



Monte Carlo Simulation and Experimental Validation of the Finapp Model 3 Cosmic-Ray Neutron Sensor

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- ❑ **Finapp 3 technical specification and modelling**
 - ❑ Model for MCNP particle transport calculations
- ❑ **Reference irradiations in the CMI neutron metrology laboratory**
 - ❑ Source type, distance, limitations,...
- ❑ **MC calculations comparison to the measurement**
 - ❑ Calibration/validation of the MC model
- ❑ **Verification of the validated MC model predictions**
 - ❑ 3" PE moderated ^{252}Cf source etc. at CMI
 - ❑ Monoenergetic neutron beams at PIAF facility at PTB
- ❑ **Example of the application of the validated MC model**
 - ❑ Description of the virtual reference CRNS field
 - ❑ Calculation of the device-specific response using validated MC model
 - ❑ Practical application of the results
- ❑ **Summary and conclusion**



Finapp 3 technical specifications

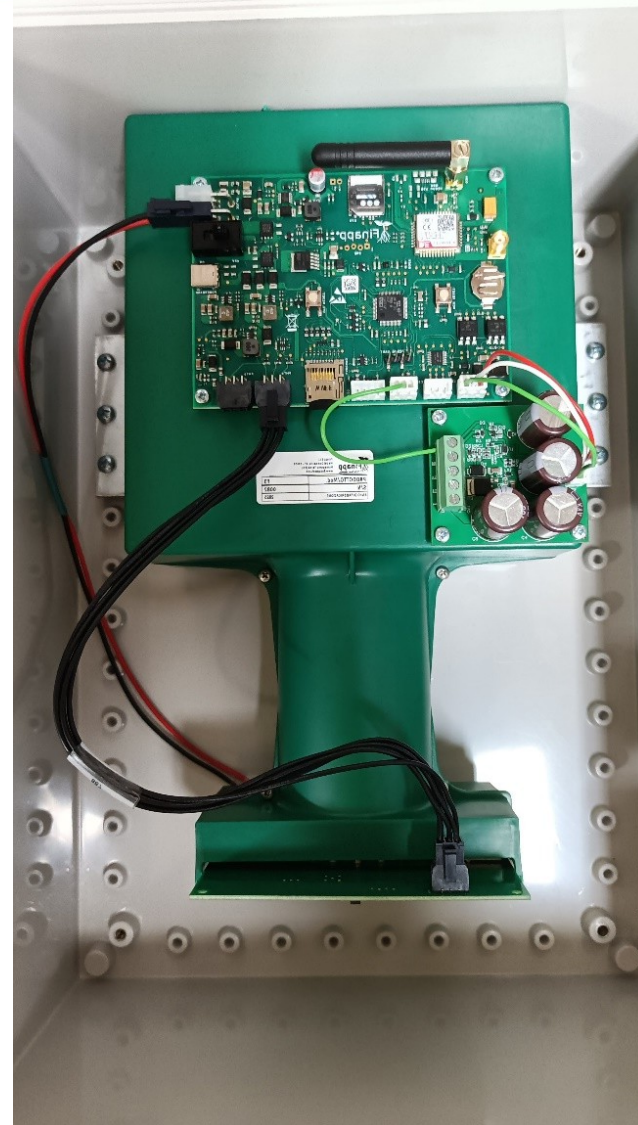
Producer	Finapp
Country	Italy
Detector	- Inorganic scintillator EJ-420/426 (Li-6 dispersed in a ZnS:(Ag)) - Plastic scintillator (EJ-299-33A) with PSD feature
Count rate	1000 cph
Size	40 x 30 x 20 cm
Weight	5 kg
Installation	static
Other sensors	GPS, time, temperature, humidity, air pressure
Data transmission	GSM

Standard data readout

- ☐ 60 min sampling
- ☐ Online data readout

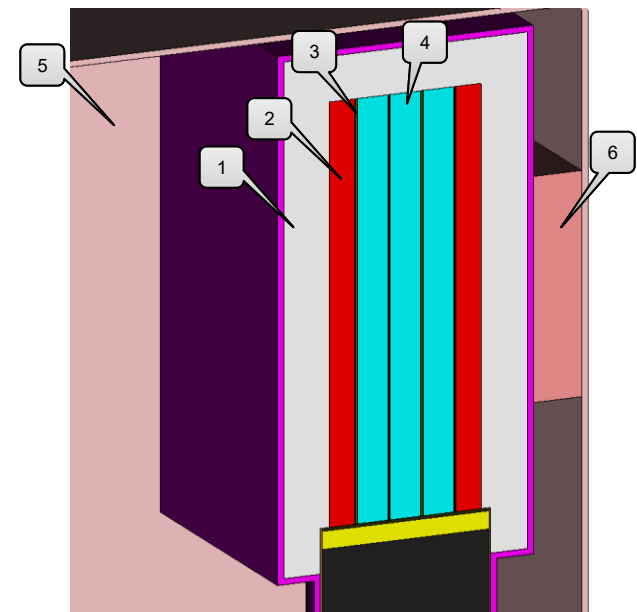
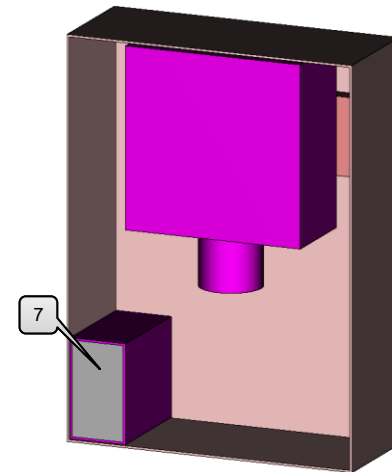
Experimental data readout

- ☐ 5 min sampling
- ☐ Readout of the data after the irradiation



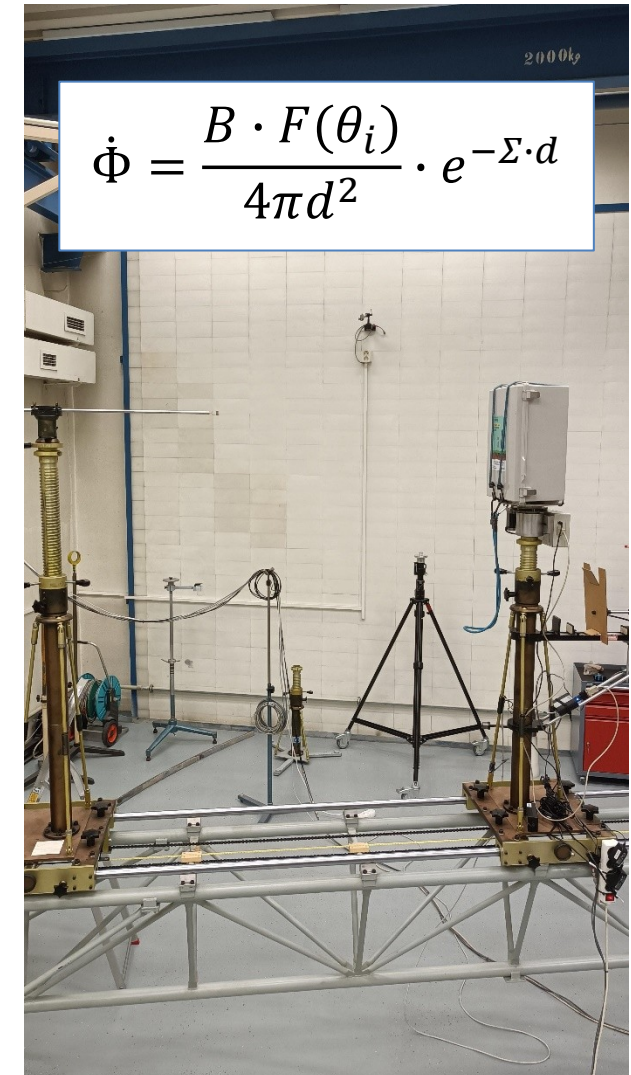
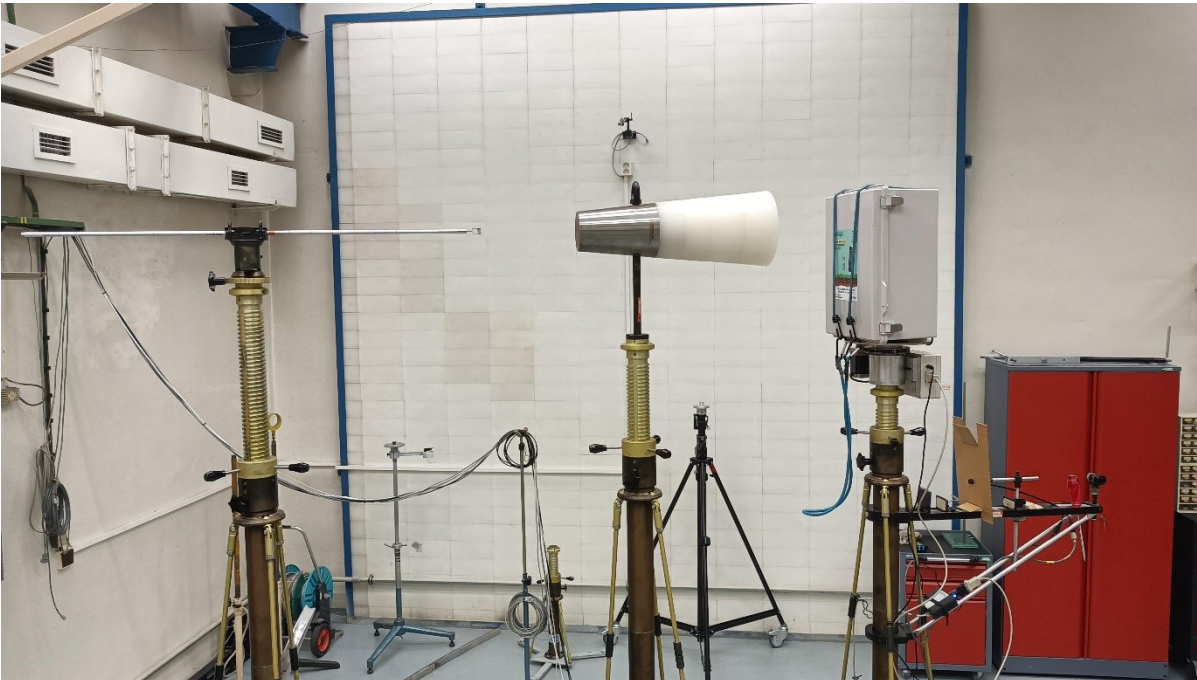
The calculations were performed using a neutron transport code MCNP6.3 with data library ENDF/B-VIII.0 at temperature of 296 K (S(α,β) treatment of low energy neutrons).

