Contributed talk (15 + 5 min, 30 slides)

ACHIEVABLE SPACE-CHARGE TUNE SHIFT WITH LONG LIFETIME IN THE CERN PS & SPS

Elias Métral

INTRODUCTION

- **2 ≠ SC ISSUES IN THE PS ($Q_{x,y} \approx 6.2\ldots$, $\xi_{x,y} \approx -1$)**
  - **LHC beam**
    - ~ Round
    - Small vs. mechanical aperture
    - ~ ½ million turns at low energy
    - Linear coupling to damp a horizontal head-tail instability
  - **CNGS beam**
    - ~ Flat (ratio of ~2)
    - Fills the mechanical aperture
    - Horizontal emittance should be kept small (≈ 4 times the vertical emittance in SPS: 5-turn CT extraction + emittance exchange in TT10)

Largest $\Delta Q_{sc,y} \approx -0.25$

Trajectory + Montague resonance

Vertical aperture in the SPS

- **SC ISSUES IN THE SPS ($Q_{x,y} \approx 26.\ldots$, $|\xi_{x,y}| \approx 0.1\text{-}0.5$)**
  - Generally not a problem (alone) for proton beams ⟹ Interplay with other mechanisms (ecloud etc.)?
  - Could be a problem for ions (foreseen $\Delta Q_{sc,y} \approx -0.1$ for ~ 40 s)

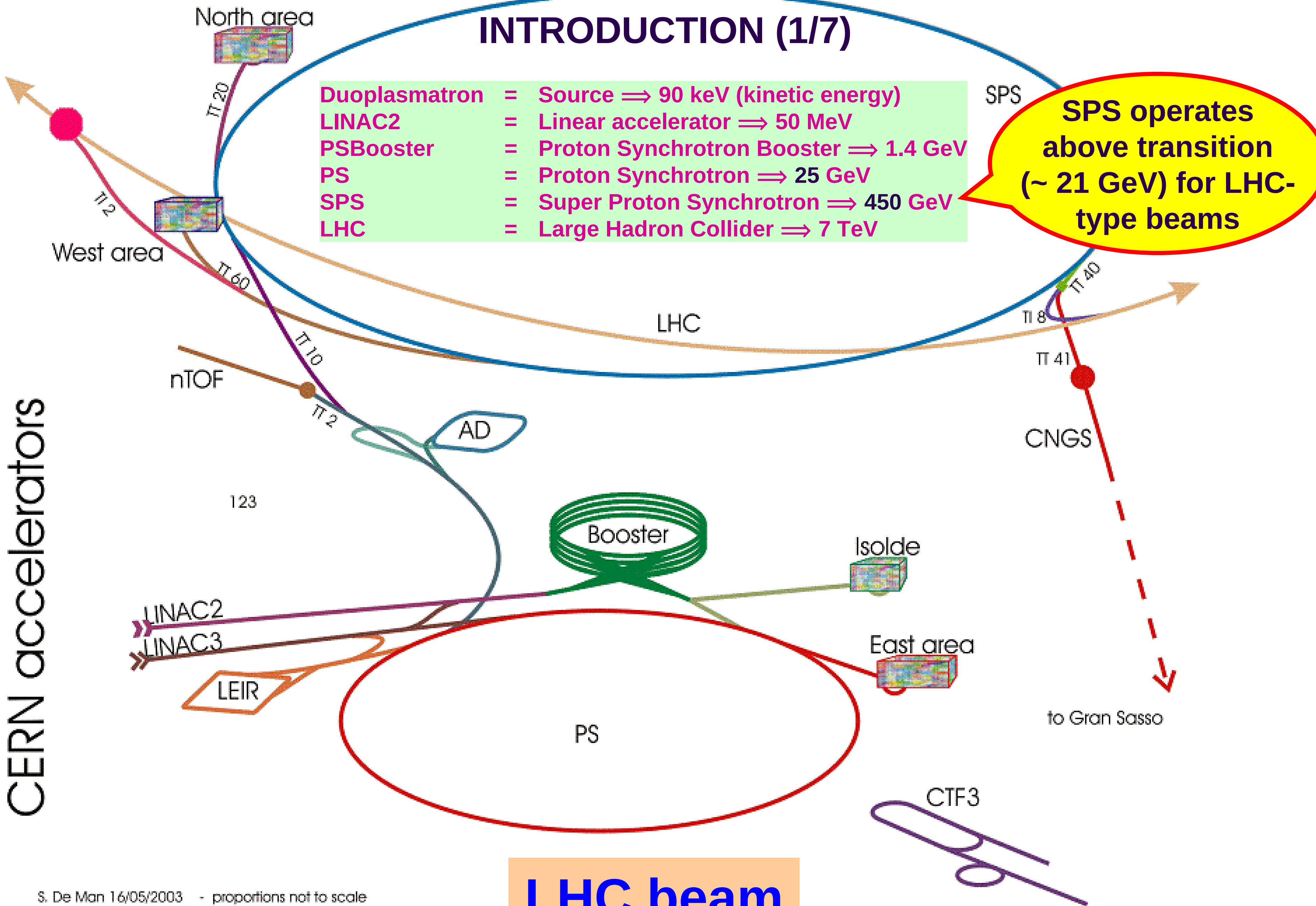
CONTENTS

- **INTRODUCTION ON LHC AND CNGS BEAMS IN PS & SPS**
- **PS**
  - **Crossing the integer or half-integer resonance**
  - **Montague resonance**
  - **Space charge driven resonance phenomena**
  - **Decoherence without and with space charge at PS injection**
  - **Why Q_h is ↓ to ~ 6.1 for high-intensity (e.g. CNGS) bunches?**
  - **RW instability with LHC beam without and with space charge**
- **SPS**
  - **Beam lifetimes studies with protons and large $\Delta Q_{sc,y}$ (≈ - 0.2)**
  - **Working point studies with a pencil proton bunch**
  - **Results from early ion (Pb^{82+}) commissioning in 2007**
- **CONCLUSION**

INTRODUCTION (1/7)

Duoplasmatron	=	Source ⟹ 90 keV (kinetic energy)
LINAC2	=	Linear accelerator ⟹ 50 MeV
PSBooster	=	Proton Synchrotron Booster ⟹ 1.4 GeV
PS	=	Proton Synchrotron ⟹ 25 GeV
SPS	=	Super Proton Synchrotron ⟹ 450 GeV
LHC	=	Large Hadron Collider ⟹ 7 TeV

SPS operates above transition (~ 21 GeV) for LHC-type beams

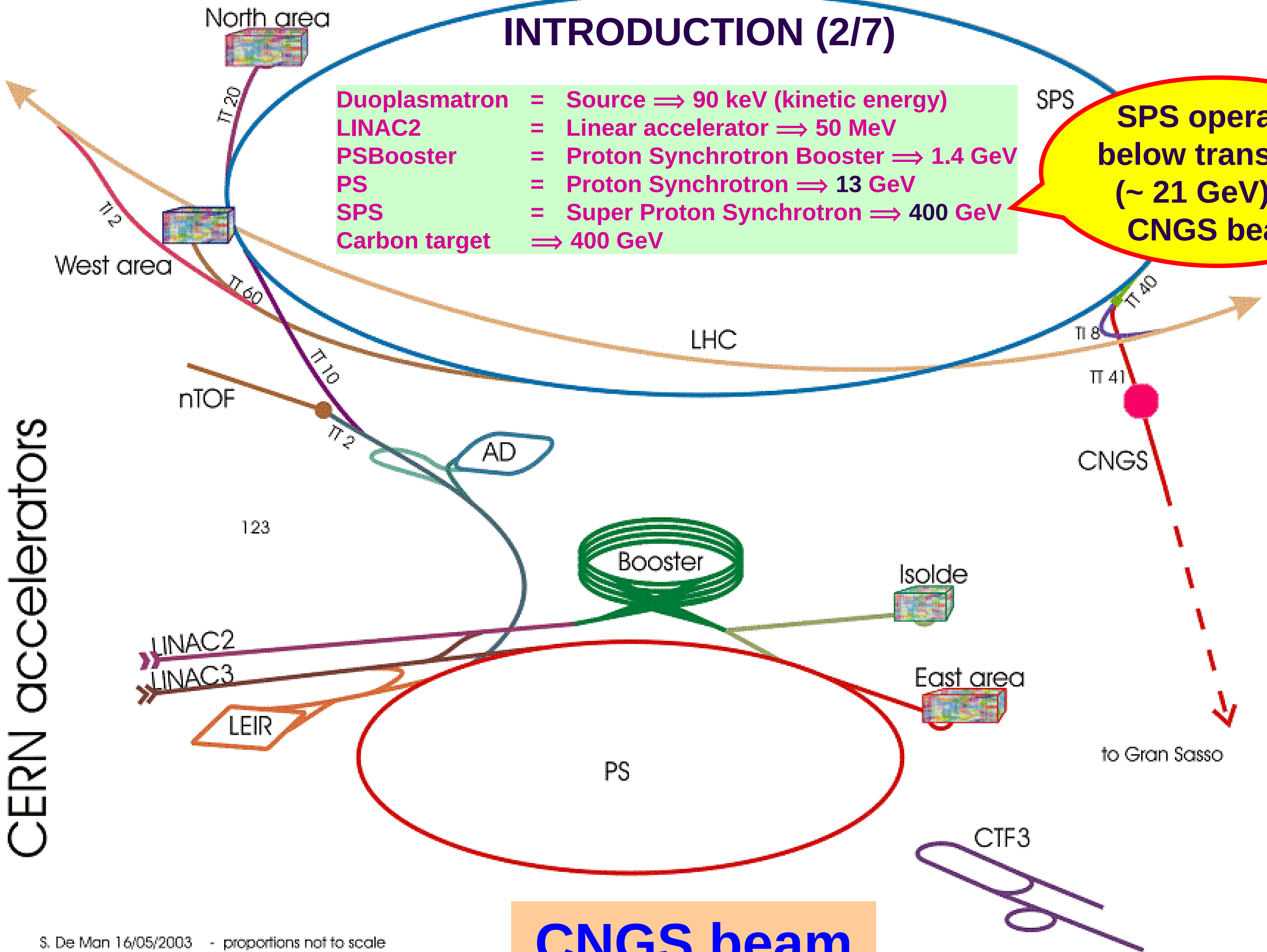


LHC beam

INTRODUCTION (2/7)

Duoplasmatron	=	Source ⟹ 90 keV (kinetic energy)
LINAC2	=	Linear accelerator ⟹ 50 MeV
PSBooster	=	Proton Synchrotron Booster ⟹ 1.4 GeV
PS	=	Proton Synchrotron ⟹ 13 GeV
SPS	=	Super Proton Synchrotron ⟹ 400 GeV
Carbon target		⟹ 400 GeV

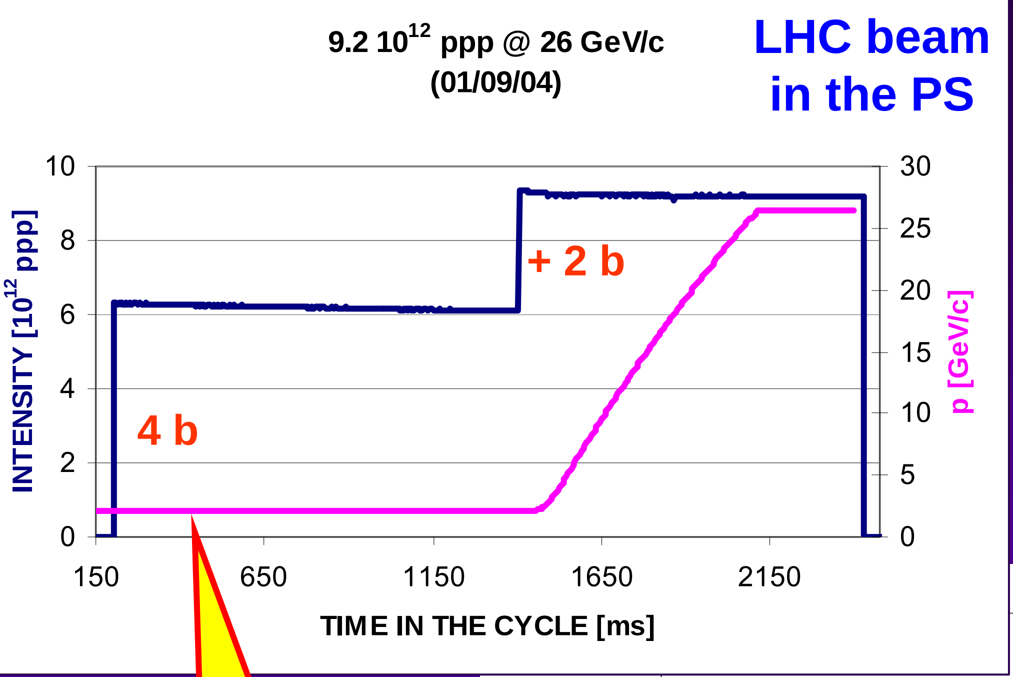
SPS operates below transition (~ 21 GeV) for CNGS beam



