Bunch filling schemes for early running scenarios

M. Ferro-Luzzi and W. Herr

Issues for bunch filling scheme:

- **LHC collider issues:**
  - **Luminosity**
  - **Experimental conditions**
  - **Beam-beam effects**
  - **Other collective effects**
  - **Diagnostics**
  - **....**
- **Injector chain (input from Elias, Gianluigi)**

Luminosity considerations - reminder

- **proton-proton operation:**
  - **ATLAS and CMS: maximum integrated luminosity**
  - **LHCb:** $\mathcal{L}_{opt} = \mathbf{2\text{ - }5 \cdot 10^{32}\ cm^{-2}\ s^{-1}}$
  - **ALICE:** $\mathcal{L}_{opt} = \mathbf{1 \cdot 10^{29}\ cm^{-2}\ s^{-1}}$
    - **→ Requires reduction even for small number of bunches (43) !**

Filling schemes versus beam-beam effects

- **Aim: minimize bunch-to-bunch variations (orbit, tune, chromaticity ..)**
- **Try to maintain a ”quasi” 4-fold symmetry**
- **Minimize number of different classes of bunches (i.e. number of interactions, strength of interactions)**
- **Allow (passive) compensation of PACMAN effects**

Present LHC filling scheme (25 ns):

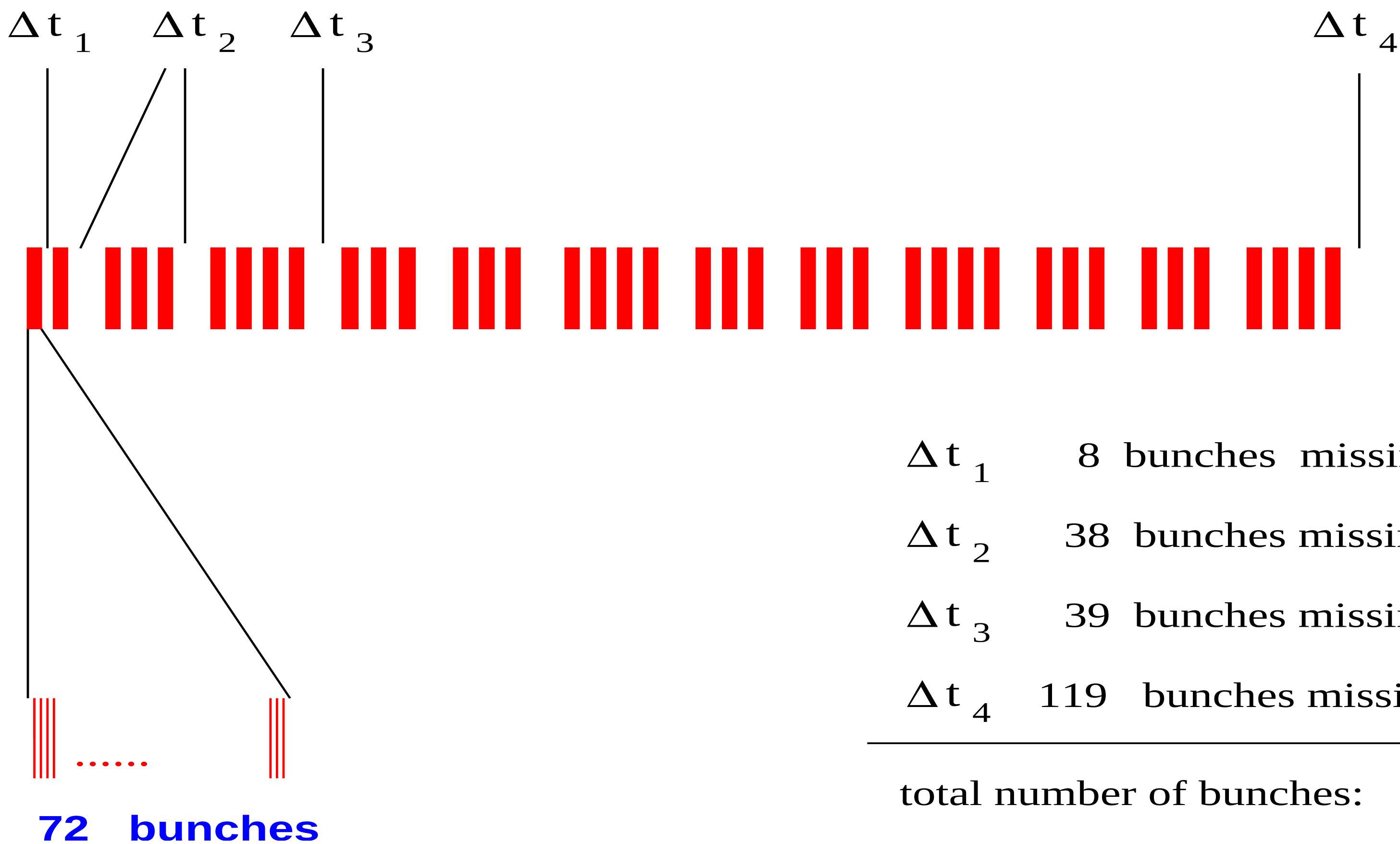
- **Present scheme for high (nominal) luminosity with 25 ns spacing, with 72 bunches per batch**

