Development of a method for the spectral characterization of bremsstrahlung photons produced by electron accelerators

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1. Elements of context

- **A few words about Aerial … a Center of Resource and Technology (CRT)**

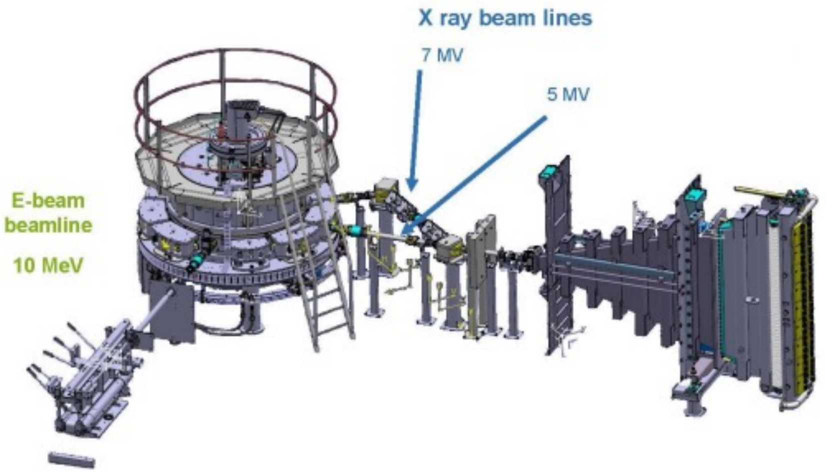
Multidisciplinary team of around 40 engineers/technicians working on issues related to **physics, biology, and the agri-food sector**.

Center of excellence for ionizing radiation processing. Support for industry: **applied research, expertise, and training.**

Some examples of applications: sterilization of medical devices, food irradiation, improvement of polymer properties, coloring of gemstones…

- **A unique platform dedicated to R&D, education and training on radiation processing :**

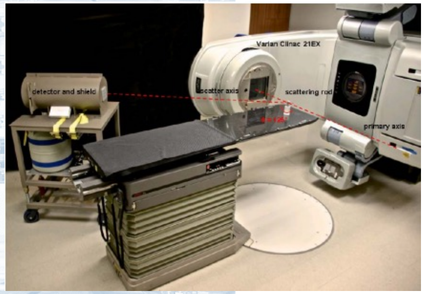
  - High Energy E-beam and X-rays :
    - 10 MV electron beam
    - 5 & 7 MV X-ray beam
  - AIEA collaborating center since 2016



1. Elements of context

- **The Importance of Monitoring the Bremsstrahlung Spectrum in Radiation Processing :**
  - Control the dose deposited in products
  - Control activation risks, with an energy limit of *E = 7.5 MeV*
  - Improve simulation accuracy

- **Indirect characterization methods** as alternatives to direct methods :
  - Direct methods are limited because of the pulsed nature of accelerators and the very high dose rates.



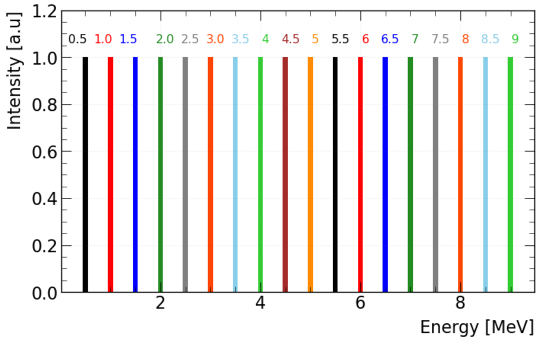
Methods	Compact Device	Simple Device	Online Measurement
Monte Carlo	✓	✓	✗
Compton Scattering	✗	✓	✓
Photo-activation	✓	✗	✗
Transmission	✗	✓	✗
Deposited Dose	✗	✓	✗