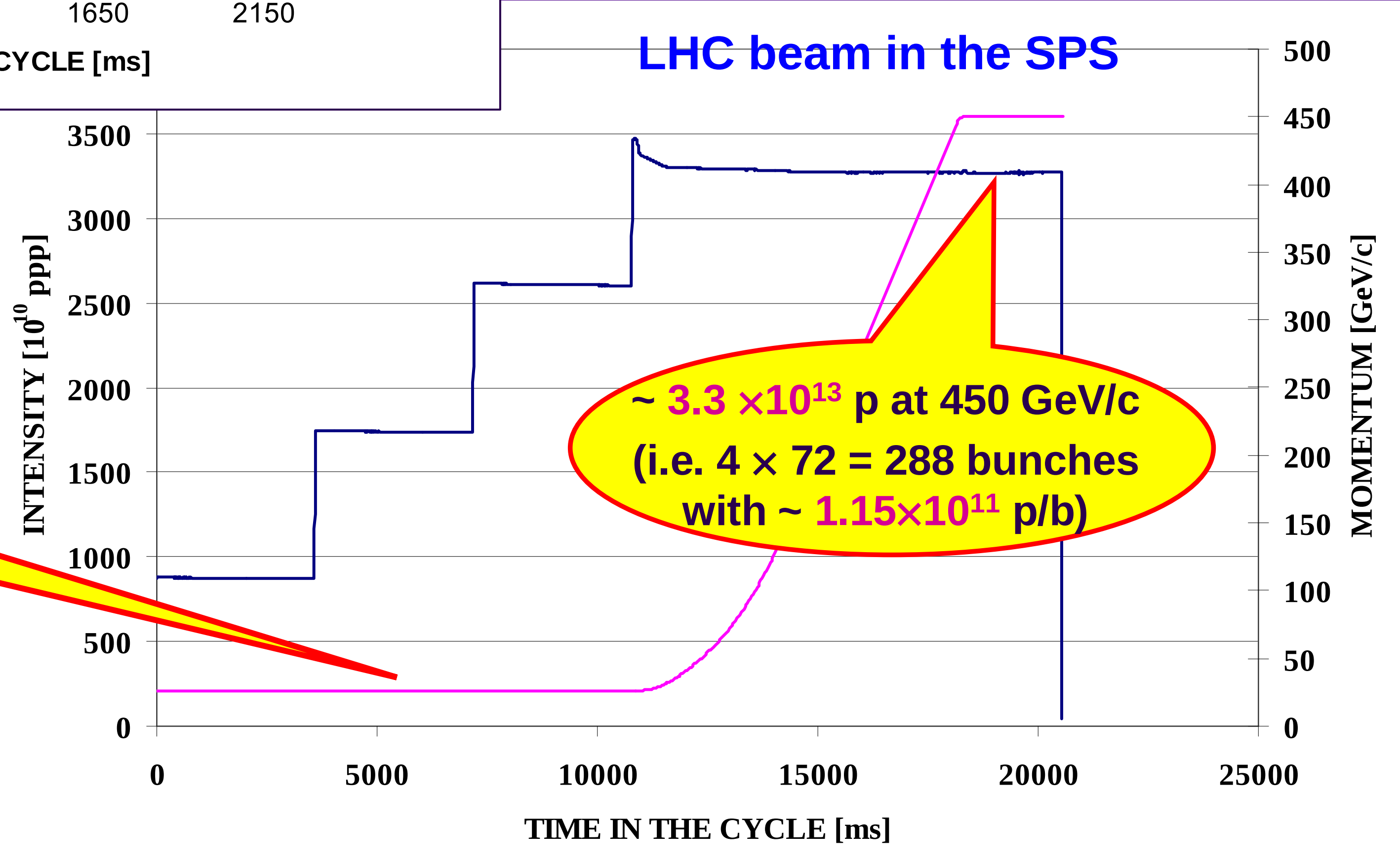
CNGS beam

INTRODUCTION (3/7)

$$\varepsilon_{x,y}^{\text{required}}\left(1\sigma,\text{ norm}\right)\leq 3.5\ \mu\text{m @ 450 GeV/c}$$



~ 6×10^5 turns at low energy

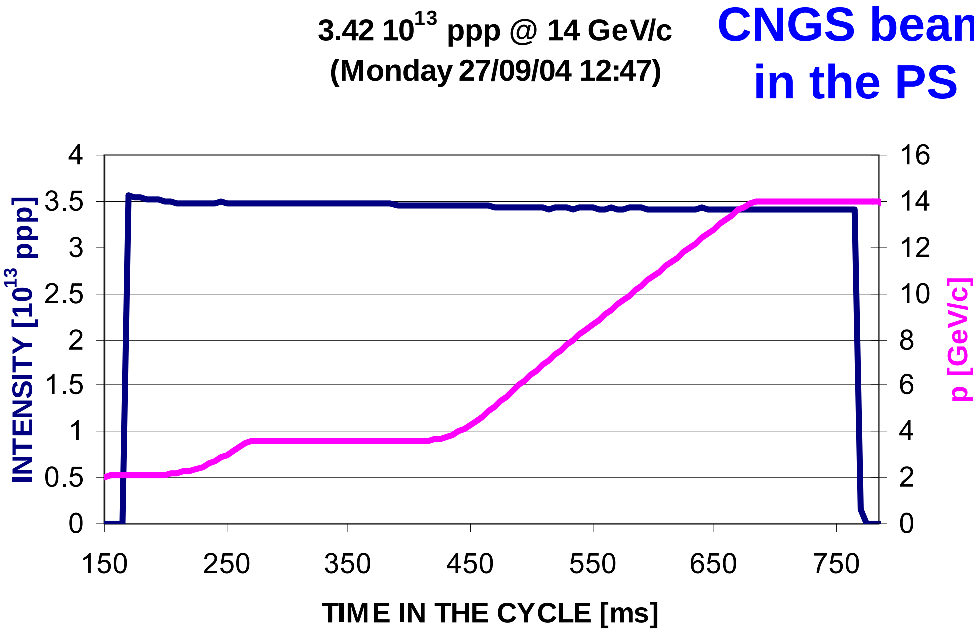


~ 5×10^5 turns at low energy

~ 3.3×10^{13} p at 450 GeV/c (i.e. 4 × 72 = 288 bunches with ~ 1.15×10^{11} p/b)

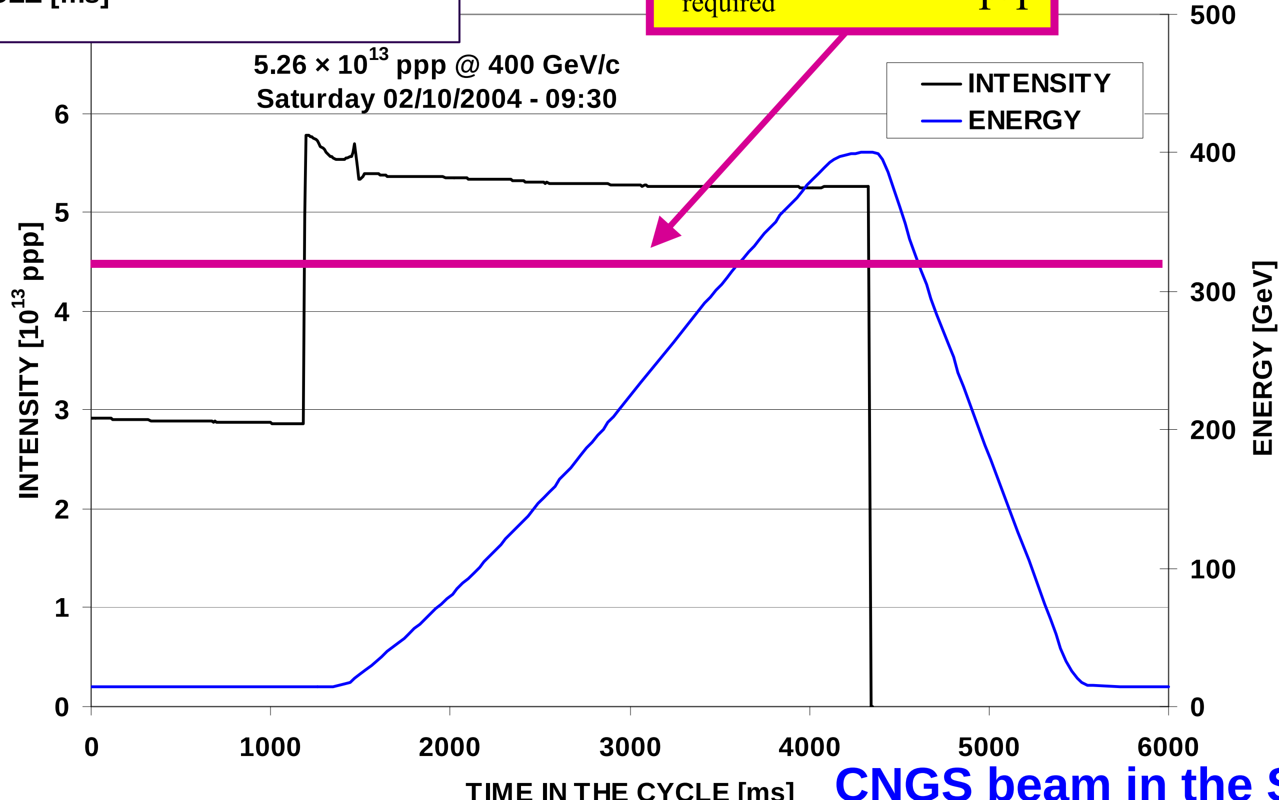
INTRODUCTION (4/7)

CNGS beam in the PS



$$\varepsilon_{x,y}^{\text{required}}\left(1\sigma,\text{norm}\right)\leq 12\ \mu\text{m}\ @\ 400\ \text{GeV/c}$$

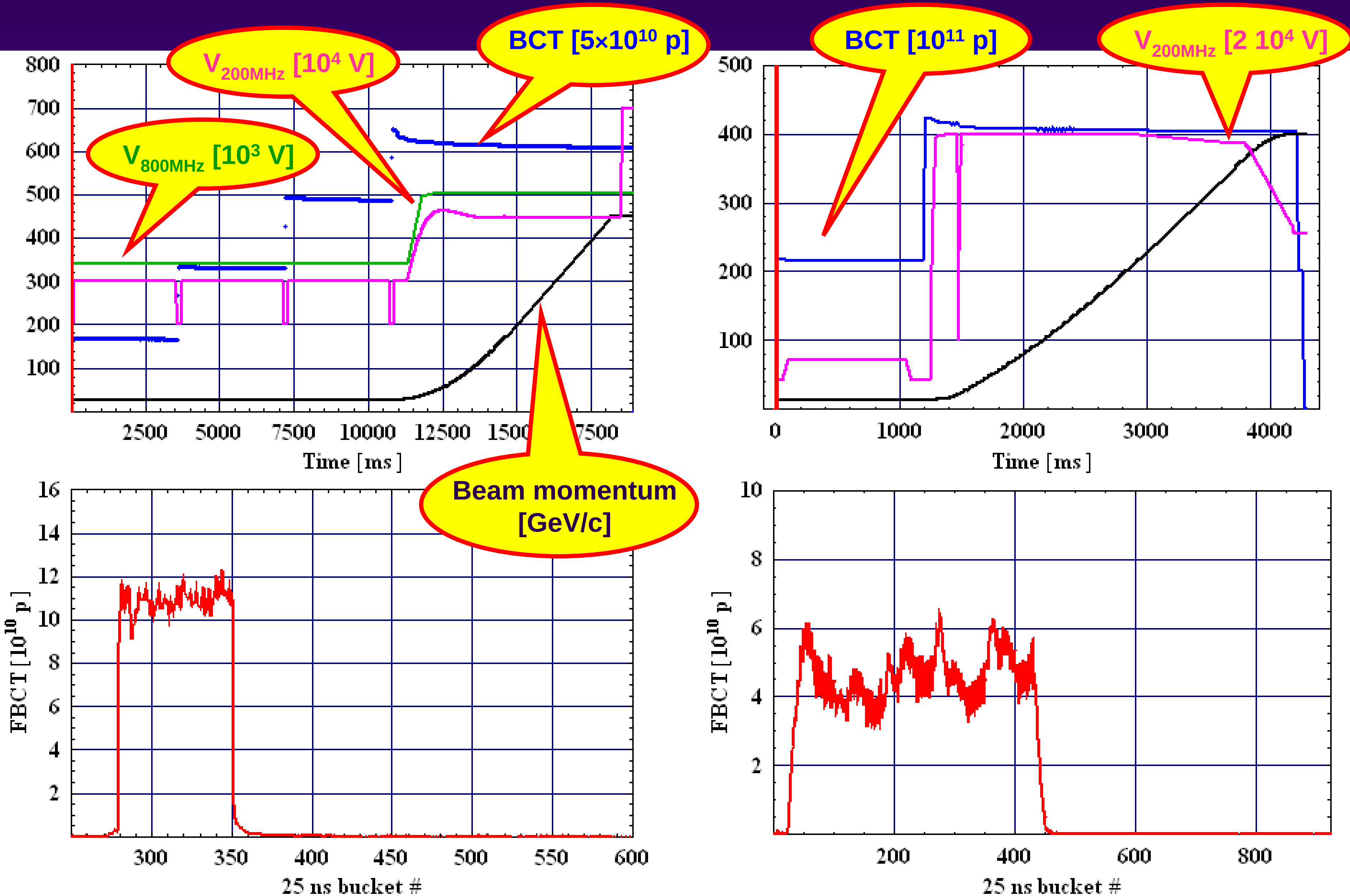
$$I_{\text{required}} = 4.4\ 10^{13}\ \text{p/p}$$