  Usually presented as:

  $$[2*(72b+8e)+30e]+[3*(72b+8e)+30e)]+[4*(72b+8e)+31e]+$$
  $$3*\{2*[3*(72b+8e)+30e]+[4*(72b+8e)+31e]\}+$$
  $$80e = 3564$$

- **Total 2808 bunches (b), 756 empty spaces (e)**
- **Batches of 72 bunches, trains of 2,3,4 batches in SPS**
- **Requires 12 SPS/LHC transfers per beam**

Present LHC filling scheme (25 ns):



Δt_1	8	bunches missing
Δt_2	38	bunches missing
Δt_3	39	bunches missing
Δt_4	119	bunches missing

total number of bunches: 2808

Beam-beam considerations

- **LHC is machine with many bunches, this dominates beam-beam effects**
- **Exact collision schedule needed for all studies**
- **Self-consistent beam-beam and luminosity computations:**
  - **Orbits, tune, chromaticity, ... (for each bunch)**
  - **Coherent motion, measurement response**
  - **Luminosity optimization**
- **Needs more appropriate, flexible description (asymmetries, missing bunches, fluctuations ...)**

Filling scheme description

We have 35640 buckets → 3564 slots for bunches spaced by 25 ns

How we count:
numbering of bunches according to slot number (or equivalent: bucket number), for any spacing

E.g. 43-bunch scheme:
(82, 163, 244, ...)

Filling scheme description

- is constructed from some input like (nominal, see e.g. LHC Project Note 344 (2004)):

72 0 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 30 0 0 0
72 1 8 0 72 1 8 0 72 1 8 0 72 1 39 0

- can be different for the two beams

Collision schedules

For 8-fold symmetry: 445.5 slots between interactions points !

