Estimates of Annual Proton Doses

Mike Lamont AB/OP

Baseline beams

Beam	No. bunches	Protons/bunch	Total Intensity	Emittance [in physics]	Luminosity
Pilot	1	5 – 10 x 10^{9}	5 – 10 x 10^{9}	1 – 3.75 μm	-
Intermediate	12	1.15 x 10^{11}	1.4 x 10^{12}	3.75 μm	-
First Year	2808	3 to 4 x 10^{10}	1.15 x 10^{14}	3.75 μm	10^{33}
Nominal	2808	1.15 x 10^{11}	3.23 x 10^{14}	3.75 μm	10^{34}
Ultimate	2808	1.67 x 10^{11}	4.7 x 10^{14}	3.75 μm	2.3 x 10^{34}
Ions	592	7 x 10^{7}	4.1 x 10^{10}	1.5 μm	10^{27}
Totem	43/156	3 x 10^{10}	1.3/4.4 x 10^{12}	1.0 μm	-

Loss Mechanisms

- **Abnormal (Fast & Ultra fast loss)**
  - **Equipment malfunction etc.**

- **Short lifetimes**
  - **Operator error**
  - **Beam instabilities, resonances**
  - **Parameter control challenges (persistent currents etc.)**

Loss Mechanisms

- **Stable beam**
  - **Transverse**
    - Beam gas
    - Collisions
    - Halo productions:
      - Nonlinearities, long range beam-beam, electron cloud, IBS
  - **Longitudinal**
    - Touschek, RF noise, IBS

Particles can be:

- **Scattered directly out of aperture**
- **Particle pushed to large betatron or momentum amplitude**
  - **lost on physical or dynamic aperture**
- **Emittance growth**
  - **slow push to large betatron or momentum amplitudes**

Beam Gas

→ mostly H, C, O from H_2, CO, CO_2, CH_4 , H_2O

- **Elastic**
  - Scattered at point-like Coulomb field of the nucleus of the residual gas atom
  - Particle transversely deflected, increasing it's betatron amplitude.
  - Also elastic scattering at the electrons - effect is negligible

- **Multiple Coulomb scattering**
  - Emittance growth at injection
  - Negligible effect at 7 TeV

- **Inelastic**
  - Nuclear interaction: 7 TeV proton beam on a fixed target
  - Fragments lost within 10 -15 metres

- **Diffractive**
  - Pomeron exchange

Beam Gas

Cross-sections

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

Inelastic:

Local losses (dominates)

Elastic:

1. small angle scattering – particle stays within beam (6 sigma) - emittance growth

