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Beam Losses, Radiation Dose and Electronic Equipment in the LHC arcs

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1 Introduction

Collisions of protons with the residual gas and protons hitting the beam screen are the main sources for the radiation dose in the LHC arcs. The dose outside the cryostat due to beam-gas collisions is relatively low and depends on the gas pressure [1]. The number of particles lost from the beam due to other effects is more difficult to estimate [2]. However, due to the high efficiency of the beam cleaning in dedicated insertions such losses are not expected to increase the dose by a large amount [3]. Therefore it has been recently decided to install electronic equipment in the LHC tunnel. This leads to substantial savings, and technical solutions which otherwise could not be envisaged (for example for the design of beam position monitors and related electronics).

A working group has been formed to discuss issues related to the installation of electronics in the tunnel. A mandate of the radiation working group is to identify radiation tolerant components, and to test the electronic equipment for radiation hardness. Electronic equipment is susceptible to the integrated radiation dose. The threshold depends on the components and ranges from some Gray to some 1000 Gray.

In a former note [1] the radiation dose from collisions of protons with the residual gas was estimated to about 1 Gray/year, and the contribution from particles lost due to other effects ("point losses") to about 3 Gray/year. If the radiation dose would substantially exceed this value, equipment might fail. In this note we therefore re-estimate the dose with a different approach.

2 Beam losses due to collisions with the residual gas

The dose depends on :

- beam current and energy
- location of the electronics inside the tunnel, and shielding, if there is any
- residual gas pressure

- particle loss rate due to collisions of particles with the wall (beam screen), and location of such losses

The dose due to beam-gas collisions was calculated in [1]. Such collisions have about equal probability along the beam axis, if the vacuum pressure is constant. The dipole and quadrupole magnets are efficiently shielding the electronics outside of the cryostats. The dose decreases from the inner part of the magnet to the outside by about three orders of magnitude. In the inter-magnet gaps the dose is significantly higher. Therefore the dose depends on the exact (longitudinal) location of the equipment.
In the case of a local pressure bump (for example due to a small vacuum leak), a local loss of particles can increase the dose by orders of magnitude without reducing the beam lifetime.

3 Beam losses due to other effects

The distribution of particles lost due to other effects is difficult to estimate and depends on the mechanism for the loss :

1. beam losses at injection, for pilot bunches with low intensity or for a full batch
2. beam losses due to orbit excursions
3. beam losses due to mis-firing of a kicker magnet
4. particles with large amplitudes may be lost due to the limited dynamic aperture and beam-beam effects
5. beam losses during the energy ramp
6. particle outside the RF-bucket can be lost
7. if the betatron tune changes and the particles are touching a resonance, or if the chromaticity changes, the beam can blow up in a short time

For 3,4,5 and 6, most protons will be lost close to focusing quadrupoles, because there the beam size is maximum (maximum value of the beta function and dispersion). Therefore the installation of the electronics under the center dipole magnet is expected to give the lowest radiation dose.
For the calculation of integrated doses it is assumed :

- In one year the LHC is operated for 182 days ($1.57 \cdot 10^7$ s)
- In two days there are three fills with nominal beam intensity
- The nominal beam intensity from the Yellow Book [4] is assumed (2835 bunches, each bunch with 1.05×10^{11} protons)

The above list is not complete. It should not be forgotten that the mechanisms for beam losses at HERA, for example during luminosity operation, are not always understood. Occasionally fast losses are observed (in some 10 ms), and the losses are distributed around the whole accelerator [5].

4 Radiation dose from injected beam

The origin of such losses can be :

- a wrong beam trajectory. Beam position monitors will measure the trajectory and it will be corrected with dipole correctors.
- a too large beam size, for example due to a quadrupole with zero current or wrong polarity. The cause for such loss is difficult to identify. Radiation monitors distributed around the ring would be very benificial.
- an obstacle in the beam pipe. To make sure, that the origin for the loss is indeed an obstacle, and to localise it is difficult and requires frequent injections of pilot bunches. Radiation monitors around the ring are an adequate tool for the diagnosis of such problem.

