LHC Injectors Upgrade

SPS Q20 – Performance and reach

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and OP crew

Outline

- **Introduction & Motivation**
- **Instability thresholds and intensity limitations**
- **Extraction from Q20 and injection into LHC**
- **Studies left to be done and conclusion**

Introduction – Instabilities in the SPS

- **Present intensity limitations for LHC proton beams with nominal optics:**
  - TMCI at injection - single bunch instability in vertical plane
    - Threshold at 1.6×10^{11} p/b (ε_L=0.35eVs, τ=3.8ns) with low ξ_y

$$N_{th} \sim \eta \varepsilon_l / \beta_y$$

  - Longitudinal instabilities
    - Threshold at 3×10^{10} p/b at for single harmonic RF

$$N_{th} \sim \eta \varepsilon_l^2 \tau$$

η	slip factor
ε_l	longitudinal emittance
τ	bunch length
β_y	vertical beta-function
γ_t	gamma transition
Q_s	synchrotron tune

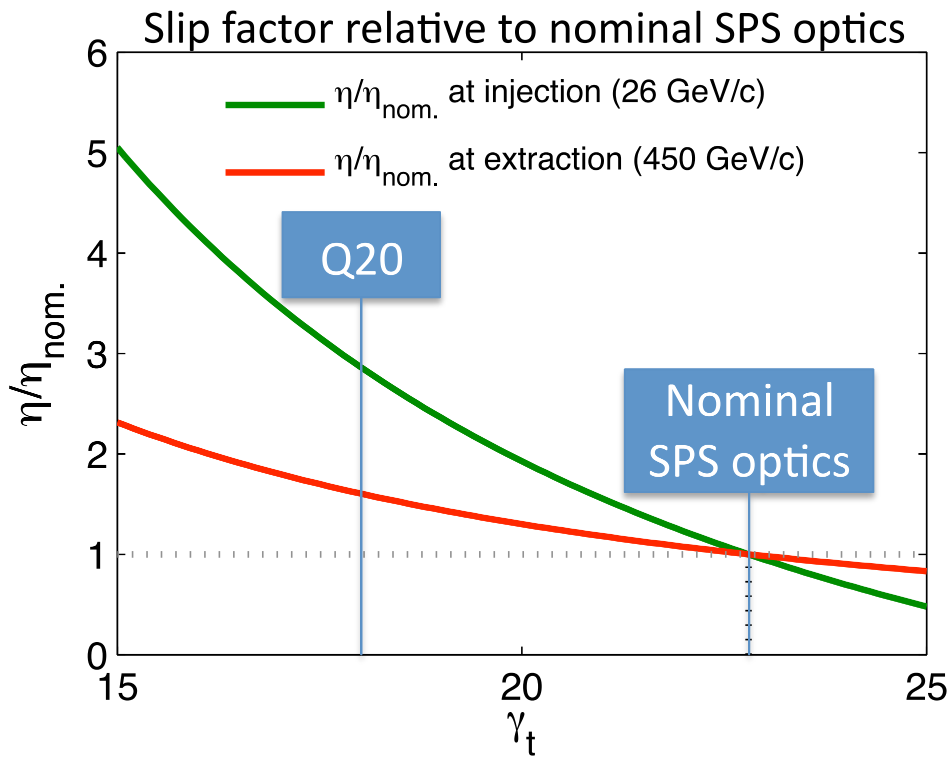
  - E-cloud effects for 25ns beam
    - Threshold? … presently not observed for nominal intensity (1.2×10^{11} p/b) due to scrubbing

$$N_{th} \sim Q_s \sim \eta$$

(for given longitudinal beam parameters)

⇒ **Instability thresholds can be raised by increasing slip factor η!**

Increasing slip factor η in SPS



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

+

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

⇒ Reduce horizontal tune Q_x!

Q20 low-γ_t optics:

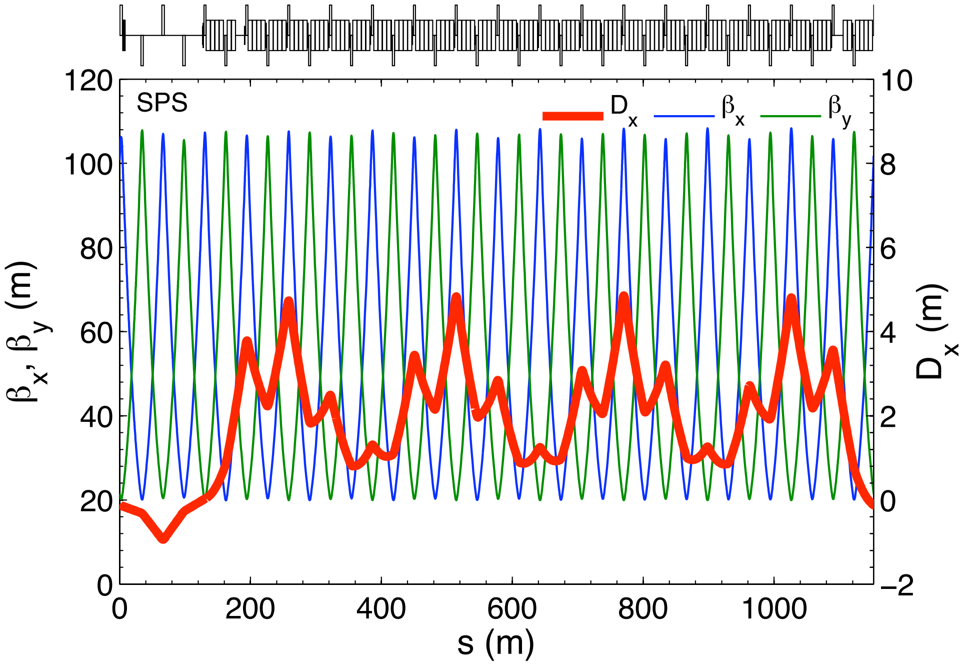
⇒ Factor 2.8 higher η at injection energy!

⇒ Factor 1.6 higher η at flat top!

