LHC Injectors Upgrade

SPS Q20 – Low transition energy optics

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and the whole OP group …

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Outline

- Introduction – why changing transition energy of SPS
- Optics comparison
- Implications of using low transition energy optics
- Single bunch studies
- Longitudinal beam characteristics
- Future studies and next steps

Introduction

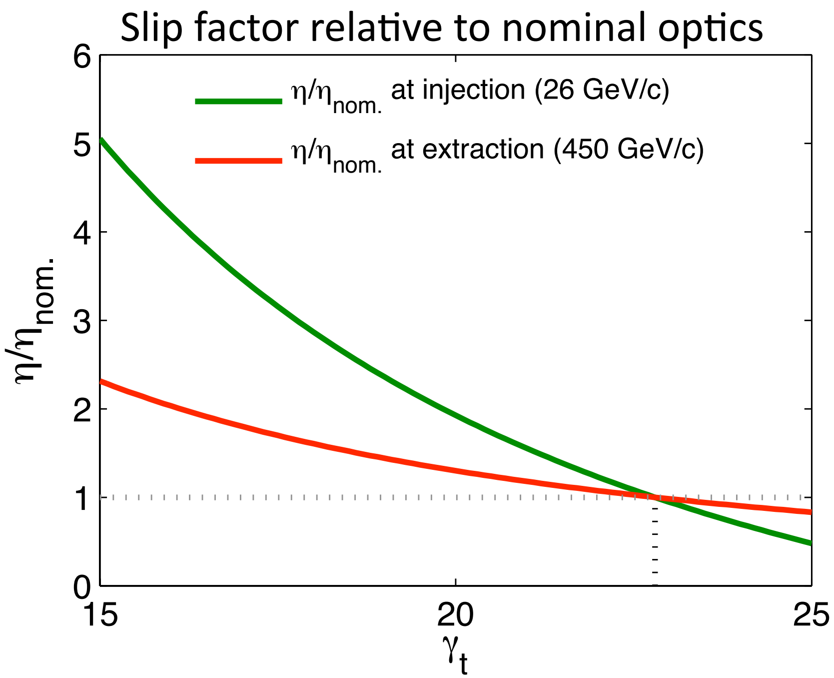
- **Intensity limitations for LHC proton beams in the SPS due to:**
  - Transverse mode coupling instability (TMCI) at injection - single bunch instability in vertical plane for intensities above threshold of 1.6×10^{11}p/b (ε_L=0.35eVs, τ=3.8ns) and low ξ_y: $N_{th} \sim \eta\varepsilon_L/\beta_y$ (for matched voltage)
  - Loss of Landau damping due to longitudinal reactive impedance: $N_{th} \sim \eta\varepsilon_L^2\tau$
  - E-cloud effects mainly for 25ns beam (for given longitudinal parameters: $N_{th} \sim \eta$)

- **Instability thresholds can be raised by increasing slip factor η**
  - Damping of instabilities due to faster synchrotron motion
  - Factor of about 3 higher η can be reached at injection energy in the SPS by reducing transition energy γ_t by a few units

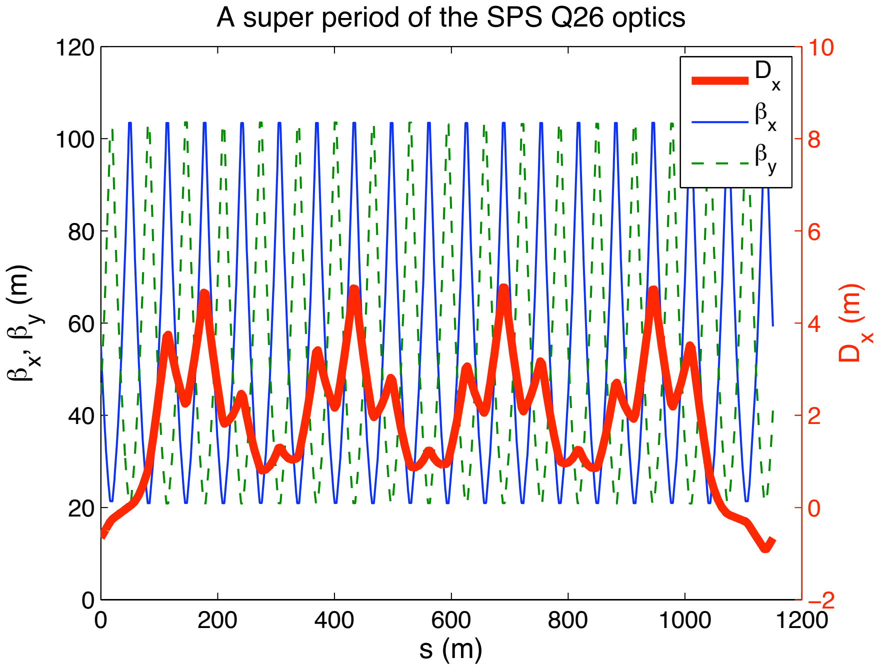
$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

