ESTIMATION OF BEAM LOSSES AND RADIATION DOSE
TO COMPONENTS IN THE CPS BOOSTER (PSB)

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1. Introduction

In a previous paper\(^1\) it was tried to relate the beam loss patterns found at the CPS to losses expected in the booster (PSB). Several models of a loss distribution were assumed and extrapolated from CPS to PSB energy. The reasonable agreement of secondary particle flux and dose rate measurements at the CPS with the calculations was an encouragement for the present estimation of beam losses and dose rates in the PSB.

However, it has to be pointed out that the dose values given below are estimations and may only be correct within a factor 2 to 3, which is acceptable from the Health Physics point of view. Furthermore, the assumptions on the position of the loss points and the percentage of protons lost are only based on theoretical considerations and might turn out to be either too optimistic or too pessimistic, when the PSB has passed the set-up period. Therefore, it has been thought wise rather to overestimate the dose rates to components, taking the loss assumptions as correct.

Knowledge about radiation levels in the vicinity of the accelerator vacuum chamber is important not only from the Health Physics point of view (doses to personnel operating and maintaining the machine) but as well for the estimation of the life time of machine components.

Special attention is drawn to the behaviour of magnet coil insulation materials. Recent developments in this field are organic materials like epoxy resins, which can take up to \(10^6 - 10^9\) rad before they change their most important properties considerably\(^2,3\)). But up to now conclusions drawn from irradiation experiments of these resins are not convincing, especially because only \(\gamma\)- and reactor neutron (up to \(14\) MeV) irradiations have been performed at high fluxes during short time intervals. There is no direct relation between the absorbed dose calculated in this case and the absorbed dose in the complex and not well known field of charged and uncharged secondary particles in the vicinity of an accelerator. Besides, the damage created by \(10^6 - 10^9\) rad of \(\gamma\) and neutrons during one hour of irradiation may be different from the damage
by the same "dose" of high energy secondary particles irradiating the material during one year. "Healing"-effects in the material and interpretation errors when calculating the absorbed dose may result in a larger radiation resistivity as predicted. Relation of fluxes of secondary particles of different energies to damage of organic insulation materials would allow better conclusions, but such measurements are not available. Therefore, for the best resins as chosen for the PSB magnet coil insulations, a value of approximately $10^3$ rad absorbed dose ("rad" as calculated below for fast neutron, high energy particle and $\gamma$-ray contribution) should be acceptable before considerable damage can be found.

2. Proton loss estimations

It is planned to run the CPS-Linac at a current of up to 100 mA and a burst length of 100 $\mu$s to feed the PSB. This would mean that $6.25 \times 10^{13}$ protons of 50 MeV are produced per burst. The cycle time of the PSB is not yet definitely fixed, it may be 2 s or 1.15 s. For a cycle time of 1.15 s the number of protons lost per unit time will obviously be somewhat larger than for the 2 s cycle. In order not to underestimate the radiation doses near loss points, preference is given to the shorter cycle time, i.e. the larger number of protons lost. With a cycle time of 1.15 s, $6.25 \times 10^{13}$ p/burst correspond to $5.4 \times 10^{13}$ p/s.

The final results can be easily modified for any change of the loss structure by simply multiplying the estimated dose rate with the quotient of the real number of protons lost in a place and the number applied below. The loss distribution scheme given here has been elaborated in discussions with C. Bovet, during SI Parameter Meeting No. 45 4), and with E. Weisse 5).

