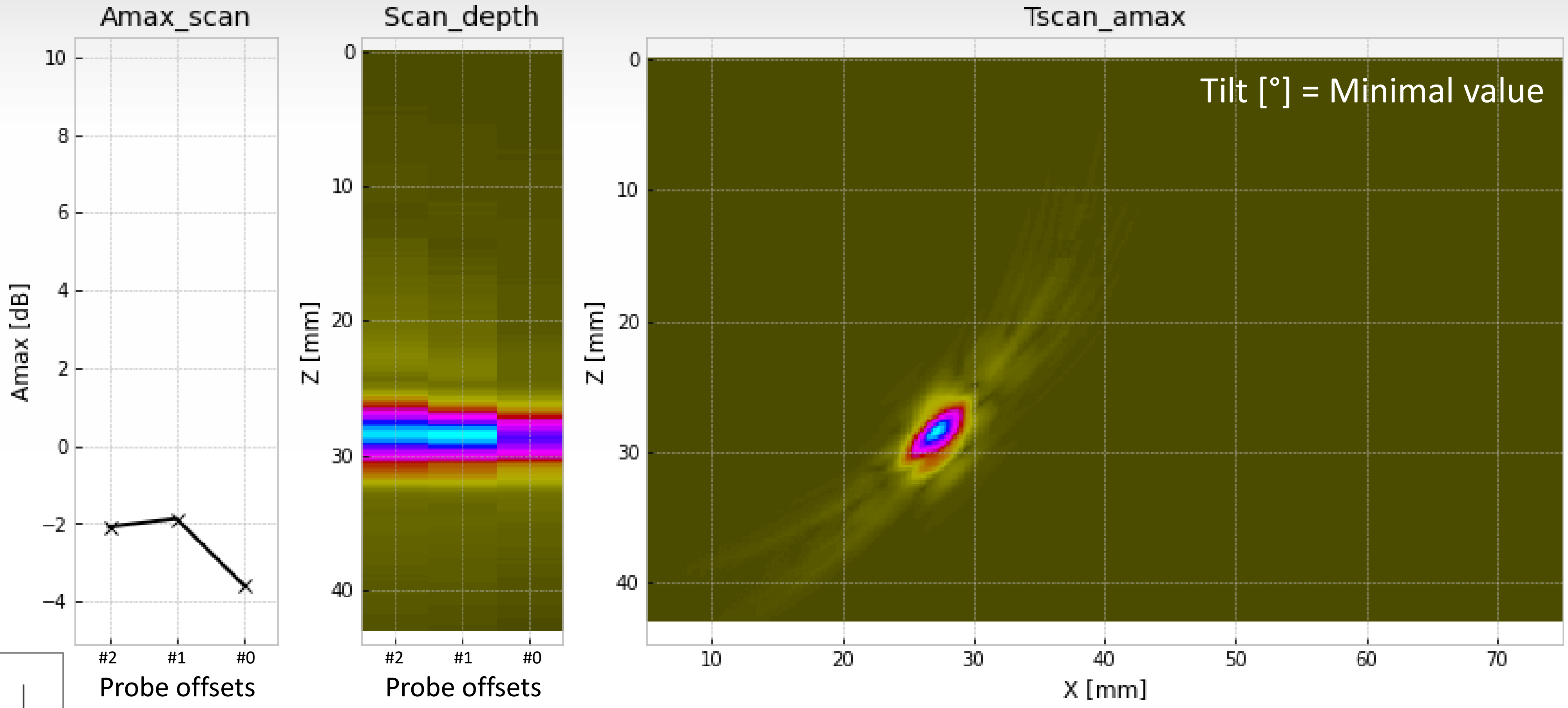

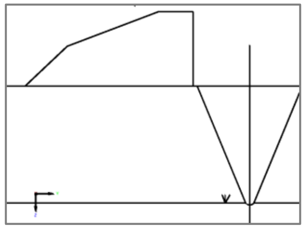

T12p-4MHz – Parameter: Tilt [°]

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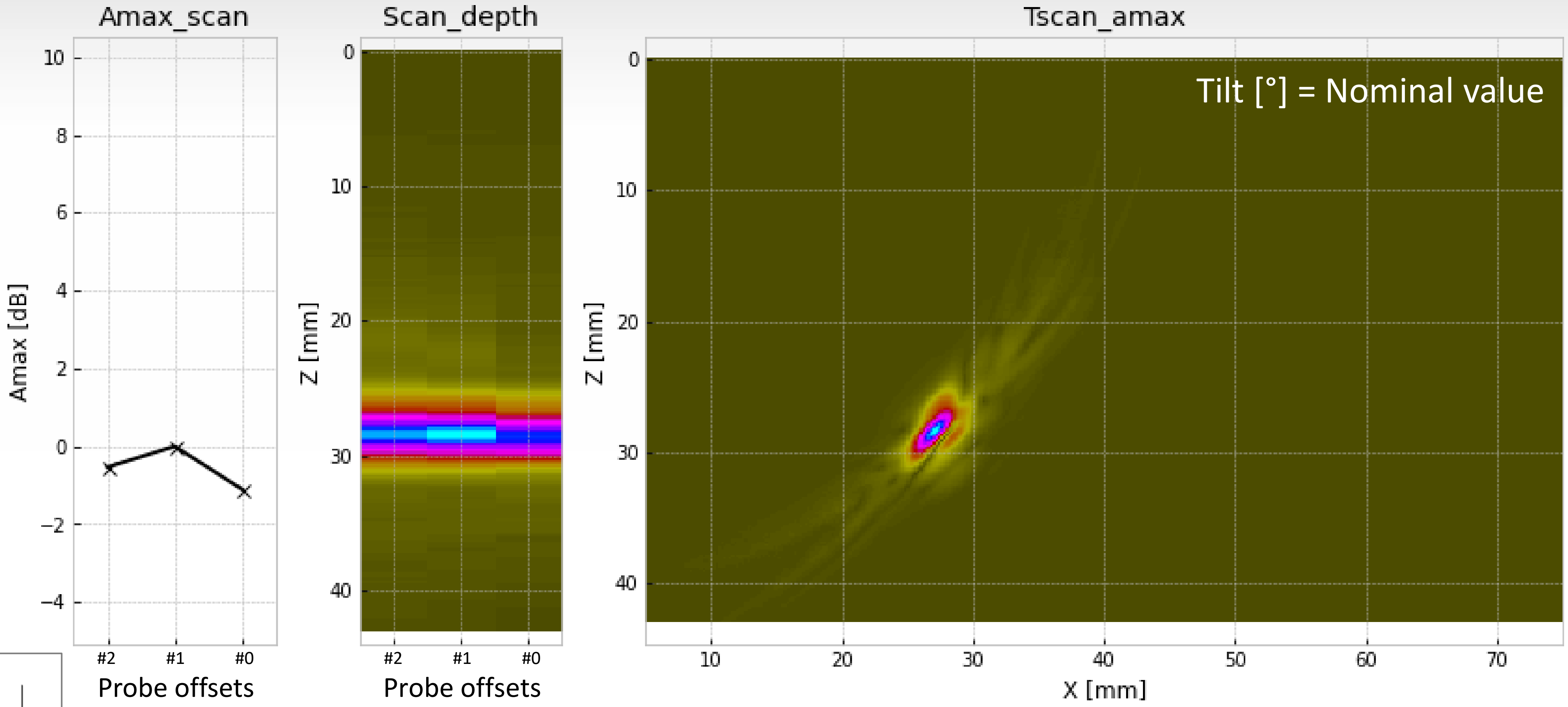

