Brief history of RF Gymnastics in the PS

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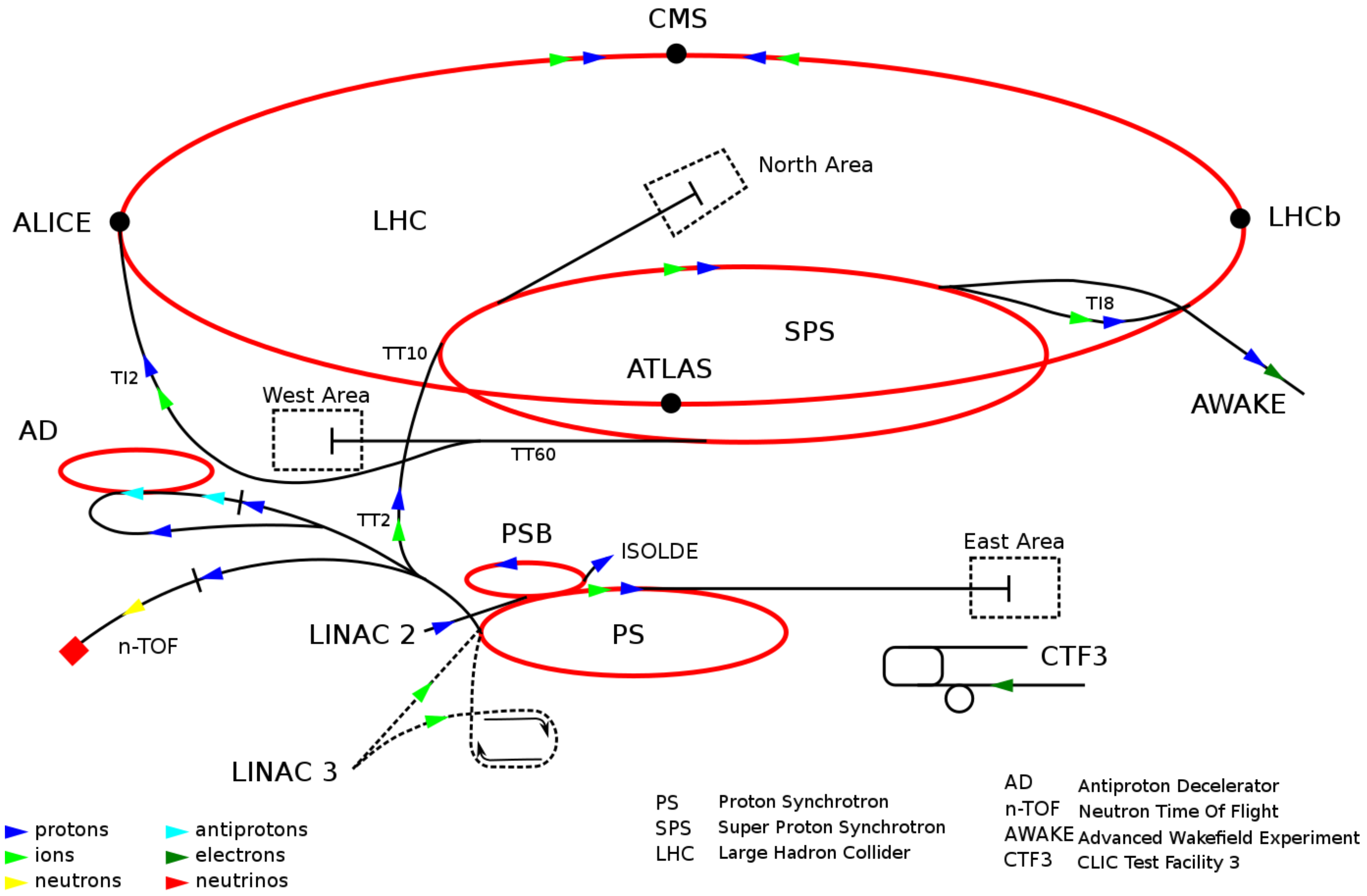
The PS is a mandatory gateway for high energy physics at CERN

The successive high energy physics Programmes (PS fixed target experiments, ISR, SPS fixed target, SPS p-pbar collider, LEP, LEAR, AA/AC/AD, Heavy ions, CNGS, LHC, HL-LHC…) have all counted on the PS.

Modifications/improvements including special RF gymnastics* were often necessary to meet their changing requirements.

- Non-trivial modulation of RF parameters (amplitude, phase, frequency) to modify the longitudinal characteristics of the beam.



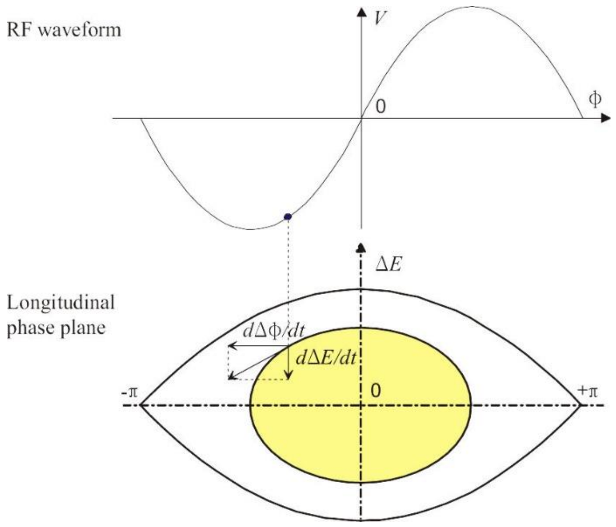
Initial period (1959 ~1965)

- **RF Equipment**

  First generation of h=20 main accelerating system (50 MeV injection); 16 cavities.