The beam can be lost anywhere in the ring, and the location of a loss is not limited to a focusing quadrupole magnet.
In order to the quench a magnet, the intensity of a single bunch at injection must exceed 10^{10} [2]. Therefore it has been suggested to inject pilot bunches with an intensity of $5 \cdot 10^9$ protons [12]. This assumes that the loss is distributed over a range of 11 m. The proton losses during one year due to beam-gas interactions are $1.6 \cdot 10^{11}$ p m^{-1} for both beams and corresponds to 1 Gray/year [1]. At injection energy the radiation dose is reduced by about a factor of 15 (7 TeV/450 GeV) for the same number of lost protons. The radiation dose due to particles lost at the same spot is therefore : $N_p/(15 \cdot 11 \cdot 1.6 \cdot 10^{11})$, with N_p the number of lost particles.
The dose for one year would be reached after about 5300 single bunch injections lost at the location of the electronics. This corresponds to injection of pilot bunches with the same machine settings during 29 hours (with the length of the SPS cycle time of 20 s).
In the case of a loss of a batch with an intensity of $2.5 \cdot 10^{13}$ the radiation dose is equivalent to the dose from collision with the gas for one year. The magnets in that zone would quench, this can be considered as an accident which will not happen frequently. Before starting with the injection of batches, the injection of pilot bunches is always required to check out the injection process.

5 Radiation dose with stored beam

For losses of particles from the stored beam it is assumed that the loss takes place close to the centre of the focusing quadrupoles.

5.1 Monte Carlo Simulations

The Monte Carlo program GEANT 3.21 [9] was used to simulate the hadronic showers stemming from point losses of protons inside the quadrupole of the short straight section (SSS), in order to evaluate the radiation dose. The geometry of the SSS was approximated so as to minimize the number of boundaries, thus reducing computation time. Figure 1 shows the cross section through a quadrupole, as used in the simulation. Innermost one finds the beam screen, surrounded by the beam pipe, coils, collar, yoke, shrinking cylinder, etc.. The thermal shield and vacuum vessel are not shown in Fig. 1. The geometry includes the quadrupole and dipole magnets as well as corrector magnets. Magnetic fields in the quadrupole and the dipoles are taken into account [10].

Protons with energies between 450 GeV (injection) and 7 TeV are incident on the beam screen in the middle of the quadrupole at an angle of 0.25 mrad. For 7 TeV the losses at 1 m into the first and second dipole were also simulated. The absorbed dose in electronics due to these point losses is estimated by computing the energy deposit in an aluminium box with the size of an electronics crate (CIM 25543) underneath the middle of the second dipole. Blocks of shielding concrete [11] of 5 m length are positioned on either side of the 'crate' (in longitudinal direction), as well as a 20 cm thick plate on top to determine the effect of such a shielding on the radiation doses in the crate. If an installation of a 20 cm concrete plate is not possible due to lack opf space, a less thick lead plate could be employed.

For point losses in the quadrupole Fig. 2 shows the absorbed dose in the crate as determined in the simulation for various proton energies between injection and 7 TeV. The absorbed dose per lost proton scales roughly with the energy. For 7 TeV the 5 m shielding blocks reduce the dose rate by a factor 1.5. The 20 cm thick plate on top provides a further reduction by a factor 1.8.

Eventually, protons may be lost inside the dipoles rather than the quadrupole. The radiation dose per proton in the crate would then increase by about a factor 5 (for a loss in the second dipole).