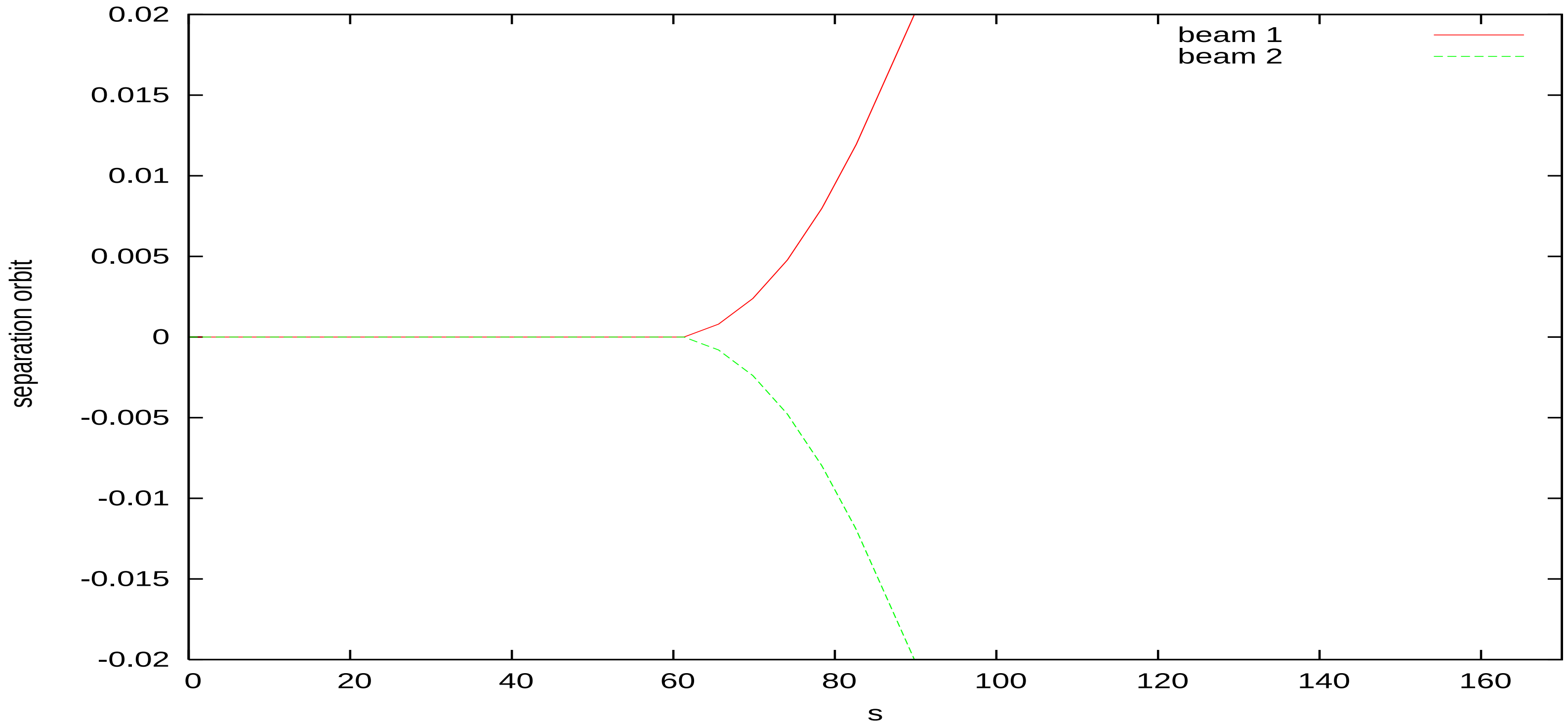
In IP1, IP5 and IP8:
collisions of even-even and odd-odd (slots)
In IP2 (... and DELPHI):
collisions of odd-even and even-odd

