High-Accuracy Ion Range Measurements using Fluorescent Nuclear Track Detectors

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INTRODUCTION

- **Fluorescent Nuclear Track Detectors (FNTDs)** (Fig. 1) are based on biocompatible single aluminium oxide crystals doped with carbon and magnesium (Al_2O_3:C, Mg).
- Their superior spatial resolution allows for **monitoring single particle tracks** with a detection efficiency close to 100% for ions with LET greater than approximately 0.2 keV/µm [1].

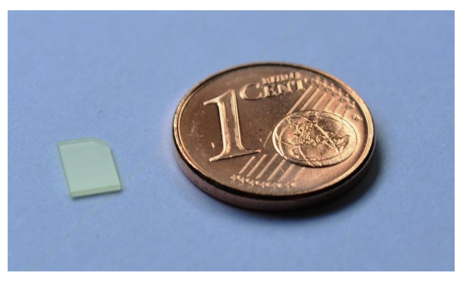


Fig. 1 *Size of a FNTD compared to a one cent coin*

- Implanted detectors or detectors in body cavities can help **accessing direct information on a radiation treatment** such as ion fluences, energies or ranges.
- We therefore measured ion ranges for particle beams of low and clinical fluence in order to investigate the **feasibility of future in-vivo FNTD applications**.

FNTDs

- Because FNTDs are grown in a highly reduced atmosphere, they contain **high concentration of clustered oxygen vacancy defects** charge compensated by magnesium ions substituting aluminium ions in the crystal lattice (Fig. 2).

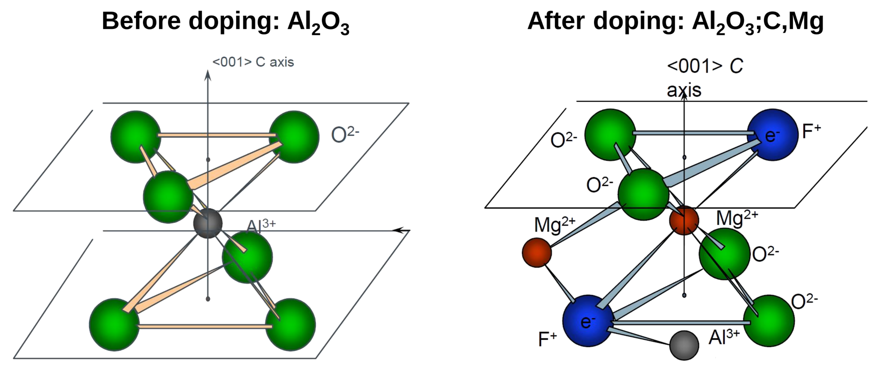


Fig. 2 *Crystal structure of corundum (left) and model of an aggregate oxygen vacancy defect (right); image courtesy of M.S. Akselrod (Landauer Inc.) [2]*

- Depicted $F_2^{2+}(2Mg)$ colour centres undergo **radiochromic transformation** under ionising radiation (Fig. 3) by capturing secondary electrons: $F_2^{2+}(2Mg) + e^- \longrightarrow F_2^{+}(2Mg)$.

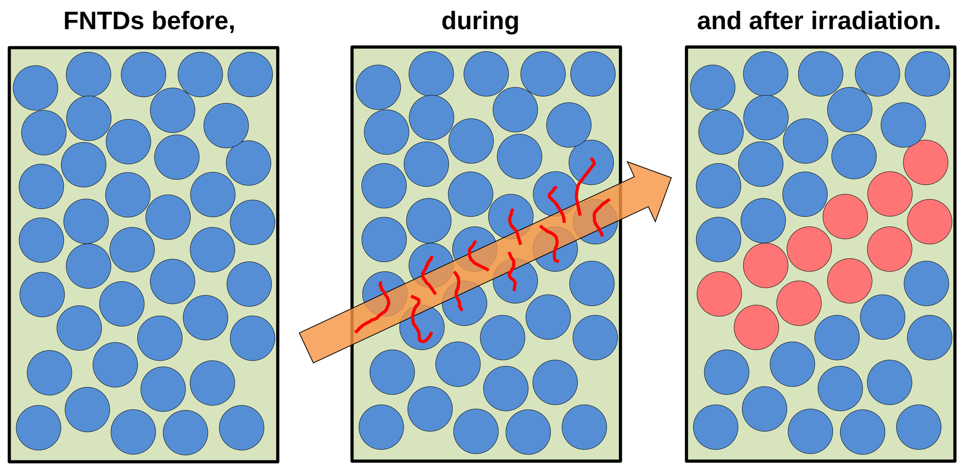
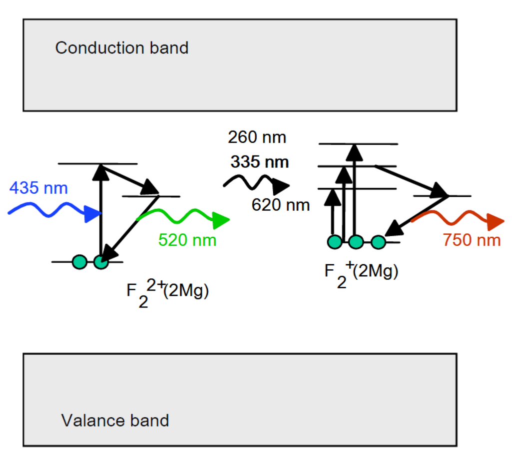


