framatome
Intercontrôle

Development of an industrial inspection system based on High Energy Photon Counting Detectors and off-line Time Delay Integration

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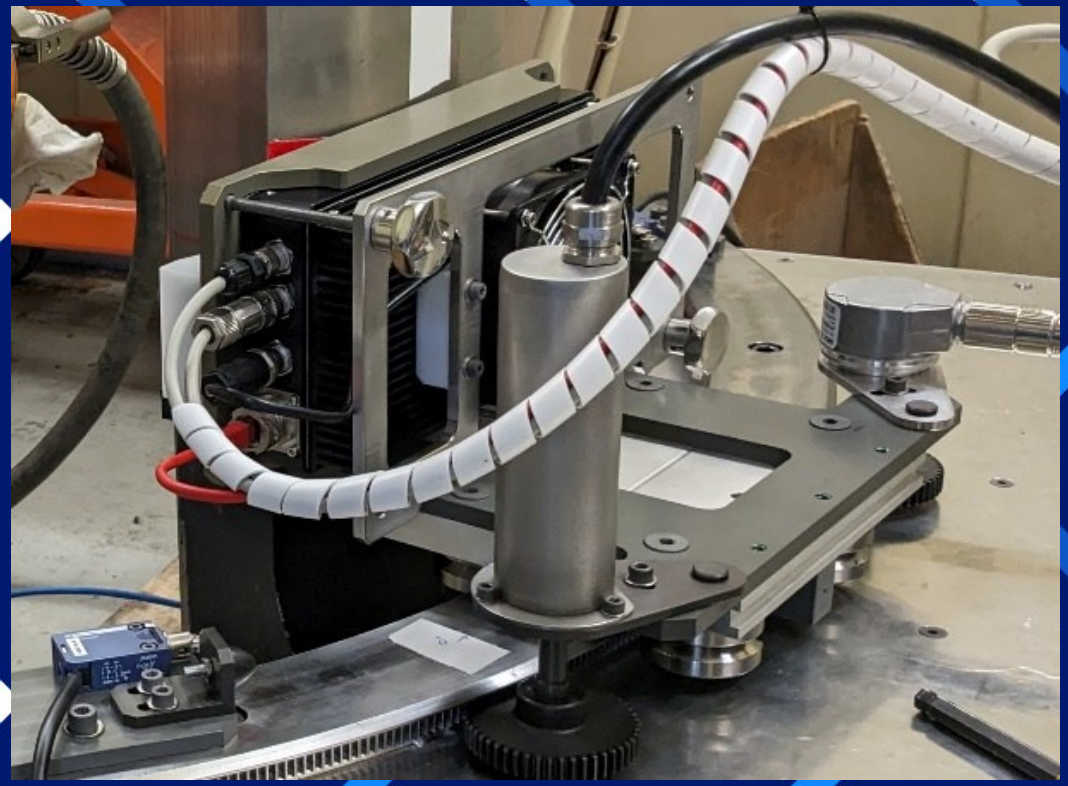
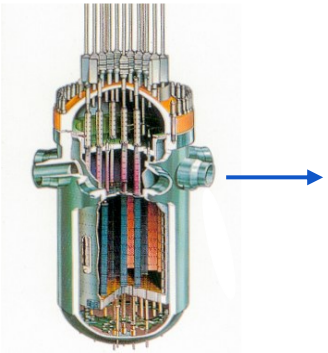


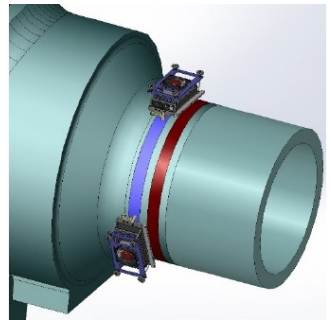
Digital RT Project – Context and Objectives

- Objectives : film replacement for NDT and END in nuclear applications
  - improve quality
  - digitize data
  - reduce HOF and CFSI risks (real-time image)
  - improve control profitability
  - remote interpretation/monitoring
  - catch up with other fields (aero, oil & gas, automotive, etc.)
  - anticipate supply chain developments, etc., …

- Context : main project application: on-site inspection of RPV dissimilar welds (DMW)

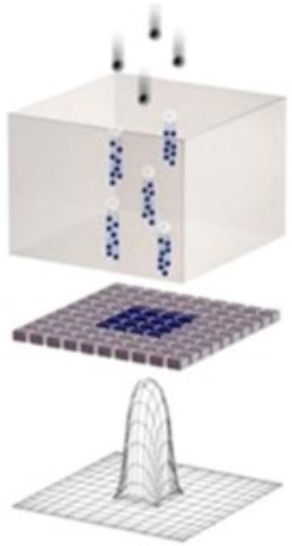


- Thickness comprised into 75 – 91mm
- Panoramic configuration ^{192}Ir gamma source
- RB Environment:
  - Cassettes Positioning in Orange Zone
  - Ghost image
- No possibility of monitoring the support in real time (significant number of retakes)

