CAS RF

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RF GYMNASTICS IN SYNCHROTRONS

- Part 1 -

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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

1. Introduction

Frequent need for changing the longitudinal beam characteristics In an accelerator complex. Example:

Conflict between the requirements of high energy hadron colliders and the ones of the lower energy Synchrotrons:

	HIGH ENERGY HADRON COLLIDER	INJECTORS' SYNCHROTRONS
RF frequency	Large because of need for: - high voltage for acceleration - high focusing for luminosity	Small because of need for: - acceptance - large frequency swing - gap without beam for kicker
Bunch frequency	<< RF frequency to maximize luminosity - limited by detector saturation	= RF frequency to maximise bunching factor and minimise Laslett tune-shift

1. Introduction (cont.)

COLLIDER			INJECTOR COMPLEX
Name (Lab.)	RF (MHz)	Bunch freq. (MHz)	Injector / Collider bunches
RHIC (BNL)	197	4.7	8/1
LHC (CERN)	400	40	~ 1/12
HERA (DESY)	208	10.4	1/1
Tevatron (FNAL)	53	2.5	~ 11/1

1. Introduction (cont.)

⟹ ***Need for beam gymnastics in the chain of injectors to change the number of bunches while satisfying the following constraints:***

- **minimum blow-up of longitudinal emittance,**
- **minimum (no ?) losses,**
- **high reliability / high stability of performance,**
- **low cost (minimum modifications to existing injectors hardware)**

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Modulation of RF parameters (amplitude, phase, frequency)

Non-trivial manipulations are called <u>"RF gymnastics"</u>

Preliminary comments:

- **Synchrotron radiation is not considered.**
- **Large numbers of gymnastics have been invented. Only the most typical and common ones are described.**

2. Longitudinal beam dynamics [ref. 1 + 2]

- **Particle parameters:**
  - **charge, energy (rest energy): q, *E* (*E_0*)**
  - **speed, momentum, relativistic parameters: *v*, *p*, β, γ**
  - **revolution period (frequency), orbit length: *T* (ω_R/2π), 2π*R***
- **Synchrotron parameters:**
  - α_P , γ_T , η

$$\frac{\Delta R}{R} = \alpha_P \frac{\Delta p}{p}, \qquad \alpha_P = \frac{1}{\gamma_T^2}$$

$$\frac{\Delta \omega}{\omega} = -\eta \frac{\Delta p}{p}, \qquad \eta = \frac{1}{\gamma_T^2} - \frac{1}{\gamma^2}$$

  - **nominal orbit length: 2$\pi$$R_0$**
  - **energy etc. on nominal orbit: E_0, v_0, p_0, β_0, γ_0**
- **RF parameters**
  - **frequency, harmonic number:** h, ω_R $\qquad \omega = h\omega_R$
  - **voltage (peak voltage), phase:** $\hat{V}, \varphi$ $\qquad V = \hat{V}\sin(\omega t + \varphi)$

2. Longitudinal beam dynamics

◆ Equations of motion

- **Synchronous particle = "*the particle whose energy E_S and phase φ_S are such that it sees the same voltage at the next revolution*"**
- **Phase slip:**

$$\text{per turn}: \quad d\Delta\varphi = h\omega_{RS}\left(T - T_S\right)$$

$$\text{per second}: \frac{d\Delta\varphi}{dt} = h\omega_{RS}\frac{\Delta T}{T_S}$$

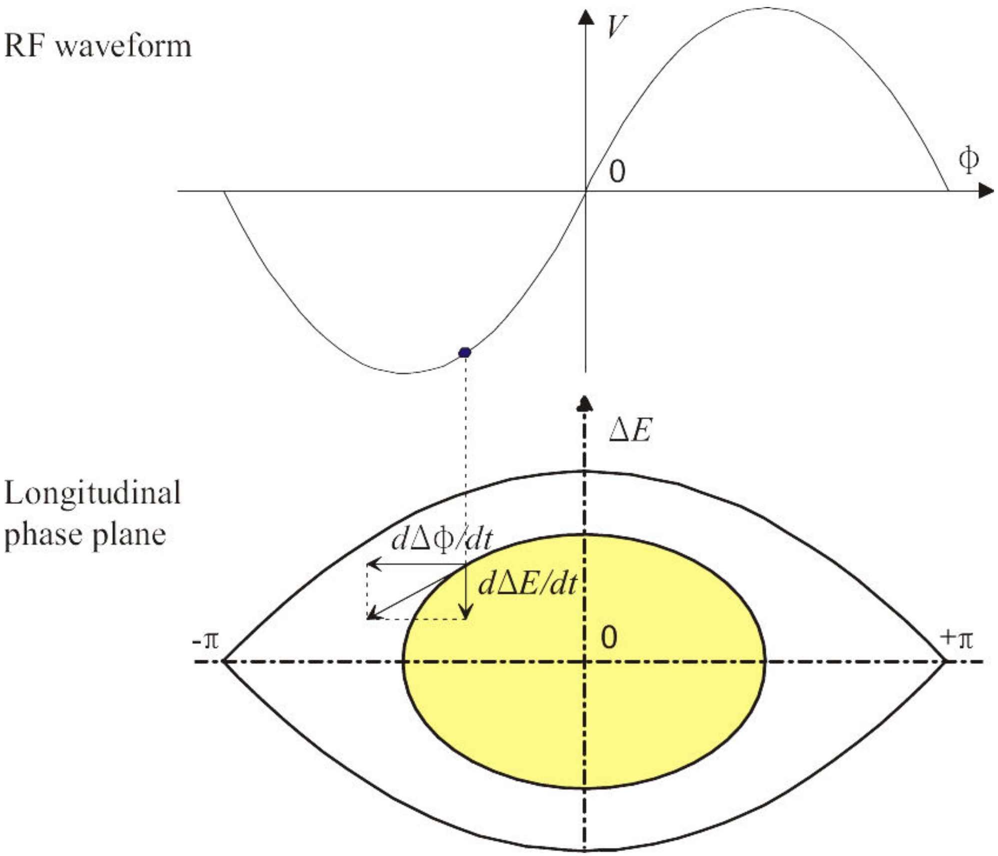
$$\Rightarrow \quad \boxed{\frac{d\Delta\varphi}{dt} = \frac{h\eta\omega_{RS}}{\beta^2}\frac{\Delta E}{E_S}}$$

- **Energy variation:**

$$\boxed{\frac{d\Delta E}{dt} = \frac{q\omega_{RS}}{2\pi}\left[V\left(\Delta\varphi + \varphi_S\right) - V\left(\varphi_S\right)\right]}$$

2. Longitudinal beam dynamics

◆ **Phase stability** **(sinewave & stationary bucket)**



Comment

On the unstable fixed points (±π, 0):

$$\frac{d\Delta\varphi}{dt} = 0, \ \frac{d\Delta E}{dt} = 0$$

2. Longitudinal beam dynamics

- **Basic relations and effects of parameters** (case of a stationary bucket)
  - Synchrotron frequency (for small amplitude oscillations around the synchronous particle)

$$\omega_S = \sqrt{\frac{h|\eta|\omega_{RS}^2 q\hat{V}}{2\pi\beta^2 E_S}}$$

  - Bucket height

$$\Delta E_{MAX} = \sqrt{\frac{2E_S\beta^2}{\pi h|\eta|} q\hat{V}}$$

  - Bunch dimensions at constant emittance

$$\Delta\hat{\varphi} \propto \left[\frac{|\eta|}{hE_S q\hat{V}}\right]^{\frac{1}{4}} \qquad \Delta\hat{E} \propto \left[\frac{hE_S q\hat{V}}{|\eta|}\right]^{\frac{1}{4}}$$