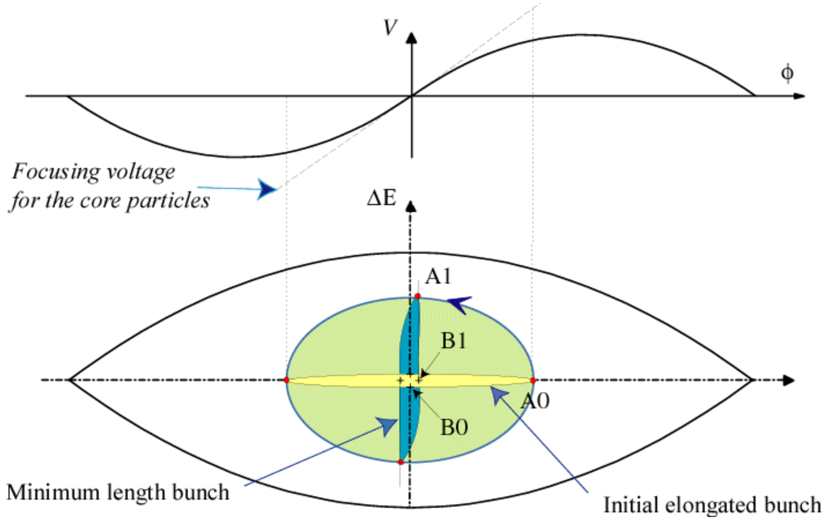
- **RF Gymnastics**

  Longitudinal phase plane: phase stability

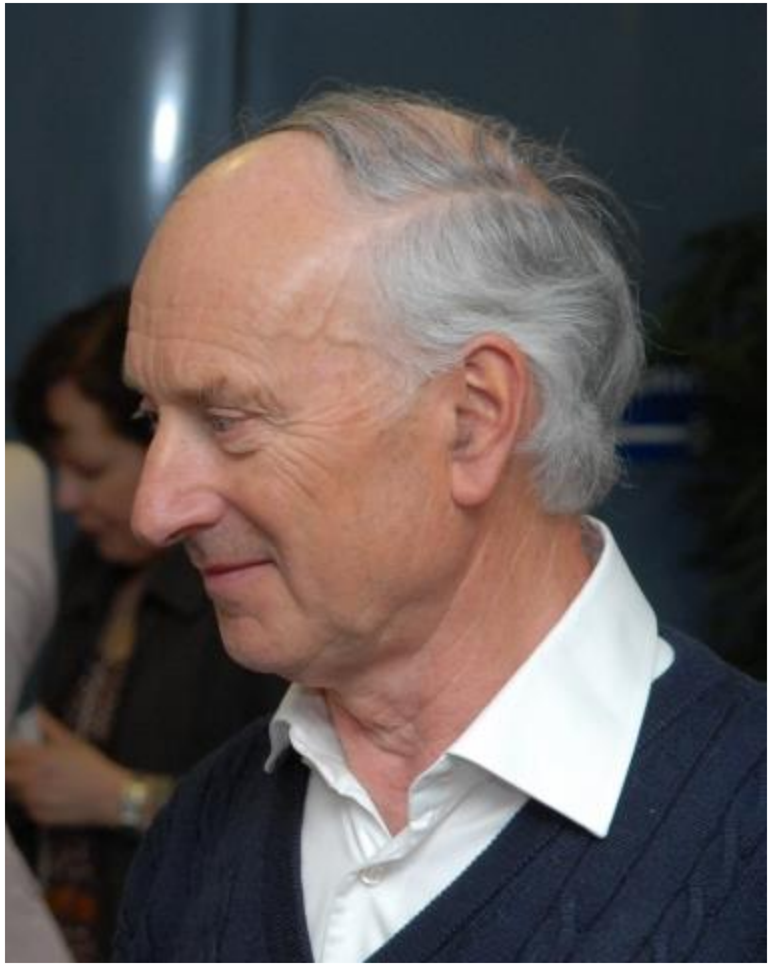


24 November 1959
First successful acceleration of beam through transition!

Bunch rotation



Ten-fold increase of intensity with PSB (800 MeV) SPS construction and commissioning (until ~1978)



During that period Daniel Boussard (1937-2018):

- Diagnosed and explained many high beam intensity effects (e.g. Microwave instability)
- Led the development of hardware solutions to beam dynamics issues (e.g. Feedforward beam-loading compensation)
- Proposed and implemented innovative RF gymnastics including for the p-pbar programme
- Inspired the accelerator community and set the scene for his successors…

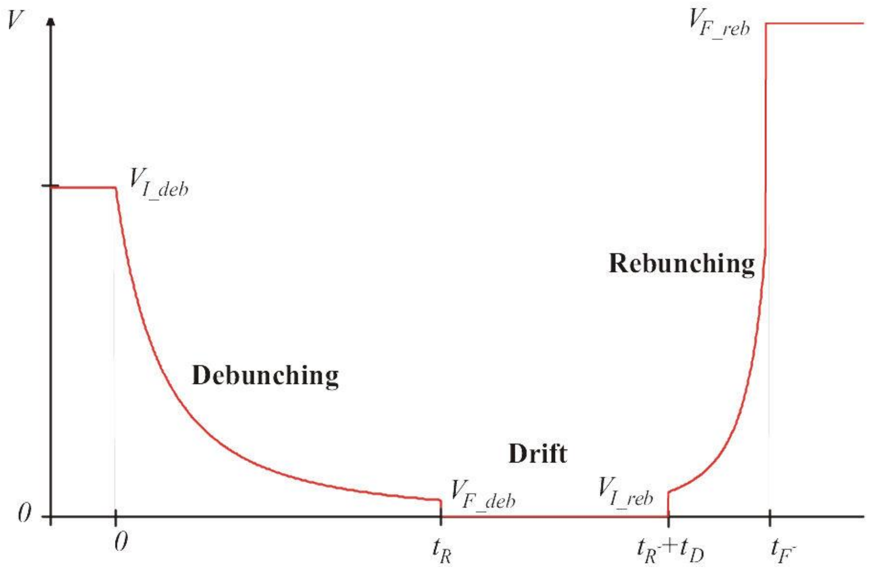
Ten-fold increase of intensity with PSB (800 MeV) SPS construction and commissioning (until ~1978)

- **RF Equipment**
  - Second generation of h=20 accelerating system (800 MeV injection); 10+1 cavities equipped with gap short-circuiting relays and feedforward beam-loading compensation
  - Installation of 200 MHz RF cavities (h=420 at 14 GeV) equipped with impedance reduction solutions when active and when idle

⇒ **« Quasi-adiabatic debunching-rebunching »**

from h=20 to h=420 with decomposition of cavities in 3 groups successively short-circuited to minimize the final voltage (V_{F_deb})

- Implementation of feedforward beam-loading compensation
- Observation and diagnostics of microwave instability during debunching



Ten-fold increase of intensity with PSB (800 MeV)
SPS construction and commissioning (until ~1978)

⇒ **« Controlled longitudinal blow-up »**

of a beam bunched on a low harmonic number (h<20), superimposing a phase modulated 200 MHz RF voltage

Example: Longitudinal controlled Blow-up at 1.4 GeV

V(h=8) = 55 kV

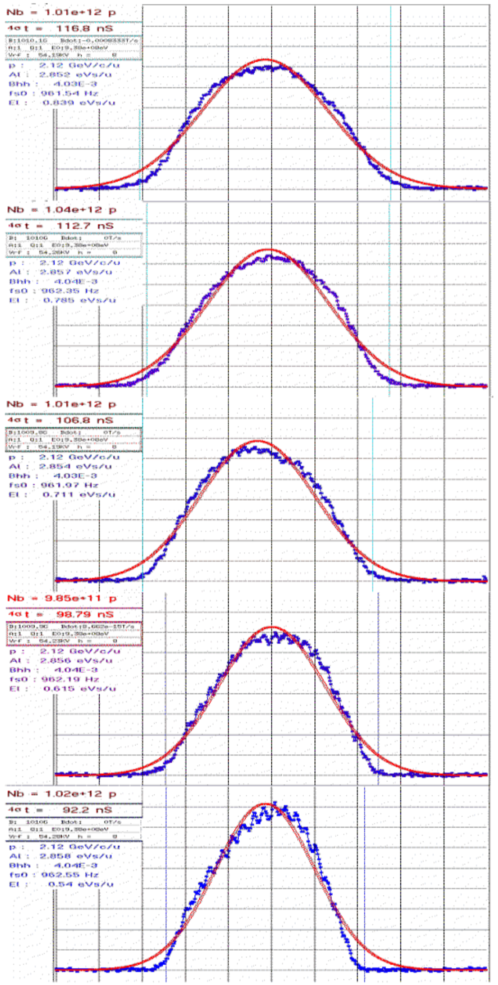
V(h=458) = 3 kV

$\alpha = \pi$ rad

f_{Synch} = 0.95 kHz

f_{Mod} = 7 kHz

Duration = 20 ms



t = 20 ms (final bunch) ε = 0.84 eVs

t = 15 ms ε = 0.78 eVs

t = 10 ms ε = 0.71 eVs

t = 5 ms ε = 0.62 eVs

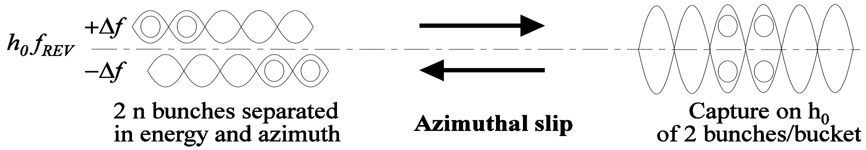
t = 0 ms (initial bunch) ε = 0.54 eVs

P-Pbar programmes (1978-1996)

