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Ion range measurements using fluorescent nuclear track detectors

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HIGHLIGHTS

- FNTD irradiation (3–9 MeV/u) covered a broad range of particles and fluences.
- All measured ion ranges deviate less than 3% from tabulated SRIM data.
- Detector irradiations at HIT serve as a precursor for FNTD in-vivo feasibility tests.

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ABSTRACT

Fluorescent nuclear track detectors (FNTDs) show excellent detection properties for heavy charged particles and have, therefore, been investigated in this study in terms of their potential for in-vivo range measurements.

We irradiated FNTDs with protons as well as with C, Mg, S, Fe and Xe ion beams (3–9 MeV/u) over a broad range of fluences (4.5e5–1.0e11 cm^{-2}) with the detectors' optical *c*-axis positioned perpendicular to the beam direction. All measured ion ranges (for single track as well as track bulk intensity irradiations) deviate less than 3% from tabulated SRIM data (Ziegler et al., 2009), independent of particle type, energy, fluence and linear energy transfer.

Proton irradiation of detectors placed inside a polymethyl methacrylate (PMMA) phantom at the Heidelberg Ion-Beam Therapy Center showed promising results for future in-vivo FNTD applications.

1. Introduction

The sharp dose fall-off in proton and ion radiotherapy offers maximal dose deposition in a well-defined, narrow depth range at the distal track end. In order to fully benefit from this dose profile, precise knowledge of ion ranges in the patient is substantial, since imaging, planning and particle field composition uncertainties due to fragmentation can largely jeopardized dose conformity.

Because of their superior spatial resolution, fluorescent nuclear track detectors (FNTDs) are promising candidates for novel in-vivo treatment plan verification tools. Implanted detectors or detectors in body cavities could help accessing direct information on a radiation treatment such as ion fluences, energies or ranges. FNTDs show excellent detection efficiency of fast neutrons and swift heavy charged particles with linear energy transfer (LET) greater than approximately 0.2 keV/μm (Akselrod et al., 2006). At the same time, they might serve as x-ray markers because of their high density.

FNTDs are based on single Al_2O_3:C,Mg crystals. These crystals contain high concentrations of $F_2^{2+}(2Mg)$ color centers, which exhibit radiochromic transformations under ionizing radiation. Laser-induced fluorescence allows fast and non-destructive readout using confocal laser scanning microscopy (CLSM) (Akselrod and Sykora, 2011).

Irradiations of FNTDs with protons as well as with C, Mg, S, Fe and Xe ions at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, and at the Accelerator Laboratory in Jyväskylä, Finland, serve as a basic feasibility study of future in-vivo FNTD applications. We measured projected ranges of these mono-energetic ion beams for various particle fluences. Measurement accuracy was analyzed using single track (low fluence) and track bulk evaluation routines (high fluence) and the influence of

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ion type, kinetic energy, particle fluence and LET on range precision has been investigated.

In addition, FNTDs have been irradiated at the Heidelberg Ion-Beam Therapy Center under clinical conditions in order to simulate detector use in radiation therapy.

2. Materials and methods

2.1. Detectors

We used single crystals of Al_2O_3:C,Mg produced by Landauer Inc., which have been cut along the optical *c*-axis into small rectangular plates ($4.0 \times 6.0 \times 0.5$ mm^3) polished on one of their large sides for optical quality (Fig. 1).

2.2. Irradiations

These samples have then been irradiated in vacuum with beam direction perpendicular to their edges in order to obtain full information on projected ion ranges. The entrance angle has carefully been adjusted to avoid range over- and under-estimation (Fig. 1).

The 12 MV Tandem van-de-Graaff Accelerator of the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, delivered total kinetic energies of 3 (p), 6 (p), 48 (C-12), 96 (Mg-24) and 100 MeV (S-32). By changing the beam widening with quadrupole magnets and the total irradiation time, desired particle fluences have be adjusted.

The Jyväskylä Accelerator Laboratory in Finland delivered 519 MeV Fe-56 ions and 1221 MeV Xe-132 ions.

2.3. Detector readout and image processing

The Zeiss LSM 710 ConfoCor 3 was used in the configuration described in Greilich et al. (2013), (i.e. 633 nm Helium–Neon laser line for excitation, avalanche photodiode with 655 nm longpass filter for detection) together with the 2009 ZEN control software for FNTD readout.