2. Longitudinal beam dynamics

◆ Adiabaticity

- **Adiabatic = *"Parameters are changed at a slow enough rate so that the distribution of particles is always at equilibrium."***
- **Adiabaticity parameters:** ε

$$\varepsilon = \frac{1}{\omega_S^2}\left|\frac{d\omega_S}{dt}\right|$$

◆ Emittance preservation (Liouville's theorem)

Longitudinal motion is conservative (no energy dissipation effect like synchrotron radiation)

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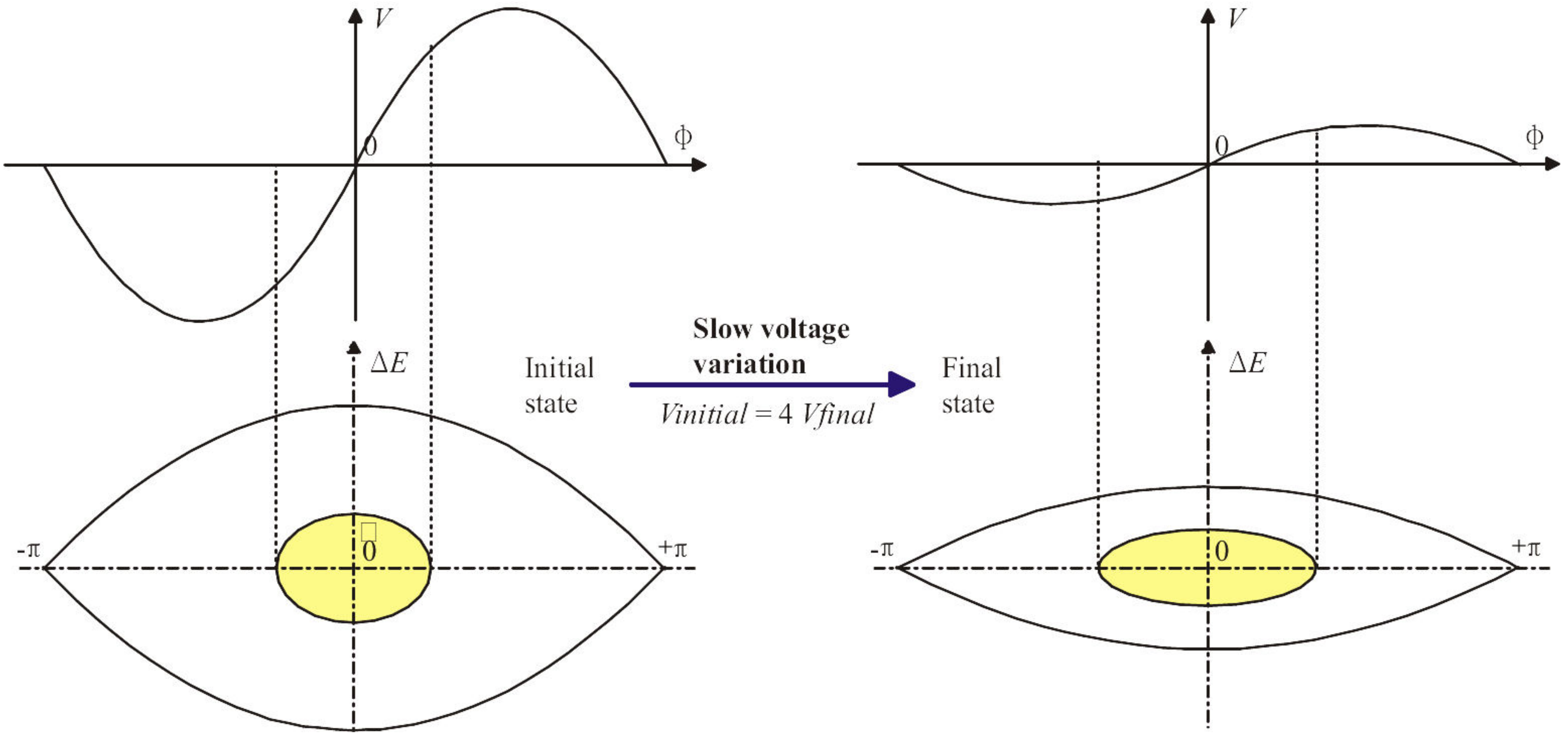
Constant local density of particles in the longitudinal phase plane

2. Longitudinal beam dynamics
"Micro-" and "Macro-scopic" emittances

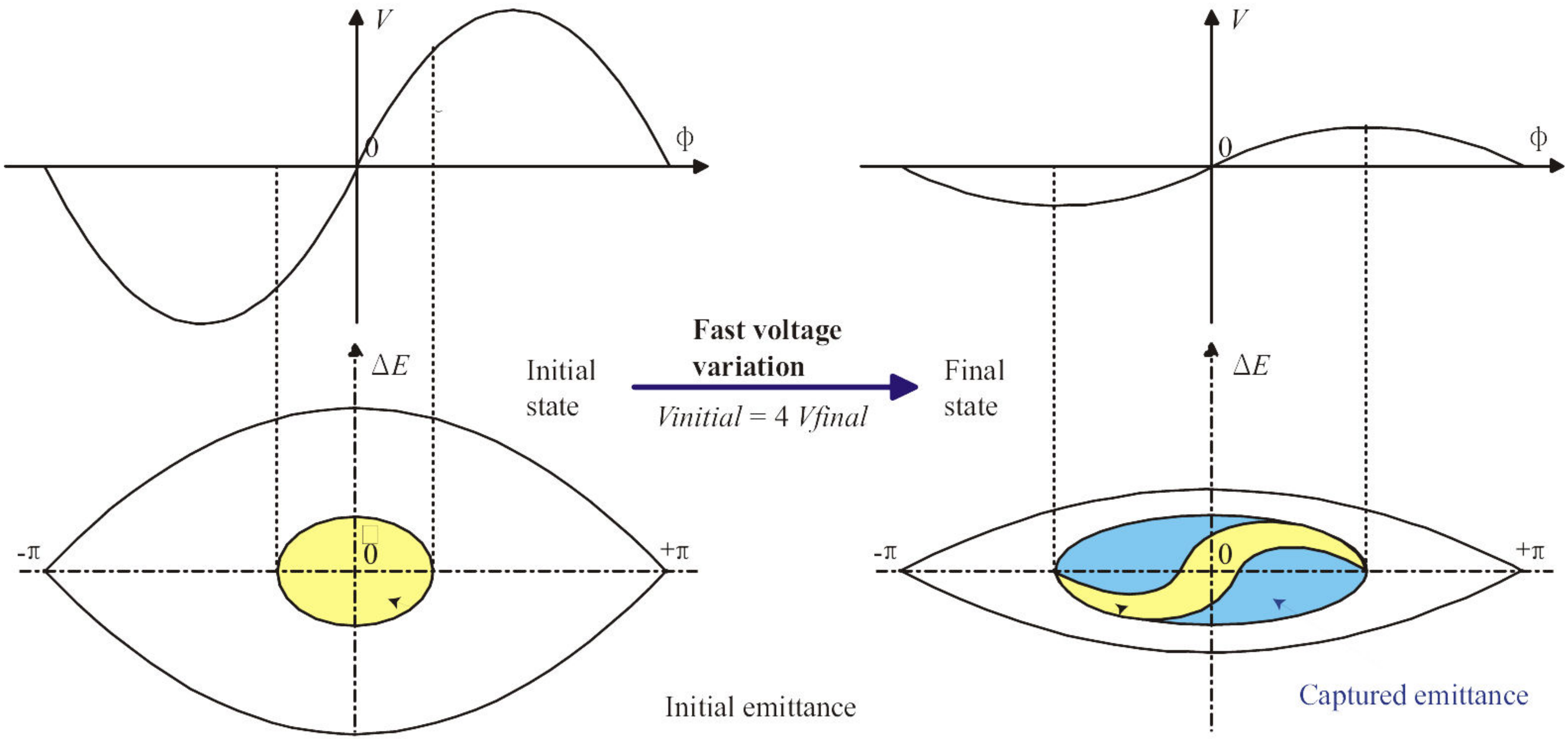
- **Adiabatic RF voltage reduction**



2. Longitudinal beam dynamics

“Micro-” and “Macro-scopic” emittances

- Non-adiabatic RF voltage reduction



3. Single bunch gymnastics
Bunch compression [ref. 3, 4, 5]

- **Required to get:**

  short bunches and/or large energy spread (Liouville !)