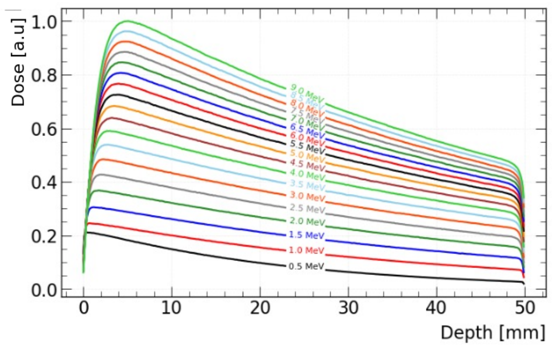
- <u>**PhD Objectives:**</u>

Development of an online spectral characterization method for Bremsstrahlung photons produced by an electron accelerator. The approach is based on solving an inverse problem that enables the reconstruction of the incident Bremsstrahlung spectrum from a measured depth-dose profile.

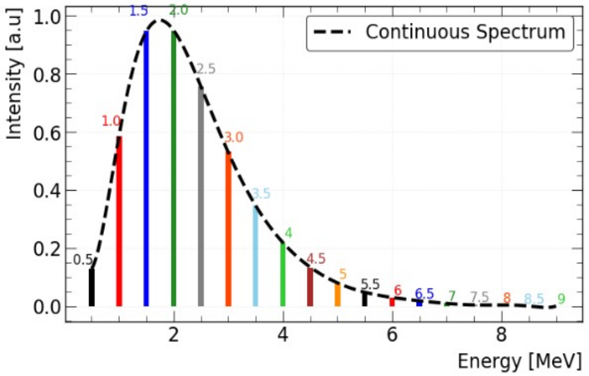
2. Reconstruction of the Bremsstrahlung spectrum from dose measurements

- **The relationship between the spectrum and the dose distribution:**



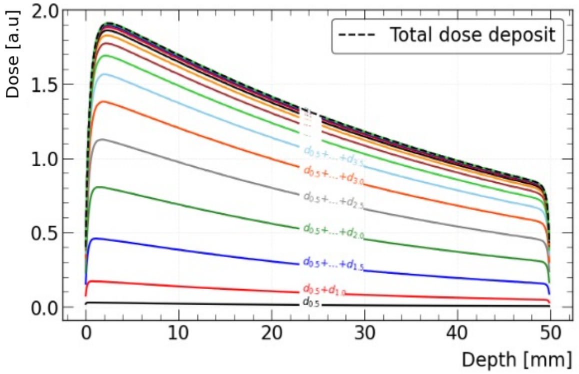


The measured depth dose is a linear combination of the dose profiles corresponding to each energy group, weighted by their respective intensities in the spectrum.



