Optics Measurements, Corrections and Modeling for High-Performance Storage Rings

Low γ_t optics in the SPS

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Outline

- The background
  - Benefits for reducing transition energy in the SPS, as LHC injector
  - Methods for reducing the transition energy
- New optics based on "resonant arcs"
- Machine studies
  - Optics and non-linear model
  - Tune scans for resonance identification
  - Emittance vs. intensity, beam loss and space-charge limit
- Summary and perspectives

SPS as LHC injector

- LHC upgrade considerations require high bunch intensities (≥1.8e11 p/b) with small transverse emittances to be extracted from the SPS
- Known intensity limitations for LHC proton beams in SPS at present
  - Instabilities leading to emittance blow up and/or beam loss
    - TMCI (transverse mode coupling instability) due to transverse impedance $N_{th} \propto \eta$
    - Longitudinal instability due to loss of Landau damping, $N_{th} \propto \eta \epsilon_l^2 \tau$ (stationary bucket)
    - Longitudinal coupled bunch instabilities due to longitudinal impedance, $N_{th} \propto \eta \epsilon_l^2 / \tau$
    - Electron cloud instability
  - Other limitations
    - Beam loss (resonances, injection mismatch?)
    - Beam loading in the RF systems
    - Heating and out-gassing of machine elements
    - Space charge

(E. Shaposhnikova, Chamonix 2011)

N_{th} … Instability threshold
ϵ_l … longitudinal emittance
τ … bunch length
η … slippage factor

- **Increase in instability thresholds** can be expected for the same bunch parameters for **higher slippage factor** due to faster synchrotron motion ($\Omega_s \propto \sqrt{|\eta| V_{RF}}$) and damping of instabilities

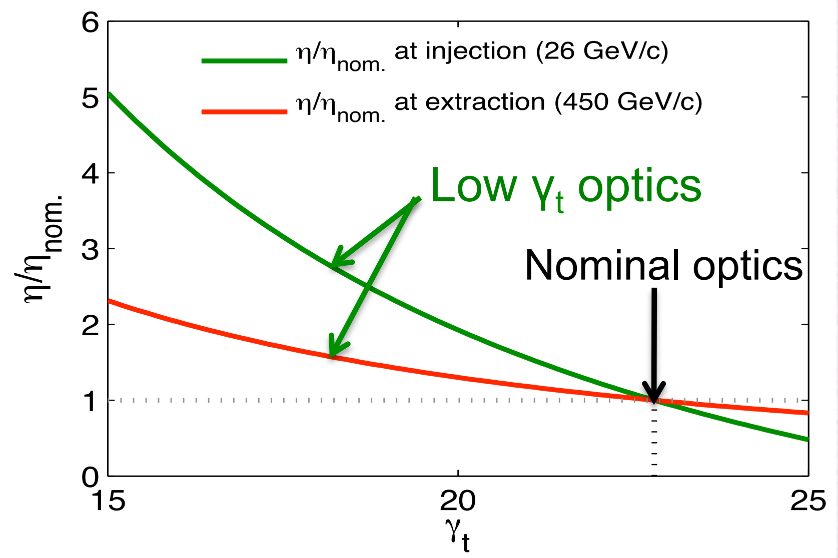
Increasing the slippage factor – lowering transition energy

- Transition energy of "nominal" SPS optics for LHC beams is 22.8 - tunes of (26.13,26.18) through the cycle
- Above transition, slippage factor increases by reducing transition energy (increasing momentum compaction factor)

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

  - Higher effect @ injection (26GeV)
  - Smaller but appreciable effect @ extraction (450GeV)

Slippage factor in SPS relative to nominal optics



- For keeping constant longitudinal emittance, RF-voltage has to be increased accordingly $V \propto \eta$ (already presently limited for applying controlled longitudinal emittance blow-up at high energies)
- Only partially solved by RF system upgrade

Transition energy manipulation

- Transition energy (or momentum compaction factor) is defined as

$$\frac{1}{\gamma_t^2} = \alpha_p = \frac{1}{C}\oint \frac{D(s)}{\rho(s)} ds$$

- The higher the dispersion oscillation in the bends, the lower the transition energy

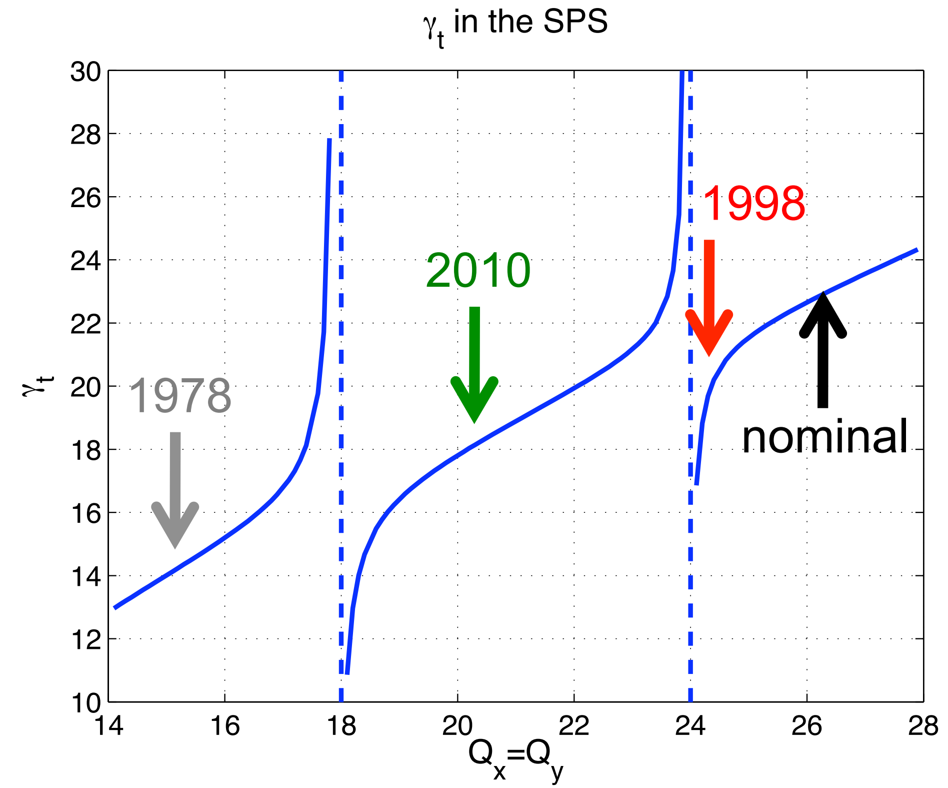
Quadrupoles

- Note also that, for FODO cells (SPS lattice), $\gamma_t \approx, Q_x$ meaning that lowering the transition energy implies **lowering the horizontal tune**

Transition energy change in the SPS

- In the past
  - Install 2 new quadrupole families in phase advance of $\mu_x=(2k+1)\pi$ for inducing dispersion waves (K. Cornelis, Chamonix 1999)
    - Tests with "resonant integer tune" of 24 in 1998 demonstrated change of transition energy from 23 to ~20) (G. Arduini et al. 1998)
    - Reduction of unstable mode amplitudes due to microwave instability (T. Bohl et al., 1998)
    - "Difficult" beam conditions…
- New optics studies in 2010
  - Flipping quadrupole polarity (from FODOFODO to FODODOFO) for moderate increase in beta functions and notable change in γ_t (requires bipolar power supplies)
  - Individually powering central quadrupole of 2 consecutive FODO cells allows to induce dispersion wave for obtaining imaginary γ_t (requires additional power supplies and increased magnet strength)
  - For keeping dispersion low in the straights, phase advance of the arcs of the SPS can be reduced to a lower multiple of 2π ("resonant arcs") → increase of dispersion in the arcs (no hardware limitation)

Transition energy versus SPS working point



Resonant oscillation of dispersion function close to the "Resonant integer tunes" (multiples of super-periodicity 6) → asymptotic behavior of γ_t (difficult for routine operation)