1. High-density polyethylen; CH_2 ; density 0.97 g/cm^3
2. "very light plastic polymer" approximated by PVC; $\text{C}_2\text{H}_3\text{Cl}$; density 0.007 g/cm^3
3. EJ-426 thermal neutron detector; LiF:ZnS in ratio 1:3; density 1.544 g/cm^3
Enriched in ^6Li to $>95\%$; ^6Li density $8.81 \times 10^{21} \text{ atoms/cm}^3$
Support layer polyester = PET = Mylar; density 1.40 g/cm^3
4. EJ-280 wavelength shifter; Polyvinyltoluen; density 1.023 g/cm^3
5. Outer box approximated by PVC; $\text{C}_2\text{H}_3\text{Cl}$; density 1.406 g/cm^3
6. Aluminium alloy EN-AW-5083; material data sheet by supplier; density 2.66 g/cm^3
7. Lead in battery approximated by literina; density 3.05 g/cm^3
obtained from the battery weight (2168 g total incl. PP) and volume (678 cm^3 lead only)



Irradiation conditions was a major challenge!

- ❑ CRNS probes are designed to measure in the environment where neutron fluence rate is in the order of $10^{-2} \text{ cm}^{-2} \cdot \text{s}^{-1}$ ($\sim 1000 \text{ cph}$)
- ❑ Neutron metrology laboratories standardly operates with the fluence rates $10^2 - 10^4 \text{ cm}^{-2} \cdot \text{s}^{-1}$
- ❑ Optimal fluence rate for testing was found $\sim 0.5 \text{ cm}^{-2} \cdot \text{s}^{-1}$ ($\sim 10 \text{ cps}$), source with emission rate **3 orders of magnitude lower** than usually



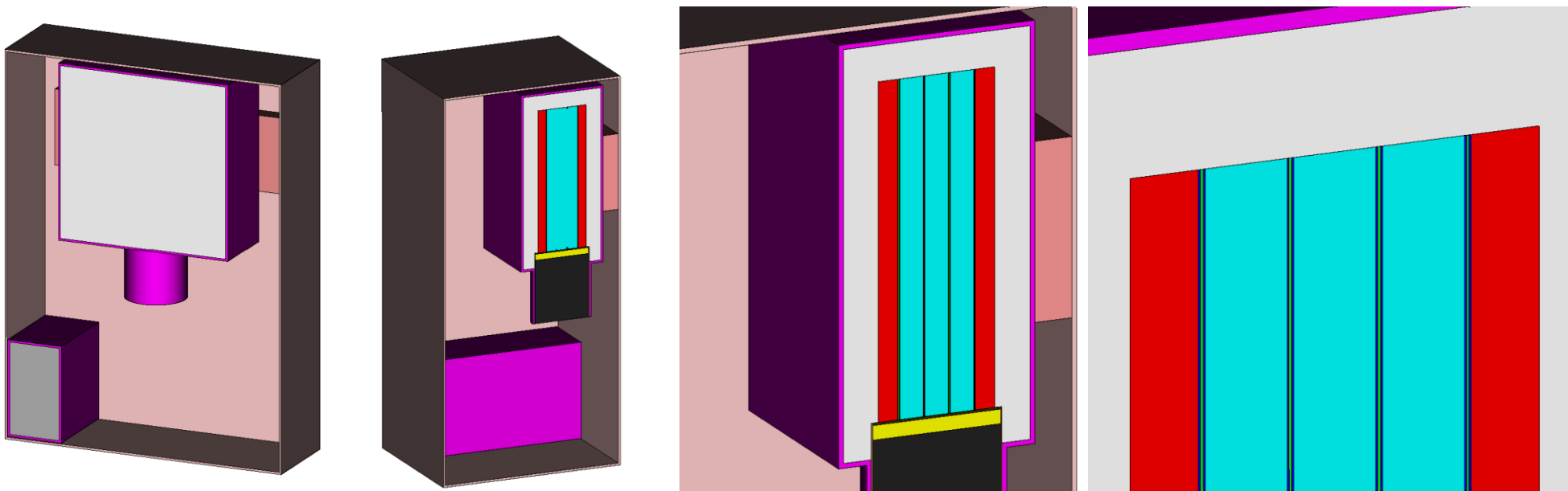
MC calculations comparison to the measurement

Simulated quantity:

- ❑ number of ${}^6\text{Li}(n,\alpha)\text{T}$ reactions, neutron absorption (per sheet + total)
- ❑ fluence at the detector position in the absence of the detector (in air for moderated ${}^{252}\text{Cf}$ source, otherwise in vacuum because the used spectra were measured at the detector position)

Irradiation geometries:

- ❑ ${}^{252}\text{Cf}$, Am-Be, ${}^{252}\text{Cf}$ moderated by 3" PE sphere, front and side detector irradiation direction
- ❑ separated into direct and scattered spectrum components
 - ❑ direct component: point source at the given distance from the detector
 - ❑ scattered component: isotropic source on a sphere around the detector
- ❑ ${}^{252}\text{Cf}$ and Am-Be taken from ISO spectra; ${}^{252}\text{Cf}$ in 3" PE generated by Watt spectrum (inside the 3" PE sphere)



First MC calculations – Finapp device only

Normalized to reference *neutron fluence rate*

First MC calculations show more than **50% discrepancy** depending on the neutron spectrum so it was necessary to modify the parameters of the model.

