LHC Injectors Upgrade

Space charge in the CERN SPS

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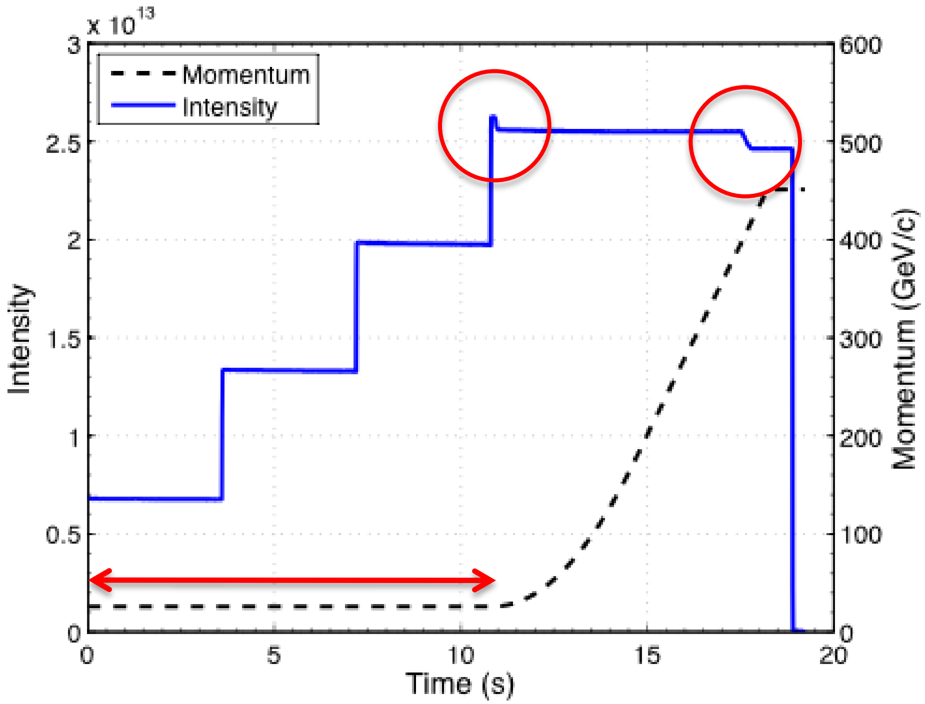
Introduction – SPS cycle for LHC beam



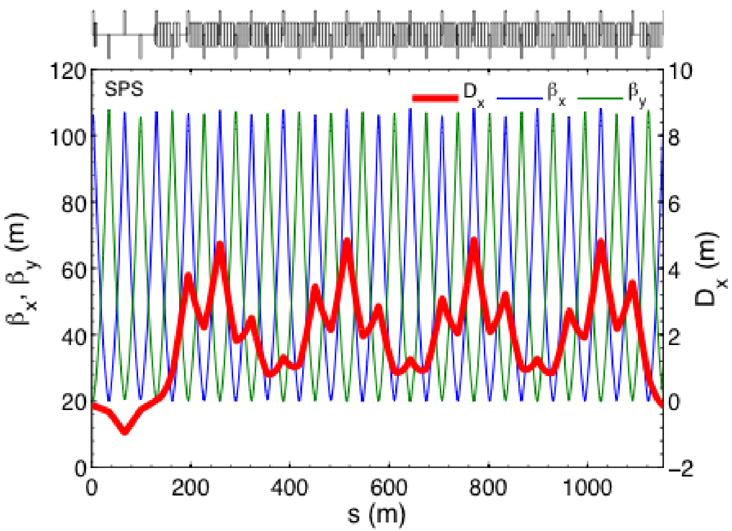
- **Long injection plateau (10.8s)**
  - 4 injections, 26 GeV/c
  - Maybe even longer in case of BCMS beam
- **Budget for total losses: 10%**
  - Losses at start of acceleration ~3-5%
  - Scraping at flat top ~3%
- **Budget for emittance growth: 10%**
  - Small optics mismatch at injection
  - Avoid different emittance per batch

⇒ Need to preserve high brightness for >10s with $\Delta Q>0.2$ with “practically no degradation”

