

Dosimetry of “everything”

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Dosimetry

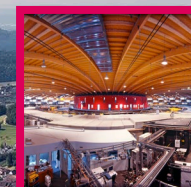
- with luminescent detectors
- of hadrons for
 - ion beam therapy
 - linear energy transfer (LET) measurements
- of neutrons at
 - CERN (accelerator field)
 - NPP (castor)

ETH zürich

EPFL



Swiss Neutron Sources SINQ and UCN



Swiss Light Source SLS



Swiss Free Electron Laser SwissFEL



Energy System Integration

Proton Therapy



Swiss Muon Source S μ S



High-precision Particle Physics CHRISP

Hotlab

Radiopharmacy

PSI East

PSI West

... with optically stimulated luminescent detectors (OSLDs)

Dose to water

$$\text{Absorbed dose} = \frac{\text{energy imparted}}{\text{matter}}$$

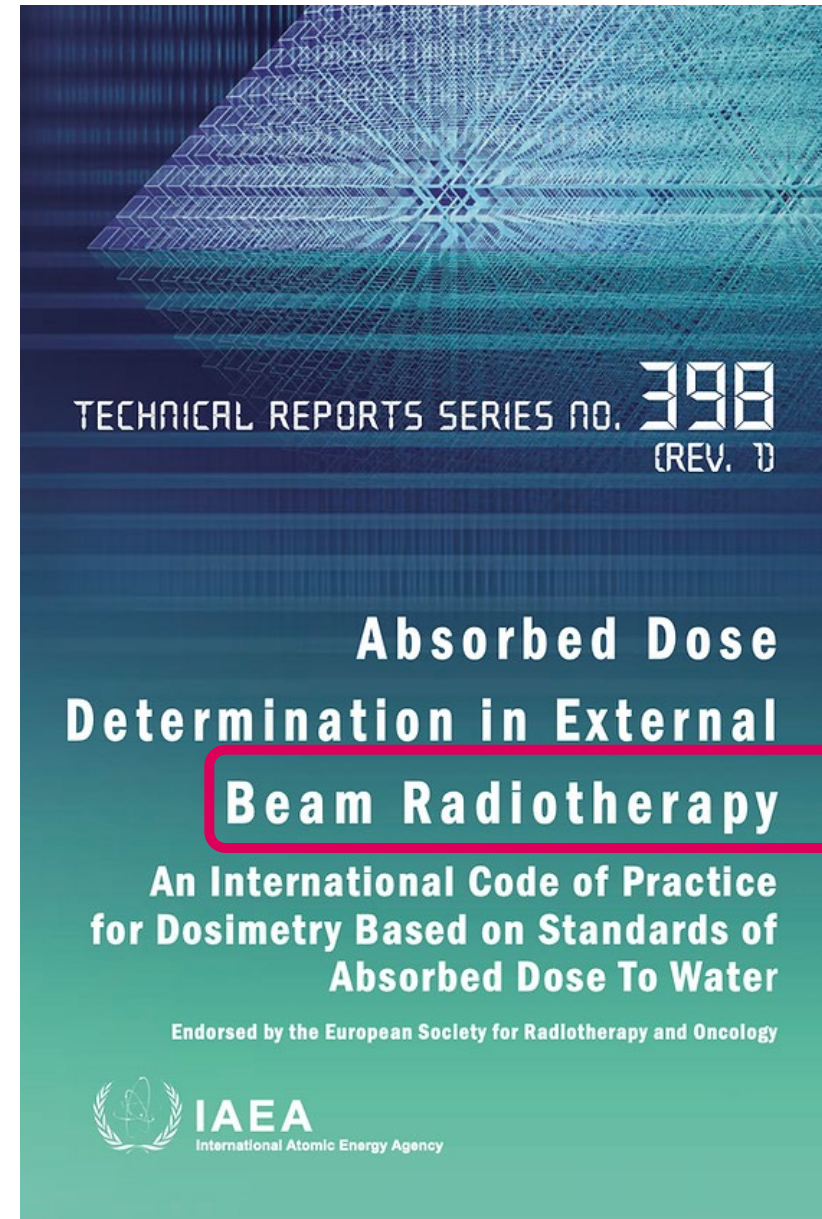
$$1 \text{ Gy}^* = \frac{1 \text{ joule}}{1 \text{ kg}}$$

Protocols and standards, e.g. TRS-398:

$$D_{\text{water}} = N \cdot M \prod k_i$$

Where

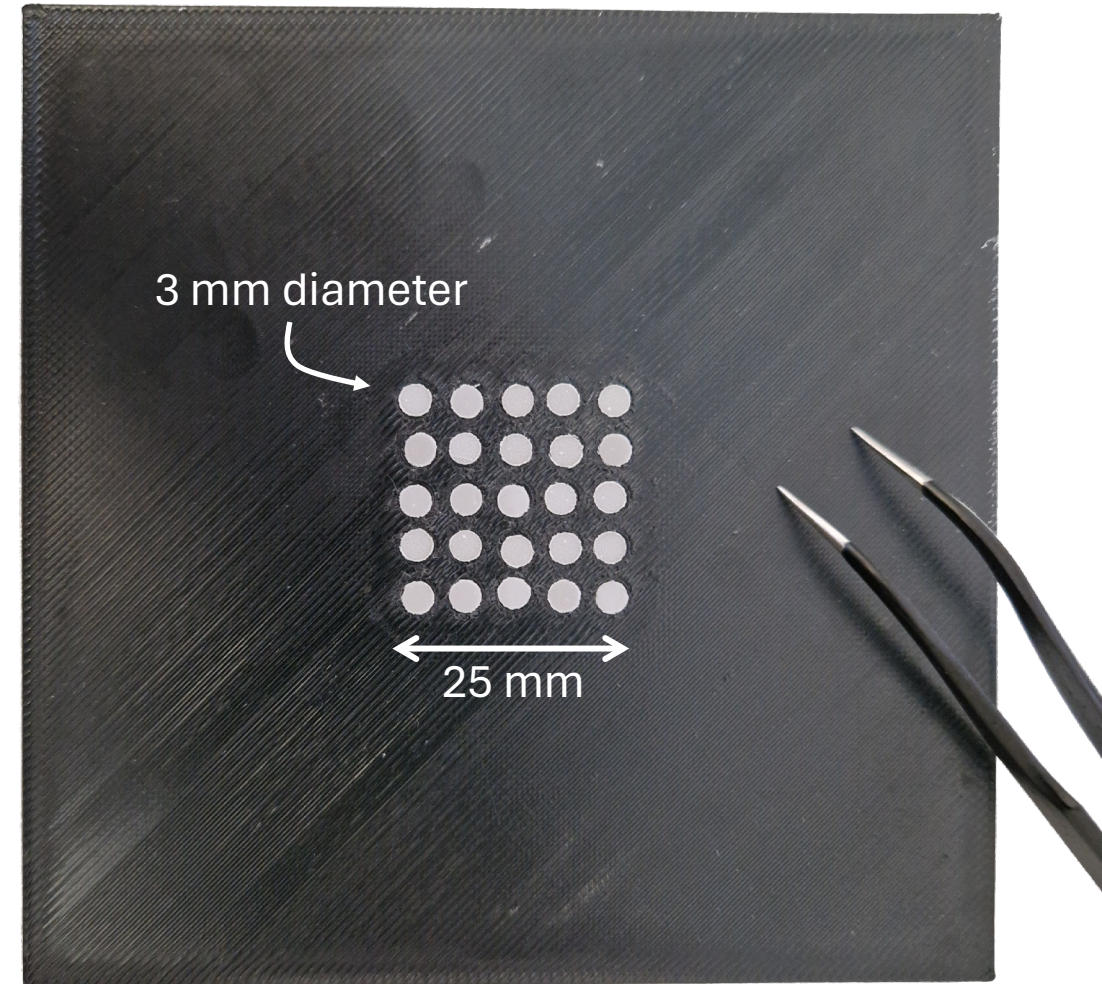
- N is calibration (signal \rightarrow Gray)
- M is the detector reading (signal)
- k_i are correction factors



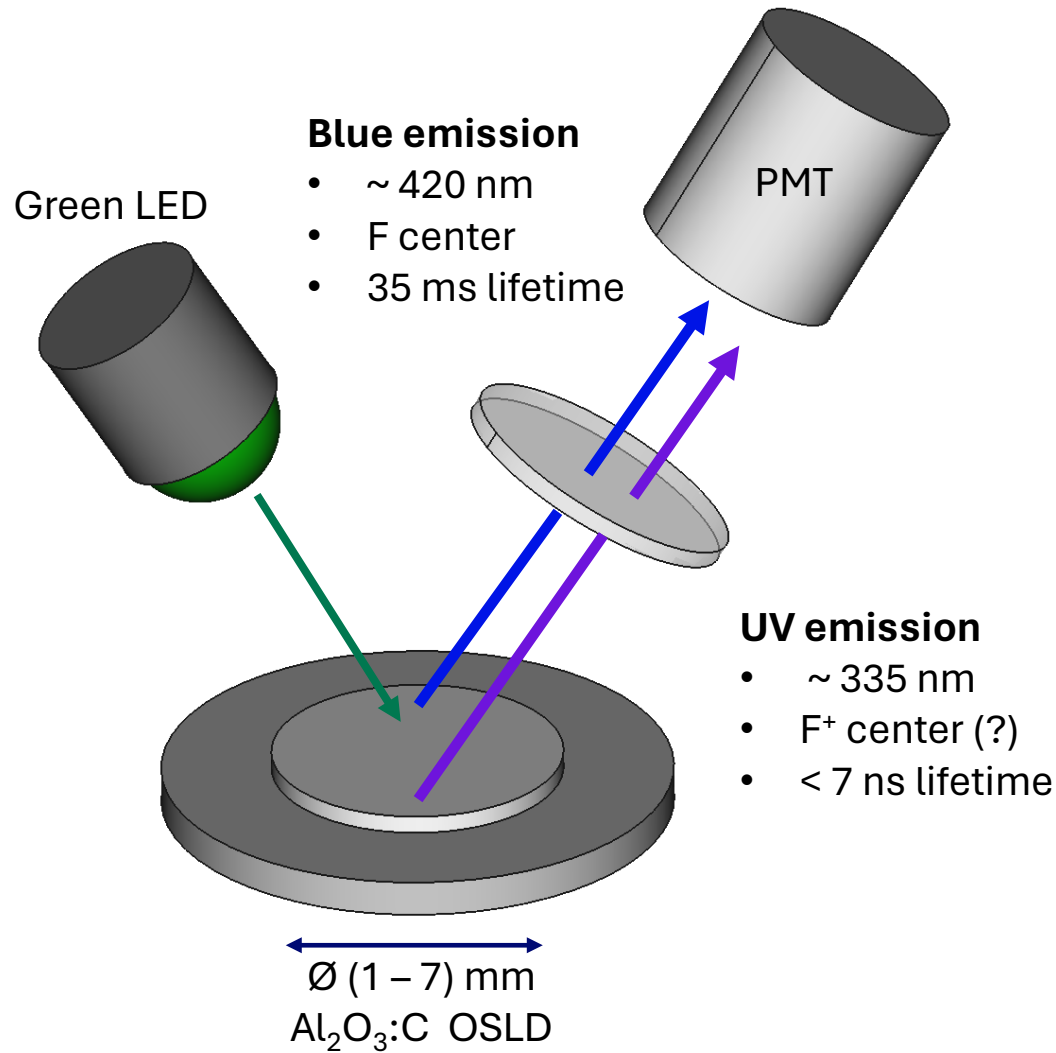
Optically stimulated luminescence (OSL)

$\text{Al}_2\text{O}_3:\text{C}$ OSL detectors

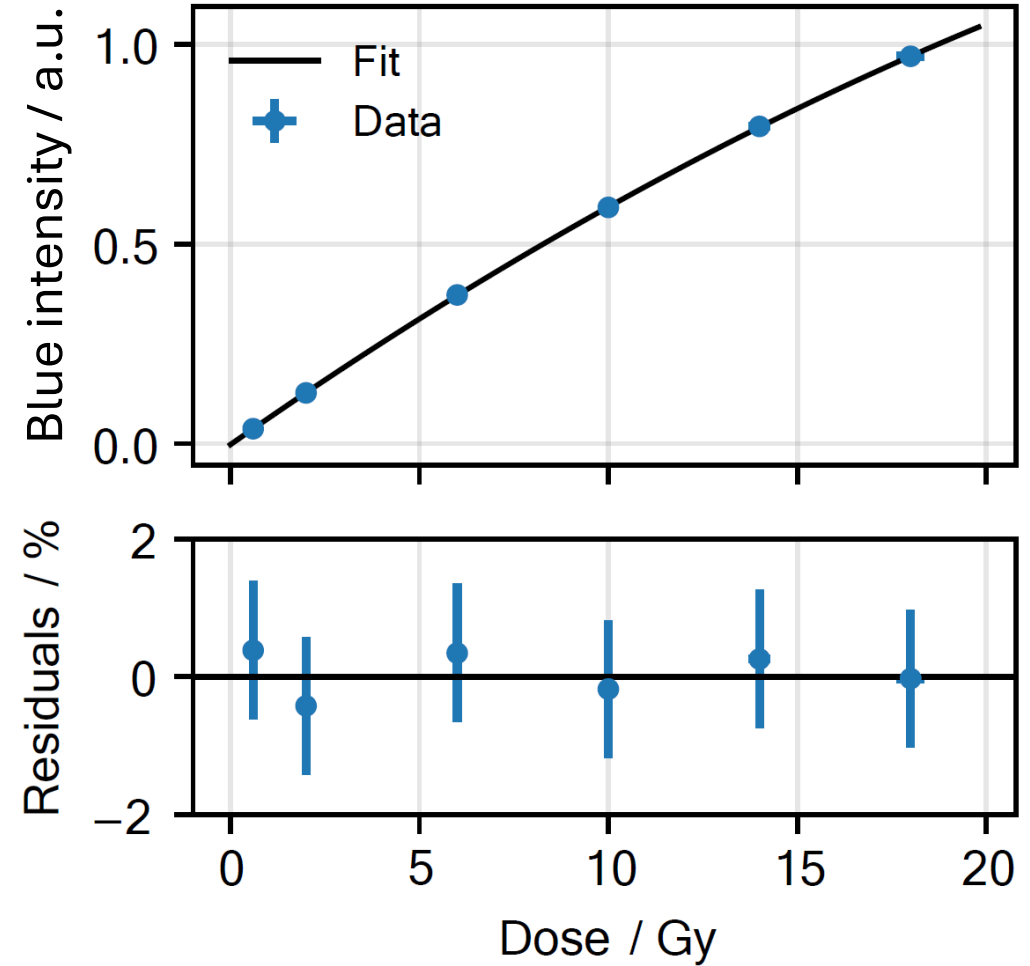
- 38 μm grains mixed with a binder
- OSL film < 100 μm
- Cut with a scissor, punch plier, ...



OSL readouts



Example: OSL dose calibration



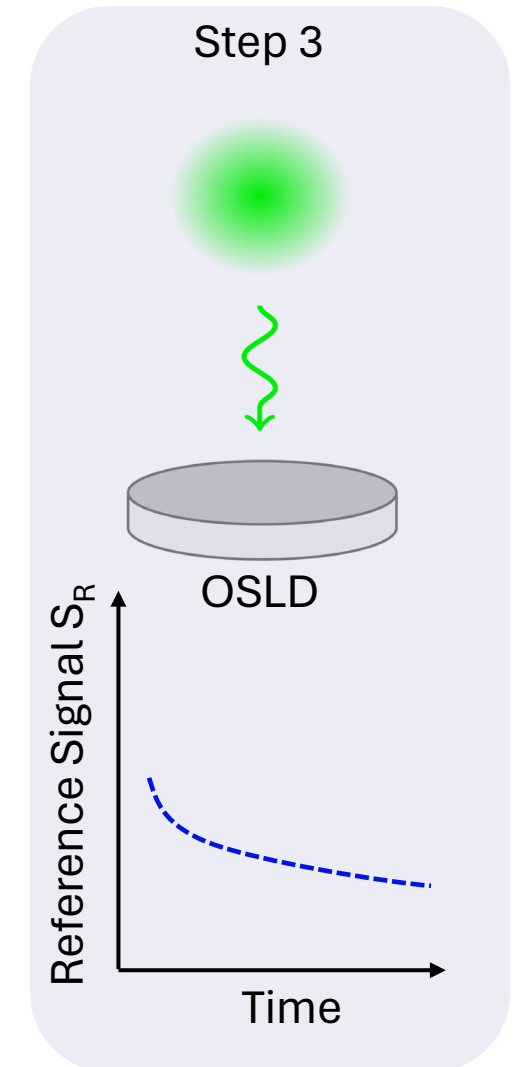
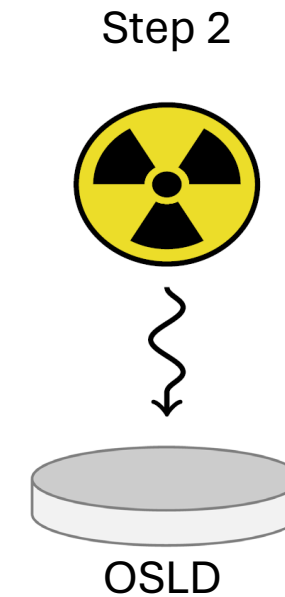
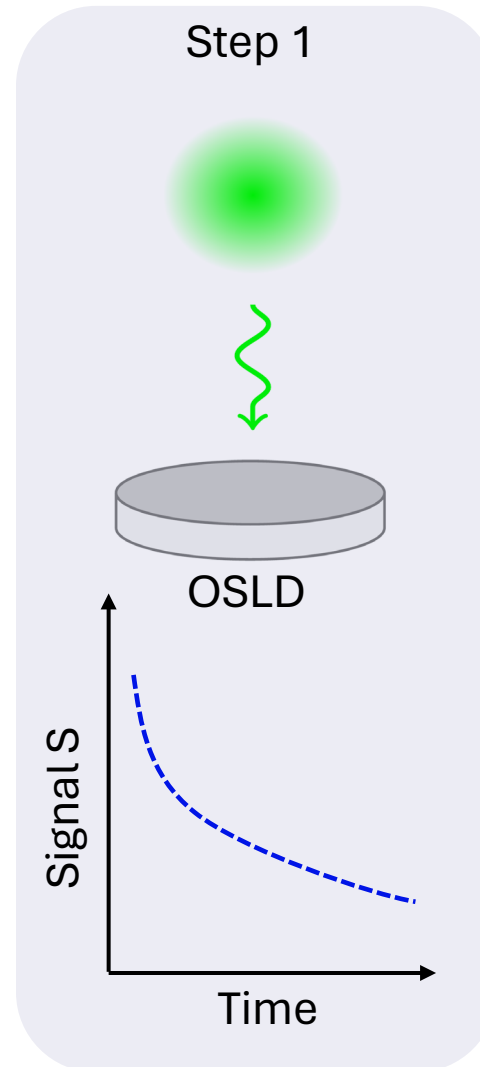
Automatic corrections (S / S_R)

Define (automatic) readout sequence

$$\frac{S}{S_R} \equiv \frac{\text{Signal (Exp. readout)}}{\text{Signal (reference readout)}}$$

Aim:

- Correct for OSLD differences
- Improve precision

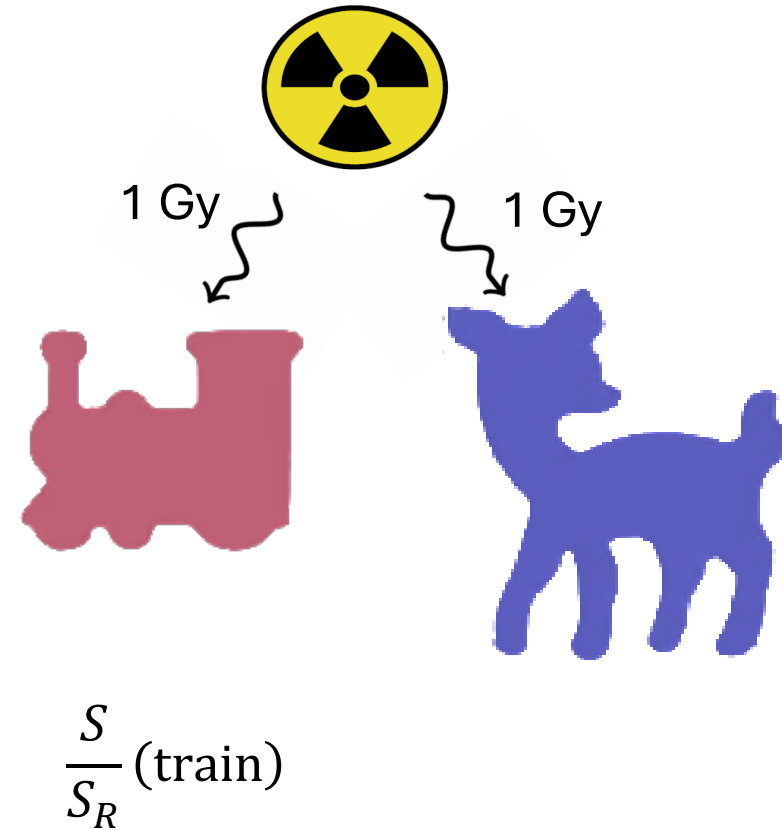


Take home message: Reference irradiations are powerful!

Al₂O₃:C OSL film



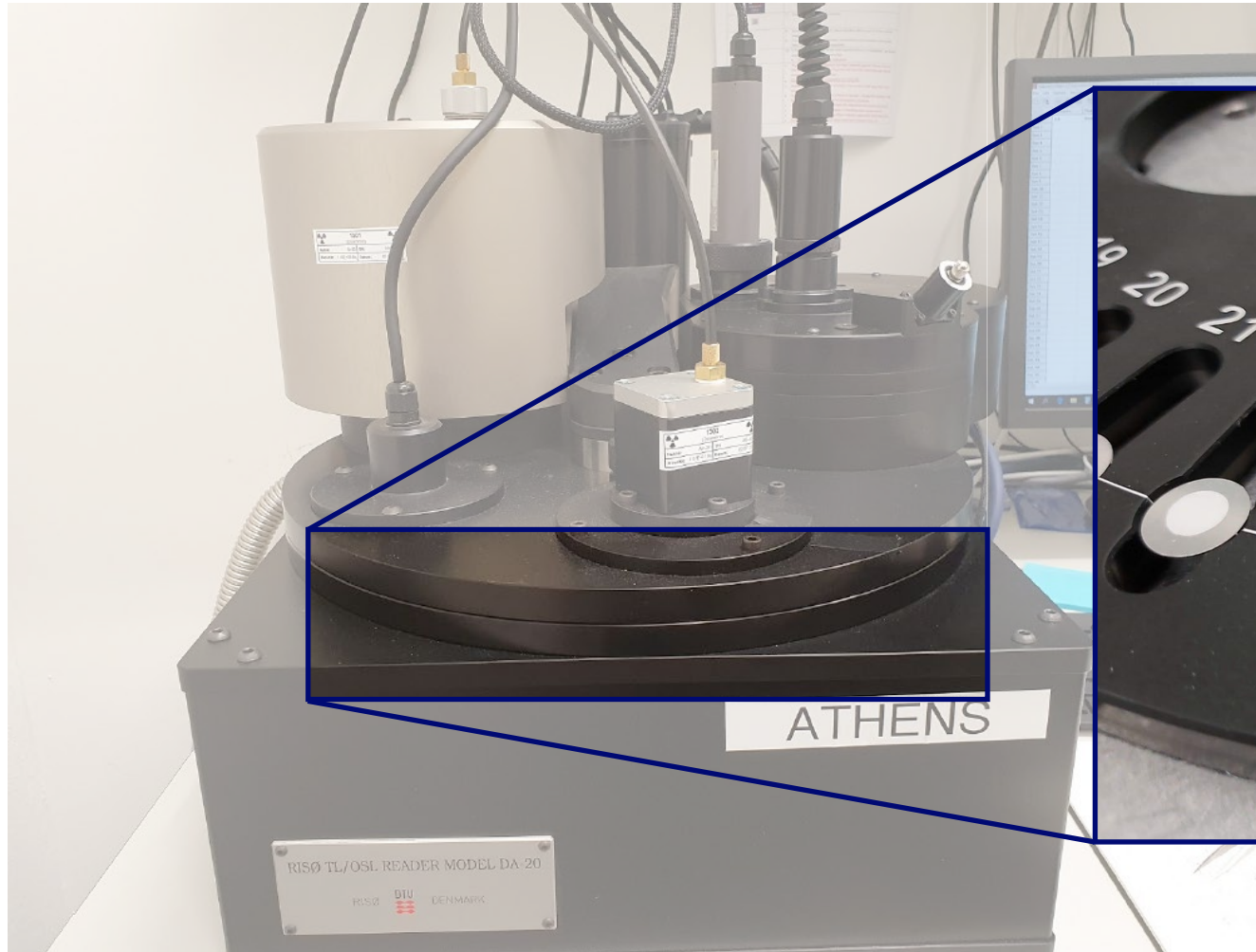
Advanced
research
equipment



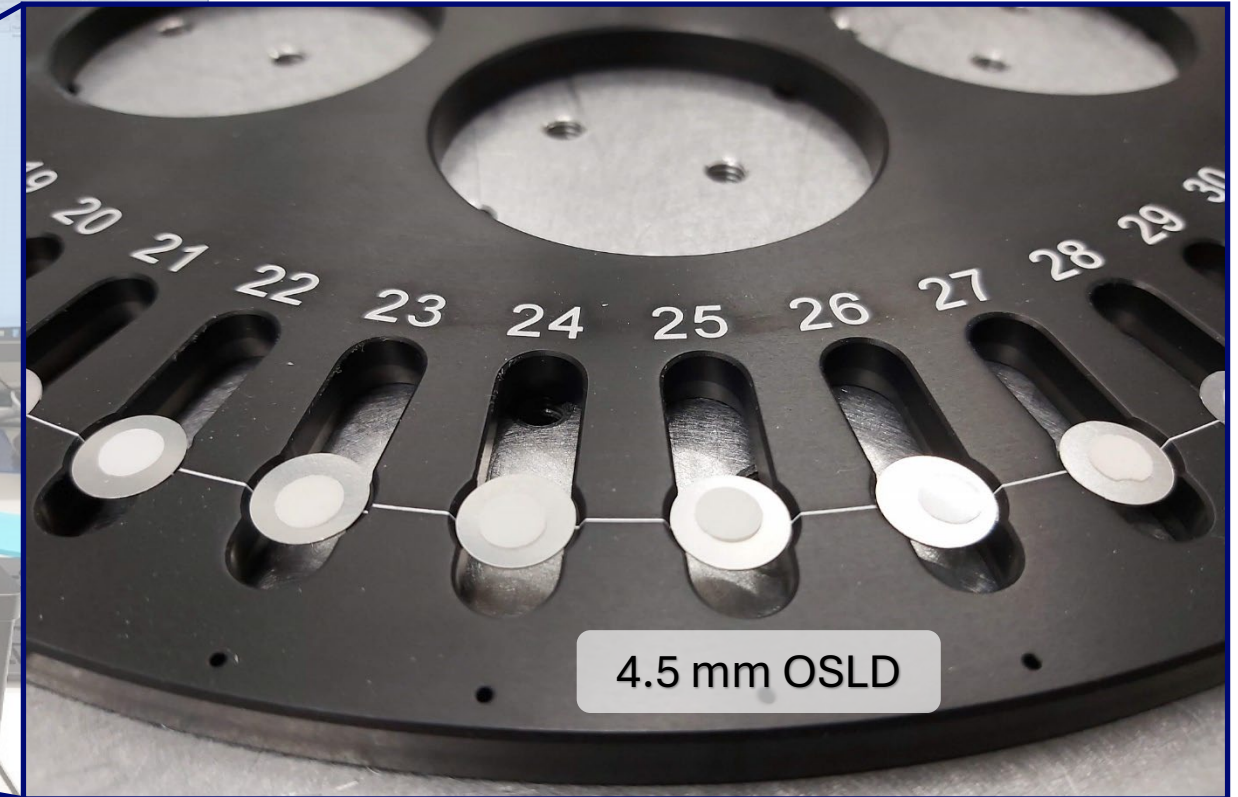
S/S_R readout protocol:
Most sensitivity and size differences cancel out

