# Alanine/EPR dosimetry for kilovoltage X-ray applications

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Council on Ionizing Radiation Measurements & Standards

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# Why kilo-voltage (kV) X-ray generators?

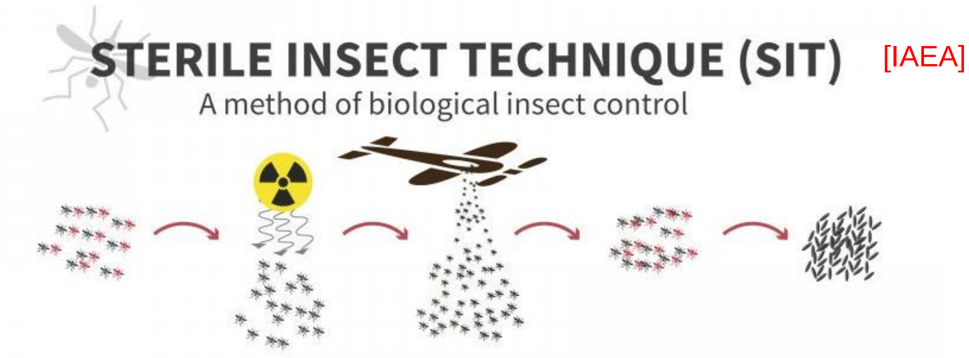

- Small self-shielded (usually) cabinets
- Smaller investment compared to high energy X-ray or E-Beam installations
- No need to procure, handle and transport radioactive sources
- Irradiation using kV X-rays can ensure “good” DUR (dose uniformity ratio = $D_{max}/D_{min}$) even for thick products

# Applications using kV X-rays

Blood irradiation
15 – 50 Gy

[RADSOURCE]

Sterile Insect Technique (SIT)
40 – 150 Gy




[IAEA]

Food irradiation
Phytosanitary treatments
0.1 – 1 kGy

[IAEA]

Bacterial decontamination
up to 30 kGy

[RadPro]

# Which dosimetry system for kV X-ray applications?

- Key quantity: Absorbed dose to water $D_w$ [Gy]
- Many dosimetry systems can be used :

| Dosimeter | Dose range | Photon energy range | Typical Dose uncertainty *(k=2)* | Influence quantities | International standard |
|---|---|---|---|---|---|
| Fricke solution | 20 Gy – 400 Gy | > 600 keV | +/- 3 % * | $T_{irr}$ – impurities – dose rate | ASTM E1026 |
| Alanine/EPR | 1 Gy – 150 kGy | > 100 keV | +/- 2 to 6 % | $T_{irr}$ – $H_r$ | ISO/ASTM 51607 |
| TLD | 1 Gy – 10 kGy | > 100 keV | +/- 6 to 13 % | $T_{irr}$ – $H_r$ – dose rate – ambient light | ISO/ASTM 51956 |
| Dichromate solution | 2 kGy – 50 kGy | > 600 keV | +/- 3 % * | $T_{irr}$ – impurities – particle type | ISO/ASTM 51401 |
| Ceric-Cerous solution | 0.5 kGy – 50 kGy | > 600 keV | +/- 4 % | $T_{irr}$ – ambient light | ISO/ASTM 51205 |
| Radiochromic dye films | 1 Gy – 150 kGy | > 100 keV | +/- 6 % | $T_{stock}$ – $T_{irr}$ – $H_r$ – dose rate – ambient light | ISO/ASTM 51275 |
| Lithium fluoride | 50 Gy – 300 kGy | > 50 keV | +/- 6 % | $T_{stock}$ – $T_{irr}$ – $H_r$ – dose rate – ambient light | ASTM E2304 |

* *If prepared in reference conditions*

# What's the problem with alanine?

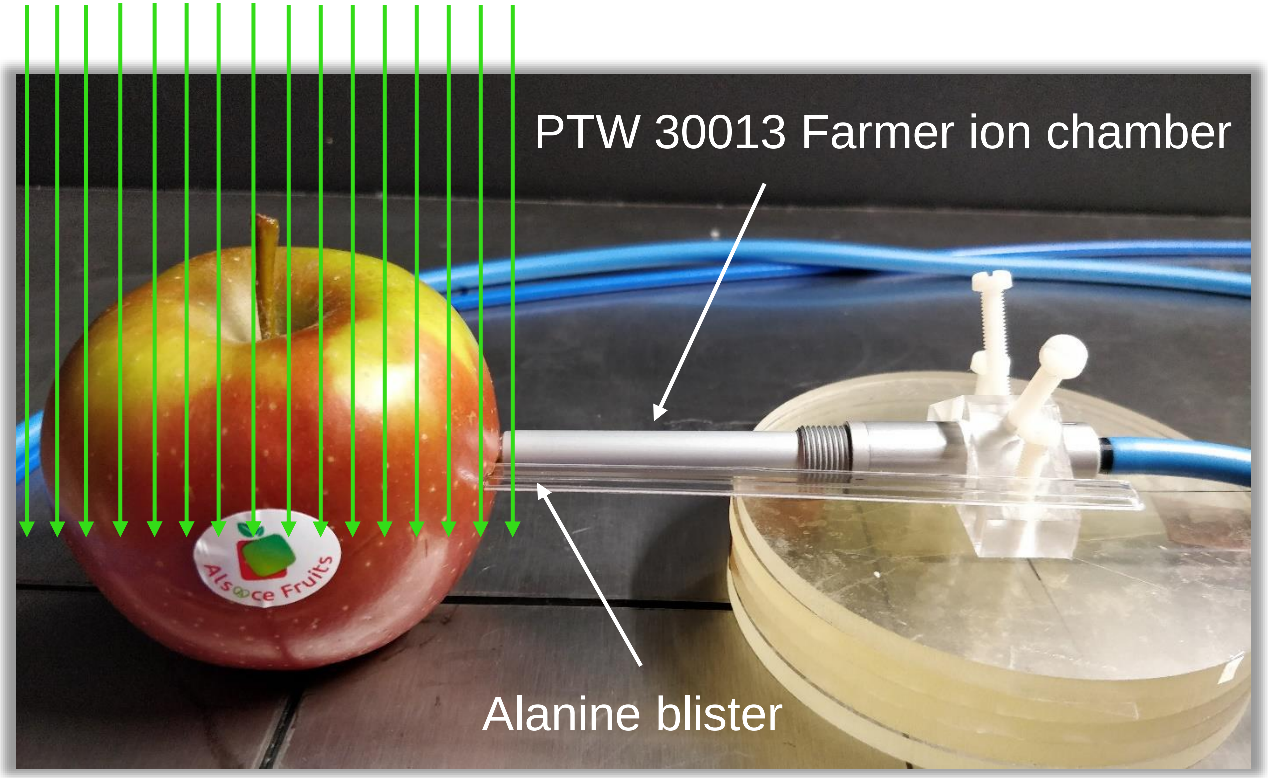
- An example: Apple irradiation as a phytosanitary treatment
- 100 kV – 2.39 mm Aluminum – 75 cm source to apple
- PTW 30013 Farmer ion chamber: $D_w$ kV X-rays calibration
- Alanine blister: $D_w$ $^{60}Co$ calibration

1 kGy limit!

