Amorphous track models: a numerical comparison study

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Motivation: luminescence dosimetry

- Luminescence is 'cold light' emission, e.g. under ionizing radiation.
- Radioluminescence (RL) and optically stimulated luminescence (OSL) can be related to dose-rate and absorbed dose.
- Al_2O_3:C crystals on optical fibres can be used for active and passive *in-vivo* dosimetry in radiotherapy treatments and diagnostics (Figs. 1).
- In particle beams, detector efficiency (light output per dose, dose-rate) becomes dependent on particle type and energy (LET, Fig. 2).

→ **For application in mixed or unknown radiation fields or the use as an LET-meter, we want to predict this dependency.**

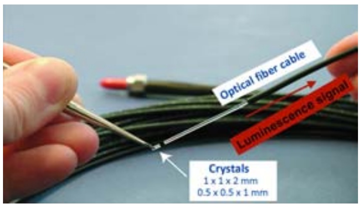

Figure 1: Fiber dosimeters with Al_2O_3:C single crystals.

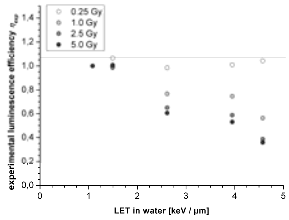

Figure 2: Example of relative RL efficiency dependent on LET and dose (measured at PSI proton beam-line).

Amorphous track models (ATMs)

- ATMs can be used for prediction of solid state detector efficiency in heavy charged particle beams, i.e. also for Al_2O_3:C.
- Their basic approach:
  - Replaced the detailed track structure by an average 'radial dose distribution' (Fig. 3).
  - Suppose the local effect of radiation is equivalent for photons and particles.
- The main computational task: combine local dose distribution (from particle field) with known detector response under photon (gamma or X-ray) irradiation to obtain particle response / efficiency (Fig. 4).

→ **However: several types of ATMs and many submodels around, sometimes with fierce discussion on their benefits — for one's own situation, how to know which one performs best when?**

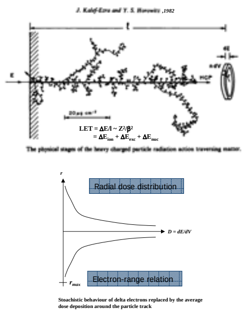

Figure 3: Reduction of detailed track structure.

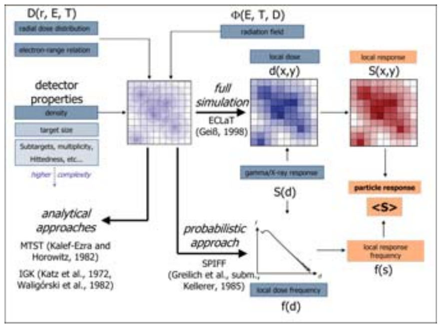

Figure 4: Schematic of the basic approaches in AT modelling.

The libamtrack project

- The program library 'libamtrack' is intended to faciliate the application of and the comparison between different ATMs and their submodels.
- It is open-source, portable, and can be freely downloaded at:

  libamtrack.dkfz.org

- Tabs. 1-4 and Figs. 5-7 give an overview on presently implemented models.

→ **libamtrack is a generic ATM library — we use it for Al_2O_3:C luminescence dosimetry as a test-case here, but it can be applied to almost any solid state dosimeter response.**

→ **ATMs are also popular for computation of cell survival and RBE in particle beams — and are used clinically today.**

Name	Description	Reference
Ion-Gamma-Kill (IGK)	Get activation cross-section by fusing photon response (activation probability) and RDD, get particle response by cross-section and fluence (ion-kill, intratrack action), for multi-hit systems and lower LET consider also intertrack action (gamma kill).	Waligórski, 1980
Grid summation (GSM)	‚Throw' of particle tracks on a Cartesian grid for local dose, apply photon response for local response, then average response.	Geiß et al., 1998
SPIFF	Derive local dose frequency distribution analytically from RDD for single particle case, assume ‚none or one'-impact situation for low fluence, convolute resulting distribution with itself until desired high fluence / dose is reached, apply photon response.	Greilich et al., subm.
SPISS	Derive local dose frequency distribution analytically from RDD for single particle case – as for SPIFF. But then use statistical sampling to add single impact doses according to relative fluences in the particle field.	Greilich et al., subm.

Table 1: ATMs in libamtrack.

Name	Expression	Reference
Test	$d(r) = c \cdot \Theta(-r_{\max})$	*simple step function*
Katz' point	$d(r) = \frac{N_e \cdot e^4}{m_e c^2} \cdot \frac{1}{\rho_m} \cdot \frac{z^2}{\beta} \cdot \frac{1}{\alpha} \cdot \frac{1}{r^2} \cdot \left(1 - \frac{r}{r_{\max}}\right)^{\alpha^{-1}} = d_{\text{point}}(r)$	Zhang et al., 1985
Katz' extended target	$d(r) = \frac{1}{A} \int_{\lvert r-a_0 \rvert}^{\lvert r+a_0 \rvert} 2 \cdot \phi \cdot \hat{r} \cdot d_{\text{point}}(\hat{r}) \cdot d\hat{r}$	Waligórski, 1988
Site	$d(r) = c \quad [r < a_0] \quad d(r) = d_{\text{point}}(r) \quad [\text{otherwise}]$	Hansen and Olsen, 1984
Geiß	$d(r) = c \ \ [r < a_0]; \quad d(r) = \frac{c}{r^2} \ \ [a_0 \le r \le r_{\max}]; \quad d(r) = 0 \ \ [r > r_{\max}]$	Geiß et al., 1998

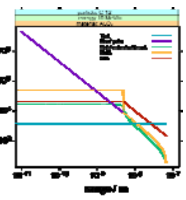

Table 2 / Figure 5: Radial dose distributions (RDDs) in libamtrack.

