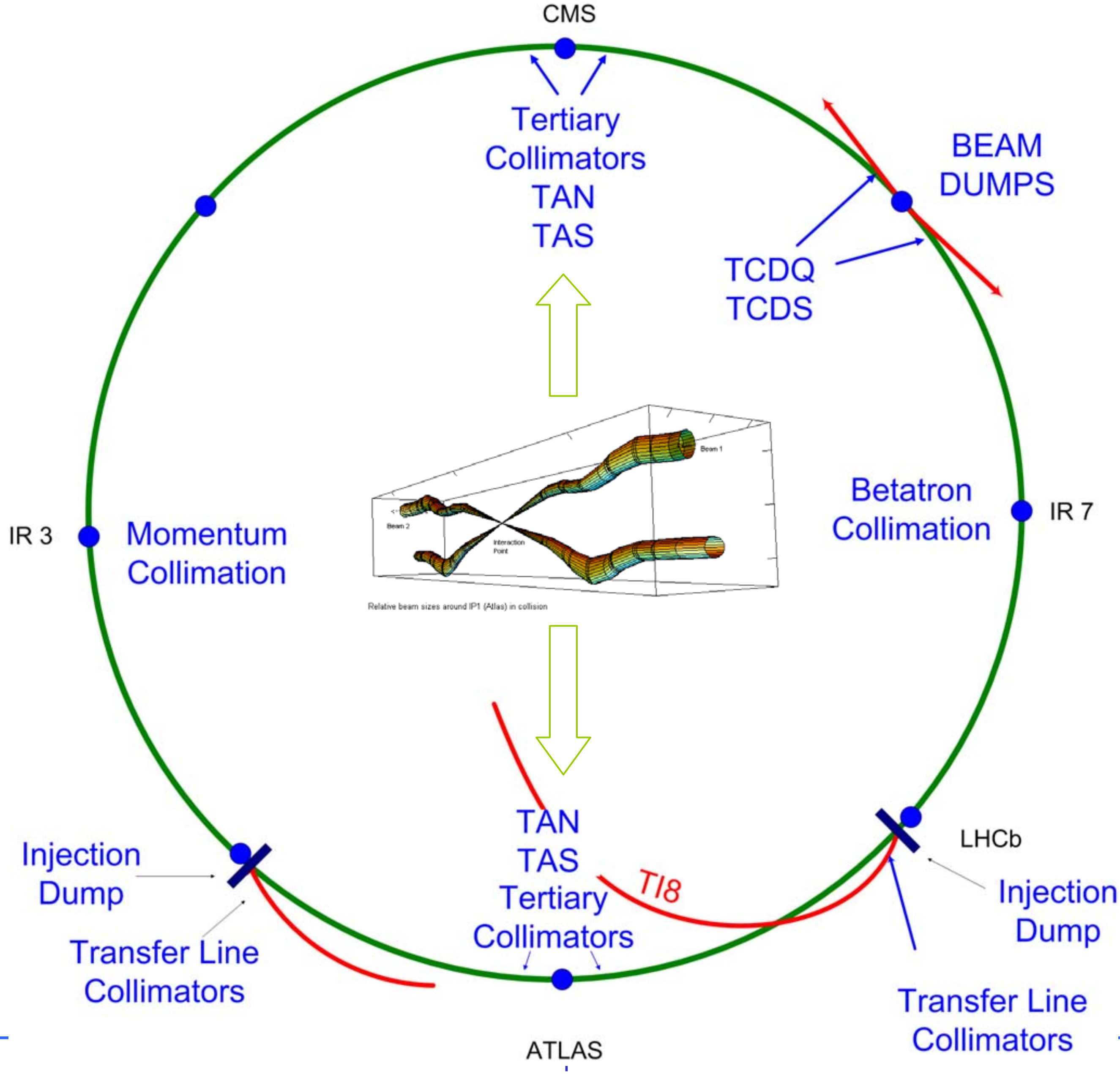
LHC Beam Parameters

Mike Lamont AB/OP

1. **Baseline Parameters**
2. **Operational Sequence**
3. **Beam Loss mechanisms**
4. **Beam loss in cycle**
5. **Operational assumptions**
6. **Totals per fill, totals per annum**
7. **Comparison with 1995's estimates**
8. **Evolution: first year, nominal, ultimate**