Fig. 3 *FNTD containing only untransformed colour centres (left); liberation and capture of secondary electrons under ionising irradiation (middle); radiochromic transformation (right)*

- Untransformed $F_2^{2+}(2Mg)$ (light blue) and untransformed $F_2^{+}(2Mg)$ colour centres (light red) have different absorption and emission bands (Fig. 4) which can be stimulated using **confocal microscopy**.



high quantum yield and short lifetime ($\tau = 75 \pm 5$ ns) [1]

Fig. 4 *Absorption and fluorescence of untransformed (left) and transformed colour centres; commercial confocal laser-scanning microscopy allows for fast and non-destructive detector readout; image courtesy of M.S. Akselrod (Landauer Inc.) [3]*

EXPERIMENT 1: Range measurements

FNTDs were irradiated with **mono-energetic ions** using a broad range of particle types (hydrogen to xenon), kinetic energies, and particle fluences Φ (from 4.5×10^5 up to 1.0×10^{11} cm^{-2}) (Fig. 5).

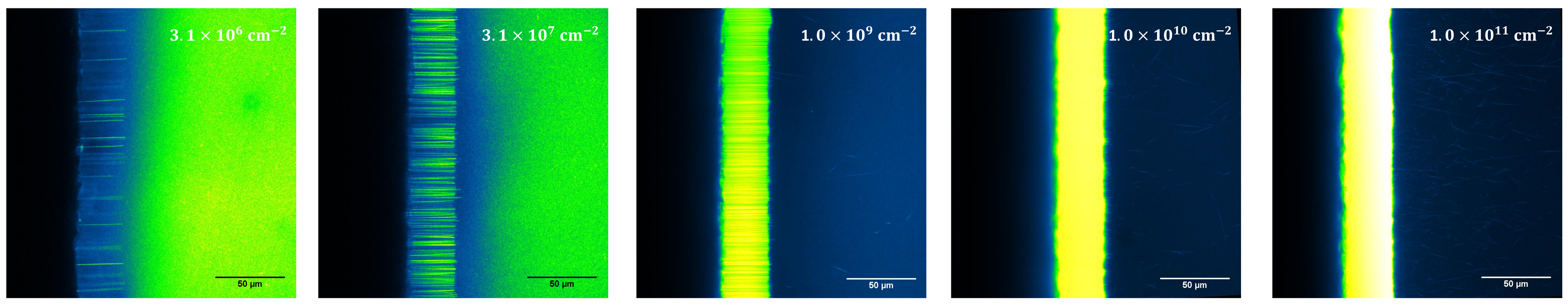


Fig. 5 *Comparison of carbon irradiated FNTDs; theoretical SRIM range of 33.05 µm [4] at a total kinetic beam energy of 48 MeV*

- **Single track evaluation ($\Phi < 10^7$ cm^{-2}):** determine entrance and end point individually for each particle track yielding projected range and lateral straggling; time-consuming but precise measurement routine
- **Track bulk evaluation ($\Phi > 10^7$ cm^{-2}):** determine inflection points in corresponding intensity profiles yielding projected range only; fast and automated measurement routine with the same level of precision (pinhole reduction advised for very high particle fluences)

All measured ranges deviate less than 3% from tabulated SRIM data [4] (Fig. 6). Measurement accuracy does not show any significant dependency on ion type, energy, fluence or LET.

