Recent beam-beam observations

(... and some beam-beam basics)

reported by W. Herr

Key issues for $\mathcal{L} \geq 10^{32}$ cm^{-2}s^{-1}

As discussed at special LMC ..

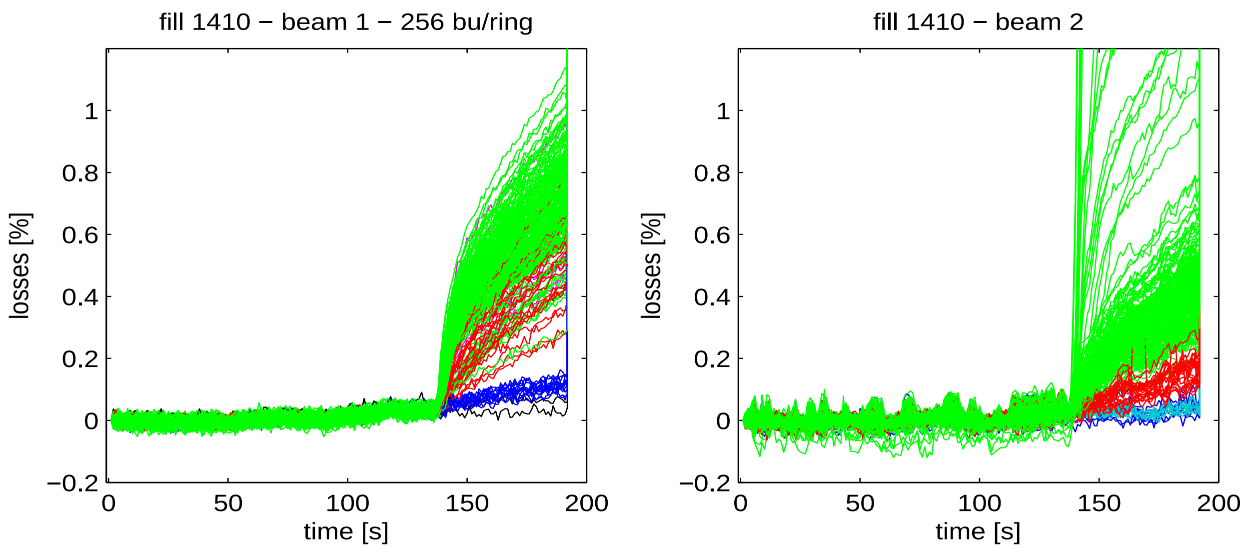
- **High intensity**
- **Small ϵ**
- **Bunch trains**
- **(smaller β^*, not done/needed)**
  - **Can expect effects on beam-beam interactions ..**

Expected effects on beam-beam interactions

	$\mathcal{L}$	HO beam-beam	LR beam-beam
High Intensity	++	−	−
Small ϵ	++	−	+
Number bunches	++	o	−
(**Smaller** β^*	+	o	−−)

➡ **Are changes sufficient to see the expected effects ?**

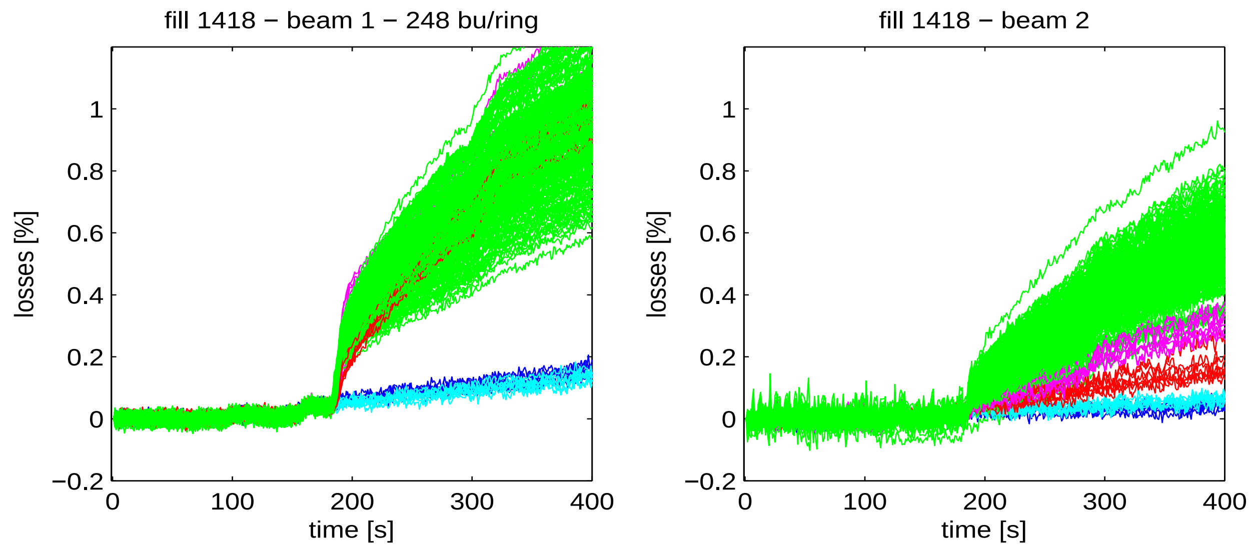
Recent fills ...



(Prepared by G. Papotti BE-OP-LHC)

- **High luminosity, a bit too short (1410, not 1409)**
- **Losses "sorted" according to number of collisions**
- **Is 1% loss in 1 minute (beam 1) a problem ?**

