Hadron Beam Dosimetry

CERN Brainstorm Meeting, 15th February, Divonne-les-Bains

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Also on behalf of Hugo Palmans, Heikki Tölli and Michael Waligorski

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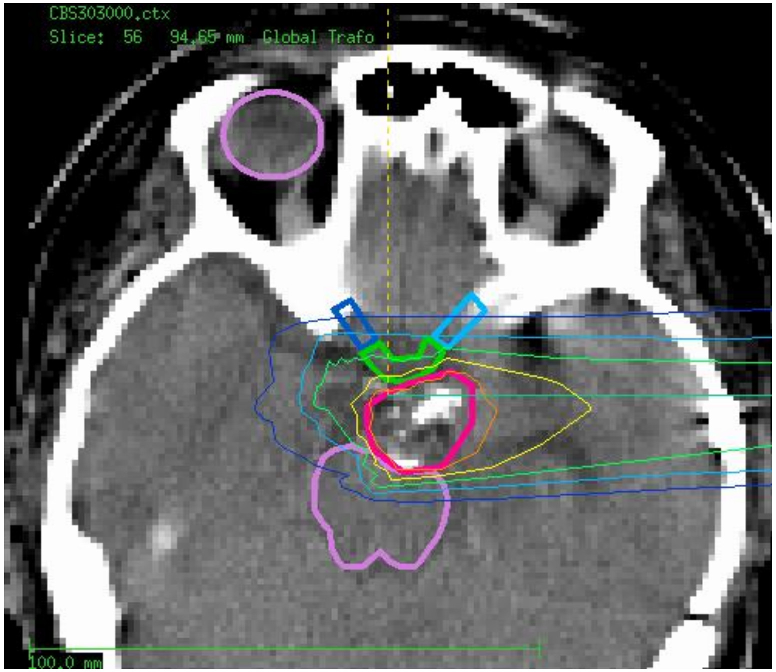
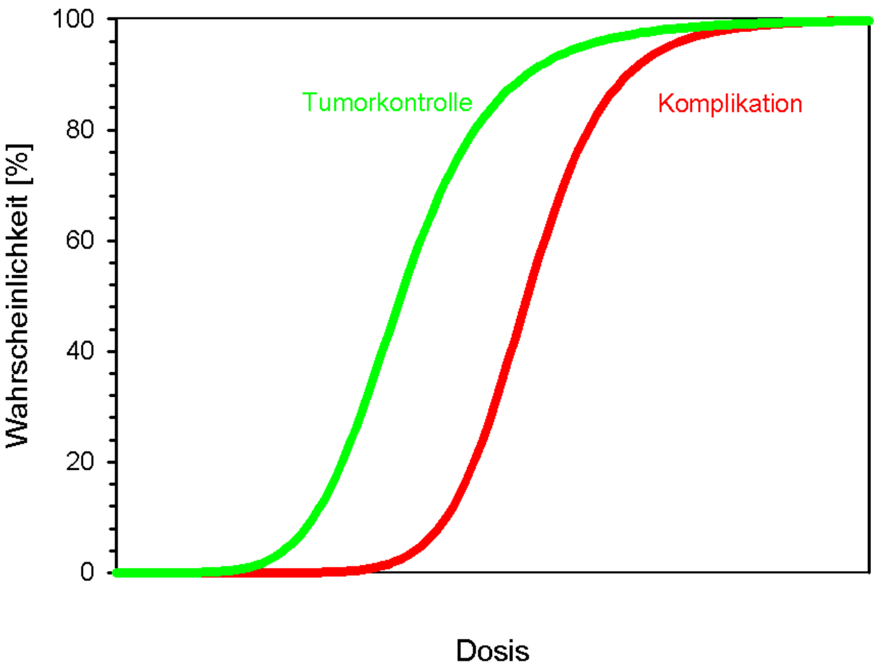
Motivation

Why should we worry about dosimetry?

Motivation: The need for accuracy





AAPM report #85 (Papanikolau et al 2004)

- Due to steep slope of TCP and NTCP a ***5% dose error*** can lead to a TCP change of ***10-20% and worse*** for NTCP.

TCP = Tumour Control Probability

NTCP = Normal Tissue Complication Probability

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OUTLINE

- The best we have:
  - **Calorimetry**
  - Fricke dosimeter (passive detector)
  - **Ionization chambers** (active detector)
- Understanding **solid state dosimetry** – *the quenching trouble*
- Verifying IMPT - **3D solid state detectors**
- At the frontier of dosimeter research
  - Measure **other quantities than dose**?
  - **Primary standards**?

(Review Karger et al. PMB 2010)

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Ideal Dosimeter Properties

- Linear over whole dose range
- Dose rate independence (non-linear effects at higher dose rates, e.g. recombination effects) (no fading for passive detectors)
- No energy/particle dependent response
- No dependence of direction (isotropic)
- High spatial resolution (image, small effective volume)
- Readout convenience
  - Online (= active)
- Convenience of use
  - Is it reusable, rugged, easy to setup

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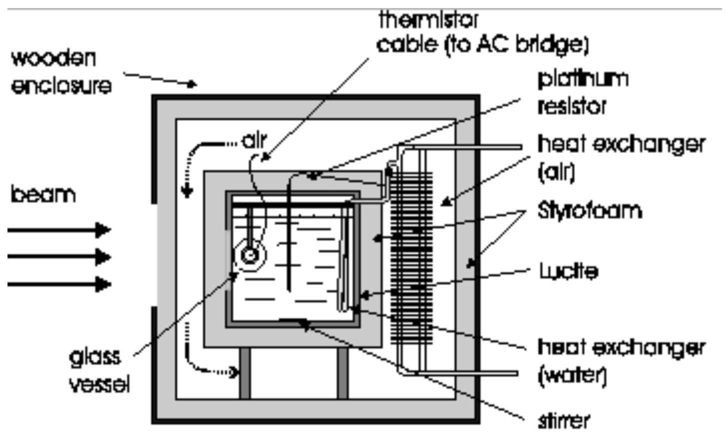
Calorimetry

- Most direct way of measuring dose
- Very cumbersome to deal with, since careful isolation and temperature equilibrium required
- Portable Graphite calorimeter by Palmans et al, but measures dose to graphite



Co-60 unit and water calorimeter at PTB Braunschweig

Calorimetry – Current Challenges

- All correction factors are not fully characterized in ion beams.
(chemical and physical heat defect, gap corrections, impurity corrections, heat transfer corrections,...)

Reasons:

- Time consuming experiments
- Where clinical beams are available, extended blocks of beam time are difficult to get.

(Hugo Palmans, NPL, private communication yesterday)

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Dosimetry

- Dose to some medium (e.g. Water):

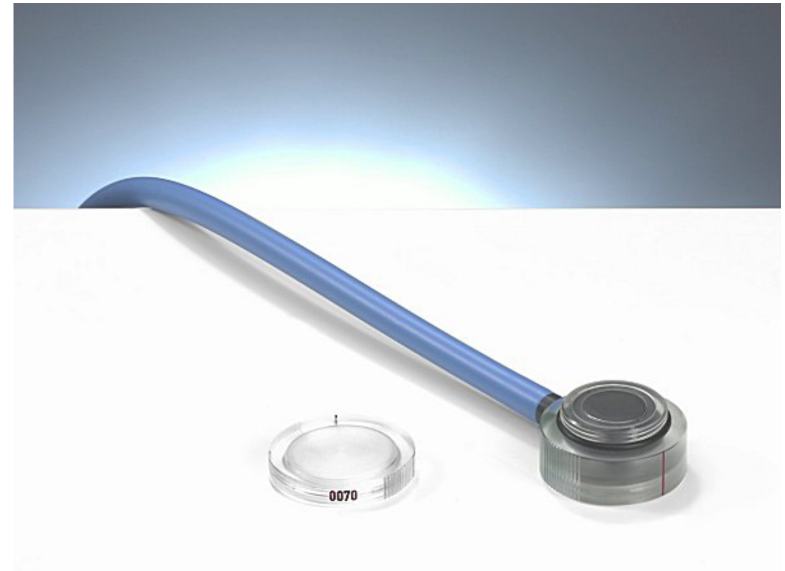
Fluence * mass stopping power

$$D_w = \int_0^{T_0} \Phi_T^e \left(\frac{dT}{\rho dx}\right)_w dT$$

How to measure dose:

$$D_w = \int_0^{T_0} \Phi'_T \left(\frac{dT}{\rho dx}\right)_w dT$$

Not applicable in clinical routine, since fluence spectrum is unknown.



Real life dose verification in regular quality assurance:

- verification of absorbed dose to water
- but standard dosimeter: air-filled ionization chamber

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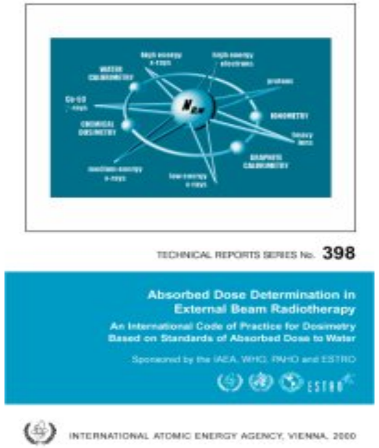
$$D_w = \int_0^{T_0} \Phi'_T \left(\frac{dT}{\rho dx}\right)_w dT$$

$$D_{w,Q} = M_Q N_{D,w,Q_o} k_{Q,Q_o}$$



TRS-398 formalism can be applied to ions:

- $D_{w,Q}$: absorbed dose to water
- M_Q recombination corrected electrometer reading
- $N_{D,w,Q0}$: calibration factor at reference condition
- $K_{Q,Q0}$: correction factor for different beam quality

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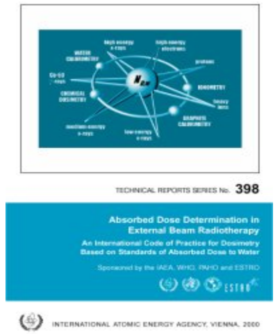
Dosimetry Uncertainties

Ratio of stopping power ratios (!)

$$k_{Q,Q_0} = \frac{(s_{w,air})_Q}{(s_{w,air})_{Q_0}} \cdot \frac{(W_{air})_Q}{(W_{air})_{Q_0}} \cdot \frac{p_Q}{p_{Q_0}}$$



	$(s_{w,air})$	(W_{air})	p	Total
^{60}Co	0.5 %	0.2 %	0.6 %	~ 0.82 %
Protons	1.0 %	0.4 %	~ 0.5 %	~ 2.0 %
Ions	2.0 %	1.5 %	1 %	~ 3 %

Plane parallel chamber
(cylindrical is a little lower)

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Electronic stopping power

- Unknown electronic stopping powers remains as the primary source of uncertainty for I-chamber dosimetry
  - Geithner et al. PMB 2006
  - Henkner et al MedPhys 2009
  - Lühr et al PMB 2011
  - And many papers by P. Andreo (IAEA TRS-398)

- Stopping power measurements
  - Absolute range measurements used to define mean excitation value (I-value)
    - Few experimental measurements in particular for compounds are missing
    - (think of the ongoing debate on I-value of water)
- Development of a perturbation-free ion chambers?

