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DEVELOPMENT OF IMAGING TECHNIQUES FOR MEDICAL ACCELERATORS IN THE QUASAR GROUP

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Abstract

Ions offer an increased precision in radiotherapy due to their specific depth-dose properties. This precision can only be fully exploited if exact knowledge of the particle beam properties, as well as the exact range of the particles in the inhomogeneous target, is available. The QUASAR Group has addressed the key issues in a number of different ways: Using a monolithic active pixel sensor, designed for dead time-free operation, a beam monitoring system capable of monitoring pulsed and continuous beams at typical therapeutic energies and intensities in real time during patient treatment has been developed; using a non-intrusive detector system based on the VELO detector, variations in beam properties without intersecting the beam core altogether will be developed; using liquid ionization chambers, the group aims at obtaining information on the biological quality of the beam; using a simple set-up based on a silicon pixel detector, developed for the ALICE experiment, the feasibility of detecting the distal edge of the Bragg peak in antiproton beams by detecting the pions resulting from pbar-nucleon annihilations has been demonstrated. This paper gives an overview of these studies.

INTRODUCTION

Particle accelerators have been used for medical purposes since many decades. Their use ranges from the provision of radioactive isotopes in clinics, to cancer treatment by x-rays, electrons or ion beams.

Since its foundation, the QUASAR Group [1] has carried out an R&D program into medical applications of particle accelerators, see e.g. [2]. Since 2009, the Group is a member of the international Antiproton Cell Experiment (ACE) collaboration that studies biological effects of antimatter at the Antiproton Decelerator (AD) at CERN, with a particular focus on a potential future use of these exotic particles for medical applications. In addition, the QUASAR Group has started collaborating with the Clatterbridge Centre of Oncology, UK on the development of an innovative beam monitor for medical accelerators. Recent research outcomes of these projects are summarized in the following sections.

RESEARCH RESULTS

Beam Monitoring with Dead Time Free Pixel Detectors

Modern treatment modalities call for 3-dimensional spot scanning of the incoming beam close to the patient. For precise fulfilment of prescribed treatment plans exact knowledge of position, spatial distribution, and intensity of each individual spot position is necessary. Detectors for this purpose need to be thin enough to not disturb the beam unnecessarily, sensitive enough to produce a good signal-to-noise ratio in a fraction of the irradiation time needed for the particular spot, and dead-time free to produce a continuous record of the geometrical properties of the incoming beam in real time.

The Mimotera (Minimum Ionizing MOnolithic active pixel sensor (MAPS) for the TERA foundation) is constructed from crystalline silicon. The epitaxial layer is 14 µm thick and has an entrance window of only about 100 nm. The sensor consists of 112 x 112 = 12,544 pixels, each of the size of 153 x 153 µm^2. This leads to an active area of 17 x 17mm^2, which is divided into four sub-arrays of 28 x 112 pixels that are read out in parallel. The readout rate for one single pixel can be chosen by external software, with a maximum rate of 20 MHz. The readout of one sub-array, including 2 rows and 2 columns of virtual dummy marker pixels, therefore takes 50 ns x (112 + 2) x (28 + 2) = 172 µm. As the four sub-arrays are read out in parallel, this is identical to the readout time for one frame of the whole detector. The unique feature of Mimotera is the design of one single pixel. Each of the pixels consists of 2 x 81 interconnected diodes, 5 x 5 µm^2 each, building two independent readout matrices. This architecture makes the Mimotera a completely dead time free detector: While matrix A is collecting the generated charge carriers, the charges stored in the diodes of matrix B are read out, the diodes are reset, and afterwards the process is inverted. Hence, no signal charges get lost during the readout process.

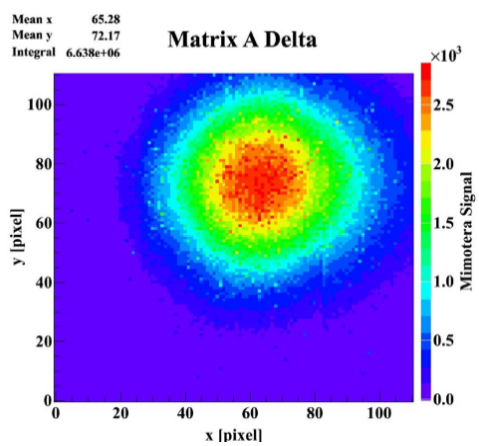

Figure 1: Profile of one shot of antiprotons in the Mimotera detector. Mean values in x- and y-direction are displayed, as well as the integral of the signal over the whole detector surface [3].

