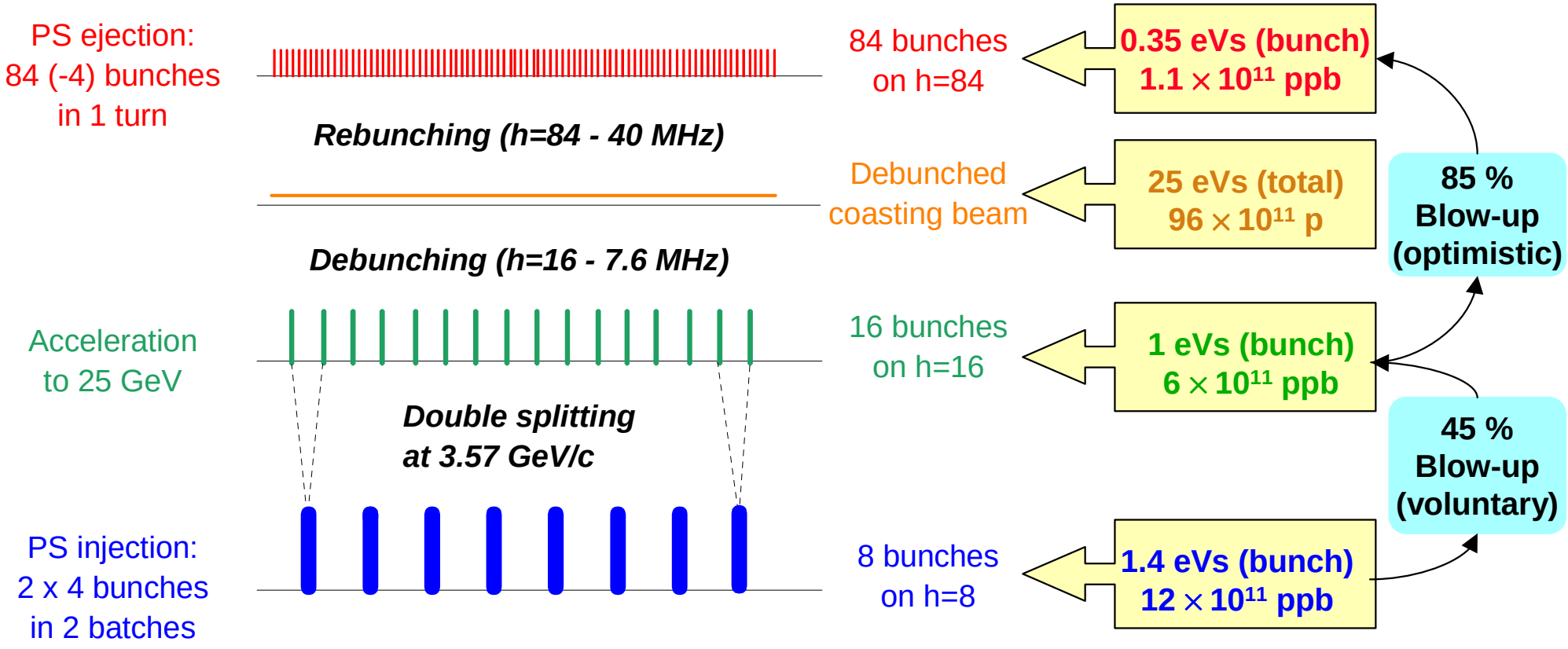
DEMONSTRATION OF TRIPLE BUNCH SPLITTING IN THE CERN PS

OUTLINE

1. PS role in the LHC injection chain
   - 1.1 Nominal scheme
   - 1.2 Multiple splittings scheme
2. Principle of Bunch Splitting
   - 2.1 Double splitting
   - 2.2 Triple splitting
3. Experimental results
   - 3.1 Triple splitting at 1.4 GeV
   - 3.2 Other gymnastics
   - 3.3 Lessons
4. Future plans
5. Conclusions

1. PS role in the LHC injection chain

1.1 Nominal scheme



1. PS role in the LHC injection chain

1.1 Nominal scheme

- **Major steps in the process:**
  - Double splitting (h=8 -> h=16) at 3.57 GeV/c
  - Debunching (h=16 - 7.6 MHz) / rebunching (h=84 - 40 MHz) at 26 GeV/c
- **Beam characteristics at ejection:**

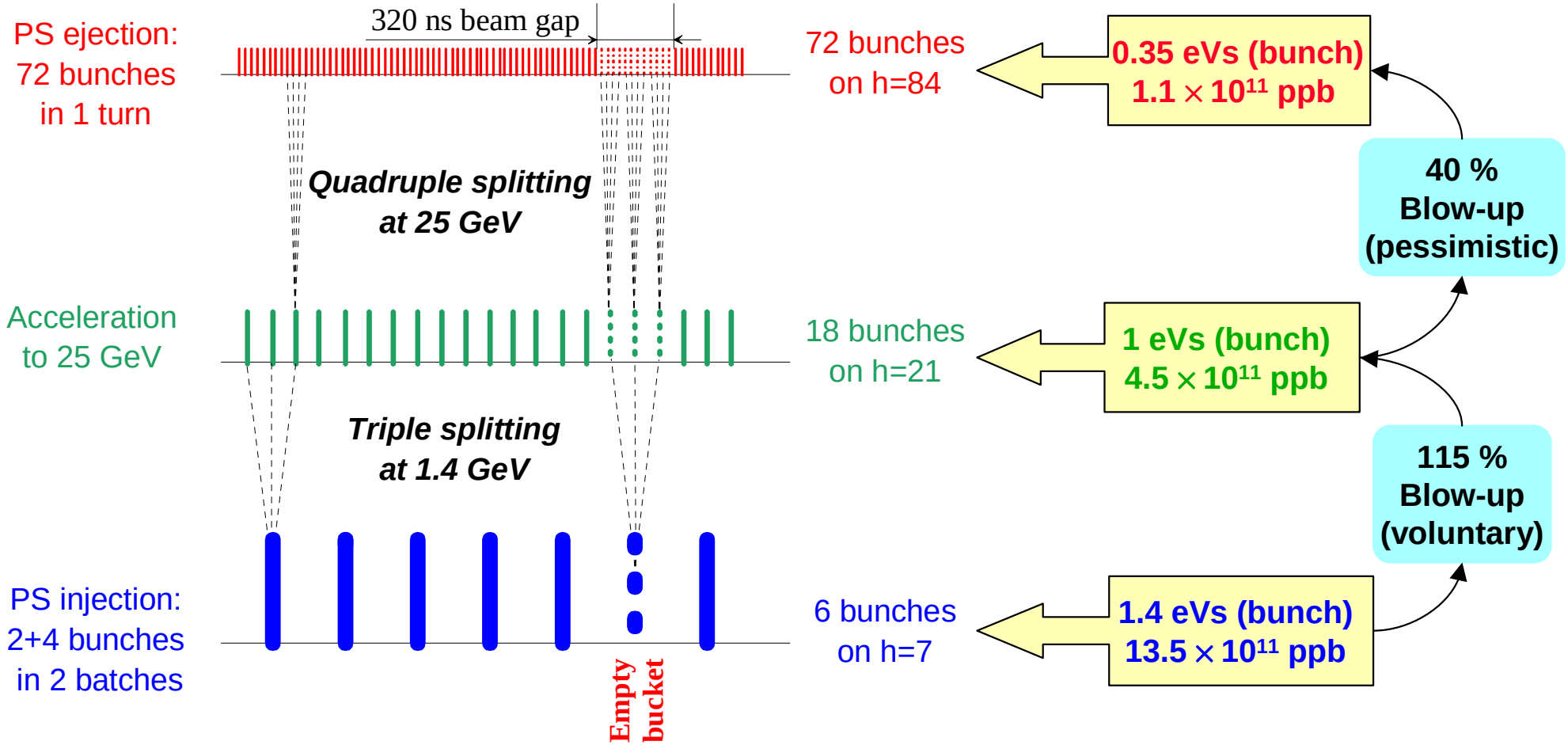
Performance level	Bunch emittance (eVs)	Bunch length (ns)	Number of bunches
Achieved ☹	0.5	5	84
Nominal 😐	0.35	4	84
Ideal ☺	0.35	4	< 81

- **Factors limiting present performance:**

  Drawbacks of debunching / rebunching (emittance blow-up, microwave instability, lack of reproducibility)