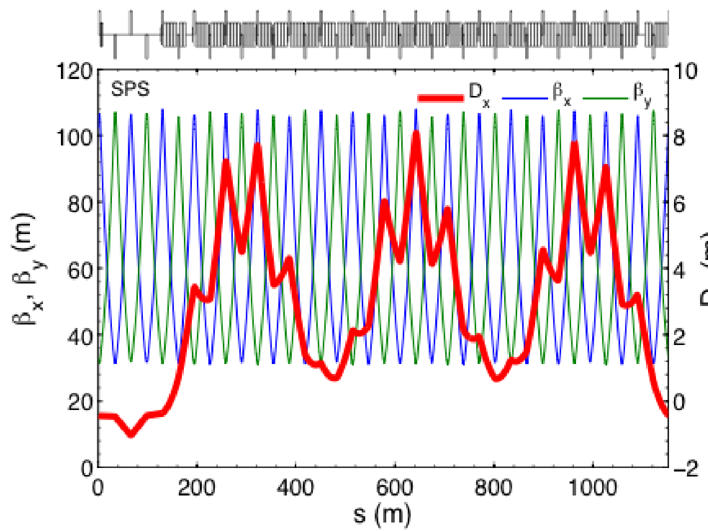
Q20 - low transition energy optics

- **Lower γ_t means higher slip factor η → instability thresholds scale proportionally!**
  - Lowering SPS working point by 6 units: “Q26” → “Q20” (γ_t=22.8 → γ_t=18)
  - Significantly larger slip factor η **(factor 2.85 at injection, 1.6 at extraction)**
- **Implications for space charge**
  - Higher synchrotron tune (almost factor 3 higher at injection)
  - Larger dispersion → smaller space charge tune spread

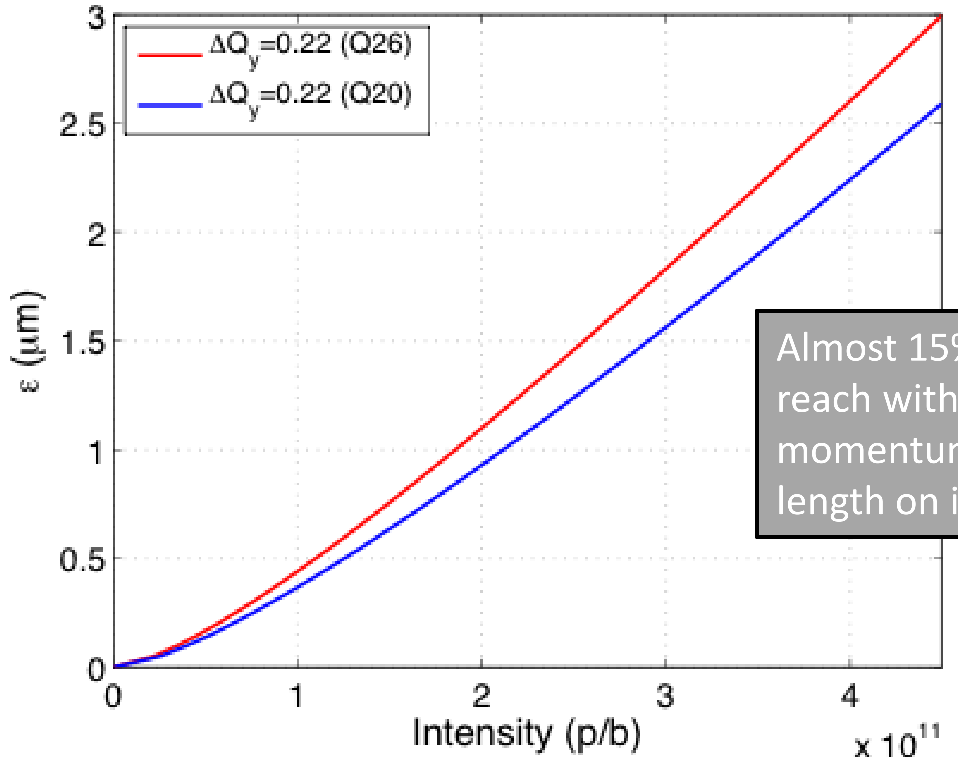
Q_x/Q_y=26.13/26.18 (“Q26”)



Q_x/Q_y=20.13/20.18 (“Q20”)