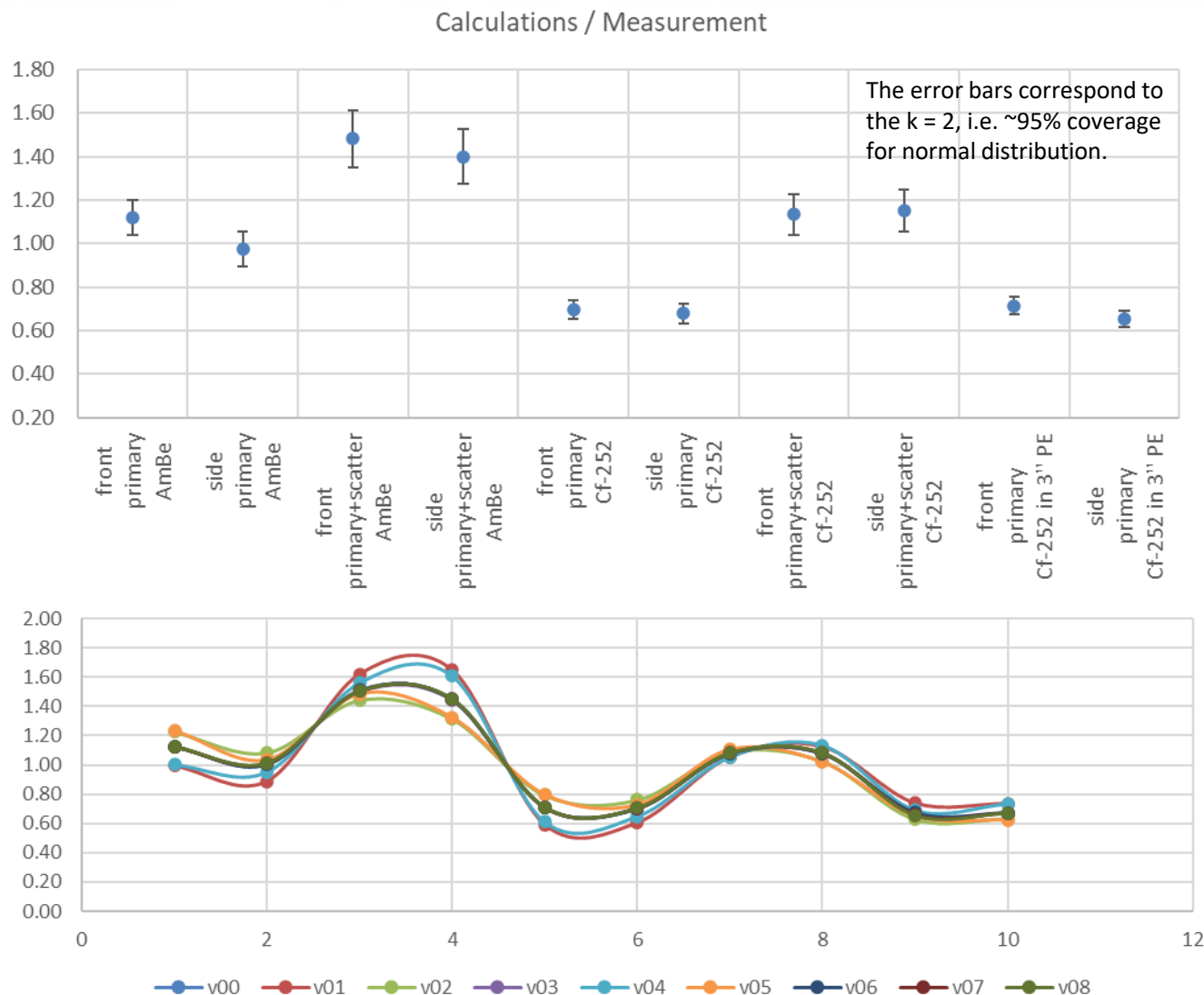
Model parameters variation:

- ❑ HDPE moderator density
- ❑ Light plastic density
- ❑ Wavelength shifter density
- ❑ Scintillator density

Non of the parameters above has significant influence to relative comparison!

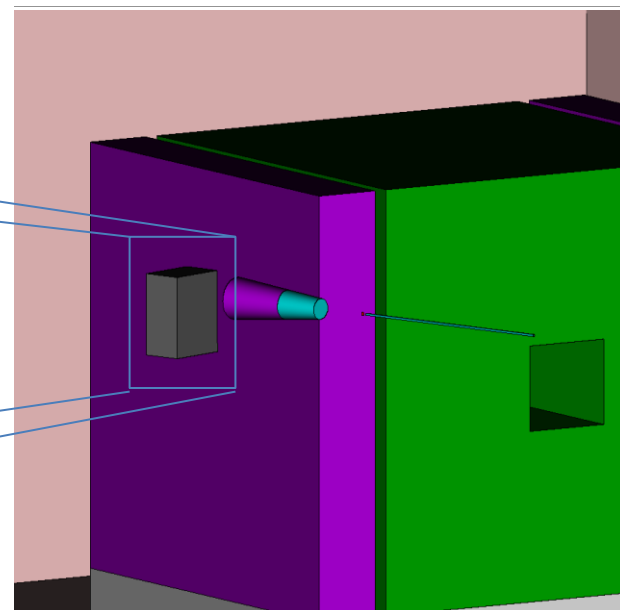
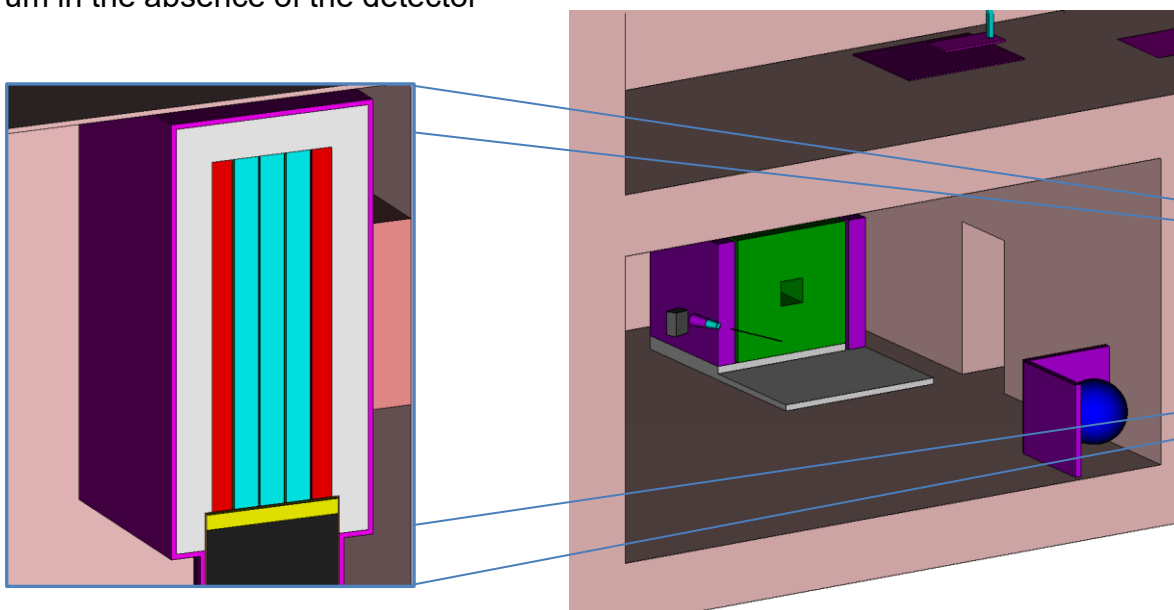
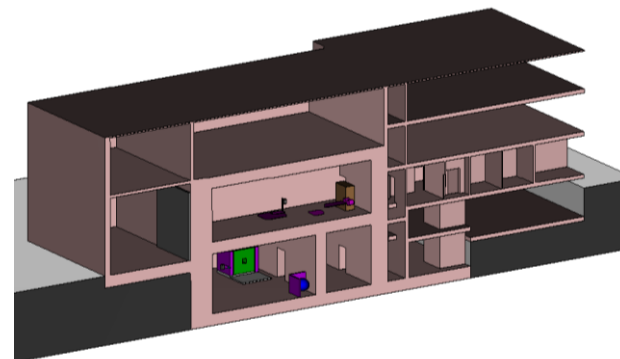
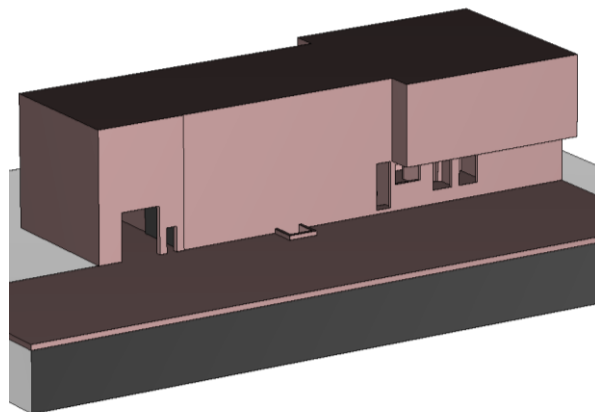
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Simulation of full irradiation room



