LHC Project Note 367

Simulation of the radiation levels and shielding studies at the BDI positions in IR4

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Summary

Monte Carlo simulations have been performed to estimate the radiation levels at the positions where BDI electronics will be installed in IR4. Special shielding was necessary to protect the synchrotron radiation telescope and its electronics. The shielding proposed by this study assures a reduction of more than two orders of magnitude at the position of the BDI synchrotron radiation (SR) monitors, reaching a value of ~10 Gy per year.

1.   Introduction

Any semiconductor device operating in a radiation field can undergo degradation due to radiation damage effects. Energetic particles incident on the semiconductor bulk lose their energy to ionising and non-ionising processes as they travel through the material. The ionising processes involve electron-hole pair production and subsequent energy deposition (dose) effects. The non-ionising processes result mainly in displacement damage effects, i.e. displaced atoms in the detector bulk and hence defects in the semiconductor lattice like vacancies and interstitials.

During the ionisation process (electron-hole pair creation) and under appropriate operating conditions in a device, the electron-hole recombination can be prevented by the intrinsic, strong, internal electric fields. This can generate a single event effect (SEE), i.e. an electrical pulse large enough to disrupt normal device operation. The result can be a non-observable effect, a transient disruption of circuit operation, a change of logic state or a permanent damage to the device or integrated circuit [1], [2]. High energy hadrons cause SEE through the highly ionising secondary fragments they produce when they collide with silicon nuclei. In the current technologies the energy threshold to induce a SEE has decreased to 20 MeV (in respect with that of 50 MeV at early 1990s) and tends to be further decreased to below 10 MeV due to the continuous decrease of the critical charge (lower applied voltage, smaller charge-collection volumes, increased device density per chip) [1].

The solid state image sensor arrays (CCD, CMOS, CID) use a structure of metal-dielectric-semiconductor that makes them sensitive to ionising radiation due to energy deposition in the gate dielectric and displacement damage in the semiconductor substrate [3]. In the LHC tunnel and close to the beam lines (where solid state cameras are foreseen to be installed), a great variety of high-energy particles is expected, which might result in radiation damage and subsequent malfunction of the LHC optical monitors.

A FLUKA [4],[5] Monte Carlo simulation was performed in order to simulate the beam-gas interactions, assuming standard beam intensity and vacuum conditions for LHC start-up [6]. The energy deposition (dose), the 1 MeV neutron equivalent fluence of all particles and the fluence of particles with energies >20 MeV were calculated in order to estimate the lifetime of the electronic equipment at the regions of interest.

This work extends a previous study for the radiation levels in IR4, which estimated the radiation damage in the digital electronics of the RF low-level system [7].

2. Monte Carlo Simulations

2.1 Geometry

Figure 1 shows part of the geometry that was used in the Monte Carlo simulation. The BDI equipment is shown (in purple boxes) as foreseen originally to be installed between the quadruples Q5, Q6 and Q7 and mainly between the dipoles D3 and D4. This is an extension of the geometry described in [7], with the cryogenic cavities (ACS) and the wideband pickups (APW) further upstream to IP4 serving as potential sources of radiation due to residual gas interactions.

2.2 Sources of Radiation

Figure 2 and Table 1 summarize the radiation sources as also used in the previous study [7]. For each element a different beam-gas composition and density used according to data supplied by the AB/RF group [8] and nominal values published for the straight sections of IR1 and 5 [6]. A beam intensity of 1/3 of the LHC nominal value (i.e. 1.15_10^{11} protons per bunch, 2808 bunches and 11.245 kHz revolution frequency) was taken, as used in the LHC start-up scenario of [6].

In the current study the contribution of the residual gas in the ionisation profile monitors (IPM or BGIH/V – beam gas interaction horizontal/vertical) has been also examined, taking into account Nitrogen gas (100% N_2) of 1.0_10^{-9} Torr pressure and 3.2_10^{13} m^{-3} population density. With this input, the contribution of the IPM in the hadron fluence at the BDI positions is ~0.2% (Figure 3). As a result, the IPM residual gas was not considered as an important radiation source and was not taken into account for the simulation results that follow.