CNGS beam in the SPS

INTRODUCTION (5/7)

LHC beam (in the SPS) — CNGS beam (in the SPS)



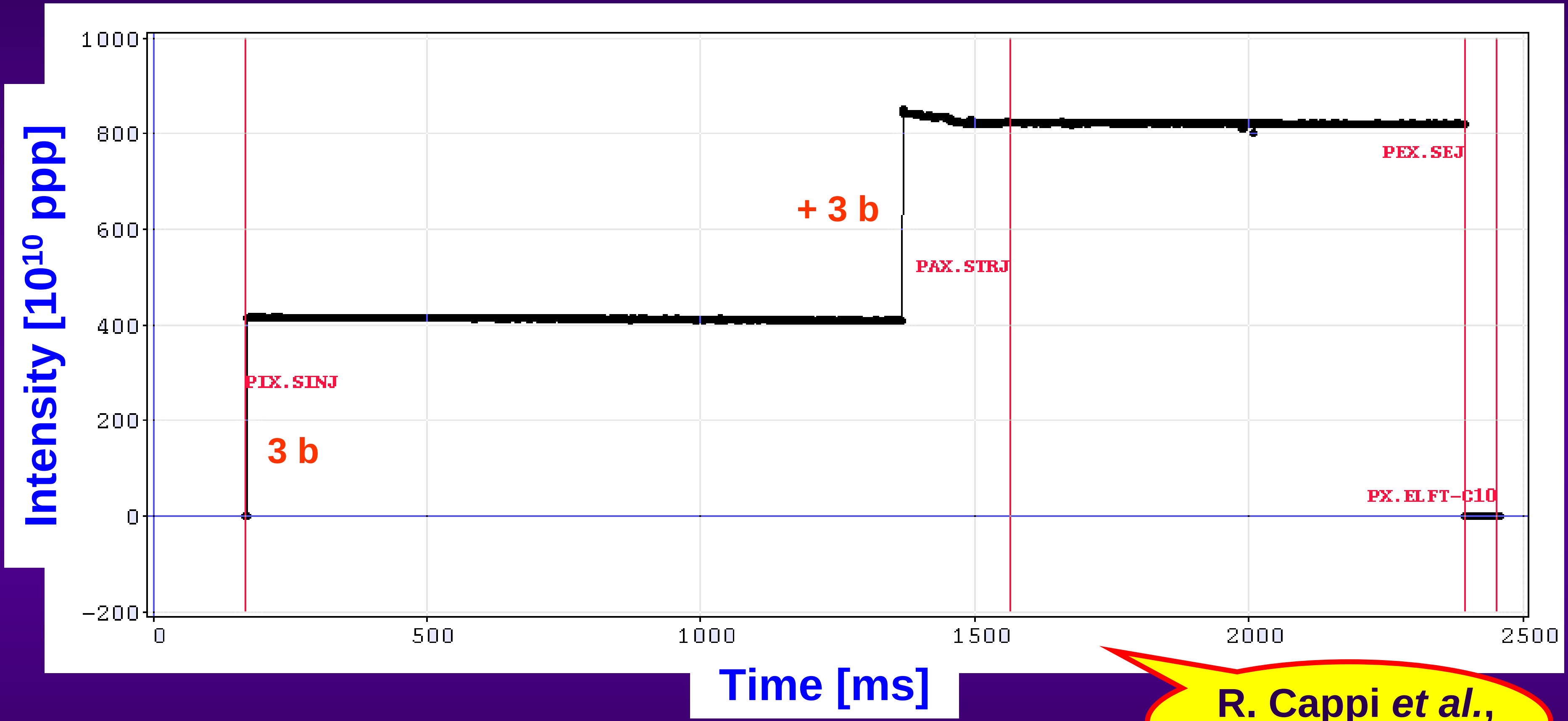
INTRODUCTION (6/7)

- **Over the years the intensity / bunch in the PS for the LHC increased for several reasons**
  - **Initial scenario = debunching/rebunching (84 b of 1.15E11 p/b on h = 84 at top energy) $\Longrightarrow$ 8 b on h = 8 at injection**
  - **Then, triple and double splittings instead + gap for kicker (72 b of 1.15E11 p/b on h = 84 at top energy) $\Longrightarrow$ 6 b on h = 7 at injection**
  - **Then, compensation for the losses in the SPS (72 b of 1.3E11 p/b on h = 84) $\Longrightarrow$ 6 b on h = 7 at injection with more intensity / bunch**

    $\Longrightarrow$ Losses of few % on the injection plateau are now observed (without emittance growth)

INTRODUCTION (7/7)

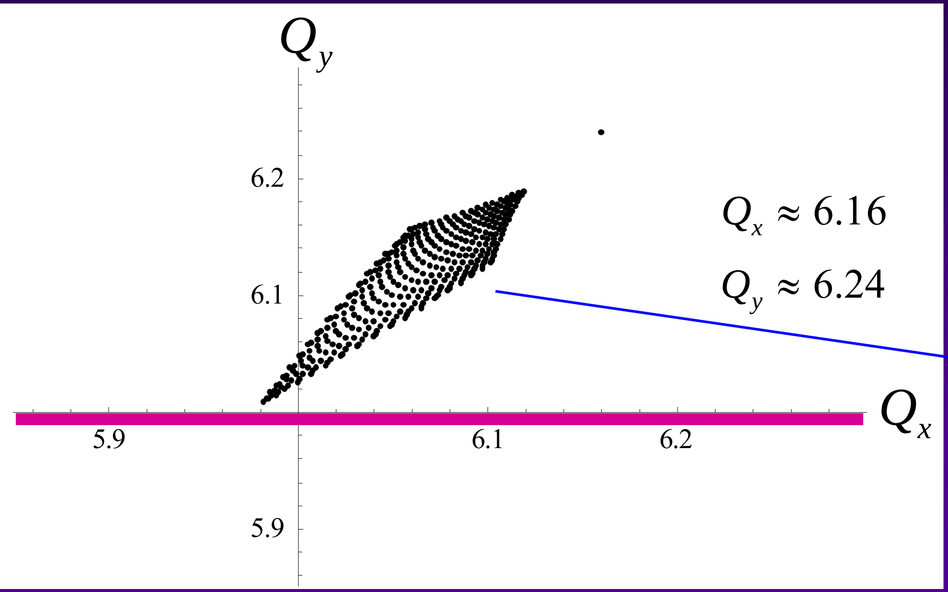
- **Reminder in 2000 (with 1.15E11 p/b at extraction instead of 1.3E11 now)**

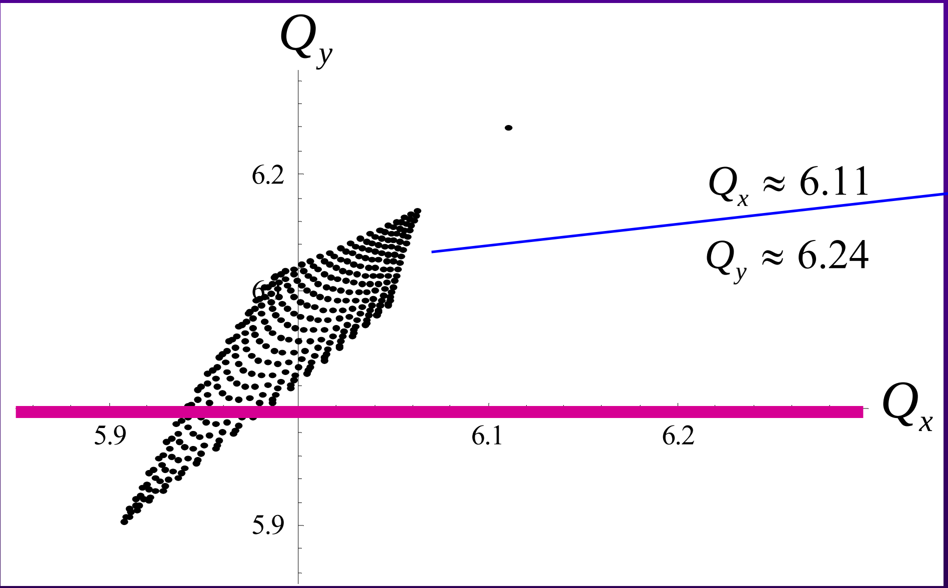


R. Cappi *et al.*, HEACC2001

$\Delta Q_{sc,y} \approx$ - 0.21 $\Longrightarrow$ ~ No losses on the injection flat-bottom

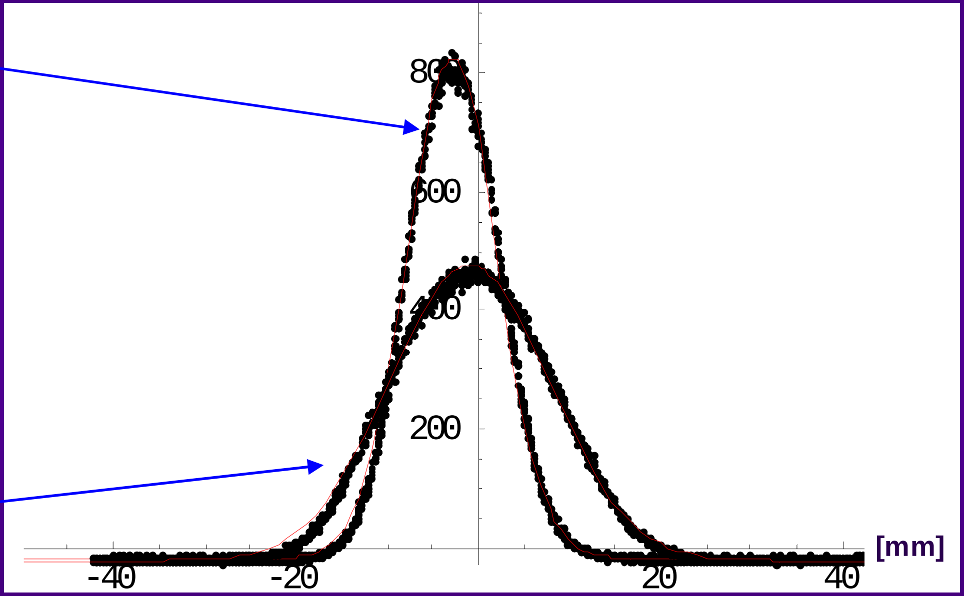
Crossing the integer or half-integer resonance in the PS (1/2)





