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Estimation of the machine induced background for the commissioning period with tertiary collimators in the IR1 of the LHC

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Summary

This note presents the first results for the estimation of the machine induced background in the high luminosity insertion of the LHC for the period of the machine start–up with the recently introduced tertiary collimators in the straight section upstream of the IP1.

Introduction

The study of the machine induced background performed for the high luminosity experimental insertion of the LHC project [1] and supplemented by the analysis of the high momentum background component [2] allowed the identification of the characteristic features of the background formation in this region of the collider. The response of experimental sub-detectors to the background signal of this type was analyzed and the signal has been found significant enough to be useful for alignment and calibration during the experiment commissioning stage [3]. The vacuum and optics parameters used in these studies corresponded to the machine operation at high luminosity and the results for the commissioning period were obtained using several assumptions on the background scaling with the change of the machine filling scheme.

Recently the set of the calculations on residual gas dynamics was completed that covered both the cases of machine conditioning with a beam of reduced intensity [4] and machine commissioning with a reduced number of the bunches [5]. At the same time the new tertiary collimators were proposed and integrated into the layout of experimental insertions to protect the superconducting magnets of the inner triplet from quenching [6]. These collimators are expected to be in place from the start of the machine operation and will be located in

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experimental insertions on the incoming LHC beam upstream from the interaction point. These elements must be taken into account in the estimation of the background for any machine operation scenario, including during the period of commissioning.

The current note continues the studies of the machine induced background in the high luminosity experimental insertion IR1 of the LHC. It concentrates on the finalizing of the previously presented estimations of the background for the machine operation at the commissioning stage [7] in the presence of the new collimators (TCTs) in the straight section upstream of the interaction point [8].

1 Vacuum quality at the machine commissioning

The commissioning of the LHC with the beam will be a staged process with different goals that have to be achieved during each phase and with different machine parameters [9]. It is foreseen that during the LHC start-up at top energy the machine will operate with reduced bunch intensities below the electron multipacting threshold for conditioning purposes [4]. Estimation of the machine induced background for the early stages of the LHC running requires as one of the parameters the profiles of the residual gas density that correspond to the beam parameters and the vacuum chamber surface properties in the region of interest for the studied period of the machine operation. An overview of the estimations for gas component densities in the elements of IR1 which were used in the present study is given in Table 1. These numbers were taken from [4] for the case of the machine conditioning with a current of 1/3 from nominal one and from [5] for the machine start-up with the current of 0.01 A. For the reference in the same Table are given the values for the gas density that were used in the previous estimations of the machine induced background in the high luminosity insertion of the LHC and were taken from [10] for the nominal current I_n and the case of conditioned machine.

Element	**L, [m]**	$\mathbf{I = I_n}$	$\mathbf{I = 1/3\, I_n}$	$\mathbf{I = 0.01\, A}$
Q1	7.7	6.0	110	3.7
Q1–Q2	1.4	150	710	4.7
Q2	12.58	3.0	120	3.7
Q2–Q3	1.90	150	720	4.4
Q3	8.4	6.0	110	3.7
D1 (RT)	~ 25	5.0	76	0.4
'Conus'	~ 57	1.0	73	0.64
D2	11.67	150	240	3.8
Q4	8.65	20	130	3.7
VC (RT)	19.38	5.0	230	1.1
Q5	8.25	20	120	3.7

Table 1: Average hydrogen equivalent gas density $n_{<H_2>}$ $[10^{12}\,\mathrm{mol/m^3}]$ in the IR1 elements for three considered cases of the machine operation.

The relatively flat, with the mean value of a few $10^{12}\,\mathrm{mol/m^3}$ profile of the gas density in the IR1 for the case of $I = 0.01\,\mathrm{A}$ can be understood taking into account the assumed value of the current. The gas desorption stimulated at such low current determines the level of the gas pressure which under these conditions is not far from the static one that is 6.6×10^{11} mol/m^3 and 4.52×10^{11} mol/m^3, for cryogenic elements and ambient sectors with NEG coating respectively [11]. The relatively high (in comparison with the first column of the Table 1) gas pressure for the case of 1/3 of nominal current reflects the effect of the unconditioned surface of the vacuum chamber while the values from ref. [10] were taken for the period of stable running, starting from the third year operation of the conditioned machine. A specific case of conditioning with the current of 0.03 A is also given in [5] that corresponds to the machine operation with 156 bunches during the high β^* runs [12]. The average gas density in the experimental insertion in this case is larger than for the $I = 0.01$ A by a factor of 2.4–3.6 depending on the particular element, representing the quasi-linear scaling of the gas pressure at such low currents.