Automatic OSL reader

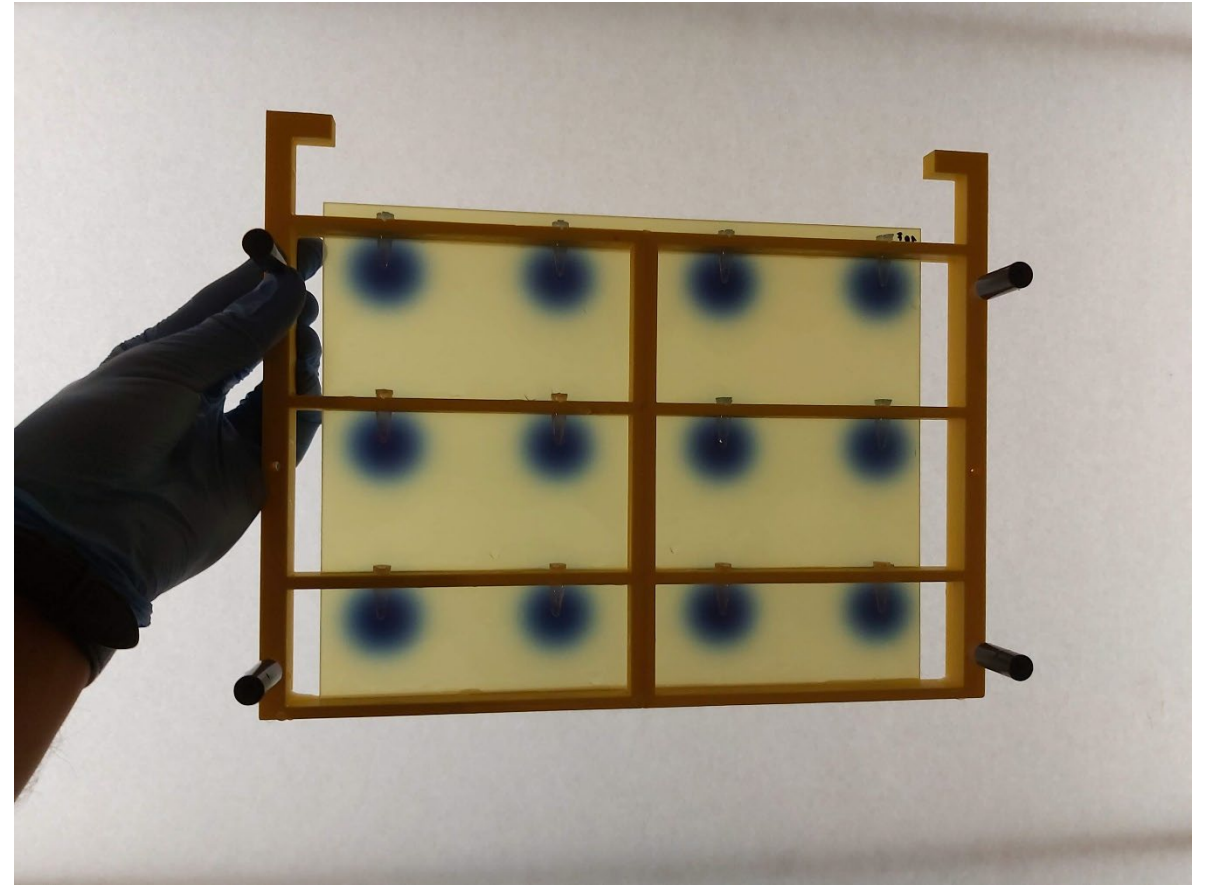
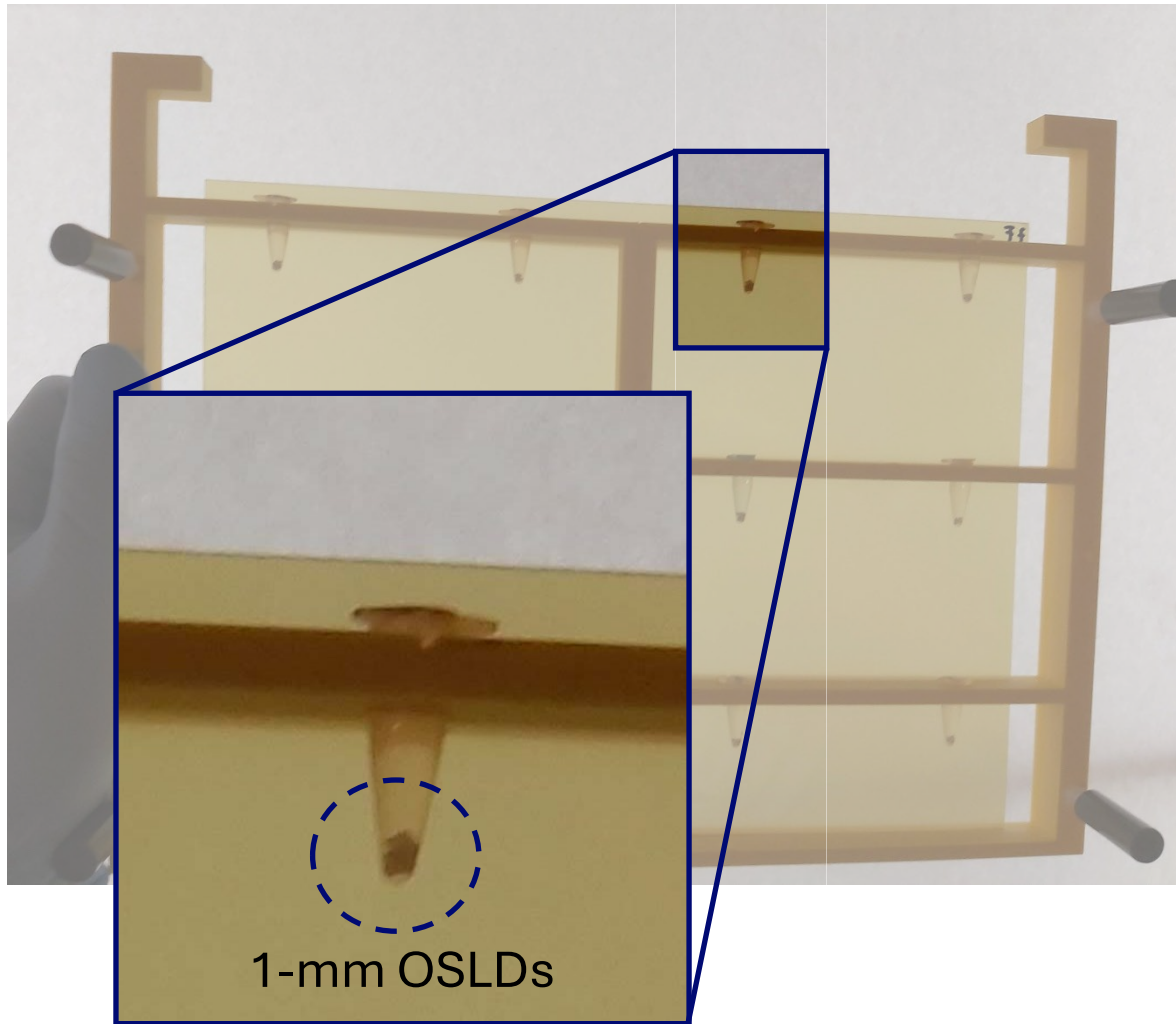
Enables OSL/TL read-out + irradiation



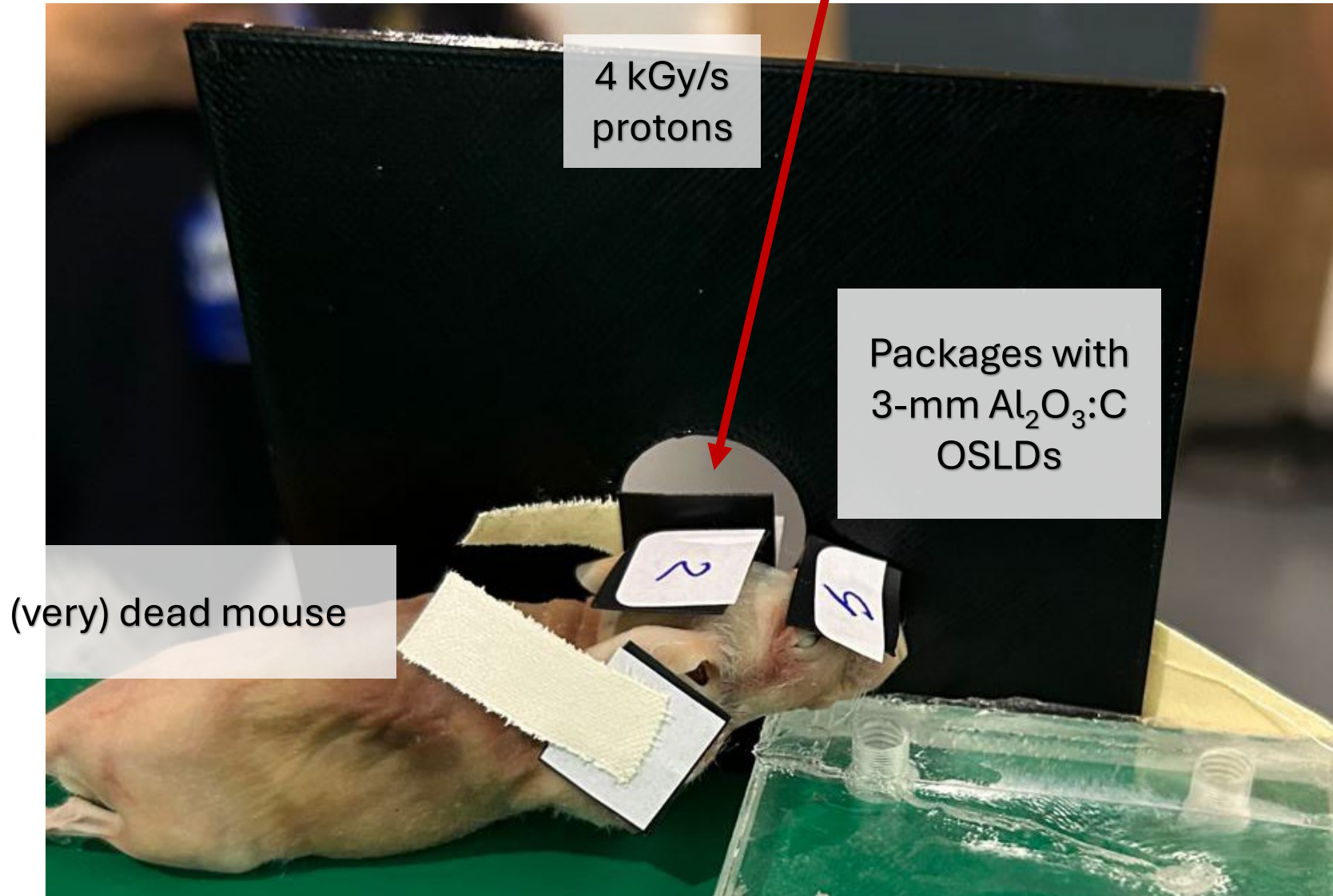
Wheel accommodating 48 OSLDs



OSLDs for ultra-high dose-rate dosimetry



OSLD FLASH proton dosimetry

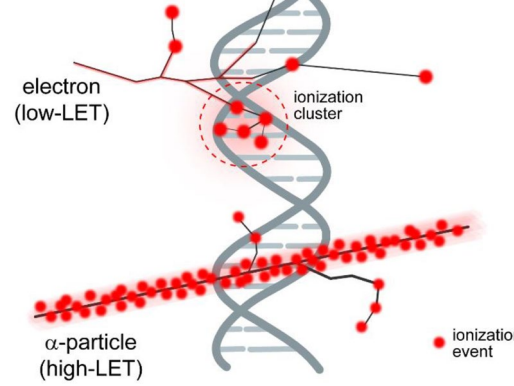


Ion beam dosimetry

Why don't we just use photons?



Hadron therapy



Spare healthy tissue

Increased relative biological effectiveness (RBE)

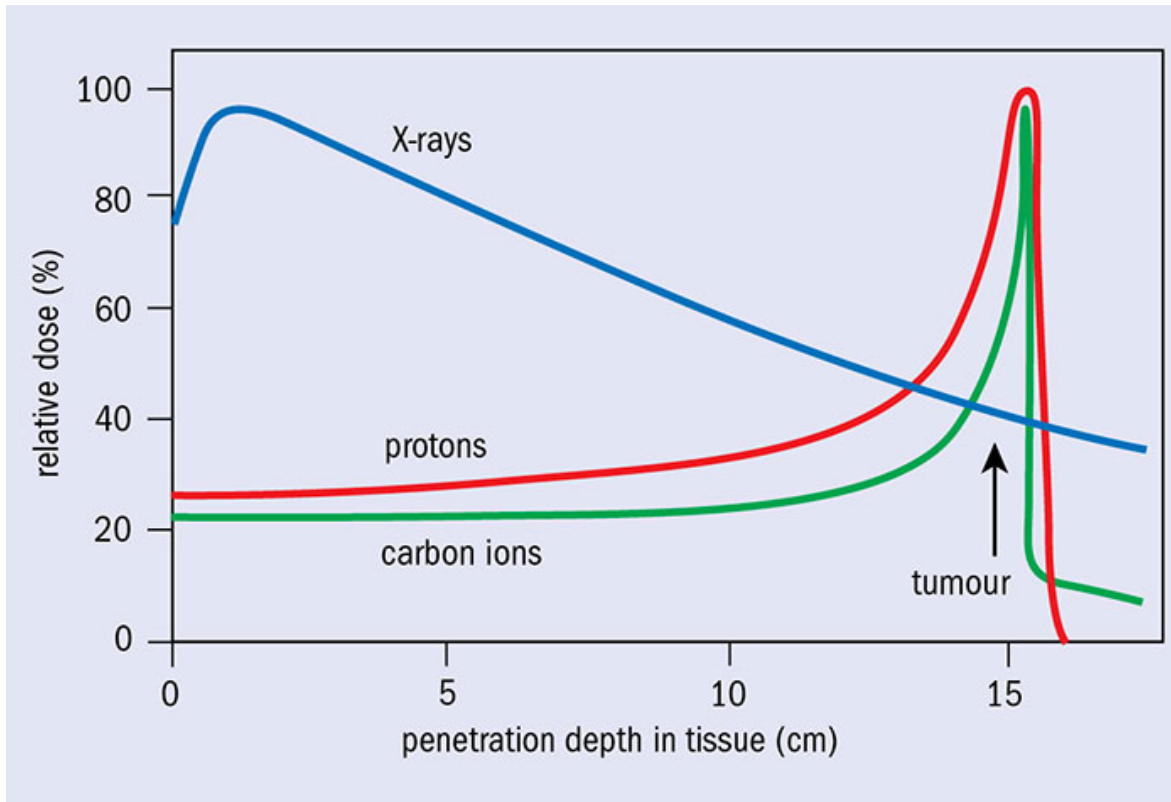
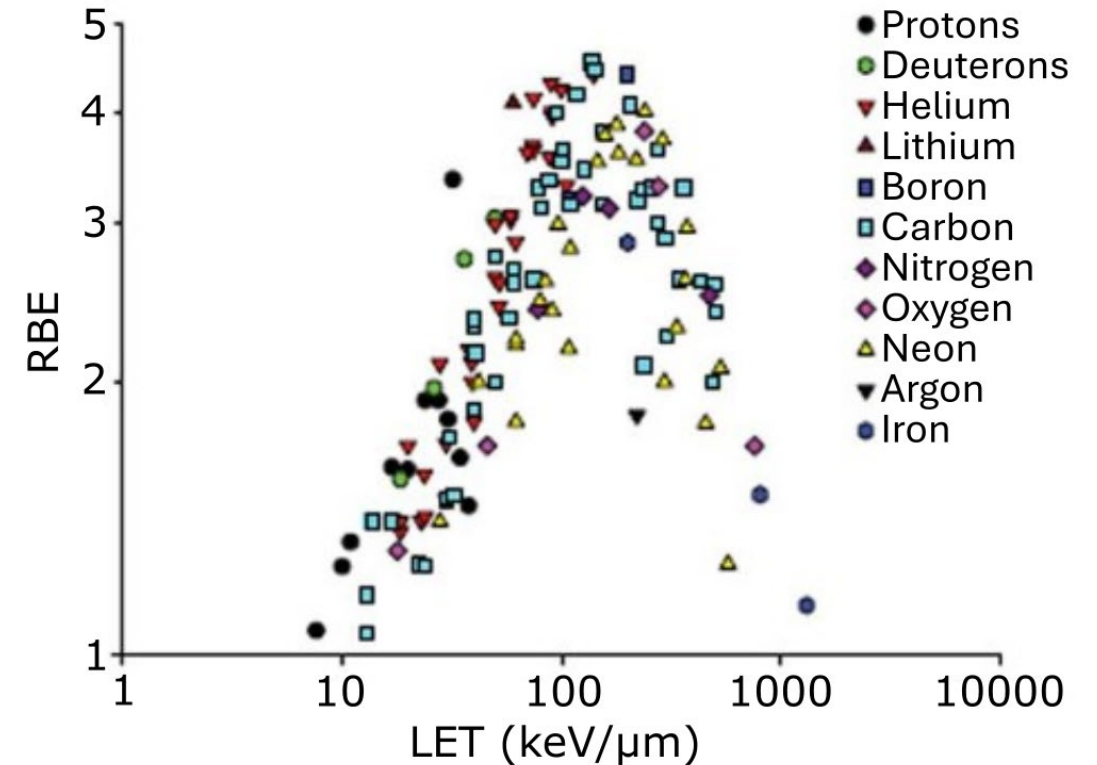


Figure: CERN Courier



Sørensen *et al* (2011) Acta Oncol 60 6

Linear energy transfer (LET)

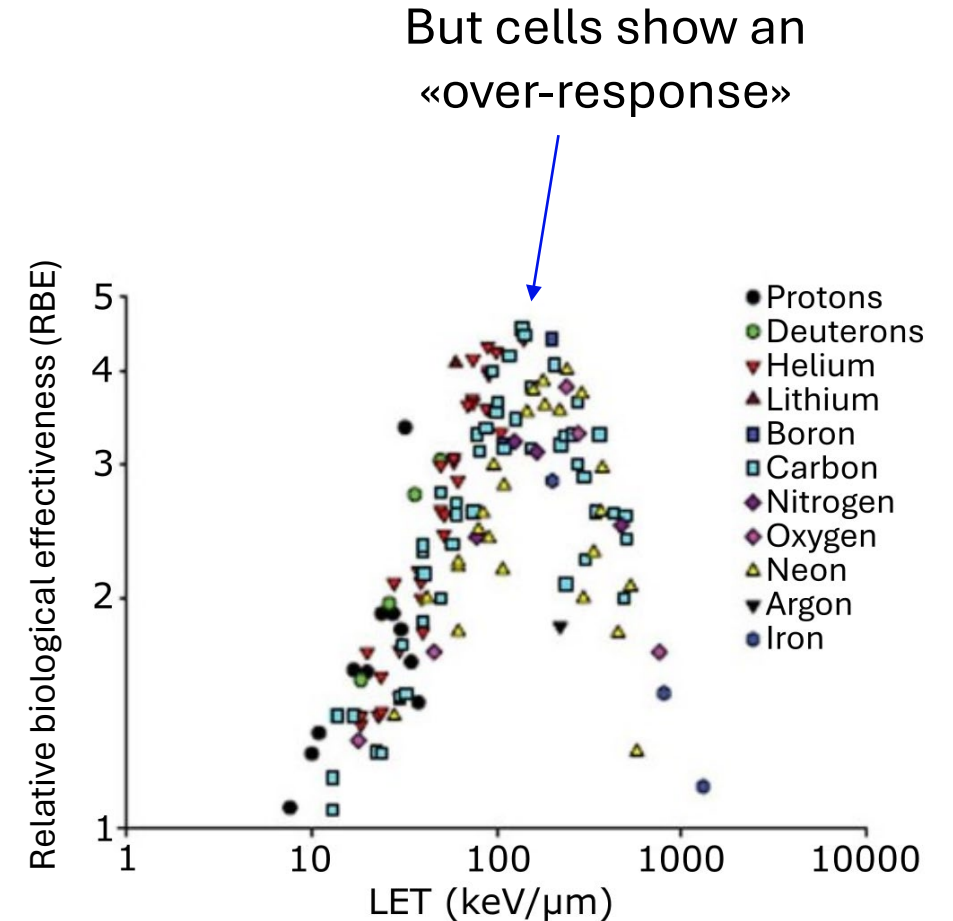
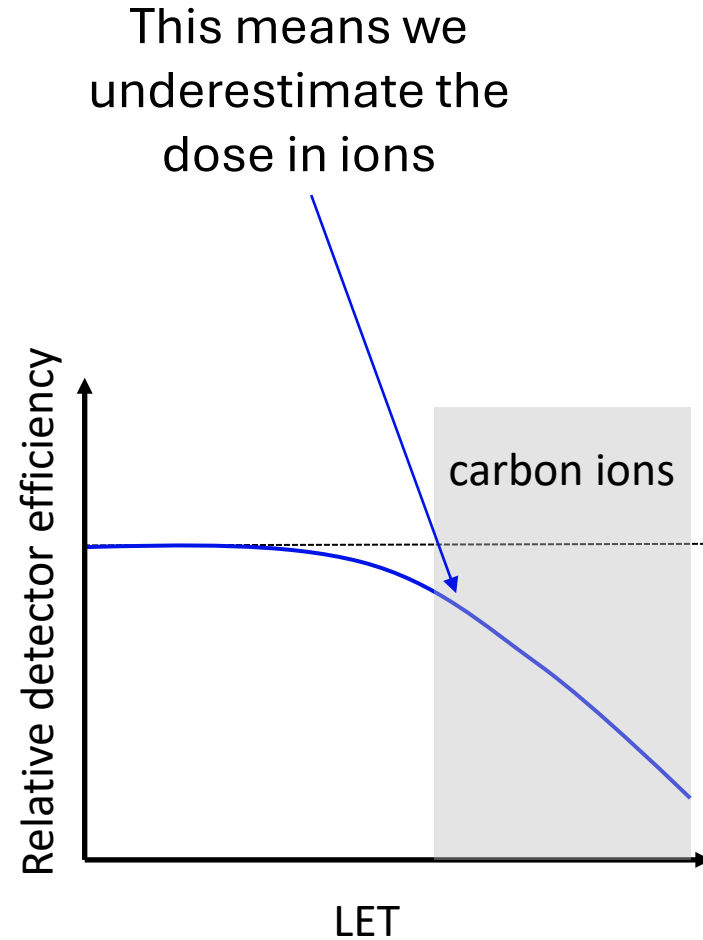
Dosimetric challenges

Detector efficiency

$$\eta = \frac{D_{\text{quality}}}{D_{\text{photons}}}$$

Linear energy transfer

$$\text{LET} = \frac{dE}{dx}$$



Sørensen *et al* (2011) *Acta Oncol* 60 6

Linear energy transfer (LET) in proton/carbon ion beam therapy:

- Causes the radiobiological effect to increase
- Causes the detector response to decrease

What do we need to measure?

- Absorbed dose (Gy)
- LET (keV/um)

Problem: «Energy deposition per unit length» is not measurable



LET «measurements»

Objective:

Estimate the LET in ion beam therapy to

- correct the absorbed dose for ionisation quenching
- estimate the RBE

Idea:

Exploit that the detector response (η) varies with the LET

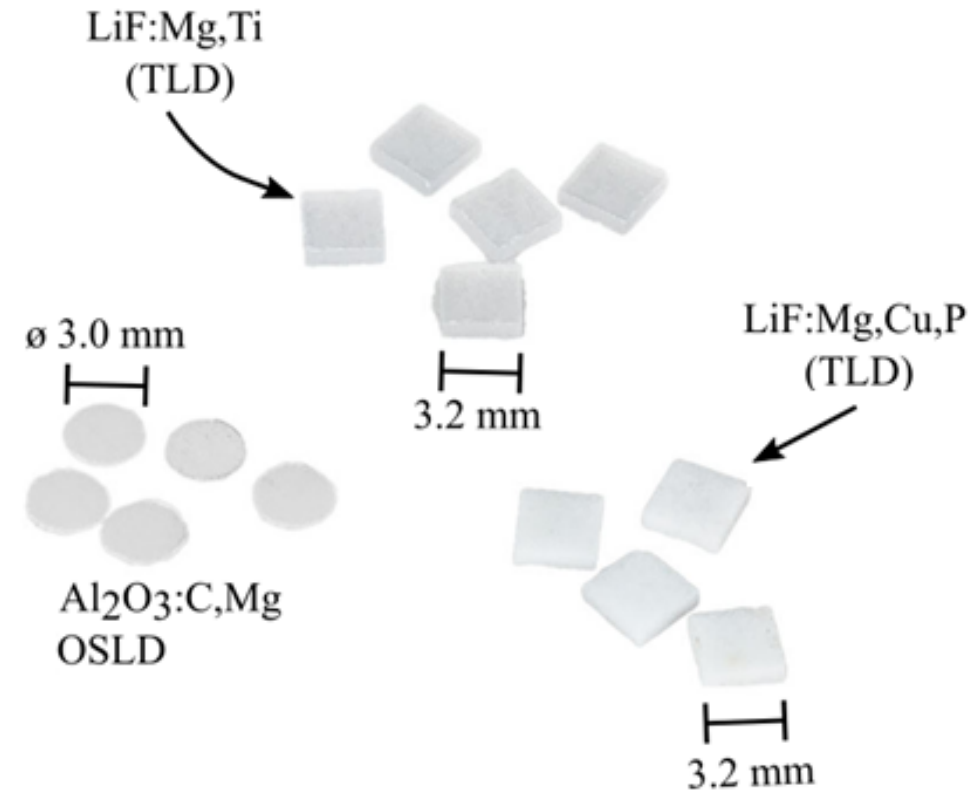
Test for:

- Thermoluminescent detectors (TLDs)
- Optically stimulated luminescent detectors (OSLDs)

