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Estimates of Annual Proton Doses in the LHC

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Summary

Given certain operational assumptions, estimates are made for annual total number of protons lost in the cleaning insertions (IR3 and IR7), the arcs, and the high luminosity insertions (IR1 and IR5) during the first full year of physics, nominal and ultimate LHC running conditions. The results are compared with previous estimates.

1. Introduction

During the LHC operational cycle there are a number of ways in which particles can be lost from the beam. The destination of the lost particles depends on the loss mechanism. This paper enumerates the loss mechanisms and attempts to proportion losses to the various regions of the machine during the LHC cycle. The estimates were originally performed for the cleaning sections but have been extended to cover the arcs and high luminosity insertions. The estimates only attempt to proportion total losses to coarsely defined regions. Detailed analyses elsewhere have simulated the precise spatial distribution of the losses [see, for example, 1,2,3,4,5,6].

Under normal operating conditions the cleaning sections in IR3 and IR7 are designed to provide efficient cleaning of the beam halo during the full LHC beam cycle, such that beam-induced quenches of the super-conducting magnets are avoided during routine operation. They also provide passive protection of the machine aperture against abnormal beam loss and will inevitably receive high particle dose rates.

The principle loss mechanism in the arcs is from collisions with atoms of residual gas molecules. The high luminosity insertions and associated dispersion suppressors receive significant doses from the interaction point collision products.

2. Operation Assumptions

2.1. Overall Operations

The baseline operational assumptions used here are:

- 200 days assigned for running with beam per year. Of this, around 140 days will be for physics, with the remainder used for machine development, machine setup, preventative maintenance etc. [7]. Some of the non-physics time will be with beam (e.g. set-up, scrubbing, and machine development); to make allowance for this non-physics beam time, 160 days of physics running per year are assumed in the estimates presented here.

- 70% operational efficiency. That is, for 70% of the total time assigned for physics running, the machine is available for beam.
- Fill lengths. The optimal fill length depends on the average turnaround time and the luminosity lifetime. In the analysis the fill length is varied between 8 and 20 hours.
- Turnaround. This is the time between consecutive physics coasts and includes the time to ramp down, prepare for injection, inject, ramp & squeeze and prepare stable condition for physics data taking. The absolute minimum turnaround time between physics coasts, taking into account ramp down, preparation, injection, the ramp and squeeze is about 90 minutes. Realistically three hours will be good. In the analysis the turnaround time is varied between three and ten hours.

2.2. Initial conditions

The planned beam intensities and associated parameters for first year, nominal and ultimate operations are shown in table 1. These numbers represent the totals at the start of a physics coast. Here first year refers to the first full year of physics running during which the intensities are expected to be limited.

	No of bunches	Particles/bunch	Total particles/beam	Initial luminosity
First Year	2808	$3 – 4 \times 10^{10}$	1.1×10^{14}	10^{33} cm^{-2}s^{-1}
Nominal	2808	1.15×10^{11}	3.2×10^{14}	10^{34} cm^{-2}s^{-1}
Ultimate	2808	1.67×10^{11}	4.7×10^{14}	2.3×10^{34} cm^{-2}s^{-1}

Table 1: Design beam intensities and initial luminosities.

2.3. Operational cycle

The operational cycle can be broken down into a number of well-defined phases [8]. For each of these phases, an estimate is made of the average expected losses during a routine fill.

- **Injection:** losses will include those from injection oscillations and imperfect RF capture. The beams will be large transversely; there will be relatively low dynamic aperture, full buckets, long range beam-beam, crossing angles and persistent current decay. For these reasons the lifetime is likely to be poor and a 10 hours lifetime will be acceptable.
- **Start ramp:** un-captured beam will be lost immediately.
- **Snapback:** persistent current snapback will cause shift in multipole errors with large potential beam parameter shifts.
- **Ramp:** once past snapback, things should calm down, 10 hour lifetime is assumed.
- **Squeeze:** the change in optics will imply tune, chromaticity, and orbit shifts. Collimator and TCDQ adjustments will be required. Lifetime dips can be expected.
- **Collide**: beam finding and background optimisation will be necessary.
- **Physics**: here the main losses in steady conditions will be collisions, beam-gas, and halo production. Synchrotron radiation damping will help significantly to counter halo production.

The minimum lifetime acceptable during each of these phases has been quantified as input into the collimator design [9]. These are summarised in table 2.