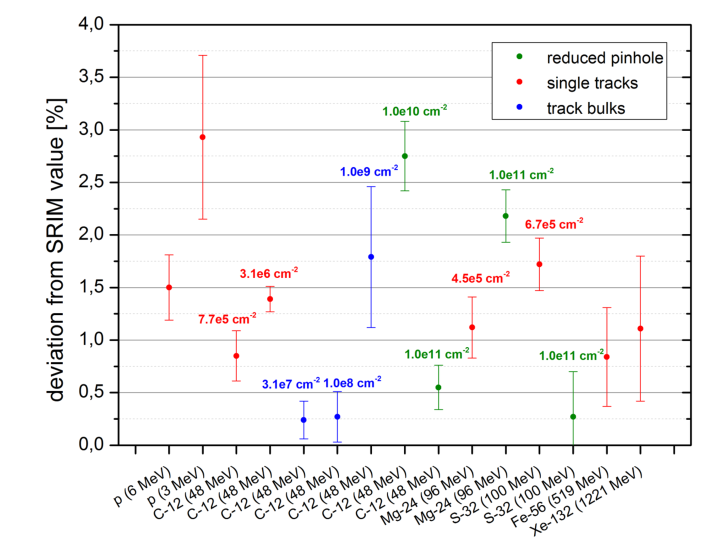


Fig. 6 *Results of the high-accuracy ion range measurements for mono-energetic particle beams of various ion sources; all deviations from theory below 3%*

EXPERIMENT 2: Absorbed dose measurements

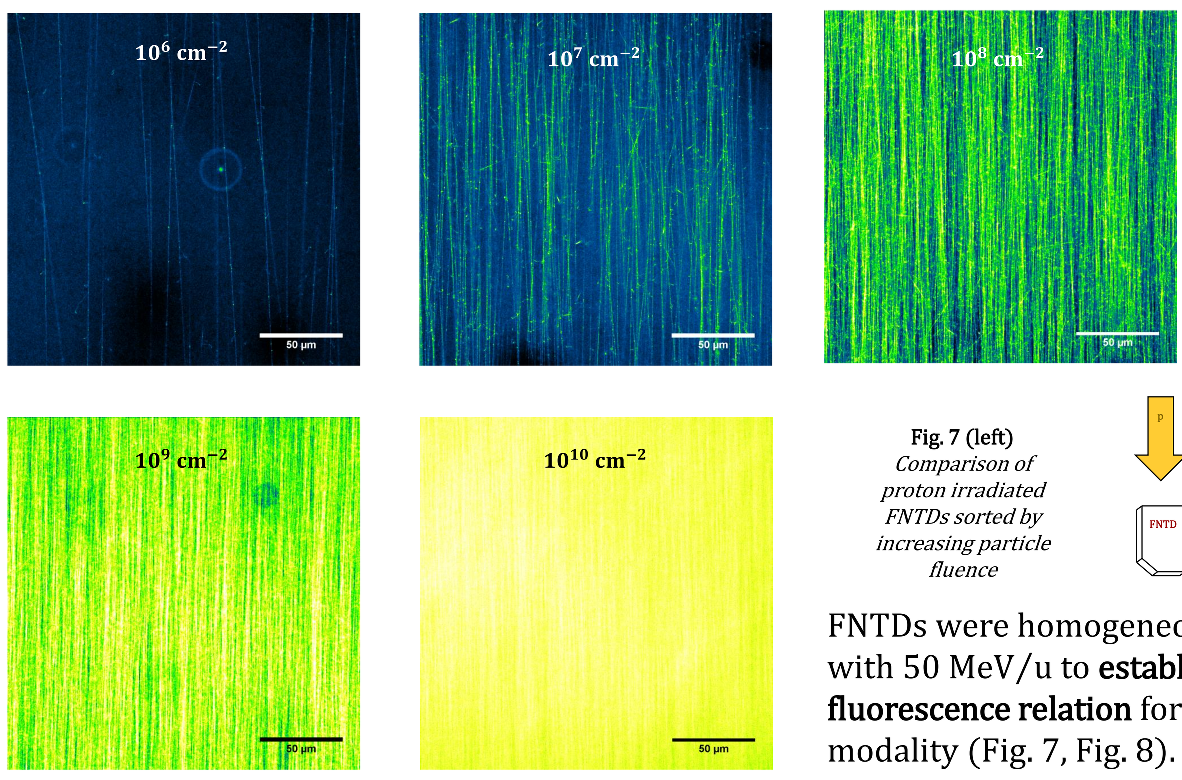
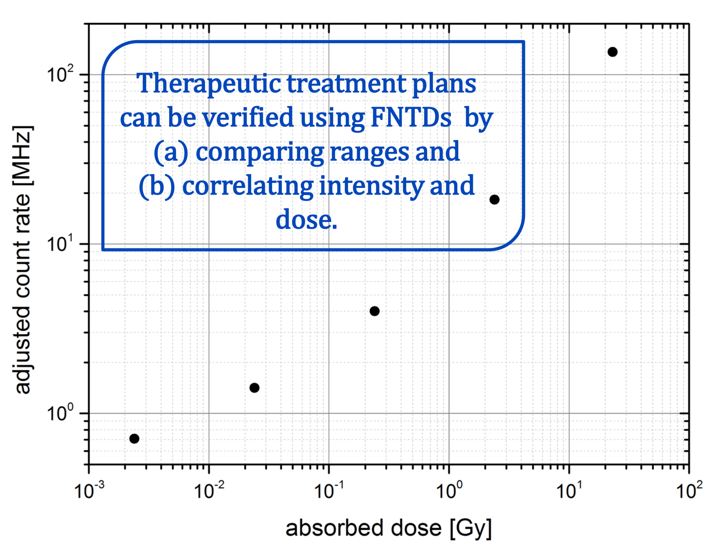