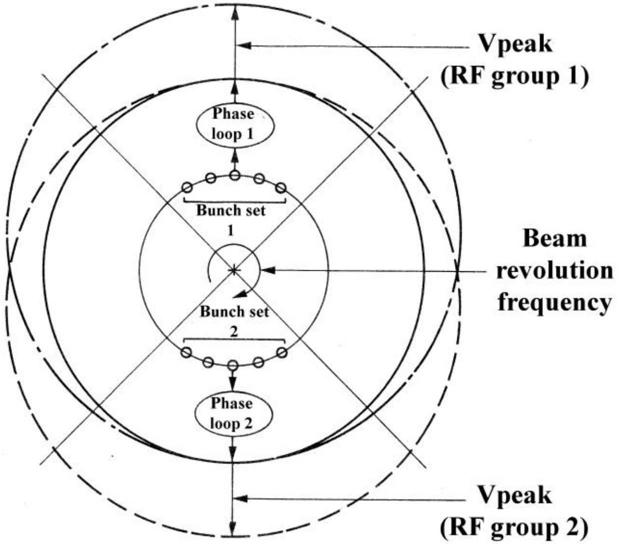
- Demanding requirements for anti-protons production because the duration of the proton pulse cannot exceed the revolution period of the Pbar Accumulator/Collector (~1/4 of the PS).

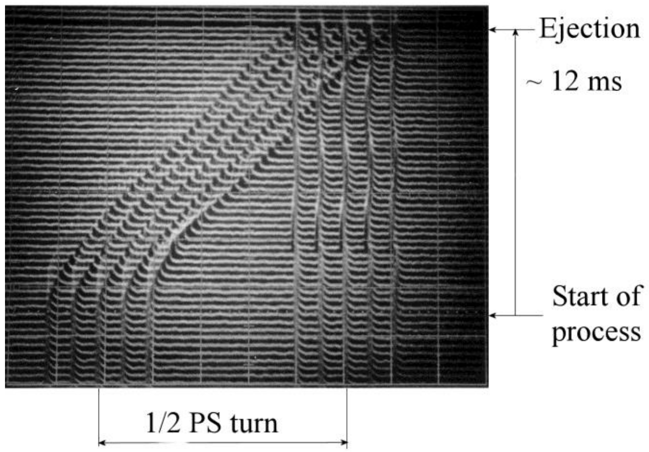
⇒“Slip stacking” was tried at injection from the PSB and used in operation at 26 GeV

Principle:



Implementation at 26 GeV
« Recombination » (D. Boussard):
Two different RFs modulated in amplitude at the revolution frequency control two sets of bunches intially located in diametrically opposite locations.



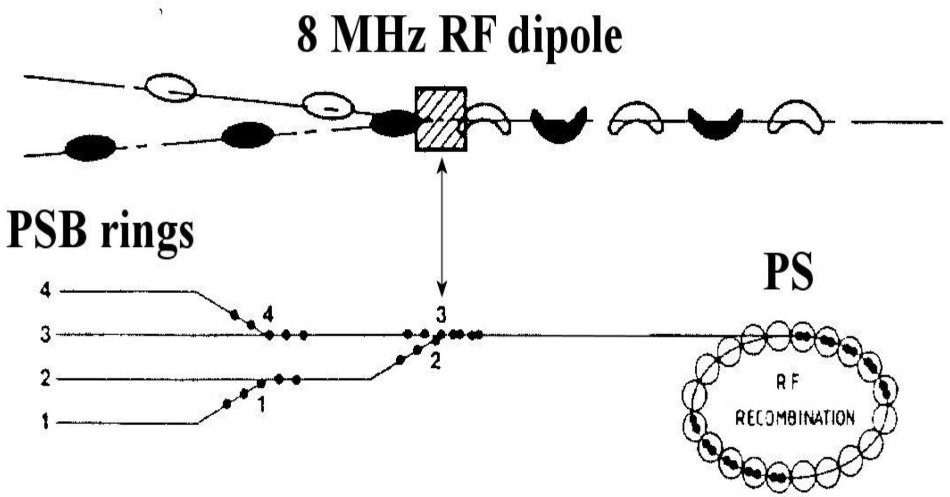


P-Pbar programmes (1978-1996)

⇒“Funneling” was also used at injection from the PSB and used simultaneously with “Recombination”

Principle:

An RF dipole in the PSB to PS transfer line deflects the beam transversely so that PSB bunches can be interlaced and captured two by two in PS RF buckets (h=20). Imperfect process both in the longitudinal and transverse phase planes.



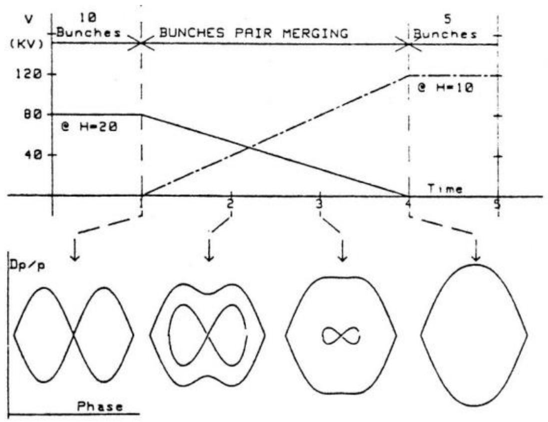
P-Pbar programmes (1978-1996)

⇒"Merging and Batch compression" was proposed in 1985

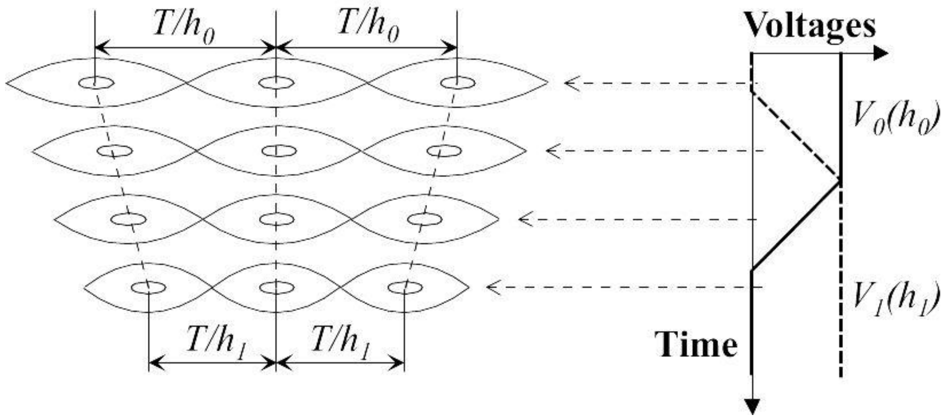
Principle:

Two steps process with

- Merging of 10 consecutive bunches (h=20) filling ½ of the PS circumference into 5 (h=10)