- **Principle:**

  rotate a mismatched and long bunch in a large bucket.

Required characteristics are only momentarily achieved

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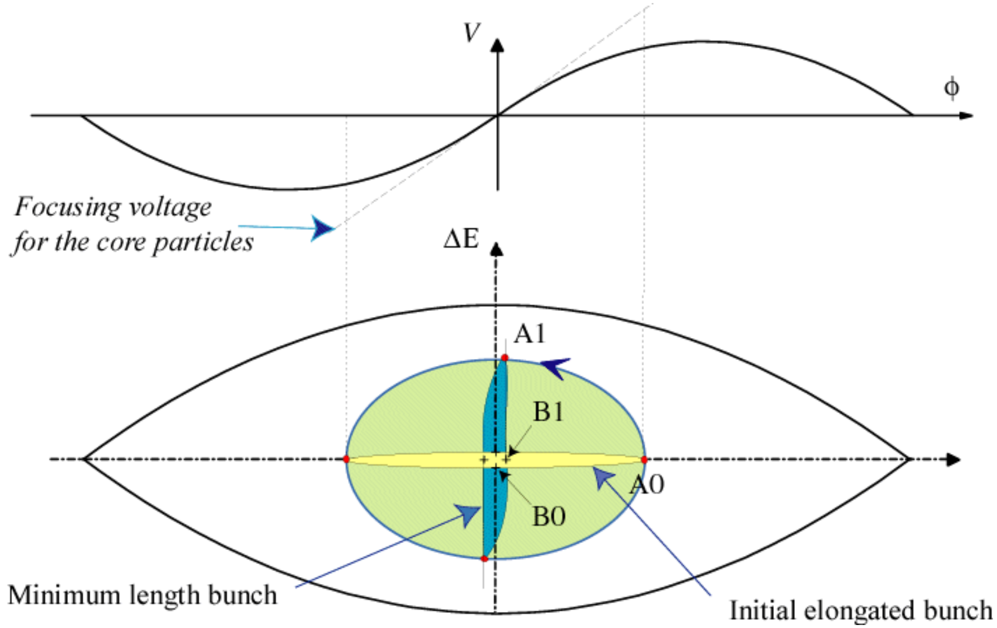
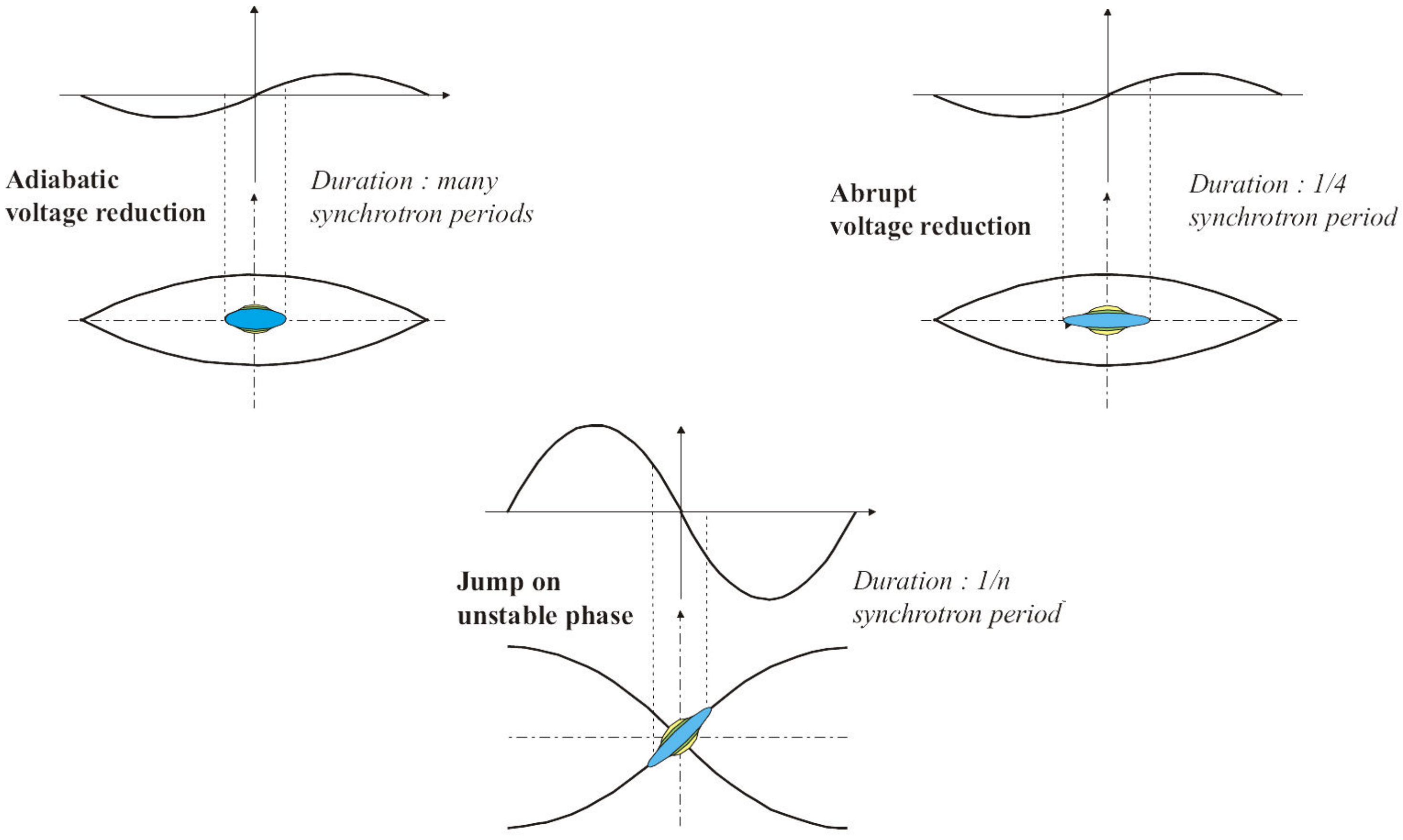
precise timing for ejection or RF turn-off



