ENERGY FOR MOTION
Department of Excellence 2018-2022

POLITECNICO MILANO 1863

NUCLEAR MEASUREMENTS LAB.

10th Jubilee RAD INTERNATIONAL CONFERENCE ON RADIATION IN VARIOUS FIELDS OF RESEARCH
Summer Edition
July 25-29, 2022
Palmon Bay Hotel
Herceg Novi, Montenegro

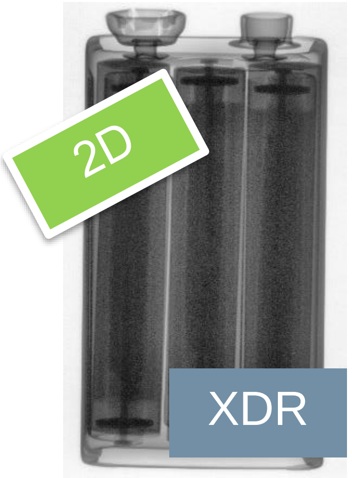
Design and development of an irradiation facility for X-ray radiography and tomography at Politecnico di Milano

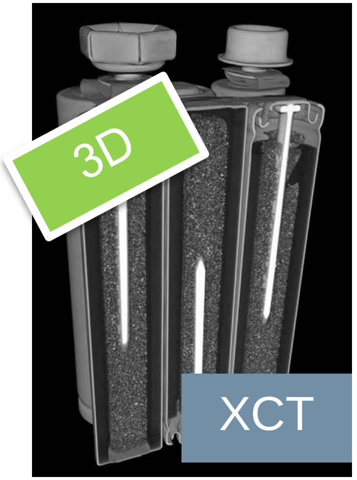
F. Casamichiela[1], D. Mazzucconi[1], D. Bortot[1], A. Pola[1], S. Agosteo[1]

[1]Department of Energy (DENG) - Politecnico di Milano, Via La Masa 34, 20156 Milan, Italy

- 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

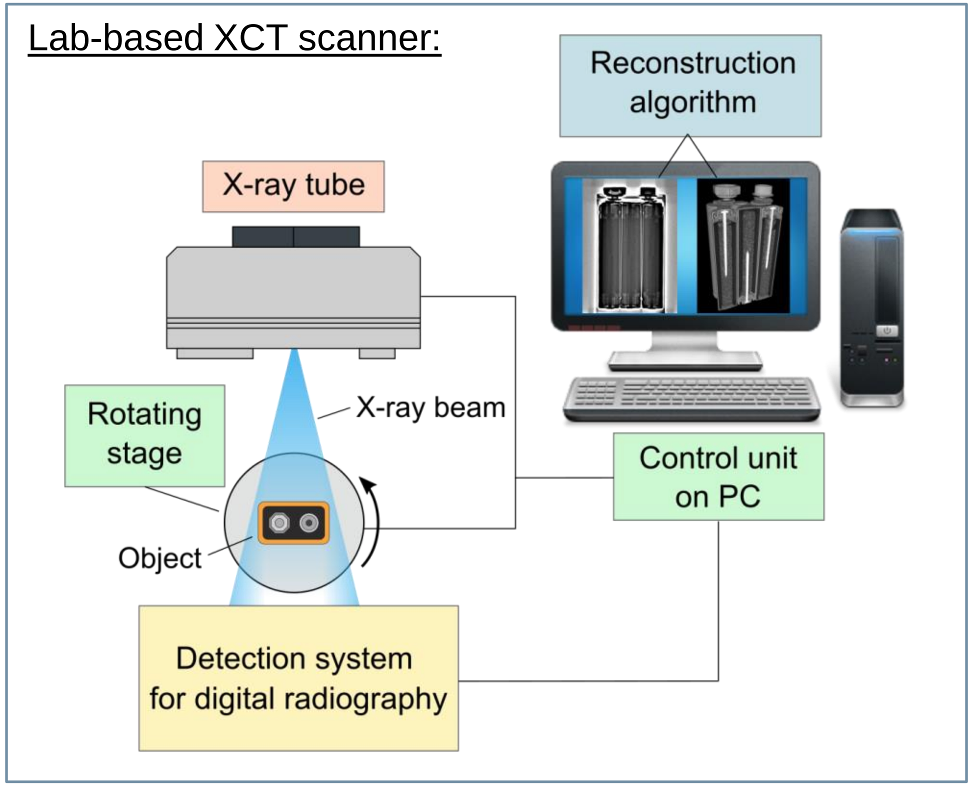
<u>Desired features</u> → <u>Design constraints:</u>

- ✓ **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:

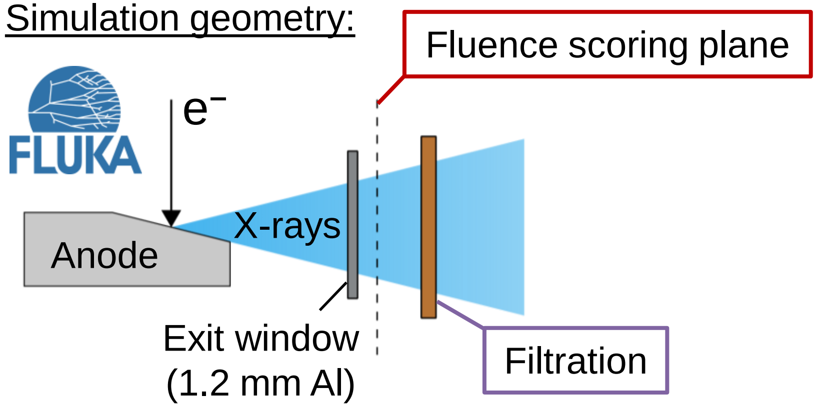
- Designed and assembled the sample positioning system

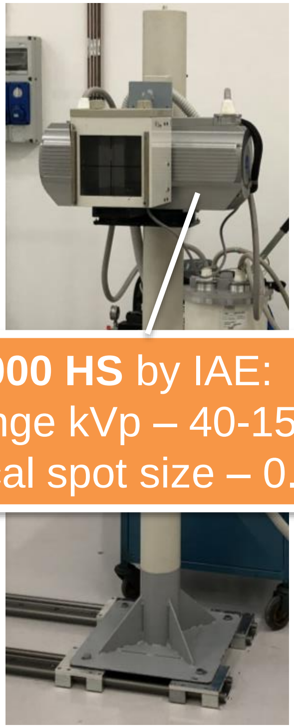
3. X-RAY SOURCE: NUMERICAL CALCULATIONS OF THE ENERGY SPECTRUM

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:

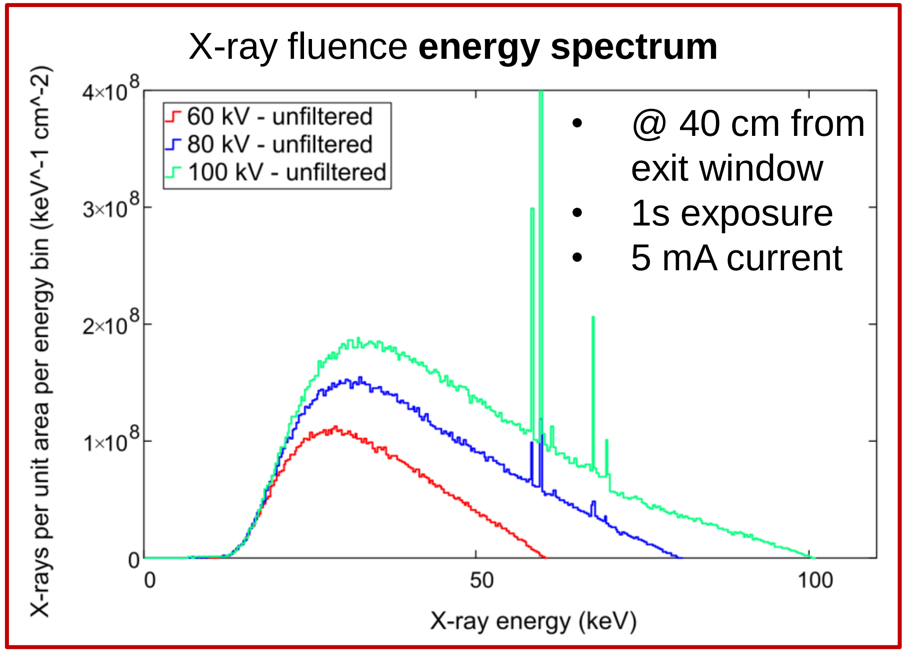
- voltage from 40 to 150 kV (in steps of 10)
- distance from exit window (assuming **$1/r^2$** propagation)
- tube load factor (i.e., anode current * exposition time)
- added filtration (X-ray attenuation data from NIST are used)

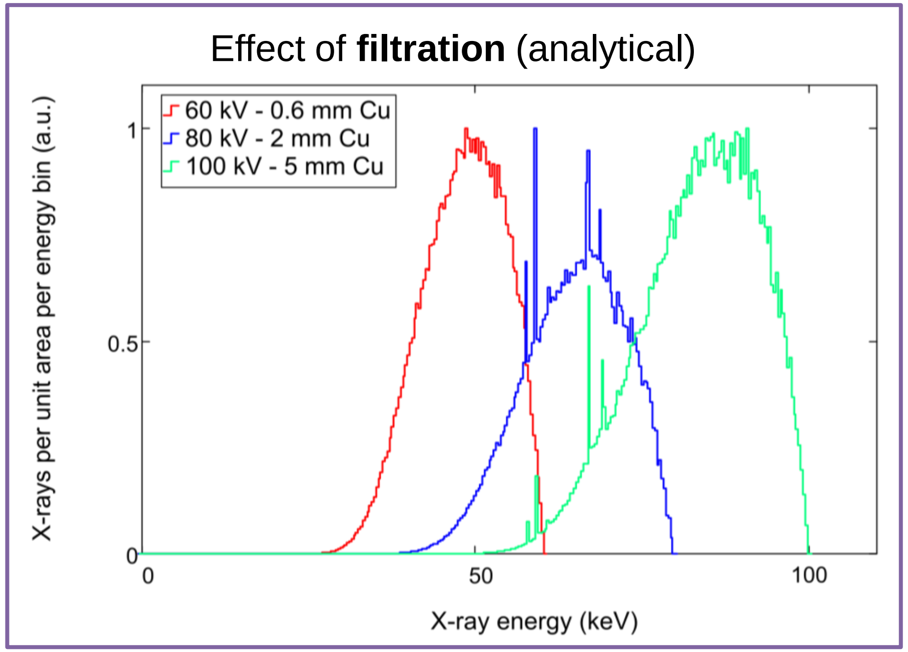
Simulation geometry:





RTC1000 HS by IAE:
- Range kVp – 40-150 kV
- Focal spot size – 0.6 mm



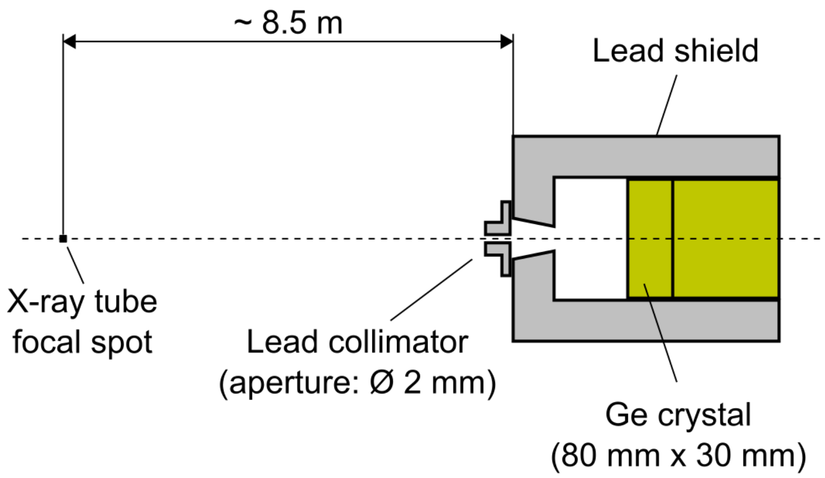


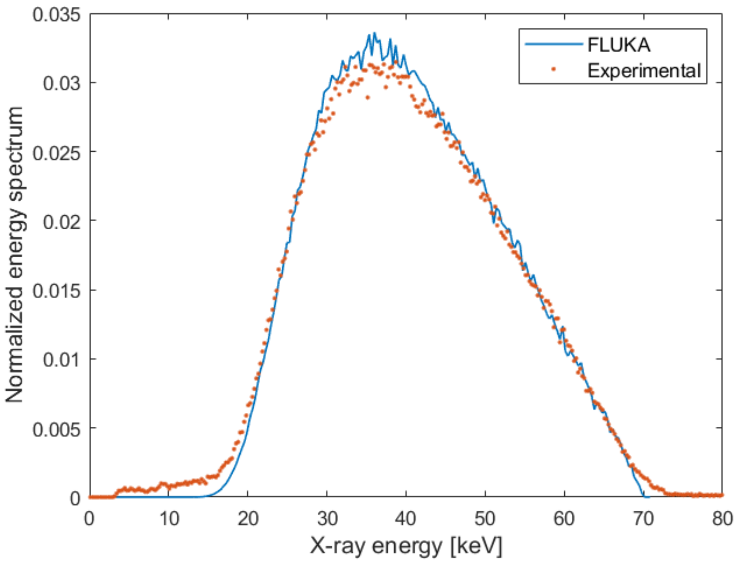
3. X-RAY SOURCE: FIRST MEASUREMENTS OF THE ENERGY SPECTRUM

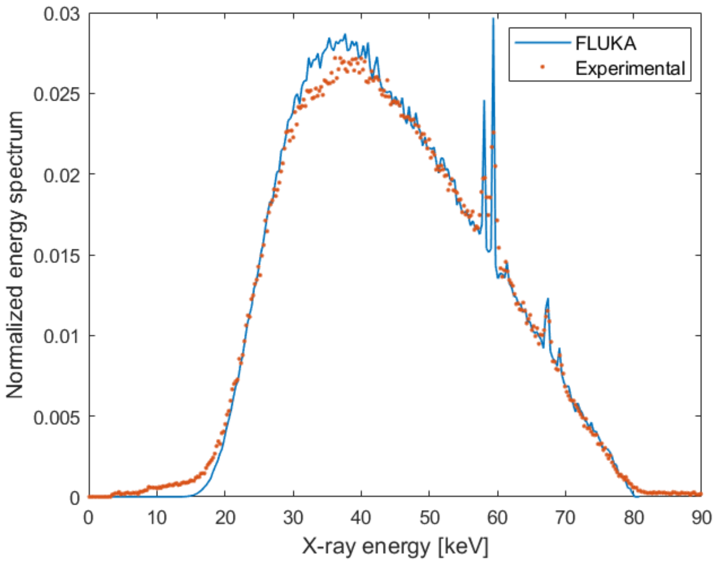
- A first set of **measurements** of the X-ray energy spectrum was carried out with an HPGe detector (ISOCS by Canberra)

