# LHC Ion beam at the SPS with Q20 optics

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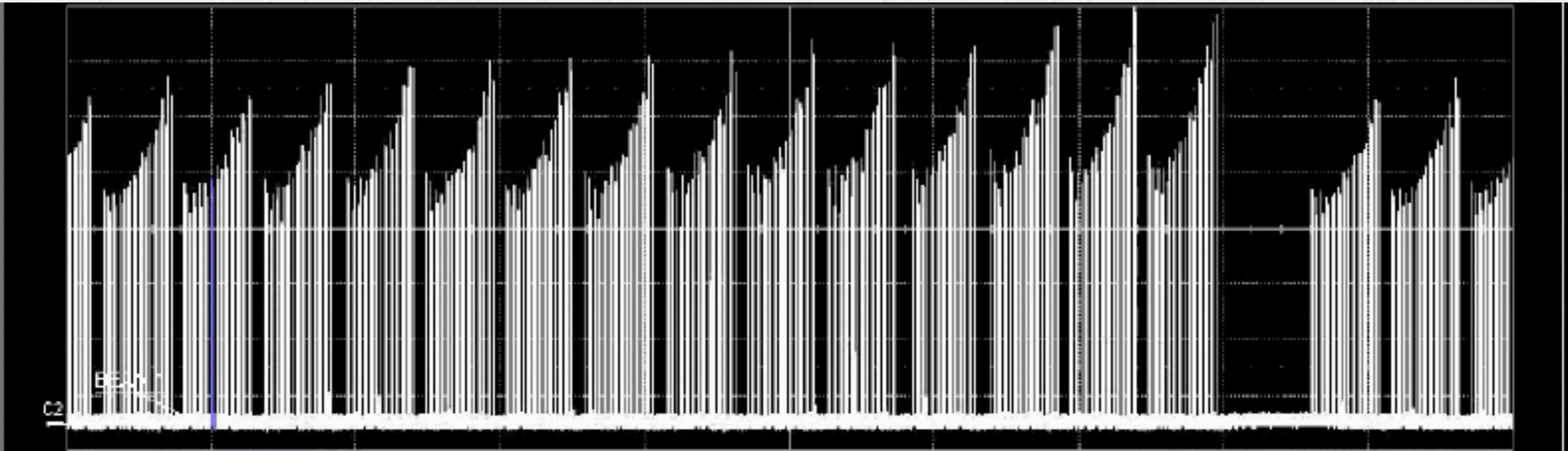
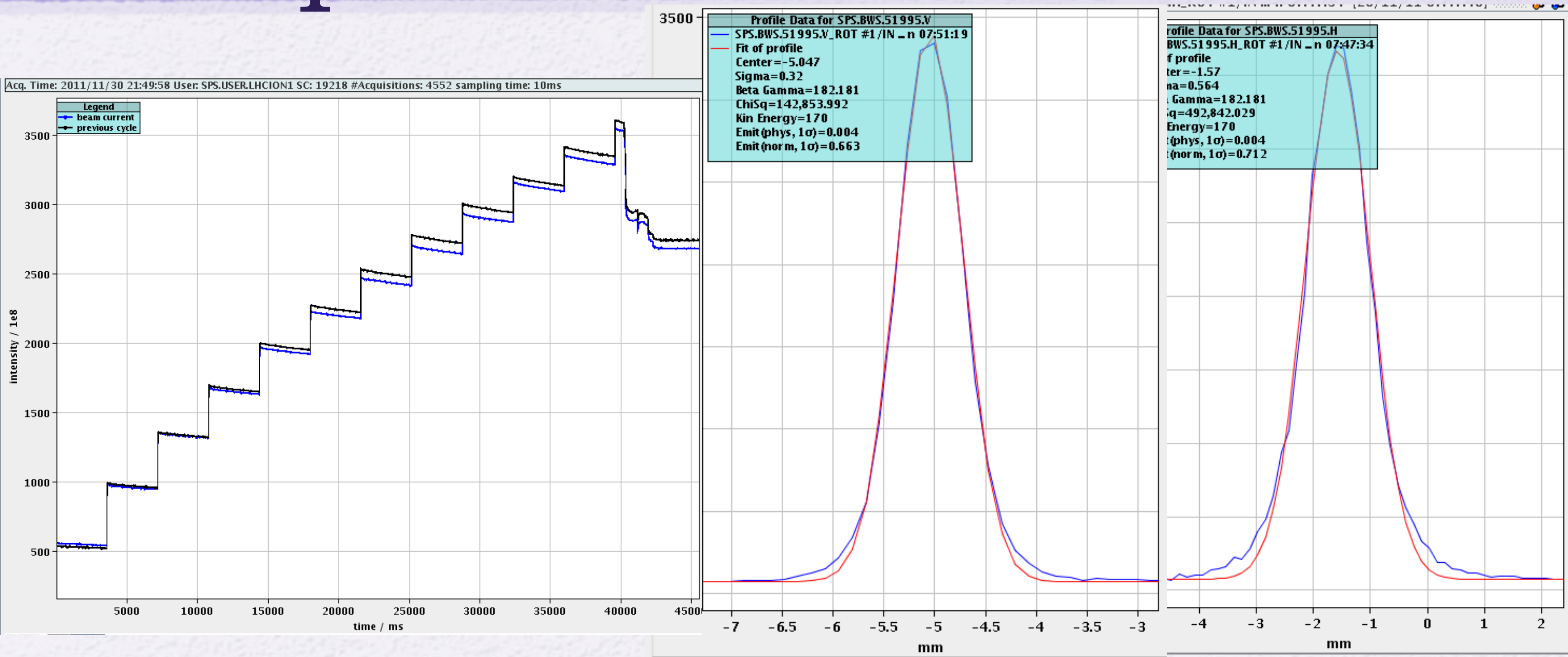
# Motivation