Mode	T[s]	τ [h]	R_{loss} [p/s]	P_{loss} [kW]
Injection	Continuous	1.0	0.8×10^{11}	6
	10	0.1	8.6×10^{11}	63
Ramp	≈1	0.006	1.6×10^{13}	1200
Top energy	continuous	1.0	0.8×10^{11}	97
	10	0.2	4.3×10^{11}	487

Table 2: Minimum acceptable lifetimes during the operational cycle. T is the maximum permitted length of time that a lifetime of τ can be sustained.

Given the acceptable lifetimes and the breakdown of the cycle, a quantitative estimate of the losses at each of the phases during a routine fill has been made. This is shown in table 3.

Phase	Assumptions
Injection	2% total beam lost on IR7 collimators due to transverse injection oscillations. 1% total beam lost on IR3 collimators.
Injection plateau	10 hour lifetime for 20 minutes – mainly transverse losses.
Start ramp	Out of bucket flash, 5% of beam lost in momentum cleaning section. 1 second at around 20 second lifetime.
Start ramp	Snapback – lifetime to 1 hour for 1 minute – transverse losses.
Ramp	20 minutes at 10 hour lifetime.
Squeeze	10 minutes at 1 hour lifetime plus two 10 second dips to 0.2 hour lifetime – transverse losses to IR7 collimators.
Physics	Stable beam with the lifetimes as detailed in section 5 below.

Table 3: Quantitative estimates of losses during routine fill.

2.4. Lost fills

Some attempt is made to take into account a percentage of fills that don't make it into physics, via unsuccessful injection or heavy losses in the ramp or squeeze. These are time consuming and with the associated energy scaling tend to reduce the overall dose rates. This will be true for the duration of LHC operations.

5 to 10% of the total beam time is assumed to be taken by lost fills; the variation coming from the different turn around times used.

3. Beam Loss mechanisms

3.1. Collisions

In physics one of the main contributions to beam lifetime are collisions at the interaction point between counter-rotating protons. Here only the high luminosity insertions are considered: Alice and LHCb make only a minor contribution and are ignored. Collisions can be divided into three types: inelastic, elastic and diffractive. Collisions involving elastic scattering and diffractive events will not be seen by the detectors; only the inelastic scatterings give rise to particles at sufficient high angles with respect to the beam axis. Elastic and diffractive collision products will come down the beam pipe, along with inelastic debris.

Elastically scattered particles receive a kick and subsequently perform betatron oscillations. The destination of the kicked particle depends on the kick amplitude.

- If the scattering angle is small enough, the scattered particle will remain within the machine aperture and, potentially, populate the beam halo. This will contribute to emittance growth.
- Larger amplitude oscillations will cause the particle to be lost at the nearest aperture restriction; this could be the cleaning sections or the tertiary collimators.
- Large angle scattering will lead to quasi-local beam loss in the interaction regions. This contribution will be small and is ignored.

The differential cross section for elastic processes goes as:

$$\frac{d\sigma}{dt} = ae^{-b(t,s,A)|t|} \tag{1}$$

where t is the momentum transfer [$t \approx (p\theta)^2$], s is the centre of mass energy squared, and b is the slope factor which depends on the momentum, momentum transfer and atomic mass of the target nucleus. The variation of b in the momentum range of the LHC is reasonably well established [see, for example, 10]. The mean scattering angle follows from (1):

$$\sqrt{\langle\theta^2\rangle} = \frac{1}{p\sqrt{b}} \tag{2}$$

At 7 TeV, and assuming $b = 18.1$ GeV^{-2}, the mean scattering angle is around 34 μrad. This is comparable with the r.m.s. beam divergence at the IP. Nearly all scattered particles will stay well inside the beam (3σ), and only a small percentage of scattered particles will be pushed directly outside of the beam core. The emittance growth rate can be calculated via [11]:

$$\left(\frac{d\varepsilon}{dt}\right) = \frac{\left(\beta_{1x}^* L_1 + \beta_{2x}^* L_2\right) \cdot \sigma_{el} \cdot \langle\theta_x^2\rangle}{M \cdot N_b} \tag{3}$$

Here β_i^* is the beta function at the *i*th IP; L_i the luminosity; M the number of bunches and N_b the number of particles per bunch. Putting in the standard numbers gives an emittance lifetime of around 87 hours (one degree of freedom). Here we are interested in particle loss, and the contribution of this emittance growth to the beam lifetime. Making some crude assumptions, using

$$\frac{1}{\varepsilon}\frac{d\varepsilon}{dt} = \frac{2}{\sigma}\frac{d\sigma}{dt}$$

and taking an aperture limit of 6σ, the emittance growth gives a beam life time of around 310 hours. The assumption is made that the associated losses take place on the betatron collimators and that the growth is not damped by synchrotron radiation (more below on emittance growth in general).