indirect

direct

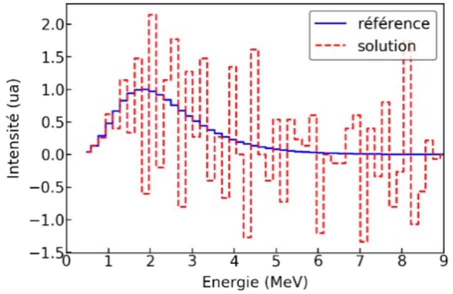


Simulation ← $\boldsymbol{Ms = d}$ → Measurement

To be determined

Ill-posed inverse problem

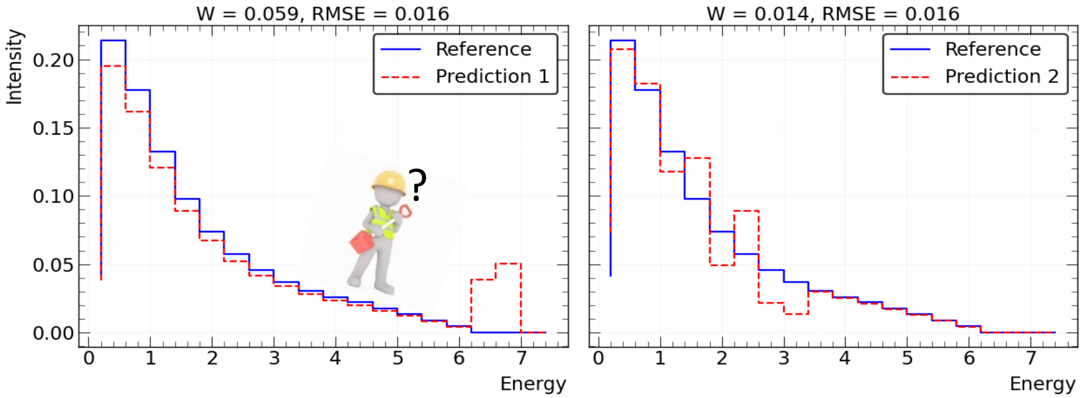
!



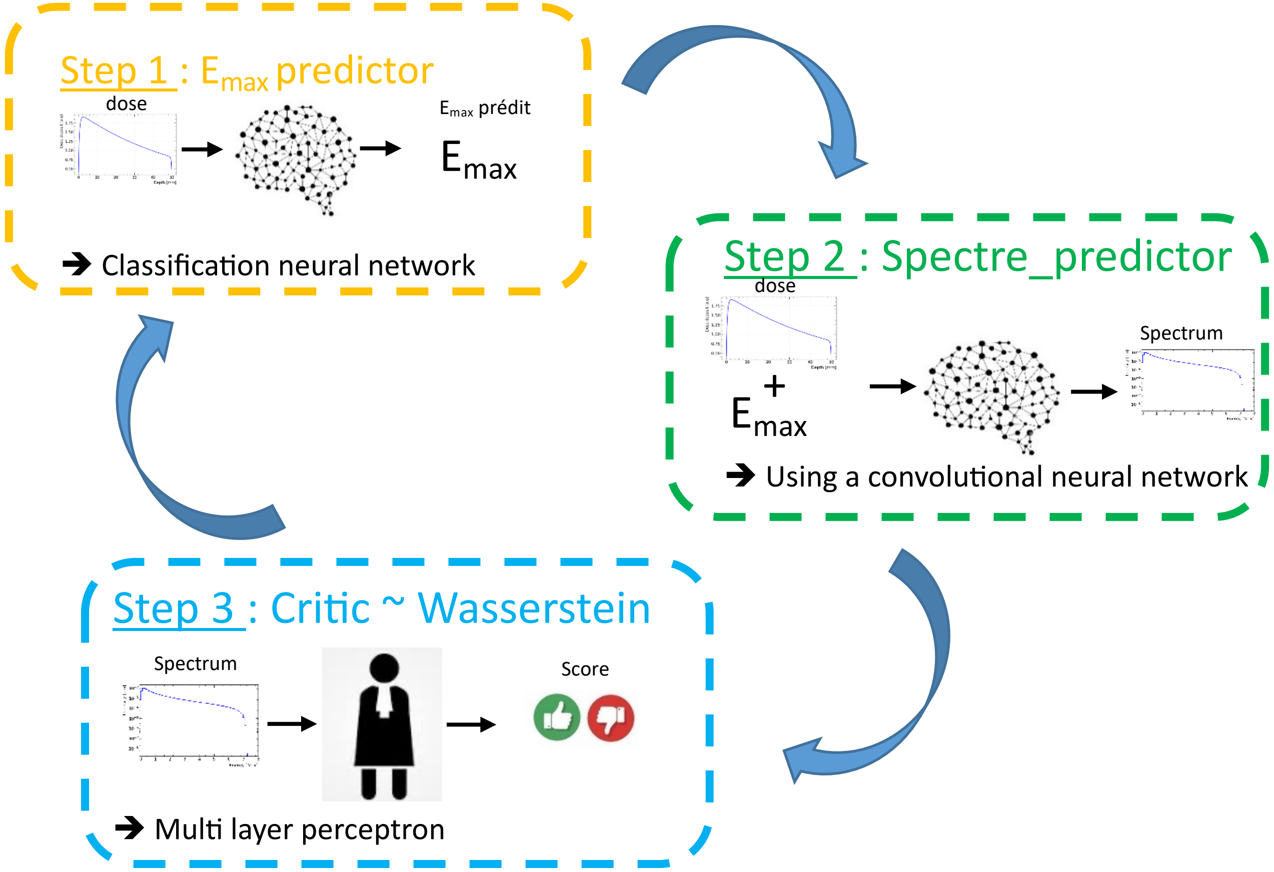
3. Development of a Deep Learning approach