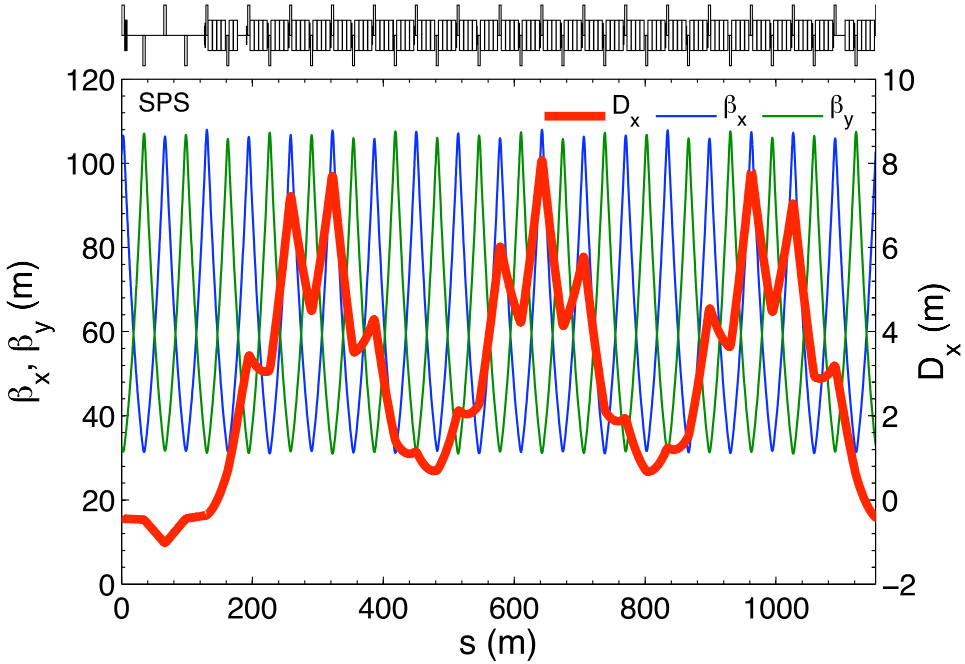
… compared to nominal SPS optics Q26

Optics comparison

Q26 nominal SPS optics



Q20 low-γ_t optics



- **Working point lowered by 6 integer units in both planes (Q_x/Q_y = 20.13/20.18)**
- **No increase of β-function maxima, but higher dispersion (→ lower γ_t)**
- **Q20 optics obtained by reducing quadrupole strength by 30%**
- **Dispersion in long straight sections similar to nominal optics**

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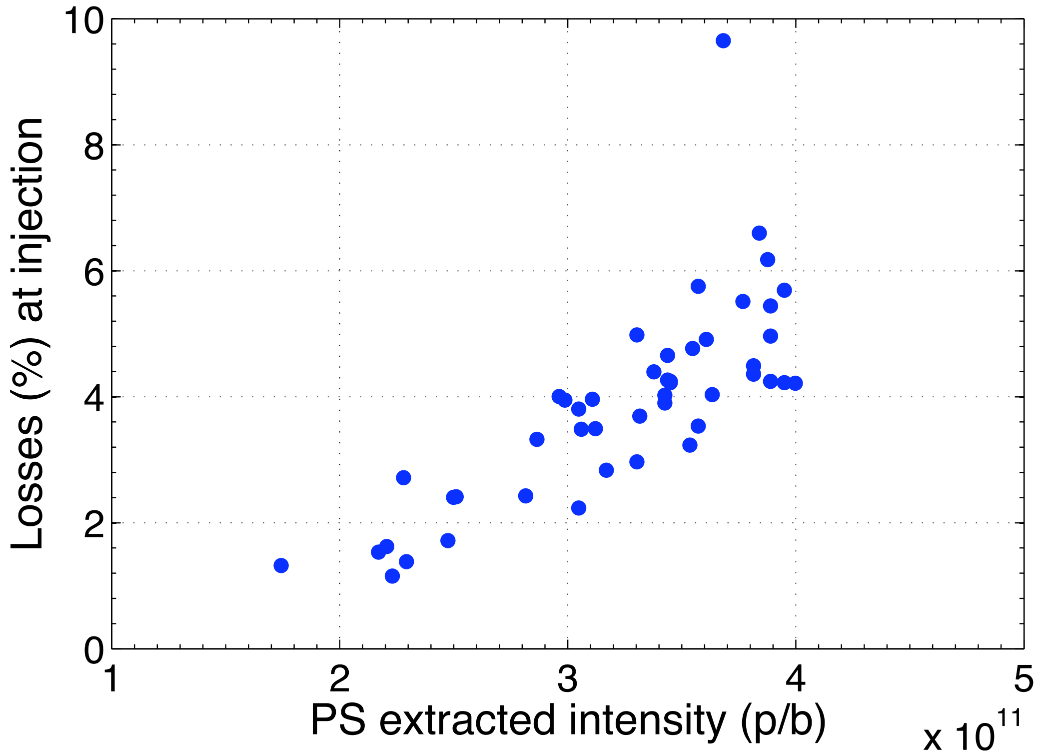
Q20 – TMCI intensity threshold

- **Scaling from SPS nominal to Q20 optics:**
  - η_{Q20}/η_{Q26}=2.85 (at injection)
  - Average β_y around 1.3 times lager in Q20

  ⇒ **Expect N_{th} ~ 2.85/1.3*1.6x10^{11}p/b = 3.5x10^{11}p/b**

N_{th} ~ $\eta\varepsilon_l/\beta_y$

- **TMCI with Q20 not clearly observed experimentally yet**



⇒ **Injected up to 4x10^{11}p/b with small vertical chromaticity and moderate losses within first 100ms**

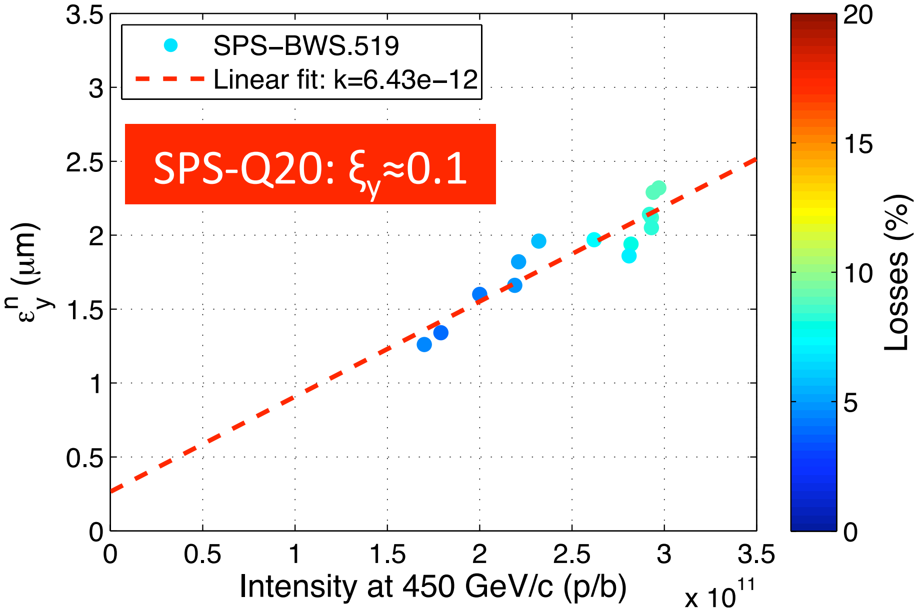
⇒ **Margin for increasing intensity per bunch especially for HL-LHC parameters**

