HIGH-INTENSITY AND HIGH-DENSITY BEAMS IN THE PS

E. Metral (AB-ABP)

FOR

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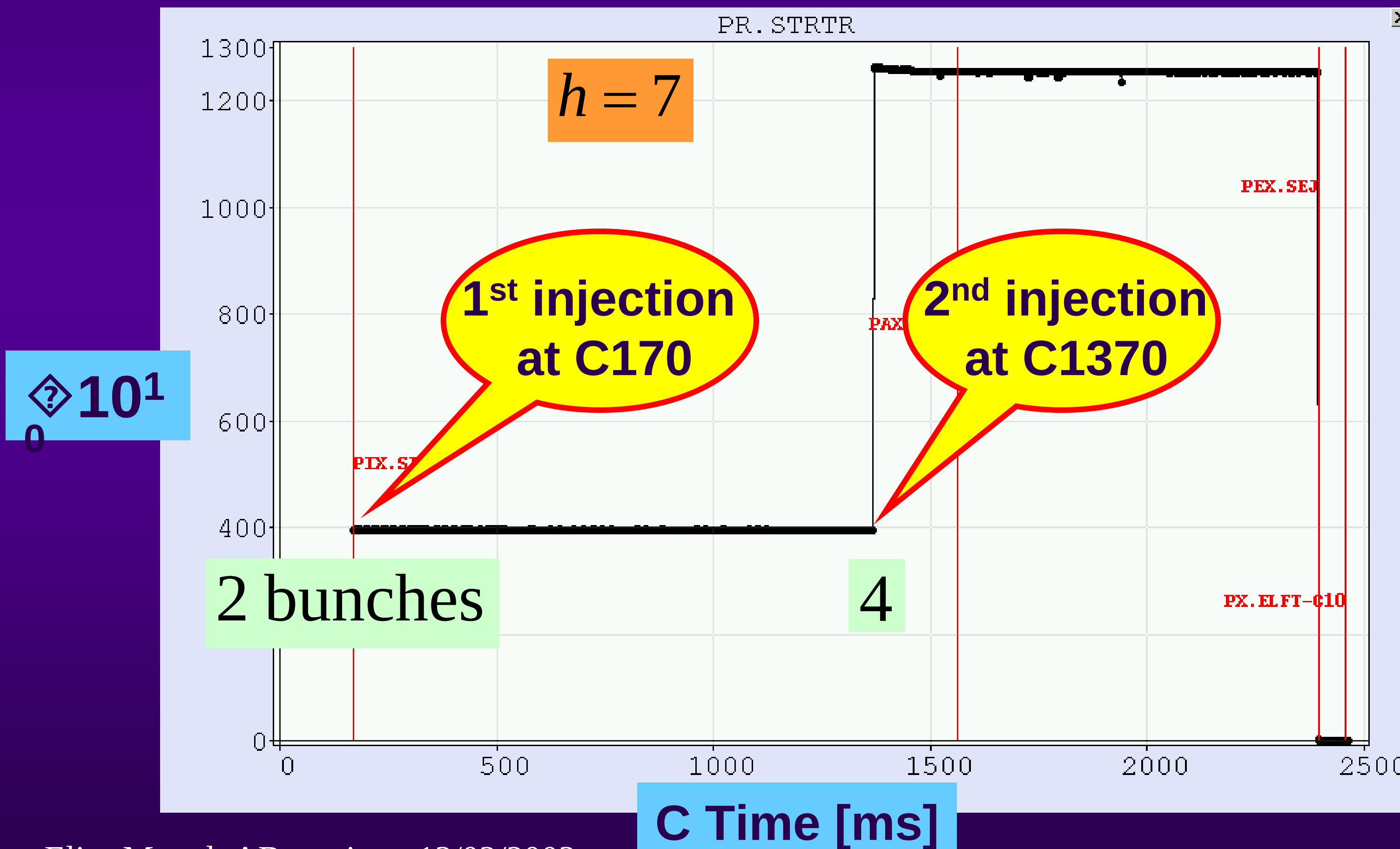
INTRODUCTION (1/3)

- **High-intensity beams :** $N_b \geq \sim 3-4\times10^{12}$ p/b $\varepsilon_{x,y}^{\mathrm{norm},1\sigma} \geq \sim 10\ \mu\mathrm{m}$ $\varepsilon_l^{2\sigma} \geq \sim 2\ \mathrm{eVs}$
  - SFTPRO (and future CNGS)
    - Goal : 4.8×10^{13} p/pulse
  - n-TOF
  - AD
  - EASTC = EAST + parasitic n-TOF
- **High-density beams :** $N_b \leq \sim 2\times10^{11}$ p/b $\varepsilon_{x,y}^{\mathrm{norm},1\sigma} \leq 3\ \mu\mathrm{m}$ $\varepsilon_l^{2\sigma} = 0.35\ \mathrm{eVs}$
  - LHC
    - Different flavours

Normalised rms emittances

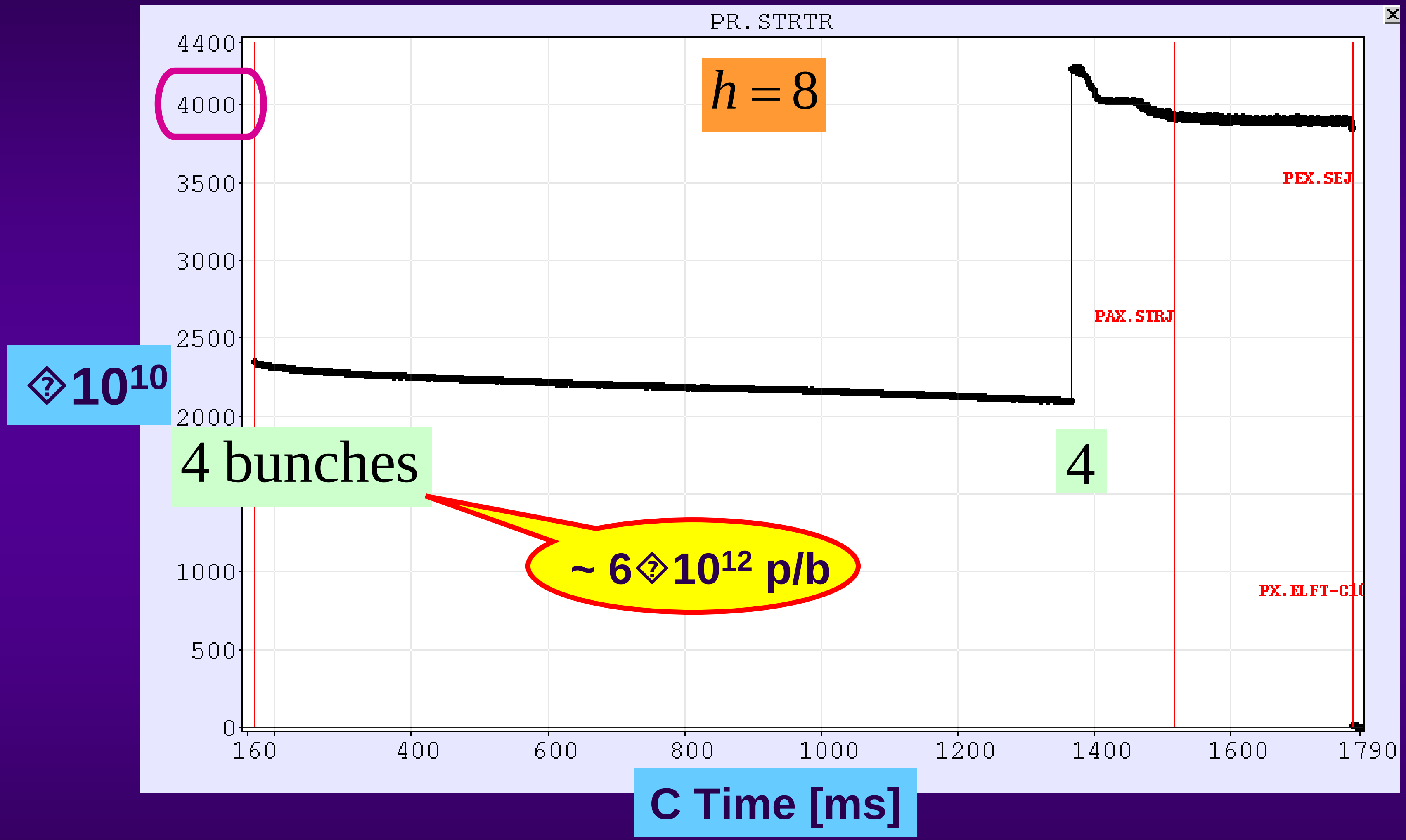
Ultimate LHC beam

- Done with a remarkable transmission in 2001
- The transverse and longitudinal emittances need to be optimised (slightly too large : ~ 4 µm in transverse and 4.5 ns bunch length, instead of 3 and 4)



INTRODUCTION (3/3)

CNGS ⇒ Best global result obtained in 2001 (PS record)



… but a lot of work remain to be done to obtain the desired performance with acceptable losses ⇒ Detailed study of all the bottlenecks

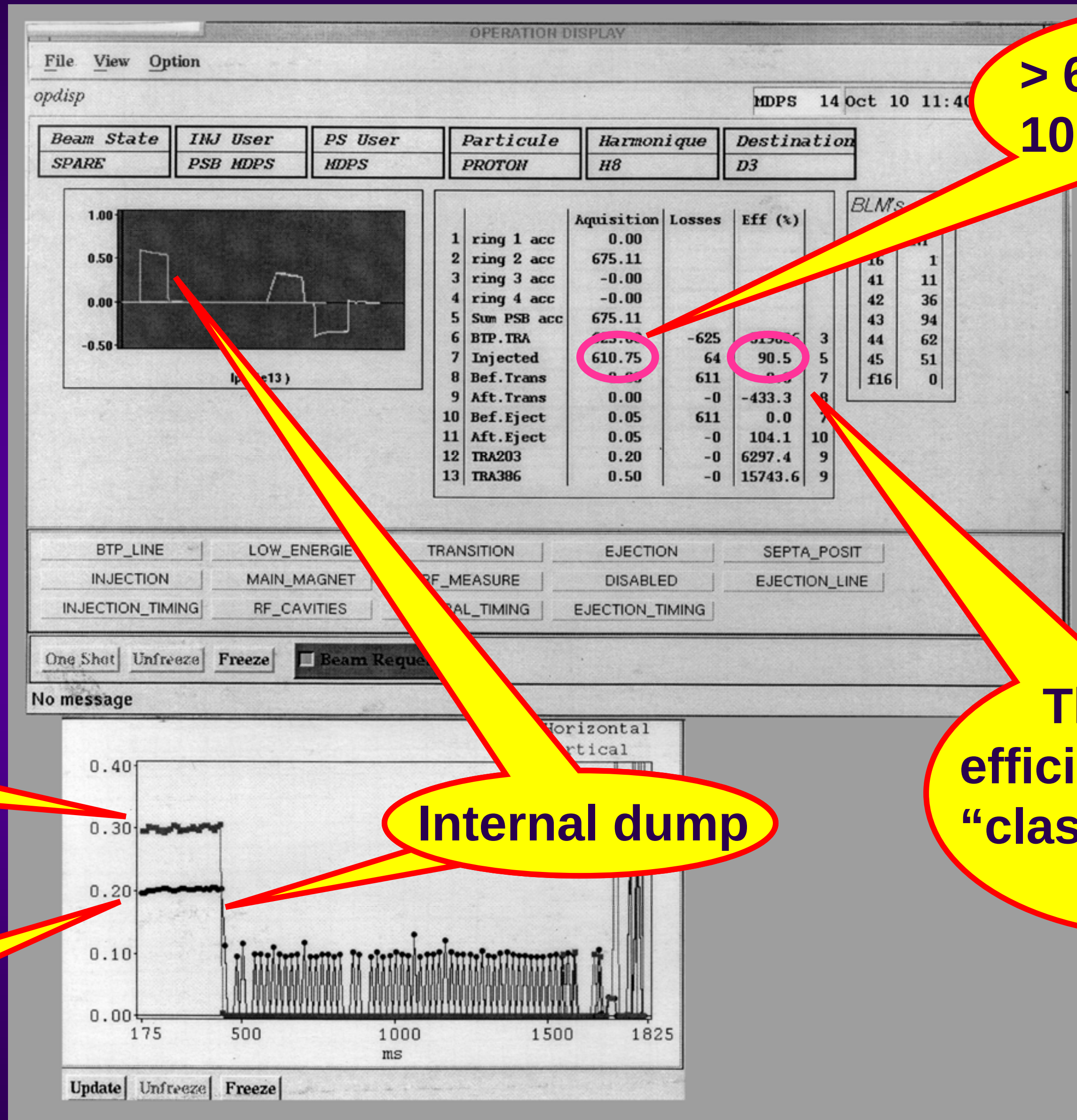
INJECTION PROCESS (1/5)

- Why did one need to have $Q_h \approx 6.1$ at injection for $N_b \geq \sim 3-4 \times 10^{12}$ p/b ?

Otherwise ~ all the bunch was lost in few turns

INJECTION PROCESS (2/5)

New set-up



> 6 $\times 10^{12}$ p/b after 10 ms in the PS

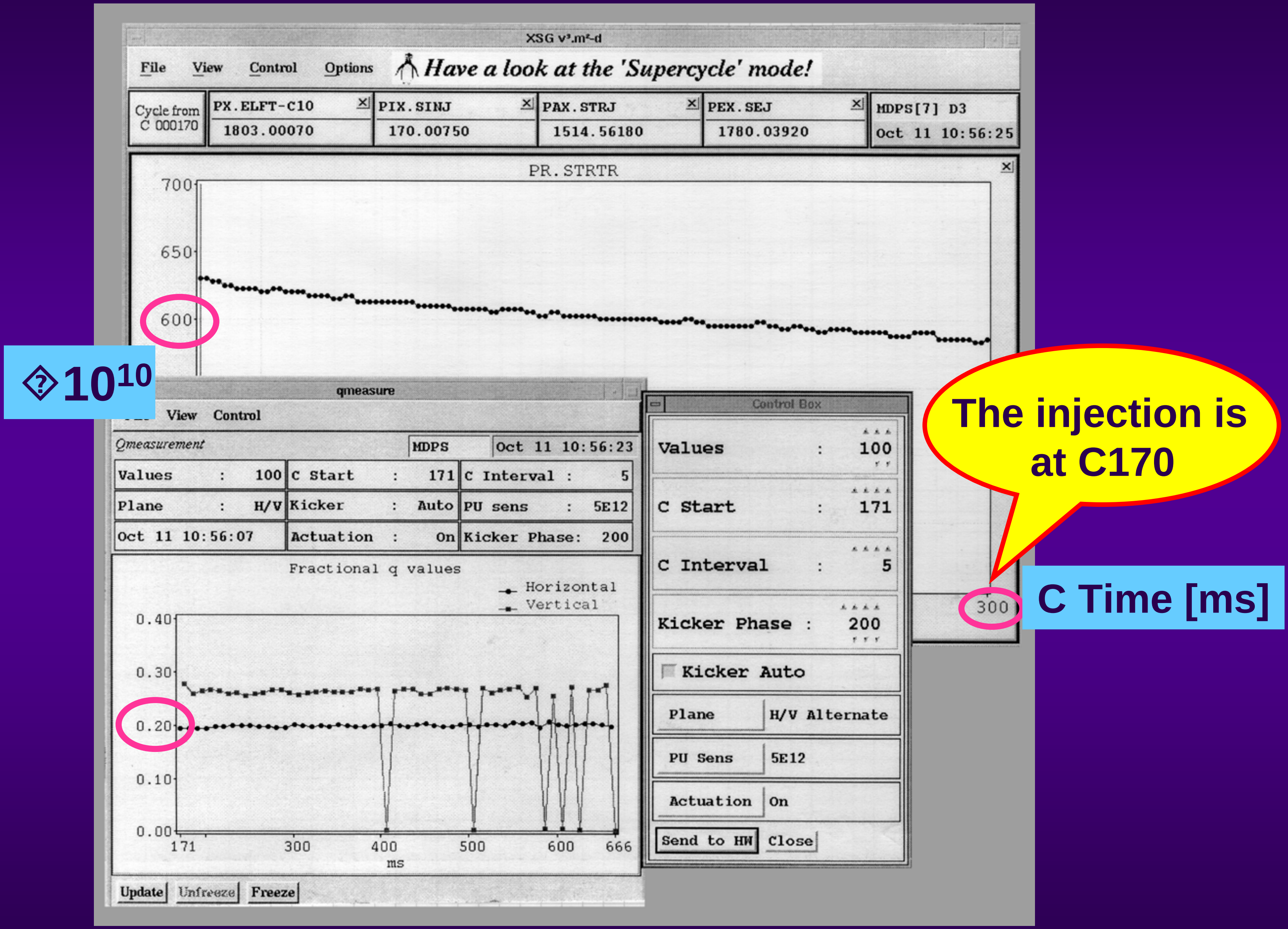
$Q_v = 6.30$

$Q_h = 6.20$

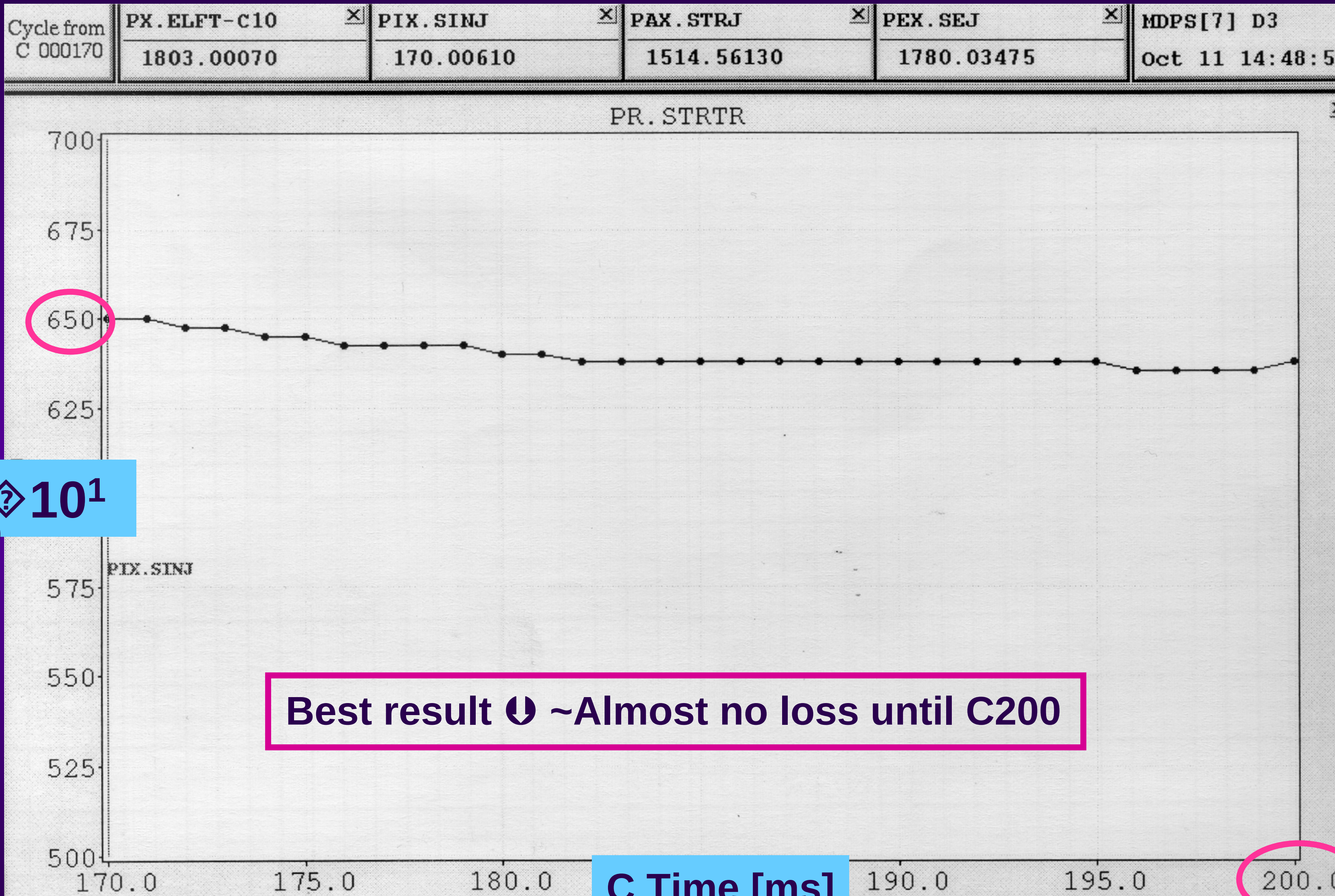
Internal dump

The same efficiency as with "classical" tune : ~90%

INJECTION PROCESS (3/5)



INJECTION PROCESS (4/5)



INJECTION PROCESS (5/5)

- The improvement seems to come only from the correction of the injection coherent oscillations !!!