- **A hybrid parametric/full spectrum architecture trained on a Wasserstein distance loss :**

The Wasserstein distance : A measure of the minimum amount of work required to transport the exceeding intensity from my predicted spectrum distribution to the theoretical spectrum distribution

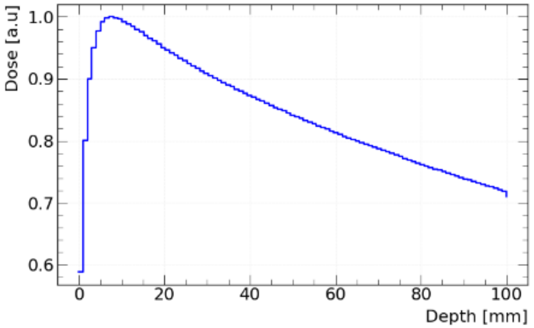


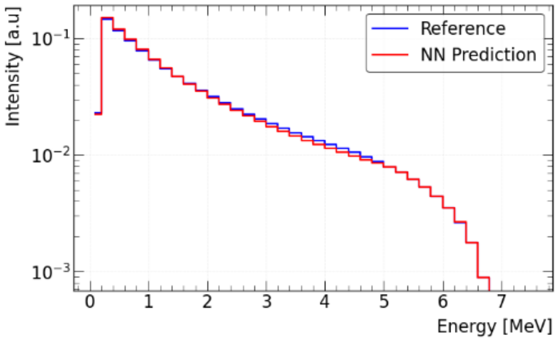
The advantage of the Wasserstein distance, in our context, is that it allows us to quantify **the realism** of our predictions is.

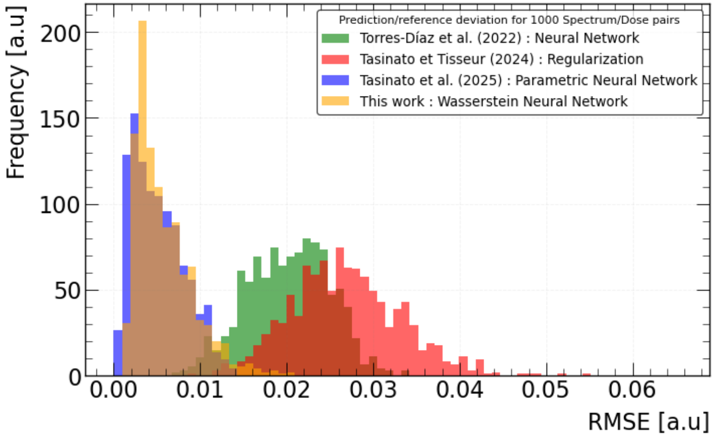


3. Development of a Deep Learning approach

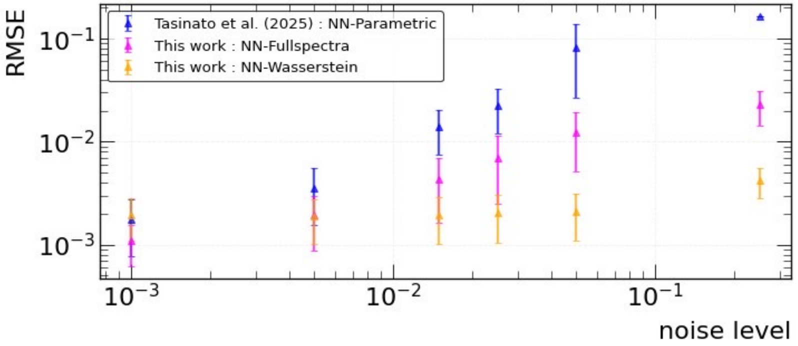
- **Validation on synthetic data**
  - **Improved unfolding efficiency**