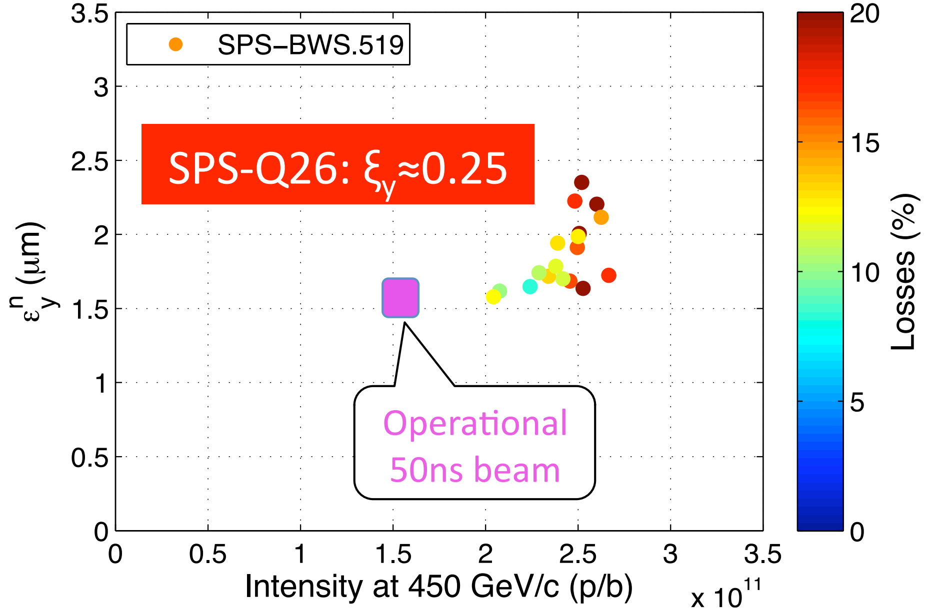
⇒ **Very interesting for high intensity single bunch MDs in LHC**

- High pile-up (already used 9/7/2012)
- Beam-beam
- Instability thresholds

CERN

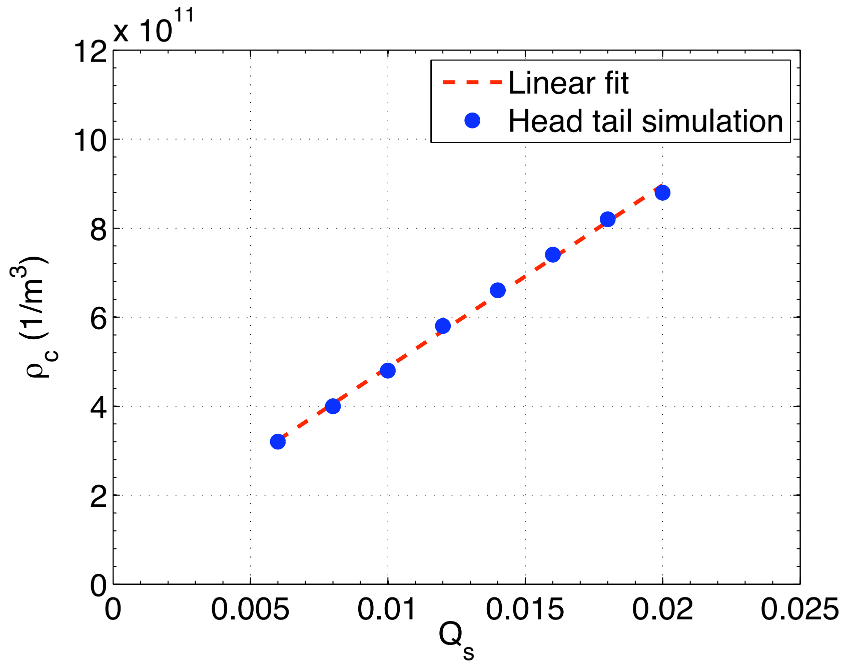
Space charge – high intensity single bunch

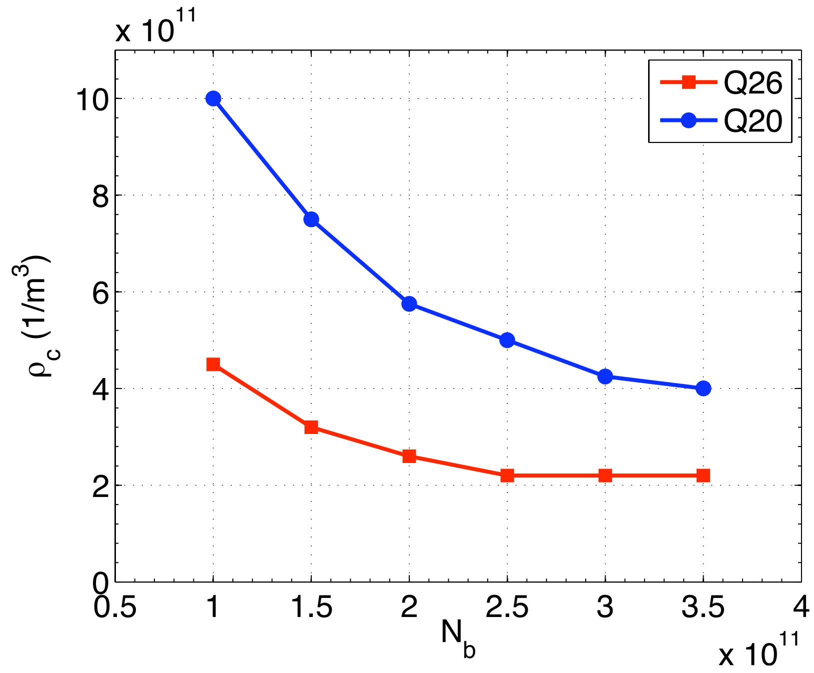




- **Working point adjusted to xx.13/xx.18 for each intensity step**
  - Space charge tune spread around $\Delta Q_x/\Delta Q_y \approx 0.13/0.18$
  - Brightness is similar in both optics, slightly smaller tune spread in Q20 due to larger dispersion
- **High intensity**
  - Can be accessed with Q20 even with low chromaticity
  - In Q26 significant increase of chromaticity required to mitigate TMCI

