# BENCHMARK STUDIES OF INDUCED RADIOACTIVITY PRODUCED IN LHC MATERIALS, PART II: REMANENT DOSE RATES

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ABSTRACT

A new method to estimate remanent dose rates, to be used with the Monte Carlo code FLUKA, was benchmarked against measurements from an experiment that was performed at the CERN-EU high-energy reference field facility. An extensive collection of samples of different materials were placed downstream of and laterally to a copper target, intercepting a positively charged mixed hadron beam with a momentum of 120 GeV/*c*. Emphasis was put on the reduction of uncertainties such as careful monitoring of the irradiation parameters, the use of different instruments to measure dose rates, detailed elemental analyses of the irradiated materials and detailed simulations of the irradiation experiment. Measured and calculated dose rates are in good agreement.

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## INTRODUCTION

Previous attempts to estimate the remanent dose rates from activated LHC components were typically performed by using the so-called omega factors [1] by relating the dose rates measured on contact with the respective object to the density of inelastic interactions. However, this approach has several significant limitations which strongly restrict its range of application. Therefore a method, to be used with the Monte Carlo (MC) code FLUKA [2,3], that is based on an explicit simulation of the production of radioactive isotopes as well as their decay for a certain cooling time [4] has been developed. Decay photons are sampled according to their emission intensities, electrons and positrons are sampled according to the decay energy spectra. These particles are then transported with FLUKA and dose equivalent can thus be calculated at any point-of-interest in the respective geometry.

In order to benchmark this approach, an irradiation experiment was performed at the CERN-EU high-energy Reference Field (CERF) facility [5]. It is a continuation of an earlier study [4,6], where the new study is based on analyzing a larger variety of materials and aiming at a further reduction of uncertainties in both the experiment and the simulation. The study combines activation and dose rate measurements, the former being discussed in a separate paper [7].

## BENCHMARK MEASUREMENTS

### Irradiation Experiment

Samples of different materials, typically used for LHC machine and shielding components (concrete, marble, carbon composites, boron nitride, aluminium, titanium, iron, stainless steel and copper), were irradiated at the CERF-facility. At this facility a mixed hadron beam (about 1/3 protons and 2/3 pions, 120 GeV/*c*) strikes a 50-cm long copper target creating a stray radiation field around the target that is typical for loss points at high-energy accelerators. Details of the samples used as well as the CERF facility and the experimental setup are given together with the results of the activation benchmark study in Refs. [7,8].

The samples were irradiated with exposure times ranging from a few hours to several days and total number of accumulated beam particles ranging from $1.6 \times 10^{11}$ to $1.5 \times 10^{12}$. The beam profile as well as the number of particles in each beam spill (cycle length of 16.8 s) was recorded for later use in the post-processing of the FLUKA results.

### Dose Rate Measurements

Following the irradiation of each sample, remanent dose rates were measured with two different instruments, a portable Microspec spectrometer (see footnote 1) as well as a Thermo-Eberline dose-meter (see footnote 2) of type FHZ 672, at various cooling times and distances to the surface of the samples. Further details can be found in Ref. [8].

The physical centres of the detectors, which are needed for an absolute comparison with the simulation, were determined with standard calibration sources in the CERN calibration laboratory to be 2.4 cm and 7.3 cm for the Microspec and Eberline instruments, respectively.

For the dose rate measurements the irradiated samples were placed on a holder to allow for distances of 12.4 cm, 22.4 cm and 32.4 cm, between the surface of the sample (the surface which was facing the CERF target during the irradiation) and the centre of the detector. The dose rate at the latter distance of 32.4 cm was only measured with the Microspec instrument. In addition, the samples were directly placed in contact with the detectors. All measurements were carried out in a laboratory with a low background radiation dose rate of 55 nSv/h.

## FLUKA SIMULATIONS

Remanent dose rates were calculated following the two-step approach as already introduced in Ref. [4]. For the first step ("calculation of isotopes"), the FLUKA implementation of the geometry of the CERF experimental area is identical to the one used for the activation benchmark (see [6,7]). Isotope information was written into files for a total of 12 cooling times ranging from 6 minutes to 1000 hours (~42 days) and for the exact profile of the respective irradiation considering each beam pulse and the actual number of particles.

In the second step of the simulation ("dose rate calculation") the FLUKA geometry consisted only of the respective sample surrounded by air which roughly represents the situation during the dose rate measurements in the laboratory. A dedicated simulation of the electromagnetic cascade caused by gamma and positron emitter was performed for each cooling time and the ambient dose equivalent was calculated up to the maximal measured distance from the sample

surface by folding the particle fluence with appropriate fluence-to-ambient dose equivalent conversion factors [9]. The emission of electrons was neglected as it was found to give a negligible contribution to the total dose rate.

