LHC Injectors Upgrade

Q22 optics

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SPS injection losses review, 30 November 2017

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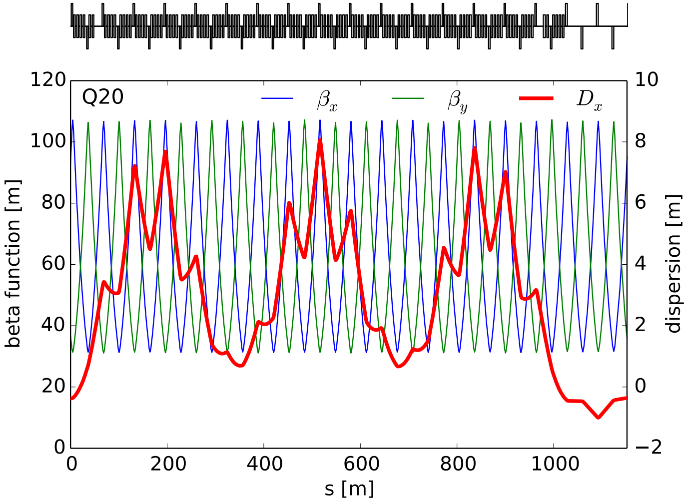
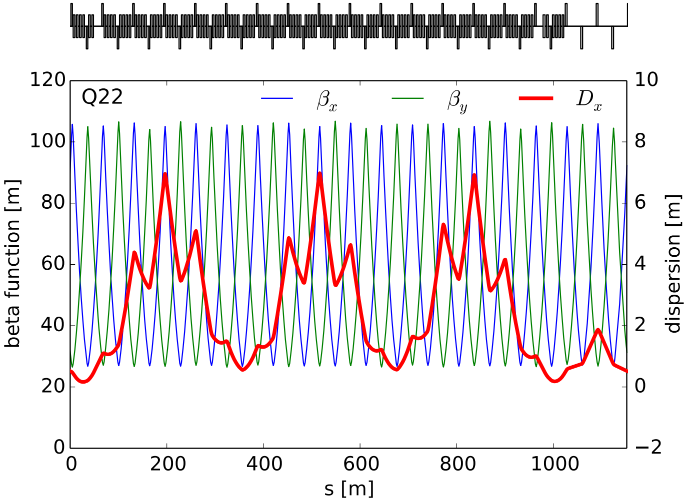
Introduction





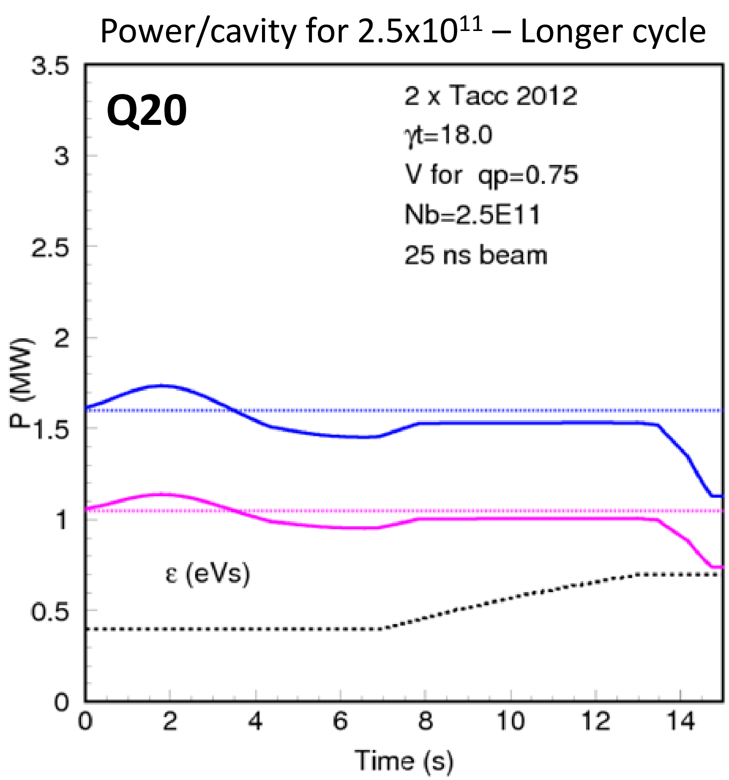
- **Q22 in comparison to Q20**
  - **gamma at transition 20 instead of 18**
  - **less voltage required for same bucket area → less impact of limited RF power during first part of the ramp?**
  - **lower TMCI threshold → expected close to HL-LHC intensity, to be checked experimentally**
  - **lower longitudinal instability thresholds → need larger longitudinal emittance for stability during the ramp**
  - slightly smaller peak dispersion → larger momentum acceptance
  - smaller average dispersion → non-linear chromatic detuning is smaller