Diffractive events, depending on the momentum transfer, will lead to quasi-local losses in the neighbouring straight sections and dispersion suppressors, or, for particles which remain within the immediate momentum acceptance of the ring, losses in the momentum cleaning section. Following [6] it is assumed that if $\delta p < 0.01$ the particles are lost in IR3; particle with $0.01 < \delta p < 0.25$ are lost downstream of the TAN; particles with $\delta p > 0.25$ are assumed lost in the TAN.

The total proton-proton cross section (σ_{tot}) at 7 TeV is approximately 110 mbarns. This total can be broken down in contributions from inelastic, elastic and diffractive events as shown in table 4.

Collision type	Momentum transfer	Cross-section [mb]	Destination
Inelastic		60	IR: triplet, D1, TAN, TAS, Expts.
Single Diffractive	$0.01 < \delta p < 0.25$	2.4	Downstream of TAN
Single Diffractive	$\delta p < 0.01$	9.6	Momentum cleaning
Elastic		40	Emittance blow-up → IR7

Table 4: Proton-proton scattering cross-sections, 7 TeV on 7 TeV.

The rate of loss of particles from one beam at one IP due to p-p collisions is given by:

$$\frac{dN}{dt} = L \cdot \sigma_{pp} \tag{4}$$

where σ_{pp} takes into account the fact that the elastic contribution is not lost immediately. The evolution of beam population follows (assuming equal beams):

$$N_b = N_0 \left(\frac{1}{1 + t / \tau_N} \right)$$

where the beam lifetime due to collisions is given by:

$$\tau_N = \frac{N_0}{L_0 \sigma_{pp}}$$

where τ_N is the beam halving time. This will be combined with other contributions to the overall lifetime below.

3.2. Scattering on Residual Gas

Scattering on the residual gas molecules (mostly H, C, O from H_2, CO, CO_2, CH_4, H_2O) can be broken down into the following components:

3.2.1. Coulomb Scattering [Rutherford]

Particles are scattered at point-like Coulomb field of the nucleus of the residual gas atom (scattering from electrons is totally negligible). The particles are transversely deflected, increasing the betatron amplitude. This is a small effect at LHC energies.

3.2.2. Multiple Coulomb scattering

Multiple Coulomb scattering at 7 TeV causes minimal emittance growth with an emittance lifetime of 500 hours with H_2 density compatible with 100 hours lifetime to nuclear scattering [13].

3.2.3. Proton-Nucleus scattering

Proton-nucleus scattering can be broken down into the following possibilities:

- **Inelastic:** i.e. there is a nuclear interaction between the incident proton and a nucleus of a gas molecule. Secondary particles are swept out by the magnetic field and energy dissipated locally within ~15 m of the collision [14]. These processes give losses all around ring which are dependent on the local gas density and composition.

- **Elastic:** depending on the scattering angle, the incident proton can, again, do a variety of things.
  - Small angle scattering leads to emittance growth,
  - Scattered particles with a betatron amplitude larger than the acceptance of the collimator system will be lost in betatron cleaning sections,
  - Larger angle scattering will lead to quasi-local losses on the physical aperture.
- There is lower probability for **diffractive** scattering

The limiting case, in terms of atomic masses, is proton-proton scattering. This is applicable to hydrogen atoms, in particular, those of H_2. The cross-sections for the various possibilities are shown in table 5.

Incident proton energy [GeV]	**Centre of mass energy [GeV]**	σ_{pp}^{tot}	σ_{pp}^{el}	σ_{pp}^{SD}
7000	114.6	~46.9 mb	~8 mb	~5.2 mb
450	29.1	~40 mb	~7 mb	~3.3 mb

Table 5: Proton-proton scattering cross-sections

From table 5 we see that beam gas scattering is dominated by inelastic scattering (~70% at 7 TeV). For the elastic component, using equation (1) and taking b = 13.6 GeV^{-2} at a centre of mass energy of 114.6 GeV, the mean scattering angle of a 7 TeV proton from a proton at rest is around 4.7 mrad in the centre of mass system. In the fixed target system this translates to an average kick of around 40 μrad.