2. mid-range: particle kicked outside 6 sigma but within local aperture

betatron oscillations until aperture limit

3. large: lost locally

Beam Gas - Arcs

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

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

COM 4.7 mrad → ~40 μrad Lab

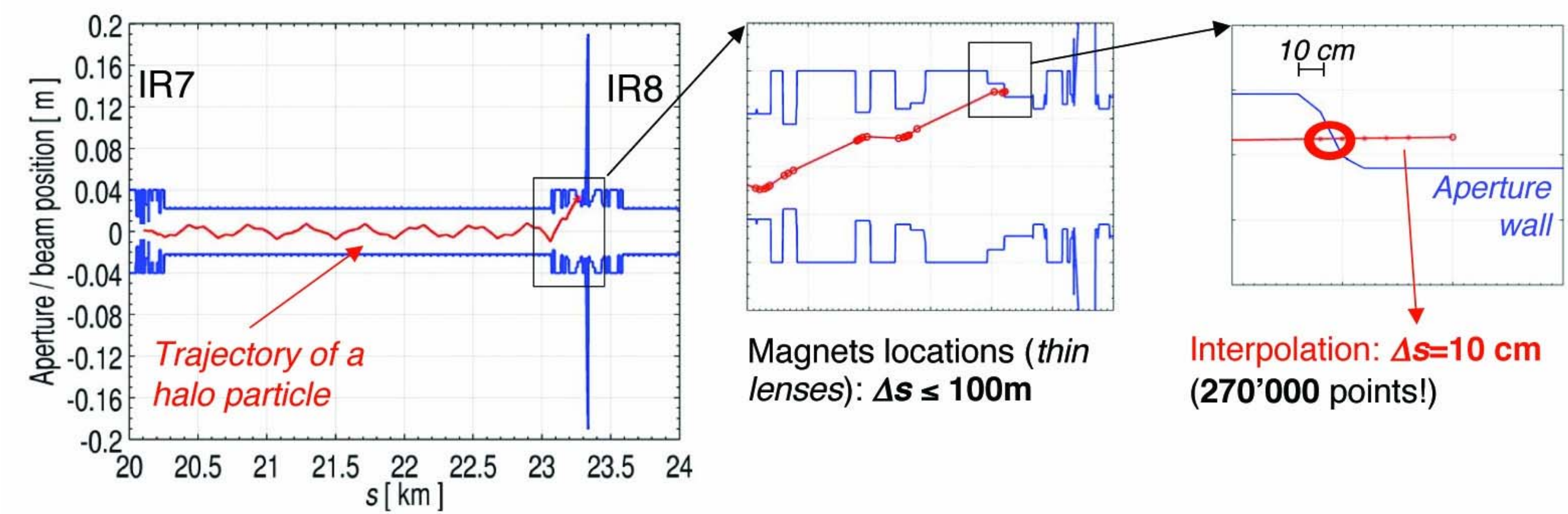
<β> of around 110 m

7 TeV – large arc aperture

roughly 70% of the scattered protons might be expected to stay within the 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


0.2
0.16
0.12
0.08
0.04
0
-0.04
-0.08
-0.12
-0.16
-0.2
Aperture / beam position [m]
IR7
IR8
Trajectory of a halo particle
20
20.5
21
21.5
22
22.5
23
23.5
24
s [km]
Magnets locations (thin lenses): Δs ≤ 100m
10 cm
Aperture wall
Interpolation: Δs=10 cm
(270'000 points!)

c/o Stefano

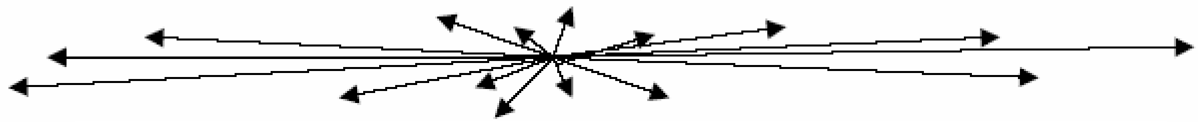
Beam Gas

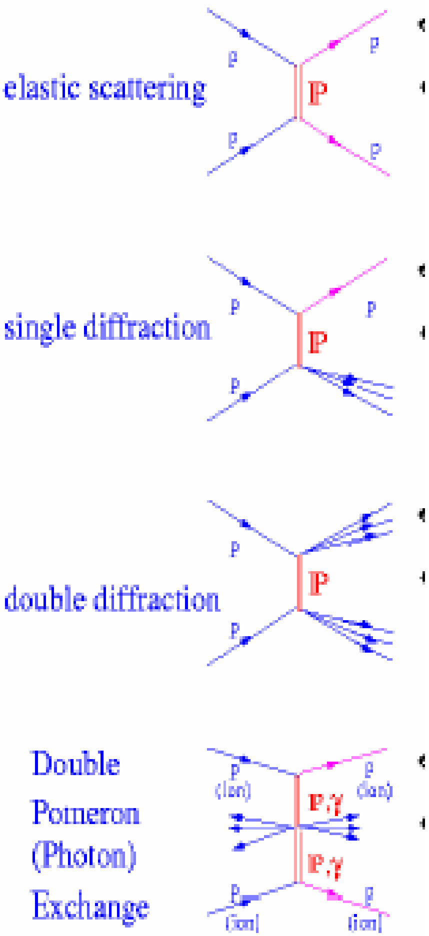
- **τ_{gas} ≈ 100 hours.**

- **Break 100 hours down:**
- **Inelastic component**
  - local
- **Elastic & diffractive**
  - local
  - quasi-local
  - small emittance growth

