COMPARISON OF HIGH-DOSE DOSIMETRY SYSTEMS
IN ACCELERATOR RADIATION ENVIRONMENTS

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ABSTRACT

The estimation of the lifetime of components in high-radiation environments is of great importance in high-energy particle accelerators. Therefore, the measurements of absorbed dose around primary-beam areas are carried out at CERN in order to give advice on radiation damage and the preventive maintenance of materials.

In the framework of a collaboration between CERN and the Istituto Superiore di Sanità (ISS), the following high-dose dosimeter types were intercompared using the ISS alanine dosimetry as the reference system: radio-photoluminescence (RPL), hydrogen pressure, phosphate glass, LiF crystals, and colour indicators. Results suggest that the most suitable dosimetric systems for use in the radiation field of high-energy particle accelerators are RPL, hydrogen pressure, and alanine. Some preference should be given to the alanine one, because of the wide dose range covered, the low energy dependence, the low fading, and its small size.
1. INTRODUCTION

The need for a reliable high-dose dosimetry system is apparently growing with the increasing requirements for the determination of radiation dose in industrial applications (e.g. for the sterilizing of medical supplies and the preserving of food), and for estimating the lifetime of components in high-radiation environments. For CERN, it is this latter aspect which is of great importance. For over 15 years, doses in all CERN accelerators and in primary-beam areas have been measured in order to give advice on preventive maintenance, and to collect live information for future specifications and for comparison with calculations.

An intercomparison of high-dose dosimeters in accelerator fields was carried out about 15 years ago at CERN [1]. The irradiations were performed at a few typical positions in the CERN Proton Synchrotron (PS) operating at an energy of 19.2 GeV/c. Seventeen high-dose dosimeter systems were compared; these were: optical transmission dosimeters (phosphate glass, cobalt glass, red Perspex systems, and polystyrene dosimeters); chemical dosimeters (Fricke dosimeter); hydrogen pressure dosimeters; and luminescence dosimeters [radiophotoluminescence (RPL) and thermoluminescence (TL)]. Another, similar intercomparison was made, also at the PS, during a 4-week running period, at 100 positions on the vacuum chamber [2].

The aim of the present programme is to carry out an intercomparison of selected high-dose dosimeter types in the stray radiation fields of proton and electron accelerators at CERN and DESY, respectively. In addition to RPL dosimeters, various types of optical transmission dosimeters, such as phosphate glass, LiF crystals, and Plexiglas were studied, as well as hydrogen pressure dosimeters and colour dose indicators. All the dosimeters of the experiment were calibrated in a $^{60}$Co gamma source up to $10^6$ Gy and normalized to the readings of alanine dosimeters, as will be explained in Section 3. The alanine-based dosimetry was already used for the international high-dose photon dosimetry intercomparison organized by the IAEA, and was chosen as a transfer dosimeter [3]. This system uses radical formation by radiation in tissue-equivalent material, which is the most likely radiation-induced process in living matter and in organic polymers. It is therefore most suitable for assessing the risk of radiation damage in polymers and to living organisms [3-5].

2. HIGH-DOSE DOSIMETER SYSTEMS

In this experiment, only relative dosimetry methods were used. Primary standards such as ionization chambers or calorimeters are inconvenient for this purpose. Furthermore, there is no absolute system for calibrating dosimeters in the complex radiation field that occurs in the vicinity of high-energy accelerators [6]. The intercomparison of the dosimeters calibrated with a $^{60}$Co gamma source, whose radiation is significantly different from that produced around accelerators, can be done in relative terms only. Some characteristics of the high-dose dosimetry systems used are described below; more details can be found in the cited literature. The main parameters are summarized in Table 1.

2.1 Radiophotoluminescence (RPL) [7, 8]

The present CERN routine high-level dosimetry (HLD) programme uses RPL dosimeters [9]. This method is based on stable colour centres, which are created by high-energy radiation. Excited by appropriate optical frequency radiation, e.g. UV light, they act as luminescent centres. All the practical RPL systems use silver-activated aluminophosphate glass as the sensitive element. The fluorescent light is measured as a function of the absorbed radiation dose. The advantage of these dosimeters lies in their large dose range ($10^{-1}$ to $10^6$ Gy), their small size (6 mm long, 1 mm $\phi$), and their reusability. Nevertheless, the measurement is imprecise in the dose range around $10^3$ Gy, which is the top region of the calibration curve (see Fig. 3a in Section 3). This is due to the fact that the
same coloration exists for the range $10^2$ Gy to $10^3$ Gy. Furthermore, there is no commercially available readout apparatus.