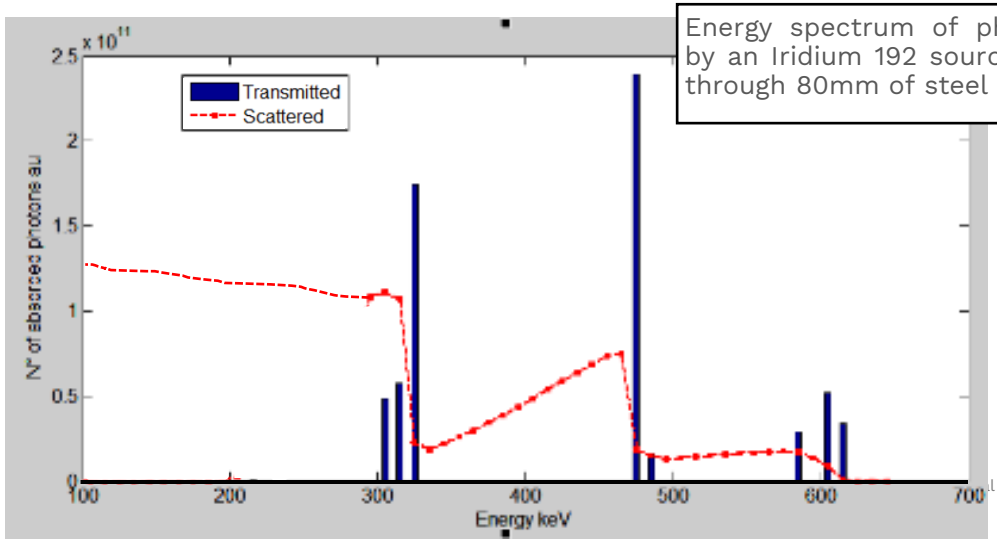


- 2016 : no digital solution can achieve image quality comparable to that of film (class C2) for very thick parts (e > 60mm) requiring the use of high energy (HE) sources (E > 200 keV).
- 2017 - 2019 : development of an optimized sensor for large thicknesses: PCD HE (photon counting detector) oriented towards High Energy (with Direct Conversion/VAREX Imaging)

Development of a DDA with photon counting and energy thresholding



- Each X-ray or gamma ray generates e-/hole pairs in the sensitive layer: CdTe (3mm)
- The electric charge is collected into each pixel and processed by a low-noise CMOS circuit
- The image corresponds to the number of detected photons, whose deposited energy is greater than a predefined threshold

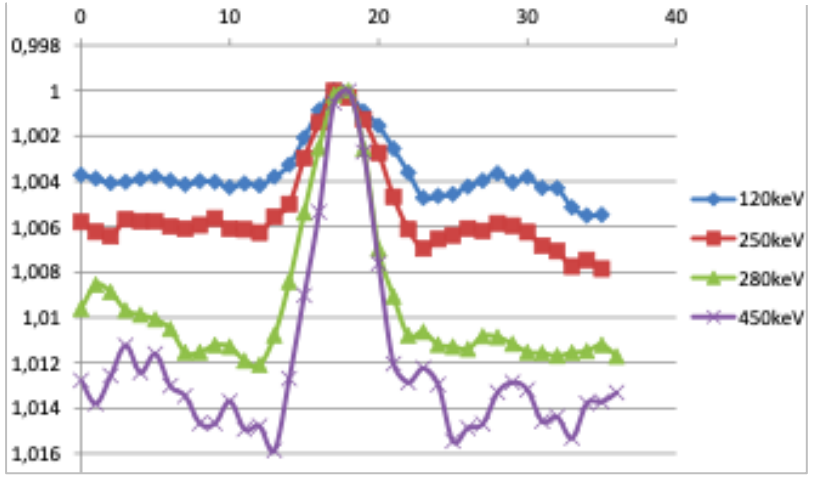


Energy spectrum of photons emitted by an Iridium 192 source after passing through 80mm of steel

- Energy thresholding allows for higher contrast levels than those achievable with films.

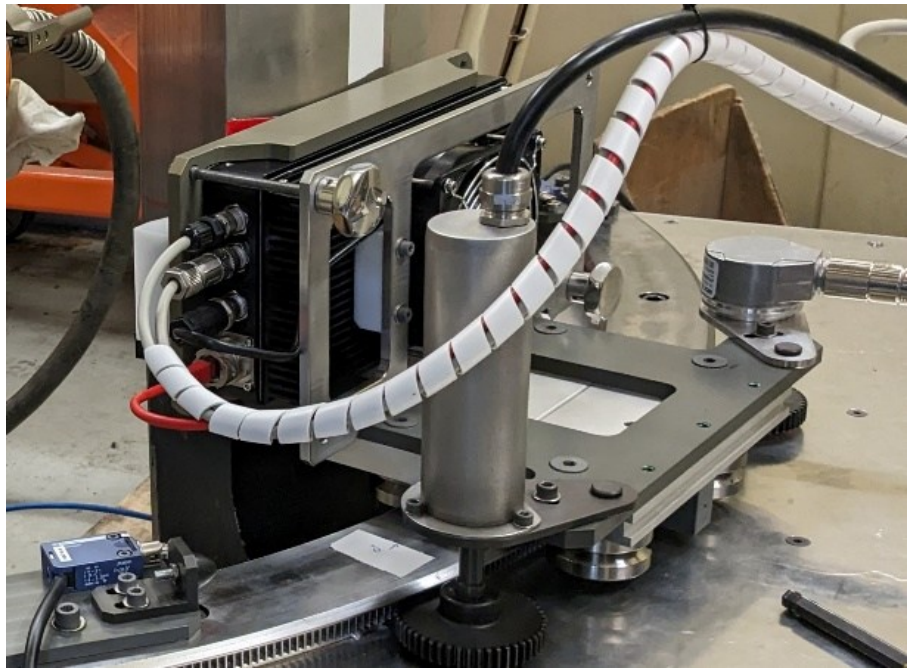
Ir192 Image of IQI FE EN W6 placed on 80mm of steel

