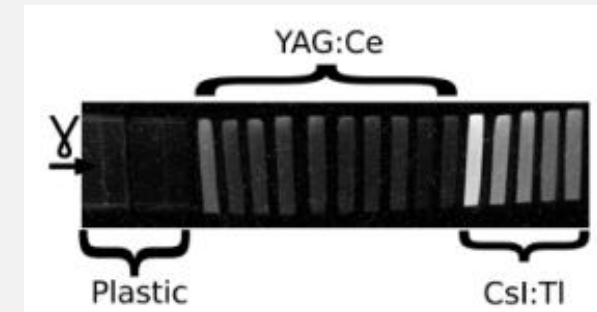
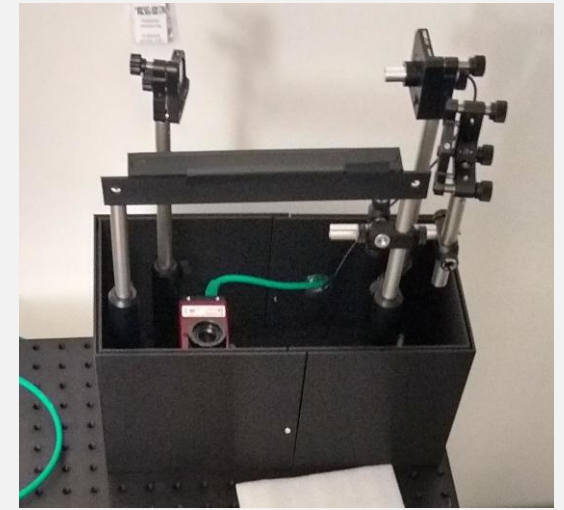


Filter Stack Spectrometers for Pulsed Radiation

31st EURADOS Webinar
13 May 2026

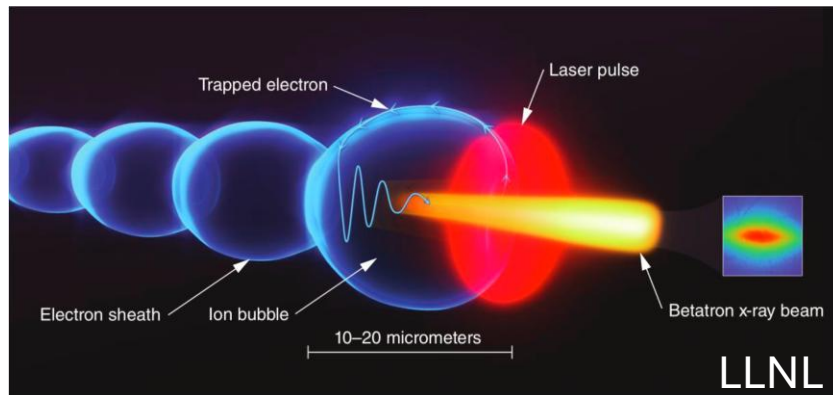
Benoit LEFEBVRE
ELI Beamlines Facility
Extreme Light Infrastructure ERIC
(Prague, Czechia)



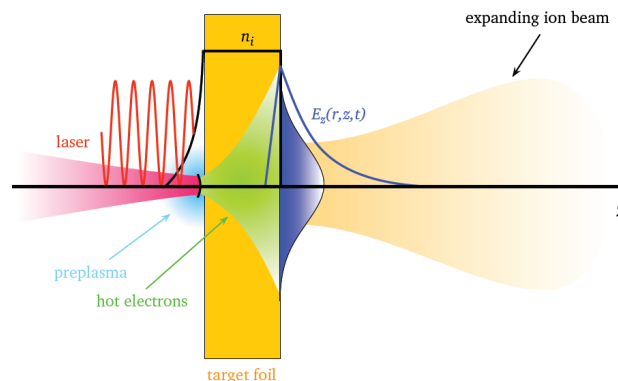
Introduction

- Intense mixed pulsed radiation fields produced at laser facilities and increasingly commonplace in scientific, medical and industrial settings.
- Characterization and spectrometry of produced γ /e fields:
 - Probe for physics processes at the source.
 - Get feedback for source (beamline) tuning and operations.
 - Precise ambient dosimetry.
 - Shielding assessment.
- **Traditional spectrometry techniques inadequate or impractical.**
 - Saturation of proportional counters.
 - Extreme number of particles detected within acquisition time window.
- **Filter stack spectrometer offer an alternative approach.**

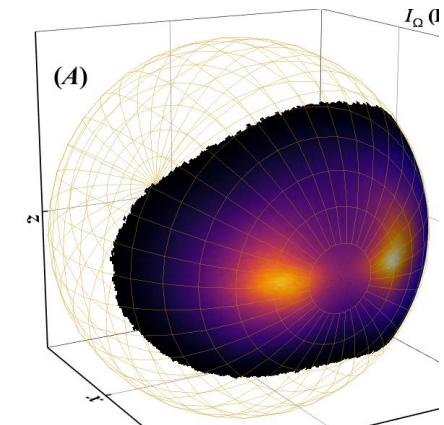
LWFA / Betatron X-rays



TNSA protons + brems X-rays



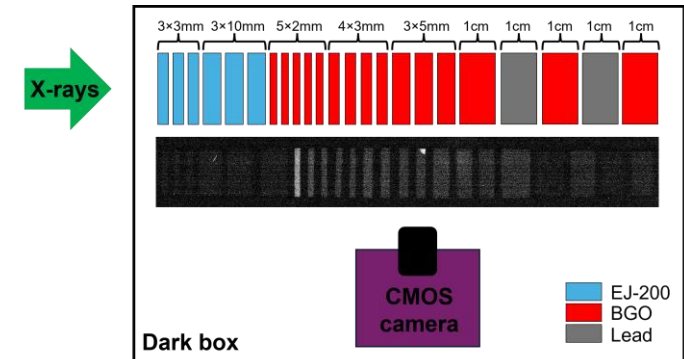
γ flash from nanostructured targets



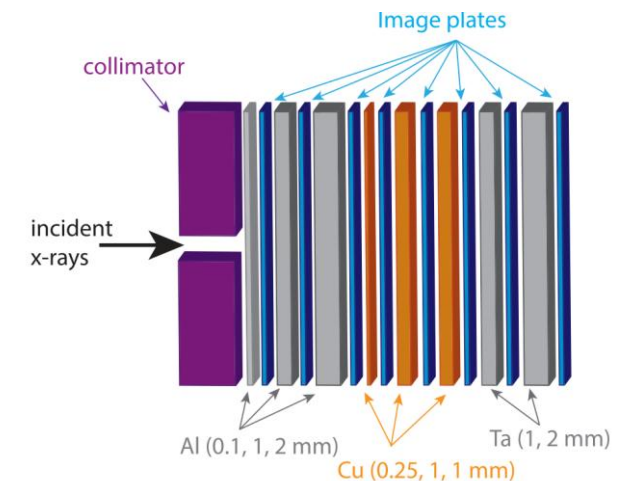
Filter Stack Spectrometer (FSS)

- Stack of dose-sensitive layers interlaced with radiation filters.
- Dose measurement:
 - **Passive:** Image plates, TLD, OSL, etc
 - **Active (high rate):** Scintillators, silicon sensors
- **Concept:** Infer characteristics of radiation field based on the longitudinal dose deposition.
 - **Unfolding** required to extract field parameters from measurements.