2.1 Losses at injection energy (50 MeV) and at the beginning of acceleration (50 - 100 MeV).

Only the main loss points have been considered. Additional random losses cannot be estimated. The respective loss points are listed below. All figures refer to the total number of protons delivered from the Linac as given above : $54 \times 10^{12}$ p/s.
2.1.1 Loss at beam distributor I-DIS\(^6\) (50 MeV) \(\sim\) 3\% of total number of protons :

\[
\begin{array}{l}
\text{rest :} \\
1.62 \times 10^{12} \text{ p/s}
\end{array}
\]

The protons left are distributed to 4 vacuum chambers, i.e.

\[
13.1 \times 10^{12} \text{ p/s per chamber.}
\]

2.1.2 Loss on inflector I-SH (50 MeV) during multiturn injection, \(\sim\) 60\% :

\[
\begin{array}{l}
\text{rest :} \\
31.43 \times 10^{12} \text{ p/s}
\end{array}
\]

The lost protons are distributed on 4 vacuum chambers, i.e.

\[
7.86 \times 10^{12} \text{ p/s per chamber.}
\]

2.1.3 Loss due to RF-trapping, space charge blow up, gas scattering, various resonances (50 - 100 MeV) rest (accelerated) :

\[
10.00 \times 10^{12} \text{ p/s}
\]

The lost protons are distributed on 4 vacuum chambers, i.e.

\[
2.5 \times 10^{12} \text{ p/s per vacuum chamber.}
\]

2.2 Losses at maximum energy (800 MeV)

It has been assumed that no beam is lost in the four PSB rings after the maximum energy has been reached. Presumable losses occur in the PSB-CPS transfer line at the ejection and recombination septum magnets. These points are listed below.

2.2.1 Loss on four ejection septum magnets (E-S, 1-4), approximately 2\% of the protons available :

\[
\begin{array}{l}
\text{rest :} \\
0.22 \times 10^{12} \text{ p/s}
\end{array}
\]

The lost protons are distributed on 4 septum magnets, i.e.

\[
0.055 \times 10^{12} \text{ p/s per septum.}
\]

2.2.2 Loss on 2 vertical septum magnets (T-SV 1, 2), \(\sim\) 1\% of beam in one vacuum chamber per septum :

\[
\begin{array}{l}
\text{rest :} \\
0.05 \times 10^{12} \text{ p/s}
\end{array}
\]
The lost protons are distributed on 2 septum magnets, i.e. 0.025 \times 10^{12} \text{ p/s per septum.}

2.2.3 Loss on 2 recombination septa (T-SD 1, 2), \sim 10\% of available protons:

\begin{align*}
\text{rest} : & \quad 1.07 \times 10^{12} \text{ p/s} \\
\text{rest} : & \quad 9.61 \times 10^{12} \text{ p/s}
\end{align*}

The lost protons are distributed on 2 septum magnets, i.e. 0.535 \times 10^{12} \text{ p/s per septum.}

It has to be pointed out that this mode of operation is only valid for the time needed for filling the ISR. Therefore, the operation time might be less than 10\% of the total operation time of the PSB.

2.2.4 Loss on vertical septum magnet (T-SV 3) \sim 0.5\% of available protons:

\begin{align*}
\text{rest} (\text{delivered to PS}) : & \quad 0.05 \times 10^{12} \text{ p/s} \\
\text{rest} (\text{delivered to PS}) : & \quad 9.56 \times 10^{12} \text{ p/s}
\end{align*}

3. Dose estimations

For the estimation of the dose due to fast neutrons (FN), high energy particles (HEP) and accompanying \gamma\text{-rays} around a loss point the source models developed in Ref. 1) were taken. From the agreement between calculations and measurements at the PS model a (point source) and model b (1 m line source with exponential decrease) are taken into consideration. Figures 1 - 4 show the secondary particle flux as a function of downstream distance from the source of secondary particles in planes of 6 cm, 15 cm, and 55 cm from the beam orbit. These distances correspond approximately to planes of 1 cm, 10 cm, and 50 cm from the surface of the vacuum chamber. The curves are normalized to $10^{12}$ p/s lost.

