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

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INTRODUCTION

- **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)

- **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 \( \Rightarrow \) Interplay with other mechanisms (ecloud etc.)?
  - Could be a problem for ions (foreseen \( \Delta Q_{sc,y} \approx -0.1 \) for ~ 40 s)
CONTENTS

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  ▪ Why $Q_h$ is $\downarrow$ to $\sim 6.1$ for high-intensity (e.g. CNGS) bunches?
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◆ CONCLUSION
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
INTRODUCTION (3/7)

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

- LHC beam in the PS
  - \( 9.2 \times 10^{12} \text{ ppp} @ 26 \text{ GeV/c} \)
  - \( 10^{12} \text{ ppp} \)
  - \( 4 \text{ b} \)
  - \( \sim 6 \times 10^5 \) turns at low energy

- LHC beam in the SPS
  - \( 3.3 \times 10^{13} \text{ p at } 450 \text{ GeV/c} \)
  - \( \sim 5 \times 10^5 \) turns at low energy
  - \( (\text{i.e. } 4 \times 72 = 288 \text{ bunches with } \sim 1.15 \times 10^{11} \text{ p/b}) \)
$I_{\text{required}} = 4.4 \times 10^{13} \text{p}/\text{p}$

$\varepsilon_{x,y}^{\text{required}} (1\sigma, \text{norm}) \leq 12\ \mu\text{m} @ 400\ \text{GeV}/\text{c}$
INTRODUCTION (5/7)

LHC beam (in the SPS)

- $V_{200\text{MHz}}$ [10^4 V]
- $V_{800\text{MHz}}$ [10^3 V]

CNGS beam (in the SPS)

- BCT [5x10^{10} p]
- BCT [10^{11} p]
- $V_{200\text{MHz}}$ [2 x 10^4 V]

Beam momentum [GeV/c]

Plot #1:
- Time [ms] from 2500 to 7500

Plot #2:
- Time [ms] from 0 to 4000

Plot #3:
- FBCT [10^{10} p]
- 25 ns bucket # from 300 to 600

Plot #4:
- FBCT [10^{10} p]
- 25 ns bucket # from 200 to 800
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) $\implies$ 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) $\implies$ 6 b on $h = 7$ at injection

- Then, compensation for the losses in the SPS (72 b of $1.3E11$ p/b on $h = 84$) $\implies$ 6 b on $h = 7$ at injection with more intensity / bunch
  $\implies$ Losses of few % on the injection plateau are now observed (without emittance growth)
Reminder in 2000 (with 1.15E11 p/b at extraction instead of 1.3E11 now)

\[ \Delta Q_{sc, y} \approx -0.21 \implies \sim \text{No losses on the injection flat-bottom} \]
Crossing the integer or half-integer resonance in the PS (1/2)

$Q_x \approx 6.16$
$Q_y \approx 6.24$

Horizontal bunch profile
+ Gaussian fit

Regime of loss-free core-emittance blow-up

M. Giovannozzi et al., PAC2003
Crossing the integer or half-integer resonance in the PS (2/2)

Measurements

ORBIT simulations

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.

S. Cousineau et al., EPAC2004
Montague resonance in the PS (1/2)

STATIC CASE
(constant tunes from injection to the measurement point)

E. Métral et al., HB2004

Asymmetrical stop-band predicted by simulations

\( Q_y = 6.21 \)

\[ \Delta Q_{inc,x0} = -0.054 \]
\[ \Delta Q_{inc,y0} = -0.109 \]
Montagne resonance in the PS (2/2)

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

\[ T_{rev} = 2.3 \, \mu s \implies \sim 44\,000 \text{ turns} \]

**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).
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

\[ 4 Q_x = 25 \]

Regime of loss-free core-emittance blow-up

Regime where continuous loss occurs \( \Rightarrow \) Due to longitudinal motion

Particles diffuse into a halo
Space charge driven resonance phenomena in the PS (2/6)

G. Franchetti et al., ICFA workshop, Bensheim, Germany, October 2004

Loss dominated regime

Emittance growth dominated regime

$\varepsilon_x / \varepsilon_{x0}$ Exp.

$I/I_0$ Exp.

$I_{oct} = -20$ A

6.25

6.265
Undershoot due to the measurement device

Regime where continuous loss occurs $\Rightarrow$ Due to longitudinal motion

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

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**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.
This mechanism is sometimes observed in the PS with the LHC beam when the tunes are not correctly set.
Decoherence without and with space charge at PS injection (1/2)

Measurements from F. Blas with a nominal LHC bunch

![Graph showing decoherence with and without space charge at PS injection.](image)

- Delta h [25mm/V]
- Time [s] Start = C320 = Kick time
- MD 29/10/2003 1.4 GeV Flat

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

HEADTAIL simulations from E. Benedetto (PHD thesis)

Comparison between HEADTAIL and theory (with chromaticity only)

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 $z_0 = 0.01$ is given to the bunch. The two curves refer to simulations with space-charge taken into account or not.
Why $Q_h$ is $\downarrow$ to $\sim 6.1$ 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 $Q_h$ is $\downarrow$ to $\sim 6.1$ 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 ($\sim 6.20$) with the same amount of losses!

The injection is at C170

$10^{10}$
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)

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

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

$\Rightarrow$ 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

Courtesy F. Roncarolo
Results from early ion commissioning in the SPS in 2007

- Intensity:
  - Design: $2.952 \times 10^8$ charges
  - Achieved: 10% smaller than design

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

- Tunes optimization: $26.13 / 26.25$

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

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 $\sim -0.1$, no transverse blow up was observed over periods of the order of one minute, confirming the expectations based on studies with protons.