Proton & Ion Bunch Disposition in the LHC, SPS & PS

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The Basics … in the LHC

LHC Harmonic number h = 35640 @ 400 MHz

h = 17820 @ 200 MHz

h = 3564 @ 40 MHz (25ns)

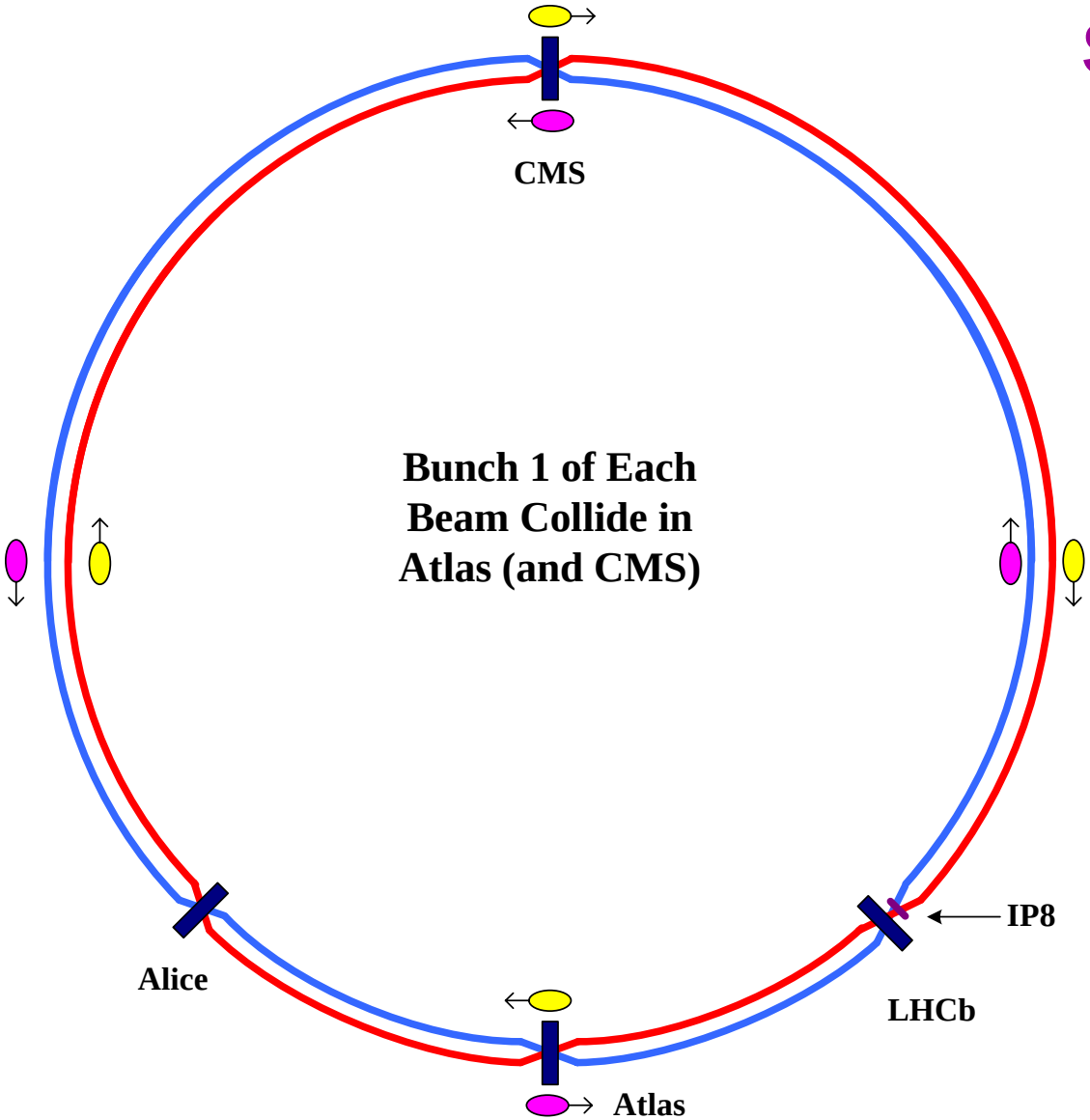
(LHC was meant to have a 200 MHz system, now staged)

LHC has Four experiments

… but they are not equally spaced around the machine.