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

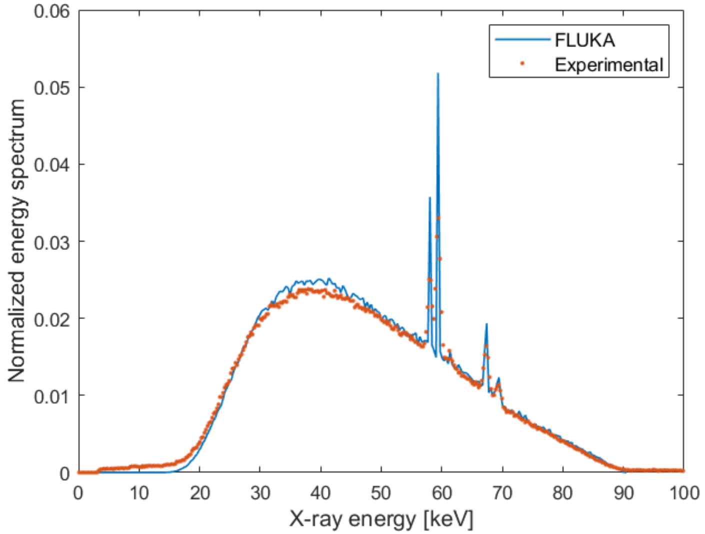
Schematic experimental setup:





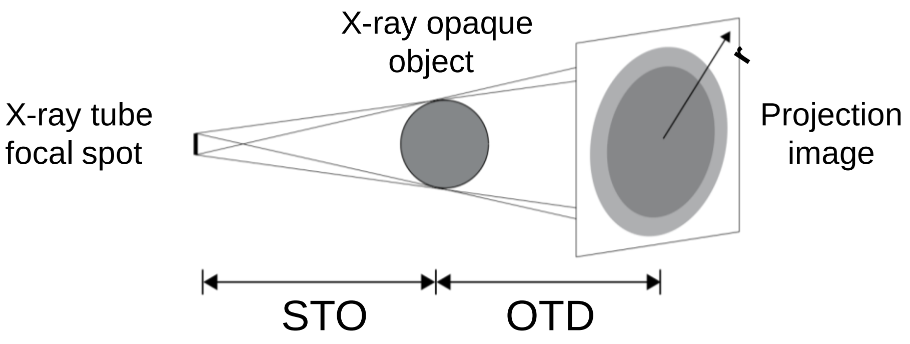


Still some **pile-up** issues.
Collimation must be improved.
However, first comparison is encouraging!



3. X-RAY SOURCE: SPATIAL RESOLUTION

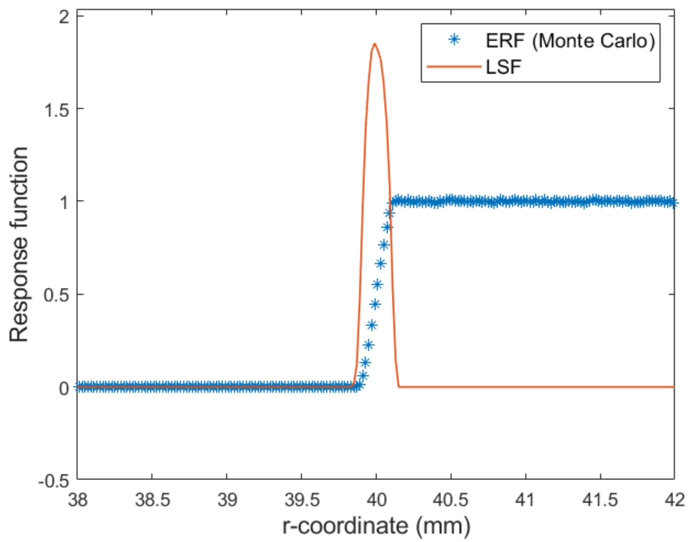
Large focal spot (0.6mm) of the source influences **spatial resolution** due to geometrical magnification. A Monte Carlo code was written in MATLAB® to explore the resolution limits of the source.