2 Background fluxes at the machine start-up

Numerical simulation of the particle interactions and transport inside magnetic and mechanical structure of the elements in the experimental insertion was performed using the methodical approach for the study of the machine induced background in the IR1 of the LHC [1]. To obtain the results comparable to the previous estimations the parameters of the background simulation were used in the same way as in the cited note except for the values of the gas density and composition. The predicted formation of the background in the straight section of the IR1 at the stage of the machine commissioning is illustrated in the Figure 1. In these plots the curves give the number of hadrons and muons produced in the proton interactions on the nuclei of the residual gas along the length of different machine elements for three considered cases of machine operation [1].

Hadrons			**Muons**		
$I = I_n$	$I = 1/3\,I_n$	$I = 0.01\,A$	$I = I_n$	$I = 1/3\,I_n$	$I = 0.01\,A$
1.57×10^6	2.66×10^6	2.07×10^3	6.77×10^4	8.17×10^4	48.9
	~ 0.6	~ 760		~ 0.8	~ 1390

Table 2: Particle fluxes [particles/s] at the machine start-up with two different values for the current, but without tertiary collimators.

The sums of the numbers from the Figure 1 that give the particle flux at the entrance to the experimental area of the IR1 are presented in Table 2. For the purpose of the comparison Table 2 also gives the corresponding total values from the previously completed analysis [2] and the bottom line gives the ratio between previous and new results. The observed increase of 30 % and 20 % for hadrons and muons respectively in the case of the start-up with the current of 1/3 from the nominal can be associated with the high gas desorption rate for the unconditioned surface of the vacuum chamber which determines the high rate of the beam–gas losses. A factor ~ 2 larger reduction for the muon flux in the case of $I = 0.01$ A reflects

[1] The curve for the $I = 0.01$ A case is given multiplied by a factor 10 for the presentation purposes.

the relative decrease of the gas density in this scenario of the operation in the D2–Q6 region that affects the hadron flux less than the flux of the muons. It is worth mentioning that for the case of the machine running with 156 bunches the particle fluxes can be estimated to be 10 times higher than for the studied case of the operation with $I = 0.01$ A taking into account the cumulative increase due to the larger beam current and higher values for the gas pressure in the elements of the IR1, as described in the section above.

From the plots on the Figure 1 it can also be seen that the peaks of the residual gas density in the inner triplet region which remain due to the features of the pumping scheme are well reproduced in the distribution of the hadrons although they are now less pronounced than in the case of previously used gas density estimates. For the case of the start-up with the current of 0.01 A both muon and hadron distributions in the matching section region are relatively flat thus representing the gas pressure profile close to the static state. For the case of the machine conditioning with the 1/3 of nominal current the visible contribution to the background flux is observed from the room temperature sections of the vacuum chamber in D2–D1 and Q4–Q6 regions. This is due to the predicted high level of CH_4 gas in the ambient sections of the beam pipe at the start of a conditioning period which defines the total pressure of residual gas. However this component of the residual gas is supposed to be removed by conditioning down to the level of 1 % from the initial pressure, making the locations of cryogenic elements in the straight section the dominant source of the background on the later stages of the operation [4].

3 Machine background in the presence of the TCTs

The next step in the estimation of the machine induced background in IR1 at the machine start–up was the evaluation of relative influence of tertiary collimators on the background formation in the insertion. At this stage vertical and horizontal collimators were introduced in the geometry model of the simulations according to the specification of the TCTs [6]. The parameters of the simulation are listed in Table 3. The losses of the beam protons were simulated along the LHC beam 1 in the left part of straight section in experimental insertion using a beam current of 0.01 A and corresponding estimates for residual gas density from [5]. The collimators were located between the D2 dipole and TAN with the jaws positioned parallel to the beam at the angle of 1.12 mrad in order to follow the envelope of the beam in this region. The distance from the jaws to the beam was taken equal to 13.5 $\sigma_{(x,y)}$ as proposed for the early physics running [13]. No equipment other than the jaws themselves with the geometry described below was introduced in the simulations and tungsten was used for the material of the collimator.