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First tests have been carried out at the AD-4/ACE experiment at the AD [3]. The beam spill of 500 ns duration is contained in only one readout frame, allowing to analyze the data differentially, subtracting the frame with the spill from the previous one without beam, thus eliminating the need to record pedestal files, as all dead pixels and time-dependent background signals are eliminated automatically.

It was shown in these measurements that the detector is capable of coping with the high momentary intensity of the AD. Investigations into possible saturation effects in the beam core were carried out. If such effects were present, they would limit the detector's capability of measuring the full beam intensity and determining the beam profile with high precision.

As an example, figure 1 shows the profile of one single beam spill in the Mimotera. Comparing the integrated signal in the Mimotera to the nominal beam intensity given by the accelerator operations, a deviation from linearity of less than 1% has been observed, caused by saturation at the highest intensities in the centre of the beam.

Real Time Imaging of Antiproton Stop Distribution

Once an ion beam enters the human body, its exact range is not known with a precision matching the sharpness of the Bragg peak due to uncertainties in converting CT image densities to actual material densities. Therefore, in vivo imaging of the stopping distribution of such a beam in real time would be highly desirable.

Again in tests at the AD, a single detector plane set-up was used in an unconventional way where the origin of the secondary pions were faced with the detector edge, rather than its front face. This way, it was possible to observe tracks of pions in the detector plane. An analysis of the track length distribution alone then allowed detection of the annihilation vertex distribution along the beam axis [4].

A ladder of 10 silicon pixel detector chips provided by the ALICE collaboration at CERN was used for these measurements. In total, this detector has 256 x 320 pixels, each with dimensions of 50 µm x 425 µm, and a thickness of 200 mm. This detector was mounted with the long edge (136 mm x 200 µm) perpendicular to the beam direction pointing towards the distal edge of the depth dose distribution in a water phantom. The phantom was irradiated with 500 MeV/c antiprotons.

The AD provides about $3x10^7$ antiprotons in a 500 nanosecond pulse every 90 seconds. The detector properties allow a maximum occupancy of roughly 8 %, which was accounted for by placing it 1.4 meters away from the beam axis and setting the integration time to the last 100 ns of the antiproton pulse.

Pions, emitted by annihilation events then enter the detector under an oblique angle. The angle with respect to the 12.8 mm side determines the length of the tracks the particles leave in the detector. The annihilation vertex distribution measured in this set-up was broadened due to multiple scattering of the pions within the water phantom, which was then magnified by the large distance between phantom and detector.

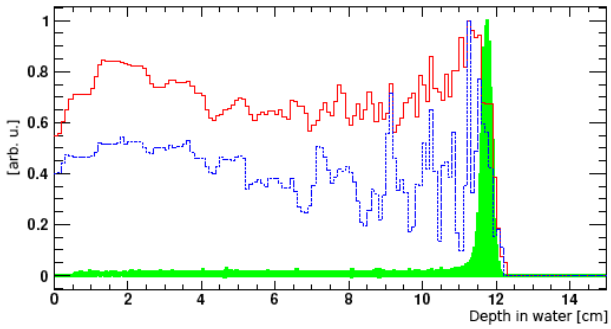

Figure 2: Simulation for a 30 cm distance between water target and detector. Red solid line: reconstructed annihilation vertex distribution (2 x 10^9 antiprotons), green filled in histogram: differential antiproton fluence, blue dashed line: reconstructed annihilation vertex distribution using only 10^8 antiprotons [4].

Nevertheless, the Bragg peak was identified and agreed well with the results from numerical simulations. For a more clinical example, a slow spill of 2 x 10^9 antiprotons was simulated with the distance between the detector and the water phantom decreased to 30 cm. It was found that the maximum of the differential antiproton fluence, the green histogram in Figure 2, coincided perfectly with the shoulder of the reconstructed annihilation vertex distribution (red line). Thereby, the range of the antiprotons can be determined with a precision in the order of a few millimeters after the very first fraction of the irradiation. This is shown by the blue line, where a signal of only 10^8 antiprotons was evaluated.

In-beam Determination of Radiation Quality

Even when the beam geometry and the location of the energy deposition are known, there is still a missing piece to the puzzle. Different types of particles have different relative biological effectiveness (RBE) and can be present in the beam due to fragmentation processes in the target. To obtain information on this distribution and correct the treatment plan for the variable biological effectiveness the dependence of recombination of ion-electron pairs in liquids can be used.