The assumed number of lost protons (see chapter 2) corresponds to a certain number of secondary particles at a given distance from the loss point (shielding by machine components has been disregarded in this consideration). For the dose calculation this number has to be multiplied by a conversion factor of secondary particle flux to dose. The conversion factor for secondaries from 50 - 100 MeV protons is $2 \times 10^{-8}$ rad/FN, the conversion factor for secondaries from 800 MeV protons is $6 \times 10^{-8}$ rad/HEP. These conversion factors correspond to the total dose from FN, HEP and \gamma\text{-rays.}
It has to be pointed out that the 50 - 100 MeV models assume 0.1 FN per proton lost. For 50 MeV protons this production rate is exaggerated, because only about 2 - 3% of all protons lost undergo a nuclear interaction and about 5 of these reacting protons will produce one FN. From this it follows that only about 0.005 FN are produced by one 50 MeV proton lost. Therefore, the secondary particle fluxes taken from the models (Figs. 1 and 2) should be divided by 20, if all the protons lost have injection energy (50 MeV).

3.1 Calculation of dose near the loss points at injection energy (50 MeV) and at the beginning of acceleration (50 - 100 MeV)

The calculated dose values are given for the maximum of the secondary particle distribution and for 1 m and 2 m distance from the loss point. The dose per hour represents the dose after one hour of irradiation, the dose per year refers to an operation period of 6000 h per year. (The symbol ≤ is applied, when the dose from several loss points at different levels of the machine has been added up disregarding the shielding and the distance between the loss points).

3.1.1 Loss at beam distributor I-DIS (50 MeV), 1.62 \cdot 10^{12} p/s lost on three septum magnets, i.e. 0.54 \cdot 10^{12} p/s per septum.

Model : point source at the downstream end of the septum (Fig. 1).

Dose at 6 cm above beam orbit, maximum 10 cm downstream from loss point :

\[
\frac{4.3 \cdot 10^7 \text{FN/s} \cdot 2 \cdot 10^{-8} \text{rad/FN}}{20} = 0.043 \text{ rad/s} = 1.55 \cdot 10^2 \text{ rad/h} = 9.3 \cdot 10^5 \text{ rad/year}
\]

The total maximum dose from three septa about 10 cm behind the junction box wall will then be :

\[
\leq 4.65 \cdot 10^2 \text{ rad/h} \leq 2.8 \cdot 10^6 \text{ rad/year}
\]
3.1.2 Loss on injector I-SH (50 MeV) during multiturn injection. 31.43·10¹² p/s per septum.

Model: point source at the downstream end of septum.

Dose at 6 cm above beam orbit, maximum 10 cm downstream from loss point, per septum:

\[ \text{Dose} = 6.3 \cdot 10^8 \, \text{FN/s} \cdot 2 \cdot 10^{-8} \, \text{rad/FN} \]

\[ = 0.63 \text{ rad/s} \]
\[ = 2.27 \cdot 10^3 \text{ rad/h} \]
\[ = 1.36 \cdot 10^7 \text{ rad/year} \]

Dose to coil insulation of the next component (Bending magnet) ~ 20 cm downstream loss point; influence from one septum:

\[ \text{Dose} = 3.93 \cdot 10^8 \, \text{FN/s} \cdot 2 \cdot 10^{-8} \, \text{rad/FN} \]

\[ = 0.39 \text{ rad/s} \]
\[ = 1.4 \cdot 10^3 \text{ rad/h} \]
\[ = 8.5 \cdot 10^6 \text{ rad/year} \]

Maximum dose to one coil:

Dose at 1 m distance from the loss point, 6 cm above beam orbit, per ring:

\[ \text{Dose} = 2.04 \cdot 10^7 \, \text{FN/s} \cdot 2 \cdot 10^{-8} \, \text{rad/FN} \]

\[ = 2.04 \cdot 10^{-2} \text{ rad/s} \]
\[ = 73.4 \text{ rad/h} \]
\[ = 4.4 \cdot 10^5 \text{ rad/year} \]
3.1.3 Loss due to RF-trapping, space charge blow-up, gas-scattering, various resonances (50 - 100 MeV). $10 \cdot 10^{12}$ p/s lost in four rings, i.e. $2.5 \cdot 10^{12}$ p/s per ring.

Model: point source in loss point.

The place where this loss occurs is not very well defined. Therefore, different assumptions were made to distribute the lost protons and to calculate the dose around the loss point.