Possible implementations



Lefebvre (2025)



Wong (2024)

Unfolding

- Return field parameters based on dose measurements.
- Two approaches:
 - Return direct energy spectrum.
 - (But with limited degrees of freedom!)
 - Return parameters of the field.
- Detector's response matrix (RM) determined from simulation or analytical techniques.
- RM often ill-defined: cannot simply be inverted!

The diagram shows the equation $\mathbf{RM} \vec{S} = \vec{D}$ with three labels and arrows: "Response matrix" with an arrow pointing to $\mathbf{RM}$, "Spectrum" with an arrow pointing to $\vec{S}$, and "Dose measurements" with an arrow pointing to $\vec{D}$.

Response matrix

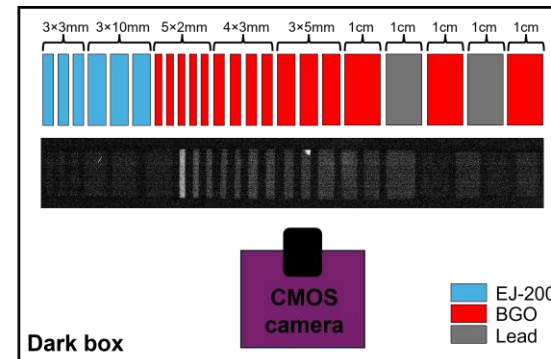
Dose measurements

$\mathbf{RM} \vec{S} = \vec{D}$

Spectrum

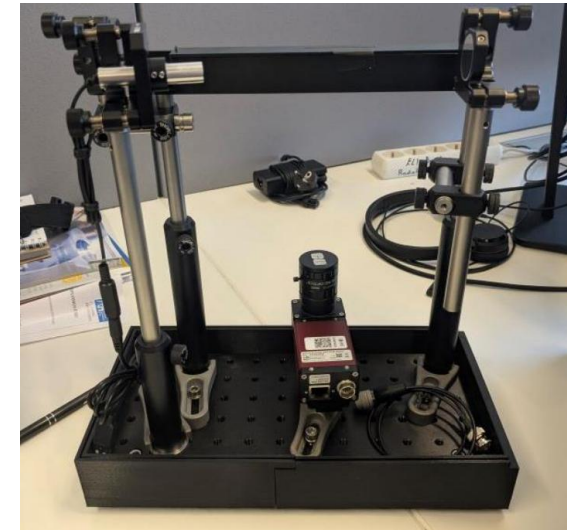
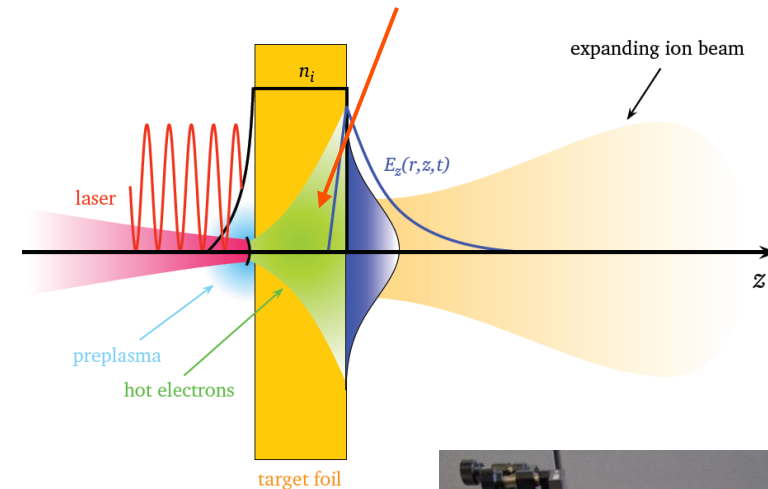
TNSA Bremsstrahlung/e measurements

- **ELIMAIA**: Ion-acceleration platform of ELI Beamlines
 - Driven by HAPLS 10Hz 1PW laser.
 - Accelerates proton at peak energies of 30 MeV.
- X-rays and electrons ejected via the Target Normal Sheat Acceleration (TNSA) mechanism.
- Hot and cold photon populations:
$$f(E) \sim A_h \exp\left(-E/T_h\right) + A_c \exp\left(-E/T_c\right)$$
- Using FSS with mix of plastic/BGO scintillators imaged by camera.
 - Scintillators act as both dose-sensitive medium and radiation filter.