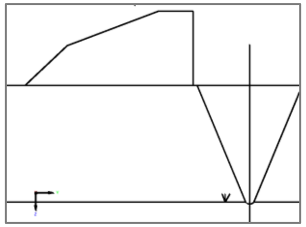

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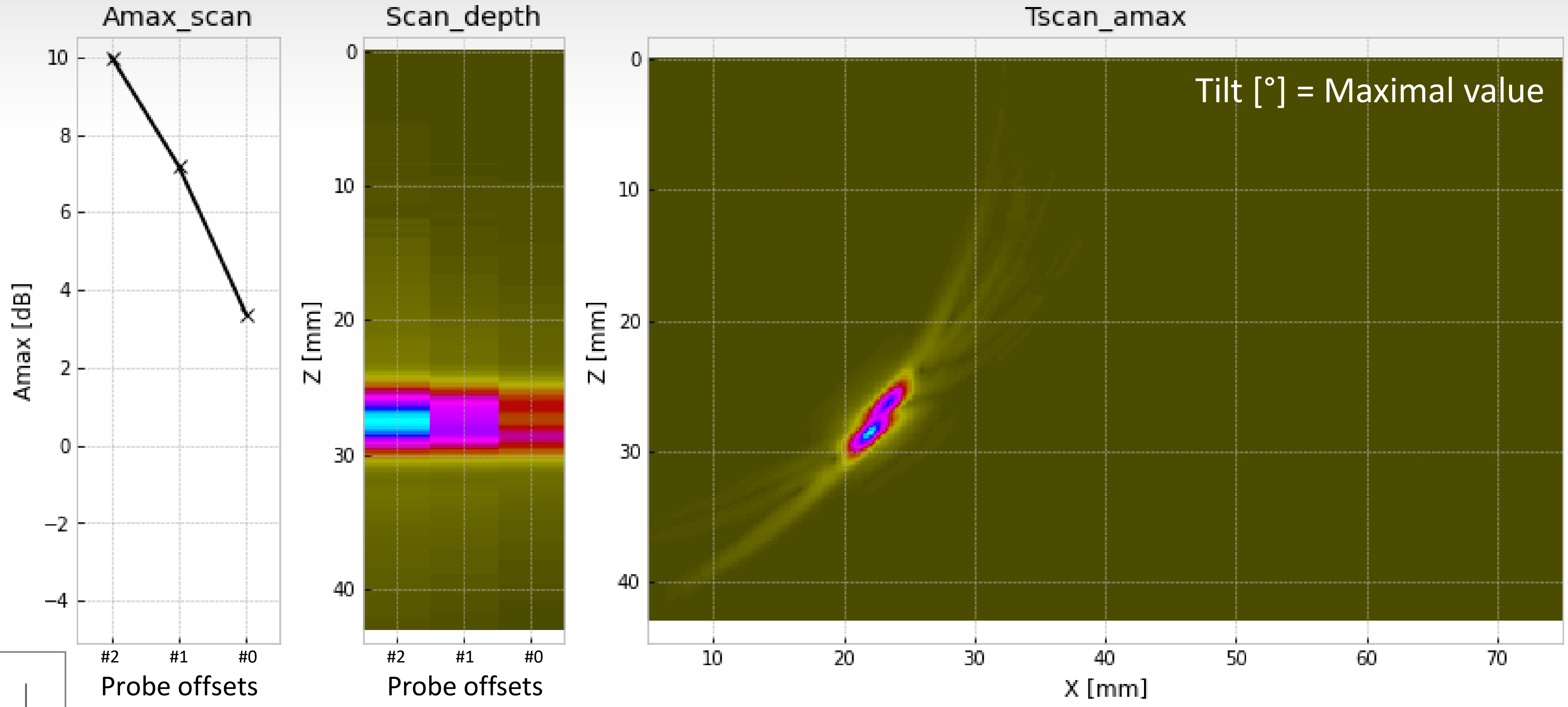