1. PS role in the LHC injection chain

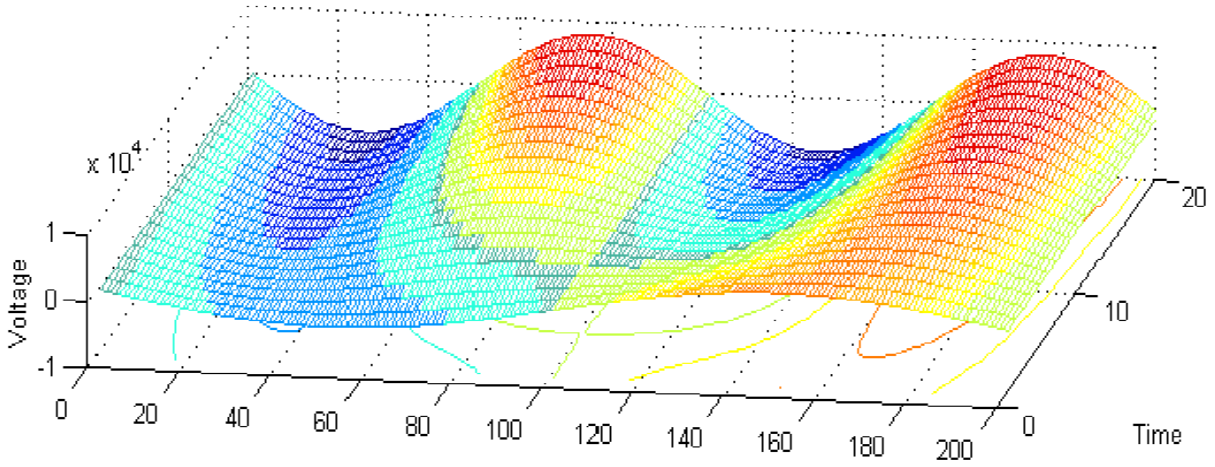
1.2 Multiple splittings scheme



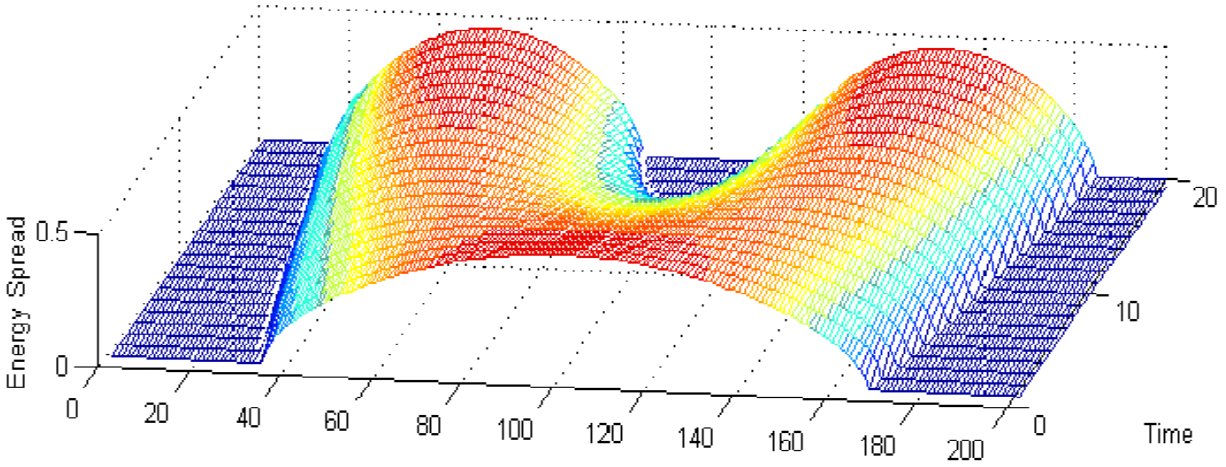
2. Principle of splitting:

2.1 Double splitting

Time evolution of the RF voltage



Time evolution of the bunch(es)

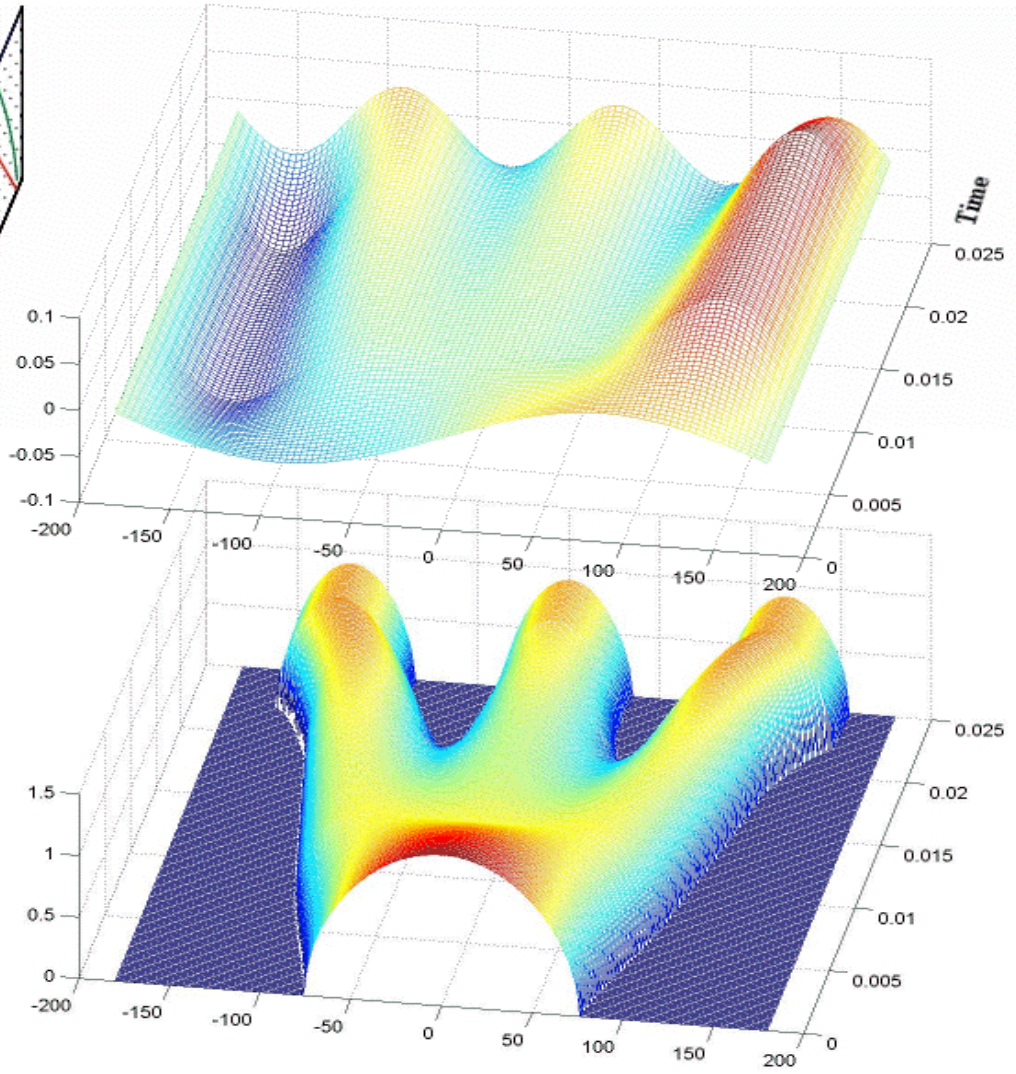


2. Principle of splitting:

2.2 Triple splitting

Time evolution of the RF voltage

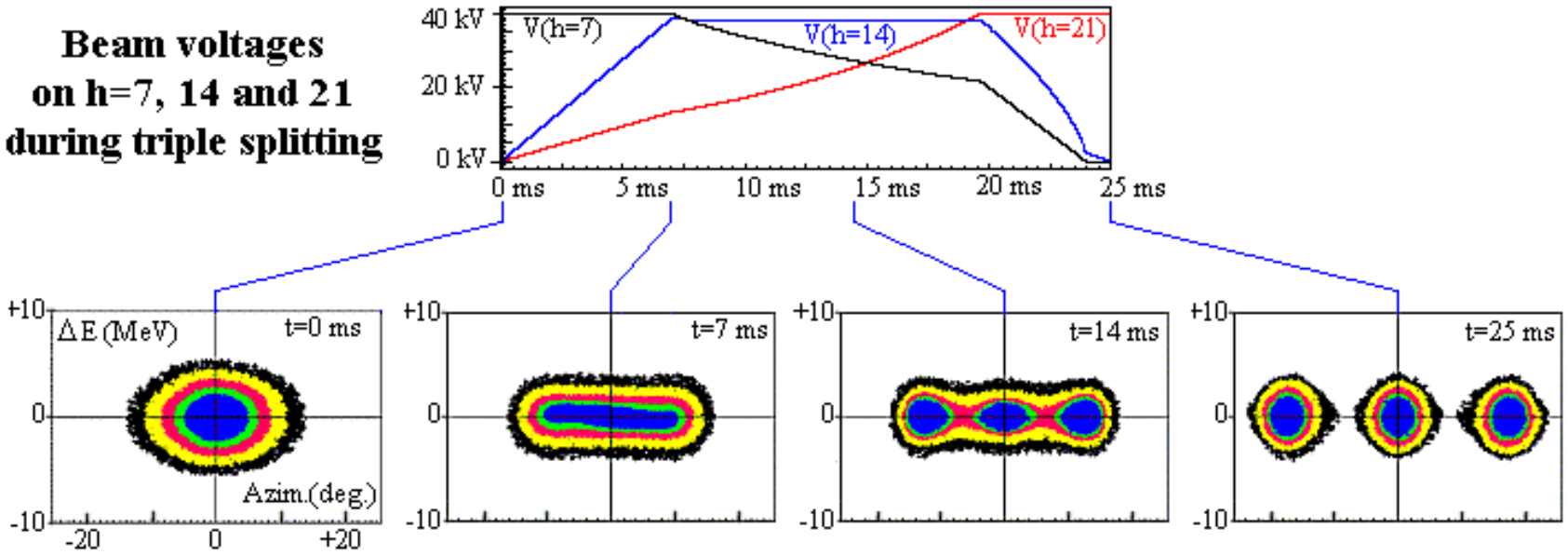
Time evolution of the bunch(es)