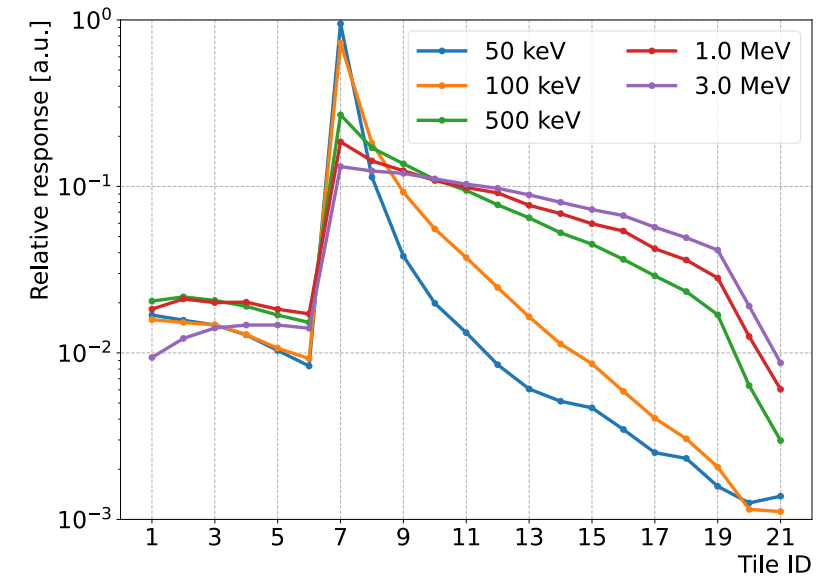
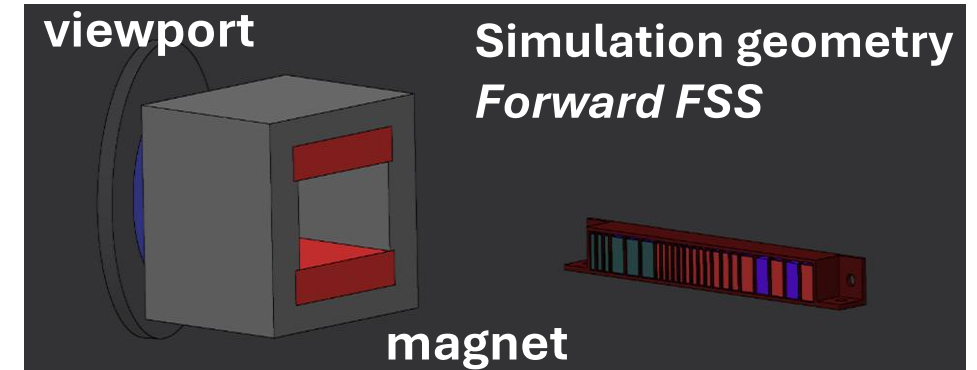
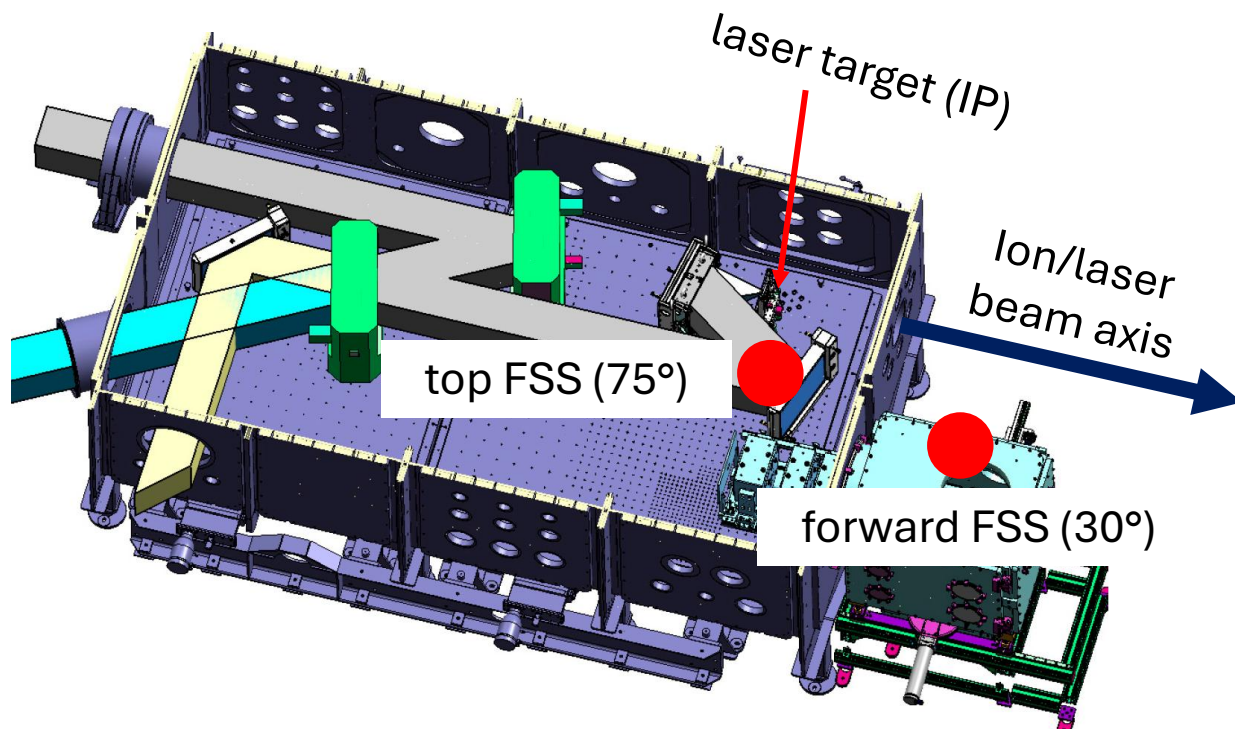
Lefebvre (2025)

Maxwellian γ /e energy distribution



Response matrix

- Simulating RM for each stack using FLUKA.
- Score energy deposition in the scintillators.

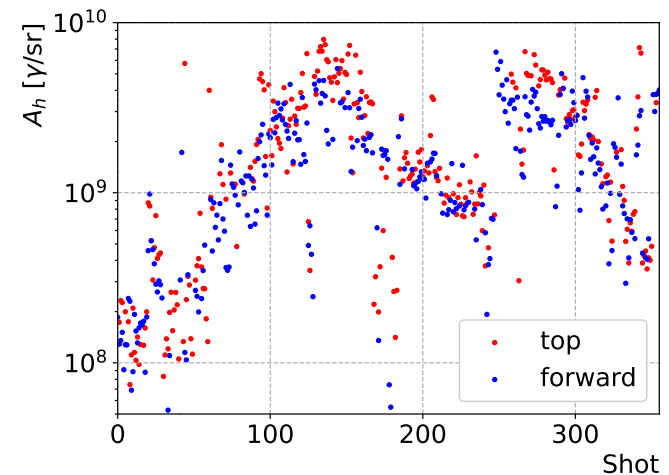
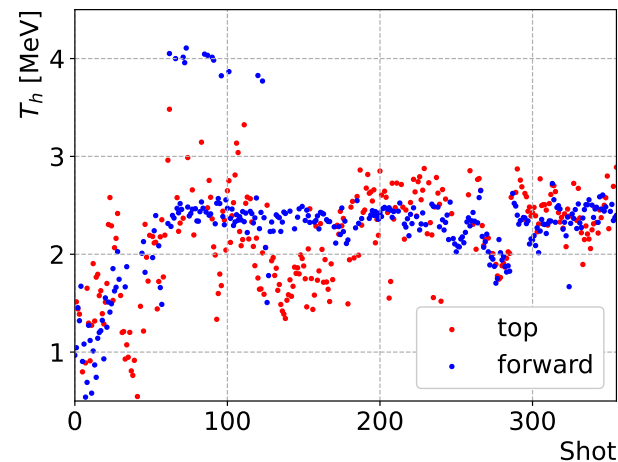
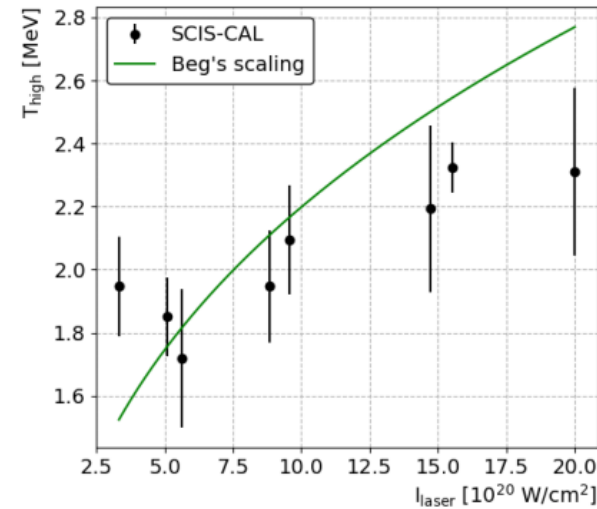
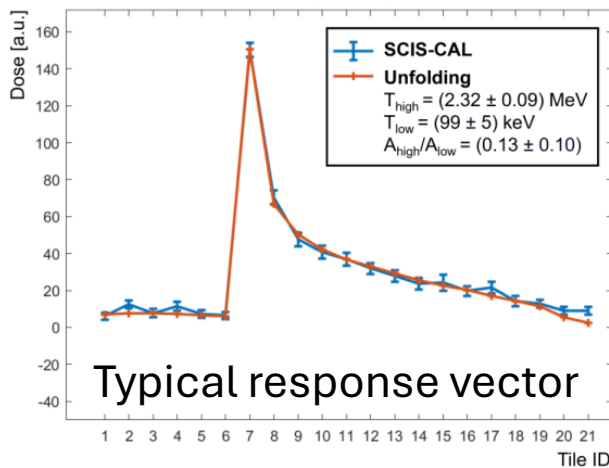


Unfolding and results

- Employing a χ^2 -minimization to infer hot/cold photon temperatures.

$$\chi^2(\overline{N}_1, \overline{T}_1, \overline{N}_2, \overline{T}_2) = \sum_{i=1}^m (S_i - \overline{S}_i)^2$$

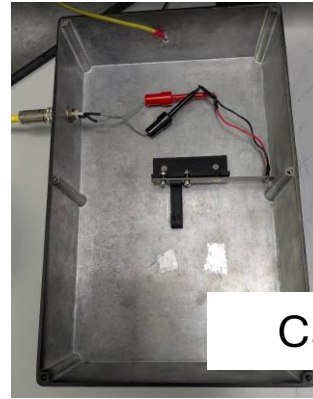
- Fit errors deduced from χ^2 contours.