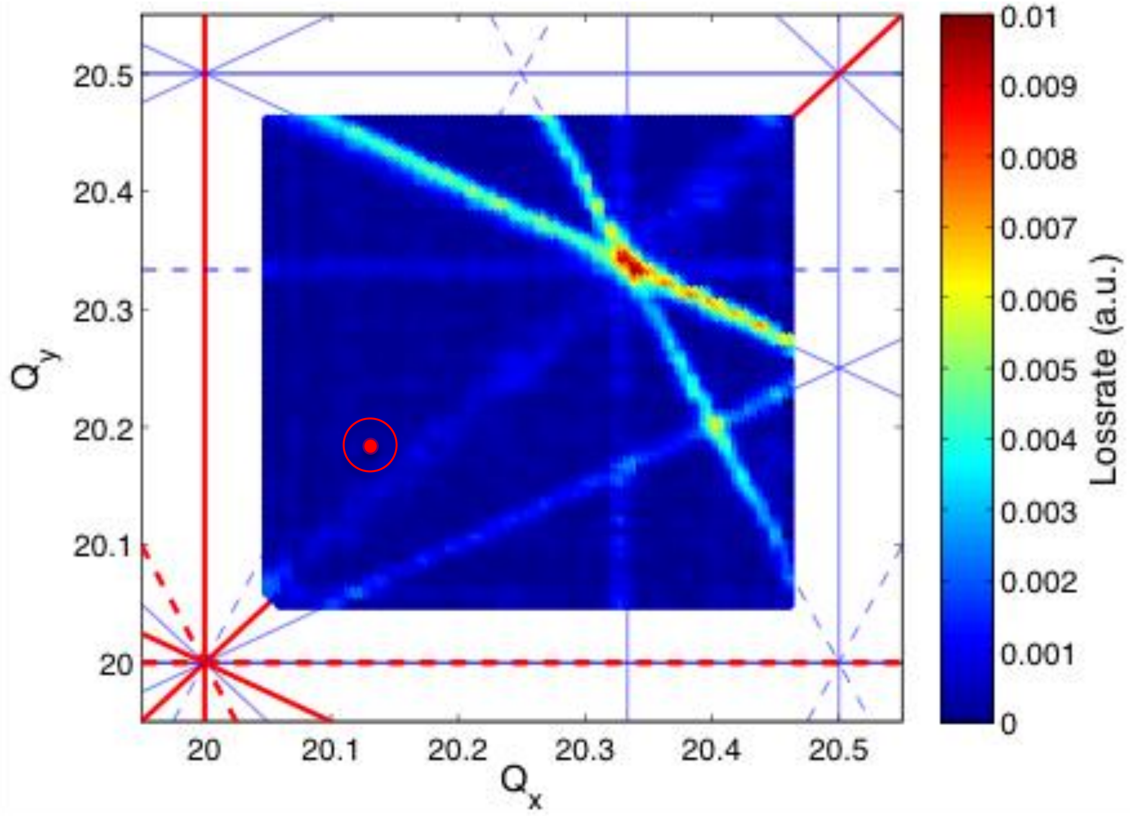
Brightness reach for given SC tune spread



Almost 15% higher brightness reach with Q20 for typical momentum spread and bunch length on injection plateau

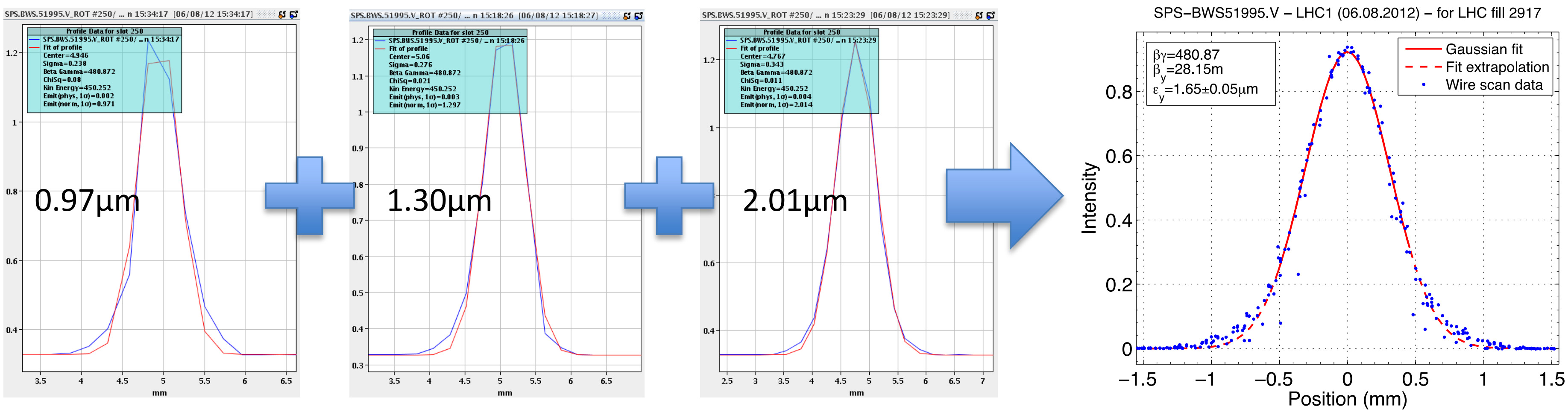
⇒ **Larger dispersion in Q20 = higher brightness reach for given Laslett tune shift**