3.1 Beam–gas losses in the straight section of the IR1

The results of the background simulation due to the beam–gas losses in the straight section of the IR1 are given in the Figure 2 using the same representation as for the Figure 1. The solid curves on the plots give the calculated distribution of hadrons and muons for the case of the operation with the current of 0.01 A without the collimators [2] and the dashed ones with

[2] The same curves as on the Figure 2.

Parameter	Description
LHC Beam	Beam 1
Number of the collimators	Two, between D2 and TAN
Position from the IP1	Vertical at 146 m (center) and horizontal at 148 m
Geometry of the jaw	1000×80×25mm (length×width×depth)
Material of the jaw	Tungsten
Position w.r.t. the beam	Parallel, at the angle of 1.12 mrad
Distance from the jaw to the beam	13.5 $\sigma_{(x,y)}$ at 7 TeV
Distance in X	12.1 mm
Distance in Y	7.4 mm

Table 3: Parameters of the collimators used in the simulation.

the collimators in the place. Since the introduction of the collimators between D2 and TAN does not affect the background formation due to the losses in the downstream sections only the beam–gas interactions in the Q7–D2 region of the IR1 were simulated in this model. In this case the difference between the values from the Figure 2 calculated for the background produced in the losses along the TAN length with and without TCTs gives the estimation of statistical error of the simulation.

As can be seen from the plots the introduction of the collimator jaws at the relatively large distance of 13.5 $\sigma_{(x,y)}$ from the beam already leads to a slight increase of the background fluxes at the entrance to the UX15 cavern. The observed increase of the background is larger for muons than for hadrons since most of the hadrons are produced in straight section due to the beam–gas interactions on the length of the inner triplet where the background conditions are not changed by the new collimators. Absolute values of the particle fluxes for two studied cases and different sections of the IR1 obtained by the sum of the numbers from the Figure 2 as well as their relative ratio are summarized in Table 4. The F_1 value in this table gives the numbers from the previous Table 2 for the $I = 0.01$ A case which are considered the baseline for the comparison. The F_2 and F_3 values give the fraction of the background fluxes produced due to the beam–gas interactions on the length of the two chosen sections of the IR1 straight section without tertiary collimators [3]. The F_4 value gives the flux of hadrons and muons observed at the UX15 entrance due to the beam–gas interactions in the Q7–D2 region in the presence of the TCTs. Comparison of the F_3 and F_4 numbers gives the increase of the flux which is reflected in the F_5 value as the sum of the unaffected F_2 and affected F_4 fractions of the background flux values.

Although for both hadrons and muons the introduction of tertiary collimators nearly doubles the background produced in the straight section region upstream of beam 1, for hadrons the total increase appears to be at a level of about 7 % because of the relatively low initial contribution of this section to the total hadron flux. For the muons the observed increase is significantly larger and amounts to ∼1/3 of the total flux. This fact can be interpreted as the result of additional contribution from the interactions of the particles with

[3] Note that the F_2 value appears twice in Table 4 since the TCTs do not affect the losses on the residual gas in the D2–Q1 region of the straight section.

the material of the jaws to the parent $\pi^{\pm}$ and $K^{\pm}$ flux, taking into account the downstream long drift space between TAN and D1 for particle decay to muons.

		Hadrons		Muons	
		F_{h_i}	F_{h_i}/F_{h_1}	F_{m_i}	F_{m_i}/F_{m_1}
Total from Q7–Q1 no TCT	F_1	2066.3	100 %	48.9	100 %
D2–Q1 with/no TCT	F_2	1891.1	92 %	28.3	58 %
Q7–D2 no TCT	F_3	175.2	8 %	20.6	42 %
D2–Q1 with/no TCT	F_2	1891.1	92 %	28.3	58 %
Q7–D2 with TCT	F_4	313.0	15 %	37.9	77 %
Total from Q7–Q1 with TCT	F_5	2204.1	107 %	66.1	135 %
Sectors 78–81 with TCT	F_6	1130.9	55 %	183.1	374 %

Table 4: Absolute and relative values for the particle fluxes [particles/s] at the UX15 entrance due to the losses in the straight section of IR1 and two upstream sectors of the LHC with and without tertiary collimators.

