Design and development of an irradiation facility for X-ray radiography and tomography at Politecnico di Milano

F. Casamichiela¹, D. Mazzucconi¹, D. Bortot¹, A. Pola¹, S. Agosteo¹

¹Department of Energy (DENG) - Politecnico di Milano, Via La Masa 34, 20156 Milan, Italy
1. NDT@DENG PROJECT

- The NDT@DENG project is born in the framework of *Energy for Motion*, a research plan of the Energy Department (DENG) of Politecnico di Milano, aiming at developing new energy-related technologies for the transportation sector;

- Many efforts are made in the study of new types of batteries for electric vehicles → interest in the non-destructive analysis of batteries!

The main goal of NDT@DENG is to develop an:

**Irradiation facility** for **Lab-based X-ray Imaging**

**Desired features → Design constraints:**

- Morphological characterization of samples
- 2D imaging – X-ray digital radiography (XDR)
- 3D imaging – X-ray Computed Tomography (XCT)
- Sample size – from 2 to 20 cm (not only batteries!)
- Resolution – from 40 μm up to 400 μm
- Perform dynamic studies and *in-situ* testing
2. THE X-RAY IMAGING FACILITY

The facility will be based on a **custom XCT** scanner instead of a commercial system. Why?

- **Cost-effective**: we have an X-ray source available
- **Flexible and open**: setup optimized for end user requirements
- **Upgradable**: components can be improved

The system is currently **under development**, the activities done so far are the following:

**X-ray tube:**
- Modelling of the available X-ray source via Monte Carlo simulations
- First run of measurements of the energy spectrum

**Detection system:**
- Developed a theoretical model of the signal and resolution response of an indirect lens-coupled X-ray detector for digital radiography

**Rotating stage:**
- Designed and assembled the sample positioning system
Monte Carlo simulations of the X-ray source with the FLUKA code, to obtain a reliable model of the X-ray fluence energy spectrum, for any:

- voltage from 40 to 150 kV (in steps of 10)
- distance from exit window (assuming 1/r² propagation)
- tube load factor (i.e., anode current * exposition time)
- added filtration (X-ray attenuation data from NIST are used)

RTC1000 HS by IAE:
- Range kVp – 40-150 kV
- Focal spot size – 0.6 mm
3. X-RAY SOURCE: FIRST MEASUREMENTS OF THE ENERGY SPECTRUM

- A first set of measurements of the X-ray energy spectrum was carried out with an HPGe detector (ISOCS by Canberra).

- Measurements of the unfiltered beam present some challenges, due to the high current of the source → need for good collimation and fast readout!

Schematic experimental setup:

Still some pile-up issues. Collimation must be improved. However, first comparison is encouraging!
3. X-RAY SOURCE: SPATIAL RESOLUTION

Large focal spot (0.6mm) of the source influences spatial resolution due to geometrical magnification. A Monte Carlo code was written in MATLAB® to explore the resolution limits of the source.

1) The code calculates the Edge-Response function (ERF) on the r-coordinate. Then, the Line-Spread Function (LSF) is derived.

Assumptions:
• no X-ray transmitted through the object;
• no scattering (to be implemented!)

2) The Modulation-Transfer function (MTF) is calculated as the Fourier Transform of the LSF.

3) Spatial resolution is obtained from frequency @ MTF = 10%

30 &mu;m resolution achievable!
The chosen configuration for the X-ray camera is an **indirect lens-coupled** detector, based on a scintillator screen coupled to a CCD sensor via a 90° mirror and a photographic lens.

Pros:  
- High flexibility  
- Low-cost  
- High X-ray dose  

Cons:  
- Low-efficiency  
- Complex signal chain  

**Detection scheme:**

- Incident X-rays  
- Absorbed X-rays  
- Emitted optical photons  
- Focused optical photons  
- Generated photoelectrons  

A **theoretical model** of the signal chain was developed to predict the performance of a given setup, considering:

- Scintillator material: **GADOX**  
- Scintillator thicknesses: 50-200 μm  
- X-ray energies: up to 120 keV  
- Generic lens + CCD camera  

The model calculates the signal propagation at each stage:

**Example:** 100 μm – 60 keV
The **scintillator** is the most critical stage in the signal chain. A model was developed to calculate the **optical photon signal** and the **resolution** (MTF) of a given GADOX screen. Good agreement is found with **FLUKA**!

1) Deposited energy

Important because:

\[ N^* \text{ generated optical photons} \propto \text{Deposited energy}. \]

Good agreement is found considering also the contribution of fluorescence photons (blue dashed line):

![Deposited energy graph](image)

**Example:** 150 um GADOX screen

2) Light-output

It is the n° of emitted optical photons/incident X-rays. Depends on the optical properties of the scintillator (refractive index, scattering coefficient etc.).

<table>
<thead>
<tr>
<th></th>
<th>20 keV</th>
<th>60 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td>519</td>
<td>579</td>
</tr>
<tr>
<td><strong>FLUKA</strong></td>
<td>523 ± 2</td>
<td>566 ± 1</td>
</tr>
</tbody>
</table>

**Example:** 200 um GADOX screen **(transparent)**

3) Resolution

Is expressed by the Modulation Transfer Function.

**Example:** 60 keV X-rays - 200 um GADOX screen

<table>
<thead>
<tr>
<th></th>
<th>20 keV</th>
<th>60 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td>376</td>
<td>485</td>
</tr>
<tr>
<td><strong>FLUKA</strong></td>
<td>392 ± 1</td>
<td>487 ± 2</td>
</tr>
</tbody>
</table>
5. SETUP: AVAILABLE X-RAY CAMERAS

Assembled detector prototype:

- **Field-of-view (FOV):** 70 mm × 70 mm
- **CCD Camera:** Moravian G31100, Full-frame sensor + Peltier cooling, 9 um pixel pitch
- **Lens:** Samyang 50 mm f/1.4 lens + 12 mm extension tube
- **Scintillator:** Microcolumnar CsI(Tl) (to be acquired soon!)
- **Resolution:** ~16 lp/mm (~30 μm)

Fast imaging camera by Neutronoptics

- **Field-of-view (FOV):** 250 cm × 200 cm
- **CCD Camera:** Atik VS60, 1" sensor + Peltier cooling, 4.54 um pixel pitch
- **Lens:** Fujinon 25 mm f/1.4 lens
- **Scintillator:** GADOX
- **Resolution:** ~5 lp/mm (~100 μm)
5. SETUP: SOME IMAGES OF THE FACILITY
Thank you for your kind attention!
EXTRA 1: LABORATORY XCT FOR BATTERIES

What can **XCT** do (in principle):

- **✓** Non-destructive: *in-situ, ex-situ* and *in-operando* imaging  
- **✓** Investigate **structure** at various spatial scales (from cell-level to microstructure level)  
- **✓** Capture **dynamics**: structural dynamics and degradation! (multiple radiographies or tomographic scans in time)

**Caveat!**

**General limits of XCT:**

- **FOV ↑ ⇒ Spatial resolution ↓**
- **Spatial resolution ↑ ⇒ Time resolution ↓**
- **Beam intensity ↑ ⇒ Time resolution ↑**

**Lab-based** sources: Spatial resolution ↑ ⇒ Beam intensity ↓

**Synchrotron** sources: very high beam intensity!