γ_t is linear function of horizontal tune Q_x elsewhere

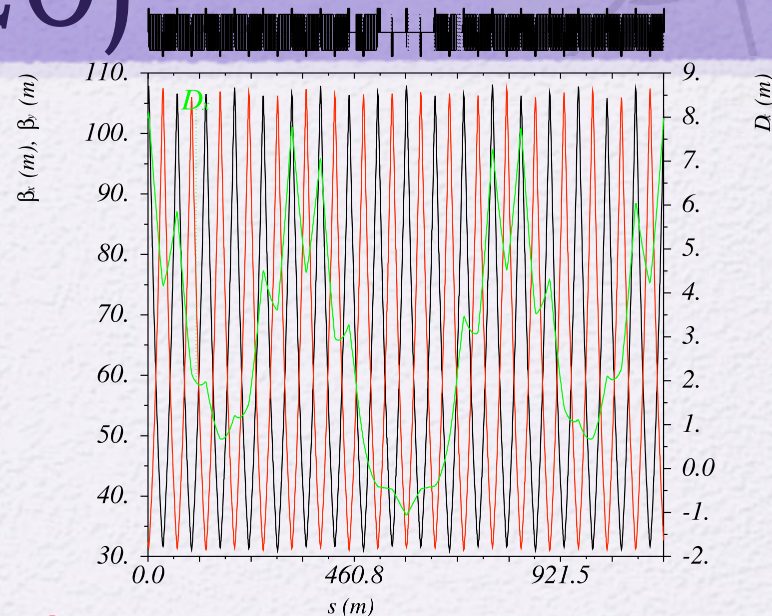
- D. Boussard et al., SPS improvement note No 147, 1978; Injection above transition as TT10 was not ready for 26 GeV/c (γ_t~14)
- Low γ_t, 2010 – "Resonant arc" with small dispersion in long straight sections (γ_t~18)
- G. Arduini et al., CERN/SL-Note 98-001, 1998; "Resonant tune" (γ_t~20)
- Nominal SPS working point for LHC proton beams (γ_t~23)

Low transition energy optics (Q20)

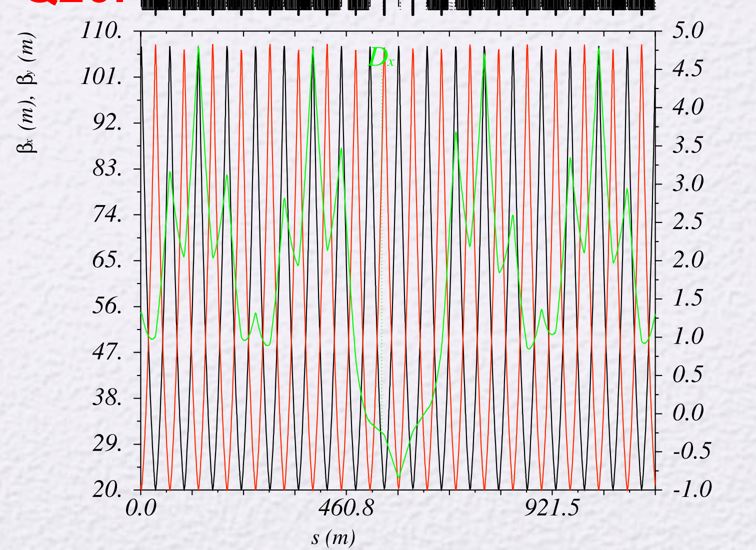
- New optics "Q20" vs. nominal optics "Q26"
  - No increase in maximum β-functions but minimum β-functions increased by 50%
  - Notable reduction in γ_t allows significant increase of η (factor of 2.85 @injection, 1.6 @extraction)!
  - 6 integer tune units below nominal optics → same resonance diagram for systematic resonances (super periodicity of 6)!
  - Confortable aperture for LHC beams although maximum dispersion almost doubled
  - Slightly increased dispersion in straight section (only small impact on injection/extraction)

Optics	Q20 (low γ_t)	Q26 (nominal)
Working point	(20.13, 20.18)	(26.13, 26.18)
Max. Dispersion	8 m	4.5 m
Max. β-functions	105 m	105 m
Min. β-functions	30 m	20 m
γt	18	22.8
η @ 26 GeV/c	1.8E-3	0.63E-3
η @ 450 GeV/c	3.1E-3	1.9E-3
Phase advance/cell	3*2π/16	4*2π/16

Q20:



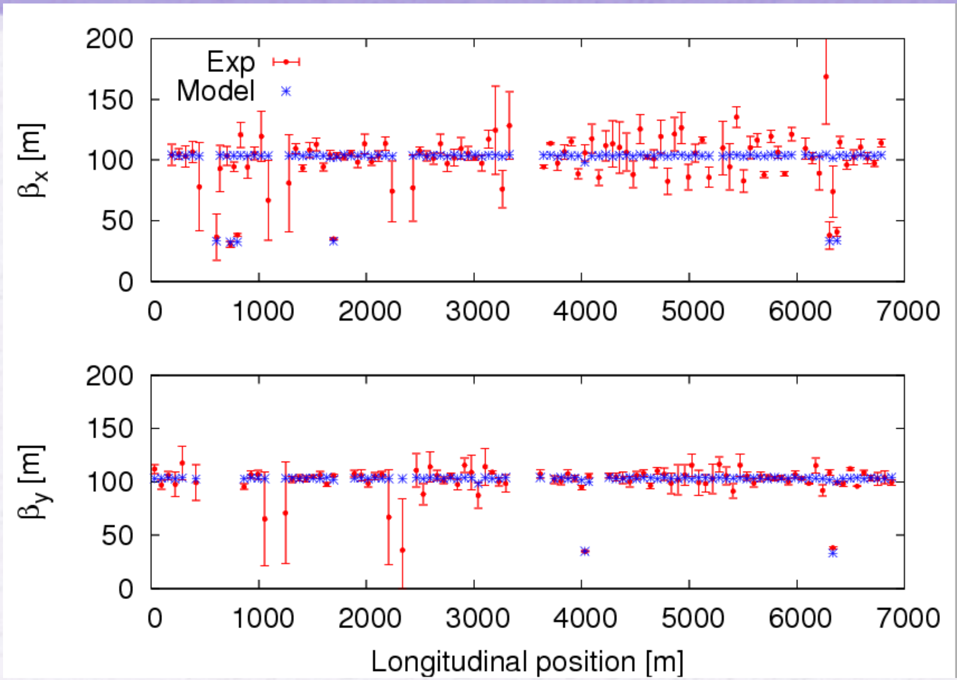
Q26:

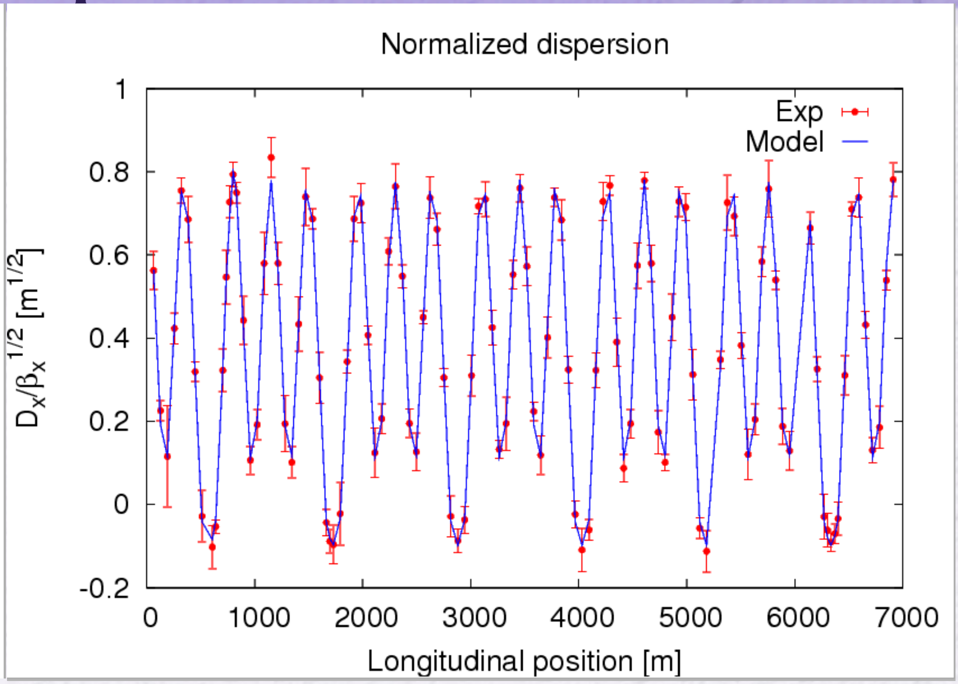


Machine studies on low transition energy optics

- Prepared several "Q20" cycles with new optics
  - Long flat bottom of about 3.7 s before beam is dumped
  - Short flat bottom of 60 ms and fast acceleration up to 450 GeV
  - Long flat bottom and slow ramp up to 450GeV of about 10s each
- Status
  - Machine model with integer tunes of 20 entered into the SPS database
  - New "zero-chromaticity" values for sextupoles and knob parameters defined
  - RF program slightly adapted from Q26 cycle
  - Most of the machine controls can be used
  - Tunes corrected along the ramp for all Q20 cycles
  - TT2-TT10 transfer-line re-matched but no significant impact yet
  - Extraction optics and TI2 transfer-line matched and ready for tests

Experimental confirmation of the new optics



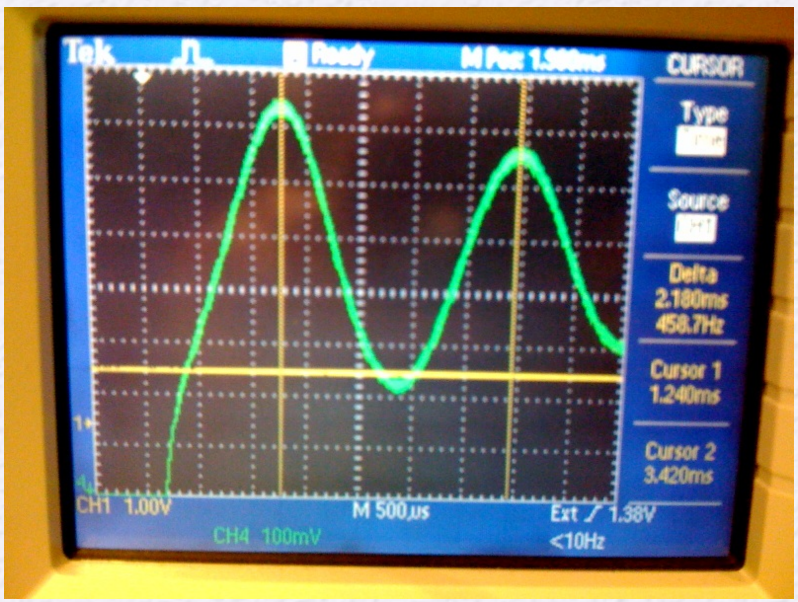


measured by R. Tomas and G. Vanbavinckhove

- Measurement of the optics functions of the new lattice
  - Beta beating around 20% in horizontal and 10% in vertical plane
  - Normalized dispersion in striking agreement with the model

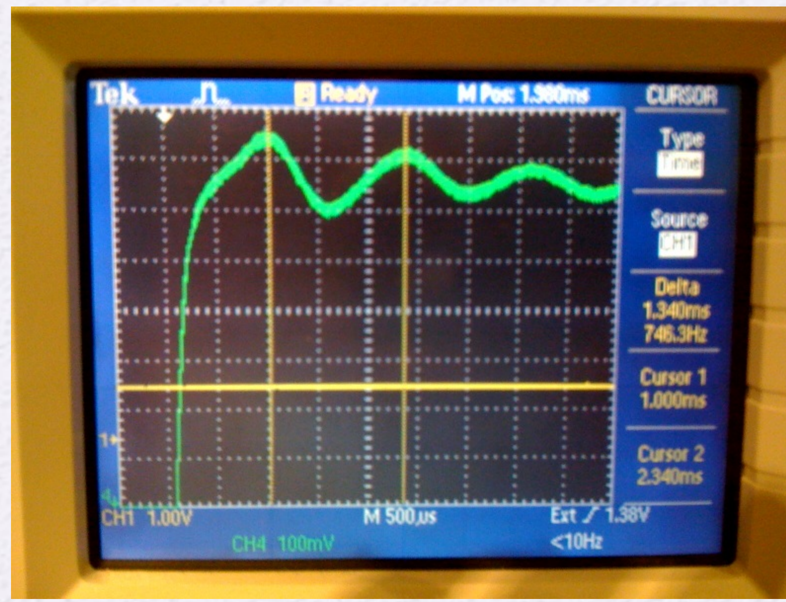
Synchrotron frequency

- Measured synchrotron frequency from "quadrupole" oscillations at injection
  - Same RF-voltage for both optics
  - "Over-focusing" RF-bucket in both cases
- Ratio of Synchrotron frequencies ~ 1.63 corresponds to an increase in slippage factor η by factor 2.65 (MADX prediction: 2.86)



Q26:

Fs=458/2=229Hz, Qs=0.0106/2=0.0053

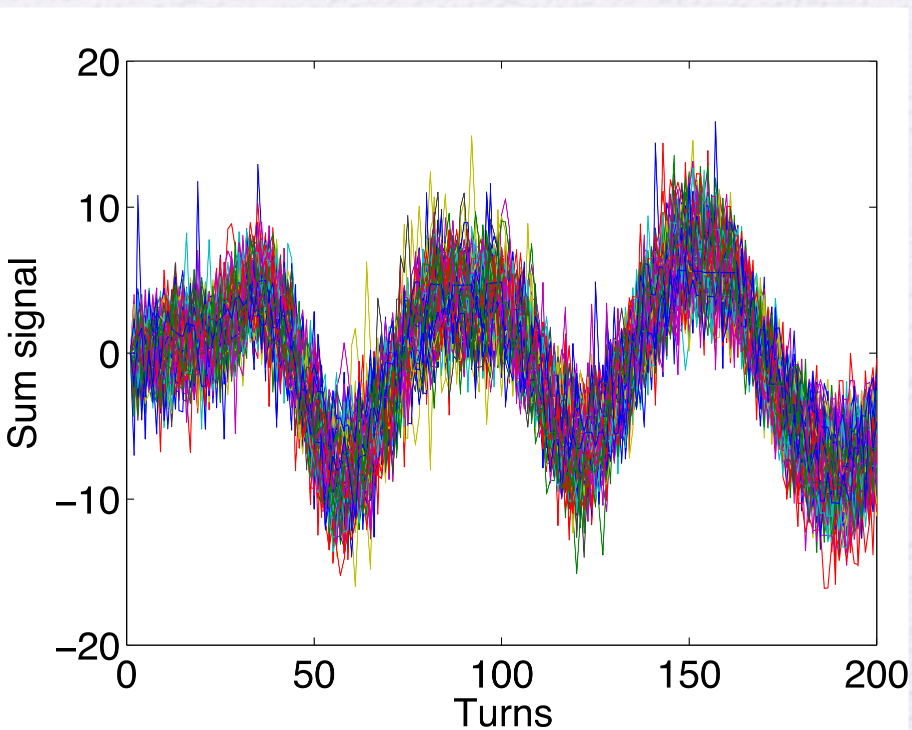


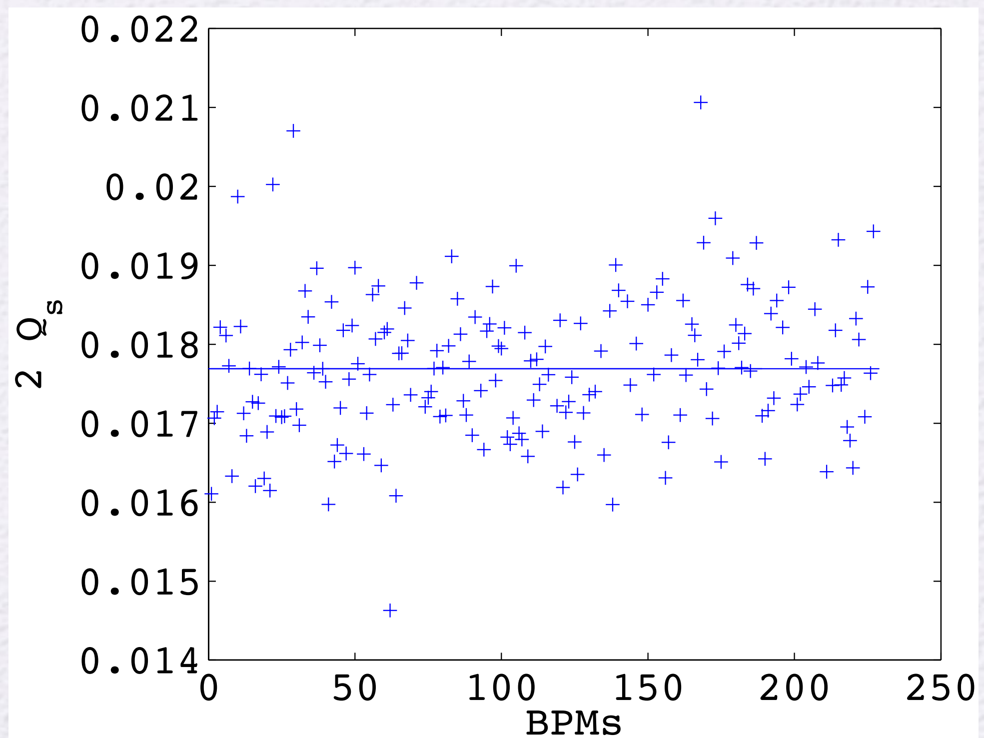
Q20:

Fs=746/2=373Hz, Qs=0.0172/2=0.0086

Synchrotron frequency: an alternative method

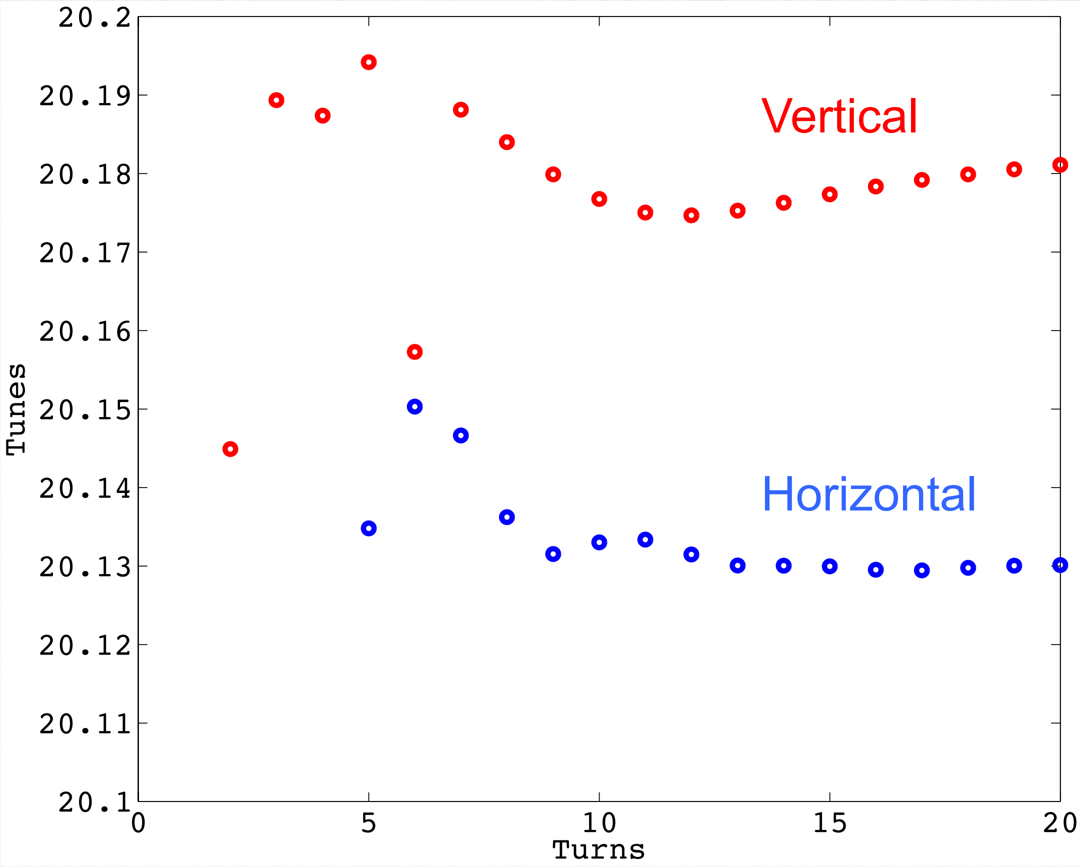
- Recording sum signal from turn-by-turn BPM system @ injection
- Estimating synchrotron tune by refined Fourier analysis (NAFF)
- Average of 2Qs=0.0176±0.0009



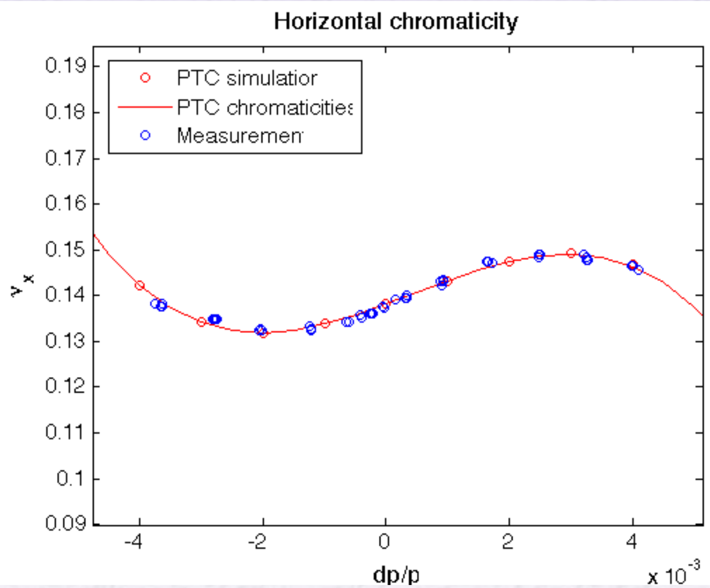


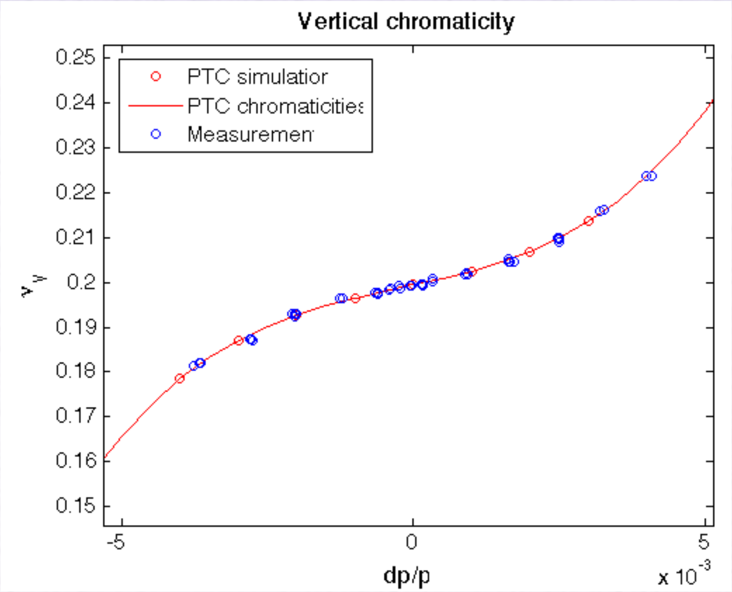
Fast tune determination

- Combining turn-by-turn positions for all BPMs within a turn
- Analyzing all data for a number of turns with NAFF
- Convergence to the tune (including the integer!) in 15-20 turns, even for 20% of the BPMs failing
- Completely model independent
- Overcome decoherence (or evaluate the tune dependence on it)
- A rapid way to measure tune-shift with amplitude or chromaticity