Tune diagram



Resonance scan with low intensity single bunch beam – average of scans in all directions

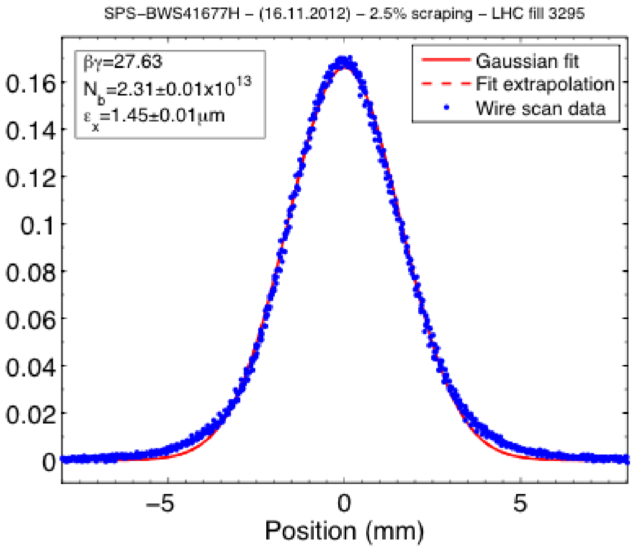
Emittance measurements – extraction energy

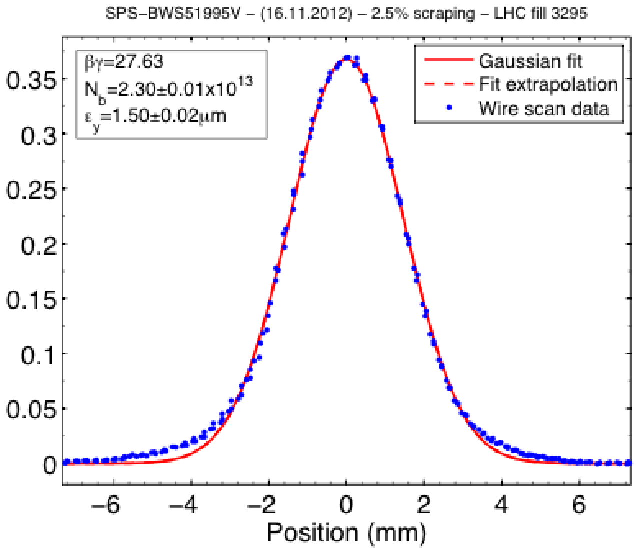


- **Low resolution due to small emittance (especially at flat top)**
  - **Turn acquisition mode:** single beam profile for all bunches (here 144)!
  - Very view data points → large scatter in measurement, even in stable beam conditions
  - **In addition: systematic errors (calibration, beta-beat, …)**
- **Combine several measurements (assuming beam is reproducible)**
  - Many measurements needed (typically 5-10) – but error significantly reduced
  - Was implemented in control room application in September 2012

Emittance measurements – injection energy

- **Further improvement by measuring at the end of flat bottom instead of flat top**
  - Higher resolution due to larger beam size
  - Good agreement with LHC measurements at injection (typically within 10%)