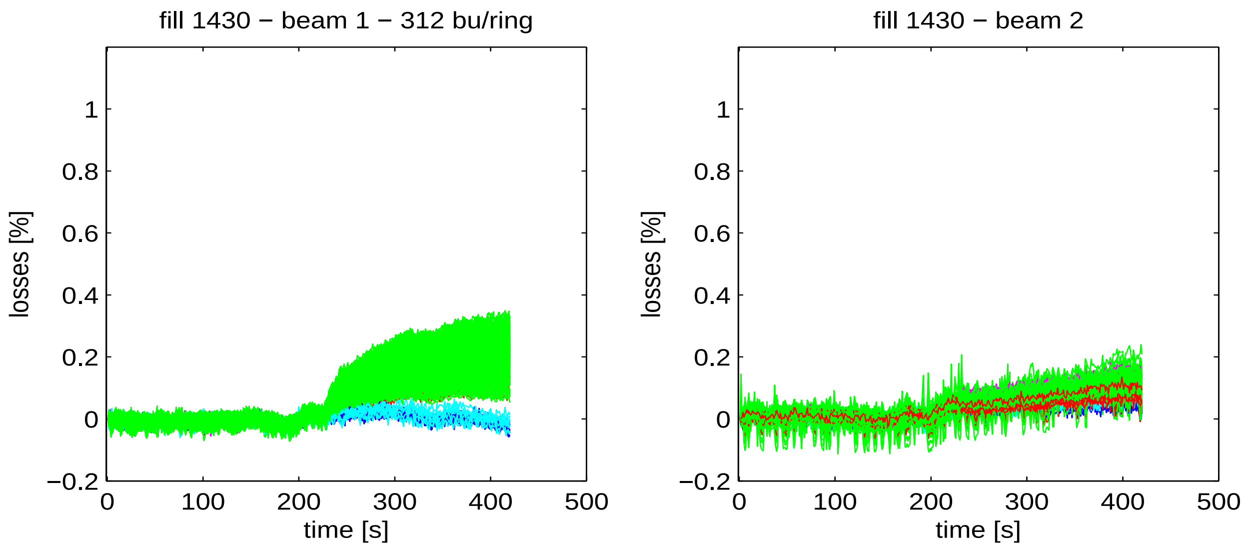
Recent fills ...



(Prepared by G. Papotti BE-OP-LHC)

- Good fill, Luminosity above $1.2 \cdot 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Beam 1 does not look too much different, but no bunches with very fast losses in beam 2

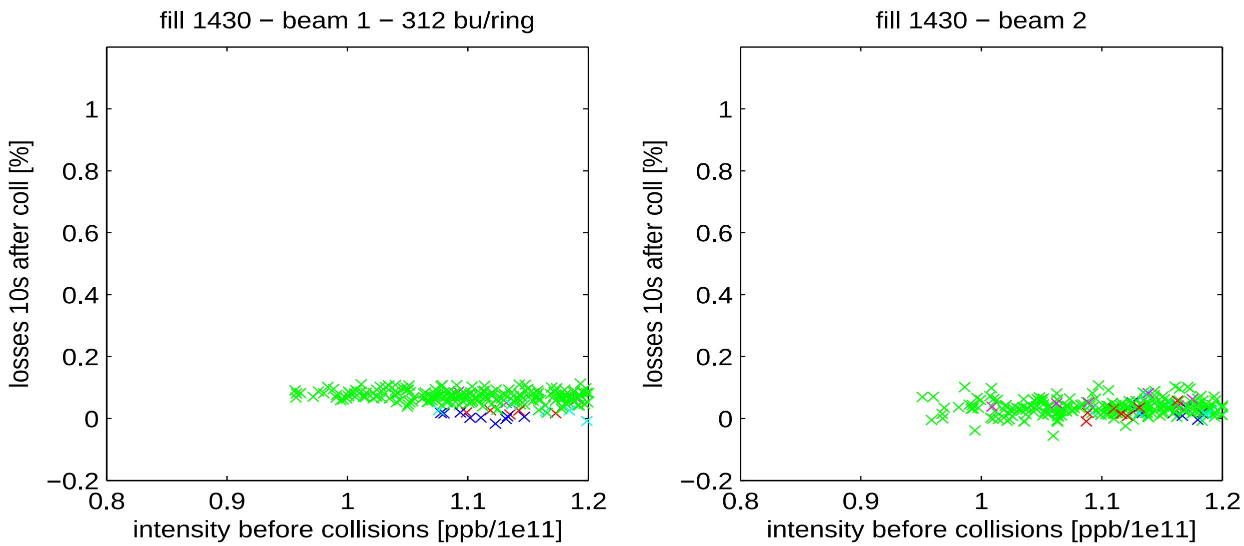
Recent fills ...



(Prepared by G. Papotti BE-OP-LHC)

➡ **Good fill, Luminosity above $1.4 \cdot 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$**

Recent fills ...



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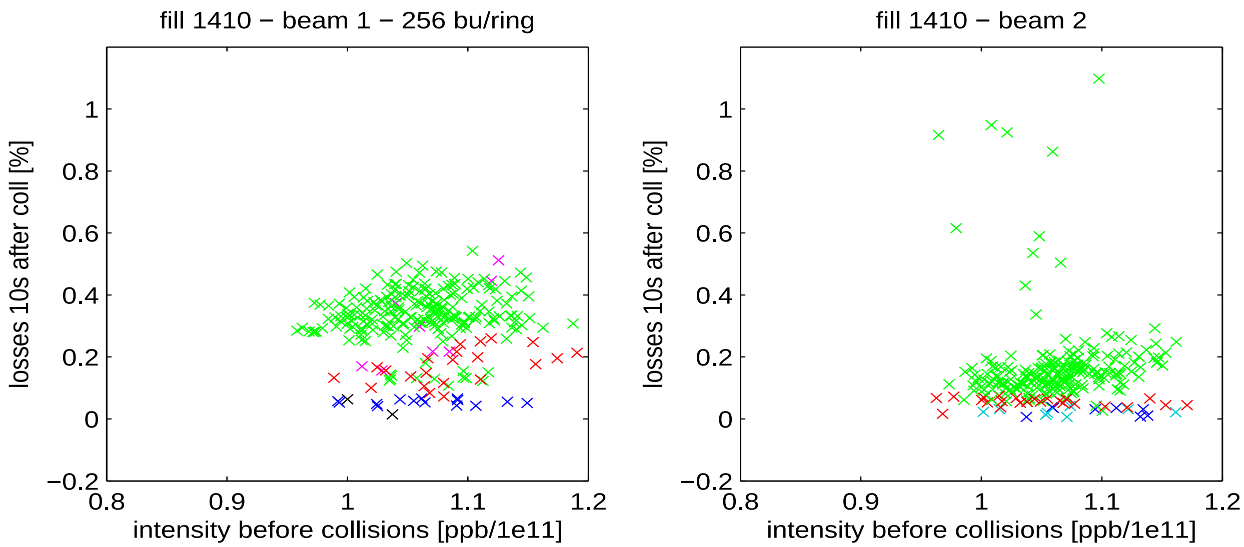
→ **Losses bunch by bunch (fill 1430)**

