# Tune spreads in the LHC

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| E [GeV] | optics | space charge | lattice | Landau oct. | beam-beam |
|---|---|---|---|---|---|
| 450 | injection | $10^{-3}$ | $2 \times 10^{-4}$ | | |
| 7000 | injection | $10^{-5}$ | $10^{-5}$ | $10^{-4}$ | |
| 7000 | $\beta$-squeeze | $10^{-5}$ | $3 \times 10^{-5}$ | | $5 \times 10^{-4}$ |
| 7000 | collision | $10^{-5}$ | $3 \times 10^{-5}$ | | $3 \times 10^{-3}$ |

Approximate tune spreads at $1\,\sigma$ r.m.s. betatron amplitude.

# Natural Tune Spreads at Injection

Single-particle betatron amplitude detuning is dominated by $b_3$ dipole field errors. The systematic $b_4$ changes sign from inner to outer channel and therefore does not contribute.

Typical detunings obtained by extrapolating the first few measured LHC dipoles are $1 - 2 \times 10^{-3}$ at $6\,\sigma$ peak oscillation amplitude (the specified value is $2 \times 10^{-3}$, see LHC-PR 501). The corresponding tune spread at $1\,\sigma$ r.m.s oscillation amplitude, obtained by dividing this number by $18 = 36/2$, is about $1 \times 10^{-4}$. A comparable tune spread is induced by the chromatic detuning.

Another detuning arises from the direct space charge; its maximum occurs for particles at the centre of the bunch and for ultimate intensity it amounts to $1.9 \times 10^{-3}$. We rely on this spread to damp all higher-order head-tail modes. The dipole modes must be damped by the transverse feedback.

## Laslett tune shifts at each new batch injection...

It is worth mentioning that the incoherent Laslett tune shift, caused by image currents induced on the beam pipe and on the ferromagnetic magnet poles (see LHC Note 313), is an order of magnitude larger than space charge for full beam intensity (with about 3000 bunches). This tune shift is the same for all particles and can be compensated by adjusting the tuning quadrupoles at each new batch injection from the SPS. One batch of 288 bunches corresponds to a 10% effect and is again comparable to the direct space charge detuning, with possible closed orbit perturbations of a few microns.