Name	Expression	Reference
Butts and Katz	$r_{\max}/(\text{g}\cdot\text{cm}^{-2}) = 10^{-6} \cdot w/\text{keV} \qquad w/\text{keV} = 2 \cdot m_e \cdot \left((E/E_0)^2 + 2(E/E_0)\right)$	Butts and Katz, 1967
Waligórski	$r_{\max}/(\text{g}\cdot\text{cm}^{-2}) = 6 \cdot 10^{-6} \cdot (w/\text{keV})^{\alpha} \qquad \alpha = 1.079\ (w < 1\,\text{keV}) \text{ or } 1.667$	Waligórski et al, 1986
Geiß	$r_{\max}/\text{cm} = 4 \cdot 10^{-5} \cdot (E/\text{MeV})^{1.5} \cdot (\rho_{\text{material}}/\rho_{\text{water}})$	Geiß, 1997
Scholz	$r_{\max}/\mu\text{m} = 0.05 \cdot (E/\text{MeV})^{1.7} \cdot (\rho_{\text{material}}/\rho_{\text{water}})$	Scholz, 2001

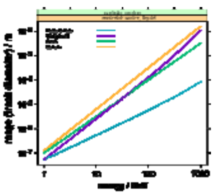

Table 3 / Figure 6: Electron range models (ERs) in libamtrack.

Name	Expression	Reference
Test	$S(D) = a \cdot D + b$	simple linear function
General hit/target	$S(D) = \left(1 - \sum_{k=0}^{c-1} \frac{(D/D_0)^k}{k!} \cdot e^{-(D/D_0)}\right)^m$	Dertinger and Jung, 1970
Radioluminescence	$S(D) = c_1 \cdot D + c_2 \cdot D^2 \quad [D < D_{\text{sat}}]$ $S(D) = c_3 + c_4 \cdot D \quad [D \ge D_{\text{sat}}]$	Andersen et al., 2006 Greilich et al., 2008
Exp.-saturation	$S(D) = c(1 - e^{-D/D_0})$	simplified case of general hit/target model
Linear-quadratic	$S(D) = e^{-\alpha \cdot D - \beta \cdot D^2}$	Chadwick and Leenhouts, 1973

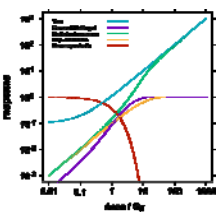

Table 4 / Figure 7: Photon response models in libamtrack.

Results

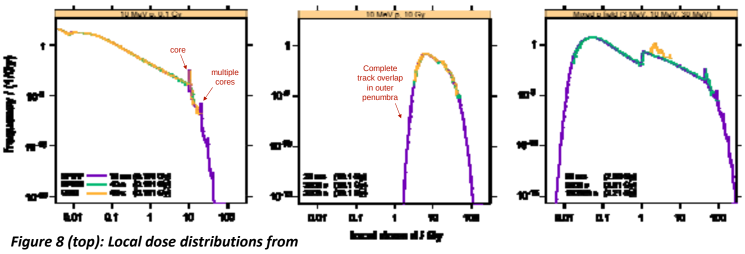

Figure 8 (top): Local dose distributions from several approaches using Geiß RDD (a_0 = 50 nm, Tabs. 1-4 for abbreviations) with Waligórski ER. SPIFF outclasses the SPISS and GSM algorithms both in speed and dose-span coverage (10^6 samples / voxels for 0.1 Gy, 10^5 for 10 Gy, 10^3 (GSM) / 10^5 for mixed field; timing for 10^6). For the mixed field case, GSM clearly fails to generate the proper distribution due to the dominance of the 30 MeV particles (relative fluences: 0.3%, 1.5%, 98.2% corresponding to 0.05 Gy, 0.1 Gy, 3.0 Gy).

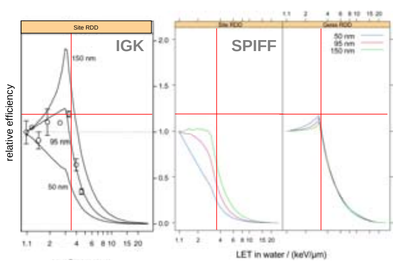

Figure 9 (right): Experimental data and model predictions for the proton beam OSL efficiency in an Al_2O_3:C fiber detector. Left panel: IGK using Site RDD (Edmund et al., 2007). Right panels: SPIFF. The chosen submodels seem to be at least as influential as the main approach.

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