

STUDY OF BEAM-GAS INTERACTIONS AT THE LHC FOR THE PHYSICS BEYOND COLLIDERS FIXED-TARGET STUDY

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Abstract

Among several working groups formed in the framework of the Physics Beyond Colliders study, launched at CERN in September 2016, there is one investigating specific fixed-target experiment proposals. Of particular interest is the study of high-density unpolarized or polarized gas targets to be installed in the LHC, upstream of the LHCb detector, using storage cells to enhance the target density. This work studies the impact of the interactions of 7 TeV proton beams with such gas targets on the LHC machine in terms of particle losses.

INTRODUCTION

In the framework of the Physics Beyond Collider study program, which investigates new experimental possibilities exploiting the CERN accelerator facilities [1, 2], a working group is studying proposals of fixed-target experiments at the Large Hadron Collider (LHC) [3]. Among them, there is a proposal to install an internal gaseous target adjacent to the LHCb detector at the insertion region (IR) 8. An unpolarized or polarized gas would be injected in a tubular open-ended storage cell (SC) traversed by the beam. Several gas species are under consideration for such an experiment. The SC technology allows enhancing the target density, while preserving the beam pipe vacuum [4], and areal target densities up to 10^{14} atoms/cm² are considered in the design.

The scattering rate of 7 TeV protons on a target with a large areal density might limit the machine availability, since too high beam losses could cause the superconducting magnets to quench. In this work, the beam-gas interaction is simulated and the scattered protons are tracked along the LHC ring in order to compare the local losses with the estimated magnet quench limit. In case the quench limit is exceeded, a restriction is given for the target density in order to assure safe working conditions. This gives important inputs to future design developments for the gas target.

More details on the technical aspects of this work can be found in Ref. [5].

SIMULATION SETUP

The interactions of 7 TeV protons impacting on a gaseous target were sampled with the Monte Carlo code FLUKA [6, 7]. The surviving scattered protons were then tracked with the SixTrack code [8–10] along the LHC lattice. The subsequent interactions of the beam with the collimators were

simulated using the FLUKA coupling to SixTrack [11–13] or built-in scattering models in SixTrack [9]. The energy threshold for tracking was set to 1 TeV, and the tracking stops either when there is no proton from the interaction above this threshold or when a proton hits the machine aperture in other elements than collimators. Simulations with SixTrack and FLUKA have been successfully benchmarked with LHC measurements in previous publications [14–17]. The machine optics was generated with MAD-X [18] for version 1.3 of HL-LHC [19].

Elastic and inelastic beam-gas interactions were studied separately, and H and Xe targets were taken as extreme cases, since all the other considered gas species have an atomic weight in-between. Six million particles were tracked for every simulation.

The position of the gas target was assumed in the interval of 1.5–3 m upstream of the LHCb collision point in the reference system of the clockwise rotating Beam 1. Because of the longitudinal asymmetry of the LHCb detector, the installation is only possible on one side of the experiment. In this way, only Beam 1 can be used for measuring forward products. For the elastic case, only one position of the center of the target was considered (1.69 m from the interaction point, or IP, as the initial design baseline). For the inelastic case, which is potentially more critical in terms of losses, different target positions were simulated in order to check for any dependence of the losses on the target location, taking the extremes at the start and end points of the interval at 1.5 m and at 3.0 m from the IP.

The simulation output gives a map of local proton losses along the beam line, divided into losses on cold magnets, warm magnets, and collimators. The loss maps were analysed by plotting the energy impacting on the machine aperture and collimators as a function of the longitudinal coordinate s , after being normalized to the specific beam-gas interaction rate:

$$R [s^{-1}] = \sigma [cm^2] \times \theta [cm^{-2}] \times I [s^{-1}], \quad (1)$$

where σ is the cross section of 7 TeV protons impacting on the selected target calculated off-line using FLUKA (the bunch energy spread is negligible to this calculation), θ is the target areal density and I the beam current calculated as:

$$I [s^{-1}] = N_b \times n_b \times f_{rev} [s^{-1}] \quad (2)$$

with N_b being the number of protons per bunch, n_b the number of bunches per beam, f_{rev} the beam revolution frequency.

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All the assumed machine parameters are summarized in Table 1. In Table 2 the cross sections and interaction rates are shown, compared with p-p interaction rates during standard physics runs.

The histograms of losses were normalized with respect to the interaction rate, the initial proton energy (7 TeV) and the bin width (10 cm) obtaining loss maps expressed in W/m.

Table 1: Parameters assumed for the calculations. Machine and beam parameters are taken as for HL-LHC, version 1.3.