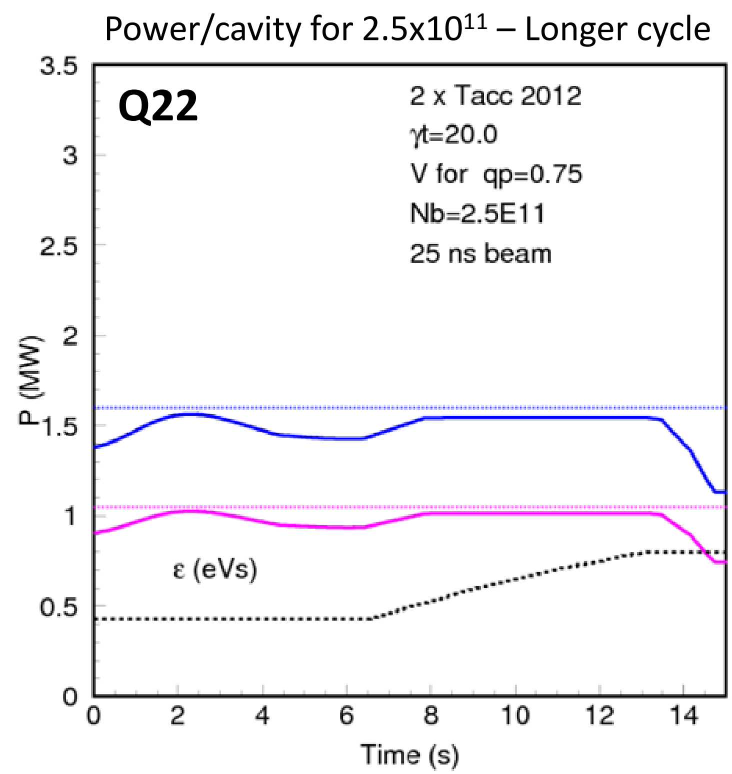
Potential benefits and potential issues

- **TMCI at injection**
  - Expected close to 2.6e11 p/b … at LIU intensity
  - Might require wide band feedback system to ensure operational margin for stability
- **(slightly) larger momentum acceptance**
  - Slightly smaller dispersion at QDs compared to Q20 (e.g. gain 1 sigma for 2 um emittance and 1.5e-3 momentum spread, see Verena's presentation) … could run with slightly higher bucket area at injection until running into momentum aperture limitations for captured particles
- **Capture losses?**
  - Capture losses are observed to increase with intensity. For the moment we seem to be still dominated by SPS intensity effects (need high voltage to compensate insufficient beam loading compensation). With better beam loading compensation, we might profit in the future from the more effective voltage in Q22
- **RF power on the ramp**
  - For the same bucket area, Q22 requires less voltage and less RF power compared to Q20. This could help overcoming RF power limitations in the first part of the ramp (in the second half of the ramp the longitudinal instability requires larger longitudinal emittance in Q22 and practically the same RF power and voltage is needed independent of optics)
- **Longitudinal instability at injection?**
  - From scaling with slip factor expect 1.5 times lower threshold compared to Q20

RF power

- **Acceleration cycle (twice longer compared to present) with 2.5x10^{11} p/b**
  - **First part: Q22 requires less RF voltage and RF power**
  - Second part: same RF power in both optics (beam stability requires larger longitudinal emittance in Q22 and thus similar RF voltage as in Q20)