Effect of energy thresholding on wire no. W7 profile



Industrialization process steps

- Feasibility tests on MU's (since 2019)
- NPP tests – RPV DMW inspection (2020)
- Development of the new PCD for On-Site Inspection (since 2021)
- Motorized system development (since 2022)
- Acquisition challenge in TDI mode (since 2022)
  - TDI feasibility tests – linear trajectory
  - Feasibility tests with Demonstrator – circular trajectory



- First implementation: Sizewell RPV DMW inspection at FRAMATOME St Marcel factory (March 2024)
- First test with a motorized solution for On-Site Inspection (2025)

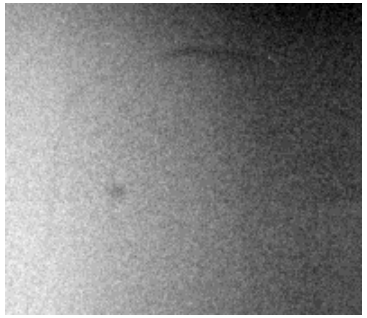
Industrialization process steps – NPP tests

- Film/PCD HE comparison during outage conditions. PCD manually positioned on a pipe section

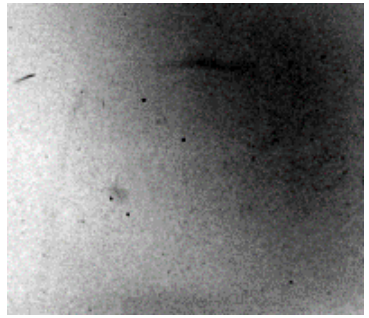
- Only laptop PC and detector
- No chemical
- Real time monitoring of inspection conditions

5 min image (vs 70min with film)

Historical flaw image



PCD

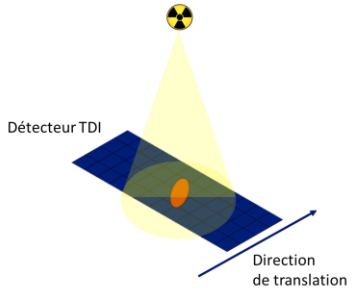


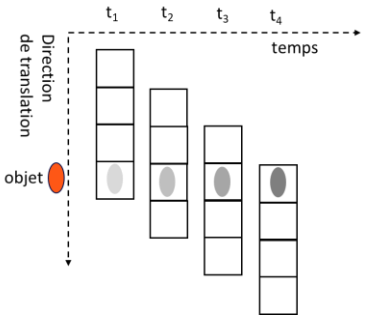
Film (Scan)

- Detector compliant with ambient radiation (orange area),
- Thanks to energy thresholding, background radiation contributed to only 2% of total signal (vs 13% with the film),
- Image quality equal to laboratory tests, and in full compliance with ISO 17636_2. This with 5’ instead of 70’ with film.
- Detection of an historical flaw “identically” as film: EDF expert conclusion

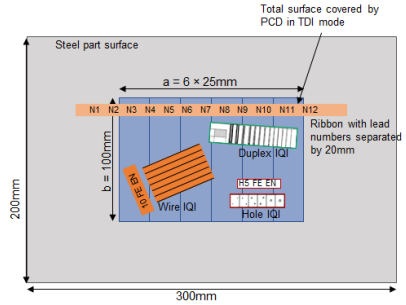
Industrialization process steps – TDI

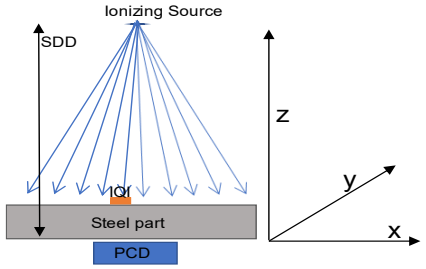
- Principle
  - At time t_1 the image of the object is projected onto the first detection line, generating a signal (charge packet).
  - At t_2, the image is transferred to the second detection line; and, simultaneously, the pixels of the second line record an additional charge, which is added to the charge created by the first detection line…
  - The signal (charge) increases linearly with the number of detector lines in TDI.





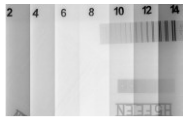
- Feasibility within linear trajectory

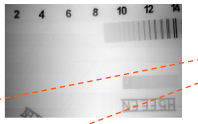




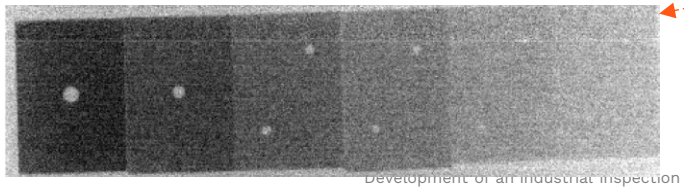
Macro-stitching

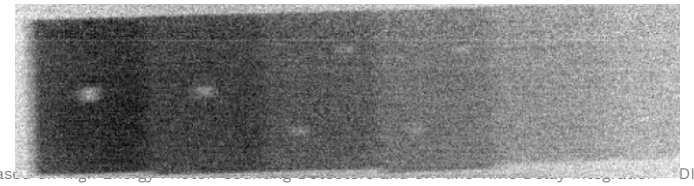
TDI





- Comparison with static measurement (Macro-sticthing): TDI image is smoother and the CNR is optimized
- Application condition: perfect synchronization between acquisition and detector movement (otherwise blur is introduced)