3. Single bunch gymnastics
Bunch compression

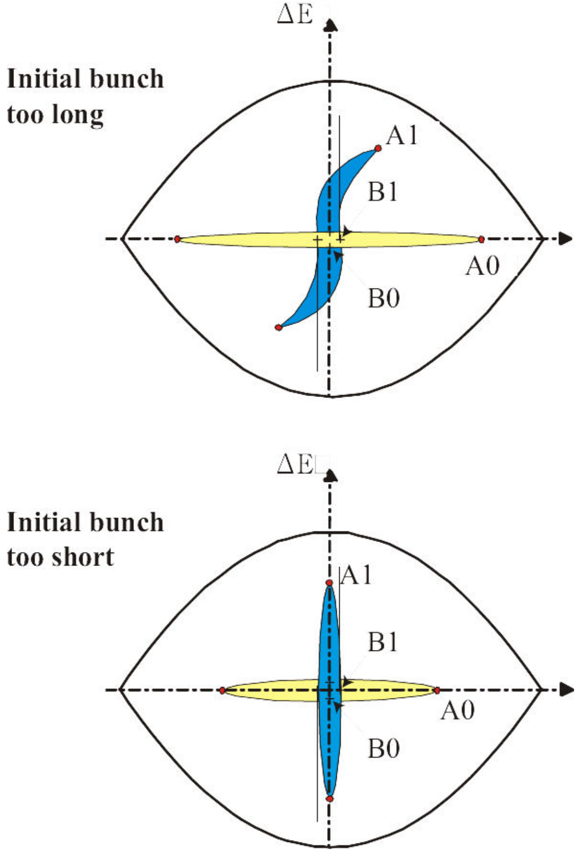
- **Bunch stretching techniques**

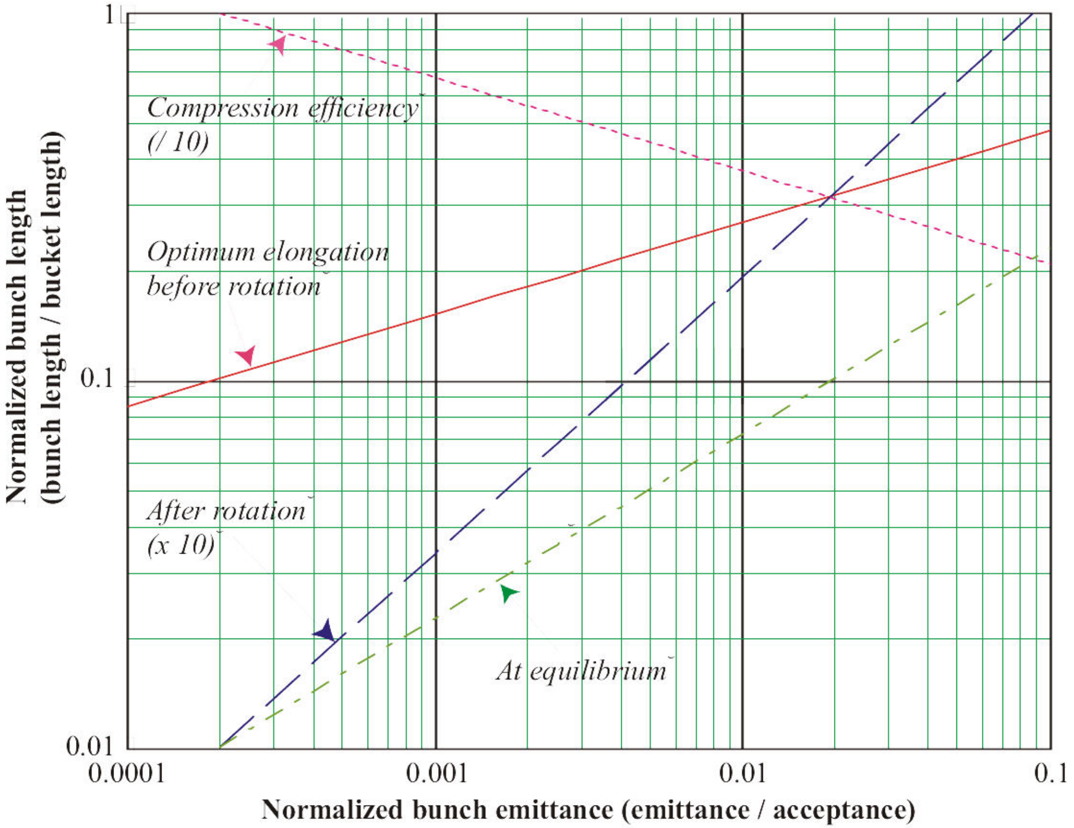


3. Single bunch gymnastics
Bunch compression

- **Performance:**

depends upon bunch length and normalized emittance

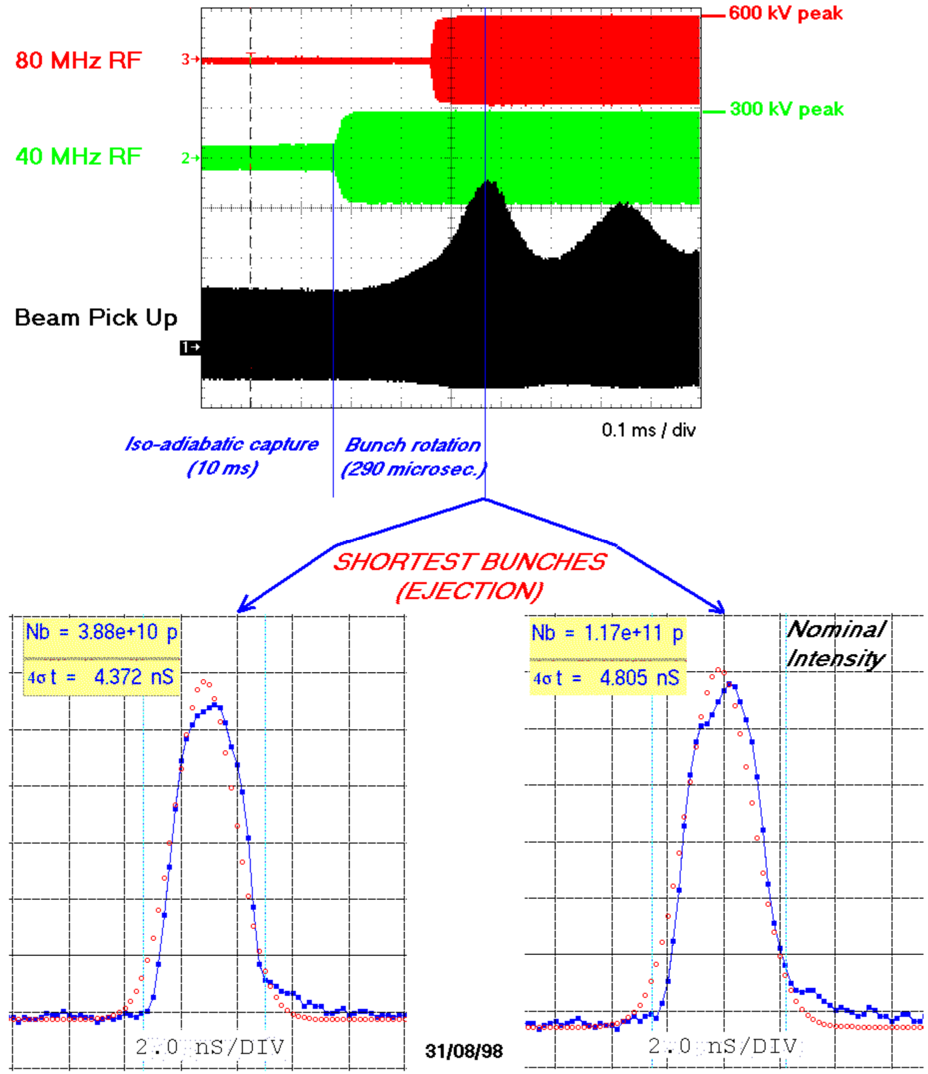




3. Single bunch gymnastics
Bunch compression (experiment)

LHC bunch Compression in the CERN-PS before ejection to the SPS

p = 26 GeV/c



<u>Comment</u>

Phase & energy errors are swapped
⇒ phase accuracy depends upon initial energy
⇒ energy accuracy depends upon initial phase

3. Single bunch gymnastics
Controlled blow-up [ref. 6, 7, 8]

- **Required for:**

stabilizing the beam at high intensity

- **Principle:**

increase the longitudinal "macroscopic" emittance creating filaments deliberately and accelerating their dilution

- **Technique:**

superpose to the RF holding the beam a phase modulated voltage at a much higher frequency

$$V_H = \hat{V}_H \sin(h_H \omega_R t + \alpha \sin \omega_M t + \theta_H)$$

Resonances are induced which redistribute density inside the bunch. High frequency increases non-linearities and helps smooth the distribution (filamentation).

