LHC ultimate filling schemes

- Baseline design choices in 1994 (PS Complex for LHC)
- Present performance and limitations for ultimate beam
- Ultimate beam via batch compression in the PS
- LHC filling schemes for ultimate beam
- Conclusions

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Baseline design (1994) of the LHC injectors' chain

⇒ "PS for LHC" project designed to enable production of ultimate beam, by fighting the space charge limit:

- at PSB injection, filling the PS with two PSB batches to halve N/ε^* and therefore the tune spread in the PS Booster.

  ⇒ ΔQ from 0.7 to 0.35 for nominal beam and to 0.55 for ultimate beam.

- at PS injection, increasing the PSB - PS transfer energy from 1 GeV to 1.4 GeV.

  ⇒ ΔQ from 0.3 to 0.2 for nominal beam and to 0.32 for ultimate beam.

⇒ Since 1994, modifications of the LHC parameters and the longitudinal procedure in the PS (bunch splitting instead of debunching rebunching had the following consequences:

- for a given luminosity in the LHC, the PSB and PS must deliver a higher intensity / brightness.
- this increased intensity / brightness implies higher space charge tune spreads at low energy.

Present performance summary

25 ns LHC beam intensity requirements 1994 - 2003

25 ns LHC beams	1994	2003	Intensity increase
LHC nominal bunch	1.00×10^{11}	**1.15×10^{11}**	1.10·1.05 = **1.15**
PSB nominal bunch	10.50×10^{11}	**16.29×10^{11}**	**1.10·1.05·1.14/0.85 = 1.55**
LHC ultimate bunch	1.70×10^{11}	**1.70×10^{11}**	**1.00**
PSB ultimate bunch	17.85×10^{11}	**25.50×10^{11}**	**1.14/0.80 = 1.42**

LHC changes (crossing, β*)

Transmission eff.

PS process change

⇒ Ultimate 25 ns beam is far out of reach of the PSB with the standard production scheme [ΔQ at injection in the PSB ~ 0.8 and in the PS ~ 0.45]

⇒ Nominal 25 ns beam can be produced but there is no longer a comfortable emittance budget. (Close to 1994 ultimate requirements)

⇒ All other beam variants (75 ns, single bunch physics beams, pilot, etc.) can be produced by the PS complex.

Increasing brightness in the PS: Batch compression

Proposed procedure (R. Garoby):