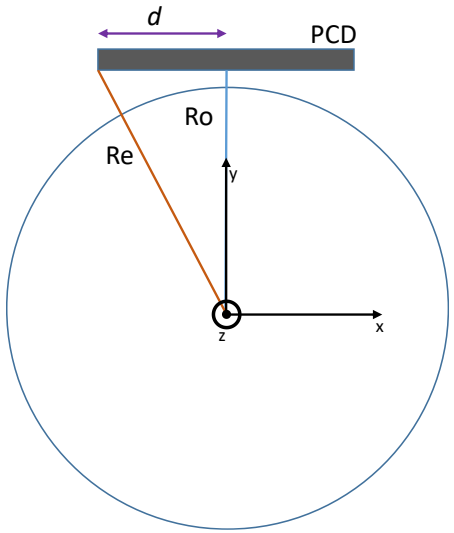




Industrialization process steps – Offline summation

- Challenge : perform TDI with 500 lines along circular trajectory!
  - Images are recorded at each displacement step, which should be equal to pixel size dp (0,100mm)
  - TDI summation after linear interpolation of acquisitions according to a real step dx
  - Search for the “true step” by image optimization (sharpness as criterion)

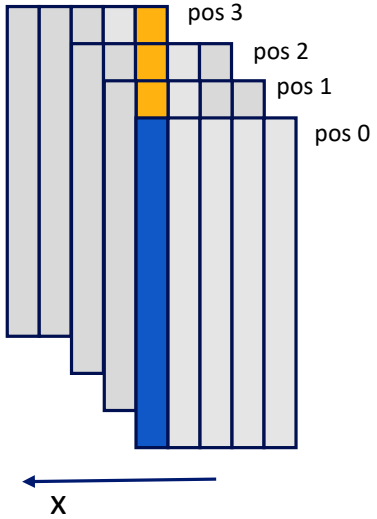
linear translation approximation



- Δpo = ΔϑRo
- Δpe = ΔϑRe
- Δpe = Re/Ro Δpo = 1,002 Δpo

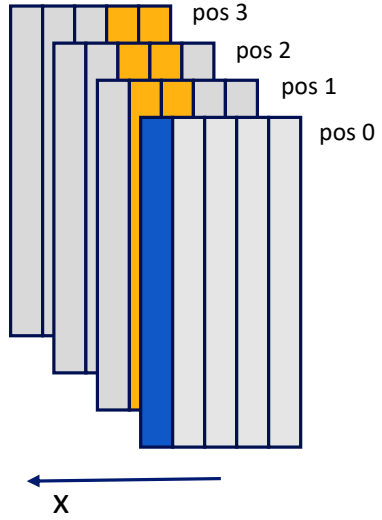
off line summation: to perform interpolation