Nonlinear chromaticity in the new lattice



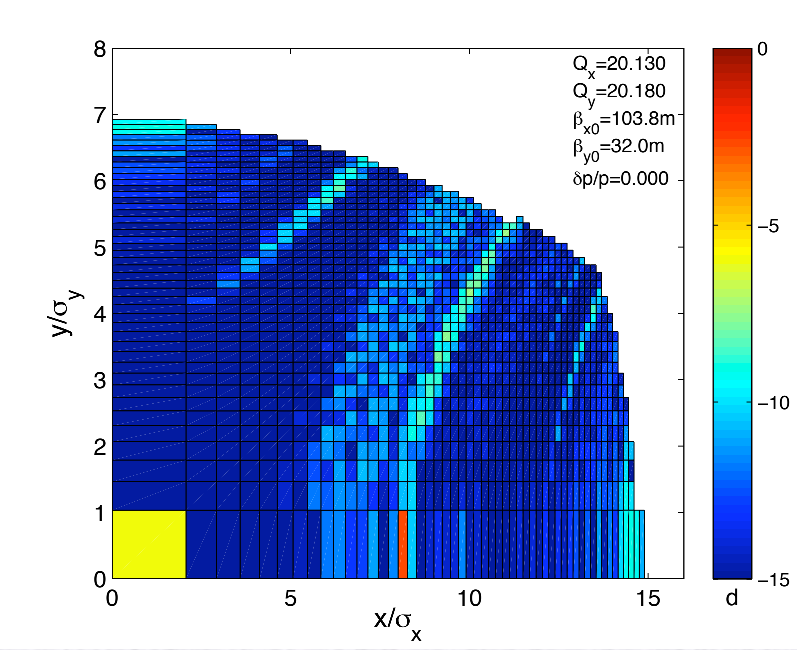


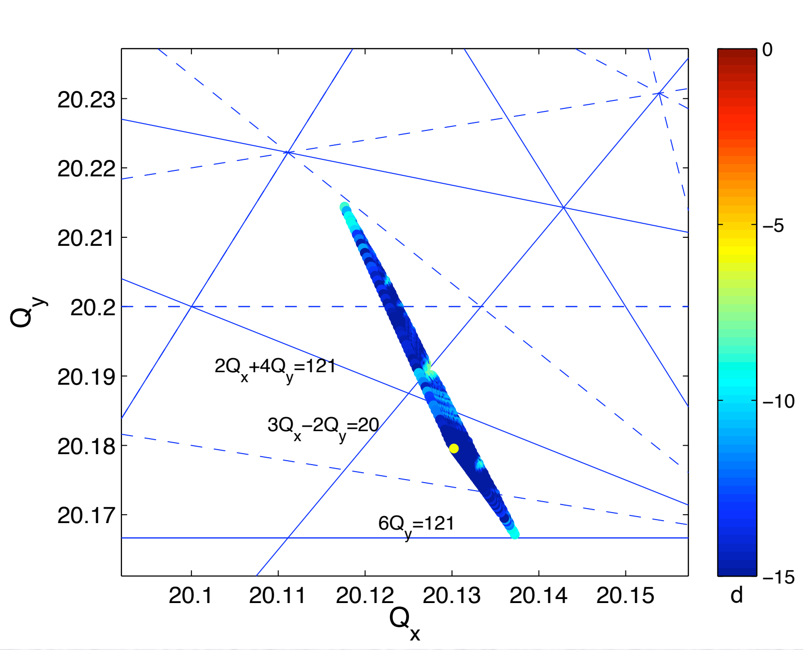
(see previous work G. Arduini et al. PAC2005)

- Sextupole strengths set with new chromaticity knobs; measurement with low intensity bunch
- MADX-PTC nonlinear model of SPS adapted/fitted to the measurements on new optics and compared with measurements on nominal optics
  - Sextupole components in dipoles in rough agreement between Q20 and Q26
  - Octupole components (assumed to be located in quadrupoles) change sign from Q20 to Q26 model!
  - Decapole components in dipoles in rough agreement between Q20 and Q26
- Chromaticity sextupole strengths needed are much smaller (1/3) in Q20 optics due to: smaller natural chromaticity, much bigger dispersion function at sextupole locations, partial compensation of chromaticity due to sextupule components of main dipoles
- On-going studies including tune-shift with amplitude and higher order chromaticity term measurements as additional nonlinear fit parameters

Nonlinear dynamics simulations

- Nonlinear model as obtained from the measurement of nonlinear chromaticity
  - Assumed misalignments, random errors in the main components and random errors in the multipole components such that the measured nonlinear chromaticity is reproduced (rms orbit ≈ 2mm, β-beat ≈ 10%)
  - Dynamic aperture much bigger than physical aperture
- Frequency map analysis allows to visualize the tune-shift with amplitude and to identify resonances
  - Tracking particles with PTC in 5D with initial conditions in configuration space evenly spaced in action
  - Aperture model included in the simulation
  - Color-code indicates the tune diffusion coefficient d in logarithmic scale, $d = \sqrt{(\nu_{x,1} - \nu_{x,2})^2 + (\nu_{y,1} - \nu_{y,2})^2}$
  - Big diffusion coefficient d means chaotic motion in phase space
  - σ (beam size) is calculated for on-momentum particles with normalized emittance $\varepsilon_x = \varepsilon_y = 3\ \mu m$

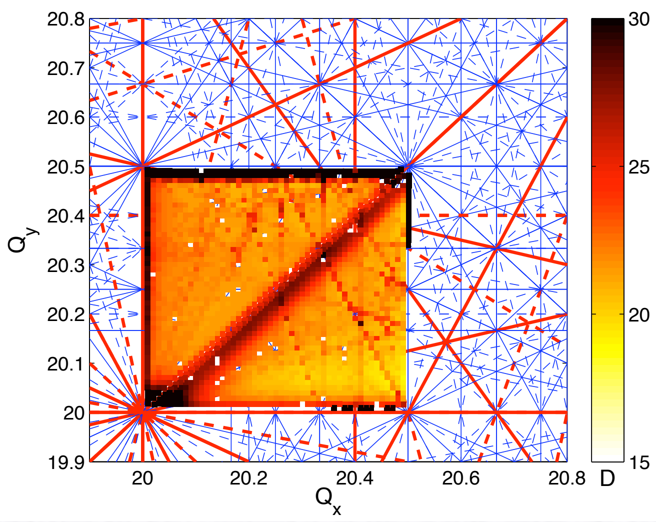


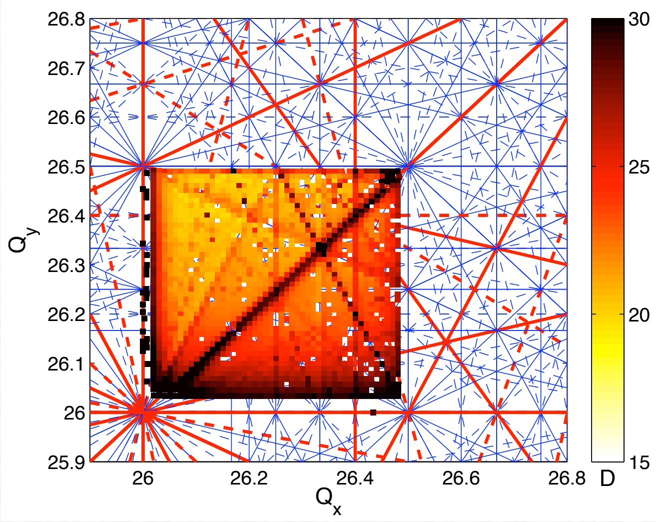


Nonlinear dynamics simulations (cont.)

