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**DOSES TO THE CERN 450 GeV SUPER PROTON SYNCHROTRON
AND AN ESTIMATE OF RADIATION DAMAGE**

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1. INTRODUCTION

Routine high-level dosimetry (HLD) has been carried out at the Super Proton Synchrotron (SPS) since its start-up in April 1976. More than 1000 passive integrating dosimeters have been placed in the SPS main ring and primary beam areas up to the target stations. They are read at regular intervals, usually at the annual shutdown, and the results are published [1]. The purpose of the present report is to extract the essential information from this very large amount of data and present the doses for typical positions of the SPS complex for its first decade of operation. In this way the present status of radiation damage can be estimated; by relating the dose to the number of accelerated protons, estimates of doses and radiation damage for the future can be made both for the SPS and for new accelerators.

2. DOSIMETER TYPES AND POSITIONS

2.1 Dosimeter types

From the start-up of the SPS (1976), we used two types of dosimeters:

- radiophotoluminescent glass dosimeters (RPLs)
- phosphate dosimeter glass (PDGs)

a) Radiophotoluminescence is based on stable colour centres, which are created by high-energy radiation. Excited by ultraviolet light they act as luminescent centres and 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 $\varnothing$), almost no fading, and their reusability.

b) The PDG is also based on the creation of colour centres, but the glasses here are measured for optical absorption at a fixed wavelength by means of a photospectrometer. In spite of a simple readout, these glasses have several disadvantages, e.g. important fading effect and limited range (10^3 to 10^6 Gy). For these reasons, since 1984 these dosimeters have no longer been used.

In addition to the RPL dosimeter, hydrogen pressure dosimeters (HPDs) are added in high-level radiation areas. In this type of dosimeter, hydrogen gas from polyethylene is created under irradiation and the hydrogen pressure in the capsule is measured in relation to the integrated radiation dose. The advantages of this dosimeter are its simple readout and its utility in high dose ranges (10^4 to 10^7 Gy).

Further experimental dosimeters were used, such as paints and films which change colour at a given radiation dose. This colour change can be measured with a reflection densitometer. The paint is made of an acrylic styrol dispersion with a pigment added, whereas the film is a thin layer with a radiochromic dye. Recently, we also included alanine in our high-level dosimetry programme. This needs a sophisticated readout apparatus [electron spin resonance (ESR) spectrometer], but high precision and stability can be reached [2]. However, most doses reported here are obtained with RPL dosimeters.

2.2 Dosimeter positions

Figure 1 represents a cross-section of the SPS tunnel and shows the three standard positions of the dosimeters: near the coil of the quadrupole magnet; on the beam-loss monitor (BLM) at the edge of the quadrupole magnet at beam height and about 30 cm from the beam centre; and in the electronic pit under a 20 cm concrete cover and at a distance of ~ 150 cm from the beam.

The positions in the long-straight section (LSS), transfer tunnels, and target areas are chosen at specific places, such as beam dumps, ejection septa, vacuum pumps, collimators, motors, electronic equipment, etc.

3. INTEGRATED DOSES

Figure 2 shows a typical dose pattern of the 36 BLMs and coil positions in the SPS sextant 6 for one year (1986) and for the first decade of SPS operation (1976 to 1986). The characteristics of these patterns are that the values between minimum and maximum doses vary by two to three orders of magnitude. This depends on operational parameters, for example α_p max, at known loss points such as ejection magnets and dumps, and occasionally on mis-steering and operational failures.

Similar data are obtained from the remaining five sextants of the SPS. Figure 1 shows the maximum, minimum, and mean doses at the magnet coil, the side of the magnet (BLM position), the cable trays, and the electronic pits of the SPS. The maximum dose to the coil, 6×10^5 Gy, is far below what has to be considered as a critical value (about 10^7 Gy for the epoxy resin). The dose on the cable trays, a maximum of 7×10^4 Gy, is close to the critical dose which is $2-5 \times 10^5$ Gy. In the electronic pits the yearly dose, 5×10^2 Gy, was so high, despite the 20 cm concrete shield, that already in 1982/83 all electronics had to be removed because of radiation damage and placed outside the radiation area of the SPS ring. After that, the dosimetry was discontinued in the pits and the doses in fig. 1 apply therefore up to the end of 1982.