- If dx = dp



We can just sum columns

- If dx ≠ dp

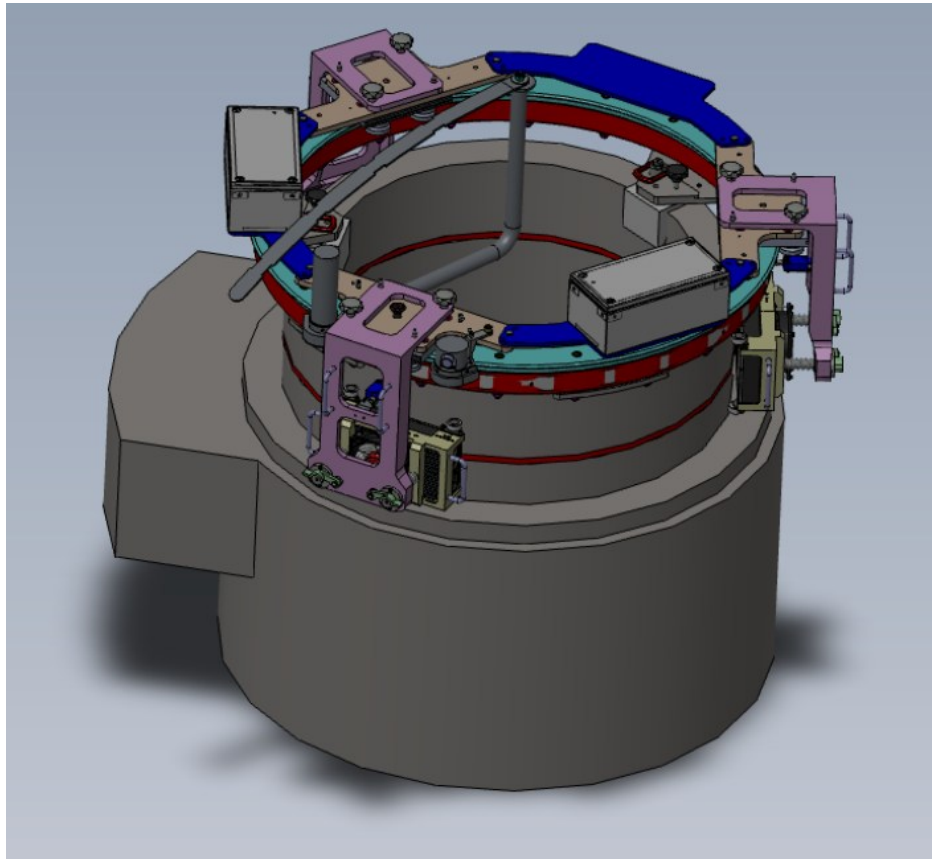


We need to interpolate first

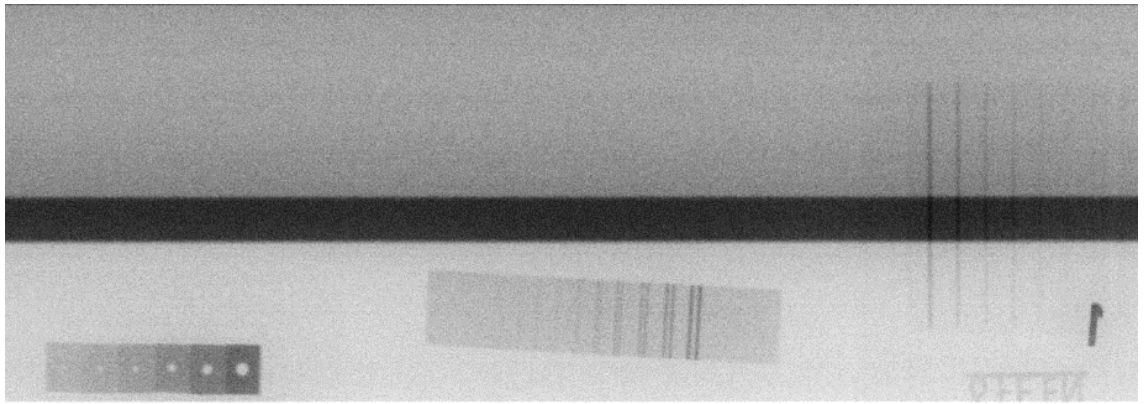
If dx = 0,105mm:

a blur of 2,5mm will be introduced if no interpolation

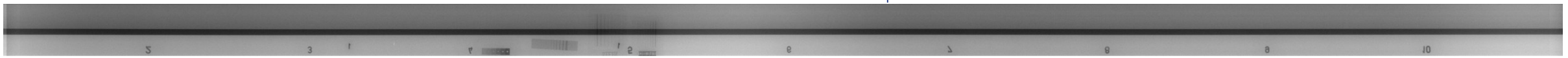
Industrialization process steps – First implementation with complete system for NDT



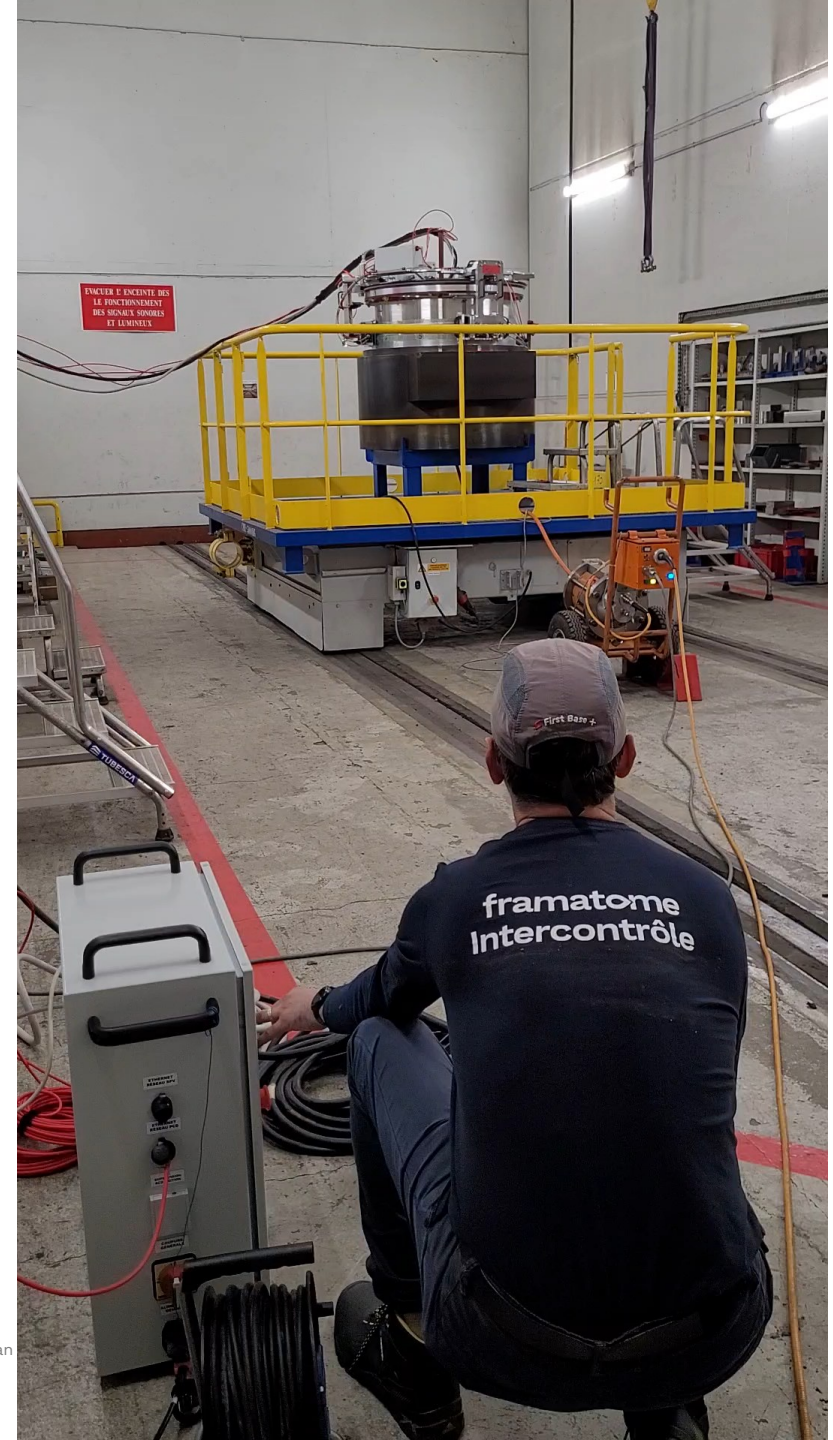
- DMW inspection of Sizewell EPR RPV pipe (t = 80mm)
- Cobalt 60 gamma source
- Energy thresholding
- 3PCDs rotate around the pipe
- Dedicated IC software for image acquisition, analysis and processing
- Image quality (at least) equivalent to film: W10 and H9

