EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

LHC Project Note 372

2005-08-09

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Studies for the radiation levels and shielding in RR73, RR77 and UJ76 in IR7 for collimation phase 1

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Keywords: IR7, RR73, RR77, UJ76, radiation levels, shielding, FLUKA

Summary

The Collimation project is one of the most crucial for the LHC performance. 54 movable, two-sided collimators will be placed in two insertions, i.e. IR3 and IR7, which will be among the most radioactive in the LHC. For a normal machine operation, it is essential that the electronics do not degrade or fail – at least very often – due to irradiation. The radiation levels initially estimated in IR7 (RR73/77 and UJ76) were too high for the electronics to tolerate. A shielding study was necessary to be done, in parallel with the study for the absorber positions. This article summarizes the shielding proposed and the radiation levels calculated for the final collimator and absorber positions as indicated by the FLUKA team.

1. Introduction

The collimation system of the LHC is a challenging project, since the transverse energy intensities of the LHC beams are going to be three orders of magnitude greater than at other current facilities. The collimators should withstand the deposited power as well as prevent from magnet quenches. In order to meet acceptable collimation efficiencies, a multi-phase collimation system has been designed. The phase 1 collimation system will be used for injection and it will ramp up to nominal or even to ultimate intensities. It is a three-stage cleaning process, which involves primary and secondary collimators at 6_ and 7_ respectively, scrapers for beam forming and halo diagnostics as well as tertiary collimators (in the experimental insertions) to provide additional shadow for the superconducting triplet magnets.

IR7 is dedicated to the LHC betatron cleaning and it is expected to be one of the most activated sections at the LHC. Extensive and detailed Monte Carlo simulations were essential to be done in order to estimate the energy power deposited on the collimation system and the radiation levels at the regions were electronic equipment will be installed. The current paper is limited to present the latest studies for the radiation levels and shielding in the RR73, RR77 and UJ76 where electronic equipment will be installed.

In order to estimate the radiation tolerance of the LHC electronics the dose rate and the hadron fluxes were scored at the regions reserved for the electronic equipment. The 1 MeV neutron equivalent flux for neutrons, protons, pions and electrons is expected to contribute to the estimation of the displacement damage [1],[2], while the scoring of all hadrons above 20 MeV serves as a good criterion for the estimation of the single event effects (SEE) expected in the areas of interest. Since the betatron cleaning area will be the hottest region in the LHC tunnel, several shielding scenarios have been applied in order to reduce the radiation levels in the regions of interest.

This work is done in parallel with the studies for the position of the absorbers in IR7. The only radiation source considered was the protons lost on the collimators.

2. Monte Carlo simulation

The FLUKA Monte Carlo code [3], [4] was used for the challenging simulations concerning the design of the LHC collimation system. The detailed geometry set-up includes the entire V6.5 lattice and optics, the primary and secondary collimators foreseen by collimation phase 1 and five absorbers, as provided by the TWISS files generated by the MAD-X program [5]. An overview of the different types of collimators used in the current study is shown in Table 1. Special attention was given on the number and the position of the absorbers in order to best protect the machine. Several iterations of the Monte Carlo Simulation took place before the presented scenario was finalised [6]-[9].

Table 1

Overview of the collimators used in the current study

Type	Name	Distance from IP7 (cm)	_ (deg)
Beam1			
Primary Material for jaws: C-C	TCP.D6L7.B1	-20497.8	90
	TCP.C6L7.B1	-20297.8	0
	TCP.B6L7.B1	-20097.8	126.9
Secondary Material for jaws: C-C	TCSG.A6L7.B1	-16148.35	141.1
	TCSG.B5L7.B1	-10225.6	143.5
	TCSG.A5L7.B1	-9825.6	40.7
	TCSG.D4L7.B1	-7692.6	90
	TCSG.B4L7.B1	-700	0
	TCSG.A4L7.B1	-300	134.6
	TCSG.A4R7.B1	100	46.3
	TCSG.B5R7.B1	9225.6	141.5
	TCSG.D5R7.B1	10825.6	51.3
	TCSG.E5R7.B1	11225.6	130.5
	TCSG.6R7.B1	14686.1	0.5
Absorber Material for jaws: Cu-W	TCL.A6R7.B1	15417.2	90
	TCL.C6R7.B1	18512.55	0
	TCL.E6R7.B1	21891.17	90
	TCL.F6R7.B1	22191.17	0
	TCL.A7R7.B1	23794.3	0
Beam2			
Primary	TCP.D6R7.B2	20497.8	90

Material for jaws: C-C	TCP.C6R7.B2	20297.8	0
	TCP.B6R7.B2	20097.8	127.5
Secondary Material for jaws: C-C	TCSG.A6R7.B2	16148.35	141.3
	TCSG.B5R7.B2	10225.6	143.6
	TCSG.A5R7.B2	9825.6	40.6
	TCSG.D4R7.B2	7692.6	90
	TCSG.B4R7.B2	1100	0
	TCSG.A4R7.B2	700	132.1
	TCSG.A4L7.B2	-900	42.1
	TCSG.B5L7.B2	-9225.6	141.5
	TCSG.D5L7.B2	-10825.6	51.4
	TCSG.E5L7.B2	-11225.6	130.5
	TCSG.6L7.B2	-14686.1	0.5
Absorber Material for jaws: Cu-W	TCL.A6L7.B2	-15417.2	90
	TCL.C6L7.B2	-18512.55	0
	TCL.E6L7.B2	-21891.17	90
	TCL.F6L7.B2	-22191.17	0
	TCL.A7L7.B2	-23794.3	0

2.1 Geometry

The geometry set-up of the IR7 simulation is a very detailed representation of the beam modules and collimators as described in V6.5 lattice and optics of the LHC machine (see references [7], [8] for more details). The only non-detailed modules in the representation are the discharge resistors (DQR) in the quench protection system and the distribution feed boxes (DFBA) in front of the RR73/77. The DQR modules consist mainly of stainless steel boxes (2.2 tons) filled with water (2.5 tons) [10]. In the simulation, a mixture of these materials was used with a mean density value. The DFBA modules are more complex stainless steel containers filled with helium. A simplified box (filled with helium) was used to represent this device (see Figure 1).

2.2 Radiation sources

The only source of radiation considered in the current study was the proton losses on the collimators for both beams. The loss distributions were initiated by the nuclear interactions of protons lost on collimators with coordinates and directions provided by the COLLTRACK V5.4 code [7],[8]. A total of the horizontal, vertical and skew distribution scenarios were used as a source file in the FLUKA simulation. The results we scaled using the number of 4.1_10^{16} protons lost per year, the ultimate scenario of a 15-hour fill length at 7 TeV equivalent (along the two beam lines in IR7) [11].