2.3 Scoring

Energy deposition (Dose in Gy), hadron and 1 MeV neutron equivalent fluences for all particles (electrons and photons included) with energies above 1 MeV were scored in a mesh covering the geometry of interest. The spectra recorded at the BDI positions are shown in Figure 4. All scorings were made in air.

2.4 Shielding materials

For the shielding the only materials considered were iron (density of 7.2 gr/cm^3) and concrete since these are widely used at CERN for this purpose. Simulations of a series of different scenarios have finally resulted in the compound shielding proposed herein for the protection of the synchrotron radiation telescope.
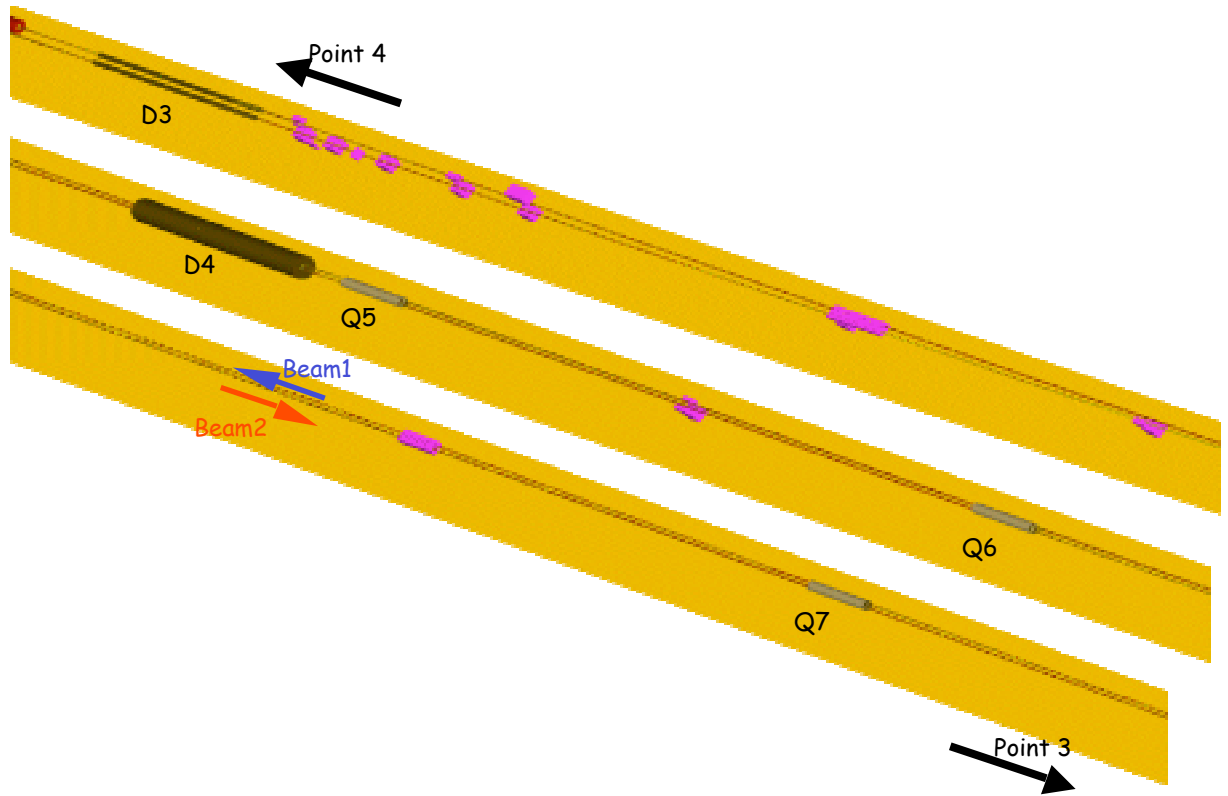
Figure 1   The geometry setup around the BDI positions. The purple colour stands for the BDI equipment, the orange colour is for the concrete walls (not all of them are shown) and the dark colour stands for the beam modules. The scoring at the BDI boxes was made in air.
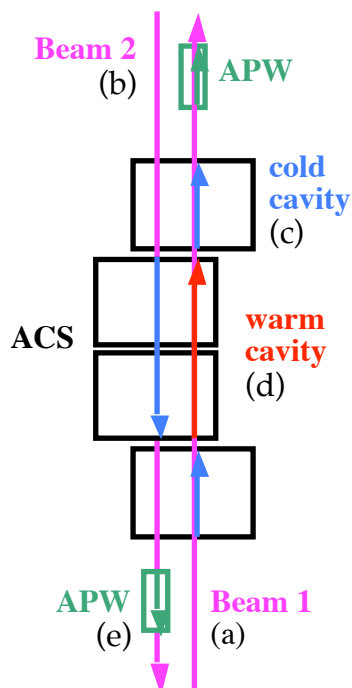