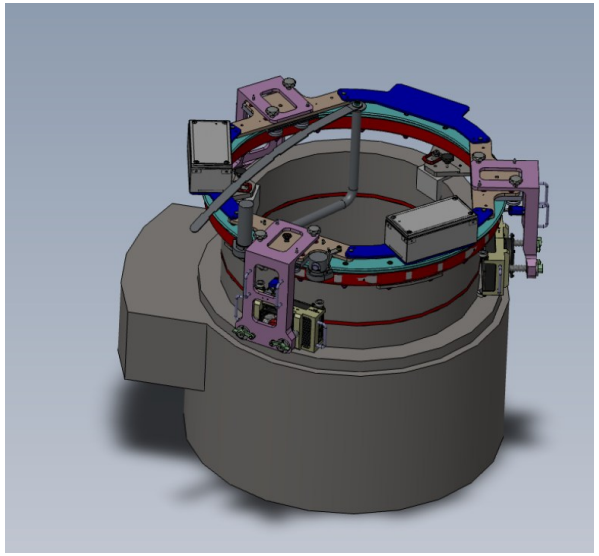


Full 360° weld acquisition

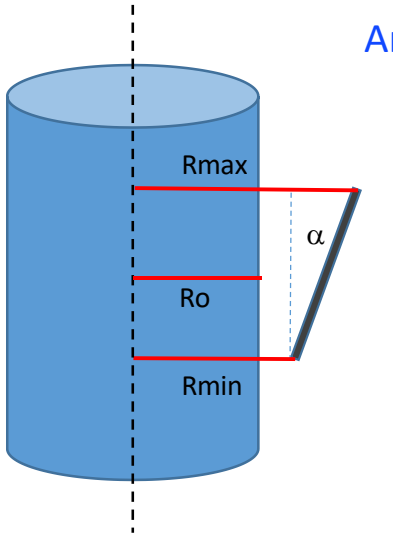


Industrialization process steps – First implementation with complete system for NDT





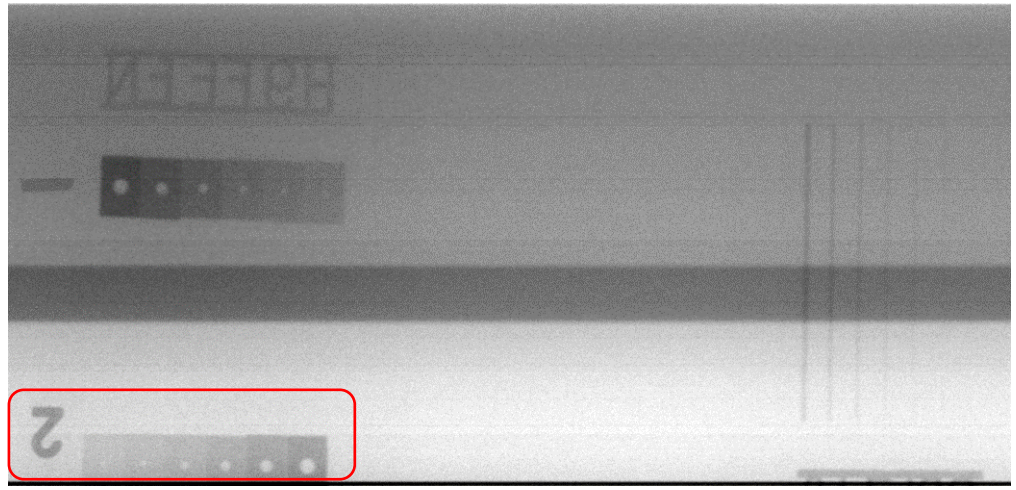
Industrialization process steps – tests in conical geometry



An angular tilt of 5° has been introduced

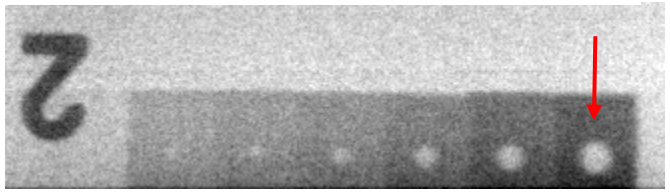
- Here, step dx_i varies along PCD lines i, and
- It depends on tilt α