Alanine reading: **786.5 Gy** +/- 31 Gy
→ Product is well irradiated

~ 30% dose underestimation using alanine

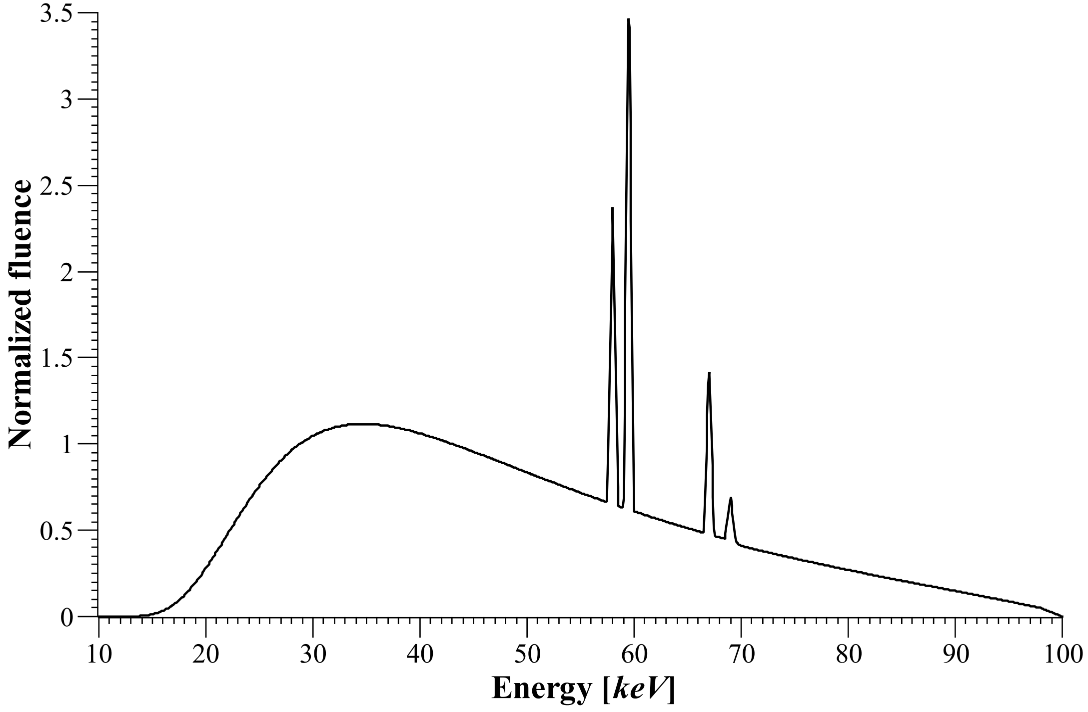
Ion chamber reading: **1089 Gy** +/- 24 Gy
→ Maximum dose was exceeded

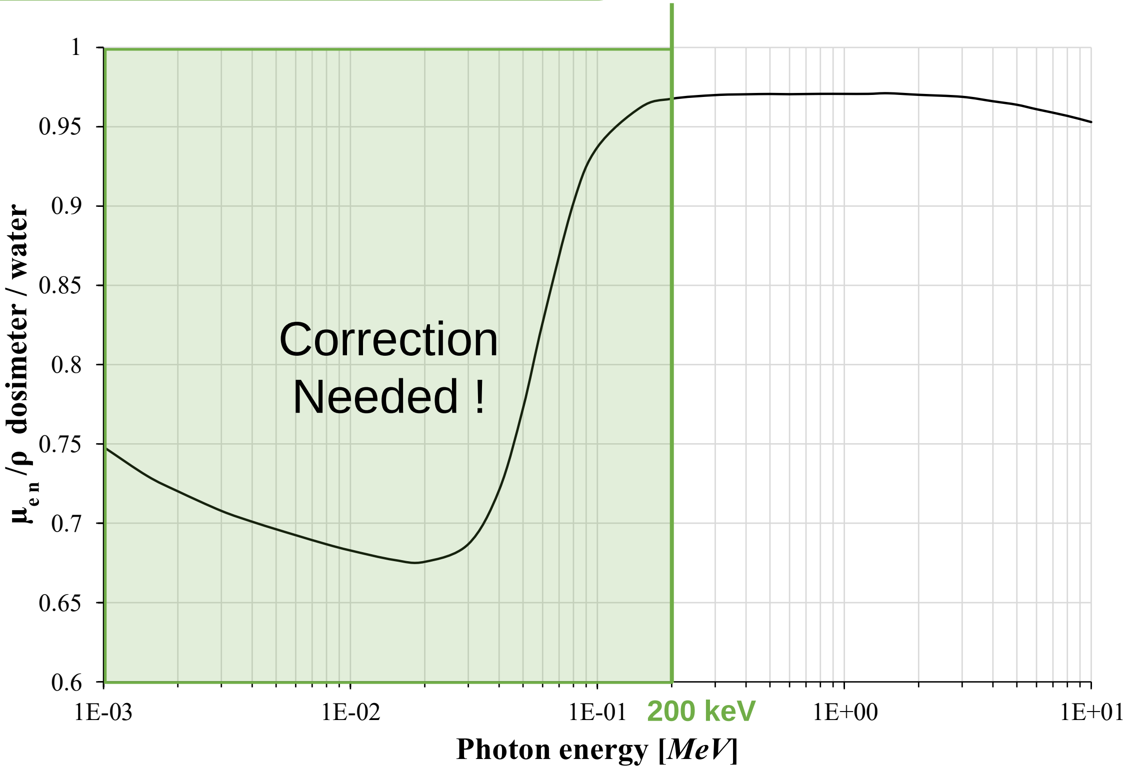


# What's the reason ?

Alanine dosimeters are not water equivalent in case of kV X-ray irradiations

$$D_{material} = \int_0^{E_{max}} \varphi\,(E)\,.\;E\;.\;\frac{\mu_{en}(E)}{\rho}\;.\;dE \qquad [Gy]$$



# Scope of the project

**Determine a correction factor to be applied to the alanine dosimeter response when calibrated with $^{60}$Co ($Q_0$) and used in kV X-ray beams (Q)**

→ How does alanine response behave with X-ray energy, compared to $^{60}$Co ?

→ Determine X-ray energy spectrum – Or beam specifier ?