- This result will be applied this year on n-ToF, AD and SFTPRO

➜ The longitudinal emittance blow-up used to avoid the crossing of the integer or ½ integer resonances could disappear

Conclusion : The horizontal tune at injection should not be a problem anymore. To be verified in few weeks…

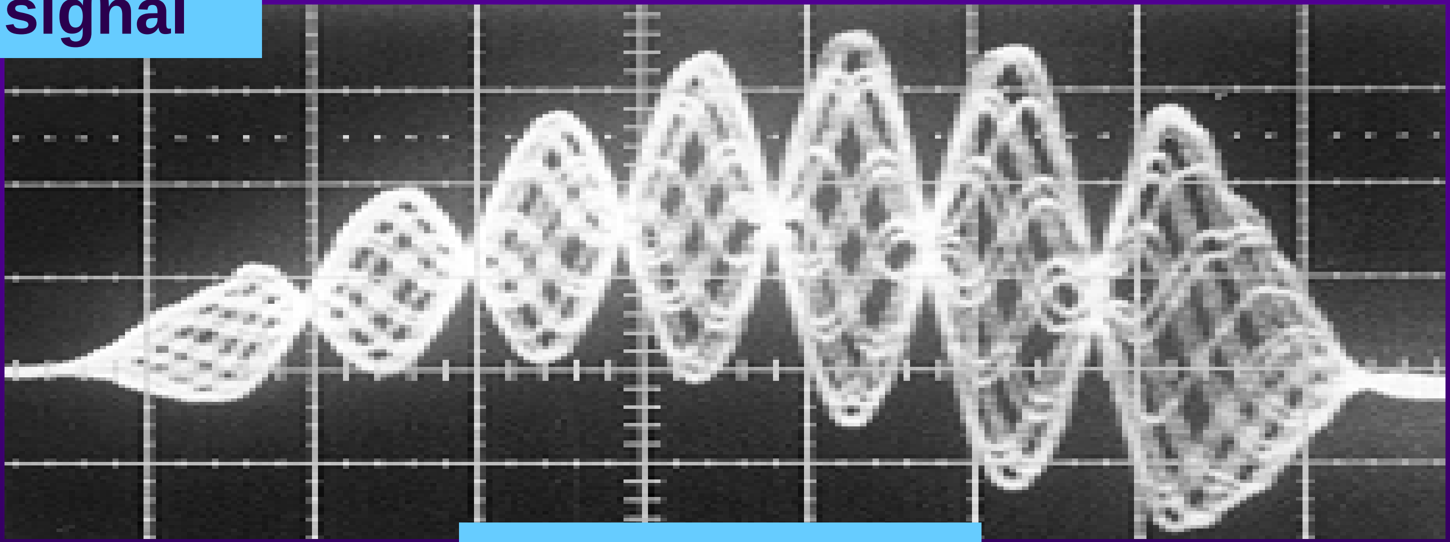
LOW-ENERGY FLAT-BOTTOM (1/24)

- **(1) Horizontal Head-Tail instability due to the resistive-wall impedance**

1D case ⇓ $I_{skew} \approx 0.33 \text{ A}$

Beam-Position Monitor
(20 revolutions superimposed)

R signal



Time (20 ns/div)

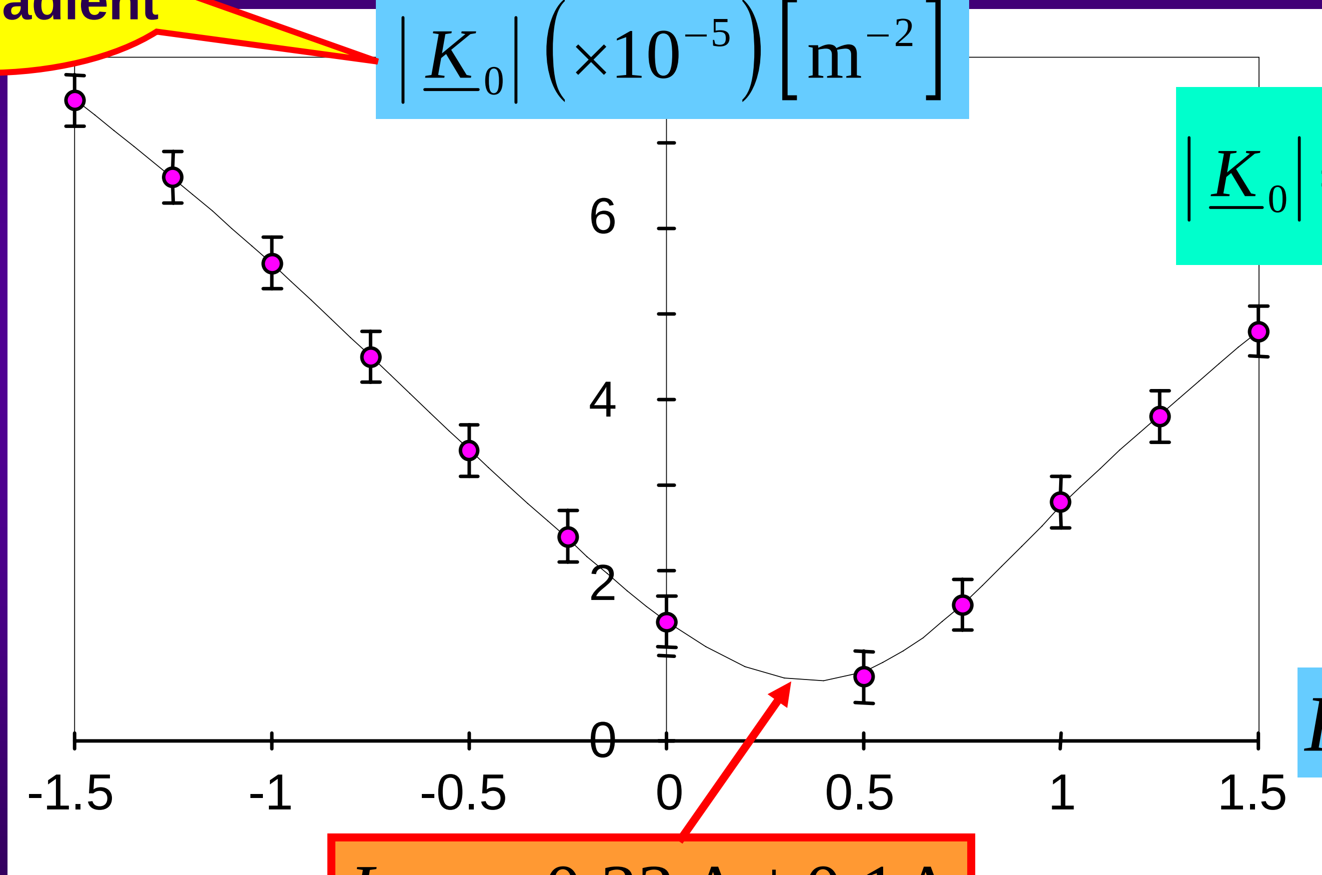
$|m| = 6$

LOW-ENERGY FLAT-BOTTOM (2/24)

Normalized skew gradient

$$\left|\underline{K}_0\right| \left(\times 10^{-5}\right) \left[\mathrm{m}^{-2}\right]$$

$$\left|\underline{K}_0\right| = \left|C\right| \frac{Q_0}{R^2}$$

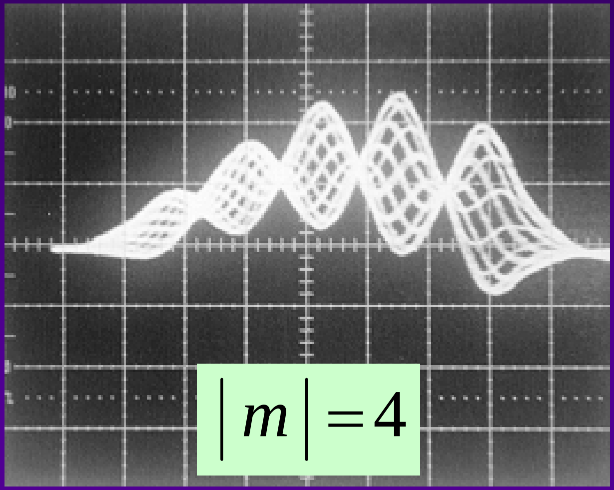


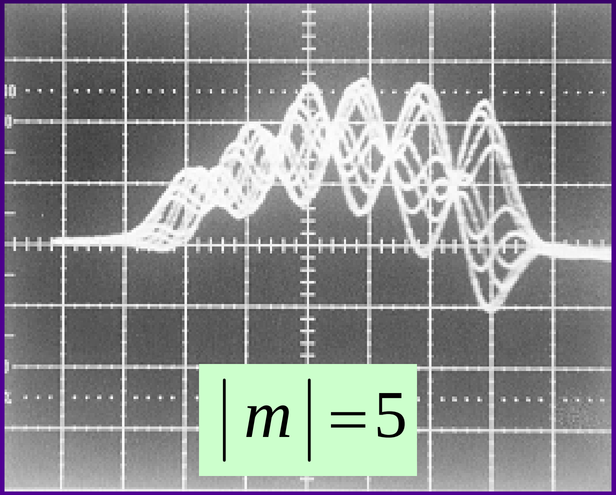
$$I_{skew} \left[\mathrm{A}\right]$$

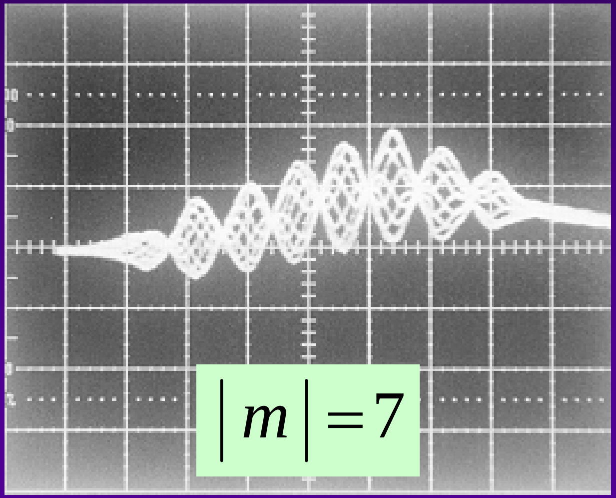
$$I_{skew} \approx 0.33\,\mathrm{A} \pm 0.1\,\mathrm{A}$$

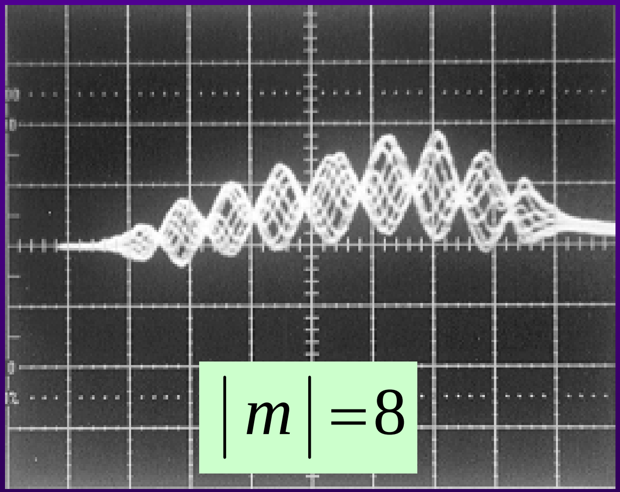
LOW-ENERGY FLAT-BOTTOM (3/24)

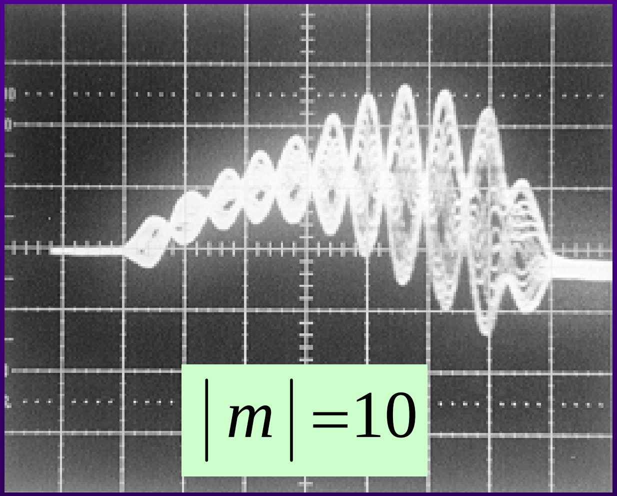
- **Chromaticity tuning**





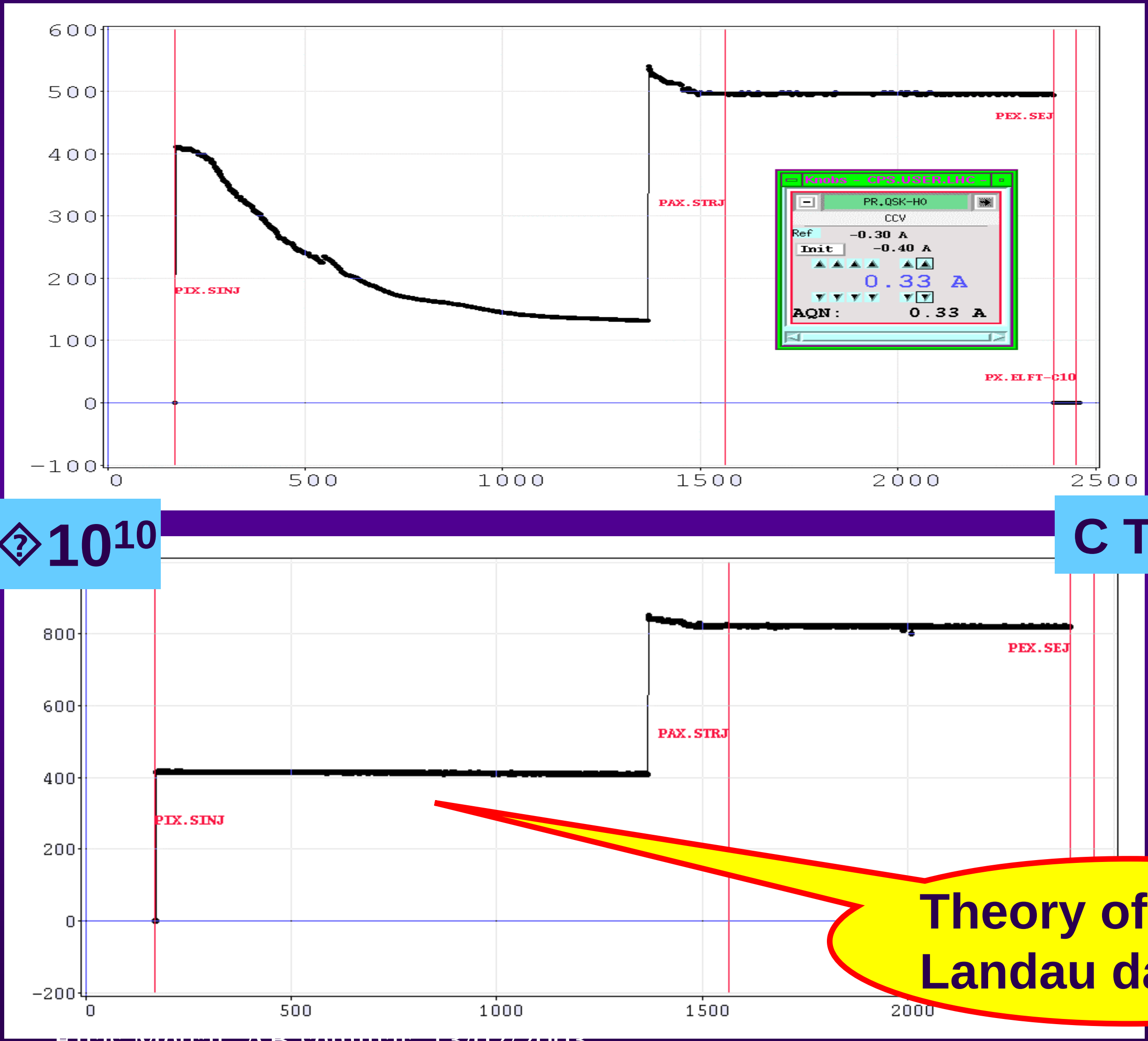






LOW-ENERGY FLAT-BOTTOM (4/24)

- **Stabilization of LHC beam by linear betatron coupling**



10^{10}

C Time [ms]

$I_{skew} \approx 0.33\ \mathrm{A}$

$Q_h = 6.22$

$Q_v = 6.25$

$I_{skew} = -0.4\ \mathrm{A}$

Theory of coupled Landau damping

LOW-ENERGY FLAT-BOTTOM (5/24)

- **Observations of the beneficial effect of linear coupling in other machines**
  - **LANL-PSR (from B. Macek)**
    - ⇓ **e^-p instability**
  - **BNL-AGS (from T. Roser)**
    - ⇓ **coupled-bunch instability**
  - **CERN-SPS (from G. Arduini)**
    - ⇓ **TMC instability in the vertical plane with lepton beams at 16 GeV**
  - **CERN-LEP (from A. Verdier)**
    - ⇓ **TMC instability in the vertical plane at 20 GeV**

- **Predicted beneficial effect of linear coupling in other machines**
  - **CERN-SPS**
    - ⇓ **e^- cloud instability**

Encouraging results (from G. Arduini)
⇓ To be studied in detail

LOW-ENERGY FLAT-BOTTOM (6/24)

- ! **Linear coupling can also have a destabilizing effect**

"Destabilizing effect of linear coupling in the HERA proton ring"
with G. Hoffstaetter and F. Willeke from DESY, Hamburg

⇩ **Stability criterion**

$$\Delta Q_{\mathrm{HWB}}^{\mathrm{spread}} \geq \left| \Delta Q_{\mathrm{normal\,modes}} \right|$$

All the measurements performed so far (since 1992) on the traditionally called *Batman* (now called *coupled head-tail)* instability can be explained by the theory of coupled Landau damping

LOW-ENERGY FLAT-BOTTOM (7/24)