Electron cloud instability - simulations





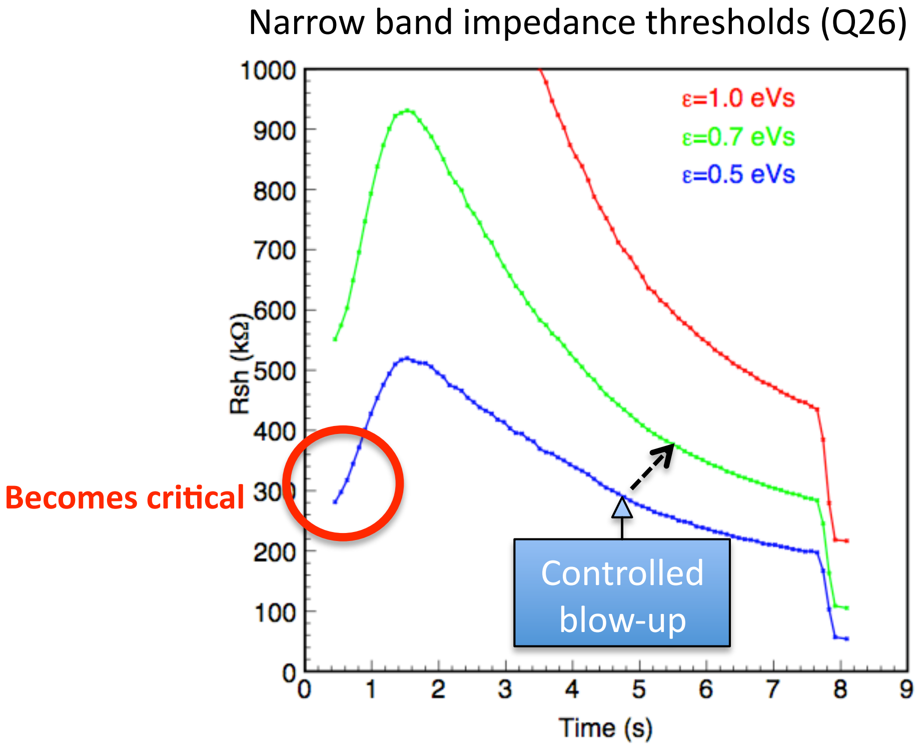
- **Head tail simulations**
  - Uniform electron cloud distribution
  - Injection energy
  - Electron cloud is located in dipole regions

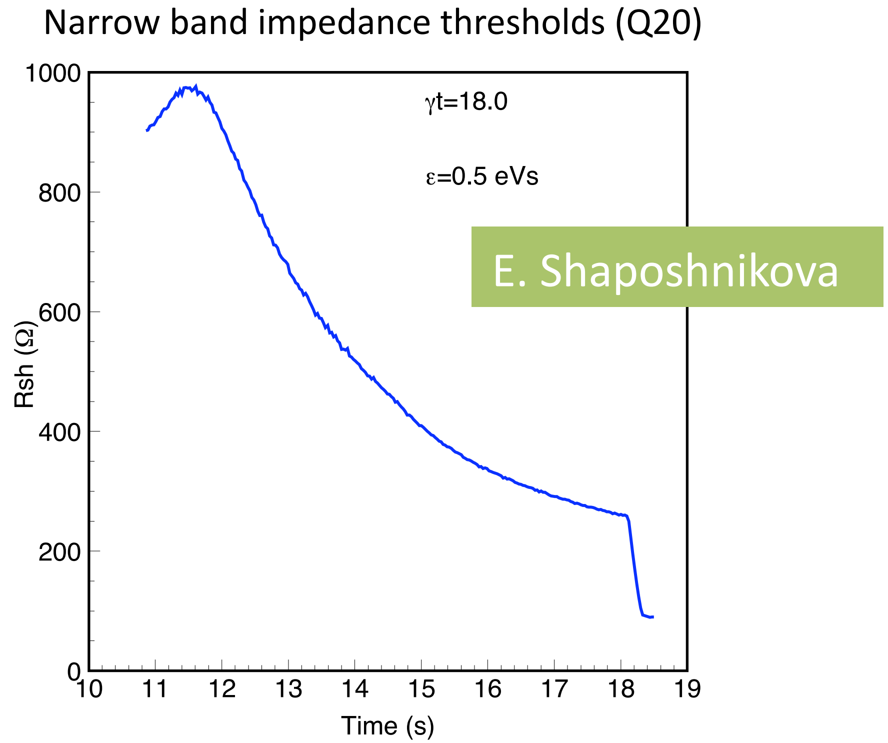
Presently the nominal 25ns beam does not suffer from e-cloud effects, but more margin with Q20 …

- **Instability threshold scales with Q_s (~η for matched RF-voltage)**

⇒ **Clearly higher instability threshold with Q20!**

Longitudinal instability threshold



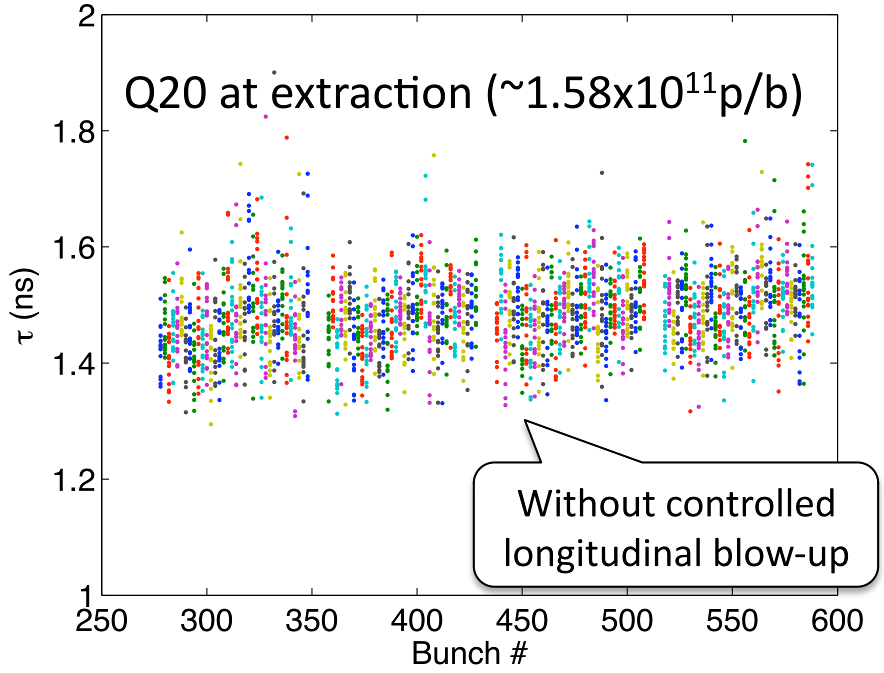


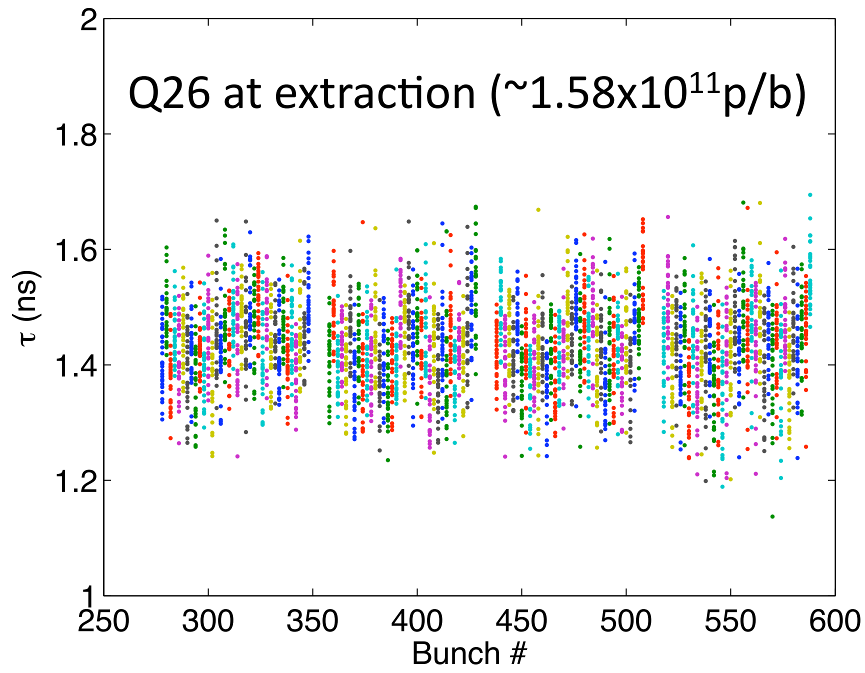
- **Instability threshold decreases with energy in second part of cycle**
  - Controlled longitudinal emittance blow-up in routine operation
  - Less longitudinal emittance blow-up needed in Q20 due to higher threshold
- **Instability limit at flat bottom**
  - **Becomes critical with Q26 optics when pushing intensity**
  - **Huge margin for increasing intensity with Q20 optics (factor ~3 higher threshold)**