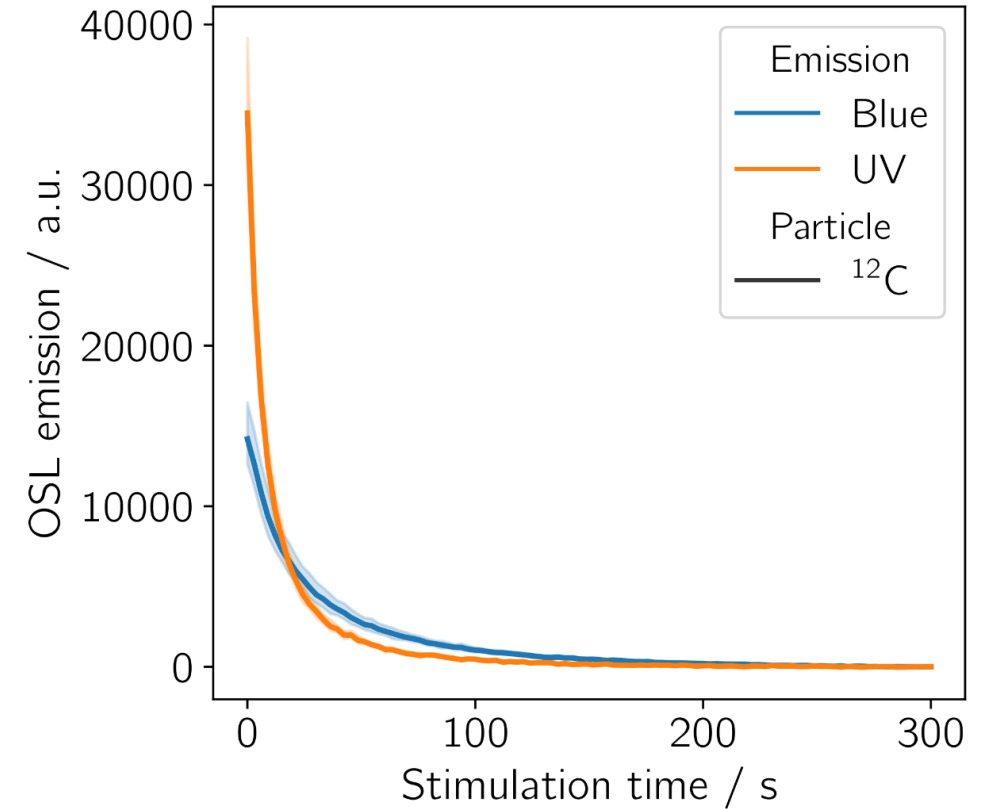
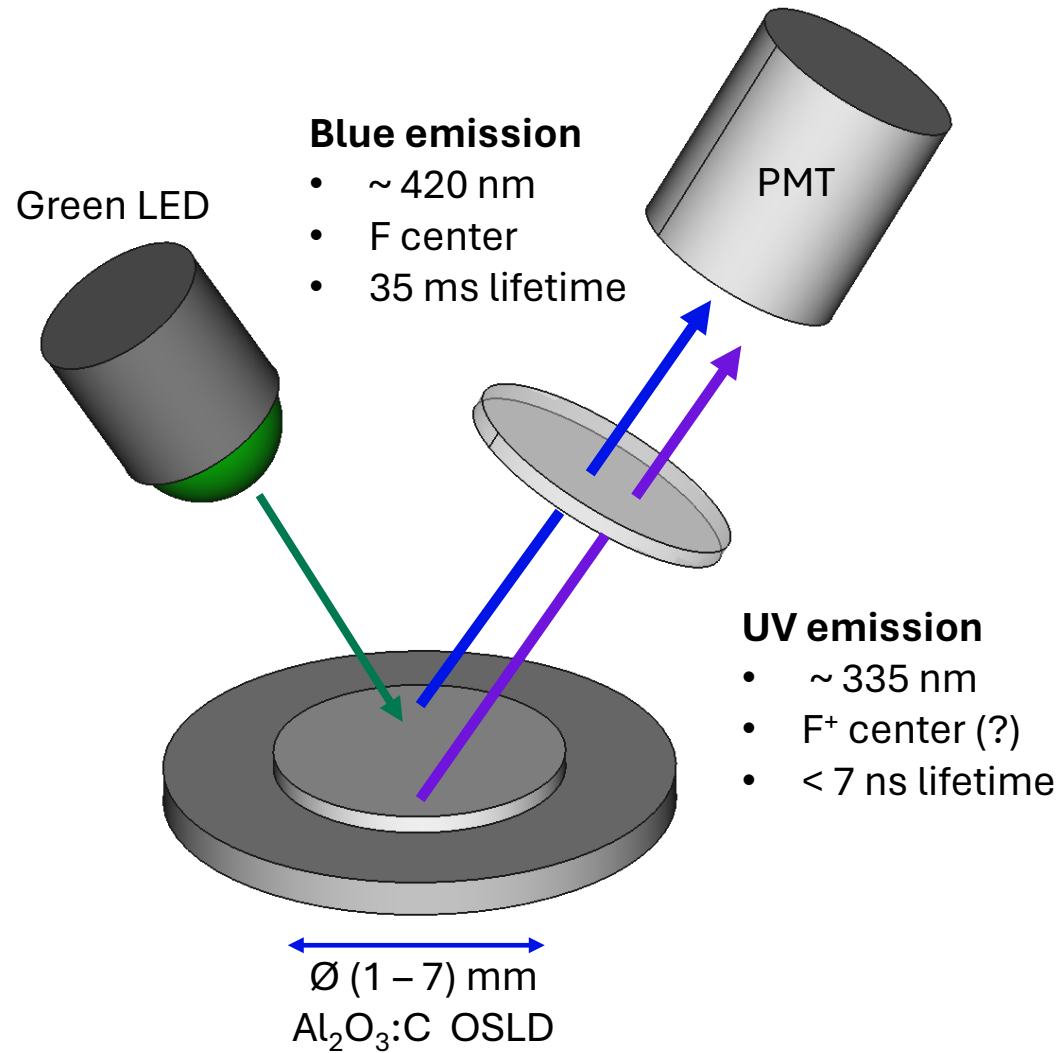
Task:

Relate luminescence features to LET

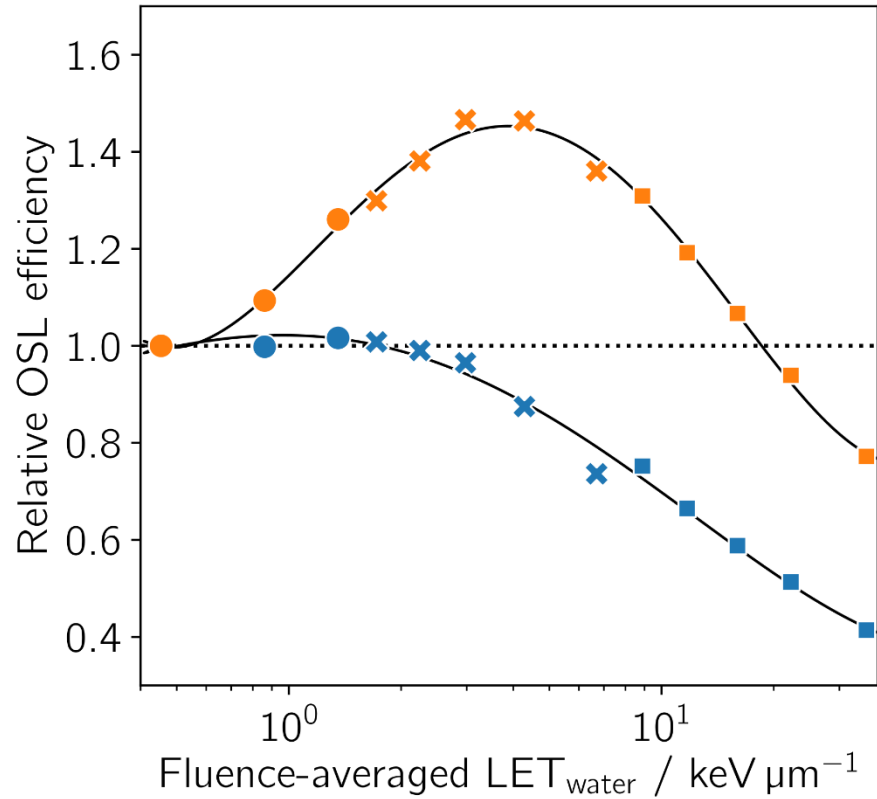
- Optically stimulated luminescence (OSL)
- Thermoluminescence (TL)



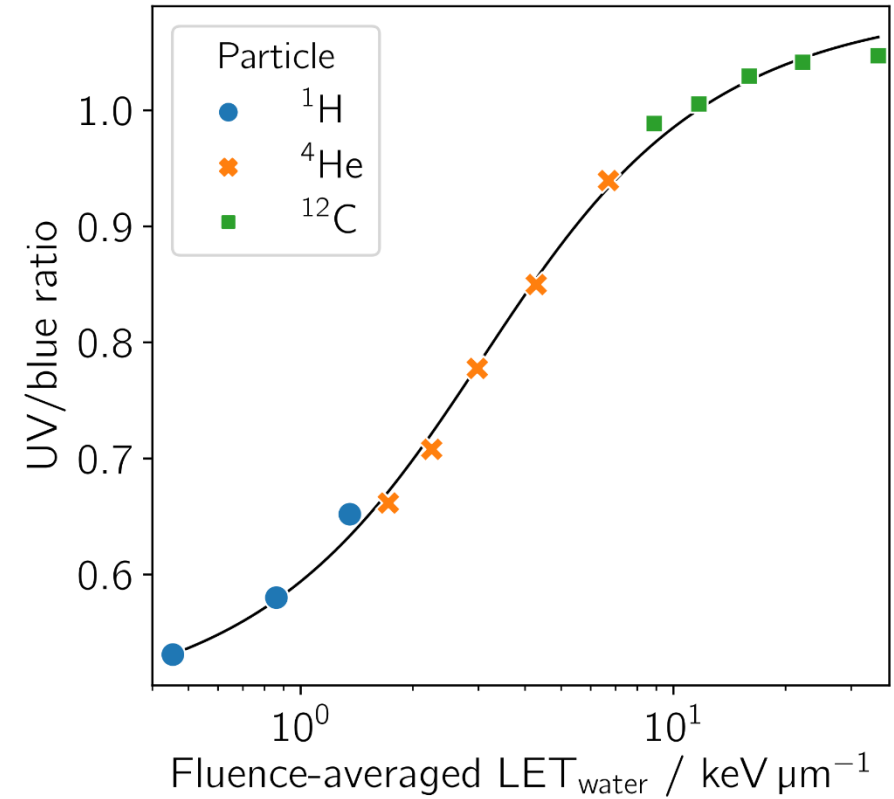
Optically simulated luminescence



LET calibration with OSLDs

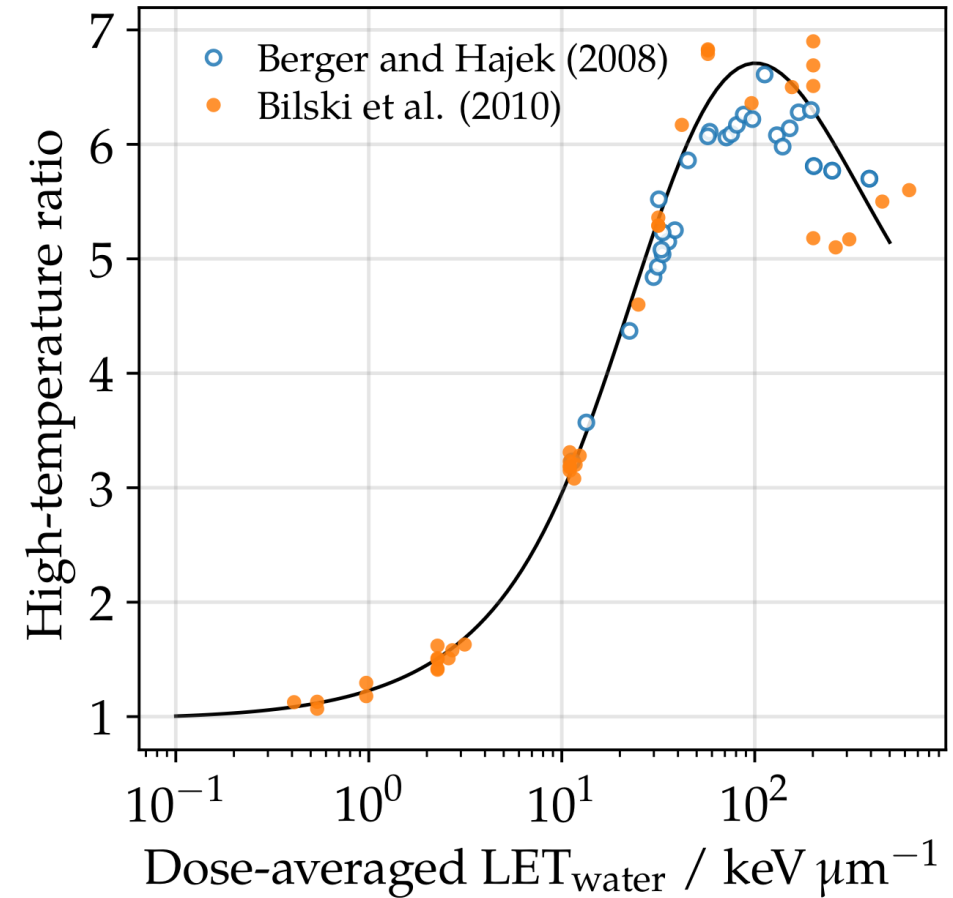
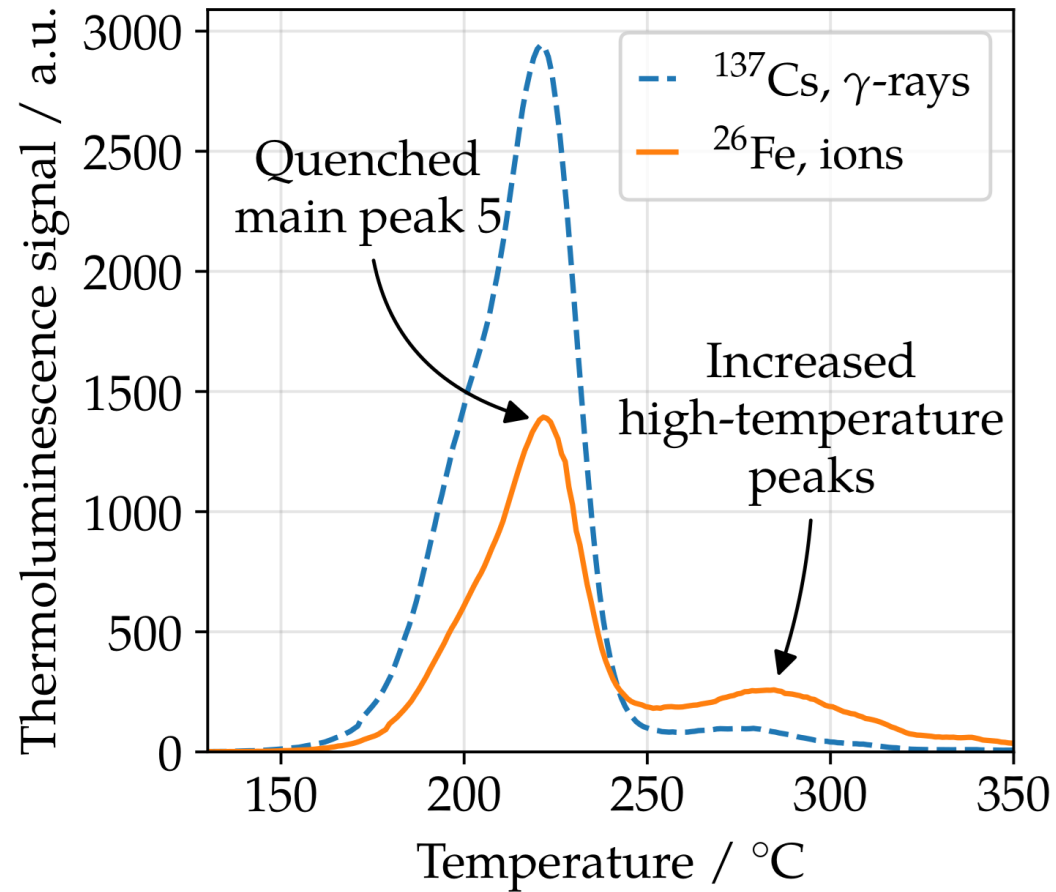


- Emission
- Blue
 - UV
- Particle
- ¹H
 - × ⁴He
 - ¹²C

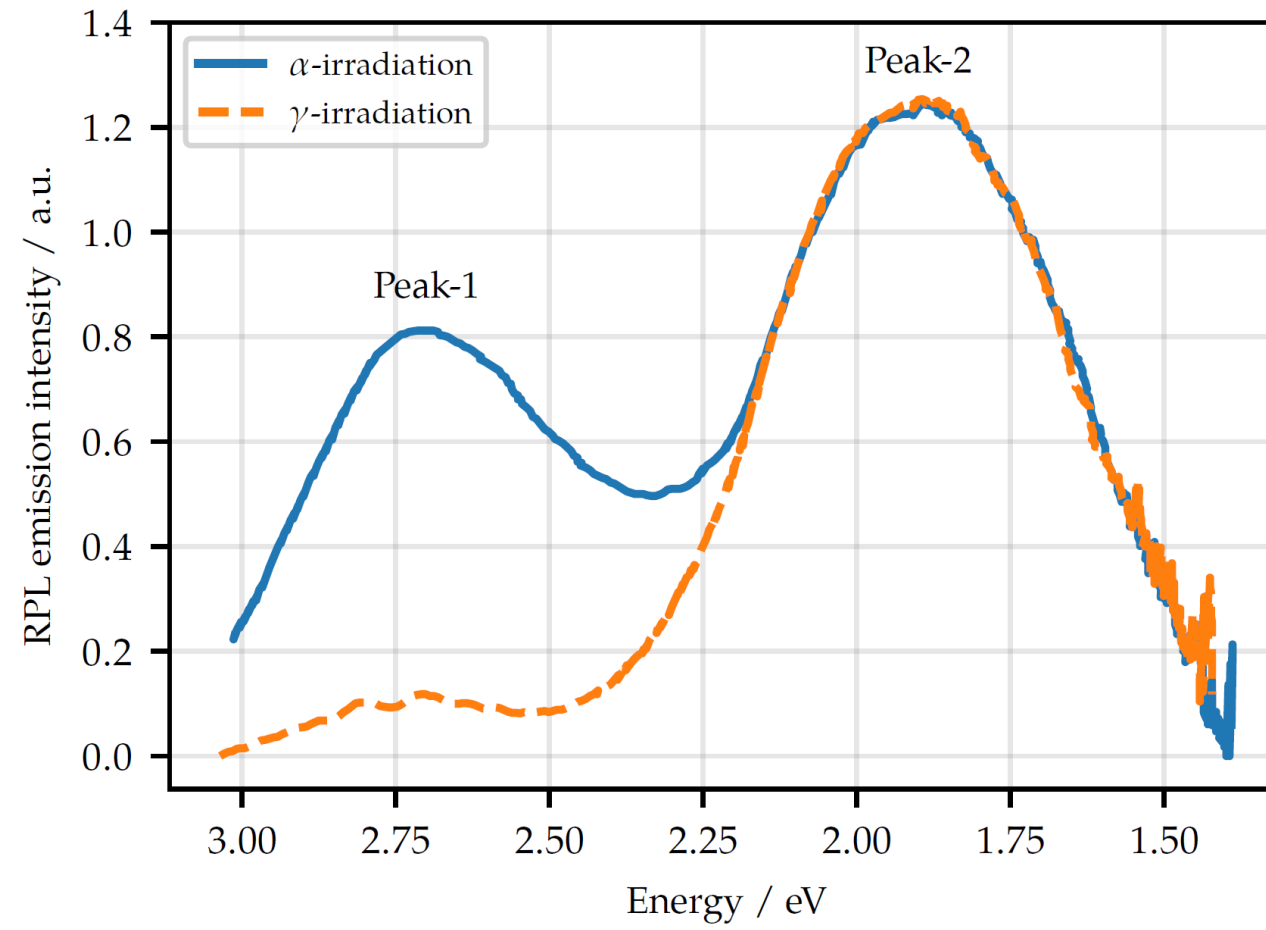


LET determination with thermoluminescent detectors (TLDs)

High-temperature ratio (LiF:Mg,Ti)

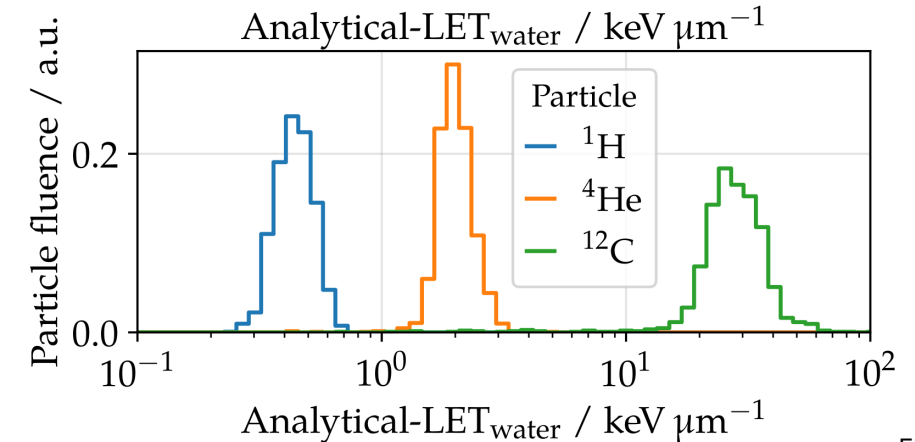
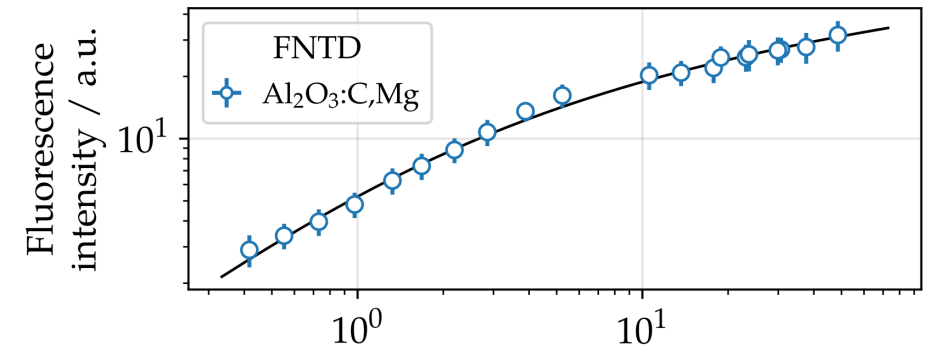
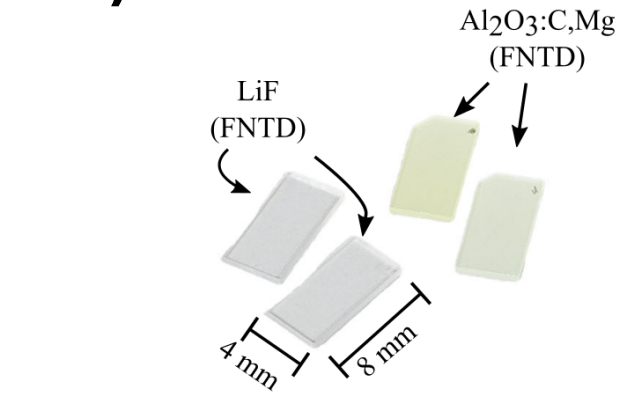
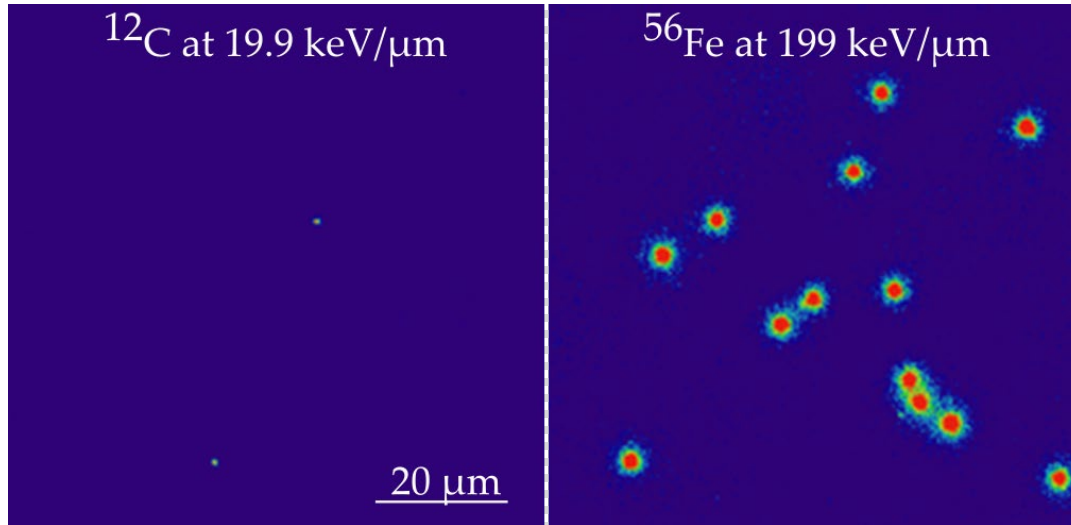


Radio-photoluminescent detectors (RPLDs)



Fluorescent nuclear track detectors (FNTDs)

$\text{Al}_2\text{O}_3:\text{C,Mg}$



- Measures spectra!
- Track overlap at clinical doses (measurements at ≈ 30 mGy)

LET «measurements»

Summary:

Exploit features in the detector response to estimate the LET

Problem:

OSLDs, TLDs, RPLDs, FNTDs are *passive* detectors (time-integrating)

That is, we measure *averaged* LET

What is averaged LET?

Linear energy transfer (LET)

Energy loss dE over distance dx

$$\text{LET} = \frac{dE}{dx}$$

Averaged LET in a volume?

$$\overline{\text{LET}}_w = \sum_i \frac{w_i \cdot \text{LET}_i}{w_i}$$

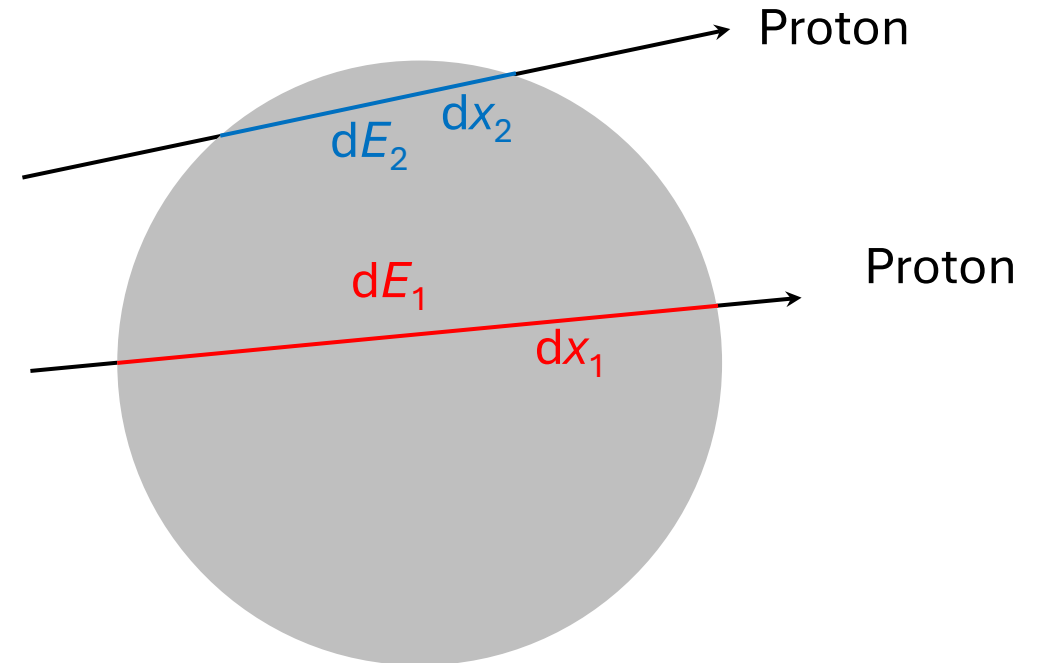
Fluence-averaged LET ($\overline{\text{LET}}_f$):

$$w_i \propto dx_i$$

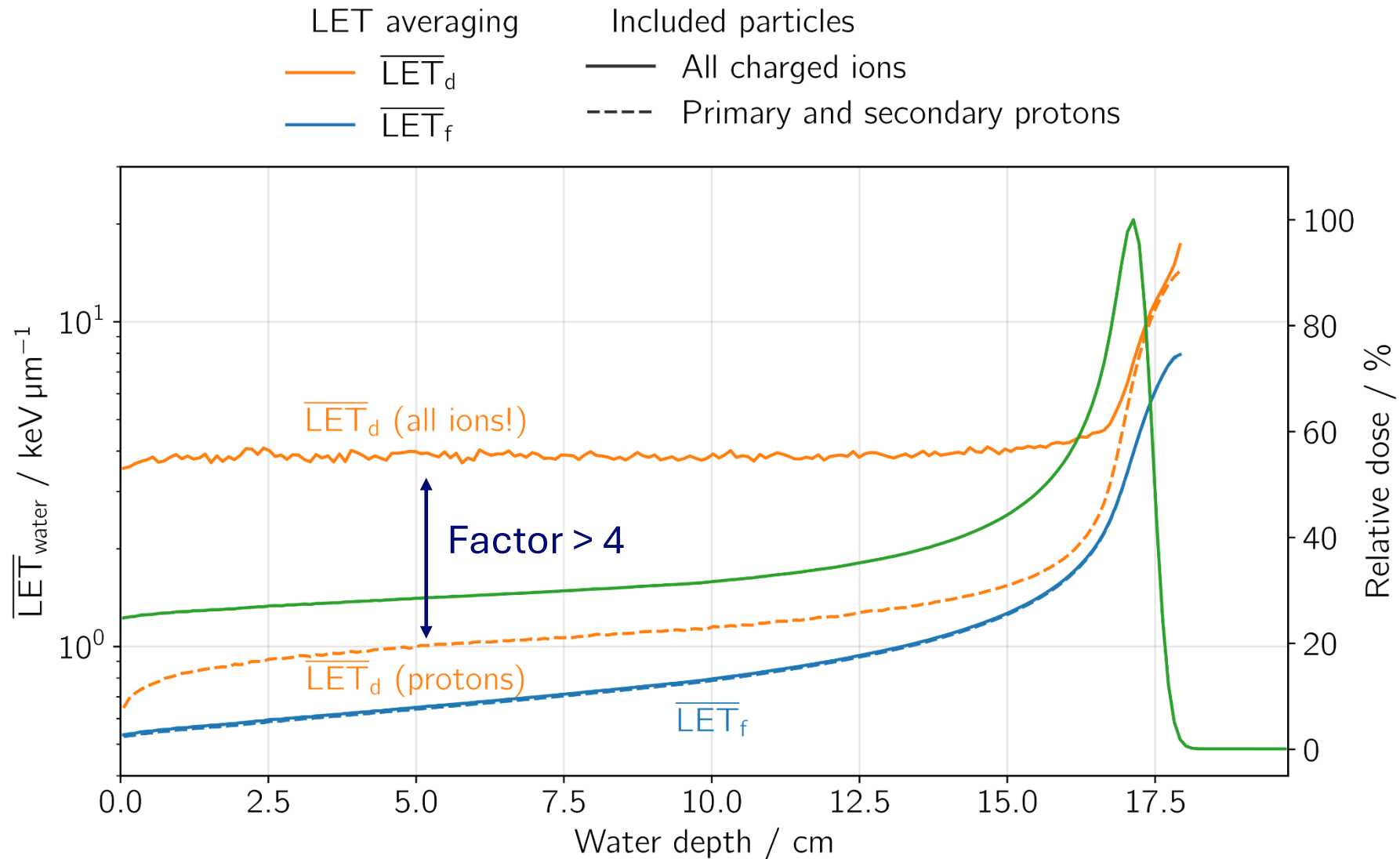
Dose-averaged LET ($\overline{\text{LET}}_d$):

$$w_i \propto dE_i$$

What is the average LET?