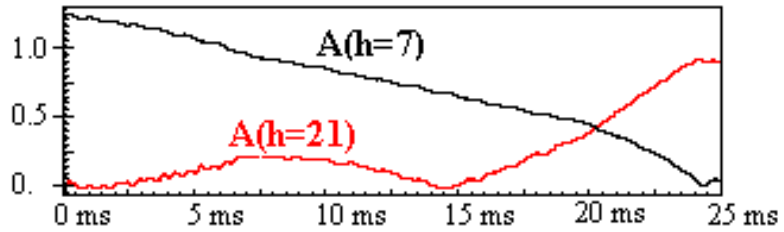
2. Principle of splitting:

2.2 Triple splitting

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



Beam spectral amplitudes on h=7 and 21 during triple splitting



2. Principle of splitting:

2.3 Advantages

(with respect to debunching / rebunching & based on experience with double splitting):

- **good control (potential preservation) of longitudinal emittance: no need for very low RF voltages to minimise blow-up,**
- **capability to preserve a gap without particles over a fraction of the circumference,**
- **good reproducibility: beam is always confined by RFs, and feedback loops can be used for stabilisation,**
- **lower risk of microwave instability thanks to the larger $(\Delta p/p)^2/I$ in the beam.**

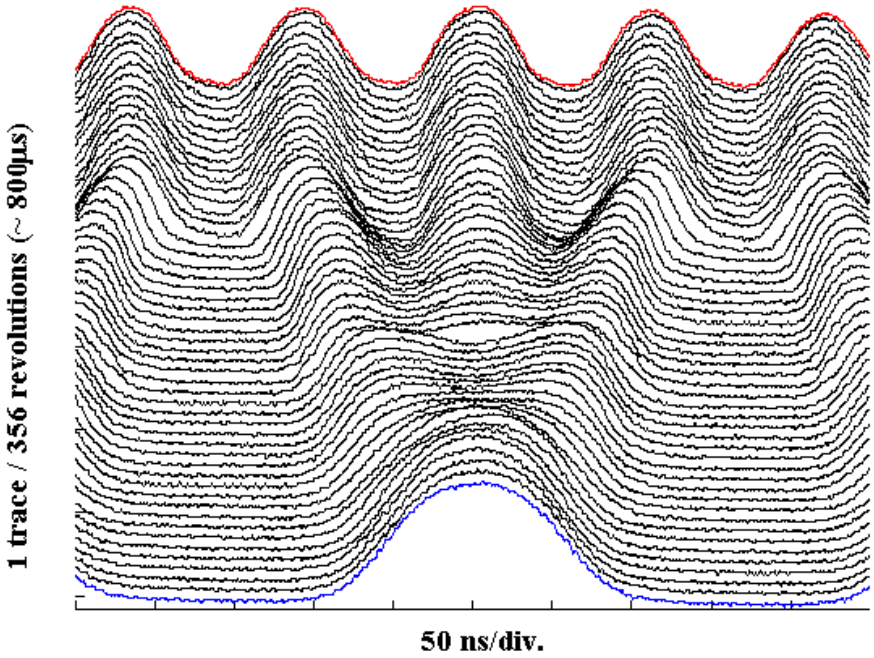
3. Experimental results:

3.1 Triple splitting at 1.4 GeV

Mountain-range display (1 PSB bunch)

T=1.4 GeV

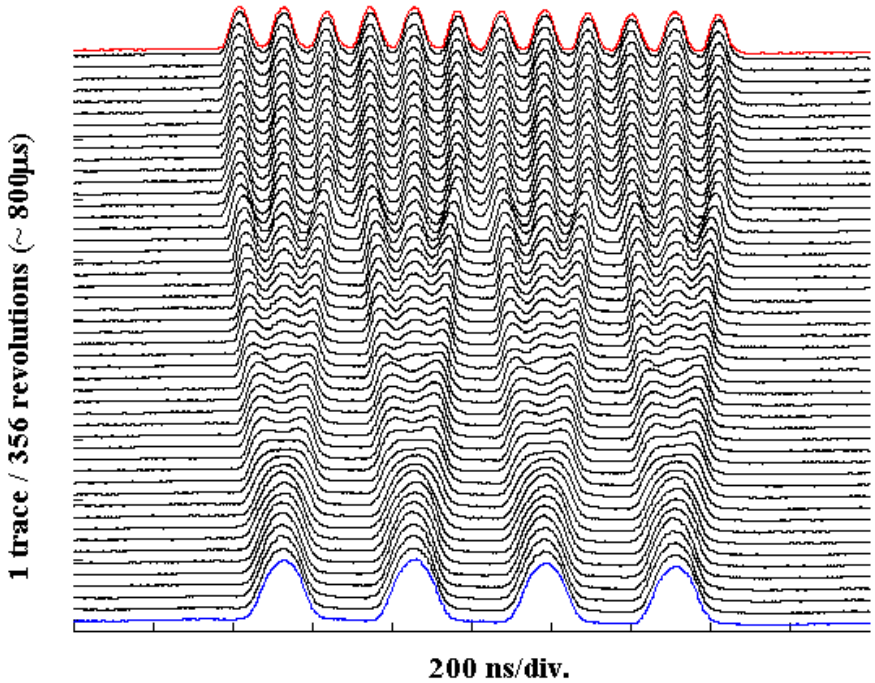
1.5×10^{12} ppb



Mountain-range display (4 PSB bunches)

T=1.4 GeV

6×10^{12} ppp



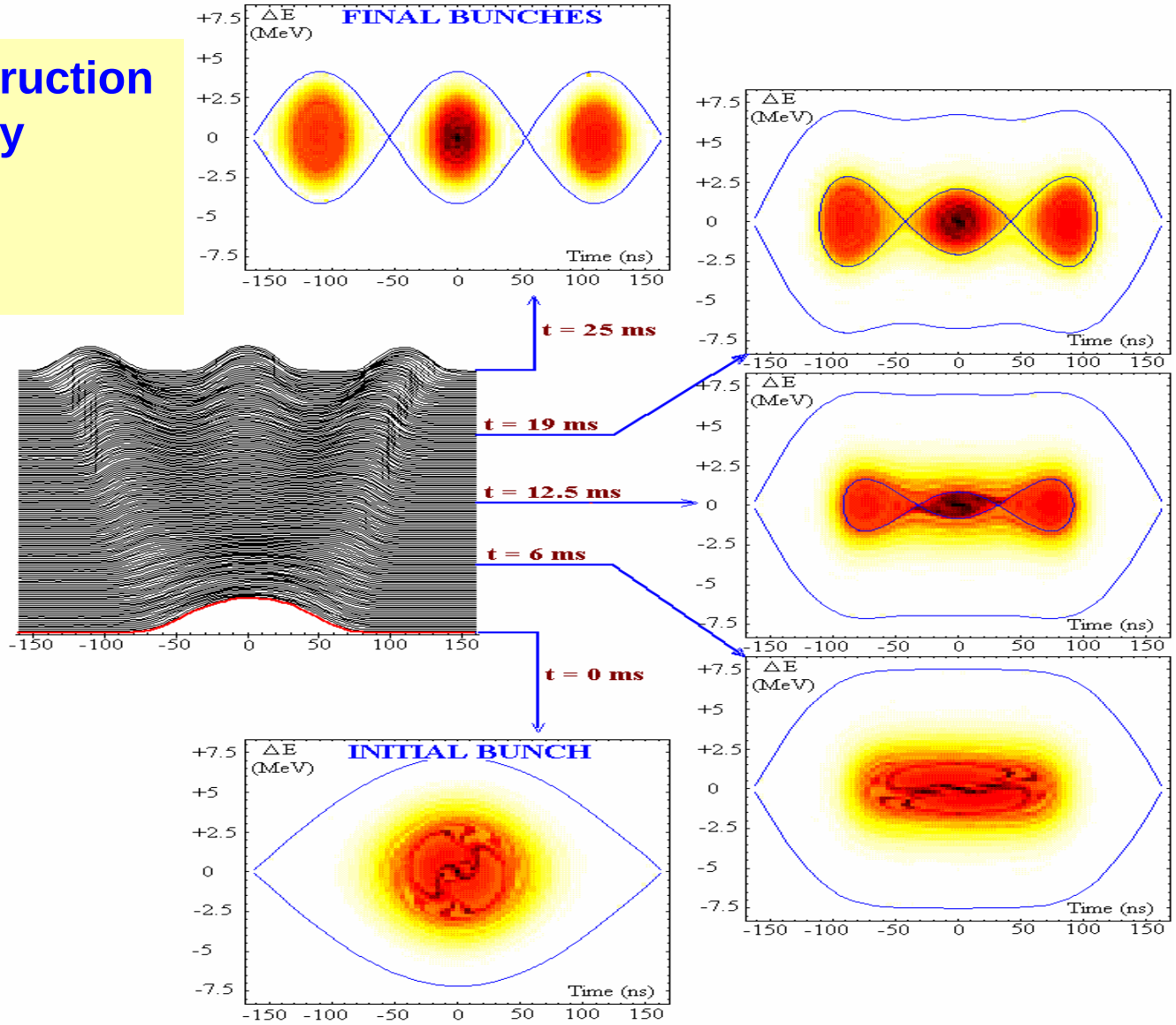
3. Experimental results:

3.1 Triple splitting at 1.4 GeV

Tomographic reconstruction of phase plane density

T=1.4 GeV

1.5×10^{12} ppb



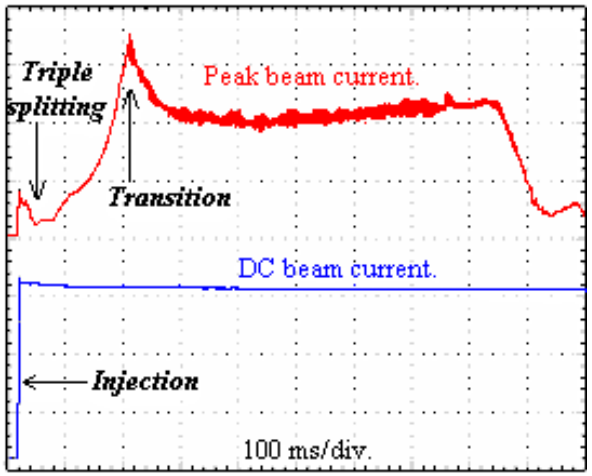
3. Experimental results:

3.2 Other gymnastics

Acceleration to 25 GeV

Capture, splitting and acceleration to 25 GeV (4 PSB bunches)

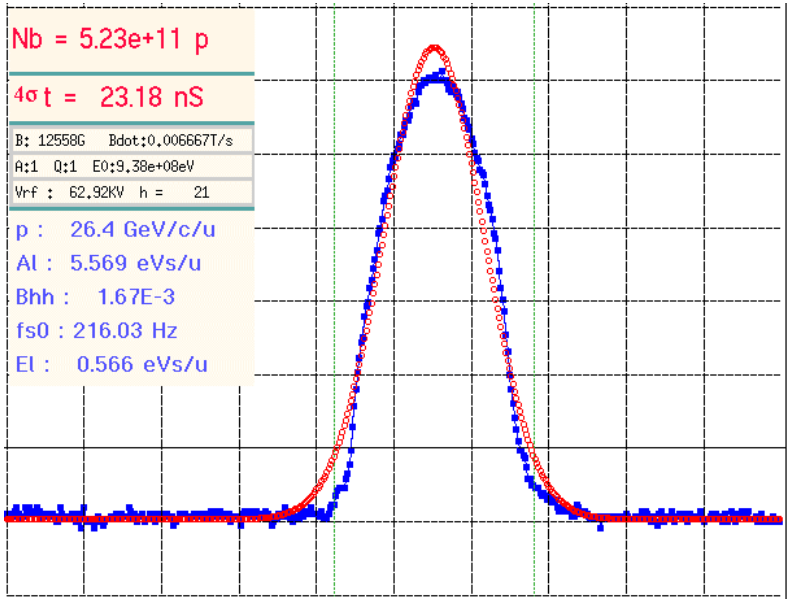
6×10^{12} ppp



Bunch (h=21) at 25 GeV

0.5×10^{12} ppb

ε_L = 0.66 eVs



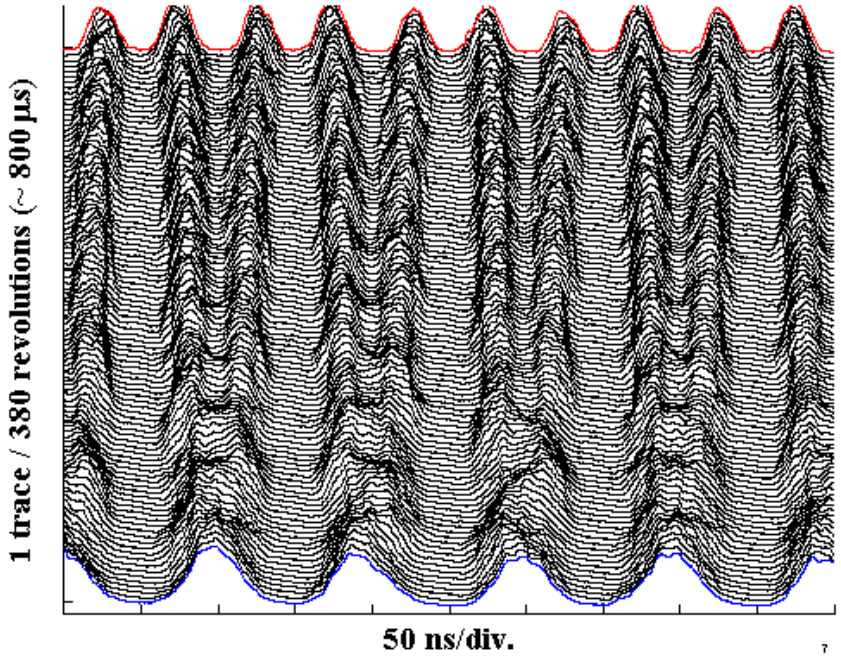
3. Experimental results:

3.2 Other gymnastics

Quadruple splitting at 25 GeV

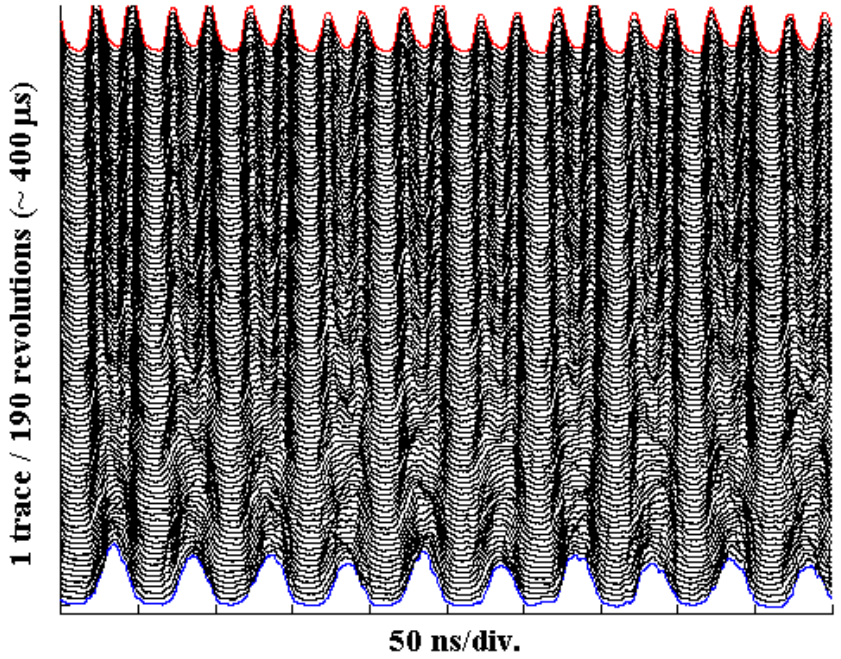
First double splitting (h=21 -> 42)

Instability of the initial beam degrades the process



Second double splitting (h=42 -> 84)