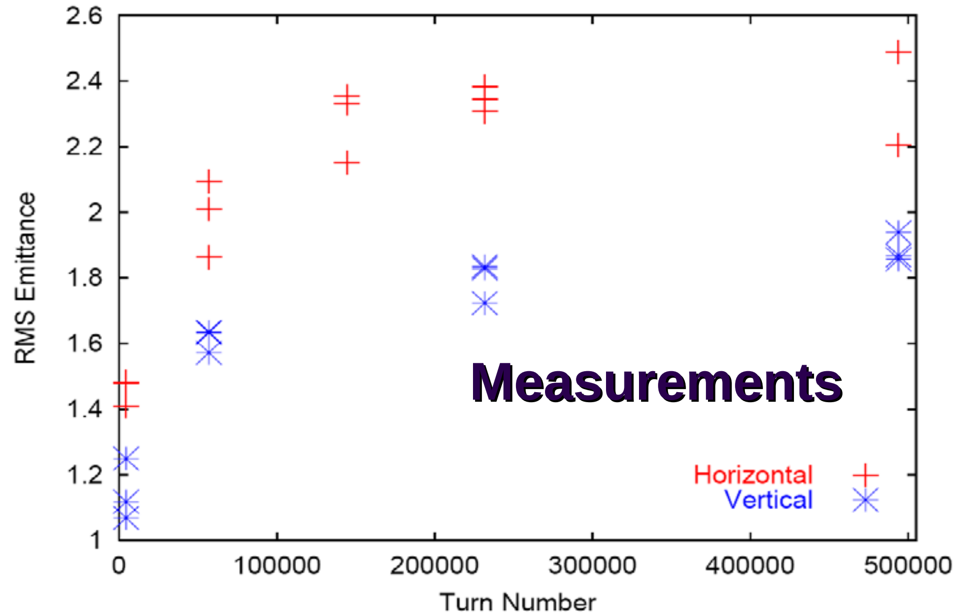
M. Giovannozzi *et al.*, PAC2003

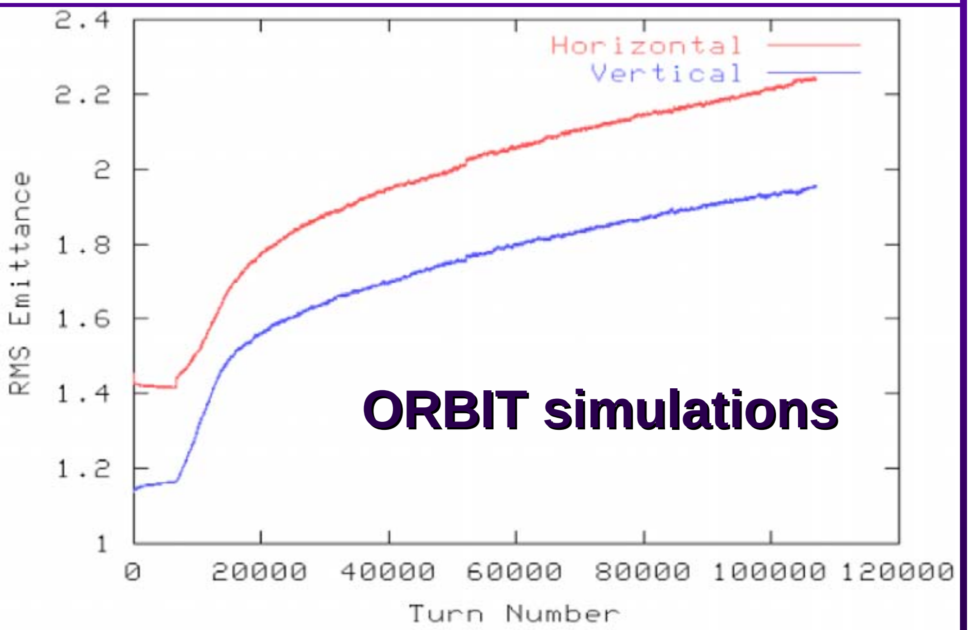
Horizontal bunch profile + Gaussian fit



Regime of loss-free core-emittance blow-up

Crossing the integer or half-integer resonance in the PS (2/2)





S. Cousineau *et al.*, EPAC2004

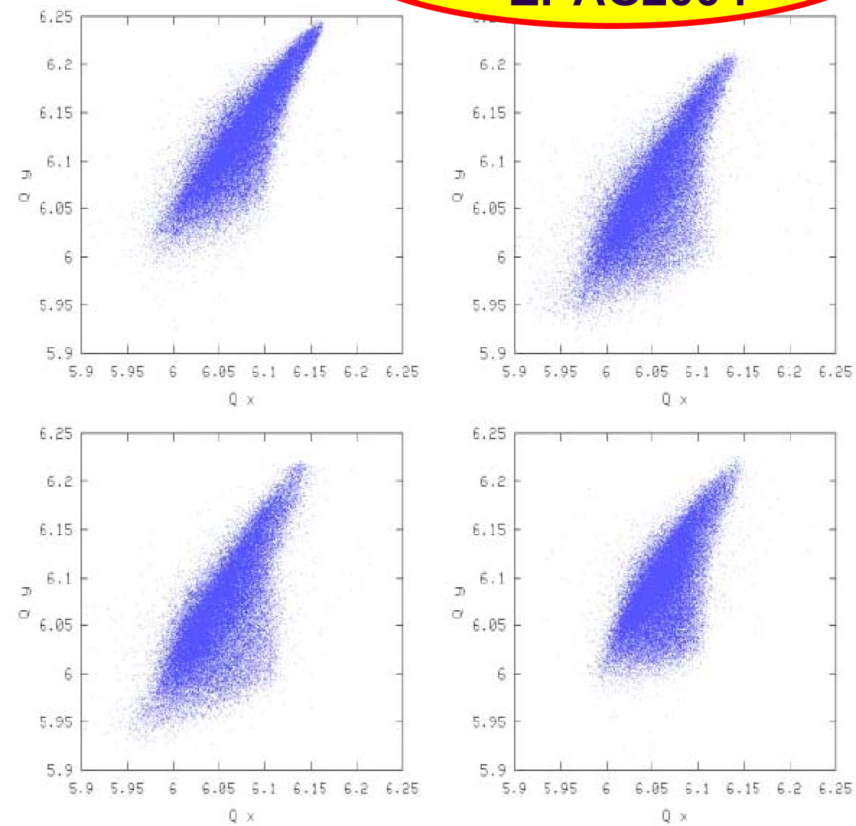


Figure 4: a) The tune footprint before the RF ramp-up and tune change. b) The tune footprint at the middle of the RF ramp-up. c) The tune footprint at the end of the RF ramp-up. d) The tune footprint 90,000 turns after the end of the RF ramp-up.

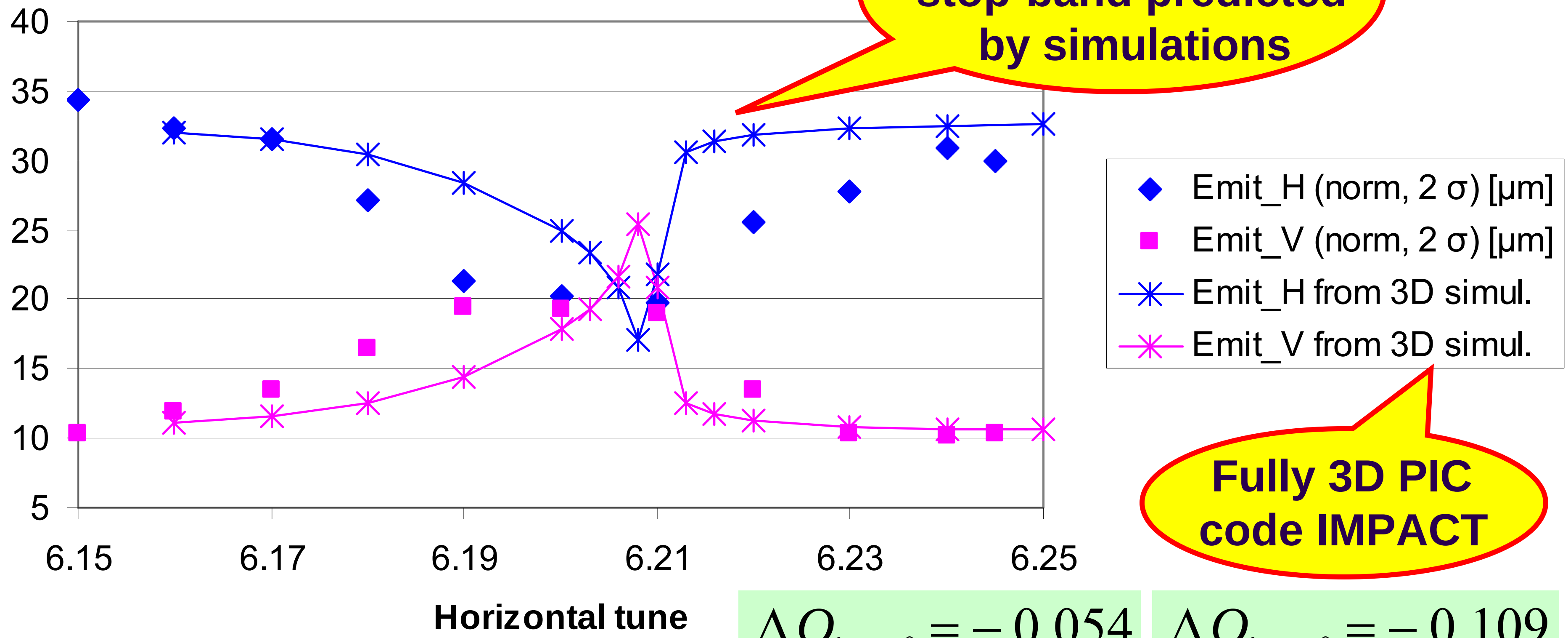
Montague resonance in the PS (1/2)

E. Métral *et al.*, HB2004

STATIC CASE

(constant tunes from injection to the measurement point)

$Q_y = 6.21$



$\Delta Q_{inc,x0} = -0.054$ $\Delta Q_{inc,y0} = -0.109$

Montague resonance in the PS (2/2)

DYNAMIC CASE

(the horizontal tune was changed linearly from 6.15 to 6.25 in 100 ms)

$T_{rev} = 2.3\ \mu s \implies$ **~ 44 000 turns**

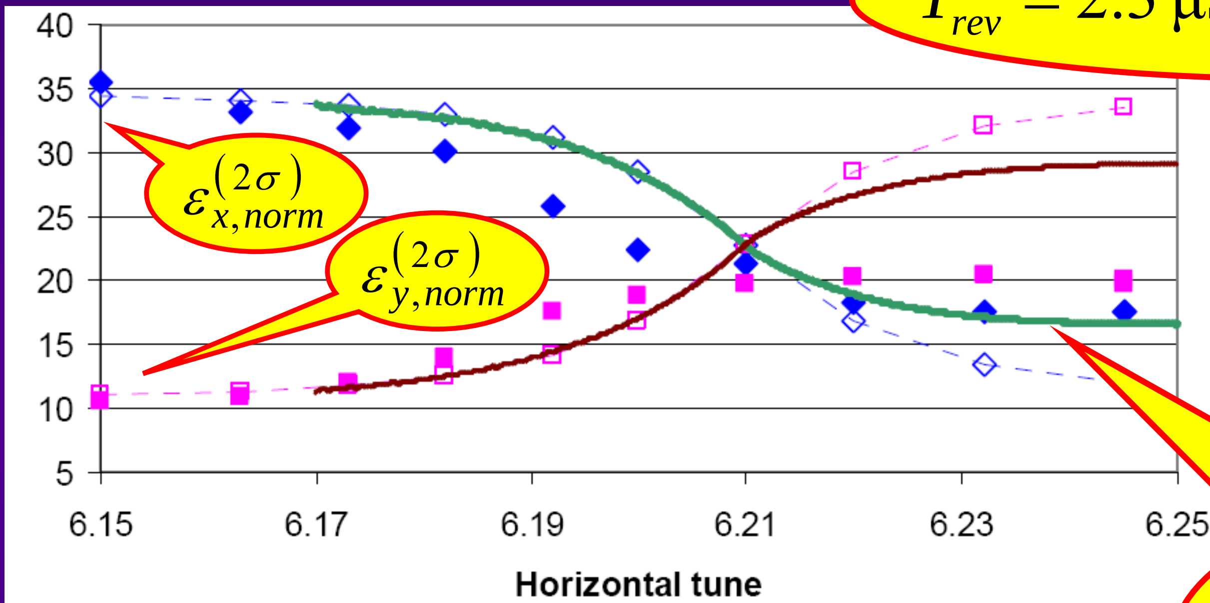
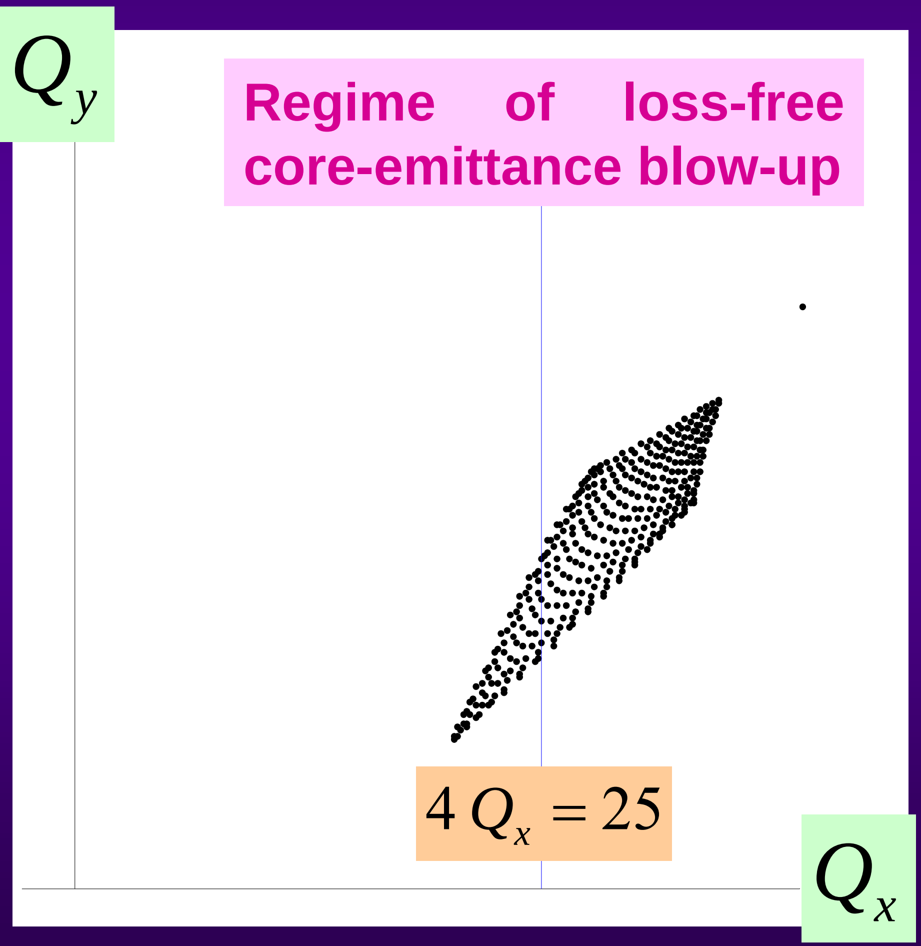