3.2 Background contribution from the LHC cold sections

Another source of the machine induced background in the IR1 which will be affected by the introduction of tertiary collimators are the protons produced in elastic scattering on residual gas in the sectors 78 and 81 of the LHC with the subsequent transport of such *quasi-beam* halo particles to the point of their interaction with the material in the straight section of the IR1 [1]. The main region of experimental insertion where these elastically scattered protons interact with the material is the high–β "bottleneck" of the inner triplet [14]. It can be presumed that some portion of this background source will also be stopped by the new collimators since the protection of superconducting triplets from the beam halo is one of the goals for the introduction of the TCTs [6]. To evaluate this effect the two-staged approach to the simulation of the background from the "distant" elastic proton losses on the residual gas was used [15]. According to this approach the source of the particles from elastic proton–nucleus collisions simulated on the length of the two sectors of the LHC was taken for subsequent transport and simulation of secondary cascades through the structure of IR1 with the TCTs installed.

The estimation of absolute values for the background fluxes with TCTs requires an estimate for the residual gas pressure in the cold arcs of the LHC. This number can be derived from the existing value of 3.7×10^{12} mol/m^3 for the gas density $n_{<H_2>}$ in the cryogenic elements of the straight section from the Table 1 using a somewhat pessimistic assumption without accounting for the cryo-pumping [16]. The flux of the synchrotron radiation which defines the photon induced gas desorption is estimated to be 10 times higher in the cold arcs than in straight sections with its critical energy also 3 times larger [17]. Since it can be assumed that the photon induced gas desorption yields scale approximately with the critical energy [18] this gives a total factor of 30 for the estimation of the difference between the gas pressure in the arcs and straight sections and the resulting value of 1.11×10^{14} mol/m^3 for the estimate of $n_{<H_2>}$ gas density in the LHC cold sections. The absolute and relative values for the background fluxes calculated using this value for the gas density are given for hadrons and muons as F_6 value in Table 4. The observed contribution to the flux of hadrons is larger than from the Q7–D2 region of the straight section upstream from the collimators and amounts to a 1/2 increase in the total hadron flux. The effect of the additional cascades created by the TCTs to the muons flux is much larger and resulting background flux is more then 3 times higher than from the losses in straight section without collimators.

The comparison of obtained estimations for the particle fluxes with the earlier simulations [1] showed that up to 90 % of the protons out-scattered in the sectors 78 and 81 from the beam which were previously lost on the limiting apertures of the IR1 are now intercepted by tertiary collimators. The resulting cascades that are initiated in the material of the collimator jaws become the additional source of $\pi^{\pm}$ and $K^{\pm}$ flux which then decay to muons in the downstream drift space. The radial distribution of charged hadrons and muons flux from this source at the entrance to the UX15 cavern is given in the Figure 3 in comparison with the background fluxes from the losses in the left part of straight section SS1. As can be seen from the plots, the maximum of the observed difference between the muon fluxes from two studied sources is obtained at the distance from the beam line above the outer radius of the UX15 inner shielding fixed tube where the secondary particles are attenuated only by the concrete layer. The corresponding spectra of charged hadrons and muons are given in the Figure 4. The muon spectrum for the losses in the sectors 78 and 81 is peaked in the region of ~ 10 GeV that can be explained by the fact that it is formed by the particles which are produced in the first generations of the cascade and hence have relatively high energies. This distribution can be compared with the typical muon spectrum from the beam–gas losses in experimental straight section which is peaked at 1 GeV [19]. Thus this first estimation of the background flux in the LHC high luminosity insertion from the proton losses in the cold sectors of the machine in the presence of tertiary collimators gives an indication that the TCTs can effectively intercept the component of the beam halo produced in the upstream cold sections of the machine and convert it in a more penetrating muon background. Under the assumptions on the residual gas pressure in these cold sections used above this muon flux can become the dominant machine induced background component in the insertion.