→ Determine correction factor to be applied to the dosimeter's response

# Outline

**PART 1: The relative response of alanine dosimeters to kV X-rays**

- General formalism
- Developed methods
  - Experimental measurements
  - Monte Carlo Simulations

**PART 2: The relative efficiency of alanine dosimeters to kV X-rays**

- Adopted formalism
- Results

**Conclusion**

# General formalism

**Relative response**

**Physical dose**

- $\mu_{en} / \rho$
- $\mu_{attenuation}$

Alanine/water dose ratio
X-ray ($Q$) / $^{60}$Co ($Q_0$)

**Dosimeter efficiency**

- *G-value*

Free radical creation yield ratio
X-ray ($Q$) / $^{60}$Co ($Q_0$)

# The relative response of alanine dosimeters to kV X-rays

Developed methods

## Experimental measurements

- Measure EPR response (*r*) of alanine per unit of absorbed dose to water ($D_w$)
- Different X-ray qualities (50 to 280 kV), compared to $^{60}Co$ reference beam quality
- Relative response direct measurement:

$$\boldsymbol{f}_{\boldsymbol{EXP}} = \frac{(r/D_w)^Q}{(r/D_w)^{Q0}}$$

- Alanine's response is measured by EPR spectrometry
- Delivered $D_w$ is measured using a calibrated PTW Farmer 30013 ion chamber
- Irradiations carried out at Aerial: 50 to 100 kV (Effective energy : 25 to 42 keV)
- Irradiations carried out at NPL: 135 and 280 kV (Effective energies of 58.9 and 168 keV)

# The relative response of alanine dosimeters to kV X-rays

Aerial Developed methods

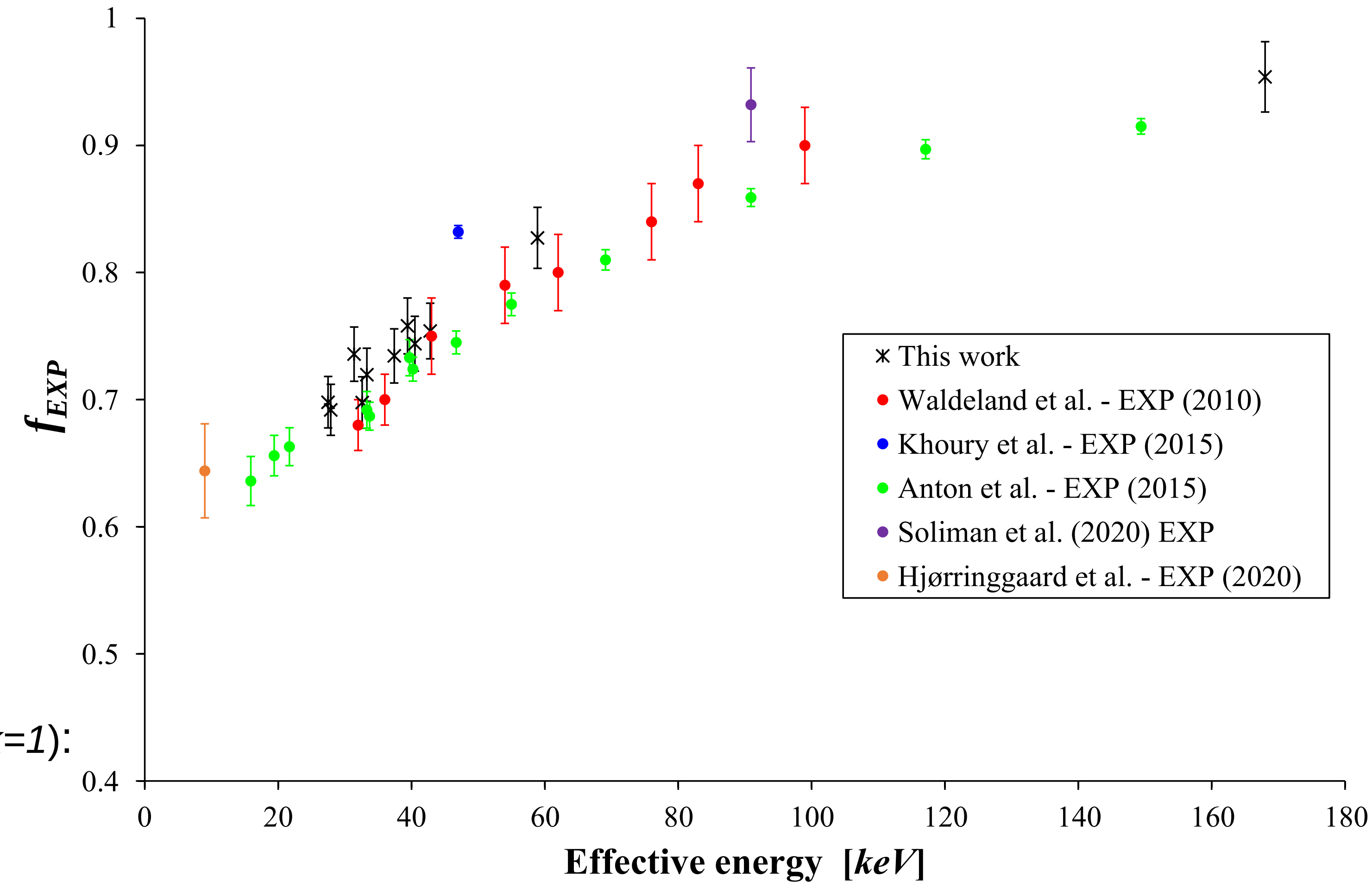
## Experimental measurements – Results

- Good agreement of obtained results with published data

- Results are slightly higher than published data:

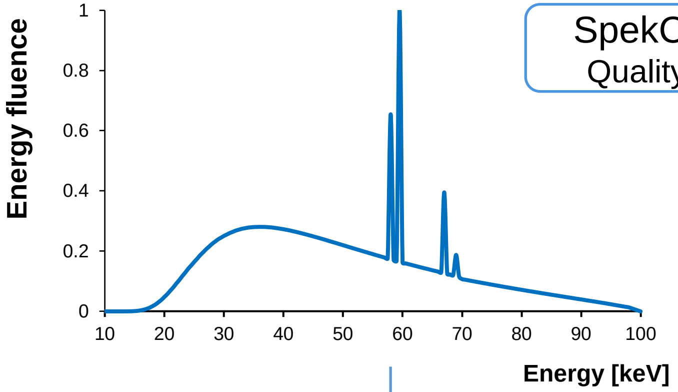
  - Difference in chemical composition of used dosimeters
  - Difference in irradiation geometries
  - Difference in used dosimetry standard ($D_w$ or $K_{air}$ formalisms)

- Overall uncertainty on relative response (*k=1*):
  - Aerial irradiations : 2.9 %
  - NPL irradiations: 2.4 %