- **In order to collide in all 4 the bunch pattern must repeat in each quadrant (call it 4-fold symmetry, but it isn't really)**
- **The repeat does not need to be perfect ⇒ leads to Pacman bunches**
- **The 2 rings are a mirror image of each other.**
- **One of the experiments (LHCb) is displaced from the IP by 37.5 ns**

Simplest Case



Minimum Number of bunches that will collide in all 4 experimental IP's is 4 … but no collisions in LHCb

Can build up more complicated schemes from this --- looking how the bunches (or the holes) in a bunch pattern collide

Injectors : CPS

- **RF Gymnastics using several RF systems to generate a series of bunches captured on harmonic h=84 at the exit of the PS.**

(3564 = 84 * 11 * 27/7)

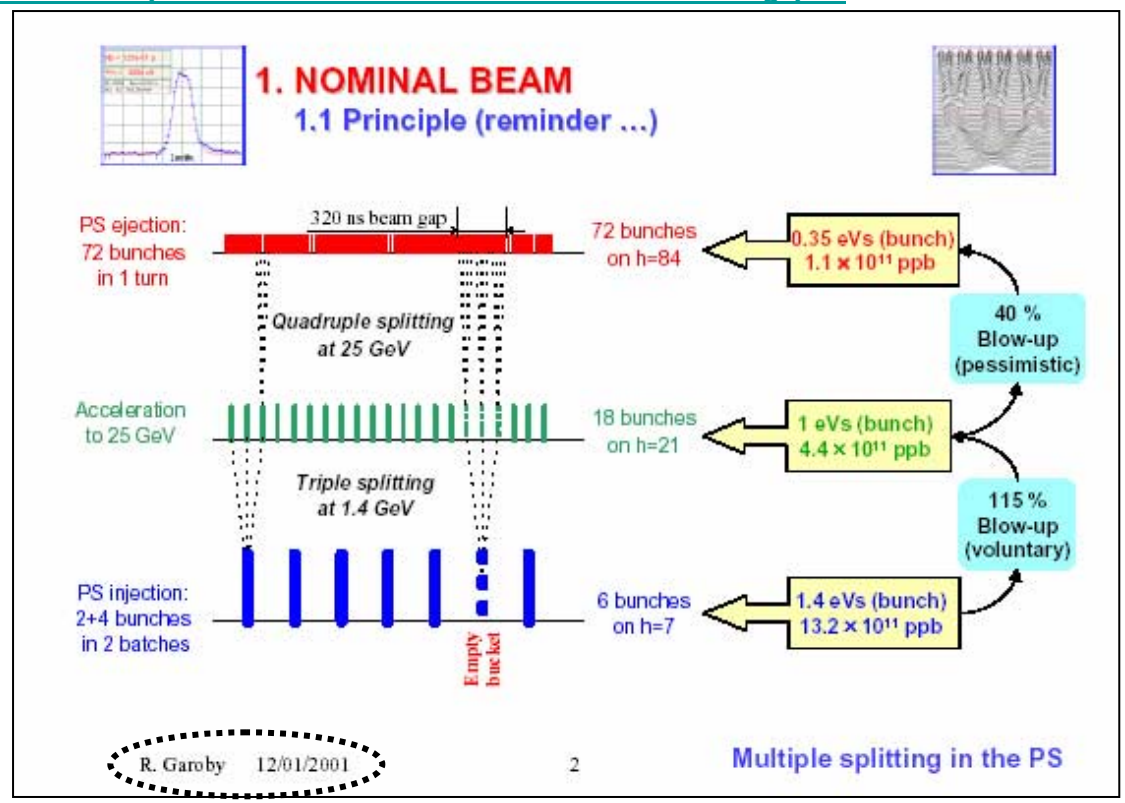
- **For more details see, for example:**

http://ab-div.web.cern.ch/sl-div/publications/chamx2001/PAPERS/1-2-rg.pdf

In one 'LHC Cycle' the CPS generates 72 bunches spaced by 25ns.