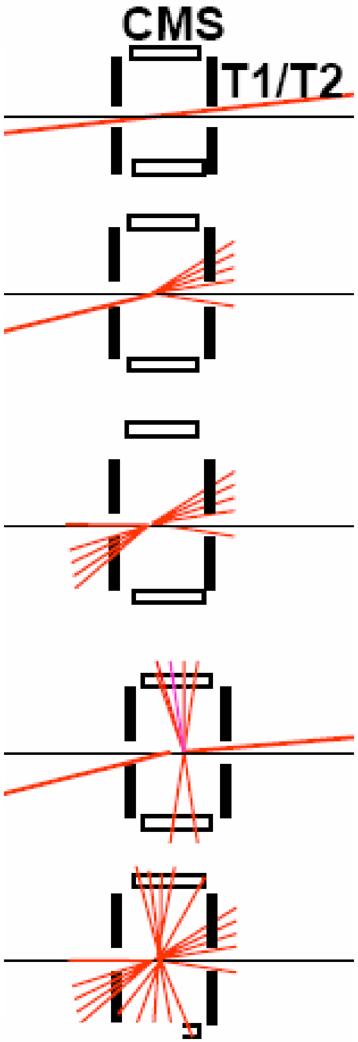
- **450 GeV – all local**

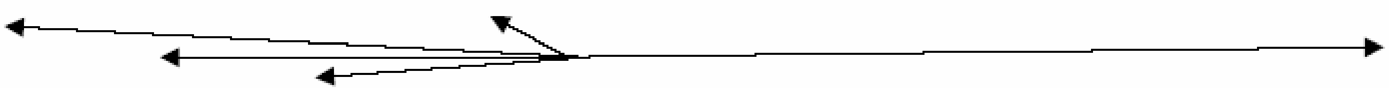
Collisions





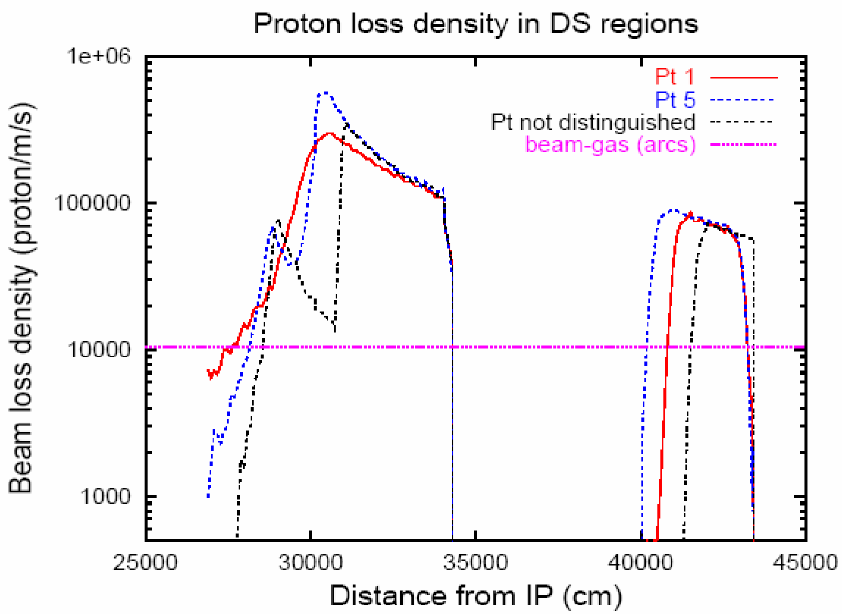
- Total cross-section 110 mbarns
  - Inelastic
  - Single diffractive [el]
  - Single diffractive [inel]
  - Elastic
- SD & elastic come barreling down the beam pipe, along with some inelastic debris