- Thomas' presentation during LMC 116 (23/11/2012) on "Dispersion of lead ion beam parameters at the SPS flat top – Longitudinal aspects"
  - Dispersion of lead ion beam bunch parameters at SPS flat top due to RF Noise IBS and Space-charge
  - Not a real limitation for LHC but interesting to investigate how to overcome this problem
  - Proposal to try the Q20 optics as an alternative for reducing IBS and space-charge due to larger beam sizes



# Typical LHC-I beam performance



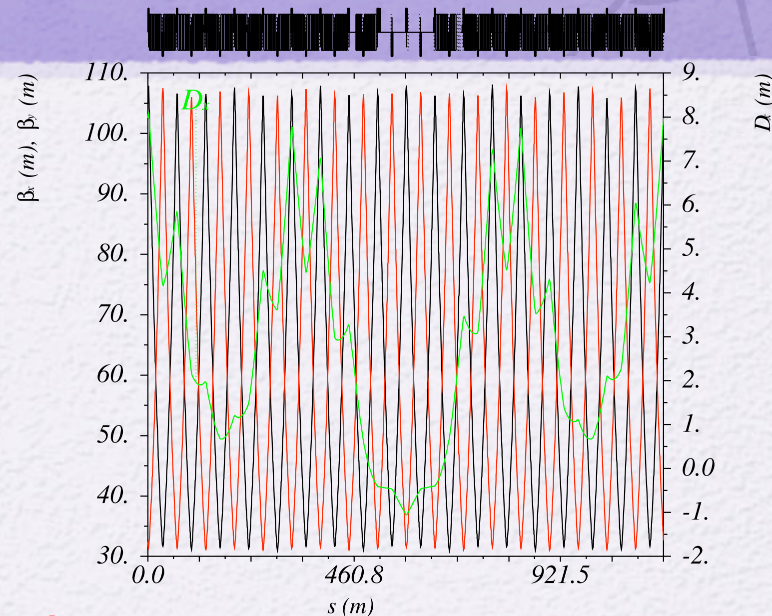

- Transmission of around 70-75%
- Transverse Emittances of 0.7-0.8mm.mrad
- Bunch length of 4ns ($4\sigma$)
- Energy spread of 6.5e-3 ($2\sigma$)

# Q20 vs. Q26 optics

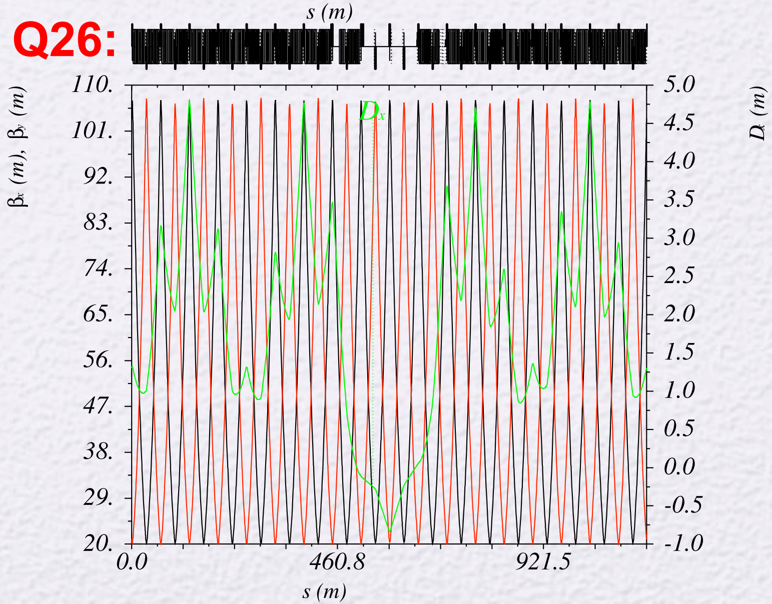
- New optics “Q20” vs. nominal optics “Q26”
  - No increase in maximum $\beta$-functions but minimum $\beta$-functions increased by 50%
  - Peak dispersion increased by almost factor of 2
  - As ions are injected way below transition for both optics ($\gamma$ = 7.3), small influence in slippage factor

| Optics | Q20 (low $\gamma_t$) | Q26 (nominal) |
|---|---|---|
| Working point | (20.29, 20.31) | (26.29, 26.31) |
| 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 @ LHC ion flat bottom | $-1.57 \times 10^{-3}$ | $-1.68 \times 10^{-3}$ |
| Phase advance/cell | 3*2π/16 | 4*2π/16 |

Q20:

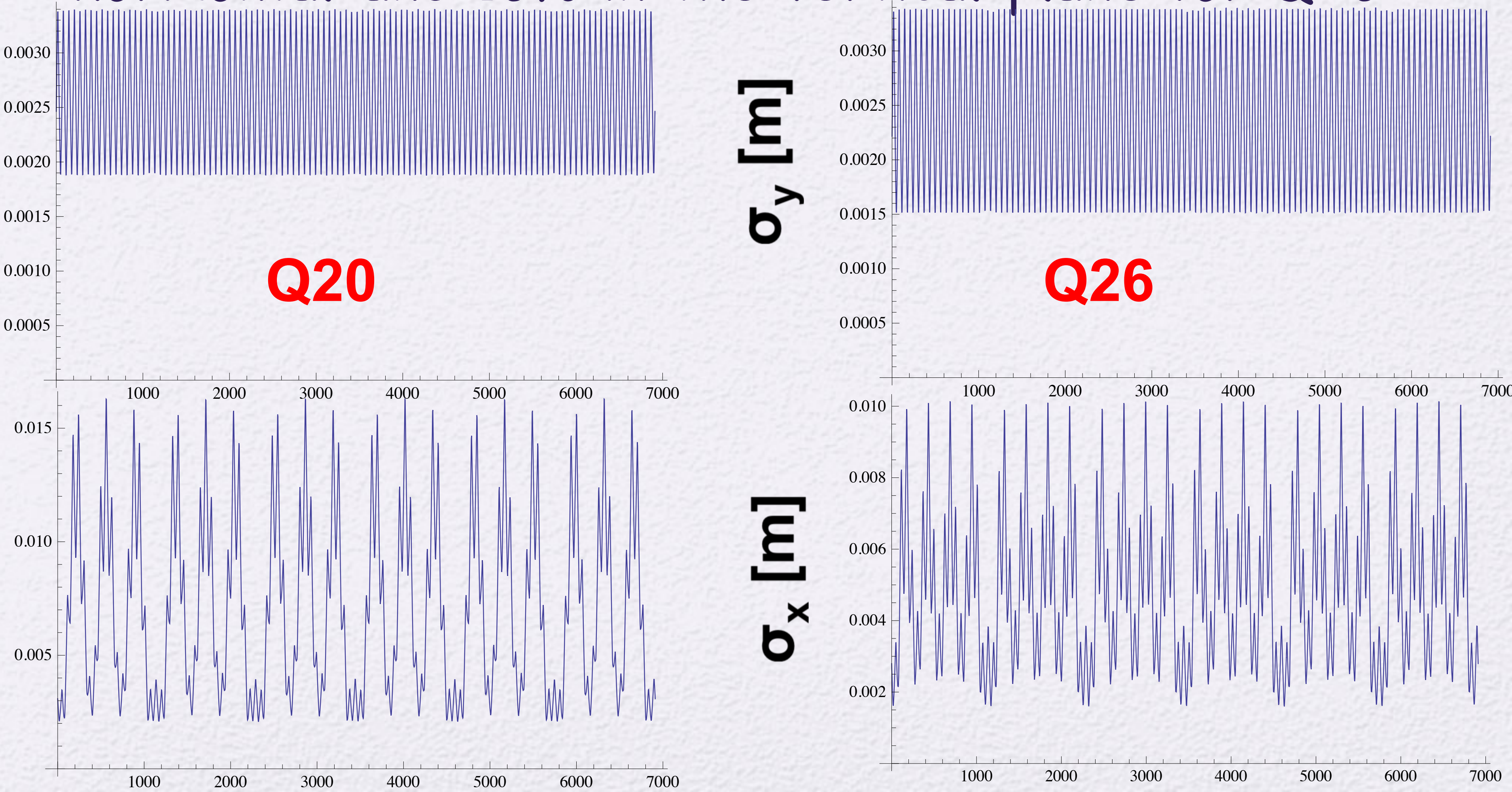



Q26:



# Beam sizes

- Average Beam sizes increased by almost 50% in horizontal and 10% in the vertical plane for Q20



# Space charge

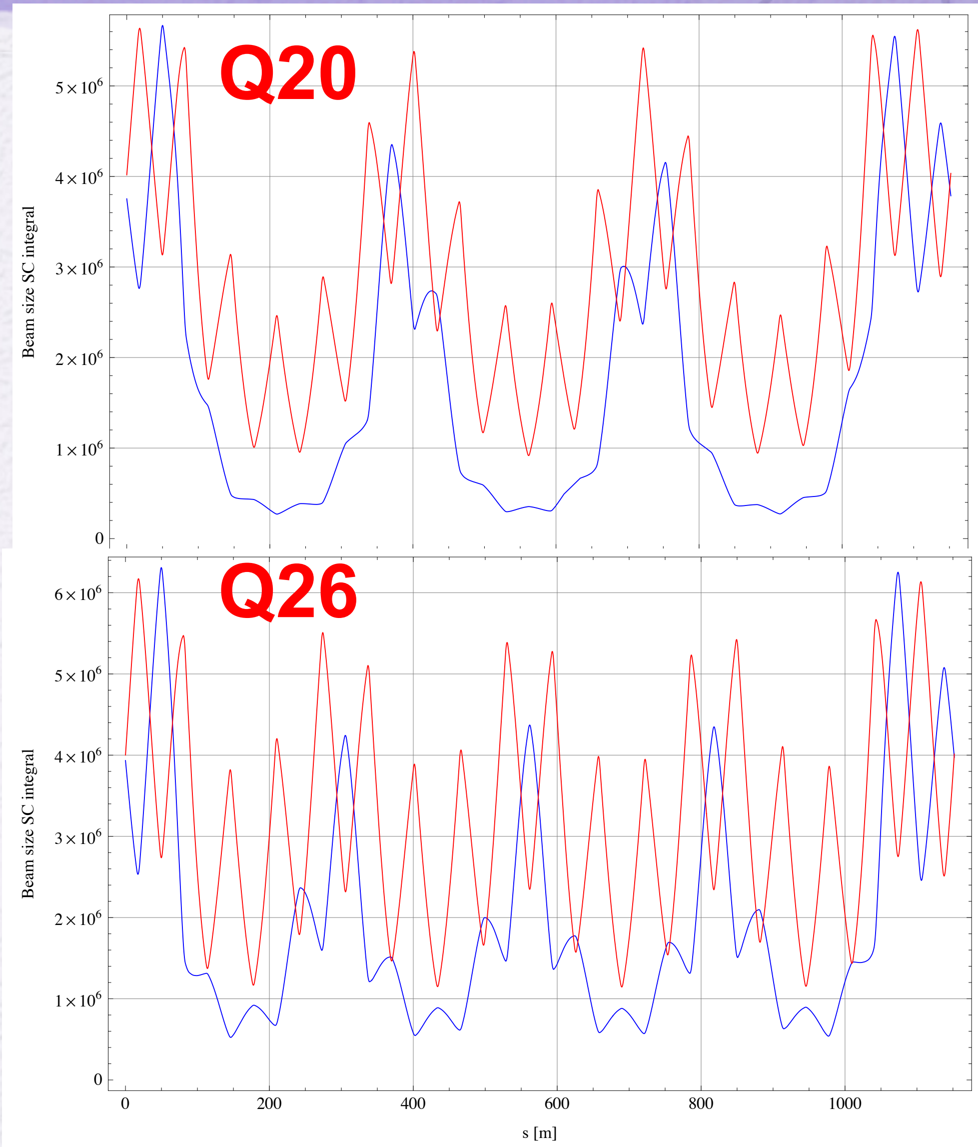
- The incoherent space charge tune-shift is given by

$$\delta\nu_{x,y} = -\frac{N_b r_i}{(2\pi)^{3/2}\beta^2\gamma^3\sigma_z}\oint \frac{\beta_{x,y}}{\sigma_{x,y}(\sigma_x+\sigma_y)}ds$$