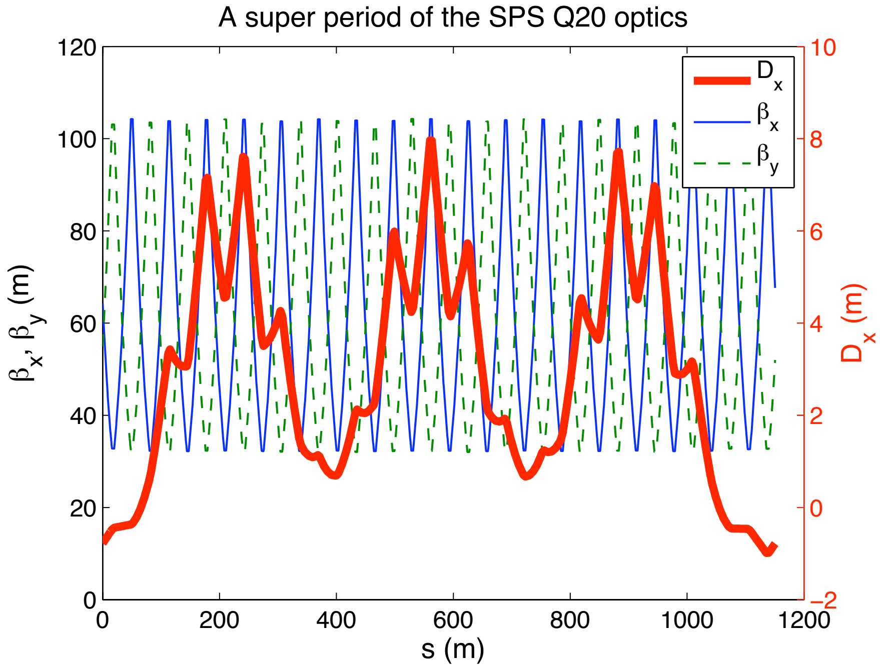
$$\gamma_{t_{FODO}} \approx Q_x$$

  - Need to reduce the horizontal tune Q_x!



SPS optics comparison



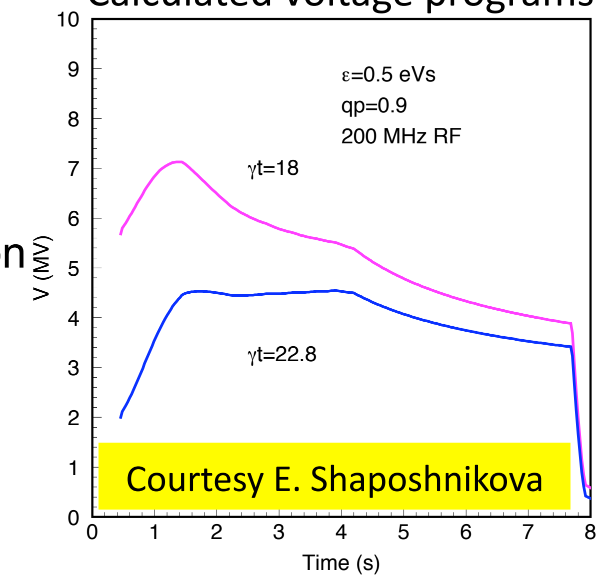


- **Low γ_t optics by reducing (integer) tunes**
  - η increased by factor 2.85 at injection and 1.6 at top energy by changing γ_t from 22.8 (Q_x~26, nominal optics "Q26 optics") to 18 (Q_x~20 → "Q20 optics")
  - Significantly increased dispersion in the arcs → lower γ_t
  - No increase of maximal β-function values; minima increased from 20m to 30m
- **Dispersion in long straight sections similar to nominal optics**
  - By choosing phase advance of μ~3x2π per arc (instead of μ~4x2π)