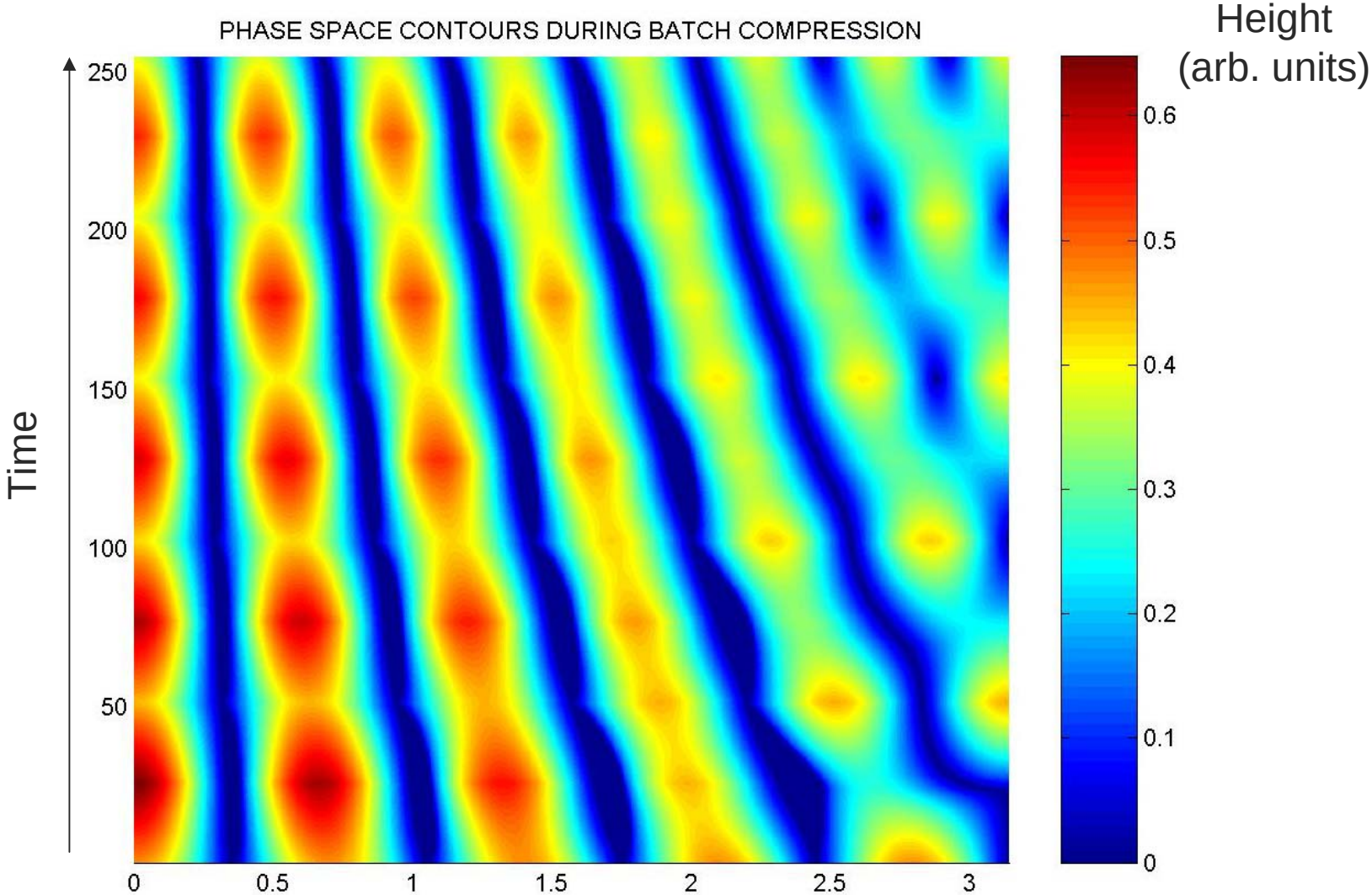
- Inject 7 (4+3) or possibly 8 (4+4) bunches **from two PSB batches** into the PS operating on harmonic 9,
- Accelerate this beam up to an intermediate energy where space charge is sufficiently reduced.
- Compress the 7 (8) bunches into 7 (8)/14 of the PS circumference by adiabatically increasing from h=9 to 10,11, 12, 13, 14. **→Needed for 25 ns final spacing!**
- Accelerate the beam on harmonic 14 up to 25 GeV,
- Triple split the bunches using rf on h=14, 28 and 42 (similar process than used at 1.4 GeV for the 25 ns bunch train),
- Double split bunches, changing the harmonic from 42 to 84, and rotate them before ejection, as in the present 25 ns bunch train scheme.

⇒ **Finally, a train of 42 or 48 bunches, spaced by 25 ns is sent to the SPS every 3.6 s.**

⇒ **Best expected performance: assuming space-charge limit (with 1.2 s inj. flat) in the PS corresponds to $84 \times 1.7 \times 10^{11}$ protons over the circumference**

⇒ **2.6×10^{11} ppb @ PS ejection**

Batch compression (7 PSB bunches):