Suffers from imperfect result of first double splitting



3. Experimental results:

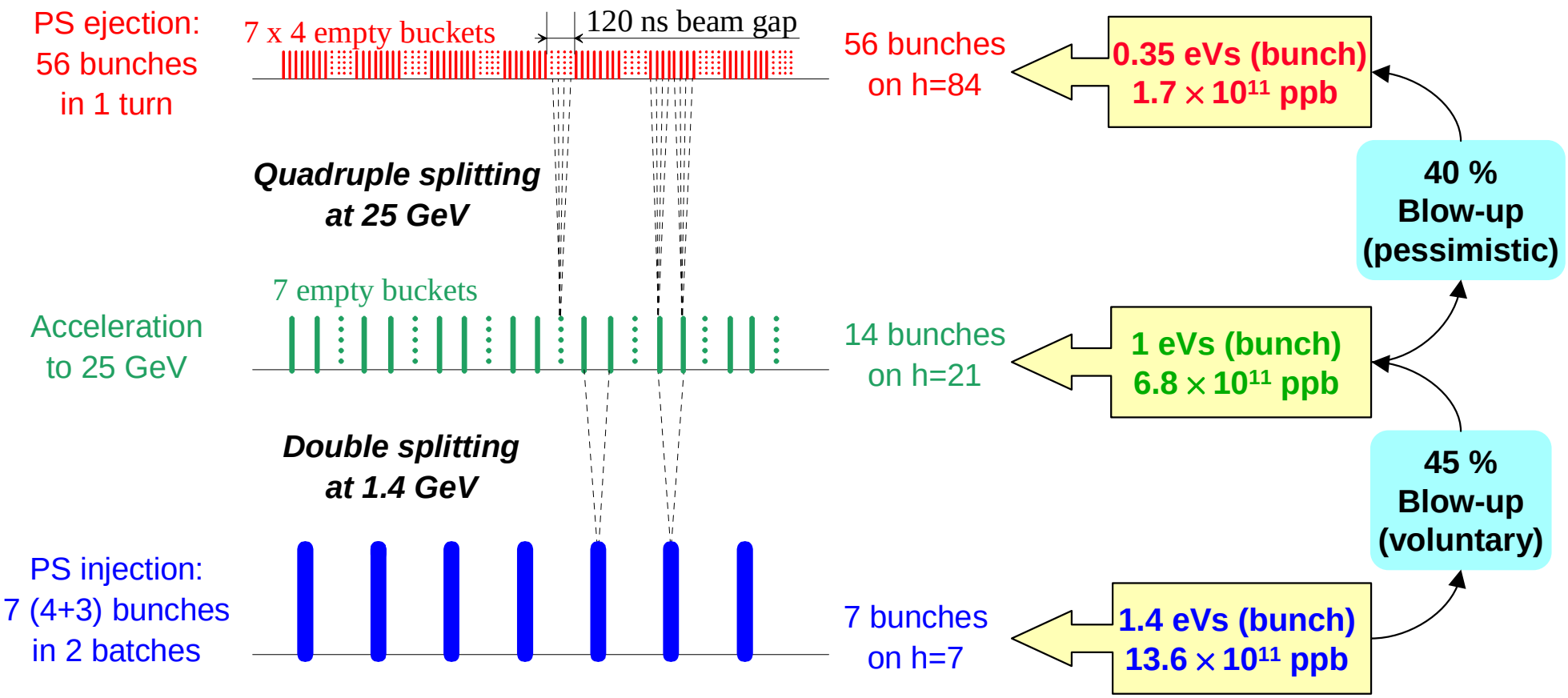
3.3 Lessons

- **Triple bunch splitting is feasible (!)**
- **Key ingredients:**
  - beam phase loop locked during the full process
  - fine adjustment of the phases between harmonics
  - stability of the initial beam
- **Reproducibility looks good (over a few days) and is independent of the number of PSB bunches to be split**
- **Bunches of small longitudinal emittance (~ 0.7 eVs) are stable during acceleration up to 25 GeV**
- **Preliminary steps before splittings at 25 GeV trigger bunch oscillations: hardware improvements are required**

4. Future plans:

"Exotic" splitting schemes

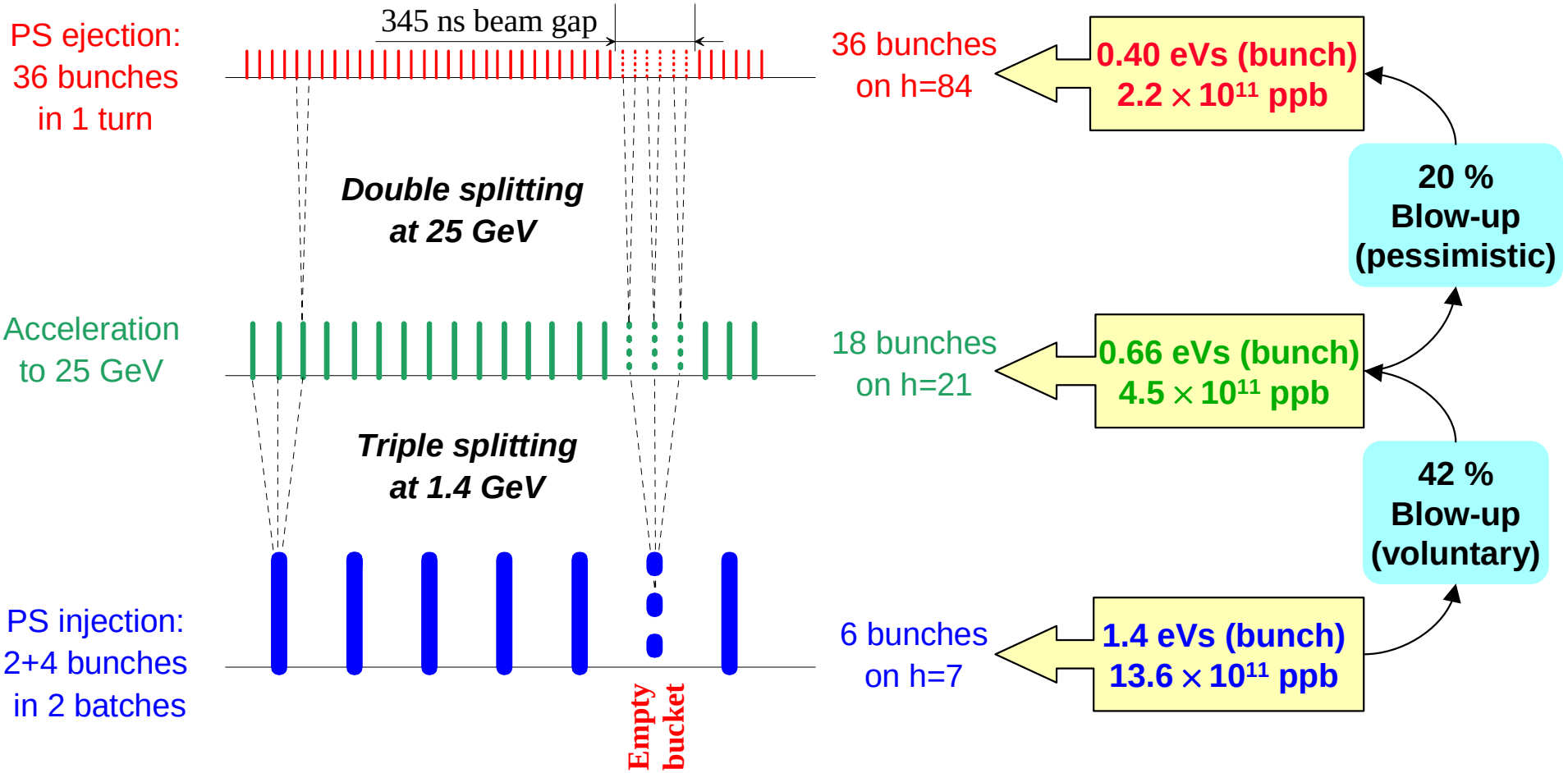
Bunch train with 120 ns gaps without beam



4. Future plans:

"Exotic" splitting schemes

Bunch train with 50 ns between bunches



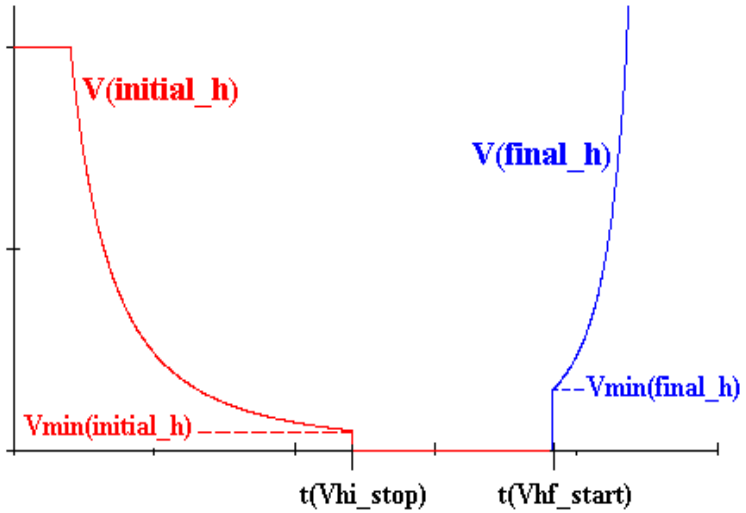
5. Conclusions

- **Triple bunch splitting has been successfully demonstrated with the nominal beam for LHC in the PS:**
  - ➔ **new possibility in the accelerator designer's toolbox**
- **Emittance is indeed preserved:**
  - ➔ **exotic bunch trains are feasible which should help study and fight electron clouds induced instabilities in SPS and LHC**
- **Hardware improvements are necessary for the proper performance of the full multiple splitting scheme:**
  - ➔ **beam experiments resume in Summer 2000**

ANNEX 1:
Problems with debunching - rebunching

- **Principle of debunching - rebunching:**
  - Iso-adiabatic debunching by slow voltage reduction down to a level where acceptance << emittance and then fast reduction to zero volt.