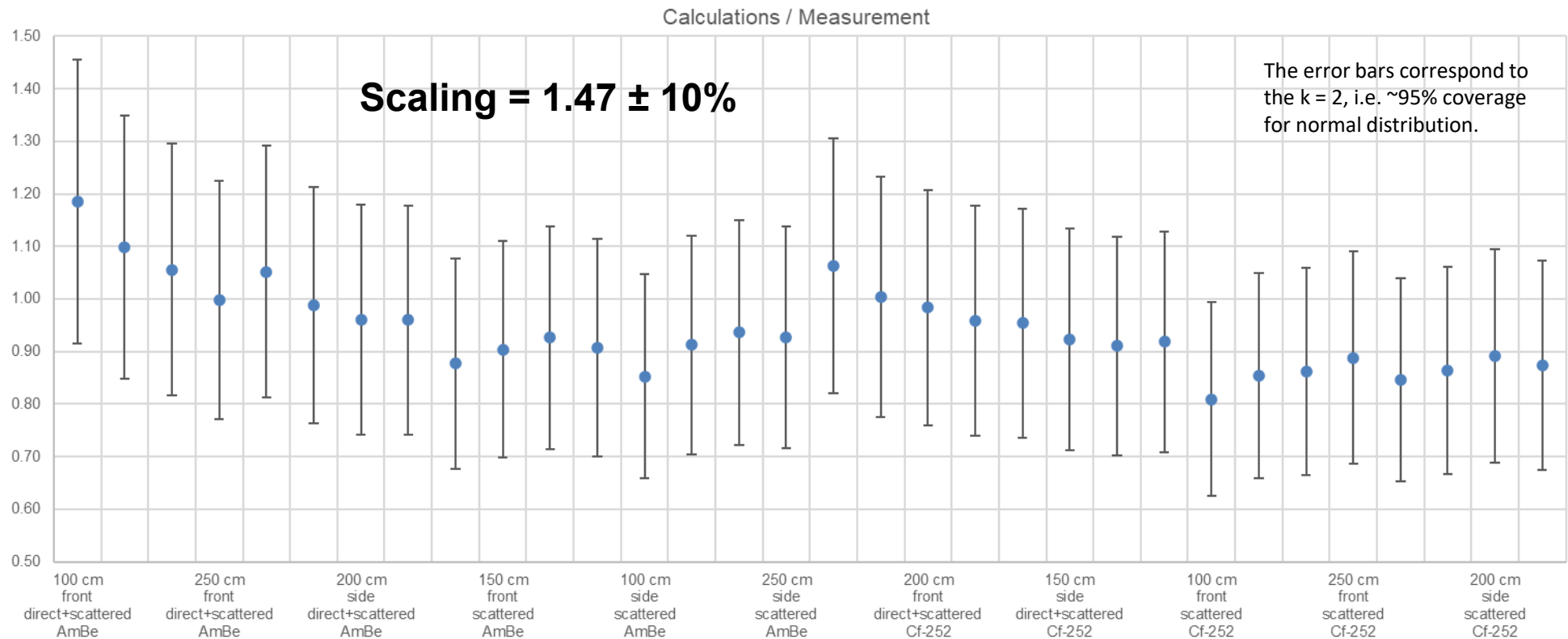
Simulated quantity:

- ❑ Number of ${}^6\text{Li}(n,\alpha)\text{T}$ interactions, neutron absorption (per sheet + total)
- ❑ Proton recoils counts in the scintillator, alphas and tritons in the scintillator (all sheets)
- ❑ Fluence at the detector position for all irradiation geometries in the absence of the detector
- ❑ Neutron spectra at the detector position and contribution of the model cells to the spectrum in the absence of the detector

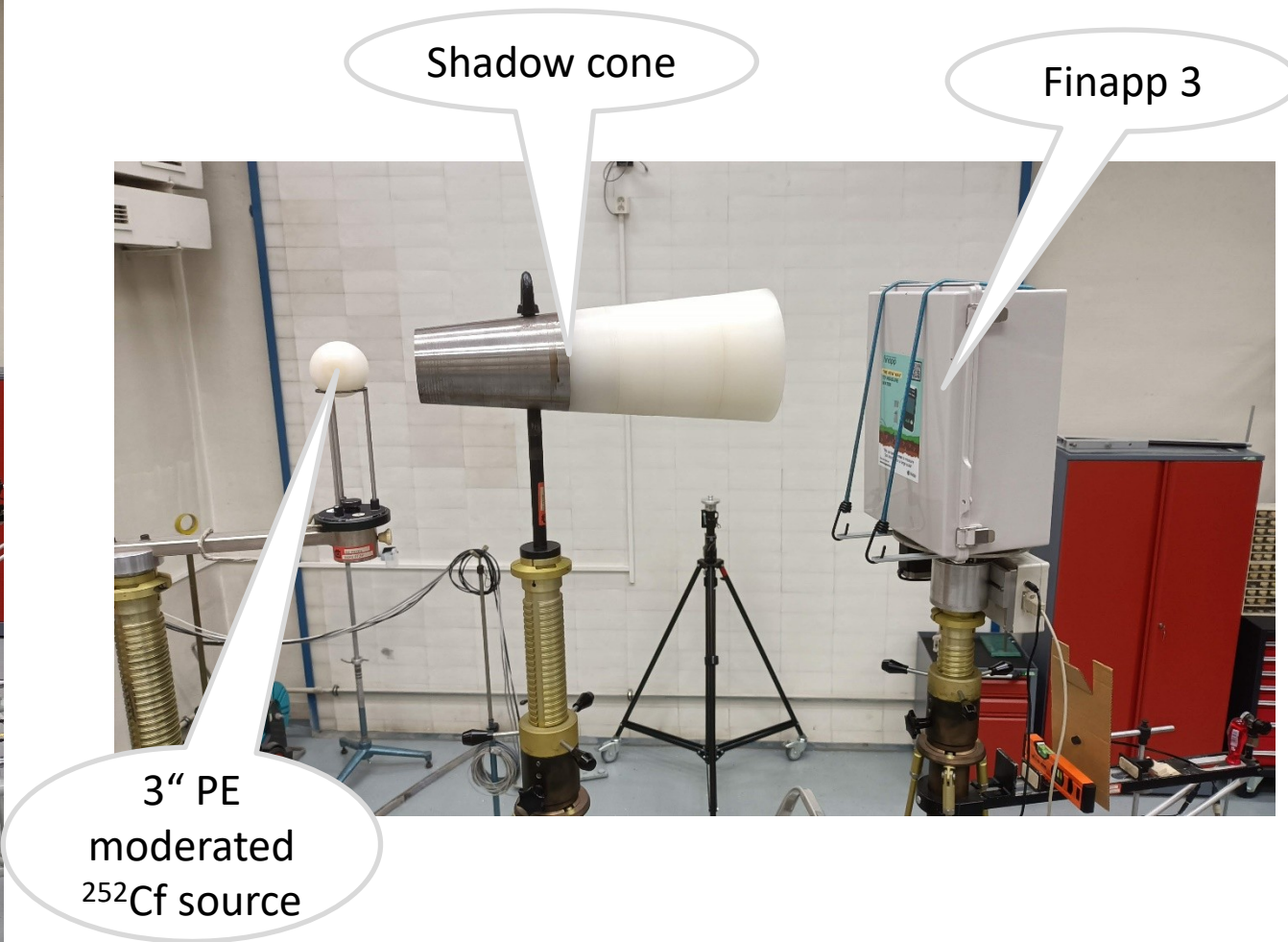
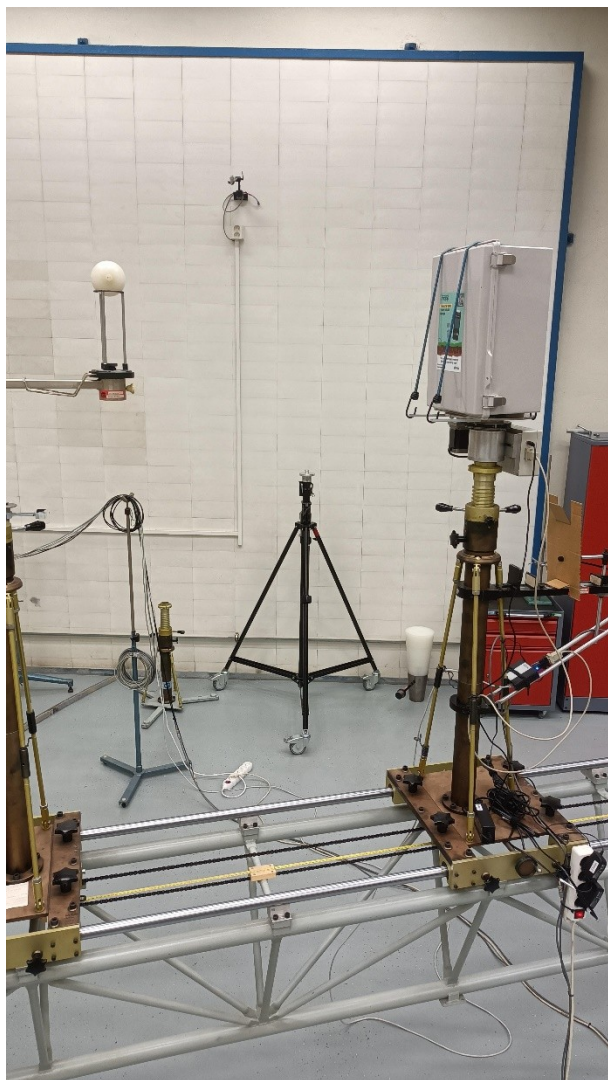