- Reduction of 15% for the Q20 optics, due to beam size increase

| Parameters | Value |
|---|---|
| Bunch population | $2.4 \times 10^8$ |
| $Pb^{82+}$ classical radius [m] | $5 \times 10^{-17}$ |
| Relativistic γ / β | 7.31 / 0.99 |
| rms Bunch length [m] | 0.3 |
| rms Energy spread | $3.25 \times 10^{-4}$ |
| Transverse norm. emittances [mm.mrad] | 0.8 |

| Tune-shift | Q20 (low $\gamma_t$) | Q26 (nominal) |
|---|---|---|
| Horizontal | -0.08 | -0.09 |
| Vertical | -0.13 | -0.15 |



# Intra-beam scattering calculation

- Using Piwinski formalism for calculating growth rates due to IBS
- A function of emittances but also dispersion invariants, i.e. optics functions
- Note that vertical dispersion is considered to be zero

$$\frac{1}{T_p} = A\left\langle \frac{\sigma_H^2}{\sigma_p^2} f(a,b,q) \right\rangle, \quad \frac{1}{T_x} = A\left\langle f\left(\frac{1}{a},\frac{b}{a},\frac{q}{a}\right) + \frac{H_x^2 \sigma_{\mathrm{H}}^2}{\varepsilon_x} f(a,b,q) \right\rangle$$

$$\frac{1}{T_y} = A\left\langle f\left(\frac{1}{b},\frac{a}{b},\frac{q}{b}\right) + \frac{H_y^2 \sigma_{\mathrm{H}}^2}{\varepsilon_y} f(a,b,q) \right\rangle,$$

$$A = \frac{\mathrm{r}_i^2 \mathrm{c}\ \mathrm{N_b}}{64\pi^2 \beta^3 \gamma^4 \varepsilon_x \varepsilon_y \sigma_z \sigma_p}$$

$$\frac{1}{\sigma_{\mathrm{H}}^2} = \frac{1}{\sigma_p^2} + \frac{H_x^2}{\varepsilon_x} + \frac{H_y^2}{\varepsilon_y}$$

$$a = \frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_x}{\varepsilon_x}}, \qquad b = \frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_y}{\varepsilon_y}}, \qquad q = \sigma_H \beta \sqrt{\frac{2d}{r_0}}$$

$$f(a,b,q) = 8\pi \int_0^1 du \frac{1-3u^2}{PQ}\left\{ 2\ln\left[\frac{q}{2}\left(\frac{1}{P}+\frac{1}{Q}\right)\right] - EulerGamma \right\}$$