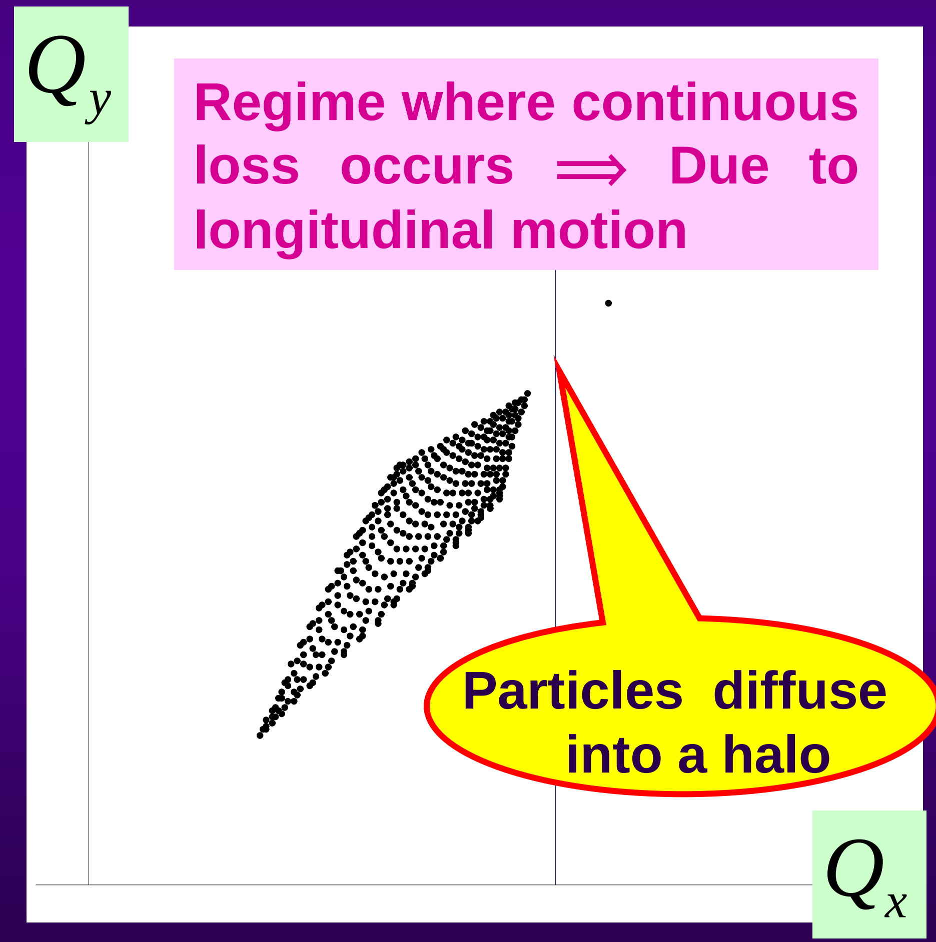
FIGURE 5. Measurements (dots, see Fig. 2), 3D simulation results (IMPACT code) in the real measured case where the synchrotron period is not much larger than the crossing time (full line), and fit of the 3D simulation results in the case where the synchrotron period is much larger than the crossing time (dotted line).

Mixing due to longitudinal motion $\implies$ See also I. Hofmann et al., EPAC04

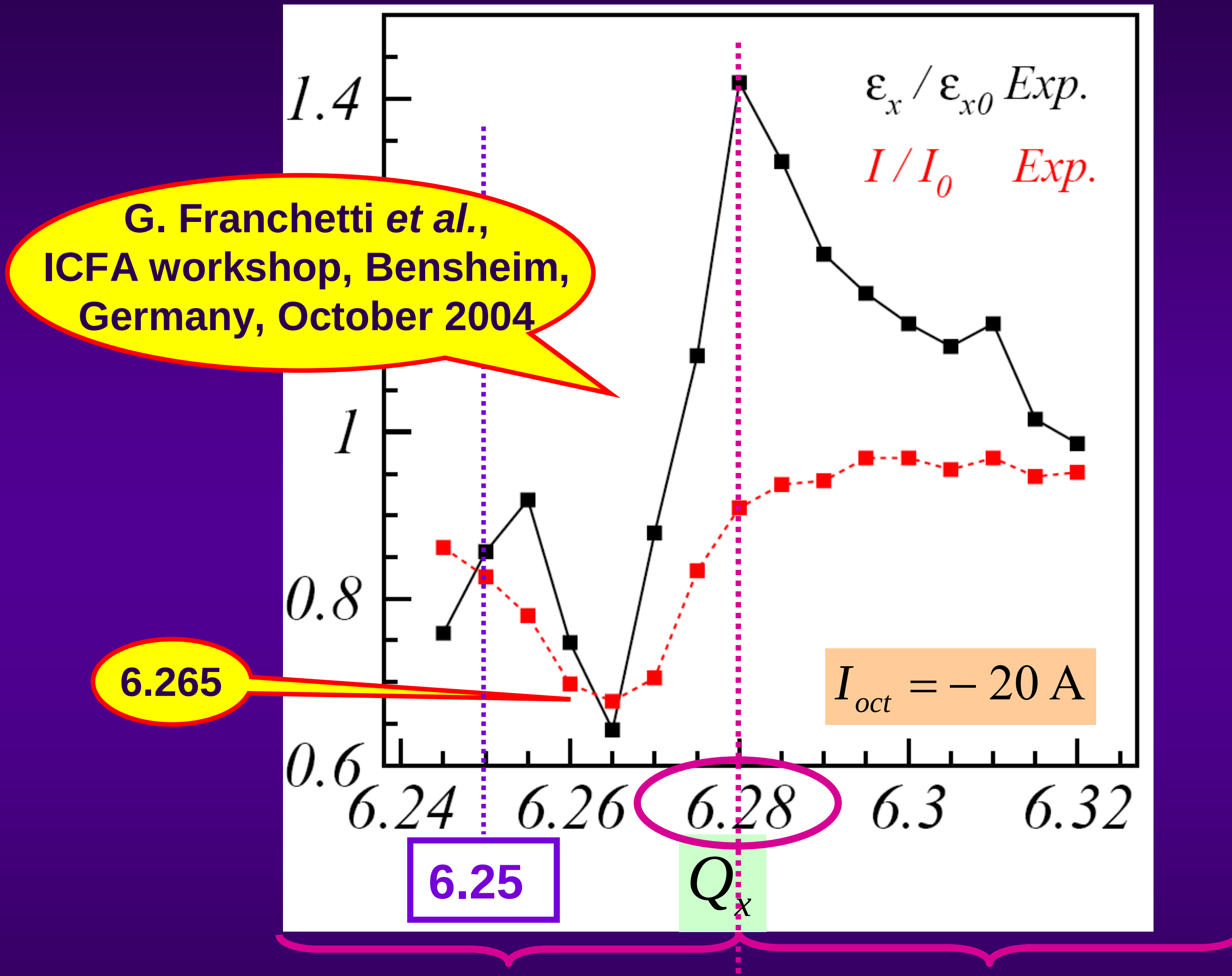
Space charge driven resonance phenomena in the PS (1/6)

- **Mechanism anticipated by G. Franchetti & I. Hofmann, which involves**
  - Space charge tune spread
  - Nonlinear (octupole) resonance
  - Synchrotron motion





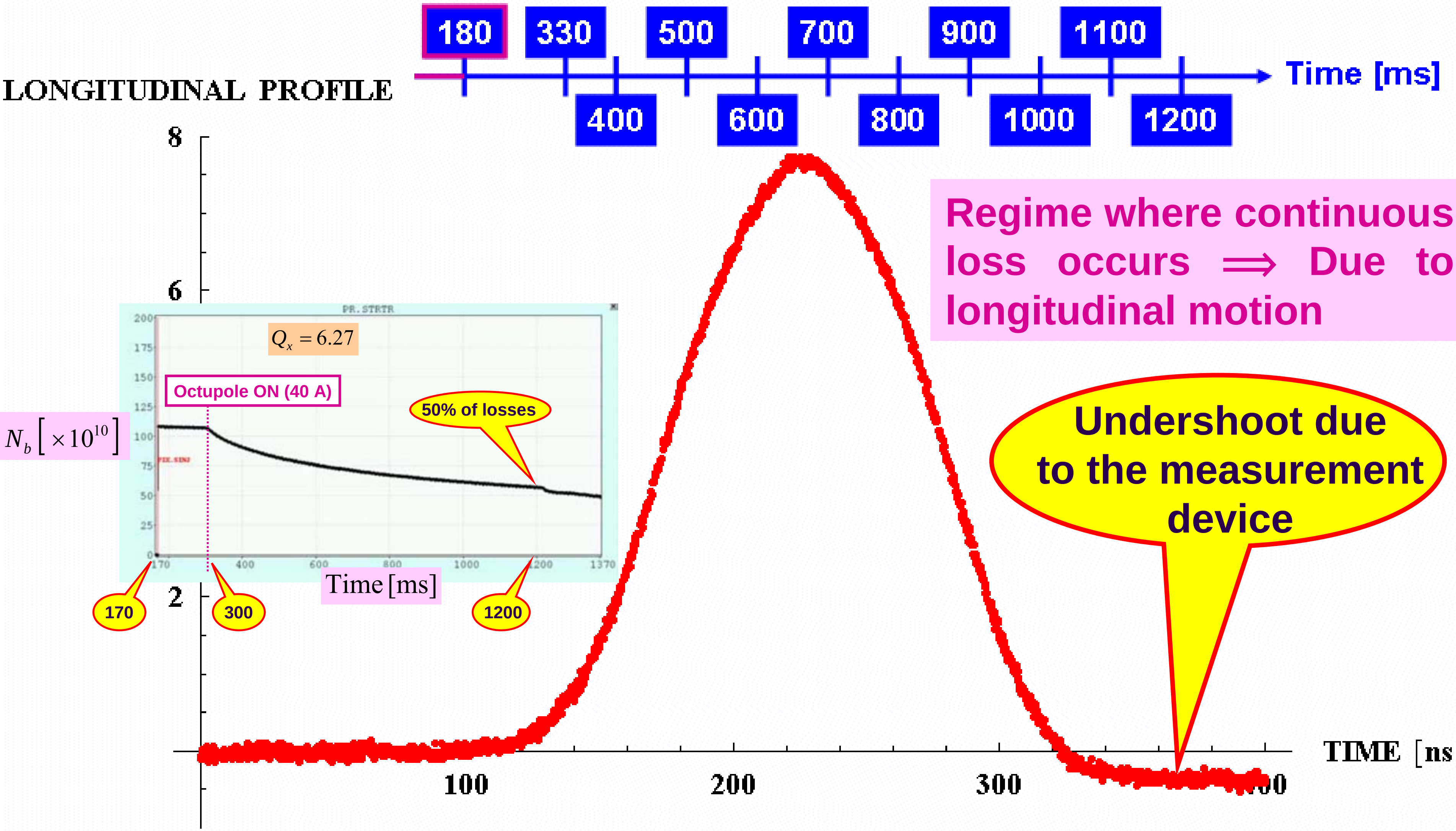
Space charge driven resonance phenomena in the PS (2/6)



Loss dominated regime

Emittance growth dominated regime

Space charge driven resonance phenomena in the PS (3/6)



Regime where continuous loss occurs ⟹ Due to longitudinal motion

Undershoot due to the measurement device

Space charge driven resonance phenomena in the PS (4/6)