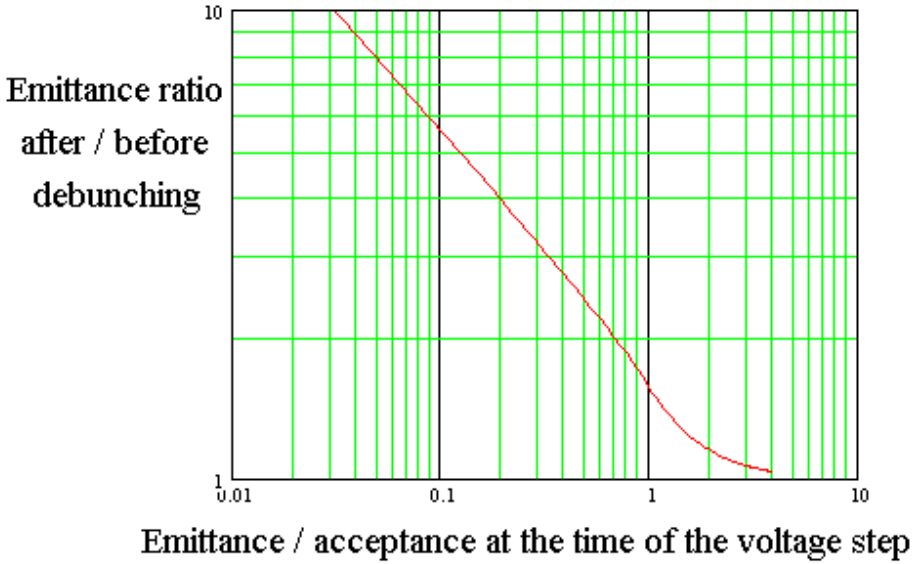
    beam drift without RF voltage
  - Iso-adiabatic capture by the reverse process at the new RF frequency



ANNEX 1:
Problems with debunching - rebunching

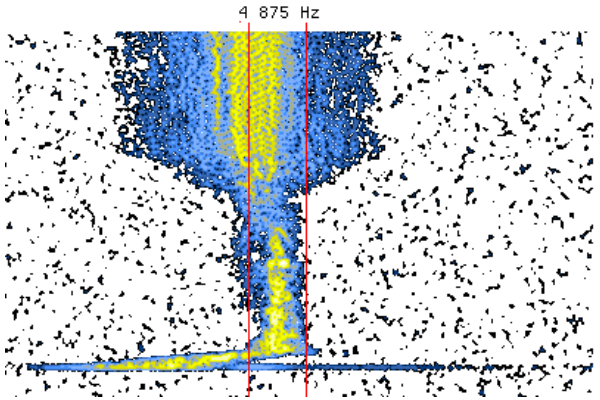
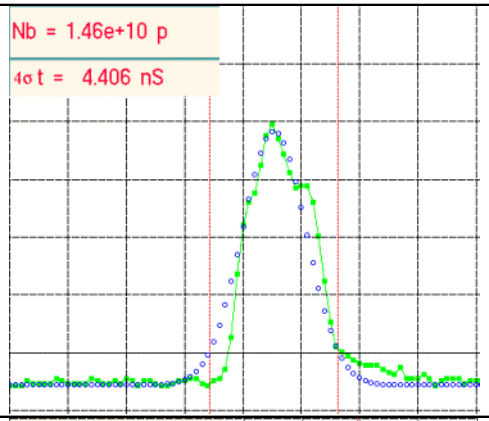
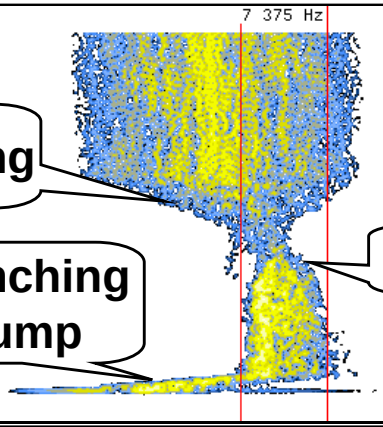
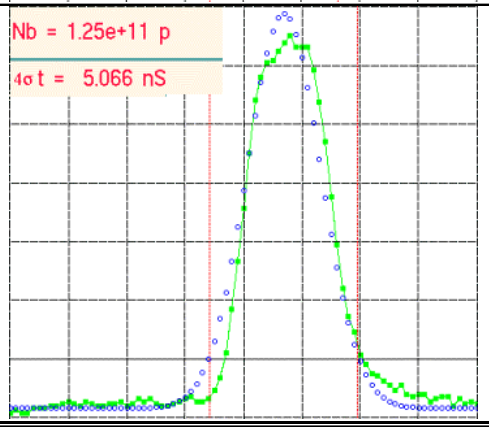
- **Drawbacks:**
  - need for control of low RF voltages to minimise blow-up.

    (emittance is multiplied by $\pi/2$ when acceptance = emittance at the time of cancellation)
  - no control on the beam while drifting,
  - the full circumference is filled with particles
  - risk of microwave instability because of the small $(\Delta p/p)^2/I$ of the debunched beam



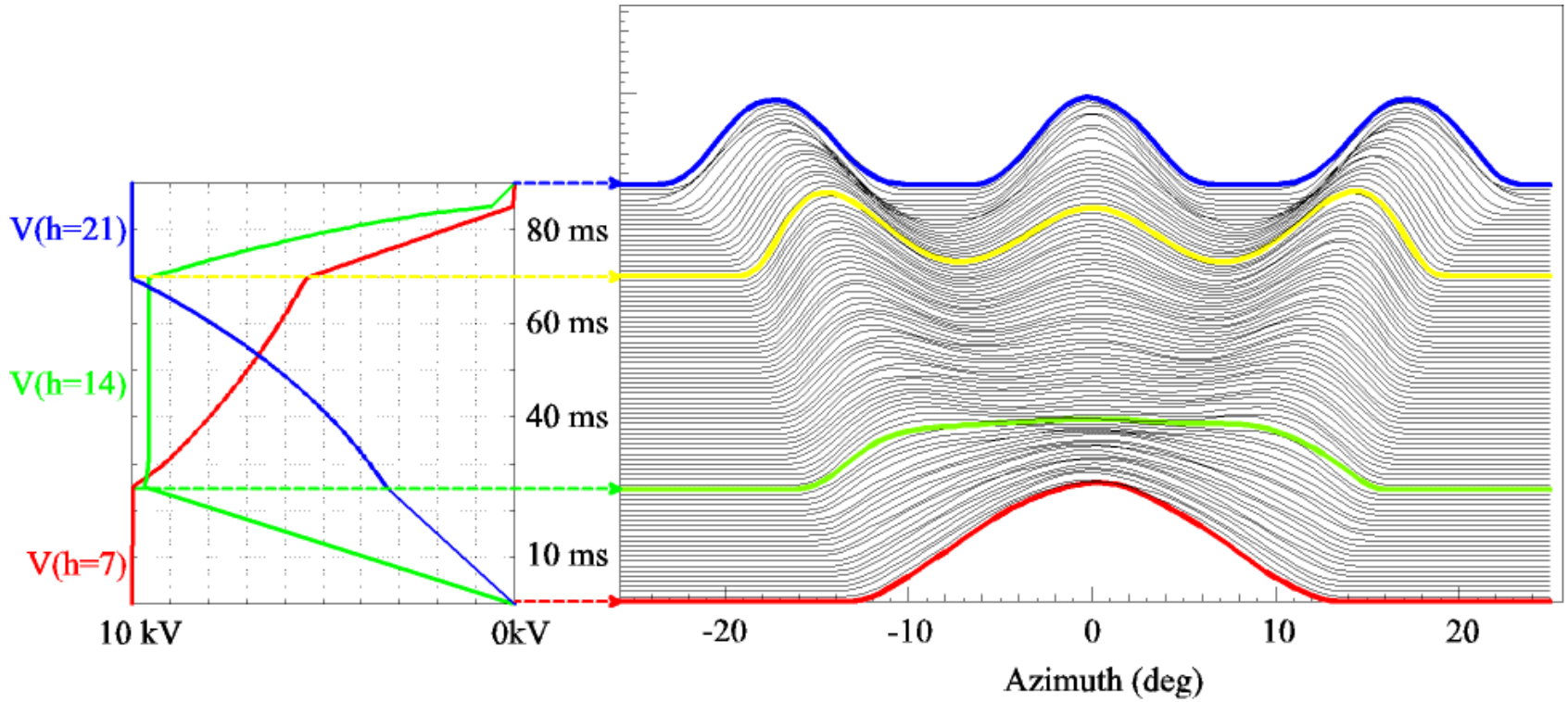
ANNEX 1:
Problems with debunching - rebunching

Typical PS results for LHC

H^+ / bunch	E_L(h=16)	Schottky spec. @ 26 GeV/c (395 MHz – 50 kHz span)	Bunch @ ejection
~ 1×10^{10} H^+ @ ejection	0.85 eVs		
~ 10×10^{10} H^+ @ ejection	1.15 eVs		