Collisions

Collision	Cross-section	Destination	τ_N [2 IPs]
Inelastic	60 mbarn	IRs [triplet, D1, TAN, TAS]	74.8 hours
Single diffractive	2.4 mbarn	Dispersion Suppressors in IR [$\delta p,min$(0.01) < δp < $\delta p,max$(0.25)]	1869 hours
Single diffractive	9.6 mbarn	Momentum Cleaning	467 hours
Elastic	40 mbarn	ε blow-up	See over



Single beam lifetime from collisions at 10^{34} cm^{-2}s^{-1} with 2 IPs: ≈69 hours

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

See: Fynbo & Stevenson et al

Collisions - elastic

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

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

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

34 μrad

Scattered within beam

Emittance growth

87 hours (one degree of freedom)

beam life time of around 310 hours

Again split out lifetime contributions and assign associated losses with defined regions

Touschek/Intra Beam Scattering

- **Touschek**
  - Coulomb scattering of one particle by another with a bunch
  - If new longitudinal momentum is outside the momentum acceptance, the particles are lost
  - Small contribution but included

- **Intra Beam Scattering**
  - Multiple small-angle Coulomb scattering inside a bunch
  - Longitudinal and transverse emittance growth

Other mechanisms

- Resonances
  - ramp/squeeze – beam parameter control
- Long range beam-beam
  - adds to problems at injection
  - not much of a lifetime problem at 7 TeV, potentially background issue
- RF Noise
- Electron cloud
- Collective instabilities
- Operators

Good news

- Synchrotron radiation damping
  - reasonably significant effect at 7 TeV
  - assume to counter ibs and beam-beam
  - damping times at 7 TeV:

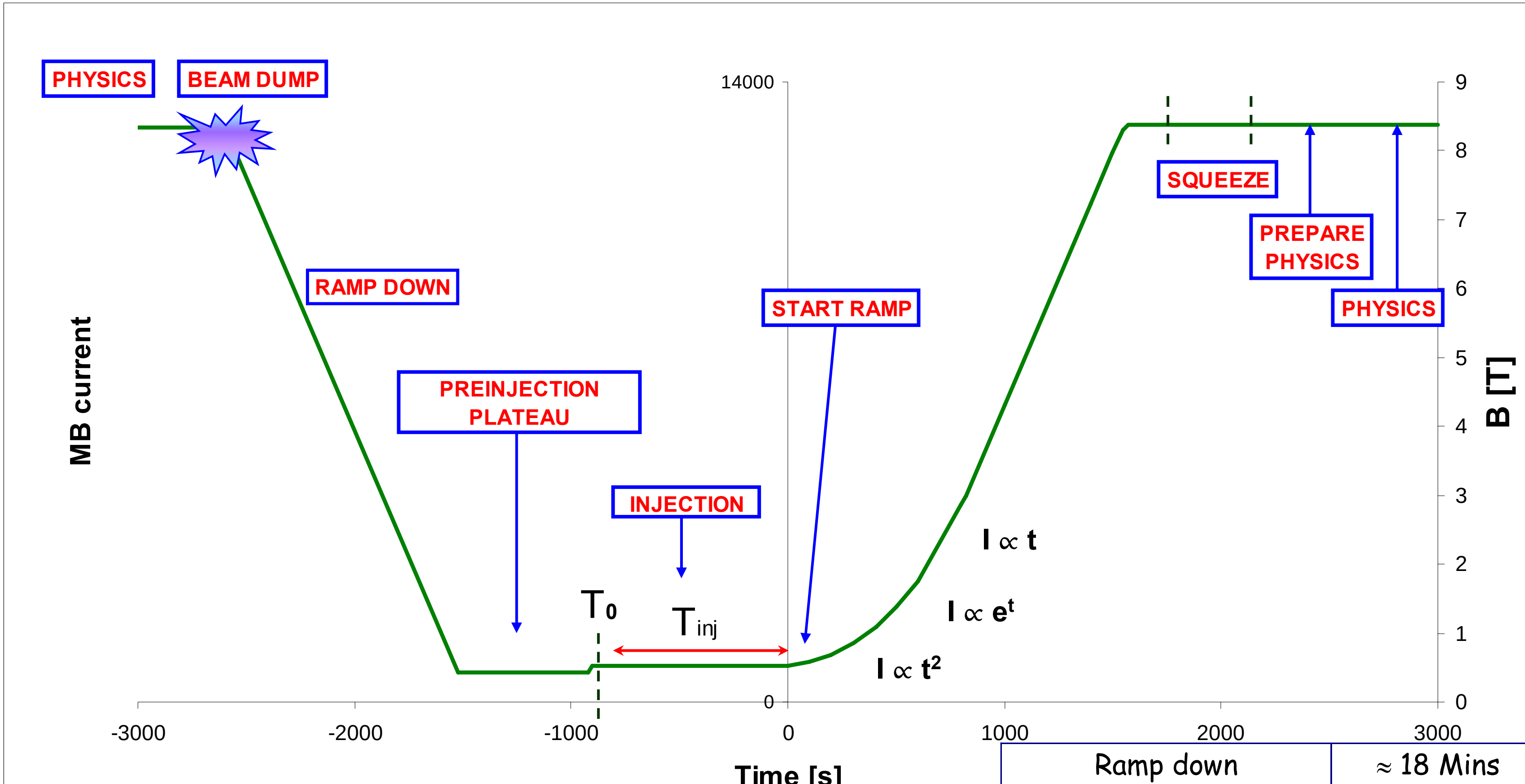
Emittance growth

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

Keep in emittance growth from collisions…

Cycle

Nominal cycle



Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

Nominal cycle – hot spots

- Injection
  - Losses at injection: injection oscillations, RF capture
- Injection plateau
  - Big beams, lower dynamic aperture, full buckets, un-captured beam, long range beam-beam, crossing angles, persistent current decay
  - Won't be pretty. 10 hours lifetime will be good.
- Start ramp
  - Un-captured beam lost immediately we start the ramp (~5% total)
  - Snapback: chromaticity, tunes all over the place
- Ramp
  - things should calm down, assume 10 hour lifetime
- Squeeze
  - tunes, chromaticity, collimator, TCDQ adjustments – expect some lifetime dips
- Collide
  - beam finding, background optimisation
- Physics
  - collisions, beam-gas, halo production
  - synchrotron radiation damping

Operational Cycle

Phase	Loss	Destination
Injection	2% transverse	IR7 collimators, TDI
	1% longitudinal	IR3 collimators
Injection plateau	20 minutes - 10 hour lifetime	IR7 collimators mainly
Start ramp – out of bucket flash	5% beam	IR3 collimators
Start ramp - snapback	1 minute – 1 hour lifetime	IR7 collimators
Ramp	20 minutes – 10 hr lifetime	Ring, collimators
Squeeze	10 minutes – 1 hour lifetime 2*10 s dips to 0.2 hr lifetime	IR7 collimators
Physics	Detailed above	Ring, insertions, IR3, IR7