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SOLID STATE DOSIMETRY

Solid State Dosimeters – what is out there?

- Most popular dosimeters
  - Radiographic films (passive)
  - TLDs / OSL (passive and active)
  - Diodes / Diamonds ...(active)
- And there are all kinds of derivations hereof such as 2D diode arrays
- No solid state dosimeter (except Fricke/Calorimeters) are used for **absolute** dosimetry in radiotherapy

Photographic dye (films) just for **relative** profile and homogeneity checking

In clinical practice: a**bsolute** dosimetry all handled by Ionization chambers.

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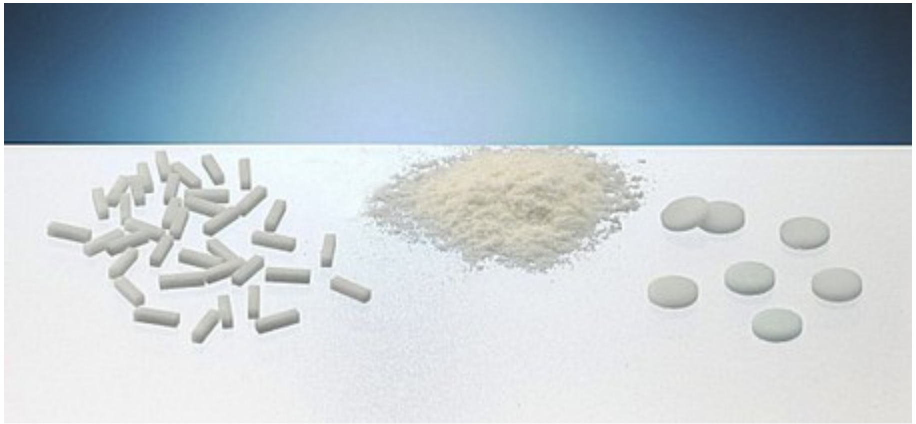
Thermoluminescent Detectors



- Available in several forms
- Used in personal dosimeters for radiation monitoring

- Recent overview on research frontiers:

Y.S. Horowitz, Radiat.Meas. 2014 (in press)

http://www.ptw.de

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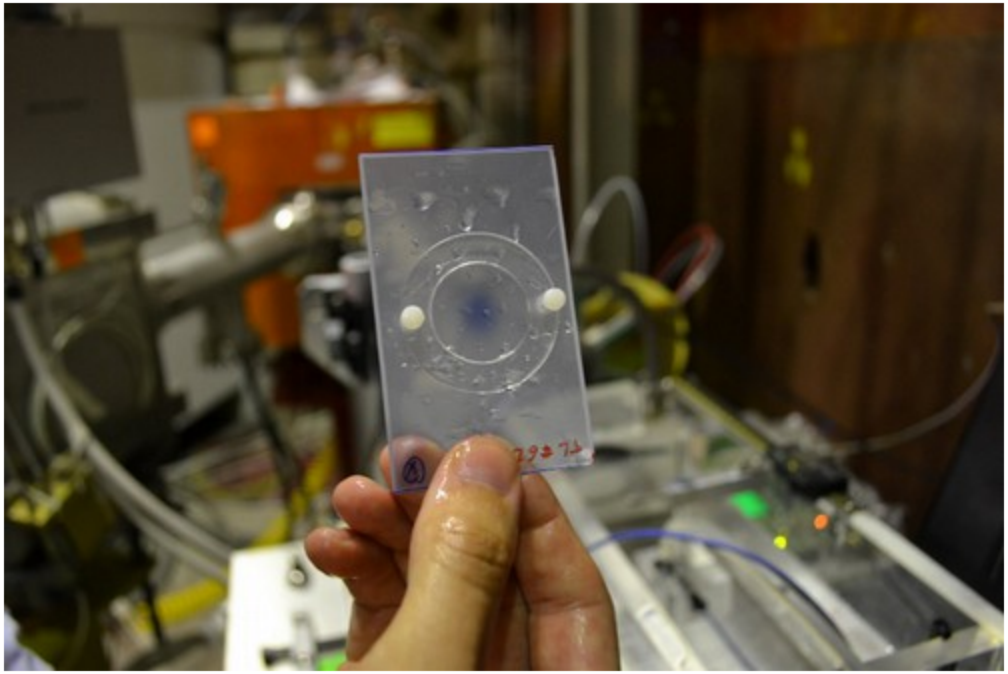
Radiochromic Film



- GafChromic
  - HS, EBT, EBT2, EBT3
- Self developing film
- Tissue-like Z
- Waterproof
- Almost light insensitive (beware of UV light)

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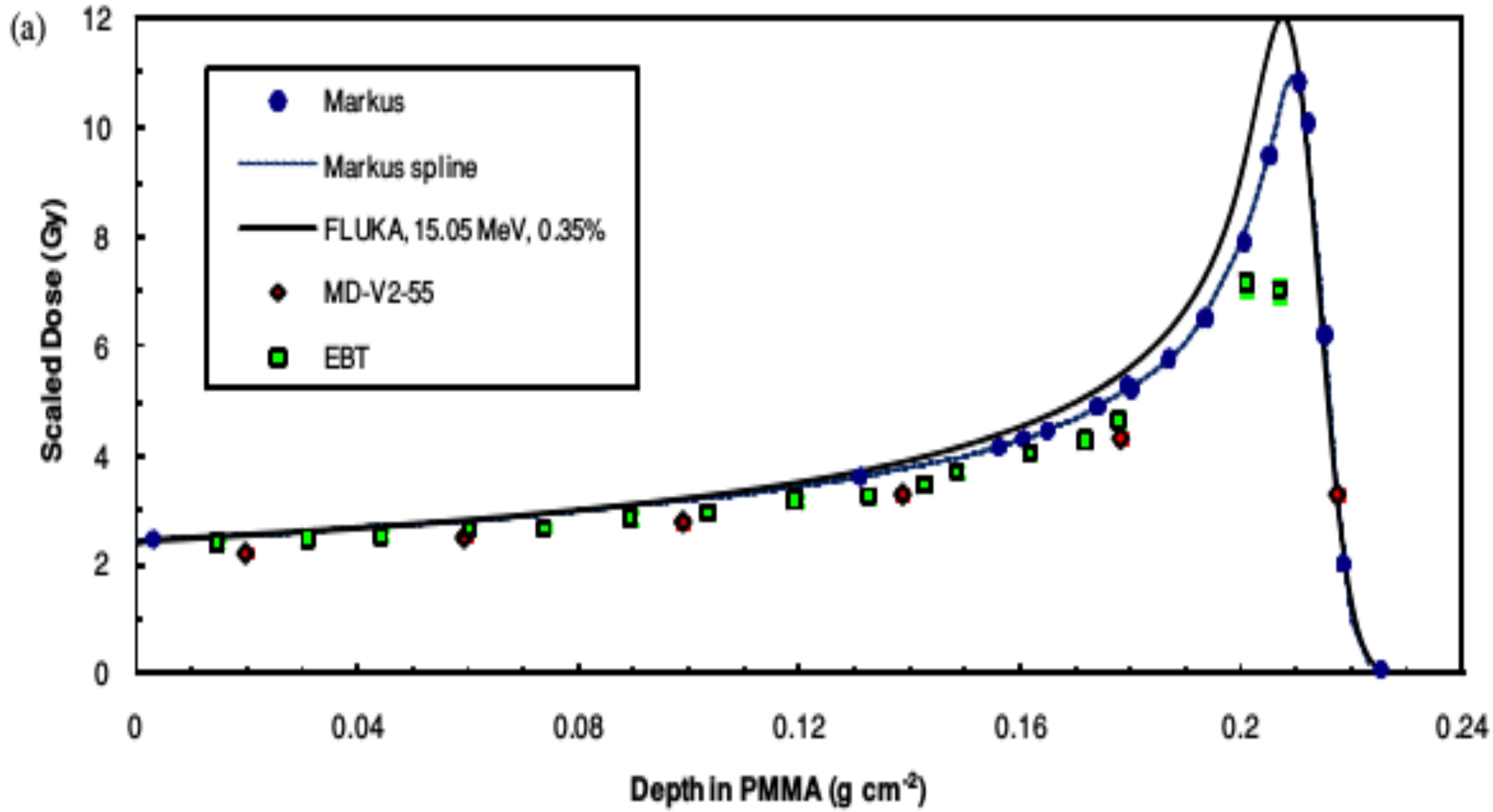
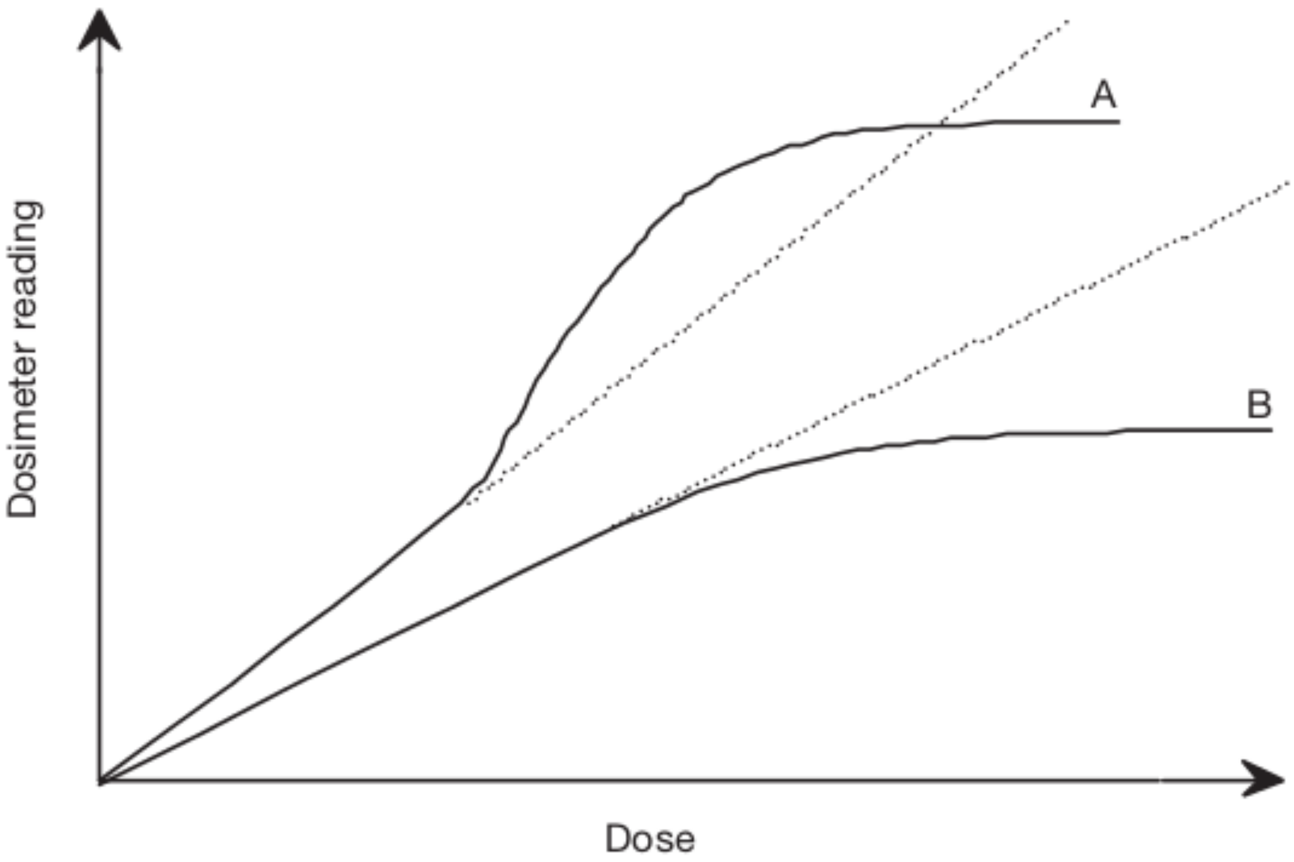
Quenching!