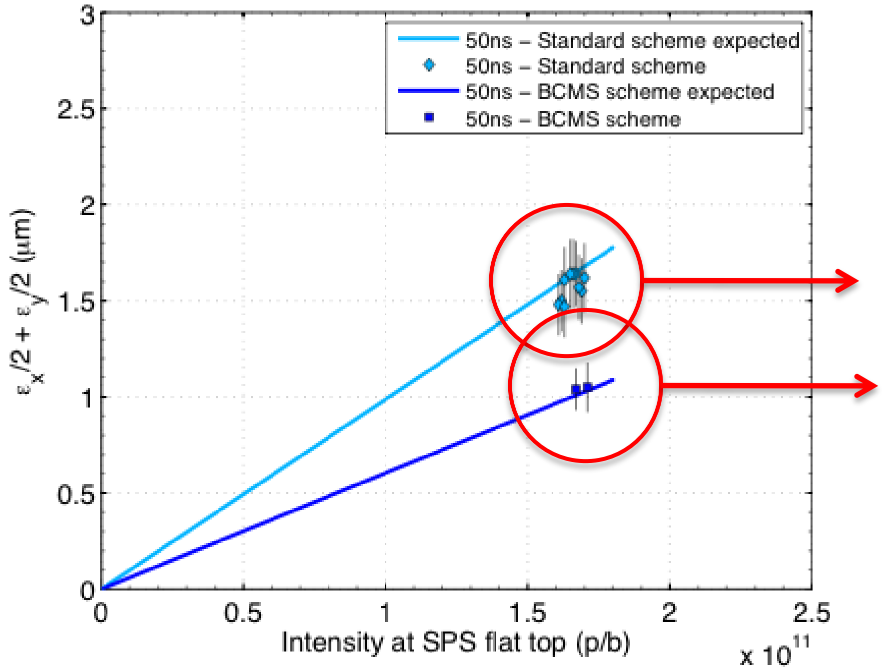


- **Method relies on reproducible beam parameters**
  - High brightness single bunch beam has large fluctuation in intensity and emittance
  - ⇒ Space charge studies with high brightness 50ns (BCMS) beam

2012 achieved beam parameters – 50ns beam

Expected performance: Scaling PSB measurements with LIU budget for blow-up and losses