3.1.3.1 The lost protons are equally distributed over the whole ring. The vacuum chamber surface is about $6 \cdot 10^6$ cm$^2$.

Dose 6 cm above beam orbit ($\sim 1$ cm above vacuum chamber) per cm$^2$, per ring:

$\frac{2 \cdot 10^8 \text{ FN/s} \cdot 2 \cdot 10^{-6} \text{ rad/FN}}{6 \cdot 10^6}$

= $0.67 \cdot 10^{-6}$ rad/s

= $2.4 \cdot 10^{-3}$ rad/h

= 14.5 rad/year

3.1.3.2 The protons are lost on two different points.

Dose 6 cm above beam orbit ($\sim 1$ cm above vacuum chamber) $\sim 10$ cm downstream loss points (maximum dose), per ring:

$2 \cdot 10^8 \frac{\text{FN/s} \cdot 2 \cdot 10^{-6} \text{ rad/FN}}{2}$

= 2 rad/s

= $7.2 \cdot 10^3$ rad/h

= $4.3 \cdot 10^7$ rad/year

3.1.3.3 The protons are lost in one point.

Dose 6 cm above beam orbit, ($\sim 1$ cm above vacuum chamber) $\sim 10$ cm downstream loss point (maximum dose) per ring:

= 4 rad/s

= $1.44 \cdot 10^4$ rad/h

= $8.6 \cdot 10^7$ rad/year

At 1 m distance, the dose will be smaller by a factor of $3.25 \cdot 10^{-2}$ at 2 m distance by a factor of $8.75 \cdot 10^{-3}$ than the given maximum dose.
3.1.3.4 80% of the protons are lost on a beam scraper.

\[ \gamma\text{-Dose around beam scraper} \approx 5 \times 10^3 \text{ rad/h} \]
\[ \approx 3 \times 10^7 \text{ rad/year} \]

\[ \gamma\text{-Dose at 1 m distance from beam scraper :} < 3 \times 10^5 \text{ rad/year} \]

3.1.3.5 For the assumption of a really bad case, 50% of the loss is taken to happen at the vacuum chamber wall inside a magnet. For this the model of the "30 cm source strip" with constant intensity (model d in Ref. 1) is applied. Protons lost:

\[ 1.25 \times 10^{12} \text{ p/s.} \]

Dose to magnet coil directly outside loss point:

\[ 5.6 \times 10^8 \text{ FN/s} \times 2 \times 10^{-8} \text{ rad/FN} = 11.2 \text{ rad/s} \]
\[ = 4 \times 10^4 \text{ rad/h} \]
\[ = 2.4 \times 10^8 \text{ rad/year} \]

3.2 Calculation of dose near the loss point at maximum energy (800 MeV)

The calculated dose values are given for the maximum of the secondary particle distribution and for the distance after which the next components can be found. Doses per hour or per year are defined as in paragraph 3.1.

3.2.1 Loss on four ejection septum magnets (E-S 1-4), \( 2.2 \times 10^{11} \text{ p/s,} \)

[\text{i.e.} 5.5 \times 10^{10} \text{ p/s per septum.}]

Model: 1 m line source with exponential decrease.

Dose at 6 cm above beam orbit, \( 1.38 \times 10^8 \text{ HEP/s} \times 6 \times 10^{-8} \text{ rad/HEP} \text{ maximum at 70 cm downstream beginning of septum, per ring:} \]
\[ = 8.25 \text{ rad/s} \]
\[ = 3 \times 10^4 \text{ rad/h} \]
\[ = 1.8 \times 10^8 \text{ rad/year} \]
3.2.1.1 Dose to next component in PSB ring (E-D 1-4). Distance from source of secondary particles 1.4 m.

3.2.1.2 Dose to next bending magnet 15R-B1. Distance from source of secondary particles 2.2 m, shielding by E-D not considered.