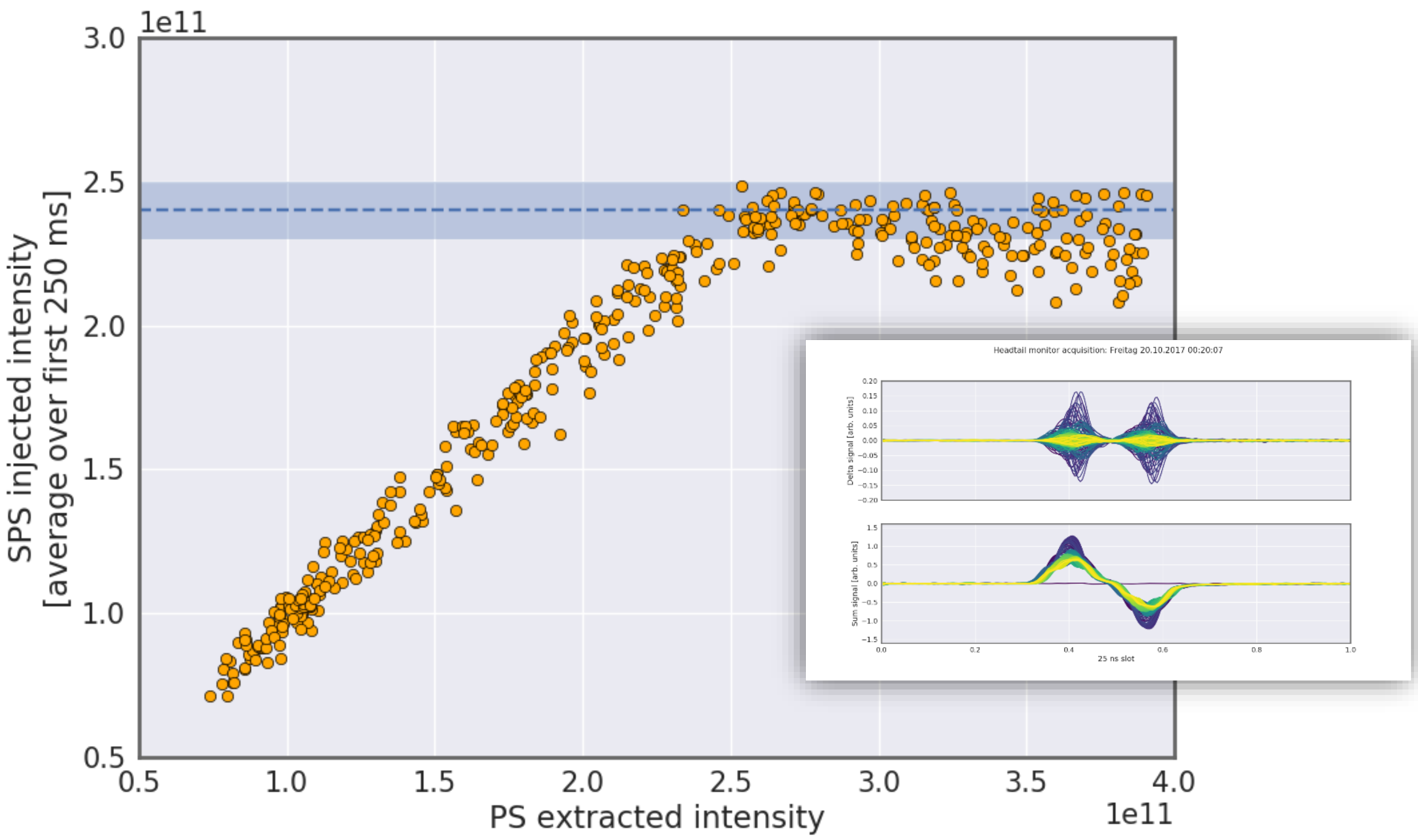


Overview of studies up to now

- **2016**
  - Preparation of optics for LSA (TT10 and SPS ring)
  - First injection into “MD” cycle (flat bottom only), chromaticity and tune knobs checked
- **2017**
  - Setting up and first studies with acceleration of LHC 25 ns beam
  - Studies with high bandwidth feedback system
  - Measurements of TMCI threshold
  - Measurements of non-linear chromaticity
  - Studies of losses (in comparison to Q20)