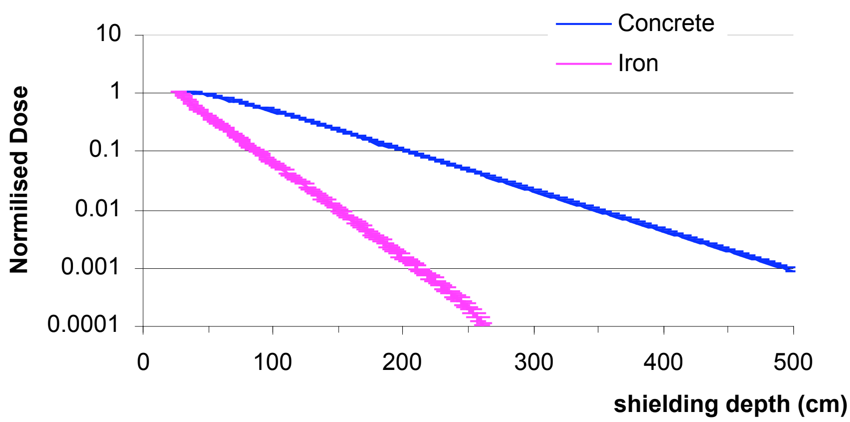
2.3 Scoring

At the regions of interest we calculated the energy deposition (dose) of all particles (E>1MeV). In addition, the 1 MeV neutron equivalent fluence and the hadrons for energies

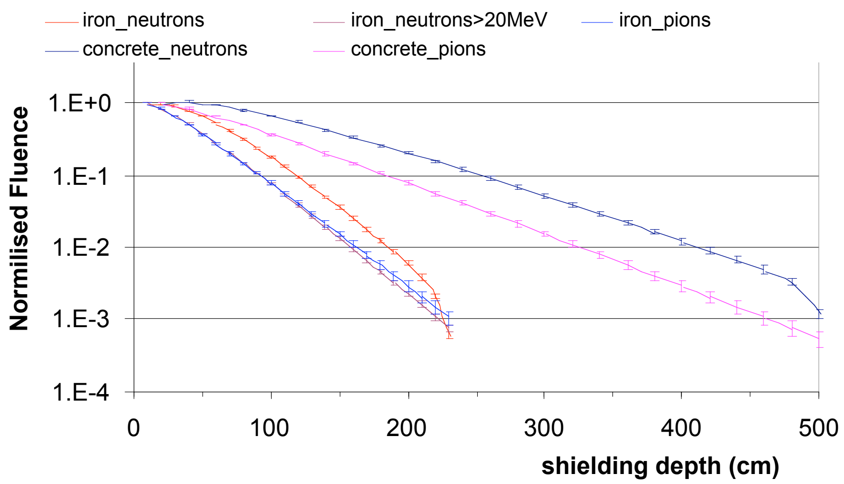
>20MeV were scored in special meshes covering the geometry at the regions were electronic equipment will be installed. All the scorings were made in air.

2.4 Shielding scenario

Initial calculations for the radiation levels in RR73/77 and UJ76 showed an unacceptable dose rate and flux for the electronics to be installed. Shielding studies were essential to be performed in order to reduce the radiation levels, especially in the RRs. To faster optimise the amount of shielding needed to be installed at the RR entrances the particle fluence and dose attenuation was calculated for concrete and iron shielding slabs using the simulated particle spectra at the RR entrances. Figure 1 shows the attenuation of the radiation at the RR entrances for the two materials.



a.



b.

Figure 1 The dose and hadron fluence attenuation for iron and concrete as calculated for the spectra at the RR entrances. In the upper graph (a.) the dose attenuation is presented and in the lower graph (b.) the hadron attenuation is given. According to these results, in order to obtain an order of magnitude less radiation we need ≤ 1m of iron or ≥ 2m of concrete shielding.

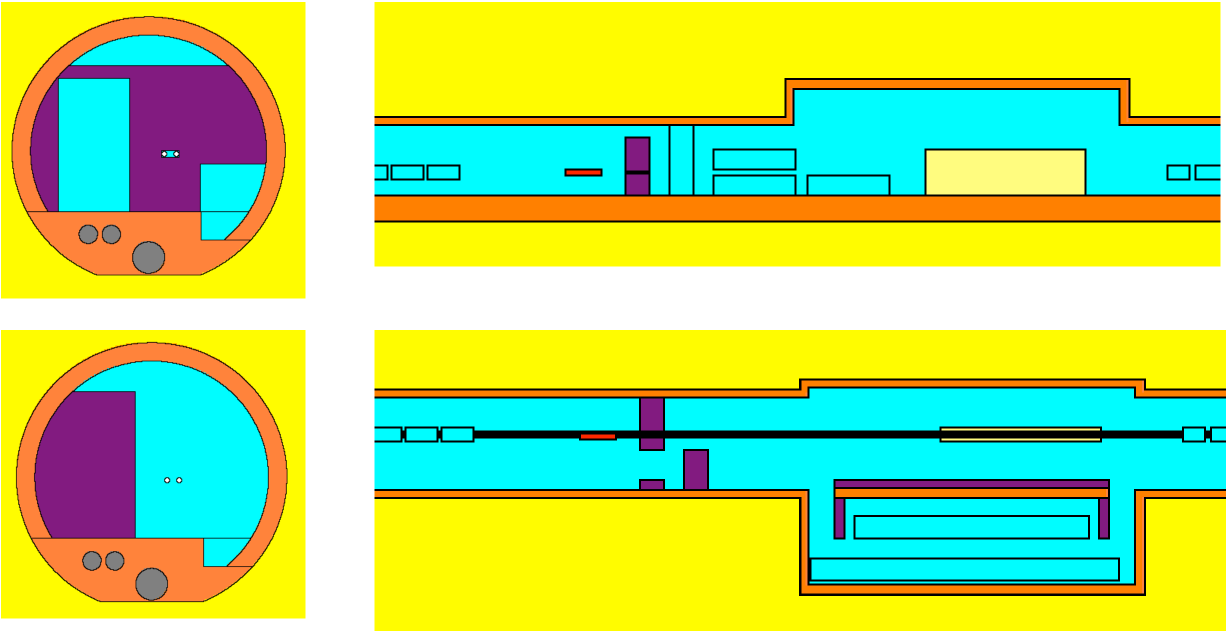


Figure 2	Schematic representation of the shielding proposed for the RR73/77 regions. The purple colour stands for iron (density 7.2 gr/cm^3), the orange colour is for the concrete walls and the blue colour stands for the air. Inside the RR region the two boxes represent the racks for the electronics, where the scoring was made (in air).