Figure 2 Schematic representation of the radiation sources in IR4. The black boxes stand for the ACS cavities and the green ones for the APW modules. The beam lines are shown in magenta colour. The current simulation results come from the superposition of nine individual calculations for different radiation sources:

(a) Beam line 1 running along the whole geometry.

(b) Beam line 2 running along the whole geometry.

(c) ACS cold chambers for i) the two central modules, ii) the first one on beam line 1, iii) the second one on beam line 1.

(d) The warm chambers for the two central ACS modules.

(e) The APW module for i) beam 1, ii) beam 2.

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Table 1

Overview of the residual gas compositions and densities [6]

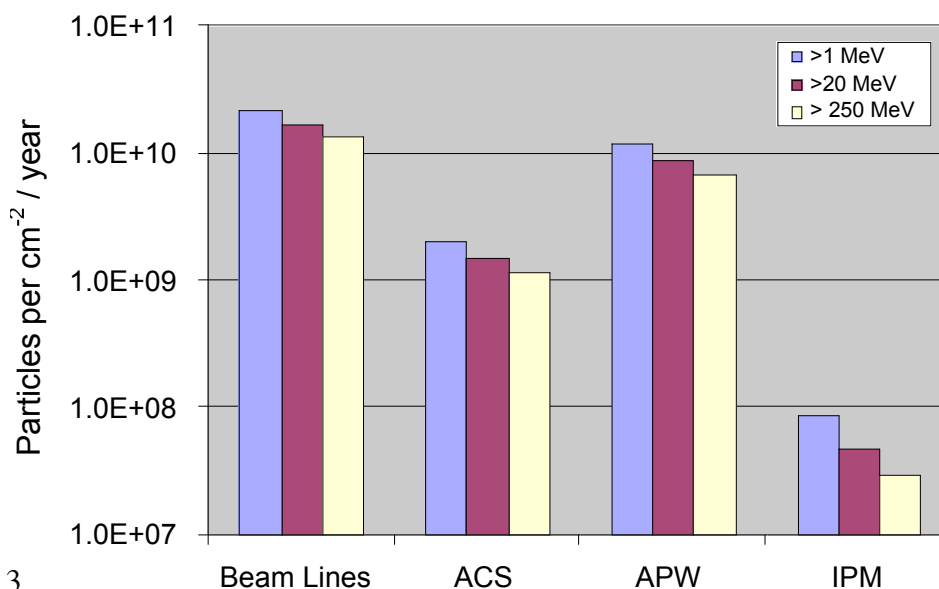| Source	Length (m)	Beam gas	Pressure (mbar)	Population Density (m^{-3})	Annual interactions
Beam 1 Beam 2	600	50% CH_4 50% H_2	2.1×10^{-9}	5.1×10^{13}	1.4×10^{13}
ACS warm tube	15	100% CH_4	1.0×10^{-10}	2.4×10^{12}	2.9×10^{10}
ACS cold cavity (beam 1, first or second)	6.5	90% H_2 10% CO	1.0×10^{-10}	1.8×10^{14}	2.8×10^{11}
ACS cold cavity (beam 2)	15				6.7×10^{11}
APW (beam 1 or 2)	2.25	40% H_2 30% CO 25% H_2O 5% CO_2	1.0×10^{-07}	2.4×10^{15}	3.7×10^{12}