LHC circumference [m]	26658.8832
primary proton energy [TeV]	7.0
ε_n [μm]	2.5
N_b	2.2×10^{11}
n_b	2760
Beam current [p/s]	6.83×10^{18}
Luminosity at IP8 [$\text{cm}^{-2}\text{s}^{-1}$]	2×10^{33}
IP8 s position (from IP1) [m]	23315.3790
Cold magnet quench limit [W/m]	8.748

Table 2: Elastic and inelastic cross sections, calculated using FLUKA, and interaction rates considered for 7 TeV protons on a H or Xe target with areal density $\theta = 10^{14}$ atoms/cm². The cross sections and event rates for 7 TeV proton-proton collisions at IP8 are also given for comparison. A proton-proton luminosity of 2×10^{33} cm⁻²s⁻¹ is assumed.

		p-H	p-Xe	p-p
Elastic Cross Section	[mb]	9.0	1000	24
Elastic rate	[MHz]	6.1	683	48
Inelastic Cross Section	[mb]	38	1408	80
Inelastic rate	[MHz]	26	962	160

In order to assess the safety of the experimental setup, the recorded losses were compared to the cold magnet quench limit. We assumed the same limit of 5 mW/cm³ that was used during the LHC design, which corresponds to about 7.8×10^6 pm⁻¹s⁻¹ [20]. Multiplied by the beam energy, it gives a limiting power load of 8.75 W/m. It is known today that this quench limit is well on the conservative side, and quench limits measured with beam are a factor ~ 3 higher [15]. Nevertheless, we used the original limit in order to introduce a safety margin in the experimental design and ensure that the presented results stay on the safe side. In the cases where the cold losses were exceeding this limit, the maximum allowed gas density was re-scaled in order to bring the highest loss to the tolerable level.

RESULTS

For the case of the elastic beam-target interactions, the H and the Xe cases are presented in Figs. 1 and 2 for Beam 1. The power lost per meter is plotted as a function of the longitudinal coordinate s , starting from the interaction point (IP) 1.

No worrying losses are recorded in the loss maps, since all the cold magnets stay well below the quench limit. Only very

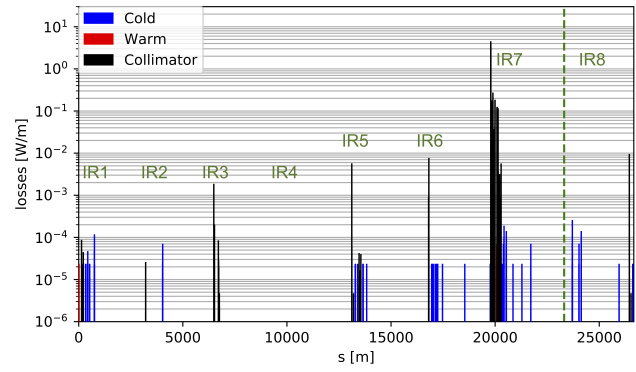


Figure 1: Simulated beam-loss distribution around the LHC, for elastic interactions with a H target with $\theta = 10^{14}$ atoms/cm² at -1.69 m from IP8, marked by a dashed green line. The bin width was set to 10 cm. The maximum cold loss was found to be 2.5×10^{-4} W/m at $s = 23707.6$ m.

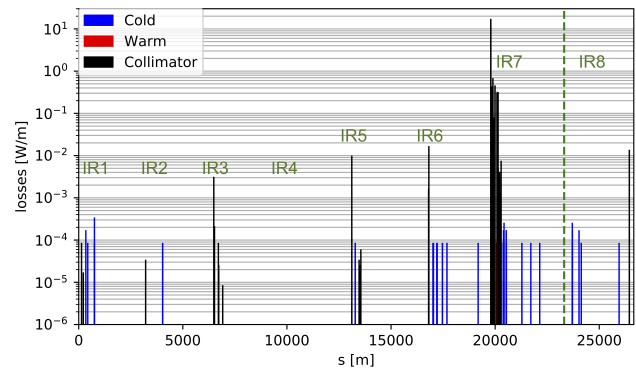


Figure 2: Simulated beam-loss distribution around the LHC, for elastic interactions with a Xe target with $\theta = 10^{14}$ atoms/cm² at -1.69 m from IP8, marked by a dashed green line. The bin width was set to 10 cm. The maximum cold loss was found to be 3.3×10^{-4} W/m at $s = 755.2$ m.

small losses are recorded close to the target position (green dashed line) and only a few losses are in the downstream region, since all the beam protons survive the elastic scattering, with only a minor angular deviation and negligible energy loss. The great majority of the losses are concentrated in the betatron cleaning insertion IR7 (at $s \approx 20000$ m), most of the protons having hit first the primary collimators, which is the behaviour expected for a standard betatron cleaning loss map [14]. In addition to the loss analysis, the effect of emittance blowup and its consequences remains to be studied.

It is more interesting to focus on the inelastic beam-target interaction case, where the deviations in energy and angle are larger. In Fig. 3 the loss map is given for the H target at -1.5 m from the IP, while in Fig. 4 the corresponding Xe case is shown.

