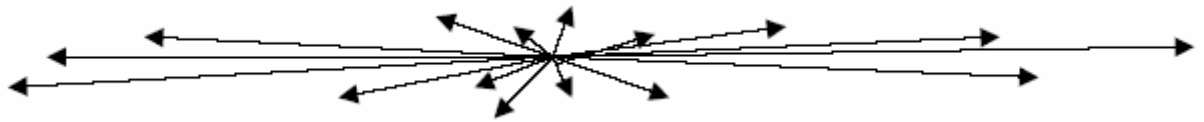
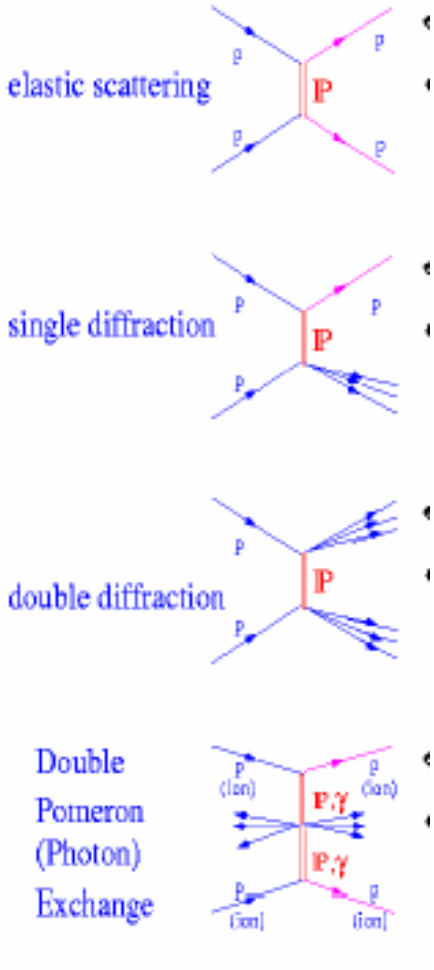
LHC Beam Loss Rates

Mike Lamont AB/OP

- **Beam Loss mechanisms**
- **Where?**
- **Beam loss in cycle – when?**
- **Totals per fill: before and during physics**
- **Totals per annum**
- **Comparison with 1995's estimates**

Collisions



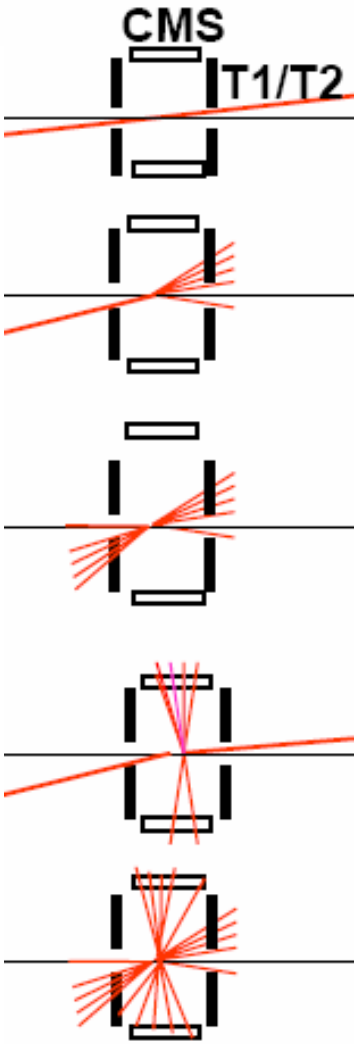


High luminosity interaction points

Ignore Alice and LHCb

$$\frac{dN}{dt} = L\sigma$$

- **Total cross-section 110 mbarns**
  - **Inelastic**
  - **Single diffractive [p < acceptance]**
  - **Single diffractive [p > acceptance]**
  - **Elastic**
- **SD & elastic come barreling down the beam pipe, along with some inelastic debris**



Collisions

Collision	Cross-section	Destination	τ [nominal]
Inelastic	60 mbarn	IRs [triplet, D1, TAN, TAS]	75 hours
Single diffractive	2.4 mbarn	Dispersion Suppressors in IR [$\delta p,min(0.01) < \delta p < \delta p,max(0.25)$]	1869 hours
Single diffractive	9.6 mbarn	Momentum Cleaning	467 hours
Elastic	40 mbarn	Betatron Cleaning (plus some ε blow-up)	112 hours