Figure 3   ... :V) at BDI positions from the different source regions. 62% comes from the beam lines, 32% is due to the APW interactions and 6% comes from the ACS cavities. The ionising profile monitors contribute with only a 0.2% and, as a result, they are excluded from the following studies.
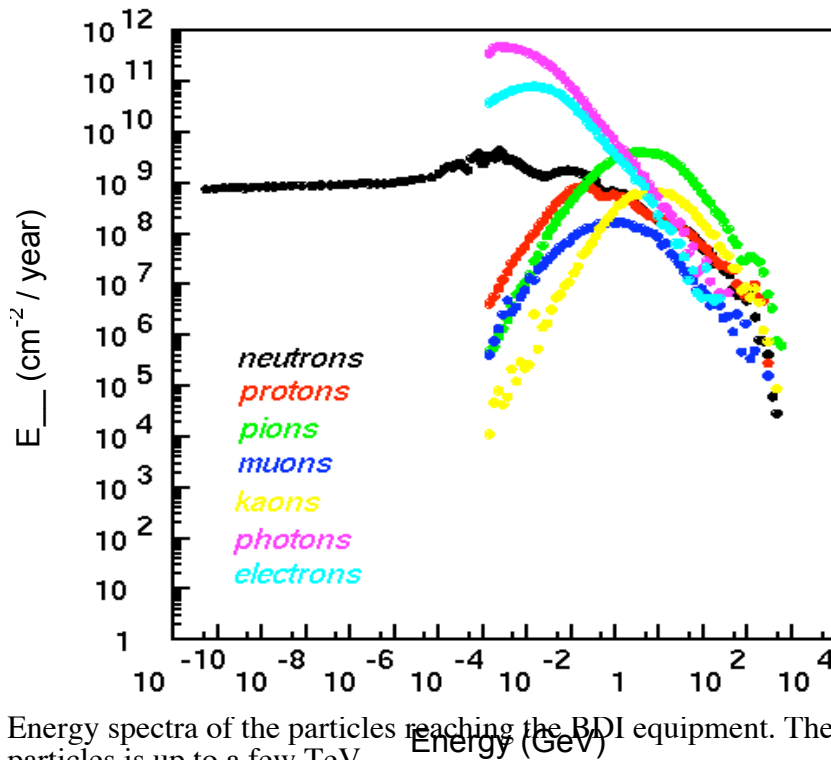
Figure 4   Energy spectra of the particles reaching the BDI equipment. The energy of the particles is up to a few TeV.

3.   Results

Two different scenarios are shown: firstly the initial case, before any measure was taken to protect the BDI equipment and secondly the proposed case, with all the suggested measures and shielding. The main concern for this study was the beam synchrotron radiation telescope (BSRT), since the solid state camera can be particularly sensitive to radiation (see Introduction and references therein).

3. 1   Initial BDI geometry (no shielding or other measures)

Extending the geometry described in [7] to the BDI equipment positions, we calculated the radiation levels around the beam lines. Figures 5 and 6 show the annual dose and hadron >20MeV fluence at the positions of interest as indicative for the high radiation levels estimated. Especially around the dogleg bends, where most of the BDI equipment was going to be installed, enhanced radiation levels were calculated. This is due to the residual gas interactions which create high energy secondaries (see Figure 4), mainly in the forward direction. These particles do not follow the dogleg bends, but further interact with the beam pipe material.

In the following table (Table 2) the radiation levels are summarized representing the mean values of all the BDI positions.

Table 2

Radiation levels at the BDI positions without any shielding or extra measures

Dose (Gy/y)	Hadrons >20MeV (cm^{-2}/y)	1MeV n eq. (cm^{-2}/y)
> 100	$3 \_ 10^{10}$	$3 \_ 10^{10}$

The above values were considered to exceed the acceptable radiation levels for a long normal operation for the BDI electronics. Especially for the BSRT, a shielding study was necessary to protect the solid state camera foreseen for that region and its electronics.