All measurements with



$\Delta Q_x/\Delta Q_y$ ~ 0.08/0.13

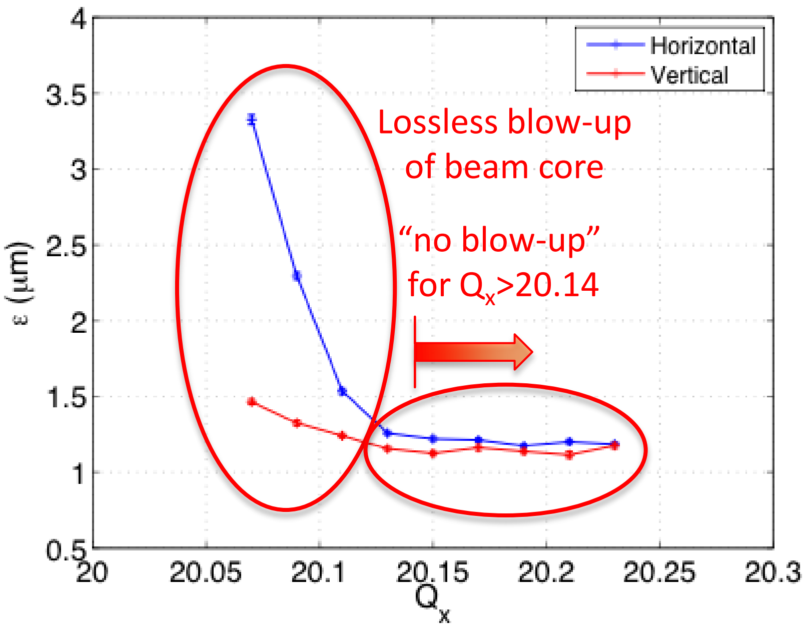
$\Delta Q_x/\Delta Q_y$ ~ 0.10/0.18

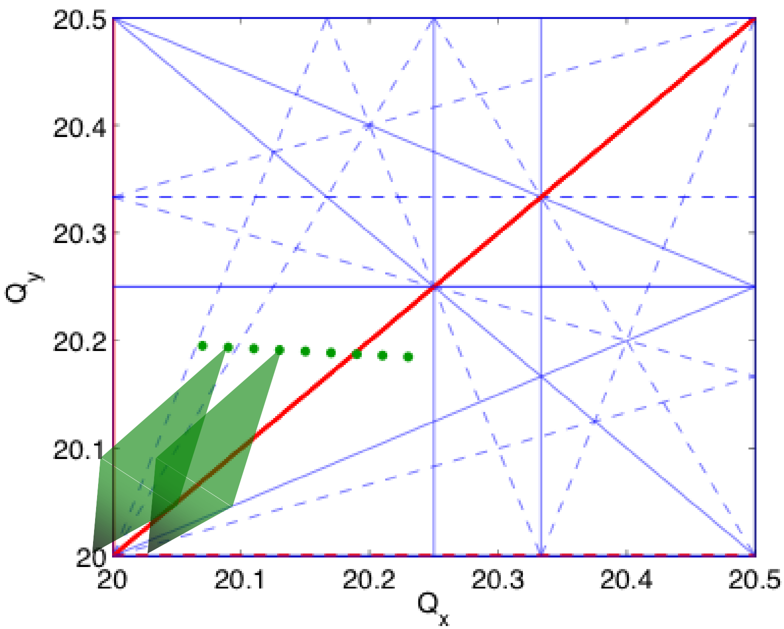
- **50ns standard scheme**
  - Regularly used to fill LHC **since September 2012 using Q20 optics**, at present PS intensity limit
- **50ns BCMS scheme**
  - Beam sent to the LHC once to check emittance preservation and luminosity gain in LHC

Space charge tune scan - horizontal

- **Machine setup for high brightness 50ns BCMS beam <u>(1 batch of 24 bunches)</u>**
  - N = 1.95x10[11] p/b (at injection)
  - ε ~ 1.15μm

  } **$\Delta Q_x/\Delta Q_y$ ~ 0.10/0.18** (from Laslett formula)
  - Transmission up to flat top around 94% without scraping (very small losses on flat bottom)
  - Combined emittance measurement of 5 shots at the end of flat bottom
  - Error bars contain only fit uncertainty

