CAS RF

Ebeltoft – Denmark

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RF GYMNASTICS IN SYNCHROTRONS

- Part 2 -

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OUTLINE

Part 1

1. Introduction
2. Longitudinal beam dynamics
3. Single bunch gymnastics
4. Multi-bunch gymnastics

Part 2

5. Beam gymnastics with broadband RF systems
6. Practical implementation
7. Conclusions

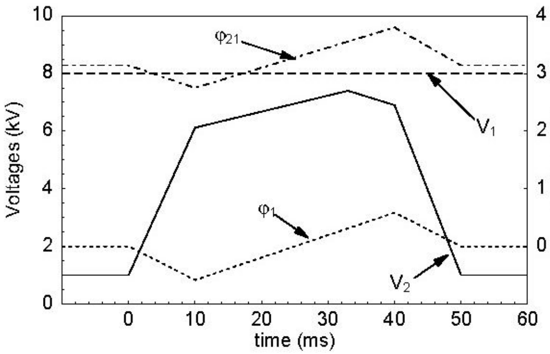
4. "Multi-bunch" gymnastics

Redistribution of particles in phase space

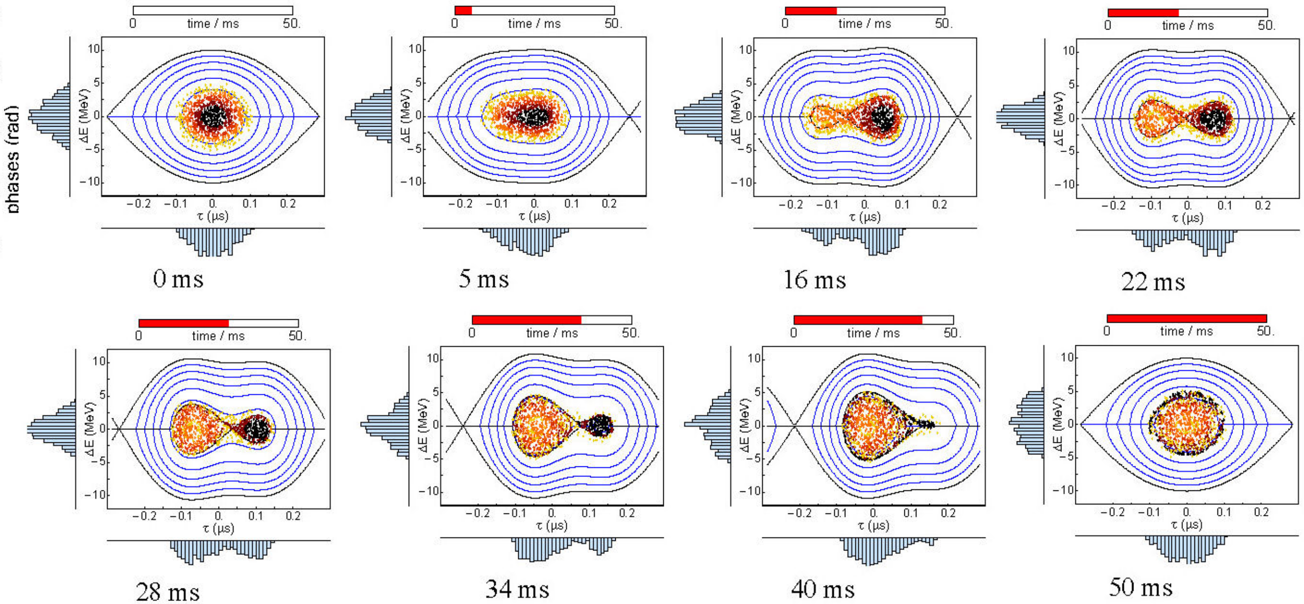
From C. Carli « Creation of hollow bunches… » in Proceedings of EPAC2002

- Goal: create a "hollow distribution" in the PS at 1.4 GeV which is favourable for space charge
- Principle: asymmetric merging

Voltages and phases on h=8 and 16



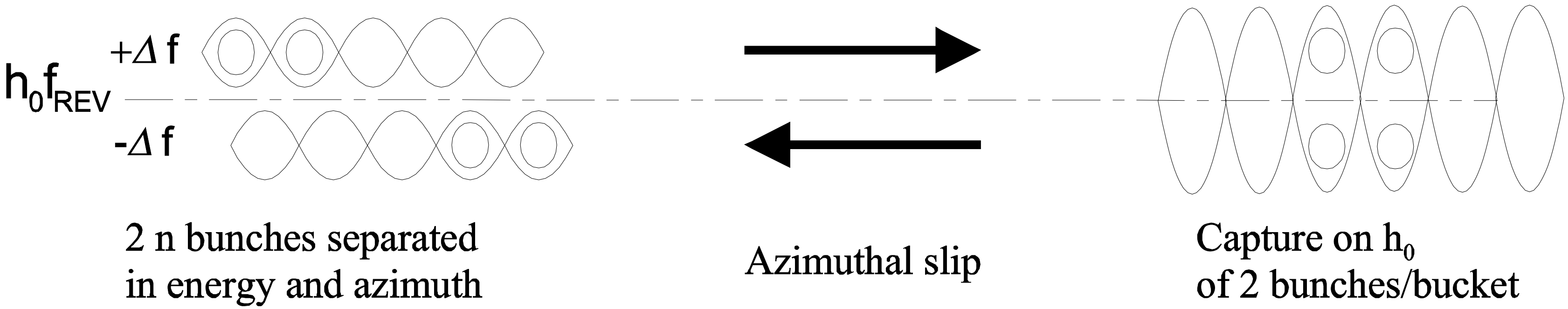
⇒ Effect in phase space as a function of time