Kirby et al PMB 55 (2010)

Linearity of a dosimeter



A: Supralinearity and saturation
B: Sublinearity / saturation

Relative Effectiveness

Different types of radiation produce different effects for the same endpoint.

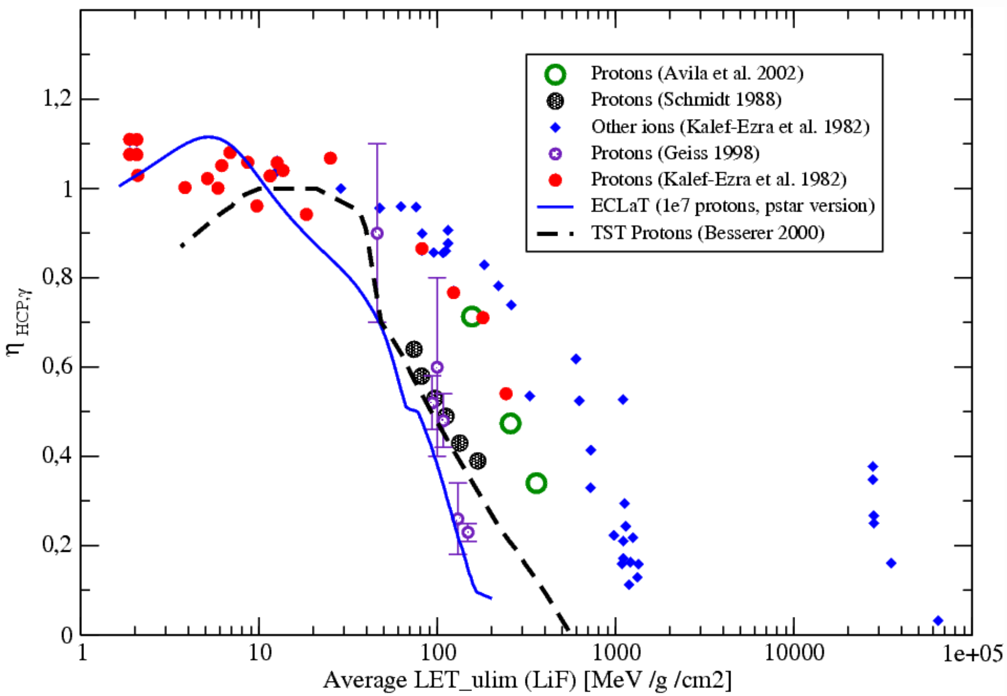
“Relative effectiveness” characterizes this effect and is usually defined as :

RE = D_{γ},isoeffect / D_{ion},isoeffect

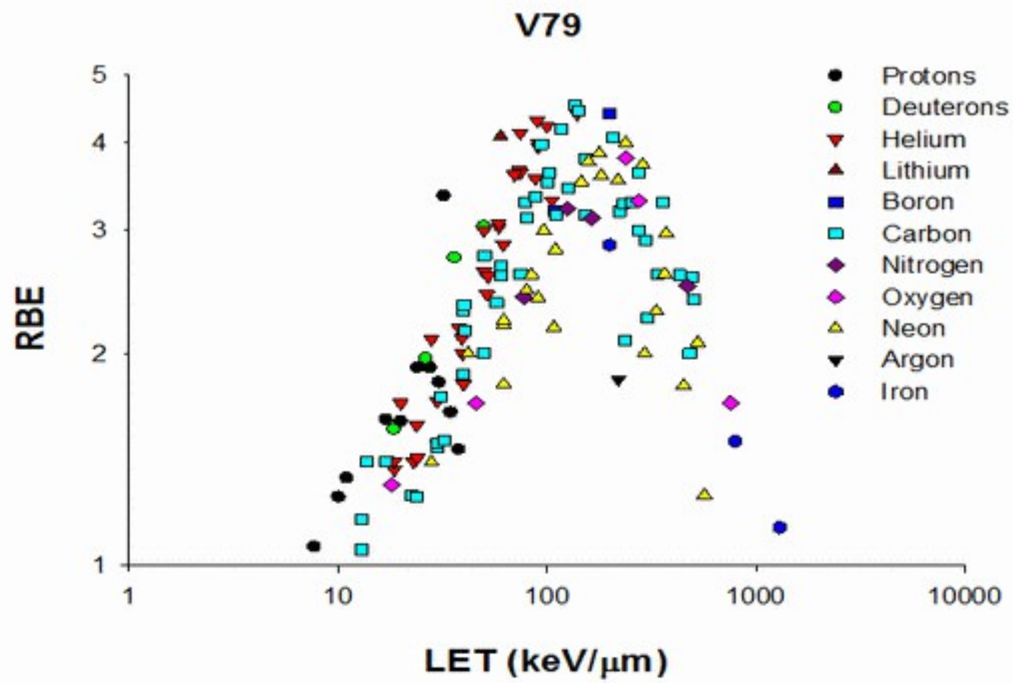
$$\eta_{Q_0,Q} = \left.\frac{D_{Q_0}}{D_Q}\right|_{\mathrm{iso-effect}}$$

$$\mathrm{RBE} = \left.\frac{D_{Q_0}}{D_Q}\right|_{\mathrm{iso-effect}}$$

Detectors



Radiobiology



$$\eta_{Q_0,Q} = \left.\frac{D_{Q_0}}{D_Q}\right|_{\text{iso-effect}}$$

$$\text{RBE} = \left.\frac{D_{Q_0}}{D_Q}\right|_{\text{iso-effect}}$$

... same thing

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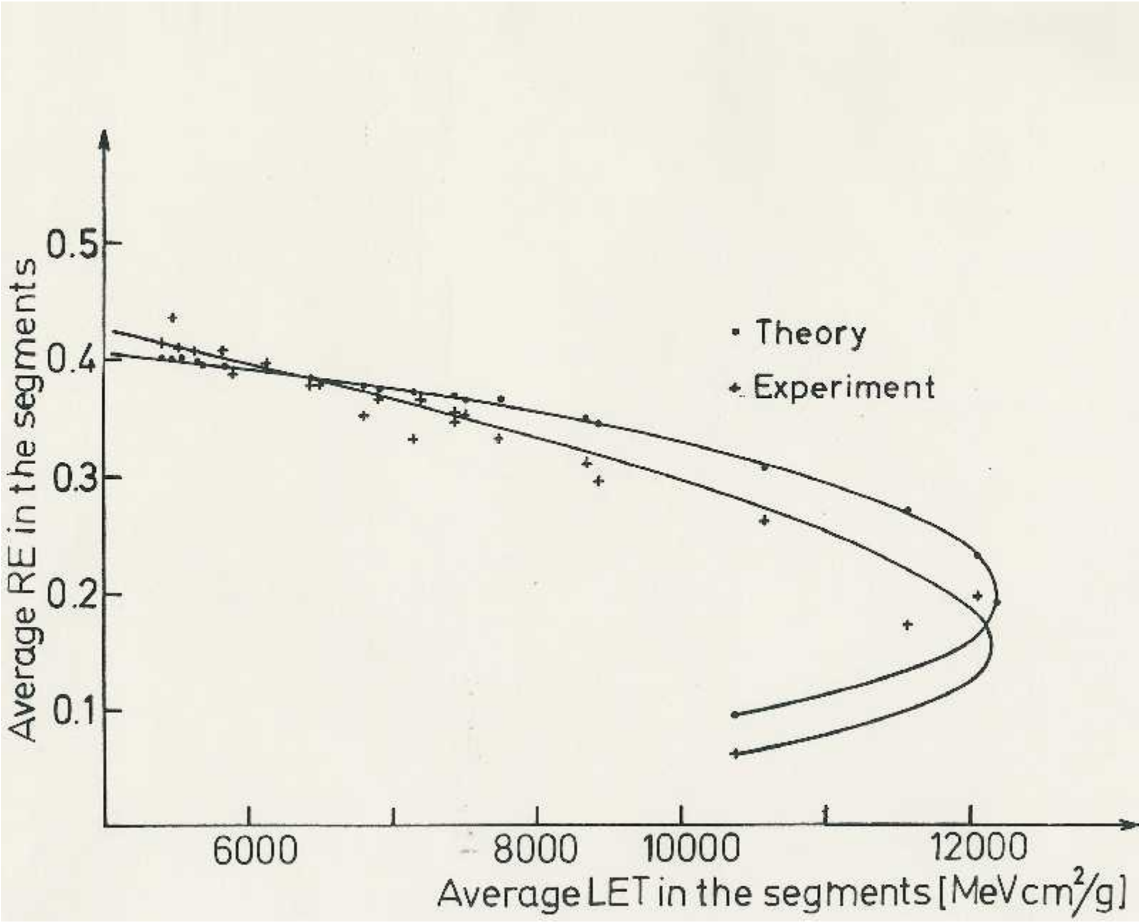
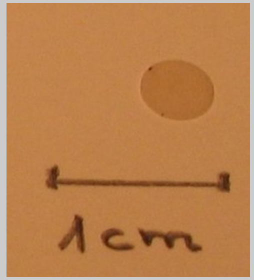
RE show no single valued dependence