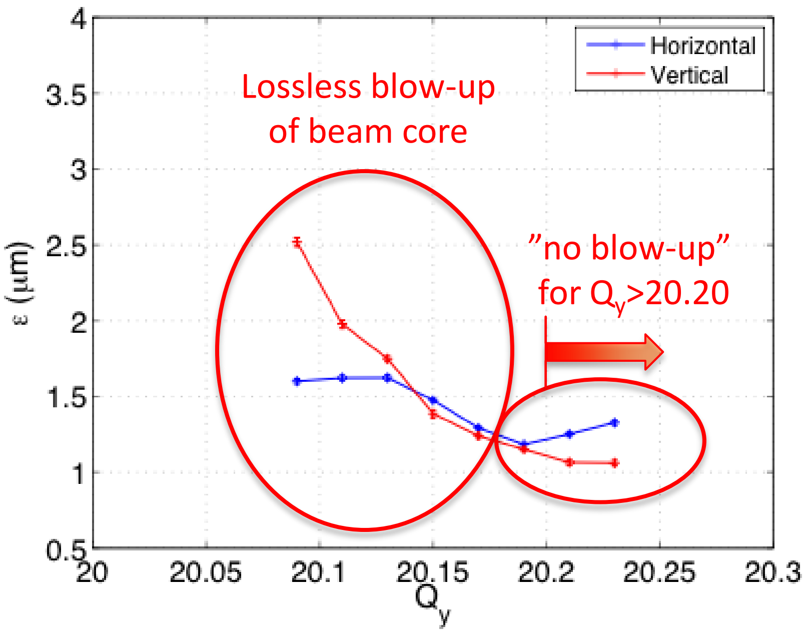


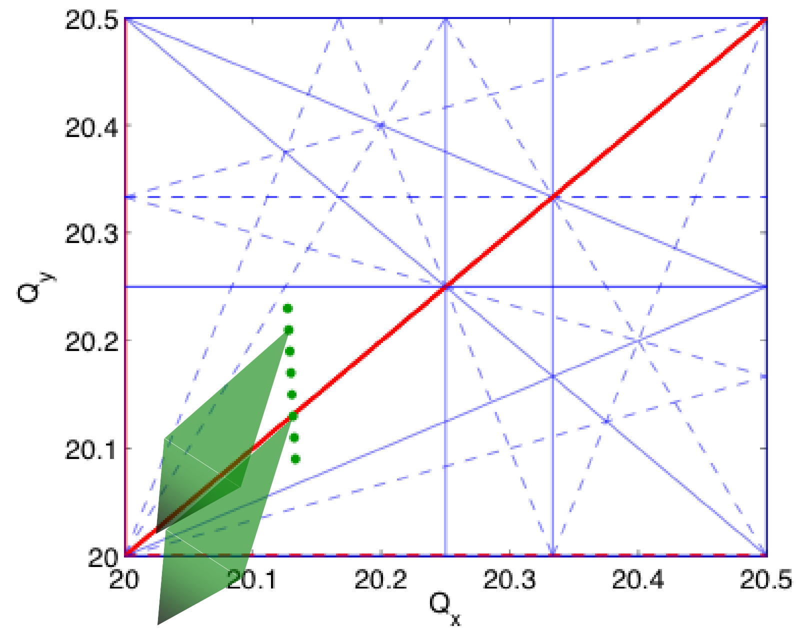


Space charge tune scan - vertical

- **Machine setup for high brightness 50ns BCMS beam <u>(1 batch of 24 bunches)</u>**
  - N = 1.95×10^{11} p/b (at injection)
  - ε ~ 1.15μm

  } **$\Delta Q_x/\Delta Q_y$ ~ 0.10/0.18** (from Laslett formula)
  - Transmission up to flat top around 94% without scraping (very small losses on flat bottom)
  - Combined emittance measurement of 5 shots at the end of flat bottom
  - Error bars contain only fit uncertainty