4. Multi-bunch gymnastics

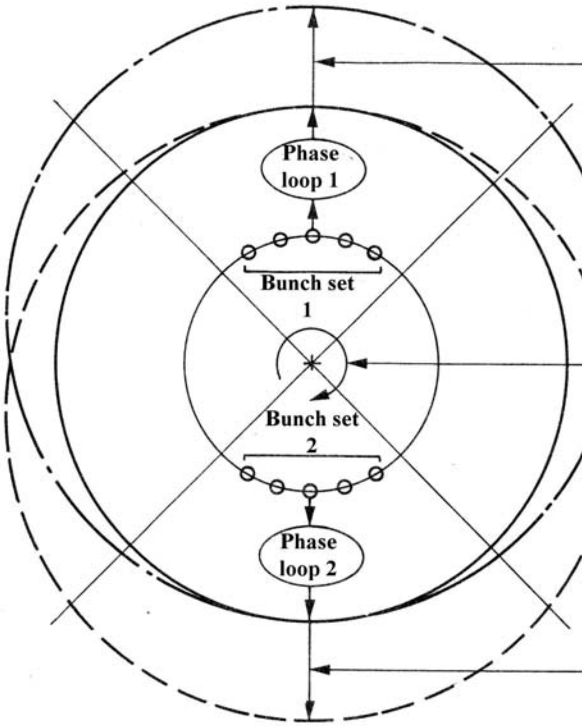
Slip stacking [ref.13, 14]

- **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 ΔE is established before injection.**
  - **Apply 2 RF carriers with 100 % amplitude modulaton 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.**

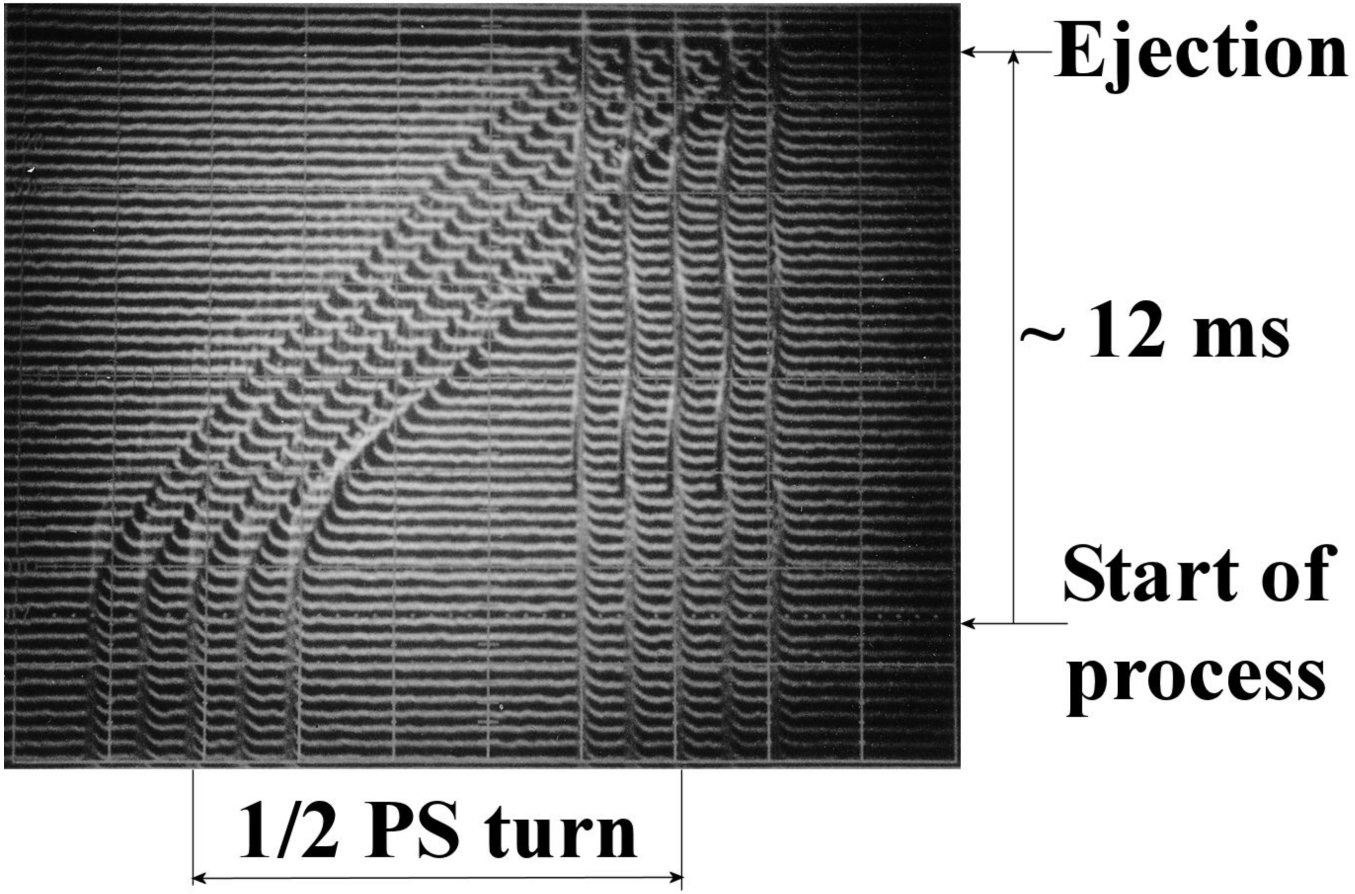


4. Multi-bunch gymnastics

Slip stacking (experiment)