3. 2   Proposed BDI geometry (shielding and extra measures)

At the dogleg bend, after the D3 magnet, there is an enlarged beam pipe of around 6m long to channel the synchrotron radiation to an extraction mirror. After the end of that pipe, we calculated increased radiation levels due to the secondaries created at the pipe material and emitted forward to the air region, where the telescope was about to be installed. To overcome this problem the following measures were suggested:

     a) to lengthen the enlarged beam pipe 6m more,
     b) to change the position of the telescope to below the beam line, close to the floor in order to be able to shield it,
     c) to examine the design and the amount of shielding required in order to reduce these limits to acceptable levels and
     d) in order to further protect the BSRT electronics, a small square pit (of 50 cm diameter) was inserted in the IR4 floor, under the telescope tube. Other instruments were moved away from this region.

After several simulations, the shielding scenario proposed is shown in Figure 7. It consists of an iron box with the following characteristics: an iron block 0.5m thick and a 30cm concrete slab towards D3, a 30cm concrete slab and an iron block 1m thick towards D4 and an iron slab of 5cm thickness at the top of these blocks to shield from the secondaries flying in large angles towards the telescope. The 30cm concrete slabs reduce the number of low energy neutrons. The small pit at the floor is also shown with a concrete slab to cover most of it in order to further reduce radiation (mainly high-energy neutrons) entering the place of the BSRT electronics. This concrete cover is optional and not considered to be essential for this shielding design.

In Figures 8 and 9 the annual dose and the hadron >20MeV flux are shown. In Figure 10 the 1MeV neutron equivalent fluence is presented for completion and Table 3 summarizes the radiation levels calculated in the positions of the synchrotron radiation telescope and the electronics pit.

Table 3

Radiation levels at the BDI positions for the shielding proposed (Figure 7)

	Dose (Gy/y)	Hadrons >20MeV (cm^{-2} / year)	1MeV eq. flux (cm^{-2} / year)
SRT position	< 10	7 _10^9	2 _10^{10}
Electronics pit	< 3	2 _10^9	6 _10^9