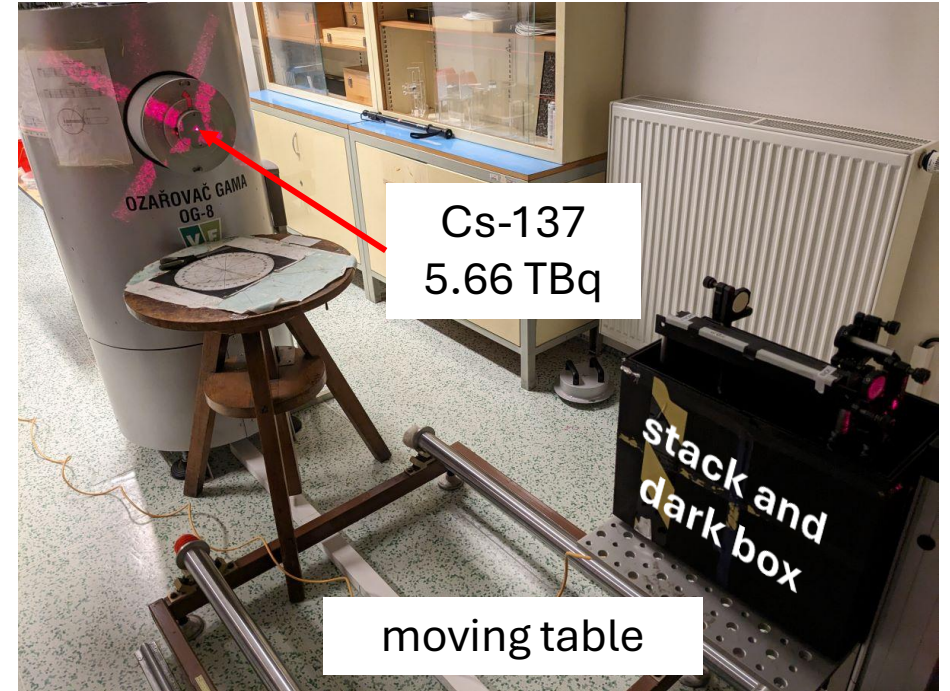
Calibration



Irradiation with ISO X-ray qualities



In-house calibration
with electrometer

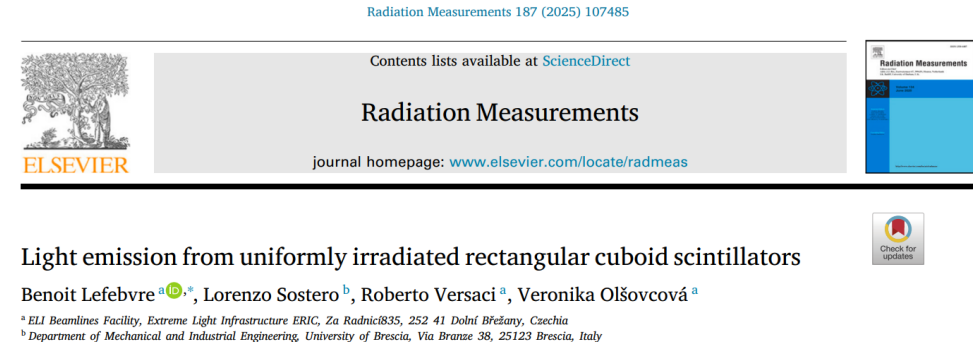
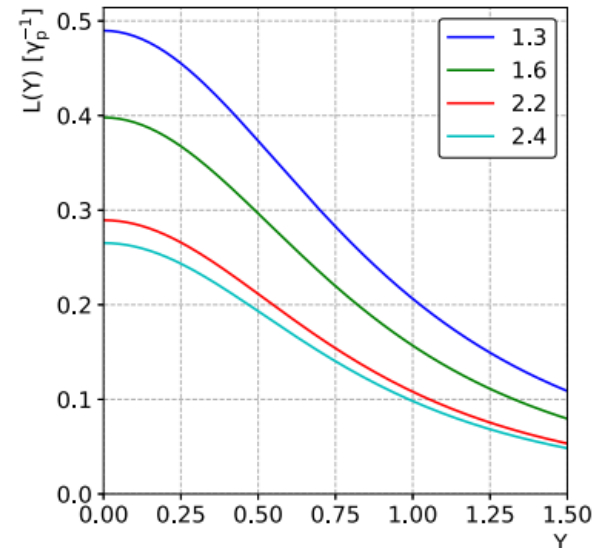
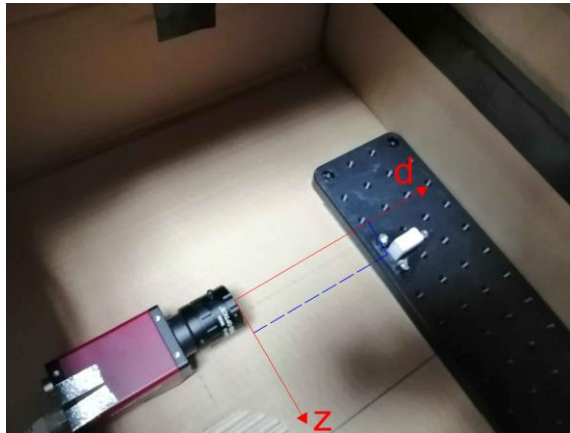


Irradiation with strong
radionuclide

- Dose calibration:
 - Unfold absolute photon count.
 - Equalize the stack channel response.
 - Validate simulation model.
- Precise pulsed radiation source seldom available for calibration.