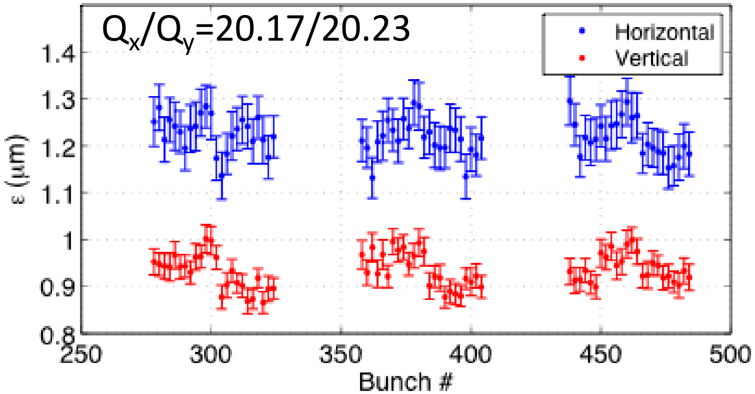


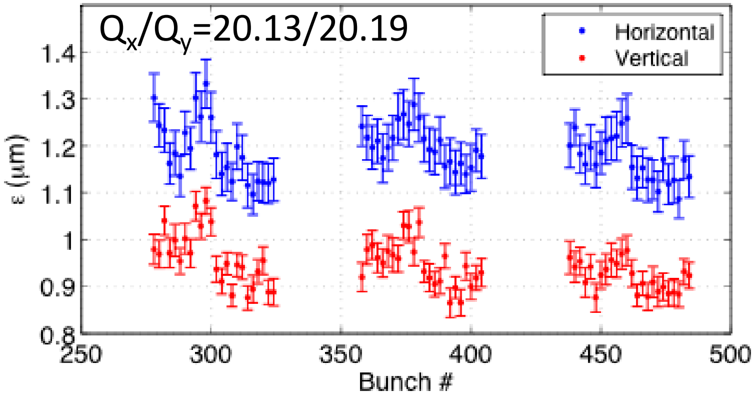


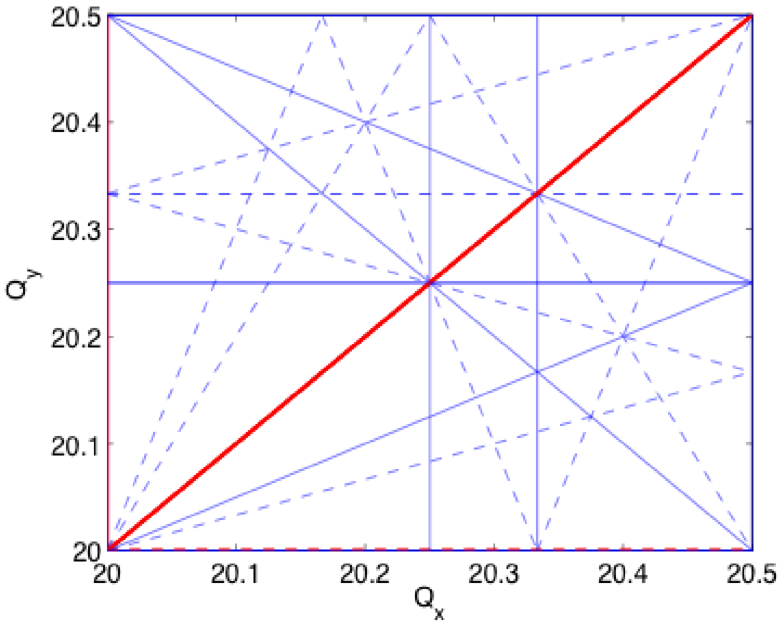
Bunch-by-bunch emittance measurement

- **High brightness 50ns BCMS beam (3 batches of 24 bunches)**
  - N = 1.95x10^{11} p/b (at injection)
  - ε ~ 1.15μm

  } **$\Delta Q_x/\Delta Q_y$ ~ 0.10/0.18** (from Laslett formula)
  - Bunch-by-bunch wire-scans: **study relative blow-up due to different storage time per batch**
  - Single measurements at end of flat bottom (error bars include fit uncertainty only!)







Simulation studies - ideas

- **Study the shown observations**
  - Short term effects with PTC-ORBIT
  - Frozen space charge model for long-term?
- **Emittance growth as function of time for tune close to integer resonance**
  - Data was taken – try to benchmark (although limited non-linear model)
- **Injection transients**
  - Generic study: possible blow-up from bunch length oscillation (injection into mismatched bucket)
  - Difference for Q20 and Q26 due to different synchrotron tunes?
  - Sensitivity to optics mismatch at injection in combination with space charge
- **Effect of different synchrotron tune in combination with resonance crossing**
  - Generic study of interplay with $4Q_y=81$ ($4Q_y=105$) as possible limitation for acceptable tune shift
- **Development of non-linear model**
  - Using beam-based measurements of nonlinearities and orbit

Summary, conclusions and questions

- **Space charge is challenging for future LHC beams**
  - Long storage time at injection energy for multiple injections from PS
  - Laslett tune shift larger than 0.2 will be required
- **Low γ_t optics Q20 (for increasing instability thresholds)**
  - Providing 15% smaller tune spread for usual longitudinal parameters due to larger dispersion
  - Operationally used for LHC filling since September 2012
- **Emittance measurements in SPS – issues with resolution**
  - Combining several measurements for reconstructing profile reduces error
- **Experimental results**
  - Tune spread of 0.18 (estimated from Laslett formula) is acceptable
  - Relative emittance growth on flat bottom can be observed on bunch-by-bunch wire scans
- **Question: Δq_y>0.25 and long (>10s) storage times “without” beam degradation?**
  - Demonstrated in existing machines?
  - General feeling about feasibility?

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Thank you for your attention!

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Motivation for low γ_t optics

- **Motivation for lowering transition energy in SPS (Q20 optics)**
  - Larger slip factor η (factor 3 at 26GeV, 1.6 at 450GeV) → **higher instability thresholds**
  - Transverse – TMCI at injection, electron cloud instability
  - Longitudinal – multi bunch instability, loss of Landau damping

- **High intensity single bunch**
  - TMCI threshold in Q26 at around 1.6×10^{11} p/b
  - Up to **4×10^{11} p/b without TMCI** in Q20 with low chroma

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

- **Longitudinal stability**
  - Longitudinal instability threshold **scales with slip factor η**
  - Clear improvement with Q20 optics wrt. Q26
    - For single and multi bunch beams
  - Less controlled longitudinal blow-up for same intensity in Q20

$$N_{th} \sim |\eta| \varepsilon_l^{5/2}$$

- **Important step in 2012: <u>Q20 used in routine operation</u>**