Following the attenuation calculations and a number of shielding scenarios, the RR shielding layout was finalized as shown schematically in Figure 1. It consists of two iron shielding blocks in the entrances perpendicular to the tunnel, another one parallel to the tunnel, next to the concrete separation wall and a small chicane a few meters upstream the IP7. No shielding is foreseen for the UJ76 region since there is no space for effective shielding volume inside or outside the cavity.

3. Results

For the sake of completeness and in order to get a global view of the radiation levels in IR7, the dose rate distribution along the tunnel (straight section) is presented in Figure 3. Figures 4-6 show the annual dose rate and particle fluxes in the region of the UJ76. Figures 7-12 show the same quantities in the RR73/77 regions. All these plots are listed at the end of the manuscript.

The following Table 2 summarizes the results in a few representative numbers (average values at the racks situated at the level of the beam line) for the position of the electronic equipment. Note that in certain areas the radiation levels might be higher (i.e. dose rates up to 1Gy/year, see figures 4-12). In all the values presented in this paper the statistical error is up to 20%.

Table 2

Radiation levels at the electronic rack positions at IR7 (average values for the racks situated on the ground floor). The statistical error is ≤20%.

	Dose (Gy/y)	Hadrons > 20 MeV (cm^{-2}/y)	1 MeVeq. flux (cm^{-2}/y)
UJ76	0.5	8 _10^8	2 _10^9
RR73/77	0.3	1 _10^8	6 _10^8

4. Safety factor

The accuracy of the present simulation is particularly high due to very detailed geometry and the state of the art simulation routines that have been created for this particular project. However, there is always the uncertainty due to the initial input of proton loss distributions (coming for another simulation) and the radiation sources that have not been taken into account, i.e. residual gas interactions (although the latter are considered to be much less compared to the losses on collimators). We might also have errors due to the particles grazing at small angles the surfaces of the collimators, where the surface roughness was not taken into account. The safety factor proposed by the authors for the FLUKA simulation presented herein is SF_{FLUKA}= 4 - 5 [see also [7] for more details].

The authors here would like to point out that before the installation of the electronic equipment and the calculation of its lifetime it is highly recommended that the above safety factor is combined with a few others. According to the ATLAS Policy on Radiation Tolerant Electronics [12] the simulated radiation levels (SRL) should take into account the simulation safety factor (SF_{sim} = SF_{FLUKA} _ $SF_{protonLosses}$), a safety factor for the low dose rate effects (SF_{ldr}), which can vary from 1 to 5 depending on the device and its response to radiation, and a safety factor for the variation of the radiation tolerance from lot to lot and within a lot (SF_{lot}), which can vary from 1 to 4 depending on the device production and whether it is tested under radiation conditions or not. Finally, the radiation tolerance criteria (RTC) to follow for choosing an electronic device should be: RTC = SRL _ SF_{sim} _ SF_{ldr}_ SF_{lot} (see [12] for more details).

5. Conclusion

The shielding proposed in this paper seems to ameliorate the initial radiation levels (results not shown, but there is an extended presentation of the evolution of the current studies in LHC Collimation Working Group website [6]). The amount of the shielding is the maximum that could be put in RR73/77 and the most effective one along the tunnel ([10] and relevant talks in [6]). In the UJ76 there was a lack of free space, so there was no possibility of shielding there. The radiation levels in IR7 were further decreased by the use of the absorber modules (see Table 1) that seemed to lower the energy deposition in the RR73/77 by an order of magnitude. As a result, the radiation levels shown by the current study are the lowest that have been ever estimated in the insertions UJ76, RR73 and RR77 (see talks of KT in [6] for further information). The doses rates in all the insertions can reach a maximum value of ~1Gy/year and the hadron fluxes for energies above 20MeV are up to 2_10^8 cm^{-2}/year in the RR73/77 and up to 2_10^9 cm^{-2}/year in the UJ76.

Nevertheless, an attention should be paid in the choice of the electronic equipment to be installed in the IR7 insertions. Under these conditions (current proton losses, phase 1) the lifetime of the LHC electronics should be estimated taking into account various safety factors (as discussed in the previous paragraph). In addition, the effect of other radiation sources should be considered and added to the presented values (in case there are relative estimations).

Especially for the sensitive equipment, it is suggested that is installed as far as possible from the separating walls in the insertions or in other “safer” galleries (i.e. TU76, TZ76) away from the radiation sources (i.e. beam lines).

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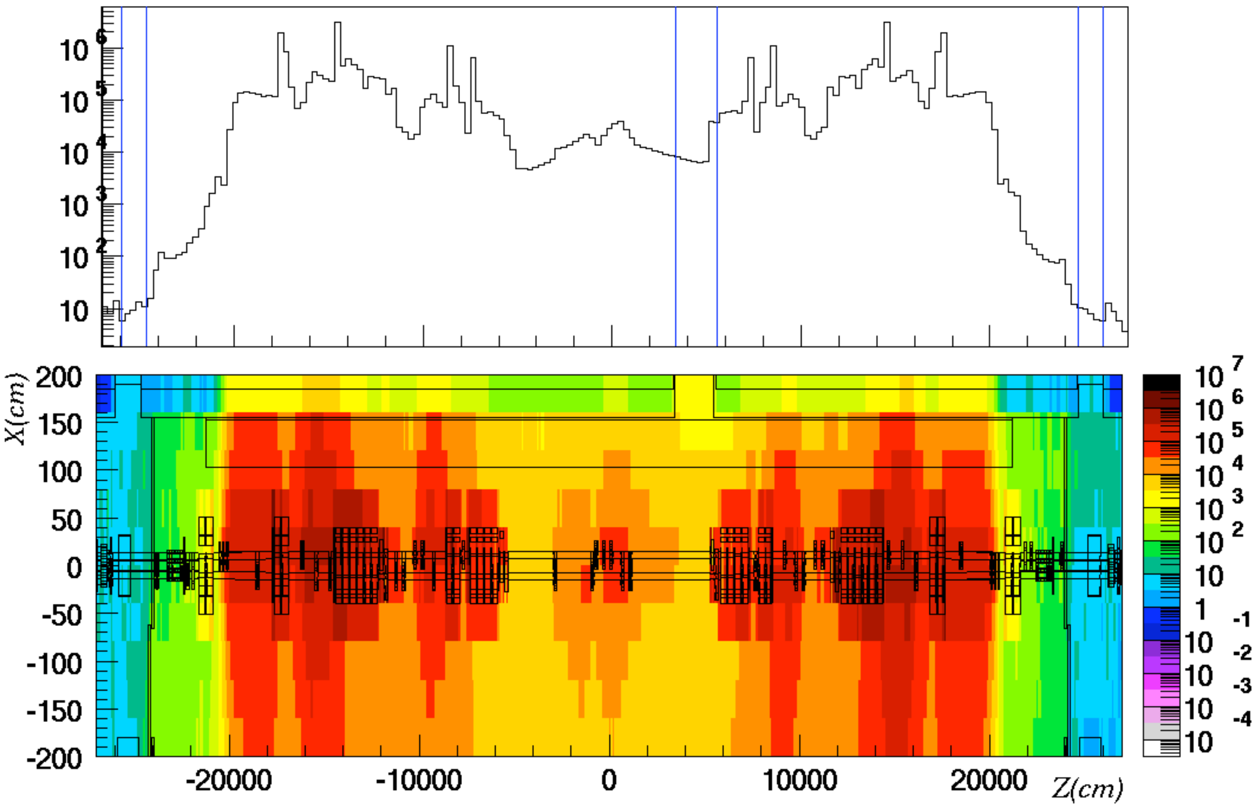