- Tune-scan for a global picture of machine resonances
  - Frequency Map produced for each working point and diffusion coefficients' sum for all particles (D) is computed
  - For direct comparison, same nonlinear model (Q20) assumed for both optics variants
  - Orbit corrected (rms orbit ≈ 2mm, β-beat ≈ 10%) before changing the tune
  - Chromaticity corrected to $\xi_x=\xi_y=0.1$ using sextupole "knobs" of the corresponding case
  - Coupling not corrected, octupoles are always switched off
- Observations
  - Same resonances can be identified in both cases
  - Resonances appear to be stronger in the nominal optics, especially the third order ones → Modified phase advance between chromatic sextupole families in low γ_t optics seems not to be an issue
  - Note the bigger stop-band widths for the integer resonances in the nominal optics

Low γ_t

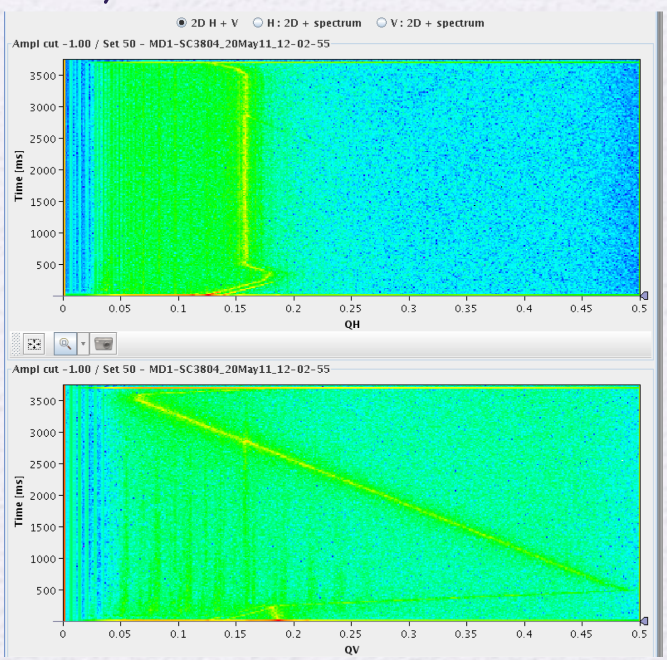


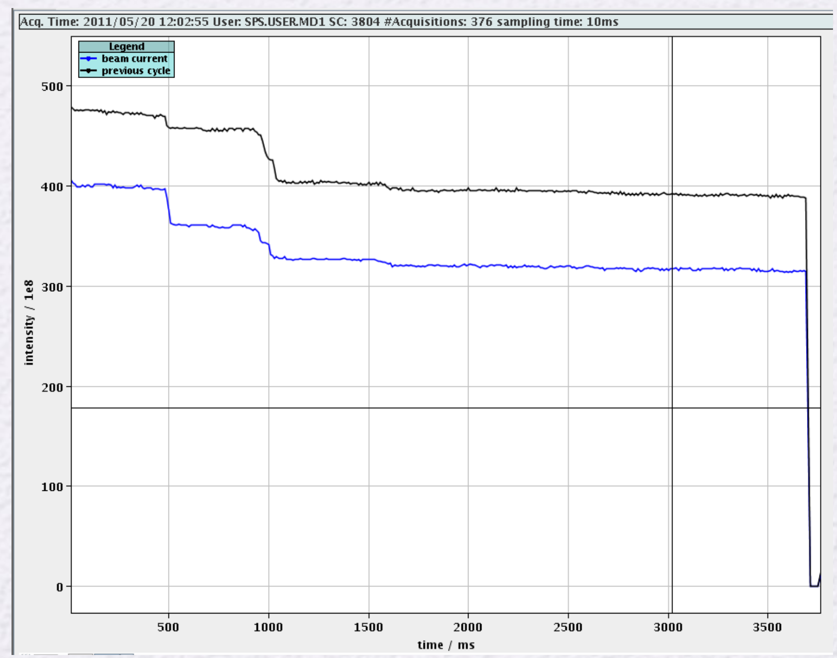


Nominal

Experimental Tune scans – Method*

- Study the resonance behavior around working points of nominal and low γ_t (Q20) optics @ injection
- Strength of individual resonance lines can be identified from the beam loss rate, i.e. the derivative of the beam intensity at the moment of crossing the resonance
- Vertical tune is scanned from about 0.45 down to 0.05 during a period of 3s along the flat bottom
- Low intensity 4-5e10 p/b single bunches with ε ~1.2 μm ("single particle behaviour") injected at nominal tunes
- Horizontal tune is constant during the same period within a super-cycle (scanned from cycle to cycle)
- Tunes are continuously monitored using the BBQ (tune post-processed with NAFF) and the beam intensity is recorded with BCT



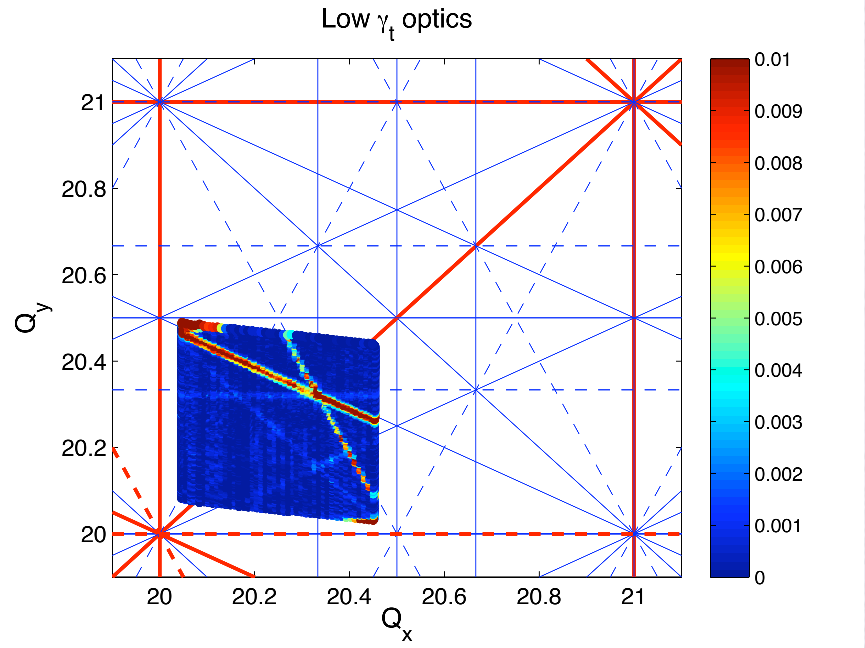


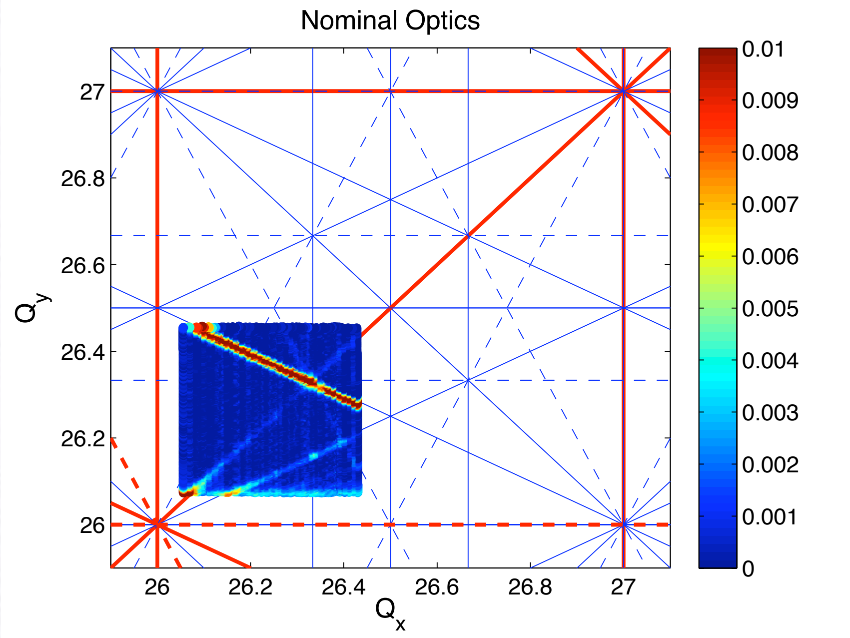
* See also method from G. Franchetti et al. in the PS