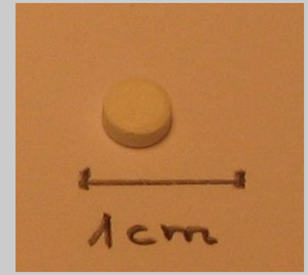
Good and Bad detectors

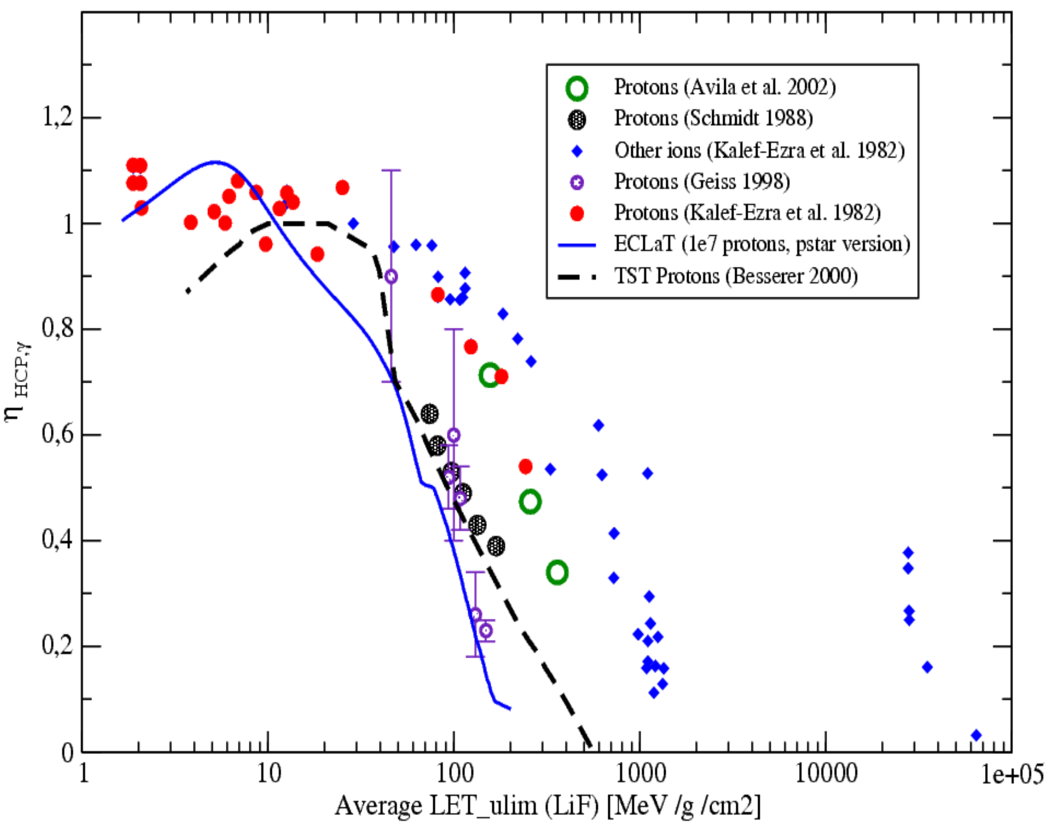
TLDs

^{7}LiF and ^{6}LiF

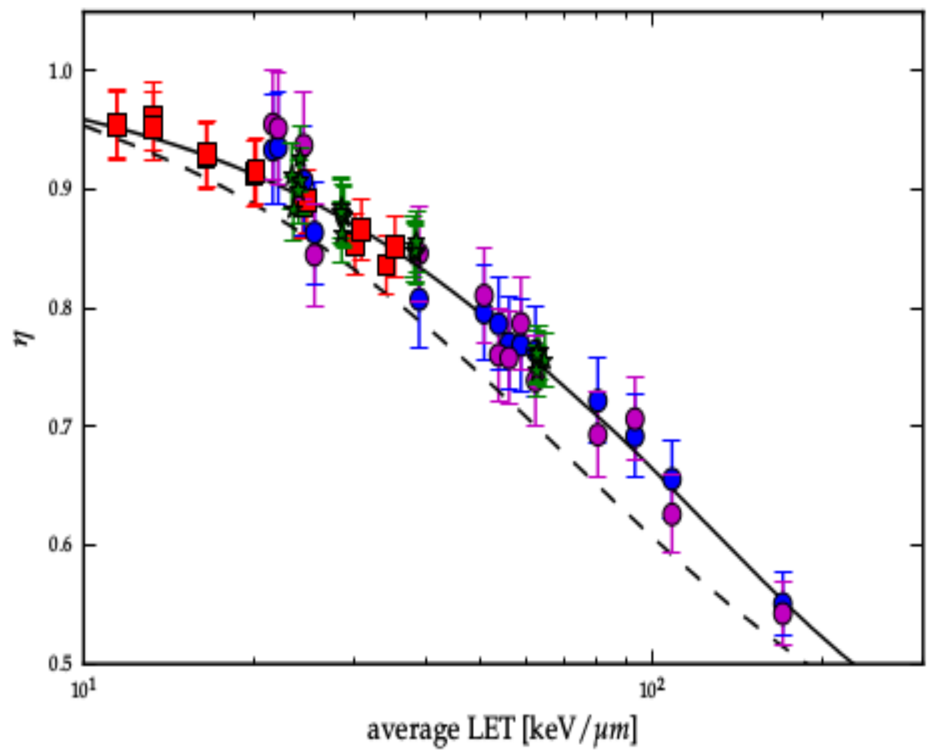


Alanine





Herrmann, PhD Thesis, C-12 ions



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Effectiveness do not add linearly

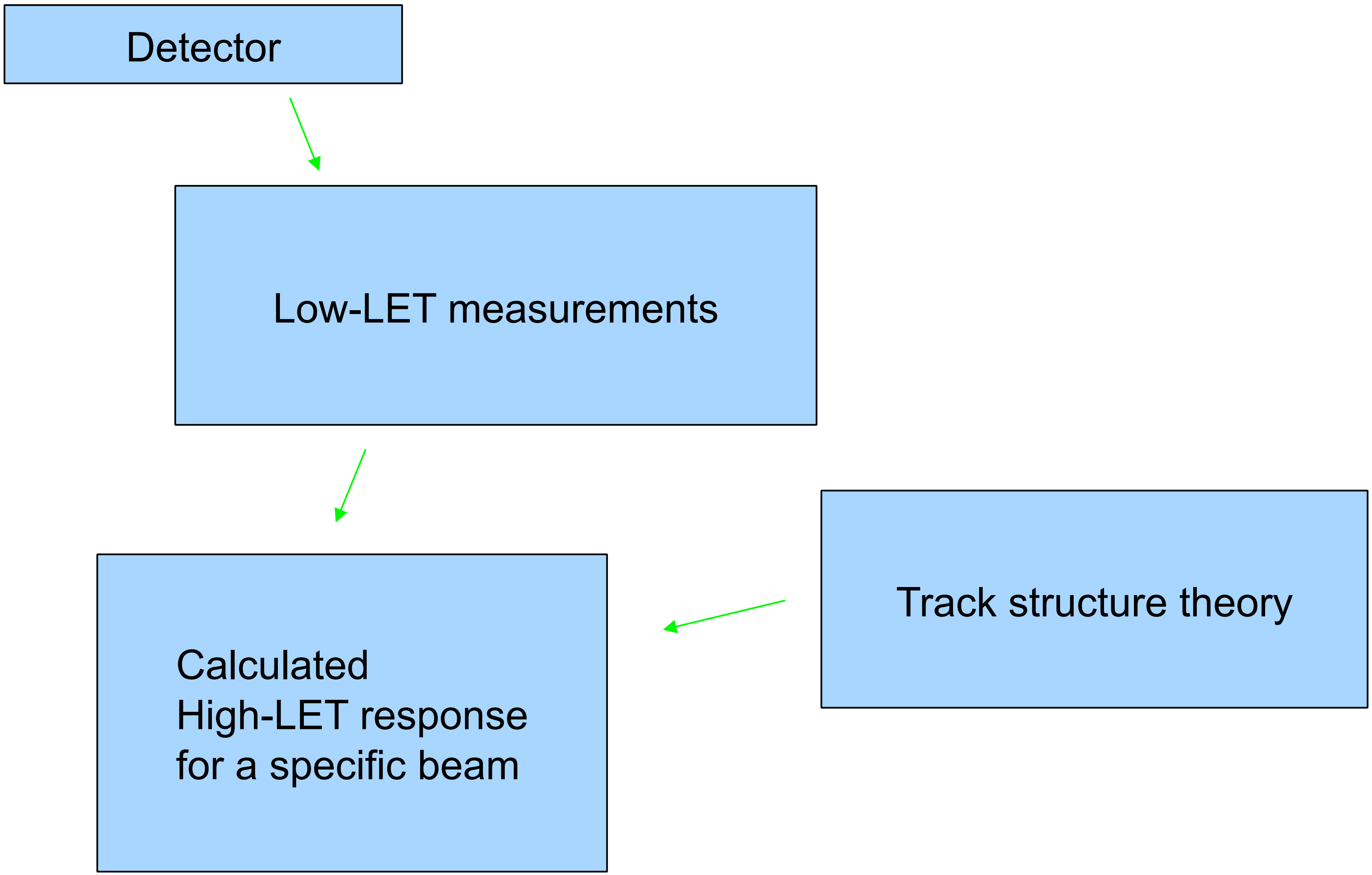
D(proton)*RE + D(carbon)*RE

!=

D(proton+carbon)*<RE>

=> calibration of entire parameter space unfeasible!