Figure 3 Dose rate distributions along the tunnel in Gy/year. The values shown are the average of ±1m vertically from the beam line. In the upper figure the dose rate distribution is plotted as a histogram and in the lower figure the same values are shown in a contour plot together with the geometry. The regions of interest (RR73, UJ76, RR77 – from left to right on the figure) are marked with the blue vertical lines.

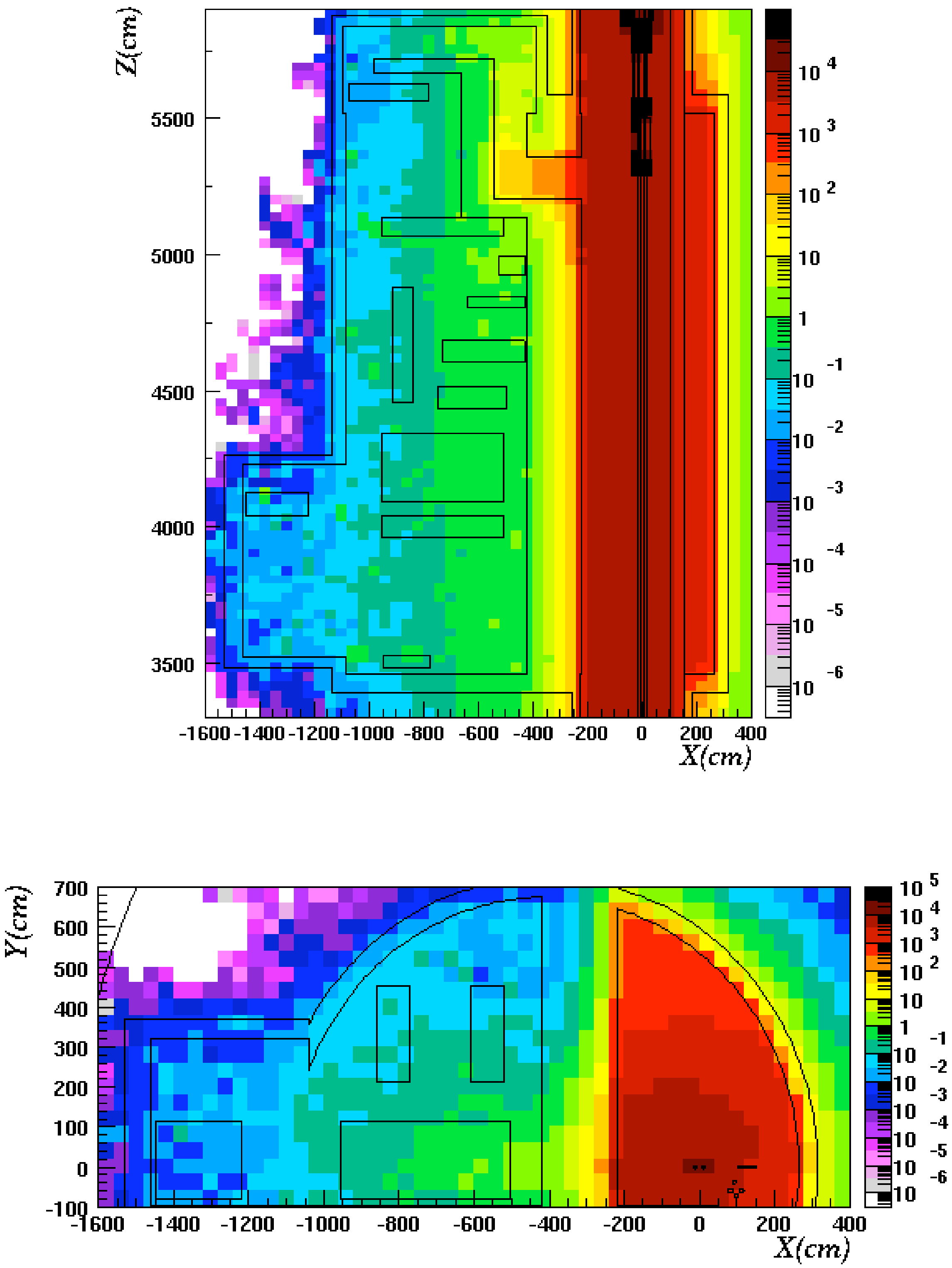

Figure 4 Dose rate distributions (in Gy/year) in the UJ76 at the horizontal beam line level (upper figure), where the mean values of -100cm to 180cm are shown and vertically (lower figure), where the values along the racks (from 3500cm to 4900cm) are averaged. The expected dose rate inside the UJ76 insertion is up to 1Gy/year.