The ultimate LHC filling scheme

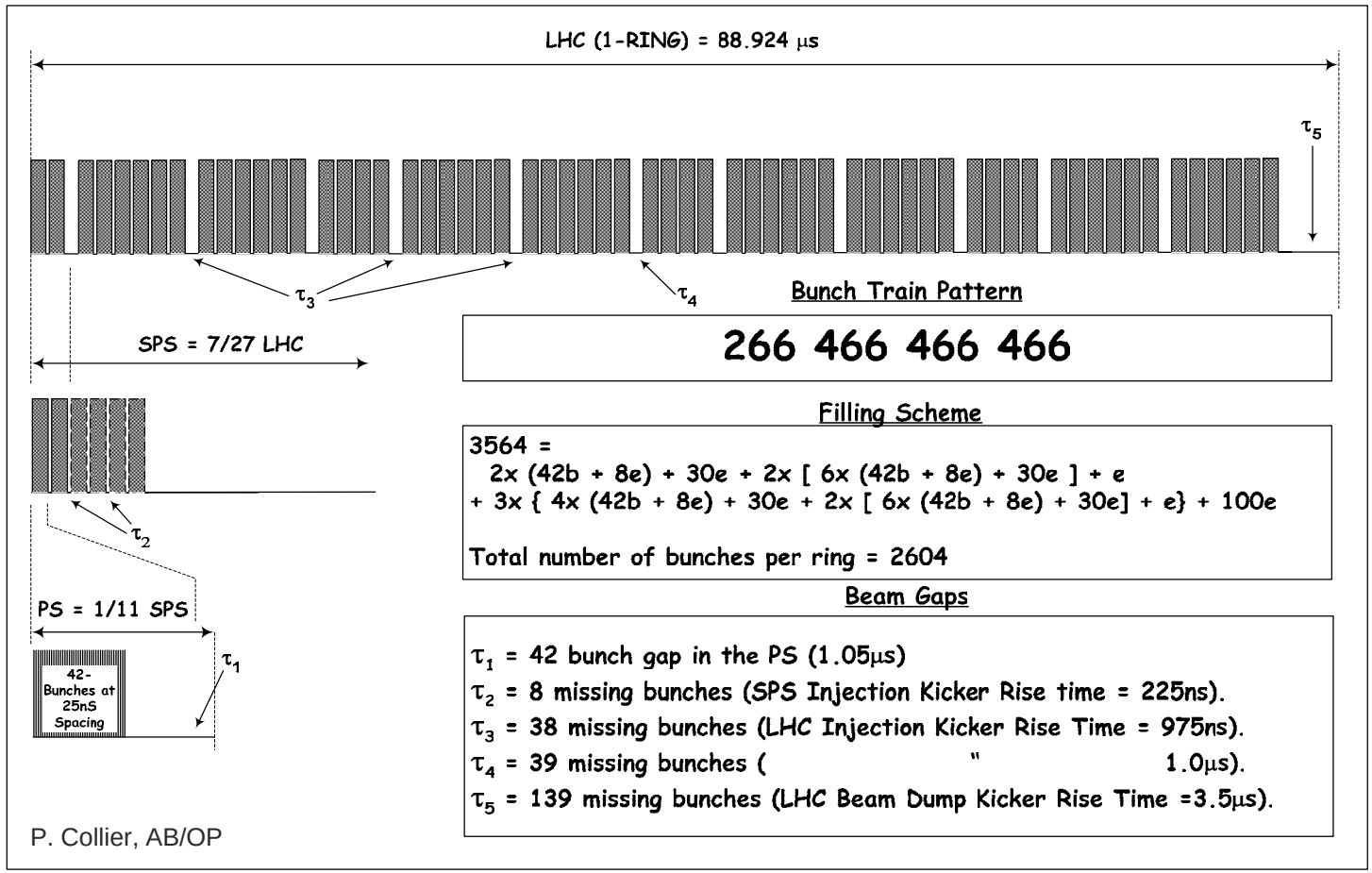
- **Nominal Scheme: 6 Booster bunches to give 72 LHC bunches.**
- **"Ultimate scheme: 7 (8) Booster bunches to give 42 (48) LHC bunches.**
- **Bunch trains with 42 (48) bunches instead of 72 bunches from PS require special filling schemes (→ P. Collier).**

Reminder of Limitations:

- LHC Beam Dump 3μs,
- Injection Kicker Rise time 950ns, flat top <7.86μs
- SPS Injection Kicker 225ns
- Last Injection longest
- 4-fold symmetry … etc …

