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PROBLEM OF WORK ON A HIGH ENERGY SYNCHROTRON SUBMITTED TO LARGE RADIATION DOSE

R. Gouiran
CERN, Geneva, Switzerland

1. Introduction

Running a high energy synchrotron towards higher and higher proton intensity begets series of problems related to equipment damages and repairs and to works in radiation areas. Maintenance should therefore become an integral part of the organization and some methods should be developed for evaluating and predicting irradiation of personnel and equipment. Firstly, organic components have to be surveyed and eventually exchanged; secondly, work done by the staff in radioactive areas should be strictly controlled and minimized. To reach these goals radiation and radioactivity should not only be measured but also predicted years in advance. Radiation doses are computed, measured and predicted according to the proton loss pattern around the accelerator. A correlation scheme of doses versus accelerator operation is then deduced to predict the dose on any sensitive part of the accelerator. In the same way a radioactive pattern is computed, measured and accurately predicted in terms of dose rate. Work on the accelerator is studied in detail in order to forecast its duration and the corresponding dose absorbed by the staff. With these methods, it is easy now not only to predict the fate of the equipment and the doses to be received by the staff, but also to organize the work accordingly and possibly to program the accelerator operation (proton intensity and proton uses like target operation, dumping, extracting etc.) following these predictions.

2. Effects of Radiation on the CPS Synchrotron Magnet

Three main effects have to be considered: on magnet laminated blocks, on main excitation coils, on pole face windings.[1,2,3,4,5,6,7,8]

2.1. Magnet laminated blocks. Each of the 100 CPS magnet units consists of 10 laminated blocks made of 1.5 mm steel sheets glued together with araldite. Under radiation and magnetic field, loose front sheets break the araldite pole face windings already weakened by radiation.

After a series of breakdowns, we have estimated the reliability f of the original magnet units as $f = 1 - p$, where p is the breakdown probability. To do so we consider the radiation dose R (in rad) absorbed by the iron at a specific point of the unit, always at the same location which is considered as the normalized reference point on all units. This point (point A in Fig. 1) is located at the entrance of the first block, 5 cm below

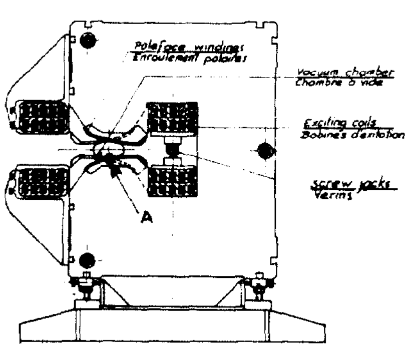

Fig. 1. Cross section of magnet pole profile, with vacuum chamber and pole face windings.

beam axis, which is the nearest place to the proton beam. This location is the most exposed and the weakest region of the magnet unit.

The reliability f (only between 0 and 1) is given by

$$f \simeq - 0.9 \log (R/8.5\ 10^8)$$

which means that there is no old unit in good condition for doses above $8.5\ 10^8$ rad, and that the reliability f starts to decrease below 1 somewhere around 5.10^7 rad.

Consequently the damaged steel blocks have to be repaired, and the pole face winding sheets have to be exchanged.

2.2. Main excitation coils. These aluminium water cooled coils are insulated by fiber glass and mica ribbons moulded in araldite. In some places the araldite is destroyed by radiation and the insulation is warranted only by the mica laminations, which shows the necessity to always provide a mica barrier in any araldite insulation submitted to radiation. The coils are no longer water proof and special care has to be taken to avoid water leaks. Some coils will have to be repaired or exchanged after a dose of around 8.10^8 rad, but where they are located, these coils receive 4 times less radiation than the magnet block and the pole face windings at the reference point A.

2.3. Pole face windings. These windings are moulded in an araldite sheet fitting the magnet pole profile and fixed by stainless steel belts (Fig. 1). Due to the CPS structure, 400 of such sheets, each 2.20 m long, provide the necessary multipole field corrections in order to adjust the magnetic field and to compensate iron saturation. Araldite and connecting cable insulation become hard and brittle. These pole face winding sheets have to be exchanged gradually, in particular where the magnet steel blocks have to be repaired, because they do not stand up very well to dismounting.

If they are not handled too much, the original pole face windings could withstand 10^9 rad. They are progressively exchanged by better ones, able to support 3.10^9 rad.