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

p = 26 GeV/c



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

⇓

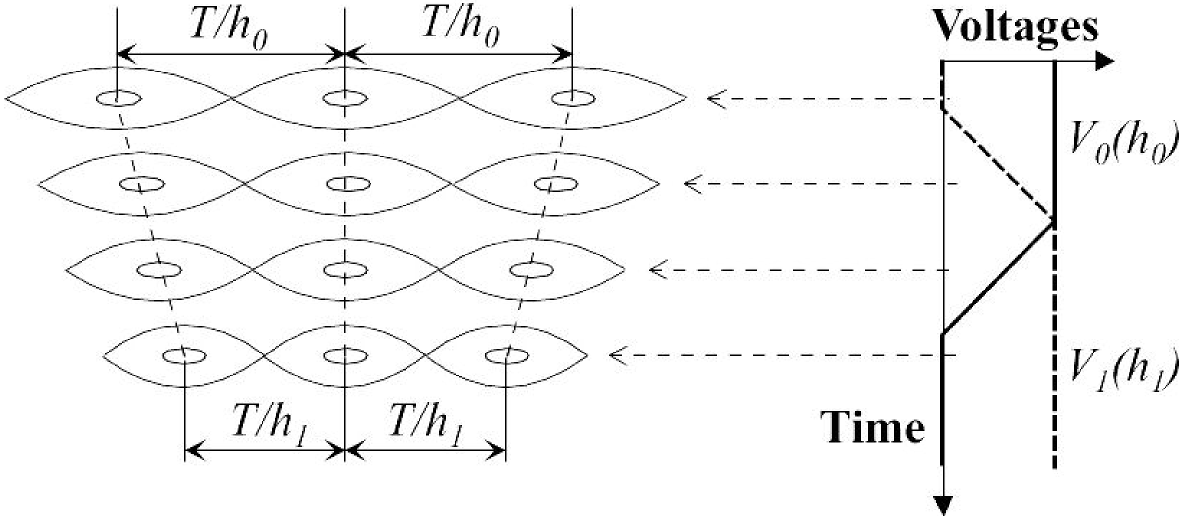
Not capable to provide short and phase synchronized bunches at ejection