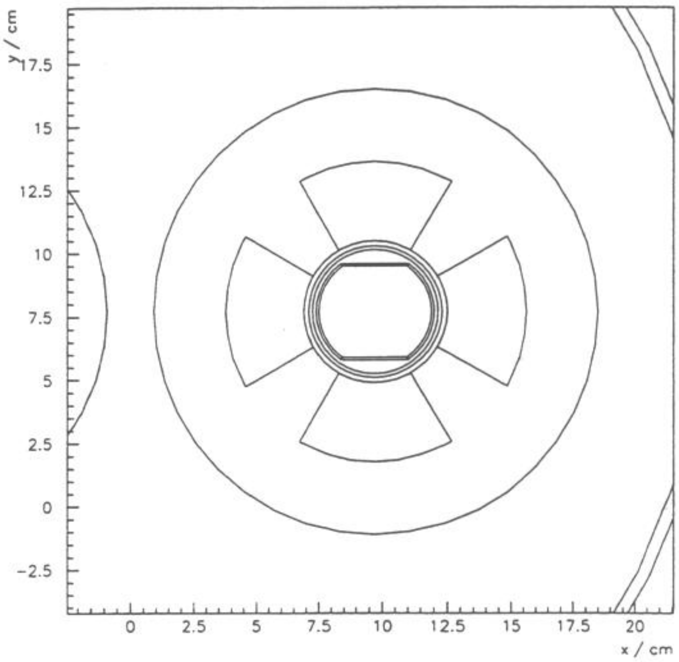

Figure 1: Quadrupole cross section which is assumed in the simulation program

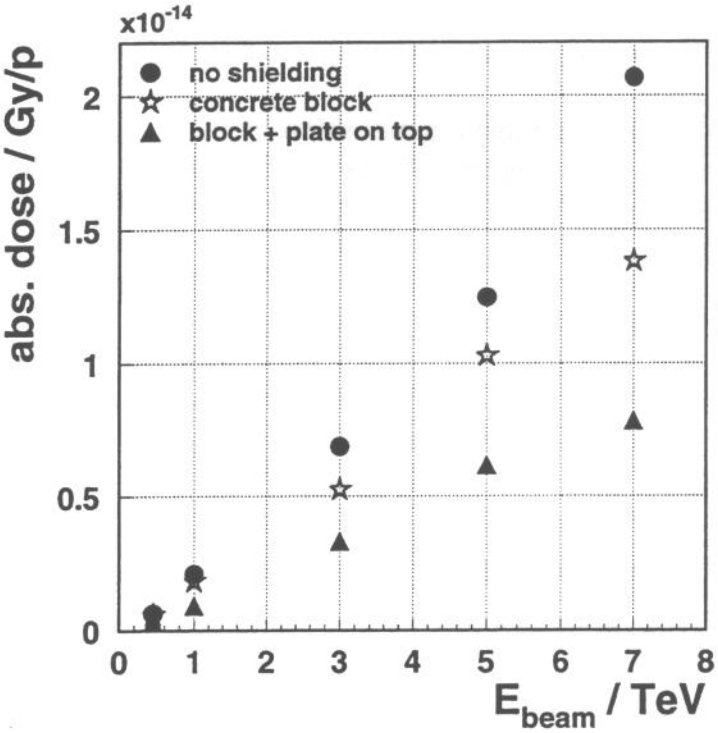

Figure 2: Radiation dose in an electronic crate under the second dipole for one proton which is lost in the quadrupole

5.2 Dose estimation

The contribution of resistive dissipation in the cable splices to the heat load at 1.8 K is about 0.11 W/m. The heat-load from particle losses due to nuclear interaction with the beam-gas has been estimated to 0.06 W/m for nominal LHC performance [4]. The yearly proton loss due to beam-gas interactions, calculated in [1], is $8.3 \cdot 10^{10}$ p m^{-1} for one beam. This corresponds to a loss rate for two beams of $1.05 \cdot 10^4$ p s^{-1} m^{-1} and a heat load of 0.012 W/m.

In [2] it was calculated that a continuous local loss rate of protons of $7.8 \cdot 10^6$ p s^{-1} m^{-1} will induce a quench. This limit has been set by studies on the heat transfer between cable and He II cooling fluid, and depends on the insulation of the cables. Experiments of the heat transfer were performed at Saclay [6]. This corresponds to a yearly dose of $1.2 \cdot 10^{14}$ p s^{-1} m^{-1} and a continuous heat load of 8.7 W/m. Such heat load is only acceptable, if it is local. The heat load in one cell is limited to 6.8 W for nominal and 10.8 W for ultimate performance [7].

In the following a very pessimistic assumption is made : protons are lost continuously in the centre (or close to the centre) of one quadrupole, and the rate of protons amounts to a power generation of 6.8 W. This corresponds to $6.0 \cdot 10^6$ p s^{-1} and a yearly dose of $9.4 \cdot 10^{13}$ protons. If the electronics is installed under the centre of the second dipole, one proton hitting the beam screen in the quadrupole centre contributes to a dose with $2.0 \cdot 10^{-14}$ Gray. The yearly dose is less than 2 Gray.