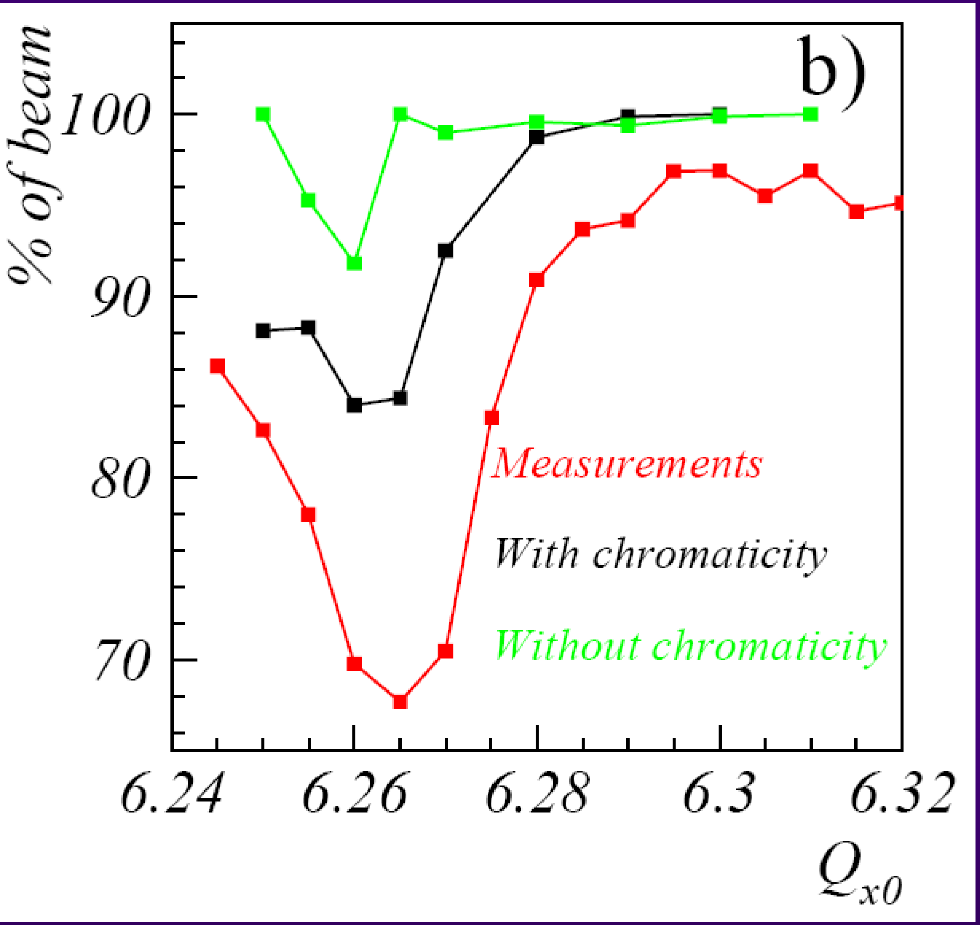
- By lowering the working point towards the resonance $4\ Q_x = 25$, a gradual transition from a regime of loss-free core emittance blow-up to a regime dominated by continuous beam loss has been observed, as expected by Ingo&Giuliano

- Emittance growth in good agreement with predictions

- The observed maximum losses (~30%) were still much larger than predicted (~8%) at COULOMB05

Space charge driven resonance phenomena in the PS (5/6)

- **Results from Ingo&Giuliano at HB2006**

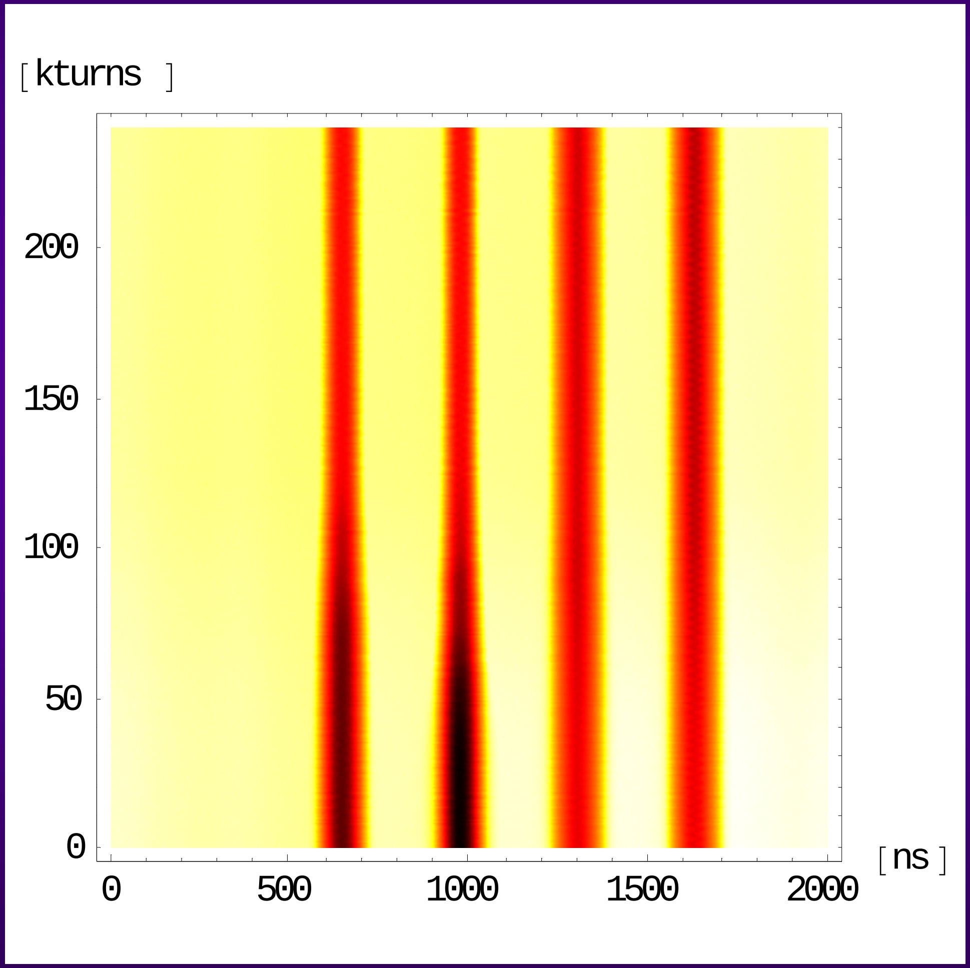


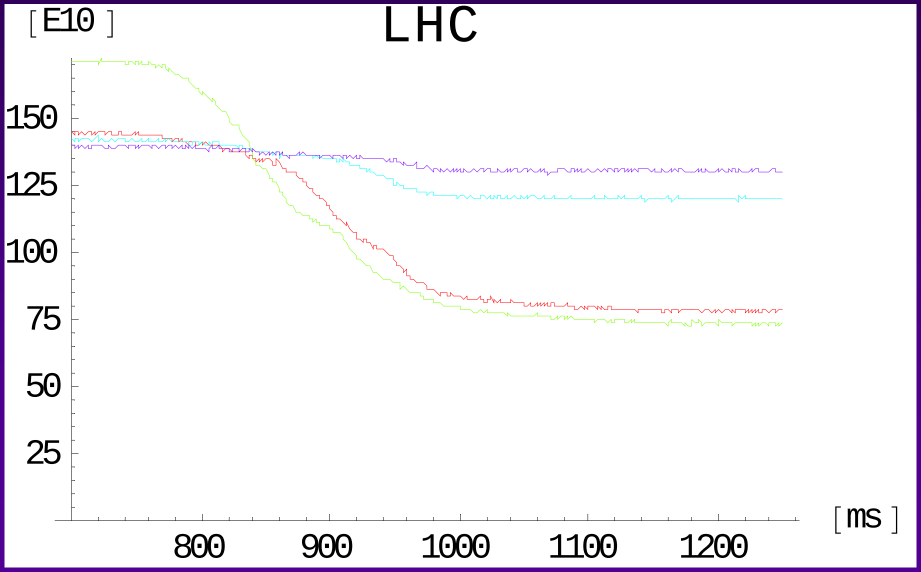
OUTLOOK

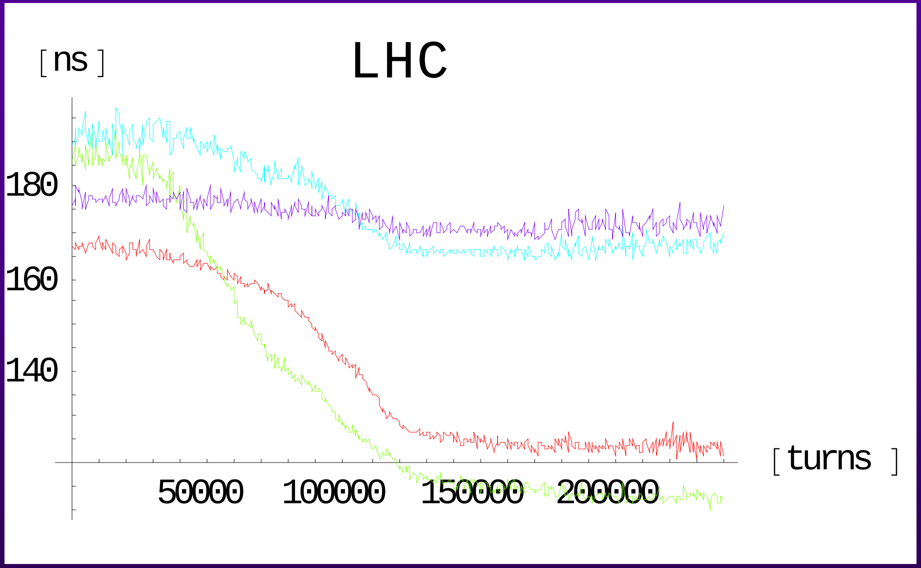
Trapping phenomena are an important subject in high intensity machines as well as in rings with electron clouds [14]. We presented here the status of the present understanding: simple formulae for asymptotic beam loss and rms emittance growth have been found. Scaling laws for trapping induced rms emittance growth are possible and will be studied in details in the near future. The chromaticity also plays an important role: the CERN-PS experiment modeling has been considerably improved by including the chromaticity bringing the beam loss prediction to 50% of that found in the experiment. The remaining discrepancy will be the subject of future studies, which should include fully self-consistent simulations.

Space charge driven resonance phenomena in the PS (6/6)

This mechanism is sometimes observed in the PS with the LHC beam when the tunes are not correctly set



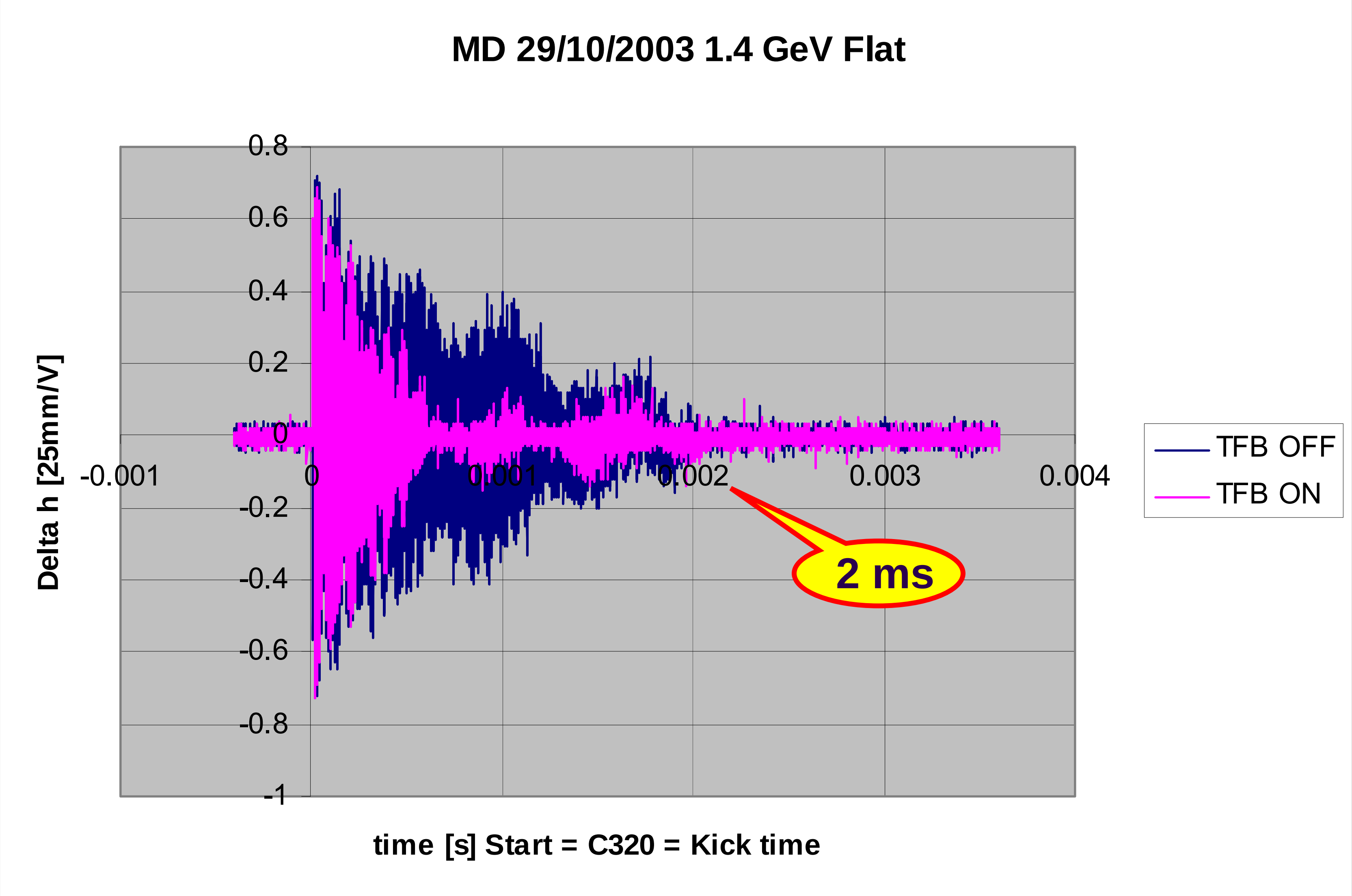




Courtesy S. Hancock

Decoherence without and with space charge at PS injection (1/2)