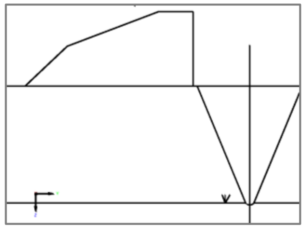

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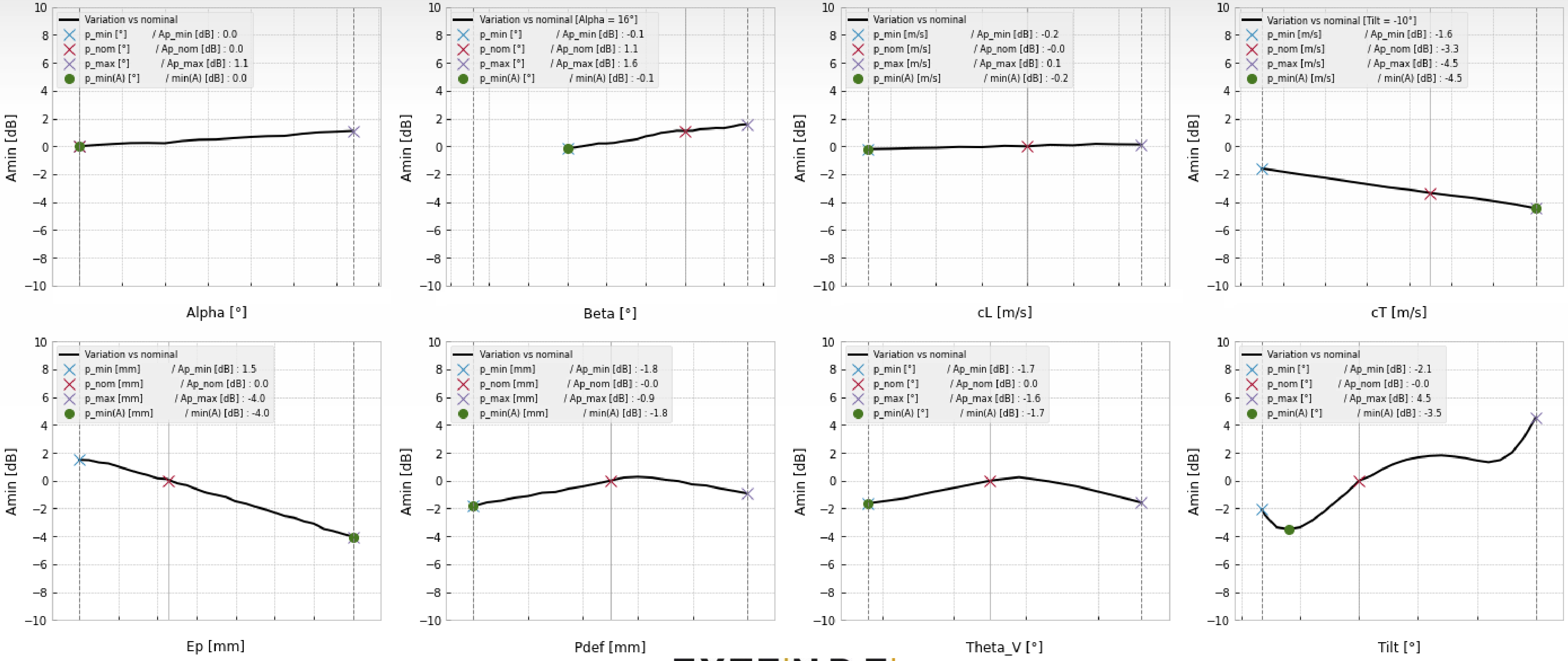
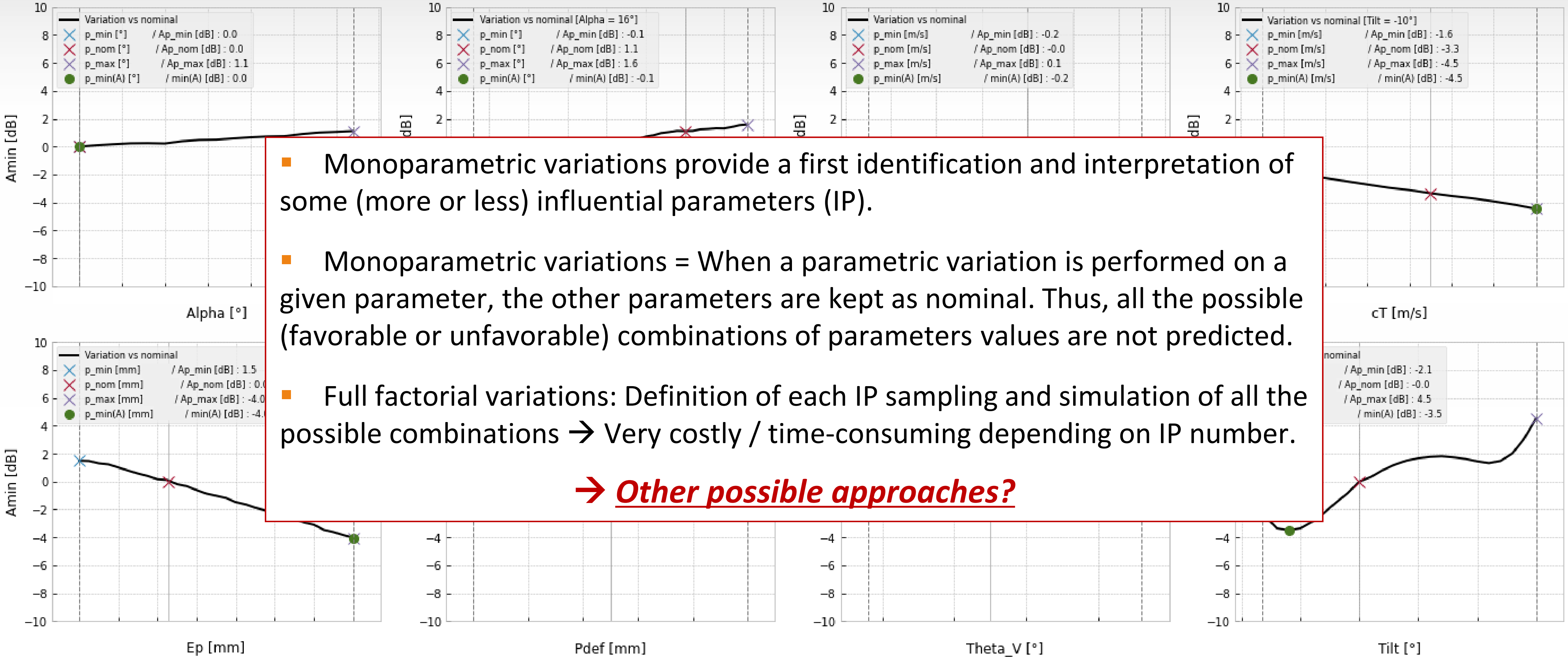


T12p-4MHz – All parameters

Simulation methodology for worst cases identification during NDE technique qualification

Monoparametric variations around a nominal inspection configuration



- Monoparametric variations provide a first identification and interpretation of some (more or less) influential parameters (IP).
- Monoparametric variations = When a parametric variation is performed on a given parameter, the other parameters are kept as nominal. Thus, all the possible (favorable or unfavorable) combinations of parameters values are not predicted.
- Full factorial variations: Definition of each IP sampling and simulation of all the possible combinations → Very costly / time-consuming depending on IP number.

→ ***Other possible approaches?***

T12p-4MHz – All parameters

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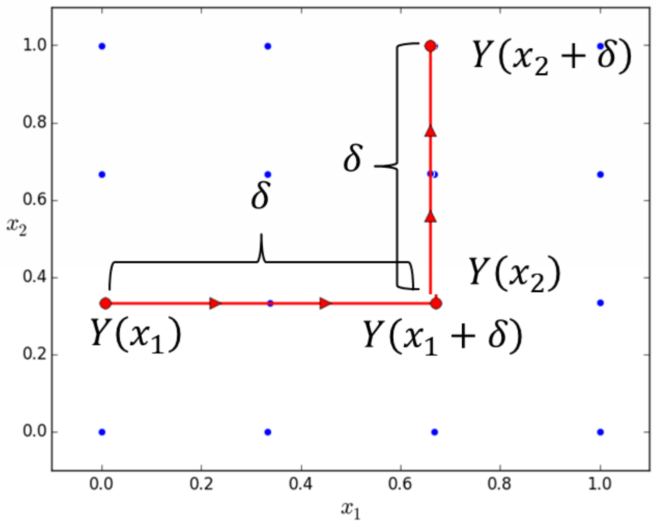
Multiparametric variations: Morris's method

- « Screening » type method which allows to “quickly” evaluate the most influential parameters to define a first selection, and to qualify their general behavior (linear, monotonic, etc.).