⇘ Using fewer booster bunches 12 bunch gaps can be generated

(not normally used)



Injectors : CPS (continued)

- **Using different bunch splitting schemes (different harmonics) bunch separations that are a multiple of 25 ns can be produced.**

- **Each one involves a significant amount of hardware and effort :**
  - **25ns … routine** — **72 bunches/3.6s cycle**
  - **50ns … done** — **36 bunches/3.6s cycle**
  - **75ns … trials in progress** — **24 bunches/3.6s cycle**
  - **100ns … on paper (for ions)** — **4 bunches/3.6s cycle**

- **In addition Single LHC bunches can be delivered**
  - **Note that this is generated in a completely different way to the above.**
  - **The single bunch can be used as a 'pilot' type beam (low intensity)**
  - **…or a physics beam.**

Injectors : SPS

SPS Harmonic numbers

h = 4620 @ 200 MHz

h = 924 @ 40 MHz (25 ns) {924 * 27/7 = 3564}

- **SPS Can take several injections from the PS.**
  - **The minimum separation between PS batches is given by the SPS injection kicker rise-time (225ns)**
- **For protons the practical maximum is 4 because of the total intensity.**
  - **With 4 cycles from the CPS the SPS is around 1/3 full.**
- **For ions many more injections are possible**
  - **Because the number of bunches in a PS batch is small …**
  - **And the intensity per bunch is much lower**
  - **However IBS and other instabilities/emittance growth mechanisms become important on a long injection plateau.**
  - **Space charge tune shift for ions is a problem (under study)**