$$P^2 = a^2 + (1-a^2)u^2, \qquad Q^2 = b^2 + (1-b^2)u^2$$

| Parameters | Value |
|---|---|
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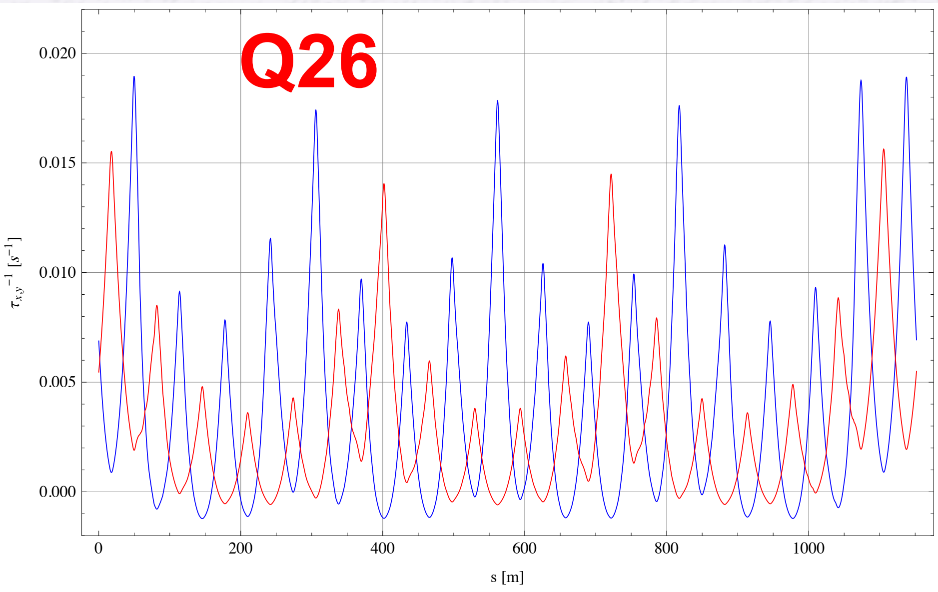
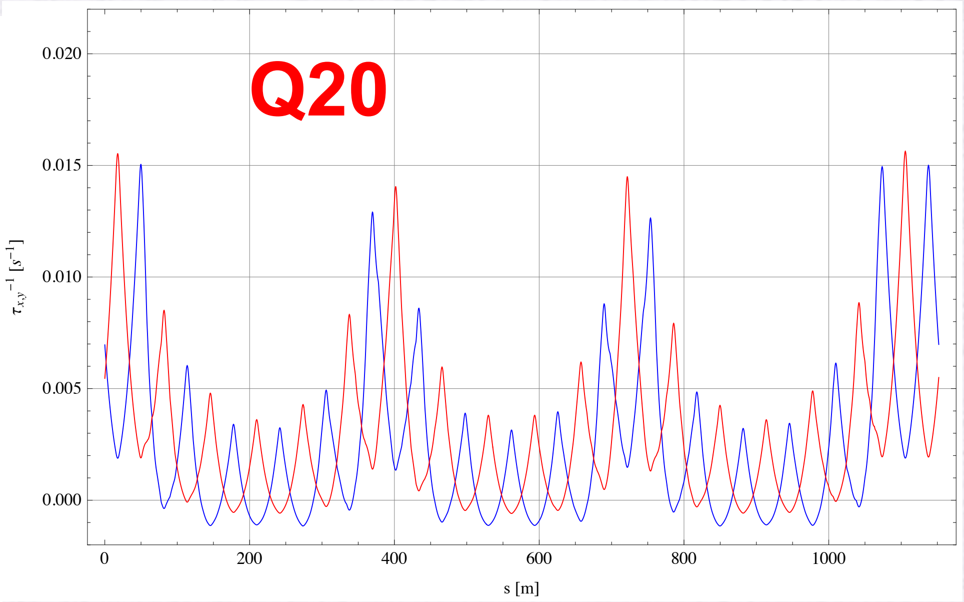
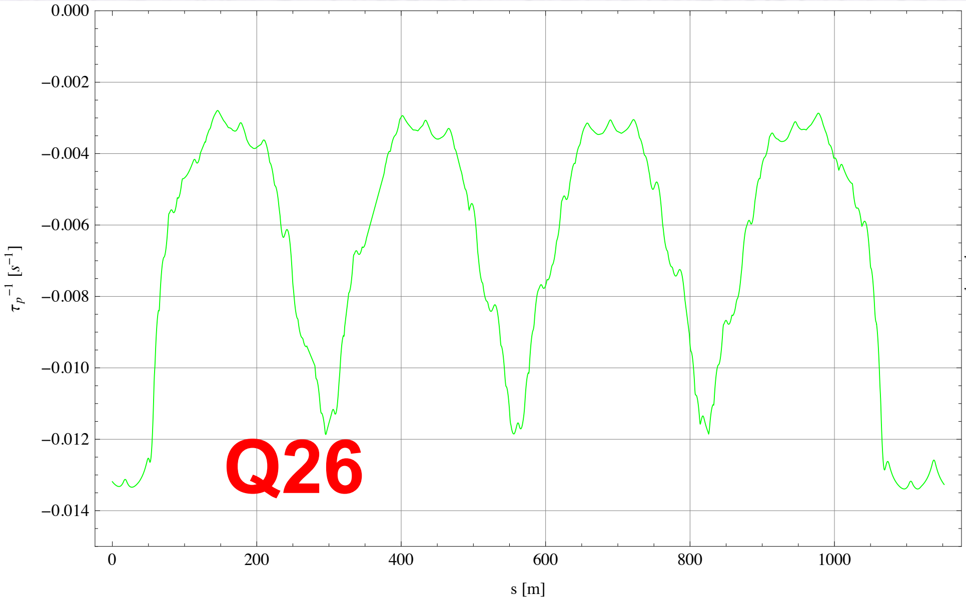
# Transverse IBS growth rates

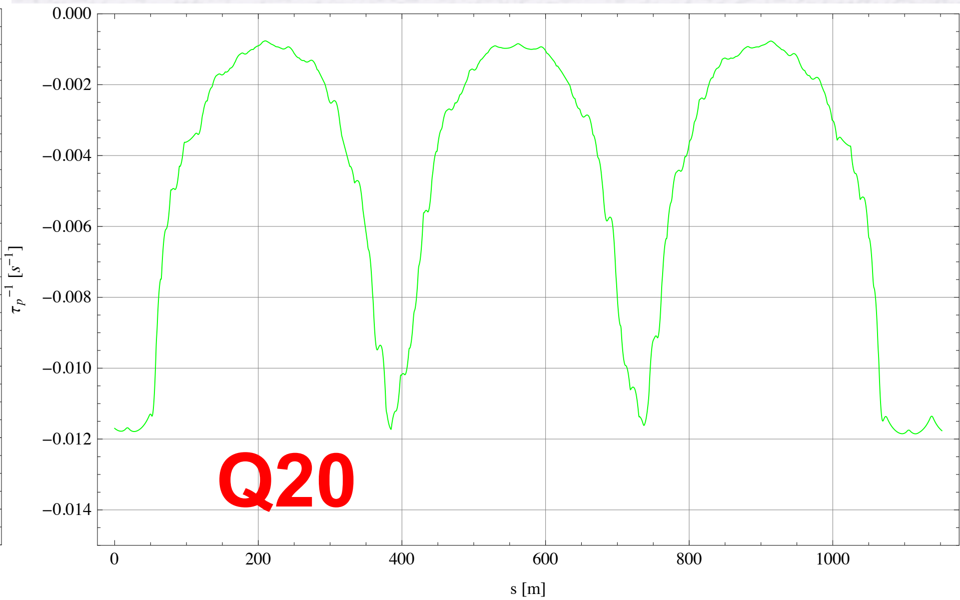



- Decrease of the growth rate especially in the horizontal but also vertical plane for the Q20 optics, mainly attributed to higher beam sizes

# Longitudinal IBS growth rates




- Longitudinal rate is negative, i.e. there is damping
- Mainly follows the dispersion evolution around the arc
- Less damping for the Q20 optics