Tune Scans - Results

- Resonances in the low γ_t optics
  - Normal sextupole Qx+2Qy is the strongest
  - Skew sextupole 2Qx+Qy quite strong !!??
  - Normal sextupole Qx-2Qy, skew sextupole at 3Qy and 2Qx+2Qy fourth order visible

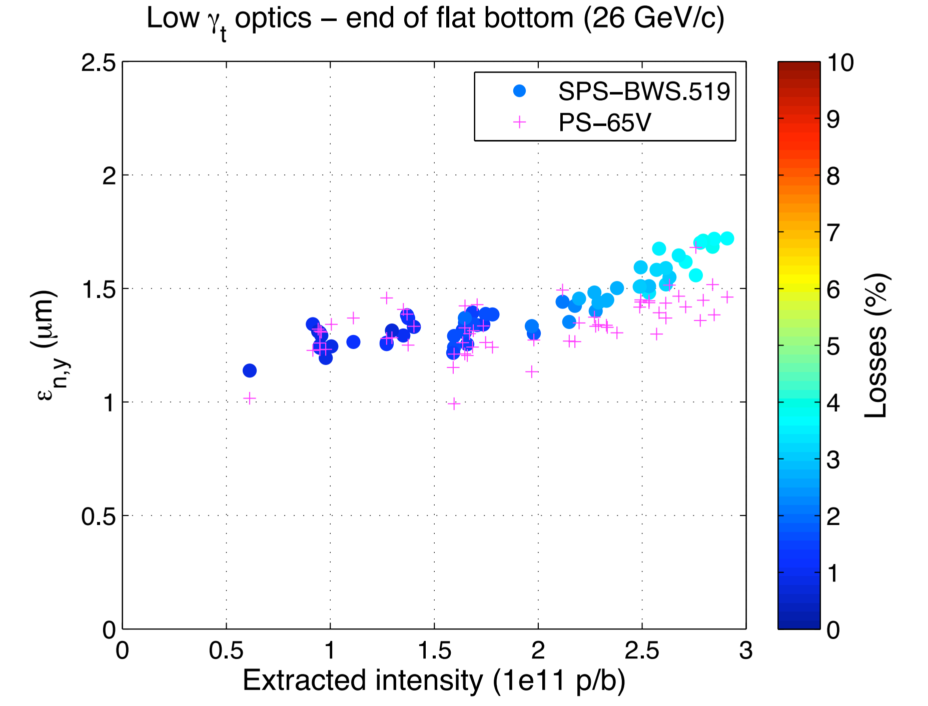
- Resonances in the nominal optics
  - Normal sextupole resonance Qx+2Qy is the strongest
  - Coupling resonance (diagonal, either Qx-Qy or some higher order of this), Qx-2Qy normal sextupole
  - skew sextupole resonance 2Qx+Qy weak compared to Q20 case
  - Stop-band width of the vertical integer is stronger than in Q20 optics, as predicted by simulations

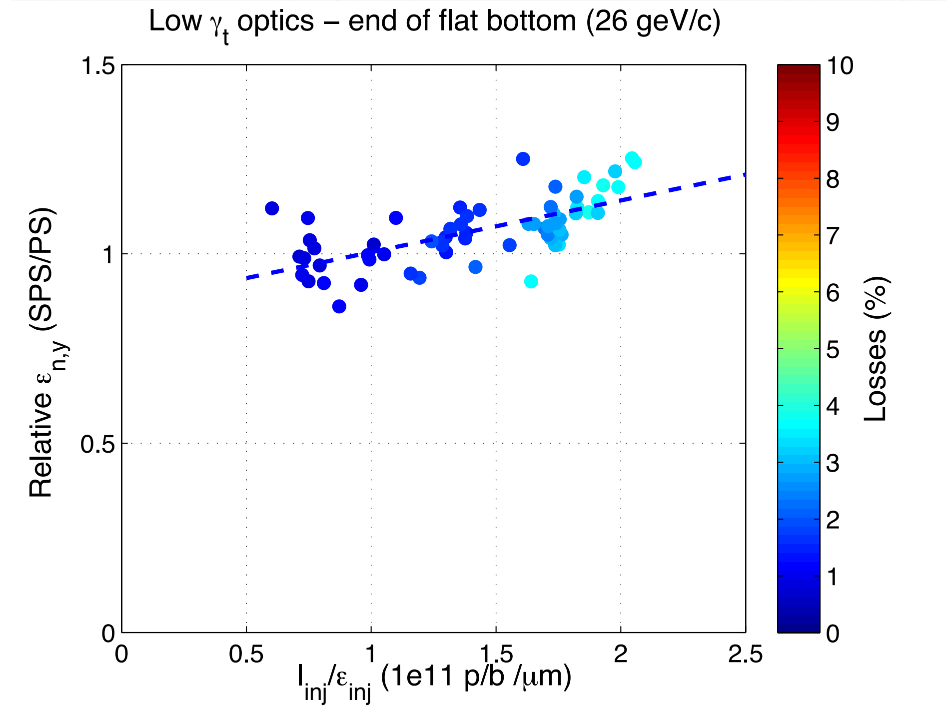




Emittance vs intensity

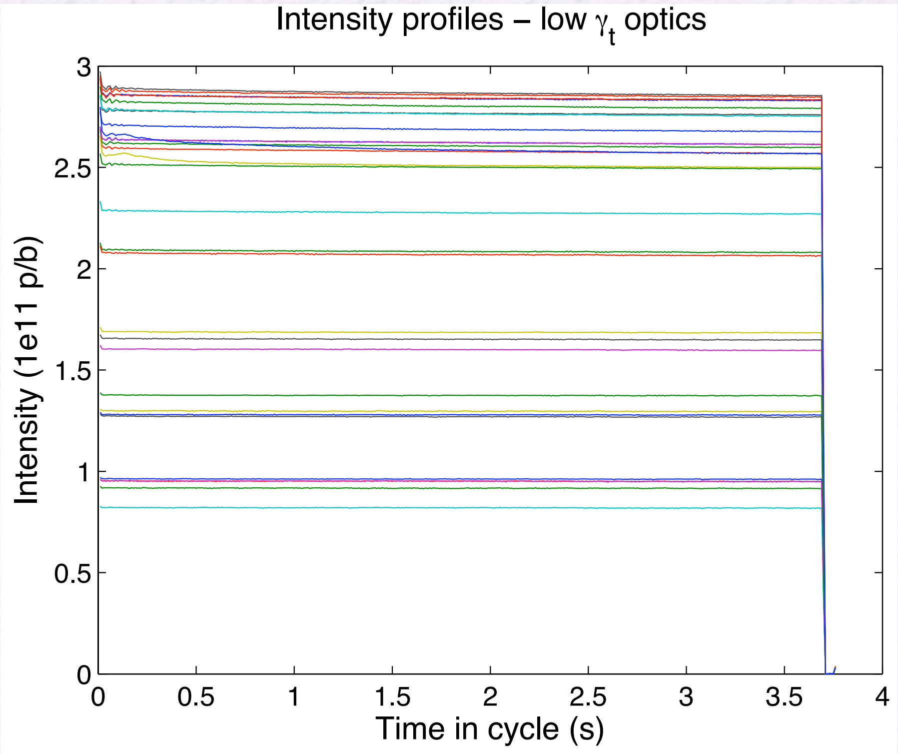
- Beams injected and accelerated in single and multi-bunch mode up to top energy without any significant emittance degradation or losses
- Large effort to quantify SPS emittance blow-up for high-intensity single bunches
- Simultaneous measurements of vertical emittance in PS and SPS
  - At extraction (just before bunch rotation) in PS and end of flat bottom in SPS
- Emittance blow-up for intensities >1.5e11 p/b with peak values of 25% at 3e11 p/b