LHC - overview



Beam Dump

R.Schmidt and J.Uythoven, June 2008, LHC Point 6.
Discussion on how the Beam Dump System reliability could be improved

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	-

Baseline initial conditions

Target intensities haven't changed much:

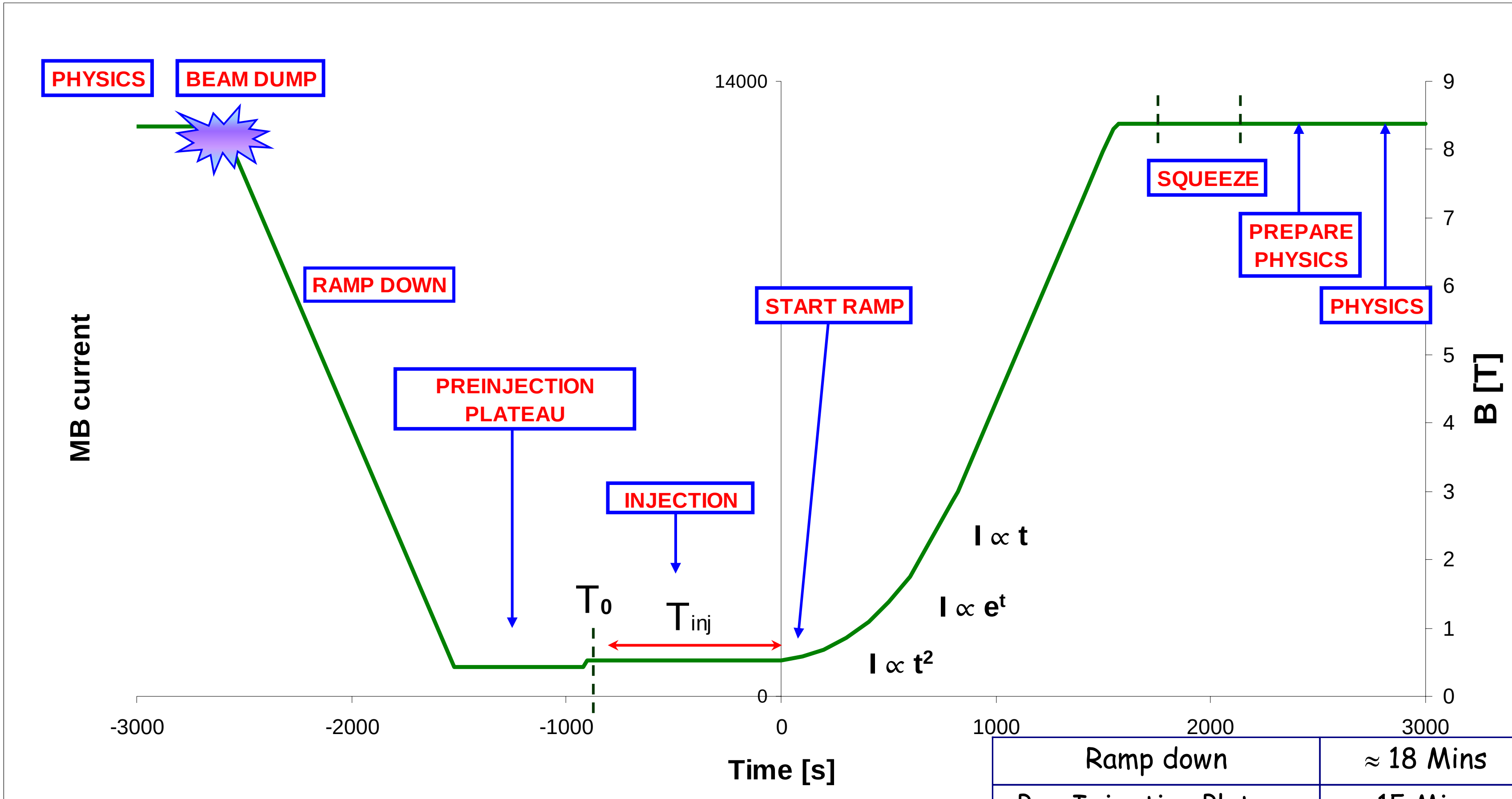
- **Number of bunches down slightly: PS**
- **Minimum β^* slightly higher: aperture in triplets**
- **Bunch current slight higher: to keep 10^{34} $cm^{-2}s^{-1}$**