2.2 Free radicals (alanine) [3–5]

As stated above, stable free radicals are created in alanine under irradiation. The unpaired electron comes from the breaking of a carbon covalent bond and is detected by the electron spin resonance (ESR) technique. Although a sophisticated readout apparatus is required, high precision and stability can be reached with ESR spectroscopy.

The dosimeters used in our experiment were made at the Istituto Superiore di Sanità (ISS), Rome. They are composed of alanine (80%) and paraffin (20%) in the form of cylinders (16 mm long and 5 mm in diameter). The lower detection limit is 0.5 Gy, and the linear dose range goes up to 3 kGy. Dosimeters were calibrated up to $10^6$ Gy (see Fig. 2). Higher doses seem to be measurable; the actual limit could be due to mechanical loss of integrity after irradiation.

2.3 Hydrogen pressure [10]

A certain amount of polyethylene (0.25 g) is sealed into quartz-glass capsules of approximately 65 mm length, with a wall thickness of 1 mm and an outside diameter of 12 mm. The polyethylene content consists of 1.2 µm thick film rolled to form a cylinder, 25 mm long and 5 mm in diameter. Hydrogen gas from polyethylene is created under irradiation, and the hydrogen pressure in the capsule is measured in relation to the integrated radiation dose. This inexpensive method uses a simple readout and has a wide dose range ($10^4$–$10^7$ Gy). An extension to lower or higher doses could be obtained by changing the sample weight in the volume of the capsule.

2.4 Optical transmission [1, 2, 7, 8]

Optical transmission dosimeters are widely used for HLD. They are all based on the creation of colour centres in glass, crystals, or plastics. Optical absorption bands are measured at various wavelengths by means of a photospectrometer. This simple readout is one of the main advantages, but the limited range at a given wavelength for glass or crystals, and the fading in glass, are disadvantages.

*Phosphate glass* [11] (PDG Schott DOS 11) with dimensions $12 \times 12 \times 1.5$ mm$^3$ has been extensively used in the past for HLD at CERN, and is now replaced by RPL dosimeters for reasons of stability and wider range. It was included in this experiment for comparison.

*LiF crystals* [12] are used only for special applications and experiments. Absorption bands are produced by radiation at various wavelengths. The dimensions of the crystals are $6 \times 6 \times 1.5$ mm$^3$.

*Plexiglas* [13] makes an inexpensive dosimeter, mainly used in industrial irradiation facilities. Such dosimeters are usually strips with an absorption band in red at 603 nm. For our experiment we used straightforward polymethyl methacrylate (PMMA), available from the CERN Store in the form of plates. The dosimeter is a 36 mm long by 12 mm$^2$ parallelepiped. The absorbance was measured at 410 nm.

2.5 Colour-dose indicators [14–16]

These are used in industrial irradiation facilities for the sole purpose of indicating whether an item (e.g. for sterilization) has been irradiated or not.

A programme was carried out at CERN to investigate whether this type of dosimeter is suitable for application in high-energy accelerators. For this reason, paints and films which change colour at a given dose level were also included in the present intercomparison experiment. Although the idea of using paint as a dosimeter is completely new, rather extensive studies have been carried out with thin films which use a radiochromic dye, e.g. a Pararosanilin Cyanide dye [14].
For the paint dosimeters, aluminium plates (4 × 8 cm²) were entirely coated with an acrylic styrol dispersion (Prozink 2000) containing TiO₂ and co-reagents, and partly repainted with the same ground substance but containing less TiO₂, and with a Pergaskript pigment added. The induced colour change in both paint and film dosimeters can be analysed by means of a reflection densitometer.

3. CALIBRATION

All dosimeter types were calibrated with ⁶⁰Co γ-rays in the range 1 to 10⁶ Gy. Up to 10⁵ Gy the 'Gammacell' irradiation facility of the ISS was used; irradiations at higher dose values were performed at Conservatome in Dagneux-Montluel, France, where a higher dose rate was available.