3. Radiation Measurements

3.1. Radiation dosimetry. After several years of study, calibration and intercomparison between different dosimeters, we decided to use only small glass dosimeters (Schott glass PDG11, 1.5 and 5 mm thick, coloured by radiation and measured via a Beckmann spectrophotometer). Of course these dosimeters are not very accurate and fade rapidly[9] but they are very easy to handle and measure, and all we ask for is a good reproducibility. All radiation measurements and equipment surveying should be made with the same dosimeters and the same methods, because we need accuracy only for relations between cause and effect, not for absolute values.

The relation between the measured glass absorbence A and the apparent dose received R (in rad) looks more or less like

$$R = 1.2\ 10^5\ (e^{A/k_\lambda} - 1) \qquad (1)$$

where k_λ is a constant for a given wavelength (k_λ = 0.377 at λ = 510 nm which is the maximum sensitivity peak, and k_λ = 0.245 at λ = 330 nm which is the minimum of sensitivity just before the UV peak).

The fading of the absorbence A_t at day t compared to the absorbence A_2 two days after irradiation, is approximatively

$$A_t = A_2\ 1.036\left[1 + 0.115 \log 1/t\right] \qquad (2)$$

The position of the dosimeter on the magnet unit is carefully noted in order to normalize, via a correction factor, its reading to the dose received at the reference point (see Fig. 1), where it is not possible to install anything. Dosimeters are changed and measured at regular intervals.

3.2. Loss and radiation pattern. Magnet irradiation comes from different origins. Protons lost in an internal target; an extraction septum (magnetic or electrostatic), or an injection deflector beget high irradiation on the following magnet unit and the two or three subsequent units. However, because of the betatronic oscillations and the closed orbit deviations, we find rather large beam losses on some specific hot spots far away from the original radiation sources. It is possible to correlate directly the doses received by some magnet units to a given proton use in the accelerator and to plot a radiation pattern correlated to a loss pattern. This correlation is made by statistical comparison between dosimeter readings on one hand, and by a careful analysis of the CPS beam loss monitors around the ring on the other hand, for each specific accelerator operation.

Another source of radiation is more diffuse and difficult to correlate to any operation, but it remains more or less proportional to the number of accelerated protons. We have called it the "banal dose", and it follows a very regular "wriggle" pattern: it is 2.5 times higher in a focusing section than in a defocusing one.

The radiation azimuthal pattern shows a series of hot and quiet regions around the ring. At the end of 1974, the most exposed reference point had received 4.10^9 rad (near internal target 1), but the magnet unit at this location has been exchanged three times! The less exposed reference point had received 2.10^7 rad in the meantime. The sum of the hundred doses at the reference points of the 100 magnet units was 1.5 10^{10} rad at that time. This sum is expected to reach 6.10^{10} rad in 1984.

3.3. Radiation prediction. Assuming that the reference point is radially 5 cm below beam axis and longitudinally between 1 to 3 m from a direct radiation source (targets, septa etc.) it is possible to compute theoretically the absorbed dose in the iron and to compare with the experimental results[10,11,12], per proton lost in the radiation source. Though it varies from case to case, it is not too far from 2.5 10^{-10} rad per interacting proton in the radiation source. Then for each proton lost, a correlation pattern of irradiation is given around the accelerator.

The exact proton losses are then determined by the knowledge of the various efficiencies of the accelerator operation for each proton use (targetting, extracting, injecting, dumping etc.).

So it is possible now to get a fairly accurate prediction of the radiation pattern around the accelerator when we know:

a) the sharing of accelerated protons between accelerator users (in %)

b) the efficiency (in proton losses) of each proton use

c) the total accelerated protons

d) the dose pattern around the ring, in rad per interacting proton in the radiation sources used in a given operation.

e) the "banal non correlated dose" which is always statistically present during any acceleration.

This method is used at the CERN synchrotron and it allows to predict the fate of a sensitive equipment years in advance and consequently to programme exchange or repairs in due time[7].

4. Radioactivity Measurements

Though radioactivity does not jeopardize the synchrotron future, it is nevertheless more important than radiation on human grounds because it is directly bound to the dose received by the maintenance staff whose duty is to give a good tool to physicists. It is of prime importance to study the impact of the machine induced activity on the accelerator maintenance in order to guarantee that the synchrotron could be safely operated in the future, and also in order to schedule proton uses for minimizing radioactivity in the ring during maintenance shut-down periods

4.1. Dose rate measurements. In order to normalize predictions, we consider always dose rates measured at 40 cm from the vacuum tubes of the hundred straight sections between magnets, after two days of machine stop (because this survey is done as a routine by the Health Physics Group on the Monday morning following the accelerator stop on the Saturday evening, every four weeks). As a general rule the machine is stopped before weekends or official holidays in order to leave the maximum possible length of cooling time before starting works inside the ring tunnel.