1. Generation of a **“one-by-one” design of experiments**:
   - 1st experiment with all the parameters fixed at a given value depending on the selected level number k (and number of trajectories r)
   - Perturbation of each parameter one **after the other** with a fixed perturbation step defined by the method (depending on k and r)
2. Calculation of the elementary effects of each parameter X_i induced by these perturbations on the output variable Y:

   $$d_{x_i} = \frac{Y(x_i+\delta)-Y(x_i)}{\delta},$$ δ being the perturbation step.
3. **Repeating the procedure** starting from another nominal state of the different parameters, several times (trajectories) and with the same perturbation step.
4. **Distribution analysis** of the elementary effects computed.

Illustration of 1 trajectory for k=4 and n=2 parameters:



Morris results T12p-4MHz Amin [dB]	|Mean| μ*
Tilt	8.3
θ_V	5.8
E_p	5.7
P_{def}	5.2
X_1	3.5
α	2.9
β	2.7
c_T	2.4
c_L	0.4

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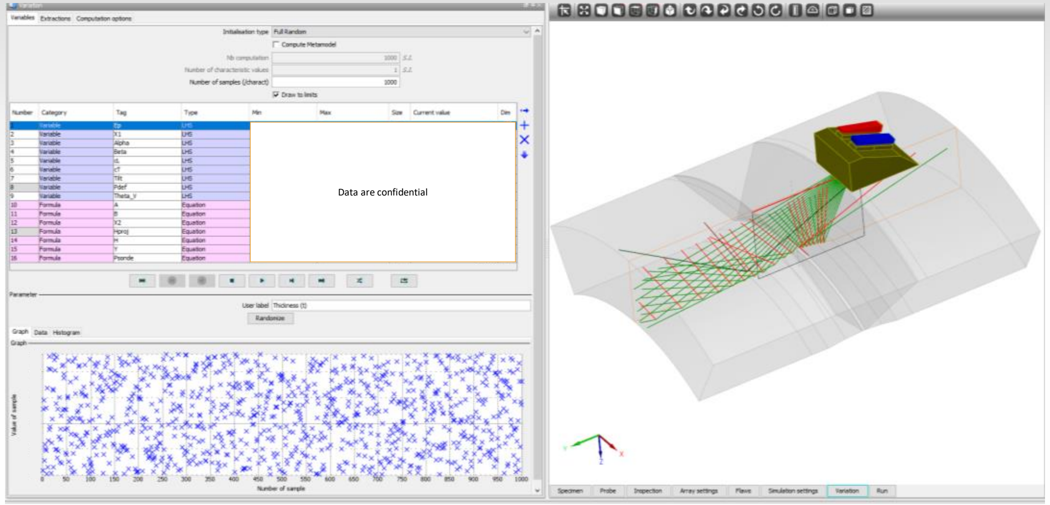
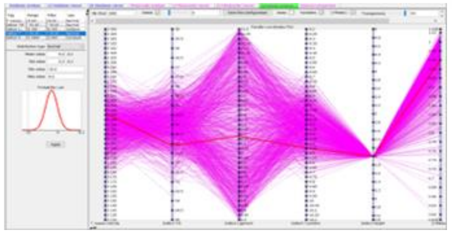
Multiparametric variations: Metamodeling

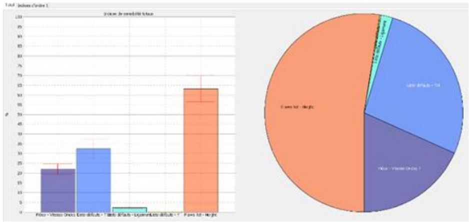
- Based on a discrete data grid obtained by varying some input parameters (simulations, calculations, or measurements), application of smart **interpolation algorithms** to build (from the previous known data) a **surrogate model** which give a **continuum of results** for the whole variation domain and **all parameters combination**.

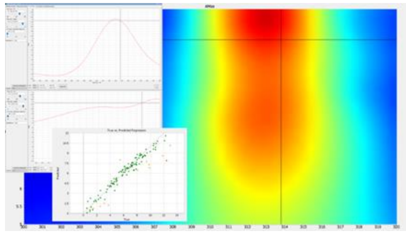


LHS random draw (with limits): 1000 IP combinations

- Application: Sensitivity analysis
  - "Realtime" predictions:
    - Large-scale data generation
  - Multi-parametric analysis:
    - Parallel plots: "worst case" or "best case"
    - 1D curve, 2D response surfaces
  - Quantitative ranking of influential parameters thanks to the evaluation of Sobol indices.