LHC filling Schemes : Limitations

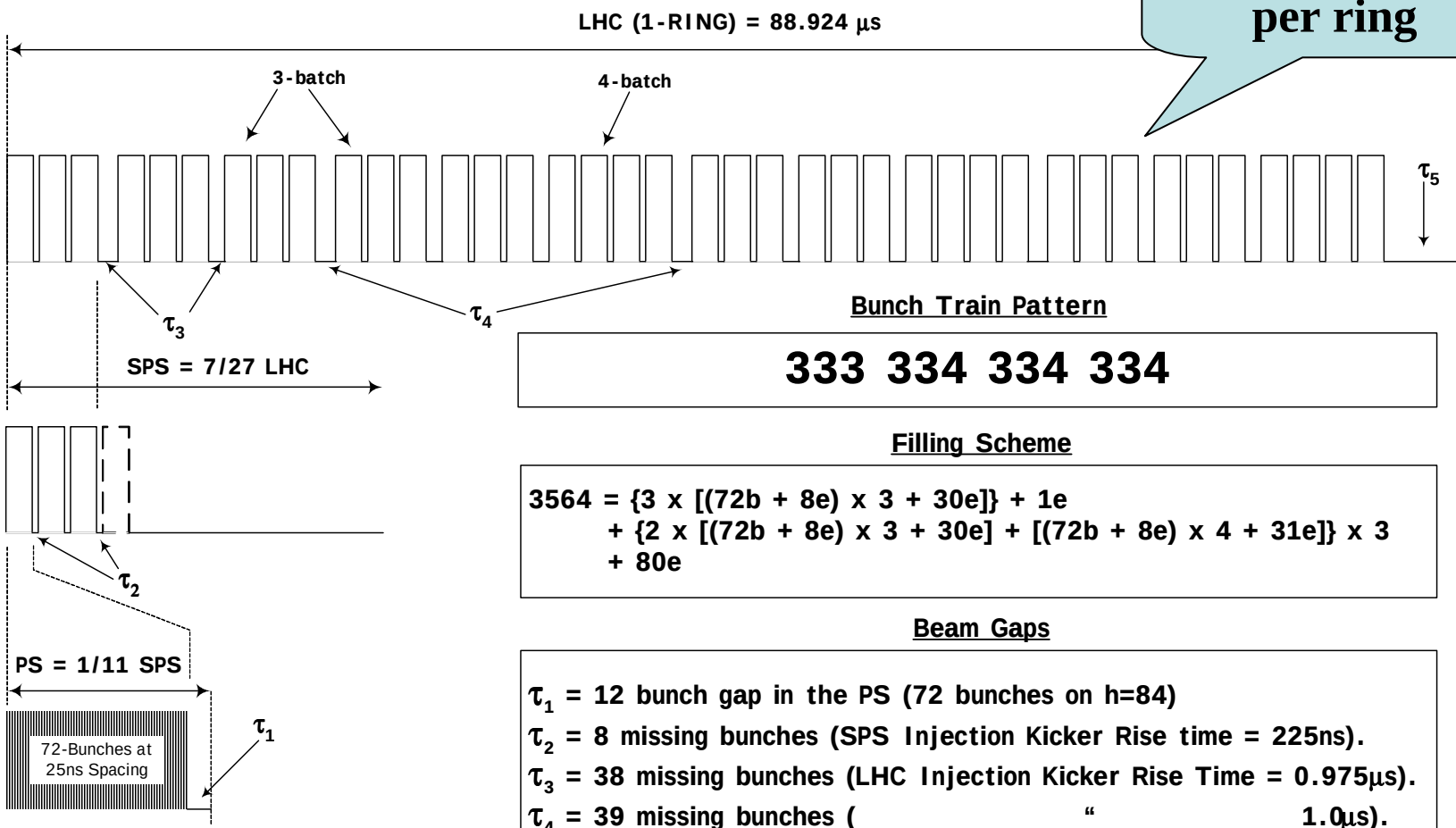
There are many limitations on the way the LHC is filled … some come from equipment, others from beam physics … some examples :

- **Beam dump gap**
  - **a 3μs gap is needed for the beam dump kicker rise-time**
- **Other Equipment Limits:**
  - **Injection kicker rise time 975ns**
  - **SPS Injection kicker rise time 225ns**
  - **LHC Injection kicker flat top length 7.86μs**
- **Other Limits**
  - **Offset collision point in LHCb**
  - **4-fold rotational symmetry (as far as possible)**
  - **Minimize Pacman bunches**

… beam-beam effects, orbit offsets, separation at the collision point, tune spreads etc. etc.

Not easy to make a beautifully regular bunch pattern!

1) 25ns Scheme



2808 bunches per ring

Bunch Train Pattern

333 334 334 334

Filling Scheme

3564 = {3 x [(72b + 8e) x 3 + 30e]} + 1e
+ {2 x [(72b + 8e) x 3 + 30e] + [(72b + 8e) x 4 + 31e]} x 3
+ 80e