Bunch length at extraction

- **Higher RF-voltage in Q20 needed for same bucket area ($V \sim \eta$)**
- **RF-voltage limited to 7.5MV**
  - Maximal voltage is used at flat top to shorten bunches for transfer to LHC
- **For given longitudinal emittance**
  - Longer bunches at extraction from Q20 *(capture losses in LHC?)*
  - RF upgrade should help
- **For given bunch length at extraction**
  - Smaller longitudinal emittance from Q20 optics *(IBS and instability on LHC flat bottom?)*
  - Similar longitudinal stability in SPS since $N_{th} \sim \varepsilon^2 \eta \tau$
- **LHC MD in August was devoted to 50ns beam with different bunch lengths from Q20**

Longitudinal beam quality at flat top – 50ns

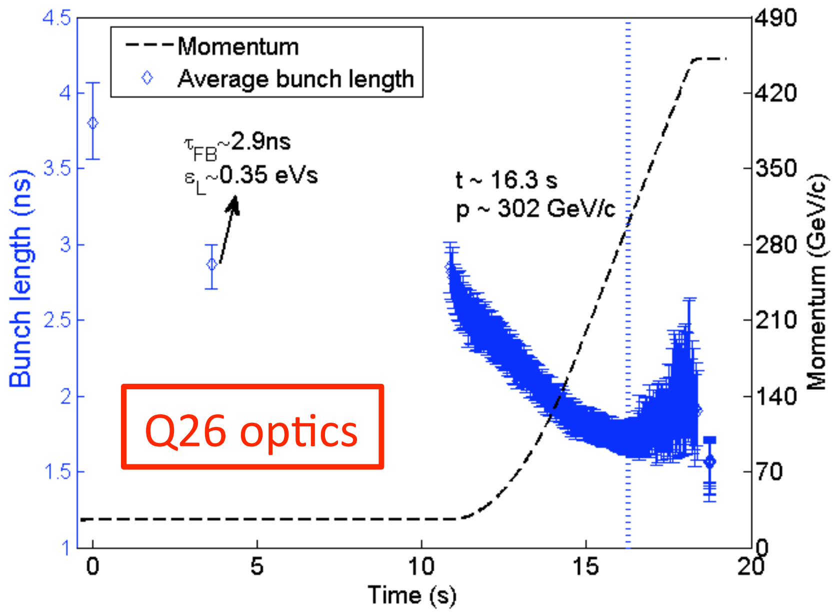


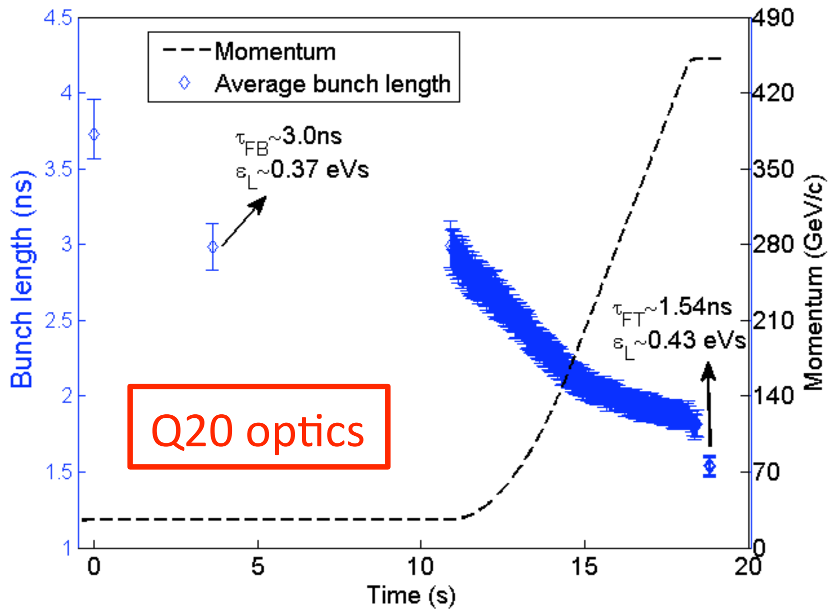


- **Less spread of bunch lengths at flat top for Q20 optics**
  - Similar bunch length in both optics, but smaller longitudinal emittance for Q20
  - No controlled longitudinal blow-up for Q20 in this case (but preferred to be used for mitigating IBS effects on LHC flat bottom, see below)
- **See talk of T. Argyropoulos for comparison of longitudinal stability**

25ns beam – results from 2011

- **Comparing stability without controlled longitudinal emittance blow-up**
  - 1 batch of 72 bunches with 25ns spacing and 1.2x10^{11}p/b
  - 800 MHz cavity is on (voltage around 1/10 of 200 MHz)





⇒ Emittance blow-up needed

⇒ no emittance blow-up needed (for this intensity)