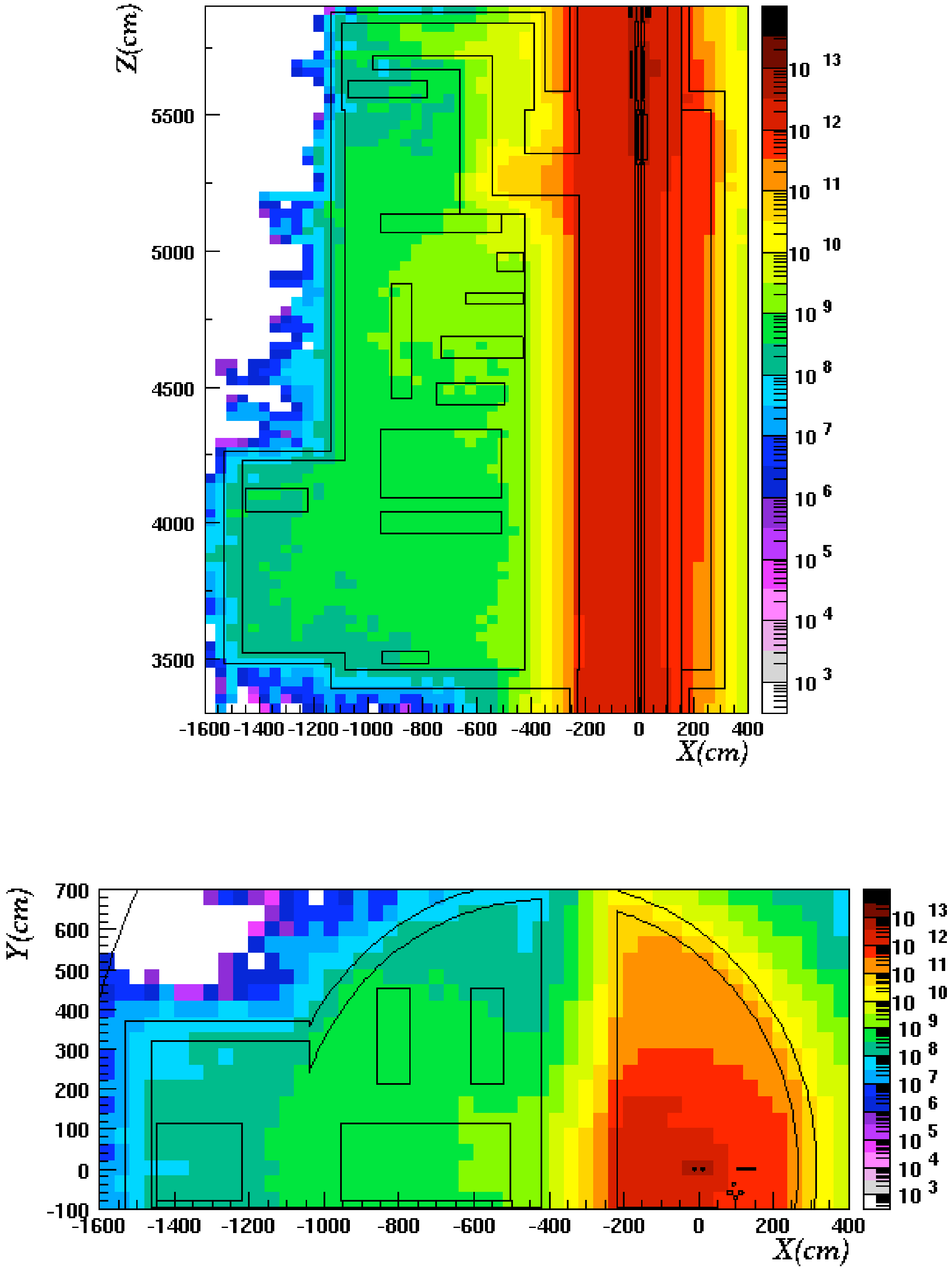

Figure 5 Flux distributions of hadrons with E > 20 MeV (in cm^{-2}/year) in the UJ76 at the horizontal beam line level (upper figure), where the mean values of -110cm to 170cm are shown and vertically (lower figure), where the values along the racks (from 3500cm to 4900cm) are averaged. The maximum expected fluence rate inside the UJ76 insertion is ~ 2_10^9 cm^{-2}/year.

