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Radiation Dose for Equipment in the LHC Arcs

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Abstract

Collisions of protons with residual gas molecules or the beam screen installed in the vacuum chamber are the main sources for the radiation dose in the LHC arcs. The dose due to proton-gas collisions depends on gas pressure, energy and intensity of the circulating beam. The dose is about equally distributed along the arc and has been calculated in previous papers. Collisions of particles with the beam screen will take place where the beam size is largest - close to focusing quadrupole magnets. For this paper the radiation doses due to particles hitting the beam screen in a quadrupole were calculated with the shower codes GEANT3.21 and FLUKA96.

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1. INTRODUCTION

For a luminosity of 10^{34} cm^{-1} s^{-1} the LHC proton beams will have about 3000 bunches each with 10^{11} protons. The beams are accelerated from 450 GeV/c to 7 TeV/c. The energy stored in one beam at 7 TeV/c exceeds 300 MJ. Superconducting dipole magnets with a field of 8.3 T operating at a temperature of 1.9 K guide the particles through the arcs. The radiation dose is due to interactions of protons with residual gas molecules, and particles lost due to collisions with the beam screen (collimation losses). The beam screen is installed in the vacuum chamber to protect the 1.9 K system from synchrotron radiation. The dose from interactions with the rest-gas depends only on residual vacuum pressure, beam intensity and energy. Collimation losses depend on beam and machine parameters and need to be kept to the minimum. At 7 TeV/c a fraction of the beam in the order of 10^{-7} lost in one superconducting dipole magnet is sufficient to start a quench [1]. Another consequence of losses is the increase of the radiation dose. To minimise beam losses around the machine, two of the eight straight sections are reserved for beam cleaning by use of collimators [1].

Machine components should be designed to withstand the radiation for at least ten years, assuming nominal operational parameters. For the magnet construction, materials not sensitive to radiation are used, for example Kapton for cable insulation. The most sensitive elements in the Helium pressure vessel are power diodes installed in parallel to each main dipole and quadrupole magnet. The diodes protect the magnets in case of a quench. First radiation tests results of diffusion type diodes indicate a radiation hardness of up to about 300 Gy [2]. An optimum position for the diode has been proposed in order to limit the radiation dose [3].

Electronics will be installed for monitoring and control of magnets and cryogenics in the tunnel close to the equipment, in order to avoid long cables. For beam monitoring and control, computing and networking additional equipment is required. Most of the electronics will be off-the-shelf. No development for radiation hard equipment is foreseen. Too high radiation doses would damage the equipment. In this paper we discuss the dose from collimation losses and degraded vacuum for electronics [4] after recalling the radiation dose from proton-gas collisions [5].

2. RADIATION FROM COLLISION WITH RESIDUAL GAS MOLECULES

The residual gas pressure and gas composition is expected to be constant along the arc. The radiation dose is uniformly distributed. In [4] it has been estimated that for a loss rate of $1.65 \cdot 10^{11}$ protons/m/year the radiation dose along the dipole magnets is 2-3 Gy/year, depending on the exact location of the equipment. If the equipment is installed close to inter-magnet gaps, the dose would increase by about one order of magnitude. Nominal parameters for the LHC operation, a beam lifetime of 250 hours and continuous operation during 181 days were assumed.

3. MONTE CARLO SIMULATIONS

Particles outside the stable region for the trajectories will, sooner of later, hit the geometric aperture. Collimators in the cleaning insertions will stop a large fraction of these particles and only a few particles will escape. The beam dimensions are maximum in focusing quadrupole magnets, and the escaped particles will hit the beam screen within a range of 5-10 m from the centre of the quadrupoles along the arcs [5][6]. The arcs consist each of 23 regular cells with a length of 106 m. A cell has six dipole and two quadrupole magnets (Fig. 1 shows a half cell). An optimum position for sensitive electronics is underneath the centre dipole magnet, since dipole and quadrupole magnets efficiently shield the equipment from radiation.