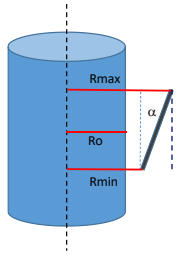
RECONSTRUCTED IMAGE



- a) Reconstruction assuming α = 5° (i.e. R varies from Rmax to Rmin)

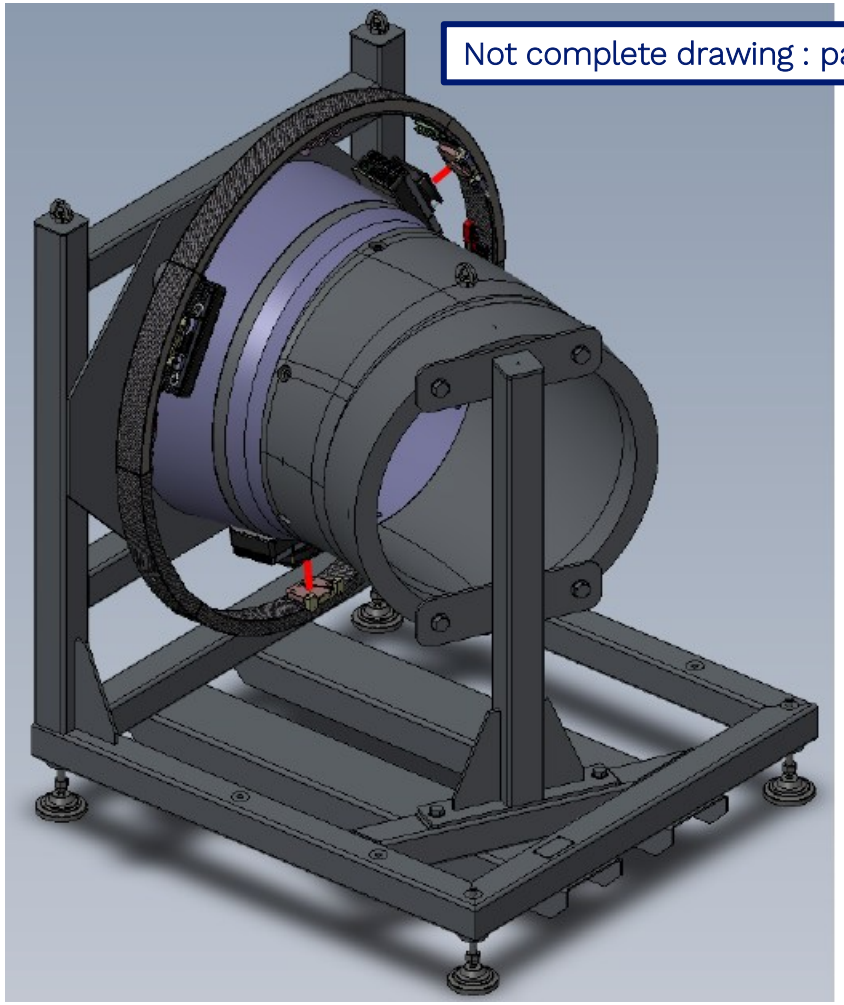
- b) Reconstruction assuming α = 0° (i.e. R = Rmax for all lines)





In b) , we added a blur of about 1mm

Industrialization process steps – developing a system for On-Site Inspection

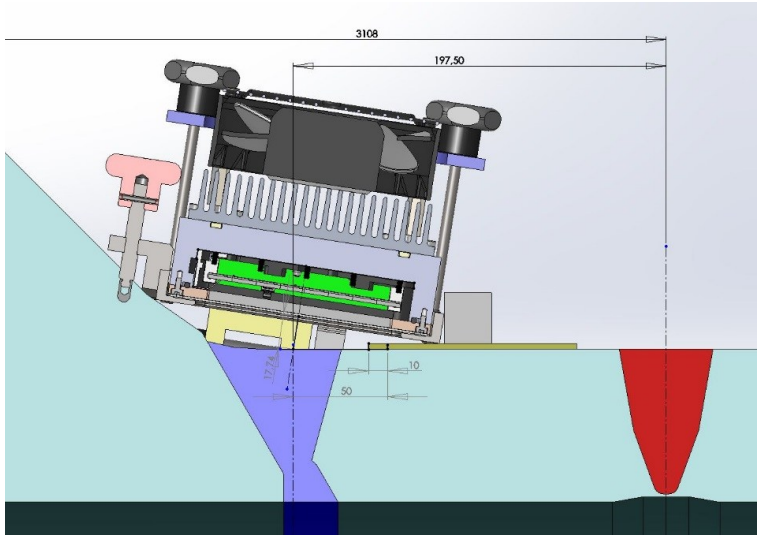


MAIN FEATURES OF FIRST PROTOTYPE

- parts are transportable by operators (less than 15kg)
- assembly takes place directly on the pipe
- 6° cone tilt
- for all PCD there is a translation axis :
  - fine positioning before rotation starts is needed
  - move to homogeneous weld without operators in orange zone
- encoder wheel for angular displacement monitoring
- adjustable speed