Full details at: LHC Parameter Page

But a lot of work has gone into:

- **Collimation system**
- **Beam absorbers**
- **Machine Protection**
- **Instrumentation**
- **Beam dump**
- **Injection**
- **Optics version 6.5, Aperture**

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 will help against IBS, noise**

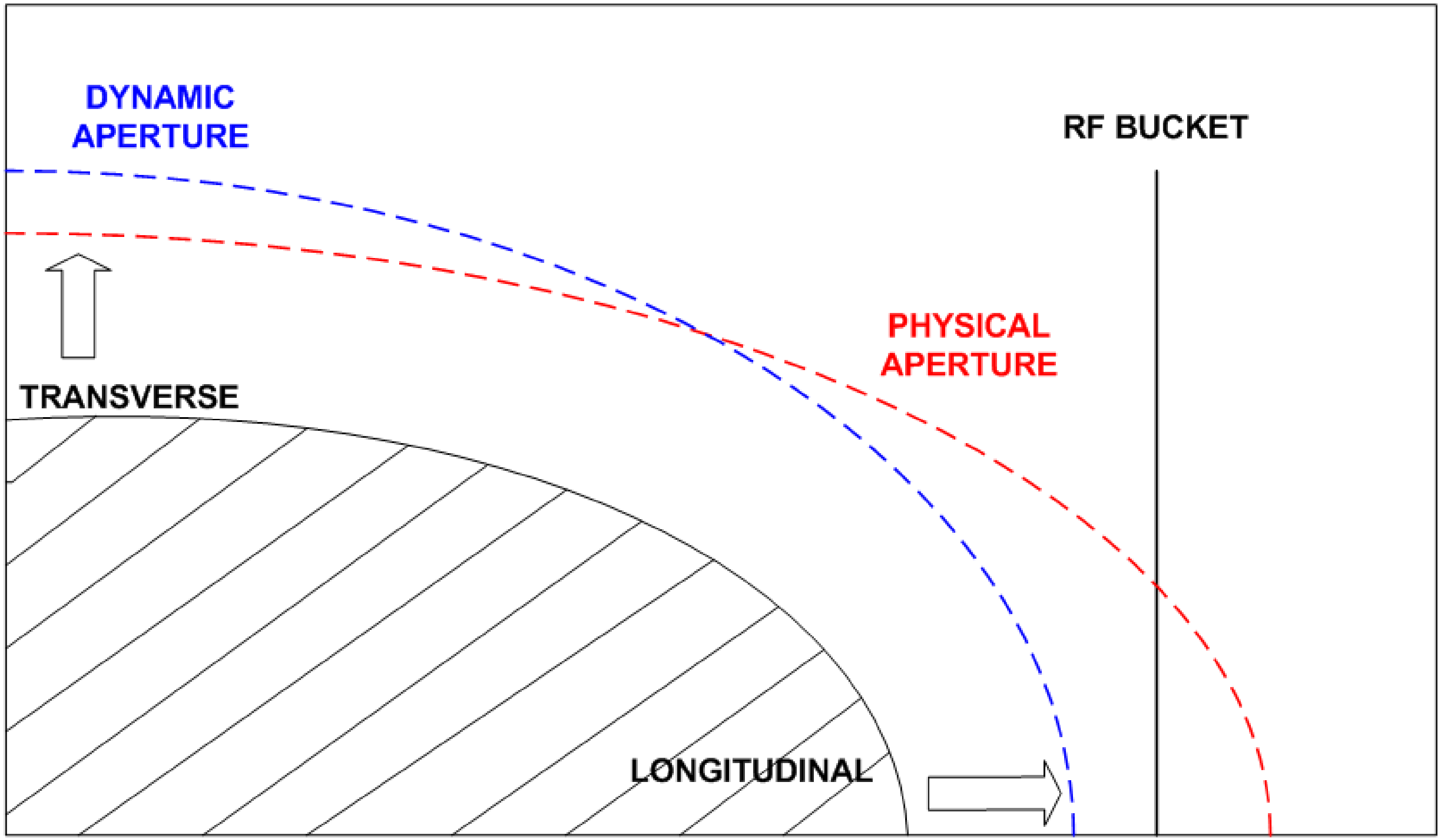
Types of loss

- **Abnormal (Fast & Ultra fast loss)**