The 'Gammacell' source consists of 48 pencils, 150 mm high, which are equally spaced around a circle; each pencil contains seven ⁶⁰Co slugs. The total nominal activity of the source was 74 TBq (2.006 kCi) in March 1986. Radioactive bars are located inside a shielded container. The samples to be irradiated are placed on a small platform, which is steered into the irradiation position by a drive system; after the chosen time has elapsed, the sample is automatically removed to the off position. Reproducibility of the irradiation time is better than 99.9%.

The dose rate in the irradiation position is obtained from the manufacturer. However, in order to use 'Gammacell' as the calibration source, an independent determination of the dose rate was done with alanine dosimeters. For this purpose a plate-like receptacle was formed out of Perspex, in which up to 18 alanine dosimeters in their build-up holders (also Perspex) could be placed.

Groups of alanine dosimeters were irradiated at various nominal dose values within the 1 to 100 Gy range, where their calibration factor had already been determined against a secondary standard [5]. The dose rate was found to be 32.84 Gy/min ± 2.8% in March 1986; uncertainty (95% confidence level) accounts also for differences between individual irradiation positions. Alanine calibration at dose values higher than 100 Gy was finally performed with 'Gammacell'.

In order that the dosimeters discussed in Section 2 could be calibrated under controlled conditions, various Perspex build-up holders, of the desired shape, were manufactured and placed in the same receptacle as that used for the source calibration (Fig. 1). Table 2 shows the type and the number of dosimeters for the selected doses. Since the irradiation geometry was different from the calibration geometry, deviations from nominal doses were to be expected; therefore also alanine dosimeters were irradiated for a more accurate evaluation of actual dose values. Slight differences between nominal and measured dose values were observed, with a maximum deviation of 6% (Table 3). Dose values evaluated with alanine dosimeters were used to calibrate the other dosimeter types (Table 4). Alanine specimens without build-up holders were also added to evaluate the degree of deviation to be expected when dosimeters are irradiated in non-equilibrium conditions, as is the case at CERN and DESY. In fact, the irradiation beam composition and the energy spectrum are almost unpredictable around the particle accelerators used at these centres; the use of build-up holders has no meaning. Because of the high level of uncertainty usually accepted in such uncontrolled conditions, the differences observed (Table 3) are not to be regarded as significant.

The irradiation source at Dagneux is part of an industrial radiation facility. The source consists of bars of ⁶⁰Co with, in February 1984, a total activity of 5550 TBq (150 kCi). The dosimeters were irradiated at the centre of the source behind 2 mm of aluminium for build-up. The dose rate, 10⁴ Gy/h, was calculated from the activity of the source and checked by means of red Perspex dosimeters.

The calibration curve of alanine shown in Fig. 2 was chosen as a basis for reference doses in our experiment. This is justified because:

i) the 'Gammacell' source was calibrated with alanine dosimeters;
ii) among the dosimetric systems compared, only alanine was traceable to a secondary standard; 
iii) IAEA has chosen alanine dosimetry as the reference system for its high-dose assurance service [6].

The calibration curves of all other dosimeters are shown in Figs. 3a to 3g and dosimeter readings are summarized in Table 4.

4. IRRADIATION POSITIONS IN ACCELERATORS

4.1 CERN
Routine high-dose dosimetry is carried out at the main CERN proton accelerators: the PS Booster, the PS, and the SPS (Super Proton Synchrotron), and in the related target areas [9]. Although basically the type of radiation does not vary very much within these installations, we chose them for our dosimeter intercomparison in order to cover the large energy range of the primary protons from 800 MeV (Booster), over 26 GeV (PS), to 450 GeV (SPS). Figure 4 illustrates these positions schematically, whereas Figs. 5a and b show photographs of the SPS coil and the beam loss monitor (BLM) irradiation position, respectively. Full details of these are given in Table 5 together with the results, which are discussed below.

4.2 DESY
In view of the LEP project and of the radiation field which is entirely different from that of the proton accelerators [17], it was essential to expose the dosimeters to the synchrotron radiation of an electron accelerator. This was done in the PETRA tunnel at DESY, of which Fig. 6 shows a cross-section and the various irradiation positions. As the radiation field in electron machines is rather uniform, these seven positions were judged to be sufficient. It should be noted that with the PETRA beam energy of 17.5 GeV and the machine radius of 367 m, the spectrum of synchrotron radiation is very similar to that of LEP.

