RF GYMNASTICS IN SYNCHROTRONS - Part 2 -

R. Garoby
OUTLINE

1. Introduction
2. Longitudinal beam dynamics
3. Single bunch gymnastics
4. Multi-bunch gymnastics
5. Beam gymnastics with broadband RF systems
6. Practical implementation
7. Conclusions
4. “Multi-bunch” gymnastics
Redistribution of particles in phase space

From C. Carli « Creation of hollow bunches… » in Proceedings of EPAC2002

◆ Goal: create a “hollow distribution” in the PS at 1.4 GeV which is favourable for space charge

◆ Principle: asymmetric merging

Voltsages and phases on $h=8$ and $16$

$\Rightarrow$ Effect in phase space as a function of time
4. Multi-bunch gymnastics
   Slip stacking [ref.13, 14]

- **Combines two sets of bunches** (non-diabatically)

- **Principle:** starting from 2 sets of n bunches separated in azimuth and energy, let them drift ("slip") with respect to each other until azimuthal superposition is obtained

- **Technique:** keep the beam bunched by 2 # RF systems
4. Multi-bunch gymnastics
Slip stacking

**Principle of RF generation:**

- Apply 2 different RF frequencies simultaneously – A given beam will not be “too much” disturbed by the other RF if $\Delta f \geq 4 f_s$ – OK if $\Delta E$ is established before injection.

- Apply 2 RF carriers with 100% amplitude modulation at the revolution frequency – Minimizes perturbation of each beam by the other RF + gives means to establish a DE between the 2 sets of bunches.
4. Multi-bunch gymnastics
Slip stacking (experiment)

Slip stacking in the CERN-PS before ejection to the AA

\[ p = 26 \text{ GeV/c} \]

Ejection

\[ \sim 12 \text{ ms} \]

Start of process

1/2 PS turn
4. Multi-bunch gymnastics

Slip stacking

**Performance:**
- depends upon adequate control of RF parameters on multiple harmonics (beam loading at harmonics of the revolution frequency)
  - fast RF feedback on cavities to minimize impedance
  - short-circuiting of gaps of idle cavities
  - non adiabatic process
  - significant blow-up
  - no synchronization with receiving machine
  - phase jitter at ejection

\[\downarrow\]

Not capable to provide short and phase synchronized bunches at ejection

(Fundamental requirements for bunch rotation of anti-protons in the Antiproton Collector as well as in the AD)
4. Multi-bunch gymnastics
Batch compression [ref. 15]

- **Changes distance between bunches** (by changing the harmonic number of the RF holding the beam)
- **Principle:** adiabatically change the focusing voltage for a continuous evolution from the original to the final state
- **Technique:** apply successively and in overlapping steps, RFs with increasing harmonic number
4. Multi-bunch gymnastics
Batch compression (experiment)

Batch compression in the CERN-PS before ejection to the AD
p = 26 GeV/c
4. Multi-bunch gymnastics
Batch compression

Performance:
- depends upon adequate control of RF parameters on the many successive harmonics (beam loading at harmonics of the revolution frequency …)

⇒ Fast RF feedback + one-turn delay feedback on cavities to minimize impedance on multiple harmonics
⇒ Short-circuiting of gaps when cavities are retuned
- no blow-up in theory
- use of beam feedback loops to avoid beam oscillations (damping of unavoidable disturbances) + phase synchronization

↓
very limited blow-up in practice ⇒ short bunches
+ minimized phase jitter
5. Beam gymnastics with broadband RF systems

Isolated sine-wave [ref. 16, 17]

- **Keeps a gap without particles in a debunched beam**
- **Principle:** single sine-wave voltage repeating at the revolution frequency
- **Generates an isolated or a barrier bucket**

- **Performance:** depends upon the precise control of the waveform (tails, beam induced voltage...)