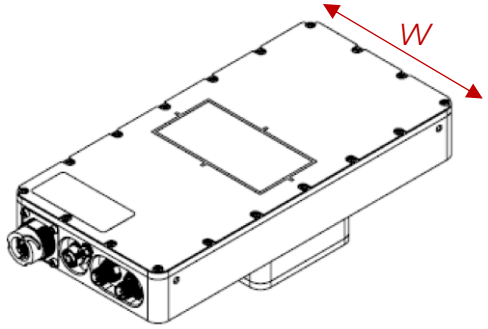
Industrialization process steps – development of a new PCD for On-Site Inspection

- The HE PCD prototype, its active surface, does not allow the Inspection Zone to be covered for all the DMWs in the French fleet



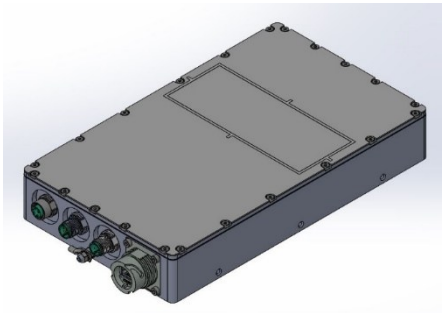
PCD proto
1024x512 px

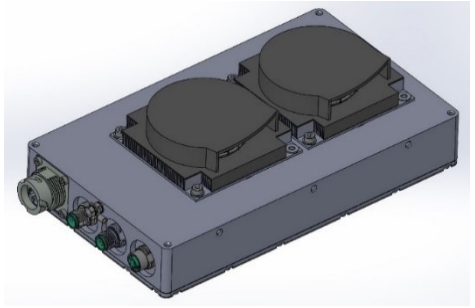
- CdTe thickness : 3mm
- Weight: 8,6Kg
- 1 fan
- *w* = 140mm
- Ethernet RJ45



New PCD
1280x512 px

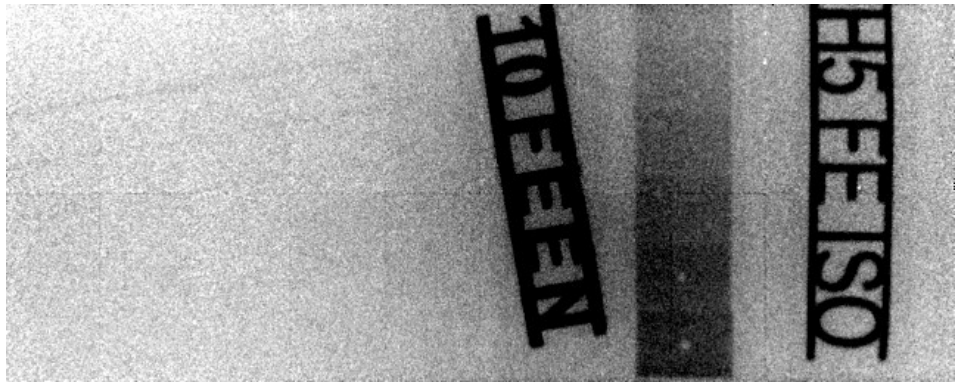
- CdTe thickess : 3mm
- Weight: 6Kg
- 2 fans
- *w* < 150mm
- Optical fiber 10G





Industrialization process steps – new (128) PCD first tests

- Iridium 192 gamma source
- Thickness = 60mm (steel)



- Wire W11 (0,32mm)
- Hole H7 (0,50mm)

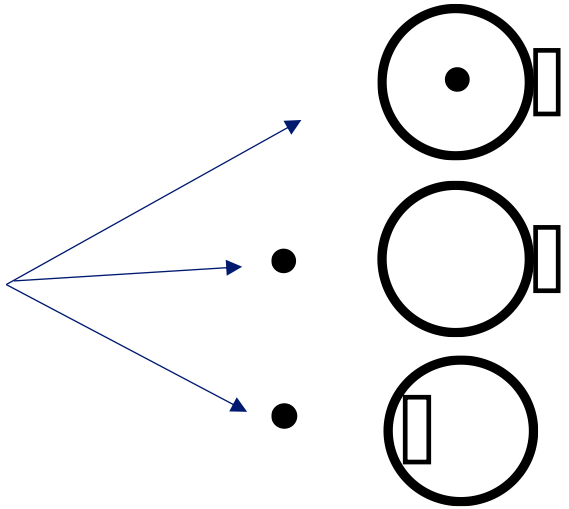
Conclusions/Perspectives

- A HE-oriented PCD has been developed, whose performance is (at least) comparable to that of film (class C2): demonstrations carried out with gamma sources such as Ir192 and Co60, as well as betatron and AL sources of 6 MeV
- The image quality requirements of the RCC-M code and the ISO 17636_2 standard are largely satisfied, and this, with an SNR_N close to the minimum required by the standard
- The industrialization process, aimed at achieving a “fully motorized system“, has focused on :

  - PCD optimization (active surface dimensions, external dimensions, cooling, weight …)
  - Mastery of the TDI modality (encoders, synchronization, off-line data interpolation and summation, cones, …)
  - Development of a motorized system (Demonstrator, functional prototype, on-site functional prototype, industrial system)
  - IC software development for acquisition, TDI reconstruction, and analysis

The next steps to take:

- Validation tests on-site (summer 2025) – during NPP outage
- Operator-oriented image processing software
- Development of systems for new applications/geometries



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Thank you