SPS Q20 – Performance and reach

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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 $1.6 \times 10^{11} \text{p/b}$ ($\varepsilon_L = 0.35 \text{eVs}$, $\tau = 3.8 \text{ns}$) with low $\xi_y$

  \[ N_{th} \sim \eta \varepsilon_l / \beta_y \]

  - Longitudinal instabilities
    - Threshold at $3 \times 10^{10} \text{p/b}$ at for single harmonic RF

  \[ N_{th} \sim \eta \varepsilon_l^2 \tau \]

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

  \[ N_{th} \sim Q_s \sim \eta \] (for given longitudinal beam parameters)

\[ \Rightarrow \text{Instability thresholds can be raised by increasing slip factor } \eta! \]
Increasing slip factor $\eta$ in SPS

Q20 low-$\gamma_t$ optics:

$\Rightarrow$ Factor 2.8 higher $\eta$ at injection energy!

$\Rightarrow$ Factor 1.6 higher $\eta$ at flat top!

... compared to nominal SPS optics Q26

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

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

$\Rightarrow$ Reduce horizontal tune $Q_x$!
Optics comparison

- Working point lowered by 6 integer units in both planes ($Q_x/Q_y = 20.13/20.18$)
- No increase of $\beta$-function maxima, but higher dispersion ($\rightarrow$ lower $\gamma_t$)
- 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:
  - \( \frac{\eta_{Q20}}{\eta_{Q26}} = 2.85 \) (at injection)
  - Average \( \beta_y \) around 1.3 times larger in Q20
  => Expect \( N_{th} \sim \frac{2.85}{1.3} \times 1.6 \times 10^{11} p/b = 3.5 \times 10^{11} p/b \)

- TMCI with Q20 not clearly observed experimentally yet

=> Injected up to \( 4 \times 10^{11} p/b \) 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
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

- Instability threshold scales with $Q_s$ ($\sim \eta$ for matched RF-voltage)

$\Rightarrow$ Clearly higher instability threshold with Q20!
• 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 $N_{th} \sim \epsilon^2 \eta T$
- 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 $1.2 \times 10^{11}$ p/b
  - 800 MHz cavity is on (voltage around 1/10 of 200 MHz)

- $\Rightarrow$ Emittance blow-up needed
- $\Rightarrow$ 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: $\tau \approx 1.45\text{ns} / \varepsilon \approx 0.37\text{eVs}$ (@SPS extraction from Q20)
  - No controlled blow-up in SPS (beam passes BQM even though slightly unstable)
  - Longitudinal injection oscillations damped as usual $\rightarrow$ no instability in LHC
Short bunches at LHC injection (1.45ns)

- Fill 2944: $\tau_l \approx 1.45\text{ns}$ / $\epsilon_l \approx 0.37\text{eVs}$ (@SPS extraction from Q20)
  - No controlled blow-up in SPS (beam passes BQM even though slightly unstable)
  - Longitudinal injection oscillations damped as usual $\rightarrow$ no instability in LHC
  - Slightly stronger bunch length growth on flat bottom, transverse emittance to be checked

![Graphs showing intensity and bunch length for Fill 2944 and Fill 2220](image)
Long bunches at LHC injection (1.70ns)

- Fill 2947: $\tau_1 \approx 1.70\text{ns} / \varepsilon_1 \approx 0.5\text{eVs}$ (@SPS extraction from Q20)
  - No increase of losses on TDI compared to short bunches!
  - Slightly weaker bunch length growth on flat bottom ($\varepsilon_1$ similar to nominal beam)

![Graph showing intensity over time for Fill 2947 and Fill 2220]
Intermediate bunch length (1.65ns)

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

![Graph showing intensity over time]

High intensity MD, nominal SPS optics

M. Kuhn from SPS Q20 optics

$\approx 1.58 \times 10^{11} \text{p/b}$

bad meas. or bad shot
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)
Thank you for your attention!

LHC Injectors Upgrade