## COMPARISON OF MEASURED AND SIMULATED DOSE RATES

Calculated and measured dose rates are compared for a few selected materials. A more comprehensive collection of results can be found in [8]. All measured data points in the graphs carry error bars which include the following: a 2 mm uncertainty for the determination of the effective centre of the detector, a 2 mm uncertainty for the positioning of the sample with the holder (*i.e.*, distance to the detector), a statistical error obtained from repetitive measurements (only Eberline dose-meter) and a systematic instrument uncertainty of 1 nSv/h corresponding to the last significant figure on the display of the respective devices. Except for the aluminium sample measured data below 10 nSv/h were systematically excluded from the comparison due to their proximity to the background value as also indicated in the user-manuals of the instruments. In case of aluminium they were kept in order to indicate the behaviour of the dose rate at large cooling times.

### Aluminium

Figure 1 shows the remanent dose rates as measured and simulated for one of the aluminium samples and for different distances. In general a very good agreement can be observed between the values simulated with FLUKA and measured with the Microspec instrument. On the other hand, the Eberline instrument measured systematically higher values that could be due to differences in the responses of the two instruments at the gamma-energies of $^{24}$Na which dominates the dose rate below $t_c$ = 100 h. The latter is still under investigation. Uncertainties of the measured data for the Microspec instrument are highest at contact as the

uncertainty on determination of the effective centre of the detector (2 mm) is most pronounced at small distances. Furthermore, fluctuations in the Microspec data at the largest distance indicate statistical uncertainties which are not included in the error bars as no repetitive measurements were performed with this instrument. The cooling time dependence is very well reproduced, especially after about 200 hours when $^{22}$Na becomes the only significant contributor to the remanent dose rates.

**Copper**

As shown in Figure 2 the measured remanent dose rates from the copper sample are remarkably well reproduced. In contrast to the aluminium sample, here the data obtained with the two instruments agree well. In this case many different photon energies contribute to the dose rate at a given cooling time and differences in the response of the two devices seem to cancel out.

**Iron**

The results for the iron sample are illustrated in Figure 3. Very good agreement can be observed between the dose rates measured with the Microspec spectrometer and the simulated values. The dose rates measured with the Eberline dose-meter are systematically larger than those obtained with the Microspec spectrometer, most probably due to the assumed average value for the energy response of the Eberline device. However, in most cases results are still within the uncertainties of both data.

**Concrete**

The results for the simulated and measured values of remanent dose rate from the concrete sample are shown in Figure 4. Both instruments show systematically higher values (by about 20%) than obtained from the simulations. However, the cooling time dependence is very well reproduced. Up to 2 hours of cooling, $^{11}C$ is the dominant isotope whereas $^{24}Na$ dominates between 2 and 20 hours of cooling time.

## CONCLUSIONS

Samples of different materials typically used in the construction of accelerators were irradiated at the CERF facility in the stray radiation field downstream of and lateral to a copper target. At this location particle spectra exhibit a significant high-energy component resembling the situation which can be expected for loss regions at high-energy accelerators, such as the LHC. Remanent dose rates were measured at different cooling times after the irradiation and results were compared to predictions from detailed FLUKA simulations.

The simulations were successfully benchmarked with the experimental results and the detailed comparison of measured and calculated ambient dose equivalent rates show generally good agreement to within 20% for most of the samples.

Remanent dose rates were measured using two different instruments. The observed differences in remanent dose rates for the two measurement devices, as well as the disagreement between measurements and simulations for locations close to large objects (not shown here, see Ref. [8]) are still subject to further investigation, but can most properly be explained by different energy responses as in the first case and limitations in the determination of the physical centre of the detector as in the latter case.

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**Footnotes**

1 Bubble Technology Industries Inc., HWY. 17, Chalk River, Ontario, Canada K0J 1J0

2 Thermo Electron ESM Eberline Instruments GmbH, Frauenauracherstr. 96, D-91056 Erlangen, Germany

**Caption of Figures**

Figure 1. Dose equivalent rate as a function of cooling time for the aluminium sample measured with the Microspec and the Eberline instruments and calculated with FLUKA at different distances between the surface of the sample and the effective centre of the detectors.

Figure 2. As in Figure 1, here for the copper sample.

Figure 3. As in Figure 1, here for the iron sample.

Figure 4. As in Figure 1, here for the concrete sample.

Figure 1. Dose equivalent rate as a function of cooling time for the aluminium sample measured with the Microspec and the Eberline instruments and calculated with FLUKA at different distances between the surface of the sample and the effective centre of the detector.