  - **Equipment malfunction etc.**
- **Short lifetimes**
  - **Operator error**
  - **Beam instabilities, resonances**
  - **Parameter control challenges (persistent currents etc.)**
- **Stable**
  - **Transverse**
    - Beam gas, nonlinearities, long range beam-beam, electron cloud, IBS, collisions
  - **Longitudinal**
    - Touschek, RF noise, IBS

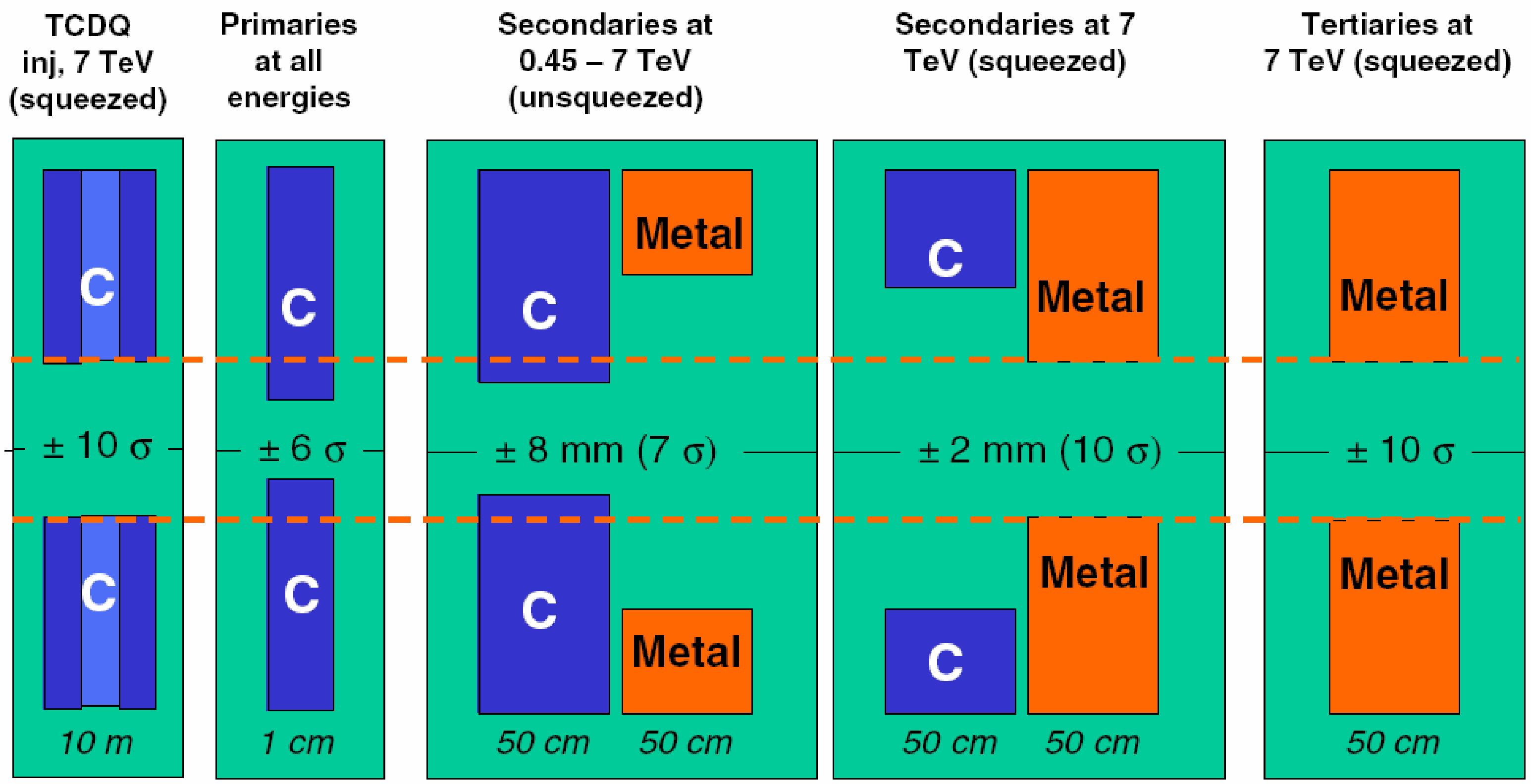
Particles can be:

- **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**

Aperture


DYNAMIC
APERTURE
RF BUCKET
PHYSICAL
APERTURE
TRANSVERSE
LONGITUDINAL

Collimation



- **IR7 collimators catch particle with large betatron amplitude**
- **IR3 collimators catch particles with large momentum offset**

Brief look at the various beam loss mechanisms

Beam Gas

$\rightarrow$ 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.
  - If the change is large enough the particle is lost at either the physical or dynamic aperture
  - Also an 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
  - Particle loses energy and consequently gets lost at the RF acceptance limit or the momentum dynamic aperture limit
  - Inelastic scattering from the electrons of the atom in which the momentum transfer excites the atom. Negligible.

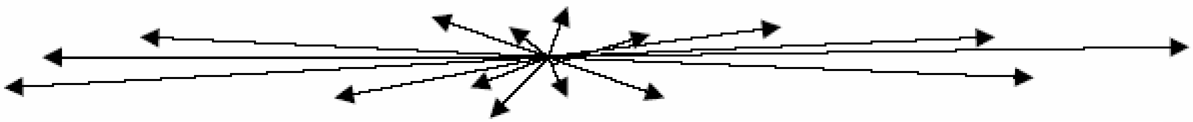
Beam Gas

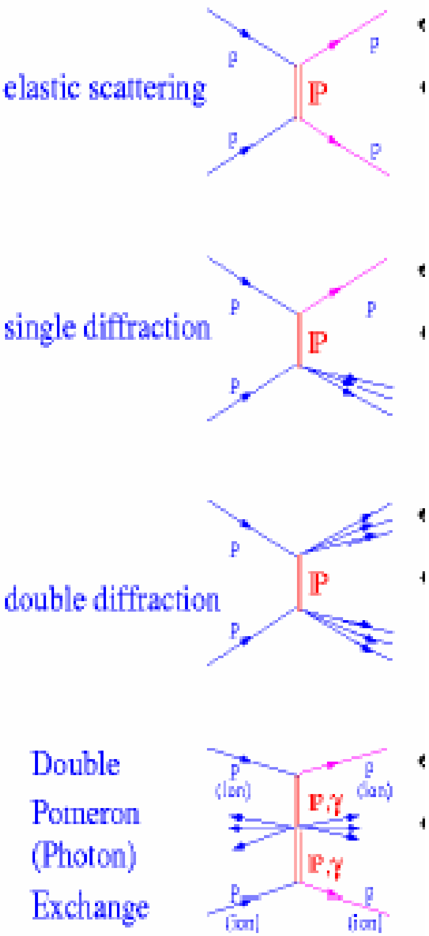
- τ_{gas} ≈ 100 hours (design report).
- 450 GeV conditions ≈ 7 TeV
- Elastic scattering: 40%
  - Losses in betatron cleaning sections
- Inelastic scattering: 60%
  - Secondary particles swept out by magnetic field – energy dissipated locally
  - Losses all around ring