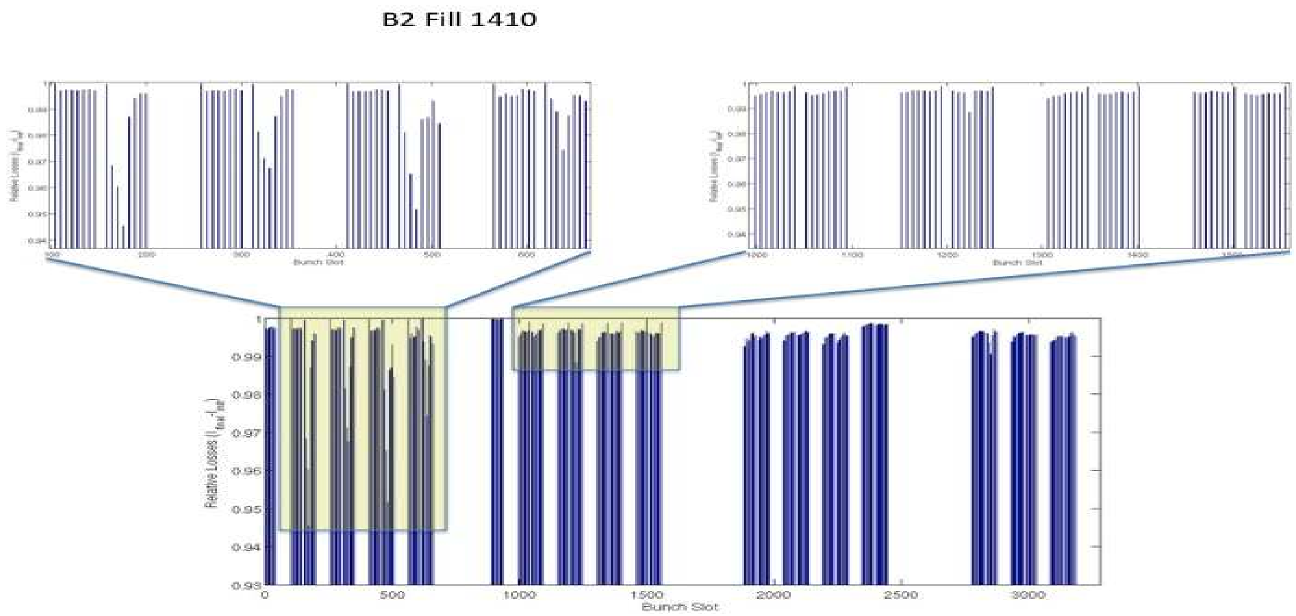
Recent fills ...



(Prepared by G. Papotti BE-OP-LHC)

- **Losses bunch by bunch (fill 1410)**
- **Beam dump due to a few bunches with bad life time**

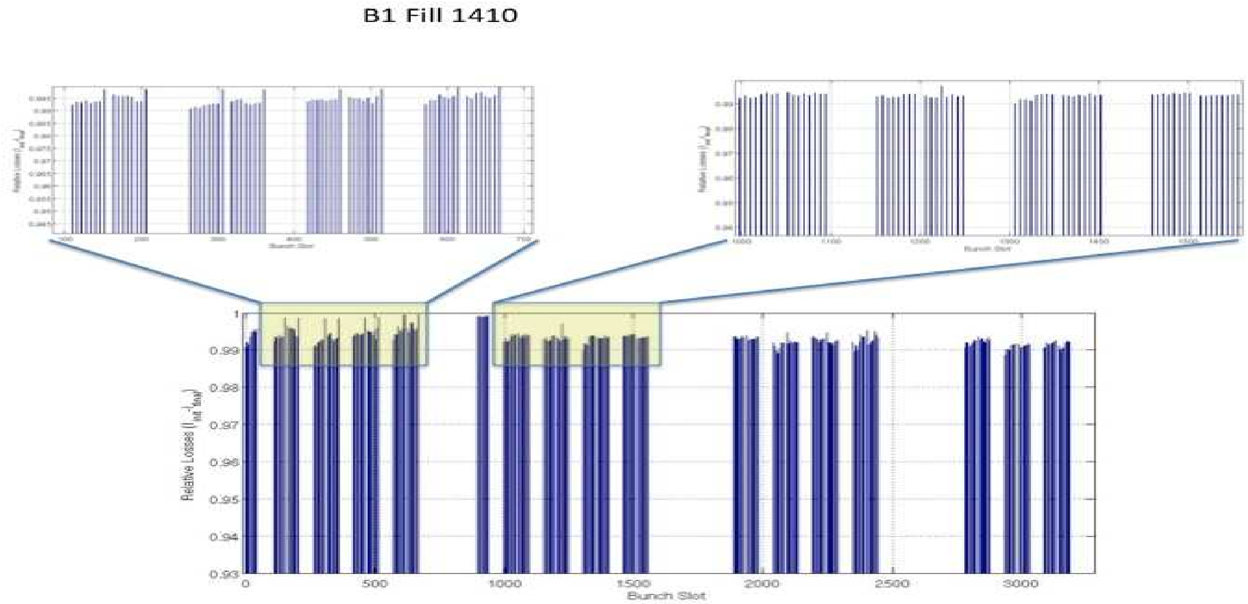
Recent fills ...



(Prepared by T. Pieloni BE-ABP)

- Losses bunch by bunch beam 2 (fill 1410)
- Losses as identified on Giulia's first plot

Recent fills ...



(Prepared by T. Pieloni BE-ABP)

➡ **Losses bunch by bunch beam 1 (fill 1410)**

Recent fills ...