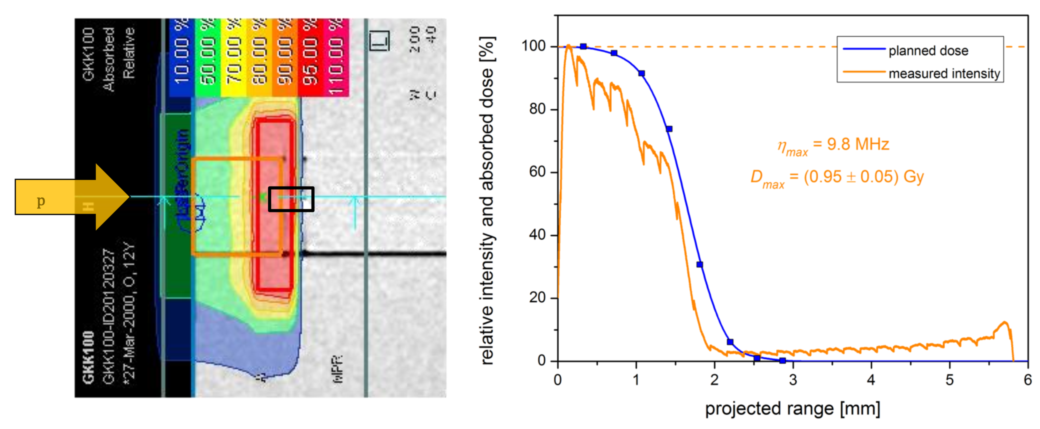
Fig. 7 (left) *Comparison of proton irradiated FNTDs sorted by increasing particle fluence*

FNTDs were homogeneously irradiated with 50 MeV/u to **establish a dose-fluorescence relation** for this treatment modality (Fig. 7, Fig. 8).

Fig. 8 (right) *Correlation between absorbed dose and fluorescence strength; obtained by taking the mean grey values of the images from figure seven*



EXPERIMENT 3: Treatment plan verification



FNTDs were placed in a PMMA cylinder as a phantom undergoing **clinical workflow**. Based on computed tomography (CT) scans, a treatment plan (applying 1 Gy protons at the detector edge) was created at HIT (Fig 9). The planned depth-dose curve at 80 % was compared to the detected intensity profile.

Detected and expected range agree within limiting CT slice thickness of 1 mm.

Correlating fluorescence strength and absorbed dose verifies the maximal planned dose.

FNTDs appear as potential fiducial marks in the CT.

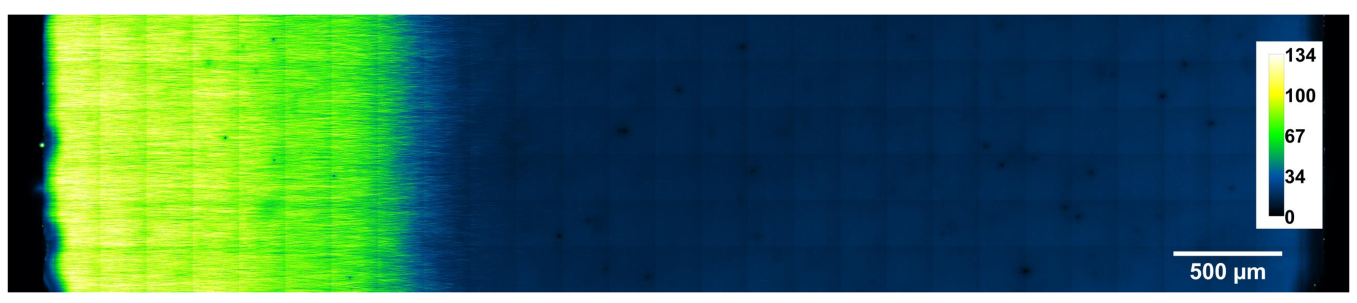


Fig. 9 *Results of the treatment plan verification: optimized dose distribution in the PMMA cylinder and the detector volume (black box) (top left); detected intensity distribution (bottom); comparison of planned depth-dose curve and detected intensity profile (top right). The equidistant minima seen in the intensity profile (Fig. 9) originate from microscope vignetting*

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