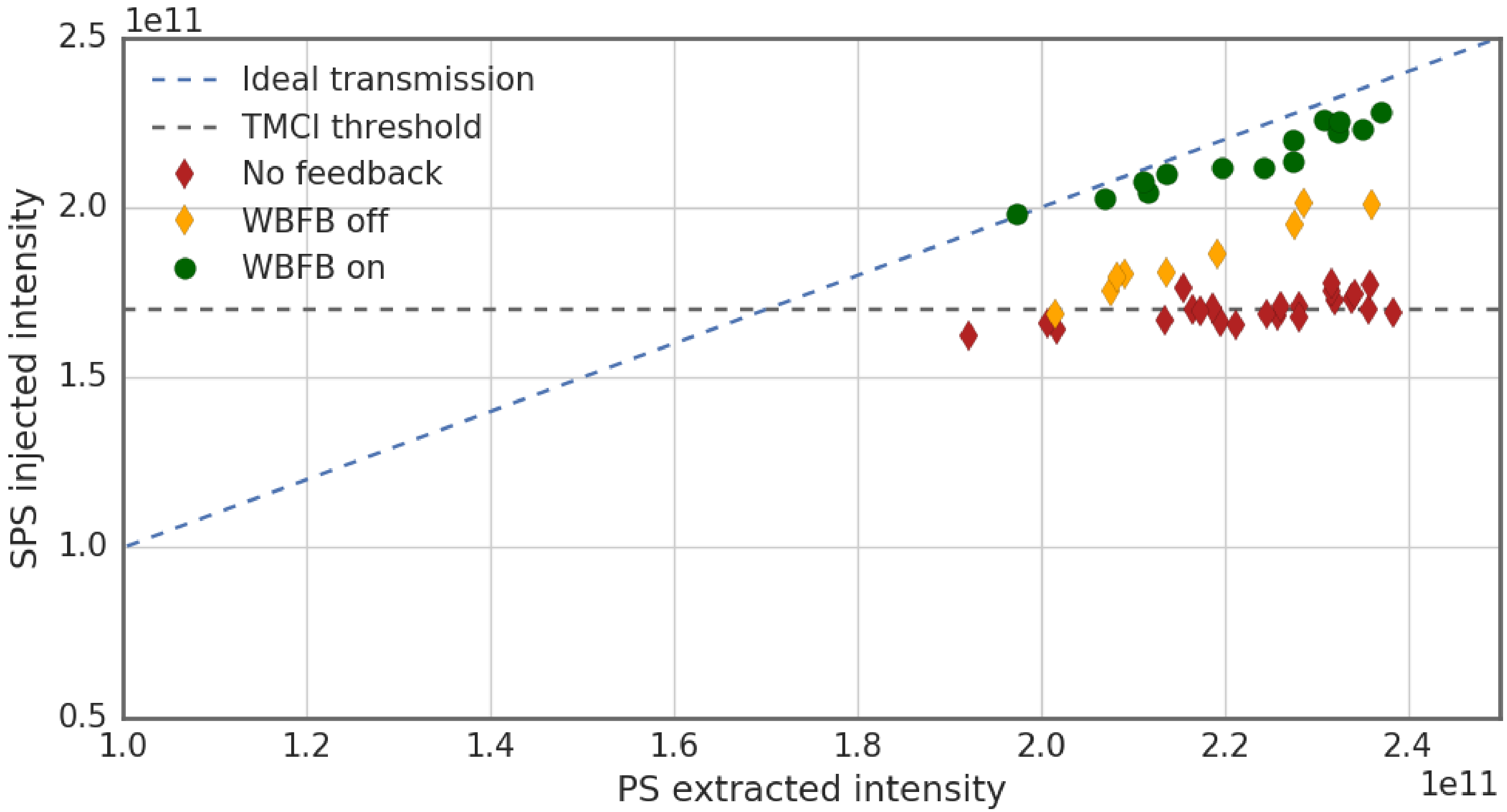
TMCI threshold measurements

- **For 2.7 MV and 0.32 eVs the threshold is around 2.4e11**
  - Close to expected values from HEADTAIL simulations
  - Would run with > 3 MV and therefore threshold for “operational” settings slightly higher



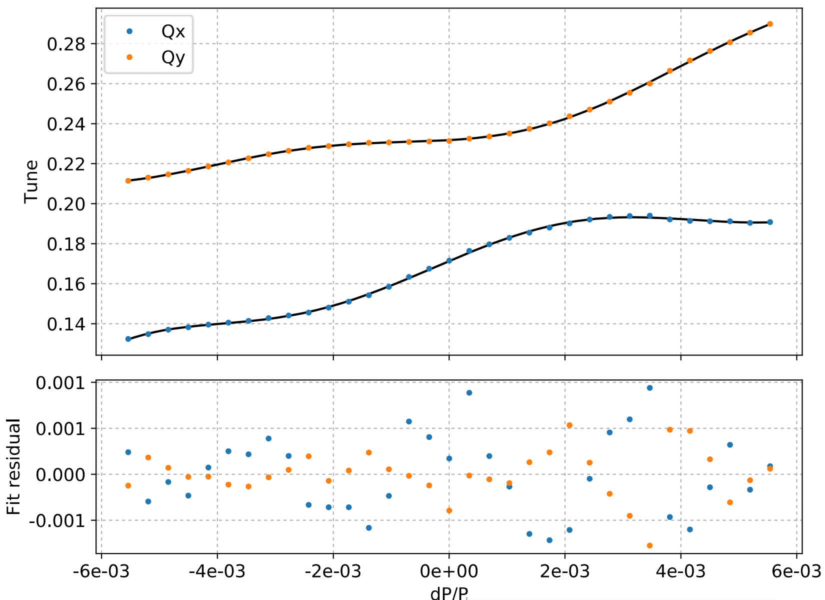
TMCI stabilization with WBFB

- **First successful stabilization of TMCI with WBFB system achieved this year**
  - Measurements with reduced RF voltage to provoke instability at lower intensities (operational limitations during ion run)
  - Very promising results, studies to be continued next year