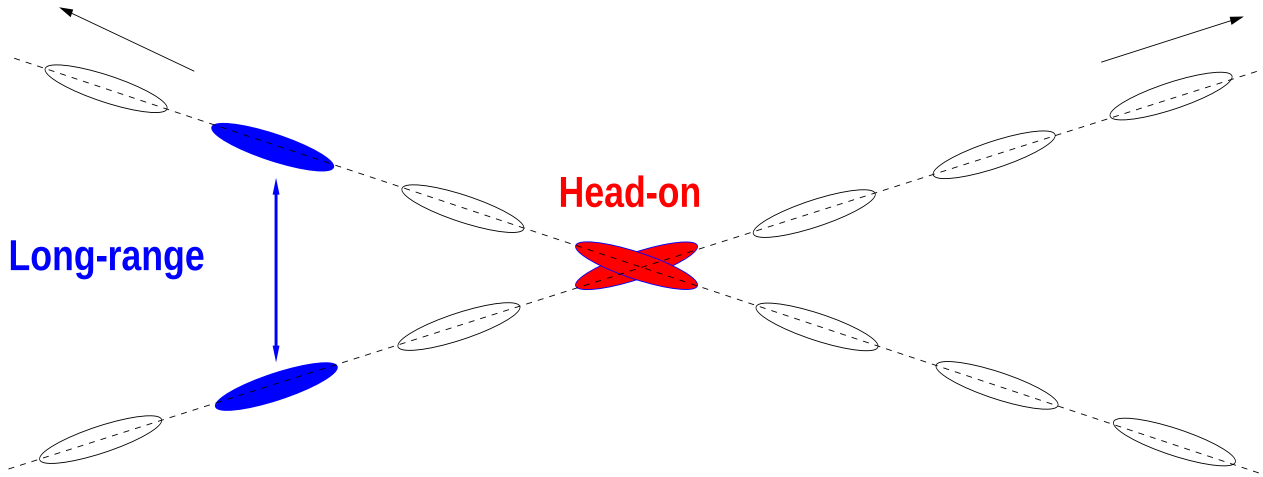
- **Clear correlation between losses and number of head-on collisions (beam-beam not only academic)**
- **Total tune shift (3 collisions) $\approx$ 0.02 (assuming: 1.0 - 1.2 $\cdot 10^{11}$, $\epsilon_n \approx$ 1.8 - 2.2μm)**
  - **Can we understand the losses ?**
  - **Directly related to beam-beam tune shift ?**
  - **Are the long range contributions important ?**

→ **Need to respond to some questions/comments I got since 24.9. 8:33 a.m.**

Beam-beam tune shifts - where do they come from ?

- **Head-on tune shifts**
  - **Depend on:** N, ϵ_n, $[\alpha, \sigma_s]$
- **Long range tune shifts**
  - **Depend on:** N, ϵ_n, β^*, α, n_{lr} **(number of bunches)**

Head-on and long range interactions



➡ **Both types around each IP**

Head-on tune shift

For round beams like LHC:

$$\Delta \, \mathbf{Q}_{ho} \;\propto\; \xi \;=\; \frac{N r_0 \beta^*}{4\pi\gamma\sigma^2}$$

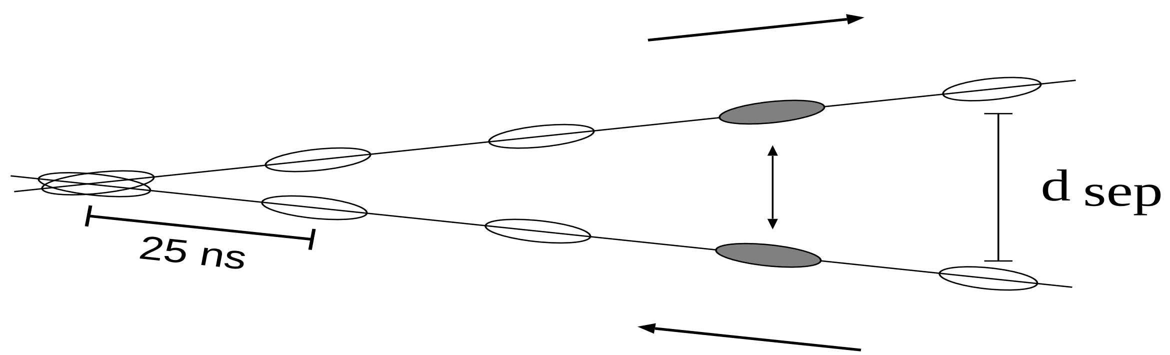
$$\rightarrow \quad \Delta \, \mathbf{Q}_{ho} \;\propto\; \xi \;=\; \frac{N r_0}{4\pi\epsilon_n} \;=\; \frac{r_0}{4\pi} \cdot \frac{N}{\epsilon_n}$$

Remark: $\Delta \, \mathbf{Q}_{ho} \neq \xi$! (depends on phase advance between IPs, for LHC tunes $\Delta \, \mathbf{Q}_{ho} \approx \xi$)

Is changed by (net) crossing angle: reduced in plane of crossing (depends on α_{net}, σ, σ_s)

$$S = \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma} \tan \frac{\alpha_{net}}{2})^2}} \approx \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma} \frac{\alpha_{net}}{2})^2}}$$

Geometry of long range interactions



- **Normalised separation:** $d_{sep} = \Delta x/\sigma = \Delta x(s)/\sigma(s)$
- **Tune shift:** $\Delta \mathbf{Q}_{lr} \propto \frac{1}{d_{sep}^2}$
- **We want a large separation** d_{sep}

Geometry of long range interactions

- $d_{sep} \;=\; \Delta x(s)/\sigma(s)$
- $\Delta x(s) \;=\; \alpha \cdot s$ **(ftp:** $\sin(\alpha) \cdot s$ **)**
- $\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$

(s **taken at long range encounter, i.e. multiple of half bunch distance)**

with $\beta(s) = \beta^* \cdot \left(1 + \left(\frac{s}{\beta^*}\right)^2\right)$

for small β^* **we get** $d_{sep} \;\approx\; \frac{\alpha \cdot \sqrt{\beta^*}}{\sqrt{\epsilon}} \;=\; \frac{\alpha \cdot \sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}}$

(but not true after first quadrupole ..)