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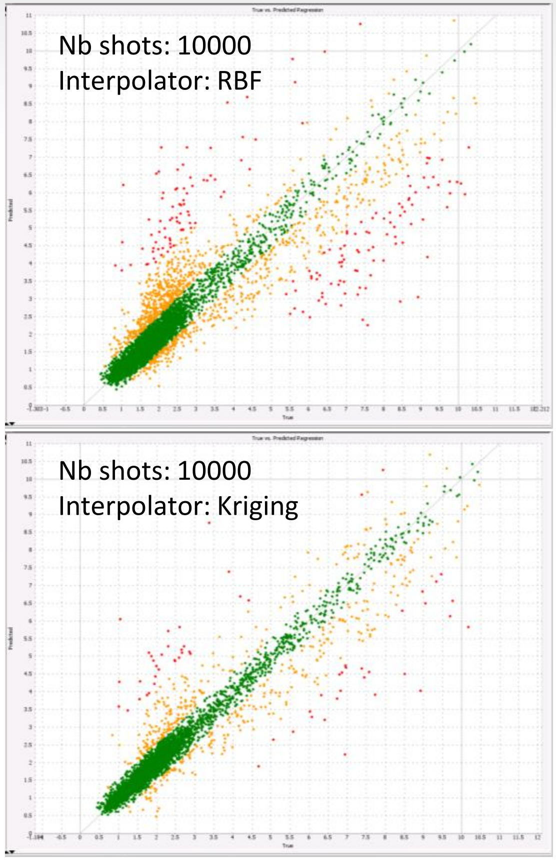
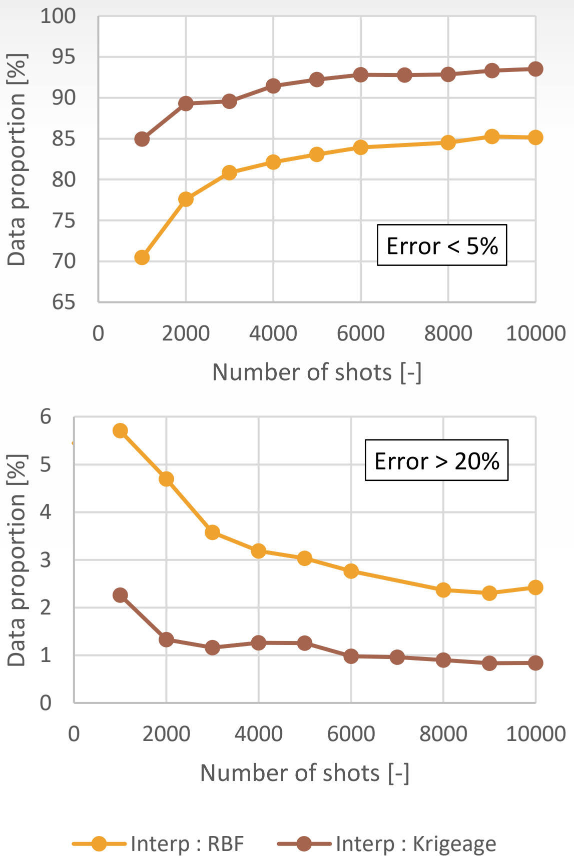
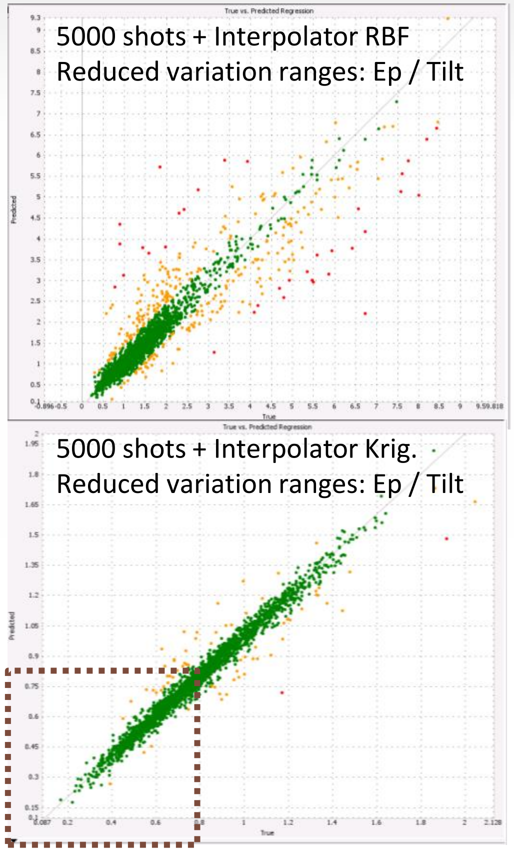
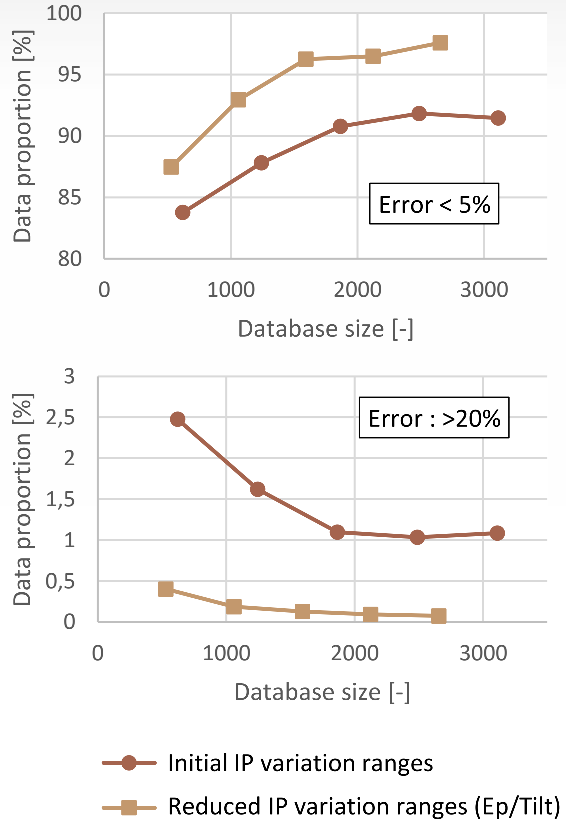