In table 1 we give the mean dose for each dosimeter position in the sextants, and typical values of the mean doses over 10 years, in Gy per accelerated proton, are shown in fig. 3.

A large number of dosimeters are also placed in the LSSs, each having a special function: LSS1-injection and internal dumps; LSS2-ejection to North Experimental Area and ejection dump; LSS3-RF acceleration; LSS6-ejection to Neutrino Target and West Experimental Areas and ejection dump; LSS4 and LSS5-underground collider experiments (for these special dosimetry is carried out, which is not included in this report).

In this review we restrict ourselves to some representative examples of a high-radiation area such as in LSS1 (fig. 4) and around the ejection dump (fig. 5). The cables in these areas have received doses of the order of 1 to 3×10^5 Gy, at which value, from past experience, serious damage must be expected. Cables were therefore changed in 1988. Also, radiation damage must be expected to other equipment such as vacuum pumps (5×10^6 Gy) and motors (2×10^5 Gy).

Main loss points in transfer tunnels are bends from the vertical to the horizontal direction and splitter magnets. The maximum doses to the magnet coils and cable trays are similar to the ones found in the main ring (6×10^5 and 6×10^4 Gy, respectively).

Clearly, the highest doses of the whole SPS complex are measured in the target areas. Figure 6 shows the situation across the tunnel behind the Neutrino Target Area. Along the beam line the doses on the cable tray have exceeded 10^7 Gy. There are, of course, no conventional cables on this side, but even for special radiation-resistant cables the critical dose is approached. On the sides of the passageway the dose approaches 10^6 Gy, and the cables were changed in 1985. They were replaced by conventional cables, which since then have received a further dose of a few 10^5 Gy.

The doses to the magnets of the narrow-band neutrino beam downstream from T11 are of the order of 6×10^7 Gy. The first two magnets have been replaced. In 1985 the operation of this beam was stopped and the beam elements were demounted.

Severe radiation damage is also observed on many components in the Neutrino Target Area, such as lighting, connectors, switches, crane, etc.

In the North Target Areas TCC2 the doses to the first elements downstream from targets T2, T4, and T6 are also very high (2×10^7 to 1×10^8 Gy). Any material that is not radiation hard (cables, hoses, etc.) must fail. The coil insulations of the first magnets behind the collimators need to be surveyed. The cables on the cable trays in TCC2 are well protected by shielding walls; the doses are of the order of $2-4 \times 10^4$ Gy and similar to those observed in the main ring.

In the region of the North Area High Intensity Facility (NAHIF), a few doses are higher than 10^6 Gy for 8 years of operation. These doses were received by the magnet downstream from target 10, a collimator, and a beam dump. The other elements around T8 and T10 received doses from 1 to 6×10^5 Gy. The NAHIF area is the best protected one for control cables because of the shielded corridor, which was built for this purpose. The integrated maximum dose in this corridor after 8 years of operation was 2.7×10^2 Gy.

The West Target Area TCC6 was built in 1982. The number of protons on T1 since then is 7.1×10^{18} . This is far below the number for the Neutrino and North Target Areas. Furthermore, the elements downstream from the target are enclosed in an 80 cm iron shield. Dose measurements are difficult in this enclosure because there is no access to the first magnet. The dose to the second magnet is between 1 and 8×10^5 Gy. Outside the shielding the doses so far have been below 10^5 Gy.

More detailed dosimetry results and figures of the layout of the cited areas can be obtained from the CERN TIS Commission reports [1].

4. ESTIMATE OF RADIATION DAMAGE

In the previous section, we already made some comments on radiation damage to the equipment in the SPS. Here, we summarize the present situation and try to make some predictions for the future.

4.1 Magnet-coil insulations

The main doses to the SPS magnet coils as measured at 216 positions are between 10^3 and 10^5 Gy. Only a few positions have received 10^6 Gy. Measurements from 1976 to 1980 on the magnet coils on all dipoles in sextant 6 did not reveal any exceptions from the dose pattern measured on the quadrupole. The end-point criterion of the pure epoxy resin used for the SPS magnet-coil insulation is reached between 1 to 2×10^7 Gy [3]; by the glass-fibre reinforcement this value might be increased by a factor of 10 [4].