Point-of-view effects

Applicable to scintillator-based FFS

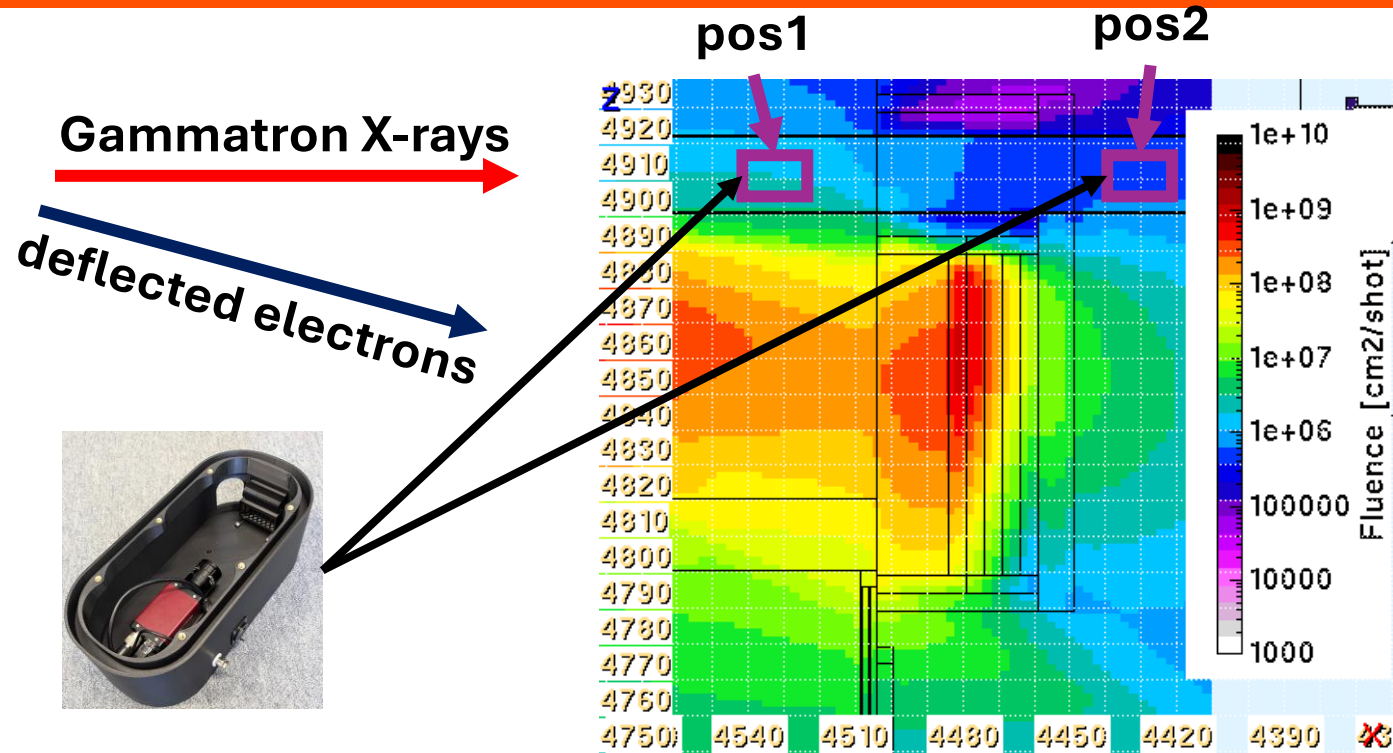


$$L(Y) = \frac{2}{\pi n} (1 + Y^2)^{-\frac{3}{2}} \left(1 - \frac{Y^2}{n^2(1 + Y^2)} \right)^{-\frac{1}{2}}$$

solution for the
simplest case

- Imaging with camera introduces important POV effects.
 - Must be corrected with large stack.
- Effect can be estimated from first principles.
 - Detailed calibration recommended.
- Designs using direct coupling with light sensor preferred (although not always practical!)

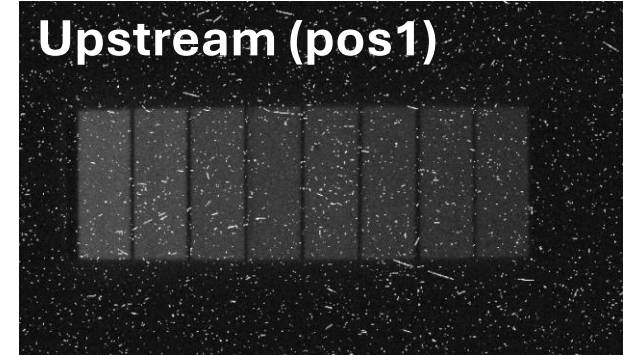
Other systematic effects



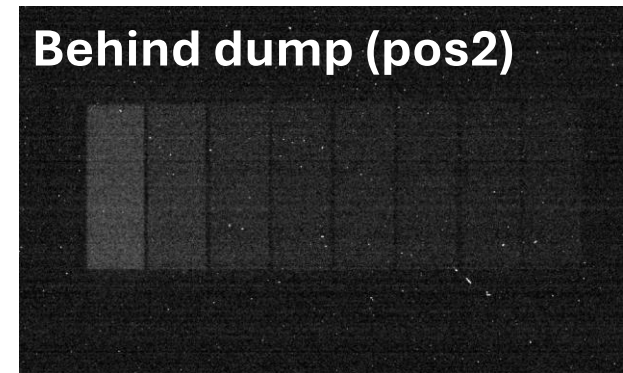
- Distortion of longitudinal dose response.
 - Stray radiation.
 - Camera noise (ambient light, stray radiation).
- Light propagation in scintillator, fibers, light guides.
- Light spill between channels and reflections.
- Birks' saturation a.k.a. "quenching" (mostly applicable to protons, ions, ...).
- Effect of other radiation species (e.g. neutrons)

CMOS camera shots

Upstream (pos1)

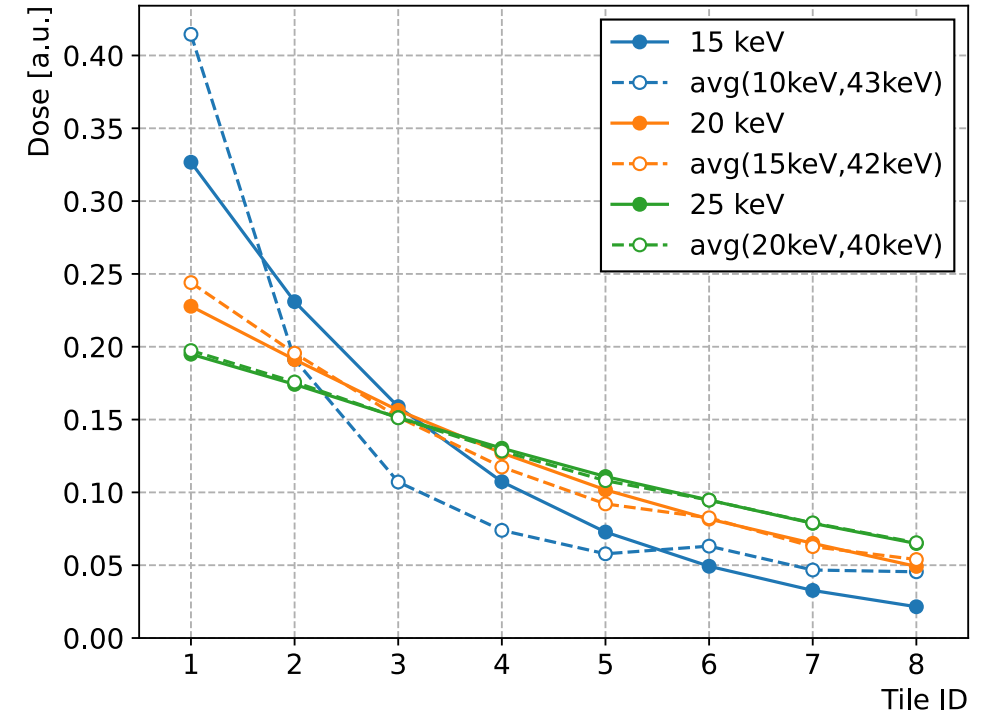
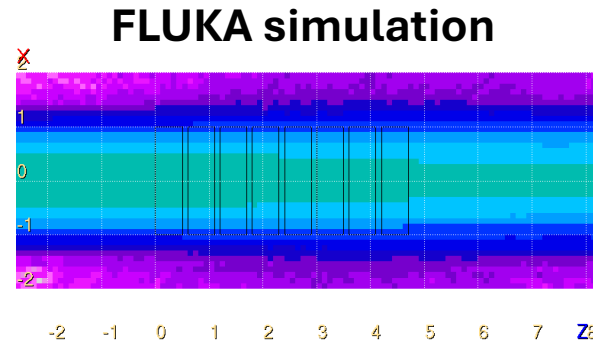
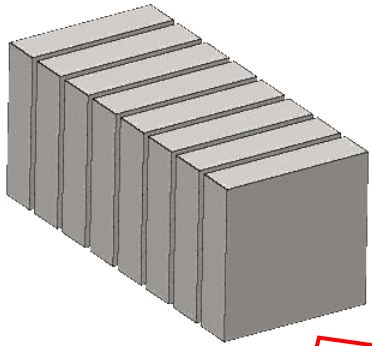