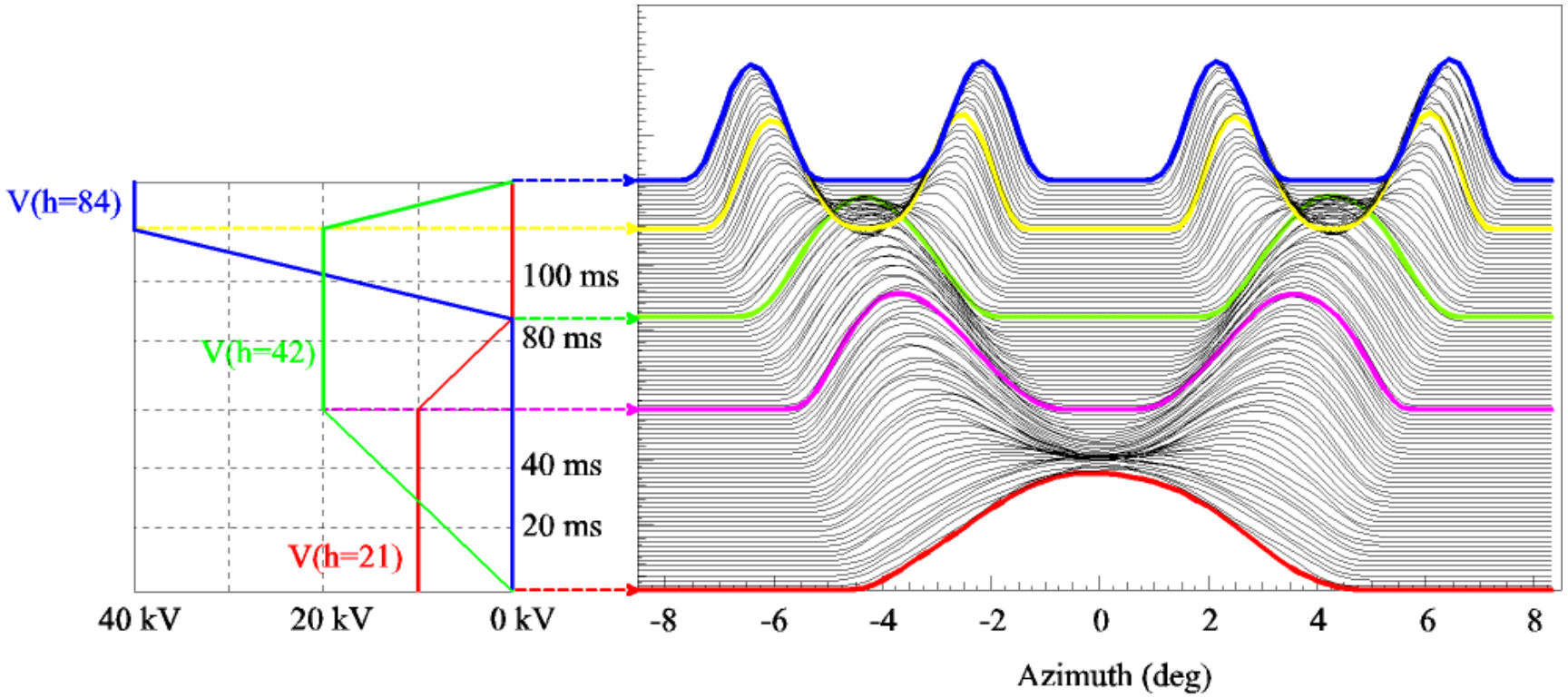
ANNEX 2:
Simulations of splitting

Splitting bunches in three at 3.57 GeV/c



ANNEX 2:
Simulations of splitting

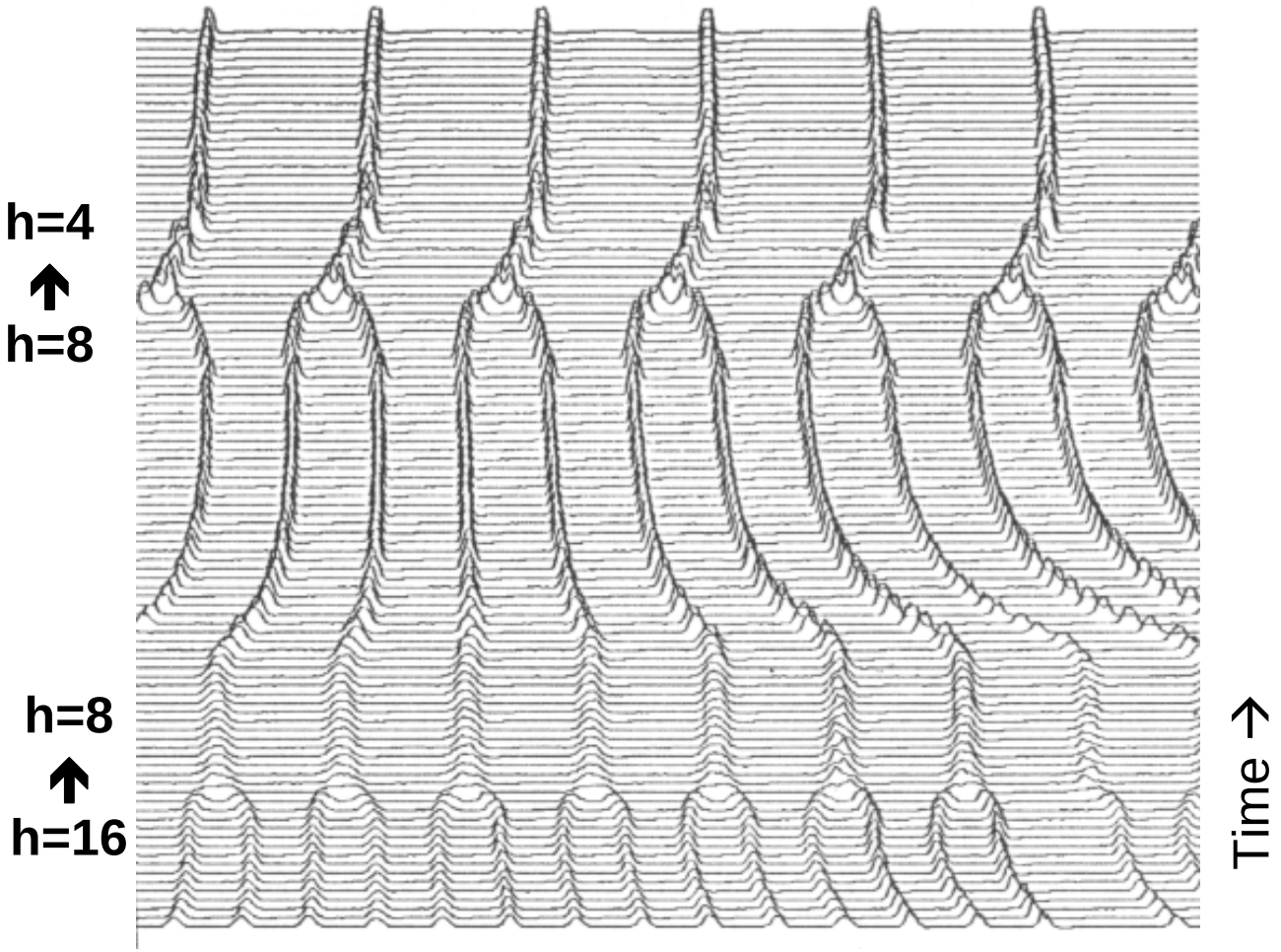
Splitting bunches in four at 26 GeV/c



ANNEX 3:
Experience with double splitting

- **Merging in the AGS (Brookhaven)**

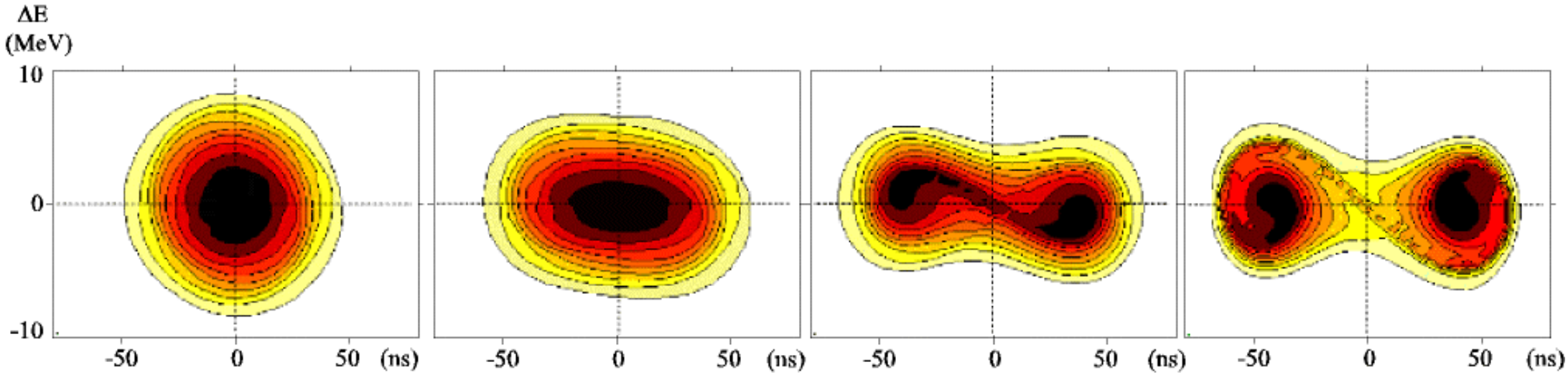
  [Mountain range of longitudinal PU signal during a full acceleration cycle of Au^{77+} in the AGS - (courtesy of J.M. Brennan / BNL)]