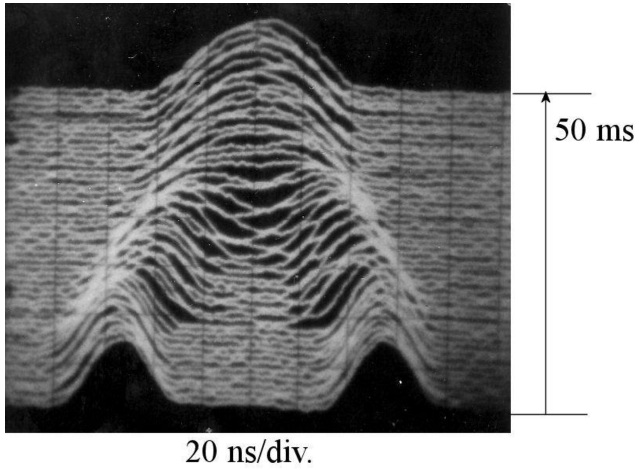


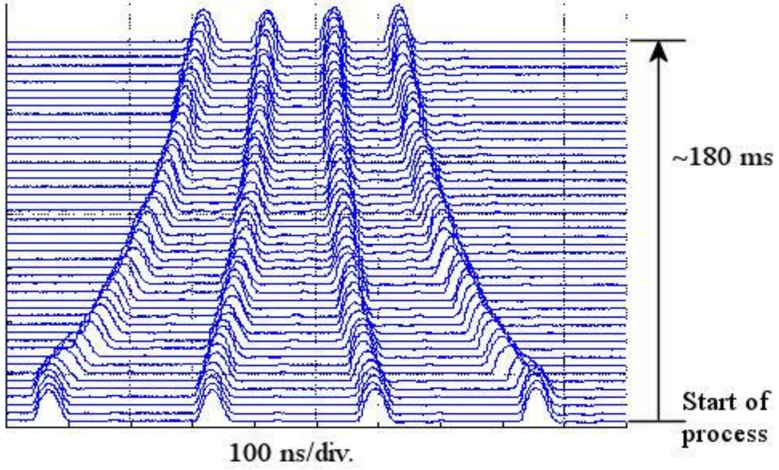
- Batch compression by progressively Increasing the harmonic number from 10 to 20



P-Pbar programmes (1978-1996)

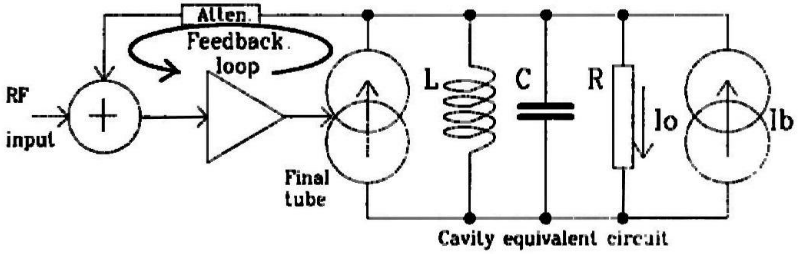
« Merging and Batch Compression » ultimately worked in regular operation at high beam intensity

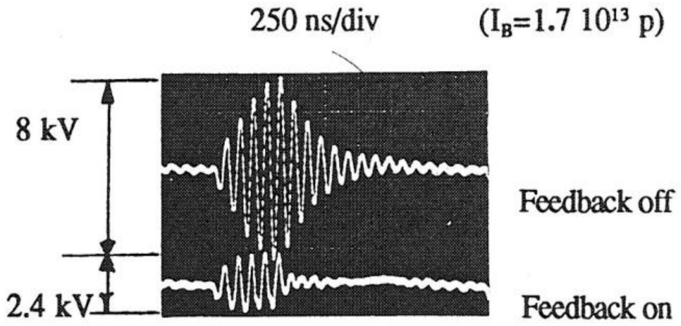




… after an extensive effort to reduce cavities impedances with

fast RF feedback **and one-turn delay feedback (invented by D. Boussard for the SPS)**

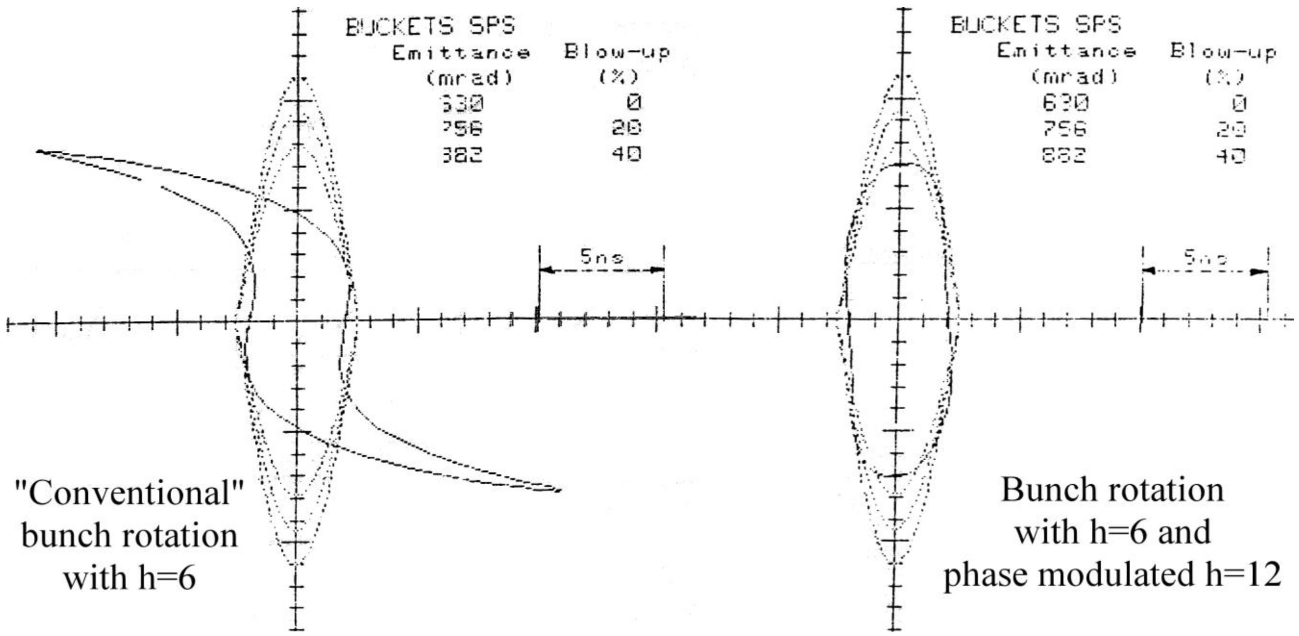




P-Pbar programmes (1978-1996)

- Demanding requirements at transfer of anti-protons to the SPS because of the need to “squeeze” the large emittance bunch to <5 ns for capture in an SPS bucket

⇒ Acceleration on h=6 and “Bunch rotation” at 26 GeV combining RF on h=6 with phase and amplitude modulated RF on h=12



"Conventional" bunch rotation with h=6

Bunch rotation with h=6 and phase modulated h=12

Protons for LHC: initial preparation (1991 ~1999)

- Need for 25 ns spaced bunches with high transverse brightness

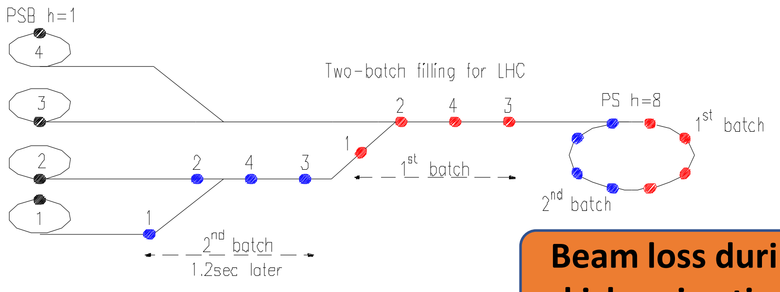
⇒ Four steps process with:

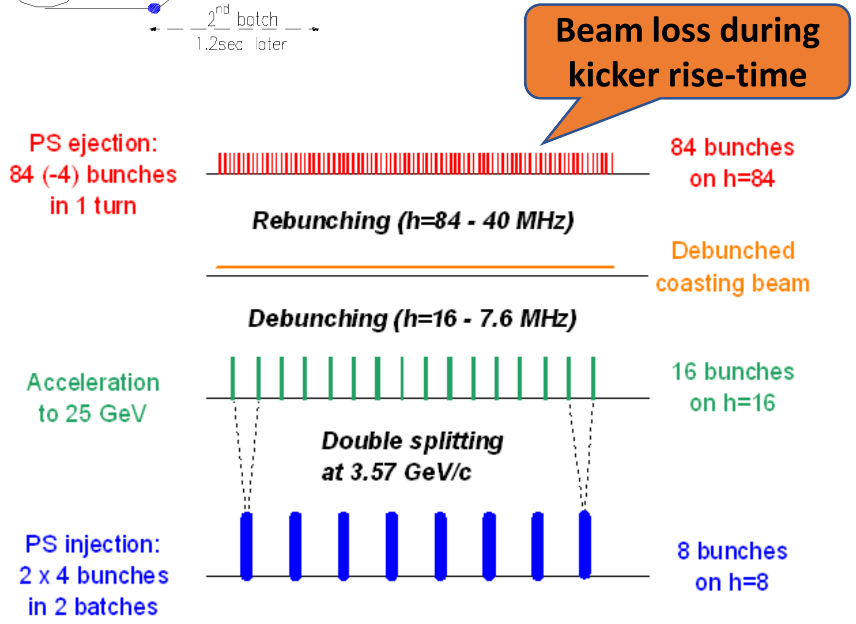
- « Two-batch filling » of the PS on h=8 with 1 bunch/ring from the PSB on h=1

Transfer energy ↗ 1.4 GeV
RF systems on h=1 in the PSB

- « Bunch splitting » (reverse of « merging »)
- Quasi-adiabatic debunching (h=16) – rebunching (h=84)
- Bunch rotation using RFs on h=84 and h=168

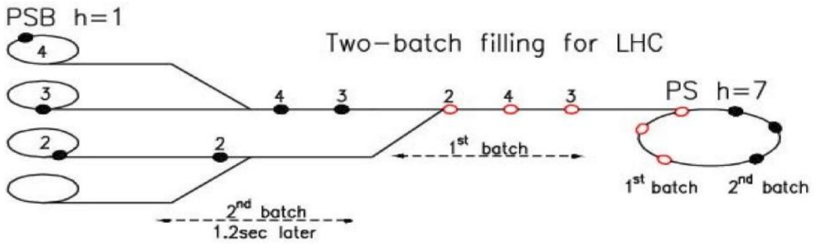
New RF systems at 20 MHz (h=42), 40 MHz (h=84) and 80 MHz (h=168)



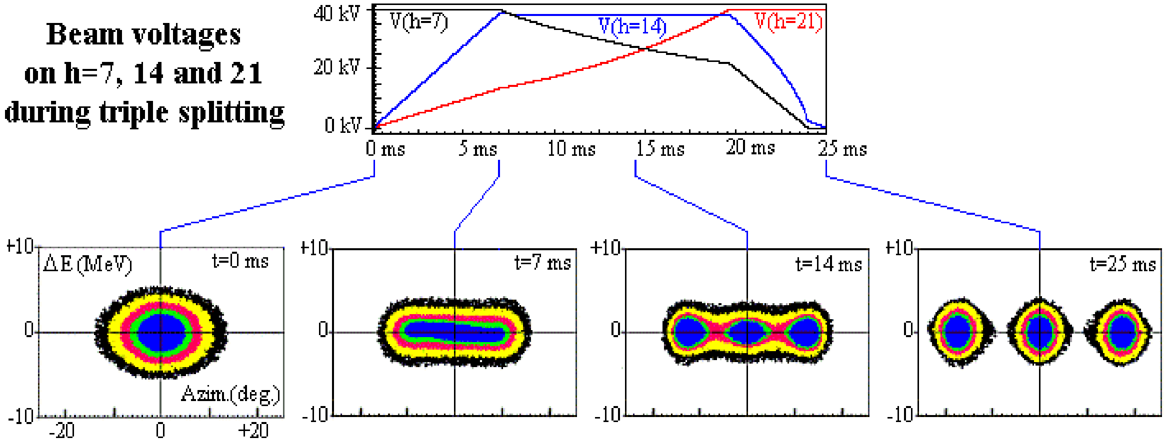


Protons for LHC: improved scheme (1999 ~2008)

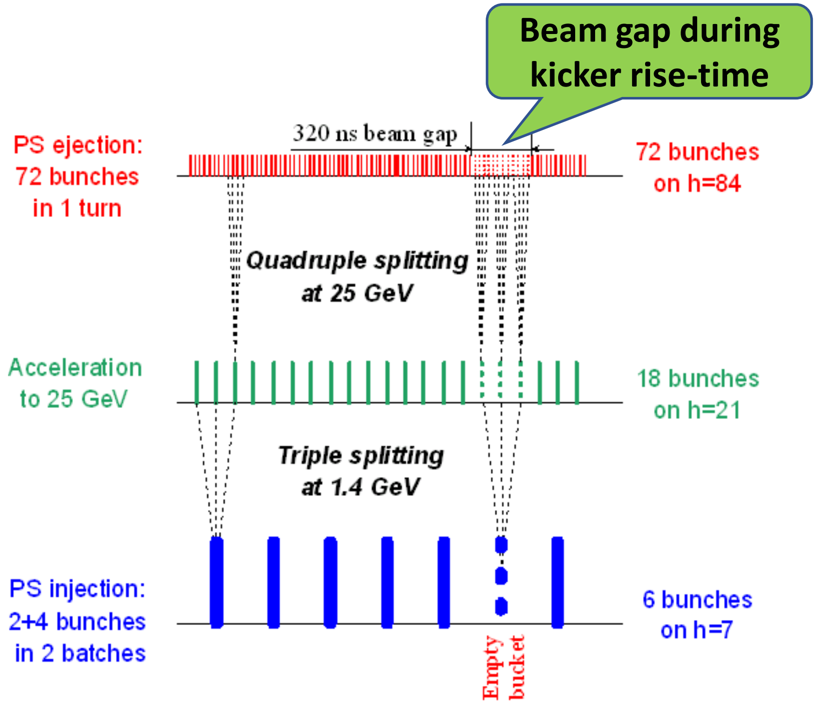
- Quasi-adiabatic scheme with:
  - « Two-batch filling » of the PS on h=7 with 6x1 bunch/ring from the PSB on h=1
  - Acceleration to 2,5 GeV and « Bunch triple splitting » giving 18 bunches on h=21



Beam voltages on h=7, 14 and 21 during triple splitting

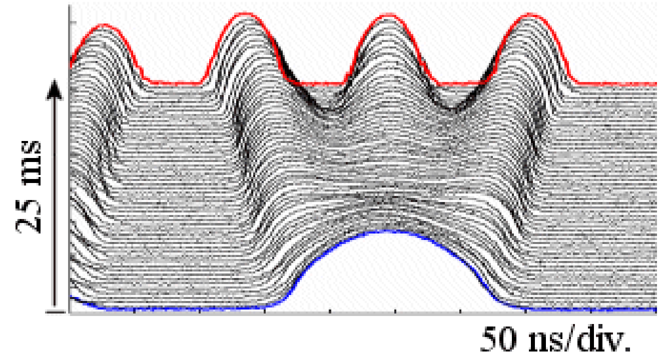


  - Acceleration to 26 GeV followed by 2 successive « Bunch double splitting »
  - Bunch rotation using RFs on h=84 and h=168