3. Single bunch gymnastics
Controlled blow-up

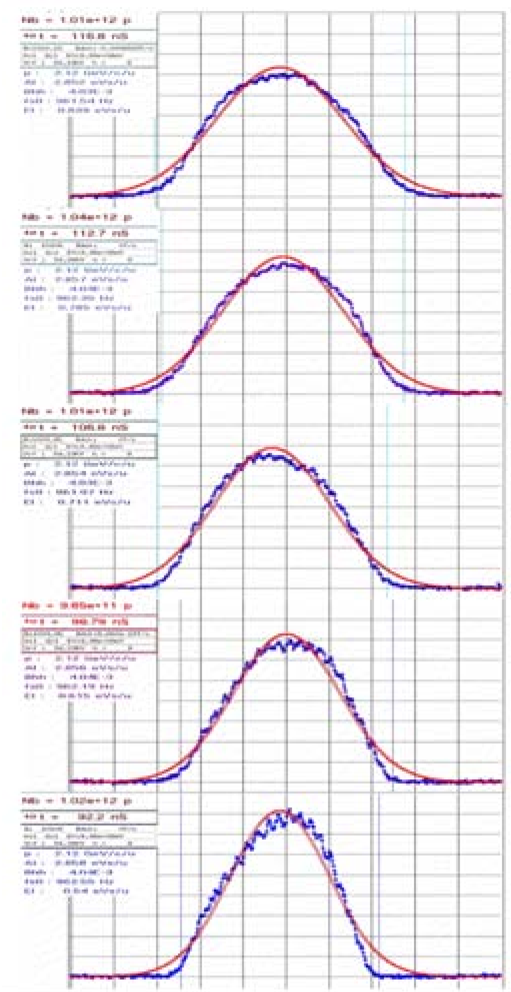
- **Typical parameters**

$\frac{\hat{V}_H}{\hat{V}}$	$\frac{h_H}{h}$	α (rad)	$\frac{\omega_M}{\omega_S}$	**Duration**
0.05 to 0.2	**> 10 for fast blow-up**	**0.8 π to 1.2 π**	**2 to 7**	**>10 synchrotron periods**

3. Single bunch gymnastics
Controlled blow-up (experiment)

Longitudinal controlled Blow-up in the CERN-PS

T=1.4 GeV



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

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

4. Multi-bunch gymnastics

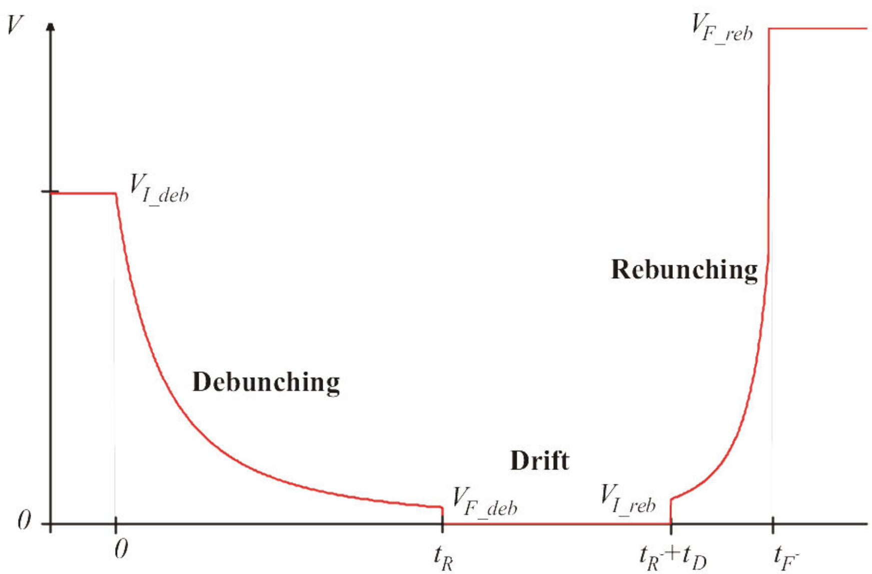
Iso-adiabatic debunching-rebunching [ref. 9, 10]

- **Used for changing the number of bunches**
- **Principle:**
  - **Slow (adiabatic) voltage reduction with fast final h_1 RF turn-off**
  - **Drift period without RF**
  - **Fast h_2 RF turn-on followed by slow (adiabatic) voltage increase**

Voltage variation at constant adiabaticity $\varepsilon = \frac{1}{\omega_S^2}\left|\frac{d\omega_S}{dt}\right|$

$$V_{deb}(t) = \frac{V_{I\_deb}}{\left[1-\left(1-\sqrt{\frac{V_{I\_deb}}{V_{F\_deb}}}\right)\frac{t}{t_R}\right]^2}$$

$$V_{reb}(t) = \frac{V_{I\_reb}}{\left[1-\left(1+\sqrt{\frac{V_{I\_reb}}{V_{F\_reb}}}\right)\frac{t}{t_F}\right]^2}$$



4. Multi-bunch gymnastics
Iso-adiabatic debunching-rebunching

- **Performance:**
  - depends upon adiabaticity and voltages at RF turn-off and -on
  - high sensitivity to disturbance during drift without RF
  - effect of beam induced voltage in cavities

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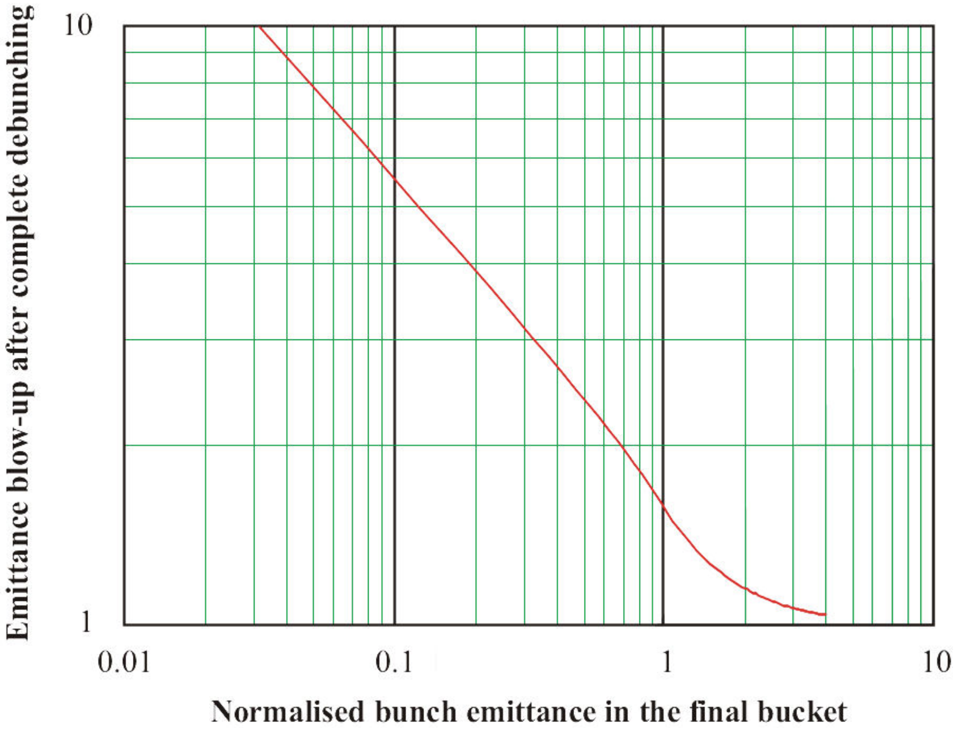
  - unavoidable blow-up