# IBS growth times

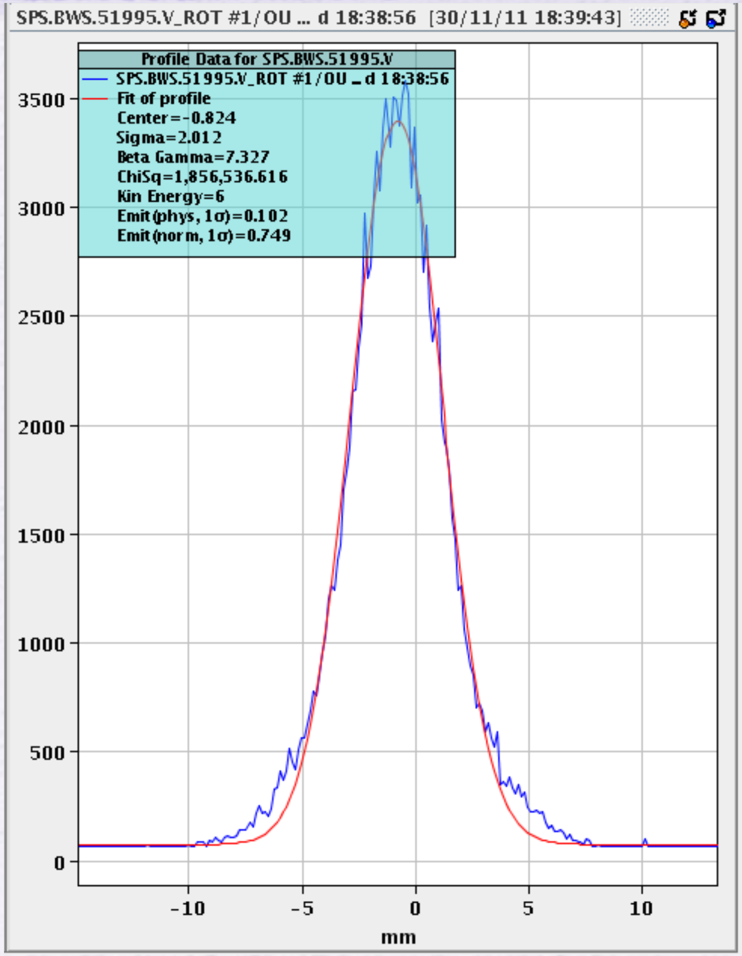
- Computing rates for just the input transverse and longitudinal emittances (average around the ring of previously plotted growth rates)
- 40 to 50% increase of growth times for the Q20 optics
- Note again that the IBS calculation foresees that there is damping of the longitudinal emittance

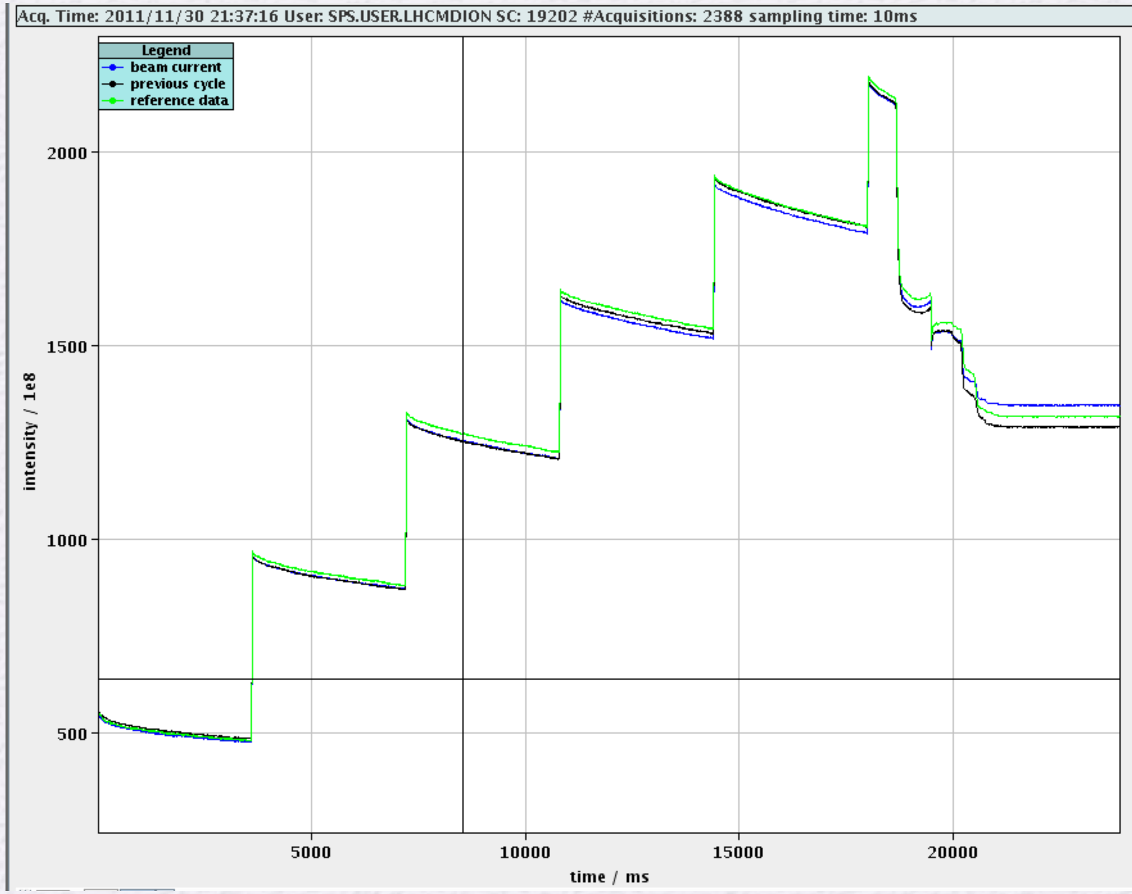
| Growth rates | Q20 | Q26 | Ratio |
|---|---|---|---|
| Horizontal [s] | 393 | 254 | 1.5 |
| Vertical [s] | 332 | 231 | 1.4 |
| Longitudinal [s] | -219 | -143 | 1.5 |