Most of the losses are recorded within the target and up to a few hundred meters downstream. Notice the presence of the magenta bars showing the particles lost in the target itself: the great majority of the protons either disintegrate in

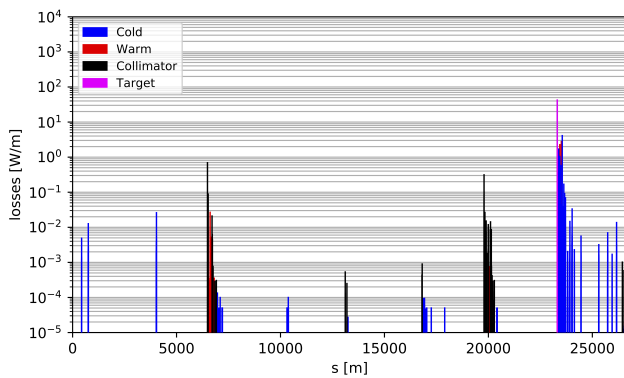


Figure 3: Simulated beam-loss distribution around the LHC, for inelastic interactions with a H target with $\theta = 10^{14}$ atoms/cm² at -1.5 m from IP8. The bin width was set to 10 cm. The maximum cold loss was found to be 4.11 W/m at $s = 23553.4$ m.

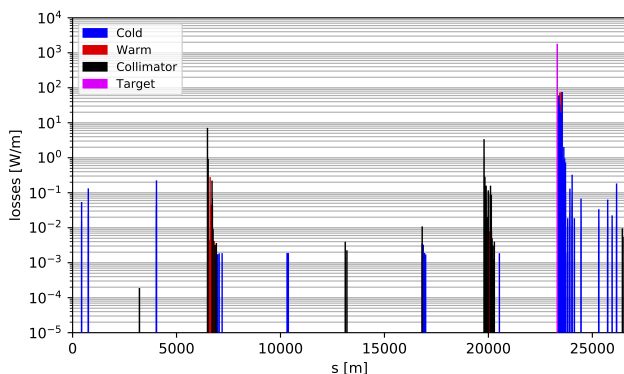


Figure 4: Simulated beam-loss distribution around the LHC, for inelastic interactions with a Xe target with $\theta = 10^{14}$ atoms/cm² at -1.5 m from IP8. The bin width was set to 10 cm. The maximum cold loss was found to be 72.24 W/m at $s = 23553.4$ m.

the inelastic interaction, or survive but have a too low energy to be tracked further.

In this case, the power absorbed is comparable in the momentum cleaning region (IR3, around $s \approx 6700$ m) and the betatron cleaning one, which is due to the wider energy spectrum of the inelastically scattered protons.

Only a very small dependence of the losses on the target location was found for the simulations with the target at -3.0 m from IP8, with differences in the losses of up to a few percent.

For both H and Xe, the counter-clockwise rotating Beam 2 was also simulated and very similar results were found, with the maximum losses being a few percent lower than the Beam 1 case.

While the beam-H interaction produces losses everywhere below the quench limit, the Xe losses exceed it, since the maximum found power load is 72.24 W/m, i.e. about one order of magnitude above the limit. This value was used to determine a safe density for a Xe target to

$\theta_{\max} \approx 10^{13}$ atoms/cm². However, this value is possibly pessimistic, since the highest losses from inelastic interactions are recorded for Beam 1 on an orbit corrector (MCBCH.6R8.B1), for which the quench limit is not well known, but likely higher than for the more sensitive main dipoles. The quadrupole just downstream is likely to intercept a large fraction of the shower, but this magnet is known to have about a factor 2 higher quench limit [15]. Almost as high losses are seen on the separation dipole D1, for which the quench limit is also not well known. Future dedicated energy deposition studies of the most critical impacted region, as well as quench limit studies on the different magnet types, could be used to improve the estimate on the maximum safe gas density. Furthermore, the impact of radiation damage on the most loaded magnets remains to be studied.

CONCLUSIONS

In this work, we presented simulations of the local proton losses on LHC magnets and collimators around the ring, due to the scattering of the 7 TeV proton beam on a fixed gaseous target installed adjacent to the LHCb interaction point. H and Xe targets were considered as limiting cases. Elastic and inelastic interactions were studied separately.

The losses resulting from elastic interactions hit predominantly the betatron collimation system for both gas species, and the leakage on cold magnets is well below the magnet quench limit.

For the inelastic interactions, both Beam 1 and Beam 2 were studied, and simulations were performed using different target positions (-3.0 m and -1.5 m from IP8 in the Beam 1 reference system). The dependence on the target position was found to be very weak. The losses induced by the beam impact on a H target of areal density $\theta = 10^{14}$ atoms/cm² are all below the estimated quench limit and can be considered safe. However, the losses recorded with a Xe target are seen to exceed the assumed quench limit, and the Xe density required to keep the maximum loss below it is less than $\theta_{\max} = 1.21 \times 10^{13}$ atoms/cm². However, since the assumed quench limit is pessimistic and the impacted magnet is not of the most critical type, the found limit could possibly be increased through a future detailed study of the local energy deposition and quench limit.

In addition to the global view of the LHC ring presented in this article, the local energy deposition on the elements closest to the LHCb experiment should be studied. It is hoped the additional protection that will be added in the future to cope with the proton-proton luminosity debris in High Luminosity-LHC (HL-LHC) [21] could be effective also in intercepting the local beam-gas debris, nevertheless, detailed simulations should be carried out to conclude, similarly to what has been done for standard proton-proton operation [22].

The presented results provide an important input to future design developments for the LHC gas targets at IP8 and the associated allowed gas densities.

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