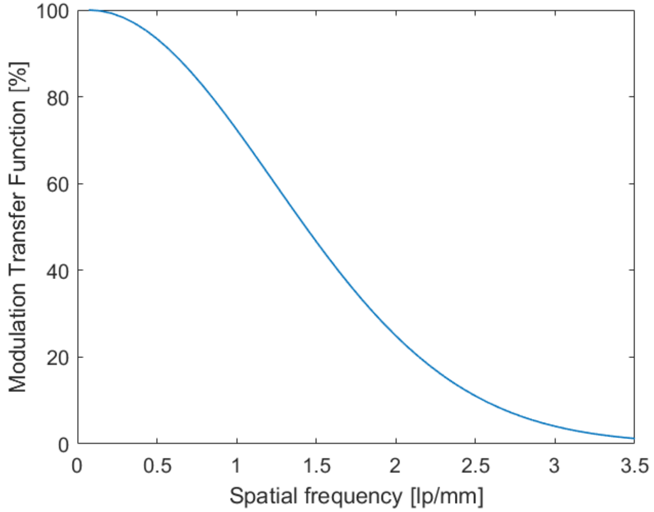
1) The code calculates the **Edge-Response function** (ERF) on the r-coordinate. Then, the **Line-Spread Function** (LSF) is derived.

Assumptions:

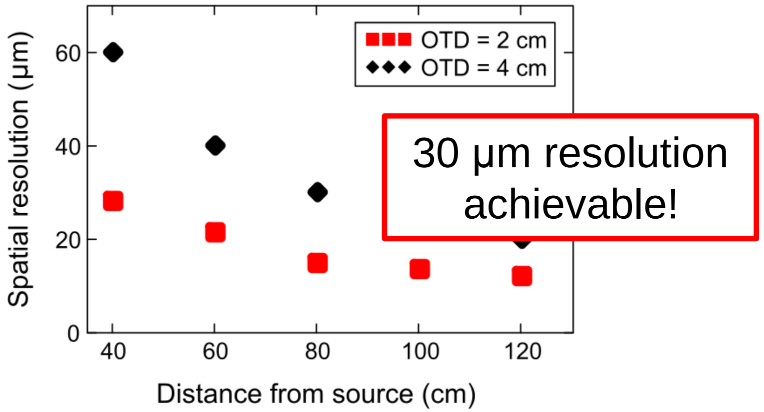
- no X-ray transmitted through the object;
- no scattering (to be implemented!)



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



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



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

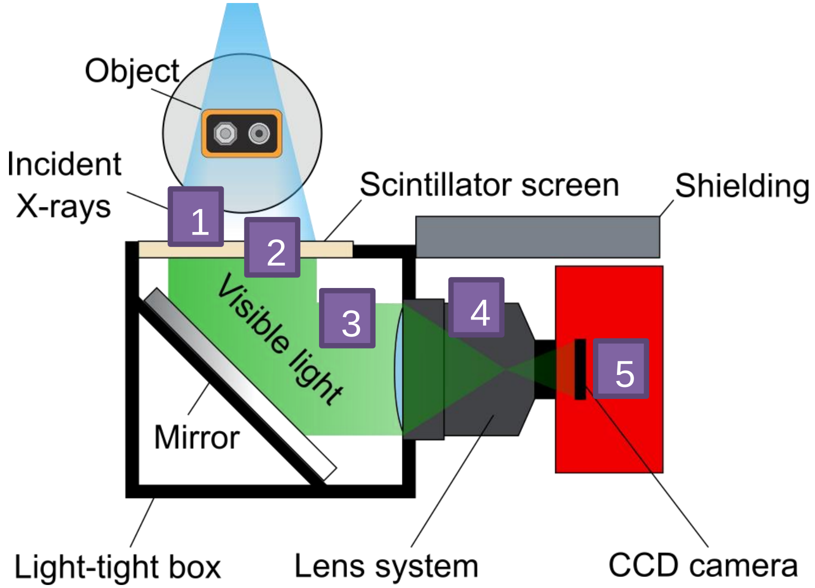
Cons:

- x Low-efficiency
- x Complex signal chain

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

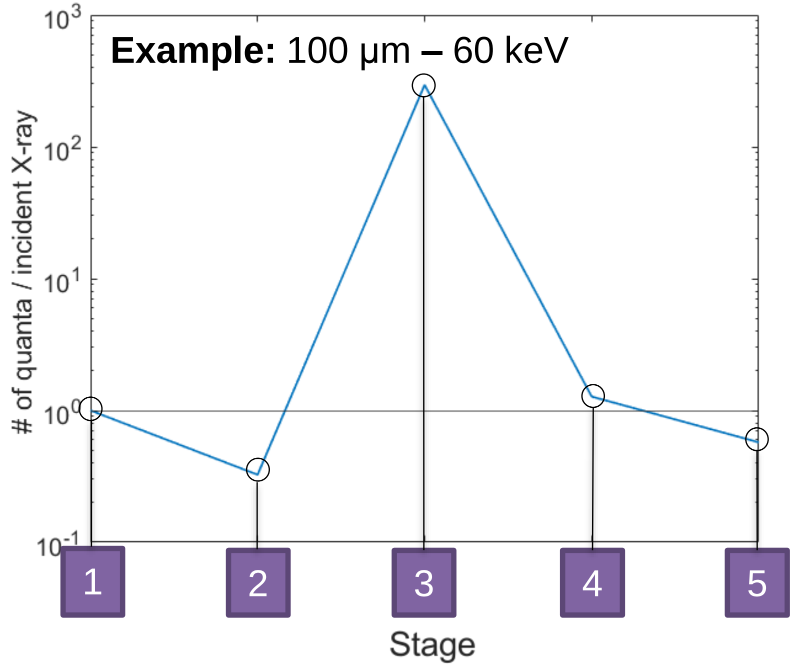
- Scintillator material: **GADOX**
- Scintillator thicknesses: 50-200 µm
- X-ray energies: up to 120 keV
- Generic lens + CCD camera