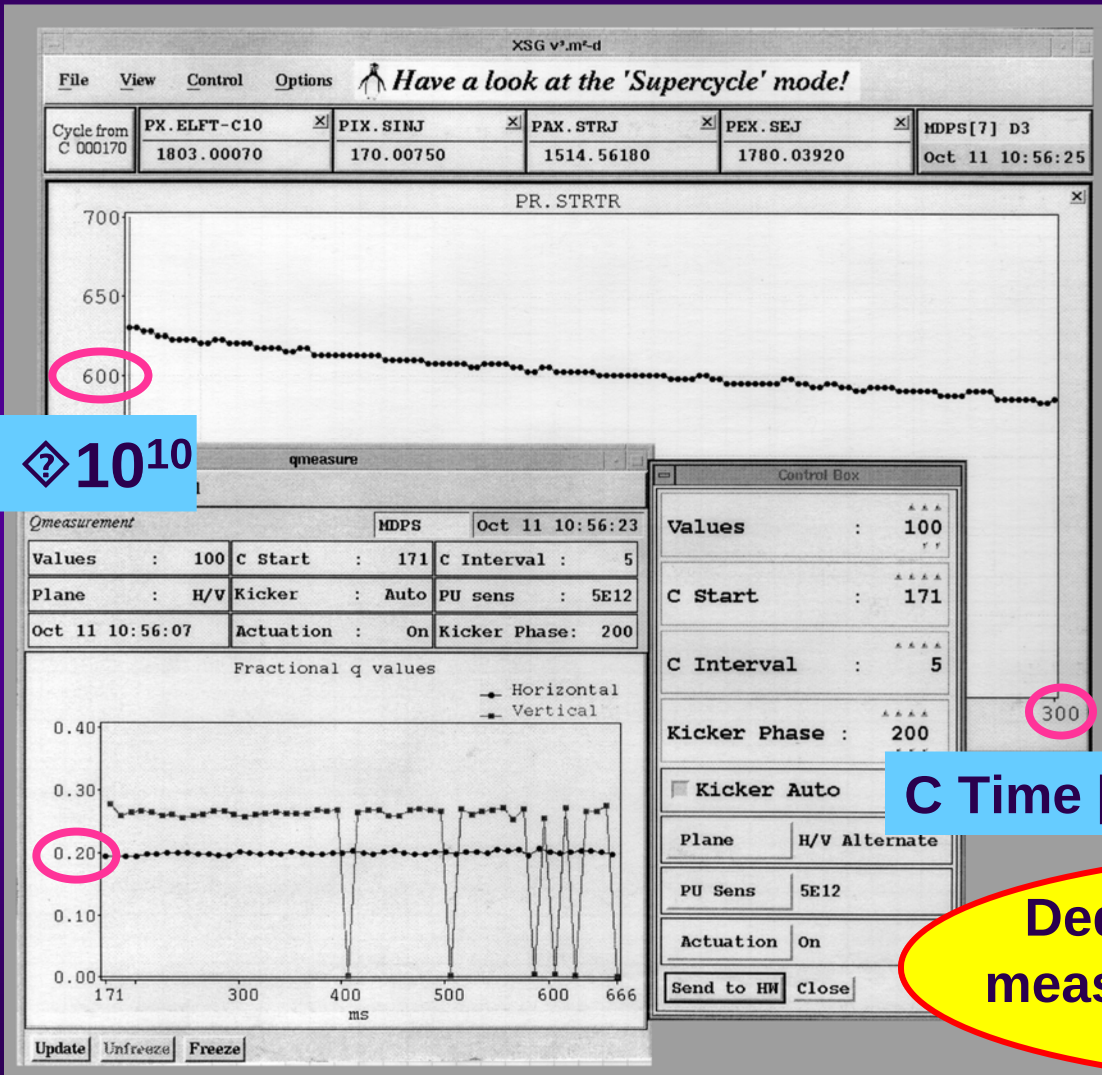
C 250

- **(2) Montague stop-band**

$$\varepsilon_x^{\text{phys},2\sigma} = 20\ \mu\text{m}$$

$$\varepsilon_y^{\text{phys},2\sigma} = 14\ \mu\text{m}$$

Montague…



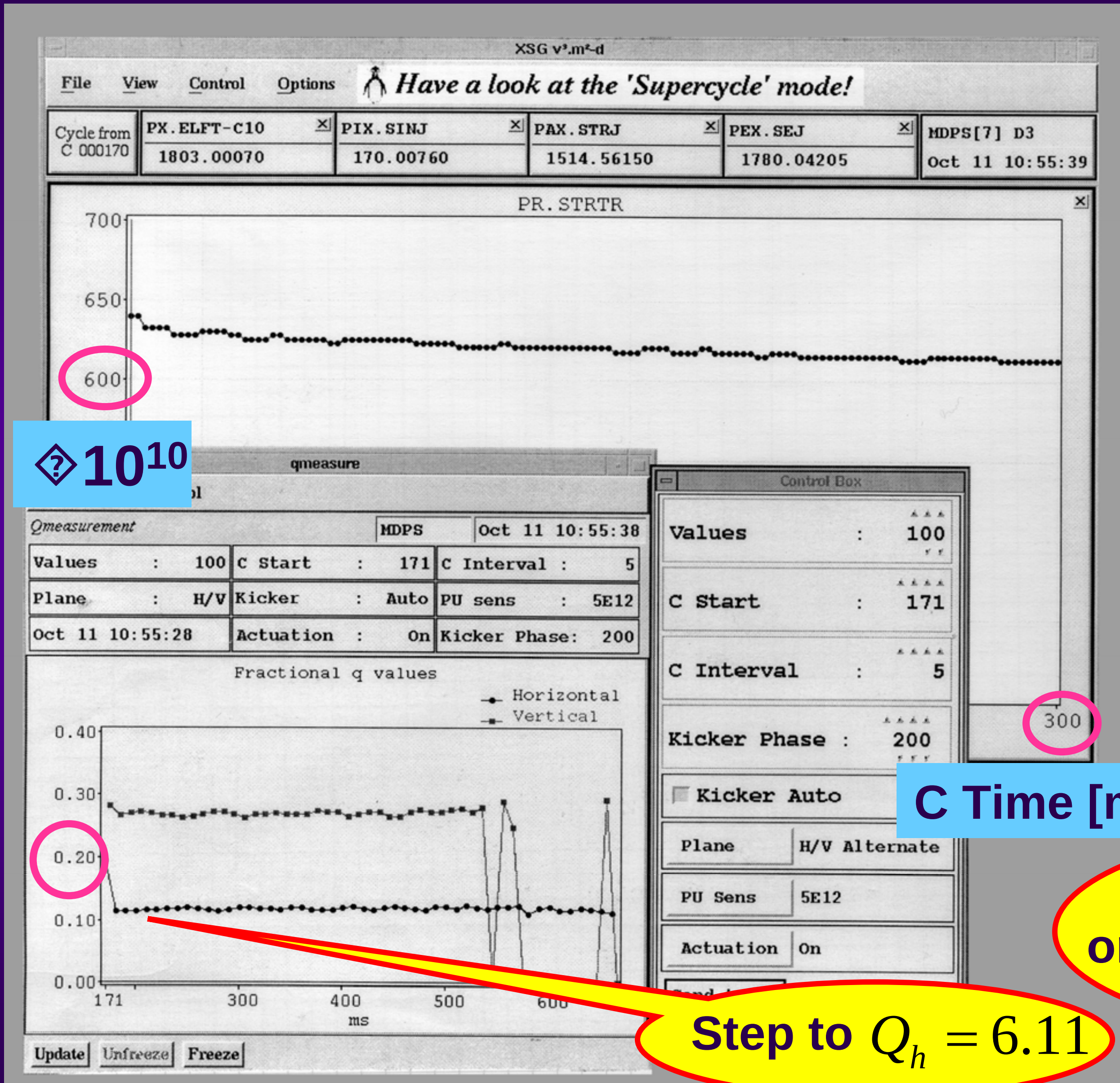
Emittance limits

$$\varepsilon_x^{\text{phys},2\sigma} \approx 22\ \mu\text{m}$$

$$\varepsilon_y^{\text{phys},2\sigma} \approx 9\ \mu\text{m}$$

Deduced from the acceptance measurements (after injection) of 1989 for 1% losses

LOW-ENERGY FLAT-BOTTOM (8/24)



$\diamond\, 10^{10}$

C 250

$$\varepsilon_y^{\mathrm{phys},2\sigma} = 11\,\mu\mathrm{m}$$

$$\varepsilon_x^{\mathrm{phys},2\sigma} = 30\,\mu\mathrm{m}$$

C Time [ms]

Crossing of the integer or ½ integer stop-band $Q_h = 6.0$

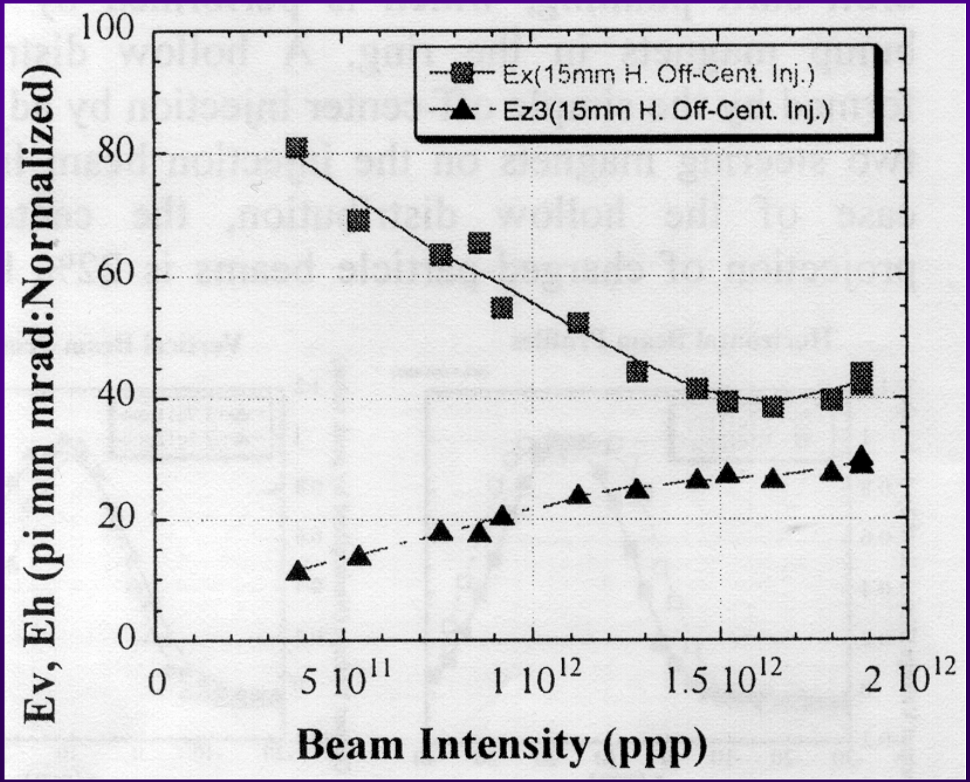
Step to $Q_h = 6.11$

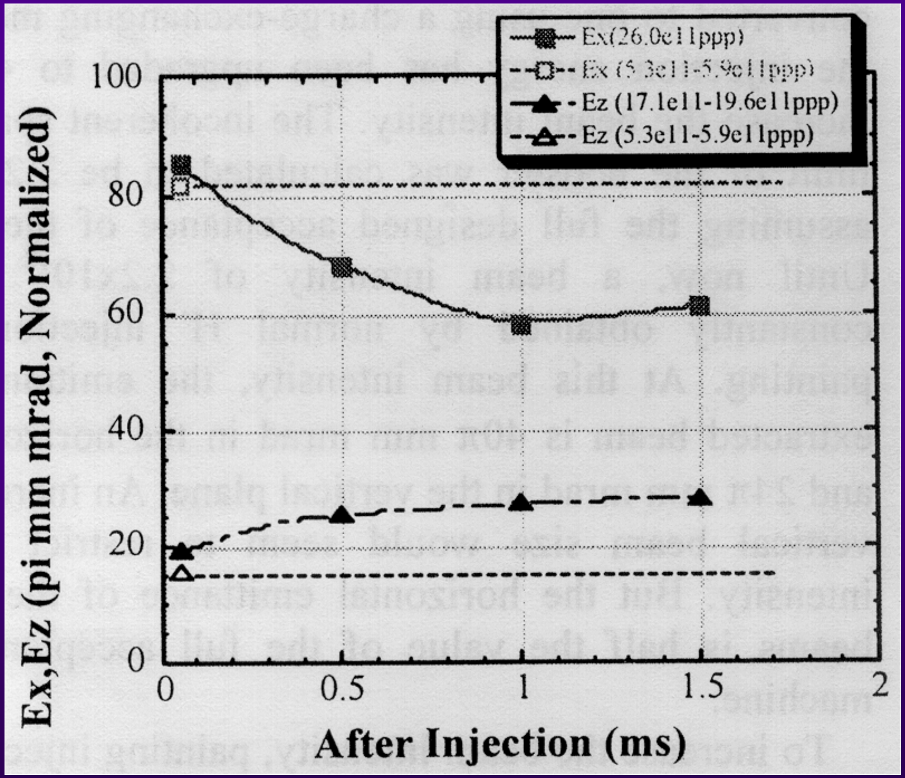
LOW-ENERGY FLAT-BOTTOM (9/24)

- **Intensity dependent emittance-exchange in the KEK Booster**

See PAC2001 paper (Sakai et al.)

MEASUREMENTS





LOW-ENERGY FLAT-BOTTOM (10/24)

SIMULATIONS for the KEK Booster

3D version of the tracking code SIMPSONS

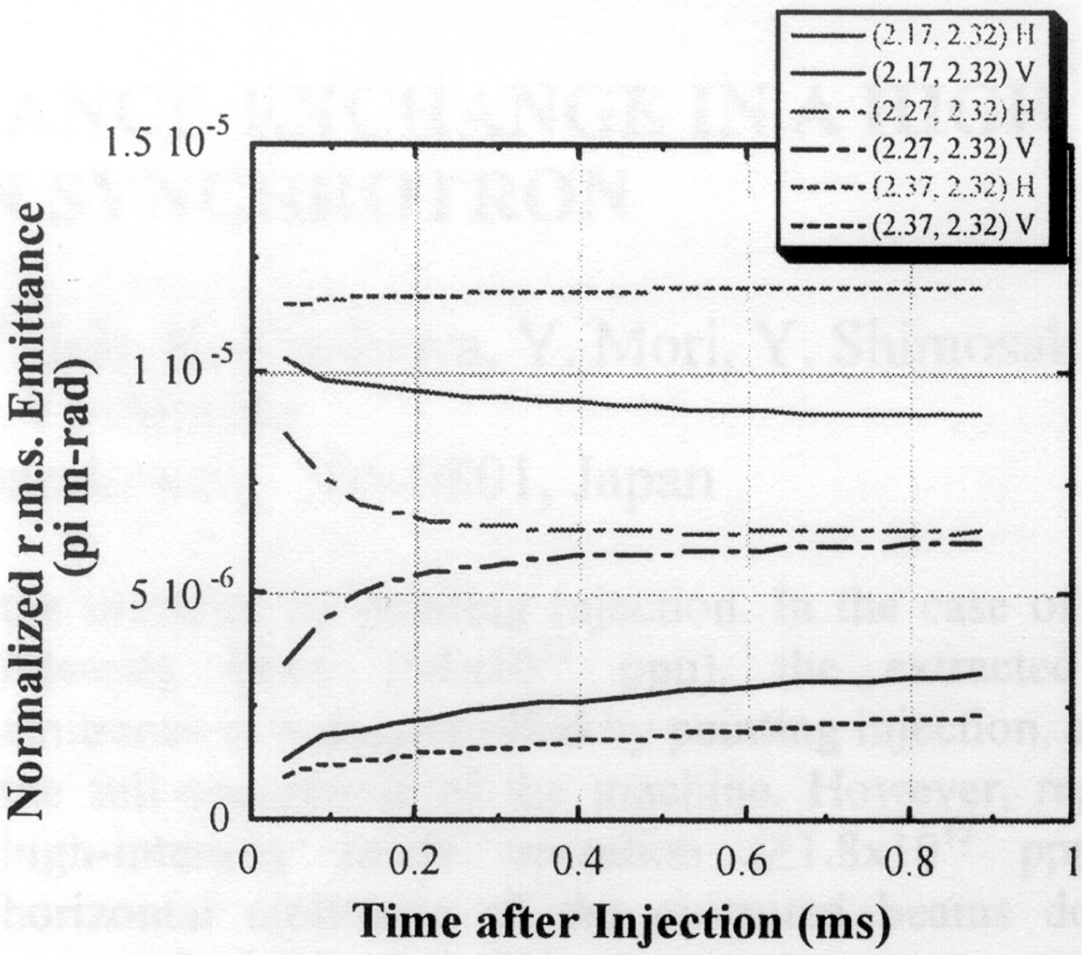


Figure 6: Emittance Exchange with Three Different Bare tunes

$Q_x = 2.17$, $Q_y = 2.32$ — **Small exchange**

$Q_x = 2.27$, $Q_y = 2.32$ — **Larger exchange**

$Q_x = 2.37$, $Q_y = 2.32$ — **No exchange**

Dissymmetrical stop-band

LOW-ENERGY FLAT-BOTTOM (11/24)

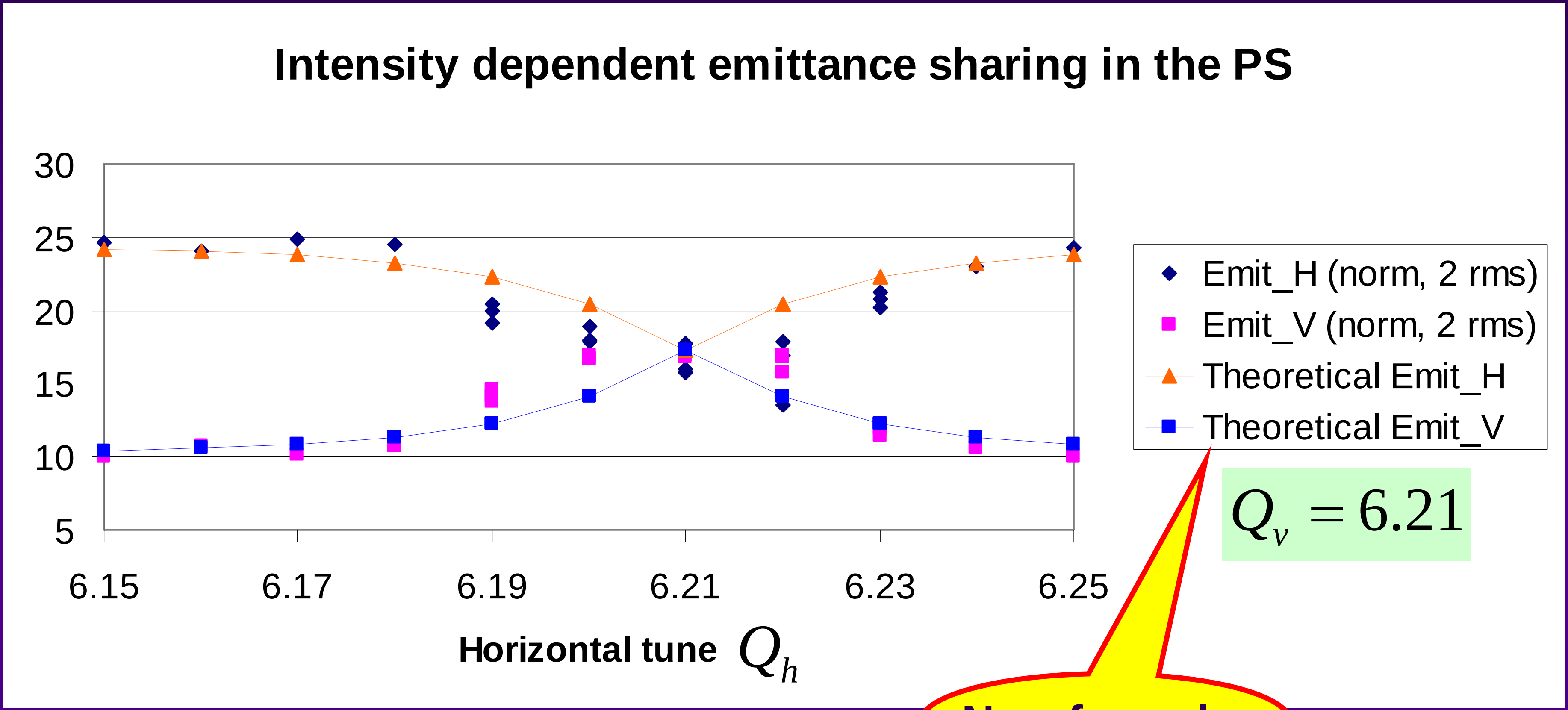
- A benchmarking experiment has been carried out in the PS

  - Study the effect of the Montague stop-band (with I. Hofmann and G. Franchetti from GSI, Darmstadt)

- Single bunch with maximum space-charge horizontal tune shift

$$\Delta Q_{inc,x0} = -0.07$$

LOW-ENERGY FLAT-BOTTOM (12/24)



$$Q_v = 6.21$$

New formulae

Theoretical coupling strength = Half stop-band (*f* = 5%) $\left| C \right| = 0.042$

f **describes the allowed amount of emittance transfer**

LOW-ENERGY FLAT-BOTTOM (13/24)