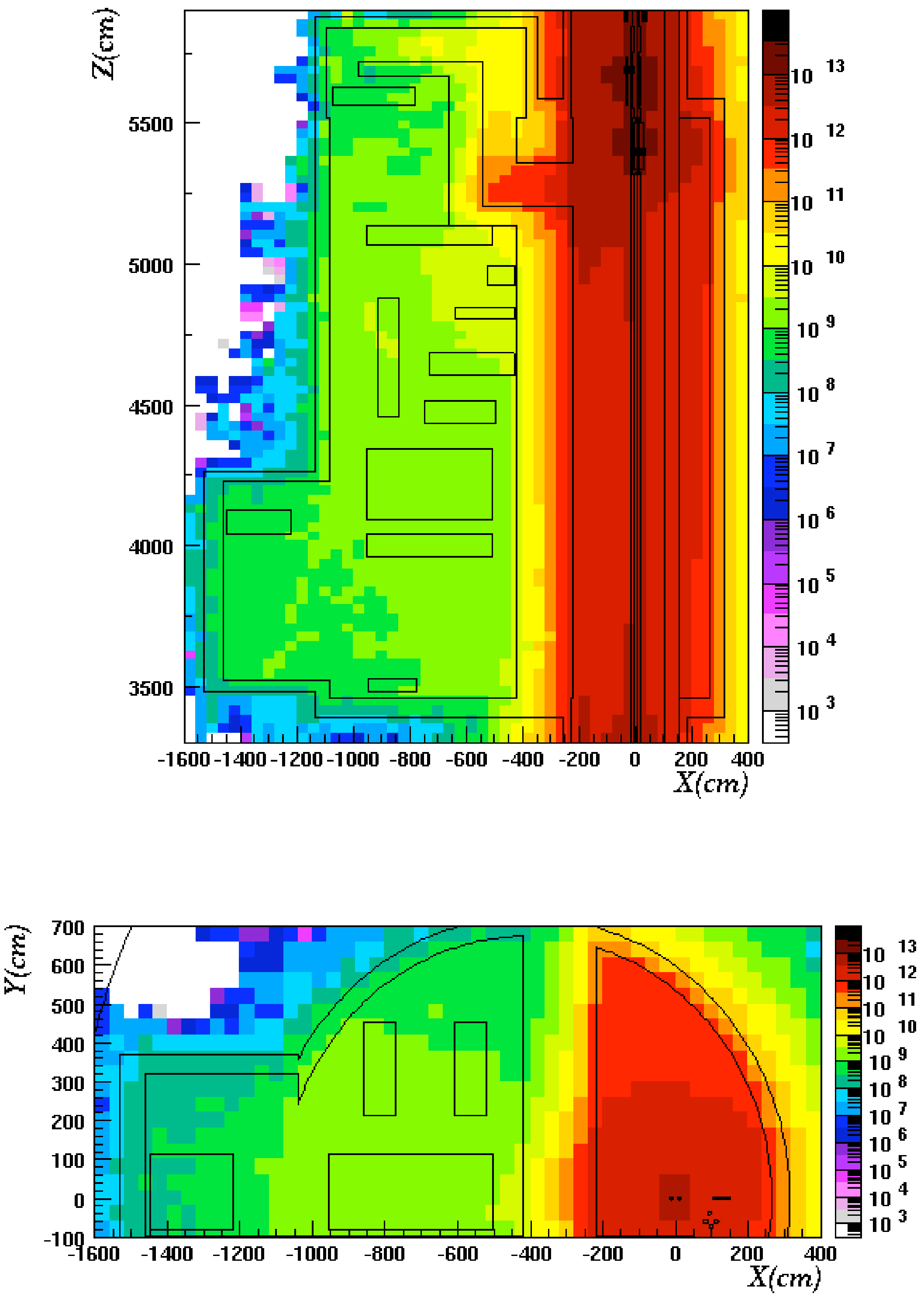

Figure 6 1 MeV neutron equivalent flux distributions (in cm^{-2}/year) in the UJ76 at the horizontal beam line level (upper figure), where the mean values of -110cm to 170cm are shown and vertically (lower figure), where the values along the racks (from 3500cm to 4900cm) are averaged.

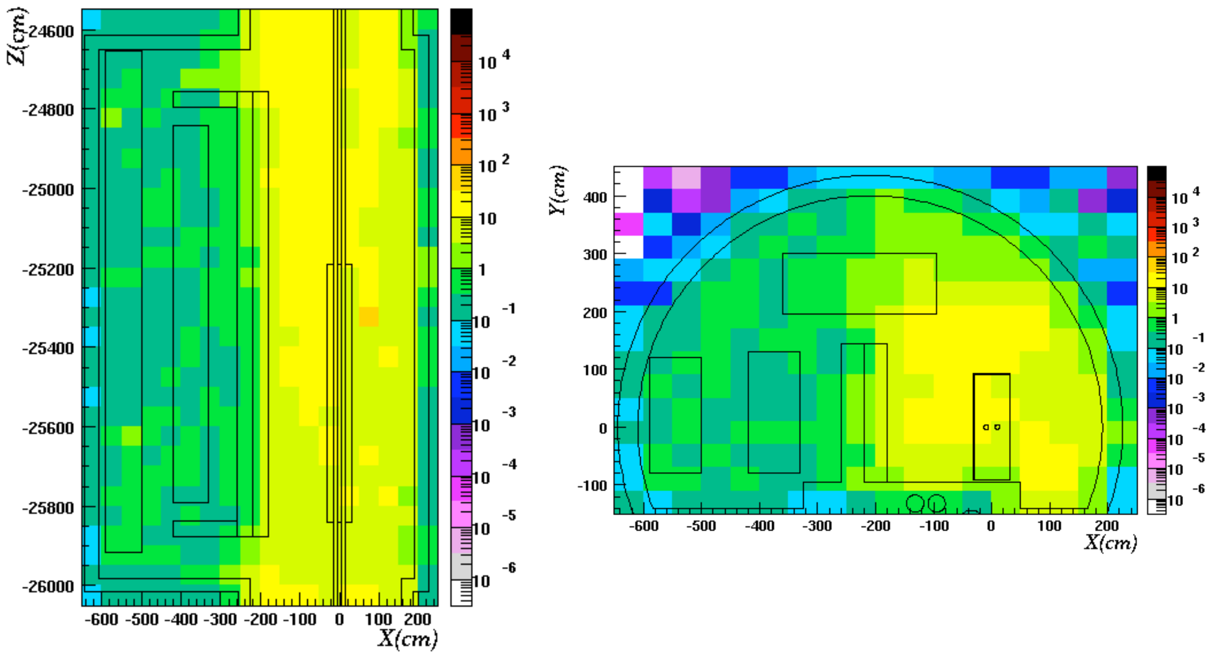

Figure 7 Dose rate distributions (in Gy/year) in the RR73 at the horizontal beam line level (left figure), where the mean values of -110cm to 170cm are shown and vertically (right figure), where the values along the smaller rack on the floor are averaged. On average, the expected dose rate inside the RR73 insertion is ~0.5Gy/year, but it can reach values up to 1Gy/year.

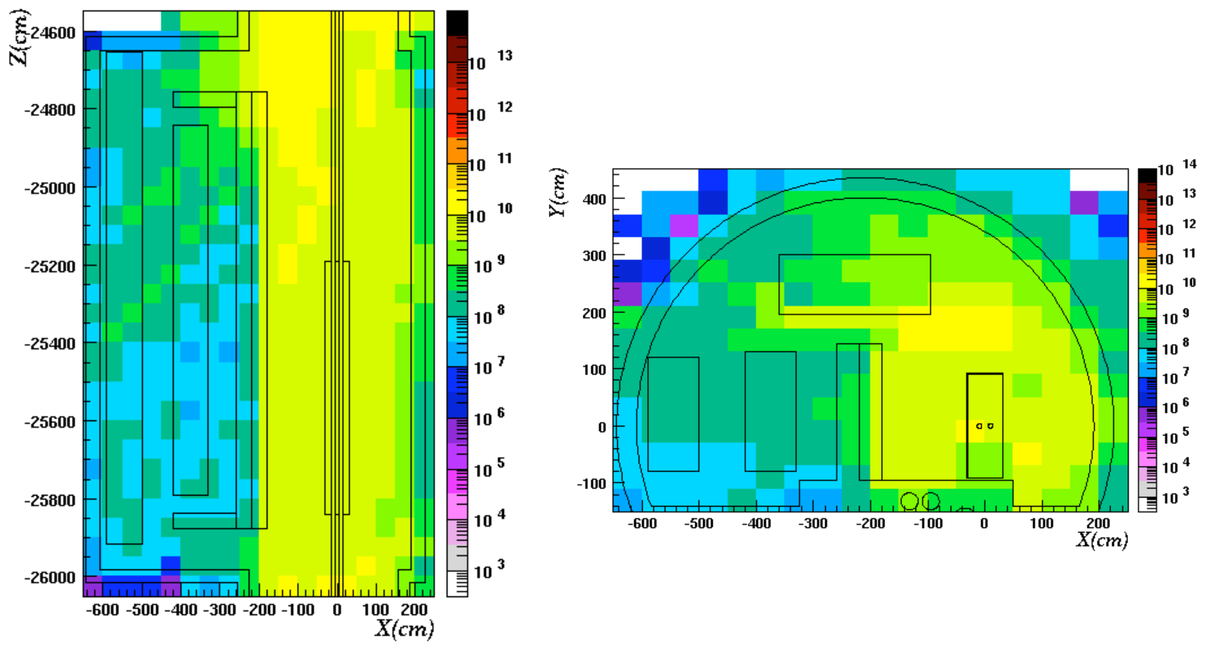

Figure 8 Flux distributions of hadrons with E>20 MeV (in cm^{-2}/year) in the RR73 at the horizontal beam line level (left figure), where the mean values of -110cm to 170cm are shown and vertically (right figure), where the values along the smaller rack on the floor are averaged. The maximum expected hadron flux inside the RR73 insertion is ~2_10^8 cm^{-2}/year.