Implications of using Q20 optics

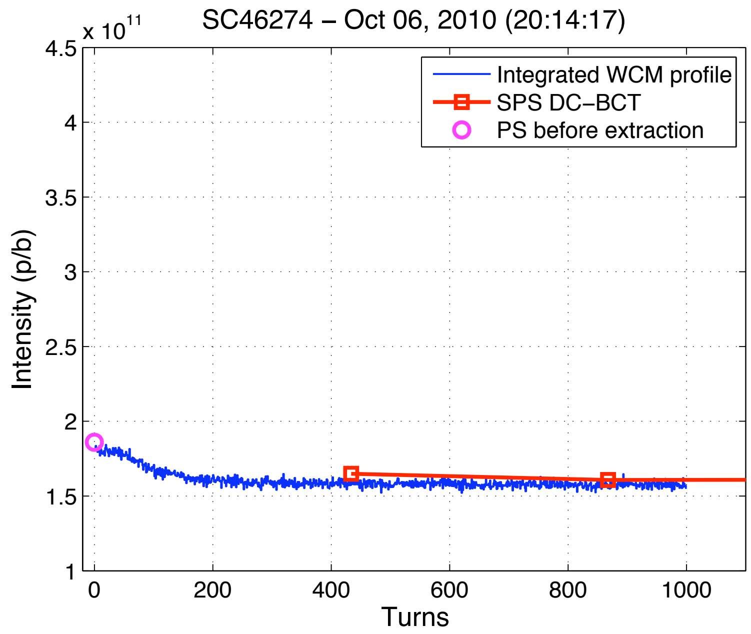
- **Available RF voltage and beam transfer to LHC**
  - Higher RF-voltage in Q20 needed (V~η) for same bucket area → better for beam loading
  - RF-voltage limited to 7.5MV (already used in Q26 at flat top) → bunch length at extraction?
  - For given longitudinal emittance → longer bunches at extraction (due to limited RF voltage → RF upgrade should help)
  - For given bunch length at extraction → smaller longitudinal emittance but similar longitudinal stability in SPS since $N_{th} \sim \varepsilon^2 \eta \tau$ (however potentially unstable in LHC, to be seen)
  - Also higher voltage of 800MHz Landau cavity needed!

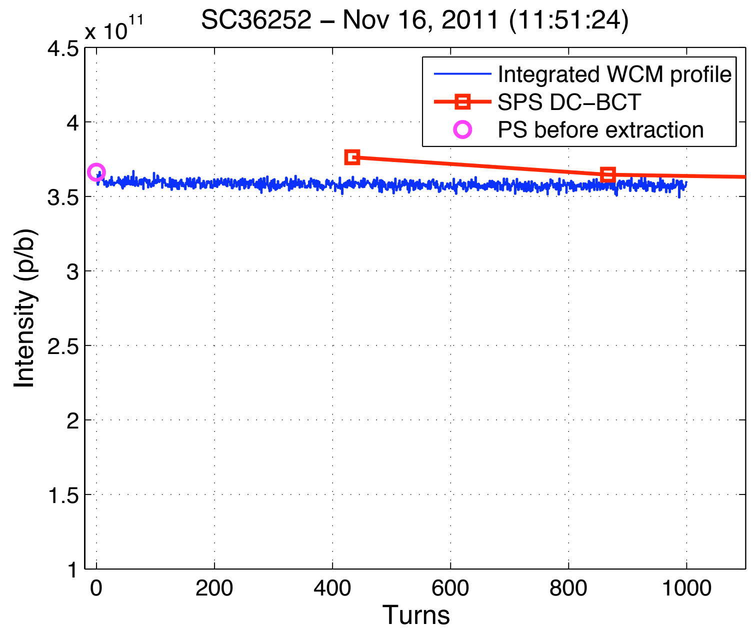
Calculated voltage programs



- **Injection dogleg and beam dump**
  - Quads in injection region (LSS1) are misaligned to gain aperture for beam dump
  - This creates non-closed orbit bump in Q20 optics which presently cannot be corrected at high energy → realign quadrupoles or install high energy orbit correctors
  - Potential complication for extraction if not corrected (dispersion beating)
  - Trajectory for high energy beam dump going off-center through main quadrupole → less kick downwards in Q20 optics (smaller quadrupole gradient) – but still within foreseen region!