Common types of LET averages in 160 MeV protons



LET averaging: Good practice faces reality

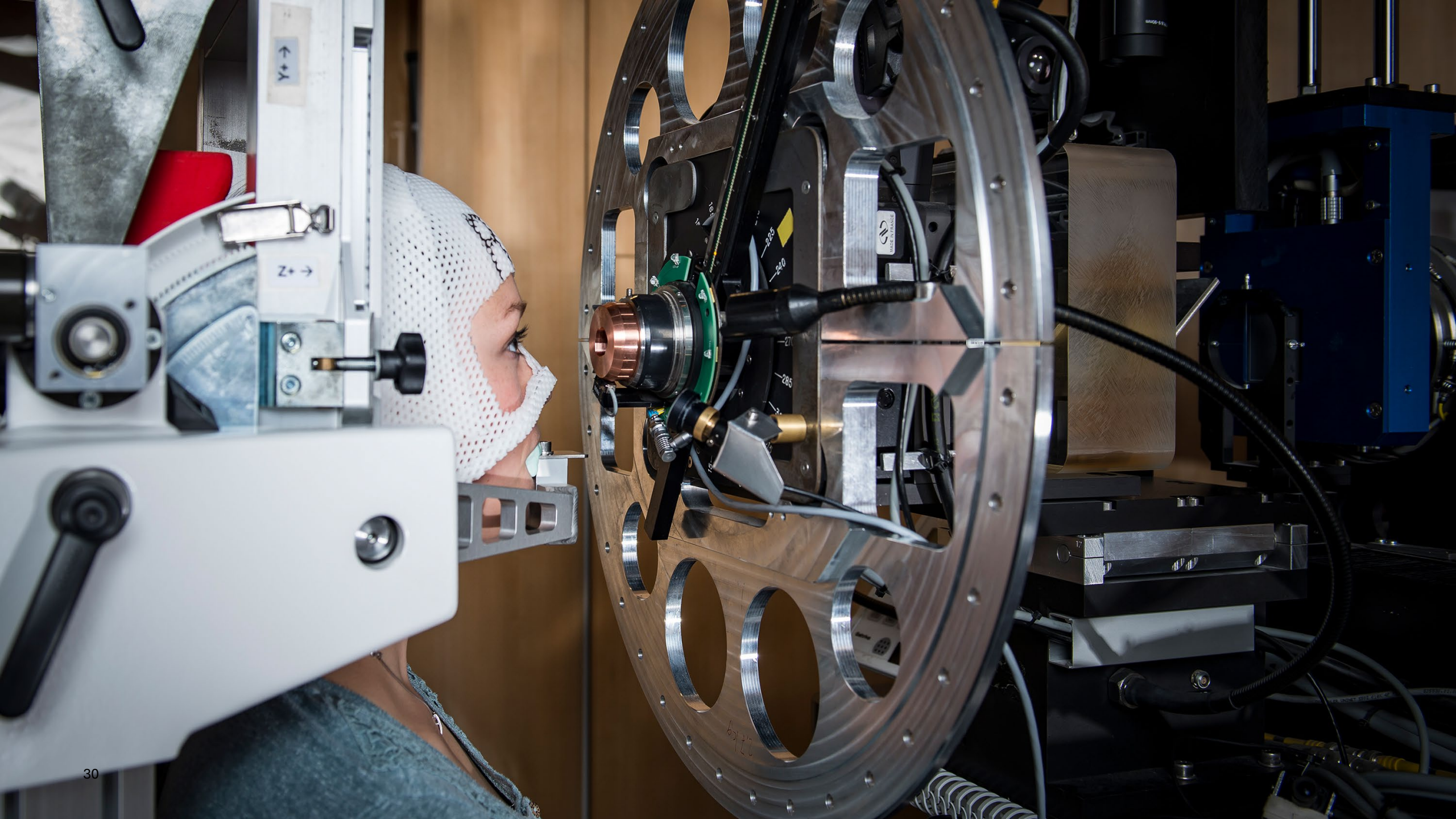


Proton publications



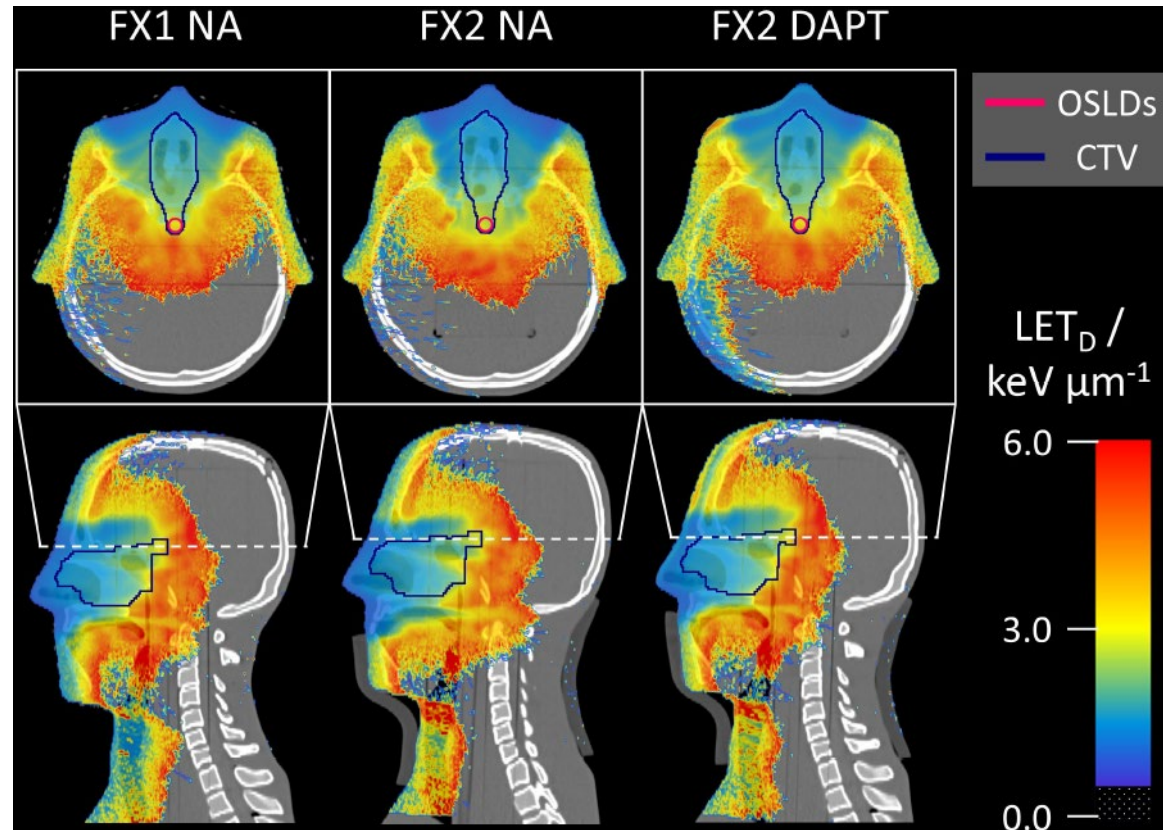
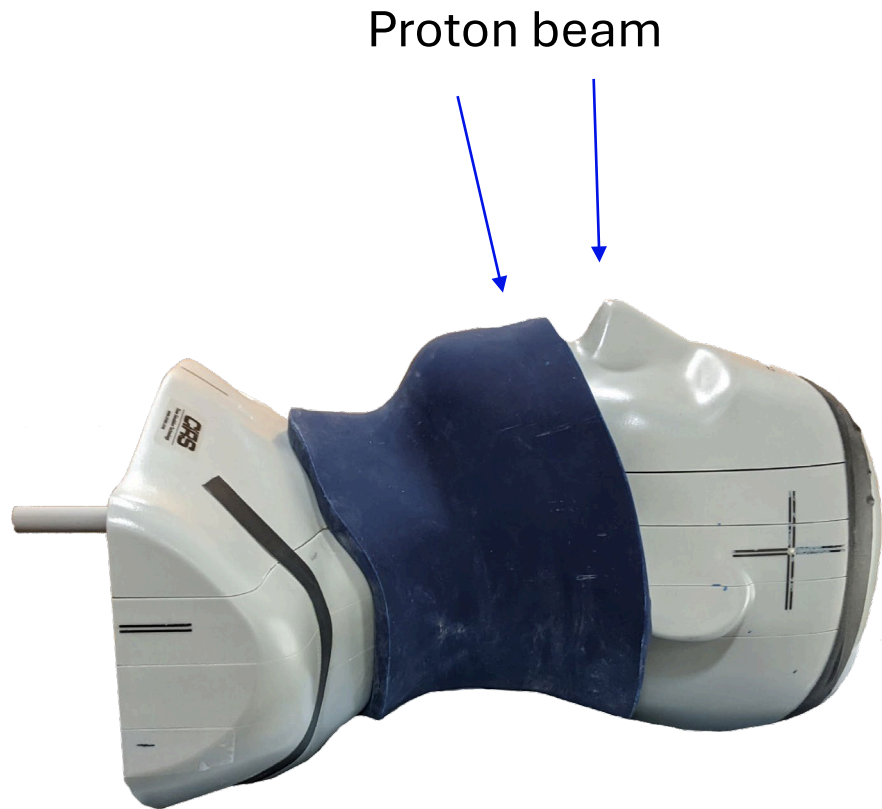
Take home:

- Different LET types can vary a factor > 4 for the same radiation field
- Majority of publications do not state how the LET is calculated!

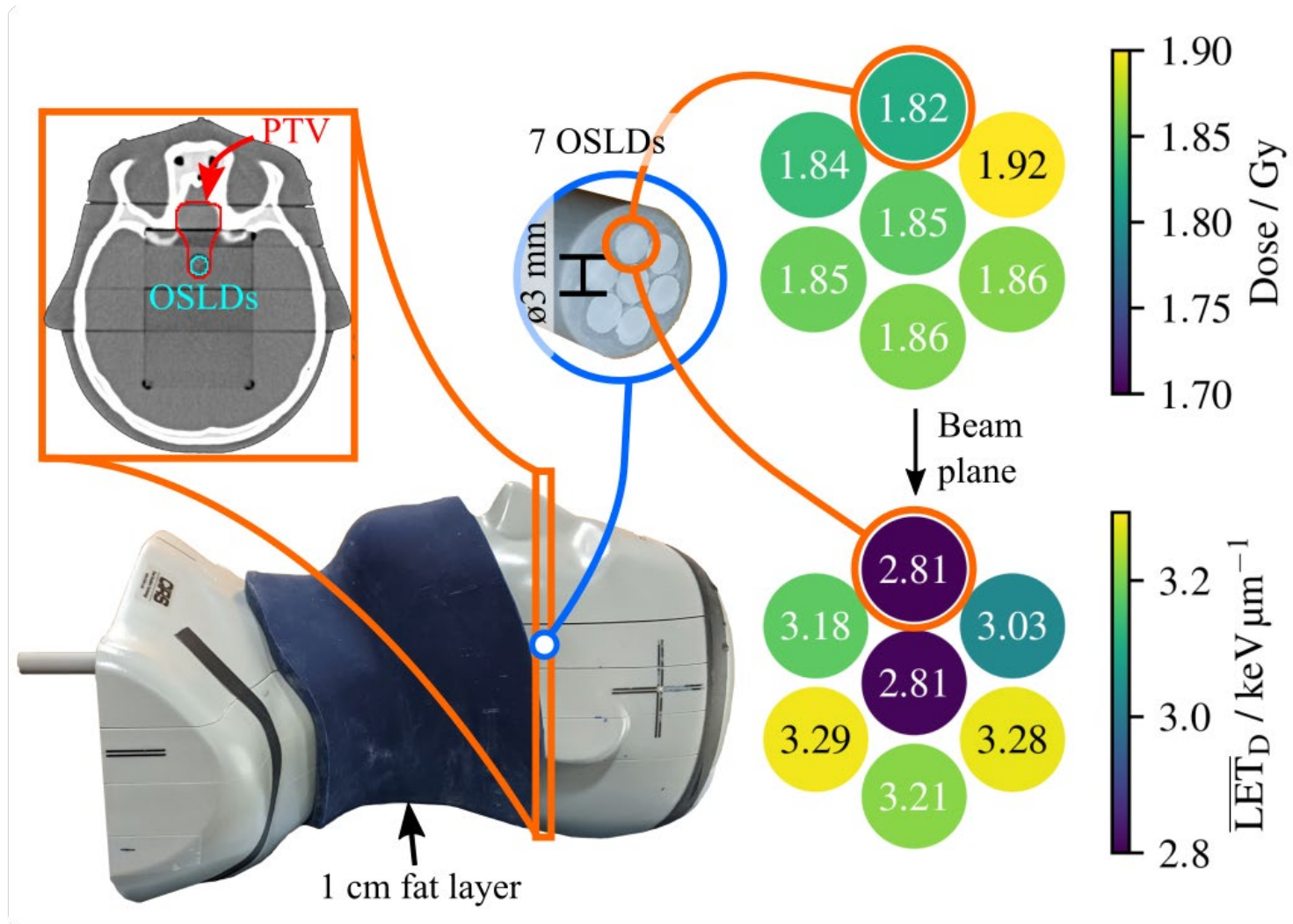


Hadron dosimetry

Simulated LET distribution



Mapping LET and dose in proton therapy



Dosimetry recipe

1. Blue intensity \rightarrow quenched dose
2. UV/blue ratio $\rightarrow \overline{LET}_D$
3. $\overline{LET}_D \rightarrow$ quenching correction

M Bobić, et al. "Optically stimulated luminescence dosimeters for simultaneous measurement of point dose and dose-weighted LET in an adaptive proton therapy workflow." *Frontiers in Oncology* 13 (2024): 1333039.

Ion beam dosimetry

We can do proton dosimetry and LET assessment.

What about heavier ions? (= higher LET, more non-linear detector response)

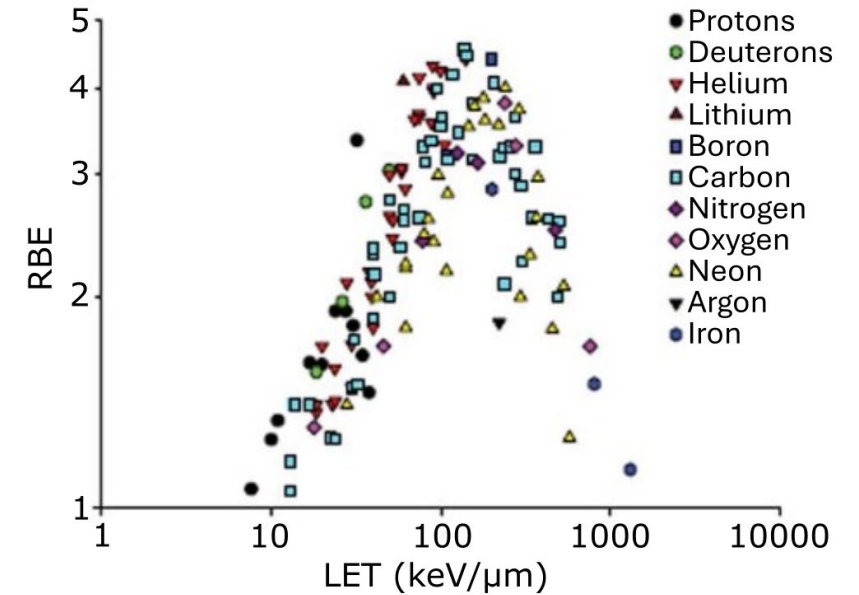
Relative biological effectiveness (RBE)

- $RBE = \frac{D_{\text{photons}}}{D_{\text{particle}}} \simeq 1.1$ (protons)

- **Problem:** There is no RBE detector

- **Model:** $RBE_{\text{He}} \simeq -\frac{1}{2D} \left(\frac{\alpha}{\beta}\right)_X + \frac{1}{D} \sqrt{\frac{1}{4} \left(\frac{\alpha}{\beta}\right)_X^2 + \frac{\alpha_{\text{ion}}}{\alpha_X} \left(\frac{\alpha}{\beta}\right)_X D + \frac{\beta_{\text{ion}}}{\beta_X} D^2}$

← LET
← LET

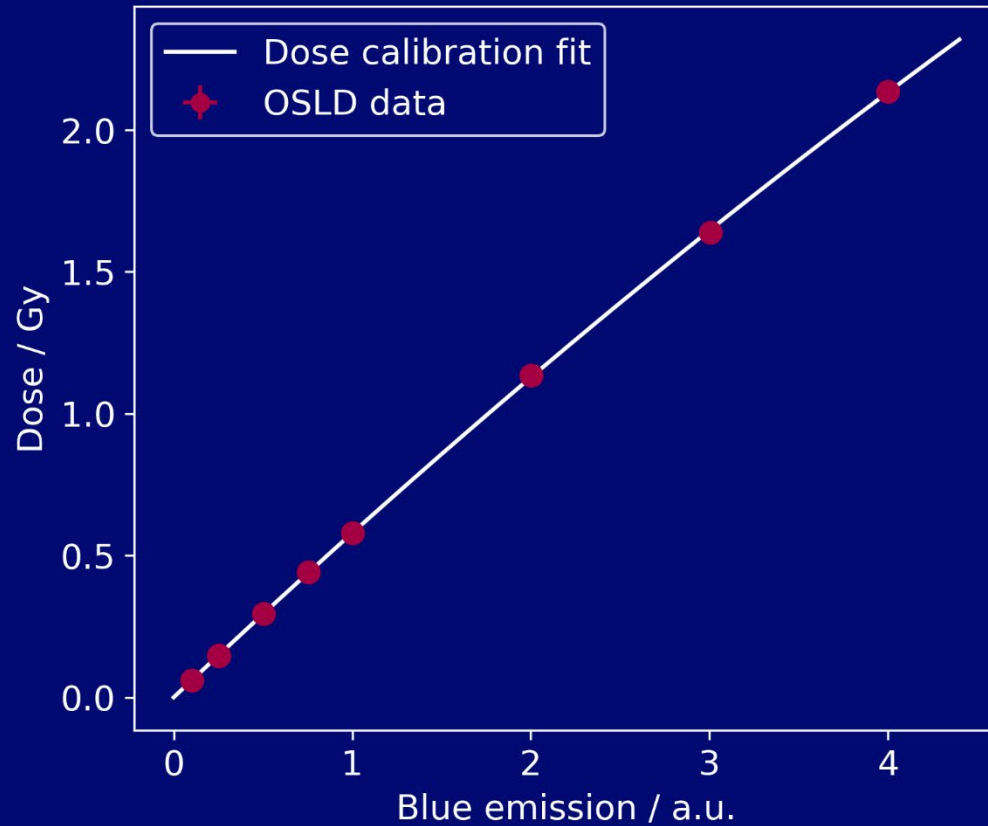


Sørensen et al (2011) Acta Oncol 60 6

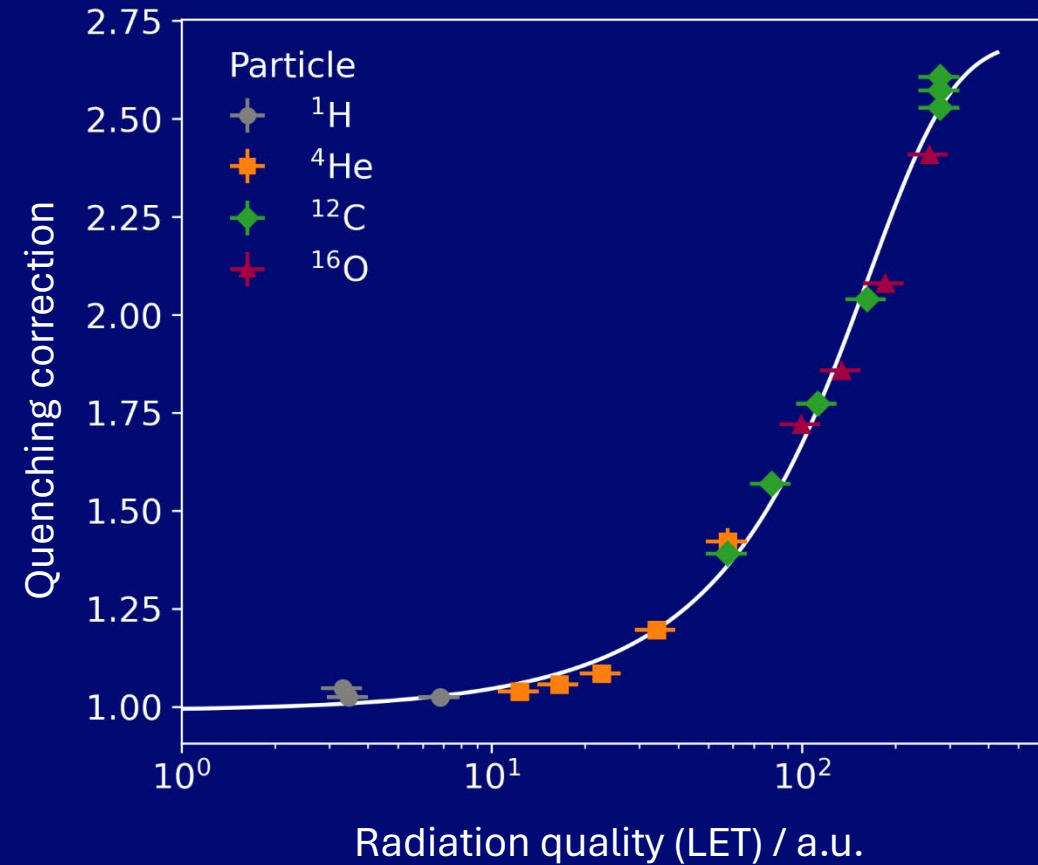
Question: Can we assess a variable RBE with OSLDs?

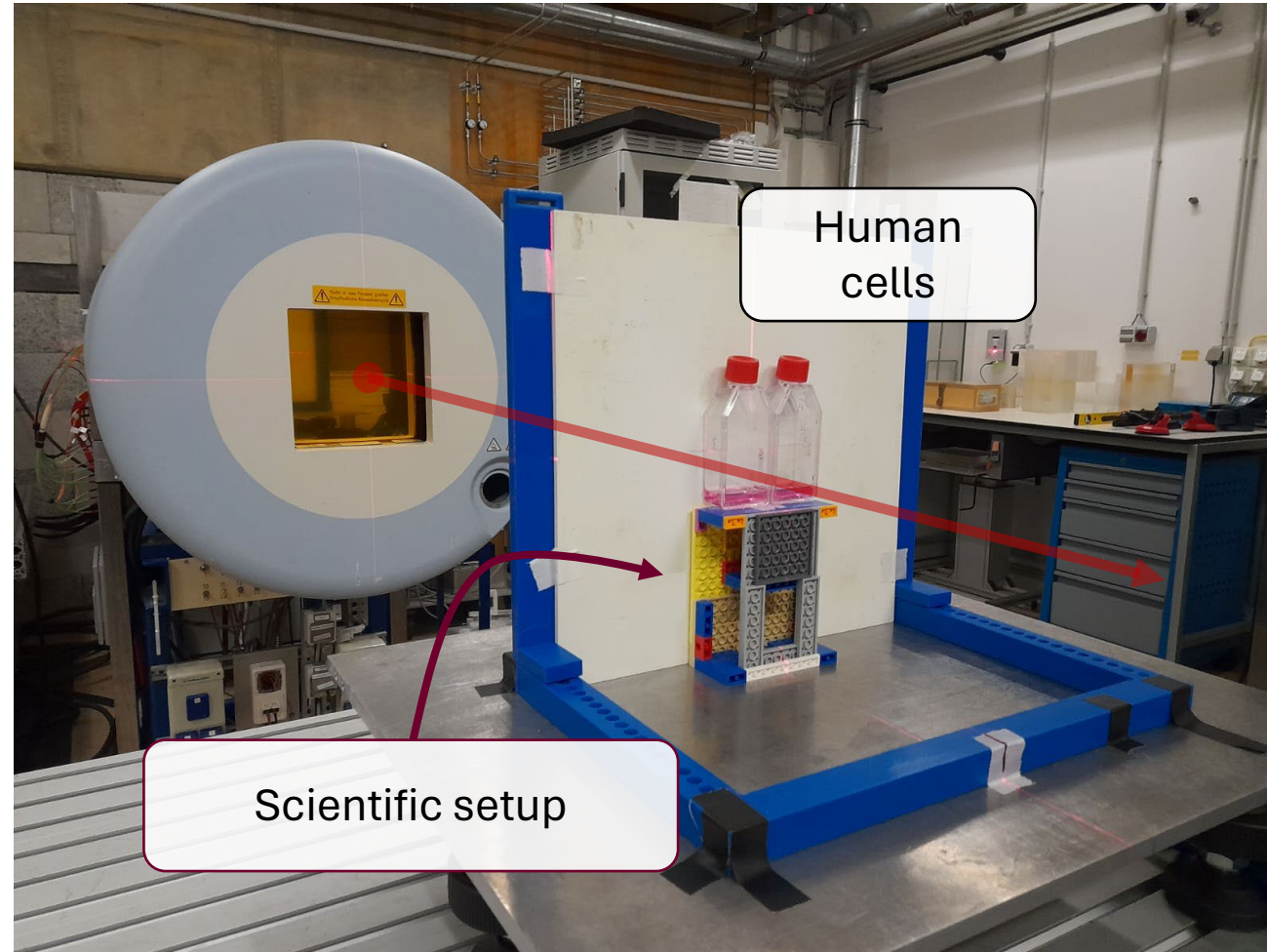
Reminder: Ion beam dosimetry

OSL dose calibration

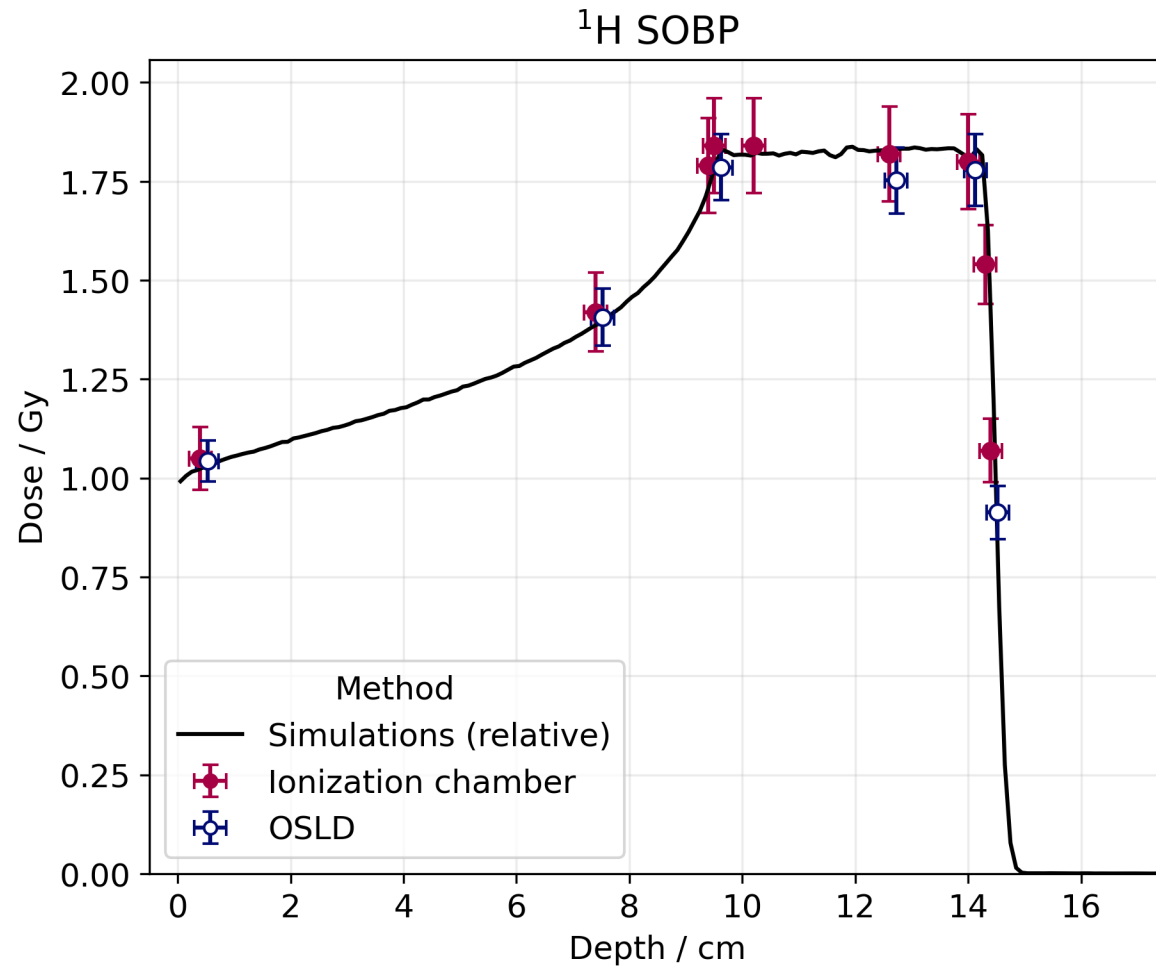


Quenching corrections for helium are large!