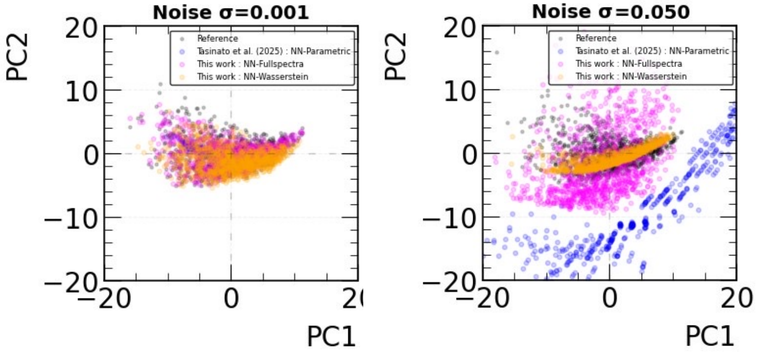






  - **Improved regularization capacity with perturbation (noise, electron contamination,…)**

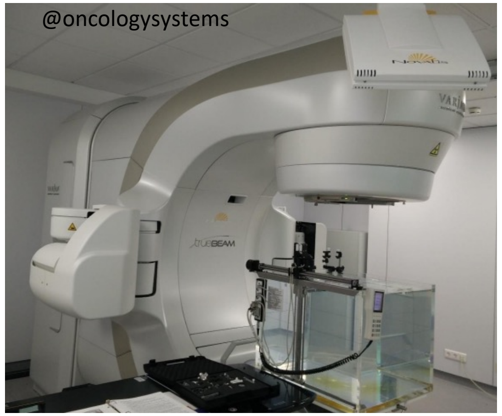




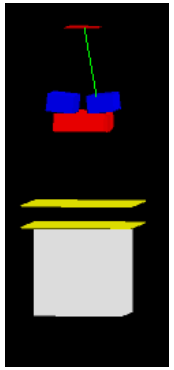
4. Experimental reconstruction

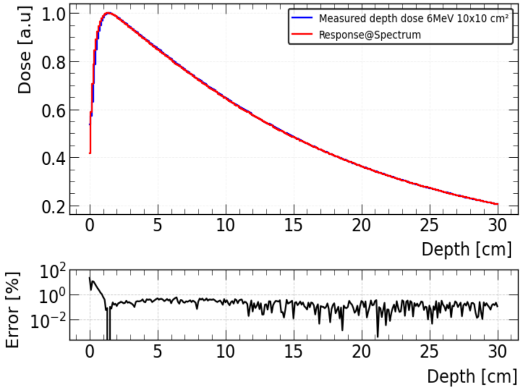
- **Reconstruction of the Varian TrueBeam 6MV spectrum from ICANS:**