Single beam lifetime from collisions at 10^{34} cm^{-2}s^{-1} with 2 IPs: $\tau_N \approx$ 40 hours

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

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.
  - Losses in betatron cleaning sections at physical aperture
- **Multiple Coulomb scattering**
  - Emittance growth at injection. Negligible effect at 7 TeV
- **Inelastic**
  - Nuclear interaction
  - Secondary particles swept out by magnetic field – energy dissipated locally
  - Losses all around ring – dependent on local gas density and composition

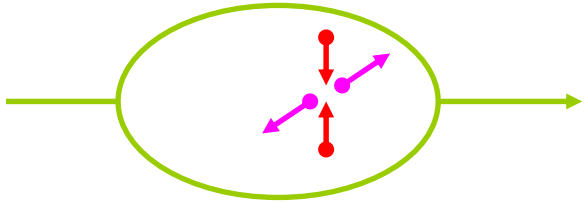
Beam Gas

- $\tau_{gas} \approx 100$ hours (2004 Design Report).
- 450 GeV conditions ≈ 7 TeV
- Elastic scattering: ≈ 40%
- Inelastic scattering: ≈ 60%

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

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



- **Intra Beam Scattering**
  - Multiple small-angle Coulomb scattering inside a bunch
  - Longitudinal and transverse emittance growth
  - Small contribution to single beam lifetime but does enter in the luminosity via the increase in beam size at the IPs

Other loss mechanisms

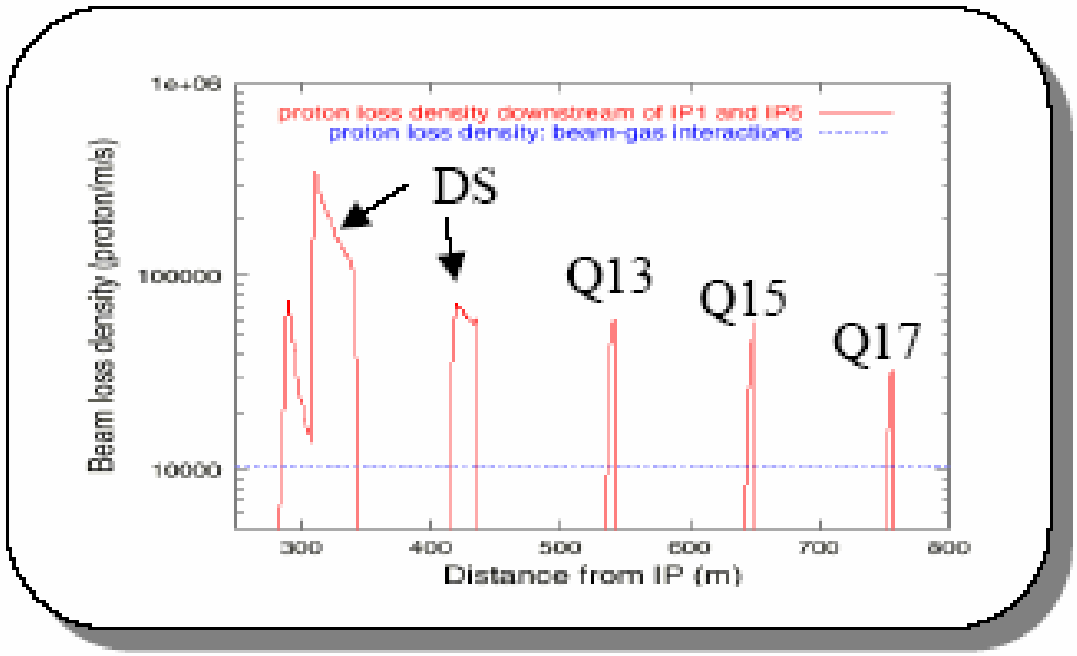
- Resonances & Beam instabilities
  - Parameter control challenges (persistent currents etc.)
- Long range beam-beam
  - adds to problems at injection
  - not much of a lifetime problem at 7 TeV, potentially background issue
- RF Noise
- Electron cloud
- Operators

Good news

- Synchrotron radiation damping
  - reasonably significant effect at 7 TeV
  - assumed to counter RF noise and beam-beam

WHERE: ARCs

- **Q12R to Q12L**
  - **Beam Gas**
  - **Point losses onto beam screen: protons escaping collimators**
  - **Point losses near IR 1 & 5**