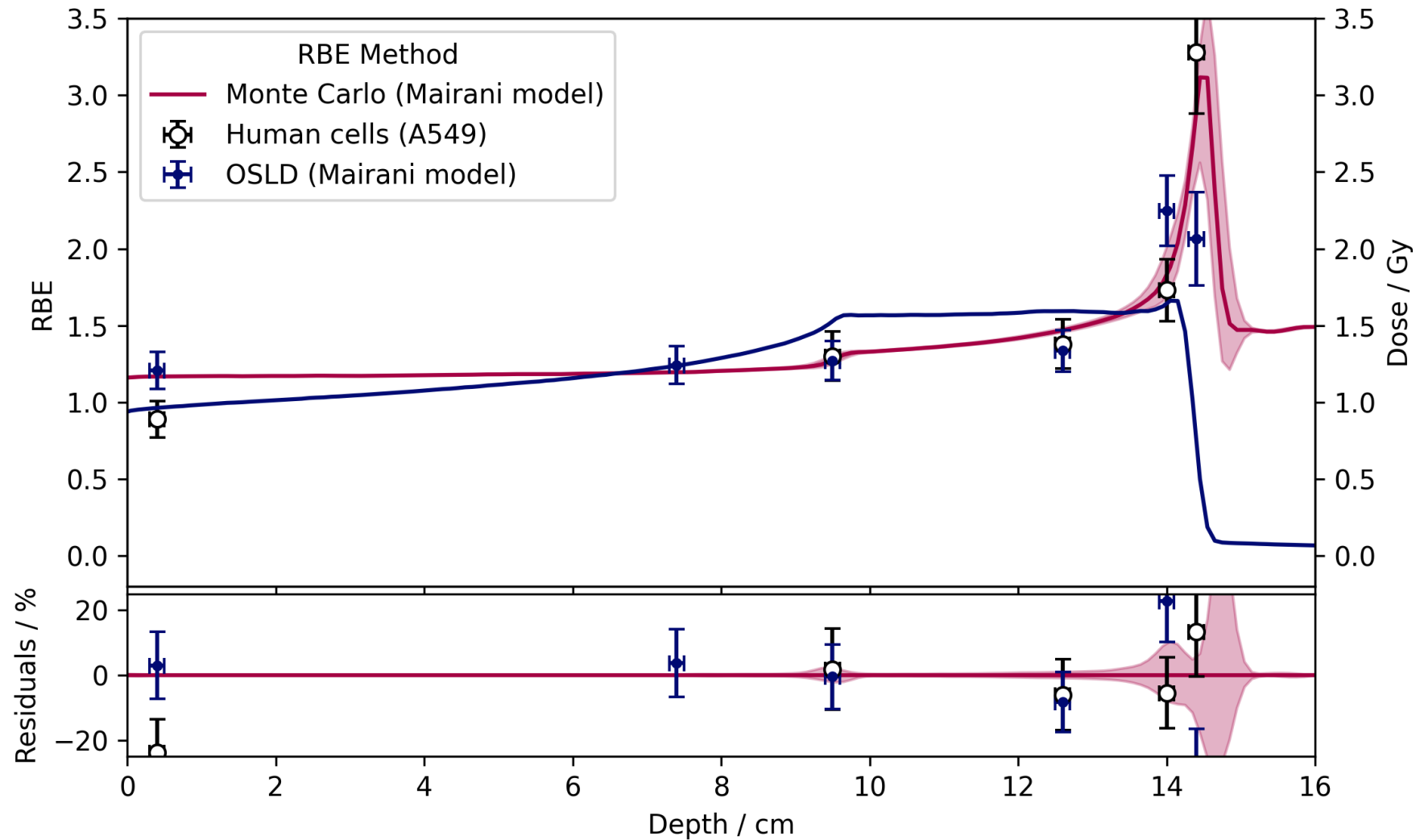




Spread-out Bragg peak (SOBP)



Helium ion spread-out Bragg peak





Al₂O₃:C OSL detectors

- 38 μm grains mixed with a binder
- OSL film < 100 μm
- Cut with a scissor, punch plier, ...

Conclusions

Cut a single detector and measure

- Absorbed dose
- Linear energy transfer (LET)
- Relative biological effectiveness (RBE)

Spatially resolved measurements



Until this point:

Single point measurements with a single detector

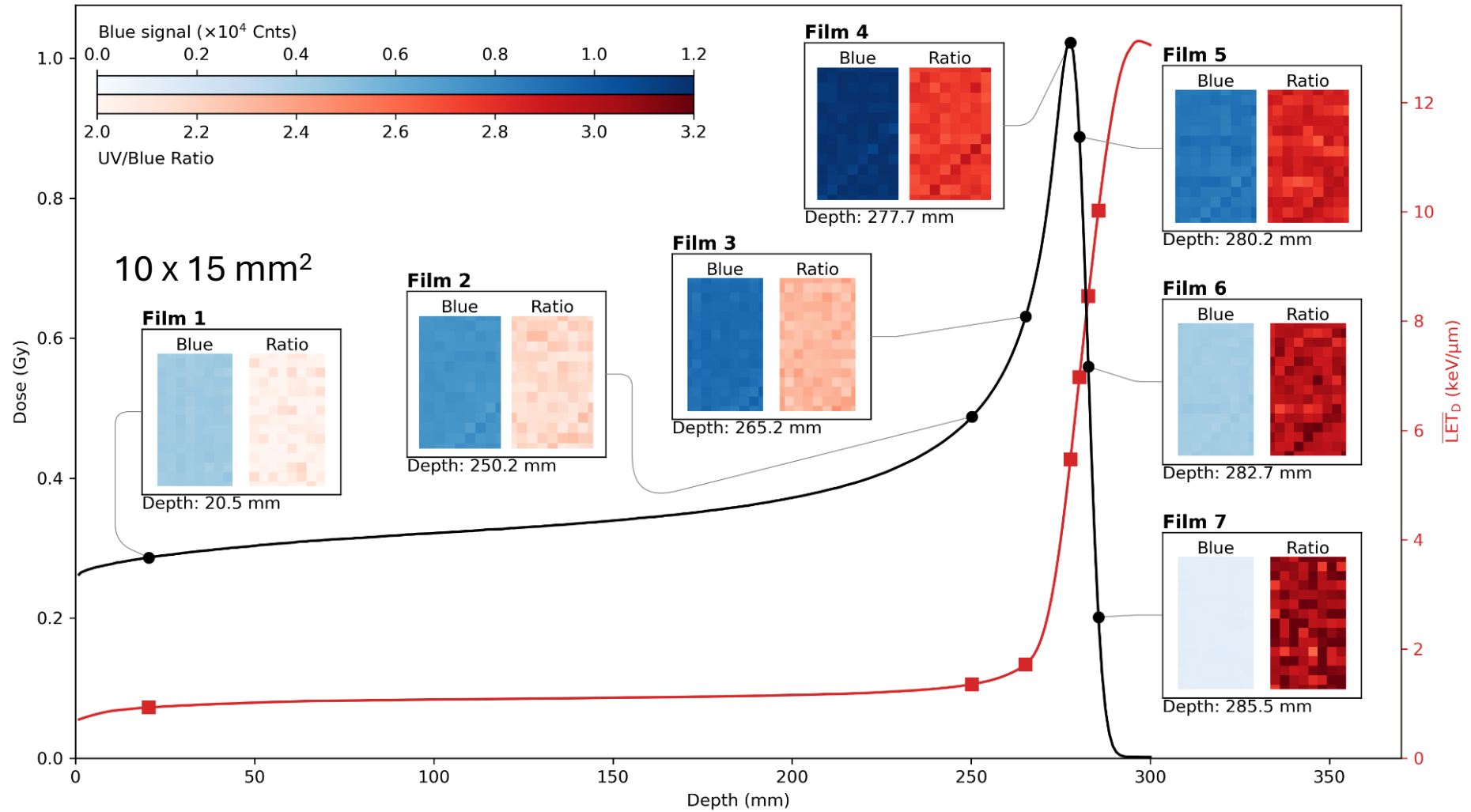
Problem:

Treatment fields are complex, we want to spatially resolve the dose!

Spatially resolved OSL dosimetry + LET



Spatially resolved OSL dosimetry + LET



Hadron dosimetry summary

- Dose and LET are needed to model radiobiological response
 - We can *measure* dose and LET with luminescent detectors
- Luminescent detectors can be placed within anthropomorphic phantoms for quality assurance/research projects
- Point-measurements or 2D measurements

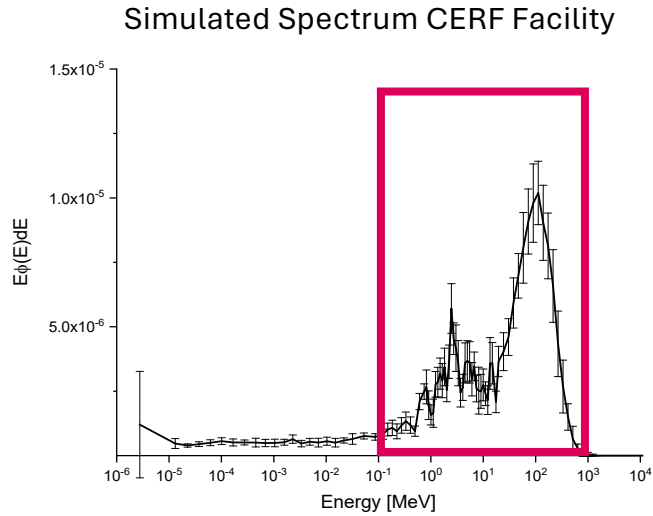
MSc projects in ion beam dosimetry?

Neutron dosimetry

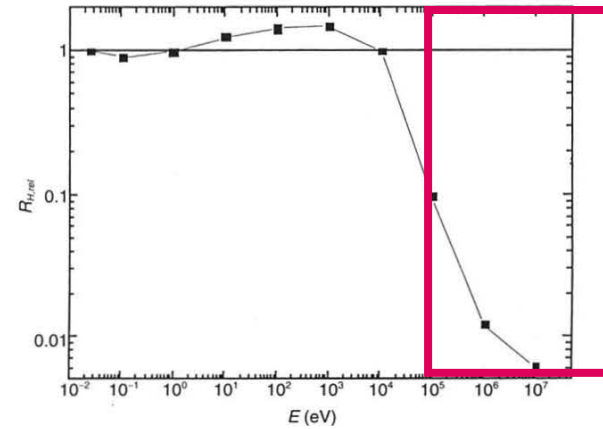
Measurements at

- CERN (CLEAR)
- ~~KK Beznau~~

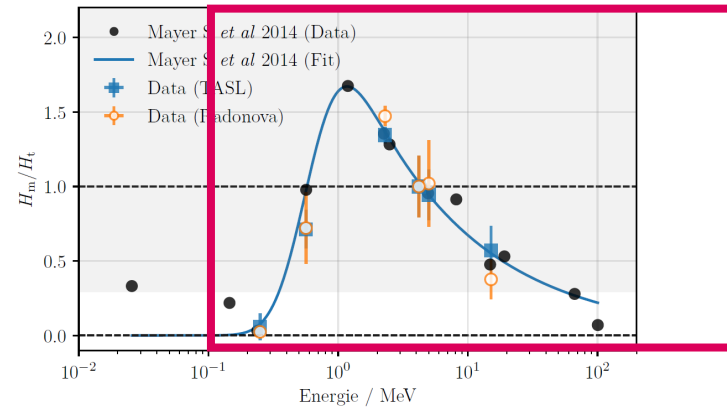
The challenge of neutron dosimetry



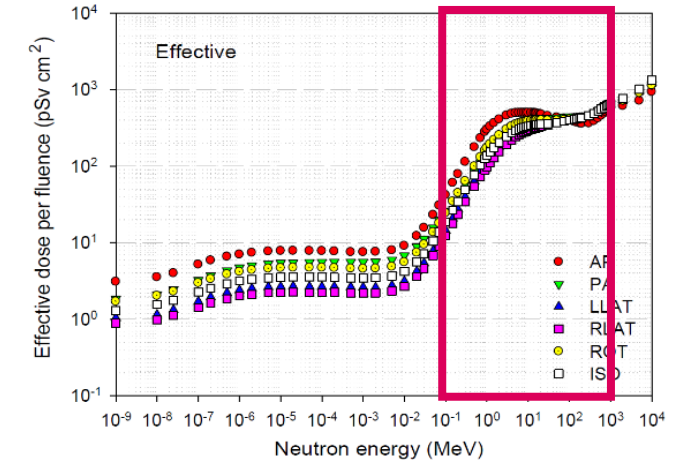
Energy response of albedo detectors



Energy response of PADC detectors



ICRU Report 57



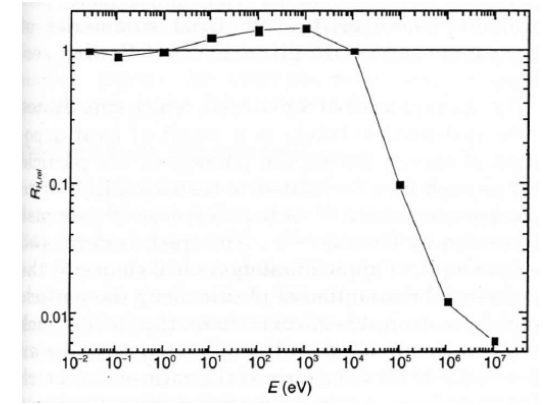
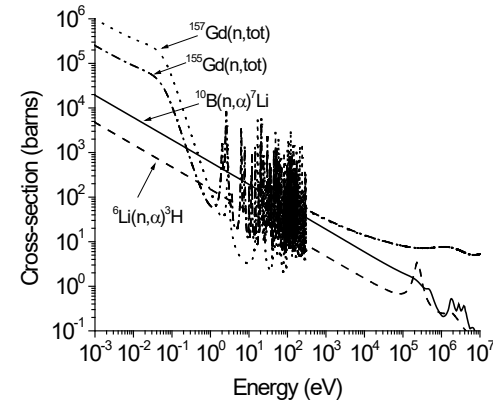
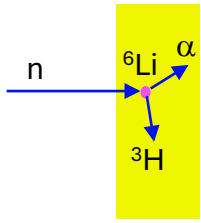
- Very **broad spectrum**
- Changes in spectrum due to **backscattering**

- **Fluence to dose conversion factors strongly variable** with neutron energy

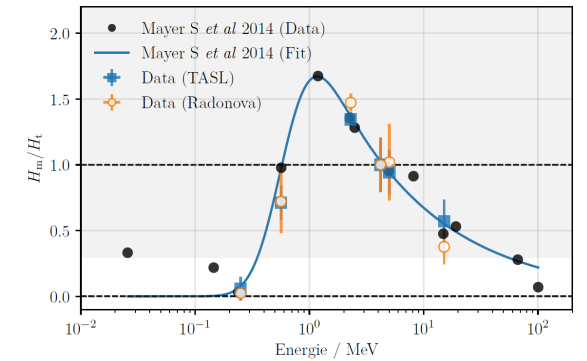
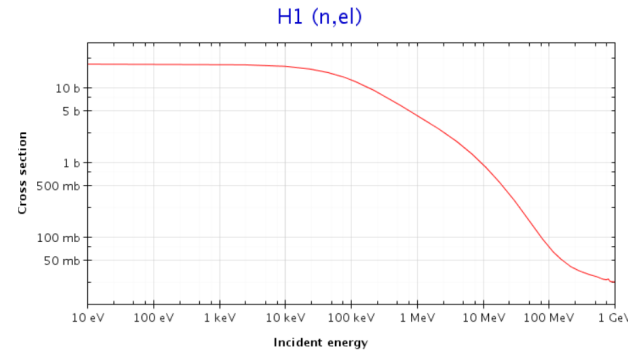
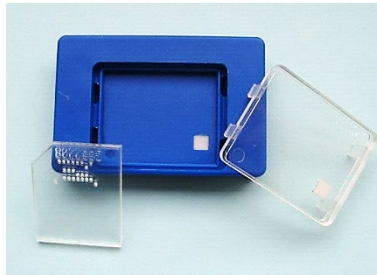
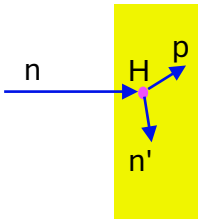
- Strong **energy dependence** of neutron interaction process and detector response

Detection principles

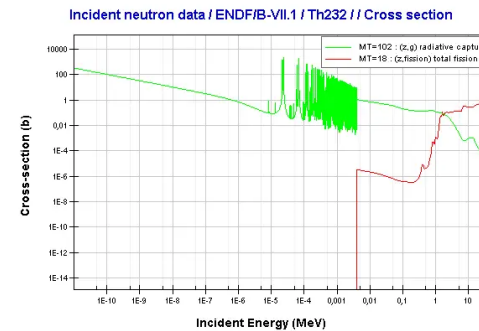
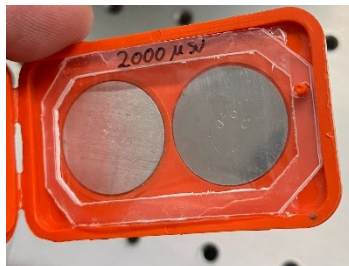
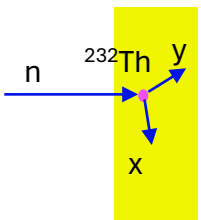
absorption



scattering



fission



Neutron dosimetry



With PADC / CR39 detectors

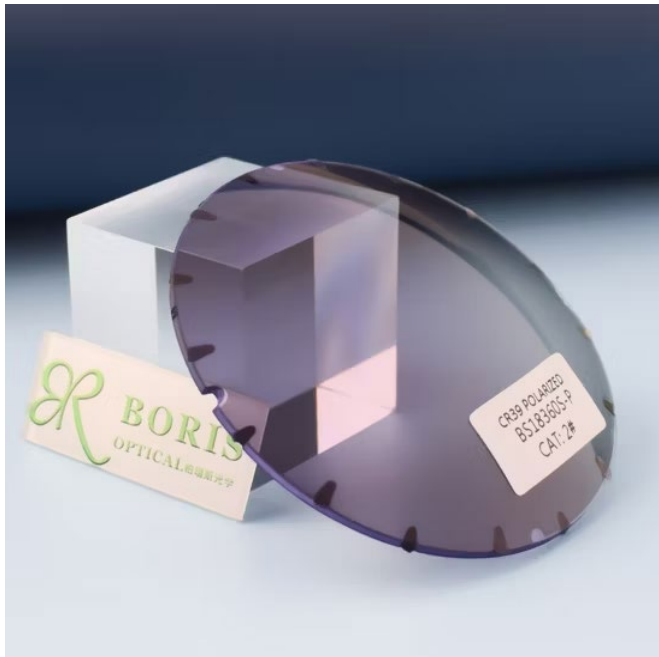
How can we measure neutrons?

Main challenge:

Neutrons are charge neutral!

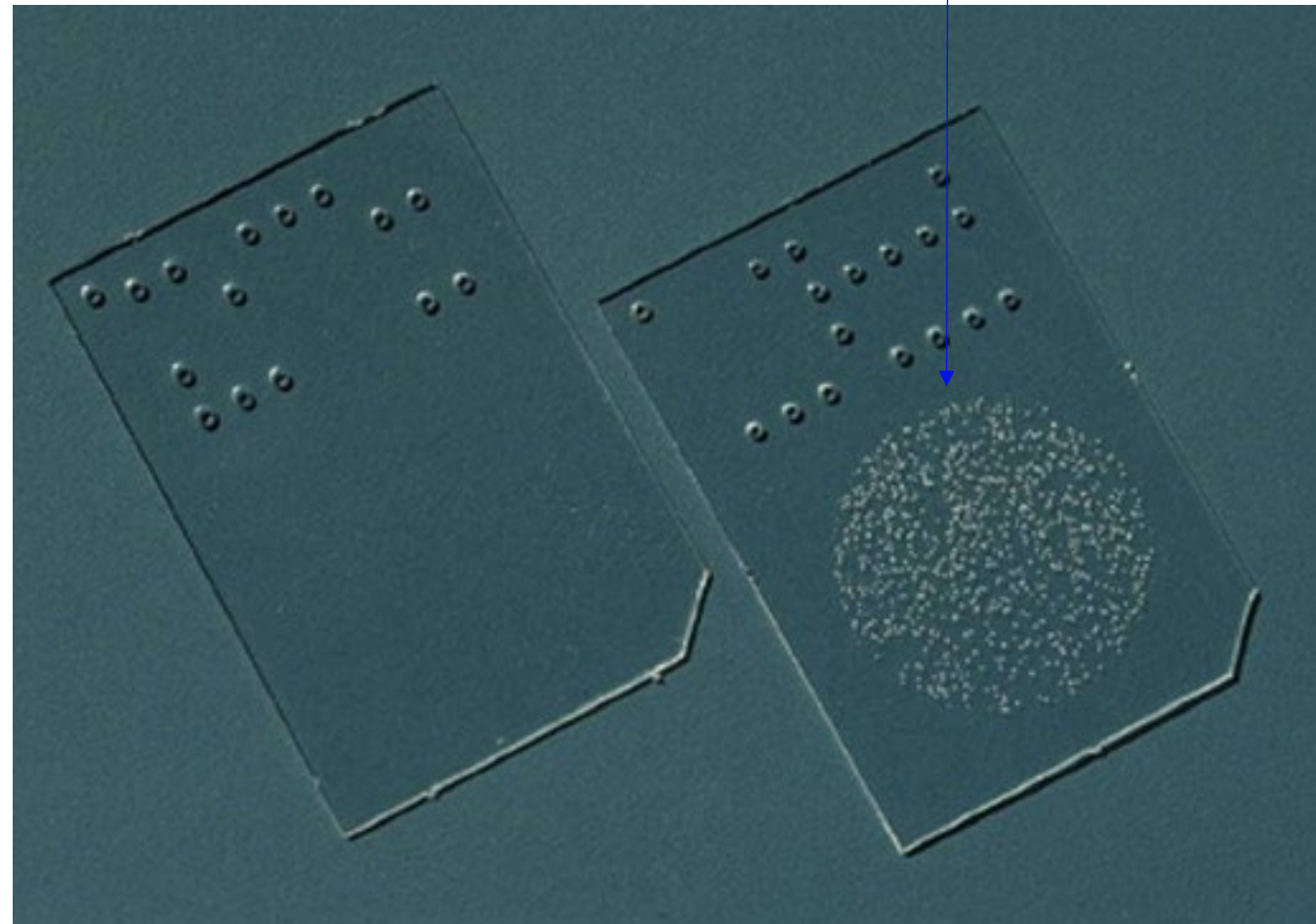
(proton measurements are much easier)

CR39 eye lens



CR39 as particle detectors

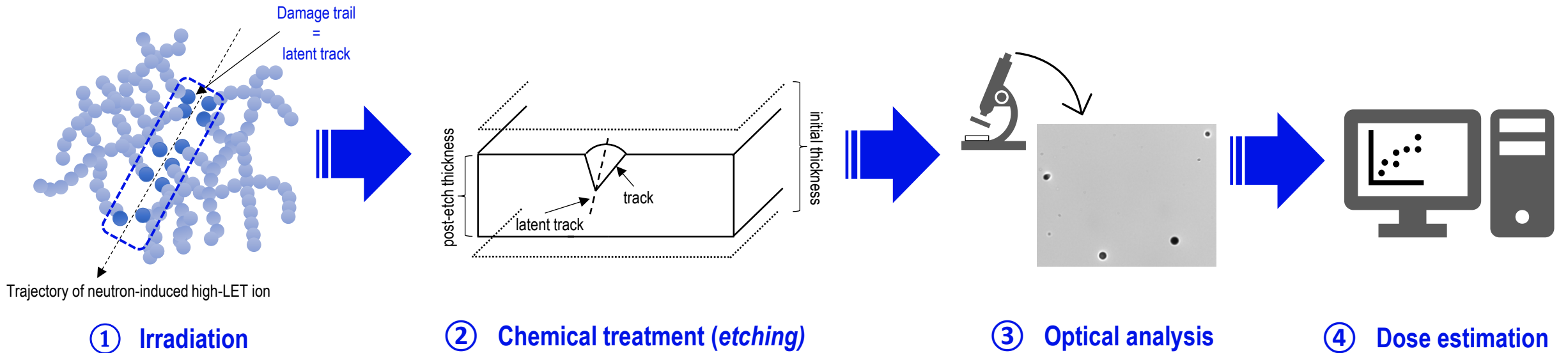
Neutron tracks



PADC dosimetry – Working principle

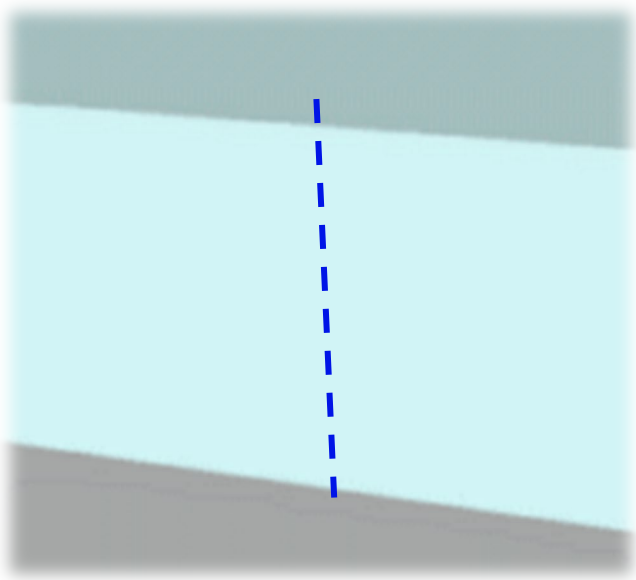
The use of PADC as a radiation detector (more specifically, a solid-state nuclear track detector (SSNTD)) dates back to the studies of B. G. Cartwright, E. K. Shirk and P. B. Price at the end of the 1970's.