Modelling of RE



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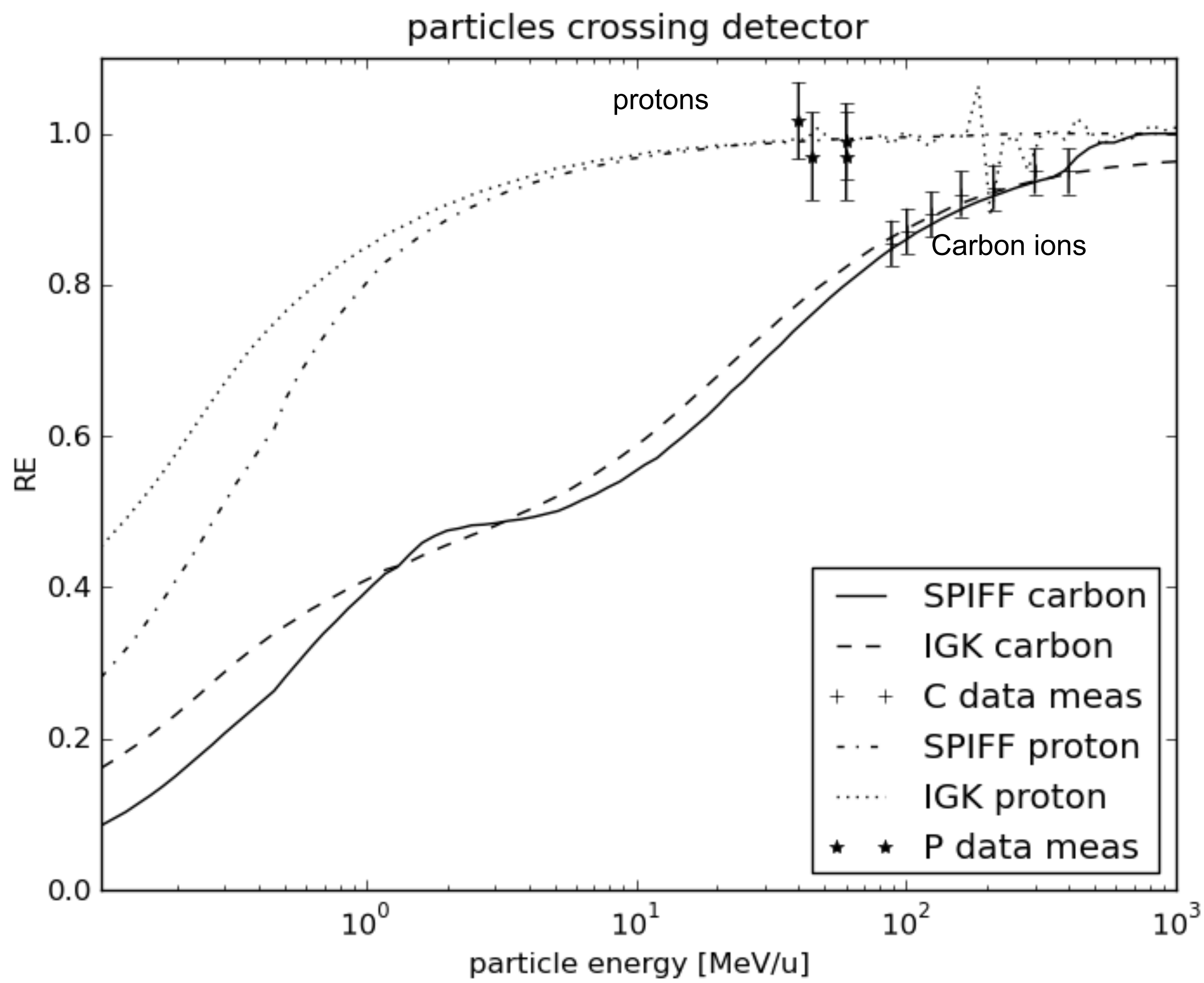
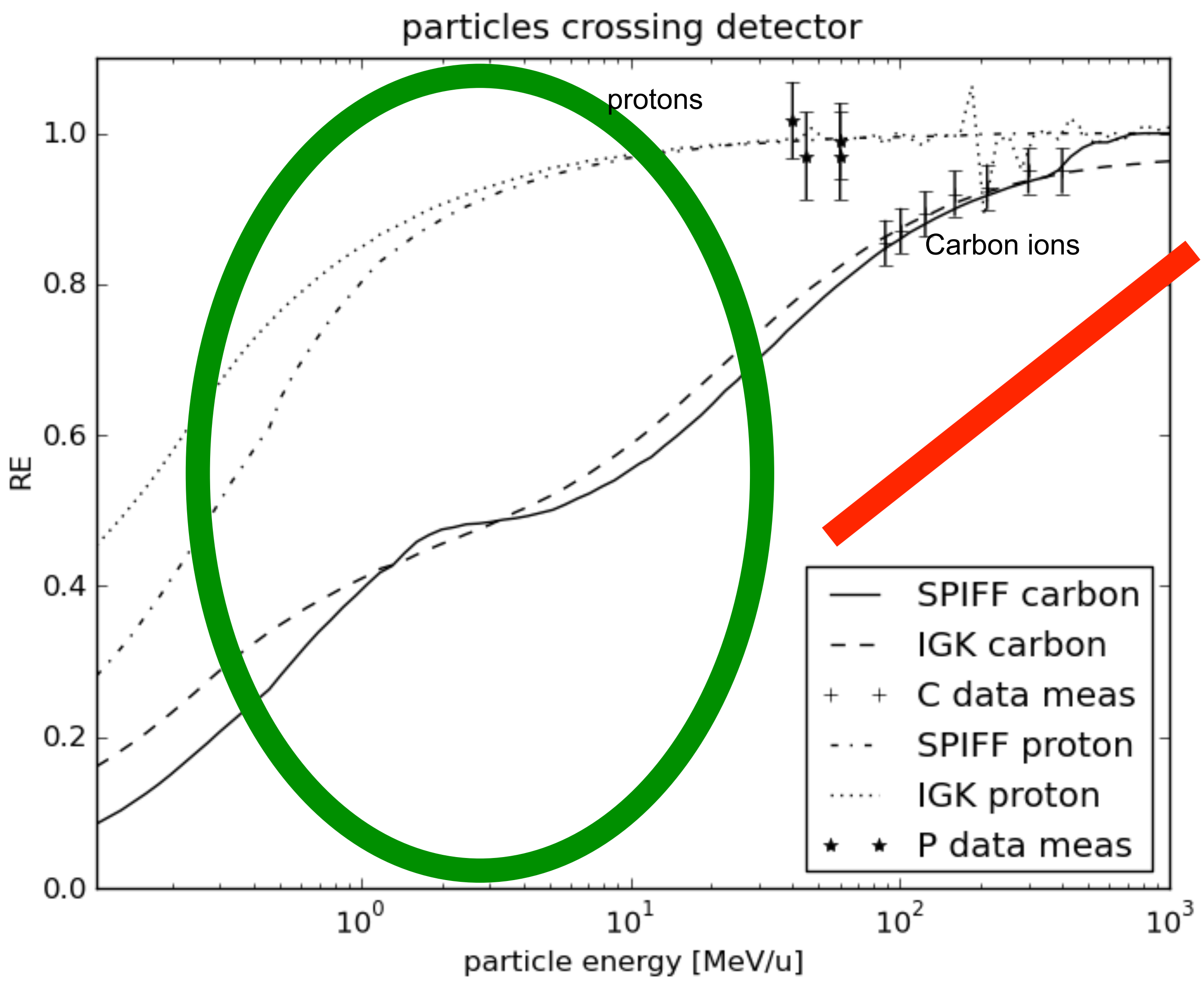
Current situation for Alanine:



Lines represent various models from libamtrack.

Dots are experimental data.

Our current situation for Alanine:



Lines represent various models from libamtrack.

Dots are experimental data.

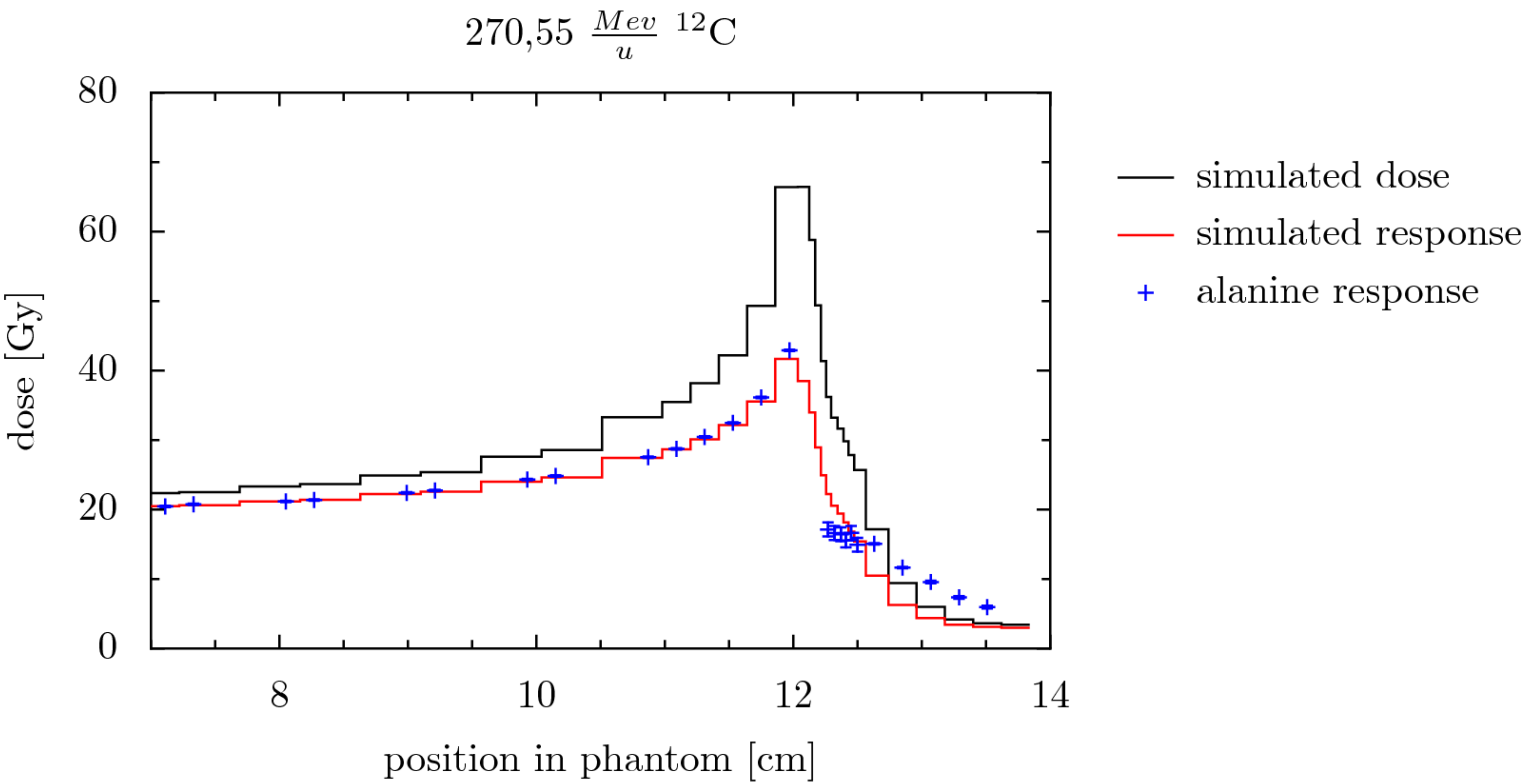
From this graph, you may see that we need two kinds of data:

1) Very low energies

2) higher-LET than for carbon ions

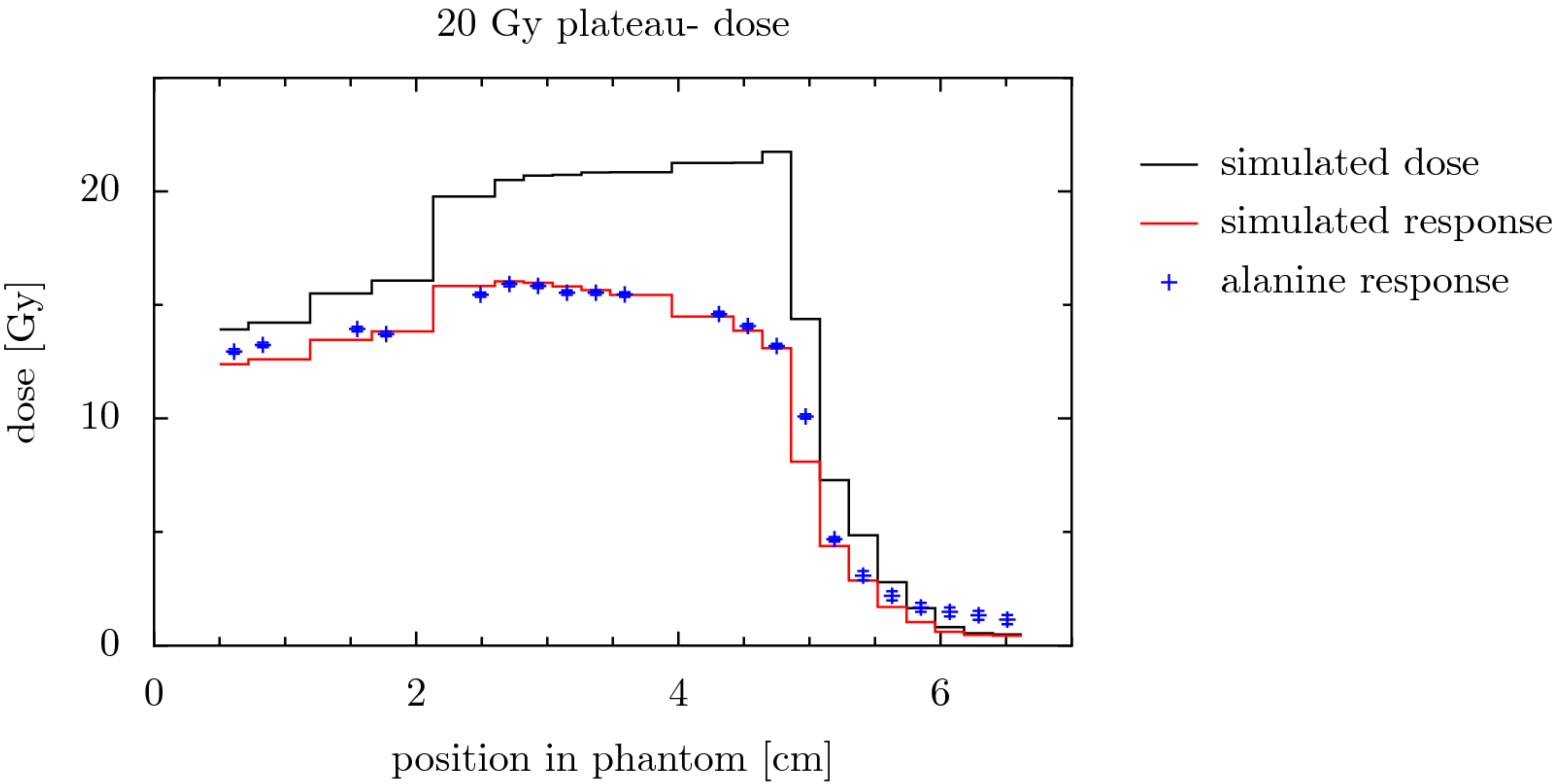
Think BioLEIR

Carbon ion pristine peak



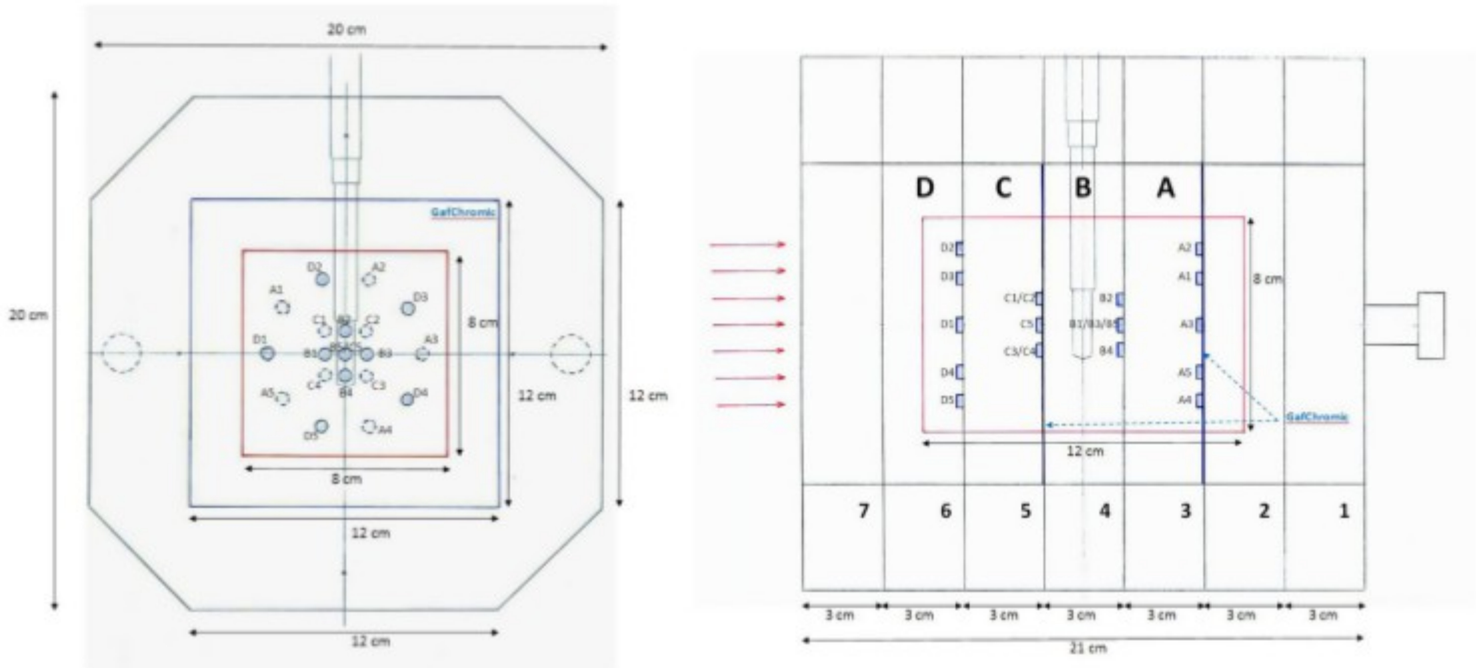
All dose values are absolute. (!!)

ALANINE: SOBP Carbon ions

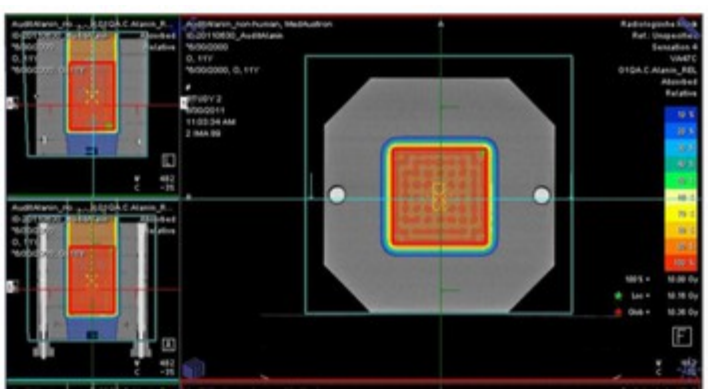


All dose values are absolute. (!!)

Dosimetry Audit



(a) (b)



Phantom loaded with Alanine and films, designed to check whether a Gray is a Gray is a Gray...

(Ableitinger et al, R&O 2013)

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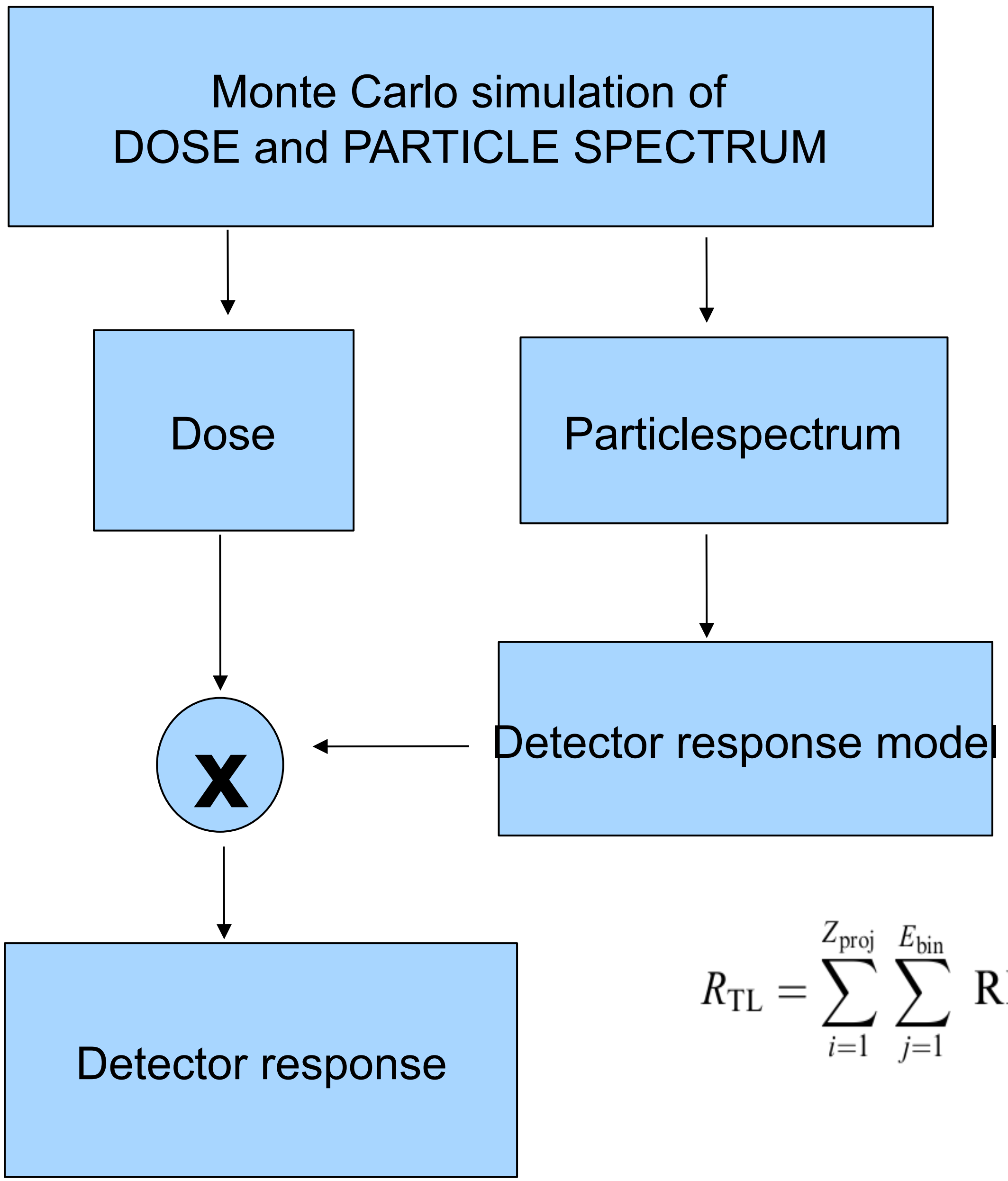
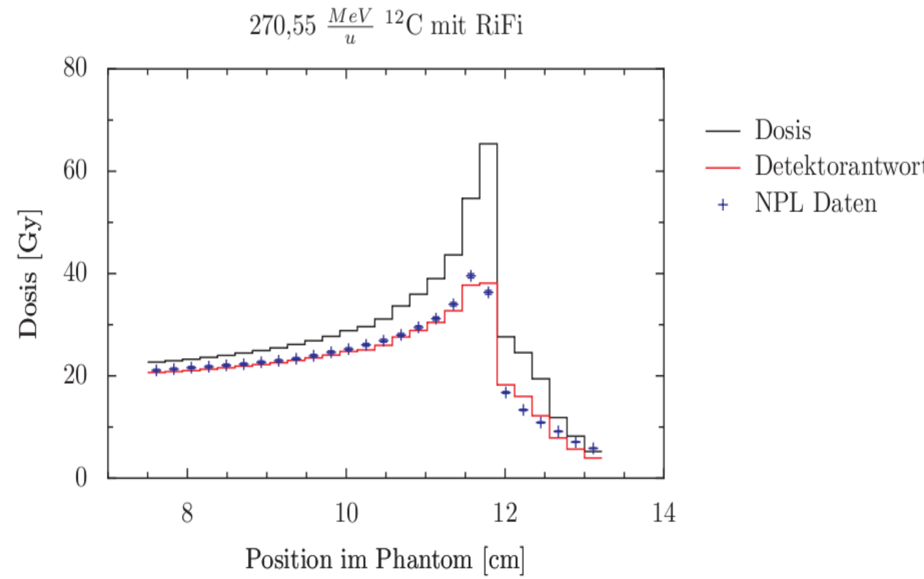
Simple Detector Response Modeling