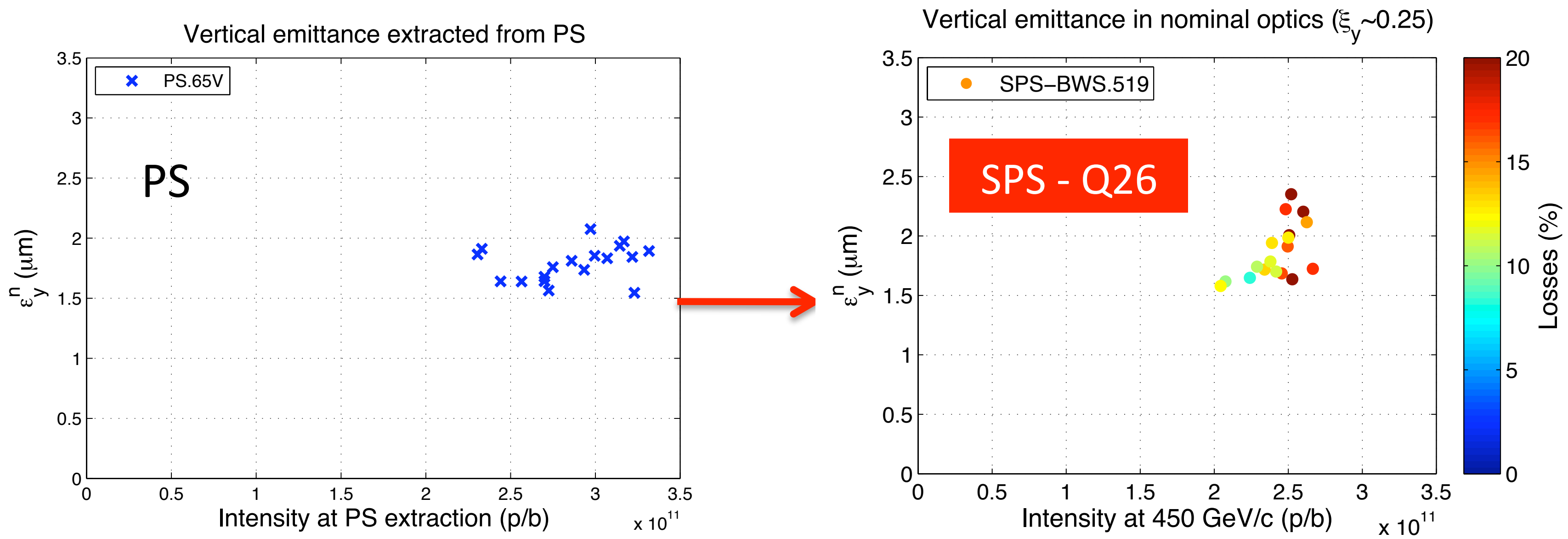
TMCI threshold in nominal optics compared to Q20





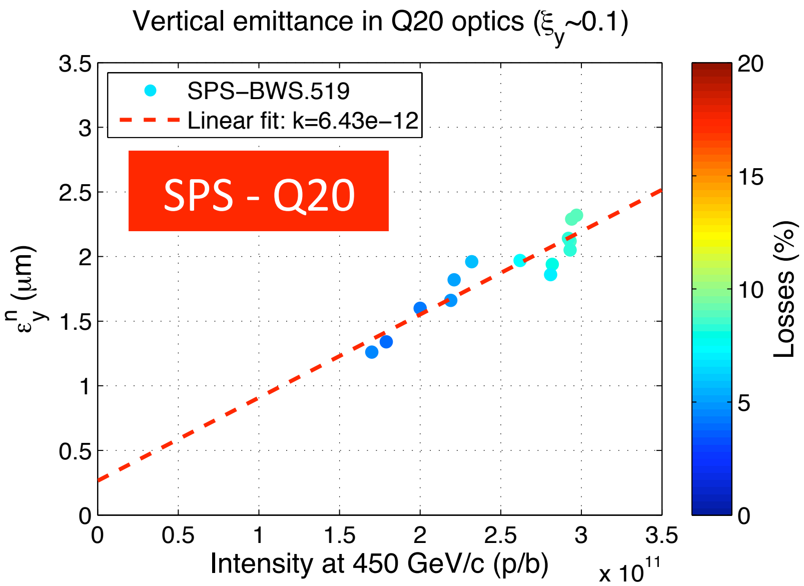
- **Nominal optics Q26**
  - Sharp losses after ~70 turns for low vertical chromaticity and injected intensity higher than 1.6×10^{11}p/b
  - Clearly observed threshold for TMCI
  - Higher intensity requires larger vertical chromaticity
- **Q20 optics**
  - Numerical simulation predict threshold at 3.2×10^{11}p/b (N_{th}~η/β_y)
  - No observation of TMCI up to 3.5×10^{11}p/b for low vertical chromaticity (ξ_y~0.03)
  - Regime of higher intensity remains to be explored systematically