Working principle of neutron dosimetry with PADC:

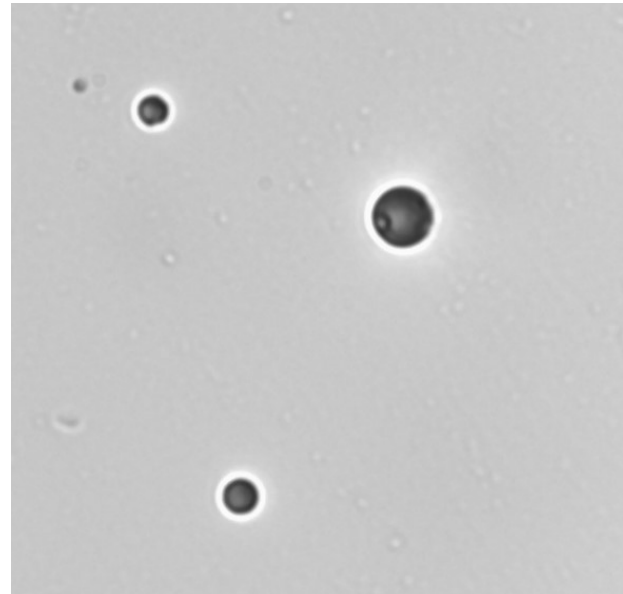


PADC dosimetry – The signal

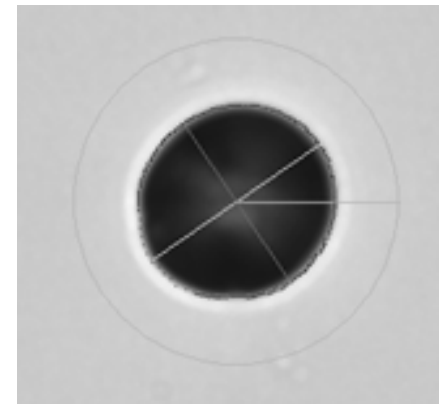
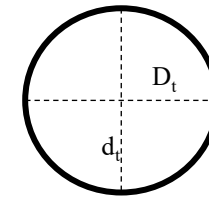
Track growth



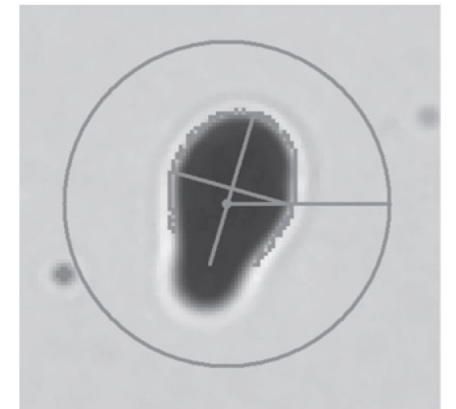
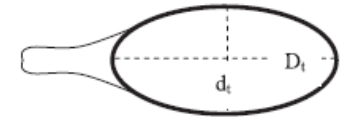
Top view



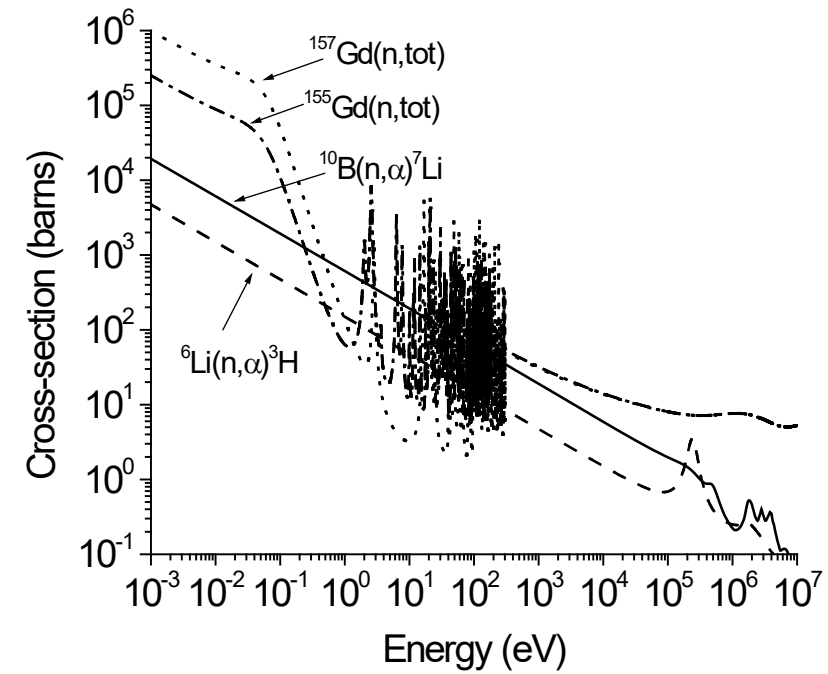
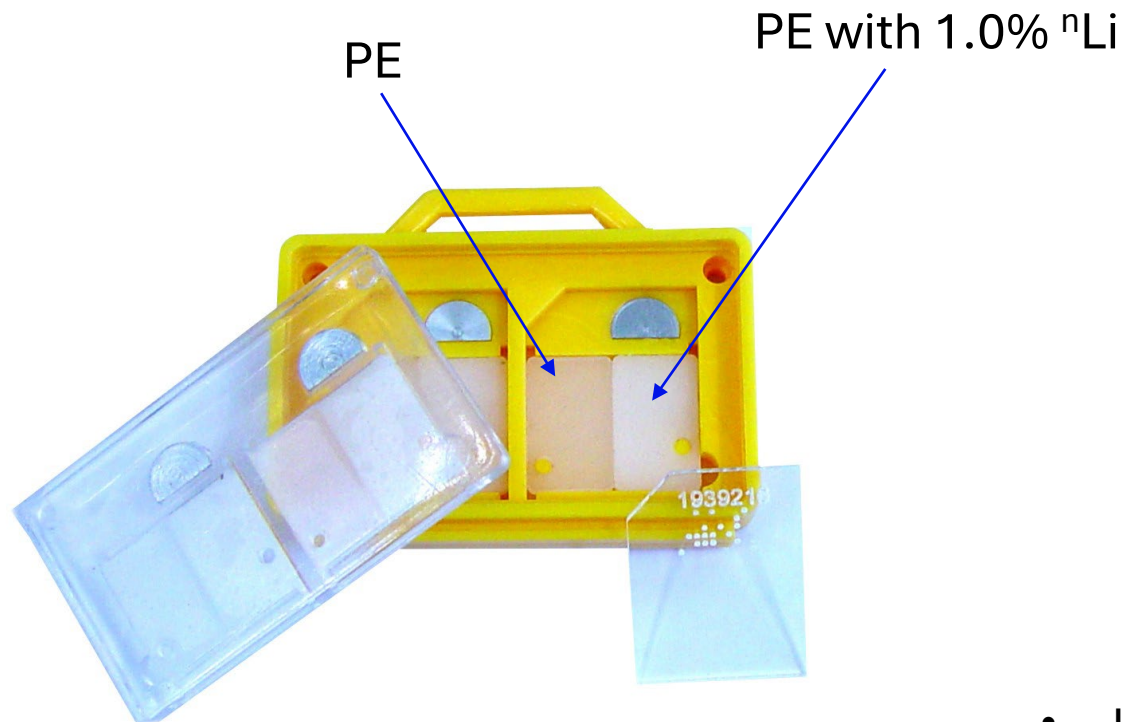
Circular track



Elliptical track



Fast and slow neutron dosimetry using PADC



- Increased response to **low-energy neutrons**
- Requires **algorithm combining the two signals**
- Larger **variability with backscattering**
- **Reduced readout area** for each converter

Develop new track counting algorithms in CR39 detectors

- Linear algebra
- Semi-supervised machine learning

Motivation:

Commercial systems are black-box*

*and expensive, but not always good.

SIMPSONS GUIDE TO RADIATION



Bequerel [Bq]
How brightly your
Cesium glows

Deterministic effects



Gray [Gy]
How brightly
Cesium will make
you glow

Stochastic effects



Sieverts [Sv]
How many extra
eyes will you have
after glowing?

O sur la dosimétrie

814.501.43

Annexe 5
(art. 18 et 21, al. 3)

Exigences concernant un dosimètre individuel pour le rayonnement neutronique

- Grandeur de mesure
 $H_p(10)$
- Dose la plus faible qui doit être mesurable
 $H_0 = 0,5 \text{ mSv}$
- Domaine de mesure
 H_0 jusqu'à 5 Sv
- Linéarité
Ecart < 30 % entre 1 mSv et 5 Sv
- Dépendance énergétique
$$0,3 \leq \frac{H_m}{H_t} \leq 3,0$$

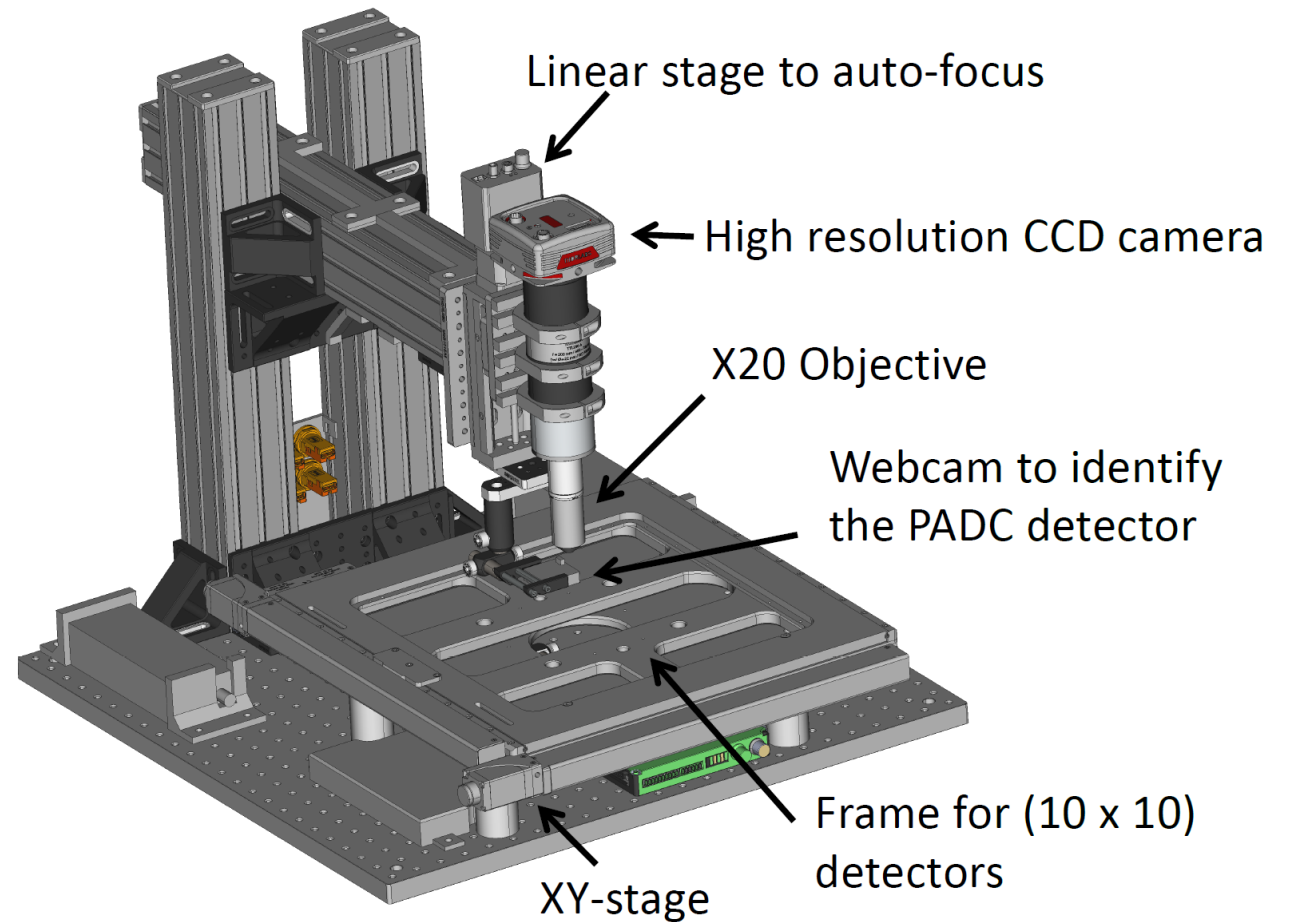
pour les spectres de radiation dans lesquels le dosimètre est utilisé.

- Reproductibilité
Ecart standard $s \leq 50 \%$
- Fading
Effet < 30 %/mois

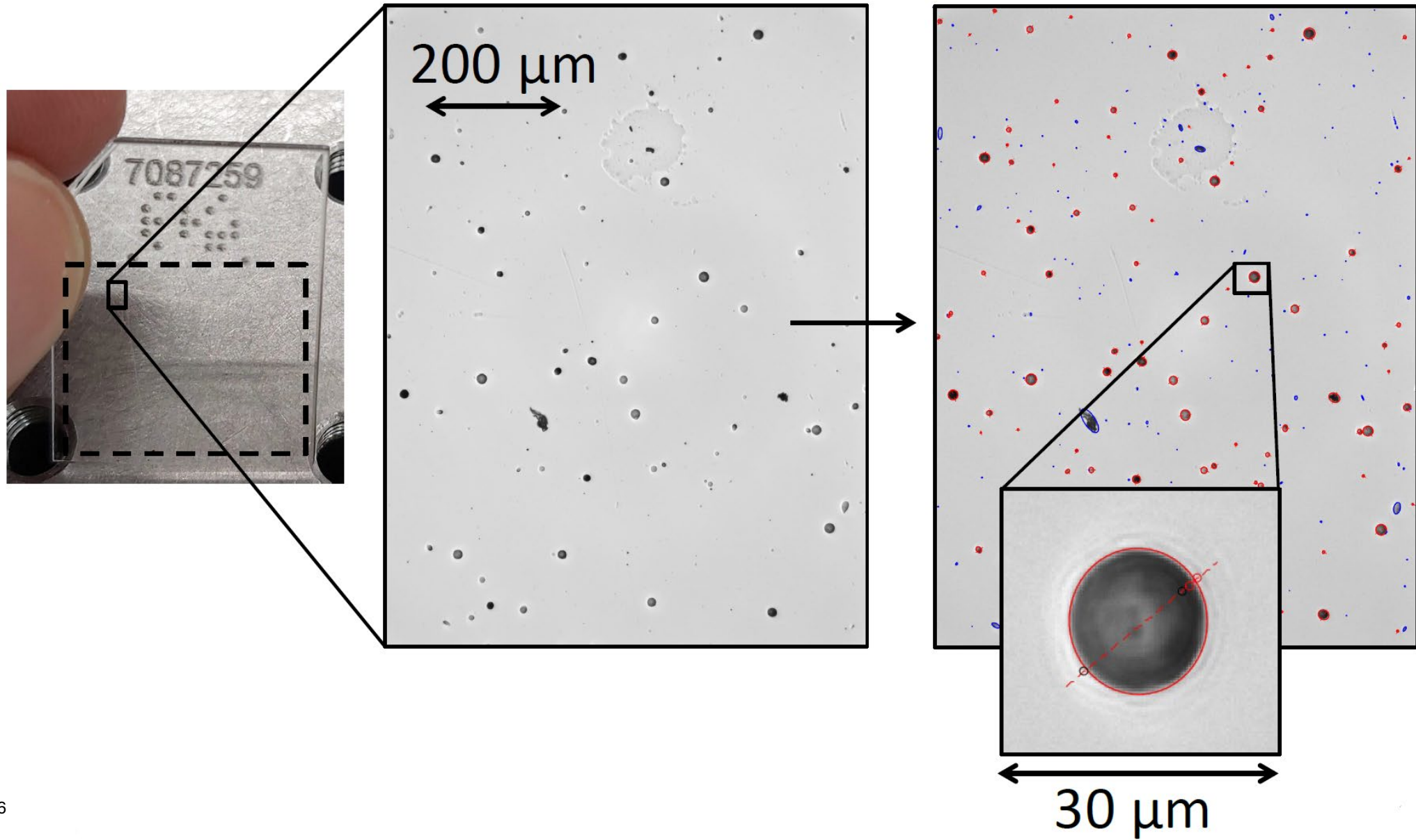
Neutron reader for dosimetry (NERD)

Reference data

- 100's of CR39 detectors irradiated with known doses
- Irradiated at accredited labs (CH/DE)
- 300 images / detector

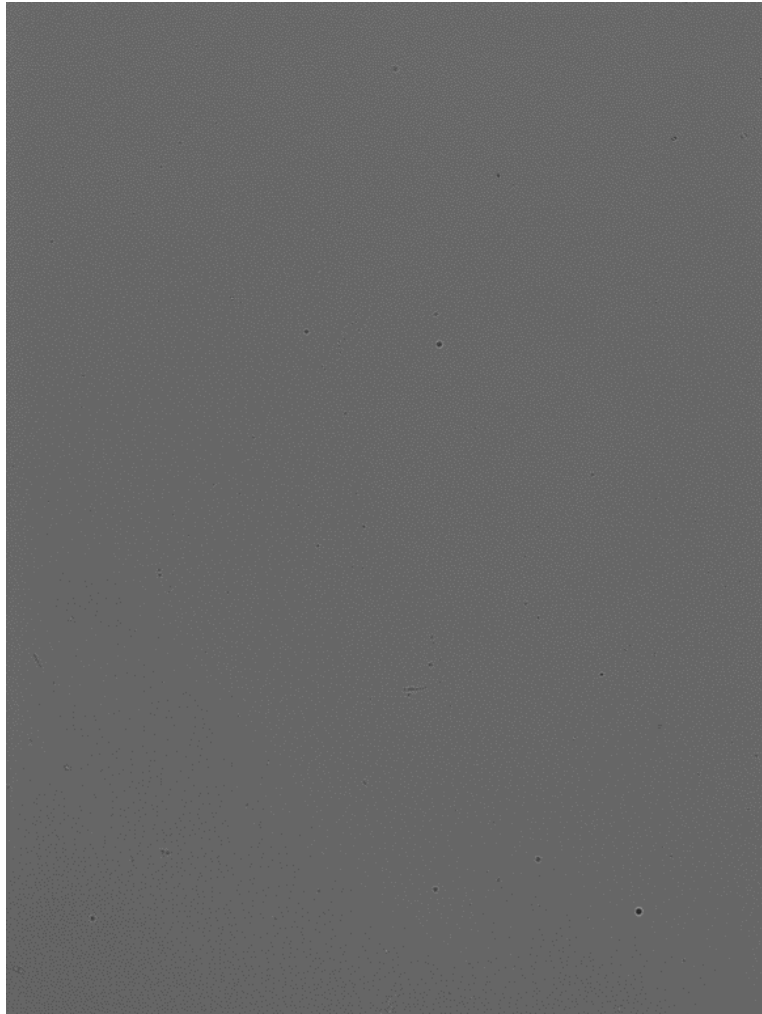


PADC detector

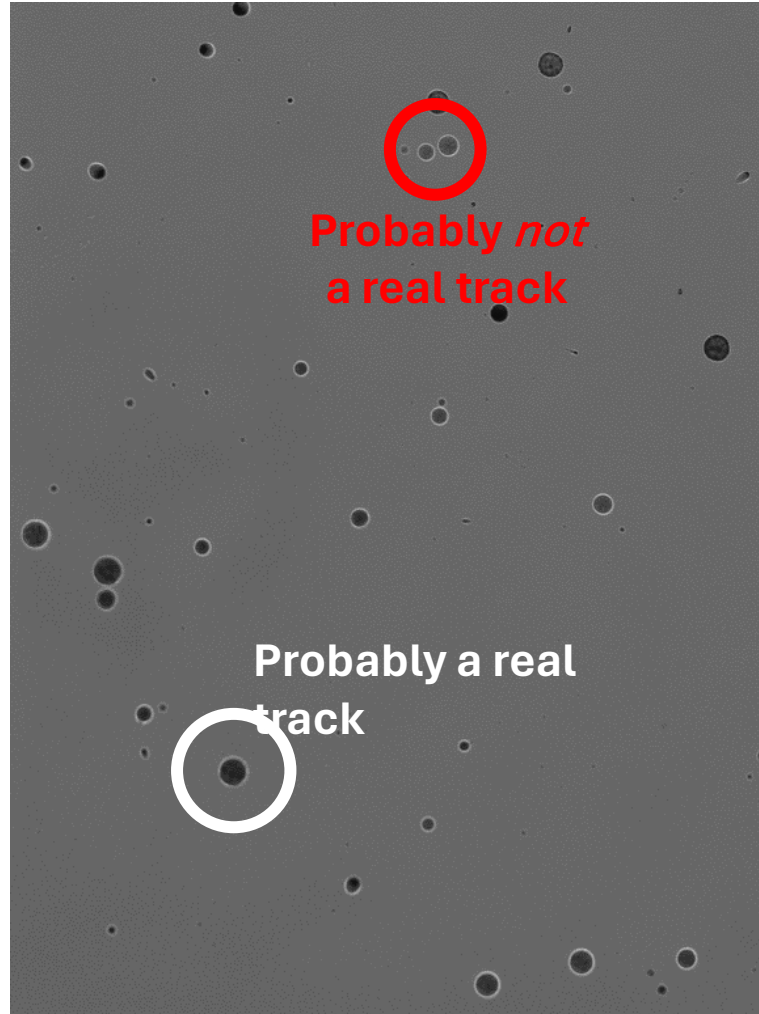


Images

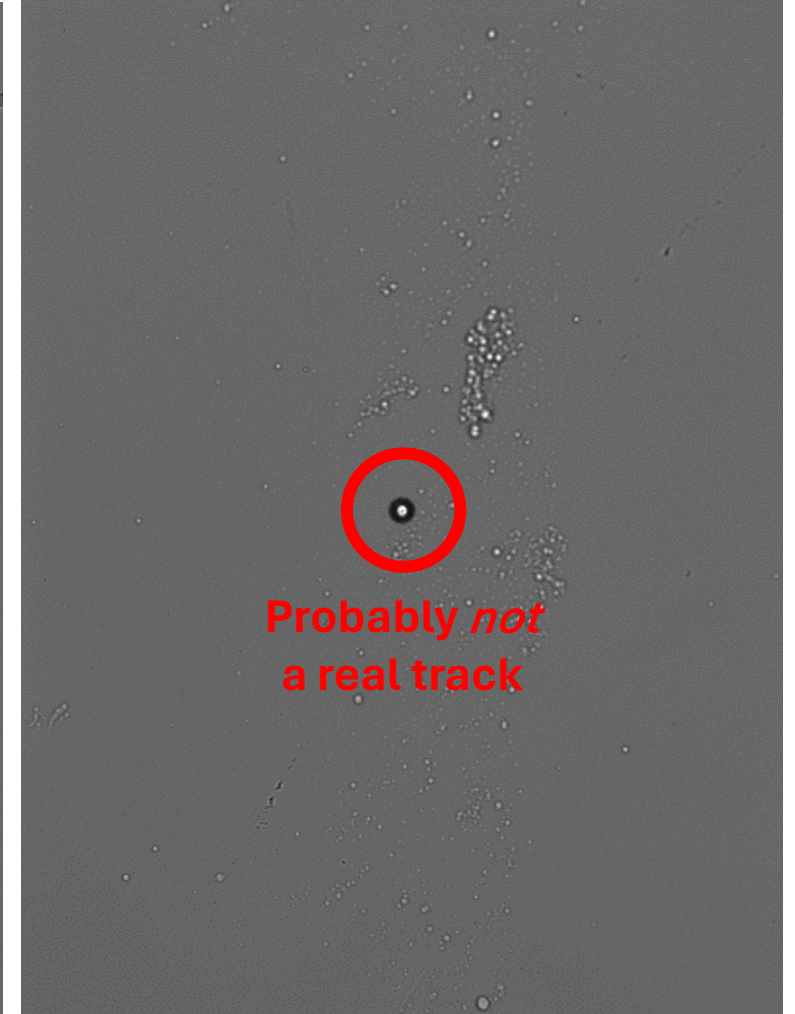
Unirradiated image



$H_p(10) = 3 \text{ mSv}$



Unirradiated image



Track counting

The problem:

- Numerous features are not *real* tracks

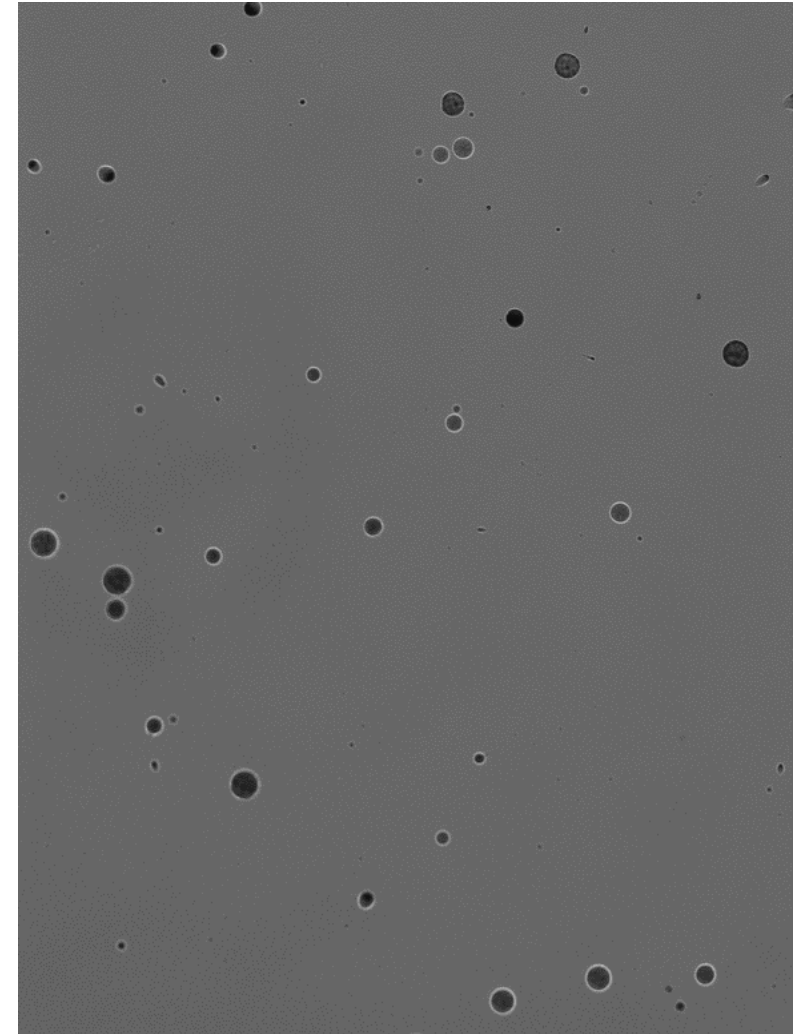
We do **not know** what a real track looks like, but we have $N \sim 1$ mio samples to develop machine learning models.