## Monte Carlo simulations – formalism

**MCNPX – V 2.7**



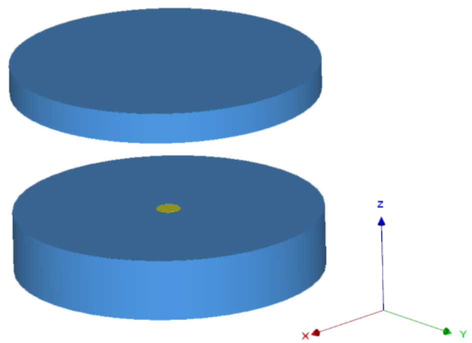

SpekCalc
Quality Q

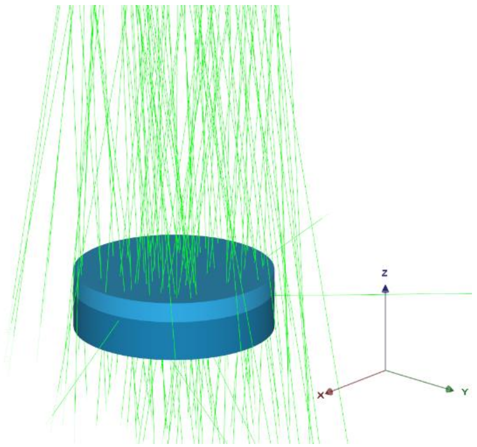
[Poludniowski, P et al. (2009)]

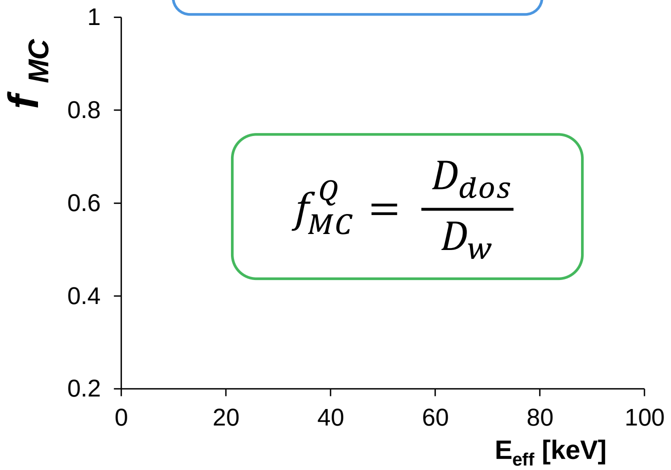
Same dose ratio was also calculated for $^{60}Co$ source ($Q_0$)

$$f_{MC}^{Q,Q_0} = \frac{f_{MC}^{Q}}{f_{MC}^{Q_0}}$$

Geometry construction → Irradiation → Results



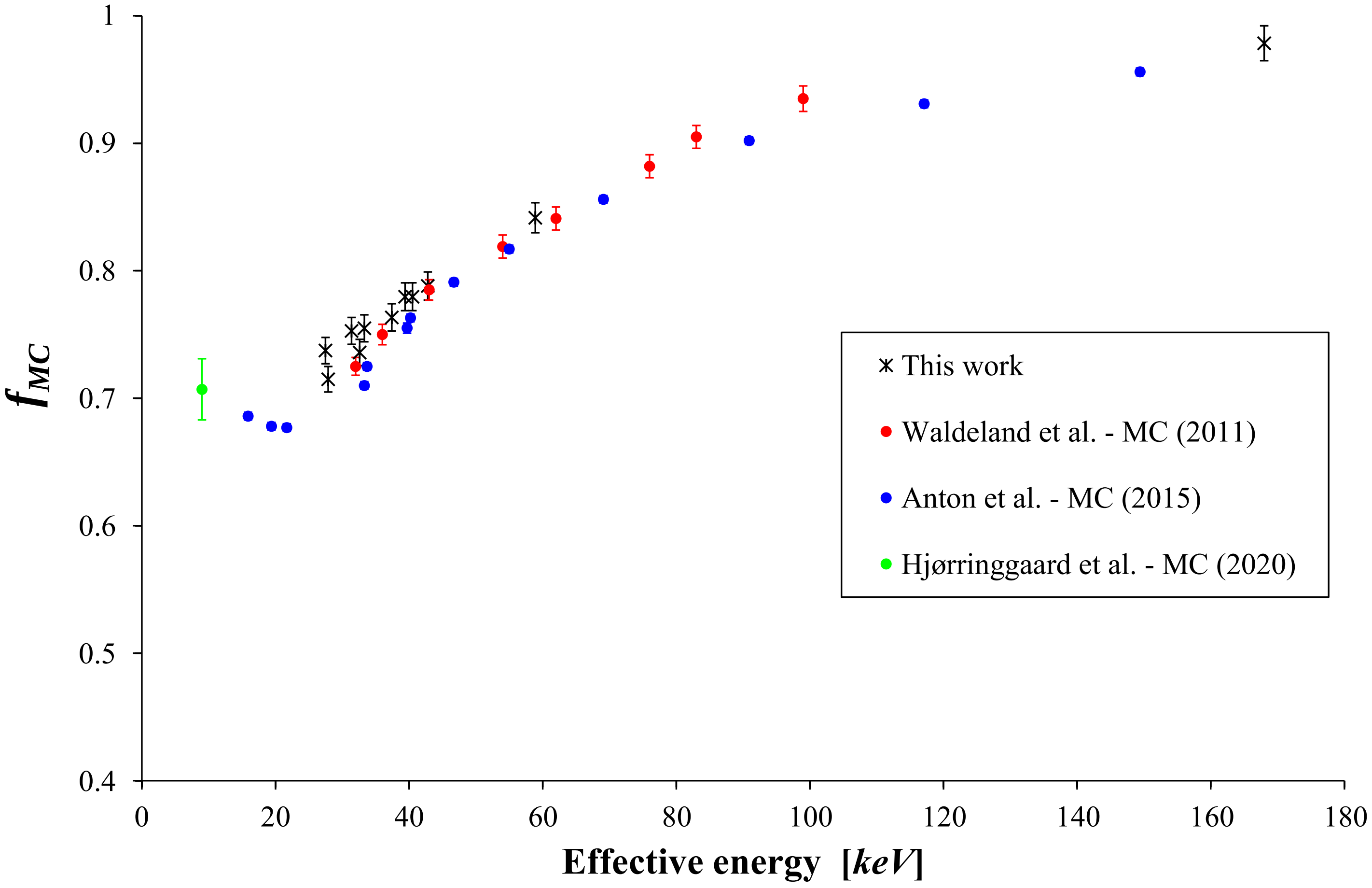





$$f_{MC}^{Q} = \frac{D_{dos}}{D_w}$$

## Monte Carlo simulations – Results

- Good agreement of obtained MC results with published data
- MC results are slightly higher than published data:
  - Difference in chemical composition of used dosimeters
  - Difference in used MC simulation code
  - Difference in irradiation geometries
- Convergence of the relative response is also observed at energies > 160 keV