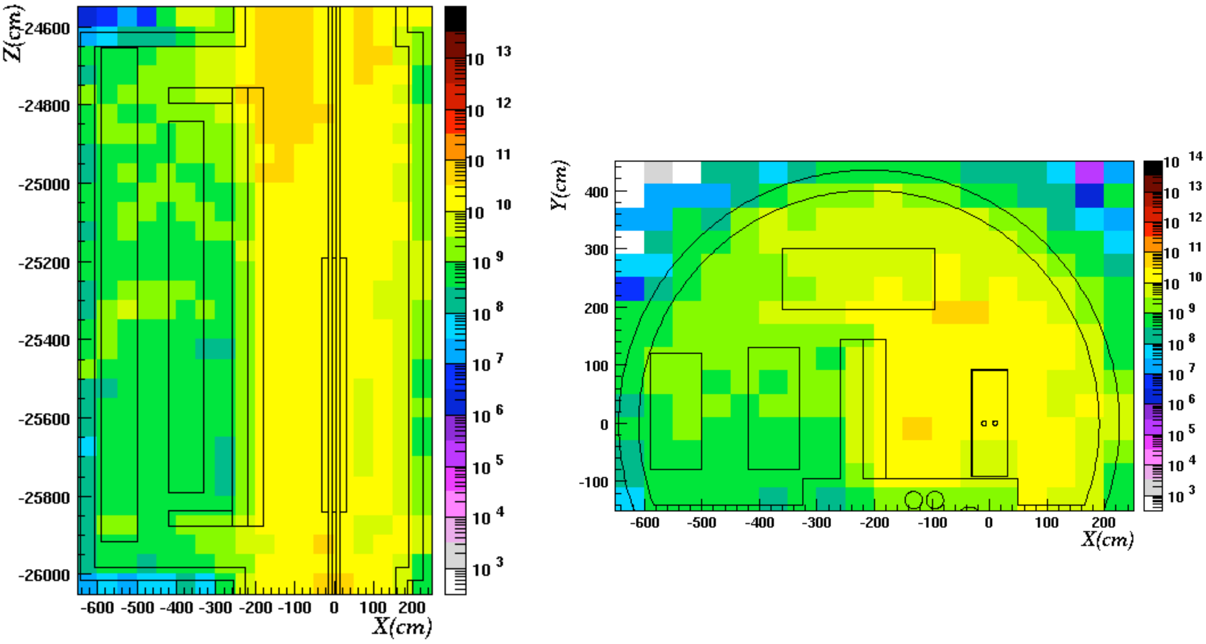

Figure 9 1 MeV neutron equivalent flux distributions (in cm^{-2}/year) in the RR73 at the horizontal beam line level (left figure), where the mean values of -110cm to 170cm are shown and vertically (right figure), where the values along the smaller rack on the floor are averaged.

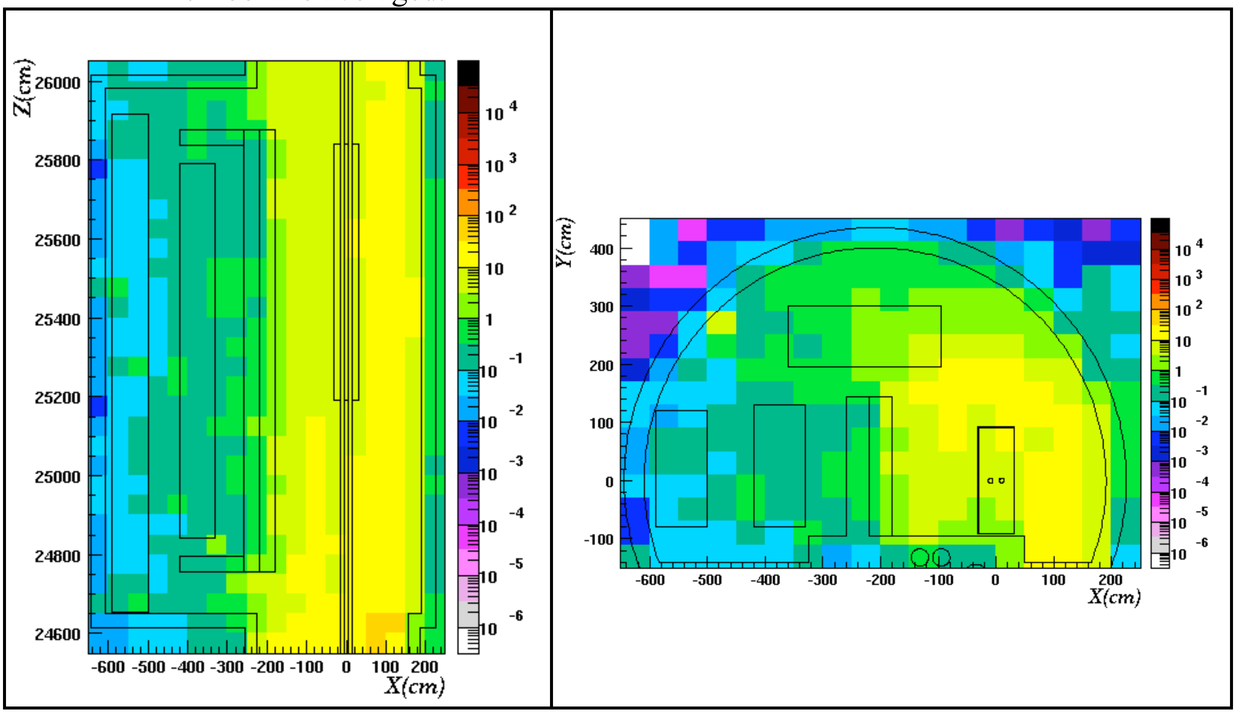

Figure 10 Dose rate distributions (in Gy/year) in the RR77 at the horizontal beam line level (left figure), where the mean values of -110cm to 170cm are shown and vertically (right figure), where the values along the smaller rack on the floor are averaged. The mean expected dose rate inside the RR73 insertion is ~0.5Gy/year, but it can reach values up to 1Gy/year.