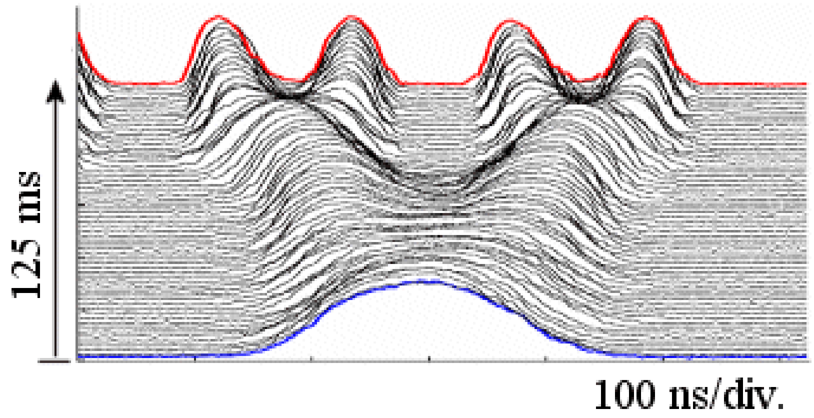


Protons for LHC: improved scheme (1998 ~2008)

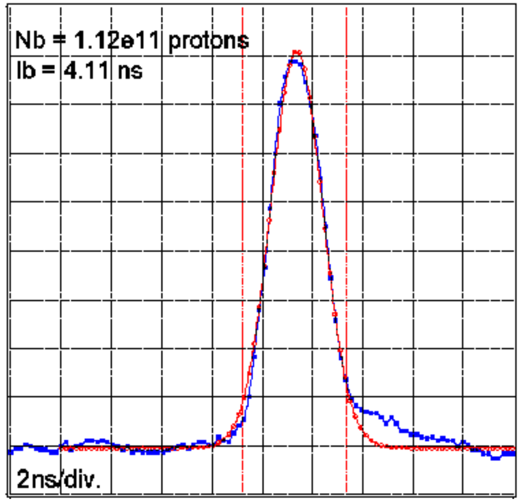
- Operational results:
  - « Bunch triple splitting »



  - Two successive « Bunch double splitting »



  - Bunch rotation using RFs on h=84 and h=168

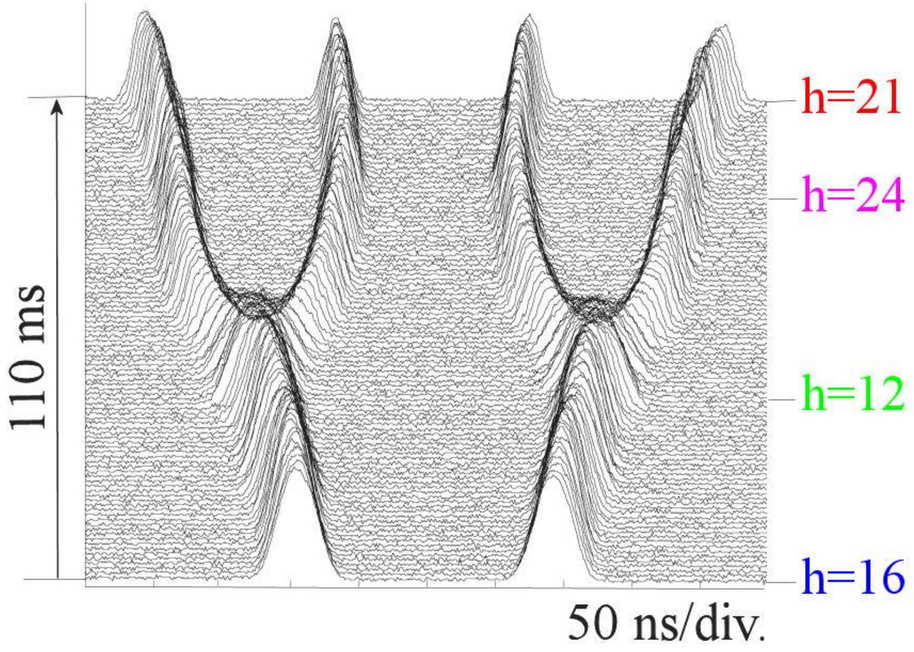


Heavy ions for LHC (1998 ~2008)

- Need for 100 ns spaced bunches (Lead ions)

⇒ Multi-steps process with:

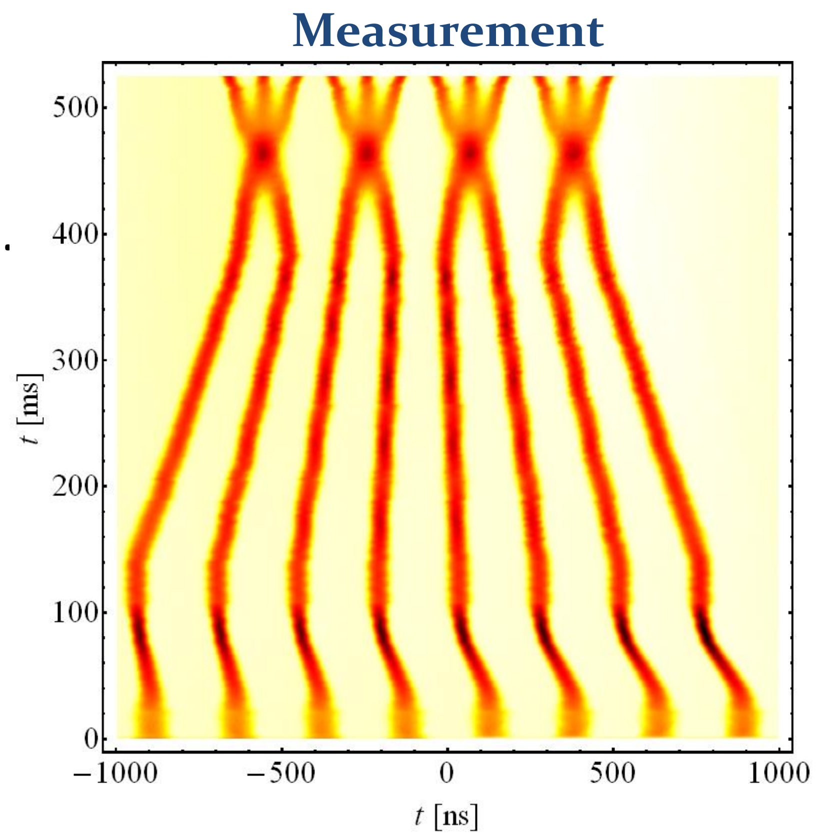
  - Capture on h=16 of 2 bunches from LEIR
  - Acceleration to an intermediate energy and « Batch Expansion » (reverse of « Batch Compression ») changing progressively the harmonic number from 16 to 12
  - « Bunch double splitting » generating 4 bunches on h=24
  - Second « Batch Expansion » changing progressively the harmonic number from 24 to 21
  - Acceleration to high energy followed by « Bunch rotation » using RFs on h=84 and h=168



Other schemes are also available for LHC…

⇒ Example: « Batch Compression Multiple Splittings » (BCMS) which provides 48 bunches per PS pulse with ~twice the brightness of the nominal scheme