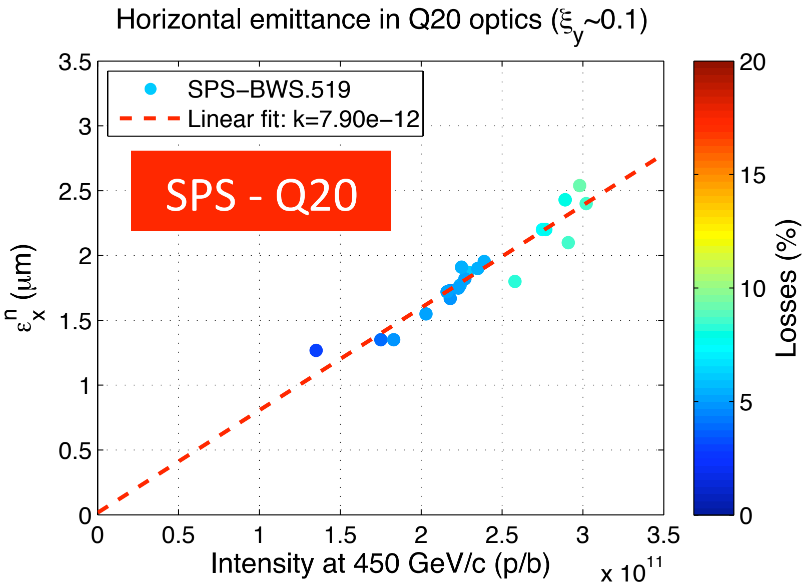
Q26 nominal SPS optics - single bunches

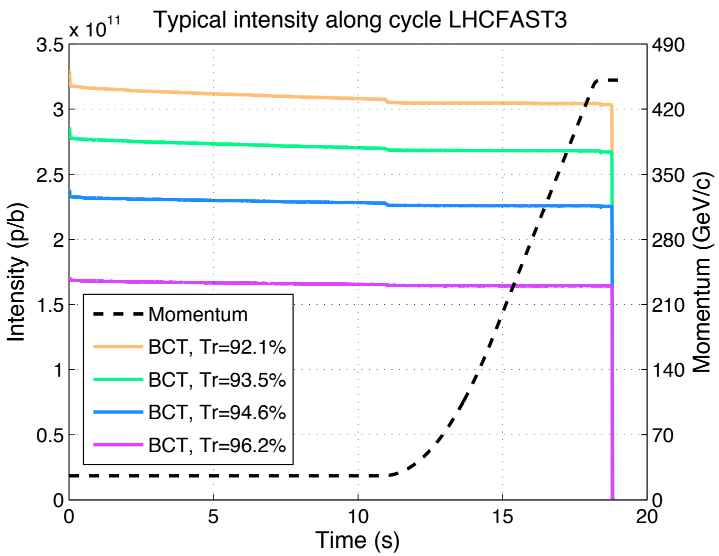


- **Measurements during preparation for LHC high pile up single bunch MD**
  - ξ_y~0.25 as optimal value to reach around 2.5x10^{11}p/b with small emittance (total losses around 15%)
  - Slightly higher intensity (2.8x10^{11}p/b) can be reached with chromaticity of ξ_y~0.4 however with emittance blowup (data not shown)
  - Smaller chromaticity (ξ_y~0.1) leads to significant losses at injection due to TMCI (data not shown)