3. 3   Safety factor

In the previous simulation work for IR4 [7], a safety factor of 10 had been proposed due to geometry simplifications and other uncertainties inherent in the simulations. We propose that the same safety factor is used as a safety margin for the BDI equipment, as well. However, since the current scoring regions are closer to the beam line and the statistics is much better in this study, the error of the current simulation should not exceed a factor of 5. It is also important to stress the residual gas properties that have been used as an input (Table 1) and prompt for re-scaling in case of different gas densities.
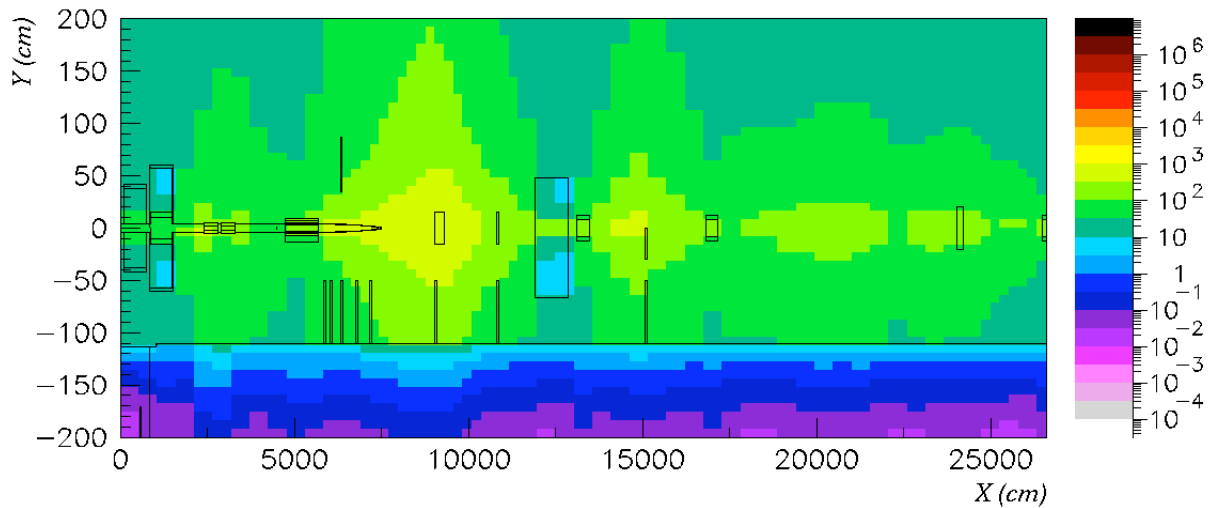
Figure 5   Dose rate in Gy/y for the positions of the BDI equipment. This vertical cut is at 22cm from the centre of the two beam lines and is the mean of the dose values ±22cm this surface. Most of the devices are going to be installed off the beam line near the dogleg bends, apart from the synchrotron radiation telescope which was to be placed very close to the beam tube. The dose levels at the positions of interest are estimated to be a few hundreds of Gy/y (right hand colour scale).
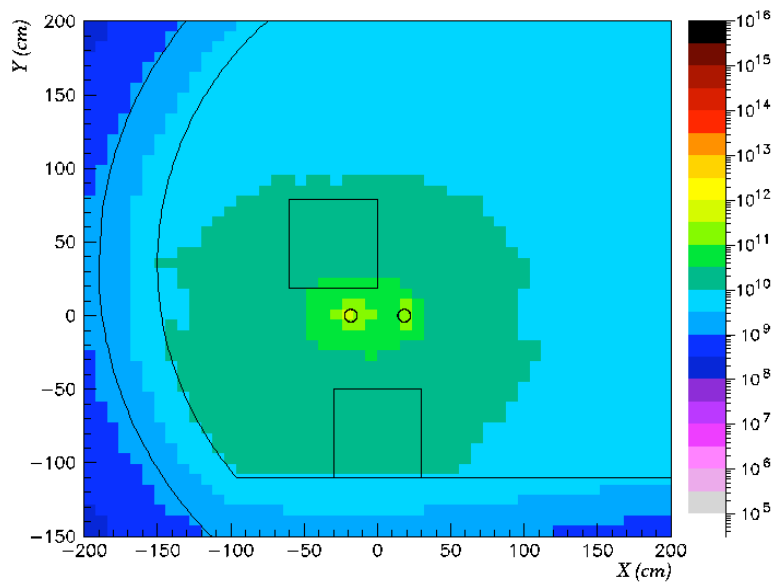