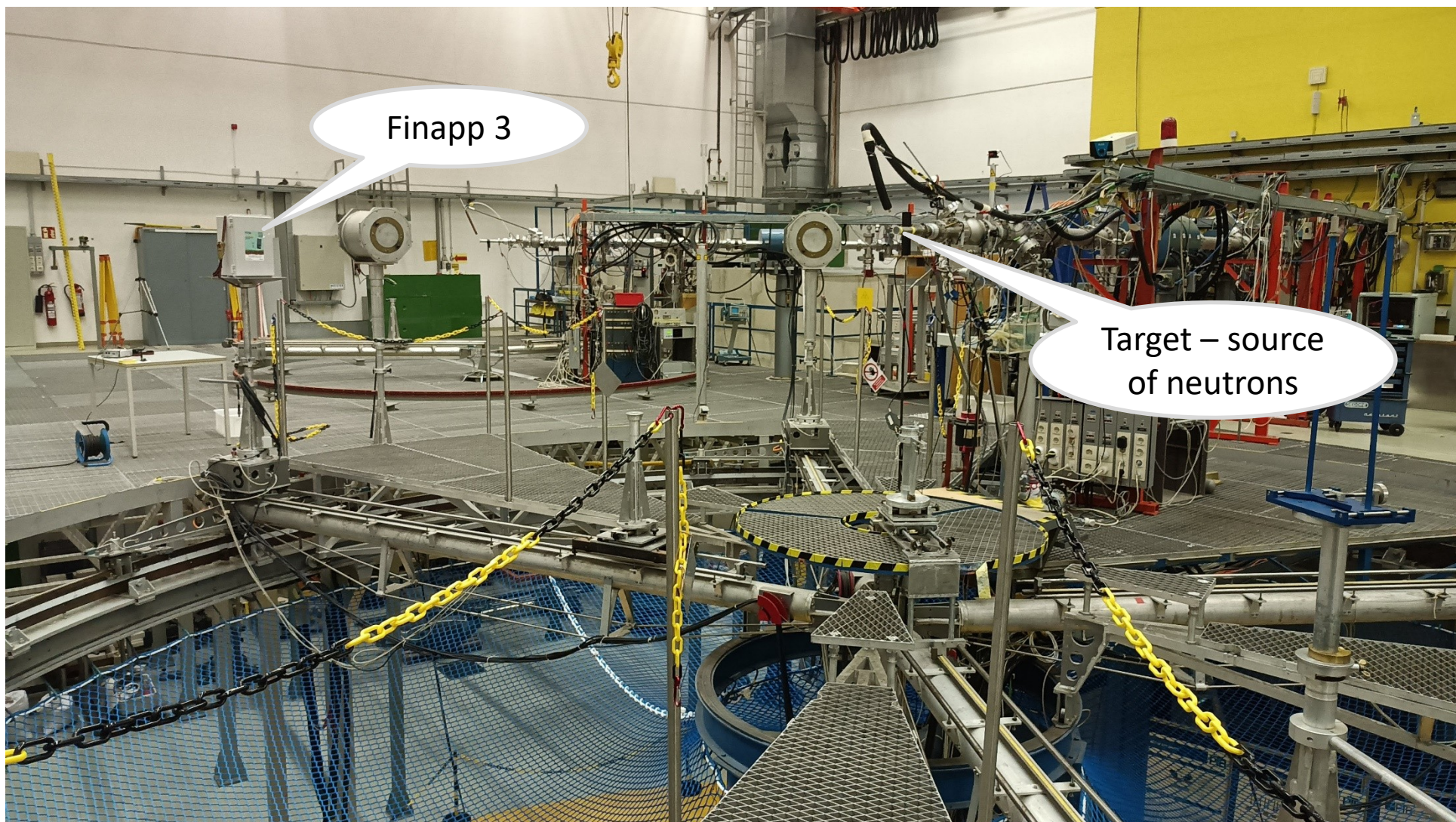
The MC model was scaled by 84 different measurements combining following parameters:

- ❑ Am-Be and ^{252}Cf source
- ❑ Direct irradiation and irradiation with shadow cone
- ❑ Front and Side detector orientation with respect to the source, 15 deg step rotation
- ❑ Source to detector distance 100, 150, 200 and 250 cm

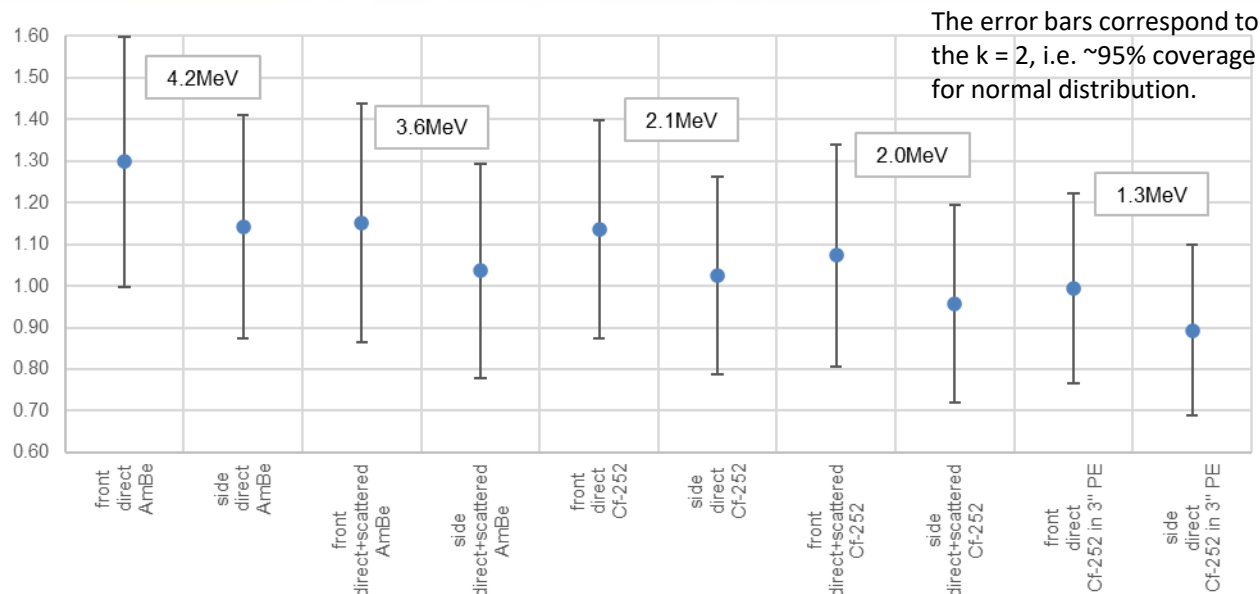


Verification of the validated MC model predictions

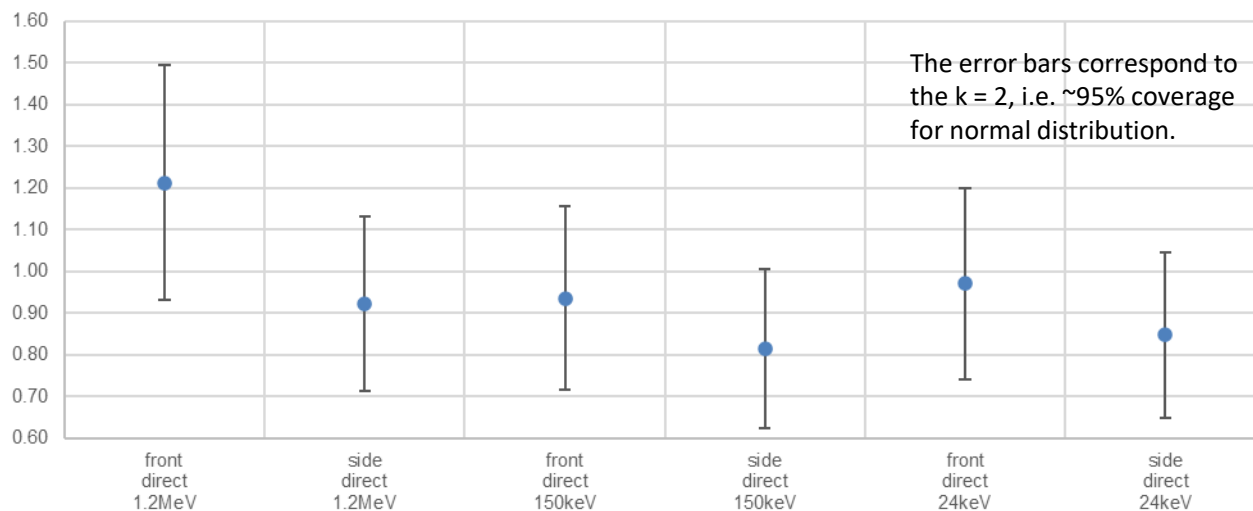




- Validated MC model calculation-to-measurement ratio for various CMI broad range fields with different mean neutron energy.



- Validated MC model calculation-to-measurement ratio for irradiations at PTB monoenergetic beams @ PIAF facility.