(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

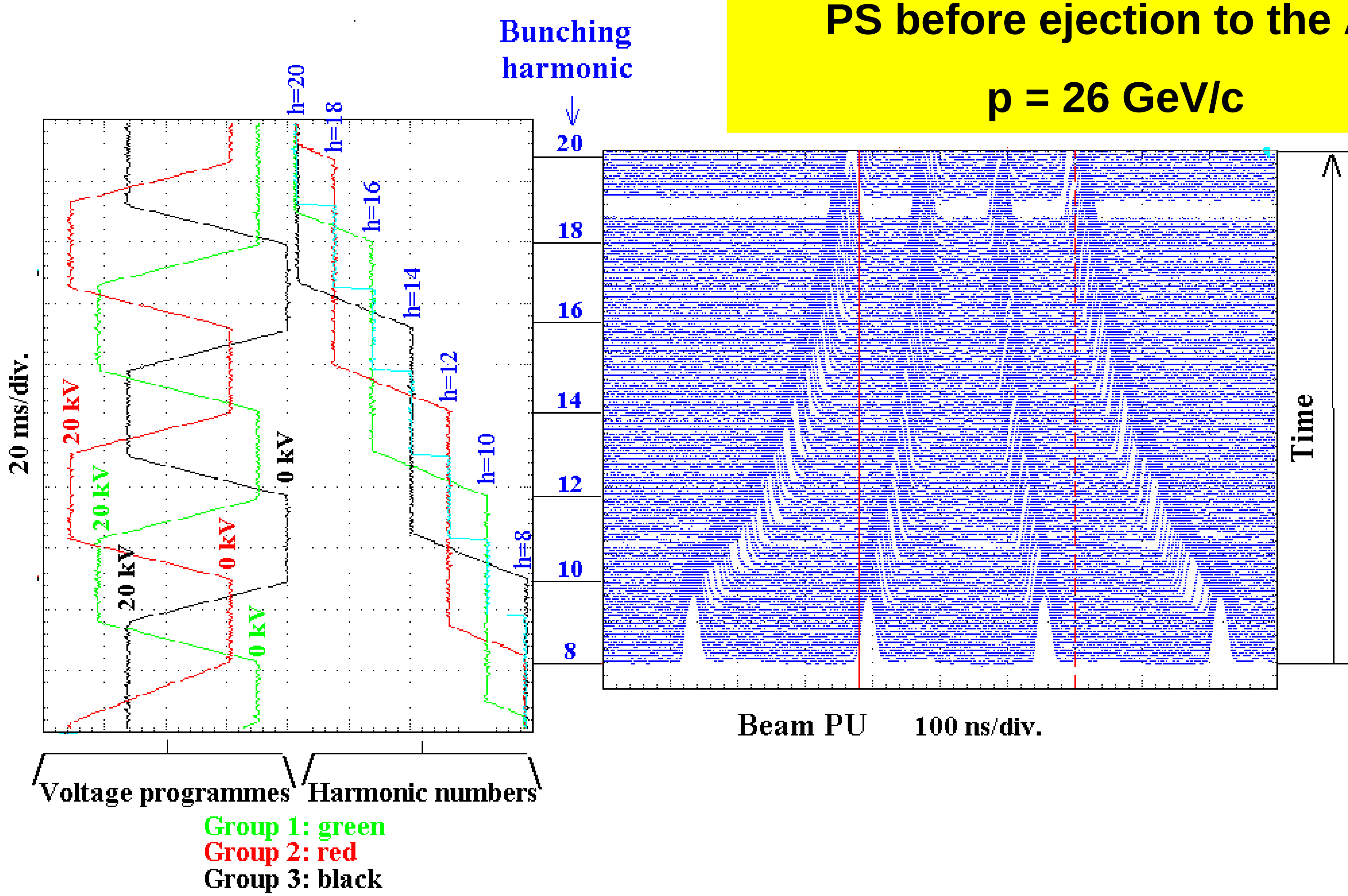


4. Multi-bunch gymnastics

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

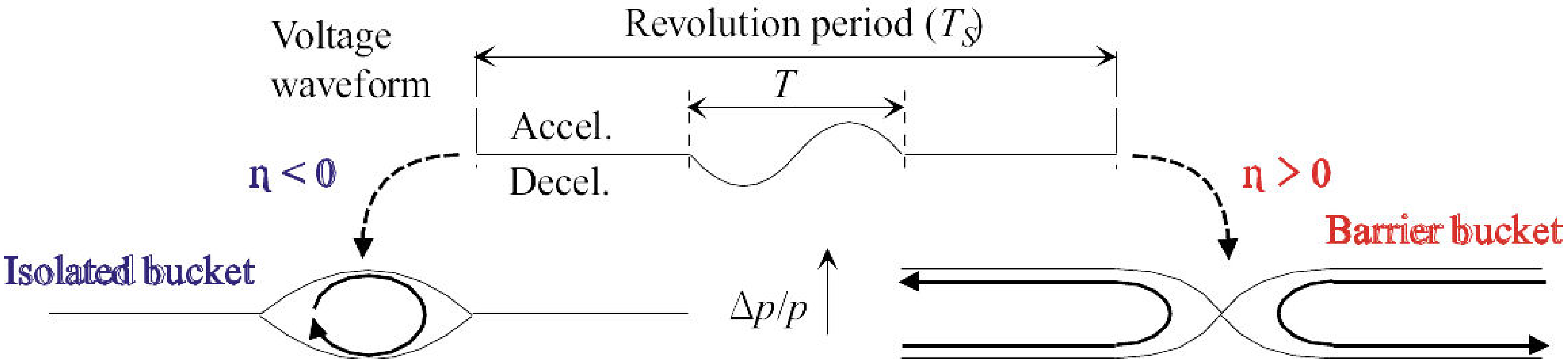
⇓

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**

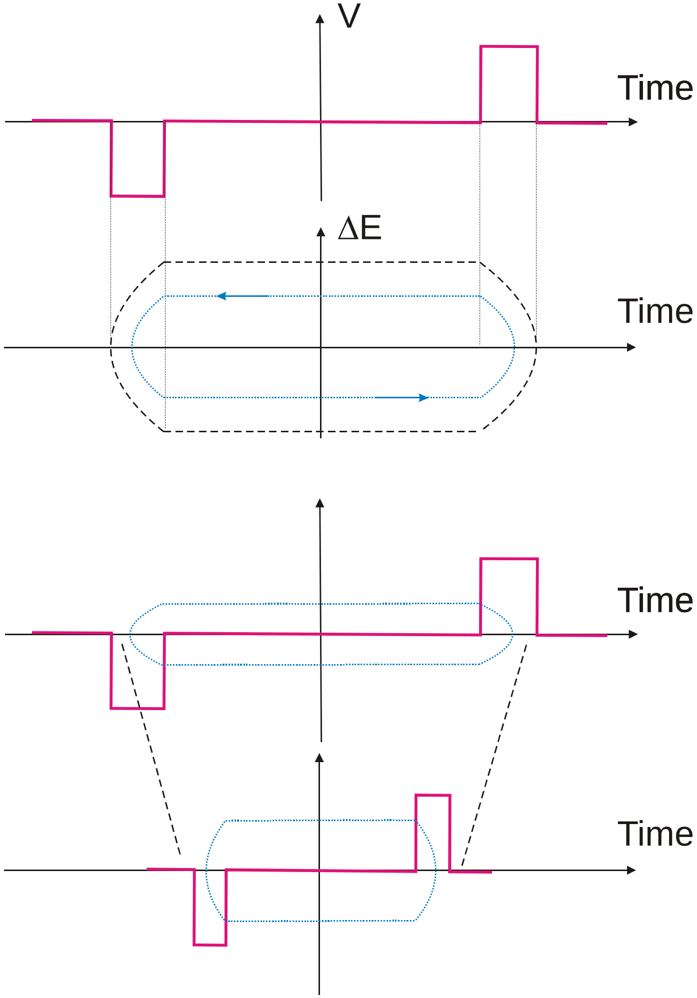


- **Performance: depends upon the precise control of the waveform (tails, beam induced voltage…)**

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 ⇒ low impedance**

  ⇒ low voltage ⇒ long processes
- **Typical example: bunch compression**

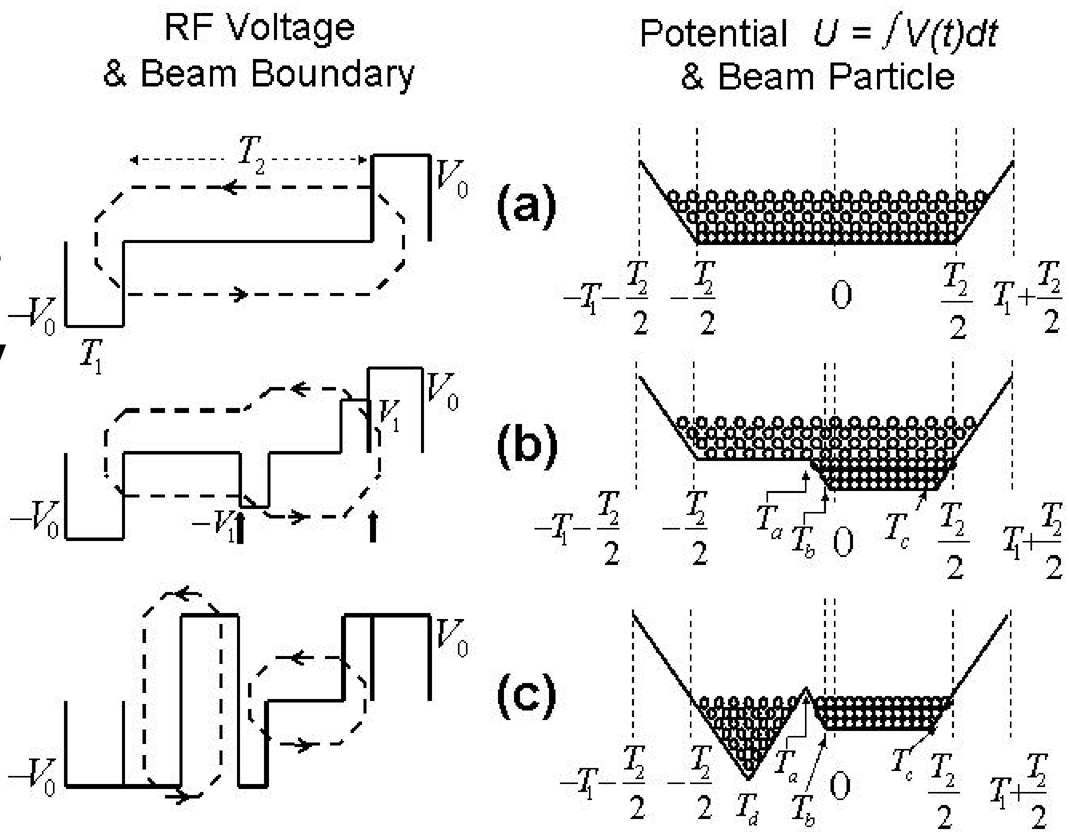


5. Beam gymnastics with broadband RF systems
"Momentum mining" [ref. 18]

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

◆ Principle:

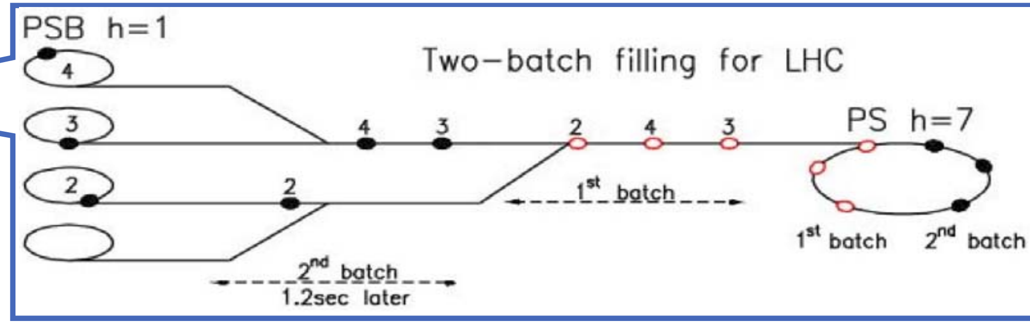
- **"Slowly" create an internal barrier bucket concentrating the particles with a small initial energy spread (= from high density stack core)**
- **Isolate these particles in a dedicated fraction of the circumference**



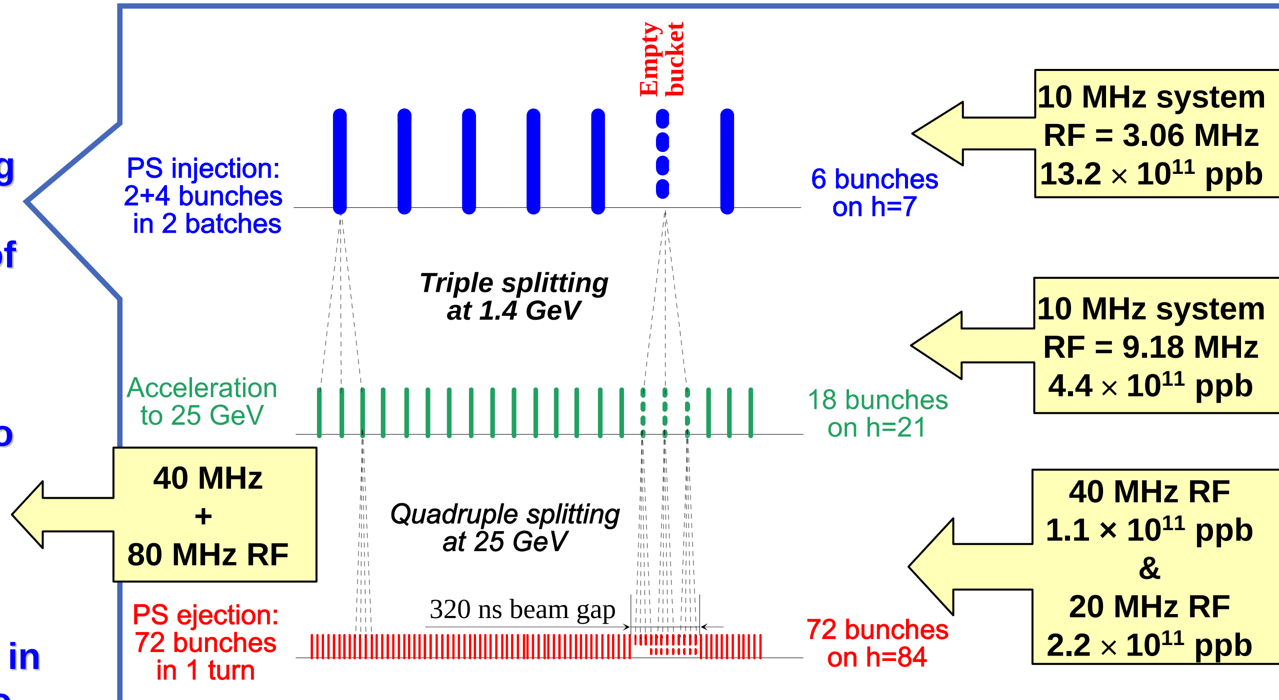
6. Practical implementation

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 ~4ns length for bunch to bucket transfer to the SPS
5. Stacking of 3-4 PS batches in the SPS and acceleration to 450 GeV



6. Practical implementation

Example 1: Comments from experience

1. It works!

- Nominal beam characteristics (N_b=1.15 10^{11} p/b, $\varepsilon_{X,Y}$ =3.5 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)