Conclusion

A numerical simulation was performed for the formation of the machine induced background in the high luminosity experimental insertion of the LHC for two cases of the machine start–up, with the current of 0.01 A and with 1/3 of nominal current. The results show the values for the background fluxes a factor of $\sim 10^3$ lower than previously estimated values [1] in the case of the beam current of 0.01 A, but with a current of 1/3 of nominal 20 % higher for muons and 70 % higher for hadrons. The background fluxes for the case of the start–up with 156 bunches can be estimated as $\sim$ 10 times higher than for the current of 0.01 A taking into account the difference in residual gas pressure and the value of the current. The relative effect on the background in the insertion for the introduction of tertiary collimators on the incoming LHC beam upstream from the interaction point has been estimated. It was found that the presence of the new TCT collimators removes a significant fraction of the proton halo produced in the upstream LHC sectors. The resulting muon flux becomes the dominant component of muon background produced in experimental insertion.

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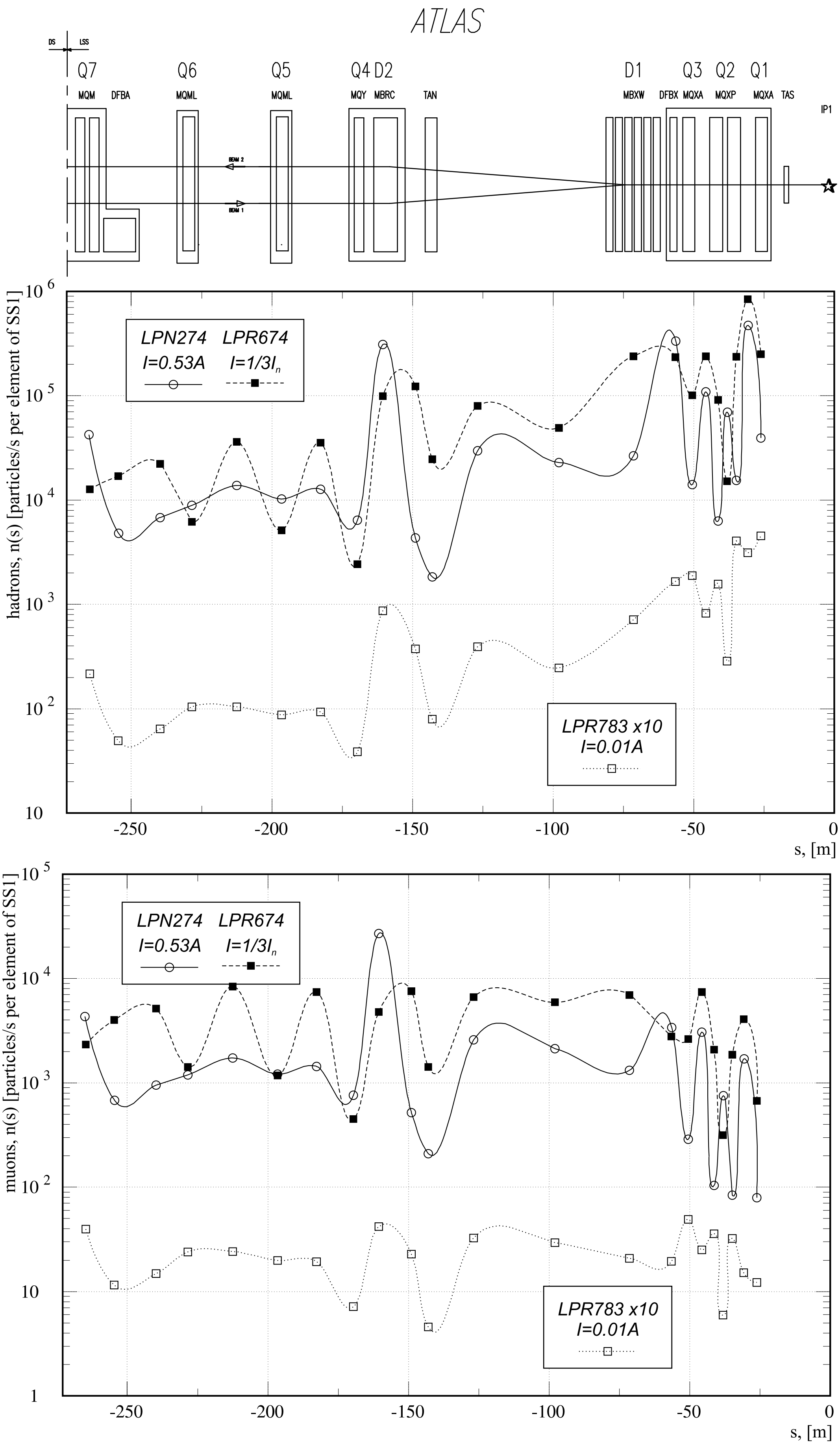