Comparison: head-on vs long range

- **Head-on tune shift**

$$\Delta Q_{ho} \propto \frac{N}{\epsilon_n}$$

- **Long range tune shift**

$$\Delta Q_{lr} \propto \frac{N}{d_{sep}^2} = \frac{N \cdot \epsilon_n}{\alpha^2 \cdot \beta^* \cdot \gamma}$$

- **Assuming separation the same for all n_{lr} encounters:**

$$\Delta Q_{lr} \propto \frac{N}{d_{sep}^2} \cdot n_{lr} = \frac{N \cdot \epsilon_n}{\alpha^2 \cdot \beta^* \cdot \gamma} \cdot n_{lr}$$

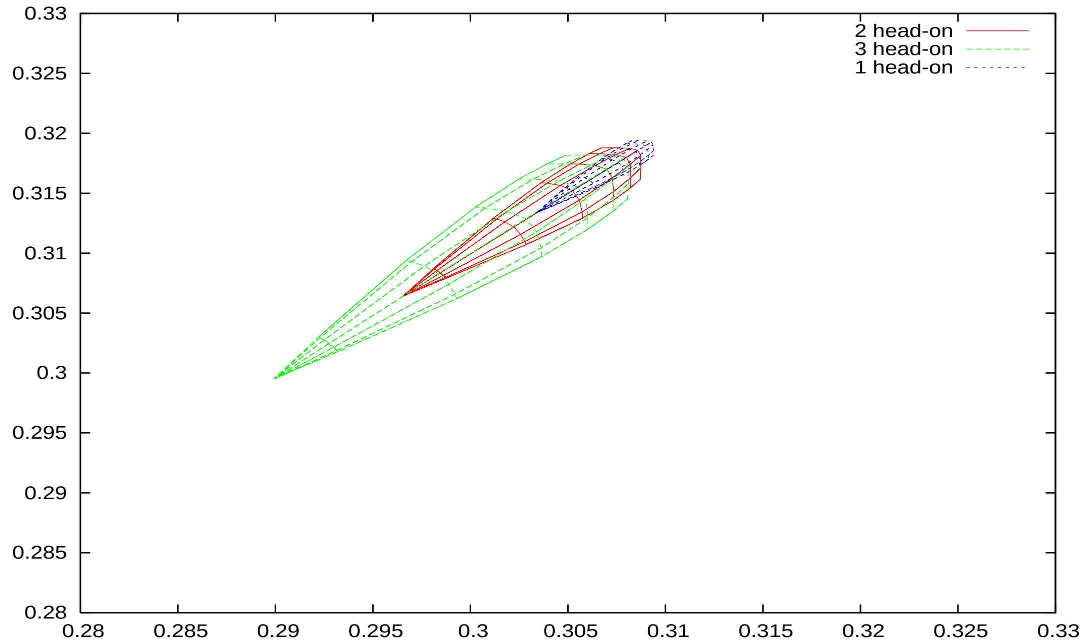
Strategy for optimization

Since:

$$\mathcal{L} \approx \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \approx \frac{N^2 f n_b \beta^* \gamma}{4\pi\epsilon_n}$$

- **Common wisdom:**
  - ➡ **If limit is <u>head-on</u> beam-beam: increase N, increase ϵ_n, reduce β^***
- **Not true if limit is due to <u>long range</u> beam-beam**
  - ➡ **Better to keep ϵ_n small as long as head-on limit it not reached**

Head-on footprints

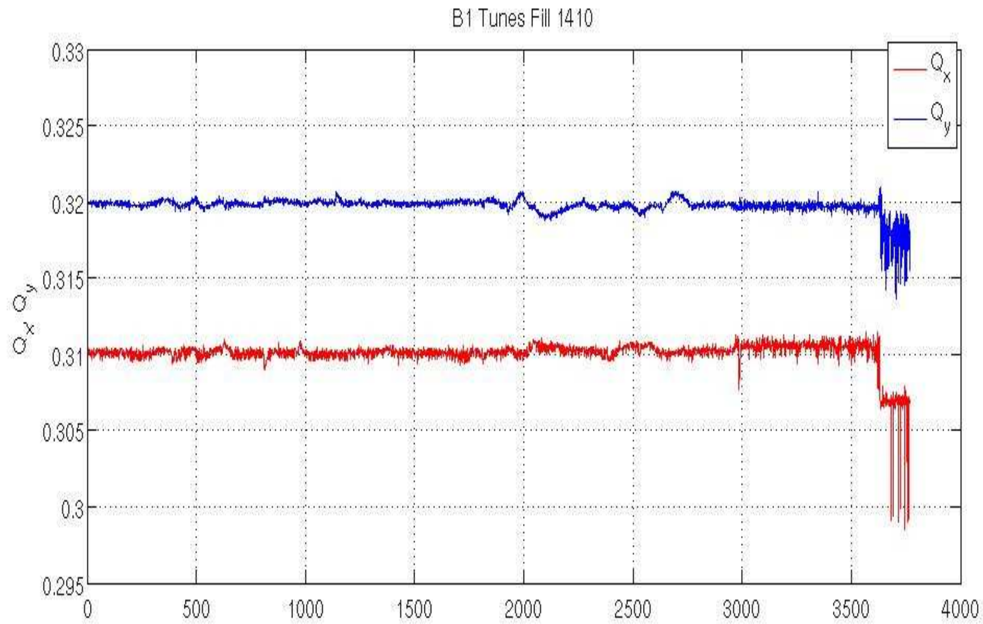


- **Tune spread for bunches with 1, 2, 3 head-on collisions**
- **Observation: for large amplitude particles: tune about the same in all cases !**

Head-on effects (protons only)

- **But: we can lose particles only at large amplitudes !**
- **What happens for very strong (exact) head-on effects ?**
  - **For single particle models: nothing (see e.g.: L. Evans ..)**
  - **With self-consistent models: small and (very) slow emittance growth (see e.g.: W.Herr, T.Pieloni, J.Qiang)**
- **When can we expect more dramatic effects?**
  - **Unequal beams (emittance, β-beating, offsets, ...)**
  - **External perturbations (noise, modulation, relative movement of the two beams, ...)**
- **Makes it difficult to analyse ...**
  - **Still looking, first look at the tunes ...**