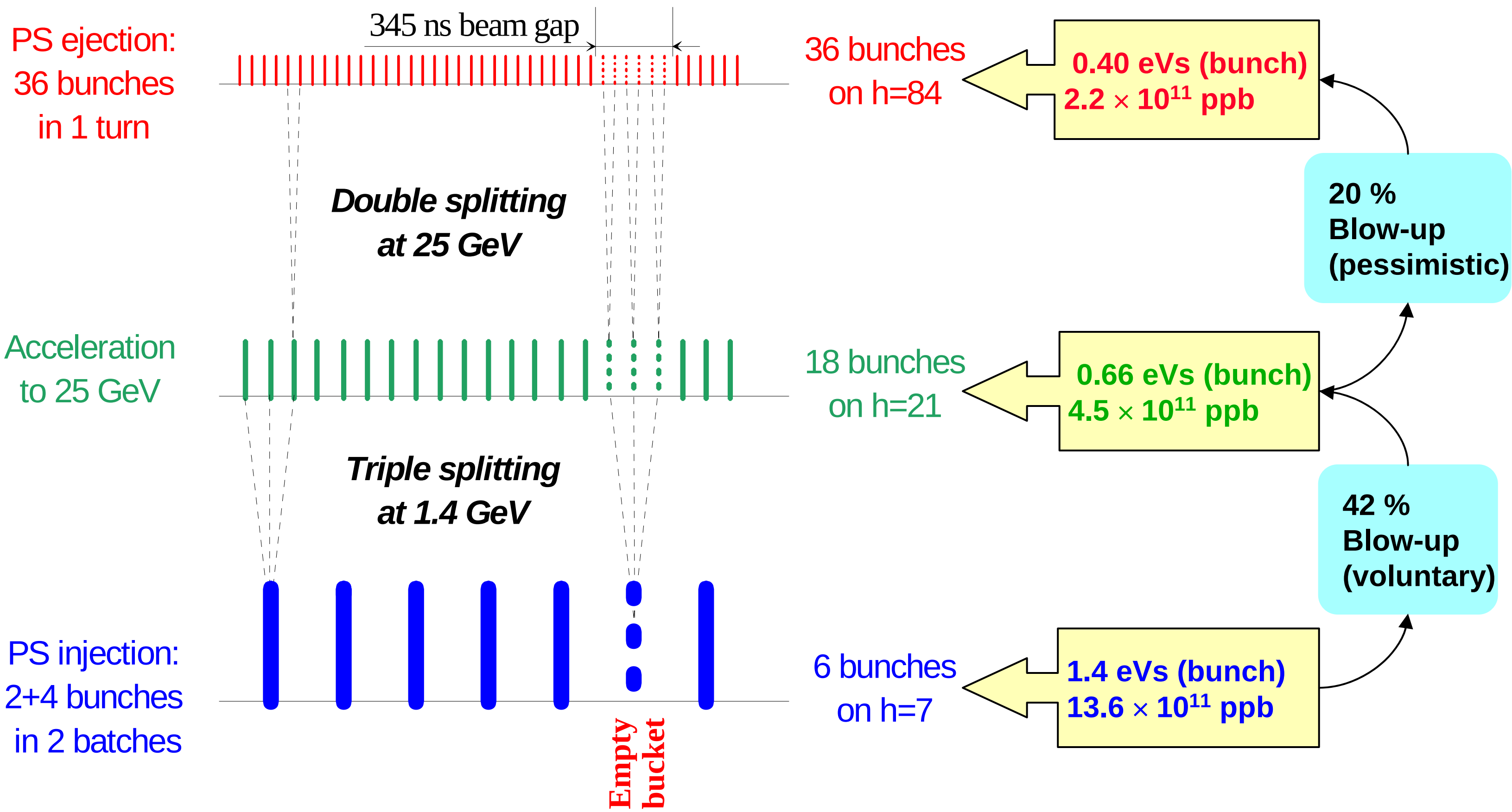
2. However:

- Beam loss is higher than foreseen: ultimate beam characteristics (N_b=1.7 10^{11} p/b, $\varepsilon_{X,Y}$ =3.5 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