- « Two-batch filling » of the PS on h=9 with 8x1 bunch/ring from the PSB on h=1
- Acceleration to 2.5 GeV and « Batch Compression » changing progressively the harmonic number from 9 to 14.
- « Bunch pair merging » bringing h from 14 to 7 and the number of bunches from 8 to 4
- « Bunch triple splitting » giving 12 bunches on h=21
- Acceleration to 26 GeV followed by 2 successive « Bunch double splitting »
- Bunch rotation using RFs on h=84 and h=168

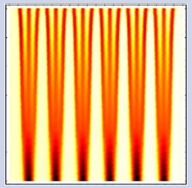
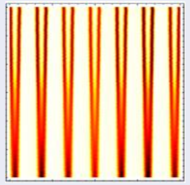
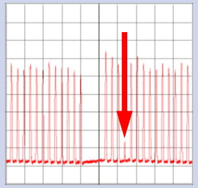
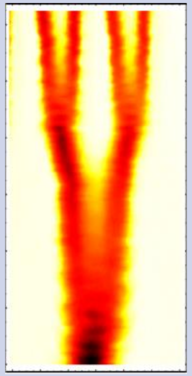
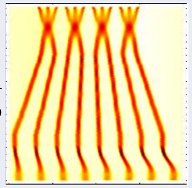
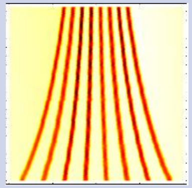


RF Manipulations for Higehr Brightness LHC-type Beams, IPAC13, pp. 2600-2602

Today's inventory of main RF gymnastics for protons

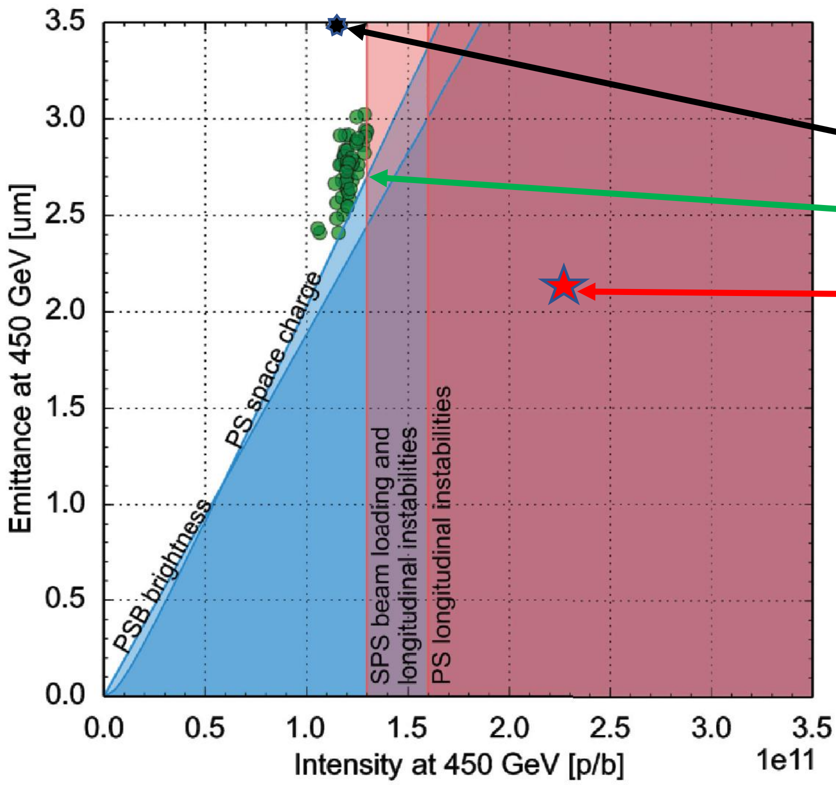
Using the same « toolbox » of RF gymnastics, many schemes have been used during LHC Runs 1 and 2.

Beam brightness from the PS has been largely above nominal and key to LHC performance.

Scheme	n_b at PSB-PS	Manipulation in PS at 2.5 GeV	Acc. n_b/h	Manip. at 26 GeV	n_b at PS-SPS	n_b at SPS ej.
Baseline LIU	4+2	3-split 	18b, h = 21		72	$4 \times 72 = 288$
8b+4e	4+3	2-split 	14b, h = 21		56	$4 \times 56 = 224$
80b	4+3	3-split Loss of 1-bunch 	20b, h = 21	Two 2-split 	80	$4 \times 80 = 320$
BCMS	4+4	Batch c. Merging 3-split 	12b, h = 21		48	$6 \times 48 = 288$
PBC	4+4	Batch comp. 	8b, h = 21		32	$8/9 \times 32 = 256/288$

LHC Injectors Upgrade (LIU) for HL-LHC (2007-2020)

- Need to increase further the intensity per bunch within slightly smaller transverse emittances (2.2 times the present brightness)



	N_b (x 10^{11} p/b)	$\varepsilon_{X,Y}$ (μm)	Number of bunches/ PS pulse
Initial LHC requirements	1,15	3,5	~80
Today's status	1,3	2,7	72
HL-LHC requirement	2,3	2,1	72

Huge challenge in all phase planes for all synchrotrons of the injector complex…

LHC Injectors Upgrade (LIU) for HL-LHC (2007-2020)

⇒ "Nominal" scheme of RF gymnastics in the PS than for LHC, adding:

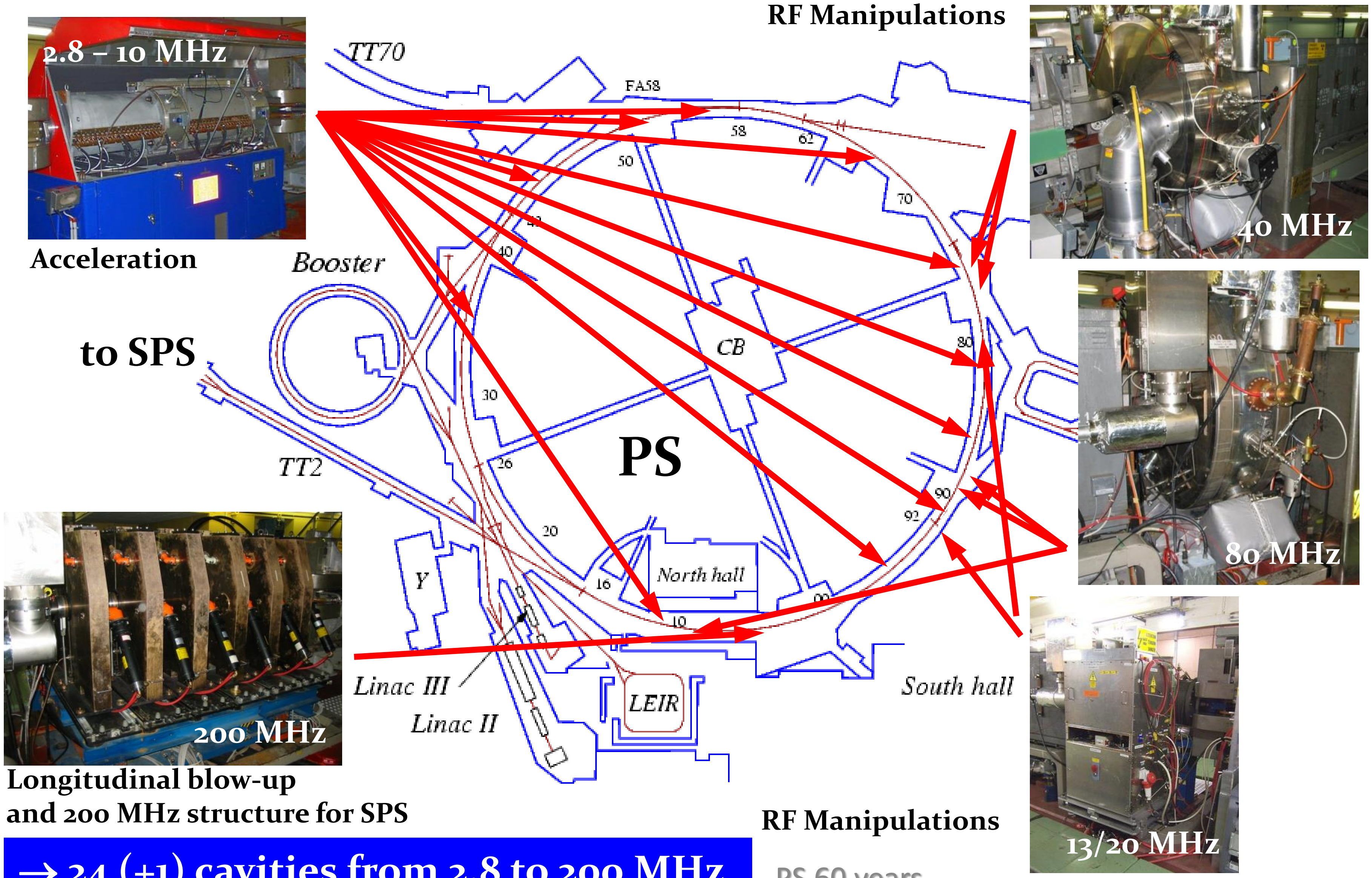
- ⇒ Reduced space charge in the PSB with H- injection at 160 MeV from a new linac (Linac 4)
- ⇒ Acceleration to 2 GeV in the PSB with new (FineMet based) RF systems and new main dipoles power supply
- ⇒ Reduced space charge in the PS with injection at 2 GeV
- ⇒ Improvement of the RF systems in the PS (higher gain RF feedback etc.) and addition of a broad band longitudinal damper (FineMet based).
- ⇒ Impedance reduction in the SPS
- ⇒ Amorphous Carbon coating of a fraction of the SPS vacuum chamber to reduce e-cloud generation
- ⇒ New beam dump in the SPS
- ⇒ New RF power amplifiers and low level RF in the SPS