During the construction of coils for the magnets of the SPS, samples were taken on a regular basis to evaluate their resistance to ionizing radiation. At that time, some of these samples were irradiated at high dose rates in accelerated tests. Since it is known that for some polymers the radiation damage to materials does not depend only on the total integrated dose but also on the dose rate, as well as on other environmental parameters [5,6], the remaining resin samples were kept back for exposure *in situ* with the magnet coils during operation in the SPS. This allows their life ageing to be studied, i.e. their degradation in normal operating conditions. The first tests on these *in situ* irradiations in the SPS main ring and near target areas were made in 1986. The maximum dose reached then was 5×10^6 Gy, where no significant damage was observed. We can therefore conclude that the insulation of the SPS magnet coils did not suffer from radiation damage during the first decade of operation and the outlook for the future appears rather optimistic. Exceptions may be those magnet units with hidden production failures and those which have been repaired during and after production.

4.2 Cable insulations

As early as 1979, evidence of radiation damage to cables appeared in the SPS, where degradation of polyethylene (PE)- and polyvinylchloride (PVC)-insulated control cables was observed in LSS2 at doses even below 10^5 Gy. At the SPS this was also the first evidence that these types of materials degrade much faster in real-life exposure than in accelerated tests [7]. As a consequence, power cables were changed in 1980 [8] and control cables in 1985 along the tunnel of the SPS Neutrino Target Area. Further problems occurred in 1985 and 1986 with the power cables in LSS2 and LSS6 which were consequently also changed. Rather extensive tests were carried out on

samples taken from these cables operating in the described radiation areas. The results which involved PE, PVC, and ethylene-propylene rubber (EPR) materials can be summarized:

- i) No evidence of radiation damage up to 10^4 Gy.
- ii) The end-point criterion for PVC and PE is reached at:
 $1-2 \times 10^5$ Gy when they are used as a sheath material,
 $5-8 \times 10^5$ Gy when they are used as insulator and protected against the environment by tapes and sheaths.
- iii) The end-point for EPR is reached at about 2×10^6 Gy when it is used as insulator and protected against the environment. It was also observed that EPR is less sensitive to long-term ageing effects than, for example, PE.

With this experience we can describe the present situation for the cables in the SPS as follows. In the standard sector of the main ring and transfer tunnels, with average loss points and doses between 10^2 and 10^4 Gy, the cables should not yet suffer from radiation damage. In specially exposed areas, such as LSS1, LSS2, LSS6, TT20A, TT60A, in the Neutrino Target Area (despite the change of cables in 1985), and TDC2, doses approach or exceed 10^5 Gy and preventive measures need to be taken in the forthcoming years.

4.3 Various materials

As already found in tests during the design stage of the SPS, active electronic components are very sensitive to radiation [9]. This was confirmed by the experience gained at the SPS and, as already mentioned above, most of the electronics was removed from the SPS ring in 1982/83 as serious damage occurred at doses exceeding 10^2 Gy.

Any other equipment installed in high-radiation areas (ejection, dumps, targets) containing organic materials such as motors, vacuum pumps, seals, hoses, lighting, telephones, emergency switches, etc., where doses approach 10^6 Gy, need special attention.

5. DOSE RATES

As already mentioned above, it is known, especially concerning cable-insulating materials, that the dose rate is an important factor and that at the same total dose the degradation at low dose rates (< 100 Gy/h) can cause more severe damage than high dose rates [5-7]. In view of the complicated pattern of dose distribution around an accelerator such as the SPS (see Fig. 2), the dose rates vary by orders of magnitude. By dividing the maximum, minimum, or mean doses by the number of hours of operation, one would come to values of the order of 0.08 to 8.0 Gy/h.

As there are about 250 SPS cycles per hour, instantaneous dose rates could go up to 4 mGy per cycle. However, during setting up, this value may occasionally be orders of magnitude higher; 0.2 Gy per cycle is a typical value measured by BLMs [10].