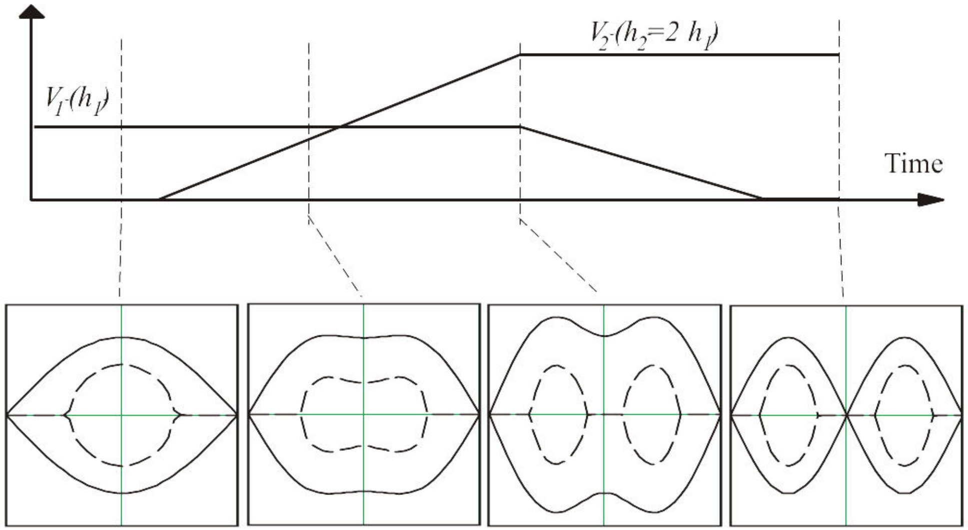
+ no gap without beam



4. Multi-bunch gymnastics
Splitting (Merging) [ref. 11, 12]

- **Changes the numbers of bunches** (in multiples of 2 and 3)
- **Principle:** adiabatically change the focusing voltage for a continuous evolution from the original to the final state
- **Technique:** apply simultaneously 2 RF voltages on h and 2h (Example of splitting in 2)

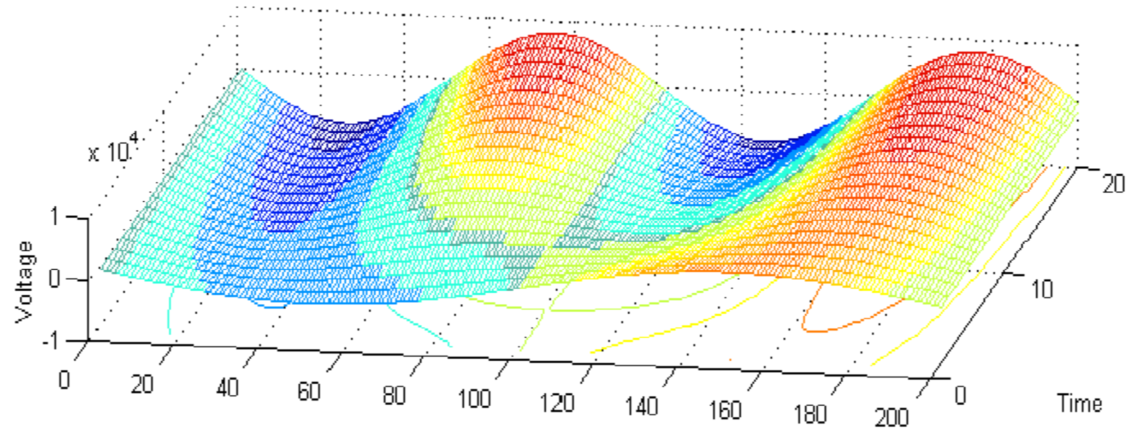
$$V_1 = \hat{V}_1 \sin(h\omega_R t)$$
$$V_2 = \hat{V}_2 \sin(2h\omega_R t + \pi)$$



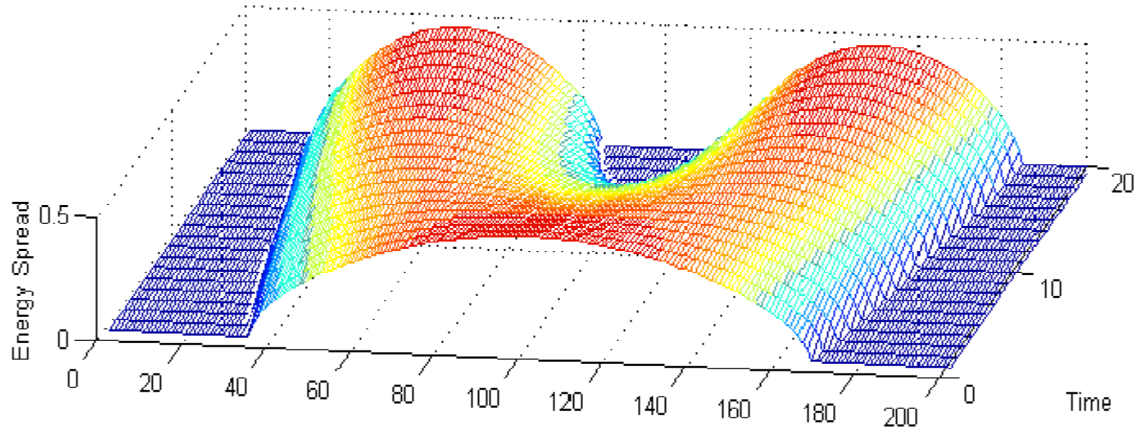
4. Multi-bunch gymnastics
Splitting in two (simulation)