Detection scheme:



1 Incident X-rays
2 Absorbed X-rays
3 Emitted optical photons
4 Focused optical photons
5 Generated photoelectrons

The model calculates the signal propagation at each stage:

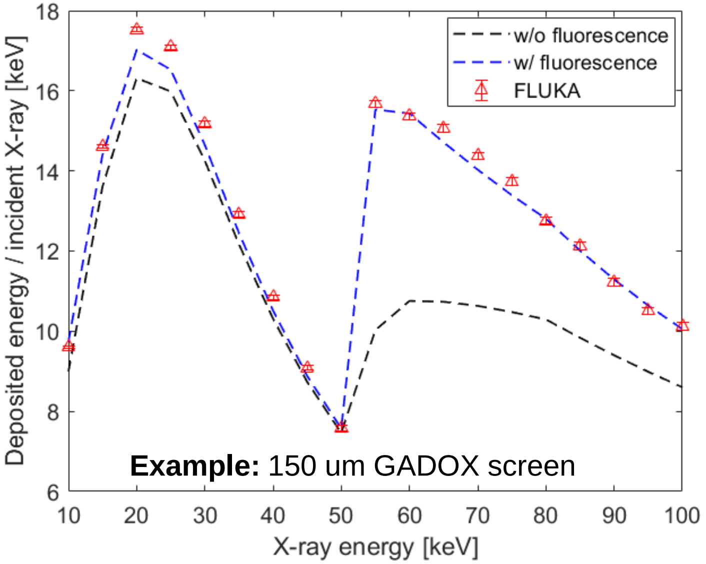


The **scintillator** is the most critical stage in the signal chain. A model was developed to calculate the **optical photon signal** and the **resolution** (MTF) of a given GADOX screen. Good agreement is found with **FLUKA**!

1) Deposited energy

Important because:
N° generated optical photons ∝ Deposited energy.

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



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.).

200 um GADOX screen (**transparent**)

	20 keV	60 keV
Model	519	579
FLUKA	523 ± 2	566 ± 1

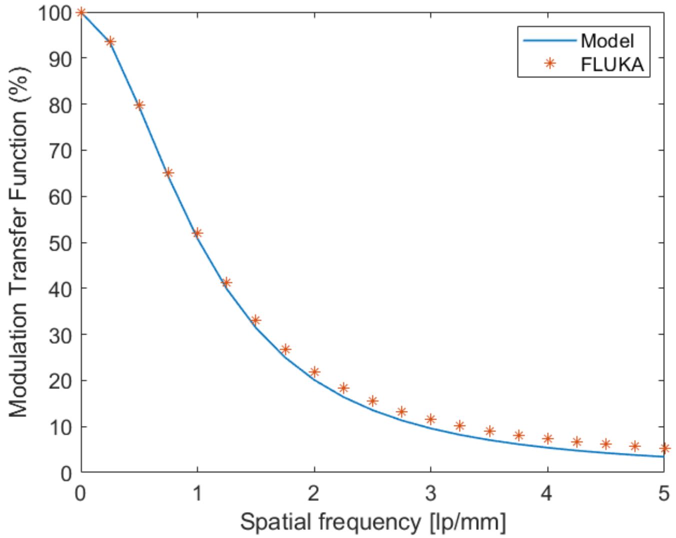
200 um GADOX screen (**including light scattering**)

	20 keV	60 keV
Model	376	485
FLUKA	392 ± 1	487± 2

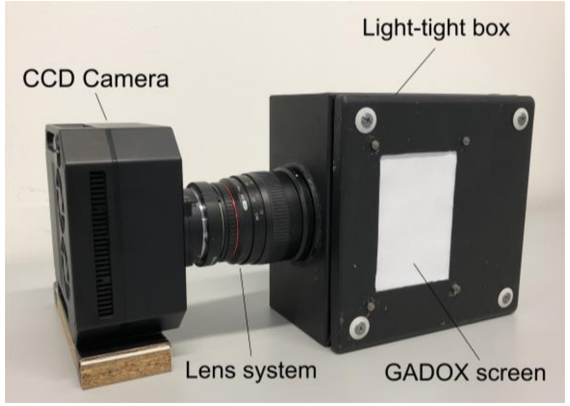
3) Resolution

Is expressed by the Modulation Transfer Function.