R. Herrmann *(in preparation)*

Model independent of dose(fluence)

-> neglection of track-overlap

Spec. components are additive

$$R_{\mathrm{TL}} = \sum_{i=1}^{Z_{\mathrm{proj}}} \sum_{j=1}^{E_{\mathrm{bin}}} \mathrm{RE}(E_j, Z_i)\phi[E_j, Z_i] \frac{1}{\rho} \frac{\mathrm{d}E}{\mathrm{d}x}(E_j, Z_i)$$

$$D_{\mathrm{TL}} = \sum_{i=1}^{Z_{\mathrm{proj}}} \sum_{j=1}^{E_{\mathrm{bin}}} \phi[E_j, Z_i] \frac{1}{\rho} \frac{\mathrm{d}E}{\mathrm{d}x}(E_j, Z_i)$$

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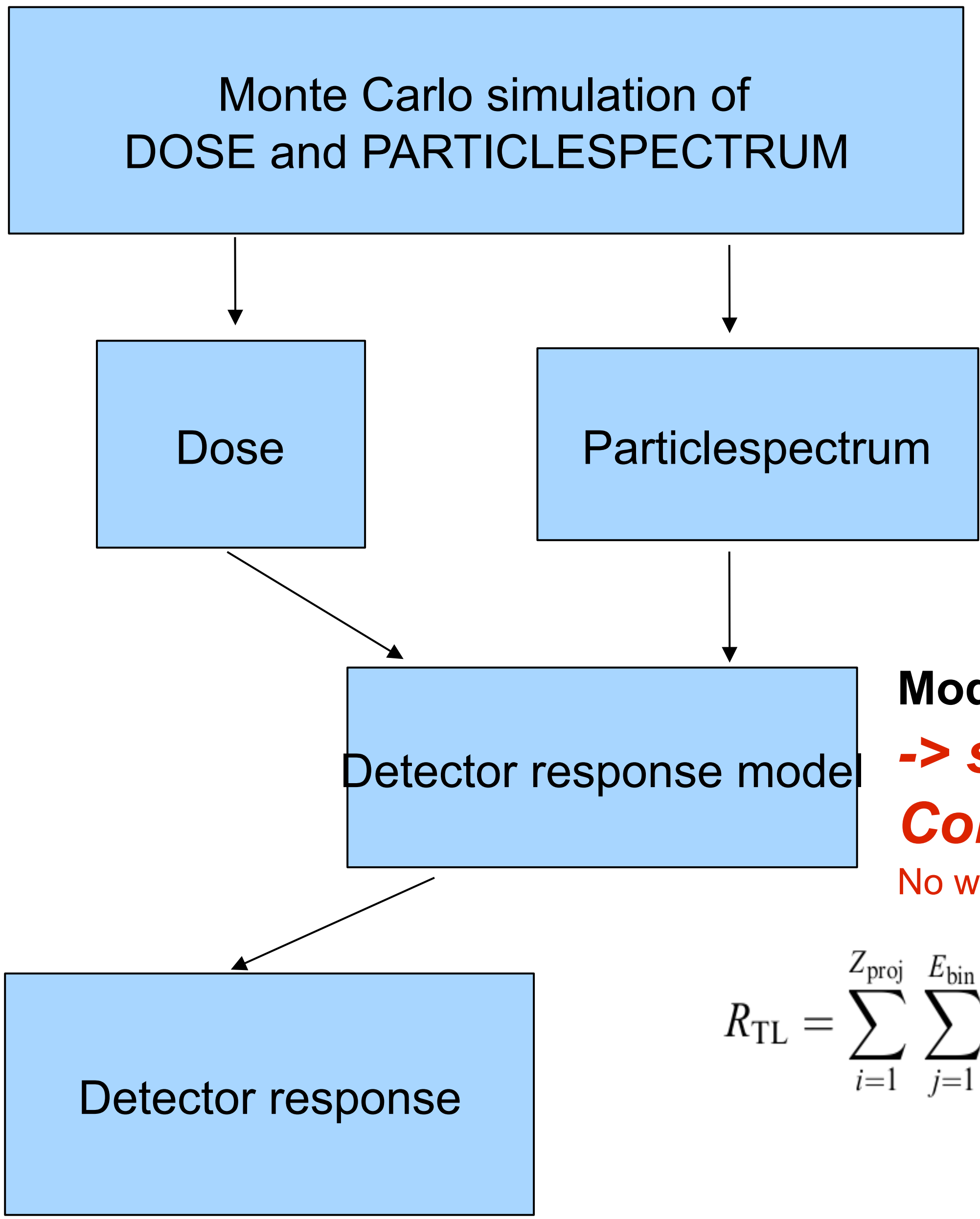
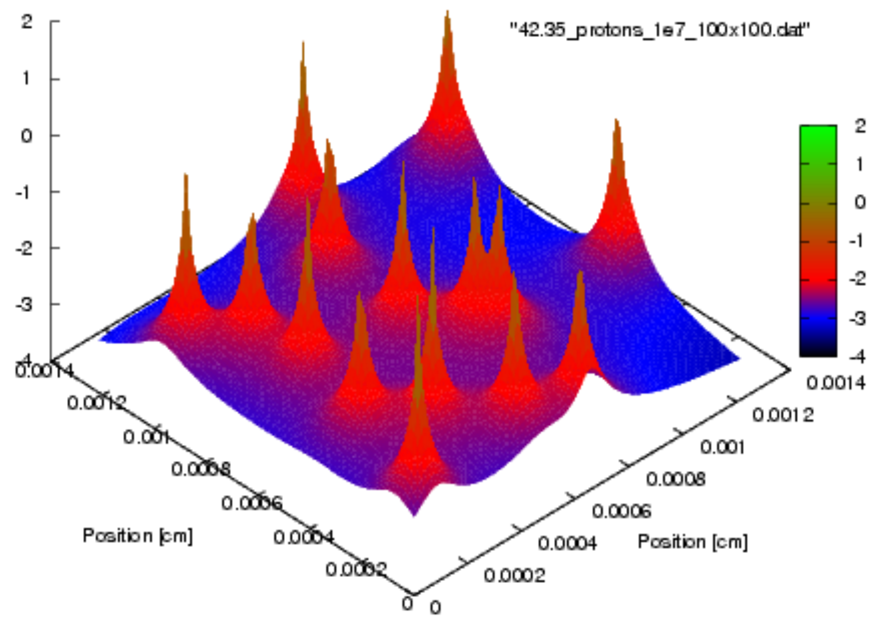
Advanced Detector Response Modeling





Model depending on dose (fluence)

-> simulation of overlapping ion tracks

Components are not additive

No way to calibrate entire parameter space (just like radiobiology)

$$R_{\mathrm{TL}} = \sum_{i=1}^{Z_{\mathrm{proj}}} \sum_{j=1}^{E_{\mathrm{bin}}} \mathrm{RE}(E_j, Z_i)\phi[E_j, Z_i]\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x}(E_j, Z_i)$$

$$D_{\mathrm{TL}} = \sum_{i=1}^{Z_{\mathrm{proj}}} \sum_{j=1}^{E_{\mathrm{bin}}} \phi[E_j, Z_i]\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x}(E_j, Z_i)$$

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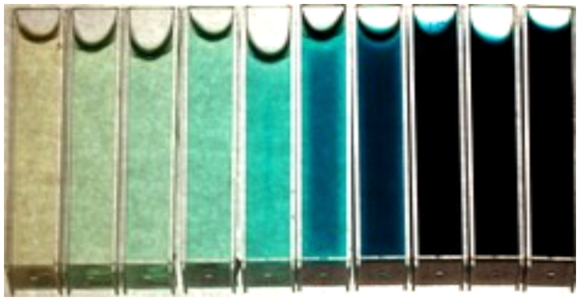
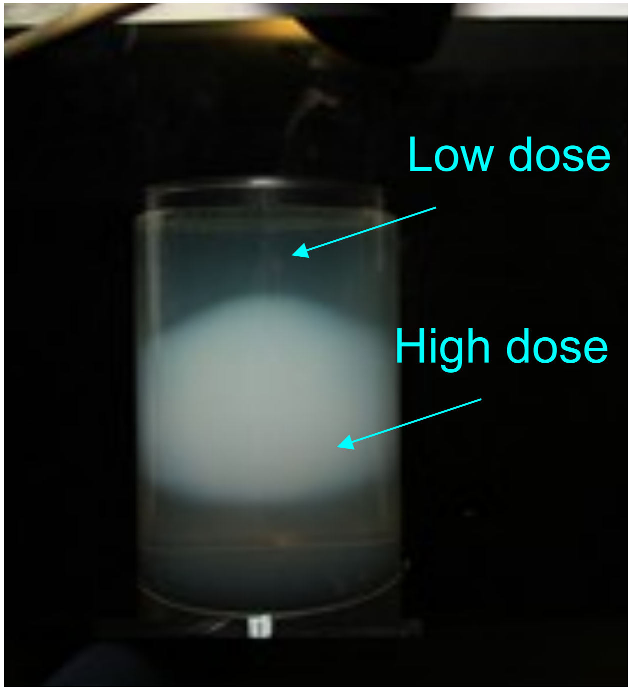
3D dosimeters

Gel Dosimeters



Increasing dose



- Top: Radiochromic
- Bottom: Polyremiyation
  - Almost water equivalent
- Dose verification in complex fields (IMRT, stereotactic, anatomically shaped phantoms, brachytherapy...)