![Diagram showing the principles of beam gymnastics with broadband RF systems](image)
5. Beam gymnastics with broadband RF systems

**Rectangular pulses [ref. 18]**

- **Principle:**
  - a single voltage pulse creates a barrier for the beam circulating in one direction
  - a pair of voltage pulses of opposite polarity creates a barrier bucket

- **Limitation:**
  - Need for dedicated RF system
  - Broadband $\Rightarrow$ low impedance
  $\Rightarrow$ low voltage $\Rightarrow$ long processes

- **Typical example: bunch compression**
5. Beam gymnastics with broadband RF systems

“Momentum mining” [ref. 18]

From C.M. Bhat « Longitudinal Momentum Mining… » in Proceedings of PAC2007

◆ **Principle:**

- “Slowly” create an internal barrier bucket concentrating the particles with a small initial energy spread (= from high density stack core)
- Isolate these particles in a dedicated fraction of the circumference

![Image of RF Voltage & Beam Boundary](attachment:image.png)

![Image of Potential](attachment:image.png)

---

R. Garoby

Ebeltoft – Denmark

8-17 June, 2010
6. Practical implementation

**Example 1: RF gymnastics in the LHC injectors (25 ns bunch spacing)**

1. Division by 2 of the intensity in the PSB (one bunch per ring and double batch filling of the PS)

2. Increase of the injection energy in the PS (from 1 to 1.4 GeV)

3. Quasi-adiabatically splitting of each bunch 12 times in the PS to generate a train of bunches spaced by 25 ns

4. Compression of bunches to ~4 ns length for bunch to bucket transfer to the SPS

5. Stacking of 3-4 PS batches in the SPS and acceleration to 450 GeV

---

**Practical implementation**

**Example 1:** RF gymnastics in the LHC injectors (25 ns bunch spacing)

- **PSB h=1:**
  - Two-batch filling for LHC
  - 1st batch
  - 2nd batch

- **PS h=7:**
  - 2nd batch

- **6 bunches on h=7**
  - 10 MHz system
  - RF = 3.06 MHz
  - 13.2 x 10^{11} ppb

- **18 bunches on h=21**
  - 10 MHz system
  - RF = 9.18 MHz
  - 4.4 x 10^{11} ppb

- **72 bunches on h=84**
  - 40 MHz RF
  - 1.1 x 10^{11} ppb
  - & 20 MHz RF
  - 2.2 x 10^{11} ppb
6. Practical implementation

Example 1: Comments from experience

1. It works!

- Nominal beam characteristics \( N_b = 1.15 \times 10^{11} \, \text{p}/\text{b}, \ \varepsilon_{X,Y} = 3.5 \, \text{mm.mrad} \) are obtained in the SPS at 450 GeV
- Nominal beam is available from Day-1 for the LHC
- Cost was minimized (construction of a limited number of equipment for beam transfer between PS and PS, and of new RF systems in the PSB and PS)

2. However:

- Beam loss is higher than foreseen: ultimate beam characteristics \( N_b = 1.7 \times 10^{11} \, \text{p}/\text{b}, \ \varepsilon_{X,Y} = 3.5 \, \text{mm.mrad} \) cannot be obtained
- Operation is complicated and involves the control of many RF systems: risk of drift and of long duration of repair/re-adjustment
- Reliability is uncertain: many equipments are old and used at the limit of their capability
6. Practical implementation

Example 2: RF gymnastics for more «exotic» bunch trains for LHC

50 ns bunch train

PS injection: 2+4 bunches in 2 batches
Acceleration to 25 GeV
Double splitting at 25 GeV
345 ns beam gap
36 bunches on h=84
0.40 eVs (bunch) 2.2 x 10^{11} ppb
20 % Blow-up (pessimistic)

Triple splitting at 1.4 GeV
PS ejection: 36 bunches in 1 turn
36 bunches on h=84
0.66 eVs (bunch) 4.5 x 10^{11} ppb
42 % Blow-up (voluntary)