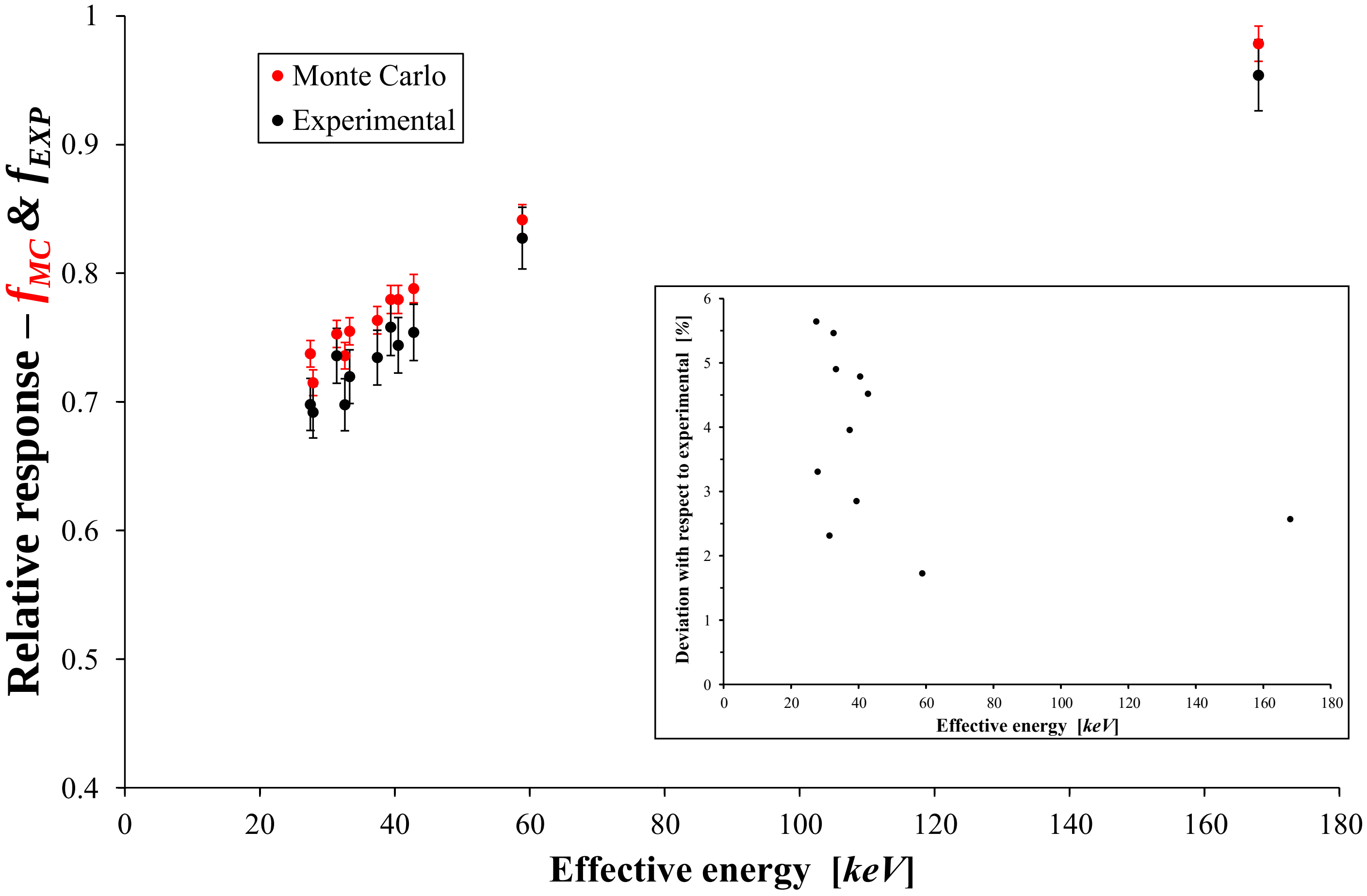


# The relative physical response of alanine dosimeters to kV X-rays

Developed methods

## Monte Carlo simulations – Results

- Good agreement of obtained MC results with experimental data (3.8% deviation)
- Results of both methods present the same tendency → convergence to unity at photon energies > 160 keV
- MC results are slightly higher than experimental data:
  - Free radical creation process not modelled in MC simulations
- Overall uncertainty (*k=1*) = 1.4 %



## PART 2: The relative efficiency of alanine dosimeters to kV X-rays

- Adopted formalism
- Results

# The relative efficiency of alanine dosimeters to kV X-rays

Adopted formalism

**Relative Response**
Experimental measurements

**Relative efficiency**
$\eta^{Q,Q_0}$

**Dose ratio**
MC simulations
Analytical calculations

$$f_{exp}^{Q,Q_0} = \frac{(r/D_w)^Q}{(r/D_w)^{Q_0}} = \frac{(r/D_{dos})^Q}{(r/D_{dos})^{Q_0}} \times \frac{(D_{dos}/D_w)^Q}{(D_{dos}/D_w)^{Q_0}}$$