Figure 1: Flux of hadrons and muons [particles/s per element of SS1] at the UX15 entrance as a function of primary interaction distance to the IP1 for three considered periods of the machine operation.

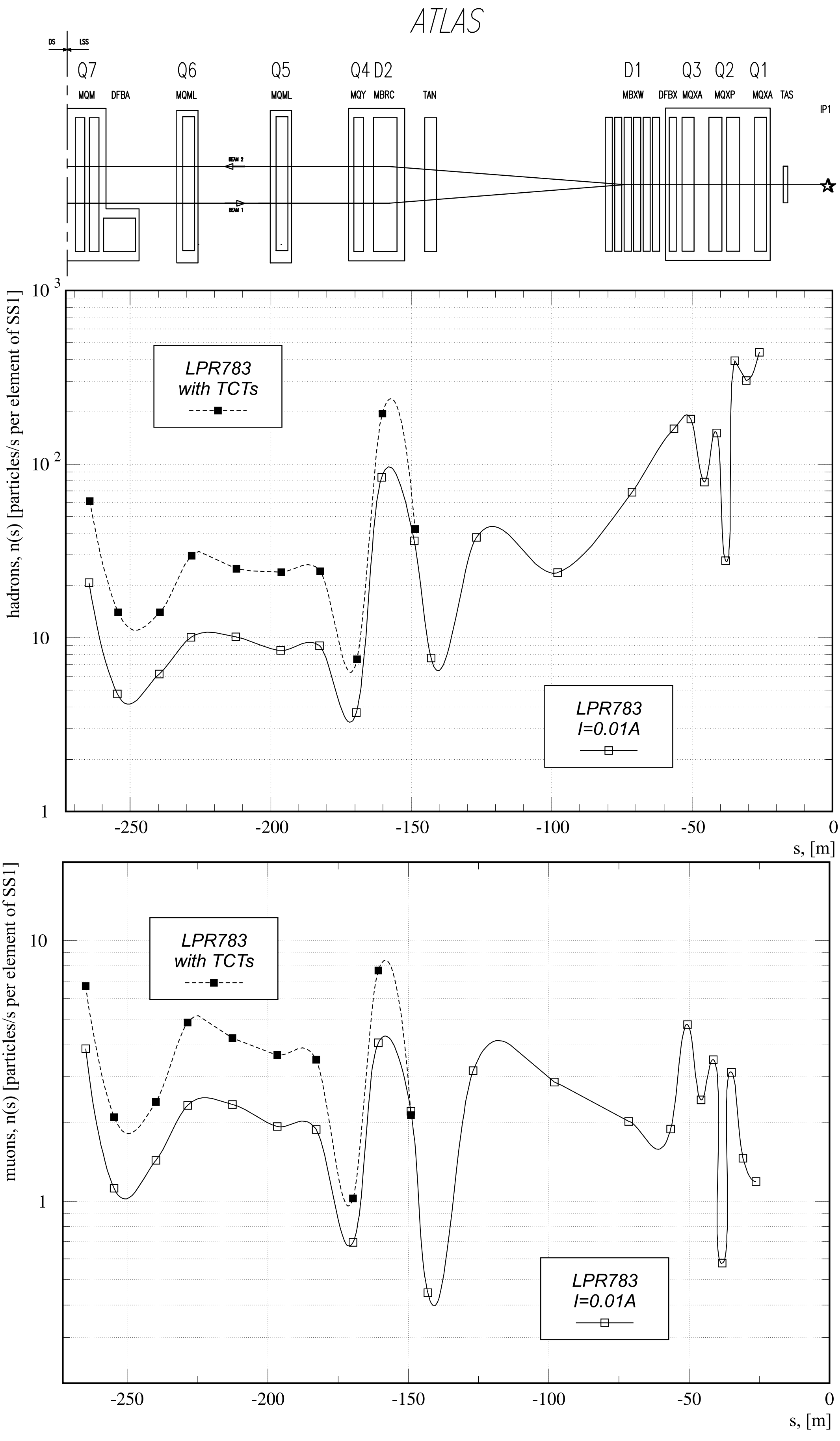

Figure 2: Flux of hadrons and muons [particles/s per element of SS1] at the UX15 entrance as a function of primary interaction distance to the IP1 for the machine start-up with and without collimators in IR1.