# Machine studies with Q20 optics

- Prepared LHCMDION cycle with "Q20" optics
- Flat bottom length of 18.620ms allowing the injection of 6 batches of I-LHC Intermediate Beam
  - Injection kicker strength had to be increased with respect to the Q26 optics (less kick enhancement due to reduced strength of neighboring quad)
  - Rise time of the kicker gets increased and incompatible with 200ns bunch spacing
  - It has been increased to 400ns (6 batches)
- Transition timing adapted to around 850ms after start of ramp
- Two short parallel MDs on 30/11/2011 and 06/12/2011
  - First one dedicated to setting up and longitudinal beam observations
  - Second dedicated to working point scanning and transverse measurements

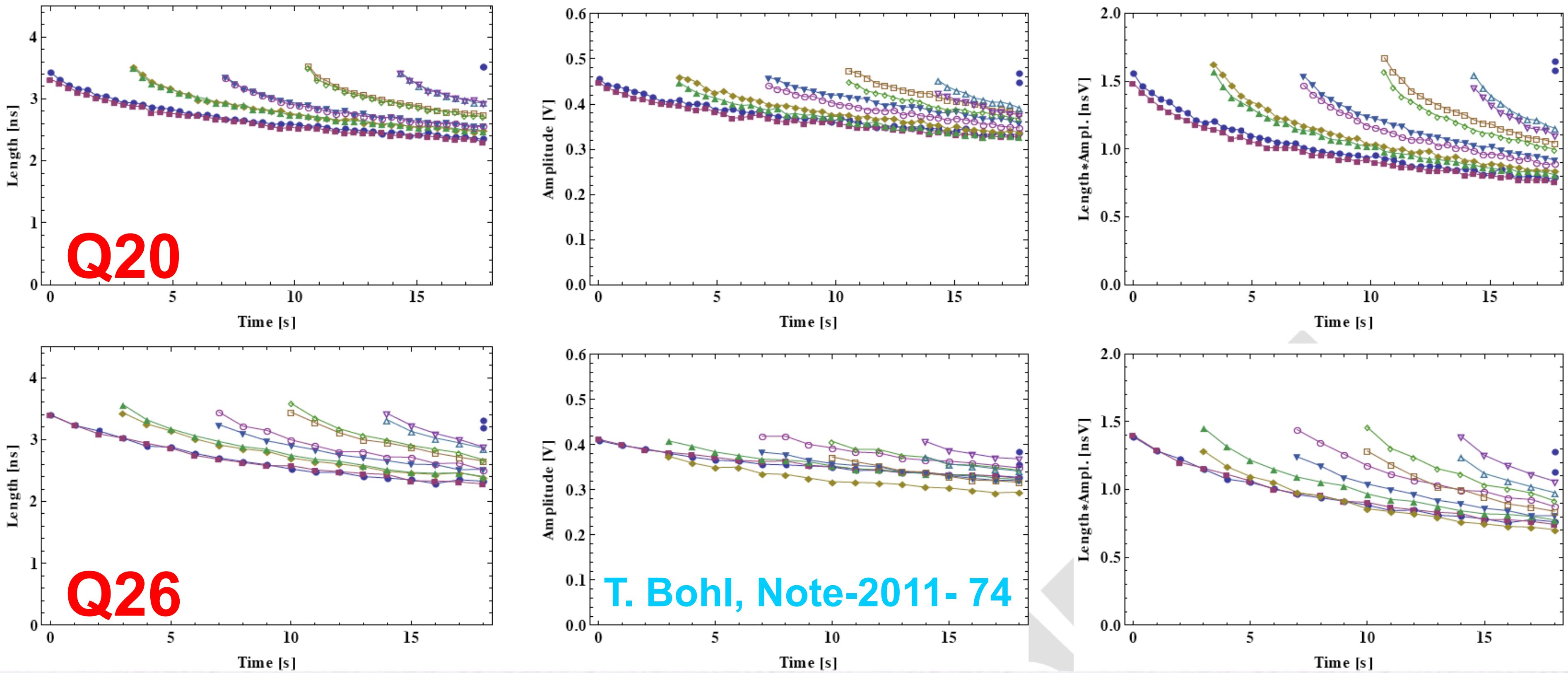
# MD on 30/11/2011 setting up



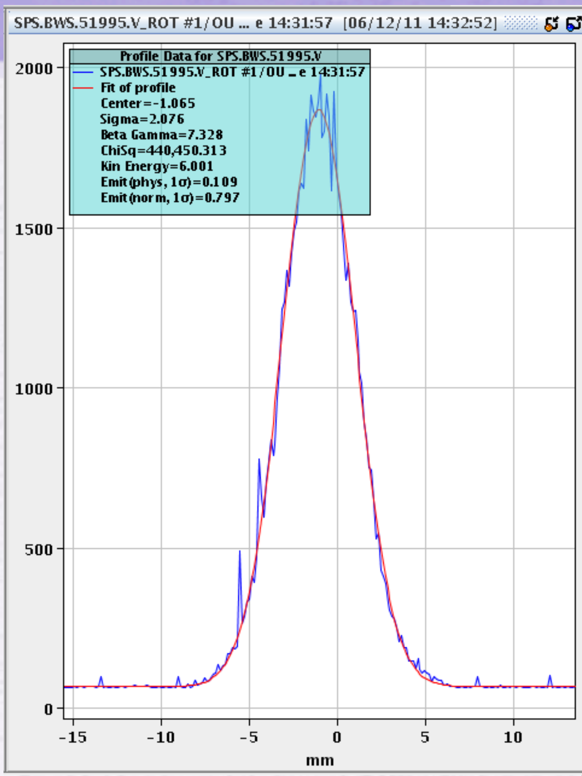

- Managed to get conditions comparable to the ones of the nominal optics but with higher loss rate
- Similar emittances (0.7-0.8mm.mrad at the flat top)