Beam Gaps

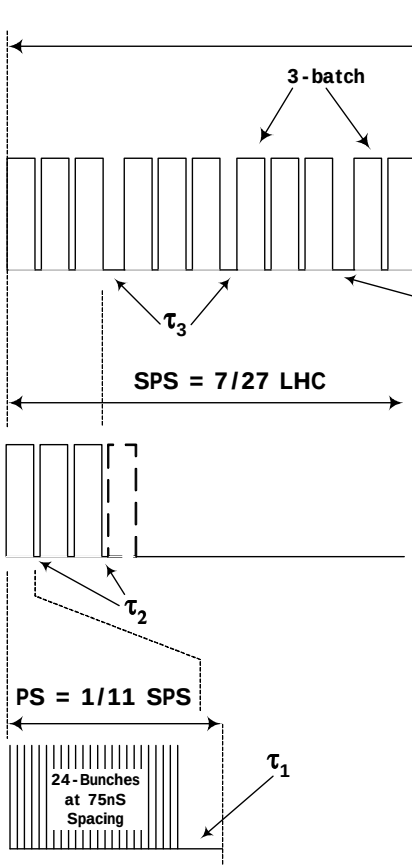
τ_1 = 12 bunch gap in the PS (72 bunches on h=84)
τ_2 = 8 missing bunches (SPS Injection Kicker Rise time = 225ns).
τ_3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.975μs).
τ_4 = 39 missing bunches (" 1.0μs).
τ_5 = 119 missing bunches (LHC Beam Dump Kicker Rise Time = 3μs).

Bunches which find partners in each IP :

IP1 & IP5 – 2808 IP2 – 2736 IP8 – 2632