- **Continue studies with 25ns beam in Q20 in remaining MD time**

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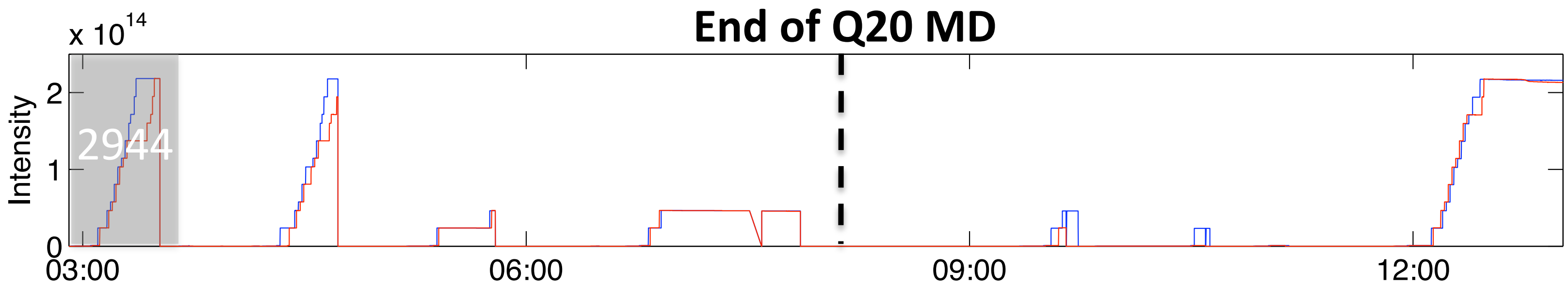
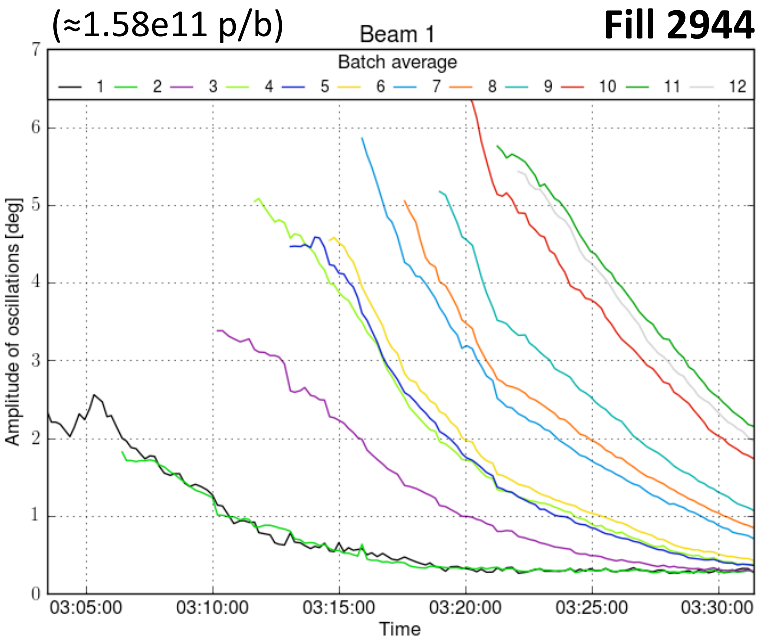
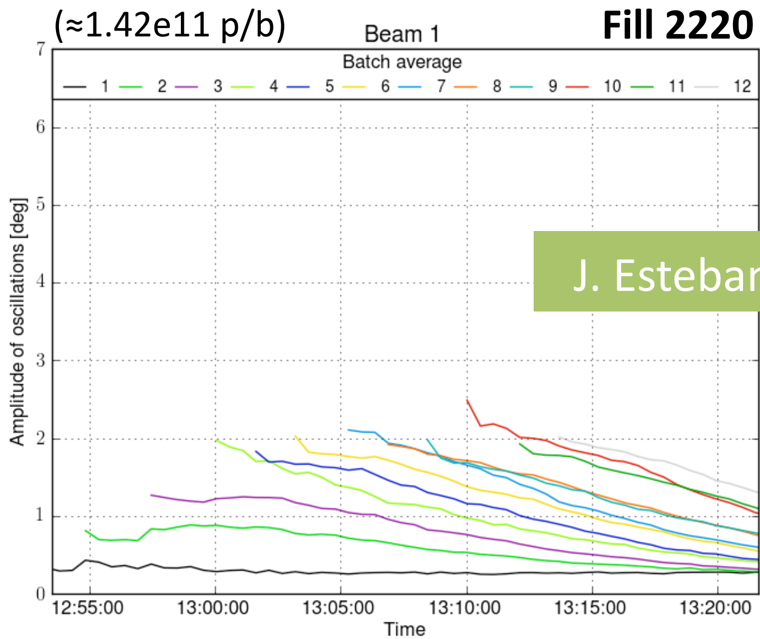
Short bunches at LHC injection (1.45ns)



- **Fill 2944: τ_l≈1.45ns / ε_l≈0.37eVs (@SPS extraction from Q20)**
  - No controlled blow-up in SPS (beam passes BQM even though slightly unstable)
  - Longitudinal injection oscillations damped as usual → no instability in LHC





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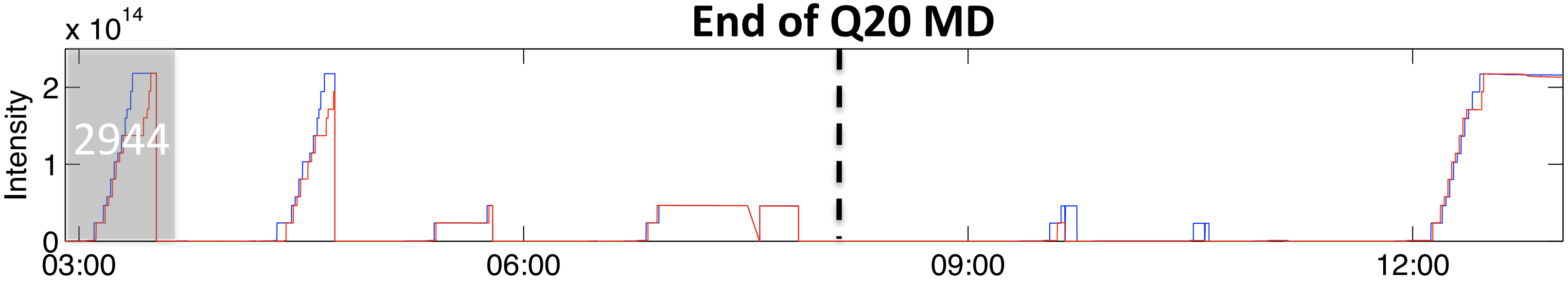
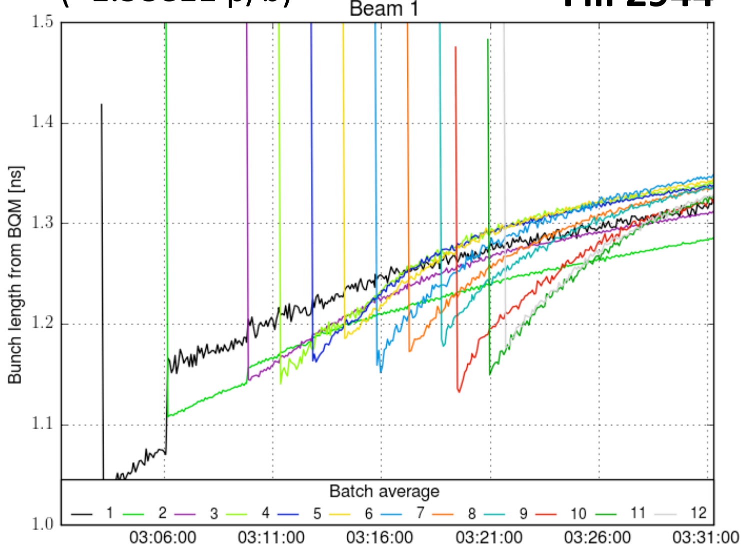
Short bunches at LHC injection (1.45ns)