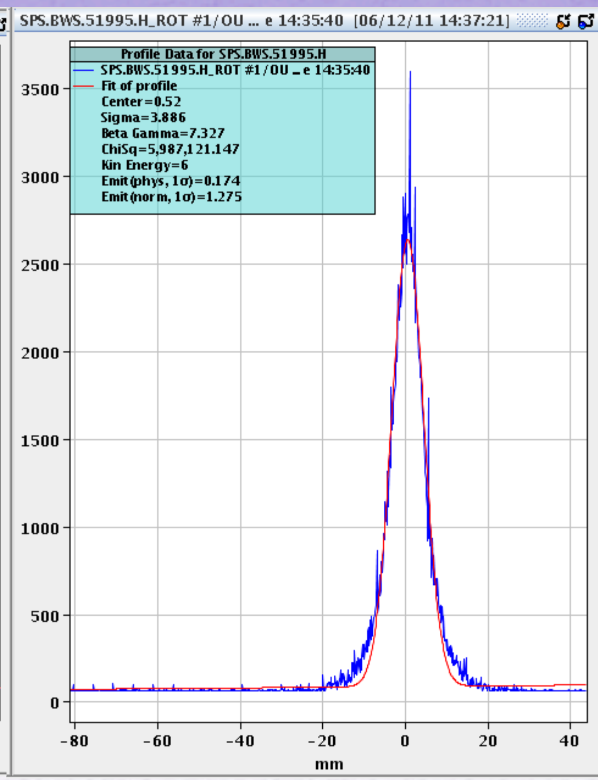
# MD on 30/11/2011 Longitudinal observations

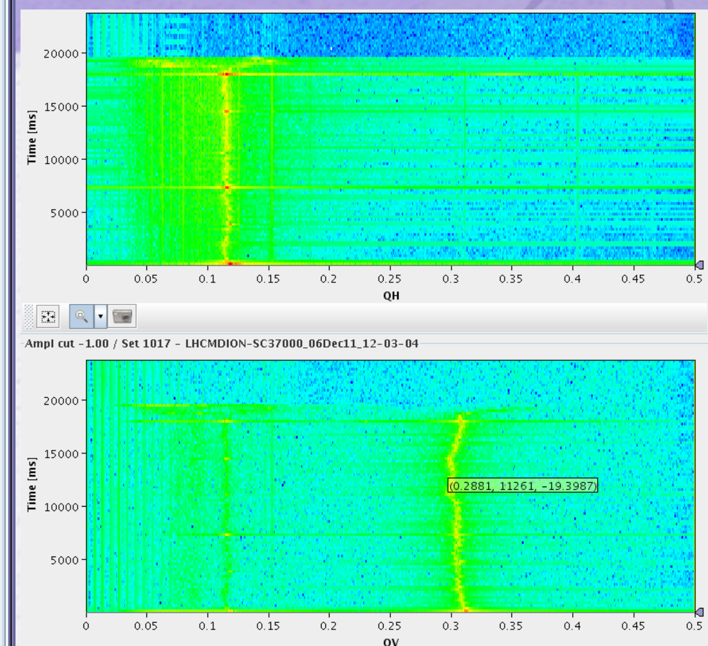



- Bunch length reduces with time (as IBS foresees!)
- Effect of RF noise already studied for Q26 (reducing damping by using generator) but not in that case.
- At first sight, bunch length and amplitude evolution quite similar in both optics

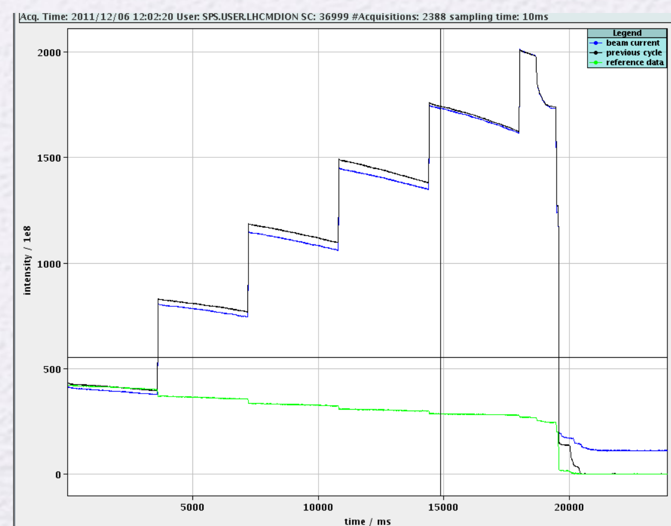
# MD on 06/12/2011




- Scanned several working points
- Observed horizontal blow up when approaching the horizontal integer
- Loss profile changed to parabolic
- Transmission improved (reduction of IBS?)



# Summary

- New low transition energy optics proposed as alternative for mitigating IBS and space-charge effects for LHC ion beam in the SPS
- Simulations predict lower space charge tune-shift and even more impressive reduction on IBS growth rates
- Predicted damping of longitudinal emittance actually observed in measurements
- First measurements did not show difference on the longitudinal beam characteristics
- Transverse plane behavior seems to indicate that there is indeed a combination of space-charge and IBS limiting the ion

# Perspectives

- Simulate IBS effect with other formalisms (Bjorken-Mtingwa, Bane,...) for comparison
- Try to use multi-particle Monte-Carlo code now available
- Repeat the same exercise for protons (IBS should be indeed visible)
- Analyze further obtained measured data (longitudinal and transverse)
- Continue machine developments for disentangling effect of RF noise, IBS and space-charge
  - Try different injected emittances (longitudinal and transverse)
  - Try to fit theory on measurements