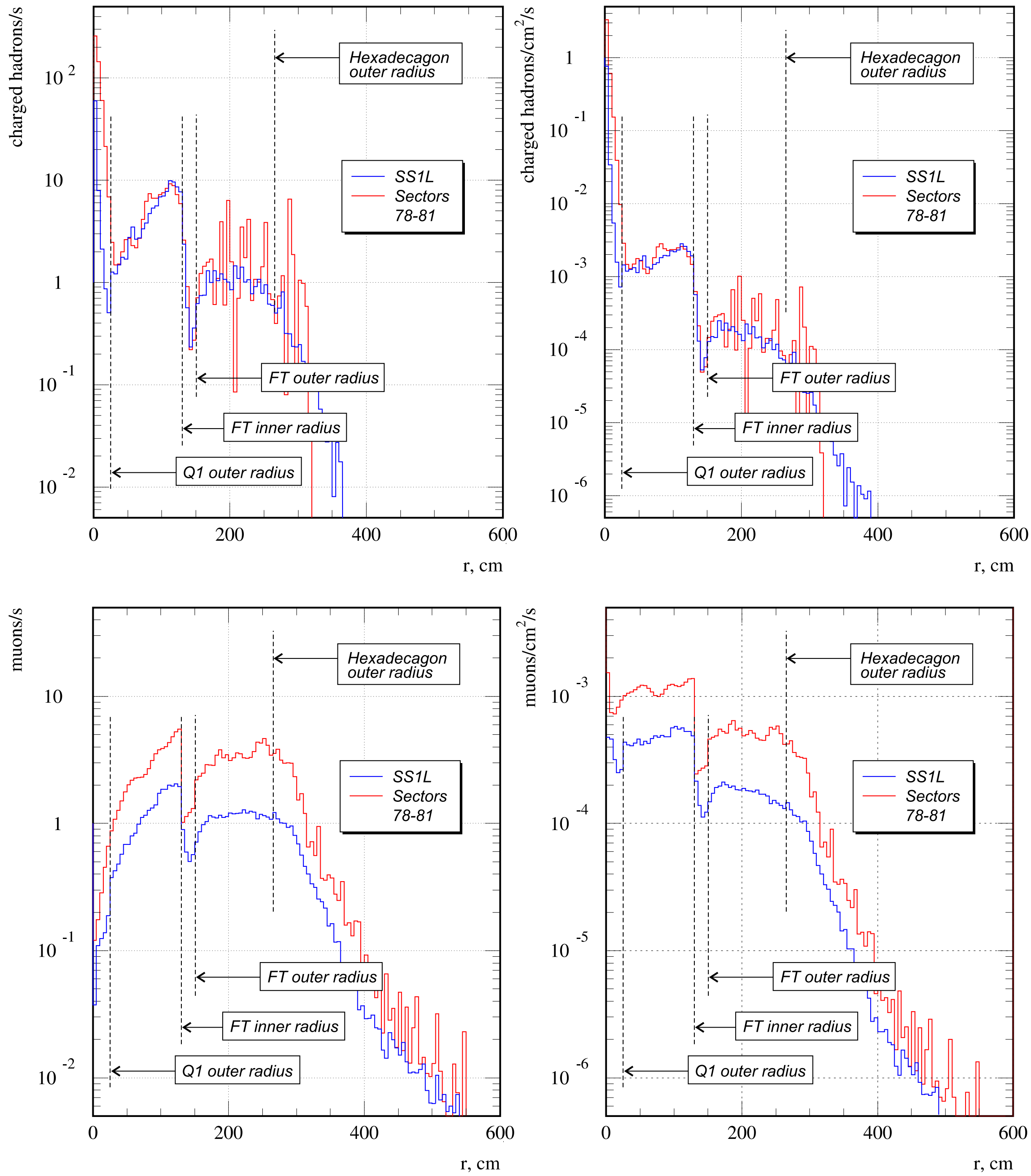

Figure 3: Charged hadrons and muons flux [particles/s] and flux density [particles/cm^2/s] at the UX15 entrance due to the beam–gas losses in the SS1L (blue) and sectors 78-81 of the LHC (red) with two tertiary collimators located between the D2 and TAN for the case of the machine start-up with the beam current of 0.01 A.