Measurements from F. Blas with a nominal LHC bunch



Decoherence without and with space charge at PS injection (2/2)

HEADTAIL simulations from E. Benedetto (PHD thesis)

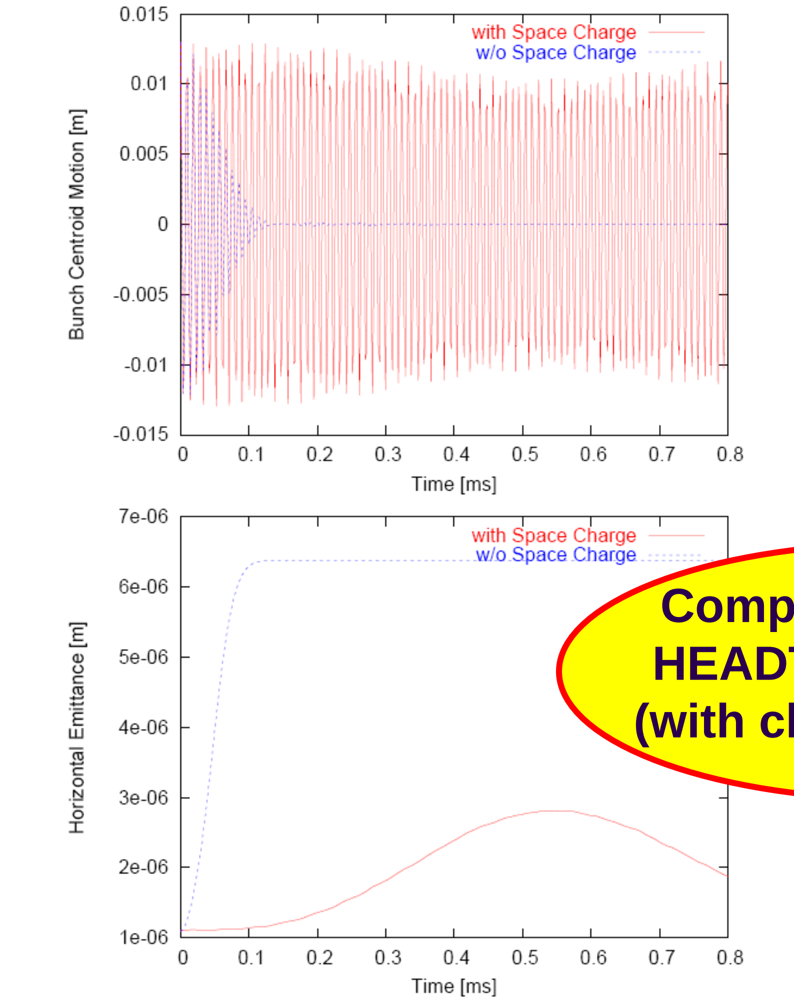
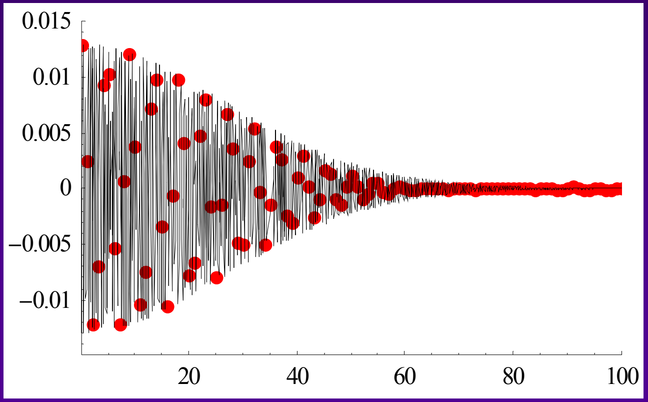


Figure B.1. Simulations with HEADTAIL. Horizontal bunch centroid (top) and emittance (bottom) vs. time during the first 0.8 ms in PS. An initial offset $x_0 = 0.013$ is given to the bunch. The two curves refer to simulations with space–charge taken into account or not.

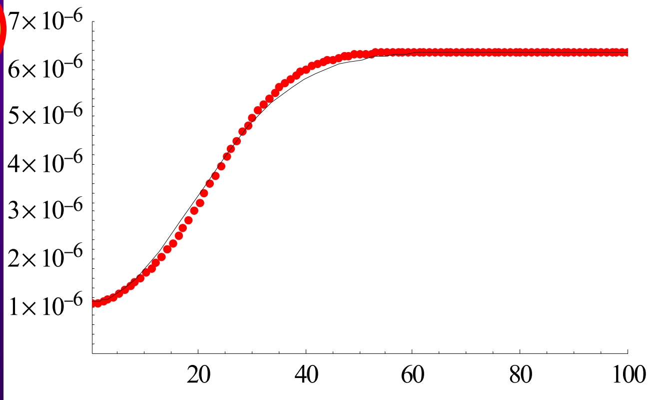
Comparison between HEADTAIL and theory (with chromaticity only)

Bunch centroid motion [m]



Time [turns]

Bunch rms emittance [m]



Time [turns]

Why Qh is ↓ to ~ 6.1 for high-intensity (CNGS) bunches in the PS? (1/2)

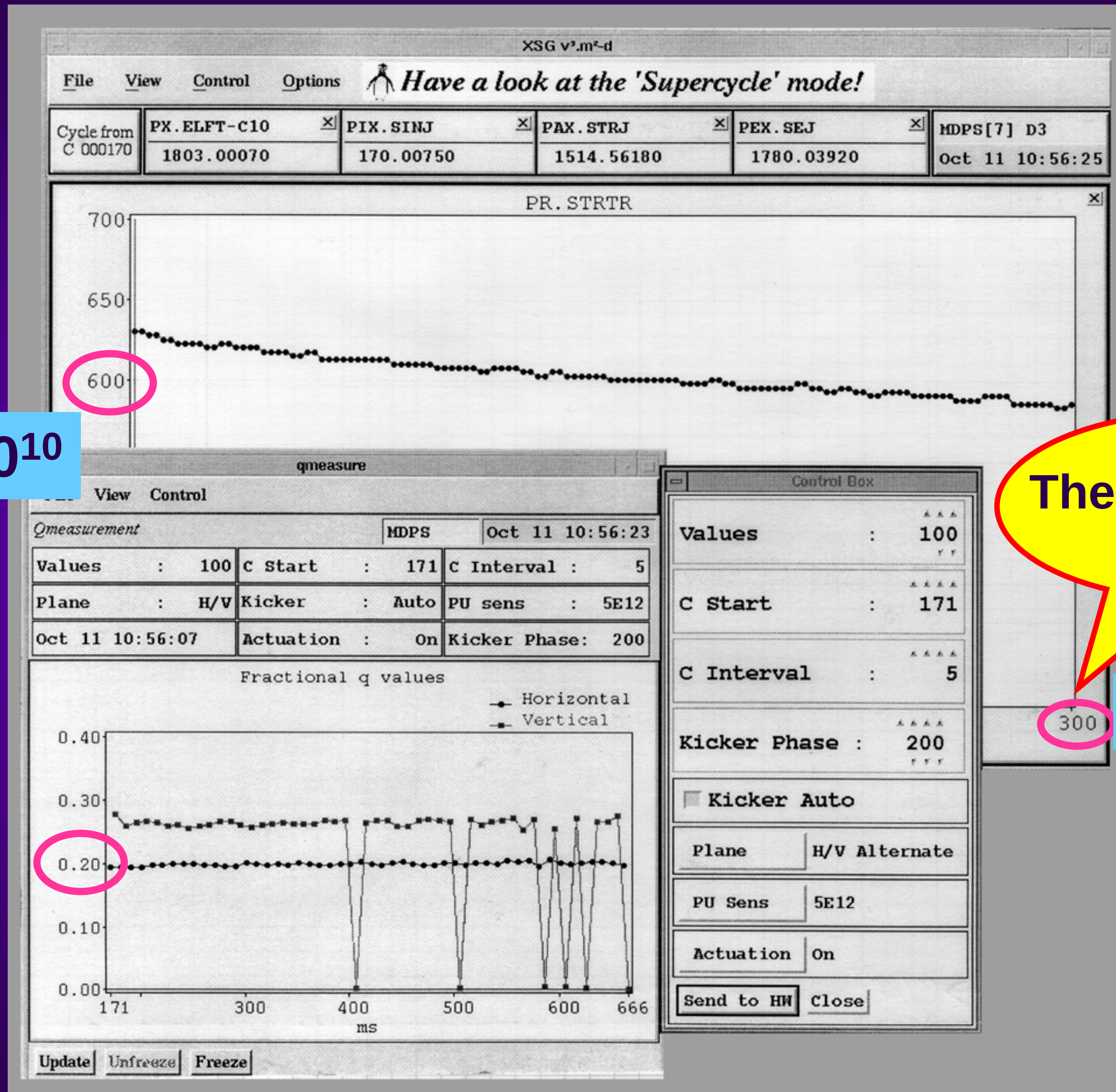
- **Does not go in the good direction for the classical space-charge effect (as it pushes the bunch closer to the integer resonance…)**
- **Could have been explained by the Montague resonance (this is why it was studied…)**
- **The other mechanism is simply the change of trajectory**

Some similarities with observations at SNS reported by John Galambos (plenary talk)

Why Qh is ↓ to ~ 6.1 for high-intensity (CNGS) bunches in the PS? (2/2)

Changing the trajectory in the injection transfer line + injection process parameters, it is possible to keep a high tune (~ 6.20) with the same amount of losses!

$\times 10^{10}$

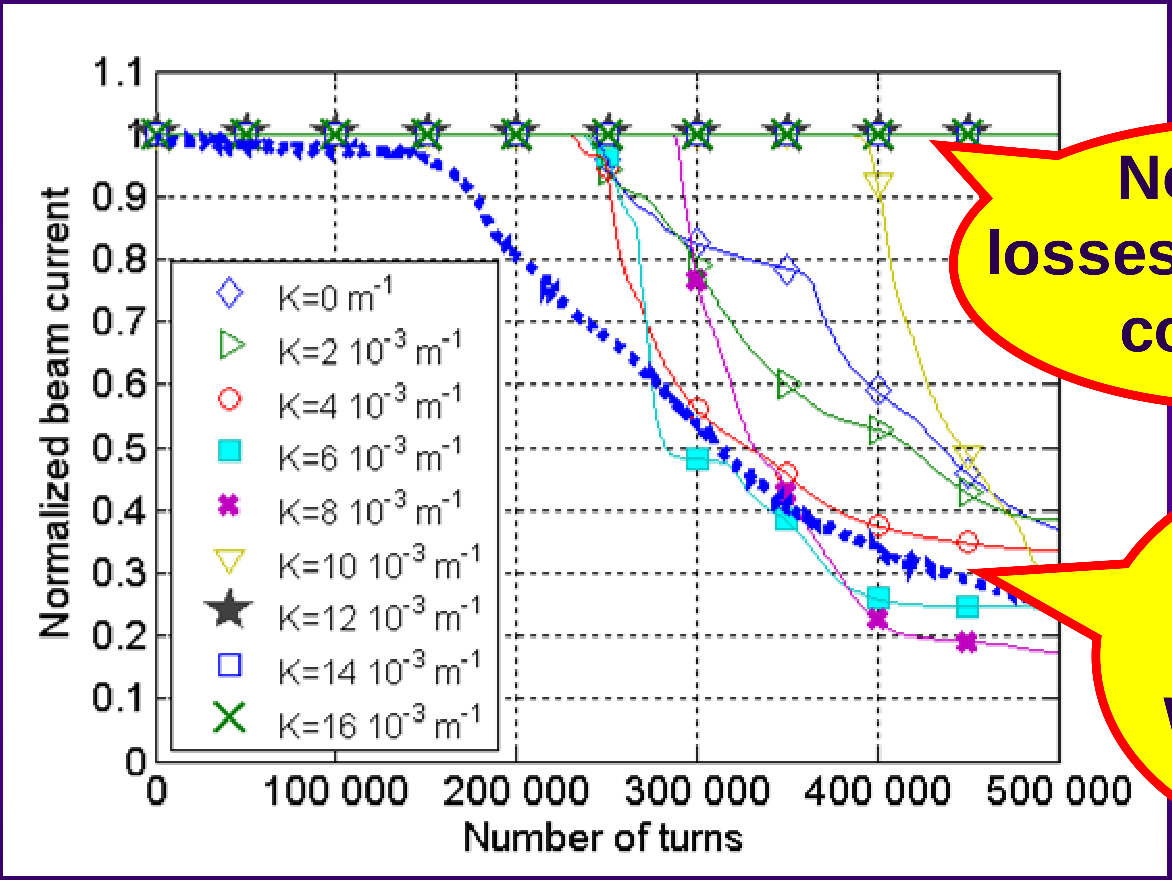


The injection is at C170

C Time [ms]