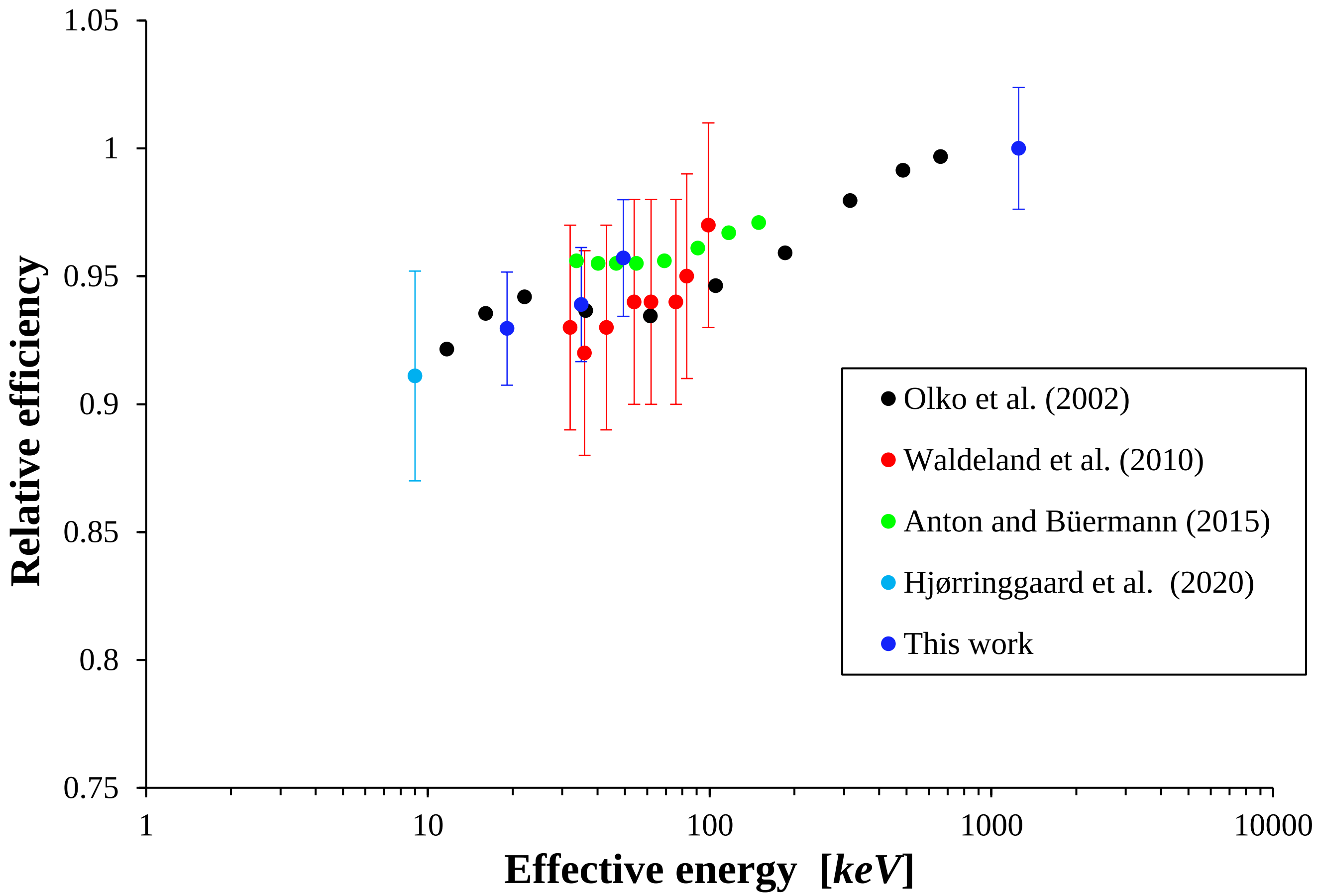
- **Goal:** Model the energy dependence of the relative efficiency of alanine

→ - 3 X-ray beam qualities have been used
- Irradiation of 16 alanine dosimeters per quality
- All dosimeters received a dose of 100 Gy
- Delivered absorbed dose to water is measured using a calibrated ion chamber
- MC simulations + Analytical calculations were used to estimate the relative efficiency of alanine

| HV [kV] | Al [mm] | $HVL_1$ [mm] | $E_{eff}$ Al [keV] |
|---|---|---|---|
| 50 | 0.47 | 0.65 | 19.1 |
| 90 | 2.88 | 3.33 | 35 |
| 100 | 9.9 | 6.83 | 49.4 |