Fynbo & Stevenson

Collimators

- **IR7**
  - **Elastic p-p collisions**
  - **Elastic beam gas collisions**
  - **Particles out at 6 σ**
    - IBS, beam-beam, resonances
- **IR3**
  - **Collision products**
  - **Longitudinal losses**
    - Touschek, RF noise
    - Uncaptured particles

WHERE: COLLIMATORS

- 99.9% of protons lost (e.g. with 1 hr beam lifetime) are captured in collimators
- Less than 0.1% of protons lost can escape and can impact on the SC magnets, which otherwise quench
- Less than 0.002% of the stored beam intensity can be lost at any place in the ring other than the collimators - > damage

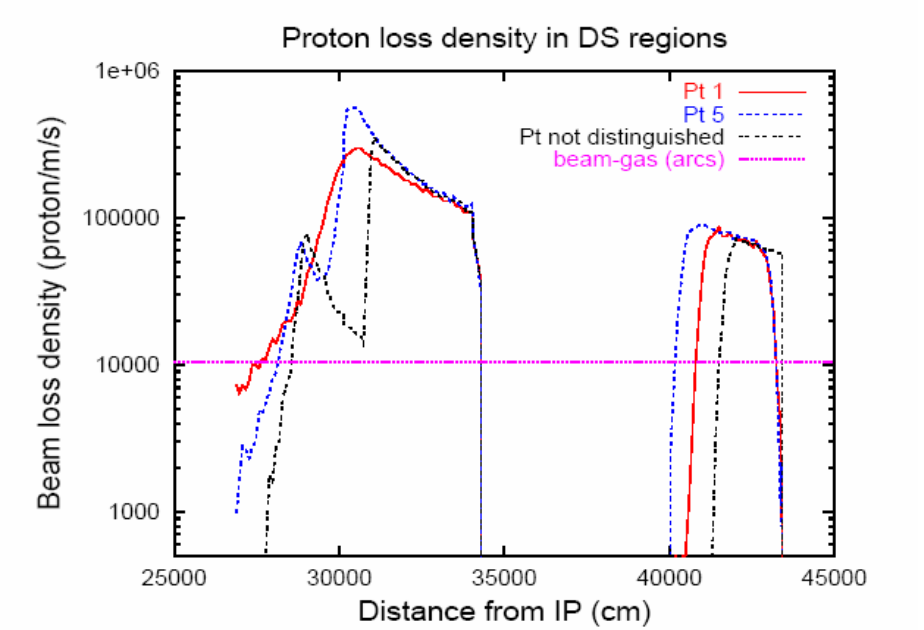
Energy [GeV]	Loss rate [10 hour lifetime]	Quench Limit [p/s/m] (steady losses)	Cleaning Requirement
450	8.4 ◈ 10^9 p/s	7.0 ◈ 10^8 p/s/m	92.6%
7000	8.4 ◈ 10^9 p/s	7.6 ◈ 10^6 p/s/m	99.91%

BY NECESSITY: NOT MUCH CAN ESCAPE

WHERE: DISPERSION SUPRESSORS

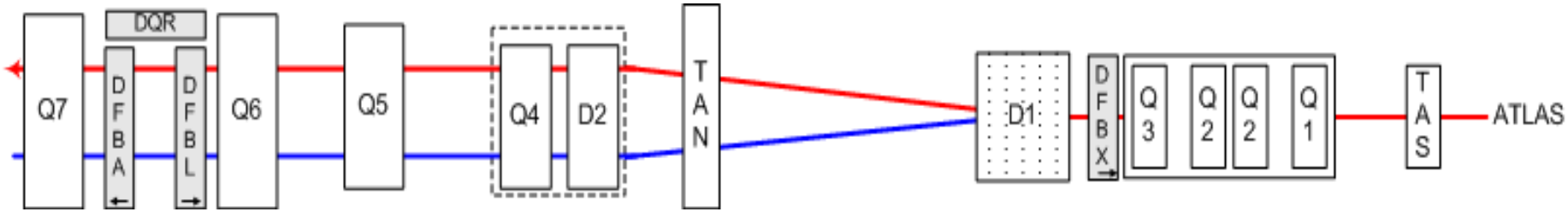
Q8 to Q12 + dipoles

- **Beam Gas**
- **Point losses near 1 & 5 from high luminosity IPs**
- **Point losses near 3 & 7 from collimators**