5. RESULTS
The readings of all dosimeters used in this experiment were converted to dose by using the calibration curves from Section 3. The results are given in Table 5. The positions without results are those where the dose was outside the range of the respective dosimeter. At DESY position 1, the dose was so high that the Plexiglas and the dye-film dosimeters were destroyed by radiation. Table 5 clearly shows that only the alanine and RPL dosimeters cover the full dose range of this experiment. But here again, DESY position 1 is at the upper limit.

As explained in Section 2, for the purpose of intercomparison the readings of the various dosimeter types were compared with those of alanine. This is shown in Fig. 7. For the DESY positions, only RPL is presented, because we do not have enough data points for the other dosimeters. Furthermore, the readings of the various dosimeter types are plotted as a function of the alanine dose in Figs. 8a to 8d. From these the following results can be deduced.

The RPL (Fig. 8a), H2 (Fig. 8c), and phosphate glass (Fig. 8d) dosimeters exposed at the high-energy particle accelerators at CERN give a mean value of the ratios near to one, and show a reasonable standard deviation (see Fig. 7). This holds particularly for CERN RPL dosimeters if one excludes the two extreme values of positions 13 and 14 of the PS Booster, which cannot be explained. The best results are obtained, however, with the H2 dosimeter.

On the other hand, the RPL dosimeters exposed at DESY all overestimate because of the low-energy component of the synchrotron radiation (Figs. 7 and 8b). The biggest difference is, as expected, in position 1, inside the lead shield (a factor of 14) and the smallest is in positions 2 and 6 (see Fig. 6) with a factor of 2. For positions 3, 4, and 7, where the high-energy component of positions 2 and 6 is reduced again to lower energies by scattering, the factor is between 5 and 7.
The remaining three dosimeter systems do not show such good results. For the LiF crystals the deviations are high (Fig. 8e), despite a reasonable mean value (from all wavelengths). When basing the interpretation of the dye film on magenta, which shows the most apparent colour change (Fig. 8f), they all tend to underestimate the dose up to a factor of 3 compared with alanine. Also, the Plexiglas shows large deviations (Fig. 8g), which is not surprising since it is a standard commercial material, as stated above.

6. CONCLUSIONS

Before drawing any conclusions, it must again be stressed that none of the dosimetry systems presented is an absolute one, and that the calibration of all systems is made with $^{60}$Co irradiations. Based on this, our findings are as follows:

1) RPL is a suitable dosimeter for use in the radiation field of high-energy particle accelerators. It could, however, be complemented, or eventually even replaced, by alanine, which covers almost the same range and has the further advantage of being an organic material.

2) RPL used around electron accelerators overestimates the dose owing to the low-energy component of the synchrotron radiation ($< 500$ keV), by a factor varying from 2 to 14, depending on the energy of this radiation.

3) The hydrogen pressure dosimeter gives very satisfactory results. For this reason, and because of the extremely simple and reliable readout procedure, it could be used more extensively in routine HLD.

4) The most suitable dosimetry system for LEP would be alanine or hydrogen pressure, with some preference given to alanine because of the larger range and the smaller size of the dosimeter. Still, RPL could be a useful complementary dosimetry system.

5) No dosimetry system, except that of LiF crystals, gives reliable results at doses approaching or exceeding $10^6$ Gy. However, these crystals are not suitable for routine HLD, mainly because of the high cost.

6) In high-energy proton accelerator environments, the dye film allows an estimate, of the order of magnitude of the dose, between $10^4$ and $10^6$ Gy. Above that dose the film is destroyed by radiation. When the dose is measured with a reflecting densitometer, it tends to be underestimated.

7) Straightforward commercial Plexiglas cannot be recommended for routine HLD.

Acknowledgements

This work was initiated by U. Amaldi and K. Goebel at CERN, and supported in part by a grant from the Istituto Nazionale di Fisica Nucleare, Italy.