A correction factor is then used to know the dose rate at contact, and which is 7 on average, although it could reach 14 near a target.

4.2. Radioactivity predictions. Several authors[13,14,15,16,18,19] have tried to define the dose rate measured at the contact of a thick and isolated iron piece after 30 days of continuous irradiation followed by 1 day of cooling, in rem/h per (stars/cm^3s). This value, known as $\omega_{30,1}$ has been taken here equal to 8.10^7.

The free cooling follows fairly well the Sullivan-Overton formula[17] which says that the dose rate D(t) after t days cooling following T days of continuous irradiation is

$$D(t) = k \log\left[1 + (T/t)\right] \qquad (3)$$

where k is just a proportional factor.

Finally the fundamental formula we use for radioactivity prediction in the straight section i is:

$$D_i(T,t) = K_i \cdot I_i(p/s) \cdot \log\left[1 + (T/t)\right] \qquad (4)$$

where $I_i(p/s)$ is the average quantity of proton per second, interacting in the source of radiation creating the activity at location i during T days, K_i is a constant for each location to be defined experimentally, and t is the cooling time in days.

This formula shows that the radioactive cooling becomes very slow after 4 months, where a factor 4 has been already obtained, compared to the two days standard cooling time.

The CPS synchrotron operation is divided in monthly periods and this feature allows an important simplification for radioactivity prediction, the so-called "two components" theory[13]: it says that, in order to know the radioactivity at a given time, it is sufficient

a) to consider in detail the last monthly period giving a "fresh" radioactivity and

b) to estimate an "old" activity as given by a mean operation during the last two years preceding this last monthly period (as long as the accelerated proton intensity has not varied too much during the last two years) and which is supposed to cool down during the last month according to the Sullivan-Overton formula (3).

This "two components" simplification does not introduce errors larger than 10 to 15%. For more accuracy the "old" radioactivity can be split into two yearly slices if necessary. These two components (fresh and old) contribute nearly fifty-fifty to the final dose rate.

4.3. Radioactivity pattern. As for irradiation the azimuthal pattern shows hot regions where 1 rem/h at 40 cm after two days could be observed (near targets, extraction or injection septa etc.) and quiet regions where the dose rate is often below 5 mrem/h, for the same conditions.

It is also possible to correlate directly the dose rate in some straight sections to a given proton use in the accelerator and to plot a radioactive pattern correlated to a loss pattern for each specific accelerator operation. We also consider the more diffuse radioactivity, difficult to correlate to any operation and which remains more or less proportional to the number of accelerated protons, and what we have also called the "banal dose rate". As the radiation, it follows the regular "wriggle" pattern, being 2.5 times higher in a focusing section than in a defocusing one.

The sum of the hundred dose rates measured at 40 cm after two days on each of the 100 straight section is called TAR ("Total Activity Ring"), and it depends strongly upon the last month operation. In the last two years it was around 5 rem/h and we expect that it could reach 10 rem/h in 1984.

We determine for each straight section i the coefficient K_i of equation 4, for a given operation leading to I (proton per second) lost in any specific operation. Though it varies from case to case, this K_i is not too far from $6.7 \cdot 10^{-12}$ rem/h per interacting proton per second for a target, and $1.7 \cdot 10^{-11}$ for a septum

As for radiation the exact proton losses are then determined by the knowledge of the various efficiencies of the accelerator operation for each proton use (targetting, extracting, injecting, dumping etc.).

So it is possible now to get a fairly accurate prediction of the radioactive pattern around the accelerator when we know

a) the sharing of accelerated protons between accelerator users (in %) and the time schedule of this use

b) the efficiencies (in proton losses) of each proton use

c) the total accelerated protons and the corresponding time schedule

d) the dose rate pattern around the ring, in rem/h per interacting proton per second in the radiation source used in a given operation

e) the "banal non correlated dose rate" which is always statistically present after each acceleration.

This method is used at the CERN synchrotron and it allows to predict the dose rate at any location where people have to work, months in advance, and consequently to programme the maintenance and the accelerator operation in order to minimize, and to maintain as low as possible, the dose received by any staff member.