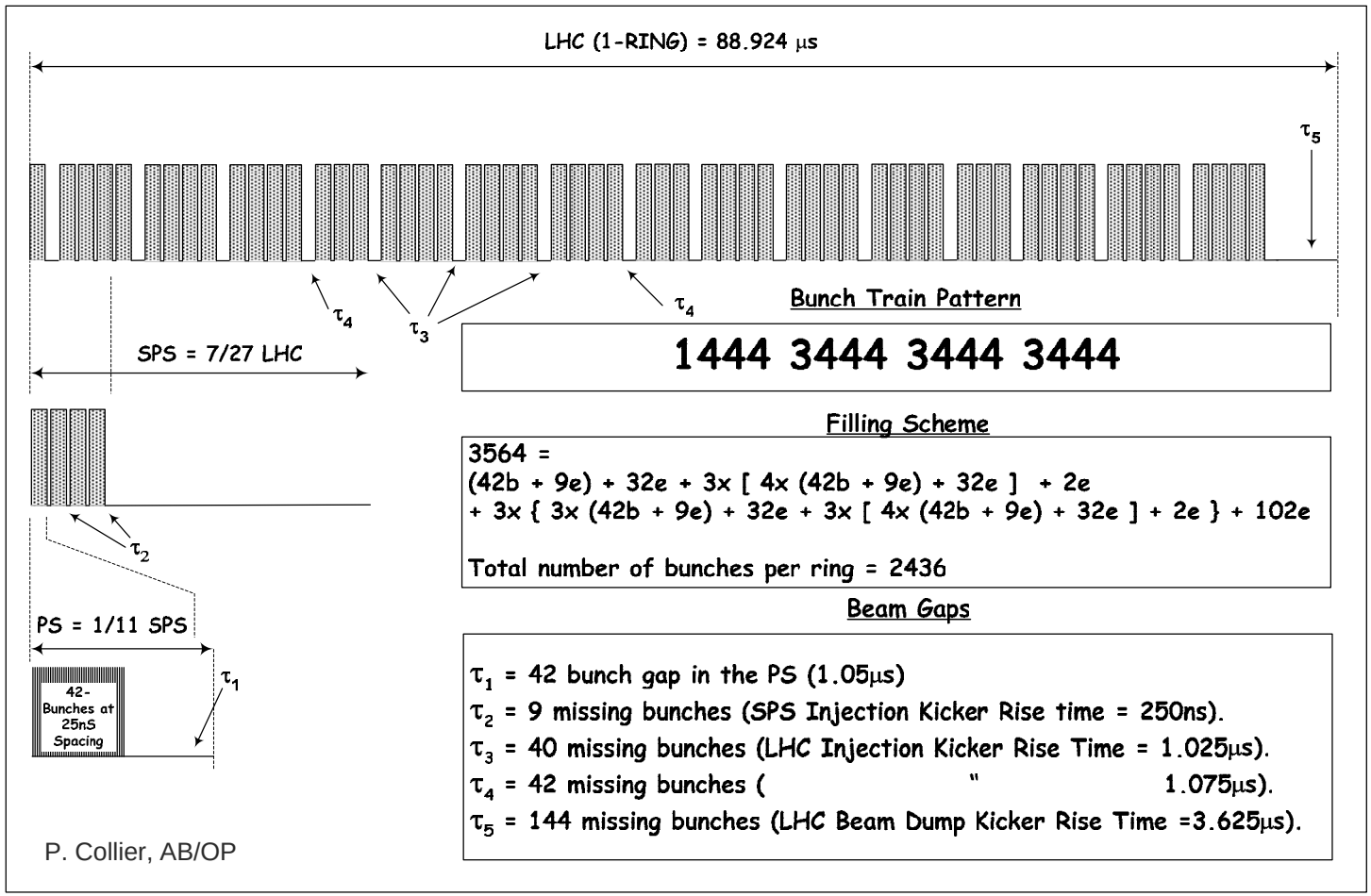
- **42 bunches preferred to 48 bunches (more bunches in LHC)**
- **2 Solutions with 42 bunches@25ns in the PS:**
- **Solution 1: 266 466 466 466 ➔ 2604 bunches**
- **Solution 2: 1444 3444 3444 3444 ➔ 2436 bunches**

Batch compression (7 bunches case) (4): "Ultimate" filling scheme for 42 PS bunches (i)



- 2604 bunches/ring: only 7% fewer than for nominal 72 bunch scheme.
- Fewer bunches in the SPS than the "nominal" scheme: 252 vs. 288
- 6 injections and 18 s SPS flat bottom: problems with high brightness?

Batch compression (7 bunches case) (5): Alternative filling scheme for 42 PS bunches



- **2436 bunches/ring: 13% fewer than for nominal 72 bunch scheme.**
- **Only 4 injections in the SPS.**

Conclusions

- **Proposed scheme allows production of “ultimate” and even higher brightness beams for LHC.**
- **Low cost, mainly manpower and machine time for MDs required.**
- **With the proposed filling scheme (up to 6 PS batches) slightly lower LHC filling factor (-7%) and increased filling time (+ 30 %, i.e. ~6 min instead of 4 ½)**
- **Ideally suited method to study limitations and effects of ultimate beams in SPS and LHC**