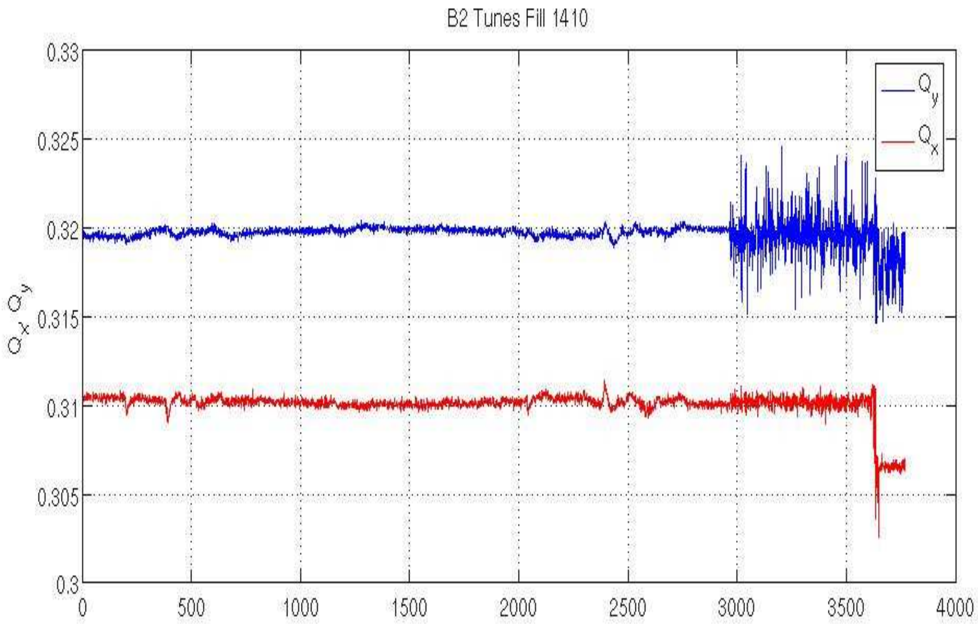
Tunes



(Prepared by T. Pieloni BE-ABP)

➡ **Beam 1 tunes, fill 1410 (the short one)**

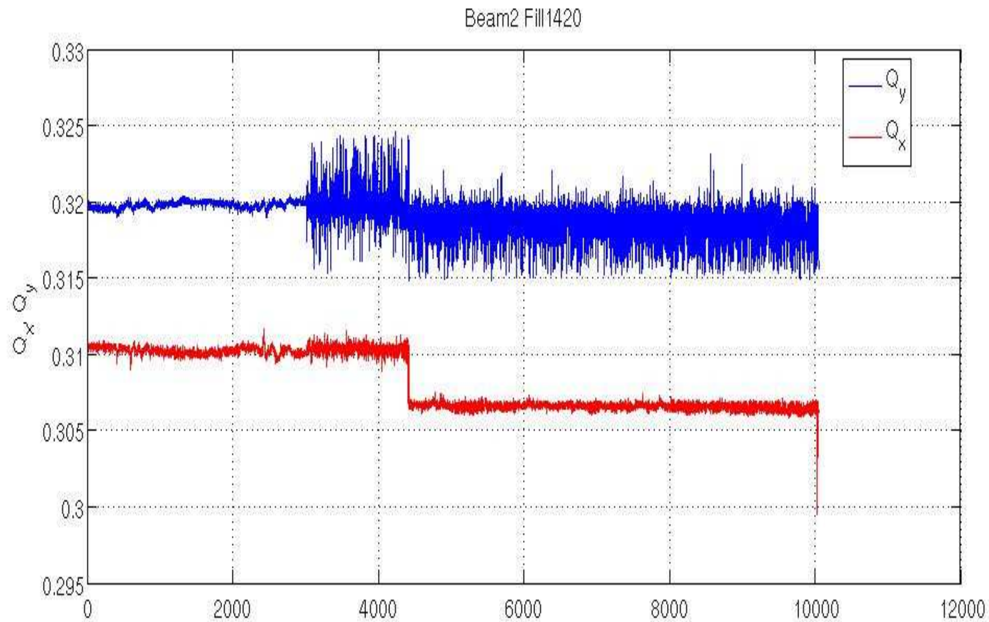
Tunes



(Prepared by T. Pieloni BE-ABP)

➡ **Beam 2 tunes, fill 1410 (the short one)**

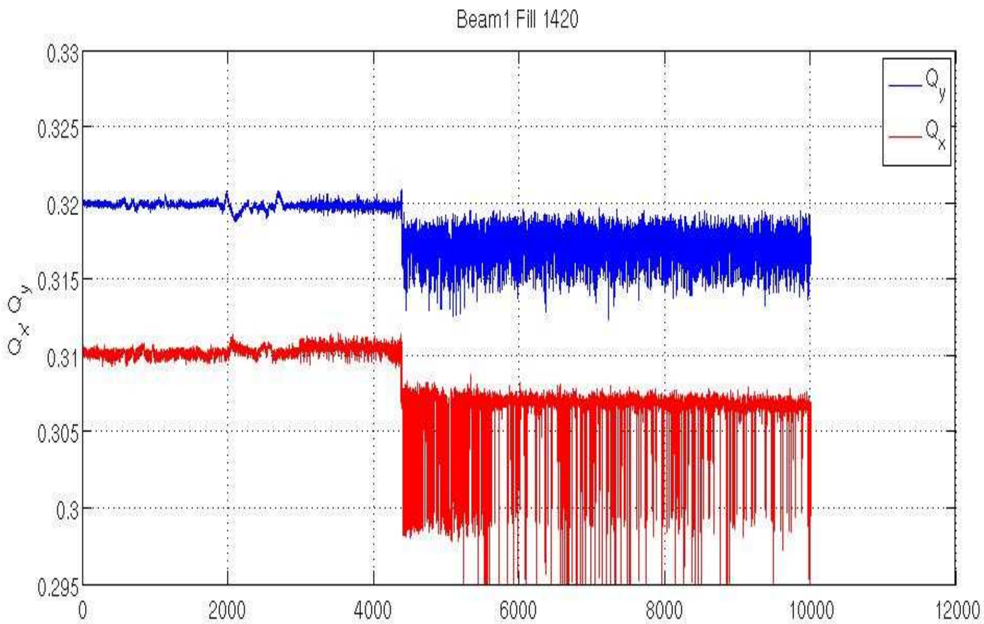
Tunes



(Prepared by T. Pieloni BE-ABP)