Behind dump (pos2)



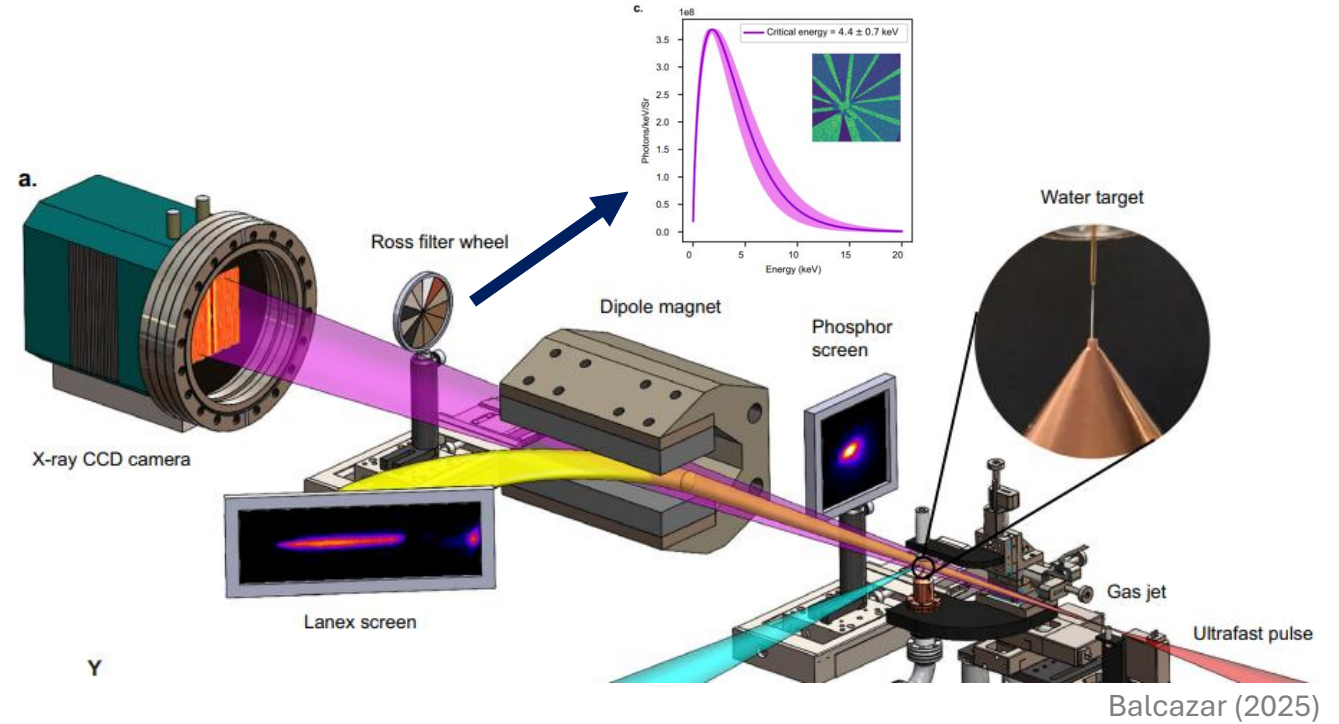
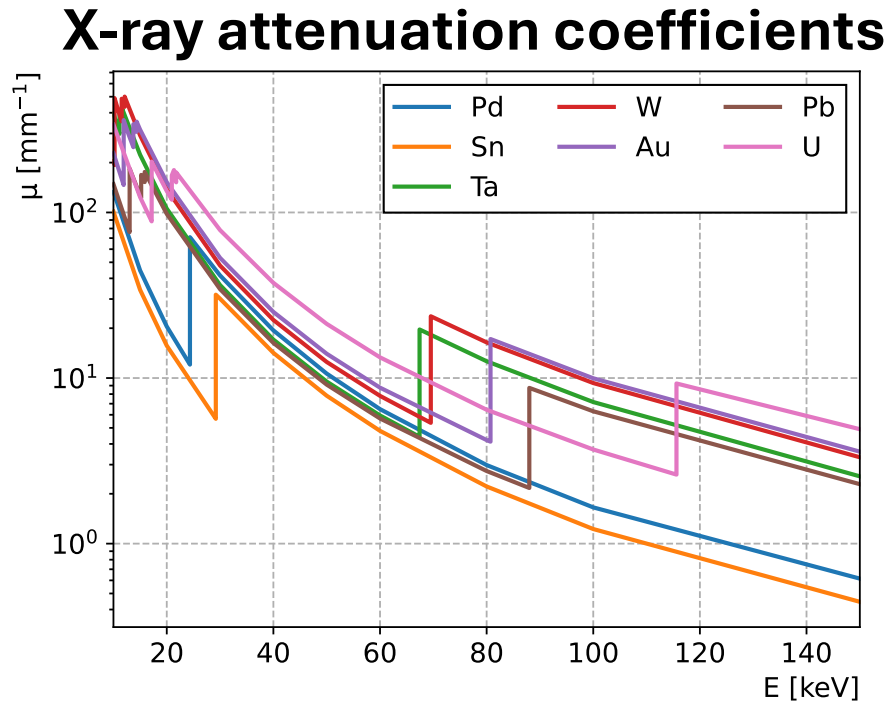
**Heavy shielding often required
for the stack and camera!**

Degeneracies



- Assume simple stack of plastic scintillator (8 tiles of 5mm).
- Simulate RM for monochromatic photons.
- Can replicate response of arbitrary energy E_c combining two energy peaks $E_1 < E_c < E_2$
- **Such degeneracies possible!**
 - Check for relative minima of unfolding.
 - Vary the material of the stack.
 - Further constrain fit with additional information.