The irradiations at DESY were carried out by H. Dinter.
REFERENCES

## Table 1a

Main characteristics of well-established dosimeter systems

<table>
<thead>
<tr>
<th>Type</th>
<th>Alanine ESR dosimetry</th>
<th>RPL glass Toshiba FD–RI–1</th>
<th>H$_2$ pressure</th>
<th>Phosphate glass Schott PDG DOS 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (mm)</td>
<td>Dia.: 5, length: 16</td>
<td>Dia.: 1, length: 6</td>
<td>Thickness: $1.2 \times 10^{-3}$ (rolled film)</td>
<td>12 $\times$ 12 $\times$ 1.5</td>
</tr>
<tr>
<td>Composition (%)</td>
<td>Alanine: 80, paraffin: 20</td>
<td>O: 53.7, P: 33.4, Al: 4.6, Ag: 3.7, Li: 3.7, B: 0.9 (in weight)</td>
<td>0.25 g polyethylene in 5.8 cm$^3$ glass tube</td>
<td>O: 49.7, P: 30.8, K: 10.0, Al: 4.8, Mg: 2.4, B: 0.9, others: 1.5 (in weight)</td>
</tr>
<tr>
<td>Physical characteristics</td>
<td>$Z_{\text{eff}} = 7.2$</td>
<td>A: 19, Z: 10, $\rho$: 2.6 g/cm$^3$</td>
<td>A: 14, Z: 8 $\rho$: 0.92 g/cm$^3$</td>
<td>A: 21, Z: 10, $\rho$: 2.5 g/cm$^3$</td>
</tr>
<tr>
<td>Range (Gy)</td>
<td>$(5 \times 10^{-1})$–$10^6$</td>
<td>$10^{-1}$–$10^6$</td>
<td>$10^4$–$10^7$ depending on the quantity of polyethylene</td>
<td>$(5 \times 10^5)$–$10^6$</td>
</tr>
<tr>
<td>Uncertainty (%)</td>
<td>± 4 up to 50 kGy, ± (4–10) above</td>
<td>± 20</td>
<td>± 10</td>
<td>± 20</td>
</tr>
<tr>
<td>Fading</td>
<td>Absent at 15–25°C and 40–60% relative humidity</td>
<td>1% per 3 months at 25°C. Accelerated by exposure to sunlight.</td>
<td>Negligible</td>
<td>&gt; 25% in first 24 h at 25°C</td>
</tr>
<tr>
<td>Energy dependence</td>
<td>Underestimation in the &lt; 120 keV range</td>
<td>Overestimation in the &lt; 500 keV range</td>
<td>Negligible</td>
<td>Overestimation in the &lt; 200 keV range</td>
</tr>
<tr>
<td>Readout</td>
<td>Electron spin resonance</td>
<td>RPL excited by UV at 365 nm</td>
<td>Remote, commercially available pressure meter</td>
<td>Optical absorbance at 510 nm</td>
</tr>
</tbody>
</table>
Some characteristics of special dosimeters still under study or development. Uncertainty, fading, and energy dependence need still to be investigated.

<table>
<thead>
<tr>
<th>Type</th>
<th>LiF crystals Korth</th>
<th>Plexiglas</th>
<th>Paints</th>
<th>Dye film</th>
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<tr>
<td>Dimensions (mm)</td>
<td>6 × 6 × 1.5</td>
<td>36 × 12 × 12</td>
<td>40 × 80</td>
<td>Polyvinyl butyral + Pararosaniline Cyanide</td>
</tr>
<tr>
<td>Composition</td>
<td>Natural abundance monocystal</td>
<td>Polymethyl methacrylate ((C_3H_5O_2)_n)</td>
<td>Acrylic styrol (\text{TiO}_2) + dye pigment</td>
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<tr>
<td>Range (Gy)</td>
<td>(10^3-10^8)</td>
<td>(10^3-10^5)</td>
<td>(10^3-10^6)</td>
<td>((5 \times 10^3)-10^6)</td>
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<tr>
<td>Readout</td>
<td>Absorbance at selected wavelength</td>
<td>Optical absorbance at 410 nm</td>
<td>Reflection densitometer</td>
<td>Reflection densitometer</td>
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<tr>
<td>Absorbed dose (Gy) (indicative planned values)</td>
<td>Package No.</td>
<td>Number of specimens for each dosimeter type</td>
<td>Place of irradiation</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-------------</td>
<td>-------------------------------------------</td>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alanine</td>
<td>RPL</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Build-up</td>
<td>No build-up</td>
<td>H₂ pressure PDG 11 LiF LiFnat Plexiglas Paint Dye film</td>
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<td>1 x 10⁶</td>
<td>17</td>
<td>- 2 5 5 2 2 2 2 2 2 2 2 3</td>
<td>Dagneux</td>
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Table 3
Calibration dose values. Irradiations and measurements at the ISS.