→ **Beam 2 tunes, fill 1420 (the good one)**

Tunes



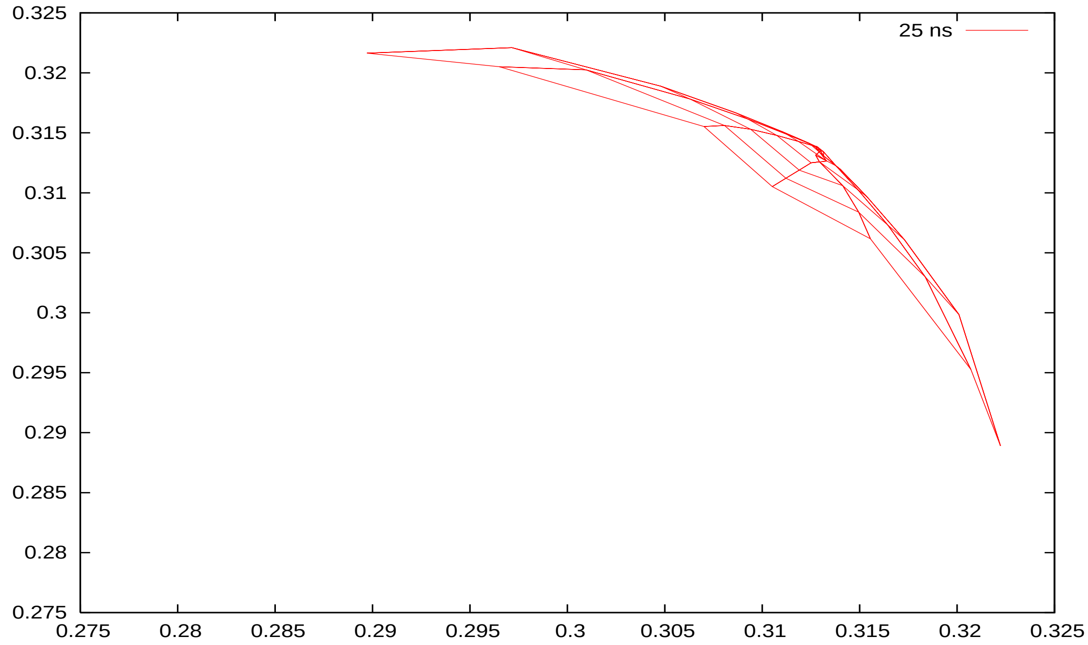
(Prepared by T. Pieloni BE-ABP)

- **Beam 1 tunes, fill 1420 (the good one)**
- **Noise transfered to beam 1**

Beam losses in fill 1410

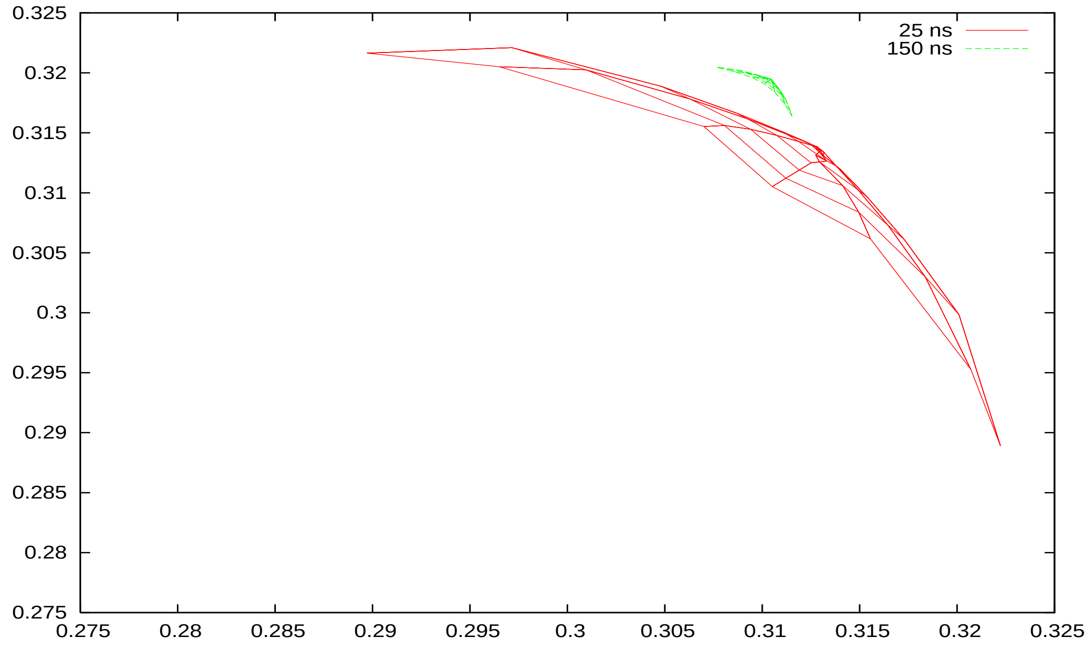
- **Difficult to conclude from single "observation"**
  - **Not observed again**
- **Bunch-by-bunch diagnostics would help ..**
- **Schottky, gated BBQ ?**
- **Test also effect of damper on tune spectra (switch off at end of fill ?)**
- **Do we maybe have already problems with long range effects ?**
  - **Look at present long range contribution**

Long range footprint



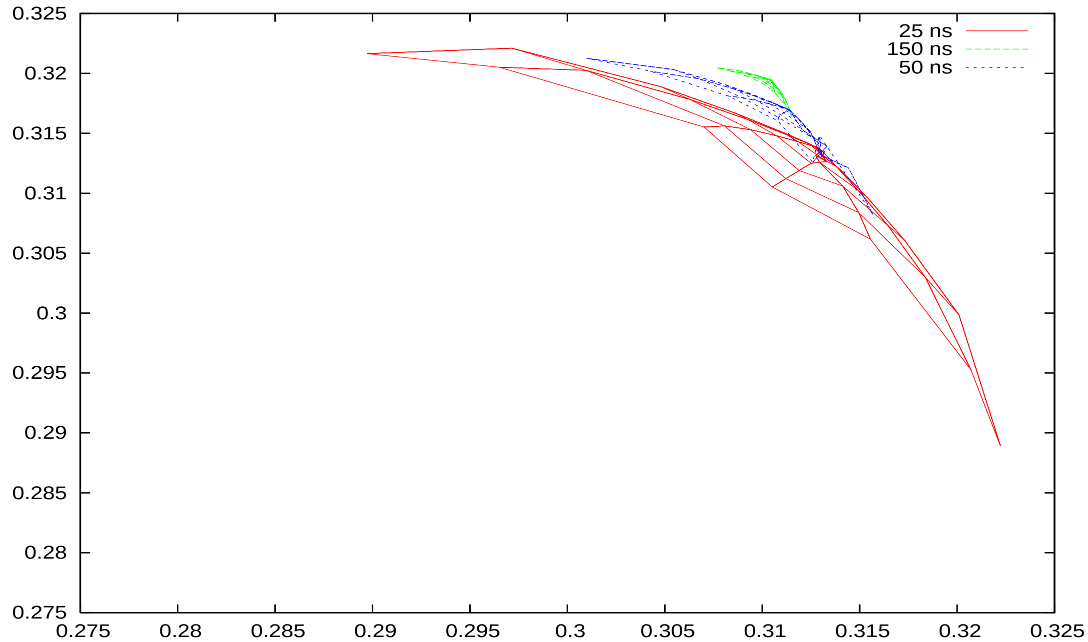
➡ **2.00 μm, 3.5 TeV, $\beta^* = 3.5$ m, but 25 ns**