Recombination of electrons and ions normally poses a problem in liquid ionization chambers, as the signal is drastically reduced. But for the purposes described above, this effect can be used beneficially: The initial recombination, where ions and electrons generated by the same incoming projectile, recombine depends on the linear energy transfer (LET) and thereby indirectly on RBE. Work was initiated to unfold this effect from the general recombination, where electrons recombine with arbitrary ions from different initial projectiles, using various dose rates and applied voltages, together with Boag's theorem [5].

A variation in the curvature of the signal vs. voltage curve with LET was found. From extrapolation of the asymptotic behaviour at larger voltages, an intercept of the ordinate was obtained that depends on LET. This way, a relative knowledge of LET can be achieved.
Work to connect this data with Jaffe's theory on recombination [6] and to extract absolute measurements of LET is ongoing.

Beam Monitoring Using the LHCb VELO Detector

The applicability of classical radiotherapy depends on various factors such as for example the tumour radio-resistance and presence of adjacent organs at risk. Posterior eye tumours very often adjoin the optical nerve and application of classical radiotherapy may result in permanent damage to the nerve. Given its specific depth-dose profile, hadron therapy has significant advantages in this area as compared to alternative treatments.
Proton-based radiotherapy with a MC-60 Scanditronix cyclotron proton source has been successfully used in eye melanoma treatment at the Clatterbridge Centre for Oncology in the UK for more than 20 years. In such a facility, it is important that all beam parameters are closely monitored, including the necessary quality assurance tools.
Within the QUASAR Group, work is presently being carried out to build up a detector phantom able to monitor all important beam parameters in a least-destructive way. The core element of this setup are several modules of the LHCb VELO detector, see Fig. 3. Because of its unique geometry, it allows for monitoring the tail distribution of the treatment beam whilst not affecting the passage of the beam core. Its potential for non-invasive beam position determination and transverse beam profile measurements was already demonstrated recently in a proof-of-principle experiment [7].
These first results indicated that this detector could be used for beam halo measurements and spot imaging. Therefore, more detailed investigations into the detector performance in 2π geometry have been started and measurements are planned for later in 2011. A particular focus will be the study of the correlation between the signal level in the beam halo and the total beam current, as determined for example with a classic Faraday Cup as reference monitor.
FLUKA studies into the optimisation of the design of the latter in terms of optimum material choice, expected energy deposition and heat distribution in the target material, secondary particle emission and nuclear reactions have been started. In addition, a multi–leaf Faraday Cup for measuring the beam energy spread with high resolution is being designed. There, a particular challenge is the optimization of the monitor in terms of high spatial resolution and sufficient signal level in the respective (thin) detector layers.

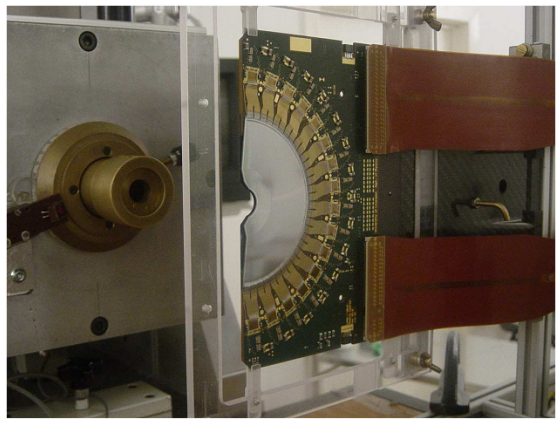

Figure 3: Beam collimator and LHCb VELO module at the Clatterbridge Centre for Oncology. [7]

The combination of the above monitors will allow to directly link measurement data to beam dynamics models of the facility. Through a detailed monitoring of the beam parameters close to the location of patient irradiation, an optimization of the overall facility performance is strived for.

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REFERENCES

[1] http://www.quasar-group.org
[2] A. Peters, et al., "Magnetic Field Control in Synchrotrons", Proc. Part. Acc. Conf., Vancouver, Canada (2009)
[3] R. Boll, et al., „Using Monolithic Active Pixel Sensors for Fast Monitoring of Therapeutic Hadron Beams", Radiation Measurements, *submitted* (2010)
[4] S. Sellner, et al., „Real Time Imaging of Antiprotons Stopping in Biological Targets – Novel Uses of Solid State Detectors", Radiation Measurements, *submitted* (2010)
[5] J.W. Boag, J. Currant, "Current collection and ionic recombination in small cylindrical ionization chambers exposed to pulsed radiation", Brit. Journ. Radiol. **53**, p 471-478, (1980)
[6] G. Jaffé, "On the Theory of Recombination", Phys. Rev. **58**, 968–976 (1940)
[7] G. Casse, *private communication*