- **New formulae**

$$\varepsilon_{x,y} = \varepsilon_{x0,y0} \mp \left(\varepsilon_{x0} - \varepsilon_{y0}\right) \frac{\left|C\right|^2 / 2}{\Delta^2 + \left|C\right|^2 + \Delta\sqrt{\Delta^2 + \left|C\right|^2}}$$

$$\left|C\right| = \left|\Delta Q_{inc,x0}\right| \times \left(1 + \frac{b_0}{a_0}\right)^{-1}$$

Symmetrical stop-band predicted (for the coherent tunes)

$$\Delta = 2Q_v - 2Q_h = 2Q_y - 2Q_x - \frac{3 K_{sc} R^2 \left(a_0 - b_0\right)}{2 Q_0 a_0 b_0 \left(a_0 + b_0\right)}$$

$$\delta_{half\ stop\ band} = \left|Q_v - Q_h\right|_{SC\ coupling} = \left|C\right| \times \frac{\left|1 - 2f\right|}{4\sqrt{f\left(1 - f\right)}}$$

Time scale $N^1_{turns} = \frac{1}{\left|C\right|}$

LOW-ENERGY FLAT-BOTTOM (14/24)

- **These formulae have the same form as the ones already derived for emittance sharing and exchange by linear betatron coupling with different meanings for Δ and $|C|$**

  - **Classical formulae**

    Sharing only

$$\varepsilon_{x,y} = \varepsilon_{x0,y0} \mp \left(\varepsilon_{x0} - \varepsilon_{y0} \right) \frac{|C|^2 / 2}{\Delta^2 + |C|^2}$$

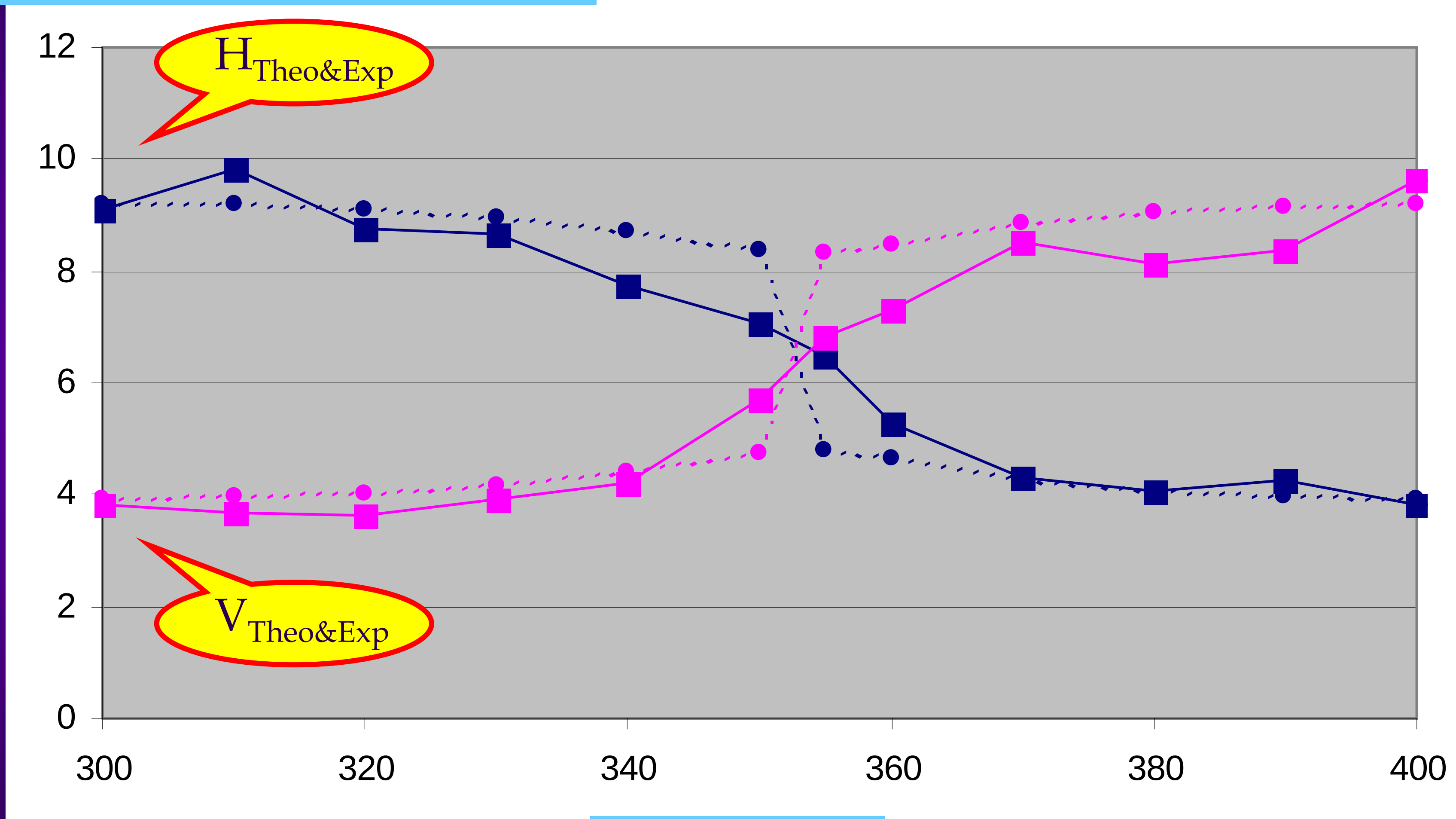
  - **New formulae** **Sharing + Exchange**

$$\varepsilon_{x,y} = \varepsilon_{x0,y0} \mp \left(\varepsilon_{x0} - \varepsilon_{y0} \right) \frac{|C|^2 / 2}{\Delta^2 + |C|^2 + \Delta \sqrt{\Delta^2 + |C|^2}}$$

LOW-ENERGY FLAT-BOTTOM (15/24)

$$I_{skew} = -0.5 \text{ A}$$

Physical emittances at 2σ [μm]



C Time [ms]

LOW-ENERGY FLAT-BOTTOM (16/24)

Possible applications of emittance exchange by linear betatron coupling

- **Precise measurement of the horizontal emittance in the vertical plane (where $D_y = 0$) ⇓ Cf. C. Carli and G. Cyvoct in the Booster**

The first who anticipated this mechanism

- **Evaluation of the vertical acceptance**

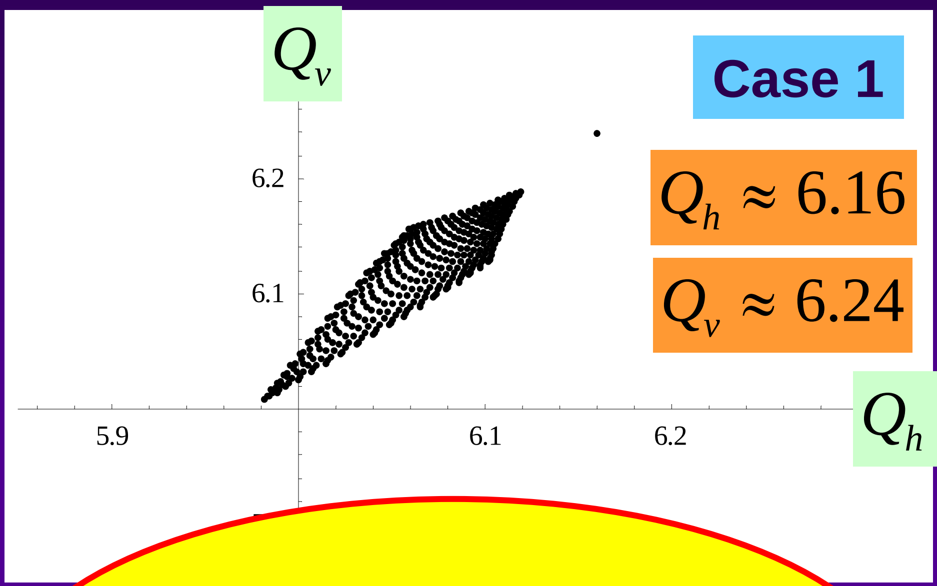
- **Reduction of the horizontal emittance for the high-intensity beams sent to the SPS, where the limitation is the vertical acceptance**

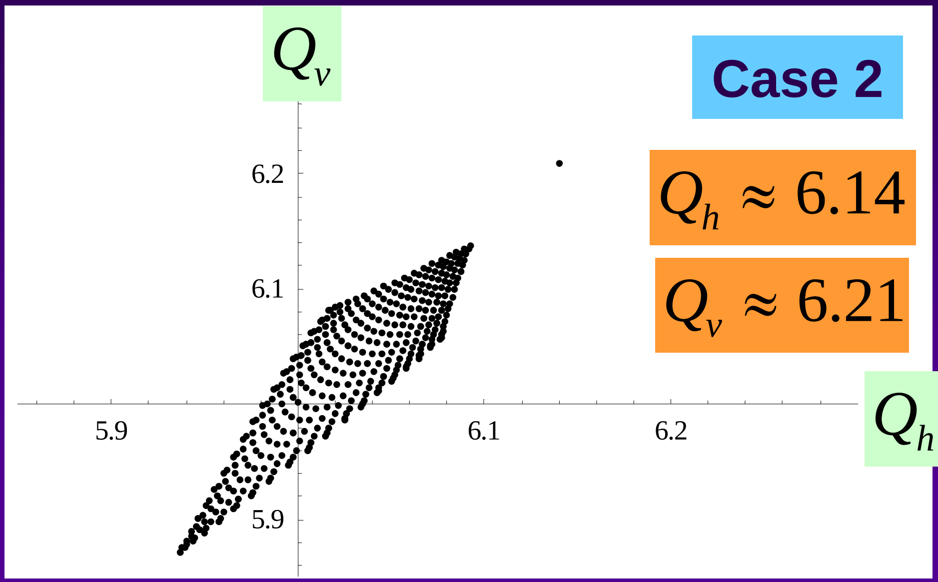
- **In theory cooling is needed only in one plane (as the damping of certain instabilities)**

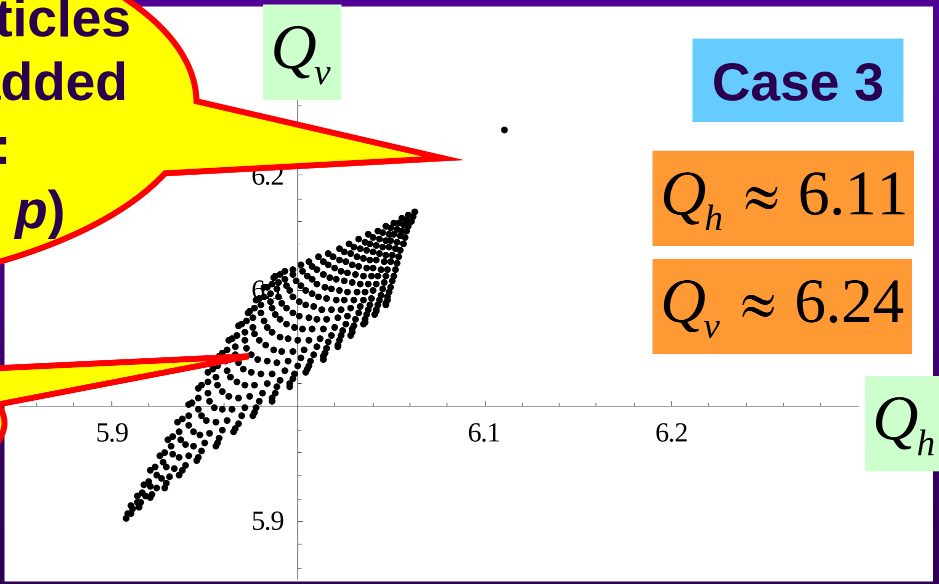
- **Coupling measurement ⇓ To see if there is coupling or not. There is no coupling in the PS at 14 GeV/c, but there is coupling at 26 GeV/c**

LOW-ENERGY FLAT-BOTTOM (17/24)

- (3) Crossing of the 1 or ½ int. resonances : benchmarking experiment





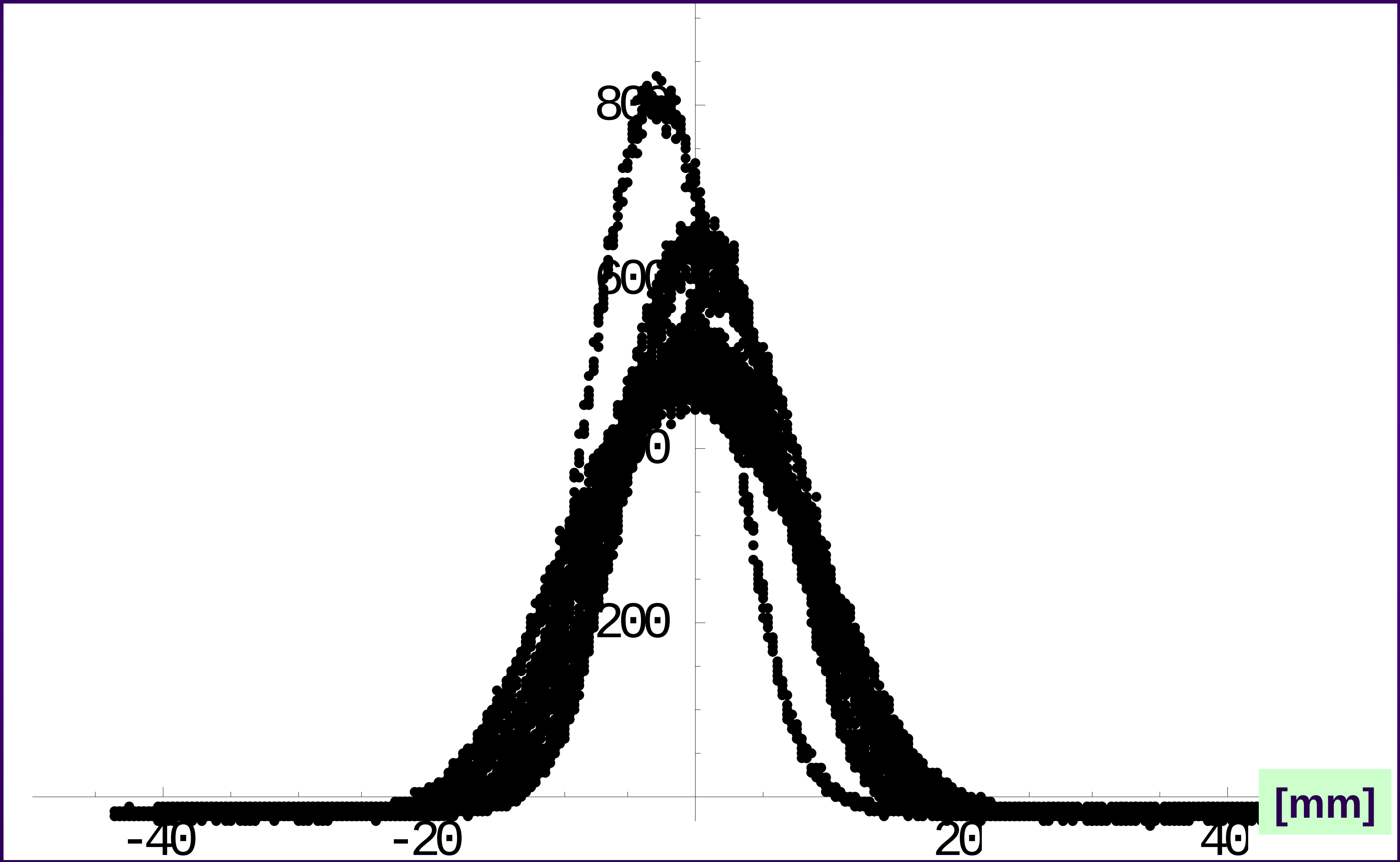


No particle here ⇓ Particles if longitudinal motion added (see Martini formula : tri-Gaussian in *x*, *y* and *p*)

From Keil formula (bi-Gaussian in *x* and *y*)

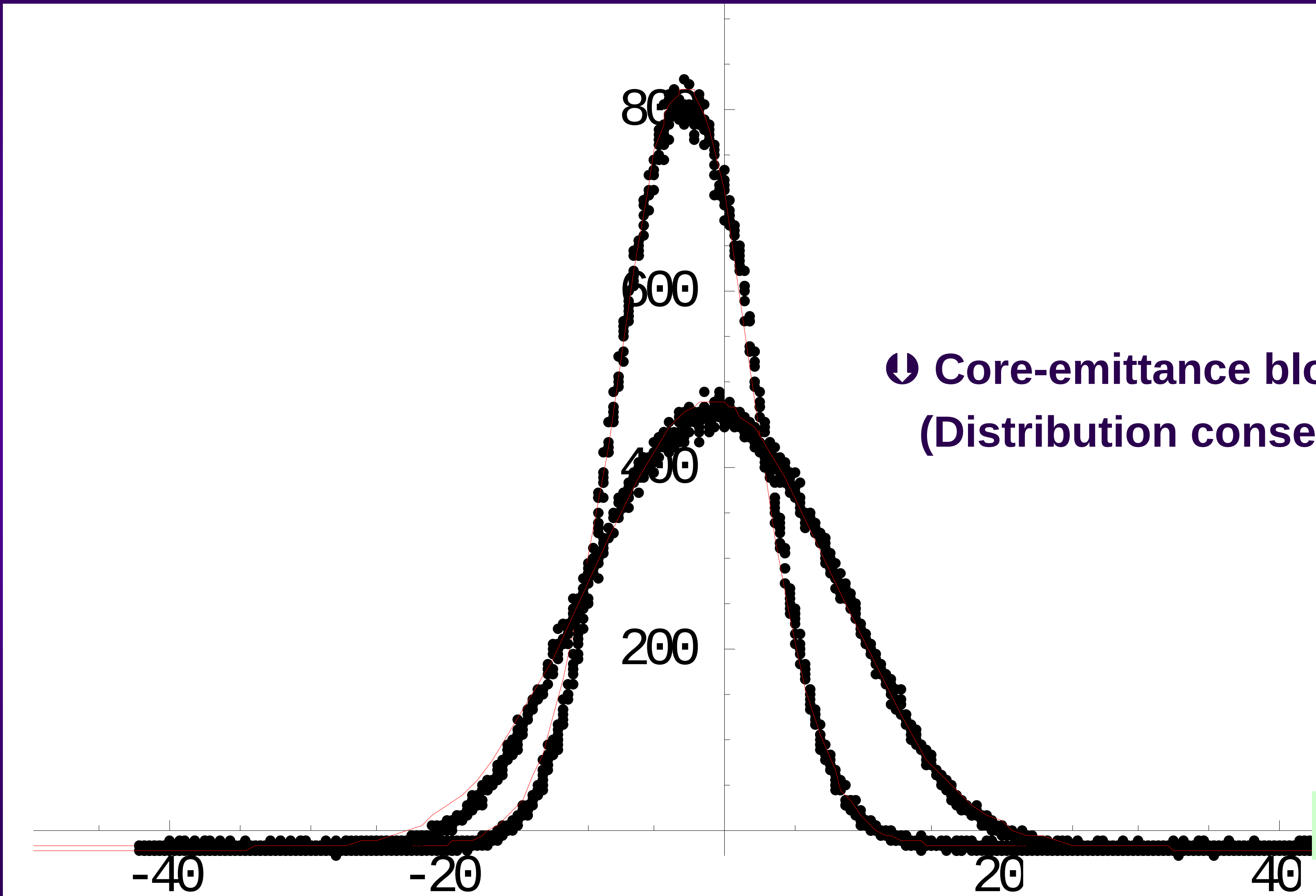
LOW-ENERGY FLAT-BOTTOM (18/24)

Case 3 : Horizontal distributions



LOW-ENERGY FLAT-BOTTOM (19/24)

Case 3 : Horizontal initial and final distributions + Gaussian fit



➋ **Core-emittance blow-up**
(Distribution conserved)