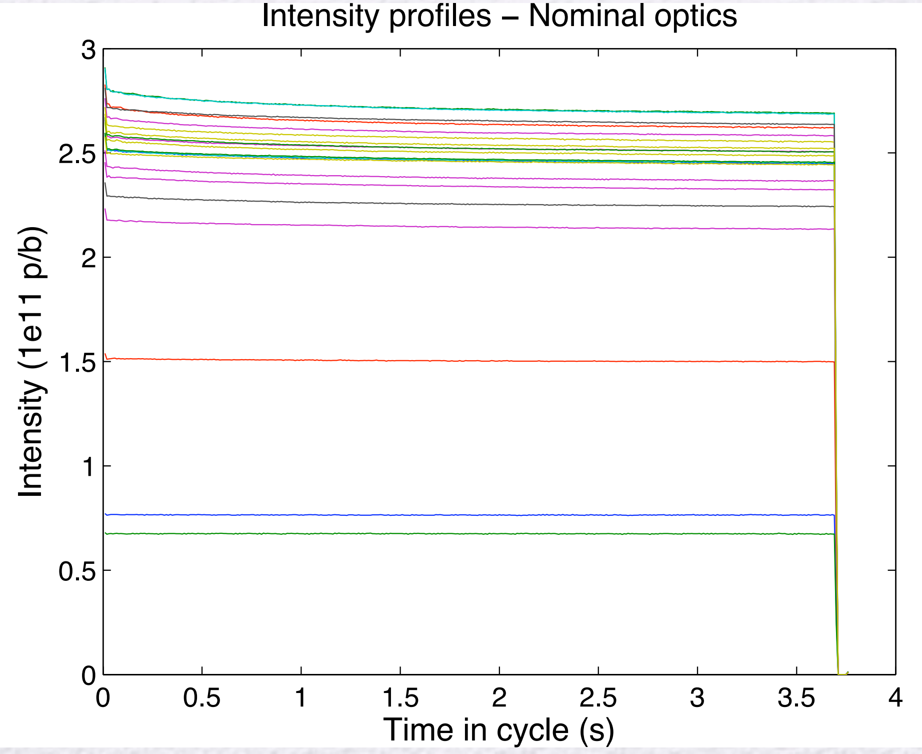




Beam loss @ flat bottom

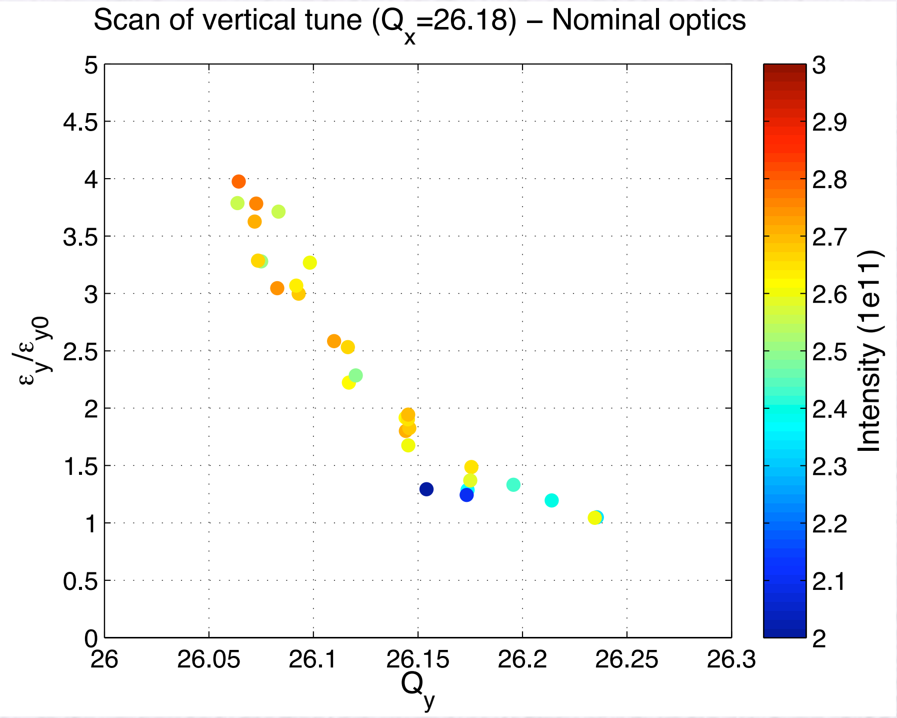
- Low γ_t optics
  - Low losses (up to 4% for 3e11 p/b) from injection to end of flat bottom
  - Flat intensity profiles even for high intensity but injection losses increase
- Nominal optics
  - Significantly increasing losses for intensities above 2.5e11 p/b up to 10%
  - Losses at injection and along the flat bottom for high intensities

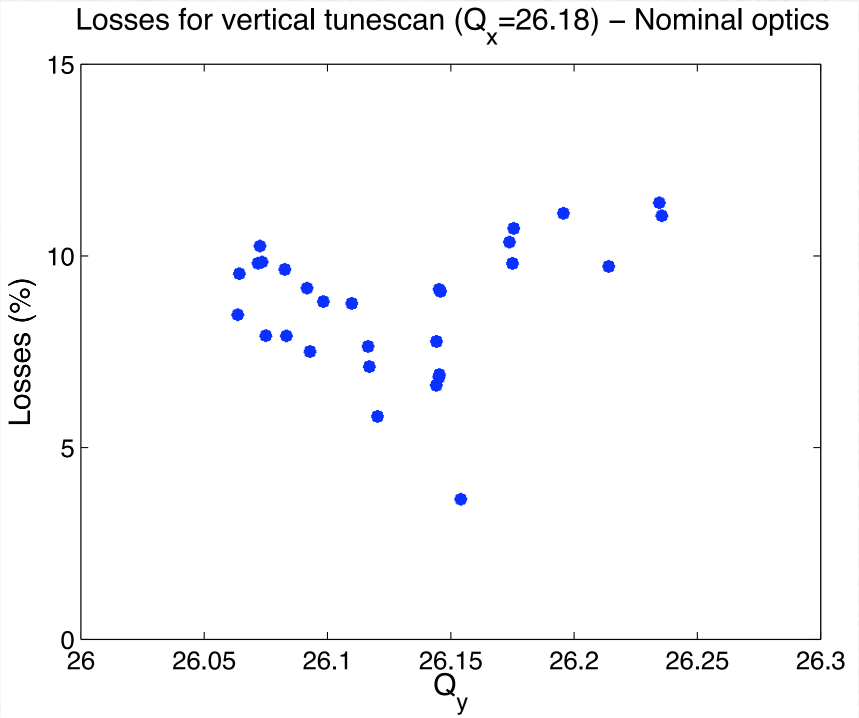




High intensity tune scan

- Tune scan with high intensity small emittance single bunches
  - "Space charge" tune scan with intensities of ~2.5-3e11 p/b and injected norm. emittances of 1.3-1.5 μm
  - Measuring emittance at flat bottom end as function of injected emittance and total losses
  - First scan of vertical tune with fixed horizontal tune of Q_x~26.18
  - To be completed with further scans for different horizontal tune settings





Summary and perspectives

- New low transition energy optics proposed and implemented in SPS for machine studies during 2010-2011, showing promising results
  - Single bunches injected and accelerated successfully **with intensities up to 3.3e11 p/b**
  - **No clear triggering of TMCI instability** even for low chromaticity settings with only small emittance blow-up
  - **Transverse emittances below 2.5μm** at the end of a long cycle for single bunches with intensities of 3e11 p/b with moderate losses
  - **Multi-bunch injection (12 bunches)** and acceleration for nominal LHC transverse characteristics
  - Yet another attempt to build a **non-linear machine model** for SPS and working point optimization for high intensity
- Ongoing studies and questions
  - Emittance blow-up for high intensity single bunches in both optics ("space charge limit")
  - Setup of extraction for new optics to LHC
  - Large simulation effort for qualifying the impact on instabilities, e-cloud, space charge
  - Reaching acceptable LHC beam parameters with the available RF-voltage?
  - Experimental confirmation of expected stability improvement for multi-bunch beams (LHC bunch trains)?