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



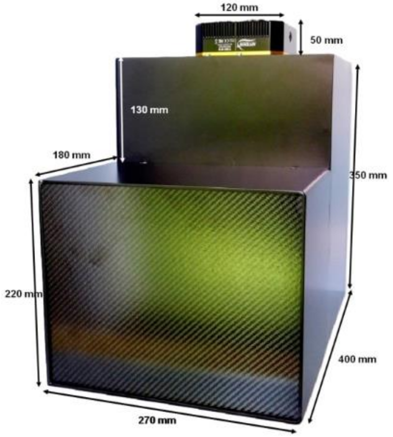
Assembled detector prototype:



Features:

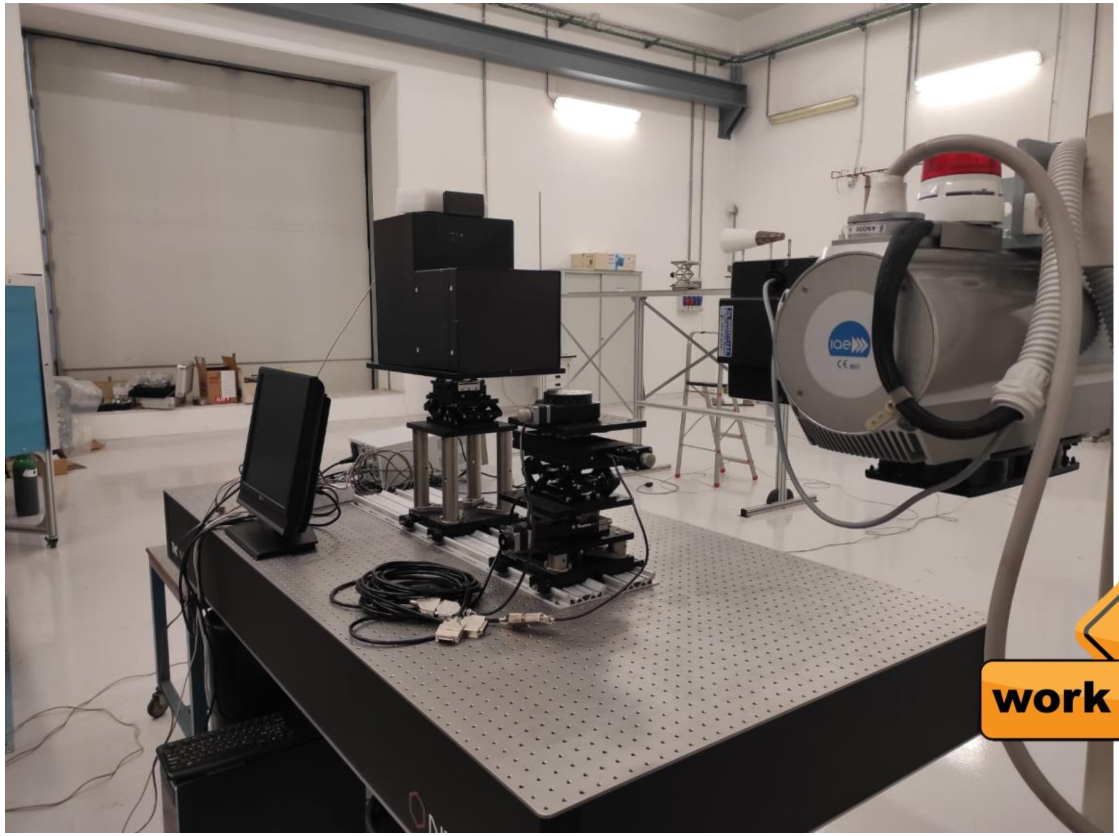
- Field-of-view (FOV): 70 mm × 70 mm
- CCD Camera: Moravian G31100, Full-frame sensor + Peltier cooling, 9 um pixel pitch
- Lens: Samyang 50 mm f/1.4 lens + 12 mm extension tube
- Scintillator: Microcolumnar CsI(Tl) (to be acquired soon!)
- Resolution: ~16 lp/mm (~30 μm)