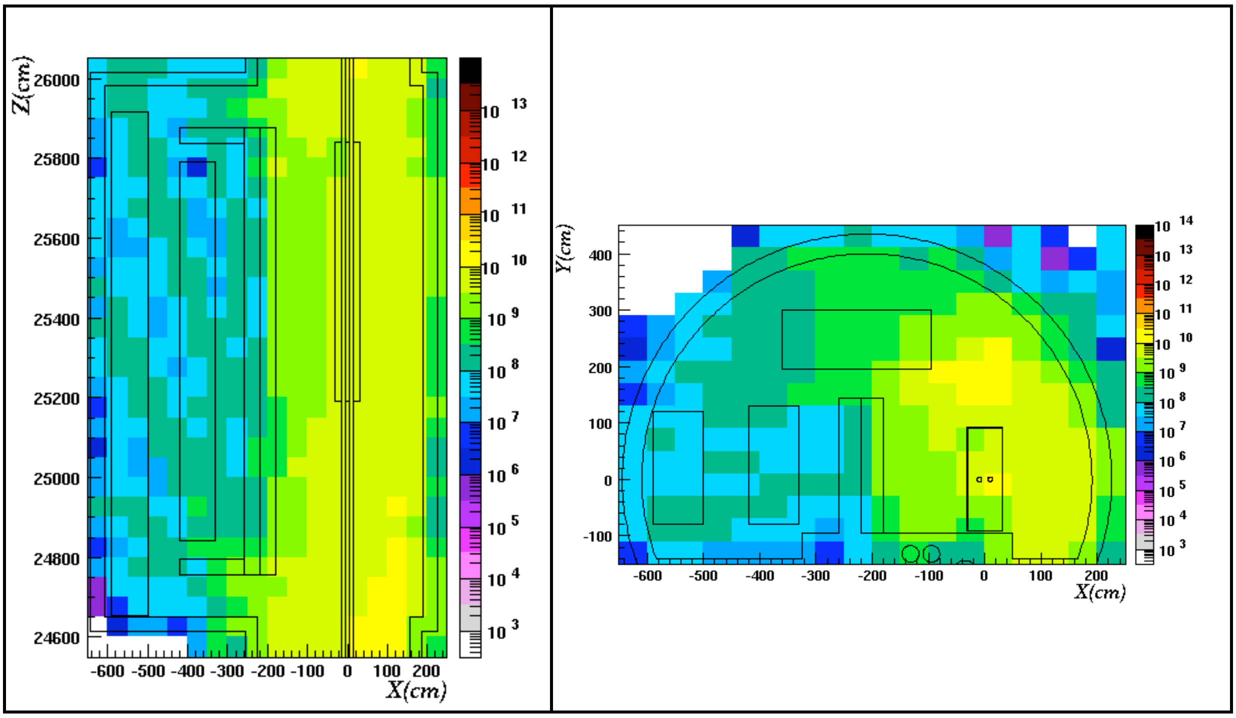

Figure 11 Flux distributions of hadrons with E>20 MeV (in cm^{-2}/year) in the RR77 at the horizontal beam line level (left figure), where the mean values of -110cm to 170cm are shown and vertically (right figure), where the values along the smaller rack on the floor are averaged. The maximum expected flux inside the RR73 insertion is ~2_10^{8} cm^{-2}/year.

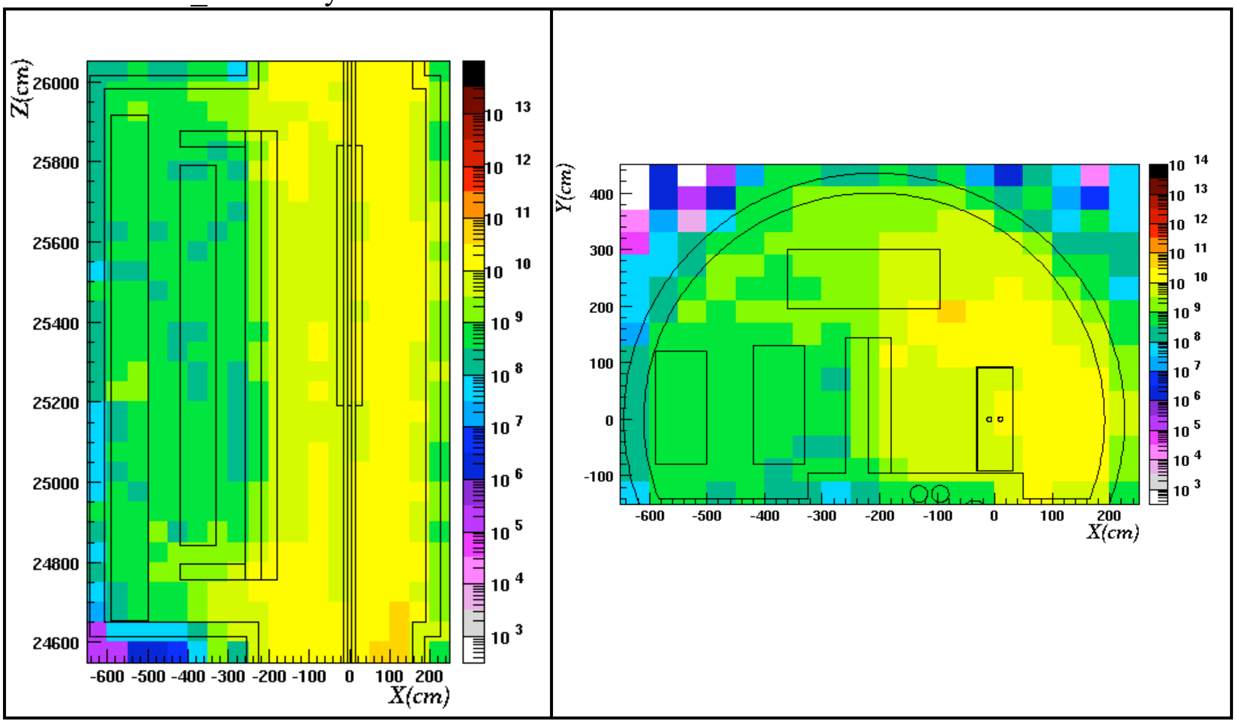

Figure 12 1 MeV neutron equivalent flux distributions (in cm^{-2}/year) in the RR77 at the horizontal beam line level (left figure), where the mean values of -110cm to 170cm are shown and vertically (right figure), where the values along the smaller rack on the floor are averaged.