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Alternative methods for heavy ion therapy dosimetry

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The studies presented in this thesis are focused on the development of detectors based on synthetic diamonds grown by Chemical Vapour Deposition (CVD) to be used for heavy-ion beams dosimetry. The way to realize this is achieved by active online beam monitoring providing non-integrating dosimetry by particle counting as well as passive offline thermoluminescence dosimetry.

It could be shown that the application of the rather new material is feasible but that further development is still needed and may be achieved in realistic time periods.

As a first task, the systematic characterization and investigation under laboratory and in-situ beam surroundings have been performed for the selection of the best-suited commercially available diamond material.

For carbon beam monitoring during patient treatment a detector which is 'transparent' for the beam which does not deteriorate the beam quality is needed thus only a thin layer of with low Z material is feasible to apply. The basic properties of high quality CVD diamond film make diamonds very interesting for this application, they also provide very fast signals, show very low leakage current, have excellent thermal properties and can be manufactured as free-standing detectors. Moreover the proven radiation hardness of diamond makes them the perfect material for heavy-ion beams monitoring.

The working principle of the online system for the measurement of the beam intensity, its position and profile is based on diamond detectors with pixelized readout systems placed in the beam.

As a proof-of-principle measurements at the UNILAC and SIS facilities of GSI Darmstadt were performed with different ion species, energies and fluences. In energy regimes, high-energy (88-430 MeV/u) and low-energy (<11.4 MeV/u), high-bandwidth electronics have been used to successfully count the number of impinging particles. In order to process the signals obtained from the diamond detectors, an electronic based on a discrete high-bandwidth amplifiers (DBA) and alternatively based on a specially designed ASICs {NINO and latest development PADI} for multi-channel applications were applied. For the intensity of 10^8 ions/spill of the carbon beam, using sc-CVD diamond for the online-counting has been proven to increase the efficiency up to (100±2) % if compared to poly-crystalline material where a counting efficiency of up to 95 % for ^{12}C ions with an initial energy of 88 MeV/u has been obtained.

For low energetic ions a counting efficiency of up to (100±7) % was obtained for ^{238}U using various types of diamond material ranging from poly-crystalline to purely single crystal structure.

As a conclusion, the beam monitor based on CVD diamond with a specially developed multichannel electronic was successfully tested with variable beams. Nevertheless there is still room for improvements of the precision of the measurement which may be realized in the near future with better quality and bigger area detector material delivered by the suppliers. This will result in a more homogeneous response between pixels and will finally also allow measuring the geometrical profile of the pencil carbon beams. A new design of the detector itself with shorter signal transmission lines will decrease the noise and thus smaller signals will be detectable which consequently increases the counting efficiency. Further work on monitoring of the delivered by UNILAC heavy-ion beam will be concentrated on the use of thin <50 μm poly-crystalline diamonds.

The most challenging task is then to achieve a sufficiently large signal out of detectors with thicknesses of the active volume of a few 100 μm e.g. by using appropriate electronics. Despite the fact that encouraging results have been achieved using the single channel discrete electronics as well as a multi channel ASIC which has been developed for a different application there is still more work necessary in order to develop a setup based on the ASIC 'PADI' dedicated to diamond like detectors. Furthermore, in order to cope with the particles fluences of up to several 10^{10} particles/spill for light-ion beam applications one may either adapt (minimize) the size of the detector pixels and/or perform a rate division using ultra fast pre-scalers e.g. increasing the maximum data rate up to 1.2 GHz in the current setup.

The spectra of the energy deposited by heavy-ions in diamond material obtained with the diamond detectors itself together with the determination of the particle numbers give very exact information about the absorbed dose in diamond. A first step which might have already been taken was to measure the energy deposited in the plateau region of the Bragg distribution with high quality thin sc-CVD diamond and charge sensitive electronics. As a result spectra with good energy resolution were registered and verified by calculated values, in order to precisely derive the dose during patient therapy treatment.

The improvement of the bulk material as well as a readout system supplying an fast analogue signal is a prerequisite for future applications in so called 'mixed-field' surrounding near the Bragg maximum e.g. in deep seated tumour sites where one might have to deal with fragmentation products of different nuclear charge and/or mass than the primary beam particles. In such places particle identification techniques are required, e.g. the determination of the nuclear charge from the energy loss spectrum, requiring a reasonable energy resolution.

There are future perspectives to use the system which has been originally developed for dosimetry purposes also for the tagging of individual carbon particles applied in particle therapy. This would help to increase the efficiency of the PET measurements by suppression of uncorrelated random coincidences. Moreover it could be used for a constant check of the intervention thresholds for the deviation in intensity and beam positioning below 1 mm (pixel size). Other possible applications are the counting and tracking of the position of single heavy-ions for biological applications, as well as the verification of the beam structure and homogeneity in time and in space, which is possible to realize at least for heavy-ions like uranium even without signal amplification e.g. directly with a fast digital oscilloscope.

First steps towards a compact multi-channel system have already been taken with the end of this work and will be continued in the near future.

Concerning the offline applications various poly-crystalline CVD diamonds have been tested as thermoluminescence detectors for heavy-ion beams dosimetry. The commercial 'mechanical grade' type diamond which was finally selected shows a single, stable dosimetric peak with constant TL efficiency for carbon ions used for hadron cancer-therapy. Therefore no additional corrections are necessary if one use diamond dosimeters at that energy regime (e.g. dose verification around the treated area). The measured relative TL efficiency shows a much stronger decrease with increasing LET of the heavy ions for standard LiF:Mg,Ti TLD than for the diamond detectors under investigation thus even the application at energies near the Bragg peaks are feasible.

The tissue equivalence of diamond material, its radiation hardness and chemical inertness as well what as the high relative TL response to heavy ion beams for selected materials makes them valuable for passive dose and treatment plan verification within phantoms and also in vivo. Unfortunately there is no diamond material available commercially by now with a dedicated composition optimized for TL dosimetry nor is the composition of the current 'best choice' known for the moment. Therefore the future work on this topic should be focussed on the development of such a material.