As for the elastic collisions at the IP, the elastically scattered protons can: remain within the beam core; scatter into the beam halo; or scatter directly into the beam pipe. In the arcs, at 7 TeV, the aperture is relatively large and, with a <β> of around 110 m., roughly 70% of the scattered protons might be expected to stay within the machine aperture. For those scattered outside 6σ this will only be until they encounter the next aperture restriction, be it the collimators, the high luminosity IRs or indeed the low luminosity IRs or the TCDQ etc.

Here it is assumed that, at 7 TeV, 50% of elastically scattered particles are lost locally; 25% make their way to the cleaning sections and 25 % make their way to the high luminosity IRs where they are lost on the tertiary collimators. A more detailed analysis would be required to refine these numbers – an interesting future exercise.

With H_2 expected to dominate, the above figures are generally applicable and in any case there is higher angle scattering off of the more massive nuclei. The diffractive component is similarly assumed to behave similarly.

Proton-Nucleus scattering is somewhat more complicated and includes the following possibilities [10]: inelastic scattering with the whole nucleus; elastic coherent scattering with nucleus; elastic scattering with one of nucleons inside the nucleus; and single diffractive diffusion between the incoming proton and a nucleon. The total cross section is the sum of the various effects

The cross section components vary with atomic mass and the centre of mass energy (√s) as do the differential cross sections. Various scaling laws exist to scale with atomic mass and s to calculate the required cross sections. The total cross section scales with atomic mass A as: $\sigma(A) \approx \sigma \cdot A^{0.77}$ with the inelastic scattering going as $\sigma_{in}(A) \approx \sigma_{in} \cdot A^{0.71}$. It can be seen that inelastic scattering continues to dominate.

For a molecule one simply sums the cross-sections of the component atoms. It is expected, after conditioning that the gas composition will contain less than 5% CO and CO_2 molecules and it will be dominated by H_2, the cross-sections of which are simply twice those of shown in table 5. The design lifetime due to beam gas is 100 hours [15] where

$$\frac{1}{\tau_{BG}} = c \sum_{i \in gases} \sigma_i n_i$$

In this study, hydrogen is assumed to dominate with the higher angle elastic scattering of off heavier nuclei taken somewhat in account in the percentage of protons assumed to be lost locally.

For the estimates here the contributions from the 100 hours beam gas lifetime are assumed to be distributed evenly between the arcs and the dispersion suppressors and IRs in proportion to the length of the respective regions. However, gas densities in the IRs will, in general, be less than the arcs. Detailed analysis of the pressure variation expected in the insertion regions has been performed [16]. For example, the average residual gas density (H_2 equivalent) is estimated to be around 5.3 10^{12} molecules.m^{-3} in IR1 and IR5 under nominal physics conditions after machine conditioning. Reasonably conservative estimates for IR3 assume 2.0 10^{13} molecules.m^{-3} [17] and a resulting beam-gas interaction rate of 1.6 10^{10} interaction per metre per year in both rings (to be compared with the estimates presented below for the arcs).

These figures are considerably less than the H_2 equivalent of 9.8 10^{15} molecules.m^{-3} quoted for the 100 hour lifetime. For the purposes of these estimates, the contributions to beam gas in the IRs are ignored.

Lower beam gas lifetimes will, of course, for a given beam current, increase the loss rates. In the IRs, for example, the average density will be an order of magnitude higher before conditioning [16].

3.2.4. Injection

At injection there is also an expected beam-gas lifetime of 100 hours to nuclear scattering; we assume the total cross section leads exclusively to local losses.

Emittance growth at injection from multiple Coulomb scattering will also be present [13] with a transverse emittance growth rate of 17 hours for a density of hydrogen compatible with a 100 hours lifetime.

3.3. Intra Beam and Touschek scattering

Intra Beam Scattering (IBS) is the Coulomb scattering of one particle by another within a bunch. Multiple small-angle Coulomb scattering causes transverse and longitudinal emittance growth. This is usually a small contribution to single beam lifetime but does enter in the luminosity via the increase in beam size at the interaction points.

If the energy change in a single scattering is large enough to shift the particle outside the momentum aperture the particle is lost; this is the Touschek effect. Again this is a relatively small contribution to the single beam lifetime but it is included below.