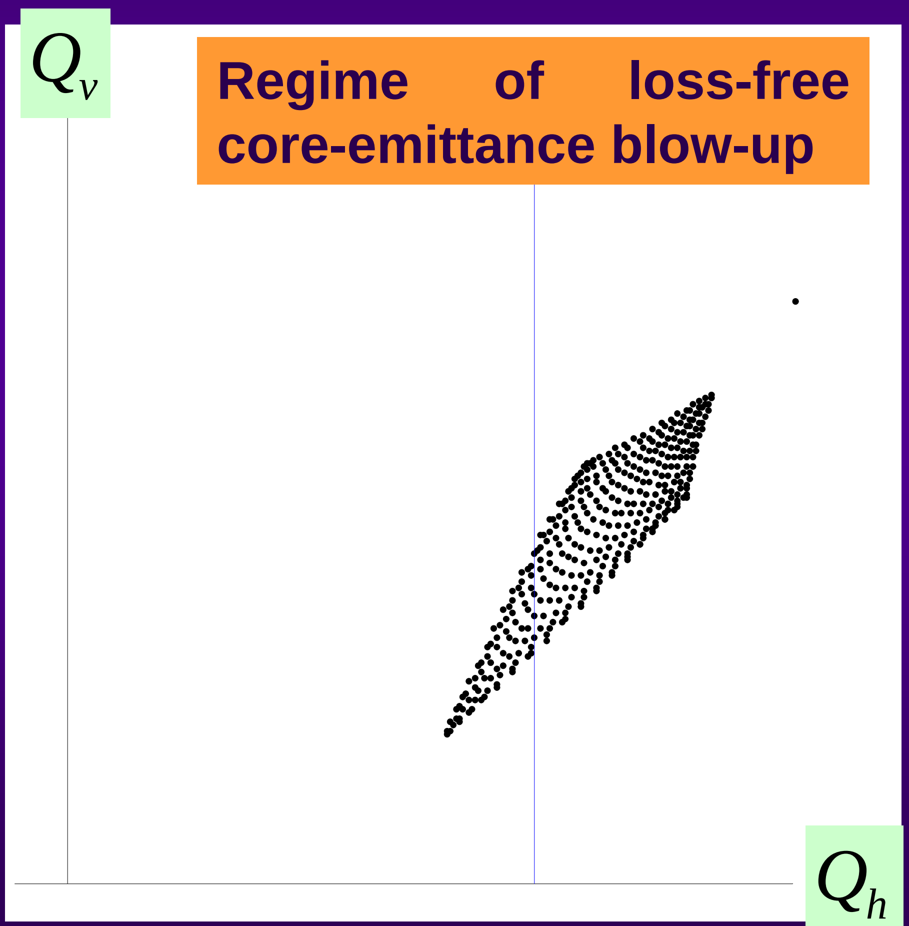
[mm]

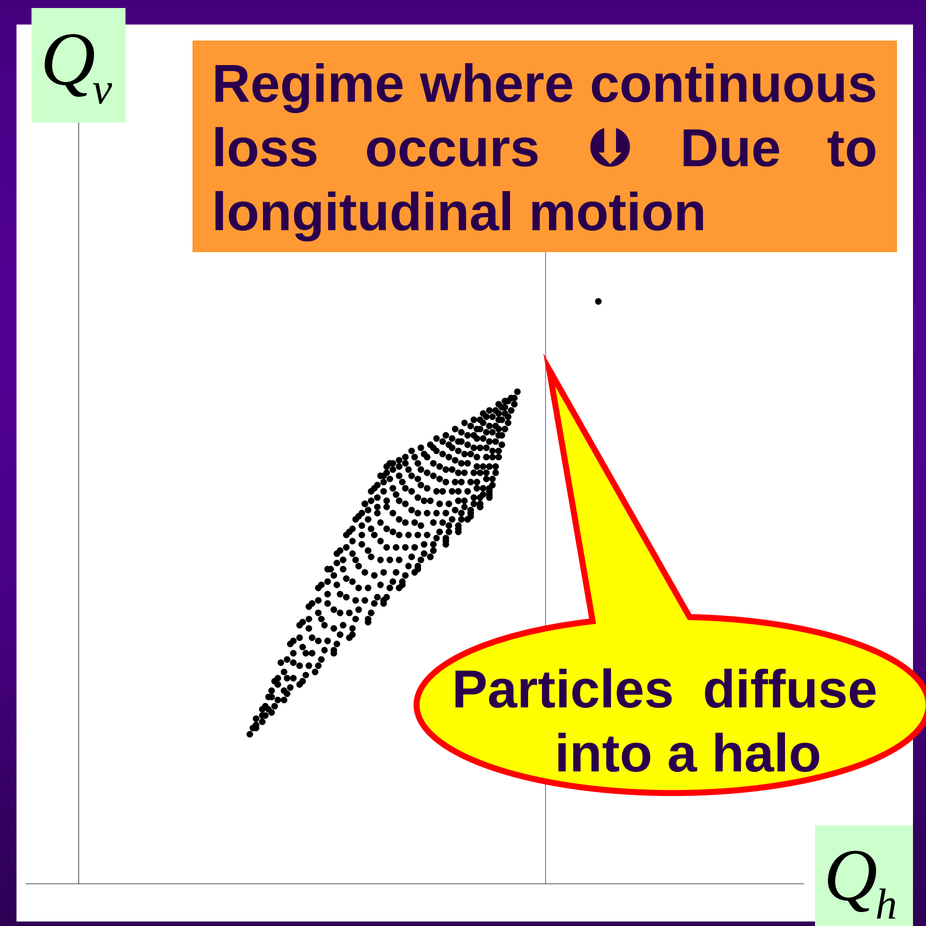
LOW-ENERGY FLAT-BOTTOM (20/24)

Flat bunches

- No measurable improvement, but…
  - The increase of the bunching factor was less significant than during the 2001 run (20-30% increase in 2001, ~10% in 2002)
  - The bunching factor was already very good with the longitudinal blow-up
- To be re-done

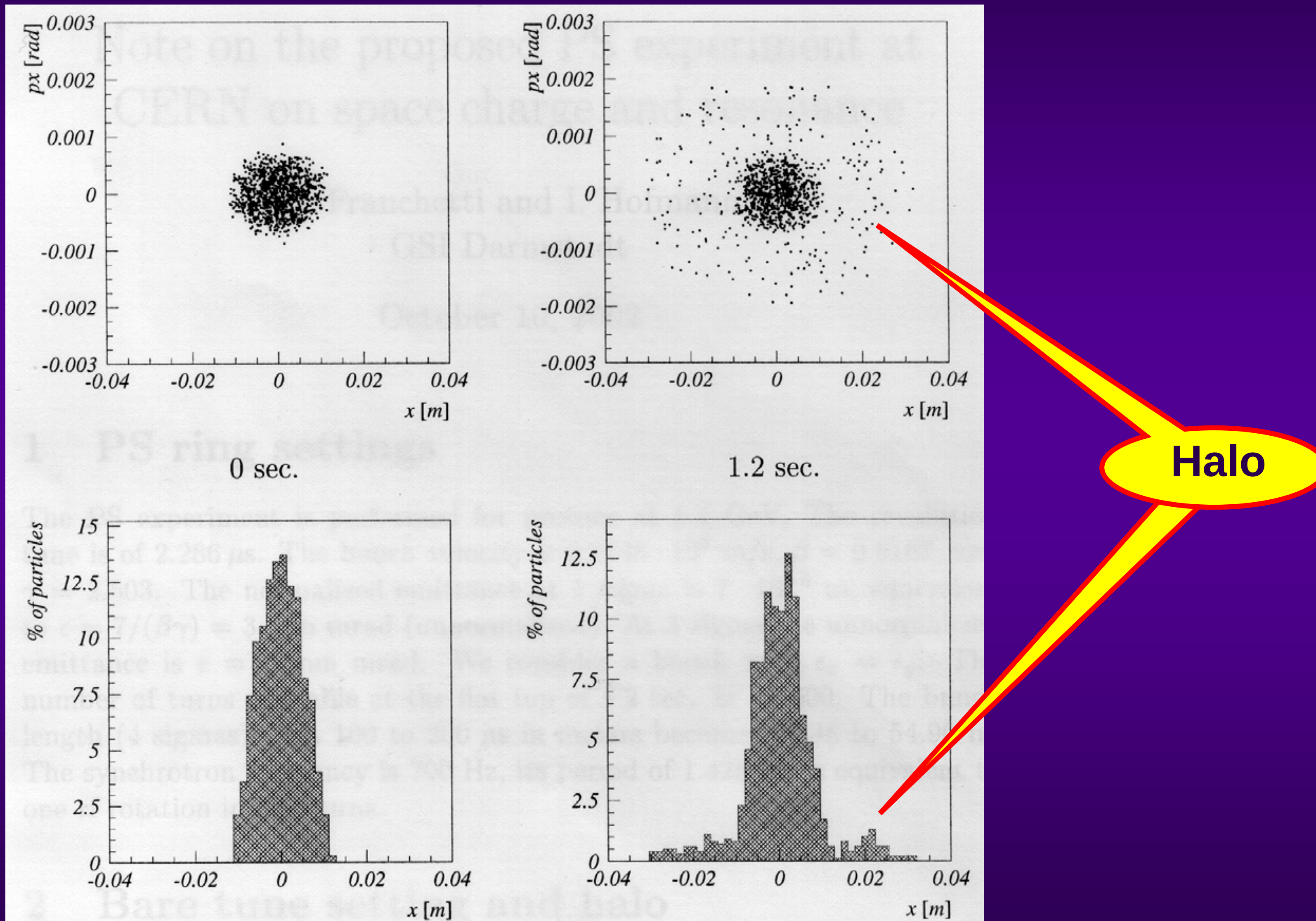
- **(4) Diffusive phenomena due to resonance crossing : benchmarking experiment ⇓ Study the effect of space-charge forces on a resonance driven by a single octupole (with I. Hofmann and G. Franchetti)**



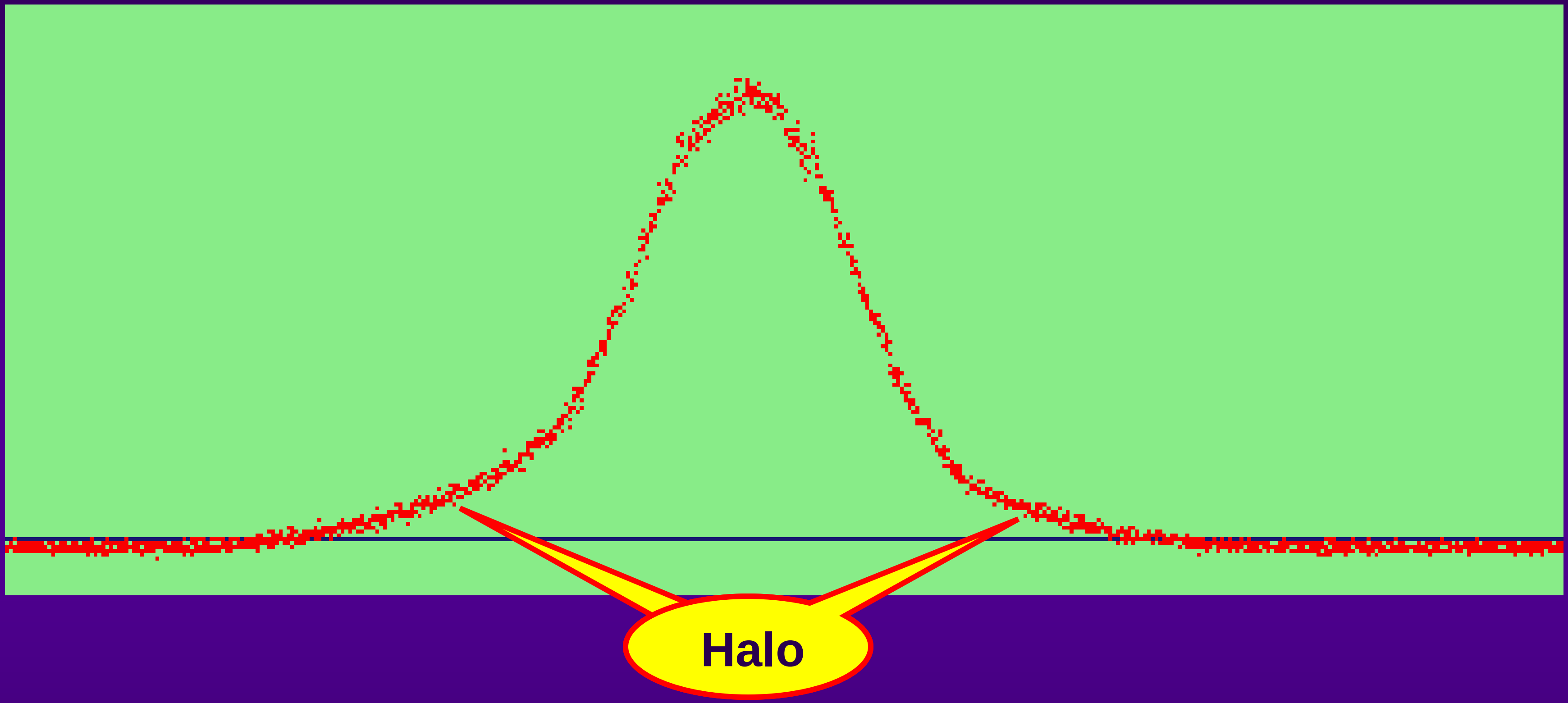


LOW-ENERGY FLAT-BOTTOM (22/24)

THEORETICAL PREDICTIONS



MEASUREMENTS



This may be the mechanism of the observed loss, where the reduced dynamic aperture close to the resonance extracts the halo particles ⇓ To be analysed in detail

LOW-ENERGY FLAT-BOTTOM (24/24)

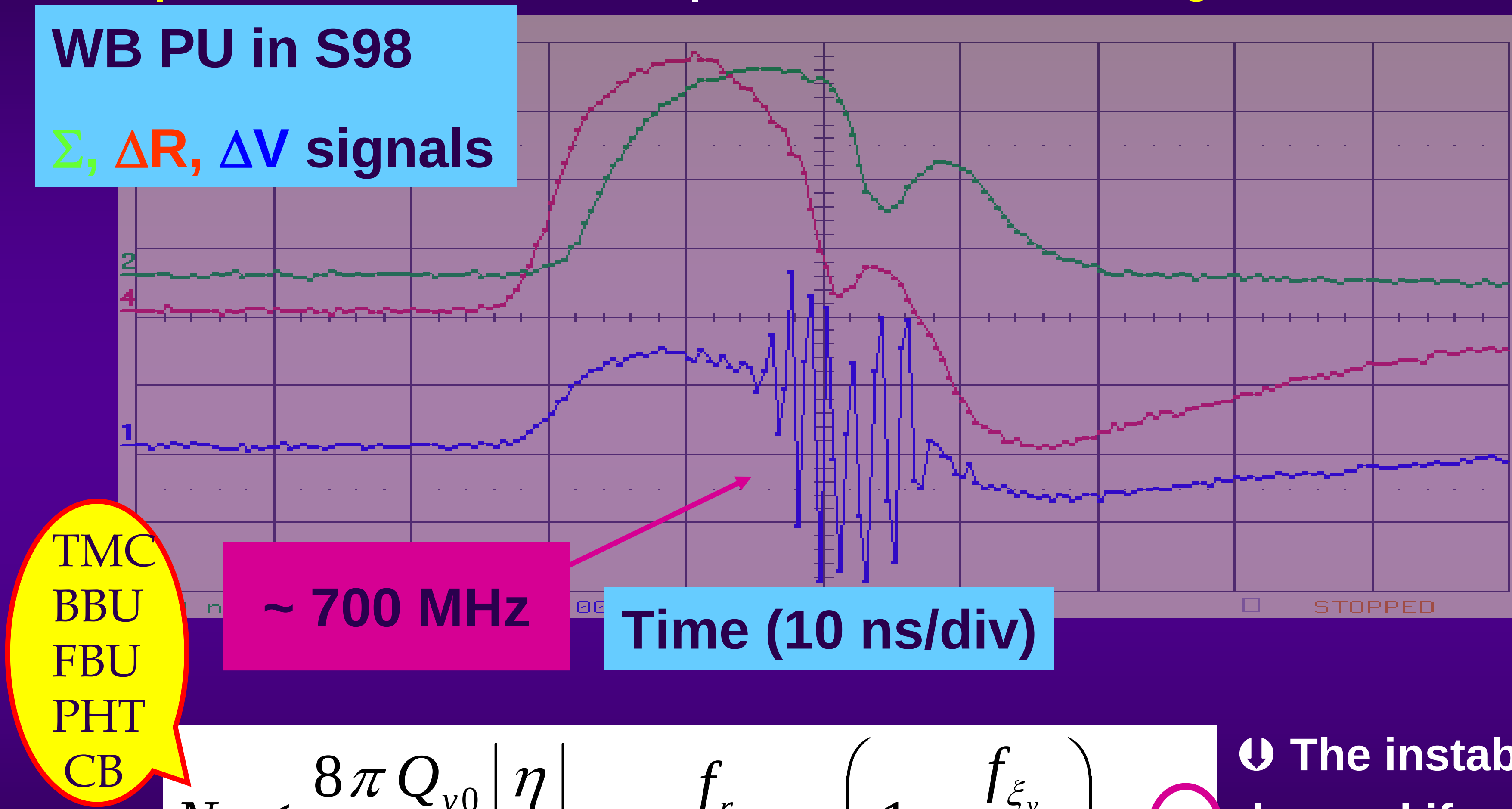
Conclusion :

Linear coupling and future Damper&Feedback

- **The Head-Tail instability is not a problem**
- **Emittance transfer by space-charge or betatron coupling**
- **Crossing of the integer or ½-integer resonances**
- **Diffusive phenomena due to resonance crossing**

⇓ **To be analysed in detail and continued**

- **(1) Vertical Mode-Coupling instability due to a Broad-Band impedance above ~4×10^{12} p/b if no controlled longitudinal blow-up**



$$N_b \leq \frac{8\pi Q_{y0}\left|\eta\right|}{e\beta^2 c} \times \frac{f_r}{\left|Z_y^{BB}\right|} \times \left(1 + \frac{f_{\xi_y}}{f_r}\right) \times \varepsilon_l$$

⇒ **The instability is damped if**

$$\varepsilon_l \geq \sim 2 \text{ eVs}$$

- **(2) Ghost bunches and blow-up losses**

  - **Longitudinal blow-up in both PSB and PS machines for 2 reasons**
    - **Incoherent space-charge tune shift at PS injection**
    - **Fast single-bunch vertical instability near transition**

Due to $Q_h \approx 6.1$ at injection (See Section 1)

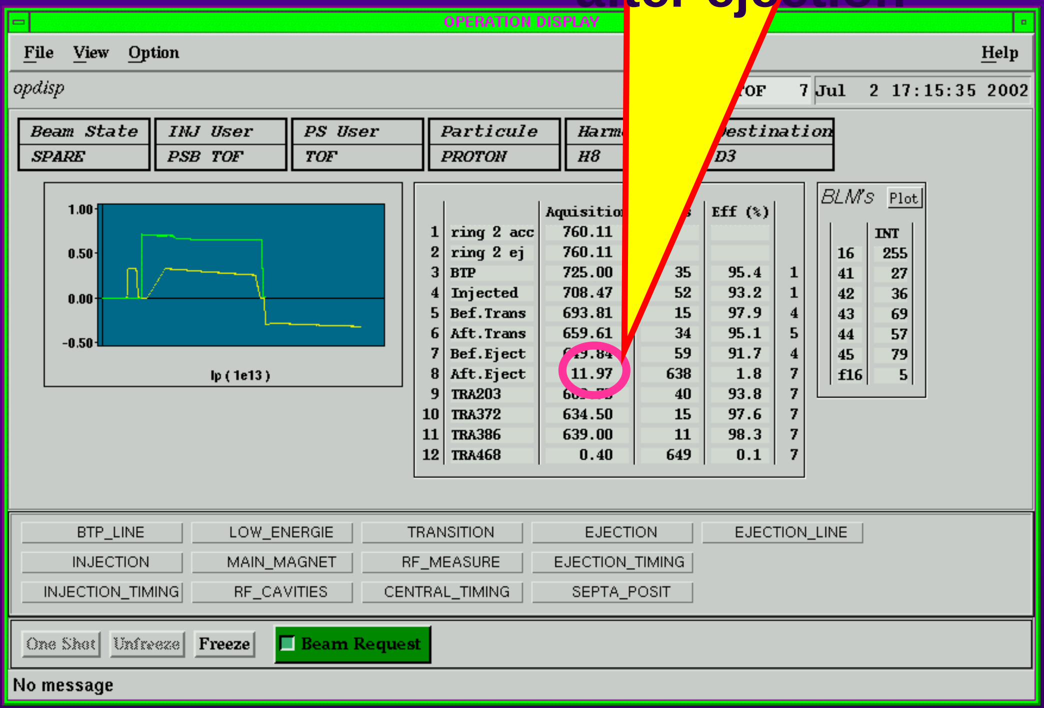
  - **Empty buckets can become populated by ghost bunches**
    - **Easiest solution : Adjust the ejection kicker length**
    - **Cleanest solution : Do not create these ghosts**