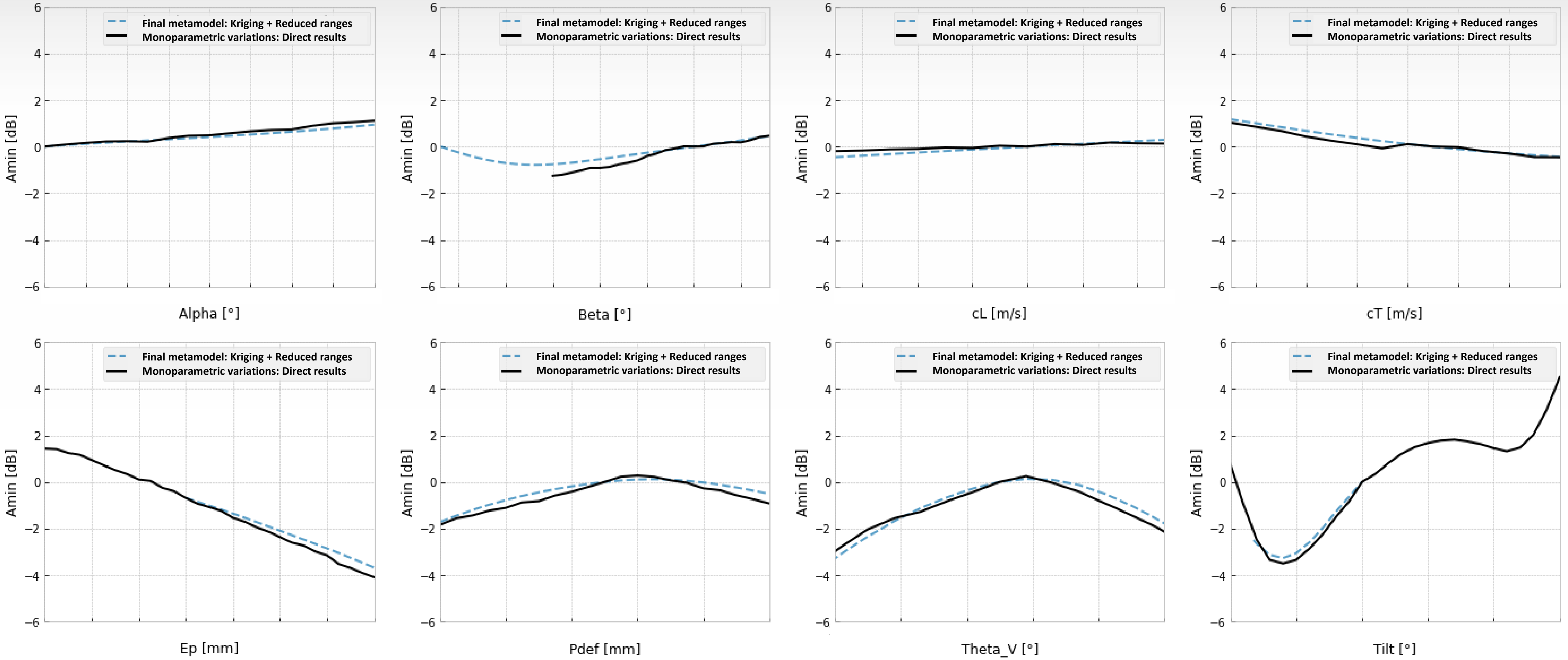




T12p-4MHz – Amin [dB]

Simulation methodology for worst cases identification during NDE technique qualification

- Database generation and interpolation accuracy of metamodels



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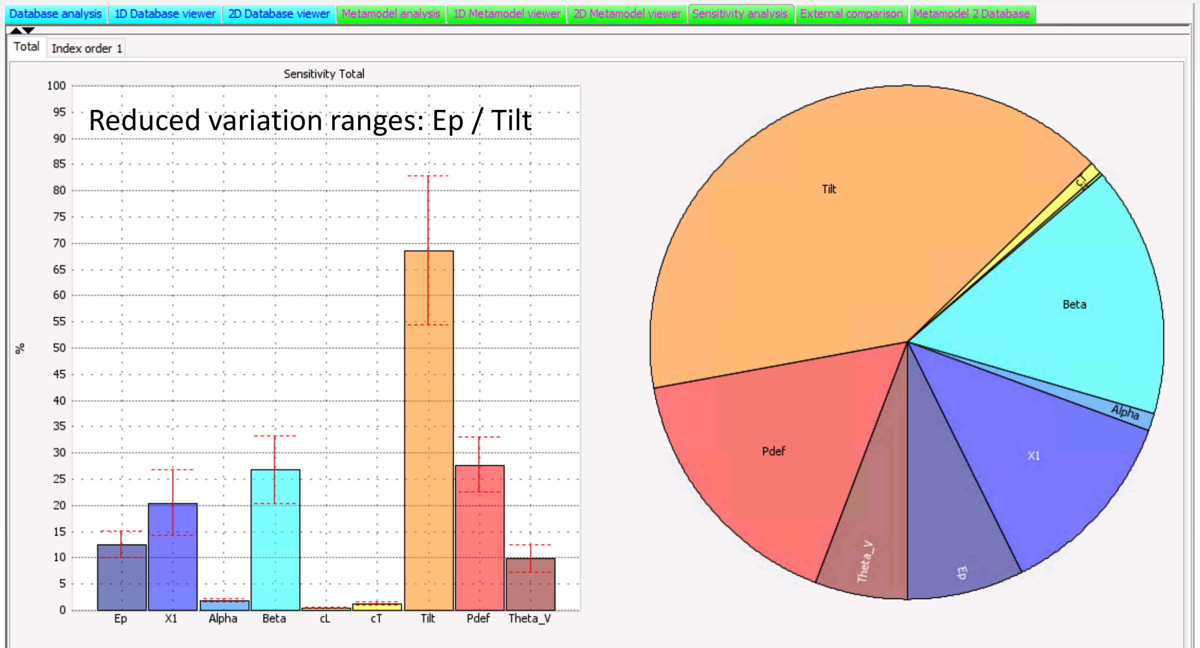
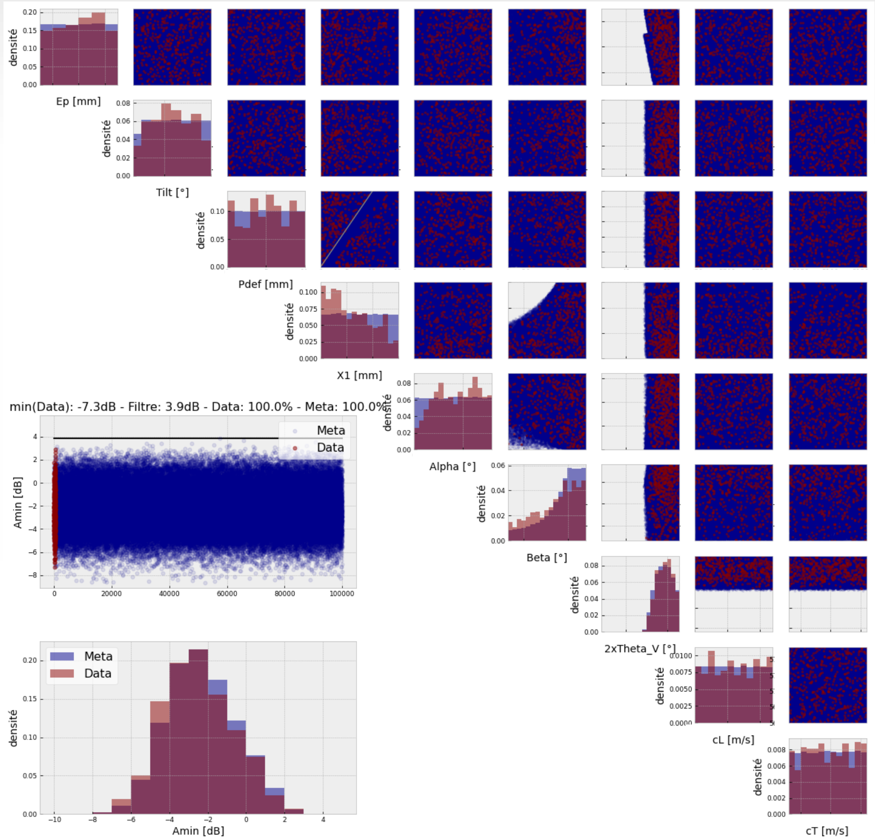