Ross filter concept

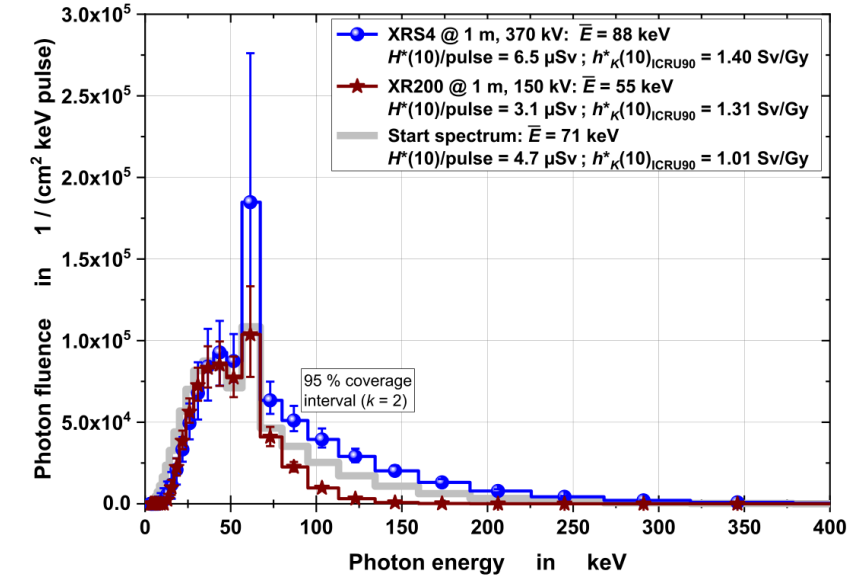
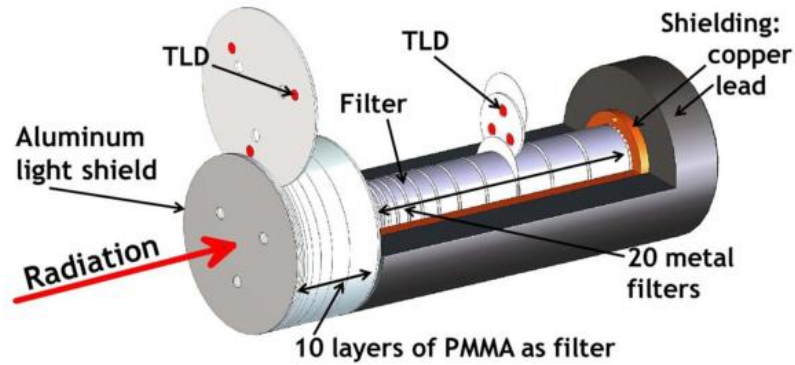


Balcazar (2025)
DOI: 10.1038/s41467-025-67224-3

- Varying the Z-number of filters mitigates degeneracies and improve the energy discrimination power.
- Ross filter configuration takes advantage of absorption peaks.
 - Roughly resolve energies between two peaks.
 - Possible up to ~100 keV and very accurate below 25 keV.

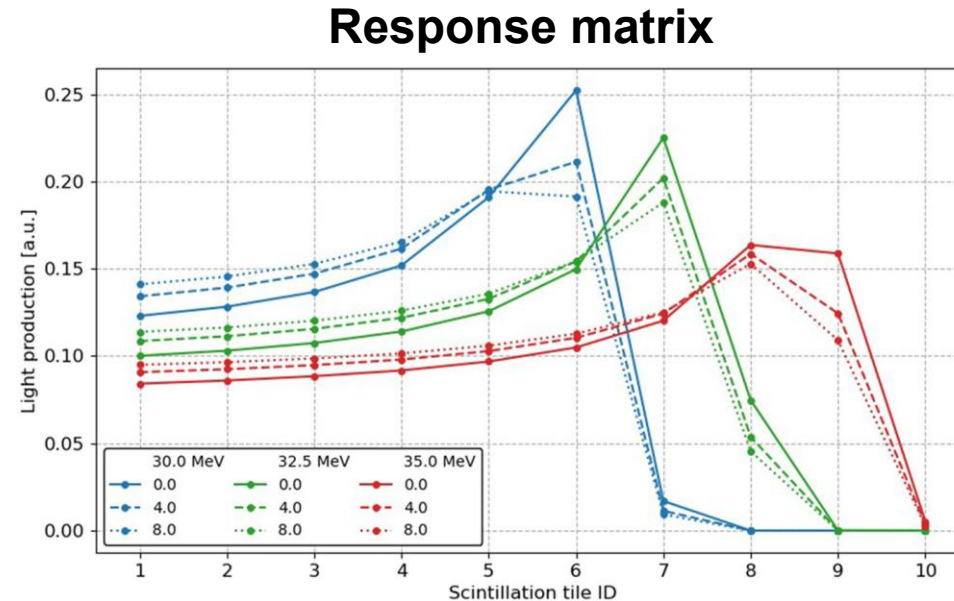
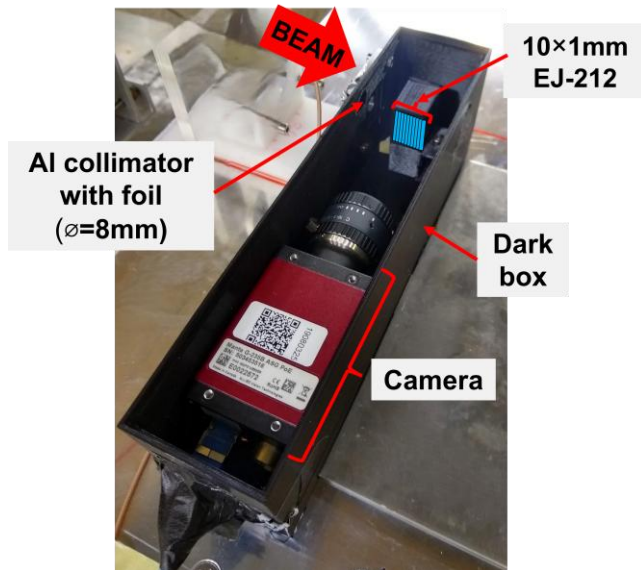
TLD-based photon spectrometer

Behrens, Zutz, Busse (2022)

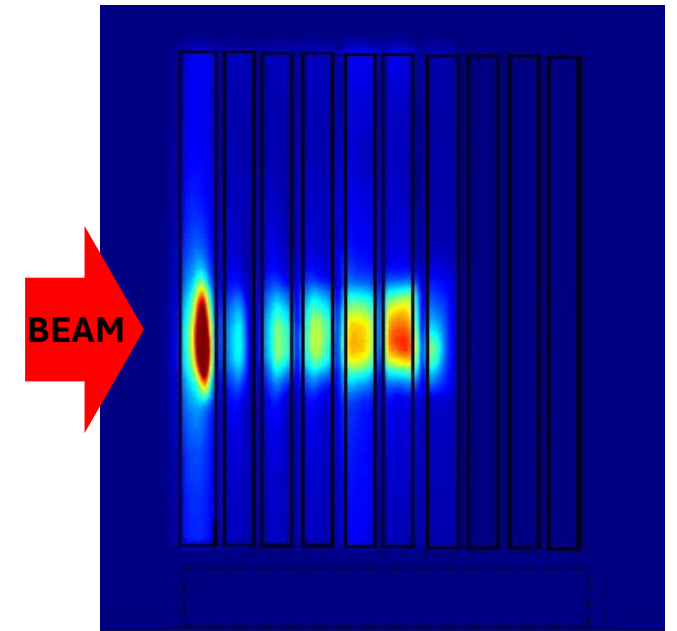


- Passive dosimeter with 20 metal filters of increasing Z-value.
- Spectrum divided in 60 energy channels. Logarithmic increase.
- Bayesian unfolding with some assumption on spectrum (8 free parameters).
 - Using WinBugs in this work. Possible alternatives: NIMBLE (R), PyMC
 - Fitter provides confidence intervals for spectrum.
- Spectrum converted to operational quantities: $H^*(10)$, air kerma, etc