2) 75ns Scheme

Planned for early operation – to minimize beam power and to avoid Electron cloud problems
75ns is the largest spacing naturally giving collisions in LHCb



Bunch Train Pattern

333 334 334 334

Filling Scheme (at 75nS Bunch Spacing)

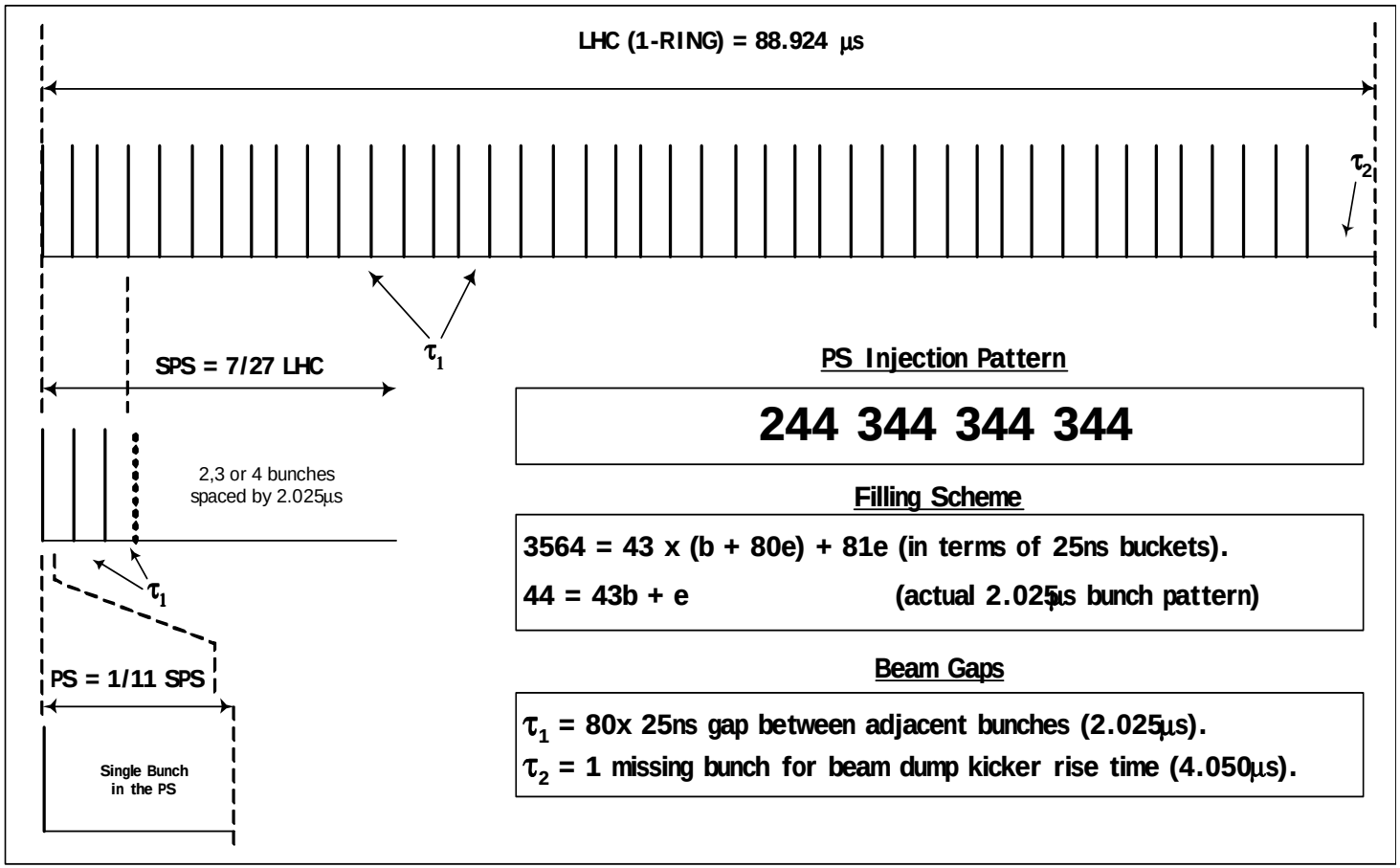
1188= {3 x [(24b + 2e) x 3 + 12e]} + e
+ {2 x [(24b + 2e) x 3 + 12e] + [(24b + 2e) x 4 + 13e]} x 3 + 26e