Example of the application of the validated MC model

Soil parameters:

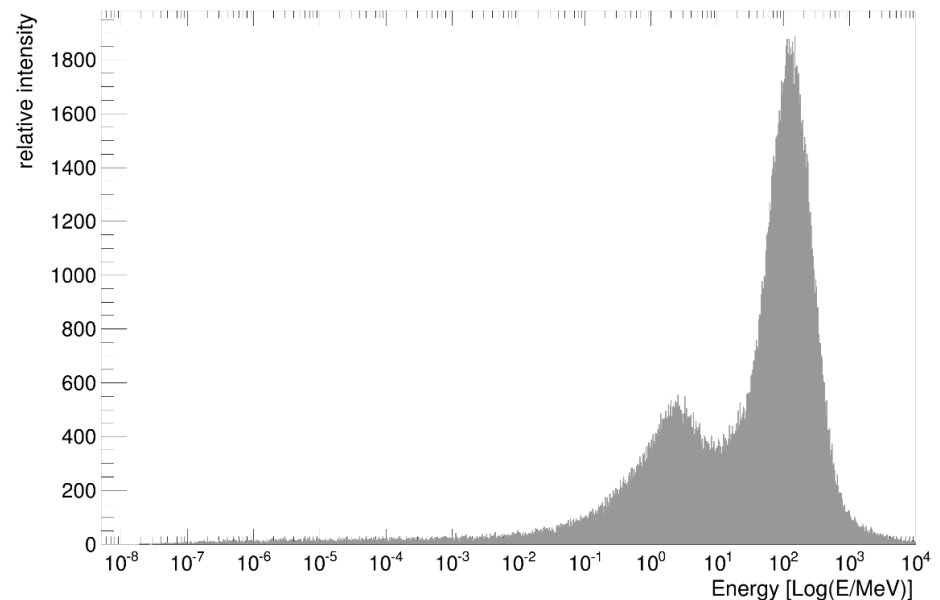
- ❑ Depth: 1.7 m
- ❑ Soil composition :
 - ❑ Soil consists of 50%Vol solids and a scalable amount of H₂O
 - ❑ The solid domain is comprised of 75%Vol SiO₂ and 25%Vol Al₂O₃ at a compound density of 2.86 g/cm³.
 - ❑ The total density depends on the volumetric water content. For example, 1.43 g/cm³ for 0% volumetric water content and 1.93 g/cm³ for 50% volumetric water content.
 - ❑ The 100% volumetric water content represents theoretical case without solid domain in the soil, so that whole “soil” volume is composed of water.

Atmosphere parameters:

- ❑ Thickness: 1600 m
- ❑ Air composition:
 - ❑ 78%Vol nitrogen, 21%Vol oxygen and 1%Vol argon at a pressure of 1020 mbar
 - ❑ Air humidity of 10 g/m³

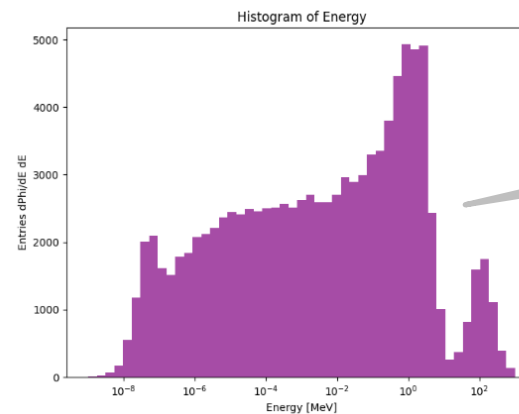
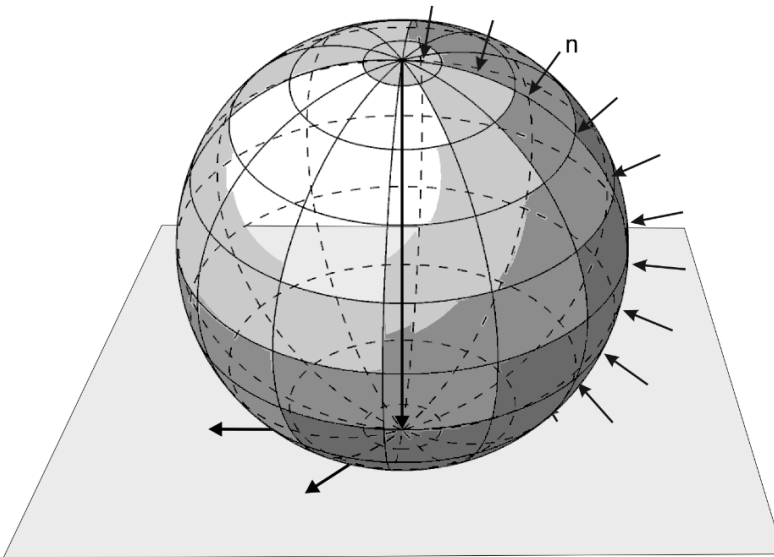
Neutron source parameters:

- ❑ Dimension (diameter) of the domain: 800 m
- ❑ Source height: 650 m
- ❑ Source neutron spectrum
- ❑ Source neutron directional distribution
- ❑ Cutoff rigidity: 5 GV



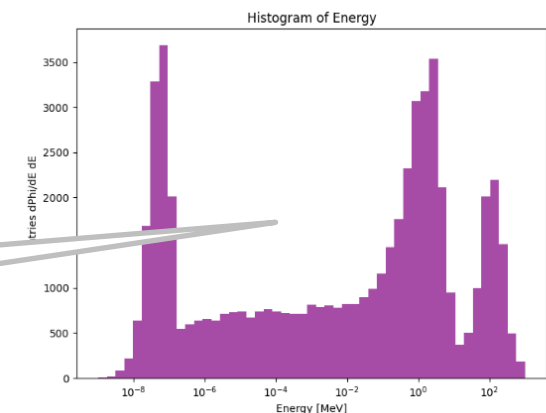
Virtual sphere:

- ❑ Virtual sphere 2 m in diameter was placed in the center of the domain and 1 m above the soil level.
- ❑ The center of the virtual sphere matches the center of CRNS probe when installed at the recommended position i.e. 1 m above the soil level.
- ❑ Each simulated neutron passing through the surface of this sphere was recorded forming the so-called **virtual reference CRNS neutron field**.
- ❑ In total nine virtual reference CRNS neutron fields were prepared for nine different relative soil moistures expressed in term of volume of 1%, 3%, 6%, 10%, 20%, 30%, 40%, 50% and 100% (theoretical case, no soil, only water) and constant air humidity of 10 g/m³.