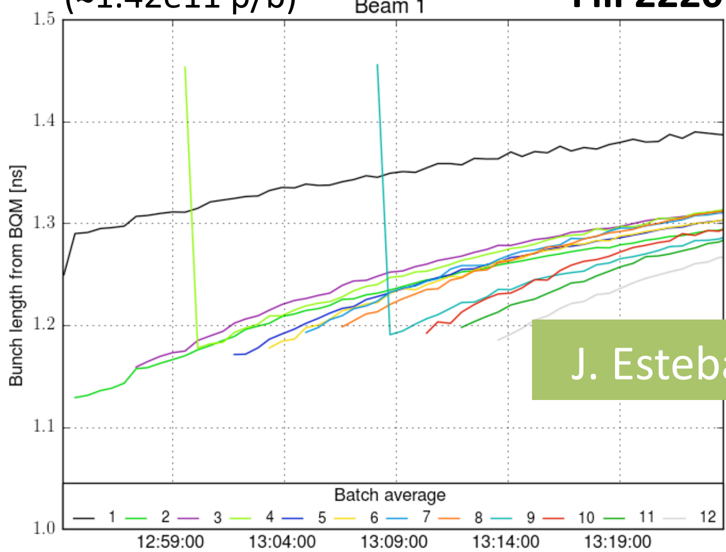


- **Fill 2944: τ_l≈1.45ns / ε_l≈0.37eVs (@SPS extraction from Q20)**
  - No controlled blow-up in SPS (beam passes BQM even though slightly unstable)
  - Longitudinal injection oscillations damped as usual → no instability in LHC
  - Slightly stronger bunch length growth on flat bottom, transverse emittance to be checked

(≈1.58e11 p/b) **Fill 2944**



(≈1.42e11 p/b) **Fill 2220**



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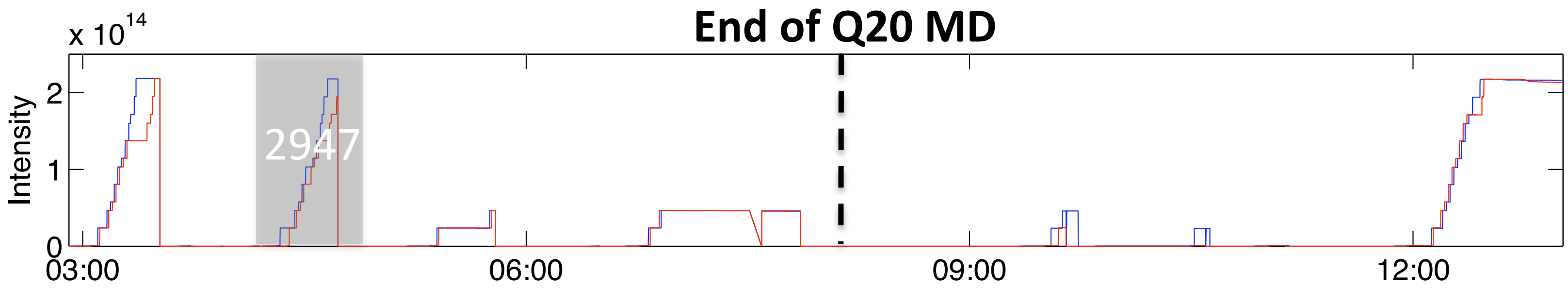
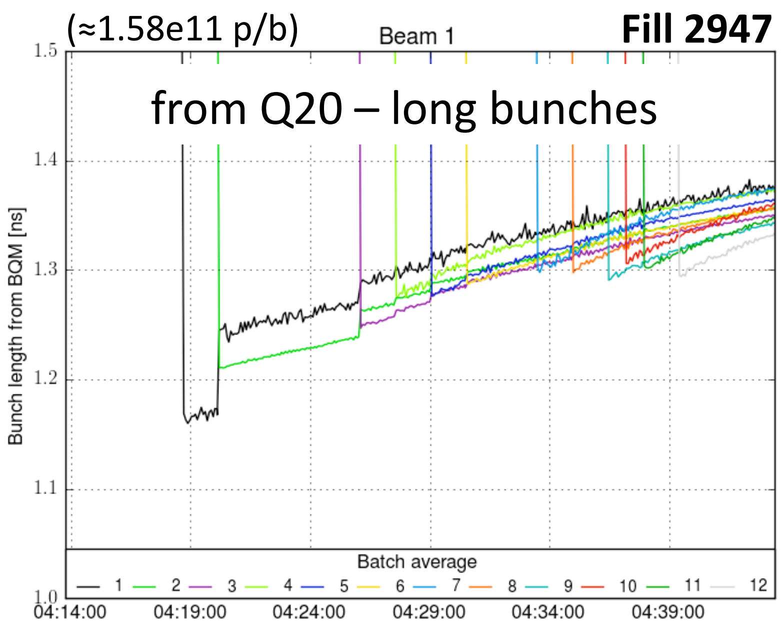
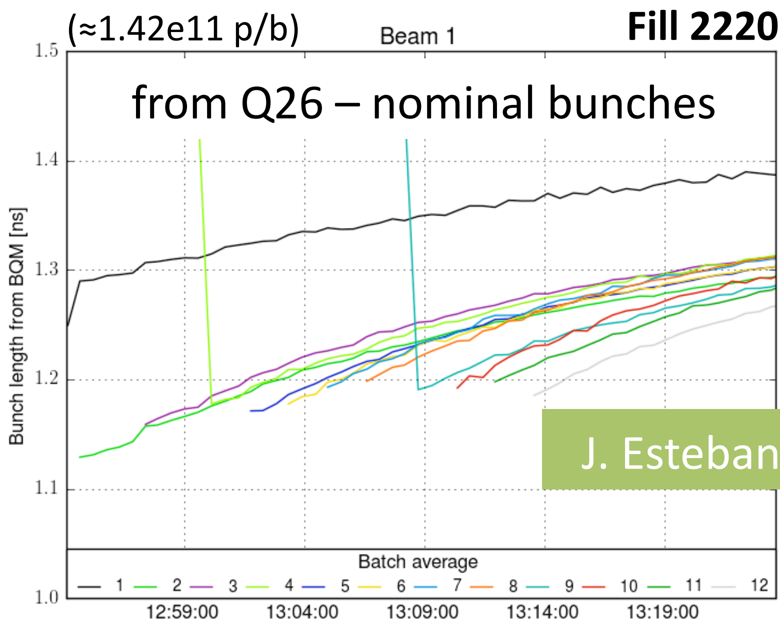
Long bunches at LHC injection (1.70ns)



- **Fill 2947: τ_l≈1.70ns / ε_l≈0.5eVs (@SPS extraction from Q20)**
  - No increase of losses on TDI compared to short bunches!
  - Slightly weaker bunch length growth on flat bottom (ε_l similar to nominal beam)