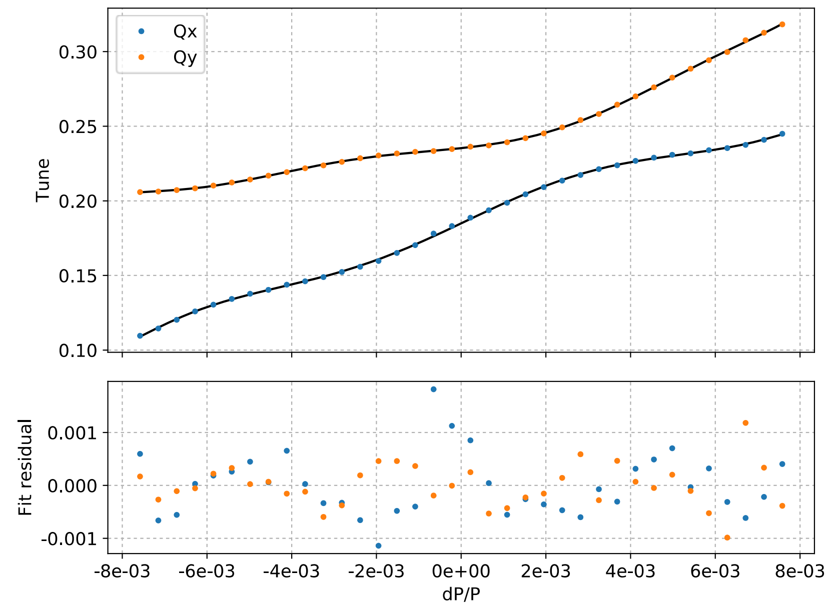
Nonlinear chromaticity

- **Smaller dispersion in Q22 results in less pronounced non-linear chromaticity**
  - Reduced chromatic detuning for same momentum spread → beneficial for incoherent losses



Horizontal (QPH: +0.45)
Q[0] : 1.71e-01 +/- 0.12 %
Q[1] : 1.23e+01 +/- 1.48 %
Q[2] : -9.13e+02 +/- 16.24 %
Q[3] : -3.28e+06 +/- 7.46 %
Q[4] : 2.84e+08 +/- 53.19 %
Q[5] : 1.58e+12 +/- 19.99 %
Q[6] : -1.75e+14 +/- 57.60 %
Q[7] : -4.64e+17 +/- 54.43 %

Vertical (QPV: -0.50)
Q[0] : 2.32e-01 +/- 0.05 %
Q[1] : 1.75e+00 +/- 6.19 %
Q[2] : 2.17e+03 +/- 4.09 %
Q[3] : 2.65e+06 +/- 5.52 %
Q[4] : -5.58e+08 +/- 16.14 %
Q[5] : -1.47e+12 +/- 12.88 %
Q[6] : 1.90e+14 +/- 31.82 %
Q[7] : 5.69e+17 +/- 26.49 %