3.2.1.3 Dose to 15 R-B1, shielding by E-D (~30 cm of iron) considered (attenuation factor ~ 0.21):

3.2.1.4 Dose to the next component in the transfer line: vertical bending magnet T-BV. Distance from beginning of E-S 3.8 m. Assumption: same number of secondary particles in this direction as in the ring line. Shielding by magnet 15R-B1 not considered.

3.2.1.5 The beam is ejected by the E-S under an angle of 3° to the ring beam orbit. From geometrical considerations it is seen that the magnet 15R-B1 partially shields the magnet T-BV from secondary particles. The thickness of iron to be traversed by the secondaries is about 40 cm of iron. This is equivalent to an attenuation factor of about $e^{-2} = 0.135$. With the factor the dose to T-BV is calculated from 3.2.1.4 to $\sim 4.6 \cdot 10^5$ rad/year.

3.2.2 Loss on two vertical septum magnets (T-SV 1, 2), $5 \cdot 10^{10}$ p/s per septum.

Model: point source at downstream end of septum.
3.2.2.1 Dose to next component (disregarding T-SD) T-Q 1 a, b. Distance from loss point 1.75 m

Dose at 6 cm above beam orbit, maximum at 10 cm downstream from loss point

$4.2 \times 10^6$ HEP/s $\times 6 \times 10^{-8}$ rad/HEP

$= 25.2$ rad/s

$= 9 \times 10^4$ rad/h

$= 5.4 \times 10^5$ rad/year

3.2.2.2 Dose to following component T - Q 2 a, b. Distance from loss point 3.75 m

Dose at 6 cm above beam orbit, maximum at 10 cm downstream from loss point

$8.25 \times 10^6$ HEP/s $\times 6 \times 10^{-8}$ rad/HEP

$= 0.5$ rad/s

$= 1.8 \times 10^2$ rad/h

$= 1.1 \times 10^7$ rad/year

3.2.3 Loss on two recombination septa (T-SD 1, 2).

$\sim 1.07 \times 10^{13}$ p/s total, i.e. $5.35 \times 10^{11}$ p/s per septum.

Model: point source at downstream end of septum.

Remark: (see as well 2.2.3) the operation time of this septum might be 10% or less of the operation time of the PSB.

Dose at 6 cm above beam orbit, maximum at 10 cm downstream from loss point.

4.55$ \times 10^9$ HEP/s $\times 6 \times 10^{-8}$ rad/HEP

$= 2.73 \times 10^2$ rad/s

$= 9.83 \times 10^5$ rad/h

$\approx 5.9 \times 10^8$ rad/600 h

3.2.3.1 Dose to next component T-Q 1 a, b. Distance from loss point 0.35 m.

$1.55 \times 10^9$ HEP/s $\times 6 \times 10^{-8}$ rad/HEP

$= 93$ rad/s

$= 3.35 \times 10^5$ rad/h

$= 2 \times 10^8$ rad/600 h

3.2.3.2 Dose to following component T-Q 2 a, b. Distance from loss point 2.35 m.

$5 \times 10^7$ HEP/s $\times 6 \times 10^{-8}$ rad/HEP

$= 3$ rad/s

$= 1.08 \times 10^4$ rad/h

$= 6.5 \times 10^6$ rad/600 h
3.2.4 Loss on vertical septum magnet T-SV 3, $5 \cdot 10^{10}$ p/s.

Model: point source at downstream end of septum magnet.

Dose at 6 cm above beam orbit, maximum at 10 cm downstream from loss point.

$$4.2 \times 10^8 \text{ HEP/s} \times 6 \times 10^{-8} \text{ rad/HEP} = 25.2 \text{ rad/s}$$
$$= 9 \times 10^4 \text{ rad/h}$$
$$= 5.4 \times 10^8 \text{ rad/year}$$

3.2.4.1 Dose to next component T-Q 3.

Distance from loss point 0.85 m.

$$3.3 \times 10^7 \text{ HEP/s} \times 6 \times 10^{-8} \text{ rad/HEP} = 2 \text{ rad/s}$$
$$= 7.2 \times 10^3 \text{ rad/h}$$
$$= 4.3 \times 10^7 \text{ rad/year}$$

4. Conclusions

The most restrictive materials in an accelerator in respect to radiation dose are organic materials as used for magnet coil insulations. Taking a radiation resistivity of up to about $10^9$ rad absorbed dose for these materials before considerable damage occurs, it follows that life times of components in the PSB injection line and ring will be longer than ten years.