- Running in ≈ conditioned machine

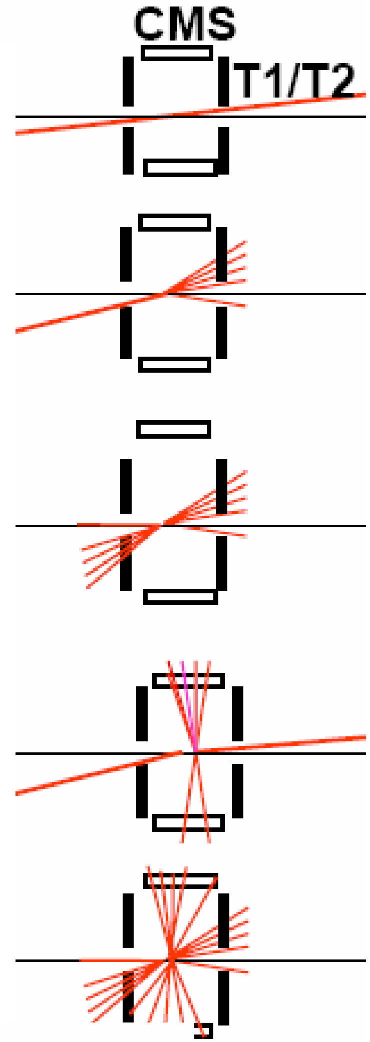
$$\frac{1}{\tau_{BG}} = c \sum_{i \in gases} \sigma_i n_i$$

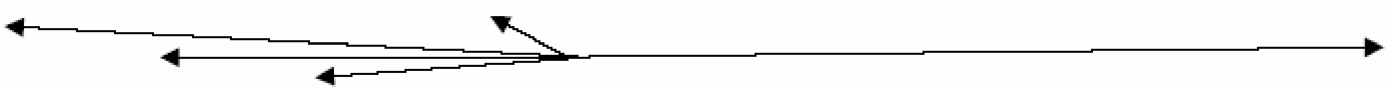
Collisions





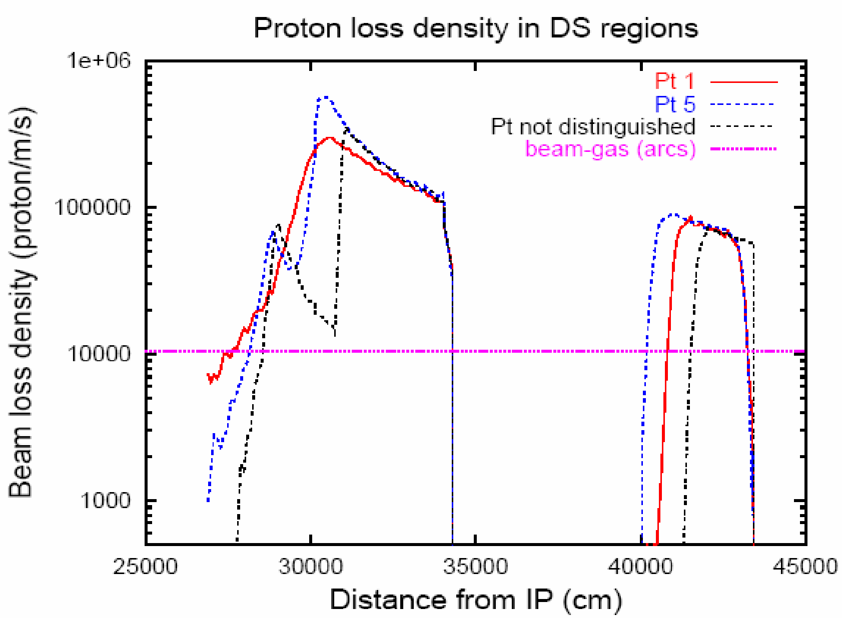
- **Total cross-section 110 mbarns**
  - **Inelastic**
  - **Single diffractive [el]**
  - **Single diffractive [inel]**
  - **Elastic**
- **SD & elastic come barreling down the beam pipe, along with some inelastic debris**