Measurements

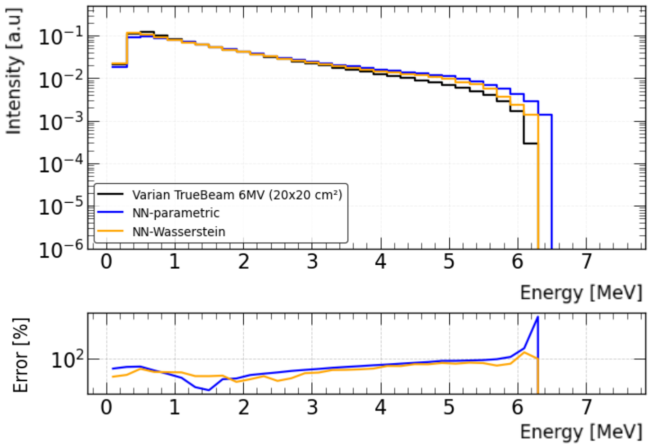


Calibration



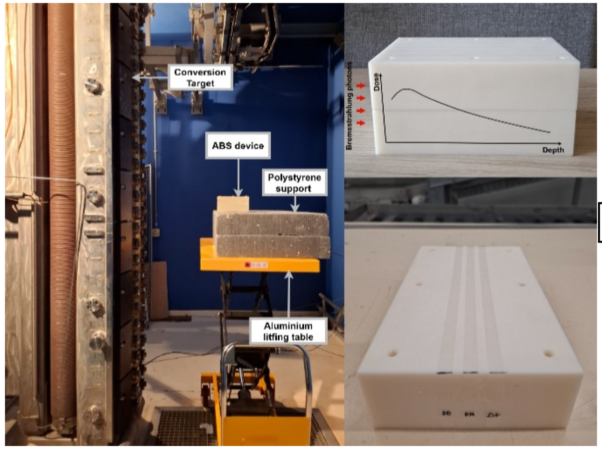


Unfolding

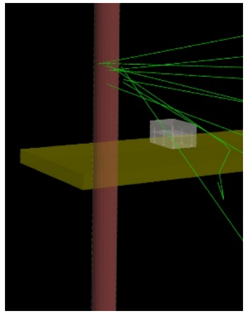


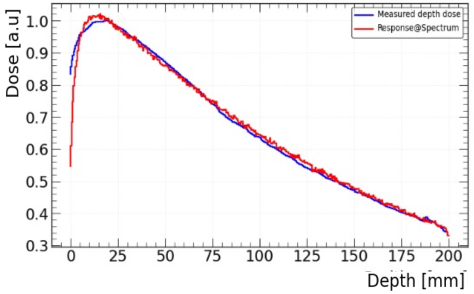
- **Reconstruction of feerix spectrum**

Measurements

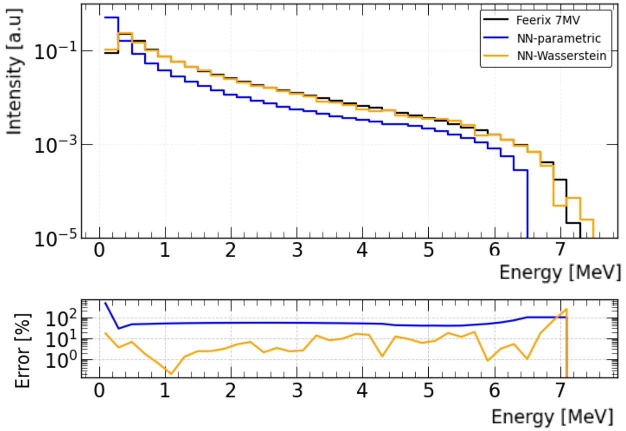


Calibration



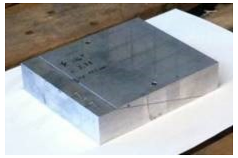


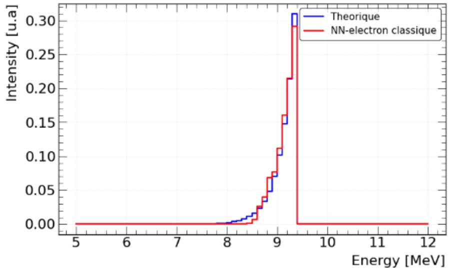
Unfolding



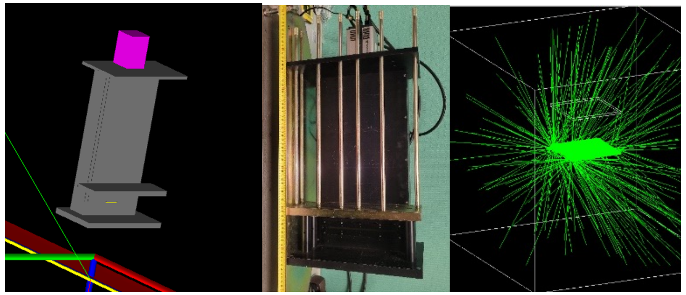
5. Conclusion and perspectives

- **Conclusion :**
  - We have developed a new neural network–based approach to accurately unfold spectra from depth-dose measurements even in the presence of perturbation in the measured depth dose distribution.
  - The method was successfully validated on experimental measurements both at the ICANS facility and in feerix. The device developed to measure the depth dose in Feerix is compatible with most of Aerial's constraints, being compact, user-friendly, and requiring minimal handling.