Long range footprint



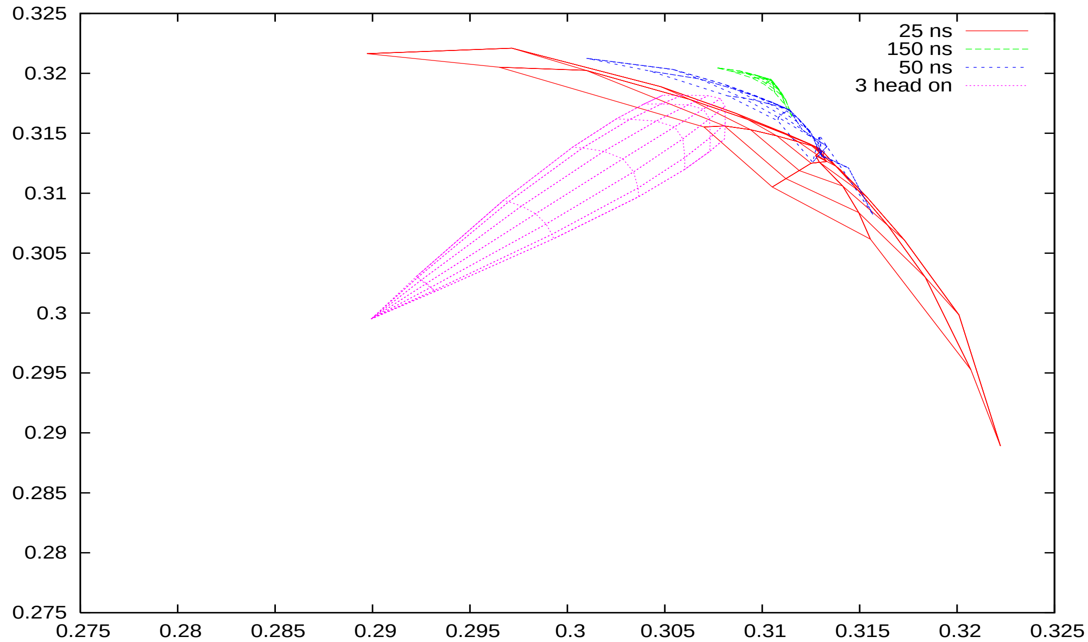
- **2.00 μm, 3.5 TeV, $\beta^* = 3.5$ m, but 25 ns**
- **2.00 μm, 3.5 TeV, $\beta^* = 3.5$ m, but 150 ns**

Long range footprint



- **2.00 μm, 3.5 TeV, $\beta^* = 3.5$ m, but 25 ns**
- **2.00 μm, 3.5 TeV, $\beta^* = 3.5$ m, but 150 ns**
- **2.00 μm, 3.5 TeV, $\beta^* = 3.5$ m, but 50 ns**

Long range footprint



- **Comparison with head-on footprint (3 collisions)**
- **Present contribution (150 ns) very small, expect more for 50 ns spacing**

Expected maximum tune shift

- **We had (total) head-on tune shifts $\approx$ 0.02**
- **Questions:**
  - **What did we expect ?**
  - **Are we at a limit ?**
  - **Can we expect more ?**

Expected maximum tune shift

- *"Design Study of the LHC"* **CERN 91-03 (May 1991)**
  - **Prudent target: overall tune spread in collision: 0.02**
  - **Assumption: 0.005 from lattice at collision**
  - **Beam-beam: 0.015, assuming strong long range contribution**
- **Quote from above:**

  "It is possible to operate the SPS collider with 3 interaction points and ξ in the range 0.003 to 0.006. No comparable experience is available for the case of a single crossing point, but it is generally admitted that $\xi \approx \Delta Q$ could reach 0.01"

Expected maximum tune shift (cont.)

- *"Beam-beam effects in the SPS collider"*
  Beam-beam workshop LHC99, CERN-SL-99-039-AP (1999)
- **Quote from above:**

  "In the first collider runs, the SPS was operated with 3 p against 3 $\bar{p}$ bunches. In this configuration total tune shifts of 0.028 were <u>sometimes</u> obtained but $\bar{p}$ life times at the beginning of a coast were poor."
- **Standard operation was with 0.02, (in the presence of 3 head-on and 9 long range encounters: never reached much more again)**

Can we do more ?

- **Certainly**
  - **Small contribution from machine non-linearities helps a lot**
    (first hints we had at 450 GeV collisions)
  - **Small emittance is always good !**
  - **Helps for luminosity**
  - **Helps to minimize long range effects (which will come)**
- **Should try to push head-on tune shift further, find a limit for N and ϵ_n**

Summary I

- **Losses in fill 1410 difficult to explain, bunch-by-bunch diagnostics necessary**
- **Schottky highly desirable, gated BBQ ?**
- **Keep the (transverse) emittance small, it helps everywhere**
- **More bunches (and maybe smaller β^*) increase long range**

Summary II

- **Should try with 50 ns spacing (with minimum 24 bunches per train, 12 bunches cannot give meaningful information)**
- **(Some) proposed tests with 50 ns spacing:**
  - **Scan separation in IP1 and IP5 (if possible: simultaneously and separately)**
  - **Try separation in IP8 for luminosity levelling (all other IPs present, 50 ns spacing)**
  - **Go into collision separately**