# Tune Spreads at 7 TeV

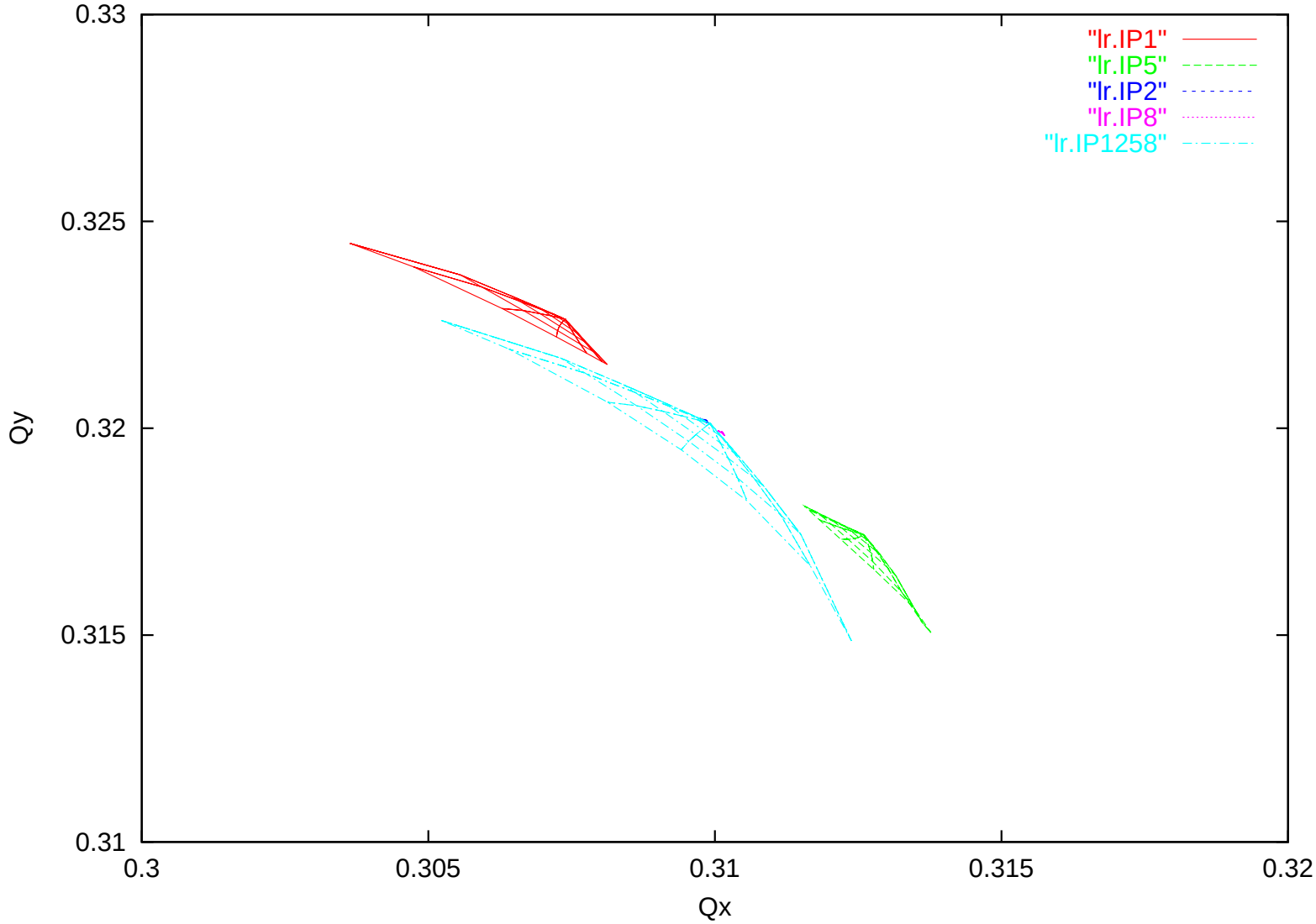
**Beams separated, Injection optics**

- The direct space charge decreases to about $1.4 \times 10^{-5}$.
- The beam emittance decreases by a factor 16, yielding a maximum single-particle detuning of less than $10^{-5}$ at $1\,\sigma$, taking into account crossing angle and triplet imperfections.
- Higher-order head-tail modes have typical coherent tune shifts of several $10^{-5}$ and can not be stabilized by the transverse feedback. Additional tune spread can be introduced by the Landau octupoles: 168 arc octupoles of length 32 cm at full strength $O_3 = 60000\,\mathrm{T\,m^{-3}}$ can provide a tune spread of about $1.3 \times 10^{-4}$ at $1\,\sigma$. To avoid a reduction of dynamic aperture we may have to operate them at a somewhat lower strength.

**Beams separated, pre-Collision optics**

- With the amplification of the triplet errors due to the high-$\beta$, the single-particle detuning can reach about $3 \times 10^{-5}$ at $1\,\sigma$.
- After $\beta$-squeeze, long range beam-beam collisions with normal separation introduce an additional tune spread as large as $5 \times 10^{-3}$ at $6\,\sigma$ peak amplitude, corresponding to a tune spread of about $5 \times 10^{-4}$ at $1\,\sigma$.

**Colliding beams** Due to head-on and long range beam-beam collisions, the tune spread becomes as large as $10^{-2}$ at $6\,\sigma$ peak amplitude, corresponding to about $3 \times 10^{-3}$ at $1\,\sigma$, and is expected to Landau damp most instabilities except perhaps some coherent beam-beam modes.




Tune footprints due to long range beam-beam collisions for nominal LHC conditions after $\beta$-squeeze. (Courtesy W. Herr)

The tune spreads at $1\,\sigma$ r.m.s. betatron oscillation amplitude can be directly compared to the coherent tune shifts induced by the machine impedance and give a figure of merit for Landau damping.

However, a consistent evaluation of beam stability limits including the combined effect of tune spreads having different origins, such as machine nonlinearities, long-range and head-on beam-beam collisions, is still missing.