In order to evaluate the radiation dose the Monte Carlo program GEANT 3.21 was used to simulate the hadronic showers from point losses of protons inside the quadrupole magnet of the short straight section. The geometry used in the simulations contains the Short Straight Section (SSS) with a twin aperture quadrupole magnet, two octupole magnets and two combined sextupole-dipole corrector magnets. Two adjacent dipole magnets are also included. Magnetic fields in quadrupole and dipole magnets were taken into account. For the calculation of the radiation dose, protons with energies between 450 GeV/c and 7 TeV/c are incident on the right side of the beam screen in the middle of the quadrupole at an angle of 0.25 mrad (see Fig.2). For 7 TeV/c the losses at 1 m into the first and second dipole magnet 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 concrete shielding [7] 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 shielding on the radiation doses in the crate. Fig.3 shows the absorbed dose in the crate as determined in the simulation for various proton energies between injection energy and 7 TeV/c. The absorbed dose per lost proton scales roughly with the energy. For 7 TeV/c the 5 m shielding blocks reduce the dose by a factor 1.5. The 20 cm thick plate on top provides a further reduction by a factor 1.9. If protons are lost at 1 m inside the second dipole magnet, the radiation dose per proton in the crate would increase by about a factor 5.

4. MAXIMUM RADIATION DOSE

Collimation losses contribute to the heat load of the 1.9 K system. For nominal operational parameters it has been assumed that about $3 \cdot 10^{6}$ protons/s contribute to the heat load in one cell, which corresponds to 3.4 W [8]. For all the protons lost in one aperture of one quadrupole magnet and with a dose of $2 \cdot 10^{-14}$ Gy/proton the radiation dose for electronics below the second dipole magnet would be about 1 Gy/year.

For a reduced geometrical aperture in a quadrupole magnet the dose could increase. One limitation is the cooling power given by the local heat exchanger. To compensate heating from beam losses about 40 W are available at 1.9 K in one cell. Continuous proton losses at the quadrupole equal to a power of 40 W would give a yearly dose of 11 Gy.

If a vacuum leak leads to a locally increased pressure, the beam-gas scattering rate could increase by orders of magnitude without reducing the beam lifetime. The limitation is again given by the cooling power at 1.9 K. For nominal pressure of 10^{-9} Torr the dose is 2-3 Gy/year. For a pressure bump close to electronics of 10^{-7} Torr, the dose could exceed some hundred Gy in one year. An early detection of such a leak using vacuum gauges is difficult, since the pressure bump travels at very low speed [9]. With beam loss or dose monitors a leak would easily be discovered. If an immediate intervention is not possible, sensitive electronics would have to be displaced to the adjacent dipole magnet.

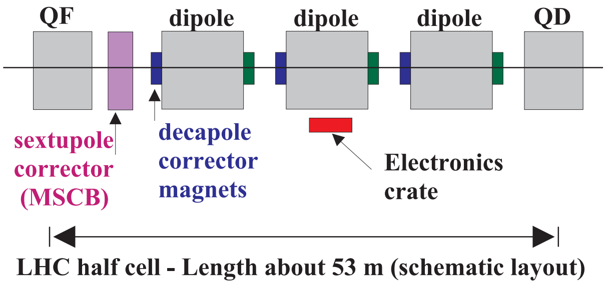

Fig.1: Schematic layout of a half cell of 53 m length

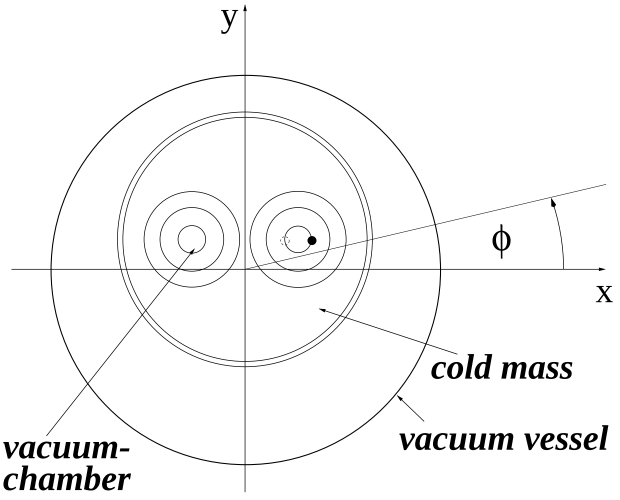

Fig.2: Cross section of the quadrupole magnet with the impact points for proton losses (small circles)

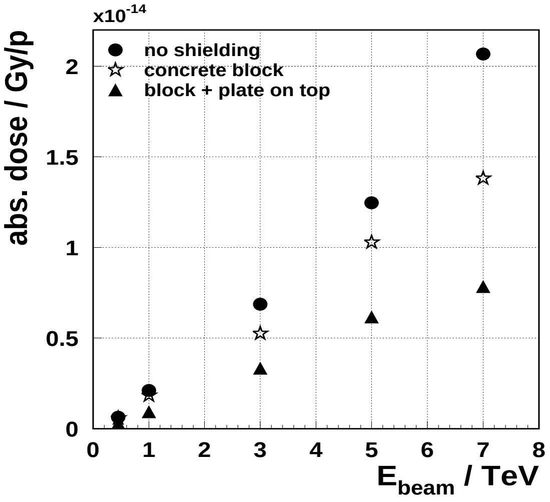

Fig.3: Radiation dose in an electronic crate under the second dipole magnet for one proton lost inside the quadrupole magnet