3.4. Other Loss Mechanisms

Short lifetimes will also arise from, for example: operator error, resonances, beam instabilities and the many parameter control challenges (persistent currents etc.). Some attempt to take these into account is made in the approach to physics. Problems in these areas under physics conditions will probably be punished by a beam dump.

3.5. Emittance growth mechanisms

There are a number of effects which will, or potentially can, lead to emittance growth. The effect of this emittance growth is two-fold: firstly it pushes particles out to the dynamic or physical aperture with a contribution to the beam lifetime via eventual loss on in the collimation systems; secondly, in physics, it leads to a drop in luminosity because of the associated beam size increase at the interaction points. The contribution to the single beam lifetime from emittance growth is generally small and an emittance lifetime of 60 hours, for example, gives a beam lifetime contribution in the order of 400 hours. Emittance growth mechanisms include [15]:

- Elastic scattering at the interaction points,
- Elastic scattering from residual gas,
- Intra-beam scattering,
- Non-linear resonances,
- Electron cloud,
- Noise, for example, power supplies, phase and amplitude noise in the RF system, ground motion,
- Long range beam-beam.

The emittance goes as: $\varepsilon_x = \varepsilon_x^0 e^{\frac{t}{\tau_x}}$ where τ_x is the combined transverse emittance growth rate. Synchrotron radiation damping is a significant effect at 7 TeV and provides damping at the rates shown in table 6 [15].

	Growth rate[hours] 450 GeV	Growth rate [hours] 7 TeV
Residual gas – multiple Coulomb scattering	~17	≈500
Residual gas – elastic scattering	-	87
Transverse IBS	38	80
Longitudinal IBS	30	61
Long range beam-beam		Cuts in above 6σ [12]
Longitudinal emittance damping	-	-13
Transverse emittance damping	-	-26

Table 6: Emittance growth rates at 450 GeV and 7 TeV

3.5.1. Emittance growth - assumptions

Following [13] we make the assumption that emittance growth to IBS, long range beam-beam and noise is negated by synchrotron radiation damping. We assume, however, that emittance growth from collisions takes place, and beam is lost eventually on betatron collimators. Thus in the estimates presented here the assumptions are:

- Transverse damping takes out the effect of IBS, long range beam-beam and noise.
- A transverse emittance growth of 87 hours due to elastic collisions at the IPs.
- Longitudinal damping takes out the effect of longitudinal IBS
- A longitudinal lifetime of 400 hours to allow for possible effects of RF noise etc
- Elastic scattering from rest gas leads to local losses or quasi-local losses (for example in the collimator systems).

4. Beam Loss: where?

Having identified the various loss mechanisms, the expected locations of the losses are enumerated.

4.1. IR7: Collimators & Dispersion Suppressors (Q12.L to Q12R – 981m)

IR7 will receive beam loss contributions from:

- Residual gas
- Particles which diffuse transversely out to around 6σ for the variety of reasons outlined above and are incident on the collimators. Showers produced by the interaction of protons in the collimation system will lead to substantial radiation doses in the down stream magnets [4].
- Abnormal losses such as dump kicker misfires etc.

4.2. IR3: Collimators & Dispersion Suppressors (Q12.L to Q12R – 981m)

IR3 will receive contributions from:

- Single diffractive p-p collisions products incident on the collimators. Again, showers produced by the interaction of protons in the collimation system will lead to substantial radiation doses in the down stream magnets.
- Residual gas
- Longitudinal losses on the collimators from:
  - Touschek, IBS
  - RF noise
  - Un-captured particles

4.3. Arcs (Q12L to Q12R → 8*2369.8 m = 18958 m)

Losses in the arcs come from three main sources:

- Beam Gas: inelastic & elastic nuclear scattering,
- Point losses onto beam screen - protons escaping the collimation system,
- Point losses near IR 1 & 5 - inelastic collision fragments and diffractive collision products. The spatial distribution of the losses has been well studied [3].

4.4. IR1 & IR5 Dispersion suppressors: Q8 to Q12 plus dipoles

The dispersion suppressors in IRs 1 and 5 will experience point losses from the high luminosity IPs collision products. Residual gas contributions are also inevitable.

4.5. Interaction regions

The long straight sections (LSS) in 1 & 5 which includes the Matching Section (Q4 to Q7), the triplet (Q1 to Q3), the separation dipoles (D1, D2) and the TAN and TAS will received doses from: inelastic collision fragments, some single diffractive (large $\Delta p/p$) collisions and beam gas.