  - GATE 9.3 and 10 played a key role in enabling the precise modeling of both ICANS' and Feerix's platforms, leading to accurate unfolding of bremsstrahlung photons.





- **Perspectives :**
  - We have begun implementing the same method to reconstruct electron spectra from depth-dose measurements using an aluminum wedge.
  - A setup compatible with measurement-only has also been tested in feerix. Its limitations are mainly due to response calibration and scintillator wear, which may cause variations in the response over time.



Thank you for your attention !

La bonne dose d'innovation*

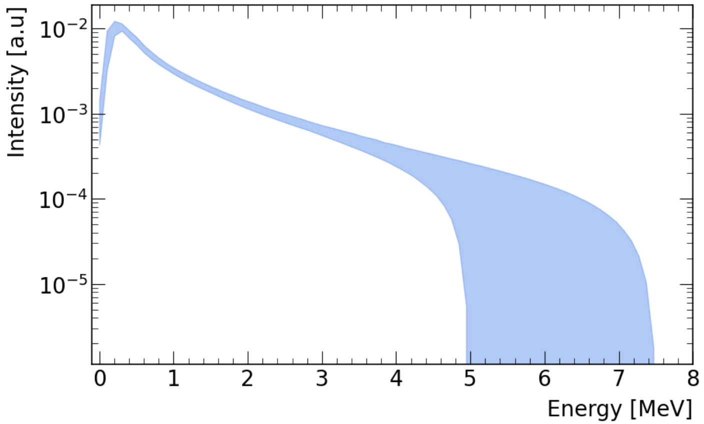
* the best dose of innovation

Annexe 1 : Dataset generation

- **Step 1:** Building a realistic dataset (Spectre – Dose)

  Starting point: Sensitivity analysis of the spectrum generated by the Feerix facility.

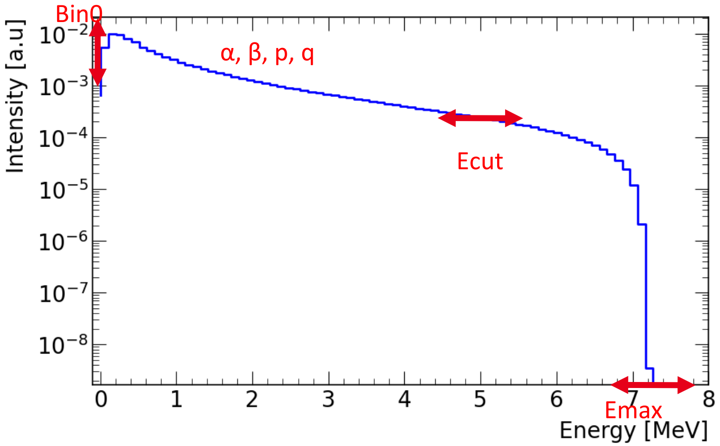
➢ Simulation of the X-ray spectrum generated by Feerix by varying the shape of the electron spectrum and the thickness and density of the conversion target.