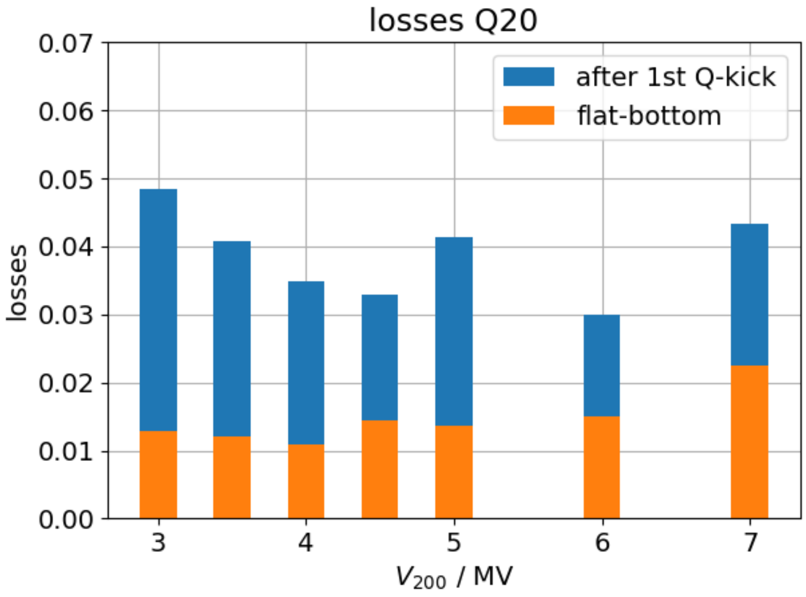


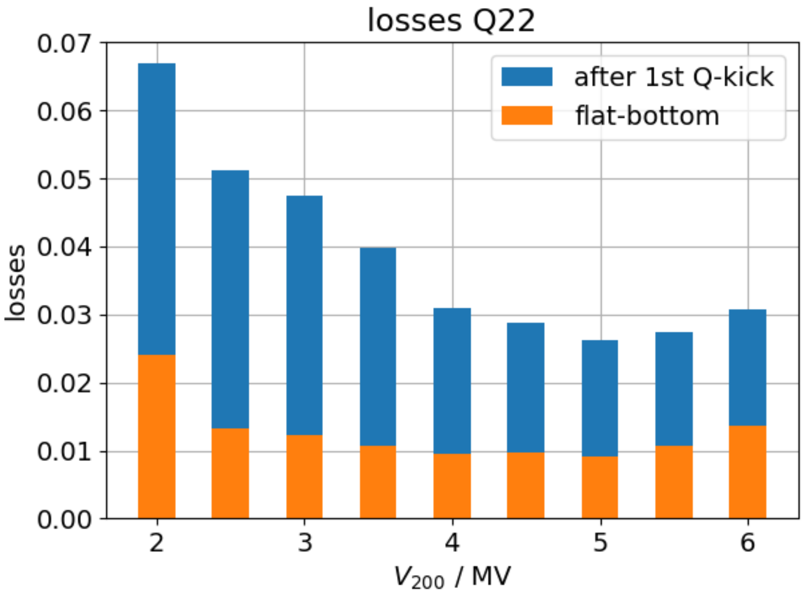
Horizontal (QPH: +0.50)
Q[0] : 1.85e-01 +/- 0.14 %
Q[1] : 1.35e+01 +/- 1.26 %
Q[2] : 2.21e+02 +/- 45.77 %
Q[3] : -1.66e+06 +/- 7.37 %
Q[4] : -1.87e+08 +/- 29.44 %
Q[5] : 6.12e+11 +/- 13.81 %
Q[6] : 4.29e+13 +/- 46.07 %
Q[7] : -1.46e+17 +/- 24.69 %

Vertical (QPV: -0.20)
Q[0] : 2.35e-01 +/- 0.07 %
Q[1] : 3.01e+00 +/- 3.82 %
Q[2] : 1.25e+03 +/- 5.51 %
Q[3] : 1.59e+06 +/- 5.21 %
Q[4] : -1.22e+08 +/- 30.79 %
Q[5] : -6.52e+11 +/- 8.81 %
Q[6] : 2.93e+13 +/- 45.88 %
Q[7] : 1.89e+17 +/- 13.01 %

Comparison of flat bottom losses

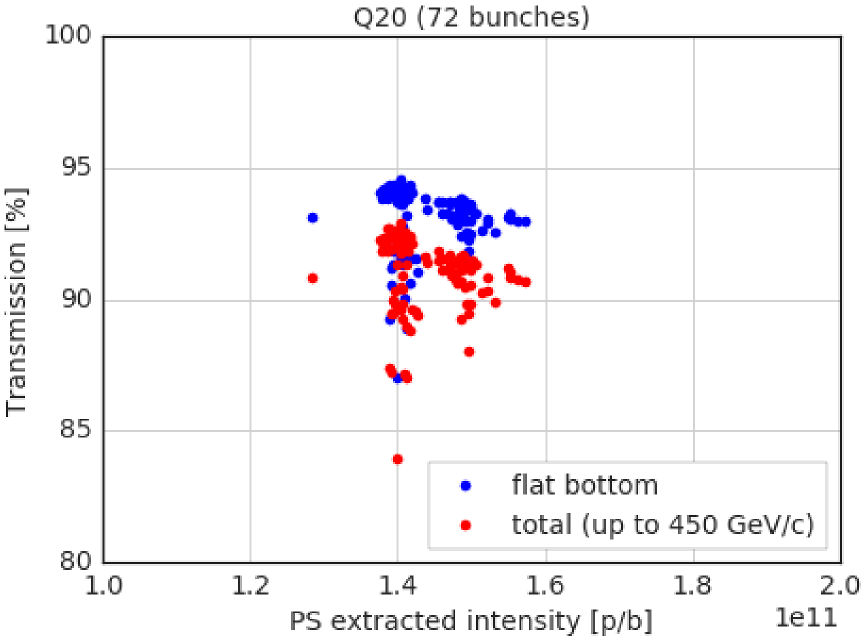
- **Measurements on long flat bottom (11s)**
  - 48 bunches BCMS with 1.35e11 p/b – Q-kick at 2s for cleaning uncaptured beam
  - Minimal losses at V_{200}=4.5MV (Q20) and V_{200}=5.0MV (Q22)
  - Some gain in Q22 (losses for this intensity dominated by long. distribution from PS)