Empty bucket
18 bunches on h=21
1.4 eVs (bunch) 13.6 x 10^{11} ppb

6 bunches on h=7

R. Garoby
6. Practical implementation

Example 2: RF gymnastics for more «exotic» bunch trains for LHC

75 ns bunch train

PS ejection:
24 bunches in 1 turn

Acceleration to 25 GeV

Double splitting at 25 GeV

Double splitting at 1.4 GeV

PS injection:
2+4 bunches in 2 batches

2 empty buckets

4 empty buckets

370 ns beam gap

Empty bucket

24 bunches on h=28

0.35 eVs (bunch) 1.1 \times 10^{11} \text{ ppb}

20 \% Blow-up

0.6 eVs (bunch) 2.2 \times 10^{11} \text{ ppb}

20 \% Blow-up

1.0 eVs (bunch) 4.4 \times 10^{11} \text{ ppb}

12 bunches on h=14

7 bunches on h=7

24 bunches

4 empty buckets

2 empty buckets

24 bunches

4 empty buckets

2 empty buckets

370 ns beam gap

Empty bucket

24 bunches on h=28

0.35 eVs (bunch) 1.1 \times 10^{11} \text{ ppb}

20 \% Blow-up

0.6 eVs (bunch) 2.2 \times 10^{11} \text{ ppb}

20 \% Blow-up

1.0 eVs (bunch) 4.4 \times 10^{11} \text{ ppb}

12 bunches on h=14

7 bunches on h=7

24 bunches
6. Practical implementation

Example 2: RF gymnastics for more « exotic » bunch trains for LHC

25 ns bunch train with 120 ns gaps without beam

PS ejection: 56 bunches in 1 turn

Acceleration to 25 GeV

PS injection: 7 (4+3) bunches in 2 batches

Quadruple splitting at 25 GeV

7 x 4 empty buckets

120 ns beam gap

56 bunches on h=84

0.35 eVs (bunch) 1.7 \times 10^{11} \text{ ppb}

40 \% Blow-up (pessimistic)

Double splitting at 1.4 GeV

7 empty buckets

14 bunches on h=21

1 eVs (bunch) 6.8 \times 10^{11} \text{ ppb}

45 \% Blow-up (voluntary)

7 bunches on h=7

1.4 eVs (bunch) 13.6 \times 10^{11} \text{ ppb}
6. Practical implementation

Example 3: Unstacking and bunching in FNAL Recycler using a broadband RF system

From C.M. Bhat « Longitudinal Momentum Mining… » in Proceedings of PAC2007

Goal: capture antiprotons in the dense core of the stack and generate 5 bunches

Principle:
- Momentum mining
- Quasi-adiabatic capture at 7.5 MHz
- Quasi-adiabatic batch expansion to 2.5 MHz
7. Conclusions

◆ Requirements:

- On cavities: accurate control of cavities fields down to very low levels
  ⇒ feedback loops for voltage & phase (I & Q) control
  ⇒ low beam induced voltage = low impedance (passive or active damping)
- On RF drive: accurate control of relative phases between cavities and beam
  ⇒ Beam feedback loop(s) but at which frequency ?
- On beam: reproducible initial conditions and stability
  ⇒ reproducibility of beam delivered by lower energy accelerators
  ⇒ reproducibility of lower energy beam manipulations
  ⇒ instabilities damping
7. Conclusions

◆ Practical limitations:

- duration of gymnastics (impossible in fast cycling accelerators)
- accelerator characteristics (acceptance, flat-top duration, …)
- RF hardware characteristics (frequency range, number of simultaneous frequencies, peak voltage, sweep rate, …)
- drift or modulation of the field in the main dipole during the process (orbit bumps before ejection for example) must be taken into account and compensated as far as possible
- adjustment and maintenance (setting-up time, compensation of intensity dependence, uncontrolled beam loss …)
7. Conclusions

◆ Other limitations:

Your imagination (and patience...)!
Simulation (in the SPS)

from S. Hancock

BUNCH PAIR MERGING IN THE SPS

Iter  0  0.000E+00 sec

\begin{tabular}{|c|c|c|c|}
\hline
$H_0$ (MeV) & $S_B$ (eV s) & $E_0$ (MeV) & $h$ \\
1.000E+03 & 1.3158E+01 & 8.4101E+05 & 924 \\
2.1221E+03 & 0.0000E+00 & 1.6143E-03 & 1948 \\
2.3085E-05 & 3.1515E+00 & \text{3500} & \text{1.000E+01} \\
\hline
\end{tabular}

\begin{center}
\text{RF VOLTAGE (MeV/c)}
\end{center}

\begin{center}
\text{E - $E_S$ (GeV)}
\end{center}

\begin{center}
\text{\theta (degree)}
\end{center}

\begin{center}
\text{\theta (degree)}
\end{center}

\begin{center}
\text{\theta (degree)}
\end{center}
References


[2] M.H. Blewett (editor), Theoretical aspects of the behaviour of beams in accelerators and storage rings, CERN 77-13, pp.63-81


[4] R. Garoby, A Non-Adiabatic Procedure in the PS to supply the Nominal Proton Bunches for LHC into 200 MHz RF Buckets in SPS, CERN PS/RF/Note 93-17


References

[9] R. Garoby, A Non-Adiabatic Procedure in the PS to supply the Nominal Proton Bunches for LHC into 200 MHz RF Buckets in SPS, CERN PS/RF/Note 93-17


References