<table>
<thead>
<tr>
<th>Package No.</th>
<th>Nominal</th>
<th>Measured with alanine</th>
<th>Overall uncertainty (%) (95% CL)</th>
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<td>Build-up</td>
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<td>3</td>
<td>$1.11 \times 10^1$</td>
<td>$1.09 \times 10^1$</td>
<td>$1.09 \times 10^1$</td>
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<tr>
<td>4</td>
<td>$9.64 \times 10^1$</td>
<td>$9.65 \times 10^1$</td>
<td>$9.68 \times 10^1$</td>
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<tr>
<td>5</td>
<td>$4.79 \times 10^2$</td>
<td>$4.79 \times 10^2$</td>
<td>$4.87 \times 10^2$</td>
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<td>$9.54 \times 10^2$</td>
<td>$9.58 \times 10^2$</td>
<td>$9.58 \times 10^2$</td>
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<tr>
<td>7</td>
<td>$4.80 \times 10^3$</td>
<td>$4.68 \times 10^3$</td>
<td>$4.83 \times 10^3$</td>
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<td>$9.29 \times 10^3$</td>
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<td>$4.59 \times 10^4$</td>
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<td>$8.98 \times 10^4$</td>
<td>$9.71 \times 10^4$</td>
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<td>14</td>
<td>$9.67 \times 10^4$</td>
<td>$9.29 \times 10^4$</td>
<td>$9.60 \times 10^4$</td>
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### Table 4
Calibration data

<table>
<thead>
<tr>
<th>Absorbed dose (Gy)</th>
<th>RPL: Luminescence</th>
<th>H₂ pressure (Torr)</th>
<th>Phosphate glass: Absorbance</th>
<th>LiFₙat crystals: Absorbance</th>
<th>Plexiglas: Absorbance</th>
<th>Dye film: Optical density</th>
<th>Paints: Optical density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indicative planned values</td>
<td>Measured with alanine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 x 1⁰</td>
<td>1.09 x 1⁰</td>
<td>13.5</td>
<td>0.105</td>
<td>0.3</td>
<td>0.09</td>
<td>0.11</td>
<td></td>
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<td>1 x 1⁰</td>
<td>9.68 x 1⁰</td>
<td>92.8</td>
<td>0.148</td>
<td>0.4</td>
<td>0.22</td>
<td>0.17</td>
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*) Arbitrary units (A.U.)
Table 5

Absorbed dose values expressed in Gy, evaluated with the various compared dosimeters in the selected positions

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<th>Positions</th>
<th>Alanine</th>
<th>RPL</th>
<th>( \text{H}_2 ) pressure</th>
<th>Phosphate glass</th>
<th>LiF_{nat} crystals</th>
<th>Plexiglas</th>
<th>Dye film</th>
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*) Extrapolated value, not included in Fig. 7
Fig. 1 Irradiation geometry for the 'Gammacell' source.
Fig. 2 Calibration curve for alanine dosimeters; $h_{\text{ESR}}$ is the peak-to-peak ESR signal height referred to gain $10^4$ and $D_w$ is the absorbed dose in water.
Fig. 3a Calibration curve for RPL dosimeters.

Fig. 3b Calibration curve for hydrogen pressure dosimeters.
Fig. 3c Calibration curve for PDG dosimeters.

Fig. 3d Calibration curve for LiF dosimeters.
Fig. 3e Calibration curve for Plexiglas dosimeters.

Fig. 3f Calibration curve for dye film (magenta) dosimeters.
Fig. 3g Calibration curve for paint dosimeters.
Fig. 4 Irradiation positions at CERN accelerators.
1. Magnet coils (insulated with epoxy resin)
2. High-level dosimeters
3. Epoxy resin samples for long-term exposure
4. SPS quadrupole magnet

Fig. 5a CERN SPS coil irradiation position.

Fig. 5b Beam loss monitor (BLM) irradiation position.
Fig. 6 Cross-section of the PETRA tunnel with different irradiation positions.
Fig. 7  Ratio between dose evaluated with the various dosimeters and dose assessed with alanine in the selected positions.
Fig. 8a RPL-alanine comparison at CERN.

Fig. 8b RPL-alanine comparison at DESY.
Fig. 8c Hydrogen pressure-alanine comparison at CERN.

Fig. 8d PDG-alanine comparison at CERN.
Fig. 8e LiF-alanine comparison at CERN.

Fig. 8f Dye film-alanine comparison at CERN.
Fig. 8g Plexiglas-alanine comparison at CERN.