The tertiary collimators aim to pick up the low level tertiary halo escaping the collimator system in IR7. The collimators will be placed at around 8.5 σ and are expected to receive relatively low dose rates (maximum permitted ~ $2\ 10^6$ protons/second [18]).

4.6. Dump

The quadratic dependence of luminosity on beam current will hopefully mean that most of the beam from most fills should find its way cleanly to the beam dumps.

5. Beam Lifetime in physics

To calculate the amount of beam lost in the various locations during steady physics conditions we need to calculate the single beam lifetime from the combined effects enumerated above and then partition the losses appropriately.

The total luminosity lifetime has contributions from:

- Single beam lifetime due to interactions of the two beams at the IPs
- Reduction in the single beam intensity from other causes (beam gas etc.)
- Emittance change

Combining the effects of collisions, beam gas and emittance growth, the single beam population follows:

$$N_b(t) = N_0 e^{-t/\tau_{gas}} \Bigg/ \left[1 + \frac{1}{\tau_N} \frac{1 - e^{-t\left(\frac{1}{\tau_{gas}} + \frac{1}{2\tau_x} + \frac{1}{2\tau_y}\right)}}{\frac{1}{\tau_{gas}} + \frac{1}{2\tau_x} + \frac{1}{2\tau_y}} \right] \qquad (5)$$

Explicitly splitting out the various components to the lifetime one gets the approximate figures for nominal physics shown in table 7.

Process	Lifetime [hr]	Emittance Growth [h]	Destination
Residual gas - inelastic	129	-	Ring
Residual gas - elastic	459	-	Ring/IR/Coll
Touschek	1250	-	IR3
Collisions - inelastic	108*	-	Low β IR/DS
Collisions – SD I	2697*	-	DS
Collisions – SD II	674*	-	IR3
Collision - elastic	310	44	IR7
IBS transverse	-	80	-
IBS longitudinal	-	61	-
Noise/beam-beam	-	55	-
SR - long	-	-13	-
SR - transverse	-	-26	-

Table7: Single beam lifetime contributions and emittance growth rates in nominal physics.
** indicates approximation to exponential.*

Given the various contributions an estimate is made of the total beam loss per fill due to the various loss mechanisms. (The nominal single beam lifetime, including emittance growth and fitting to an exponential is approximately 40 hours.)

5.1. Beam lifetimes at injection

The time spent at injection is short, or should be, compared with top energy. A 100 hour lifetime is assigned to beam gas; 300 hours to longitudinal effects (IBS etc.) and 25 hours to transverse effects which will include IBS, long range beam-beam, and control of multipole errors. The locations of the losses are distributed between the main ring, IR3 and IR7 as appropriate.

6. Total beam losses per fill

A detailed breakdown for nominal physics and the summary results for first year and ultimate physics are presented.

6.1. Getting to physics

Estimate of total losses before physics based on the assumptions outlined above are shown in table 8.

It's worth noting that, given the somewhat pessimistic assumptions, over 20% of the initially injected beam is lost before the beams are collided. To get nominal intensities into physics means starting at injection with the initial intensities increased by the appropriate amount. Herein initial beam intensity at injection has been increased to give design figures going into physics.

Phase	**IR3**	**IR7**	**RING**
Injection Oscillations - 2% - betatron		8.56×10^{12}	
Injection Oscillations - 1% - momentum	4.28×10^{12}		
Injection - 20 minutes at 10 hours lifetime	8.6×10^{11}	1.0×10^{13}	2.6×10^{12}
Scale total at injection by gamma	$\mathbf{3.3 \times 10^{11}}$	$\mathbf{1.2 \times 10^{12}}$	$\mathbf{1.7 \times 10^{11}}$
Start ramp - at 450 GeV 5% of total	2.0×10^{13}		
Snap back - 2% of total		7.6×10^{12}	
Scale total during snapback by gamma	$\mathbf{7.9 \times 10^{11}}$	$\mathbf{4.9 \times 10^{11}}$	
Ramp - 20 minutes at 10 hours lifetime	9.9×10^{11}	9.2×10^{12}	2.4×10^{12}
Scale total in ramp by gamma/2	$\mathbf{9.9 \times 10^{10}}$	$\mathbf{1.2 \times 10^{12}}$	$\mathbf{3.0 \times 10^{11}}$
Squeeze - 10 minutes at 2 hour lifetime		3.0×10^{13}	
Squeeze - 2*10s at 0.2 hour lifetime		9.2×10^{12}	
TOTAL NUMBER OF PROTONS LOST BEFORE PHYSICS PER FILL			$\mathbf{1.05 \times 10^{14}}$