Q20 single bunch studies

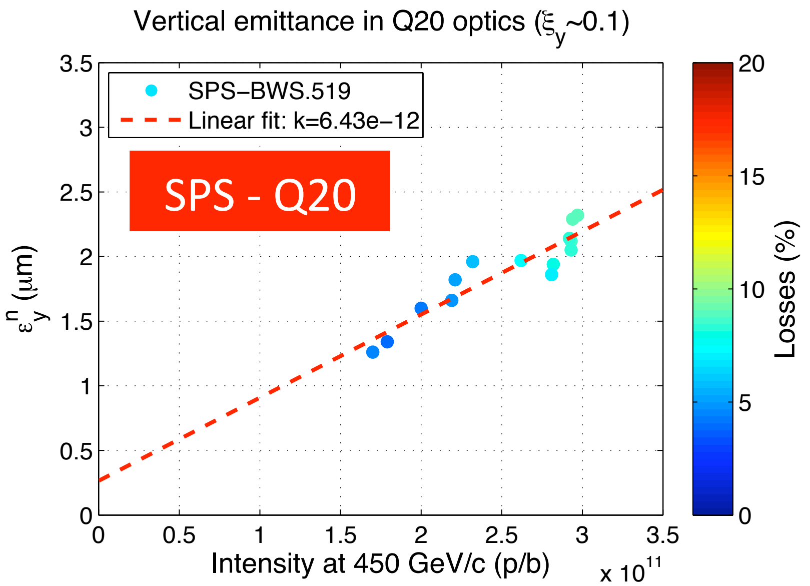


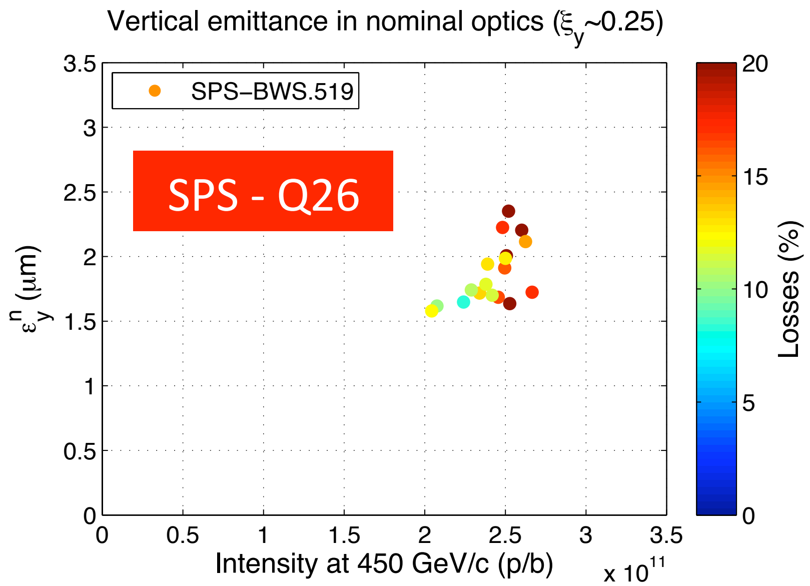




- **Single bunch emittances vs. intensity**
  - Injected up to 3.3x10^{11}p/b and accelerated to flat top using nominal LHC magnetic cycle (long FB, slow ramp) and low chromaticity **(ξ_y~0.1)**
- **Linear increase of emittance with intensity**
  - losses at injection and along flat bottom increasing for intensity above 2x10^{11}p/b (working point optimization?)

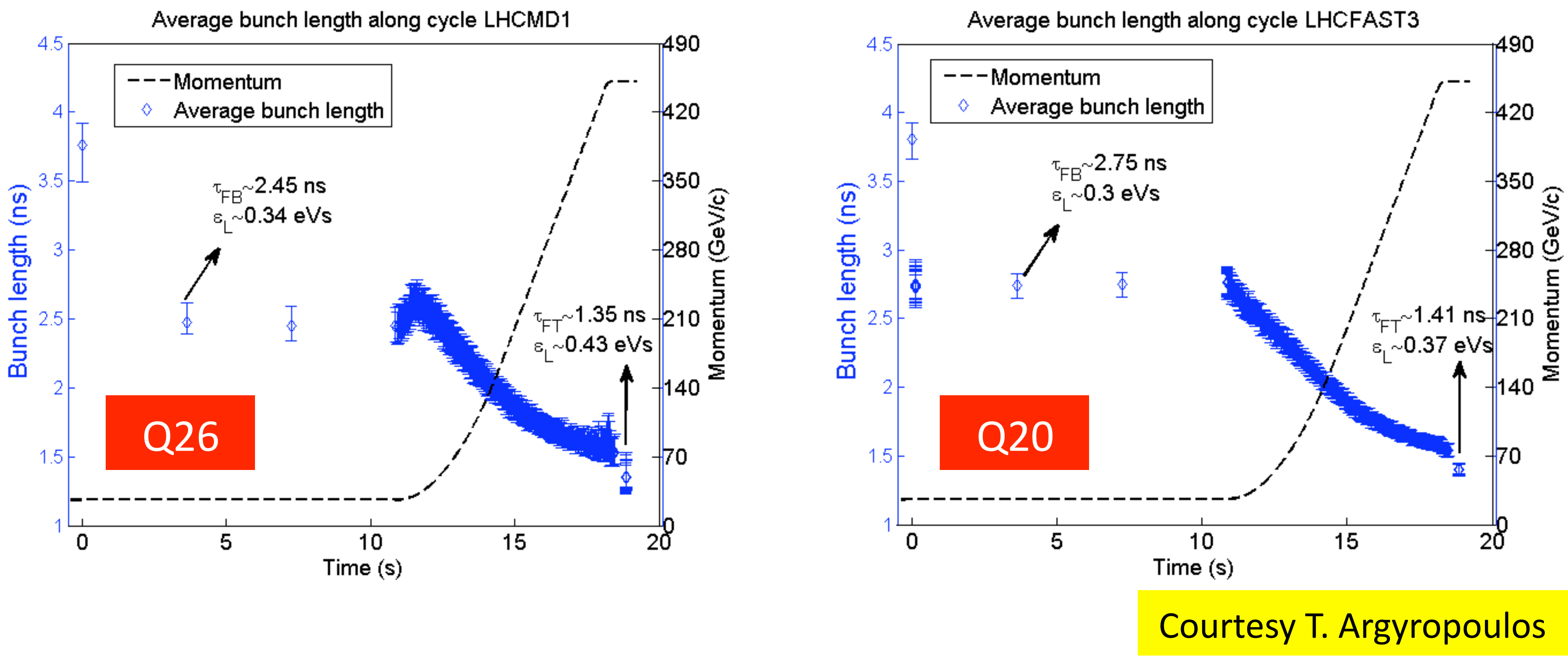
Comparison of high intensity single bunches