5. Dose Received by Working Staff

The knowledge of the dose rate repartition is not sufficient for a good estimation of the probable dose to be received by any worker. The dose received at location i is the dose rate D_i given by (4) multiplied by the number of hours spent for the job and also by three reduction factors, which we have called respectively[13]: a) the "delay factor" f_d, b) the "presence factor", f_p and c) the "equipment factor", f_e.

a) the delay factor comes from the fact that jobs on very active pieces is delayed as much as possible, and is done d days after the start of the machine shut-down where D_i has been measured or estimated. As a general rule we take $f_d \simeq 2/\log\left[1 + (200/d)\right]$ which is a fair enough approximation. We note that $f_d = 1.5$ already after 10 days.

b) the presence factor is due to the fact that for a one hour job the worker does not stay quiet at 40 cm from the vacuum pipe during this one hour! According to the job he stays at various distances and f_p should take account of this fact. This reduction factor is specific for a given well known standard job and should be accurately measured for any typical intervention. It is between 1 and 5, generally around 4.

c) the equipment factor comes when some active equipment has been removed before the job. When vacuum chamber and straight section equipment have been removed, f_e is about 2. When equipment is removed but not the vacuum chamber, f_e becomes 1.7.

So the dose received by a person working for one hour on location i, d days after the dose rate D_i has been estimated according to equation (4) is:

$$D = D_i \cdot \log \left[1 + (200/d)\right]/2 \cdot f_e \cdot f_p \qquad (5)$$

Unfortunately we should also add to these doses received for a specific well known job, a general dose received during the stay in the ring, outside the specific job time. This dose comes from multiple small tasks, going and coming, unnecessary stays in radioactive areas (the "talk-dose"!) etc.

It is proportional to the time spent in the accelerator tunnel and is: TAR(rem/h).$3.5 \cdot 10^{-3}$ rem per working day. (TAR is the sum of the 100 dose rate measured at the standard 100 points as described in § 4.3. Its value at present is around 5 rem/h).

For example, a foreman just walking in the tunnel for a 20 days shut-down, without getting close to the magnet, will recive at present 0.350 rem, which is not negligible when it has to be added to more specific doses. (At present we try to limit the total dose received during a 6 weeks annual shut-down at 2 rem per person).

The method described above has been used and is very accurate as well as useful for staff dose survey, in particular for people working on the vacuum system and on the magnets themselves.

6. An Example

We just try to figure out a very simple but fictive situation. Suppose that $1.7 \cdot 10^{19}$ proton have been accelerated per year with 10% allocated to target 1 whose efficiency is 80%. At this place K_i of equation (4) is $6.7 \cdot 10^{-12}$ rem/h per interacting proton.

We apply the two component theory. For the "old" activity, the term I(p/s) will be $1.7 \cdot 10^{19} \times 10^{-1}.2/570.24 \cdot 3600$ (for 670 days), that is to say $5.8 \cdot 10^{11}$. So after one month, the "old" components will contribute for $6.7 \cdot 10^{-12}.5.8 \cdot 10^{11}.\log\left[1 + (670/30)\right] = 0{,}531$ rem/h.

The "fresh" components will be (one month is one tenth of a accelerator year and corresponds to 24 days of acceleration):

$$6.7 \cdot 10^{-12} \frac{1.7 \cdot 10^{19} \cdot 10^{-1} \cdot 10^{-1}}{24 \cdot 24 \cdot 3600} \log\left[1 + 24/2\right] = 0.611 \text{ rem/h}$$

So D_i at 40 cm after 2 days stop would be 1.14 rem/h at this place.

Suppose a man has to change the vacuum section near this target, but 10 days after the shut-down start. So $f_d = 1.5$. We know by past experience that for this job $f_p = 4$. As nothing has been removed yet, $f_e = 1$. The work lasts half an hour, so this worker would receive $1.14 \times 0.5/1.5 \cdot 4 \cdot 1 \simeq 100$ mrem. We should not forget to add, to this dose, the "general" dose of § 5. which is, for 10 days "walking" in the ring, TAR $10.3.5 \cdot 10^{-3}$ = 175 mrem already, for TAR = 5 rem/h. So the total absorbed dose will then be 275 mrem for this simple example.

7. Conclusions

The survey of irradiation and radioactivity is possible by means of some accurate methods. It is absolutely necessary in order to not only organize maintenance and repairs but also to protect working staff against undue radioactive doses. Such surveys should become an integrated part of any particle accelerator management and they should be able to influence accelerator operating schedule.

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