	Ep	X1	Alpha	Beta	cL	cT	Tilt	Pdef	Theta_V
Sensitivity	12.45	20.42	1.82	26.73	0.34	1.23	68.63	27.70	9.79
Value %	7.36 %	12.07 %	1.08 %	15.81 %	0.20 %	0.73 %	40.58 %	16.38 %	5.79 %
Uncertainty	2.486	6.238	0.333	6.451	0.093	0.260	14.201	5.285	2.553
Uncertainty %	19.967 %	30.552 %	18.253 %	24.131 %	27.412 %	21.144 %	20.692 %	19.078 %	26.092 %

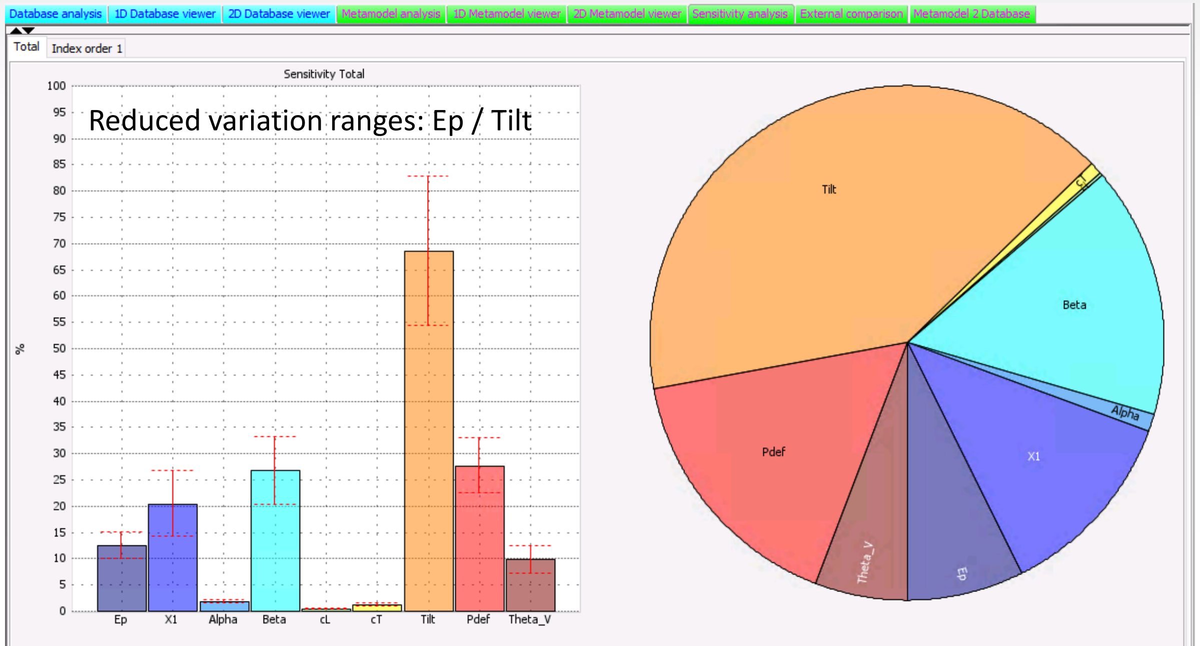
Parameters' influence classification: Sobol indices



Realtime generation of interpolated data

Simulation methodology for worst cases identification during NDE technique qualification

- Metamodel exploitation for sensitivity analysis and worst cases identification



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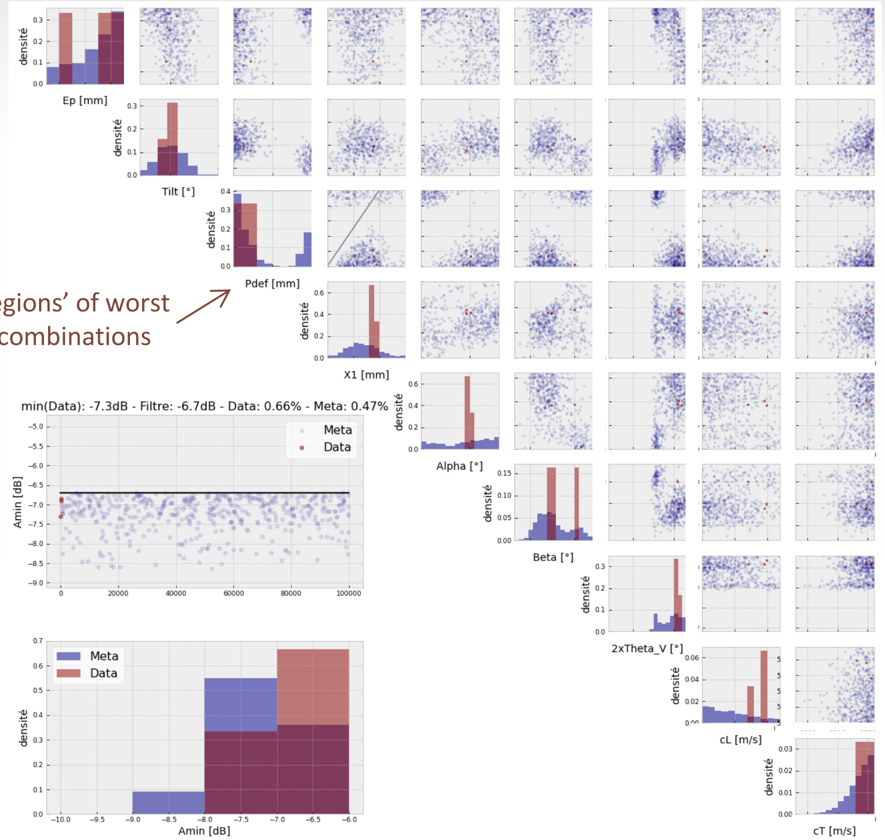
Parameters' influence classification: Sobol indices



Realtime generation of interpolated data
Identification of worst inspection configurations

T12p-4MHz – Amin [dB]