- **for any bunch spacing $\neq$ 25 ns → watch out !**

The interesting configurations

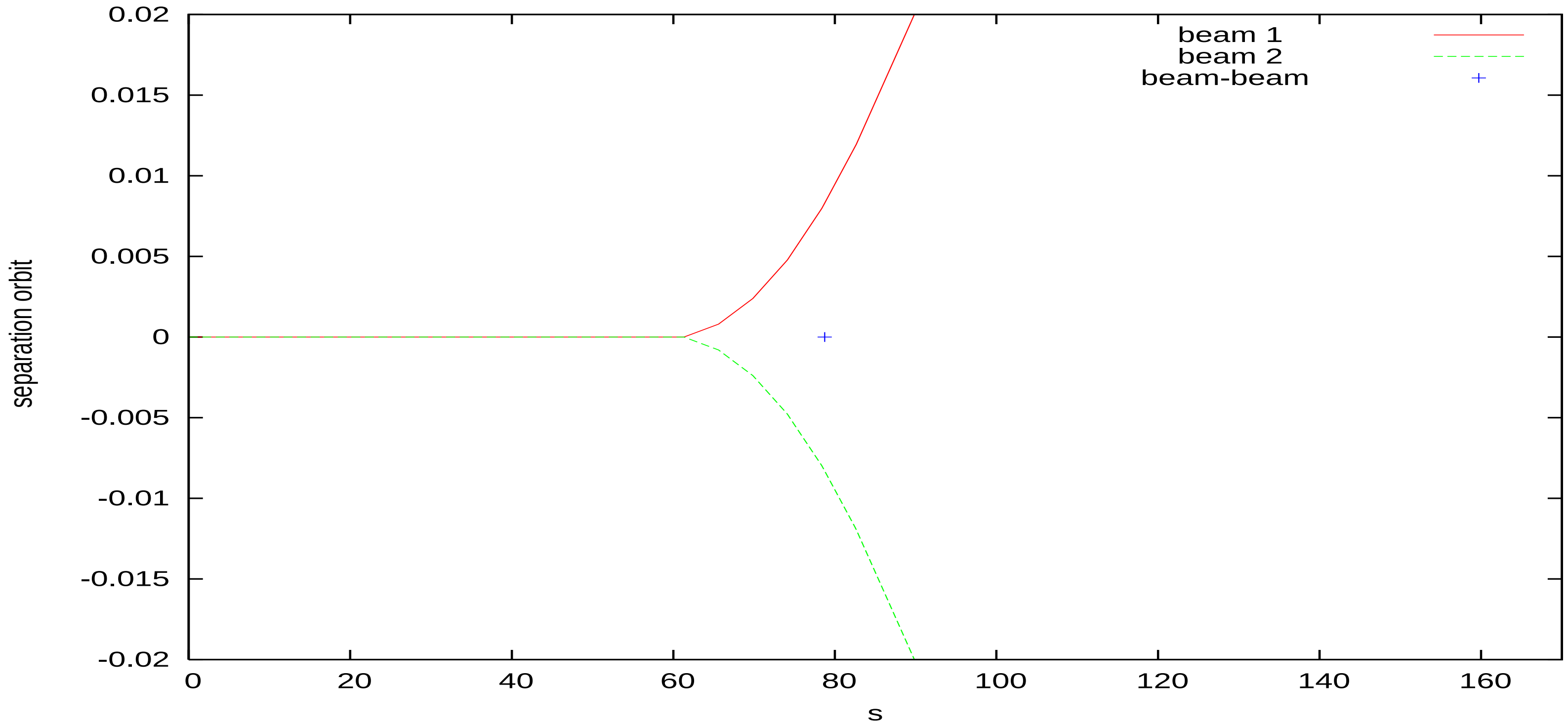
- Consider protons only:
  - Nominal 25 ns spacing - no trouble
  - For 43 or 156 bunches, optimized for IP1, IP2 and IP5
  - For 75 ns spacing - get good collision rate in all IPs (too much for IP2 ?)
  - For 50 ns spacing - watch out for IP2 and IP8
- What about crossing schemes ?

Beam separation scheme (e.g. right of IP5):



- **Beam orbits with D1 (≈ 60 m) and D2 (≈ 160 m) only**

Beam separation scheme (525 ns, 156 Bunches):



- **D1 and D2 only, no crossing angle needed**

Collisions in LHC experiments - numerology

- **Nominal bunch filling scheme with 25 ns spacing**

	collisions
collisions in IP1	2808
collisions in IP2	2736
collisions in IP5	2808
collisions in IP8	2622

Collisions in LHC experiments - numerology

- **Collisions in IPs with 43 (44) equidistant bunches**

	collisions
collisions in IP1	43
collisions in IP2	42
collisions in IP5	43
collisions in IP8	0
collisions in DELPHI	42

How to collide in LHCb ?