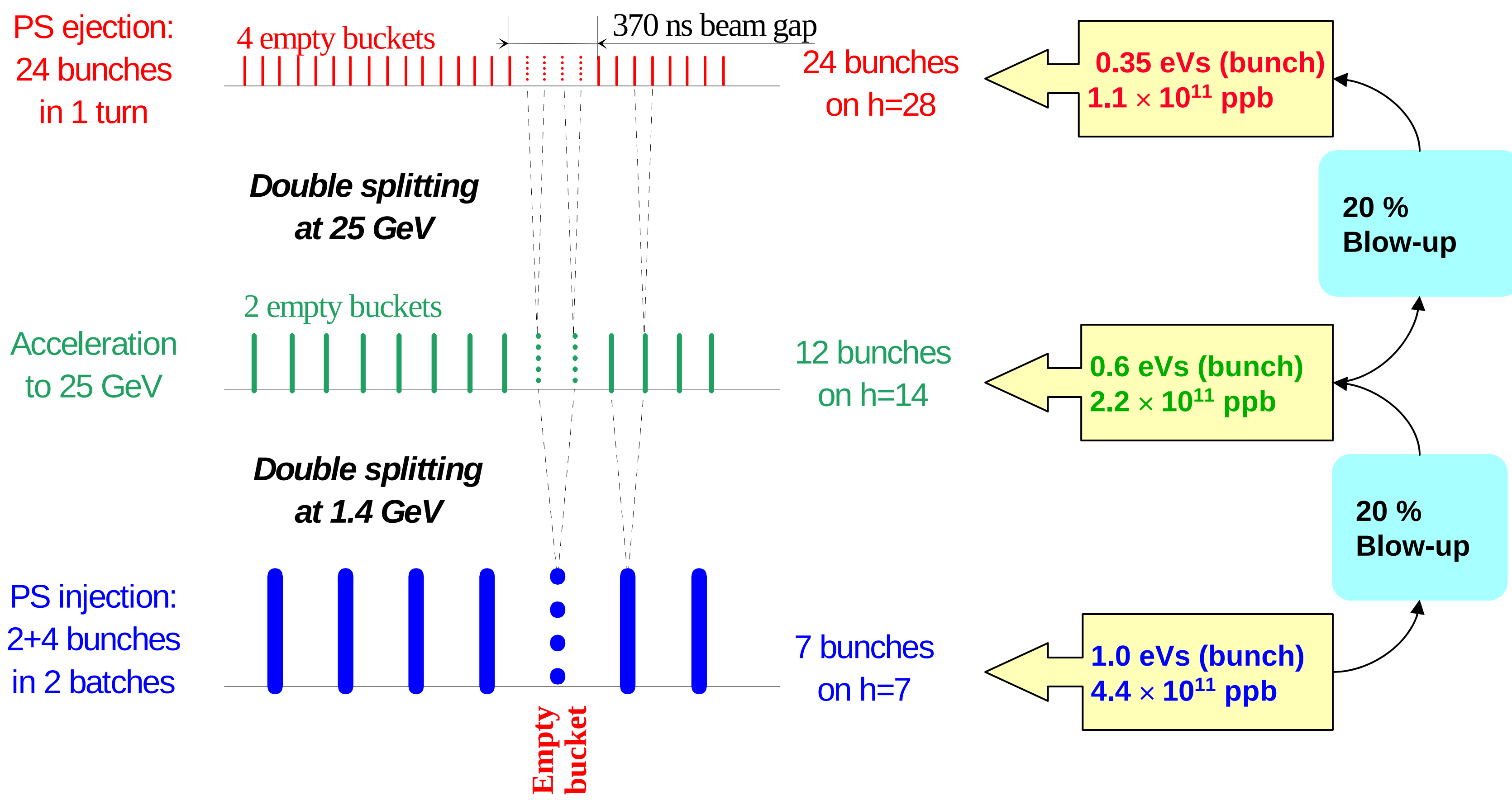
50 ns bunch train



6. Practical implementation

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

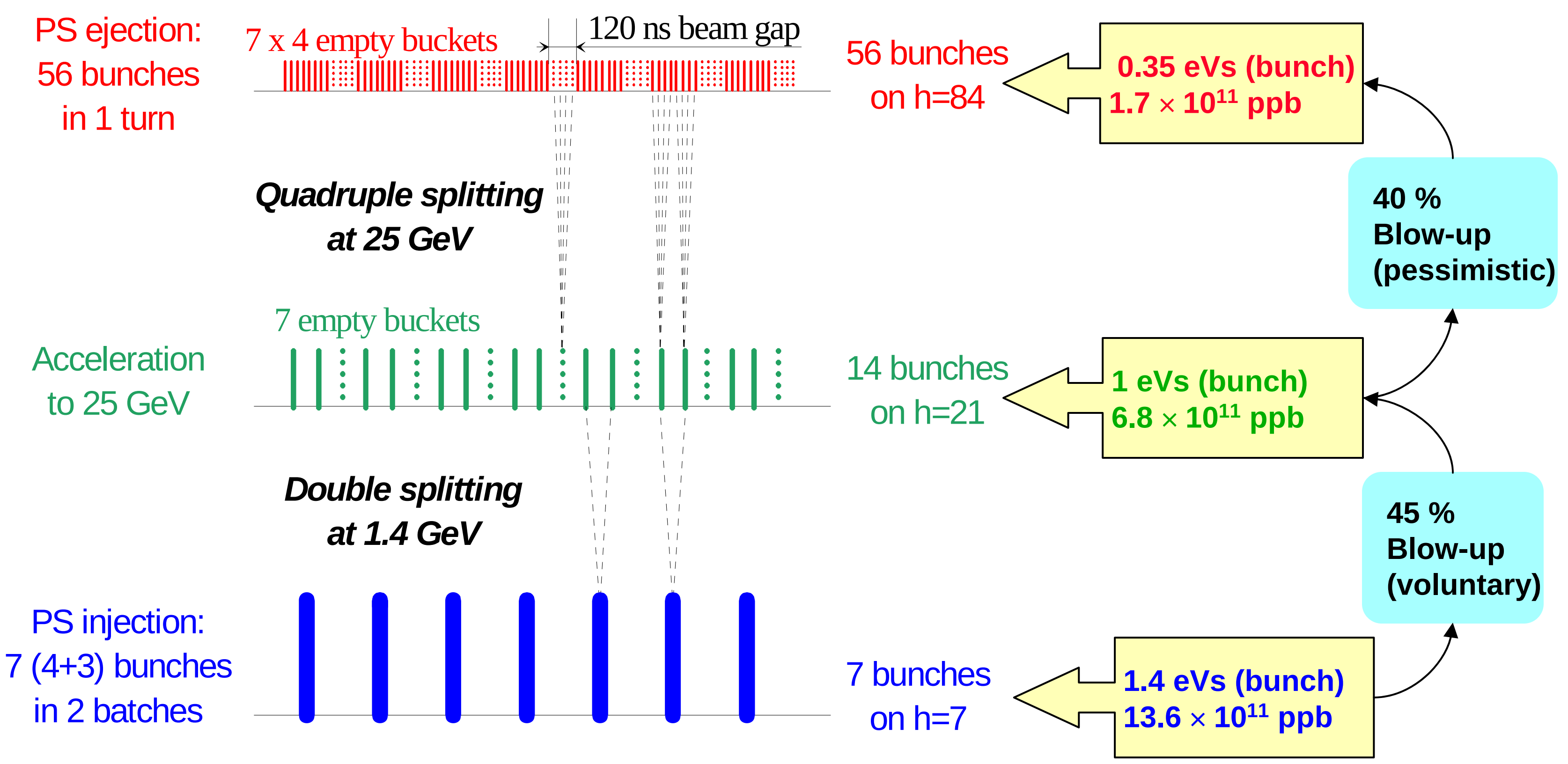
75 ns bunch train



6. Practical implementation

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

25 ns bunch train with 120 ns gaps without beam