The 1.4 Oil DIC II, 40× objective lens provided a lateral resolution and lateral diameter of the system point spread function (PSF) of about 400 nm. Furthermore, we chose an illumination time of 50 μs for each spot position (dwell time) and the maximum applicable laser power (appr. 100 μW at sample) to avoid signal saturation. The Zeiss LSM 710 allows taking multiple images in depth by shifting the focal plane in vertical direction. Typical applied step sizes are in the order of several μm. Images obtained in the same focal plane but on different lateral coordinates can be combined in a tile scan within ZEN control software. This tool was helpful when imaging a larger area of the detector edge at one defined depth. Detailed readout protocols can be found in Klimpki (2012).

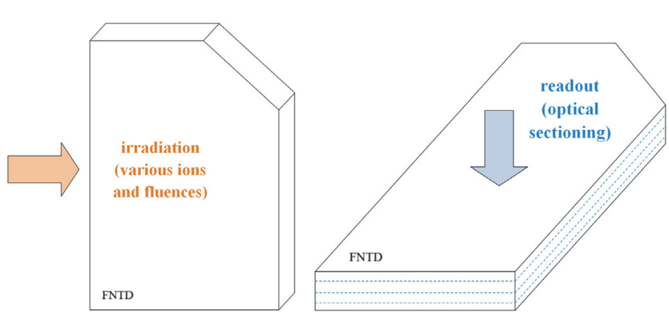

Fig. 1. Schematic diagram of FNTD irradiation (left) and readout (right) based on optical sectioning under the Zeiss LSM 710 confocal microscope; polished surface on the back of the detector.

For image processing, we used *ImageJ* (version 1.46a) (Rasband, 2011), a public domain program that is able to import readout parameters saved by ZEN, together with customized user routines.

3. Experiments and results

Fig. 2 gives an overview of carbon-irradiated FNTDs. Since irradiation covered a broad range of fluences, we established two different evaluation routines – one for low ($\Phi < 10^7$ cm^{-2}) and one for high particle fluences ($\Phi > 10^7$ cm^{-2}). They will be referred to as single track and track bulk evaluation, respectively.

3.1. Single track evaluation

For fluences smaller than 10^7 cm^{-2}, single particle tracks were well visible under the microscope (Fig. 2, panels 1 and 2). A series of 34 images was taken in a depth interval of 100 μm to ensure that track core centers lie in the focal plane of the microscope. By determining the entrance point into the detector and the end of the particle track when the track is in focus, we could calculate the projected range. Uncertainties in the cutting of the detector edge challenge the precise identification of the ion entrance point. The results for 3150 measured single particle tracks are given in Table 1.

In order to apply the described evaluation technique, detectors have to be irradiated perpendicular to their edge. We measured the entrance angles for a large number of particle tracks and estimated the maximum deviation due to imprecise positioning to be ±5°.

3.2. Track bulk evaluation

For fluences greater than 10^7 cm^{-2}, single tracks could no longer be resolved (Fig. 2, panels 3–6). Therefore, image slices of approximately 50 μm height have been acquired in one distinct depth. The grey value profile of such a slice (Fig. 3) was then ascertained via *ImageJ*. By determining the inflection points of the curve, we could calculate the projected range. This fully automated routine has been applied to up to 250 image slices per irradiated FNTD yielding a mean range.

We chose the distance between the two inflection points to be a measure for the projected range, since an ideal grey value profile should have the shape of a rectangular function: One would expect no signal in front of the detector, an abrupt increase in fluorescence at the detector edge and an abrupt fall-off at the defined ion range back to a constant background level.

1140 image slices have been evaluated using this fully automated track bulk evaluation routine. The results are listed in Table 2.

3.3. Toward in-vivo ion range measurements

In order to further investigate the basic feasibility of FNTDs for clinical in-vivo applications, we created a therapeutic treatment plan for a polymethyl methacrylate (PMMA) cylinder containing tissue surrogates (i.e. *Gammex* LN-450 lung, AP6 adipose, LV1 liver, CB2-30% cortical bone) and FNTDs at the distal edge of a rectangular target volume ($5 \times 5 \times 1$ cm^3). After applying 1 Gy protons at the Heidelberg Ion-Beam Therapy Center (multiple energy slabs for homogenous CTV irradiation), we compared the detected distal edge with the planned and forward calculated depth–dose curve (see Section 4.4 and Fig. 4 for further discussion).