I. Baishev

IRs

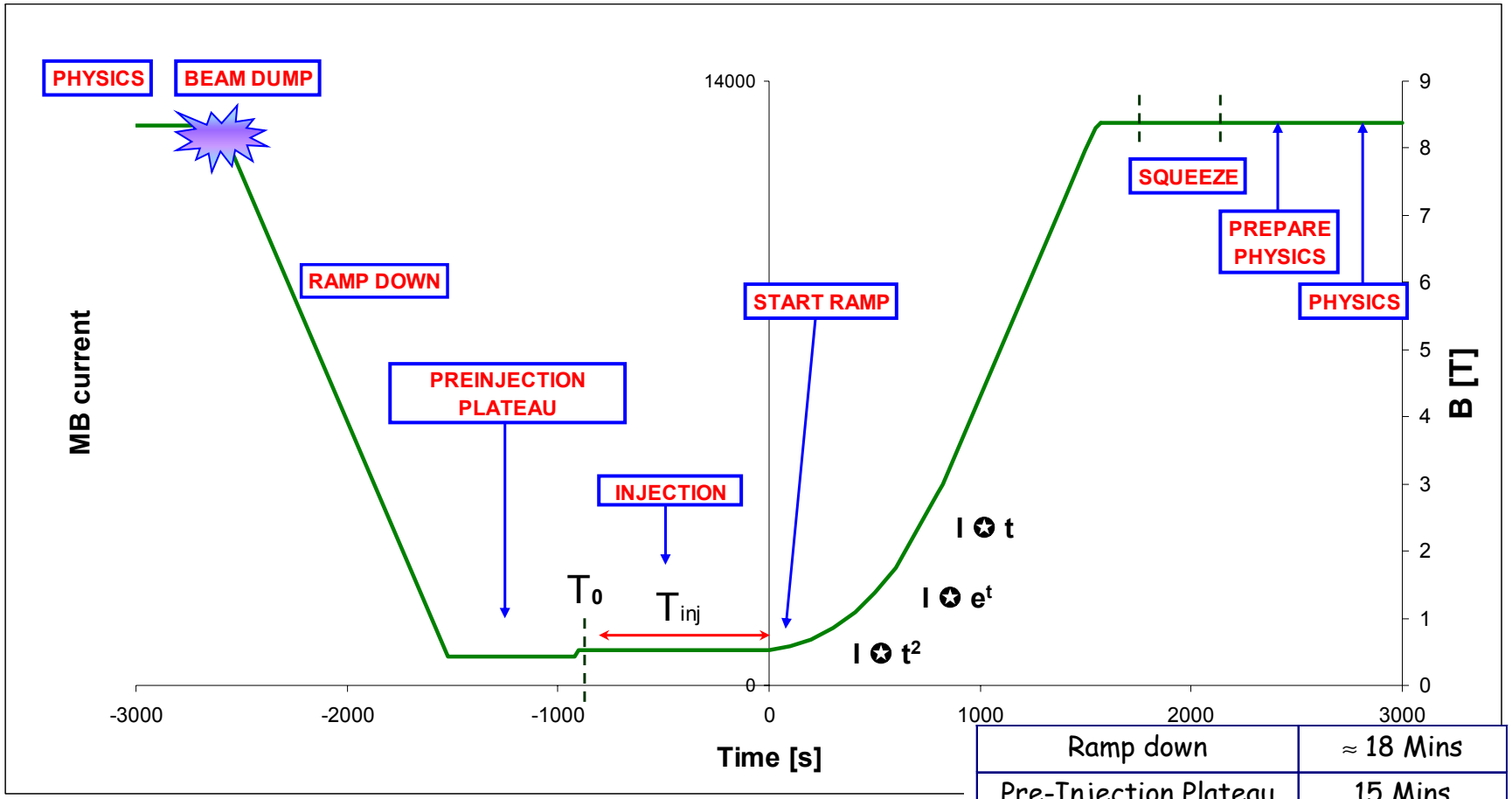


- **LSS in 1 & 5:**
  - **Matching Section: Q4 to Q7**
  - **Triplet: Q1 to Q3, D1, D2**
  - **TAN, TAS,**
- **Will catch it from:**
  - **Inelastic collision fragments**
  - **Single diffractive (Δp >acceptance)**
  - **Beam gas**

WHERE: Beam Dump

R.Schmidt and J.Uythoven, June 2010 Point 6.
Discussion on how the Beam Dump System reliability could be improved

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

Minimum beam lifetimes

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

Nominal cycle – WHEN

- **Injection**
  - Losses at injection: injection oscillations, RF capture
  - 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 (~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 will help against IBS, noise

Before Physics

BEAM GAS INEVITABLY BUT….