5. LOSS DETECTION

Different types of loss detectors have been proposed, such as ionisation chambers, scintillation counters and semi-conductor devices (for example PIN diodes, [10]). Inside the cryostat losses could be monitored using a micro calorimeter [11]. For reasons of simplicity of the installation and easy access detectors inside the cryostats are not favoured. For PIN diodes outside the cryostat, the number of Minimum Ionising Particles (MIPs) has been calculated, with a momentum cut of 0.3 MeV/c for e+/e-, 15 MeV/c for muons and pions, and 140 MeV/c for protons and kaons. Fig.4 and 5 show the angular and the longitudinal distribution of the number of MIPs per cm^2 passing the vacuum vessel per lost proton. Impacts on both sides of the beam screen ("right", towards the outside of the magnet, and "left" towards the centre) have been considered. The most likely location for beam losses is close to quadrupole magnets, where an efficient loss monitor system is required. Due to the effective shower length the point where protons are lost may vary by some meters without a serious decrease of the detection efficiency. The minimum number of protons that can be detected using PIN diodes is 2900 at 450GeV/c, and 330 at 7 TeV/c.

CONCLUSIONS

The radiation dose for equipment in the LHC arcs should not exceed about 100 Gy in ten years of operation, if some precautions are taken. The quadrupole and first dipole magnets are efficiently shielding the central dipole magnet in a half-cell magnet from collimation losses. Sensitive elements should therefore be installed under this magnet. The dose would come from beam-gas collisions; for nominal vacuum pressure this is less than 3-5 Gy/year. The sensitivity of electronics to radiation should be determined before installation into the LHC tunnel. Possibly radiation tolerant electronics could be used. Electronics should be selected which is operational up to at least 100 Gy. Beam loss monitors will be installed in the region of the quadrupole magnets, but the radiation dose at the equipment should also be carefully monitored, possibly with a simplified system. The information about losses, dose and integrated dose should be available on-line. If the beam losses or the dose are too high, action has to be taken. Whether electronics can be installed into the straight sections of the LHC needs to be further investigated. It has to be noted that neutrons will have a strong effect on radiation damage. Therefore more studies concerning neutron flux are required.

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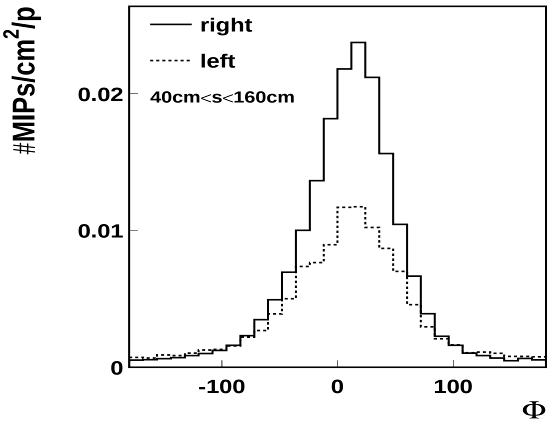

Fig.4: Angular distribution of MIPs outside the vacuum vessel for impact of proton on the right side of the beam screen, and on the left side

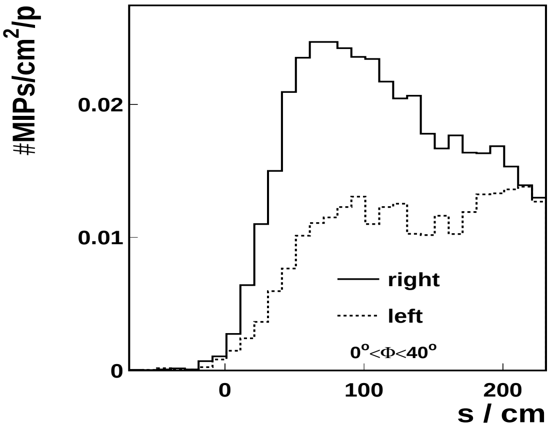

Fig.5: Longitudinal distribution of MIPs outside the vacuum vessel for impact of proton on the right side of the beam screen, and on the left side