Collisions

Collision	Cross-section	Destination	τ [nominal]
Inelastic	**60 mbarn**	**IRs [triplet, D1, TAN, TAS]**	**75 hours**
Single diffractive	**2.4 mbarn**	**Dispersion Suppressors in IR** [*δp,min*(0.01) < *δp* < *δp,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**



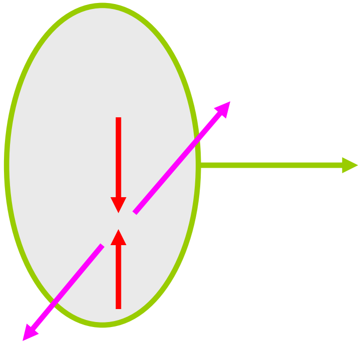
Single beam lifetime from collisions at 10^{34} cm^{-2}s^{-1} with 2 IPs: ≈40 hours

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

See: Fynbo & Stevenson et al

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
  - Small contribution to single beam lifetime but does enter in the luminosity via the increase in beam size at the IPs

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**
  - **tight parameter control**
- **Operators**

Good news

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

Put it all together

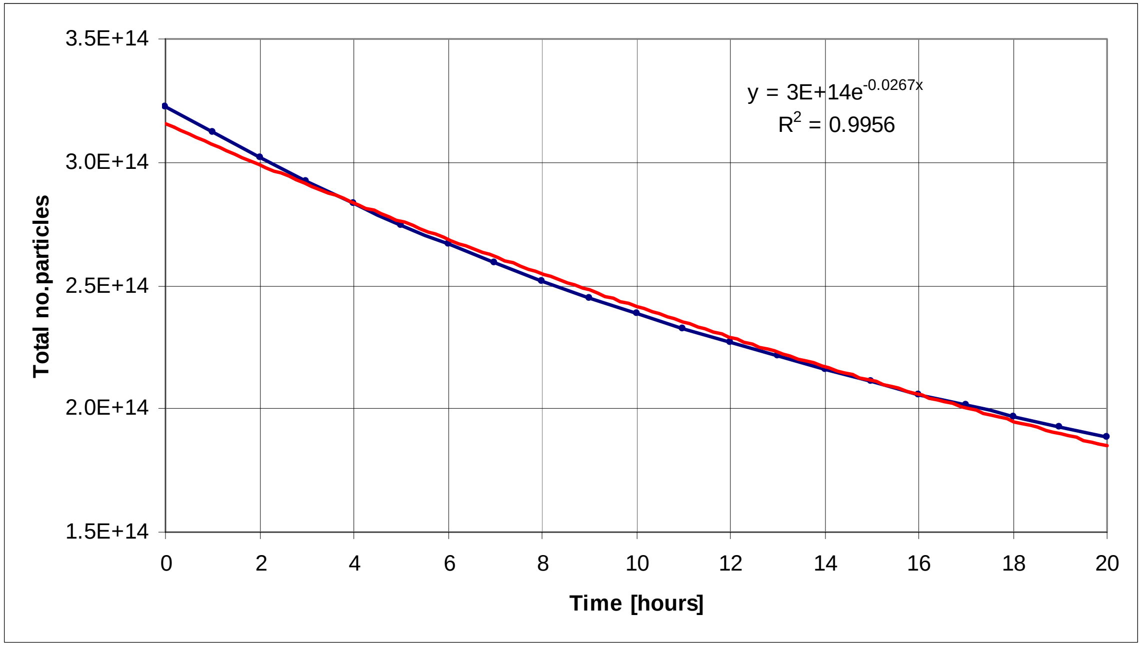
Start of physics at 10^{34} $cm^{-2}s^{-1}$