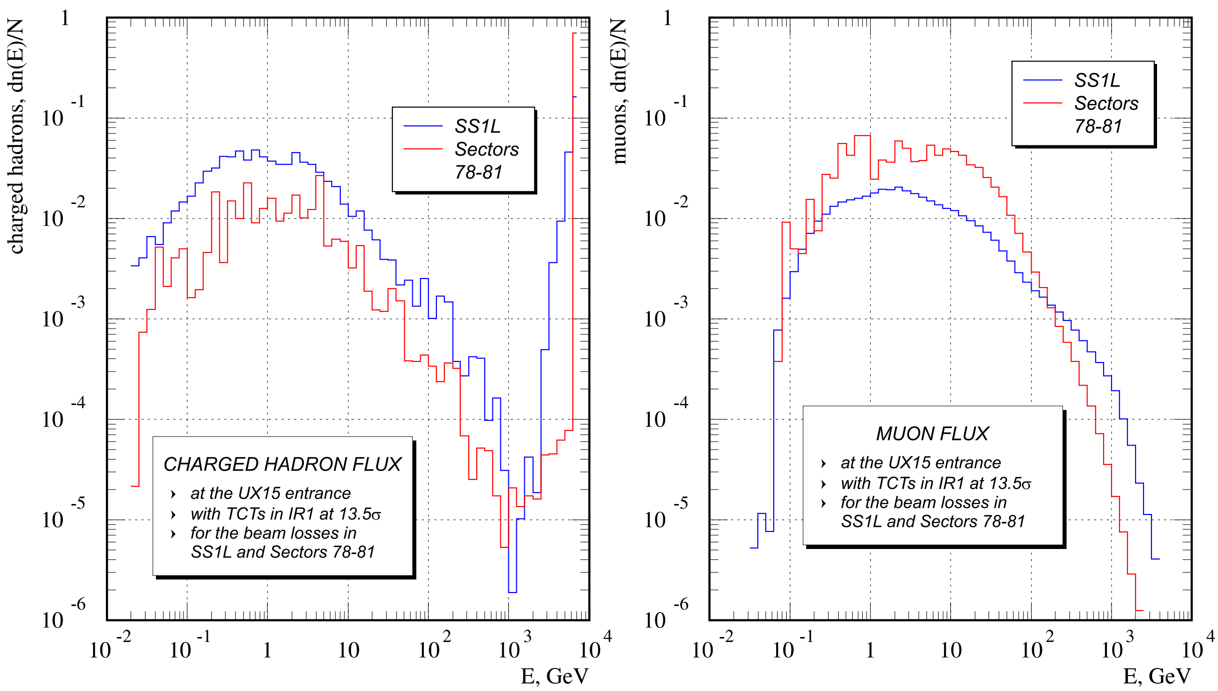

Figure 4: Spectra of the charged hadrons and muons, generated in the IR1 due to the proton losses along the beam 1 in the SS1L (blue) and two upstream sectors 78-81 of the LHC (red) with two tertiary collimators located between the D2 and TAN for the case of the machine start-up with the beam current of 0.01 A.