- **Comparison Q20 – Q26**
  - Same fractional tunes in both optics (.13, .18)
  - Low chromaticity **(ξ_y~0.1)** in Q20 cycle
  - At least ξ_y~0.25 needed in Q26 to reach 2.5x10^{11}p/b – but still very high losses due to TMC instability
  - Significantly smaller losses in Q20 (<10% even for 3.3x10^{11}p/b injected)
  - Linear increase of emittance with intensity in Q20

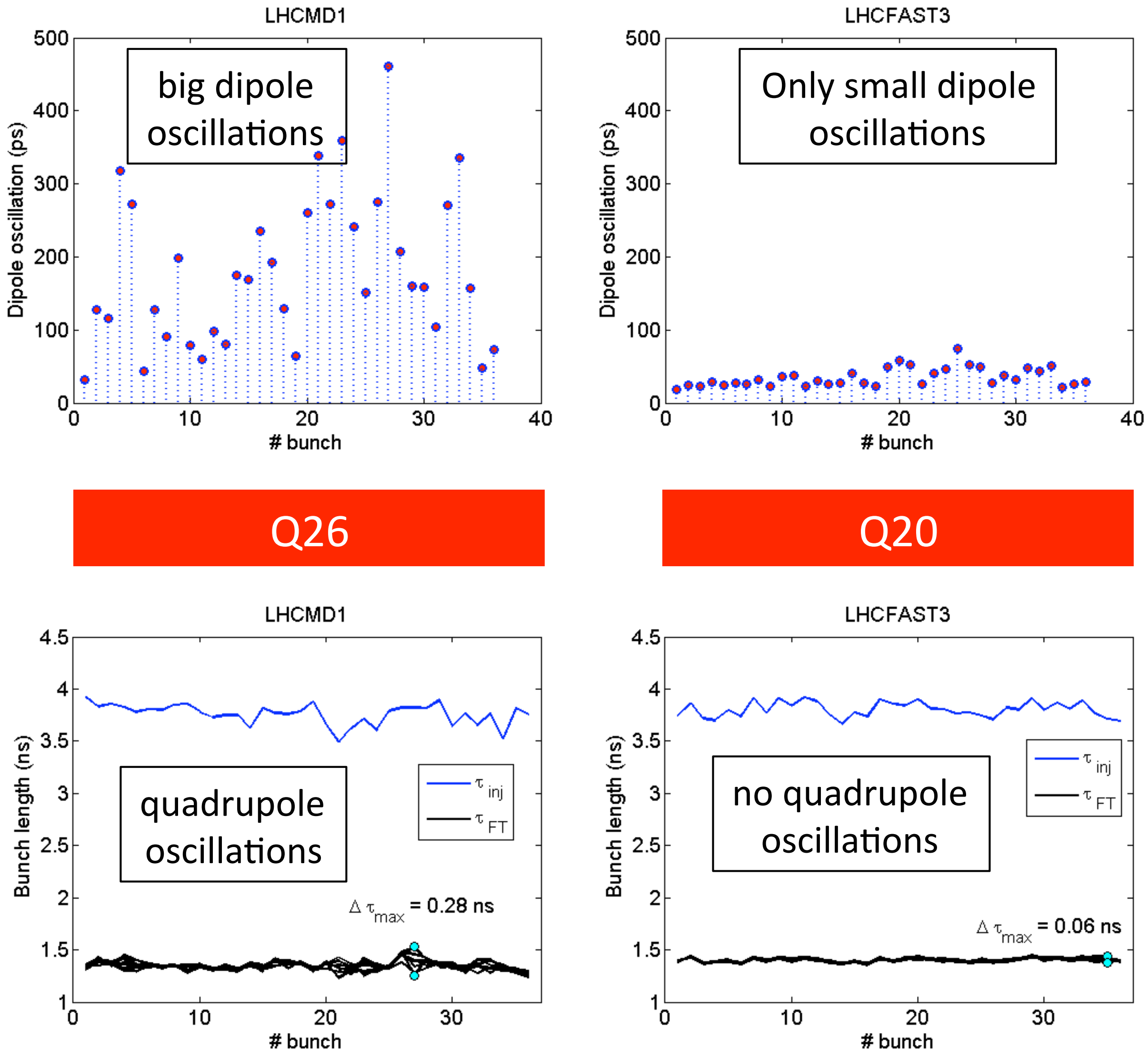
Longitudinal aspects – 50ns beam



- **Example: 50ns LHC beam (1 batch) with 1.5x10^{11}p/b**
  - With 800MHz Landau cavity in bunch shortening mode (needed for stability in both optics)
  - Without longitudinal emittance blow-up (used in routine operation for stabilizing beam)
  - Unstable during ramp in Q26 for this intensity → emittance blow-up needed
  - Stable in Q20 for this intensity (emittance blow-up needed for higher intensities)
  - Longer bunches at extraction in Q20 due to limited RF-voltage

Longitudinal stability at flat top – 50ns beam

- **50ns beam at flat top (1 batch, 1.5x10^{11}p/b)**
  - Without controlled emittance blow-up
  - 800MHz cavity on
- **unstable in Q26**
  - Phase oscillations - dipole instability
  - Bunch length oscillations – quadrupole instability
- **stable in Q20**
  - Small bunch length (emittance) - compatible with LHC bucket (margin for emittance blow-up)
  - Smaller emittance sufficient for beam stability in SPS but could be too small for LHC for higher intensity (IBS, stability)



Courtesy T. Argyropoulos

Next steps and future studies

- **Next step: Injection into LHC during MD**
  - Rematching the transfer-lines TI8 and TI2 to the new optics in the SPS → presently ongoing