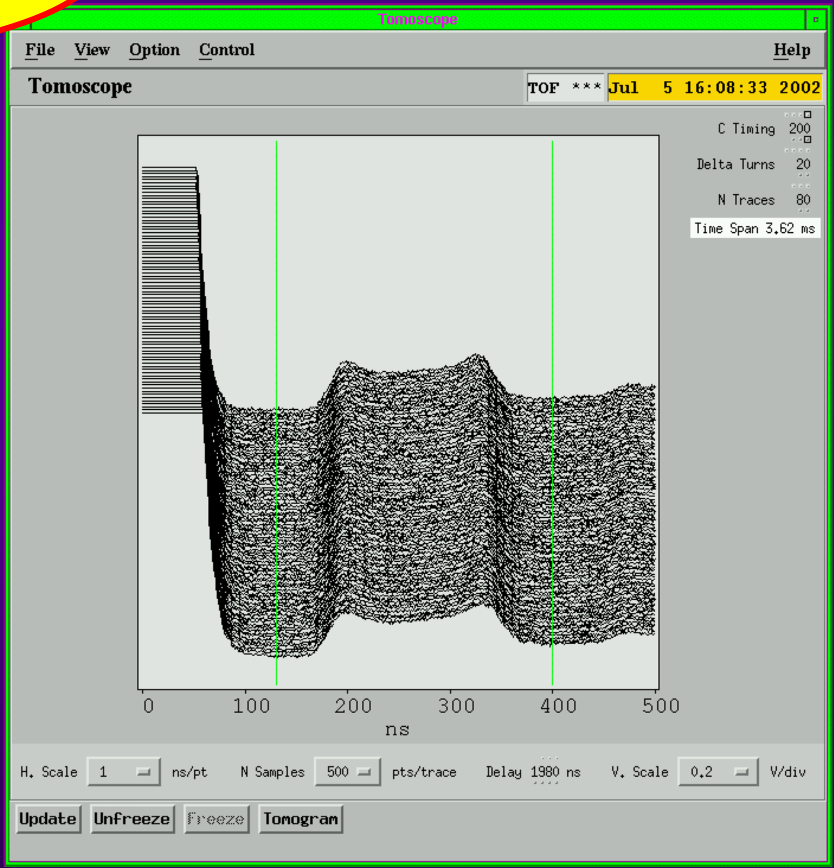
Ghost particles can easily amount to ~5×10^{11} protons per cycle, with much of this lost near transition

TRANSITION CROSSING (3/6)

Initial situation : The operational n-ToF beam on June 27, 2002

$\sim 12 \times 10^{10}$ protons lost in the PS after ejection

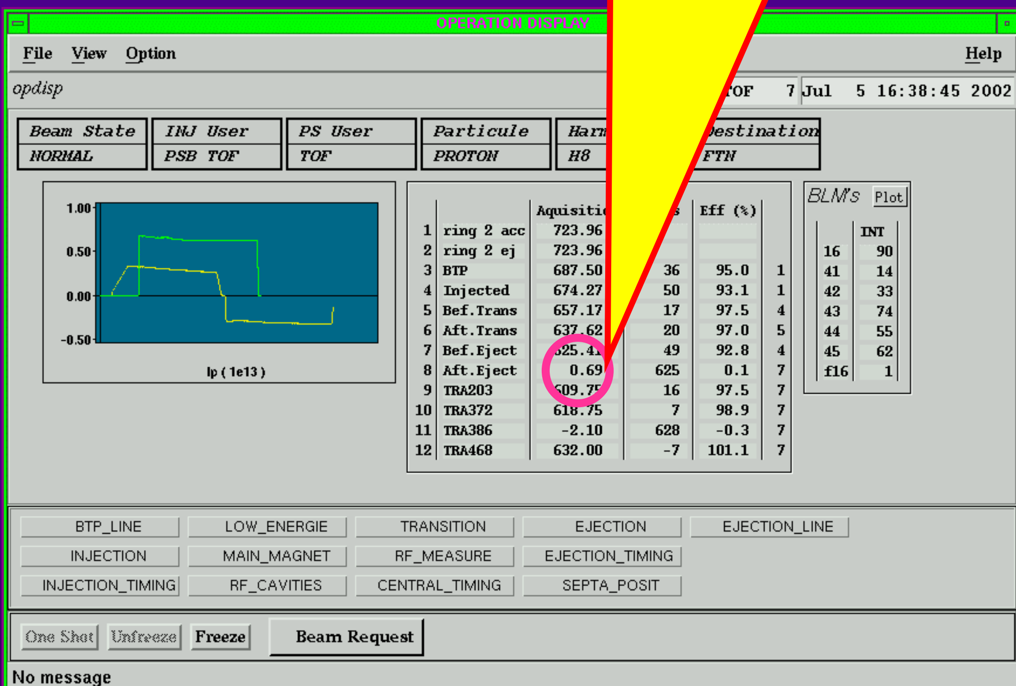


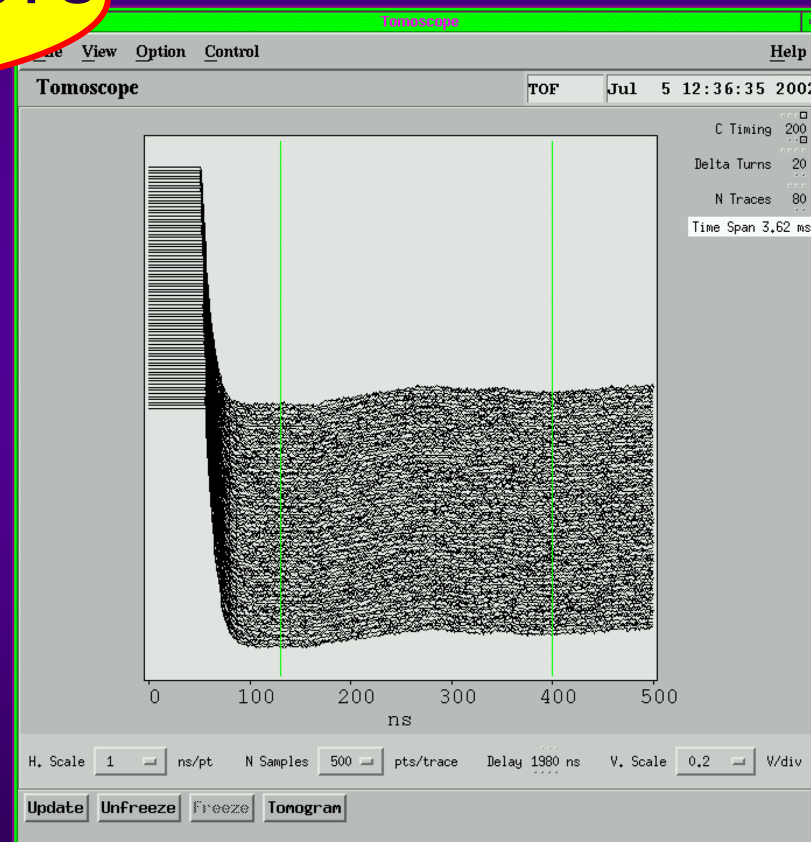


TRANSITION CROSSING (4/6)

Final situation

$\sim 0.7 \times 10^{10}$ protons lost in the PS after ejection





TRANSITION CROSSING (5/6)

~2.1 eVs

- **Beam stability near transition obtained above a certain value of ε_l independently of the shape of the density profile of the bunch**

- **Result in agreement with predictions**

$$N_b \leq \frac{8\pi Q_{y0} \left| \eta \right|}{e \beta^2 c} \times \frac{f_r}{\left| Z_y^{BB} \right|} \times \left(1 + \frac{f_{\xi_y}}{f_r} \right) \times \varepsilon_l$$

- **Very reproducible and sensitive**

- **The required emittance can be obtained by several sets of blow-up parameters ⇓ May produce ghost bunches**

- **An optimal set has been found which practically eliminates the ghosts**

TRANSITION CROSSING (6/6)

Conclusion :

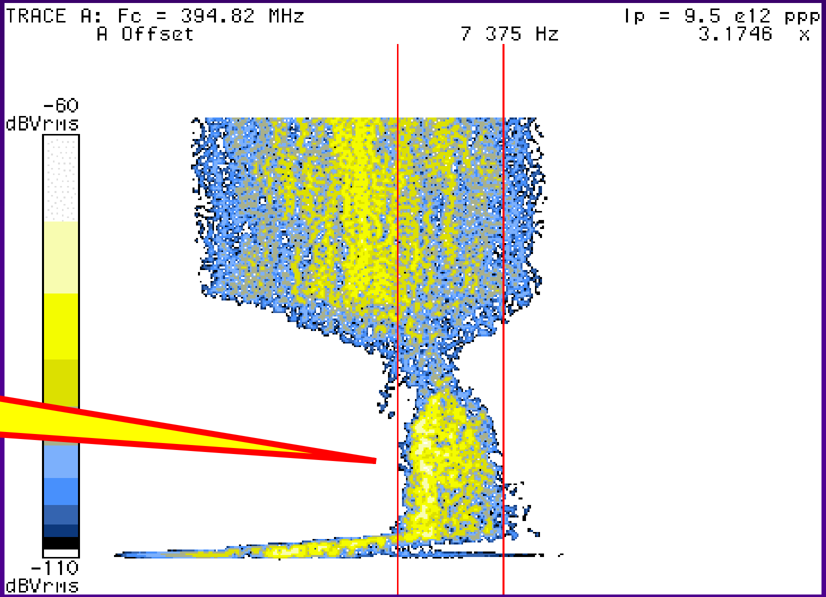
- **Fine-tuning of several equipments required, which suppresses almost all the beam losses**
- **2 types of losses may be observed near transition**
  - **Fast beam losses (due to a vertical coherent instability)**
    - **Avoided by adjusting ε_l (without creating ghosts…)**
  - **Slow beam losses (due to the working point)**
    - **Suppressed thanks to a new program, which allows precise tunings of the working point and chromaticities**

S. Baird and B. Vandorpe

- **New PS record : $\sim 8.2 \times 10^{12}$ p/b through transition with ~ no loss**
- **Main problem in the future : Reproducibility of the fine-tuning**
- **Finally, transition crossing with the nominal CNGS high-intensity multi-bunch beam remains to be carefully studied**

- (1) Longitudinal microwave instabilities have been observed during the de-bunching procedure of the 1st version LHC beam

⇓ Long. Schottky scan spectogram :



Momentum blow-up during debunching

Time
(200 ms total)

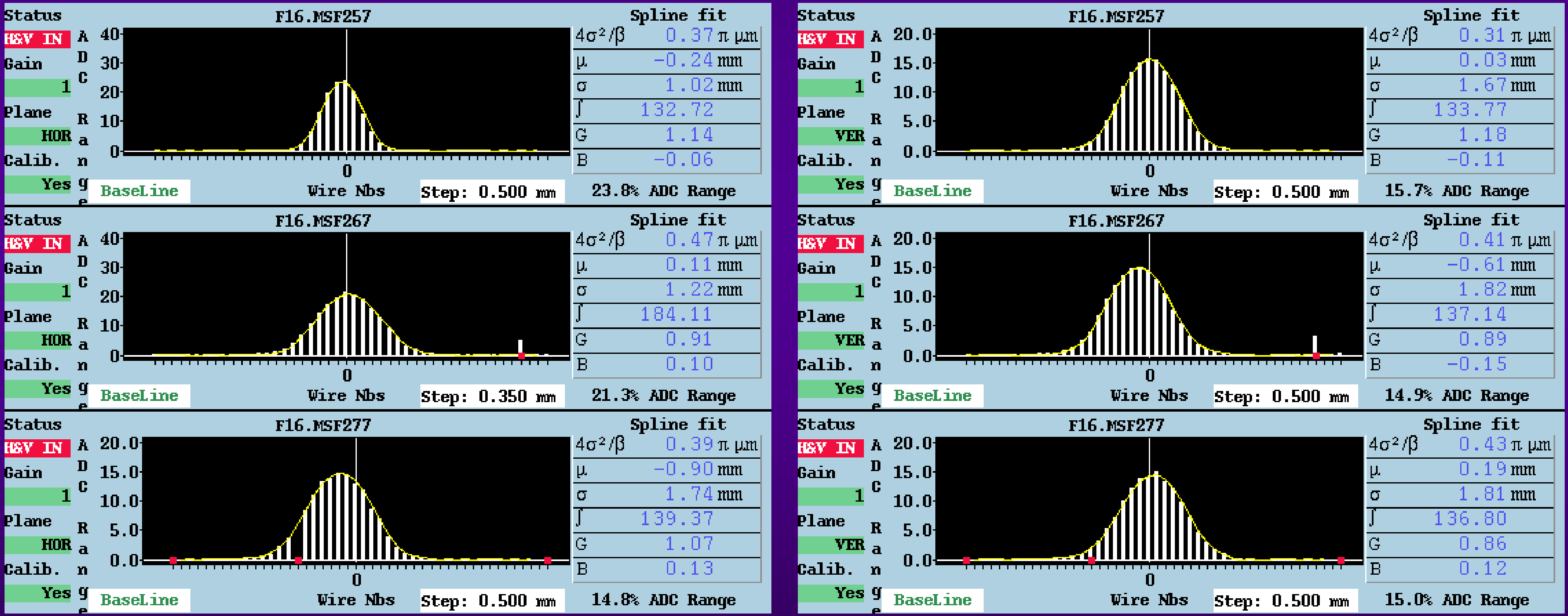
- No instability anymore for LHC with the new scheme (splittings)
- Microwave instabilities may be observed during the de-bunching procedure (if any?) for CNGS

- (2) Transverse e⁻ cloud cloud phenomena have been observed both in the PS machine and in the TT2 transfer line towards the SPS with the nominal LHC beam

HIGH-ENERGY FLAT-TOP(2/15)

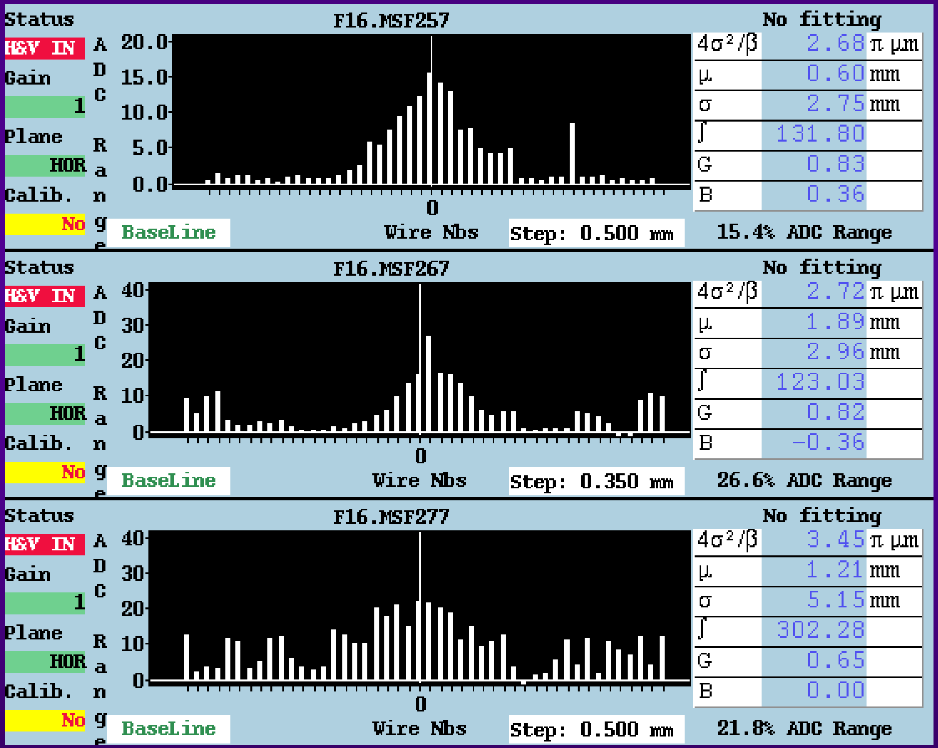
- **Emittance measurement problems with SEMwires**

Emittance measurements using the SEMwires in TT2
WITHOUT bunch rotation



H - plane **V - plane**

Emittance measurements using the SEMwires in TT2
WITH bunch rotation



H - plane

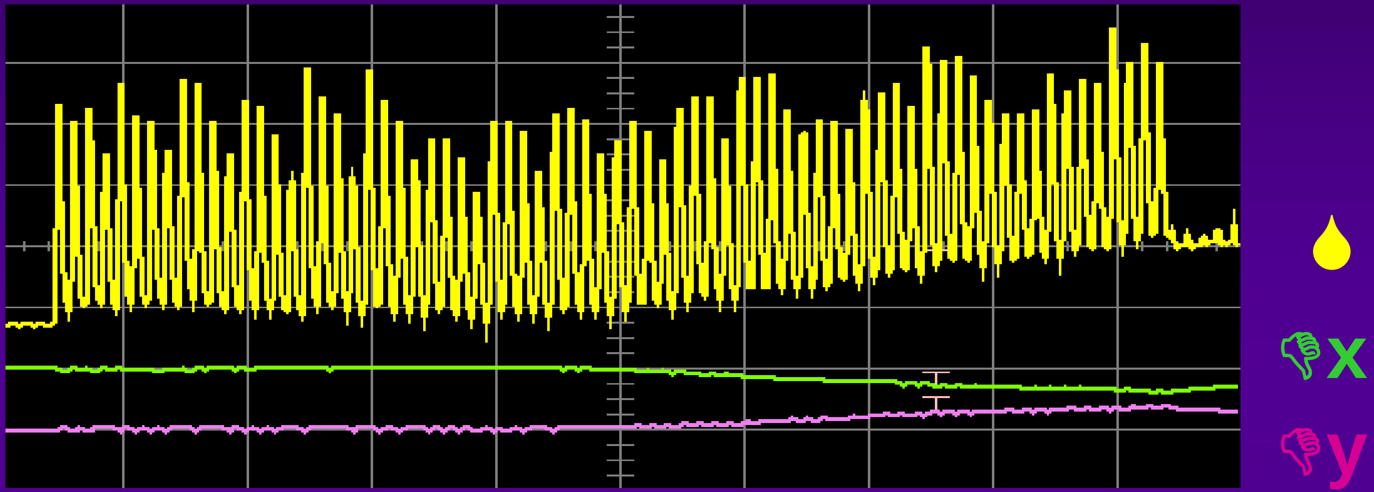
- Electrons are created ...