Table 8: Estimates of the total losses getting to ***nominal*** *physics. The scaled totals are used in the estimates below to give 7 TeV equivalent.*

6.2. In Physics

To estimate the distribution of losses in physics the procedure is:

- Combine the single beam lifetime contributions and emittance growth according to equation (5) to get the beam intensity as a function of time
- For the given fill length calculate the total number of protons lost
- Proportion this total loss to the various loss mechanisms taking into account the contribution to the overall lifetime
- Assign the losses to the specified regions

The results are shown in table 9 for nominal physics.

Fill Length [hours]	**8**	**12**	**15**	**20**
Total beam lost during physics	6.4×10^{13}	8.8×10^{13}	1.0×10^{14}	1.3×10^{14}
Physics - IR7	8.9×10^{12}	1.2×10^{13}	1.4×10^{13}	1.7×10^{13}
Physics - IR3	1.2×10^{13}	1.6×10^{13}	1.9×10^{13}	2.3×10^{13}
Interaction regions [both IPs]	2.5×10^{13}	3.4×10^{13}	4.0×10^{13}	4.9×10^{13}
Main ring	1.5×10^{13}	2.0×10^{13}	2.4×10^{13}	2.9×10^{13}
Dumped	2.6×10^{14}	2.3×10^{14}	2.2×10^{14}	2.0×10^{14}

Table 9: beam loss in various locations, per fill for differing fill lengths.
Nominal physics – one beam.

6.3. Annual totals for nominal physics

The scaled totals from injection, the ramp and the squeeze are added to the figures lost in physics to obtain a total per fill. This total is doubled, where appropriate to give the total for the two beams.

Given the operational assumption outlined above, the totals for a single fill are multiplied by the total number of fills per year to give the totals for an operational year. The results for nominal physics are shown in table 10.

Fill Length + Turn around [hours]	**8 + 3**	**12 + 5**	**15 + 5**	**20 + 10**
Number of fills	233	148	126	80
Total dumped - 1 beam	6.0×10^{16}	3.5×10^{16}	2.8×10^{16}	1.6×10^{16}
Total 2 interaction regions – both beams	1.2×10^{16}	1.0×10^{16}	1.0×10^{16}	7.8×10^{15}
Total Main ring – both beams	7.0×10^{15}	6.1×10^{15}	6.0×10^{15}	4.6×10^{15}
Total IR7 – both beams	2.3×10^{16}	1.6×10^{16}	1.4×10^{16}	9.5×10^{15}
Total IR3 – both beams	6.3×10^{15}	5.5×10^{15}	5.4×10^{15}	4.0×10^{15}

Table 10: Estimate of total beam loss per year during nominal physics operation.

6.4. Annual totals for ultimate physics

The initial bunch currents, luminosities and lifetimes appropriate to ultimate physics are then used in the same procedure. Losses before physics scale up.

Fill Length + Turn around [hours]	**8 + 3**	**12 + 5**	**15 + 5**	**20 + 10**
Total dumped – one beam	8.2×10^{16}	4.6×10^{16}	3.6×10^{16}	2.0×10^{16}
Total 2 interaction regions – both beams	2.6×10^{16}	2.2×10^{16}	2.2×10^{16}	1.6×10^{16}
Total Main Ring – both beams	9.9×10^{15}	8.3×10^{15}	8.1×10^{15}	6.1×10^{15}
Total IR7 – both beams	3.7×10^{16}	2.5×10^{16}	2.3×10^{16}	1.5×10^{16}
Toral IR3 – both beams	1.0×10^{16}	8.7×10^{15}	8.4×10^{15}	6.2×10^{15}

Table 11: Estimate of total beam loss per year during ultimate physics.