Method 1:

Condense morphological data into 2D or 3D and categorise elements

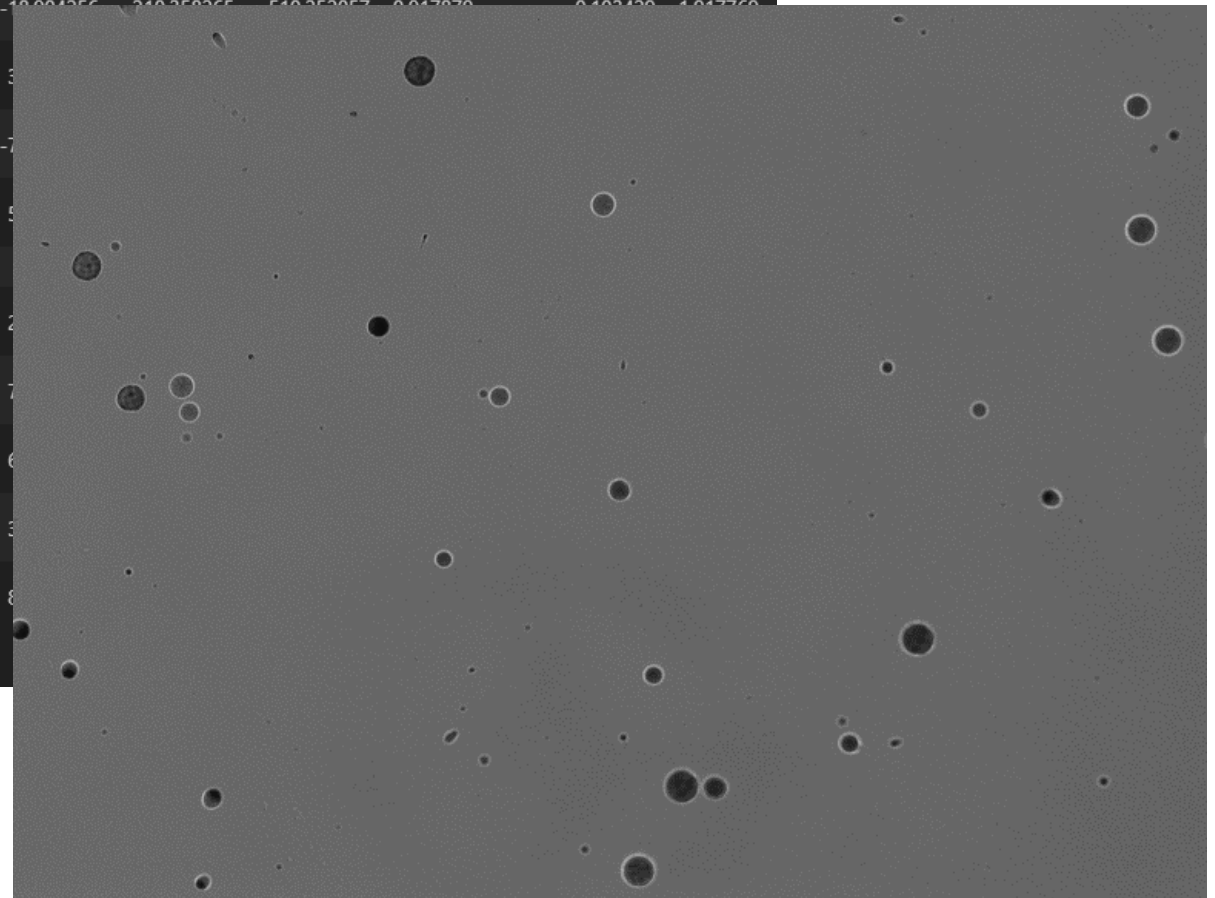
Method 2:

Apply Mask R CNN from Meta Research to count tracks



Morphological data

	Area_um2	Area_filled_um2	MajorAxis_px	MajorAxis_um	MinorAxis_px	MinorAxis_um	Orientation_deg	x_px	y_px	x_cm	...	Intensity_std	V
0	14.978846	14.978846	12.899522	4.519942	12.049998	4.222272	44.244371	207.352459	182.237705	0.906386	...	0.217810	1.061849
1	164.153420	164.153420	44.528776	15.602709	38.309956	13.423659	-10.004256	240.258265	510.252057	0.047070	...	0.402420	1.017760
2	13.014407	13.014407	11.987168	4.200257	11.277221	3.951494	3						
3	48.619861	48.619861	22.542336	7.898747	22.374139	7.839811	-7						
4	43.463209	43.463209	22.271070	7.803696	20.547359	7.199714	5						
...						
4924	54.513178	54.513178	24.307489	8.517249	23.259193	8.149931	2						
4925	19.644388	19.644388	19.775367	6.929212	12.183948	4.269208	7						
4926	18.907724	18.907724	20.532999	7.194683	9.744463	3.414422	6						
4927	38.061002	38.061002	27.821179	9.748433	16.981118	5.950117	3						
4928	167.959520	167.959520	43.463451	15.229424	40.102170	14.051644	8						
4929 rows x 30 columns													



Dataframe from
1 detector

Method 1

Train a two-step pipeline

- “Dimensionality reducer” to reduce the number of data dimensions from 19 to something visible (2D, 3D)
- “a classifier” to predict if an element is a track or noise

Step 2: Track labelling

Approach:

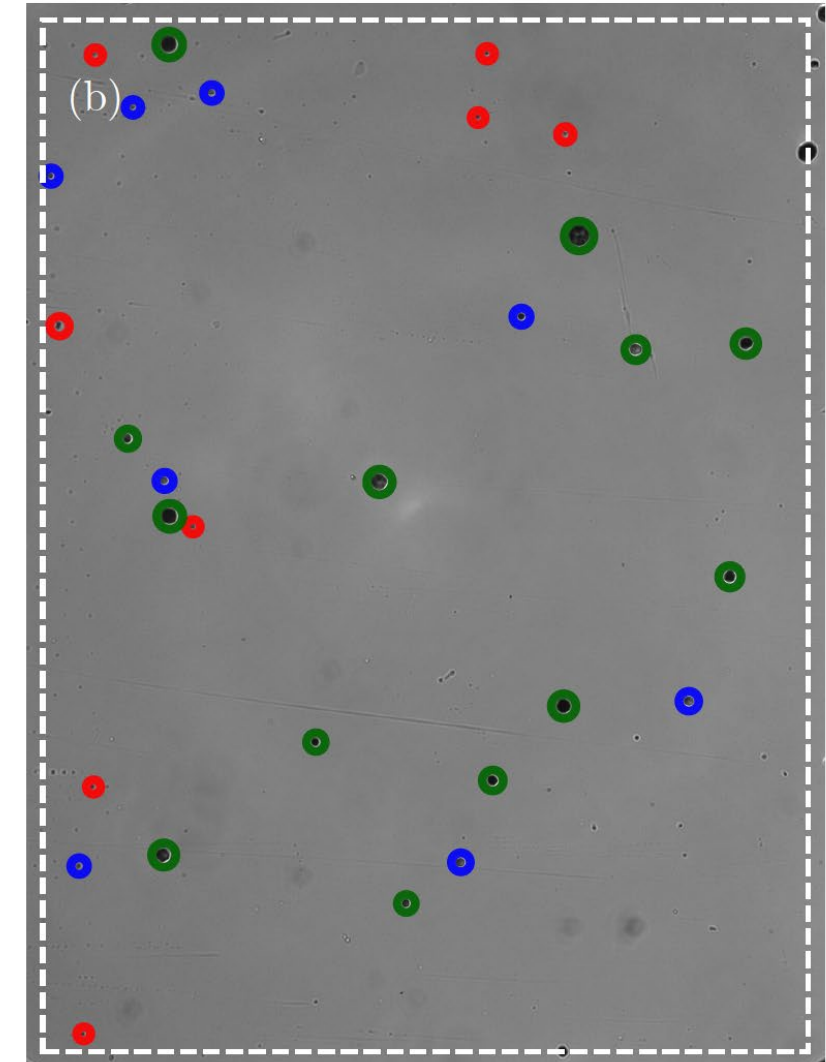
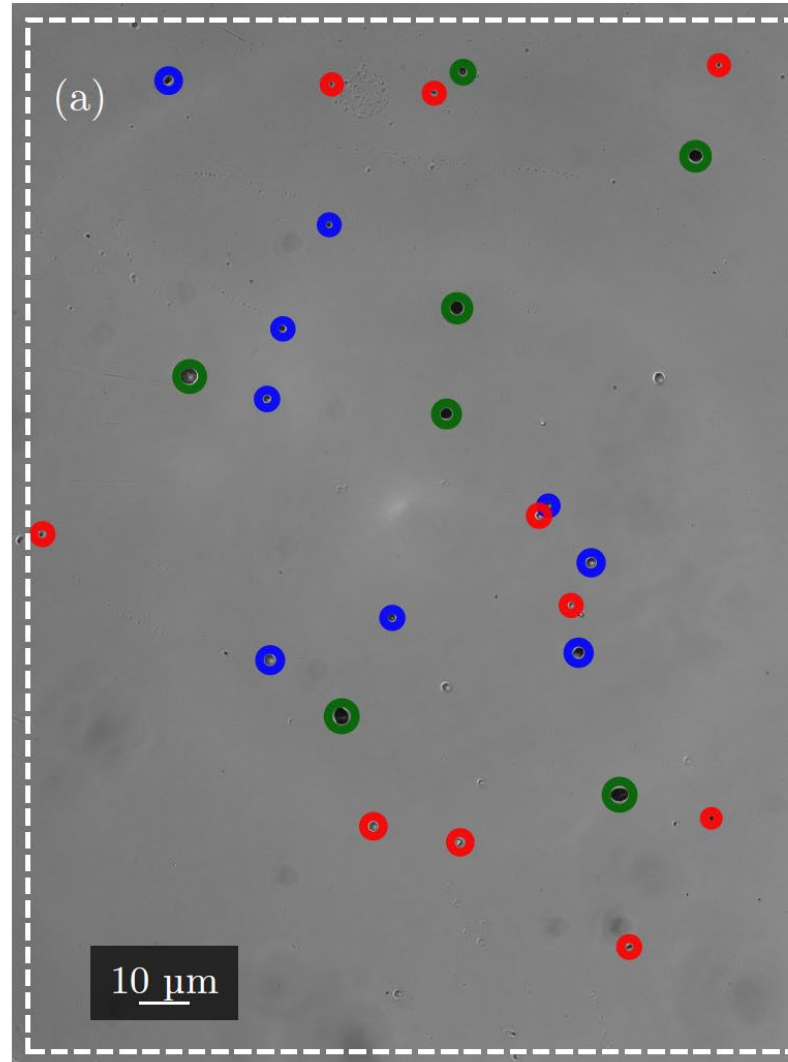
- Label elements ($N \sim 1$ mio)
- **Assign:**
-1 to all elements (default)
- **Overwrite:**
0 = Small, non-ellipsoids
1 = Dark, ellipsoid, large

Element label

○ -1: Unknown

○ 0: Noise

○ 1: Track



Step 3: Dimensionality reduction

Problem:

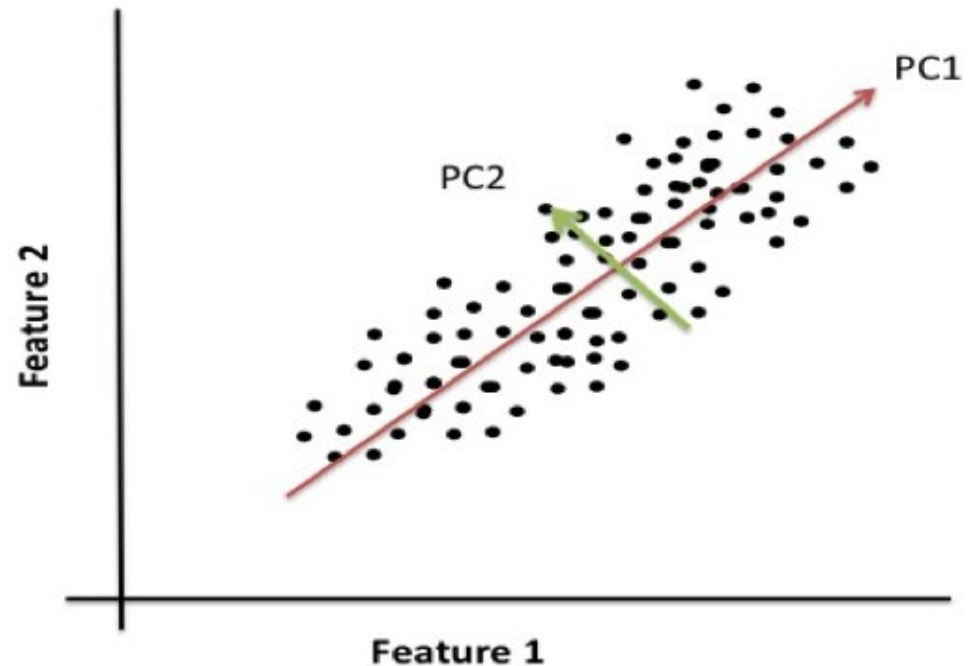
Reduce the data dimensionality from
~ 18 dimensions \rightarrow (1-3) dimensions

We expect three dimensions:

1. Shape group
2. Size group
3. Color group

Linear methods:

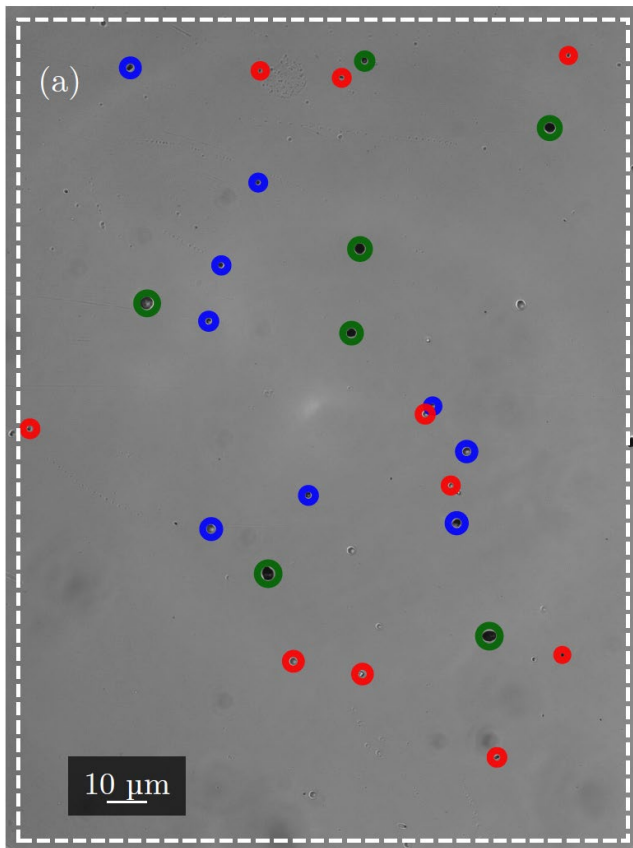
E.g. principal component (PC) analysis



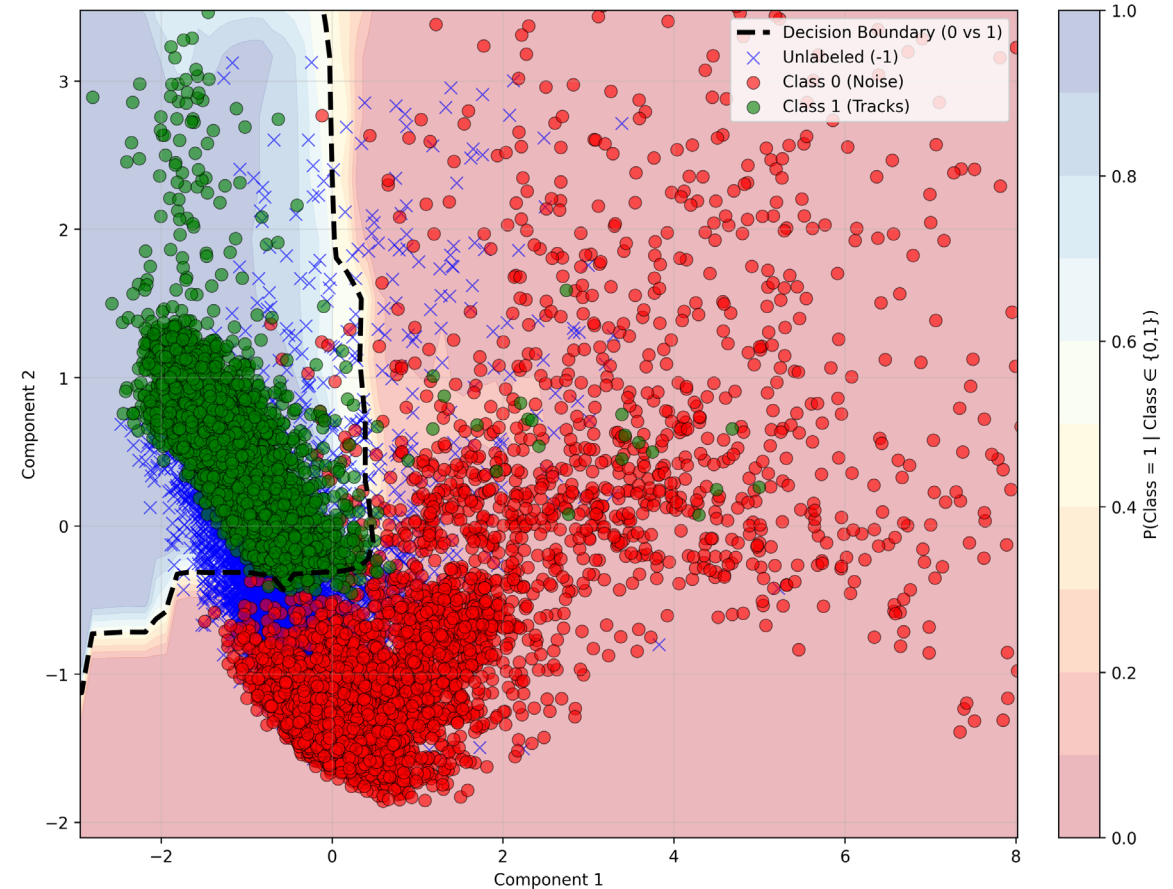
Dimensionality reduction techniques

Semi-supervised learning

- -1: Unknown
- 0: Noise
- 1: Track



Principal component analysis (PCA, linear algebra)



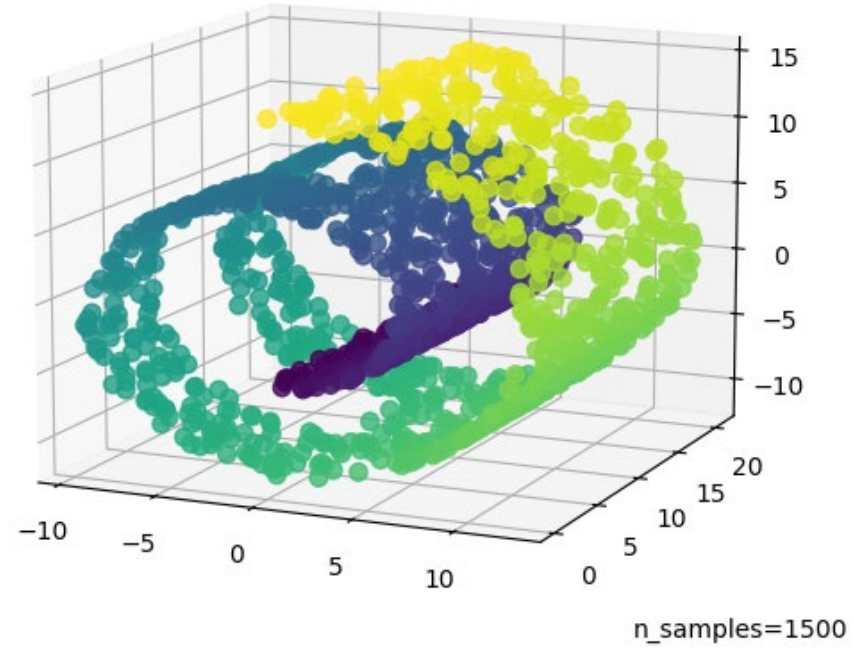
Non-linear manifold learning

(Non-linear) dimensionality reduction

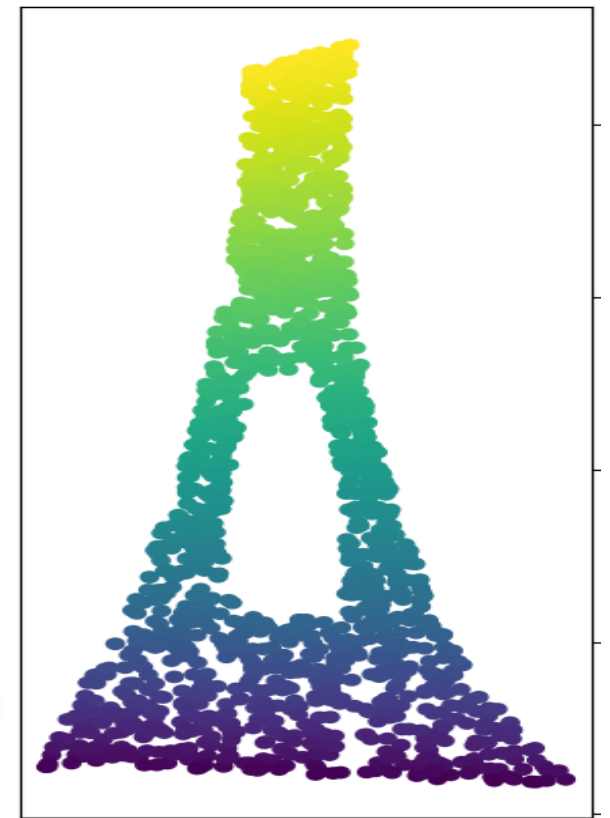
Swiss roll



Swiss roll with hole



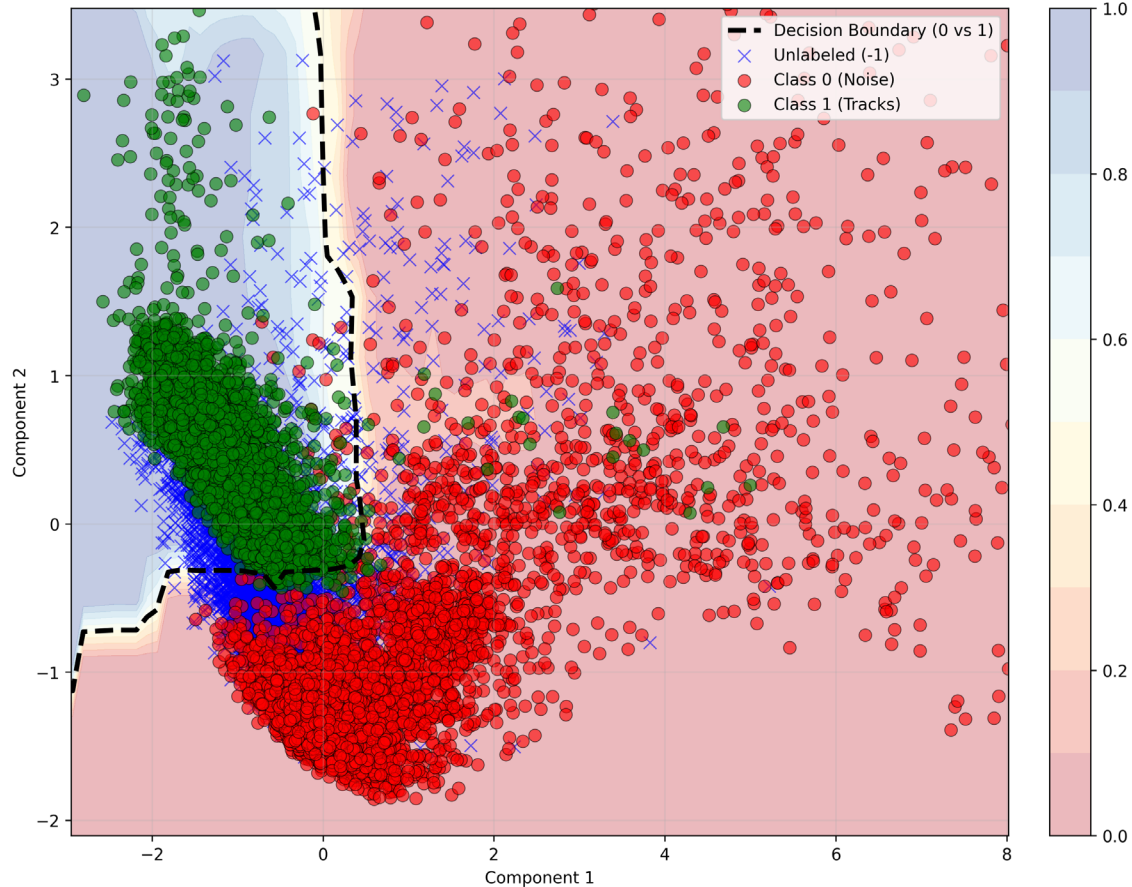
T-distributed
Stochastic Neighbor
Embedding (t-SNE)



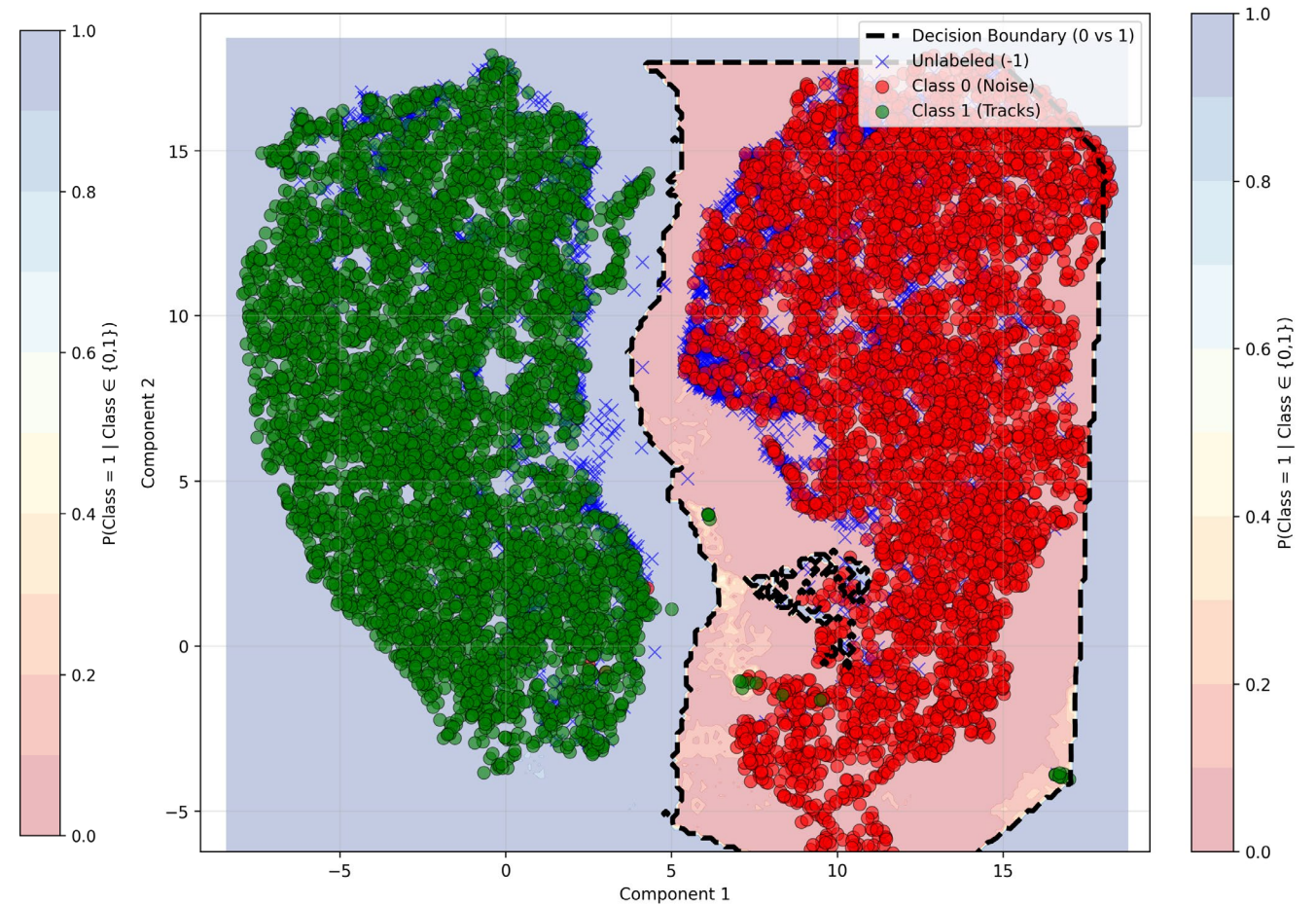
Dimensionality reduction techniques

Condense track parameters to something human «visible»

Principal component analysis (PCA, linear algebra)



t-SNE (machine learning, slow)



Method 2: Mask R CNN

Mask R-CNN with a custom dataset

- Lightweight and efficient for small objects.
- Well-suited for object segmentation without overloading resources.