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	-

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

Revisit 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…

Losses before physics

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

	IR7	Ring	IR3
Injection Oscillations - 2% - betatron	8.56E+12		
Injection Oscillations - 1% - momentum			4.28E+12
Injection - 20 minutes at 10 hours lifetime	9.42E+12	2.90E+12	1.15E+12
Scale by gamma	1.15E+12	1.86E+11	3.48E+11
Start ramp - at 450 GeV 5% of total			2.01E+13
Snap back - 2% of total	7.63E+12		
Scale by gamma	4.89E+11		1.29E+12
Ramp - 20 minutes at 10 hours lifetime	8.66E+12	2.66E+12	1.06E+12
Scale by gamma/2	1.08E+12	3.33E+11	1.32E+11
Squeeze - 10 minutes at 2 hour lifetime	2.95E+13		
Squeeze - 2*10s at 0.2 hour lifetime	9.16E+12		
TOTAL LOST BEFORE PHYSICS	1.05E+14		

Raise injected beam by 25% to get design into physics

Losses in physics

Fill Length	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 assigned for physics running per year.**
- **60% 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	8	12	15	20
TOTAL DUMPED - ONE BEAM	6.6E+16	3.8E+16	3.0E+16	1.8E+16
TOTAL INTO 2 IRS - ONE BEAM	5.0E+15	4.4E+15	4.4E+15	3.5E+15
TOTAL MAIN RING - BOTH BEAMS	6.5E+15	5.7E+15	5.6E+15	4.4E+15
TOTAL IR7 – BOTH BEAMS	3.7E+16	2.8E+16	2.6E+16	1.9E+16
TOTAL IR3 – BOTH BEAMS	5.9E+15	5.3E+15	5.1E+15	2.0E+15

ULTIMATE

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

PER BEAM PER IP

QUITE REMARKABLE!!!

Evolution

- **Initial commissioning:**
  - **Ending with Pilot physics: 43 on 43 with 3 - 4 x 10^{10} (if we're lucky)**
- **Year one[++] operation:**
  - **Lower beam intensity/luminosity:**
    - Event pileup, Electron cloud, Phase 1 collimator impedance etc. Equipment restrictions
  - **Relaxed squeeze, lower intensities, 75 ns. bunch spacing**
  - **Aiming for 10^{33}cm^{-2}s^{-1}**
- **First 3 years: phase 1 collimation - ½ total intensity**
- **6 month shutdown for phase 2 collimator installation**
  - **4 month cool-down**
  - **2 installation**
- **1 year to get to nominal**
- **Ultimate?**
  - **Whole accelerator chain will be pushed to the limit (required intensities not possible at the moment)**
  - **whole cycle will have to be extremely well optimised**
  - **whole swath of issues: electron cloud, machine protection, beam dump, beam stability, collimation, impedance**

Access/Interventions

- **LHC year**
  - **52 weeks**
  - **16 weeks shutdown**
  - **4 weeks machine checkout**
  - **32 weeks operation**
- **Operation**
  - **8*4 week operating periods with beam**
  - **3 days technical stop every month [QPS, RF, Survey etc. etc.]**
- **Beam**
  - **Setting up, machine development, physics, picking up the pieces**
  - **Short intervention every day in shadow of preparation plus access as required**

Contractors will be involved:

more formal access management foreseen

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
- Estimates represent best possible and the LHC will have to perform extremely well to get close to them.
- First 5 year plan
  - expect a slow evolution for a number of reasons
- Intervention scenarios under discussion but basic ideas outlined.