6.5. Annual totals for first year

Fill Length + Turn around [hours]	12 + 5	15 + 5	20 + 10
Total dumped – one beam	1.3×10^{16}	1.1×10^{16}	6.3×10^{15}
Total 2 interaction regions – both beam	1.4×10^{15}	1.4×10^{15}	1.1×10^{15}
Total Main Ring – both beams	2.2×10^{15}	2.2×10^{15}	1.8×10^{15}
TOTAL IR7 – both beams	5.2×10^{15}	4.6×10^{15}	3.1×10^{15}
TOTAL IR3 – both beams	1.6×10^{15}	1.6×10^{15}	1.3×10^{15}

Table 12: Estimate of total beam loss per year during the first full year of physics. Given the unlikelihood of fast turnarounds during this period, 8 hour fills with 3 hour turnaround are suppressed.

It's clear that during the first full year of operation that inefficiency is likely to be high with an increased number of lost fills. In this case the annual total would be correspondingly lower.

6.6. Average losses in the arcs

Losses in the arcs can be divided by the total length to given a loss rate per year per metre. These figures are shown in table 12.

Fill Length+ Turnaround [hours]	8 + 3	12 + 5	15 + 5	20 + 10
First Year	1.3×10^{11}	1.2×10^{11}	1.2×10^{11}	9.3×10^{10}
Nominal	3.7×10^{11}	3.2×10^{11}	3.2×10^{11}	2.4×10^{11}
Ultimate	5.2×10^{11}	4.4×10^{11}	4.3×10^{11}	3.2×10^{11}

Table 11: Estimate of loss rates in the arcs [protons per metre per year]

7. Comparison

A comparison is made with "Summary of Design Values, Dose Limits, Interaction Rates etc. for use in estimating Radiological Quantities associated with LHC Operation" by M. Höfert, K. Potter and G.R. Stevenson, which was published in 1995. In the original paper the authors produced two figures. The first figure was for use in radiation or **internal** estimates. The second, cautious, figure was to be used for radiological assessments concerning the **environment**. In table 14 these are labelled Internal and Environment. Shown in comparison are the data for Nominal and Ultimate physics as estimated here.

The totals are in reasonable agreement with 1995 figures. Given the baseline operational assumptions this is not too surprising. The total number of protons going in the interaction regions drops; this due to the more realistic luminosity evolution presented here. Figures for beam dumped and beam into the IR7 collimators are in reasonable agreement. Estimates for IR3 were not performed in 1995.

The figures for losses per metre per year can be compared with the usually quoted figures from [19,20]. There is an increase in the estimated number of protons lost per meter per year in the arcs. This was estimated to be 1.65×10^{11} protons/metre/year. In the most optimistic nominal physics running scenario presented here the figure goes up to 3.7×10^{11} protons/metre/year. (Bear in mind that optimistic for physics means pessimistic when considering accumulated radiation doses.) The higher figures can be almost completely put down to the beam gas lifetime which was assumed to be 250 hours and is now expected to be 100 hours.

It should be stressed that the 8 + 3 scenario represents extremely good running and is unlikely to be achieved within, say, the first three to four years of operation.

Mechanism	**Internal 1995**	**Nominal 2005**	**Environment 1995**	**Ultimate 2005**
Fill pattern	20 + 4	8 + 3	8 + 4	8 + 3
Total beam [one beam]	5.1×10^{16} *	1.0×10^{17} *	8.5×10^{16} *	2.9×10^{17} *
Inelastic interactions [per IP]	5.5×10^{15}	3.0×10^{15}	1.6×10^{16}	6.5×10^{15}
Dumped [one beam]	5.0×10^{16}	6.0×10^{16}	1.0×10^{17}	8.2×10^{16}
IR7 Collimators [both beams]	3.2×10^{16}	2.3×10^{16}	8.0×10^{16}	3.7×10^{16}
IR3 Collimators [both beams]	-	6.3×10^{15}	-	1.0×10^{16}
Main ring (arcs) [both beams]	4.4×10^{15}	7.0×10^{15}	6.8×10^{15}	9.9×10^{15}

*Table 14: Comparison between 1995 results and those presented here. * ramped in 1995, injected 2005. Fill pattern indicates fill length plus turn around time.*

8. Conclusions

The total beam loss per annum has been re-estimated taking into account updated baseline parameters; a more realistic operational year; beam losses before physics; intensity evolution in physics and updated figures for beam-gas lifetime.

The totals are in reasonable agreement with 1995 figures. Given the baseline operational assumptions this is not too surprising. Of note, however, is the increase in the expected dose rates in the arc; this is mainly due the reduction in the assumed beam gas lifetime from 250 to 100 hours. As noted above, the maximum figure presented here represents the outer envelope of operational performance.

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