Main challenge:

Acquire training data to the train the model



Method 2: CNN for track segmentation

Mask R-CNN with a custom dataset:

- Lightweight and efficient for small objects.
- Well-suited for object segmentation without overloading resources.

source image

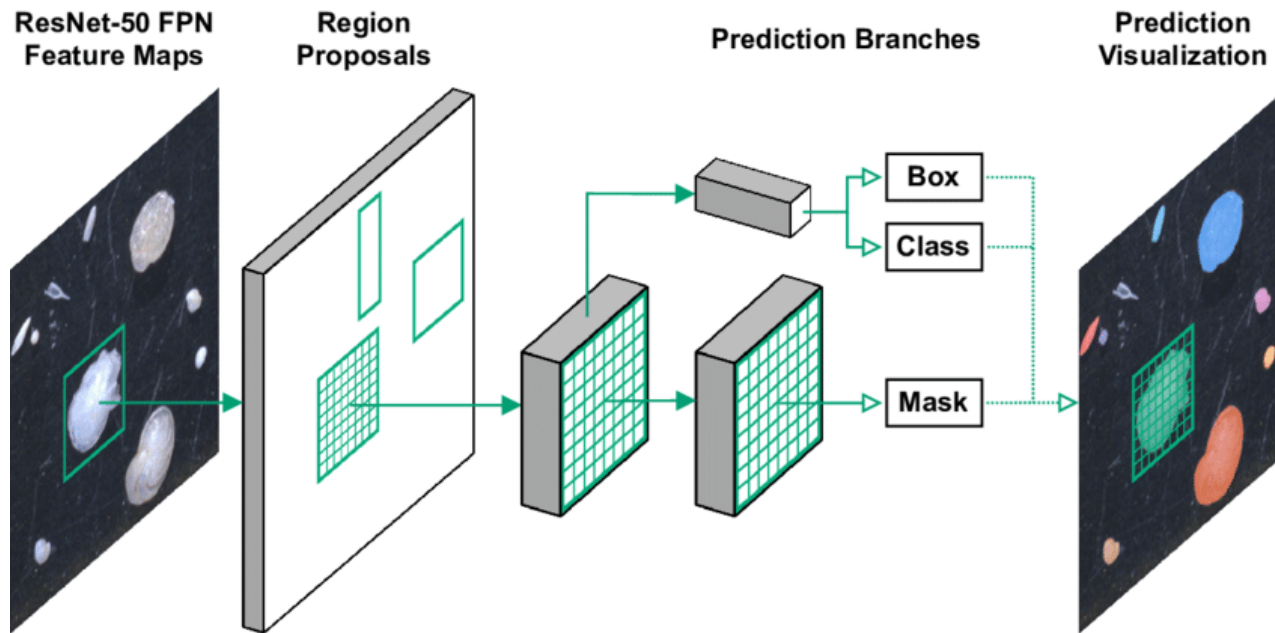


segmented image

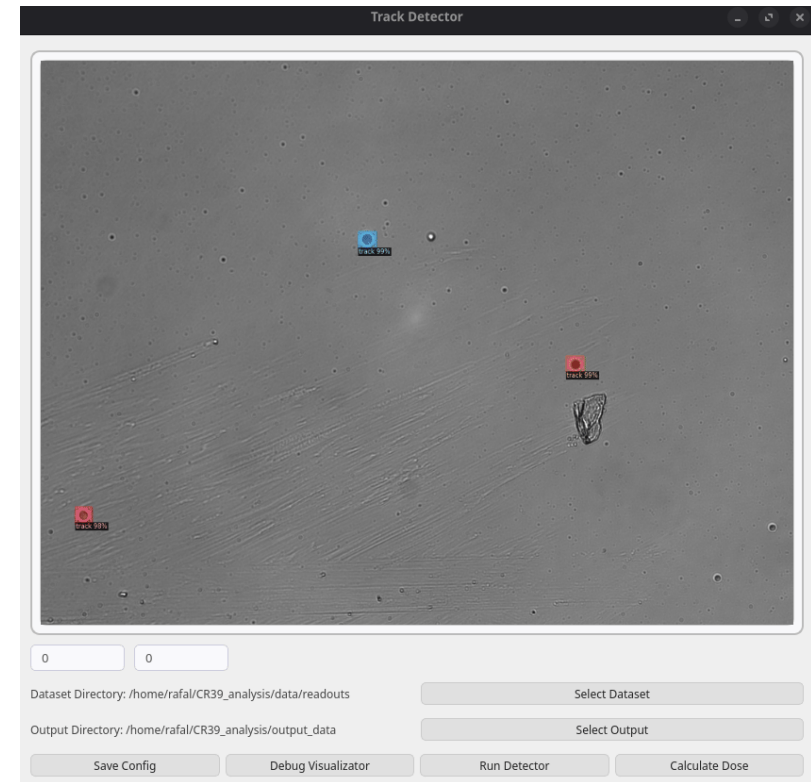


Method 2: structure

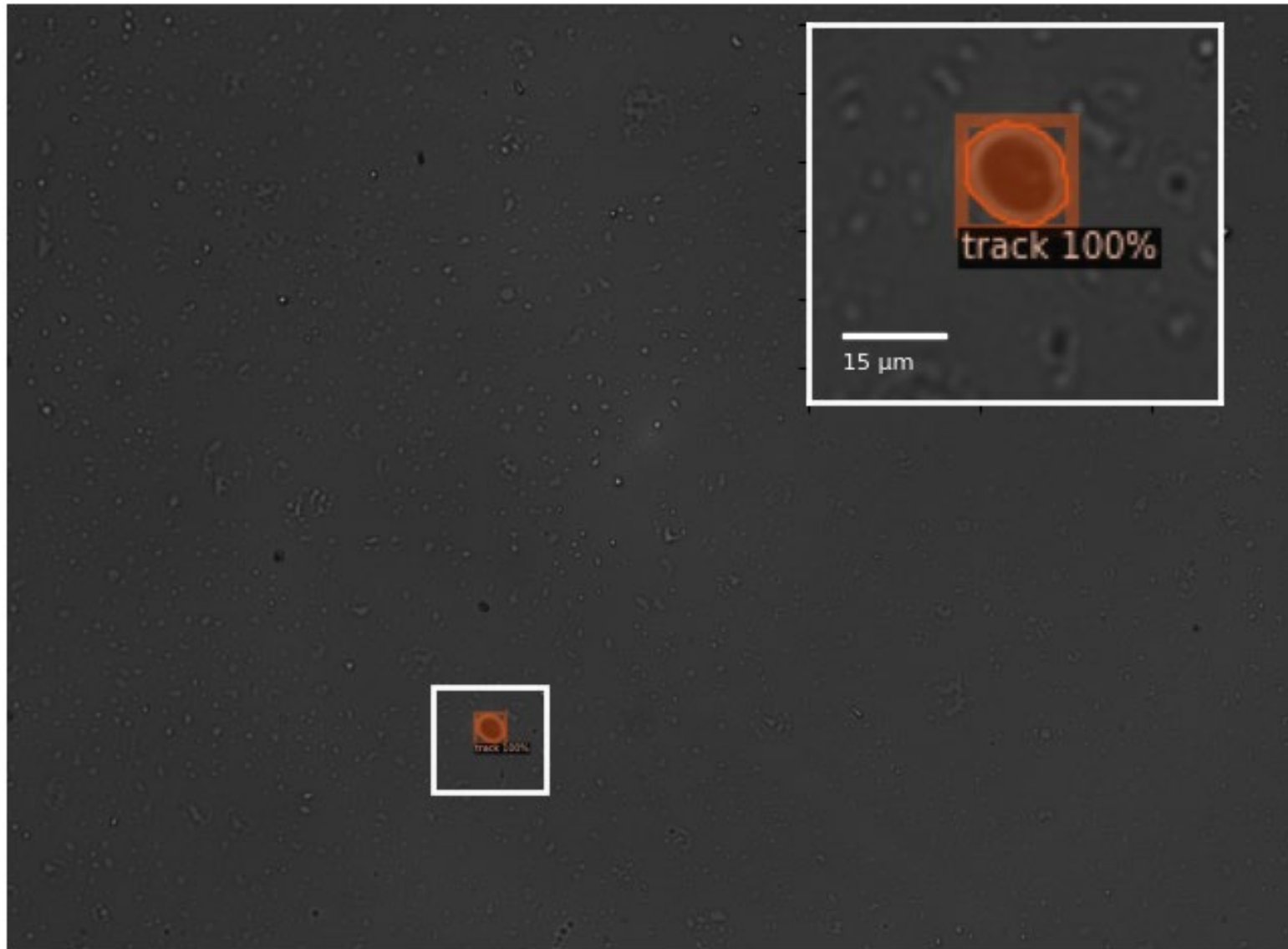
Mask R-CNN architecture



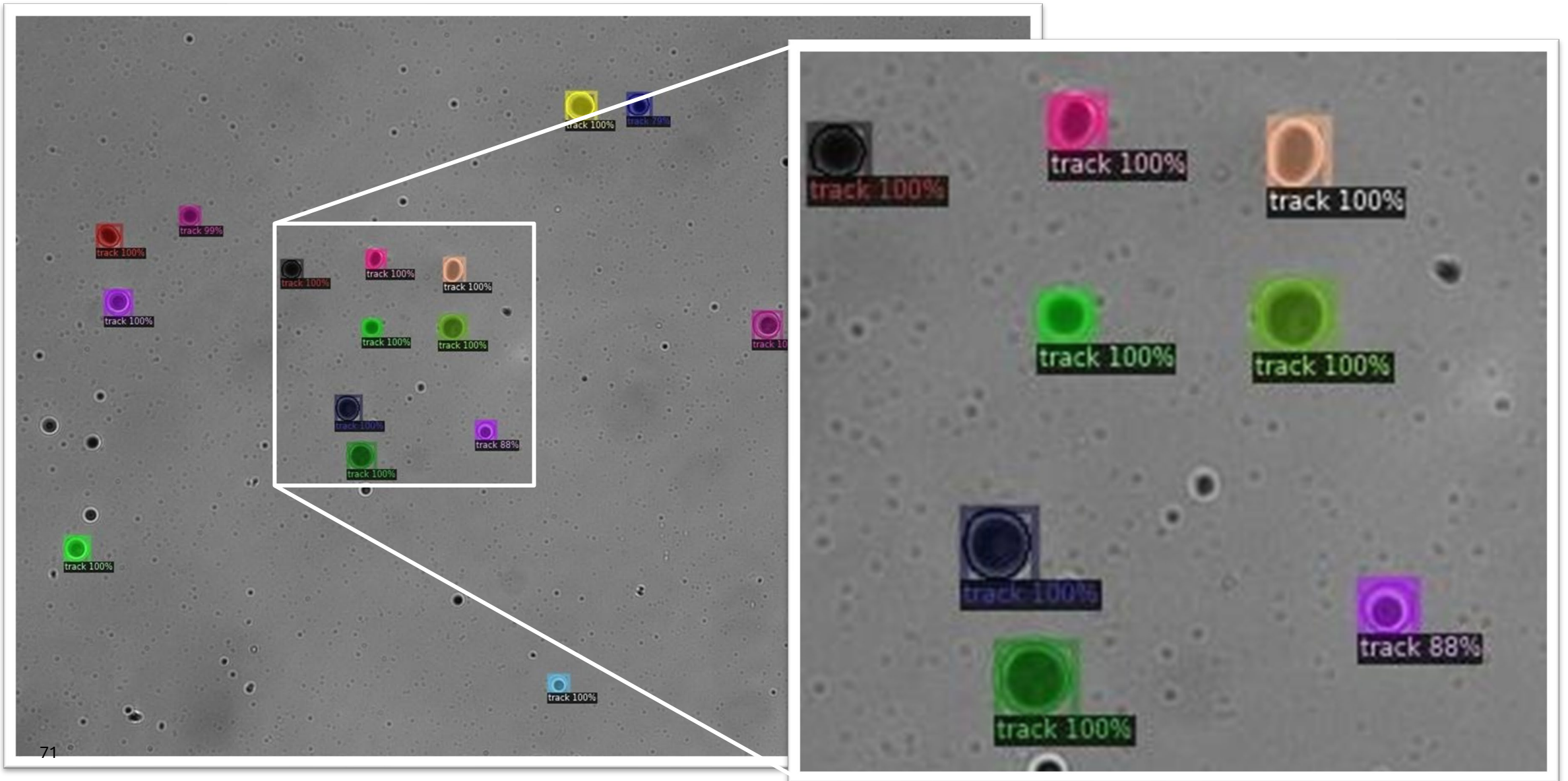
RecoilNet User Interface



Example detections (image from 0.3 mSv irradiation)

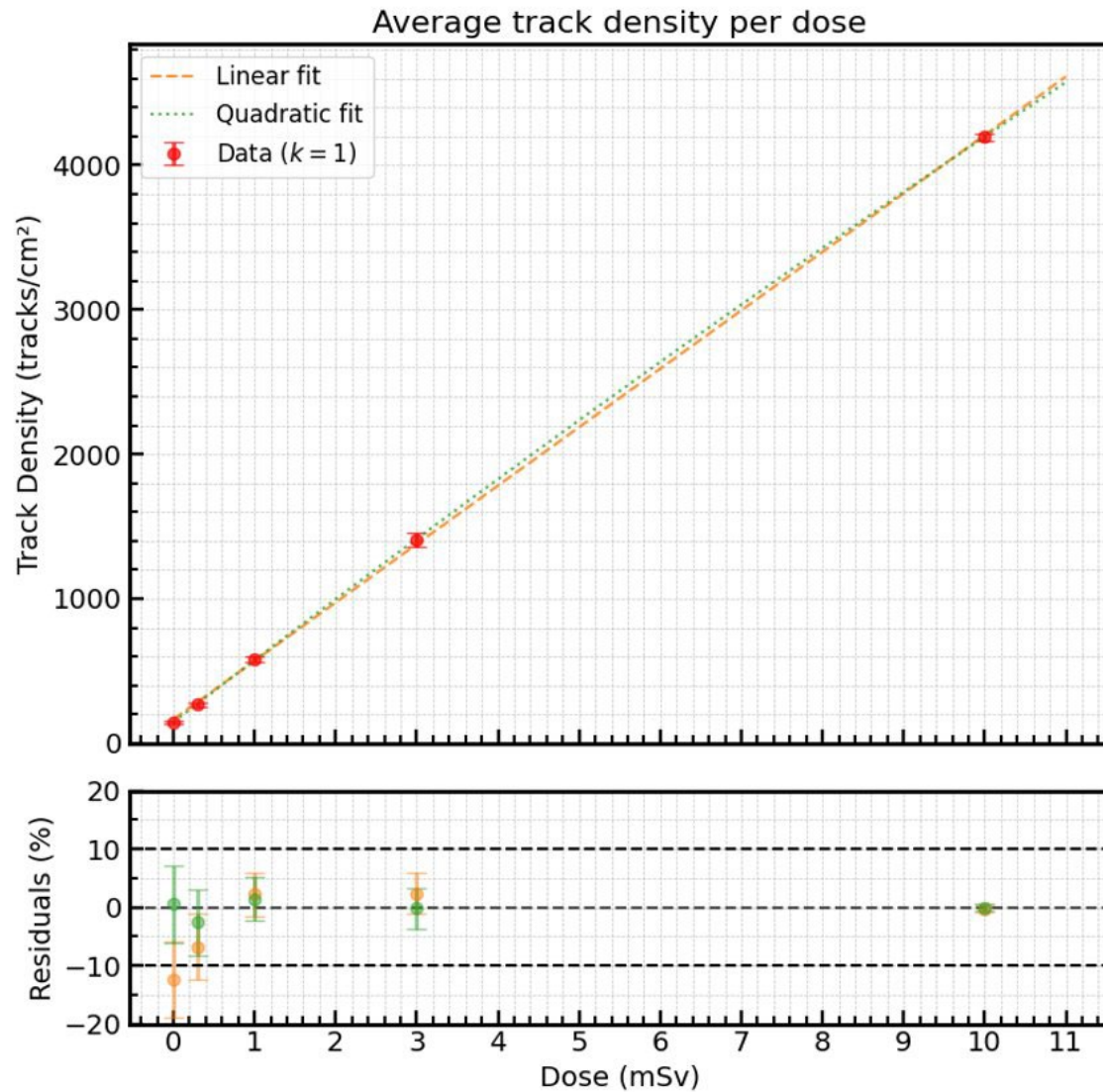


Track counting of irradiated detector images (10 mSv)



Dose linearity

Using Mask R CNN



CR39 detector

O sur la dosimétrie

814.501.43

Annexe 5
(art. 18 et 21, al. 3)

Exigences concernant un dosimètre individuel pour le rayonnement neutronique

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- Dépendance énergétique

$$0,3 \leq \frac{H_m}{H_t} \leq 3,0$$

pour les spectres de radiation dans lesquels le dosimètre est utilisé.

- Reproductibilité
Ecart standard $s \leq 50 \%$
- Fading
Effet < 30 %/mois

Two in-house algorithms for track counting

- Dimensionality reduction + classifier
- Mask R CNN (Meta Research)

Challenge (MSc thesis?):

Develop your own algorithm and demonstrate it fulfills the Swiss dosimetry requirements

(I have all the data you need)

Neutron dosimetry

Application 1:

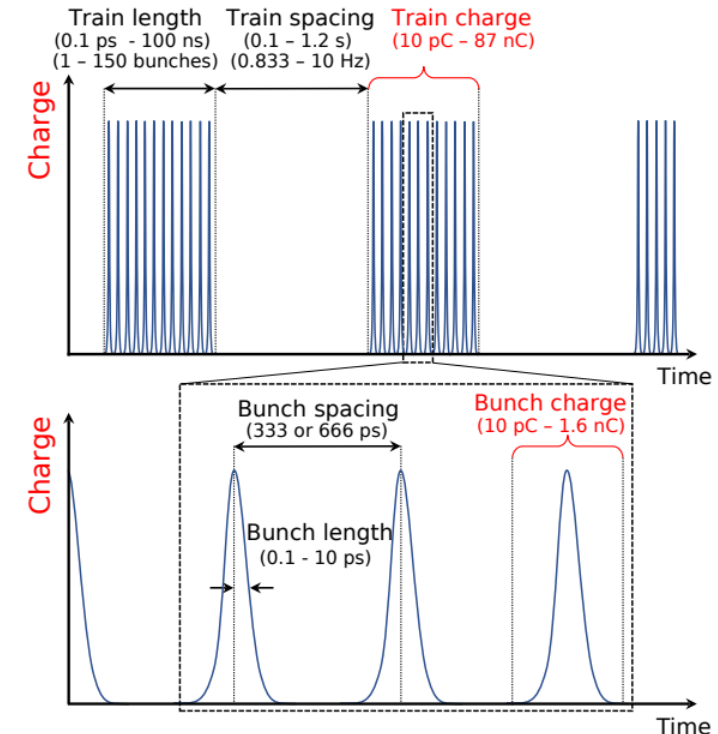
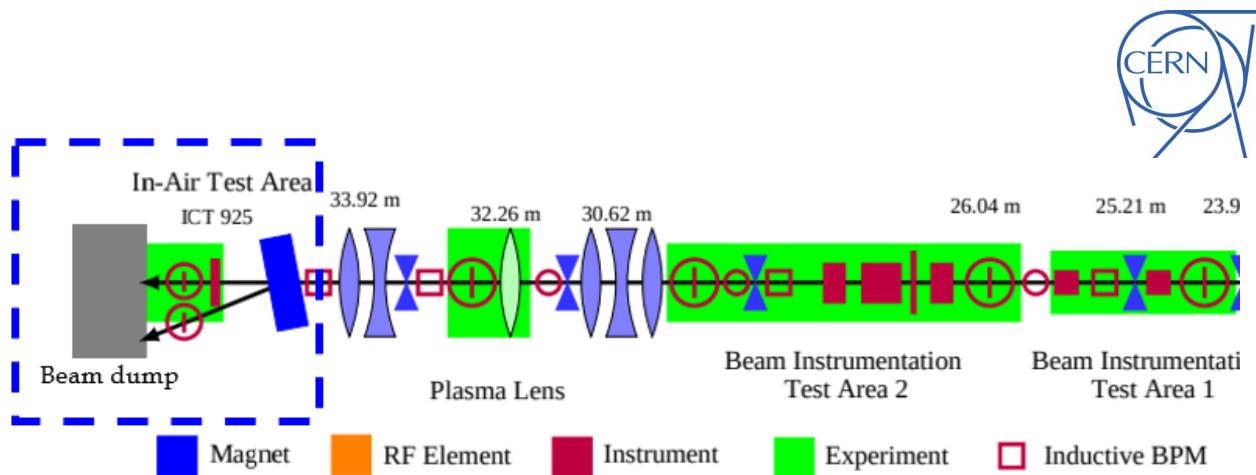
CERN, Linear Accelerator for Research (CLEAR)

Neutron dosimetry in high-energy pulsed fields @ CERN



The CERN-CLEAR (CERN Linear Accelerator for Research) facility consists of a LINAC delivering pulsed electron beams with an energy up to 220 MeV

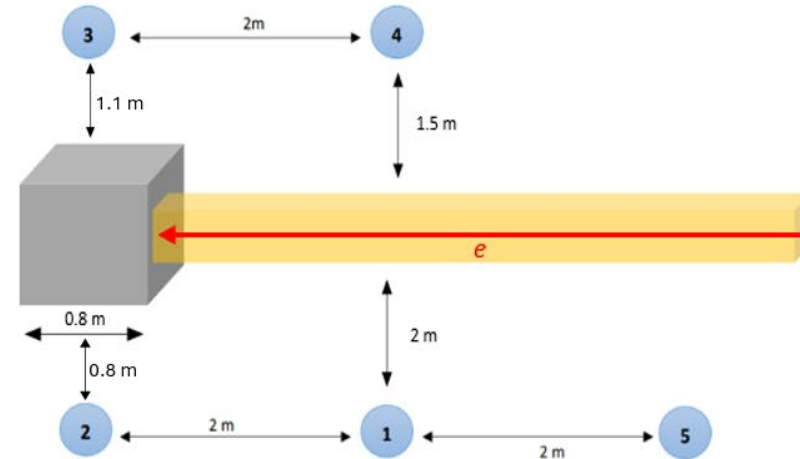
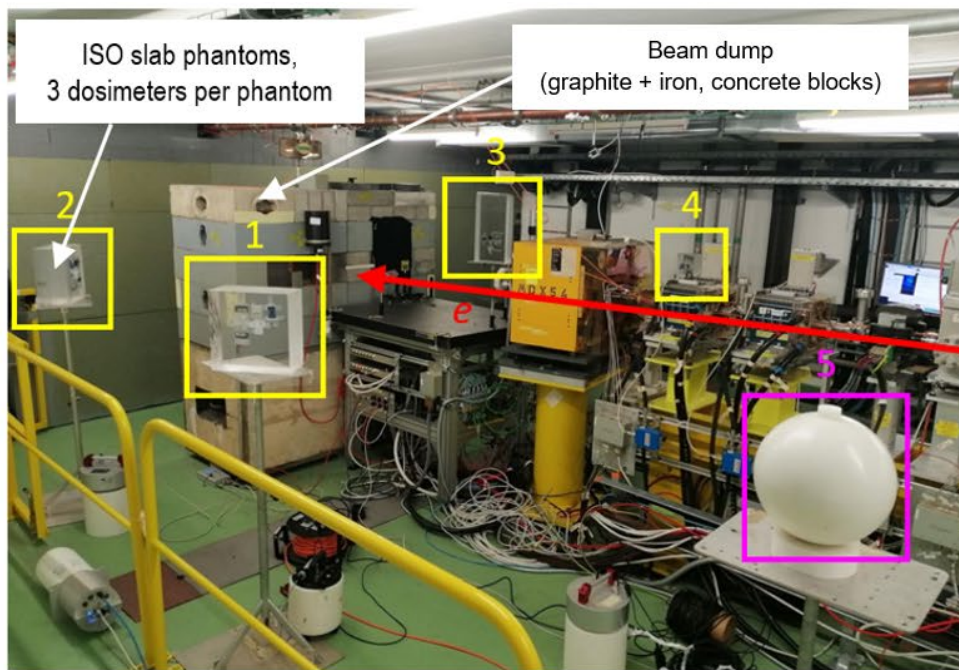
This accelerator is mainly employed for studies on medical applications of radiation fields (like FLASH therapy) and for material testing (e.g., for space applications).



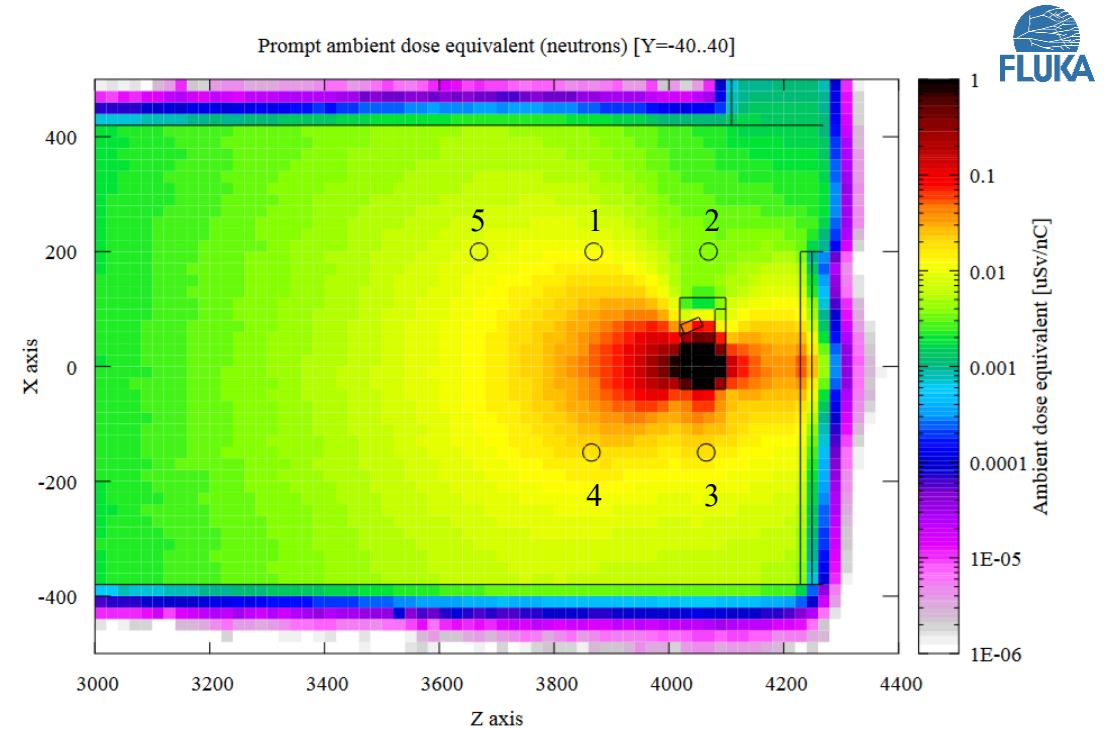
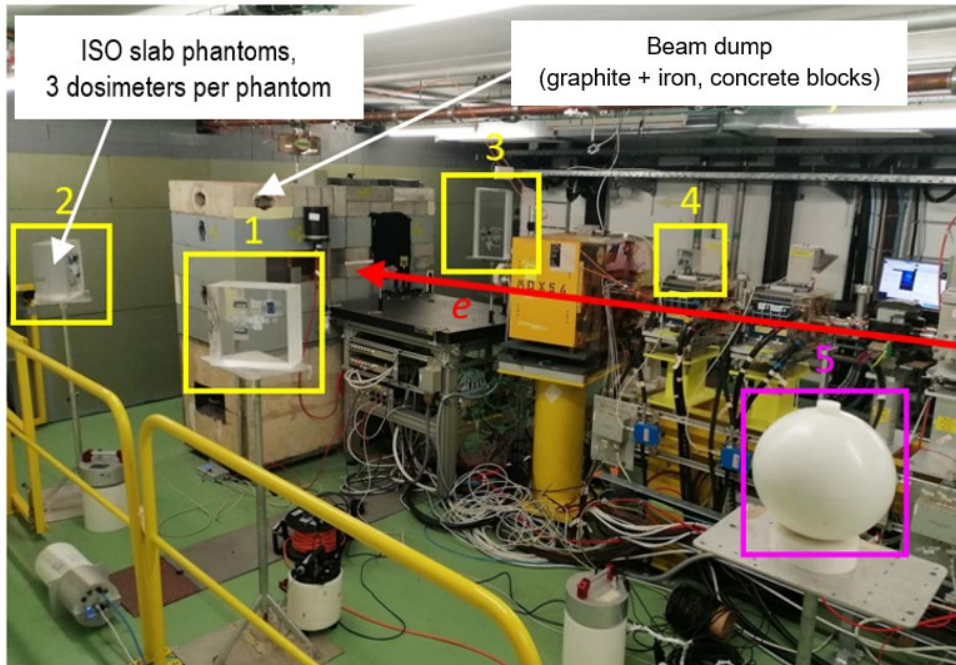
Neutron dosimetry in high-energy pulsed fields @ CERN

For the experiments, the beam energy was 195 MeV, the repetition frequency 10 Hz, and 3 levels of charge were used: 3, 25 and 50 nC per electron train.

The experimental setup is shown below: 3 PADC dosimeters were used on each ISO phantom (PMMA, $30 \times 30 \times 15 \text{ cm}^3$) in Positions 1 to 4, while the passive LINUS was positioned in Position 5. The phantom surface was oriented towards the point where the electron beam impinges on the dump.



Neutron dosimetry in high-energy pulsed fields @ CERN



Data	Dose/charge [mSv/μC] Pos 1	Dose/charge [mSv/μC] Pos 2	Dose/charge [mSv/μC] Pos 3	Dose/charge [mSv/μC] Pos 4
Measurements	15.7 ± 3.5	5.0 ± 1.7	30.3 ± 4.7	21.7 ± 4.7
FLUKA	12.2 ± 0.4	4.8 ± 0.2	29.9 ± 0.6	22.2 ± 0.6

Neutron dosimetry

Application 2: KK Beznau

Ion beam dosimetry

- Measure dose-to-water
- Radiation quality (LET) is a challenge
- Charged particles → precise measurements!

Neutron dosimetry

- Always difficult (...) due to cross-section varying orders of magnitude

Possibilities on

- Ion beam dosimetry / therapy
 - Dose + LET measurements
 - Novel 2D OSL dosimetry + LET
- Neutron dosimetry
 - CR39 detectors (algorithms, simulations)
- Particle transport simulations
 - Geant4, FLUKA, MCNP, ...

Contact us!

kerr@psi.ch / sistjen@psi.ch