Total number of bunches = 936 per ring

Beam Gaps

τ_1 = 4 bunch gap in the PS (375ns)
τ_2 = 2 missing bunches (SPS Injection Kicker Rise time = 225ns).
τ_3 = 14 missing bunches (LHC Injection Kicker Rise Time = 1.125μs).
τ_4 = 15 missing bunches (" 1.2μs).
τ_5 = 41 missing bunches (LHC Beam Dump Kicker Rise Time =3.15μs).

3) 43 Bunch Scheme (Totem and/or Initial Physics Beam)



PS Injection Pattern

244 344 344 344

Filling Scheme

3564 = 43 x (b + 80e) + 81e (in terms of 25ns buckets).

44 = 43b + e (actual 2.025μs bunch pattern)

Beam Gaps

τ_1 = 80x 25ns gap between adjacent bunches (2.025μs).

τ_2 = 1 missing bunch for beam dump kicker rise time (4.050μs).

Uses single bunches from the PS.

Gives Equally spaced bunches around the machine.

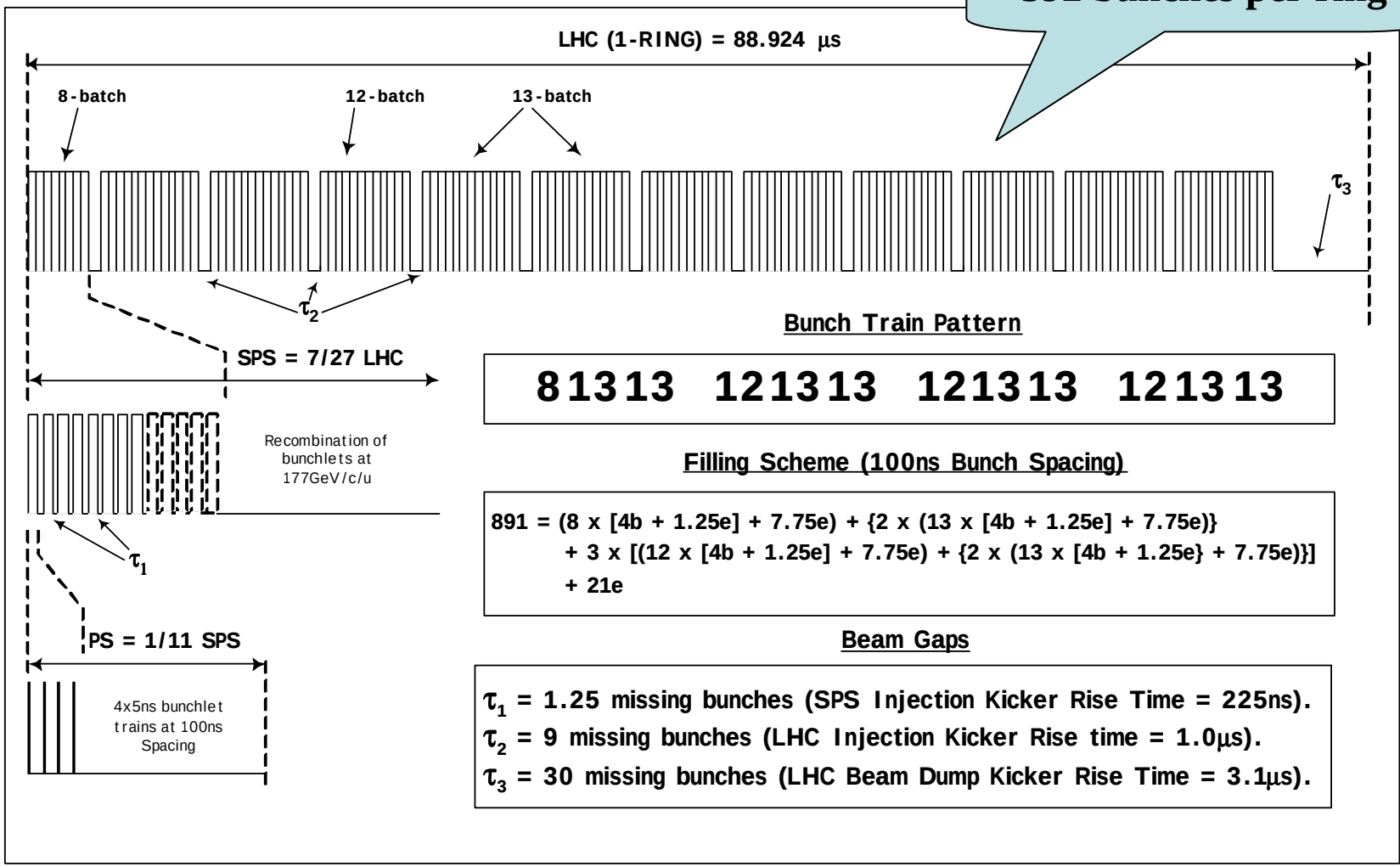
Avoids crossing schemes in the LHC

N.B. As shown above, there are no collisions in LHCb

Cure this by moving Some of the bunches in 1 ring by 75ns.