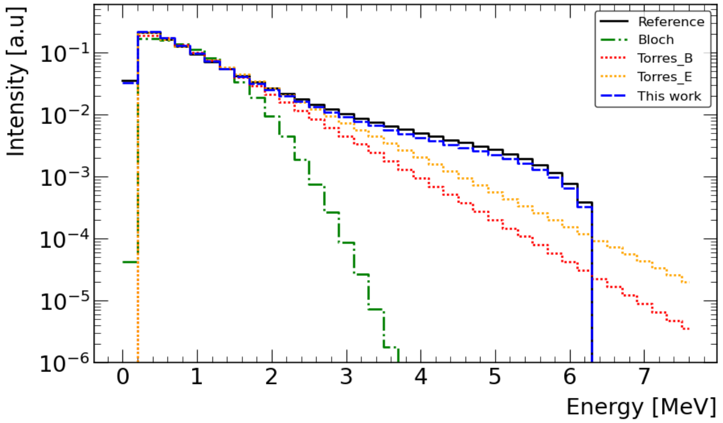


➢ We then use these spectra to derive a parametric function that allows us to adjust each of them.

➢ Adjustment of the spectra using a parametric function S that accounts for the energy maximum of the spectrum.

$$s(E, bin_0, \alpha, \beta, p, q, E_{cut}, E_{max}) \quad \begin{cases} s_0 = bin_0 \\ s_{inf} = \dfrac{p\left(\frac{E}{q}\right)^{\alpha p-1}\left(1+\left(\frac{E}{q}\right)^{p}\right)^{-\alpha-\beta}}{qB(\alpha,\beta)} \\ s_{sup} = \dfrac{s_{inf}(E_{cut})}{E_{cut}-E_{max}}(E - E_{max}) \end{cases}$$





Annexe 1 : Dataset generation

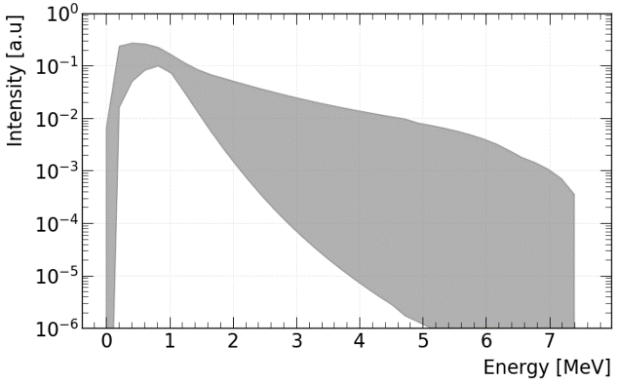
- **Step 1:** Building a realistic dataset (Spectre – Dose)

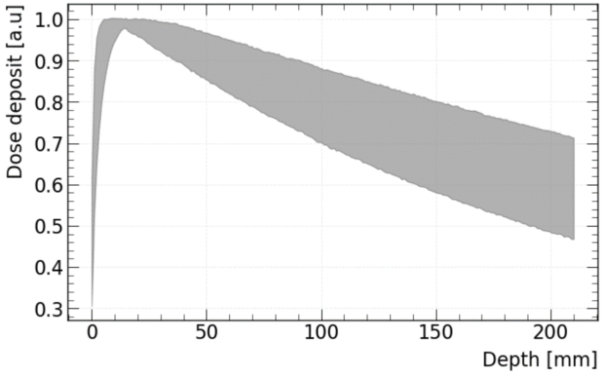
- Based on the sensitivity analysis, we can define the range of parameter variations to reproduce the conditions at Feerix.

bin_0	α	β	p	q	E_{cut}	E_{max}
[0,02-0,03]	[0,35-0,65]	[2,87-5,38]	[1,96-3,64]	[0,53-0,99]	[3,9-7,4]	[5,6-8,5]

- By randomly and uniformly selecting parameters within these ranges, we can generate a realistic dataset that captures the variations at Feerix. The dose deposit associated with each random spectrum is calculated using the response matrix: $d = Ms$.

For instance, 100 000 spectra and corresponding doses can be generated in ~ 10 s:





Annexe 2 : Electron contamination