  - Study stability of beams with smaller longitudinal emittance in the LHC and acceptable losses due to longer bunches
- **Optimization left to be done**
  - RF settings
  - Injection into Q20 optics → rematched optics of TT10 (and TT2) not employed yet
- **Future studies: split tunes**
  - Integer tune 20 in horizontal plane for lower transition energy
  - Keeping the tune in the vertical plane close to 26 for smaller vertical beta function → further increase threshold for vertical instabilities such as TMCI ($N_{th} \sim \eta \varepsilon_L / \beta_y$), e-cloud, …
  - Feasibility to be checked (potential conflict with LHC QPS) …

Summary

- **Changing optics to low transition energy as very promising option for high intensity LHC beams in the SPS**
  - Q20 optics without installation of new hardware
  - Lower transition energy requires higher RF voltage – potential limitation for beam transfer to LHC (foreseen RF-upgrade should help)
- **Single bunch studies**
  - Huge increase of TMCI threshold at injection due to (almost) 3-fold increase of slip factor → TMCI threshold above 3.5×10^{11} p/b
  - Single bunches with intensity up to 3×10^{11} p/b at flat top with emittances smaller than 2.5µm
- **Comparison of longitudinal characteristics of 50ns beam (1.5×10^{11} p/b)**
  - Nominal optics requires longitudinal emittance blowup in addition to 800MHz Landau cavity
  - Beam stable with 800MHz Landau cavity with Q20 optics → no emittance blow-up needed for this intensity
  - Longitudinal beam characteristics in Q20 optics compatible with LHC bucket
- **Major next step: injection into LHC**

LHC Injectors Upgrade

Thank you for your attention!

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