Figure 6   Hadron >20MeV flux in cm^{-3}/y for the positions of the BSRT. This vertical cut is at 72m from the IP4 and a mean of the values ±2m from this surface. The telescope was to be installed above the beam line tube (upper box) and the radiation levels for this position were estimated to be ~3_10^{10} cm^{-3}/y.
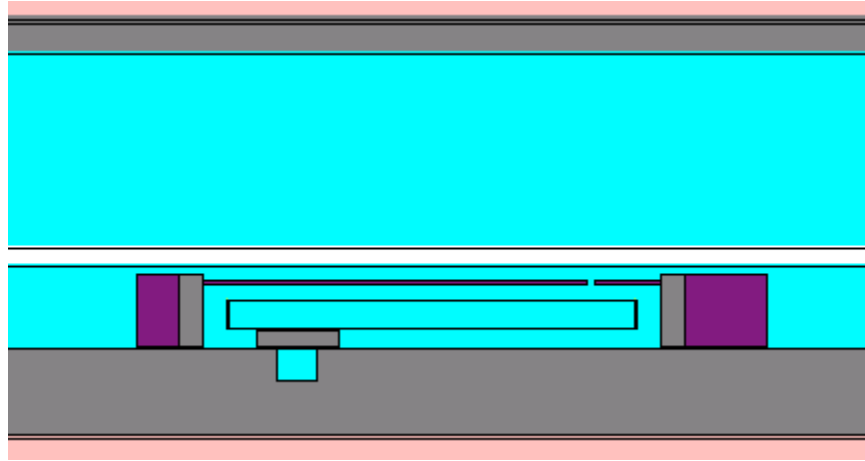
Figure 7   The shielding proposed for the synchrotron radiation telescope: An iron block 0.5m thick and a 30cm concrete slab towards D3, a 30cm concrete slab and an iron block 1m thick towards D4 and an iron slab of 5cm thickness at the top of these blocks. The iron material is shown with the dark purple colour, the concrete with the grey colour and the blue colour stands for the air. The cylinder inside the shielding box is the BSRT tube (filled with air for the scoring). The small pit (50cm_50cm_50cm) in the floor is for the sensitive electronics. Its concrete cover might reduce the high-neutron fluence.
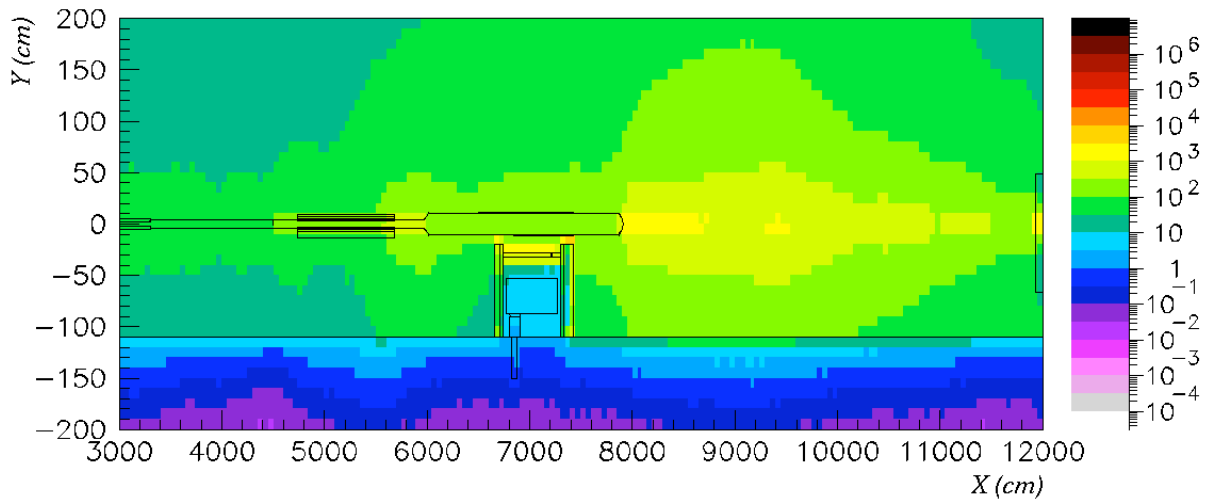