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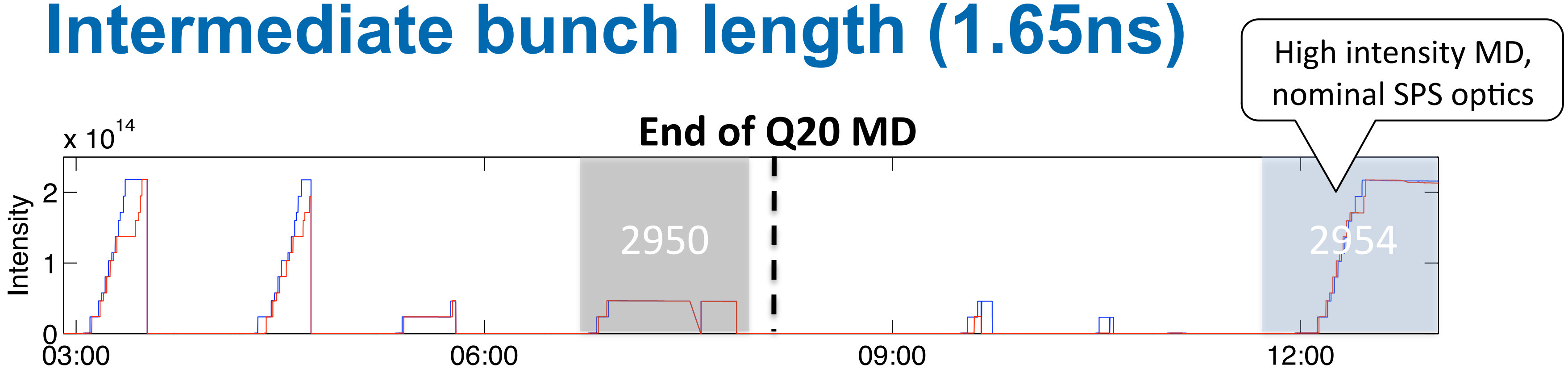
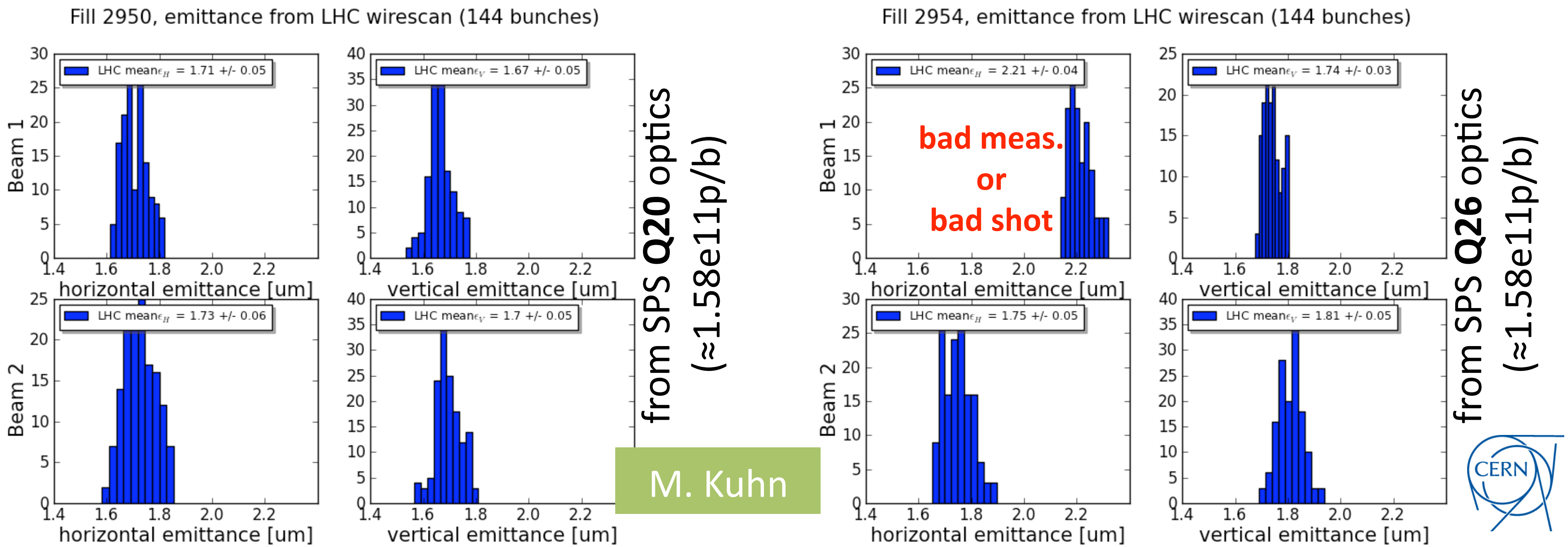
Intermediate bunch length (1.65ns)



- **Fill 2950: $\tau_l \approx 1.65$ns / $\varepsilon_l \approx 0.48$eVs (@SPS extraction from Q20)**
  - Typical bunch length growth on flat bottom (ε_l like in operational beam)
  - Transverse emittance (wire scans) in LHC similar to injection with Q26 optics later that day



Final steps for making Q20 operational

- **Prepare probe cycle with Q20 optics**
- **Final verification of extraction settings**
- **Study transverse emittance evolution on LHC flat bottom with intermediate longitudinal blow-up in SPS Q20**
- **Measure tails at SPS flat top using scrapers**
- **Find the best moment to switch**
  - Constraints due to ions for LHC MDs, 25ns beam for scrubbing (extraction with Q20 not tested yet), technical stop, …
- **Fine-tuning of SPS low-level RF and controlled longitudinal blow-up settings is expected to further improve Q20 longitudinal beam quality**

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Studies left to be done

- **Tails and transverse emittance for operational 50ns beam with Q20**
  - Using the scraper
  - Multiple wire scans and measurements in the LHC
- **25ns beam in Q20 optics: nominal and higher intensity**
  - In preparation for LHC scrubbing run when Q20 is operational
  - In preparation for post-LS1 – comparison with Q26
- **Further studies with high intensity single bunch studies**
  - Space charge – study maximal space charge tune spread
  - TMCI
- **Ions with Q20**
  - Simulations predict that IBS and space charge spread are slightly better with Q20
  - Interplay with space charge and RF noise

Conclusions

- **Clear improvement for various instabilities in SPS with Q20 optics**
  - Demonstrated experimentally and theoretically
  - Q20 enables HL-LHC / LIU parameter space for SPS
  - Q20 provides margin to increase the intensity for 50ns operation already this year

- **Q20 optics is practically ready to be put in operation for LHC filling**
  - Intermediate longitudinal blow-up setting with Q20 gave good results in LHC MD
  - Some details with extraction to be clarified
  - “Probe” cycle to be set-up
  - Using Q20 for the LHC filling allows to gain experience and identify unexpected problems

- **Further studies this year**
  - Gain operational experience with Q20
  - 25ns beam with Q20 (nominal and high intensity)
  - Single bunch limitations in view of HL-LHC beam parameters (intensity and brightness)

LHC Injectors Upgrade

Thank you for your attention!