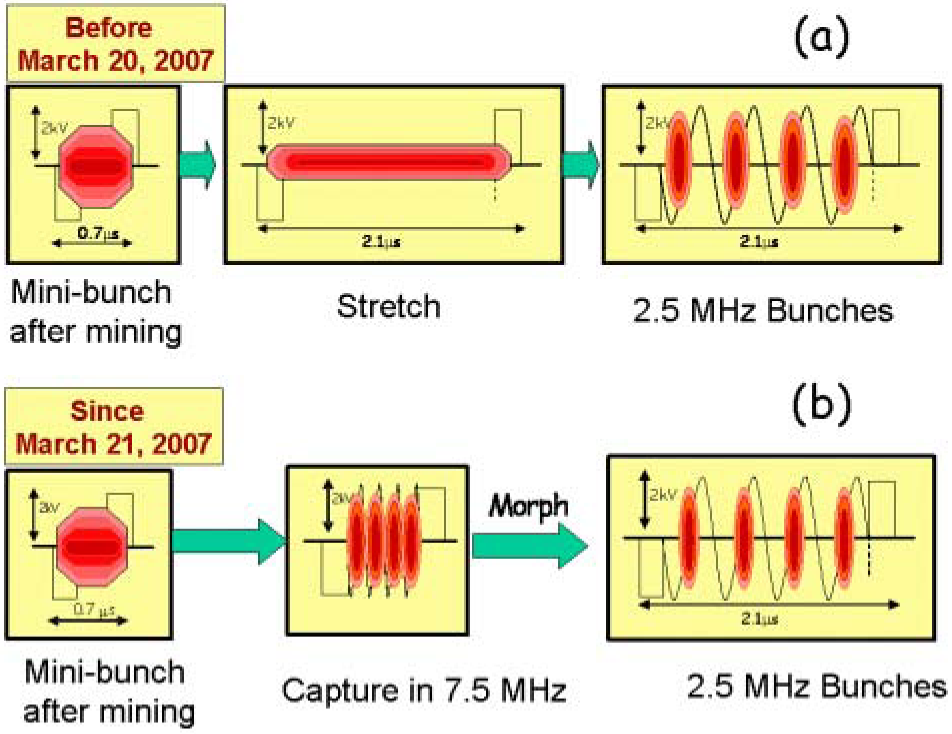
6. Practical implementation

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

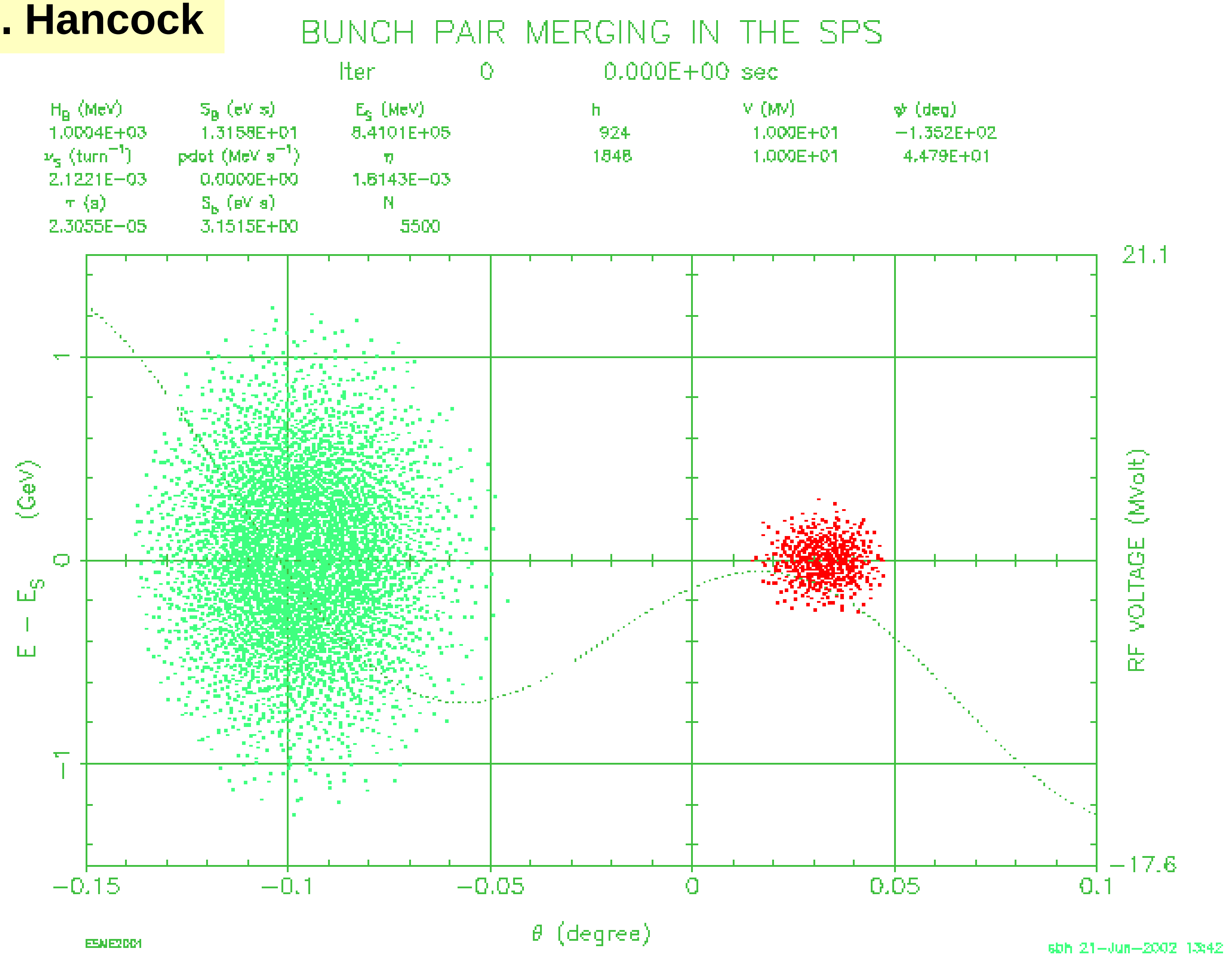
- **Other limitations:**

Your imagination (and patience...) !

THANK YOU
FOR YOUR ATTENTION

Simulation (in the SPS)

from S. Hancock



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