Figure 8   Dose rate in Gy/y around the shielding proposed for the BDI telescope. This vertical cut is at 22cm from the centre of the two beam lines and a mean of the values 0-50cm from the centre of the beam line. The dose level in the BSRT tube is estimated to be a few Gy/y.
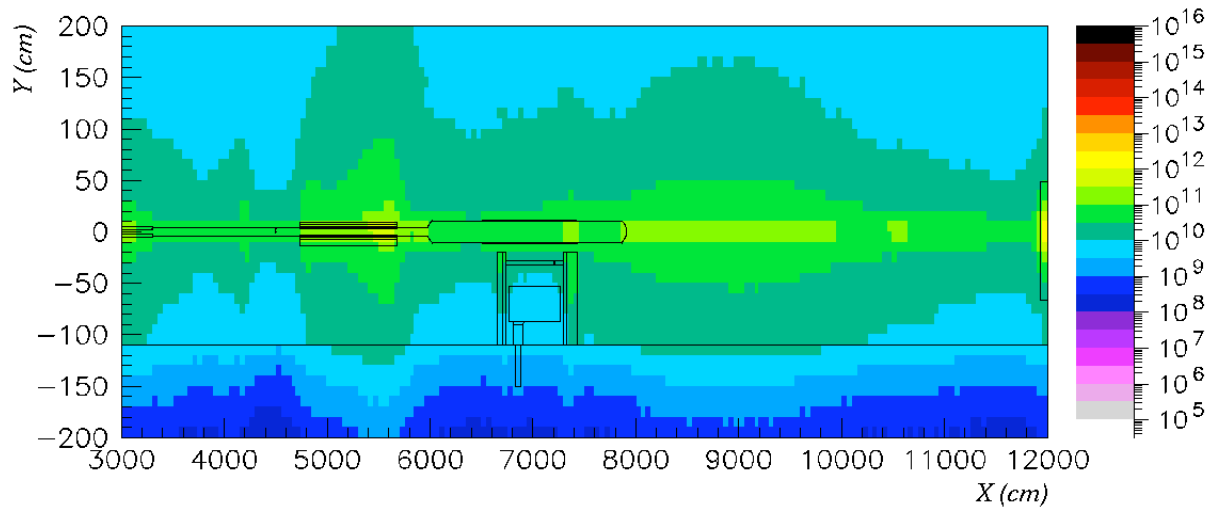
Figure 9   Hadron >20MeV flux in cm^{-2}/y around the shielding proposed for the BDI telescope. This vertical cut is at 22cm from the centre of the two beam lines and a mean of the values 0-50cm from the centre of the beam line. The hadron flux in the BSRT tube is estimated to be <10^{10} cm^{-2}/y.
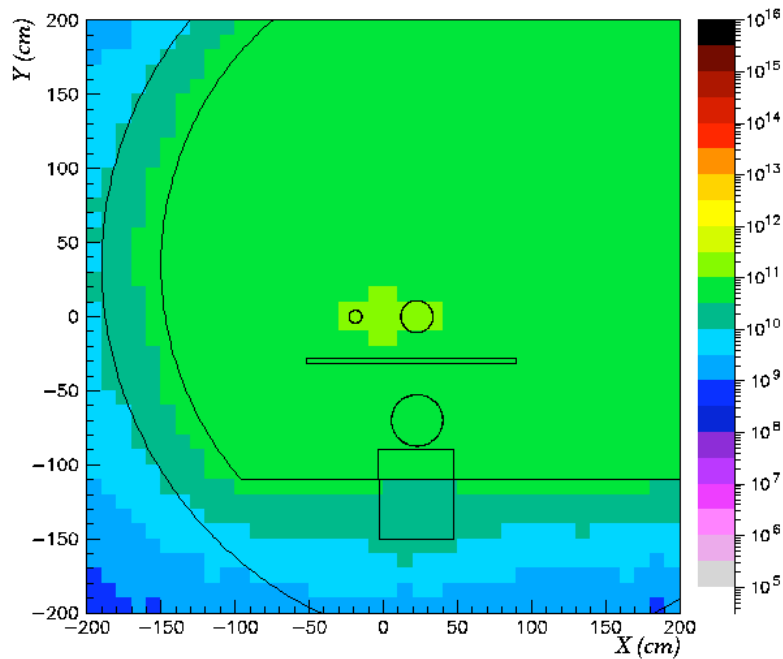

Figure 10   1MeV neutron equivalent flux in cm^{-2}/y at the position of BDI telescope and electronics pit. This vertical cut is at 68.5m from IP4 and a mean of the values ±0.5m from this surface. The 1MeVeq. flux in the SRT tube is estimated to be ~2_10^{10} cm^{-2}/y.

4   Conclusions

The Monte Carlo simulation performed for IR4 showed increased radiation levels for the BDI equipment. Special care was taken for the beam synchrotron radiation telescope (BSRT) and its electronics. The solid state cameras available for LHC/IR4 would malfunction after receiving doses ~20-30 Gy [9] and as a result it was impossible to use the initial scenario of placing the BSRT close to the beam line, above the tube. A series of measures were proposed in order to reduce the radiation levels for the SR monitors, i.e. lengthen the enlarged beam tube, move the BSRT under the beam lines and design a special shielding box for it. The electronics are proposed to be installed in a small pit in the floor inside the shielding to further protect and to cover it by a concrete slab. The monitors, like the beam current transformers (BCT), which have not to be located in the D3-D4 dogleg were displaced to other locations.

The measures proposed by the current study assure a safe environment for the BDI sensors for about a year. However, it is essential that a factor of ~10 is taken as a safety margin for the choice of the electronics involved.

References

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