Fast imaging camera by Neutronoptics



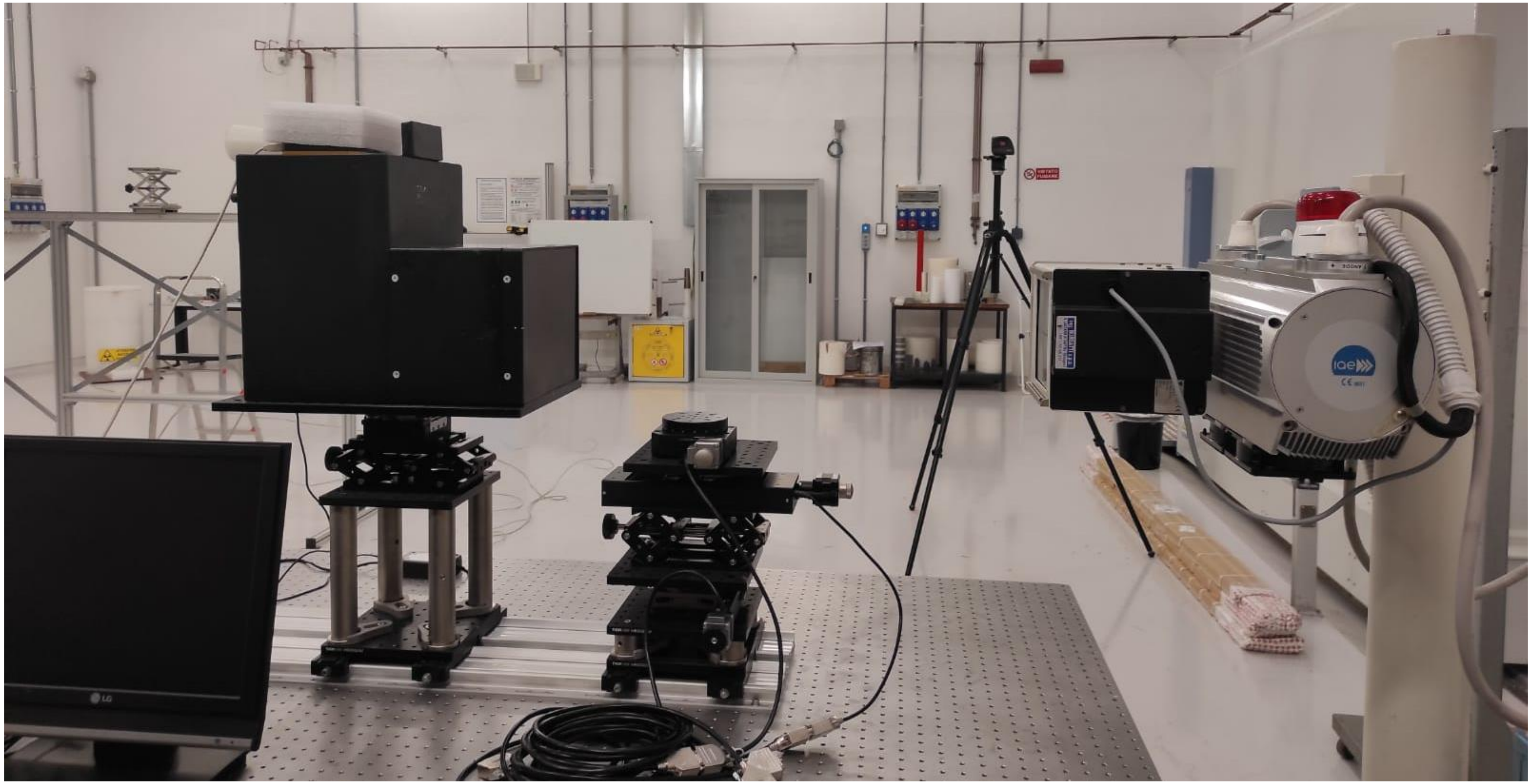
Features (see Neutronoptics site):

- 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)




THORLABS
NEXUS


work in progress



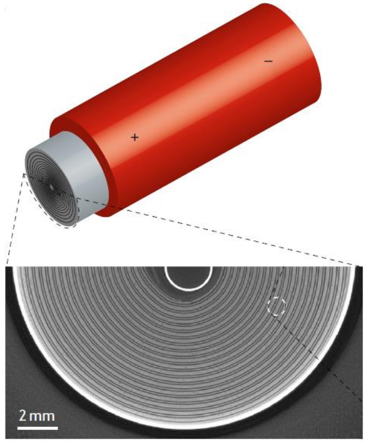
POLITECNICO
MILANO 1863

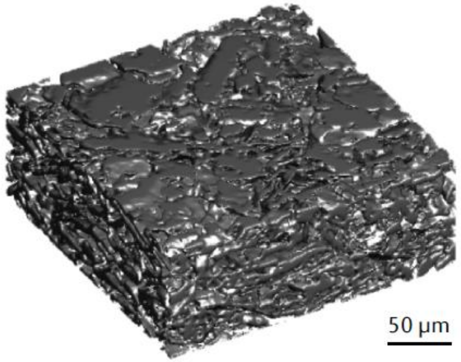
NUCLEAR MEASUREMENTS LAB.

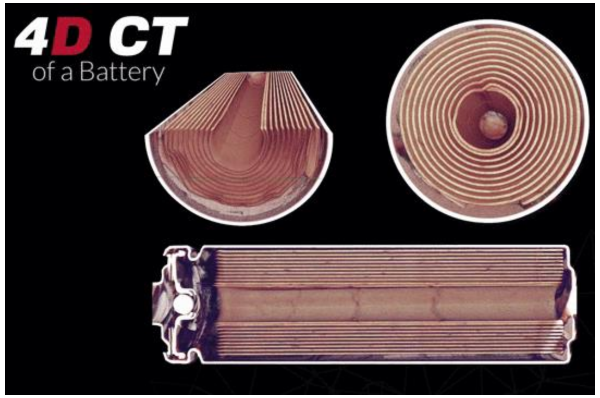
Thank you for your kind attention!

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!