Only for the assumption of paragraph 3.1.3.5 (source strip of secondary particles inside a bending magnet), a dose of about $2.4 \times 10^8$ rad could be reached after about one year. But such a bad case would be easily found during the radiation survey of the machine and precautions to avoid this loss could be taken, as for example field corrections or the introduction of a beam scraper. Therefore, the total dose for one year around such a loss point has already been put in brackets in the cited paragraph.

The situation is somewhat different at maximum energy, i.e. for losses during the ejection of the protons and in the transfer line to the CPS, because the number of secondary particles created by one incident proton increases by a factor of about 120 and the flux to dose relation by another factor of about 3 in respect to 100 MeV protons. Nevertheless,
the components following a loss point are in most cases far enough away, such that the doses to be expected will not be larger than about $5 \cdot 10^7$, resulting as well in a life time of more than 10 years for the coil insulations.

On the other hand, a very critical source could be the planned double septum magnet T-SD, situated between T-SV 1, 2 and T-Q 1 a, b. Even if this septum only works for 10% of the total PSB operation time, doses in its vicinity and specially to the quadrupole lenses T-Q 1a, b could reach $2 \cdot 10^8$ rad/year. The result of this would be a life time of only about 5 years for the quadrupole lens. If this mode of operation is applied, the radiation doses around T-SD should be well surveyed and a spare lens should eventually be at hand.

Generally one can conclude from the calculations presented that, normal conditions supposed, components of the PSB situated near loss points should have a life time of more than ten years, but a careful survey specially of the transfer line septum magnets and their loss patterns is advisable.

The calculations presented are in good agreement with Goebel's first estimation \(^7\) of the dose to magnet coil insulations of the PSB, if the secondary particle distribution around a loss of 800 MeV protons and the real geometry between loss points and irradiated components are taken into consideration.

**Acknowledgements**

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**Distribution:**

List MPS-SI/1
References:


5) E. Weisse, "Optics of the booster-CPS transfer system. Specification of magnetic elements", SI/Note MAE/69-5 (preliminary) and Private communication.


7) K. Goebel, Private communication, July 1968.
Figure captions:

Fig. 1 Protons of 50 – 100 MeV energy lost in one point in the center of the vacuum chamber.
Secondary particle flux as a function of downstream distance from the loss point in planes of 6 cm – 15 cm – 55 cm from the beam orbit, normalized to 10^{12} p/s lost.

Fig. 2 Protons of 50 – 100 MeV energy lost over a distance of 1 m in the center of the vacuum chamber.
Secondary particle flux as a function of downstream distance from the beginning of the source in planes of 6 cm – 15 cm – 55 cm from the beam orbit, normalized to 10^{12} p/s lost.

Fig. 3 Protons of 800 MeV energy lost in one point in the center of the vacuum chamber.
Secondary particle flux as a function of downstream distance from the loss point in planes 6 cm – 15 cm – 55 cm from the beam orbit, normalized to 10^{12} p/s lost.

Fig. 4 Protons of 800 MeV energy lost over a distance of 1 m in the center of the vacuum chamber.
Secondary particle flux as a function of downstream distance from the beginning of the source in planes of 6 cm – 15 cm – 55 cm from the beam orbit, normalized to 10^{12} p/s lost.
FIG. 2

secondary particle flux

distance from upstream end of loss line
FIG. 3

Secondary particle flux vs. distance from loss point.
FIG. 4

[Graph showing the secondary particle flux as a function of distance from the upstream end of the loss line, with distances labeled 6 cm, 15 cm, and 55 cm.]