RW instability with LHC beam in the PS without and with space charge

⟹ **Measurements (and theory) seem to be confirmed by HEADTAIL simulations without including space charge (see PAC07 paper)**



$Q_x = 6.22$

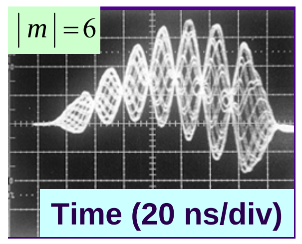
$Q_y = 6.25$

$\xi_x = -0.5$

$\xi_y = -1.0$

No beam losses with linear coupling

Beam losses measured without linear coupling

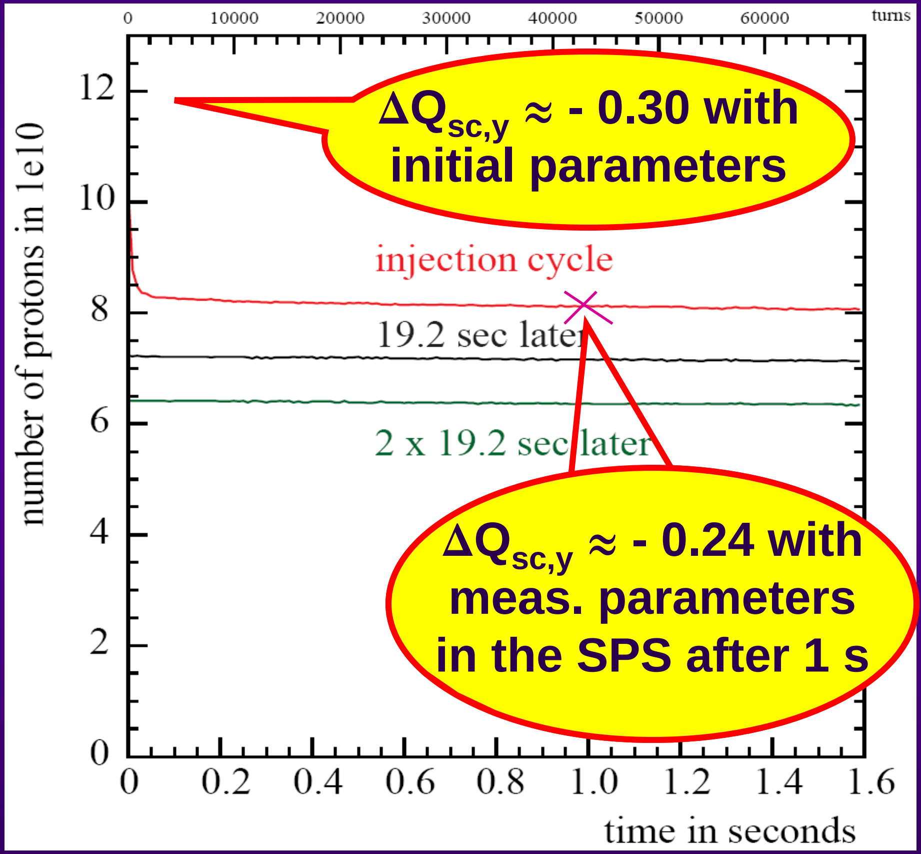


⟹ **Next step (challenge): Simulate the "real case" with space charge!**

Beam lifetimes studies with protons and large $\Delta Q_{sc,y}$ ($\approx$ - 0.2) in the SPS

H. Burkhardt et al. (CERN-AB-2003-013 ABP and CERN-AB-2004-056)

- Done on a ~ nominal (1.2E11 p/b) LHC-type bunch at 14 GeV/c (instead of 26 GeV/c)
- 2003 $\Longrightarrow$ $\Delta Q_{sc,y} \approx$ - 0.17 (rather good lifetimes over 100 s)
- 2004 (see picture) $\Longrightarrow$ Working point at that time: $Q_{x,y}$ = 26.184 / 26.13 (it was observed that better conditions were reached by ↑ Q_y to ~ 26.20)



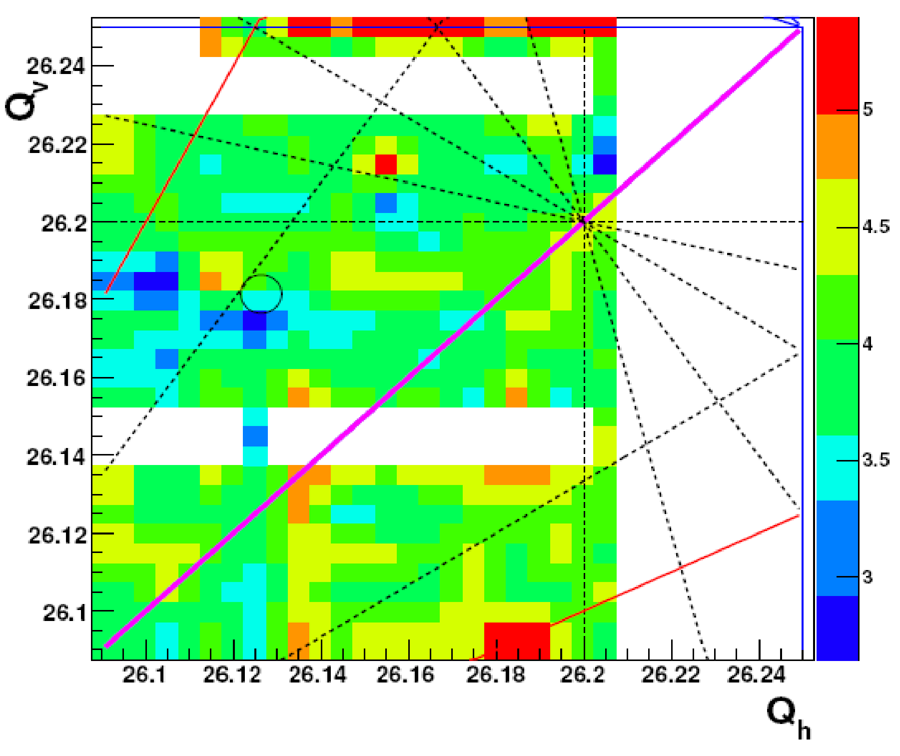
$\Longrightarrow$ Conclusion: Should be OK with ions

Courtesy H. Burkhardt

Working point studies with a pencil proton bunch in the SPS

F. Roncarolo et al.
(AB-Note-2006-008
ABP (MD))

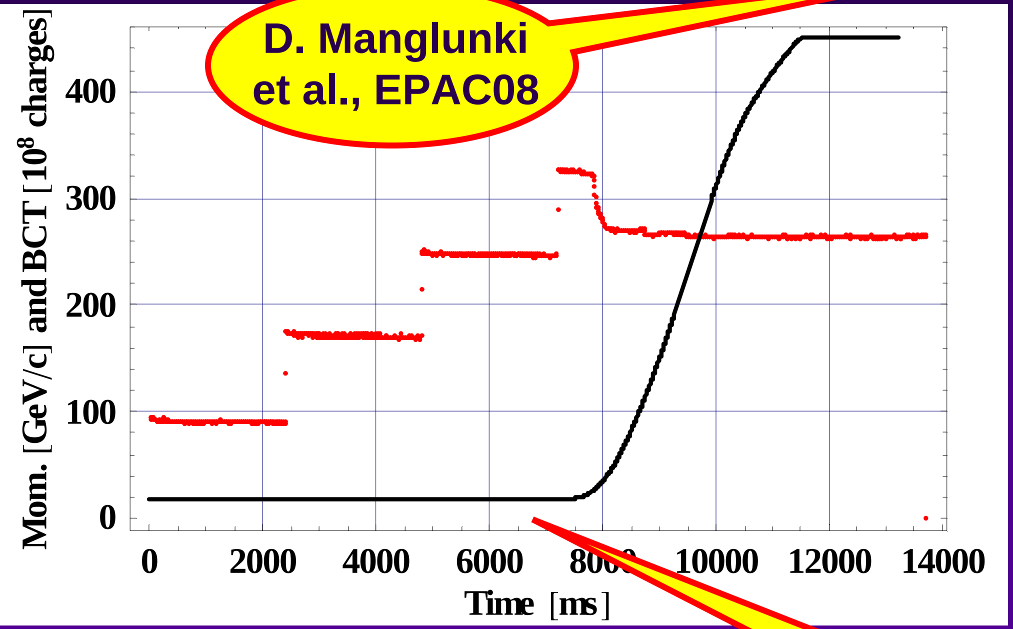
- Done on the LHC pilot bunch (5E9 p/b) at 26 GeV/c
- Stop-band of the integer resonance:
  - 0.015 in H
  - 0.020 in V
- Identification of possible stable operating region:
  - $26.11 < Q_x < 26.14$
  - $26.16 < Q_y < 26.18$



(d) Beam losses

Courtesy F. Roncarolo

Results from early ion commissioning in the SPS in 2007



D. Manglunki et al., EPAC08

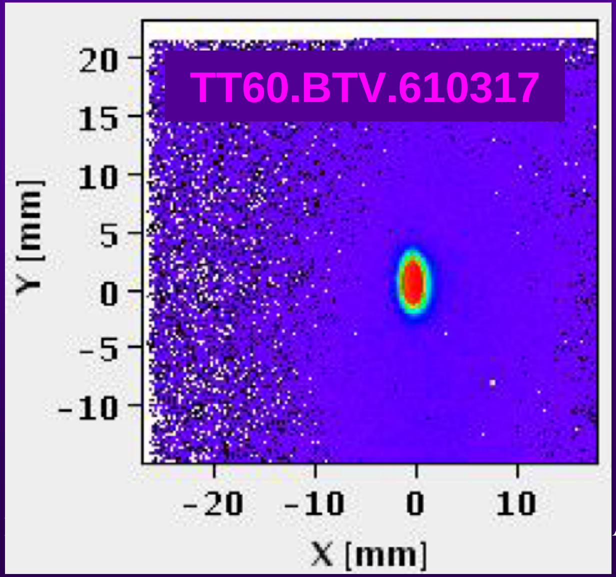
4 bunches of $9\ 10^7$ ions (Pb^{82+})

- Intensity:
  - Design: 295.2 10^8 charges
  - Achieved: 10% smaller than design

- Transverse emittances (rms, norm):
  - Design: 1.2 μm
  - Achieved: 25% smaller than design (the smaller the better!)

(- Tunes optimization: 26.13 / 26.25)

~ 7 s long injection plateau instead of ~ 40 s in the nominal scheme



Beam seen at the beginning of one of the extraction lines towards LHC (TT60/TI2)

CONCLUSION (1/2)

- **PS**
  - **Few % of beam losses are observed during the long (1.2 s = 0.6 million turns) injection flat bottom in the PS with the LHC beam for LHC ($\Delta Q_{sc,y} \approx$ - 0.25)**
  - **Almost no beam losses in the previous years when the PS did not have to compensate for the SPS losses ($\Delta Q_{sc,y} \approx$ - 0.21)**
  - **Chromaticities are high (not corrected):**
    - **Good for the head-tail instability (slower rise-times)**
    - **Not so good for the beam lifetime**
  - **Next challenge: Simulate the PS low energy resistive-wall instability with both linear coupling (used to stabilize the beam) and space charge over 0.6 million turns!**

CONCLUSION (2/2)

- **SPS**
  - **Detailed studies at low energy with Pb^{82+} ions revealed that although the space-charge detuning was as high as ~ - 0.1, ~ no transverse blow up was observed over periods of the order of one minute, confirming the expectations based on studies with protons**