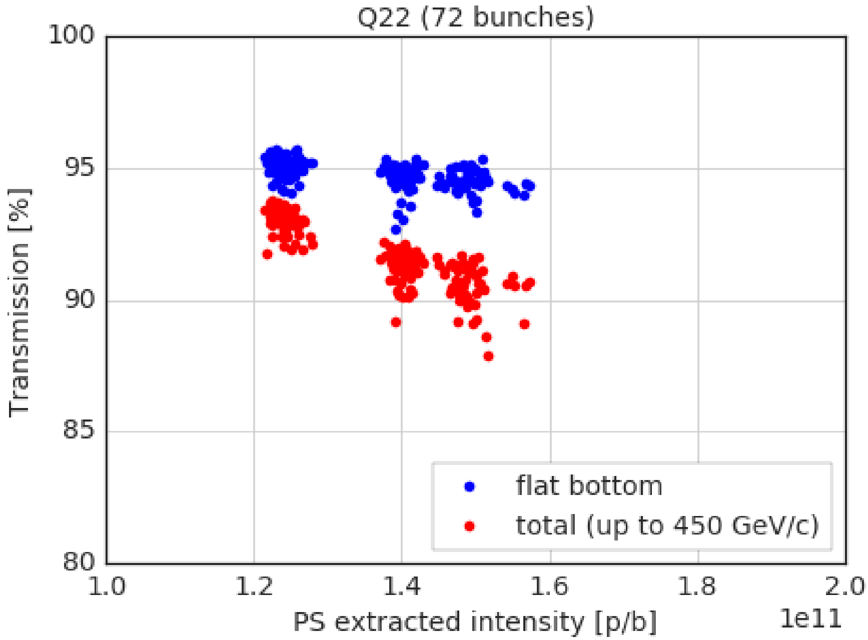




Acceleration to 450 GeV/c

- **Flat bottom losses better in Q22 but similar total transmission to 450 GeV/c**
  - LHC type cycles (long flat bottom)
  - Constant bucket area of 0.6 eVs during first part of ramp corresponding to ~3MV on flat bottom (i.e. voltage margin in Q22 not yet exploited)
  - Power limit on new solid state amplifiers was not yet in place





Summary & Conclusions

- **Status and conclusions from studies performed so far**
  - Excellent results for 1 year of MDs
  - TMCI threshold close to expected value (i.e. at around intensity required for HL-LHC)
  - WBFB demonstrated to control TMCI (WBFB might be crucial for reliable operation with HL-LHC parameters)
  - Accelerated up to 1.6e11 p/b (72 bunches) to 450 GeV/c – longitudinal stability to be studied
  - Flat bottom losses slightly better compared to Q20 as expected from larger momentum acceptance
  - Gain in total transmission when accelerating to flat top not observed so far - potential of higher bucket area on flat bottom and during ramp not yet exploited

- **Studies to be done (next year)**
  - Characterization of longitudinal instability thresholds (also flat bottom!)
  - Intensity reach with present RF and optimized RF voltage on the ramp – should see improvement compared to Q20
  - Further exploration of intensity reach with WBFB
  - Transfer to LHC (transfer line matching challenging due to inverted dispersion in SPS-LSS)

LHC Injectors Upgrade

Thank you for your attention!

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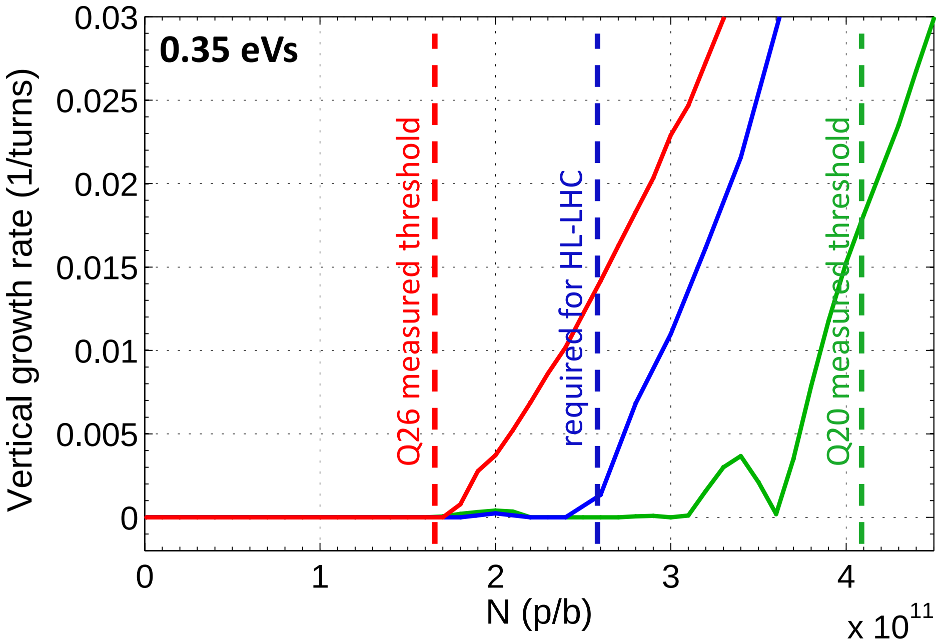
TMCI