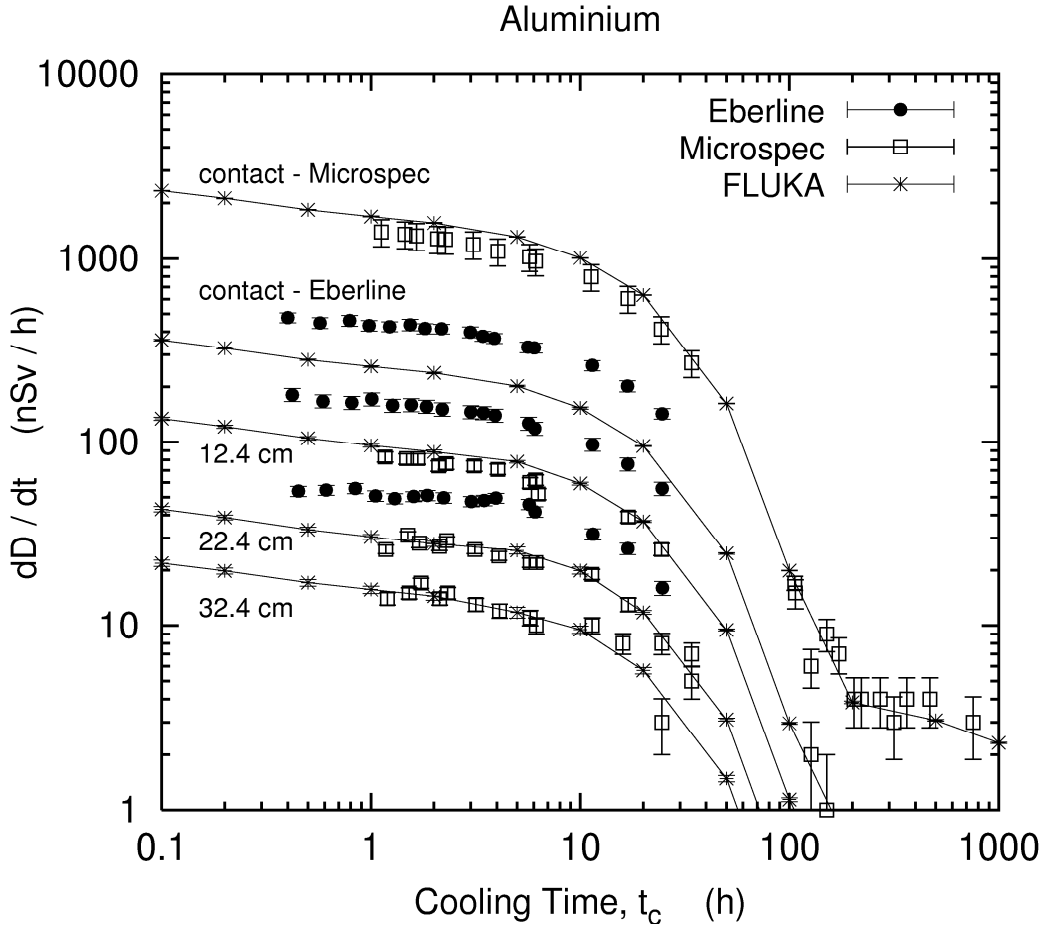

Figure 2. As in Figure 1, here for the copper sample.