- **Technique:**

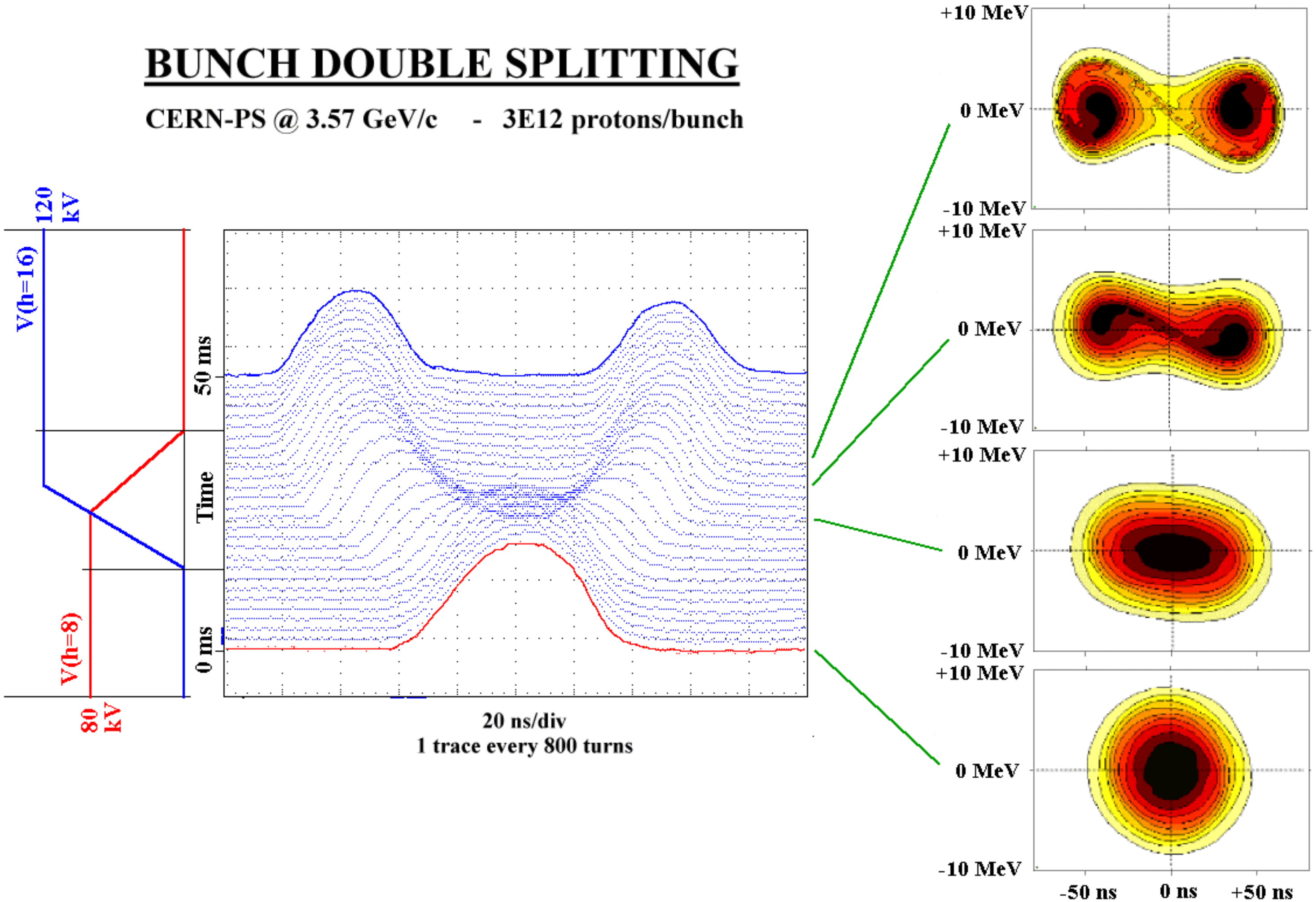
Time evolution of the RF voltage



Time evolution of the bunch(es)

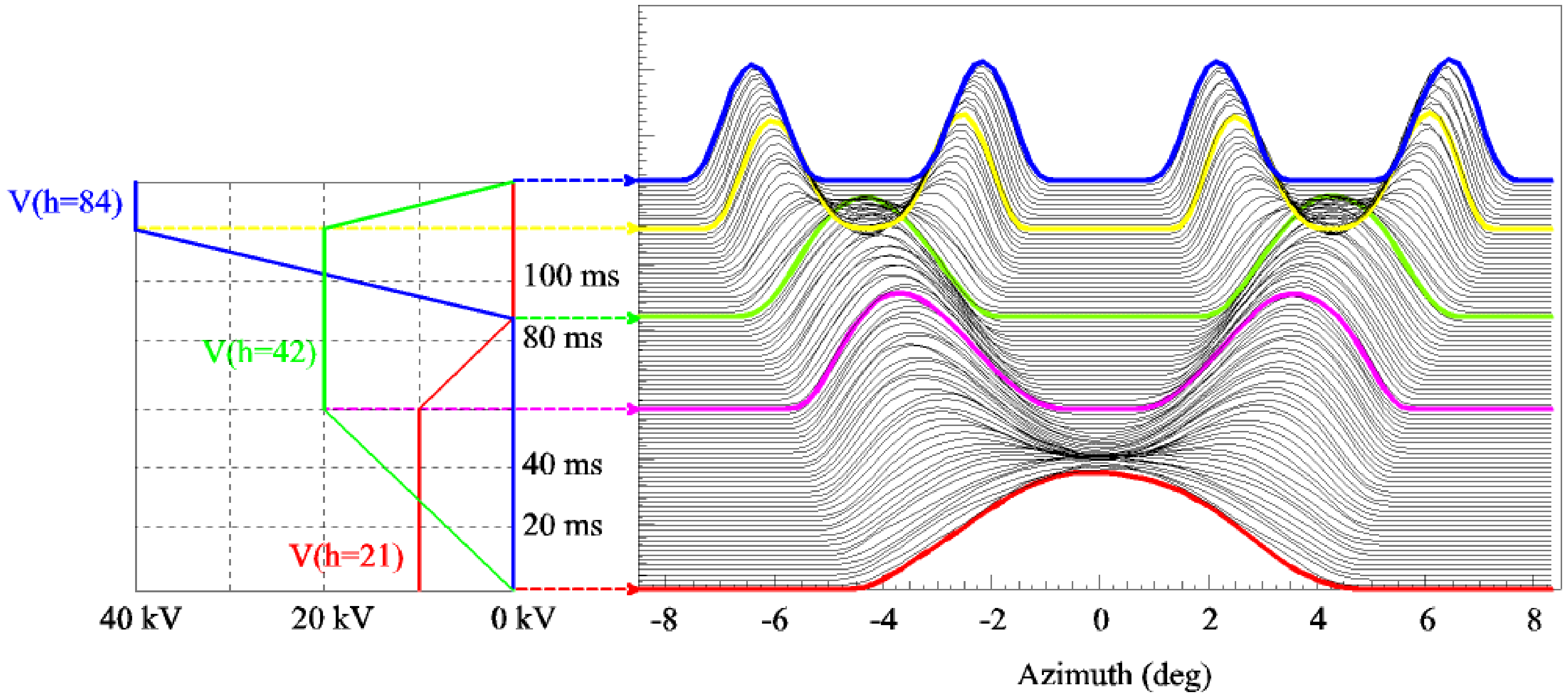


4. Multi-bunch gymnastics
Splitting in two (measurement)



4. Multi-bunch gymnastics
Splitting in four (simulation)

Splitting bunches in four at 26 GeV/c

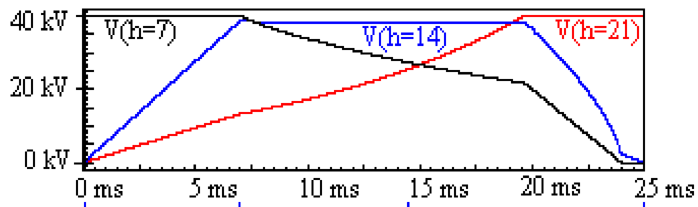


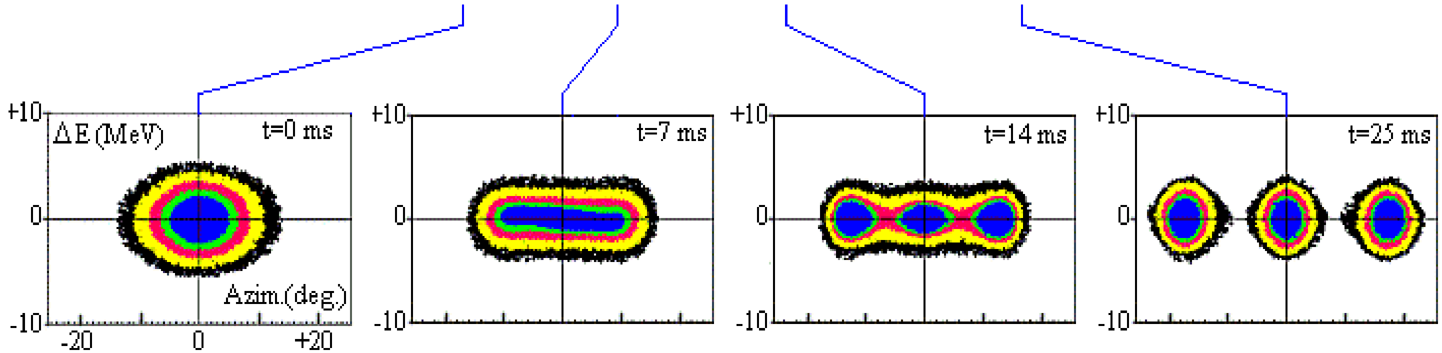
4. Multi-bunch gymnastics

Triple splitting [simulation (1)]

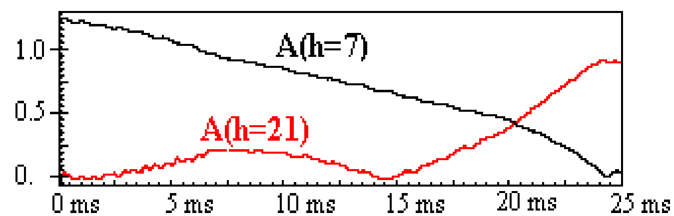
Splitting bunches in three at 3.57 GeV/c in the PS