MOST OF THIS HAS TO END UP IN THE COLLIMATORS

Losses before physics

Raise injected beam intensity by 25% to get design into physics

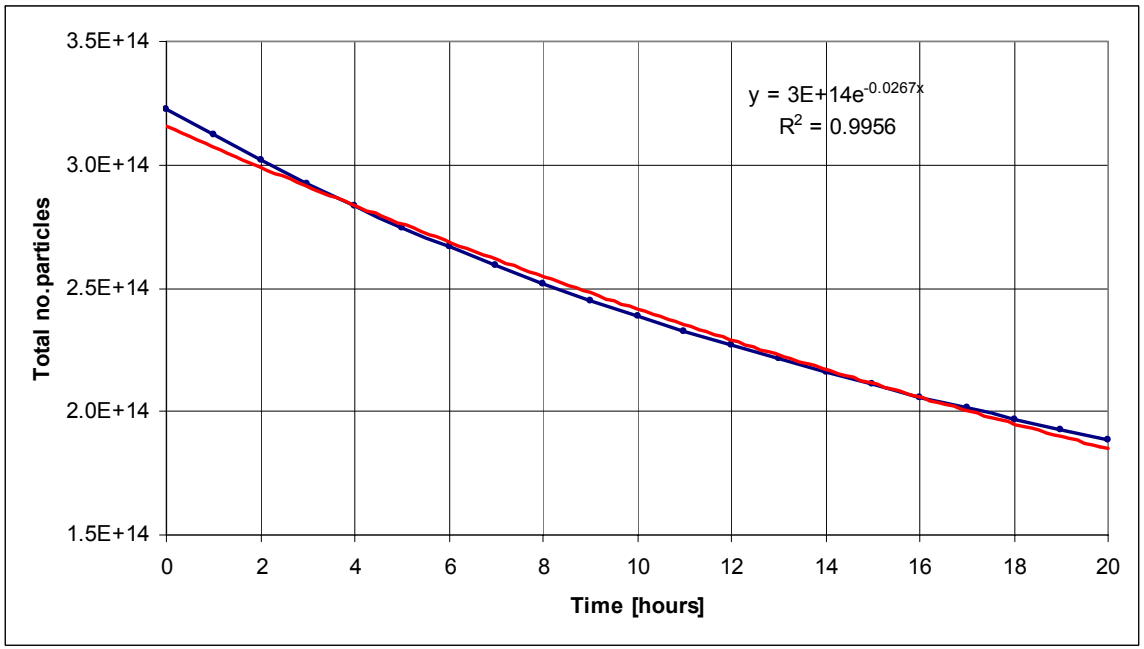
Nominal – start with 4.3 x 10^{14} protons per beam at injection

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	1.15 ◈ 10^{12}	9.42 ◈ 10^{12}	2.90 10^{12}
Scale by gamma	3.48 ◈ 10^{11}	1.15 ◈ 10^{12}	1.86 ◈ 10^{11}
Start ramp - at 450 GeV 5% of total	2.01 ◈ 10^{13}		
Snap back - 2% of total		7.63 ◈ 10^{12}	
Scale by gamma	1.29 ◈ 10^{12}	4.89 ◈ 10^{11}	
Ramp - 20 minutes at 10 hours lifetime	1.06 ◈ 10^{12}	8.66 ◈ 10^{12}	2.66 ◈ 10^{12}
Scale by gamma/2	1.32 ◈ 10^{11}	1.08 ◈ 10^{12}	3.33 ◈ 10^{11}
Squeeze - 10 minutes at 2 hour lifetime		2.95 ◈ 10^{13}	
Squeeze - 2*10s at 0.2 hour lifetime		9.16 ◈ 10^{12}	
TOTAL LOST BEFORE PHYSICS	PER FILL	10^{14}	