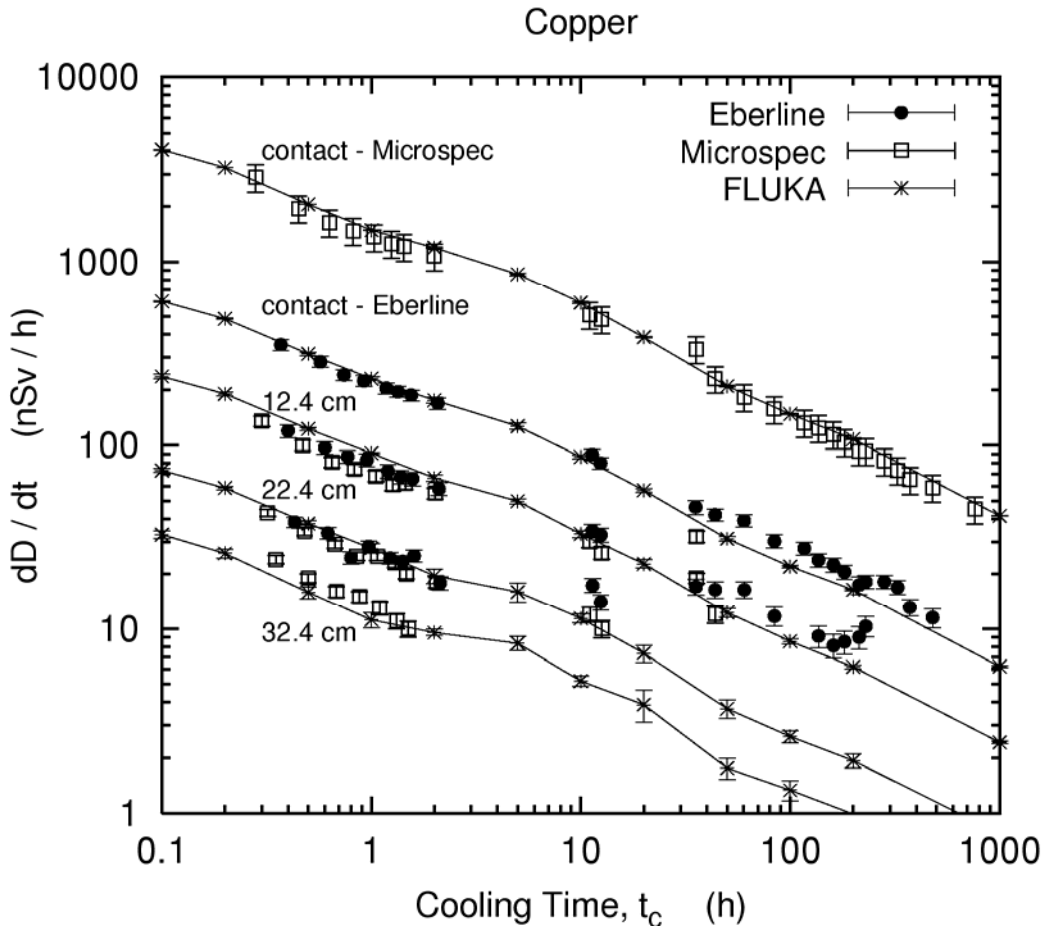

Figure 3. As in Figure 1, here for the iron sample.

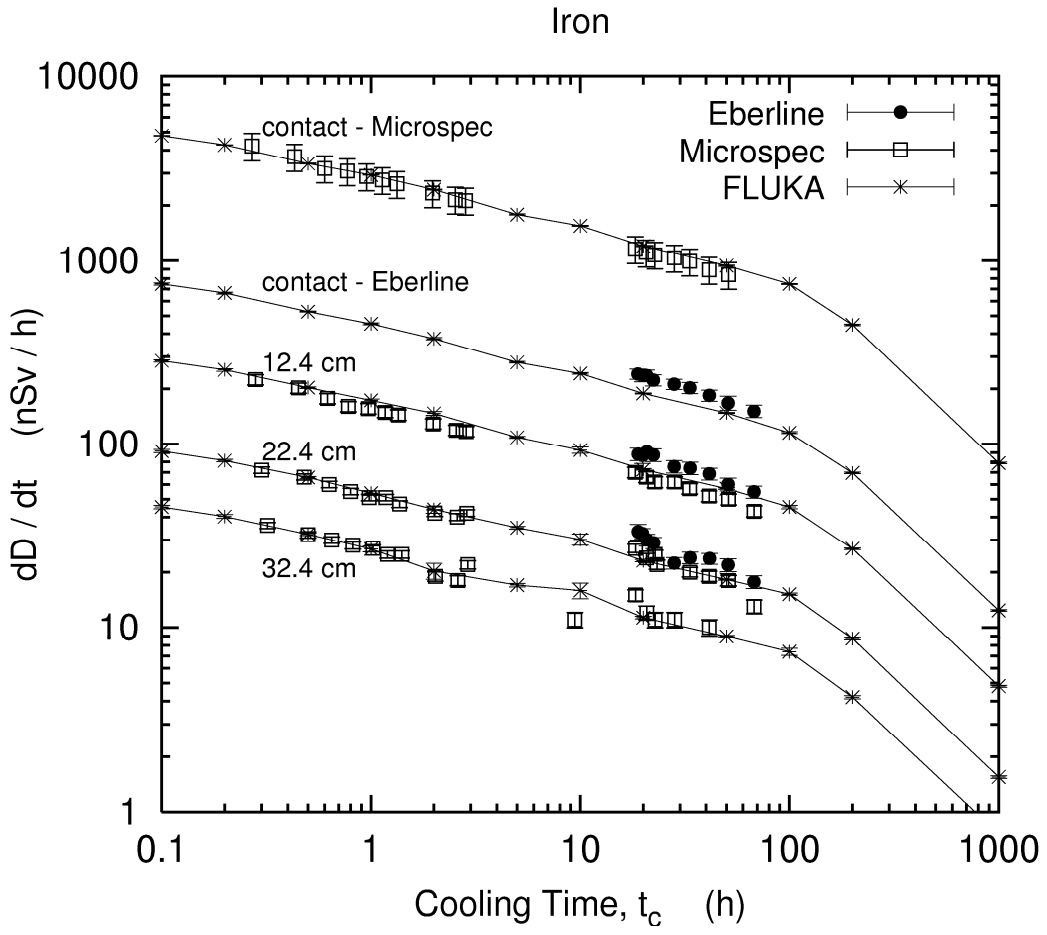

Figure 4. As in Figure 1, here for the concrete sample.