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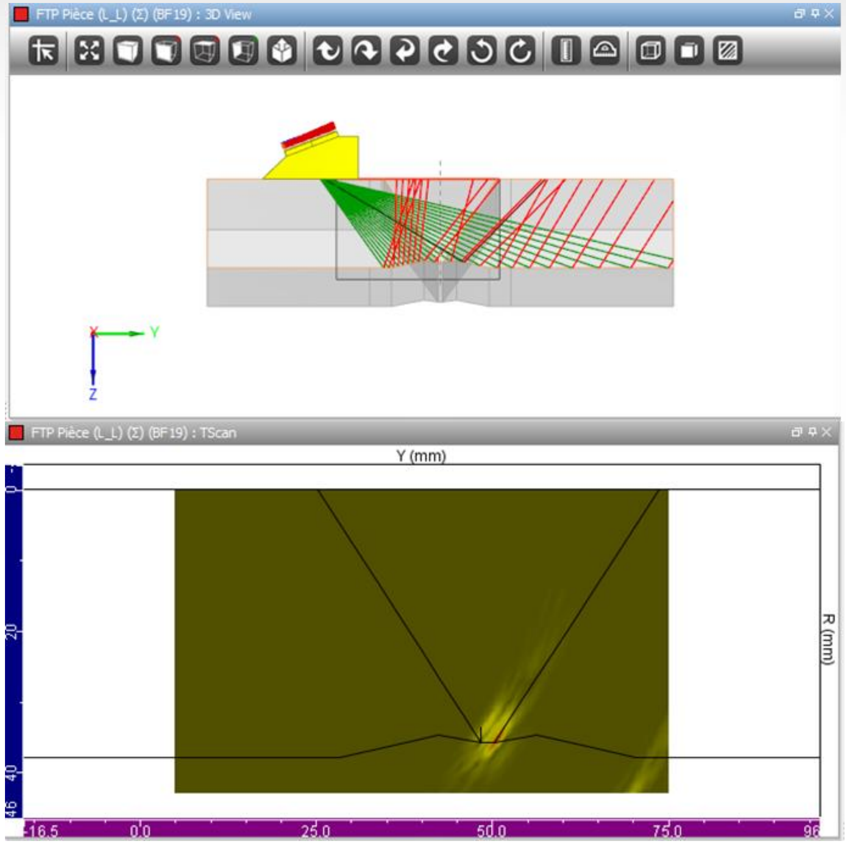
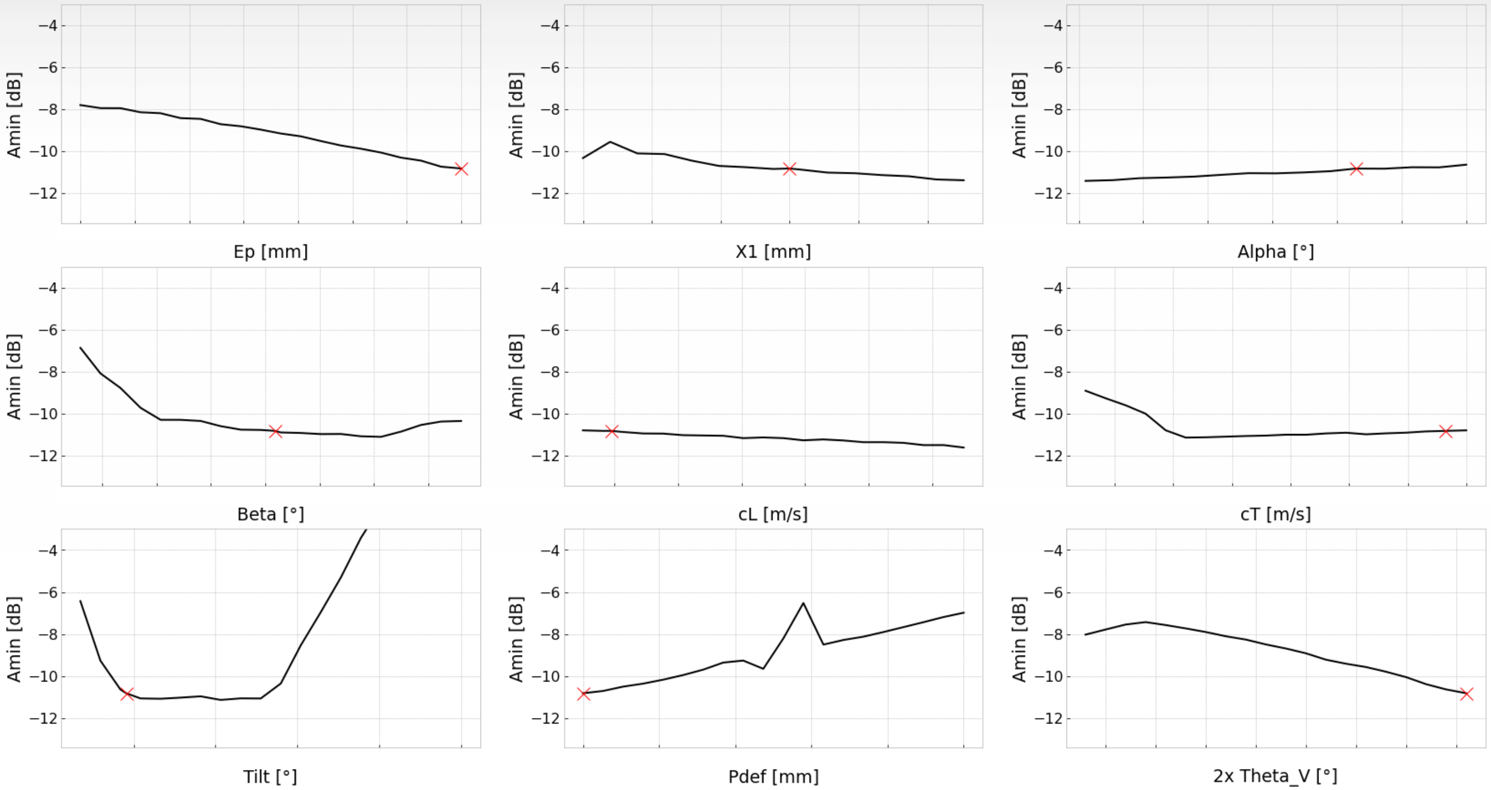
- Simulation consolidation of identified inspection configurations





– : Monoparametric variations around worst IP combination

x : NDE performance simulated for worst IP combination

Results obtained with the most accurate simulation options

T12p-4MHz

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Conclusions and perspectives

- This presentation illustrates the metamodeling methodology developed for worst inspection configurations identification (for detection sensitivity) of an advanced UT method designed by EDF for ISCC detection in safety injection system of nuclear power plant.
- A global simulation methodology has been developed and consolidated during the project. Such strategy has been repeated to various SIS geometries (tube-elbow) and diameters.
- Warning: Do not underestimate the first methodology step (IP list and simulation validation).
- The developed methodology is very robust and consolidated to be reproduced for various NDE technique qualification studies.
- Metamodeling features are very powerful and available in commercial CIVA versions for all users. CIVA Script / Data Science features (add-on) can enhance even more the sensitivity analysis possibilities with the scripted customization of NDE performances criteria and designs of experiments/simulations.
- The different parametric studies and metamodel features presented here can be used for worst inspection configuration identification (presented topic), but they can also be very valuable to assist the development of a new NDE technique (optimization of probe/method parameters).