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





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

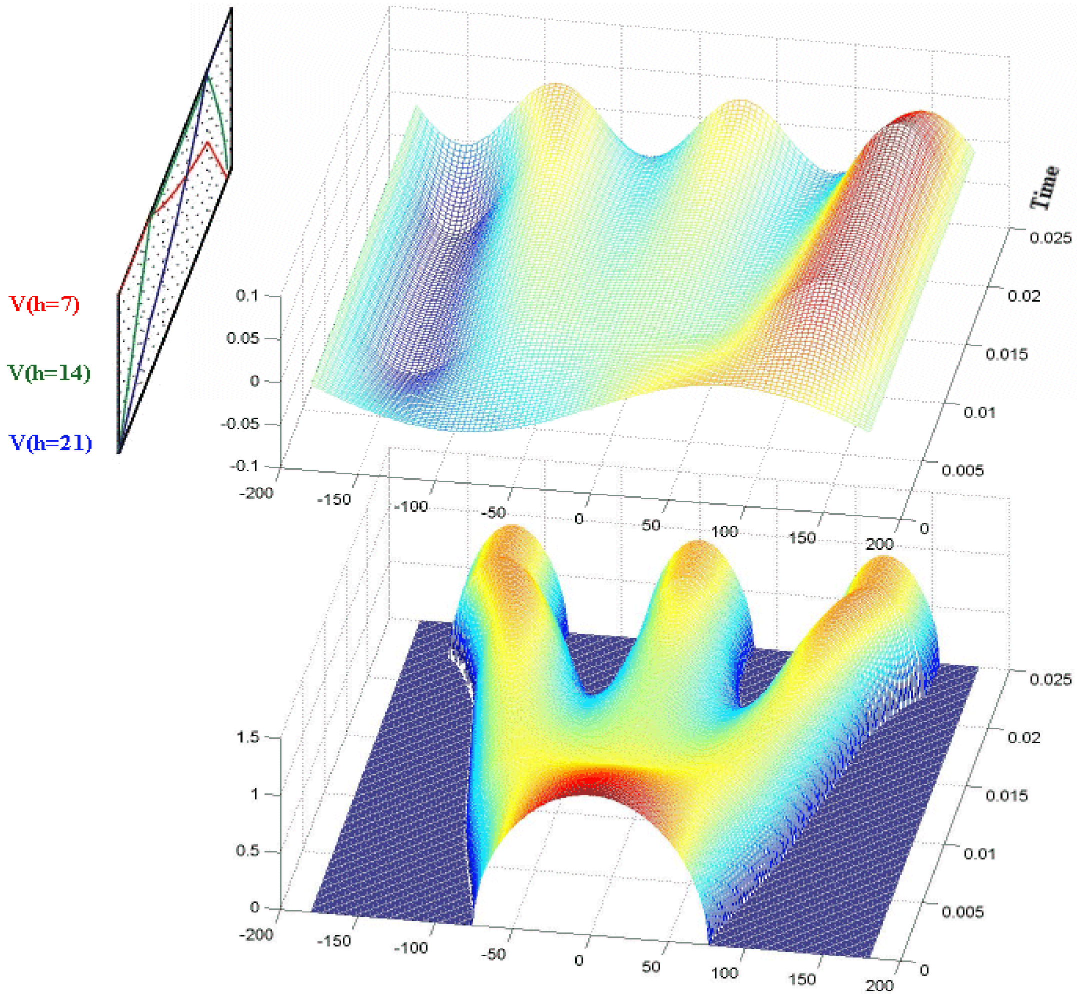


4. Multi-bunch gymnastics

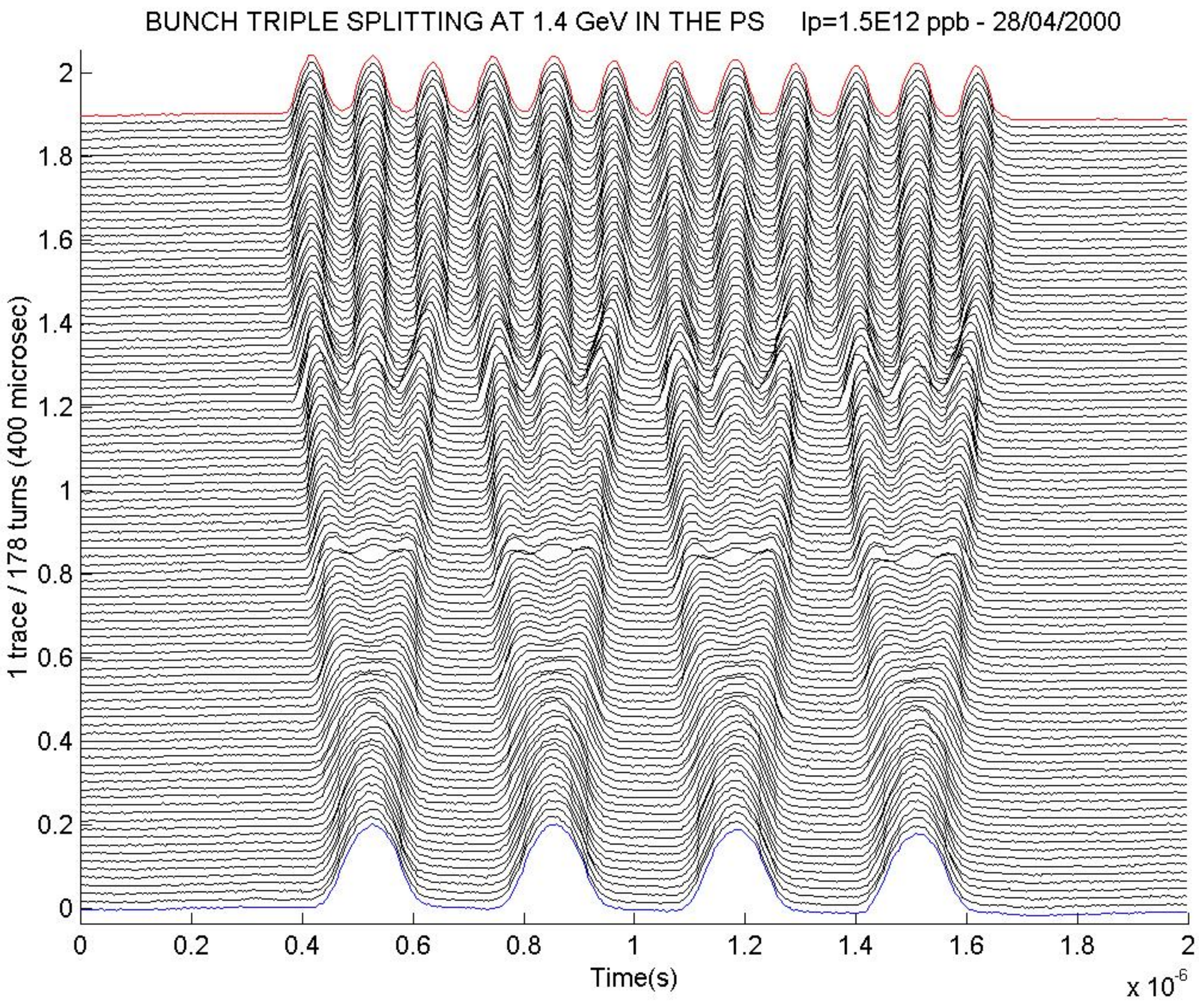
Triple splitting [simulation (2)]

Time evolution of the RF voltage

Time evolution of the bunch(es)



4. Multi-bunch gymnastics
Triple splitting (measurement)



4. Multi-bunch gymnastics
Splitting (Merging)

Advantages with respect to debunching / rebunching:

- **Capability to preserve longitudinal emittance: no need for very low RF voltages to minimise blow-up,**
- **Capability to keep 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.**