Put some numbers in a minute

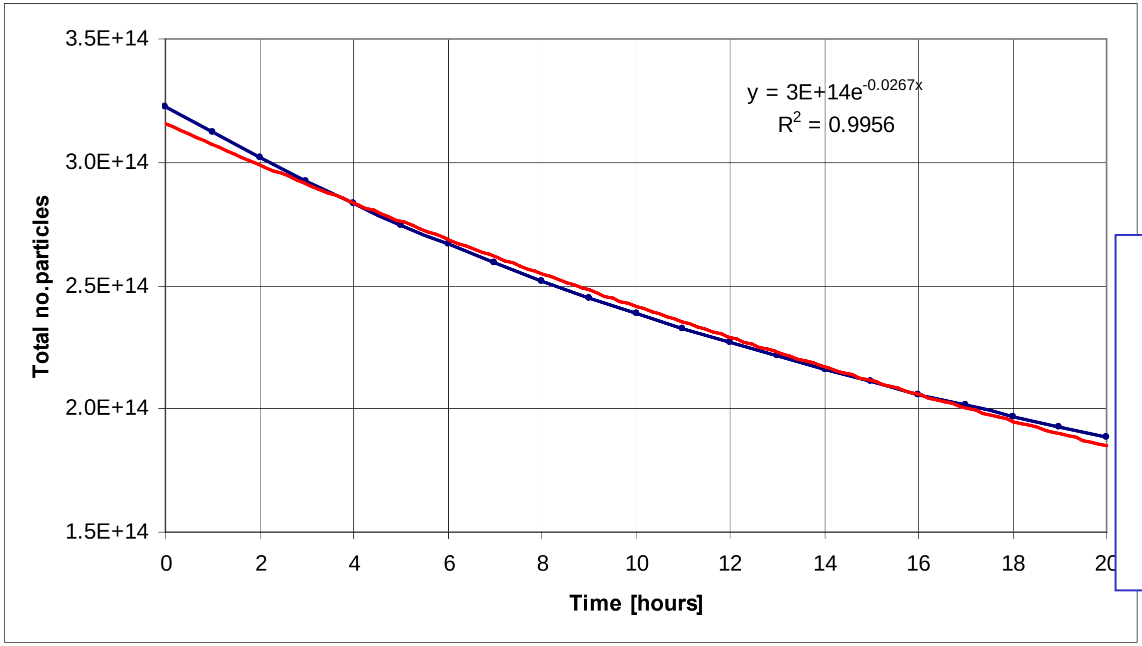
Physics

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	-

Lifetime evolution in physics

Attempt to combined the various lifetime effects and proportion the losses to their destination

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



Nominal single beam lifetime, fitting to exponential

≈ 37 hours

Luminosity lifetime

~ 18 hours

Numbers

Losses before physics

Nominal – start with 4.3 x 10^{14} protons per beam

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	**3.3×10^{11}**	**1.2×10^{12}**	**1.7×10^{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	**7.9×10^{11}**	**4.9×10^{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	**9.9×10^{10}**	**1.2×10^{12}**	**3.0×10^{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			**1.05×10^{14}**

Raise injected beam by 25% to get design into physics

Losses in 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}

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

Plug in the numbers for first year, nominal and ultimate and multiple up

Operations assumptions

- 160 days assigned for physics running per year.
- 70% operational efficiency.
  - i.e. 60% of the total assigned time, the machine is available for beam.
- Fill lengths.
  - The optimal fill length depends on the average turnaround time and the luminosity lifetime. Assume between 8 and 20 hours.
- Turnaround.
  - time between consecutive physics coasts
  - includes the time to ramp down, prepare for injection, inject, ramp & squeeze and prepare stable condition for physics data taking.
  - absolute minimum turnaround time between physics coasts, taking into account ramp down, preparation, injection, the ramp and squeeze is about 90 minutes.
  - varied between three and ten hours.

Totals per year

NOMINAL

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}

ULTIMATE

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}

7 TeV equivalent

1995 versus 2004

Compare with "Summary of Design Values, Dose Limits, Interaction Rates etc. for use in estimating Radiological Quantities associated with LHC Operation"

M. Höfert, K. Potter and G.R. Stevenson 1995

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}

Discussion

- **Lost rates per annum reevaluated taking into account**
  - **update baseline parameters**
  - **more realistic operational year**
  - **beam losses before physics**
  - **realistic intensity evolution in physics**
  - **updated figures for beam-gas lifetime**
- **In reasonable agreement with 1995 figures**
- **Estimates represent best possible and the LHC will have to perform extremely well to get close to them.**

- **Doses in cleaning sections are lower than might be expected:**
  - **Elastic collision products**
  - **Elastic beam gas collision products**
  - **Emittance growth at 7 TeV**

See LHC Project Note 375