In [1] the dose was calculated for point losses, with $2.0 \cdot 10^{11}$ p per year (assuming a collimator efficiency of 99.75 %, and the loss distributed over 200 or so α_p locations). For the electronics installed close to the location of the point loss, a yearly dose of about 3 Gray is expected.

5.3 Distribution of losses around the ring

In the above considerations we assumed that the protons at top energy are lost in the centre of the quadrupole magnets. This is true if the mechanical aperture is constant along the ring. If there is a reduction of the aperture, a particle can be lost elsewhere.

In one plane, the β-function has its maximum value of 180 m in the focusing quadrupole magnets, and its minimum value of 30 m in the defocusing quadrupole magnets. The beam size is given by : $\sigma = \mathrm{const} \cdot \sqrt{\beta}$. For a rough estimation is is assumed that the beam size changes linearly with distance and is therefore given by : $\sigma = \sigma_0 \cdot \sqrt{30}/\sqrt{180} \cdot x/ \cdot L$. x is the distance from the focusing quadrupole and L the length of a half cell. The beam size is maximum in the quadrupole, reduced to 95 % after 5 m, to 89 % after 10 m and to 84 % after 15 m.

For the purpose of getting a feeling for the numbers involved, it is assumed that the aperture is ± 22 mm and a particle just touches the beam screen in the quadrupole magnet centre (Fig. 3). Ten metres before the amplitude of the proton is about 19.6 mm. In order to loose it there, the aperture must be reduced by at least 2.4 mm.

For the maximum offset of the beam screen 1.1 mm (worst case) were estimated, but it is foreseen to change the mechanical design to reduce this value to less than 1 mm [8]. Therefore it can be assumed, that protons will be lost in a distance not exceeding 5-10 m from the quadrupole centre.

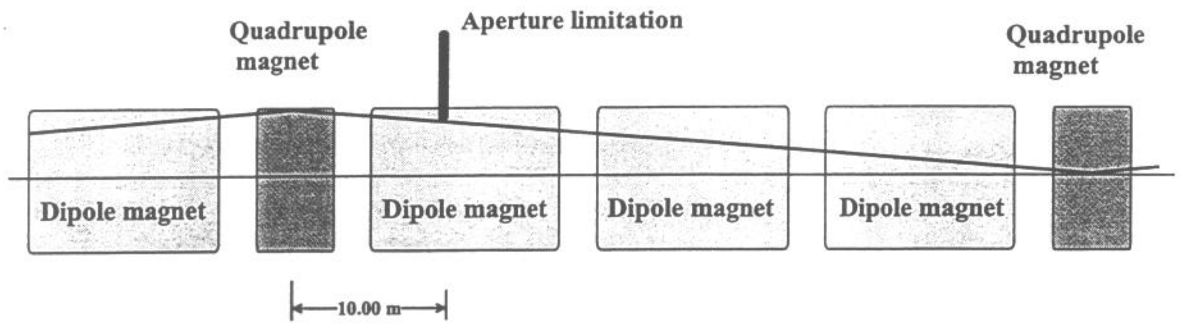

Figure 3: Trajectory of a particle in a half cell. Its amplitude is maximum in the focusing quadrupole. It would hit an aperture limitation 10 m away. If the aperture is limited by at least 2.7 mm.

6 Conclusion

The radiation dose in the tunnel will be relatively low, if some precautions are taken.

- The electronics should be installed under the central dipole magnet in a half cell.
- The radiation level at the crates with the electronics needs to be carefully monitored. An online monitoring of the integrated dose is recommended, with an integration time of 1-10 s. If losses in one area of the machine are too high, action has to be taken (change of beam trajectory, invesigation of the vacuum pressure, investigation of the geometrical aperture). In some cases it might be required to move the electronics to another location.
- At injection, low intensity pilot bunches should be injected first in order to check out the trajectory.
- Radiation-tolerant electronics should be used. Precise knowledge of the maximum tolerable radiation dose for correct functioning needs to be established by irradiating of the electronics.

In parts of the insertions the radiation dose is expected to be orders of magnitude higher (beam cleaning insertions, low-β insertions ...). At the beginning of the arc the radiation dose might be larger than further down. Further studies about the level of the dose and the positioning of the electronics in the transition between insertion and arc are required.

7 Acknowledgement

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