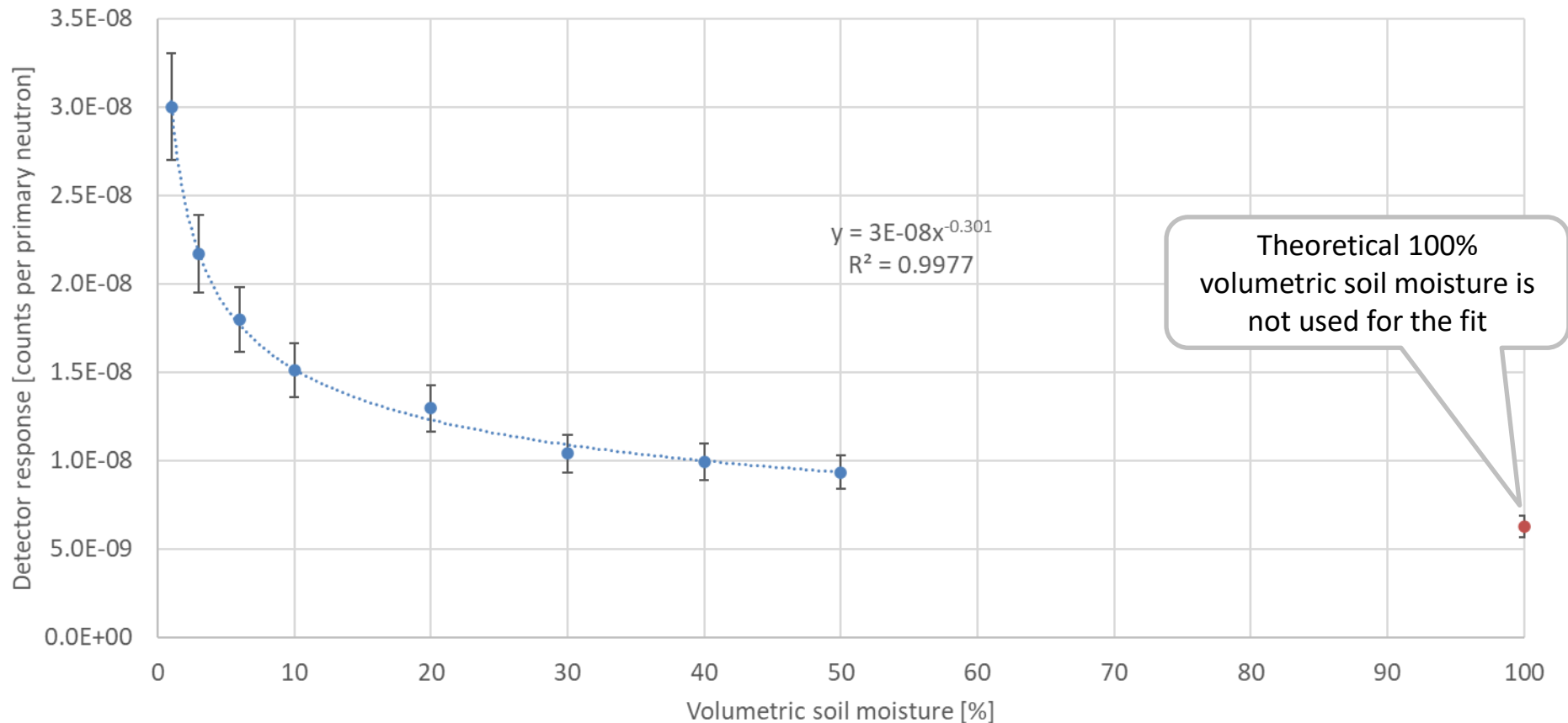


1% volumetric
water content

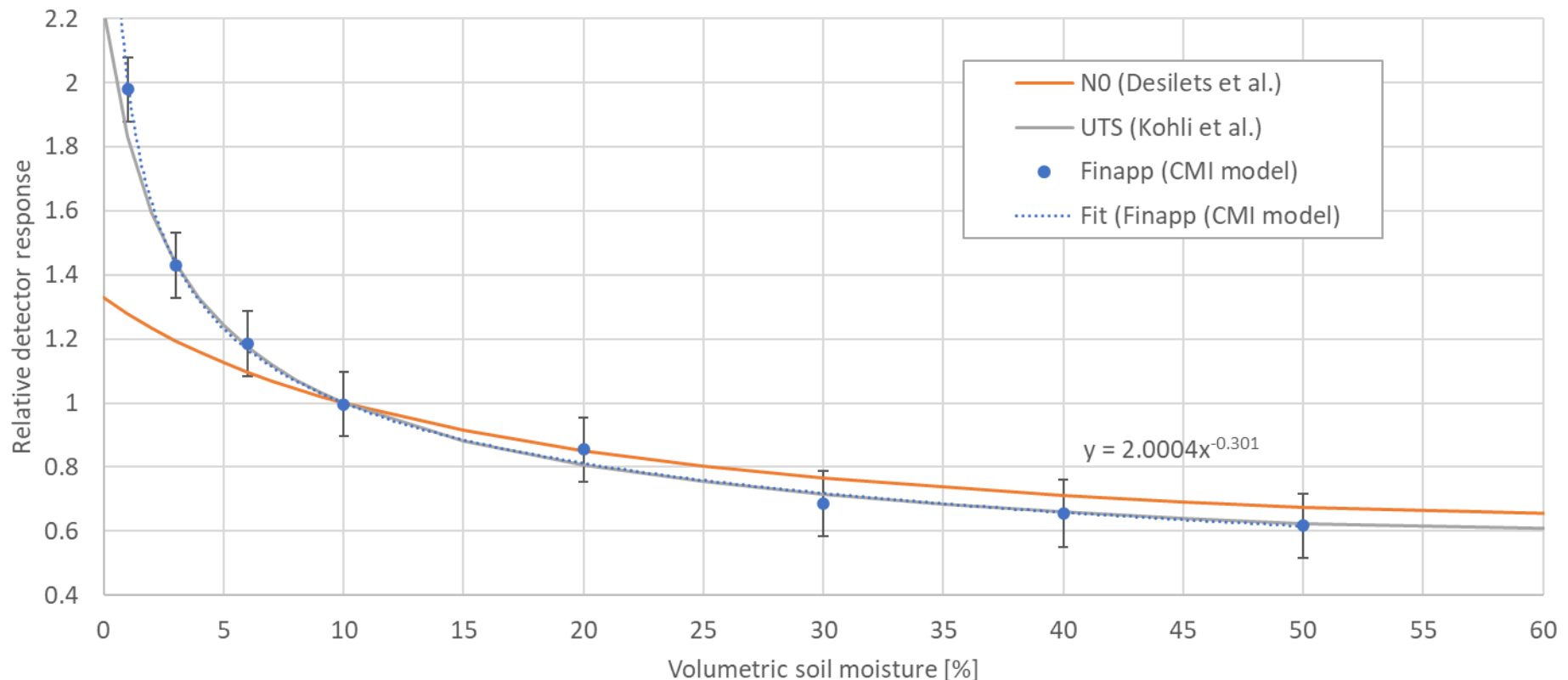
50% volumetric
water content



- ❑ Calculated points fit very well to simple power equation with two parameters
 - ❑ Exponent - detector type, installation conditions,...
 - ❑ Scaling factor – particular device calibration



- ❑ NO equation from the publication Desilets et al. (2010) with the commonly used parameters 0.0808, 0.372, 0.115, recalculated to volumetric soil moisture, inverted and scaled relatively to 10% soil moisture (doi:10.1029/2009WR008726)
- ❑ UTS equation from the paper Köhli et al. (2021) with parameter set "MCNP drf (full)" for air humidity of 10 g/m³ and scaled relatively to 10% soil moisture (doi: 10.3389/frwa.2020.544847)



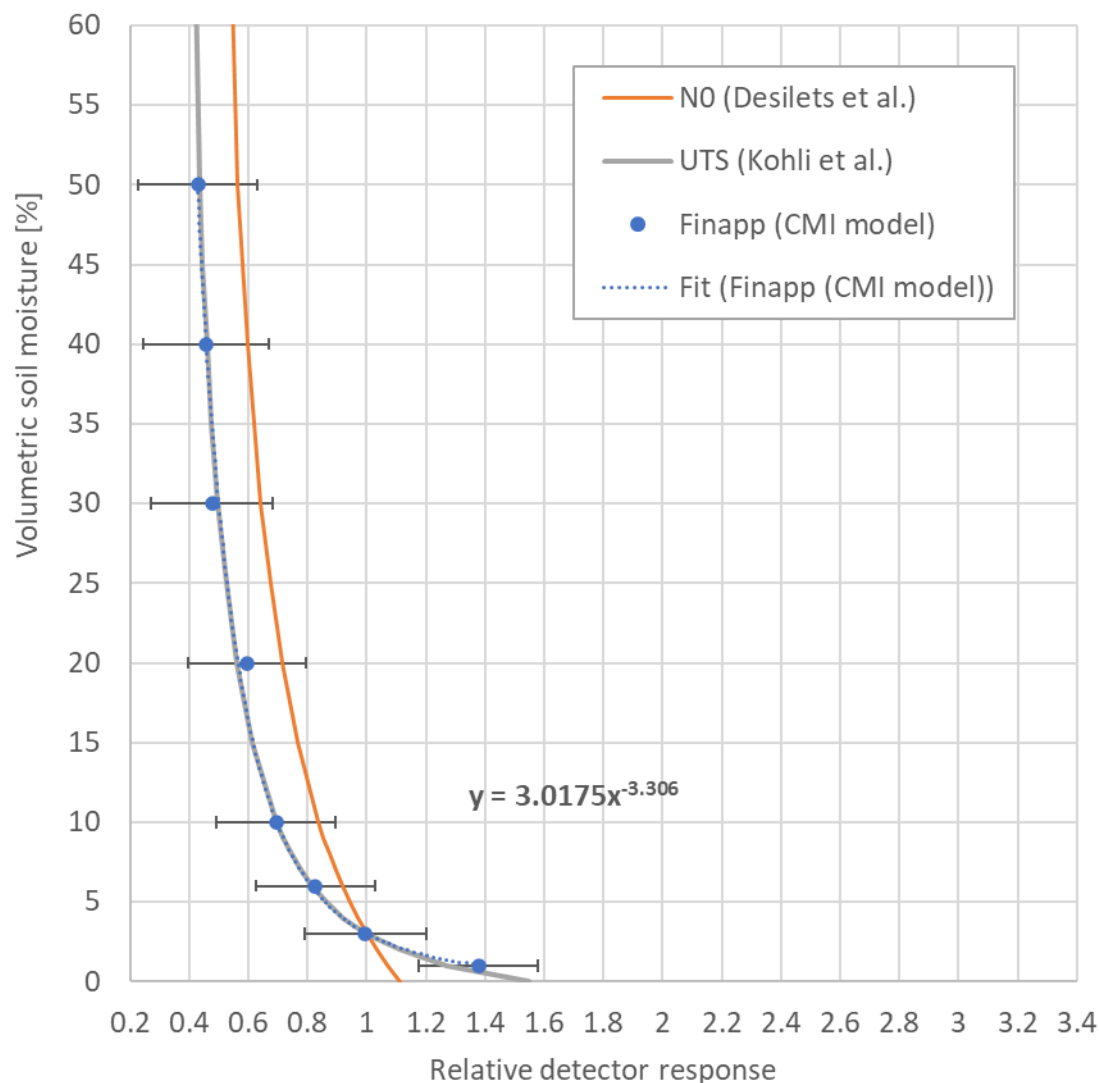
Simple power equation with only one parameter + scaling factor from the on-site calibration:

$$\theta = \theta_{cal} \times \left(\frac{N}{N_{cal}} \right)^p = \frac{\theta_{cal}}{N_{cal}^p} \times N^p$$

- ❑ $p = -3.306 \pm 2.7\%$
- ❑ θ – Relative volumetric soil moisture
- ❑ N – CRNS count rate (corrected for incoming neutron rate)

Conditions

- ❑ Finapp 3 CRSN probe
- ❑ Soil bulk density 1.43 g/cm^3
- ❑ Agree with UTS model for wide range of air humidity $0 - 40 \text{ g/m}^3$



What about other CRNS detectors?