6. PARTICLE FLUENCE

Fluence measurements with activation and spallation detectors have been carried out extensively at CERN (PS and ISR) [11,12]. Comparing those with dose measurements, empirical conversion factors have been established. One is based on fast neutron measurements (3-25 MeV) with sulfur [$^{32}\text{S}(n,p)^{32}\text{P}$] and of high-energy particles (> 25 MeV) with aluminium [$^{27}\text{Al}(h,\text{spall})^{22}\text{Na}$]. This factor is [13]:

$$D(\text{Gy}) = 5 \times 10^{-10} \phi^{22}\text{Na} + 6 \times 10^{-10} \phi^{32}\text{P} ,$$

where ϕ is the neutron or high-energy particle fluence in cm^{-2} .

At the SPS, aluminium foils are added on a routine basis in our HLD programme. However, it was only during the first years (1976–1978) that these were measured. Further exposures of activation detectors were made around the target areas. Application of the empirical formula cited above showed that the glass dosimeters described in Section 2 give a dose of about a factor of 2 higher. Applying this factor to the aluminium foil conversion of the SPS and another factor of 2 to allow for the non-measured fast neutron component, we obtain:

$$D(\text{Gy}) = 20 \times 10^{-10} \phi^{22}\text{Na} .$$

This factor was checked at several hundred dosimeter positions during the years 1976 and 1977 and was found to be valid within a factor of 2 for most of them.

With this we can, with some confidence, use the above SPS conversion factor to estimate the high-energy particle fluence from the doses given in fig. 1; this is shown in fig. 7.

7. INDUCED RADIOACTIVITY

In high-energy proton accelerators the pattern of induced radioactivity from the machine elements (mainly from steel and copper) must clearly follow that of absorbed dose. From measurements at the end of the fixed-target operation in 1985, with a few days cooling time, the following relation of induced radioactivity to absorbed dose was found [14]:

$$\text{Dose rate (Sv/h)} = 3 \times 10^{-7} \times \text{absorbed dose (Gy)} .$$

During the shutdown in 1988, the induced radioactivity was measured at all dosimeter positions in the SPS main ring. Out of about 600 measurement points, the induced radioactivity was below $10 \mu\text{Sv/h}$ for more than 80%. From those which were above $10 \mu\text{Sv/h}$, the ratio dose rate to absorbed dose is around 2×10^{-8} . The discrepancy with the factor given above is due to the different decay times between accelerator stop and the dose measurements.

8. COMPARISON WITH CALCULATIONS

During the design and construction period of the SPS, calculation of the doses to accelerator components have been carried out [15]. For this calculation, 4×10^{19} protons at 200 to 400 GeV per year were assumed. Owing to longer cycle length and the antiproton operation the value was in reality about a factor of 3 lower. Even when taking this into account the calculated values were in general higher than those measured during operation. The reason for this is that the assumption of 30–40% unwanted beam losses were too pessimistic. There are, however, only a few cases where the difference between calculation and measurement exceeds an order of magnitude.

9. CONCLUSIONS

- i) The typical dose pattern around the ring of a high-energy particle accelerator such as the SPS varies within three orders of magnitude. For 10 years of operation these values are between 7×10^2 and 7×10^5 for the magnet coils, 3×10^2 and 3×10^5 for the side of the magnet, and 7×10^1 and 7×10^4 for the cable trays.
- ii) So far, there is no evidence of radiation damage to magnet coils, and for the future we still have an appreciable safety factor (more than another decade). However, cables had to be changed on several occasions in high-radiation areas and further changes need to be foreseen for the future. Other equipment containing organic materials needs to be surveyed.

- iii) High-energy particle fluence measurements ($E > 25$ MeV) with activation detectors confirm the fluence to dose conversion factor found at the PS and ISR within a factor of 2.
- iv) The ratio between dose rate and absorbed dose for a fixed-target period of SPS operation and a few days cooling is about 3×10^{-7} .
- v) Calculated values of doses during the design stage of the SPS were higher than the ones actually measured. They agree in general within the order of magnitude.