# The relative efficiency of alanine dosimeters to kV X-rays

## Results

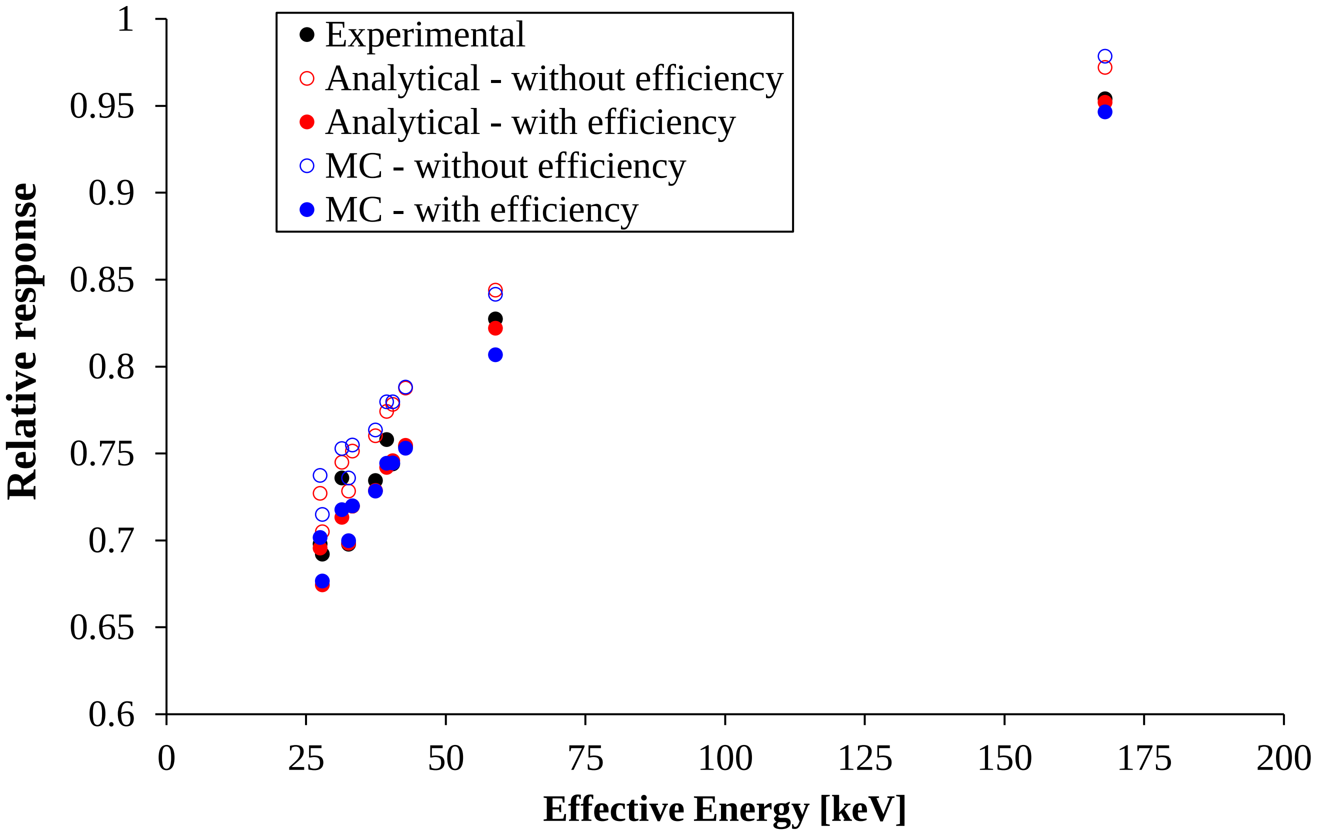


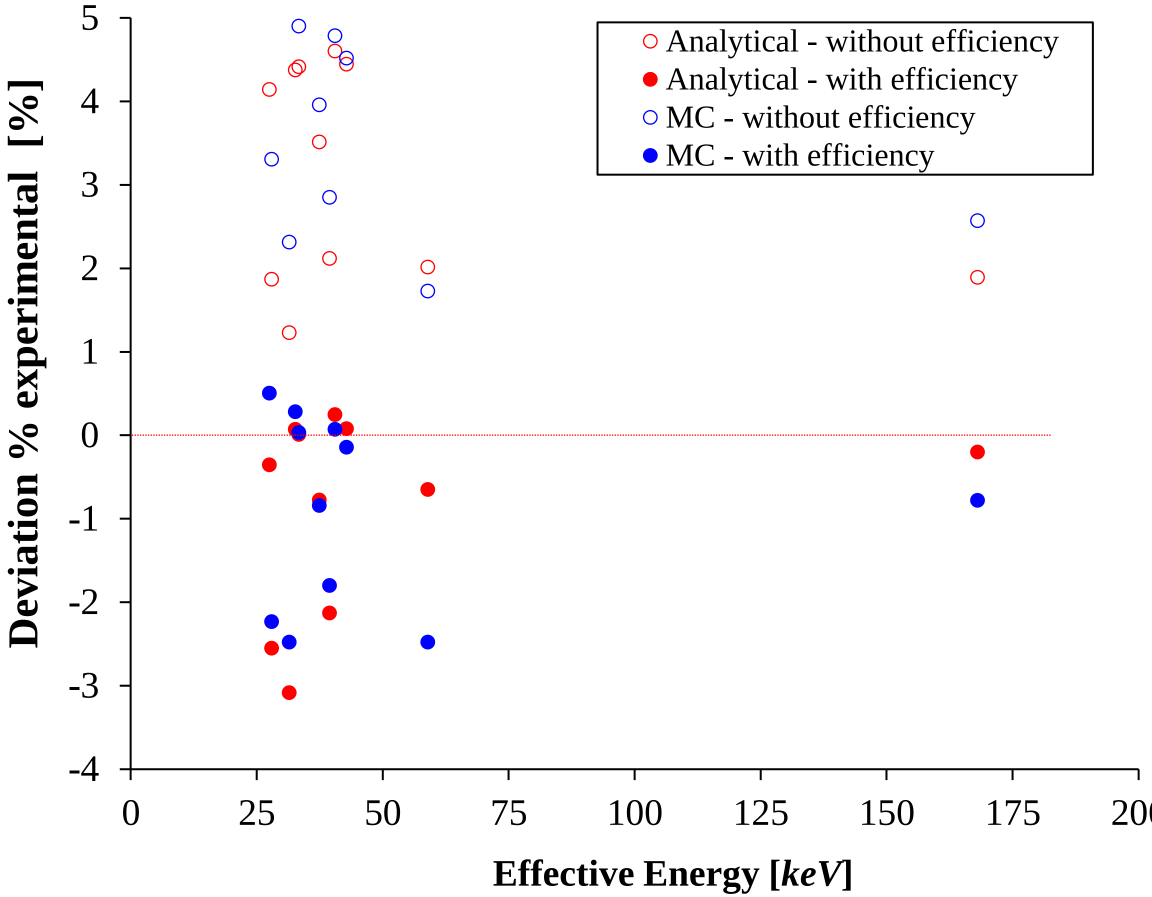

- Results of relative efficiency are in very good agreement with published data
- Slight variability due to differences in chemical composition of dosimeters, and differences in adopted formalism

# The relative efficiency of alanine dosimeters to kV X-rays

Results

- Update $f_{MC}$ and $f_{W}$ with values of the relative efficiency of alanine
- Better agreement with experimental results



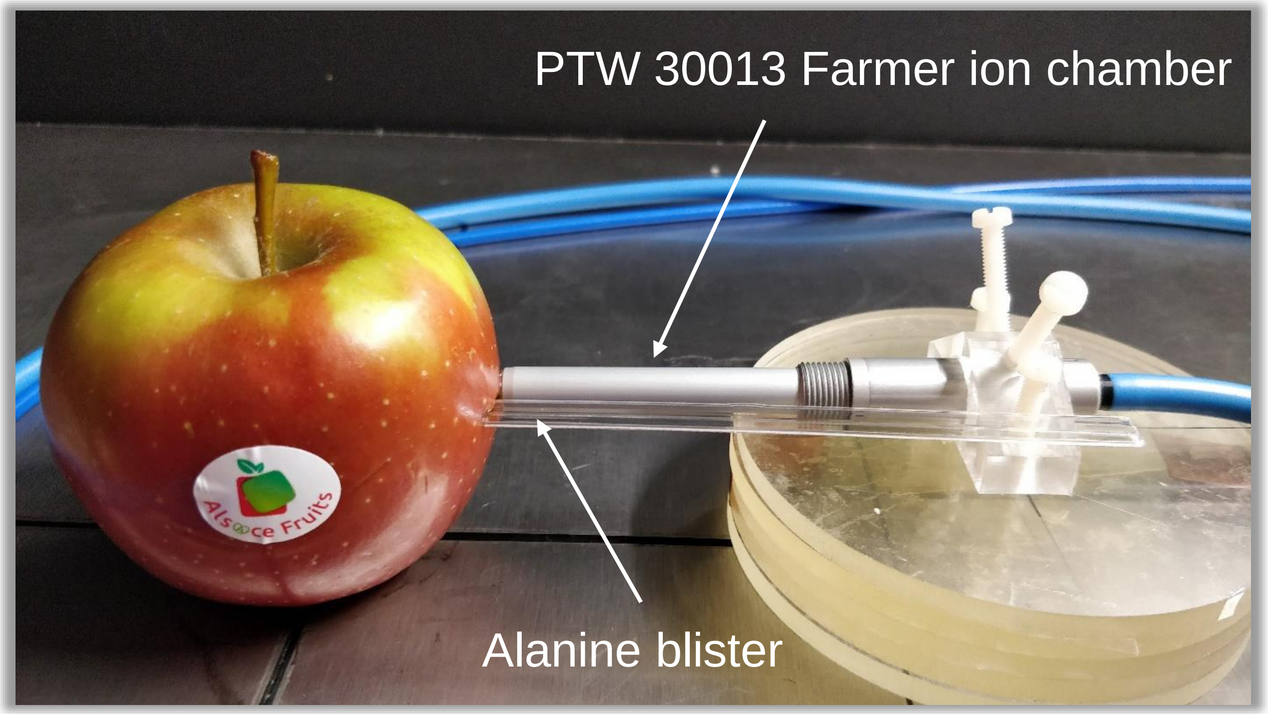
# Back to the Alsacian apple …

- $D_w$ (alanine) = 786.5 Gy
- $D_w$ (ion chamber) = 1089 Gy
- 100 kV – 2.39 mm Aluminum – 75 cm source to apple