- **Baseline drifts in electrostatic pick-ups**

Nominal beam seen on a pick-up in TT2

Time scale : 200 ns/div

PU located in a field-free region. Bandwidth : 0.006-400 MHz



$$V \approx 300 \text{ mV}$$

$$C = 500 \text{ pF}$$

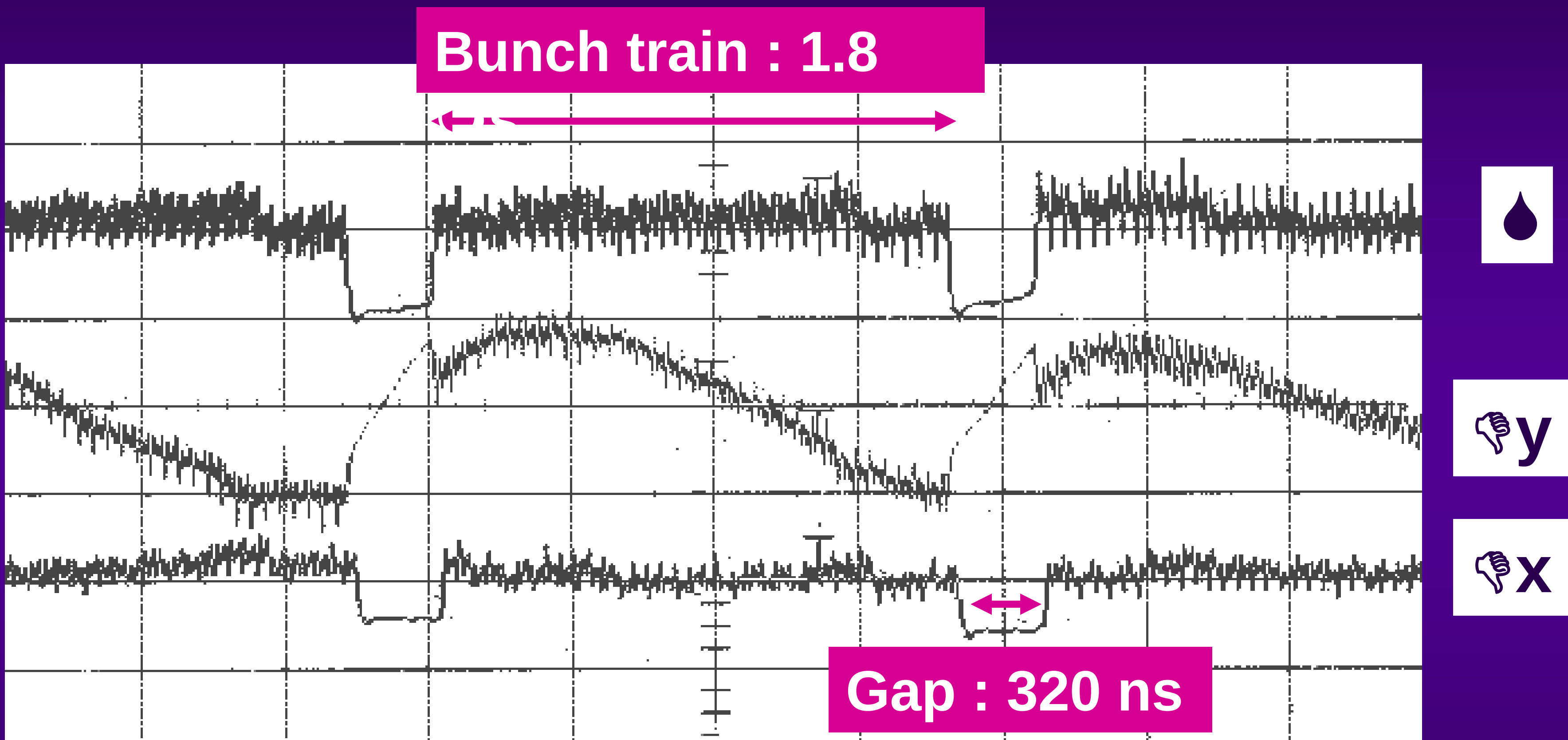
$$\Rightarrow \quad n_e = \frac{C\,V}{e} \approx 10^9$$

$$\text{vol}_{\text{PU}} = 0.12^3 \approx 0.0017 \text{ m}^3$$

$$\Rightarrow \quad \rho_e = \frac{n_e}{\text{vol}_{\text{PU}}} \approx 6 \times 10^{11} \text{ m}^{-3}$$

HIGH-ENERGY FLAT-TOP(5/15)

Nominal beam seen on a pick-up in PS



Time scale : 500 ns/div

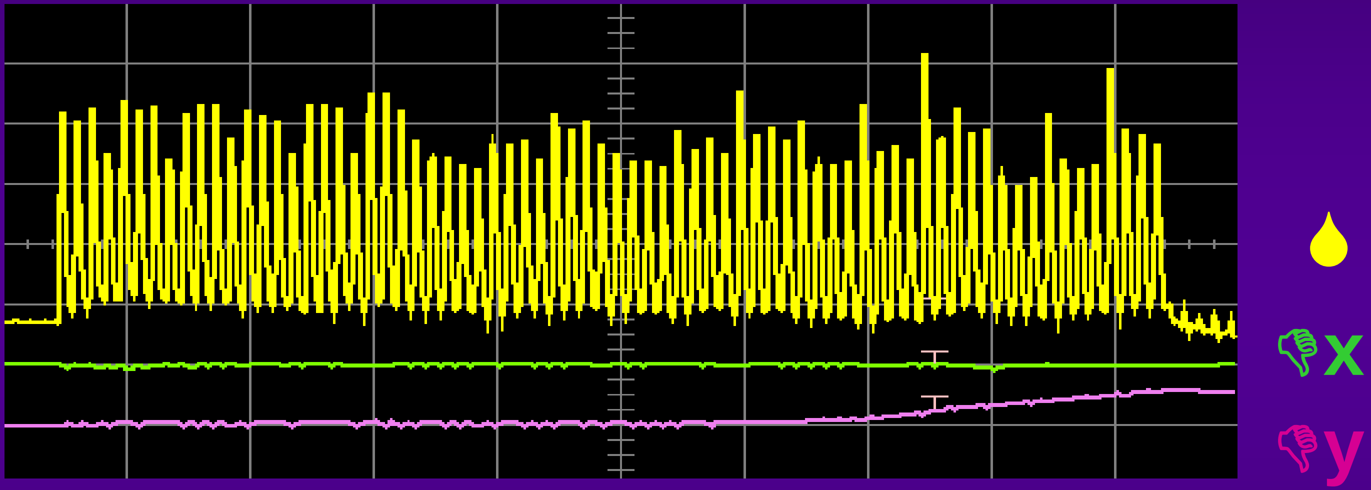
PU located in a vertical dipole field region (combined-function magnets are used in the PS). Bandwidth : 0.2-30 MHz

HIGH-ENERGY FLAT-TOP(6/15)

- **Effect of a solenoidal field**

Nominal beam seen on a pick-up in TT2

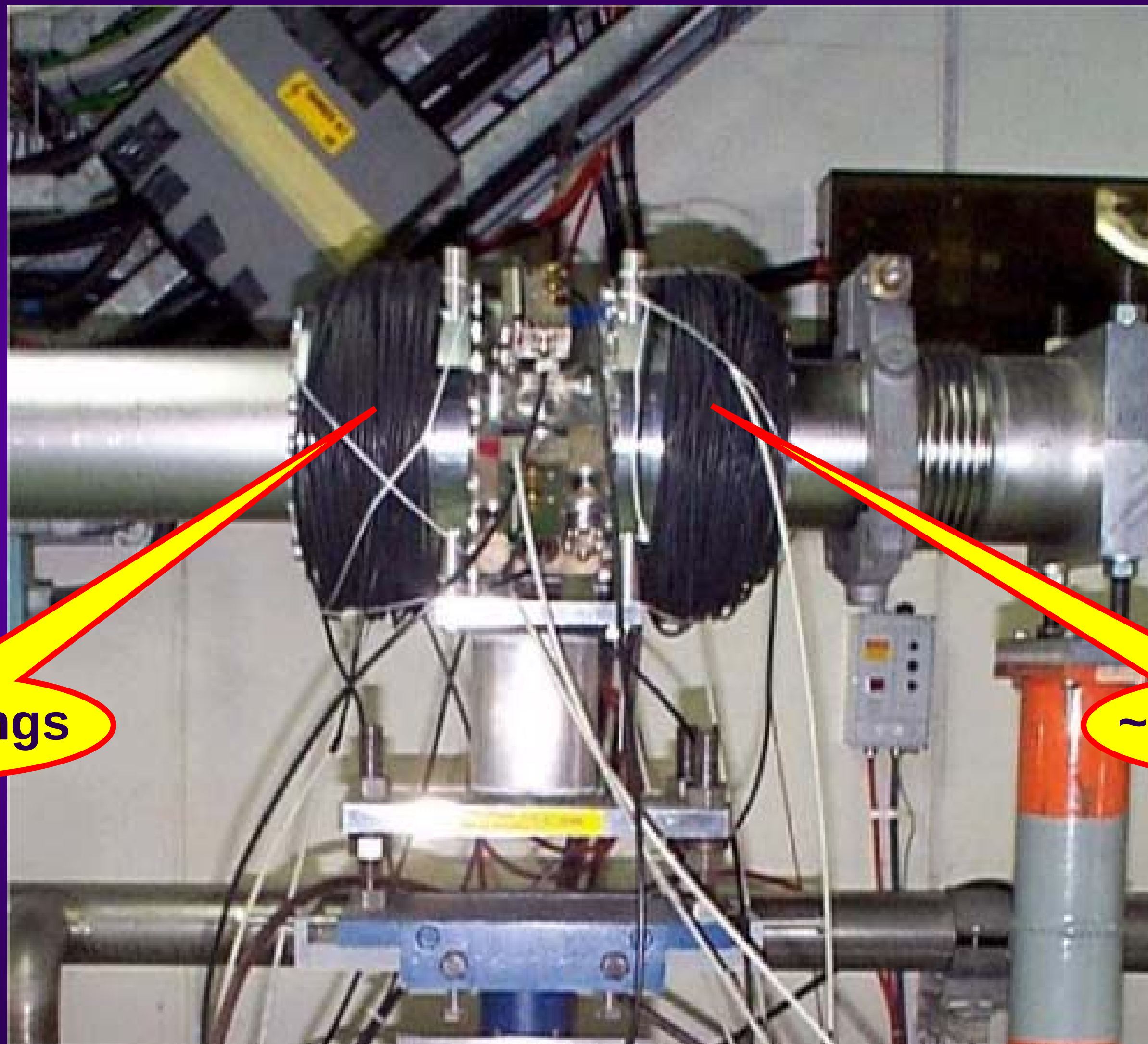
Time scale : 200 ns/div



With solenoid : ~ 50-100 G
(~70 windings before and after the 25 cm long PU device)

HIGH-ENERGY FLAT-TOP(7/15)

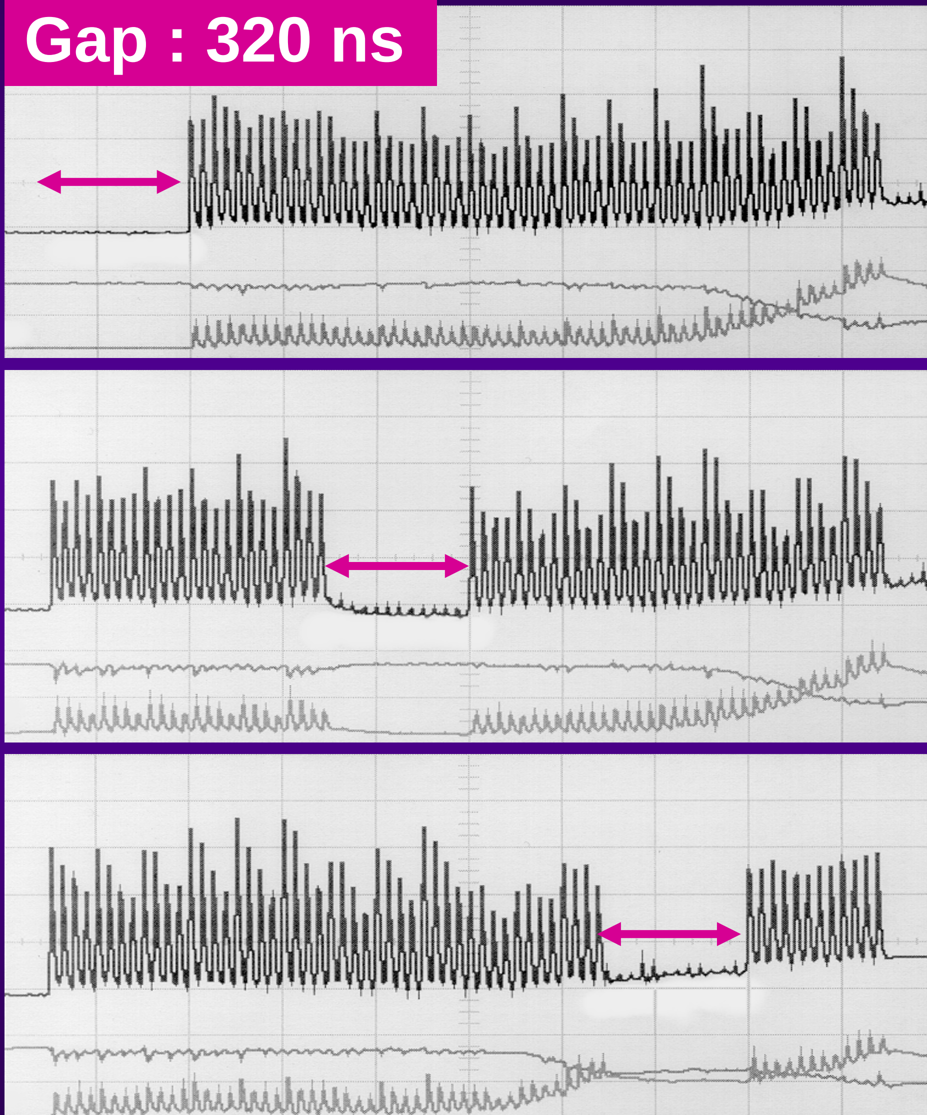
Solenoid around the pick-up in TT2



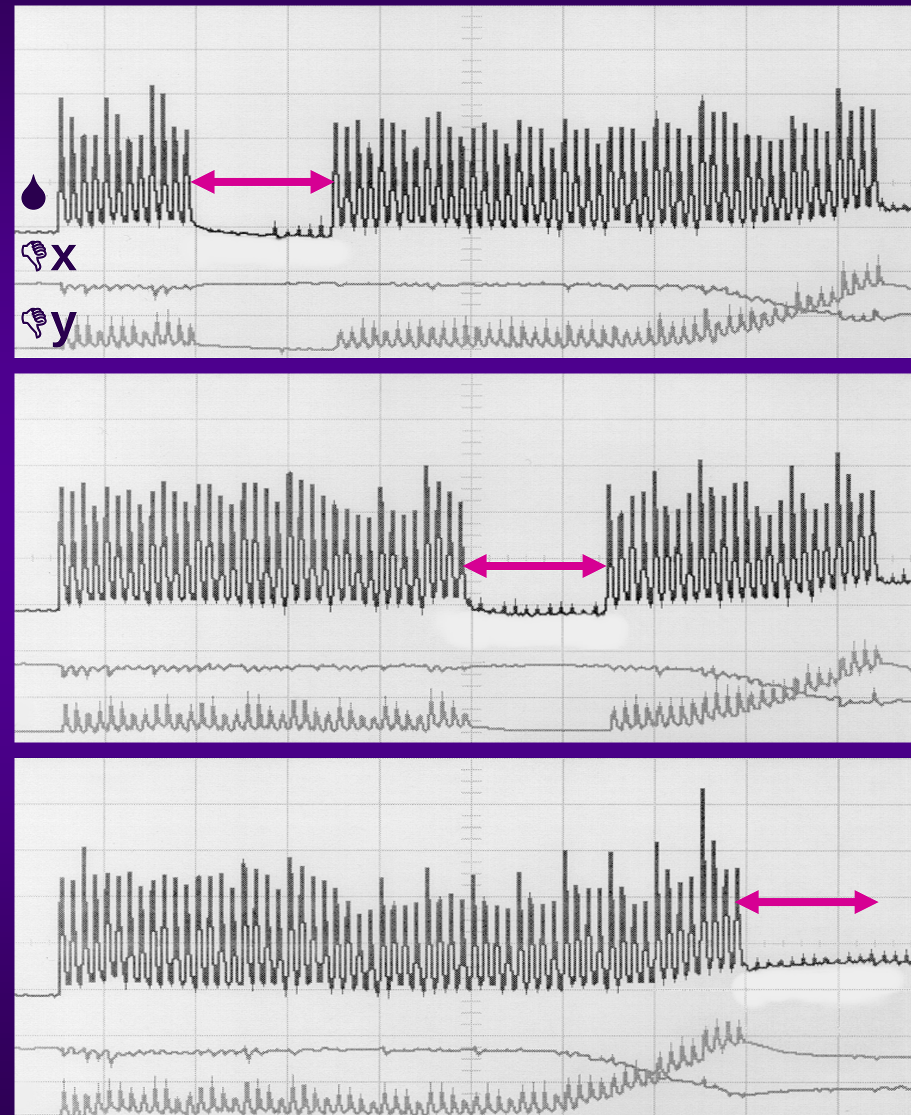
HIGH-ENERGY FLAT-TOP(8/15)

- **Effect of gaps in the bunch train**

Gap : 320 ns



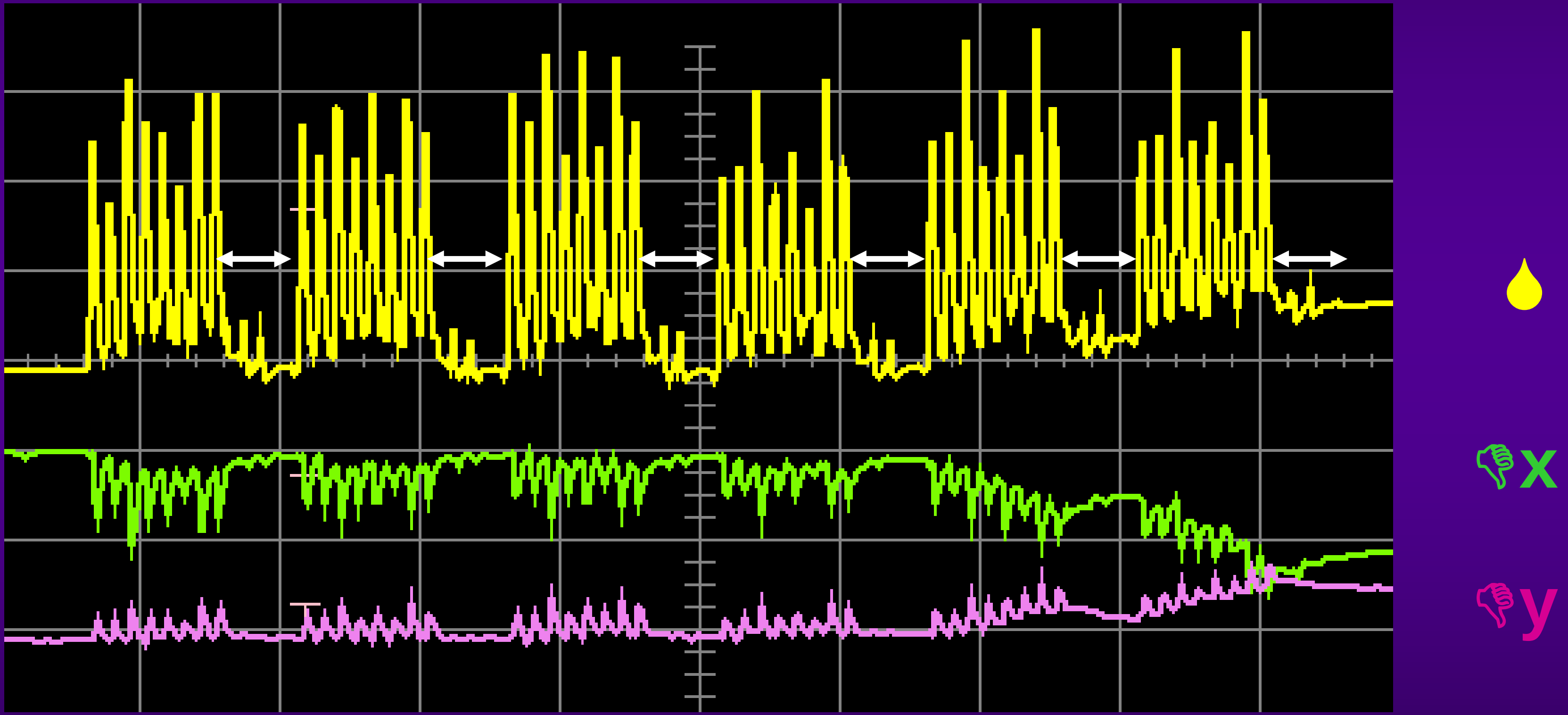
Nominal beam on a pick-up in TT2



HIGH-ENERGY FLAT-TOP(9/15)