Requires knowledge of LET response

(Courtesy Peter Skyt)

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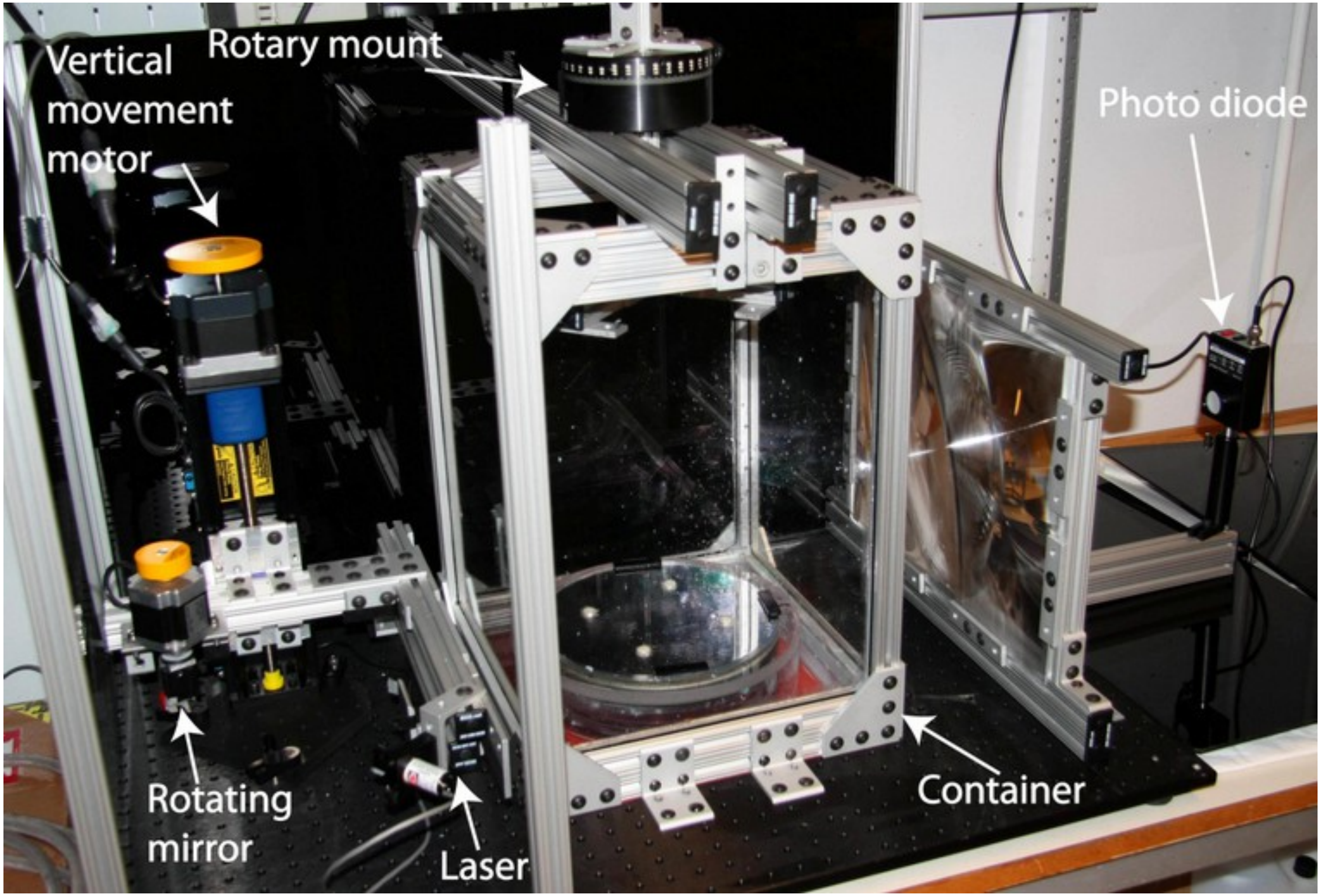
Optical CT scanner



Resolution 1mmx1mmx1mm (Courtesy Peter Skyt, Aarhus Universtiy)

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Measure new quantities

Can we have an online detector, which...

measures **dose** and **LET**

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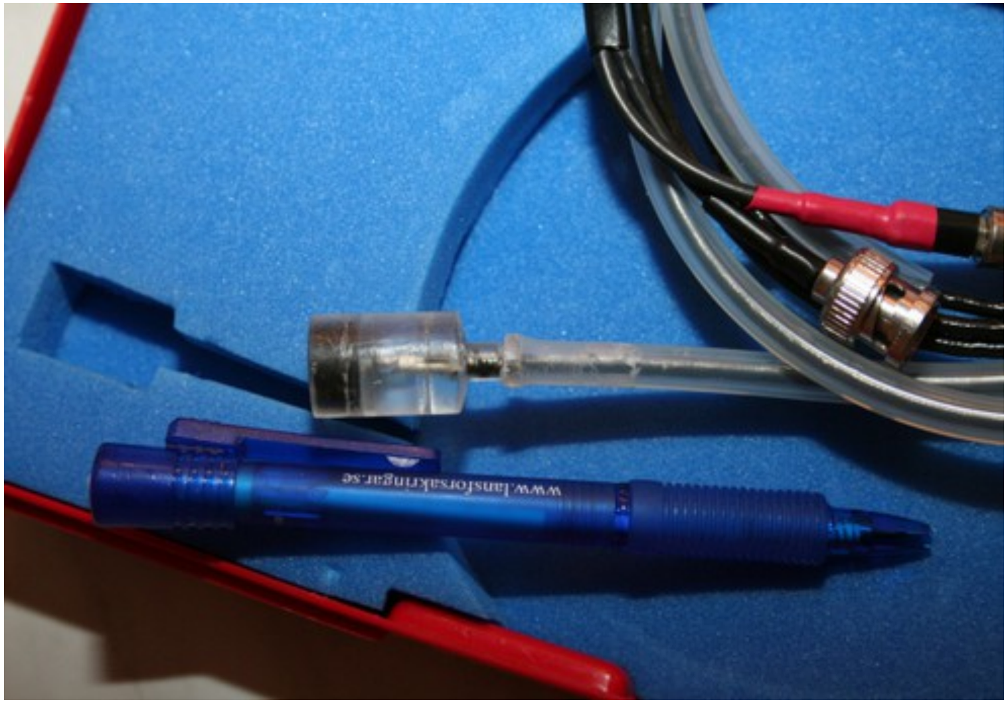
Liquid Ionization Chambers

LICs: ICs with high spatial resolution

LICs are LET sensitive, idea to develop a radiation quality detector, a **"LET-o-meter"**

Testing LICs in heavy ion beams with wide range of LETs (higher than what can be reached with carbon ions)



(Courtesy, Heikki Tölli)

Kaiser et al. Radiat. Meas. 45 (2010)

S. Tegami PhD Thesis (2013)

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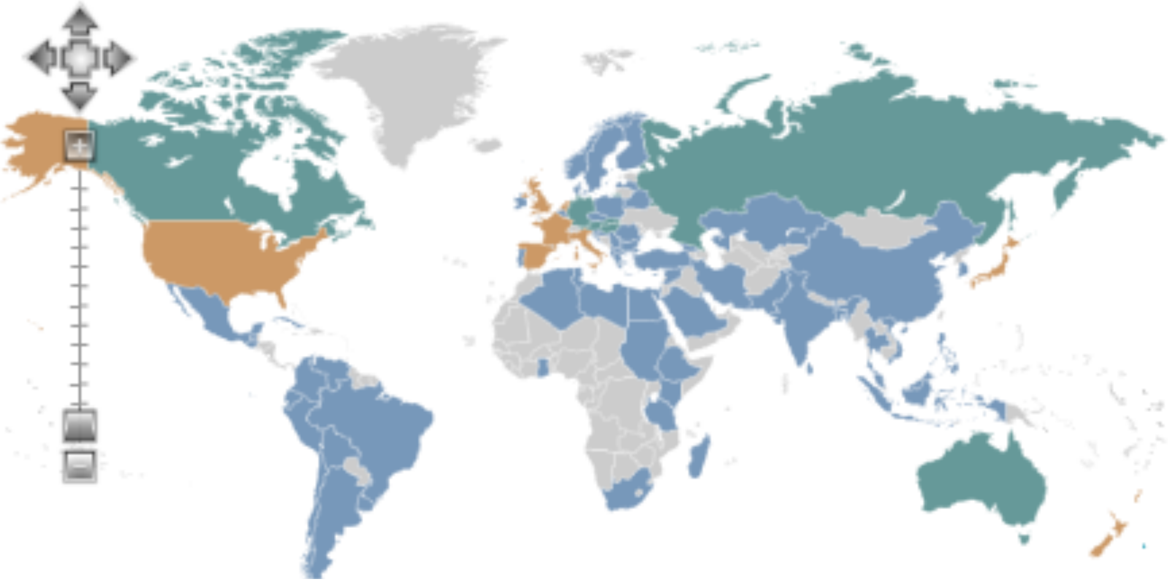
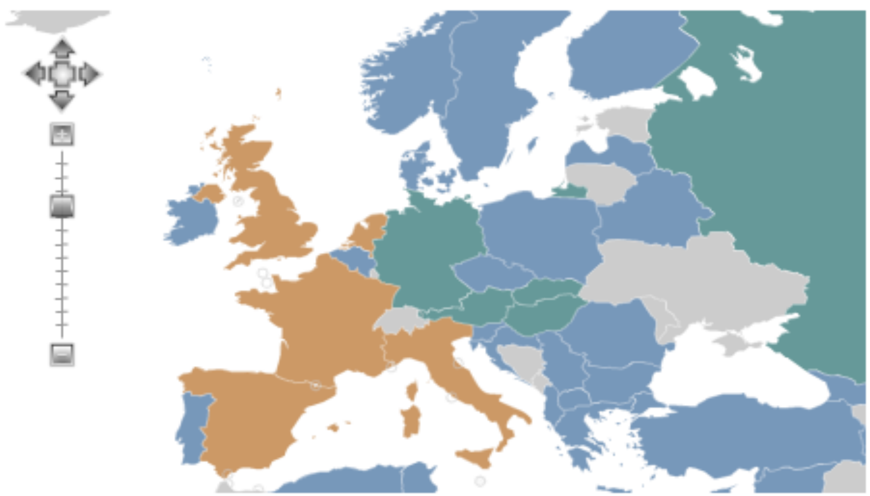
Primary standards

PSDLs and SSDLs



SSDL traceable to PSDL (Such as National Physical Laboratory, NPL or PTB in Germany).

All I-chambers calbrated in photon beams.



SSDL network member
SSDL member and affiliated PSDL
PSDL affiliated member

http://www-naweb.iaea.org/nahu/dmrp/SSDL/default.asp

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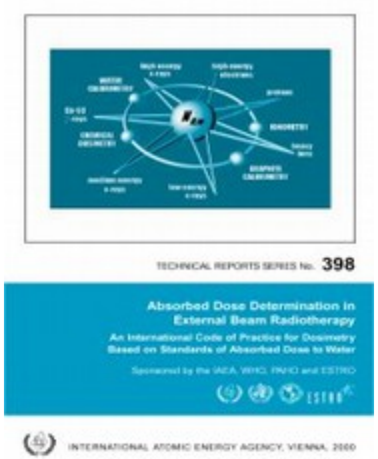
PSDLs and SSDLs

Primary standard for absorbed dose to water

- Calorimeter
  - Graphite or water
- Chemical using Fricke solution
  - (1mM $FeSO_4$ or $Fe(NH_4)_2(SO_4)_2$ + 0.8N H_2SO_4 air saturated + 1mM NaCl) Fe^{2+} oxydizes to Fe^{3+}, which absorbes at 304 nm
  - Used e.g. at the German PSDL (PTB Braunschweig)



$$D_{w,Q} = M_Q N_{D,w,Q_o} k_{Q,Q_o}$$

Radiation qualtiy at calibration: Q_0 - ALL PHOTONS ONLY

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Could CERN develop a primary standard device for ions?

More topics...

- MRI and ion beams … dosimetry in strong magnetic fields
- systematic measurement of detector perturbation factors for dosimetry protocols
- fundamental testing of cavity theories, transport theories
- testing of water and tissue-equivalence of phantom materials
- mimicking other beams, e.g. high-dose per pulse or particular pulse structure of beams
- systematic micro- and nano-dosimetric/track structure measurements
- development and study of dose enhancement methods for ion beams (nanoparticles, etc.)

(H. Palmans)