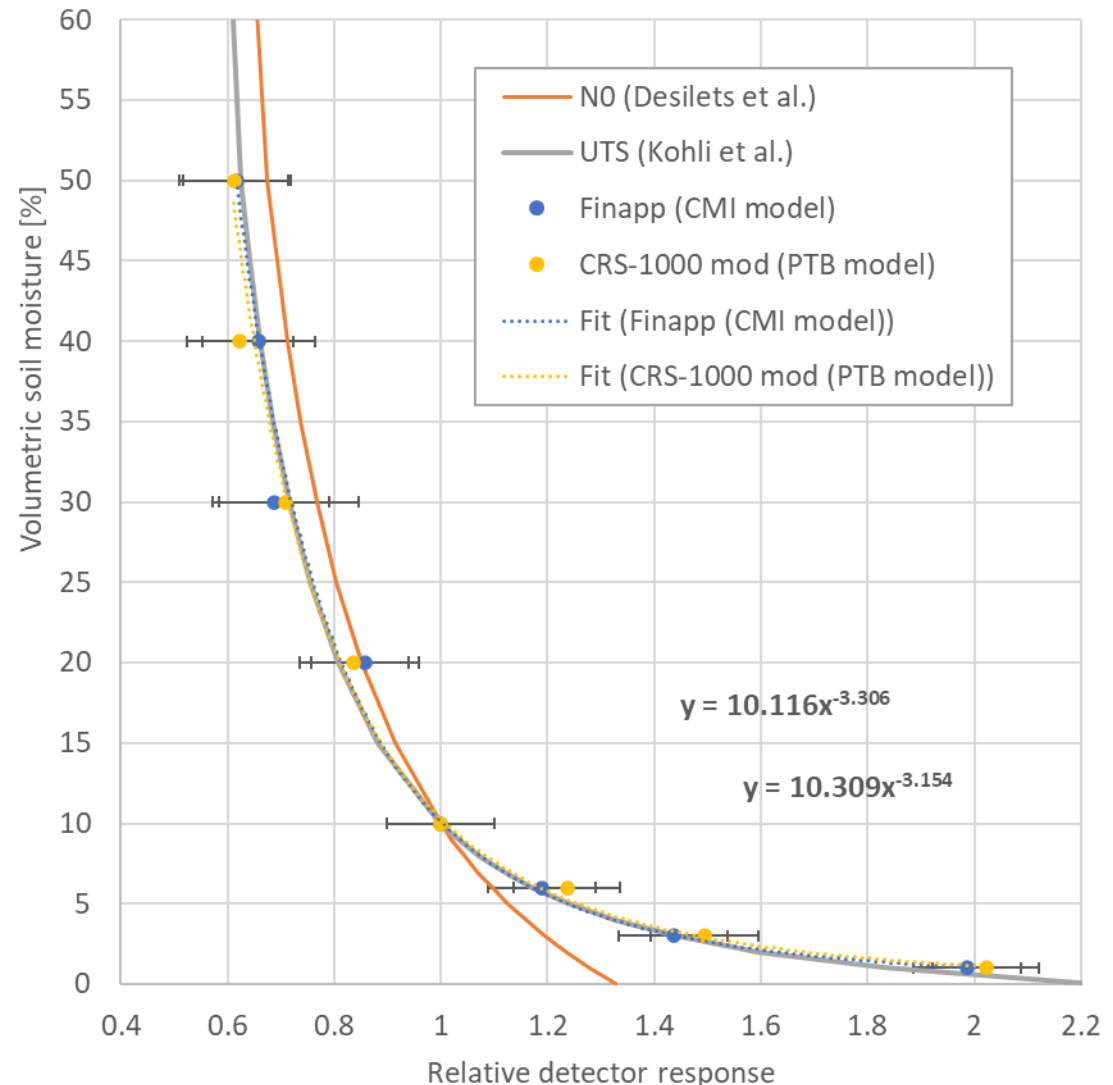
❑ **Finapp 3**

- ❑ Manufacturer: Finapp, Italy
- ❑ Detector: Sandwich of lightguide and four scintillator sheets with Li-6 dispersed in a ZnS:(Ag))
- ❑ Dimensions: 40x30x20 cm³
- ❑ Weight: 5 kg

❑ **CRS-1000 mod**

- ❑ Manufacturer: Hydroinnova, USA
- ❑ Detector: Bare and PE moderated He-3 proportional counter
- ❑ Dimensions: 80x30x20 cm³
- ❑ Weight: 15 kg

- ❑ Very different devices but very similar response!



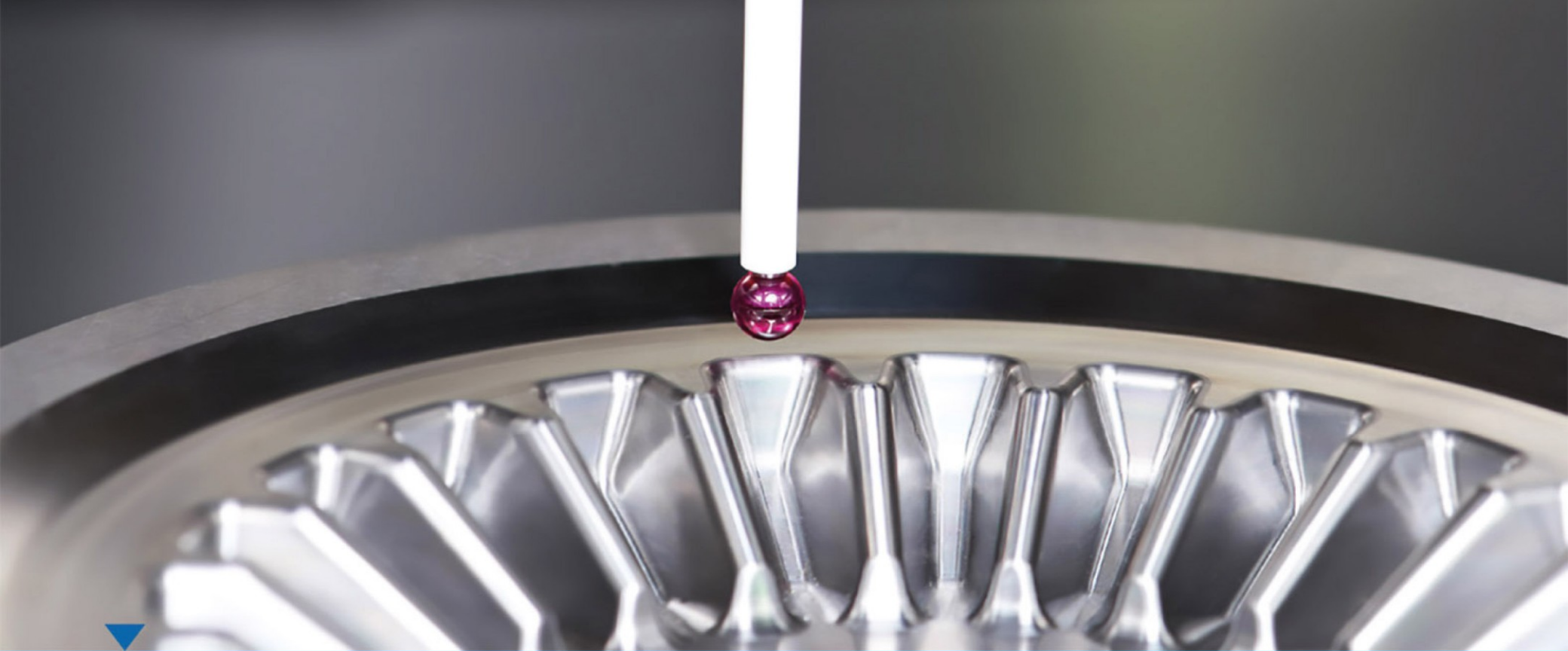
- ❑ Monte Carlo model of Finapp model 3 CRNS detector was prepared, validated and verified.
- ❑ The validated model was used for calculation of the volumetric soil moisture dependence on the relative detector response for specific soil composition
- ❑ The dependence can be characterized by simple power equation with only one parameter + scaling factor from the on-site calibration:

$$\theta = \theta_{cal} \times \left(\frac{N}{N_{cal}} \right)^p = \frac{\theta_{cal}}{N_{cal}^p} \times N^p$$

- ❑ $p = -3.306 \pm 2.7\%$ (Finapp 3), $p = -3.154 \pm 2.8\%$ (CRS-1000 mod)
- ❑ θ – Relative volumetric soil moisture
- ❑ N – CRNS count rate (corrected for incoming neutron rate)

The work has been done in frame of the Soil Moisture Metrology project, funded by European Partnership on Metrology program





THANK YOU FOR YOUR ATTENTION