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Table 1

Mean doses (in Gy) for 36 SPS coils, 36 beam loss monitors (BLMs), and 36 electronic pits (PITs)
per sextant (total 216) for 10 years of SPS operation

Period	Position	Sextant 1 ($\times 10^3$)	Sextant 2 ($\times 10^3$)	Sextant 3 ($\times 10^3$)	Sextant 4 ($\times 10^3$)	Sextant 5 ($\times 10^3$)	Sextant 6 ($\times 10^3$)	Mean of total 216 ($\times 10^3$)	No. of protons accelerated ($\times 10^{18}$)	Integrated doses per proton ($\times 10^{-18}$)
April 1976 to Dec. 1978	Coil	59.0	51.0	86.0	386.0	87.0	218.0	147.6	23.50	628.0
	BLMs PITs	32.0 2.0	48.0 1.0	25.0 1.0	68.0 5.0	55.0 2.0	42.0 1.5	44.8 2.2		190.6 9.36
Feb. 1979 to June 1980	Coil	60.0	38.0	34.0	83.0	55.0	96.0	61.1	36.71	166.4
	BLMs PITs	43.0 3.0	49.0 18.0	22.0 0.8	29.0 2.0	54.0 1.0	41.0 8.4	39.7 5.7		108.1 15.5
April 1981 to Dec. 1982	Coil	38.0	71.0	68.0	52.0	37.0	62.0	54.5	55.89	97.5
	BLMs PITs	25.0 5.0	43.0 1.0	21.0 0.5	20.0 0.4	38.0 0.4	29.7 3.3	29.5 1.7		52.8 3.04
March 1983 to Dec. 1983	Coil	31.0	17.0	14.0	10.0	10.0	22.2	17.3	11.44	151.2
	BLMs PITs	17.0 3.0	14.0 0.8	8.0 0.2	4.0 0.1	7.0 0.2	15.7 2.3	10.9 1.1		95.3 9.62
March 1984 to Dec. 1984	Coil	24.0	96.0	6.0	9.0	7.0	15.8	26.2	23.77	110.2
	BLMs	14.0	21.0	3.0	3.0	4.4	16.0	10.0		42.1
March 1985 to Dec. 1985	Coil	74.0	41.0	27.0	17.0	2.9	30.6	32.0	10.01	319.6
	BLMs	36.0	8.0	5.0	6.0	2.6	14.9	12.2		121.9
March 1986 to Dec. 1986	Coil	32.0	18.0	6.0	3.0	2.0	25.4	14.3	13.50	105.9
	BLMs	24.0	12.0	0.8	0.7	3.0	20.0	10.0		74.1
April 1976 to Dec. 1986	Coil	316.0	332.0	241.0	559.0	200.0	470.0	353.2	174.82	202.1
	BLMs	190.0	194.0	84.0	132.0	164.0	179.7	157.14		89.9

Fig. 1 Cross-section of the SPS tunnel with dosimeter positions and doses (in Gy) measured during 10 years of SPS operation (1976–1986). (1) Maximum and (2) minimum doses measured at this position. (3) Mean dose from 216 dosimeter positions. Number of accelerated protons: 17.5×10^{19} .

Fig. 2 Typical dose pattern of 36 BLM and coil positions of SPS sextant 6 for one year (1986) and for 10 years of operation (1976-1986).

Fig. 3 Mean doses to the SPS per accelerated proton from 216 dosimeter positions during the period 1976 to 1986. Number of accelerated protons: 17.5×10^{19} .

Fig. 4 Integrated doses (in Gy) in the SPS Straight Section 1 (LSS1) from 1976 to 1986.

Fig. 5 Integrated doses (in Gy) in the ejection dump area in the SPS transfer tunnel TT6 from 1976 to 1986.

Fig. 6 Integrated doses (in Gy) downstream from the SPS Neutrino Target Area from 1976 to 1986.
Total number of protons on targets: 23.7×10^{18} .

Fig. 7 Estimate of high-energy particle fluence in cm^{-2} ($E > 25$ MeV) for the SPS from 1976 to 1986: (1) minimum, (2) maximum, (3) mean. Number of accelerated protons: 17.5×10^{19} .