- **Have to displace N_s bunches of the N_b bunches**
  - **IP1,IP5: collide regular-regular, displaced-displaced**
  - **IP2: collide regular-regular**
  - **IP8: collide regular-displaced**
- **Two strategies:**
  - **Displace bunches in one beam**
  - **Displace bunches in both beams symmetrically**
- **Assumptions:**
  - **Can shift PS to SPS injection (one batch)**
  - **Can shift SPS to LHC injection (2, 3 or 4 batches)**
  - **Can replace SPS to LHC injection by single bunch**

How to collide in LHCb ?

- **Have to displace N_s bunches of the N_b bunches**
  - **IP1,IP5: collide regular-regular, displaced-displaced**
  - **IP2: collide regular-regular**
  - **IP8: collide regular-displaced**
- **Two strategies:**
  - **Displace bunches in one beam**
  - **Displace bunches in both beams symmetrically**
- **Assumptions:**
  - **Can shift PS to SPS injection (one batch)**
  - **Can shift SPS to LHC injection (2, 3 or 4 batches)**
  - **Can replace SPS to LHC injection by single bunch**

How to collide in LHCb ?

- **Two strategies:**
  - **Displace bunches in one beam**

    → **loss of collisions in IP1, IP5 and IP2, possibly other side effects**
  - **Displace bunches in both beams symmetrically**

    → **still collide in IP1, IP5, additional losses in IP2**
- **Theoretical maximum for equidistant bunches:** $N_b/2$
- **For 43 bunches → can shift up to 22 (6 SPS to LHC injections)**
- **In LHCb: 21 collisions, but 0 in ALICE**

Collisions in LHCb - numerology

- **Collisions in IPs with 43 equidistant bunches, different displacement strategies**

displaced	0	4 (asym)	4 (sym)	11 (sym)	19 (sym)
IP1	43	39	43	43	43
IP2	42	38	34	21	4
IP5	43	39	43	43	43
IP8	0	4	4	11	19

- **Consider displacement of both beams from now on**

Collisions in LHCb - numerology

- **Bunch filling scheme with 156 bunches**

	no bunches displaced	option 1	option 2
collisions in IP1	156	156	156
collisions in IP2	152	76	16
collisions in IP5	156	156	156
collisions in IP8	0	36	68

Bunch spacing 50 ns

- **Advantage: high luminosity, much fewer long range interactions**
- **Interesting if desired collision rate in IP2 very small**
- **Constructing 50 ns spacing from nominal scheme:**
  - **Start from nominal 25 ns spacing**
  - **Remove every second bunch of a train, keep first bunch (no collisions in IP8)**
  - **Shift selected trains (SPS/LHC transfers) by 1 slot to get desired sharing between IP2 and IP8**

LHCb collision options:

a) No shift

b) Shift SPS/LHC transfers 4 - 6

c) Shift SPS/LHC transfers 4 - 6, 10 - 12

d) Shift SPS/LHC transfers 1 - 3, 7 - 9

e) Shift SPS/LHC transfers 2 - 3, 7 - 9, replace transfer 1 by one single bunch

Numerology of collisions

- **Bunch filling scheme with 50 ns spacing**

	a	b	c	d	e
IP1	1404	1404	1404	1404	1333
IP2	1368	684	0	72	2
IP5	1404	1404	1404	1404	1333
DELPHI	1368	684	0	72	2
IP8	0	655	1035	1242	1173

Summary and recommendations

- **Without crossing angle: optimize collision rate in IP1 and IP5 by symmetric displacement in both beams, sharing between IP2 and IP8 can be largely adjusted.**
- **valid for 43 and 156 (54) bunches options**
- **In case $\mathcal{L}$(IP2) low: modified 50 ns scheme is a good alternative to 75 ns scheme**