The LIU project is in its final phase of implementation. Linac 4 had a multi-month reliability run before being connected to the PSB. All equipment has already been tested, some with beam.

Beam commissioning is scheduled from September 2020 till March 2021…

Behind the scene…

A large inventory of RF systems…

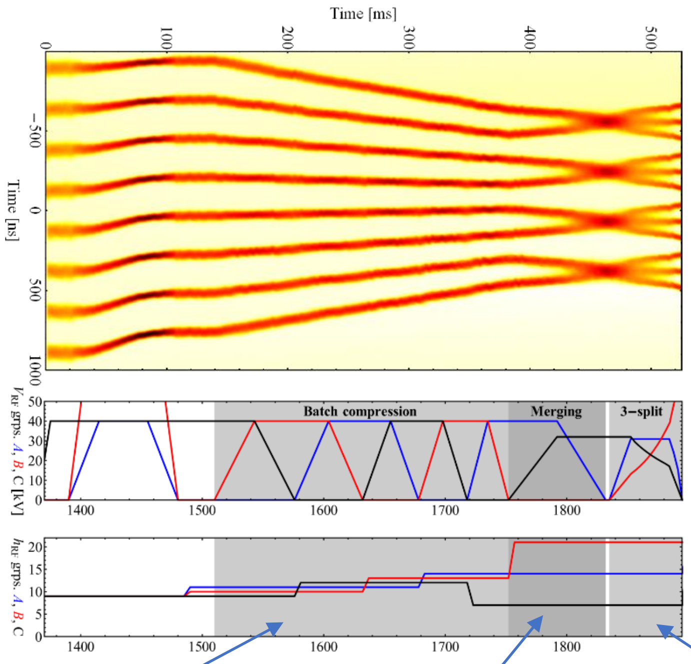


→ 24 (+1) cavities from 2.8 to 200 MHz

and a complex supportive environment!

- Sophisticated Low Level RF and feedback electronics
- Complicated controls
- Designed and used by experts
- Complemented with machine physicists looking after the transverse phase plane issues

Example: BCMS



Batch compression:

- Two active groups at harmonics h, $h + 1$
- 3rd group preparing for harmonic h+2

Bunch merging:

- Two active groups at harmonics 2h, h
- 3rd group preparing for harmonic 3h

Triple splitting:

- Three groups active: harmonics h, 2h, 3h

Acknowledgements

Many more RF gymnastics were tried and sometimes used during these 60 years than those I had the time to present today (e.g. for e+/e-, heavy ions, Multi-Turn Ejection, for the needs of beam tests etc.). I have deliberately chosen those that I consider most representative...

These achievements are the result of the collective effort of many people from all of CERN, industrial support staff and visiting scientists from other institutions.

They would have been impossible without the continued support of the CERN management and the patience of the users…

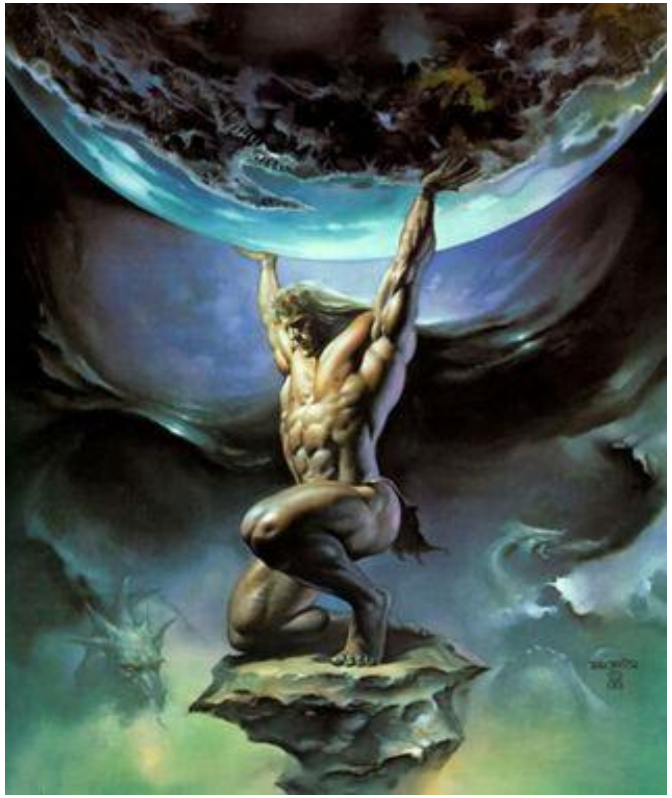
I will not take the risk of showing a list of names, but I feel important to give special credit to **Gerard Roux**, **Jean-Luc Vallet**, **Steve Hancock** and **Heiko Damerau** for their crucial contributions.

Summary

For surprises prepare…

- RF gymnastics have been a key ingredient to the success of the PS (and of CERN) during its first (!) 60 years, made possible by a continuous increase of the inventory and performance of RF equipment.
- The CERN PS is nowadays a very complex and versatile accelerator, which allowed the LHC to reach twice its design luminosity during Run-2 and which demonstrated the capability to meet the HL-LHC requirements in the longitudinal phase plane.
- The completion of the LIU project should (?) make the LHC injectors able to meet the HL-LHC requirements.

60 years old
and still going strong !



HAPPY BIRTHDAY PS!