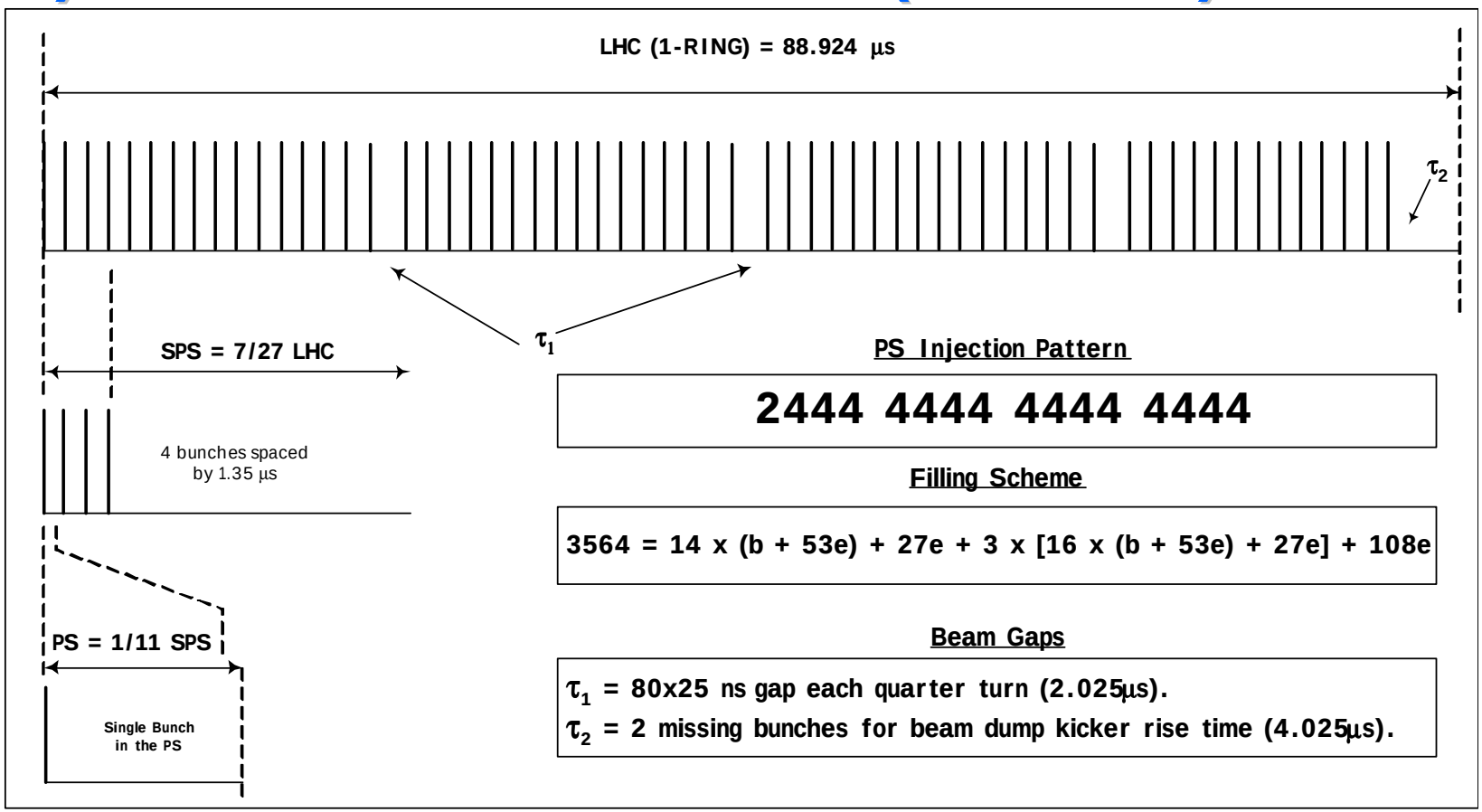
Filling time same as the nominal scheme

4) 100ns Heavy Ions Scheme



Complicated! Never more than 4 bunches in a row actually at 100ns spacing!

5) 62-Bunch Scheme for Ions (or Protons)



Designed as the 'poor mans' initial ion scheme (avoiding many complications in the injectors). Is equally valid for use with protons.

Consists of 4 long trains with 16(14) bunches spaced by 1.35μs bunches in each train.

Summary

- **There are many different filling schemes possible.**
  - **The 5 mentioned here are the present 'baseline' schemes each having a specific purpose.**
- **Often the pattern of bunches and gaps is quite complex**
  - **The data exchange needed between the LHC and the injectors is under study (LHC-OP) …**
  - **The LHC will have to 'broadcast' something that allows any equipment (or experiment) to work out what the pattern is – and synchronize to it.**
  - **bunch 1 is the first bunch after the dump gap.**
  - **The beam dump gaps are timed to 'collide' in IP1 & IP5 – so these IP's see the most collisions.**
  - **The most complex scheme is that for ions where 25% of the bunch gaps are not the standard 100ns bunch spacing.**
  - **It is likely that many other schemes will be invented during the lifetime of the LHC!**