Proton measurements



Typical camera shot

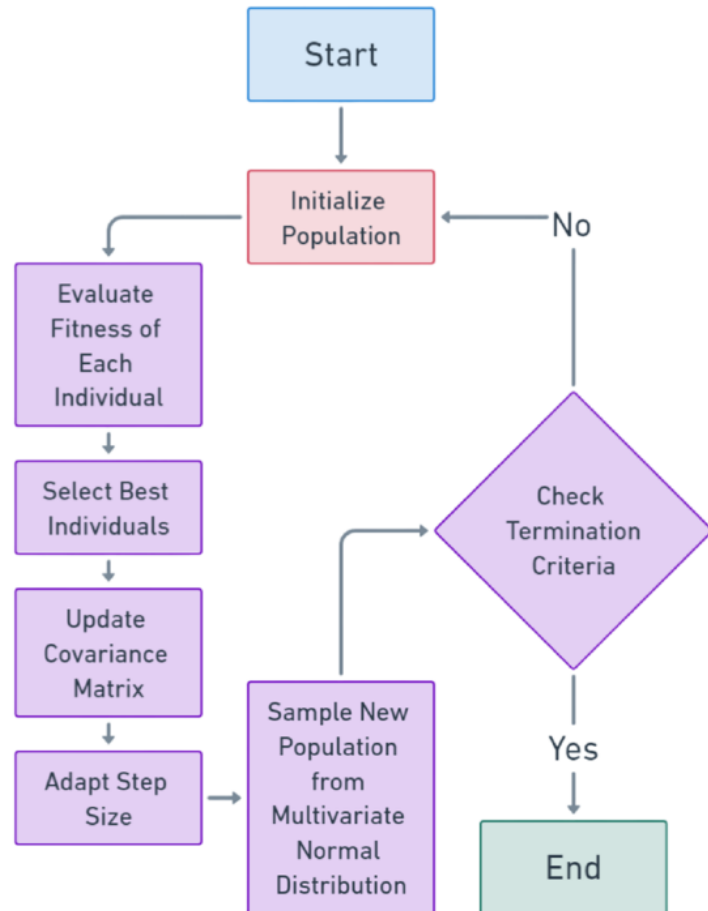


Istokskaia (2023)

- Small-scale 1cm plastic stack for protons $E \sim 30$ MeV.
- Unfolding with quenching, energy mean and width as free parameters.

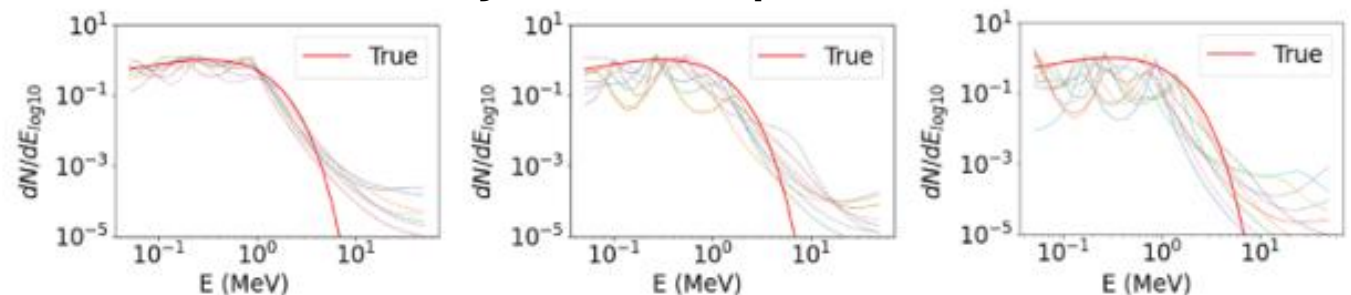
Genetic algorithm unfolding

Fauvel, Tangtartharakul, Arefiev et. al. (2025)



- Define a cost function to minimize.
- Randomly generate a “generation” of spectra.
- Select best spectra and proceed to next generation until convergence.
- Good algorithm to identify unexpected structures in the spectrum.
 - But can become too “imaginative”.

Benchmark tests with synthetic synchrotron spectrum

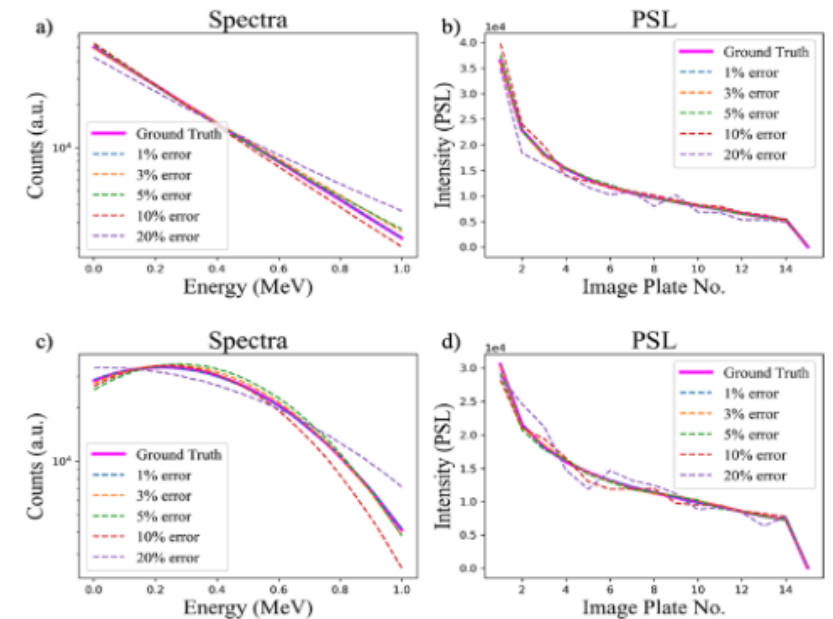


Other unfolding algorithms

- **Recent effort in improving spectrometer design optimization techniques and unfolding.**
- Genetic algorithm for tuning thickness of filters:
 - Wen, Ma, Yu et. al. (2023)
 - DOI:10.1007/s41365-024-01391-8
- Perturbative minimization algorithm:
 - Wong, Strehlow, Broughton et. al. (2024)
 - DOI:10.1063/5.0190679
 - *Similar to the genetic algorithm but with a more gradual convergence.*
- Feedforward Neural Network
 - Alvarado Alvarez, Wolfe, Wong et.al. (2024)
 - DOI:10.1063/5.0216759
 - Very fast convergence but without fit errors or confidence intervals.
 - *Requires thorough training and validation phases.*
 - *Fastest algorithm but does not directly report errors of confidence intervals!*

Benchmarking of FNN model

Testing sensitivity to detector noise



Conclusion

- Various implementation of FSS detectors developed in the last decade.
- **Unfolding algorithms** and **detector construction optimization** still the subject of active research.
- Provides limited but valuable spectral information.
- Readout rate, accuracy and range of applicability (neutron fields) likely to further improve to support emergent fields:
 - Internal confinement fusion
 - FLASH radiotherapy
 - Laser-driven sources (Betatron, gamma flash, protons).



Thank you!