- **Measurements vs. HEADTAIL simulations**
  - wake fields from SPS impedance model
  - nominal longitudinal emittance (0.35 eVs) and scaled RF voltage
  - **Threshold in Q22 to be checked experimentally**

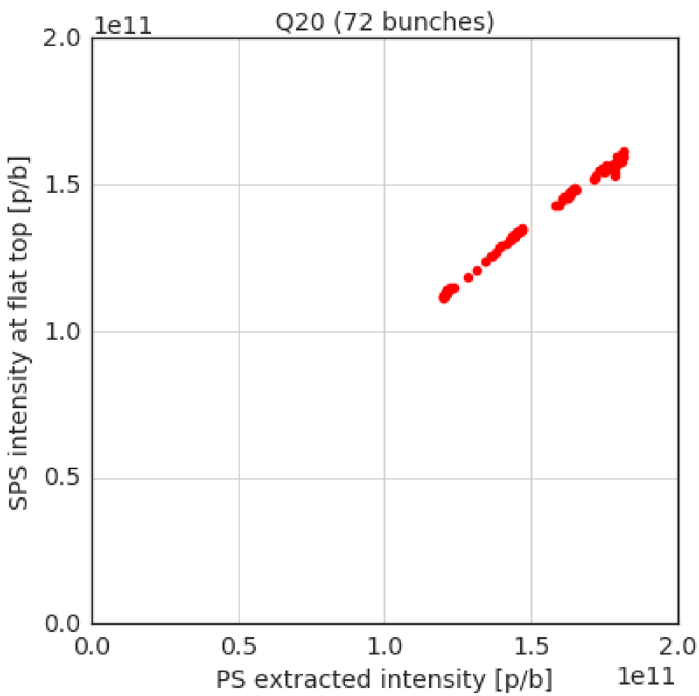


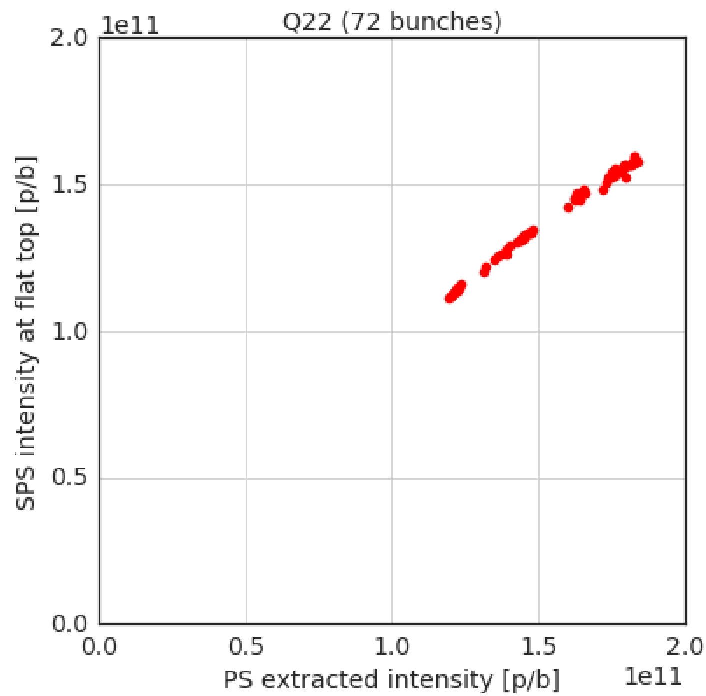
- Q26: good agreement with measured threshold (model: $Q'_y = 1 + Q''_y + Q_y'''$)
- Q20: slightly pessimistic prediction compared to measured threshold (model: $Q'_y = 1 + Q''_y + Q_y'''$)
- Predicted threshold in Q22 very close to the 2.6e11 p/b required for HL-LHC (model: $Q'_y = 2$)

Losses with acceleration to 450 GeV/c

- **Flat bottom losses better in Q22 but similar or slightly worse total transmission when accelerating to 450 GeV/c (optimization in Q22?)**

- **MD with very high intensity 25 ns beam (up to 1.8e11 p/b injected, more than 1.6e11 p/b extracted) also showed slightly better transmission in Q20**
  - During this MD (16.8.2017) the power limit on the solid state amplifiers was not yet in place
  - Voltage margin in Q22 not exploited (main losses due to uncaptured beam / losses out of bucket)





Flat bottom losses