Nominal beam on a pick-up in TT2

6 Gaps : 120 ns each



Time scale : 200 ns/div

HIGH-ENERGY FLAT-TOP(10/15)

Conclusion : Electron cloud effects on the nominal PS beam for LHC

- **Generate only beam diagnostics problems**
- **No time to develop an instability**

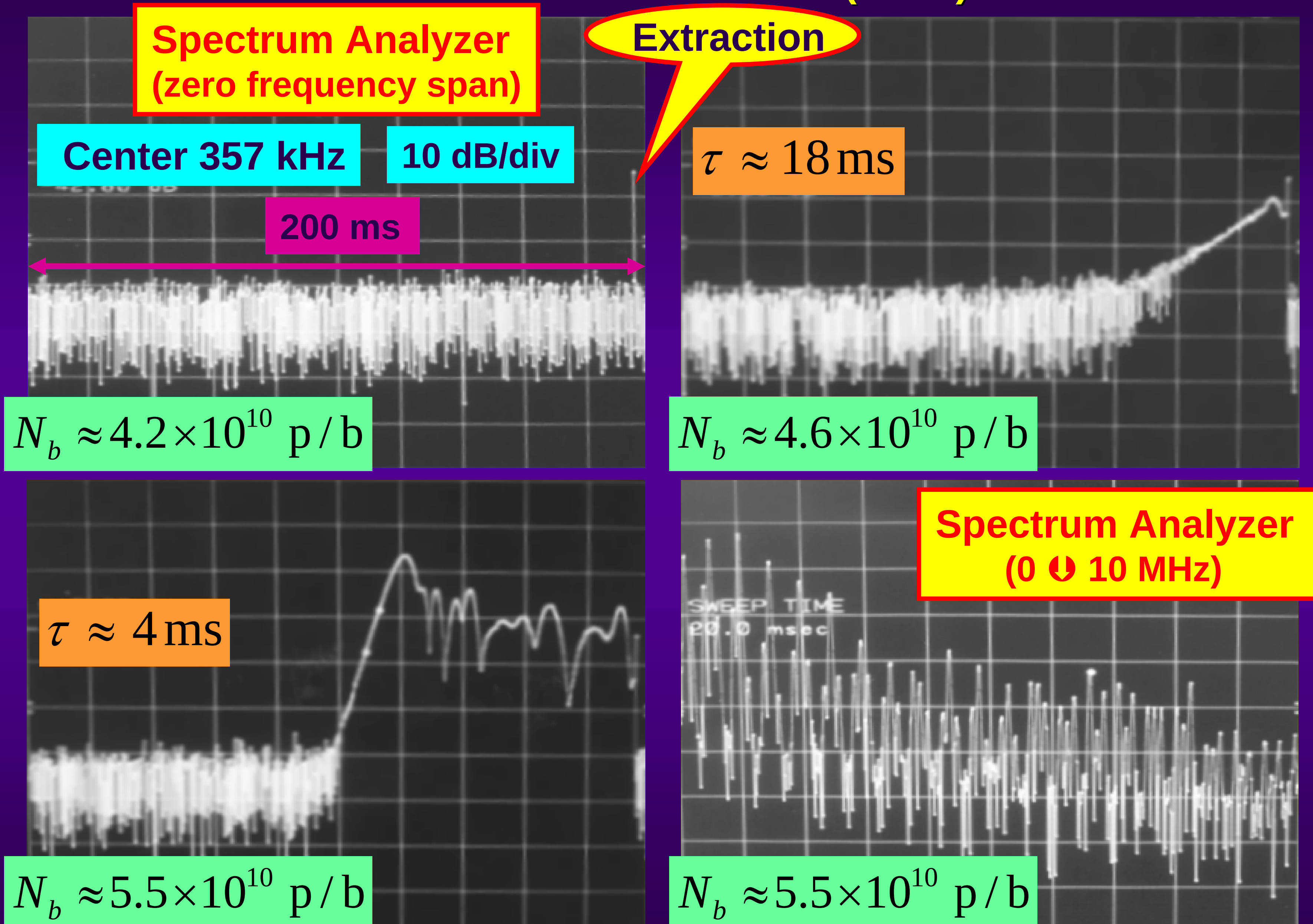
Benchmarking experiment

- **Electron cloud effects on a modified PS beam for LHC**
  - **Beam used : nominal one, but kept with a bunch length of ~10 ns during ~100 ms before extraction**
  - **The electron cloud build-up is observed**
  - **The beam is unstable**

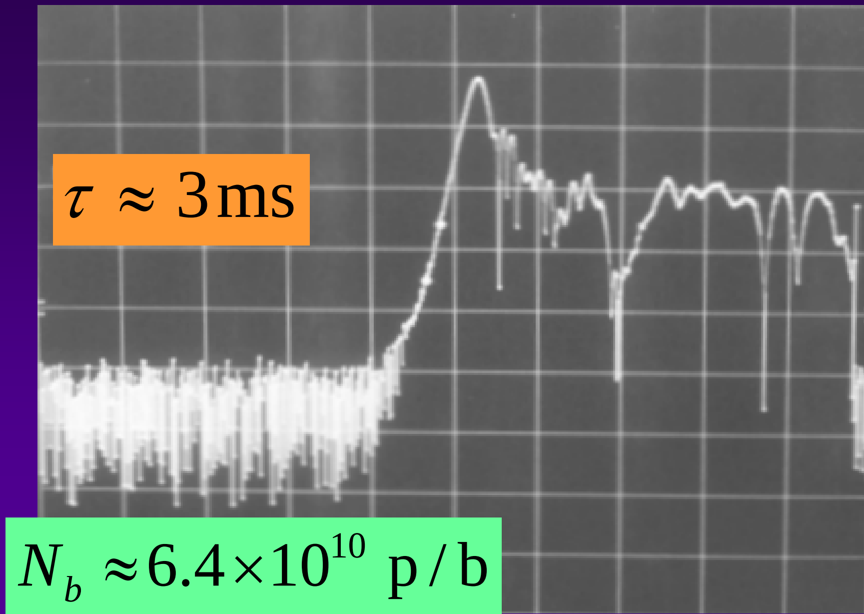
$T_s = 1.4 \text{ ms}$

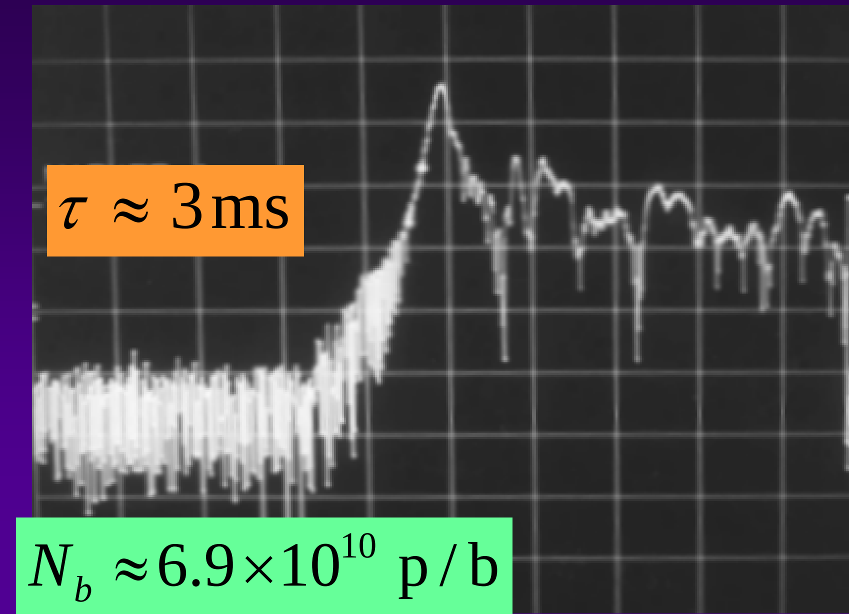
- **Single-bunch radial instability**
- **Rise-times of few ms (several synchrotron periods)**
- **No beam loss**
- **Beam size blow-up : ⇒ ~10-20 in H and ~2 in V**

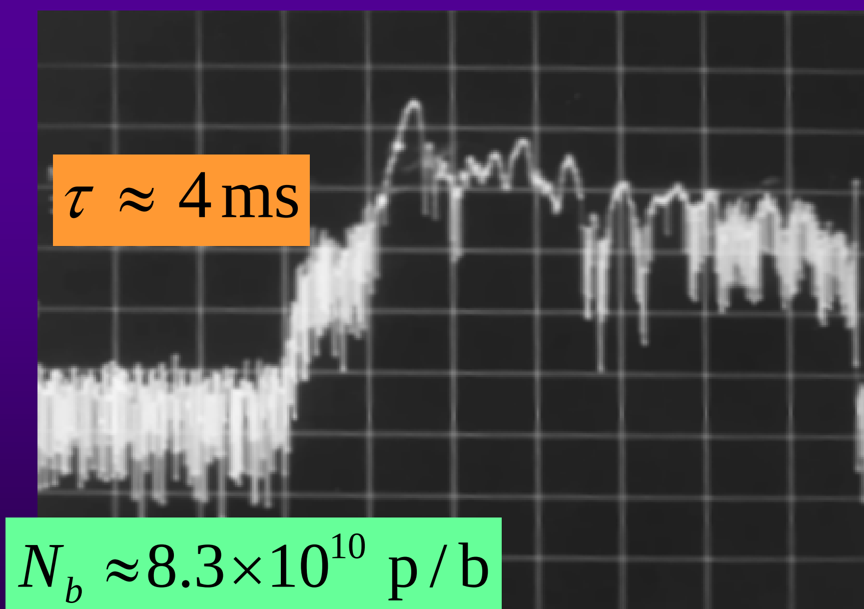
HIGH-ENERGY FLAT-TOP(11/15)



HIGH-ENERGY FLAT-TOP(12/15)





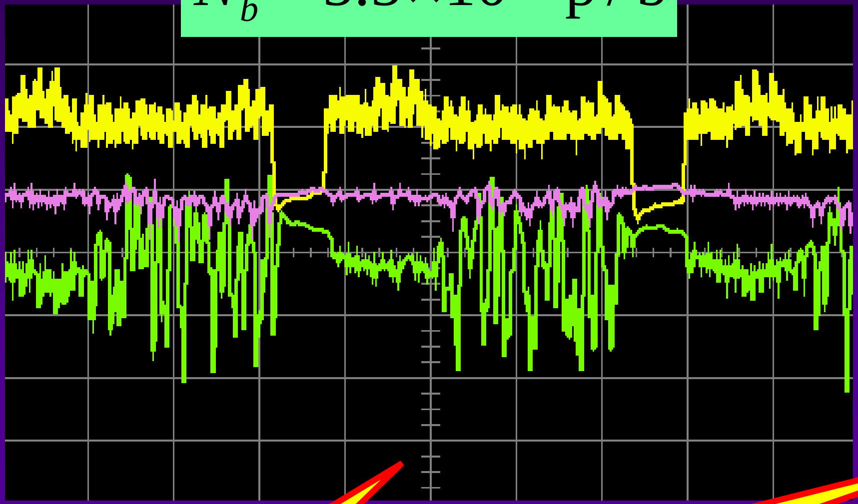


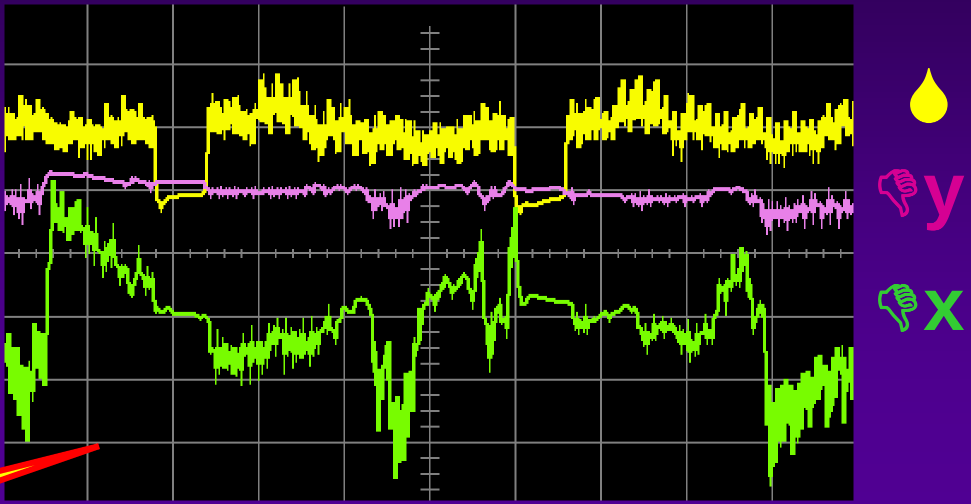
HIGH-ENERGY FLAT-TOP(13/15)

$N_b \approx 5.5 \times 10^{10}$ p / b

In PS

Time scale : 500 ns/div

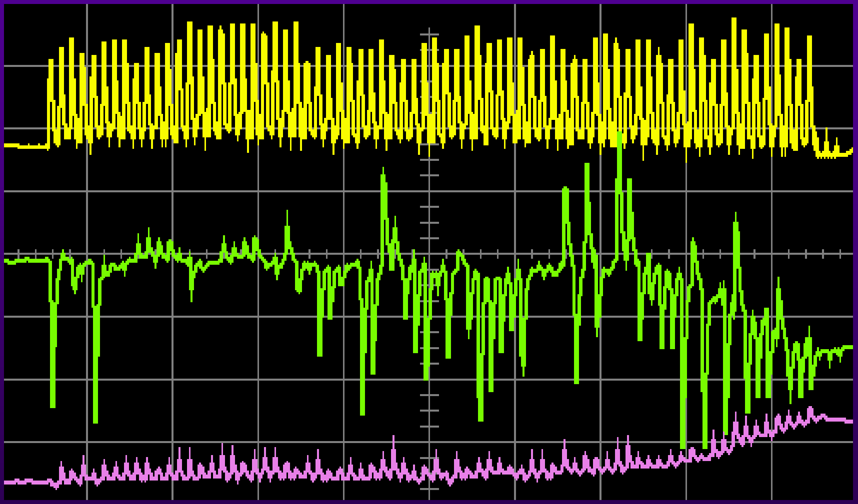




In TT2

Time scale : 200 ns/div

2 pictures in the same conditions



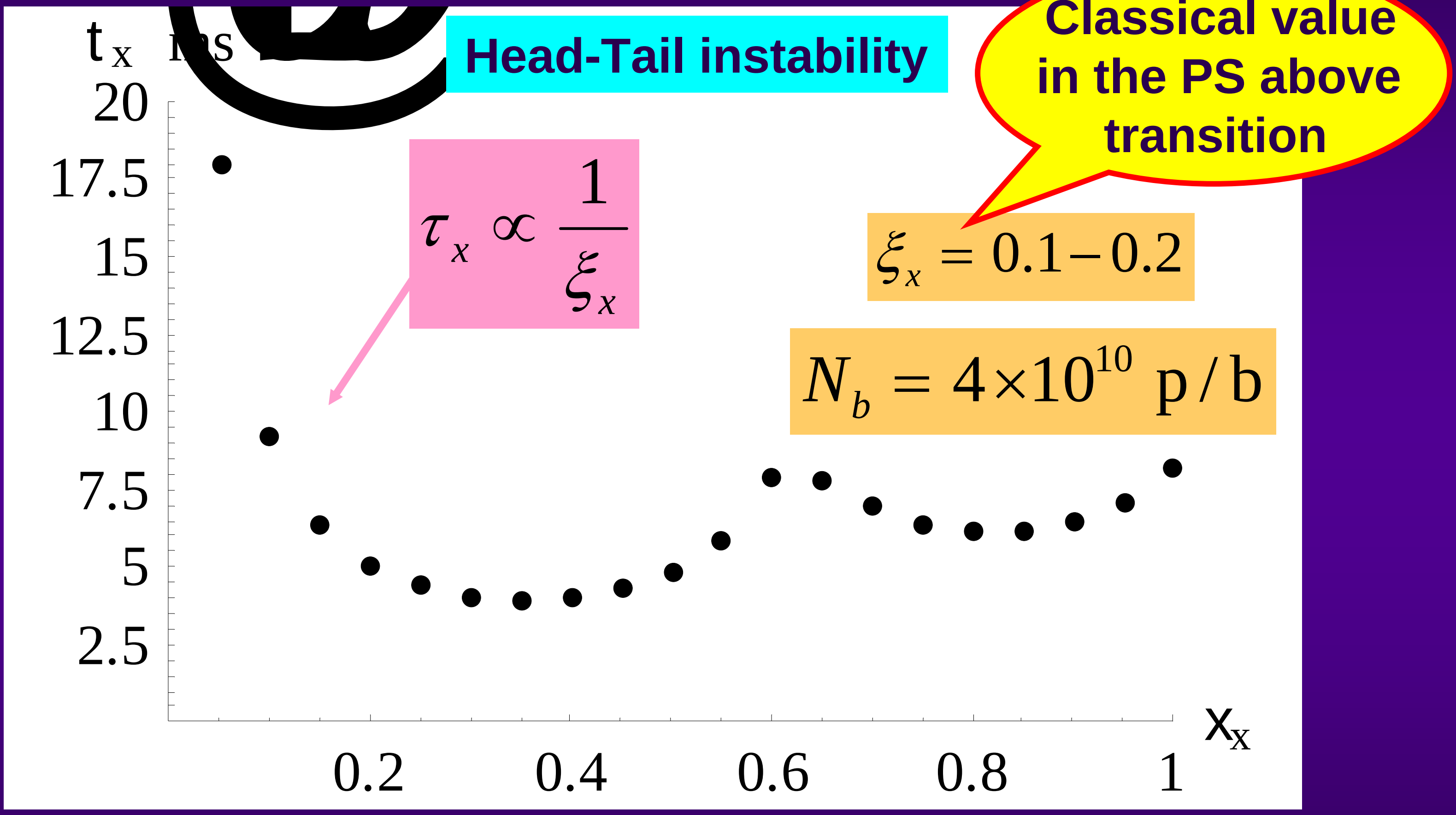
HIGH-ENERGY FLAT-TOP(14/15)

- **Chromaticity ⇒ No effect**
- **Octupoles ⇒ Some improvements with very high current values (>200 A)**
- **Horizontal instability observed in the PS, whereas it is a vertical one in the SPS**
  - **In the PS : 70% of combined function magnets and 30% of field-free region**
  - **In the SPS : 2/3 of dipole-field region and 1/3 of field-free region**
- **The simulations (with ECLOUD and HEADTAIL codes) indicate that a significant horizontal wake-field may exist in a combined function magnet, in contrast to the case of a pure dipole field, where the horizontal wake is close to zero. However, simulations predict a vertical instability with a stabilizing effect of chromaticity. To be continued…**

Study with G. Rumolo and F. Zimmermann

HIGH-ENERGY FLAT-TOP(15/15)

Using the horizontal wake-field computed by simulation in the PS combined function magnet



- **It could explain the instability in the horizontal plane, the head-tail regime, and the non-stabilizing effect of the chromaticity. To be continued…**

CONCLUSION : Main problems remaining

- **Low-energy flat-bottom**
  - **Several studies to be analysed in detail and continued to find the best working point**
- **Transition crossing**
  - **Reproducibility of the fine-tuning of several equipments**
- **High-energy flat-top**
  - **New CT**

See AB seminar "Multiturn extraction using adiabatic capture" by M. Giovannozzi on 13/03/2003

  - **Longitudinal microwave instabilities may be observed during the de-bunching procedure (if any?) for CNGS**
- **Multi-bunch effects**
  - **Both in the transverse and longitudinal planes**