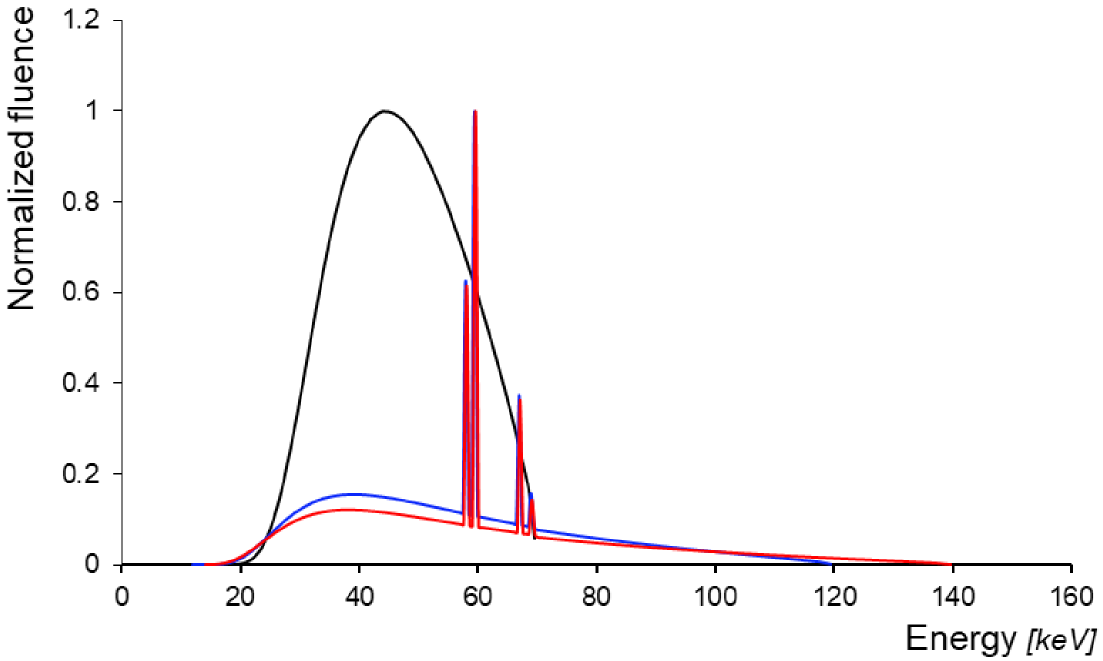
$$\rightarrow \quad f_{MC}^{Q,Q_0} = 0.714$$

- $D_w$ (alanine) / $f_{MC}^{Q,Q_0}$ = 1101.5 Gy +/- 3.9%

  → 1.1 % deviation from $D_w$ (ion chamber)



# Great ! But what is the best beam specifier?




Up to 7% discrepancy !

- Good beam quality specifier candidates:
  - $2^{nd}$ HVL (or $3^{rd}$ ?) → can be experimentally measured
  - Average energy → can be calculated/simulated
  - Other … ?

| kVp [kV] | Al [mm] | Cu [mm] | $E_{eff}$ [keV] | HVL1 [mm] | HVL2 [mm] | $E_{avg}$ [keV] | $f_W$ |
|---|---|---|---|---|---|---|---|
| 70 | 2.7 | 0.2 | 41 | 4.8 | 5.7 | 47 | 0.729 |
| 120 | 4 | 0 | 41 | 4.8 | 7.2 | 56.5 | 0.771 |
| 140 | 1.44 | 0.05 | 41 | 4.8 | 7.7 | 59.7 | 0.796 |

# Conclusion

# General conclusion and perspectives

- The relative response of alanine dosimeters to kV X-rays have been studied using three methods:
  - Experimental measurements
  - Monte Carlo simulations
  - Analytical calculations

- Novelty of this work: Analytical calculations
  - Fast method : results obtained in few seconds
  - Calculate the relative response of alanine with reasonable uncertainty of 3.1% *(k=1)*
  - No need for geometry modelling as for MC simulations

- This method is used at Aerial for $D_w$ measurements when irradiation is performed with kV X-rays.
- For now, only applicable for doses below 10 kGy due to the alanine dose response non-linearity at higher doses.

- Results of this project were published in the following references:


✓ A. Nasreddine et al. Absorbed dose to water determination for kilo-voltage X-rays using alanine/EPR dosimetry systems, Rad. Phys. Chem, 2020, 180, 108938, DOI: 10.1016/j.radphyschem.2020.108938

✓ A. Nasreddine. Alanine/EPR dosimetry for low to medium energy X-ray radiation processing control. Université de Strasbourg, 2020. DOI: 10.13140/RG.2.2.22439.88488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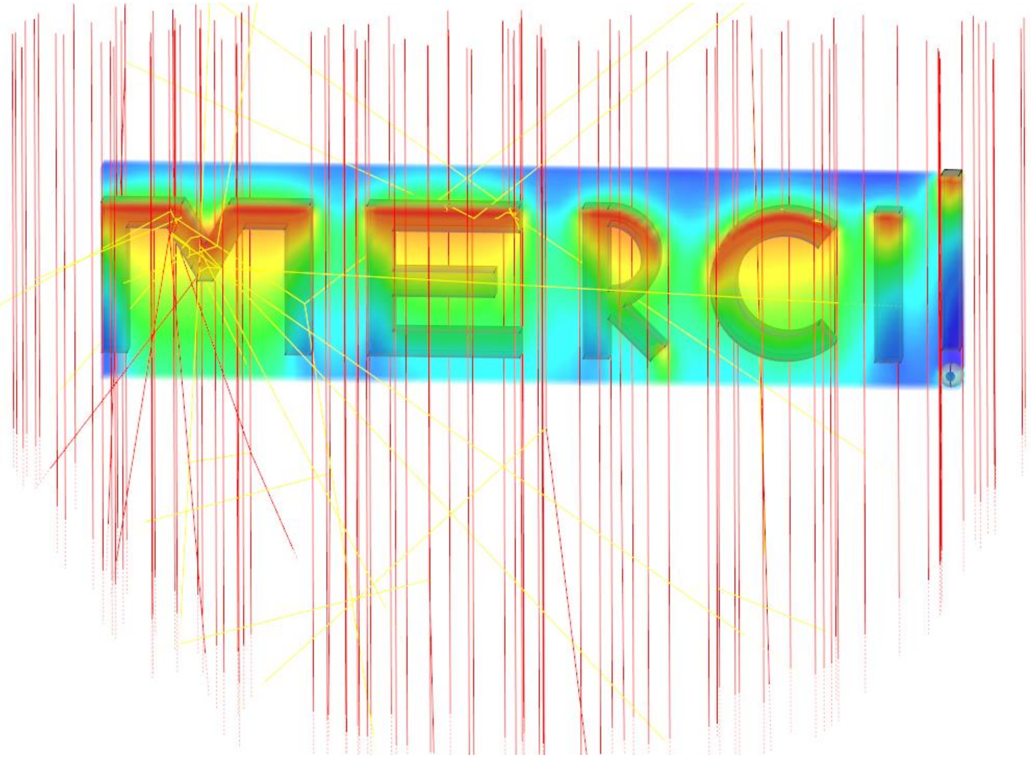



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