ANNEX 3:
Experience with double splitting

- **Splitting in the CERN-PS**

  [Tomographic reconstruction from data measured with 3 10^{12} ppb @ 3.57 GeV/c (from S. Hancock 's files)]



t = 0 ms
V(h=8) = 80 kV
V(h=16) = 0 kV

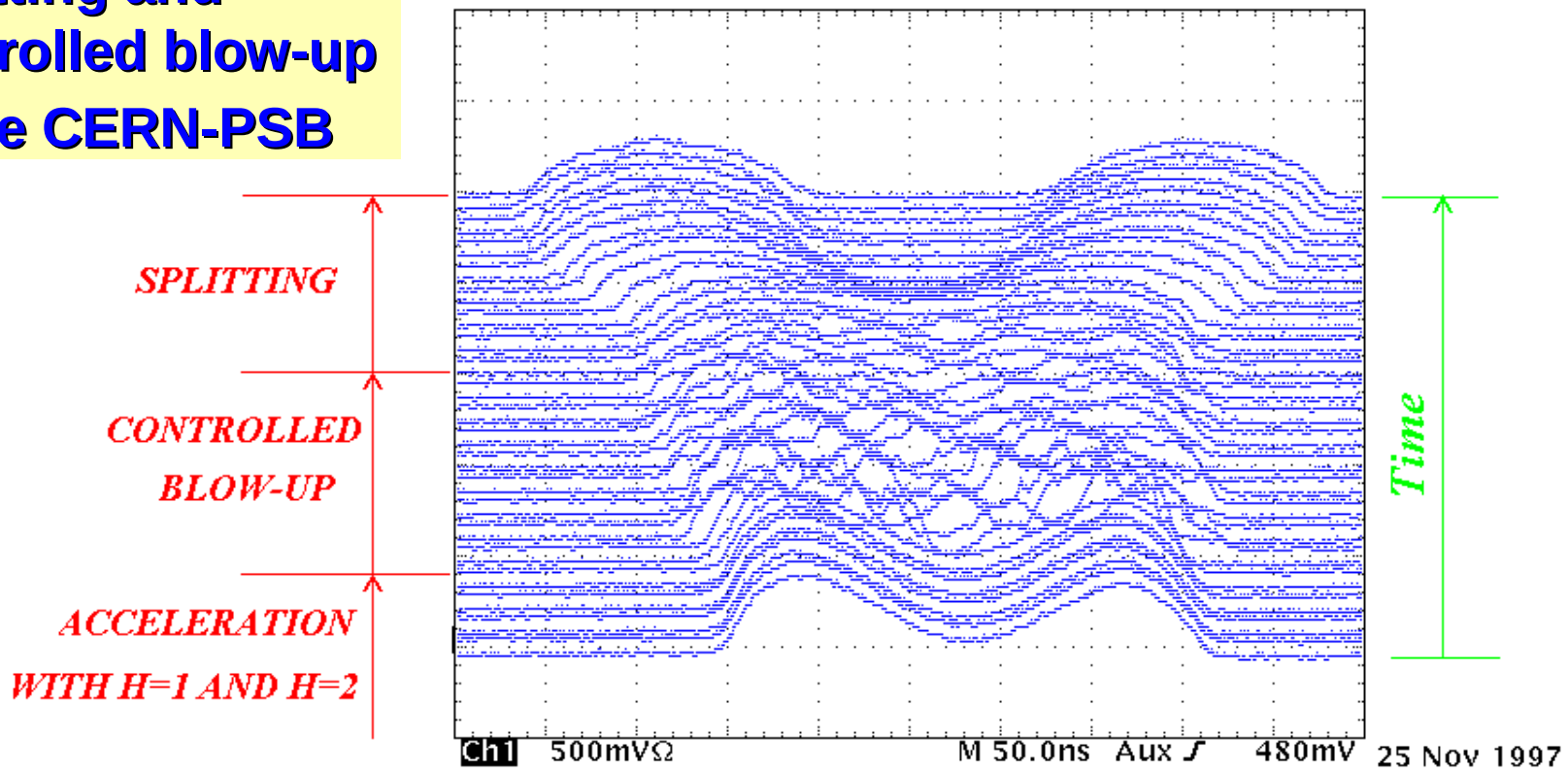
t = 5.4 ms
V(h=8) = 80 kV
V(h=16) = 40 kV

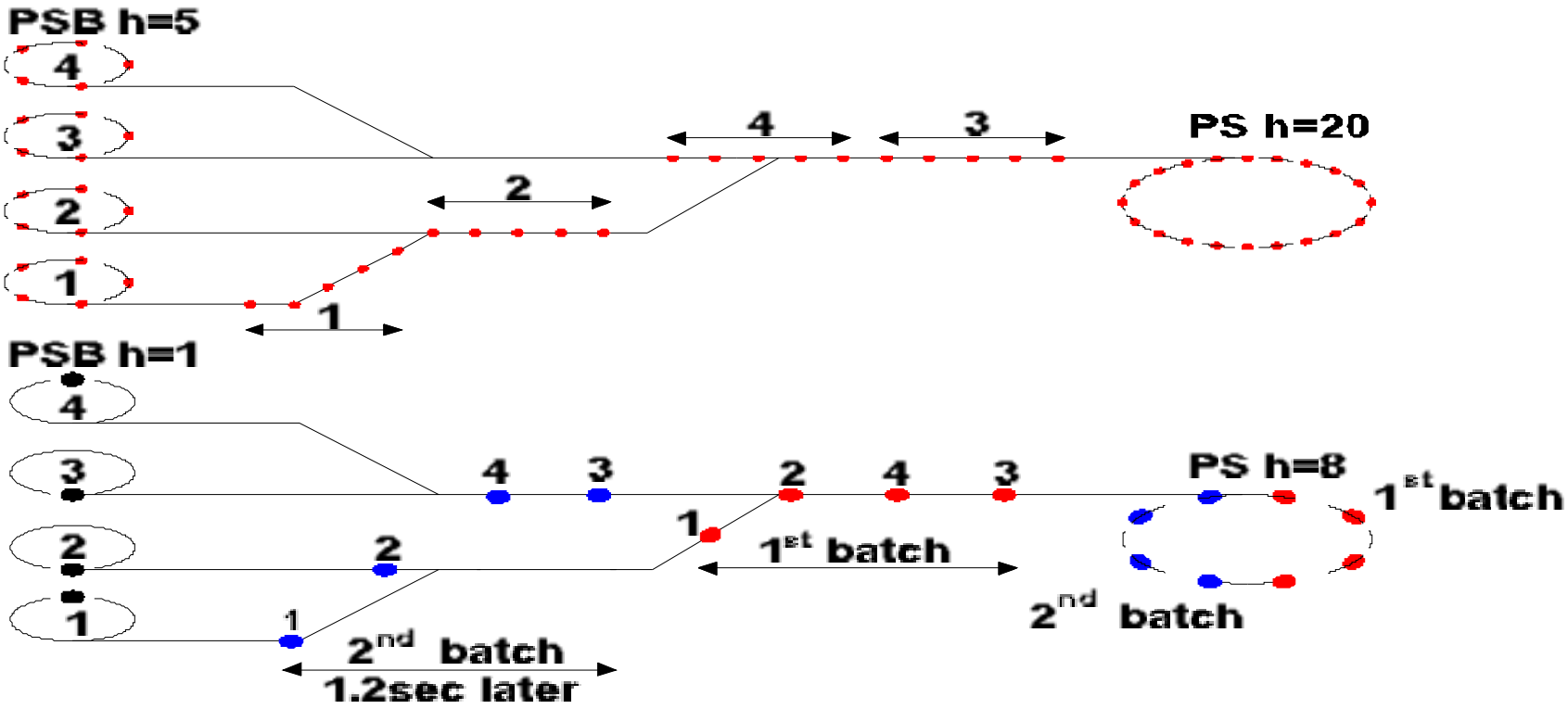
t = 8.7 ms
V(h=8) = 80 kV
V(h=16) = 70 kV

t = 9.8 ms
V(h=8) = 80 kV
V(h=16) = 80 kV

ANNEX 3:
Experience with double splitting

- **Splitting and controlled blow-up in the CERN-PSB**



Beam Pick-Up signal (50 ms at the end of the machine cycle)

ANNEX 4:
PS filling scheme for LHC