Lifetime evolution in physics

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

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



Nominal single beam lifetime, fitting to exponential ≈ 37 hours

Physics

Start of physics at 10^{34} $cm^{-2}s^{-1}$

Process	Loss Rate [p/s]	Lifetime/ε_{growth} [hr]	Destination
Residual gas - inelastic	7.50E+08	120	Ring
Residual gas - elastic	3.20E+08	280	IR7
Touschek	7.20E+07	1246	IR3
Collisions - inelastic	6.00E+08	150	Low β IR
Collisions - SD_{el}	2.40E+07	3738	DS
Collisions - SD_{inel}	9.60E+07	935	IR3
Collision - elastic	4.00E+08	224	IR7
IBS transverse	-	80	-
IBS longitudinal	-	61	-
Noise/beam-beam	-	55	-
SR - long	-	-13	-
SR - transverse	-	-26	-

Losses in physics – per fill

NOMINAL – ONE BEAM

Fill Length [hours]	8	12	15	20
Total beam lost during physics	7.1 E+13	9.6 E+13	1.1 E+14	1.3 E+14
Physics - IR7	3.0 E+13	4.1 E+13	4.8 E+13	5.7 E+13
Physics - IR3	9.5 E+12	1.3 E+13	1.5 E+13	7.7 E+12
Interaction regions [both IPs]	1.9 E+13	2.6 E+13	3.0 E+13	3.6 E+13
Main ring	1.2 E+13	1.6 E+13	1.9 E+13	2.3 E+13
Dumped	2.5 E+14	2.3 E+14	2.1 E+14	1.9 E+14

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

Operations assumptions

- 200 days physics per year.
- 60% operational efficiency
  - Machine available for beam
- Fill lengths
  - Assume between 8 and 20 hours.
- Turnaround
  - Time between consecutive physics coasts
  - Absolute minimum turnaround time between physics coasts: ≈ 90 minutes.
  - Varied between three and ten hours.

Totals Per Year

NOMINAL

Fill Length [hours]	8	12	15	20
TOTAL DUMPED - ONE BEAM	6.6 E+16	3.8 E+16	3.0 E+16	1.8 E+16
TOTAL INTO 2 IRS - ONE BEAM	5.0 E+15	4.4 E+15	4.4 E+15	3.5 E+15
TOTAL MAIN RING - BOTH BEAMS	6.5 E+15	5.7 E+15	5.6 E+15	4.4 E+15
TOTAL IR7 – BOTH BEAMS	3.7 E+16	2.8 E+16	2.6 E+16	1.9 E+16
TOTAL IR3 – BOTH BEAMS	5.9 E+15	5.3 E+15	5.1 E+15	2.0 E+15

ULTIMATE

Fill Length [hours]	8	12	15	20
TOTAL DUMPED - ONE BEAM	8.8 E+16	5.0 E+16	3.9 E+16	2.3 E+16
TOTAL INTO 2 IRS – ONE BEAM	1.2 E+16	9.8 E+15	9.6 E+15	7.5 E+15
TOTAL MAIN RING - BOTH BEAMS	9.5 E+15	8.0 E+15	7.7 E+15	6.0 E+15
TOTAL IR7 – BOTH BEAMS	6.0 E+16	4.5 E+16	4.1 E+16	3.0 E+16
TOTAL IR3 – BOTH BEAMS	9.9 E+15	8.6 E+15	8.2 E+15	3.0 E+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 **PER BEAM PER IP**

Mechanism	Internal	Nominal	Environment	Ultimate
Fill pattern	20+4	8+3	8+4	8+3
Total beam	5.1 e16 [acc]	1.1 e17 [inj]	8.5 e16 [acc]	1.7 e17 [inj]
Inelastic interactions	5.5 e15	2.5 e15	1.6 e16	6 e15
Dump	5.0 e16	6.6 e16	1.0 e17	8.8 e16
[Betatron] Collimators	1.6 e16	1.9 e16	4.0 e16	3.0 e16
Momentum Collimators	-	3.0 e15	-	4.9 e15
Main ring	2.2 e15	3.3 e15	3.4 e15	4.8 e15
Sum check		9.9 e16		1.4 e17

$1.65 \diamond 10^{11}$ m^{-1} yr^{-1} [both beams]

$2.5 \diamond 10^{11}$ m^{-1} yr^{-1} [both beams]

Conclusions

- **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**
- **LHC will have to perform extremely well to get close to the estimates presented.**