RF Manipulations I

H. Damerau
CERN

RF for Accelerators

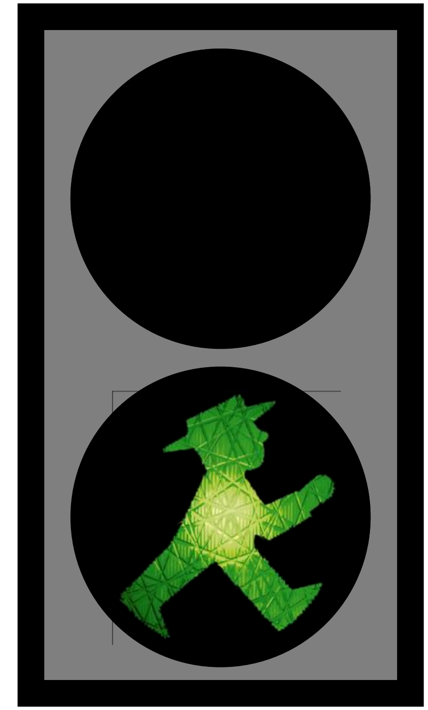
29 June 2023

The CERN Accelerator School

Copyright statement and speaker's release for video publishing

Outline

- Introduction
  - Longitudinal beam dynamics
- Single-harmonic RF
  - Bunching and de-bunching
  - Bunch rotation
  - Controlled longitudinal blow-up
- Double-harmonic RF
  - Rebucketing
  - Bunch merging
  - Multiple bunch splitting
  - Batch compression
- Double RF system
- Non-sinusoidal RF voltages
- Sequences, design and implementation
- Summary

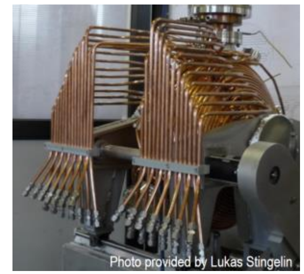


Let’s go!

Introduction

What can you do with RF in an accelerator?

Acceleration

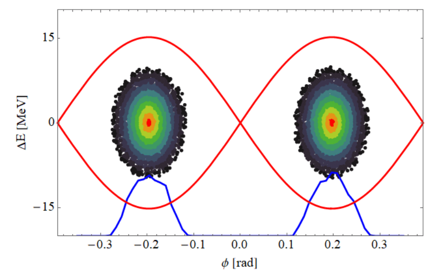


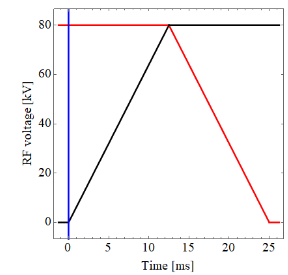
SLS

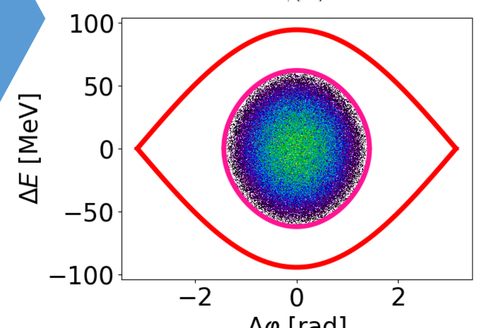
LHC

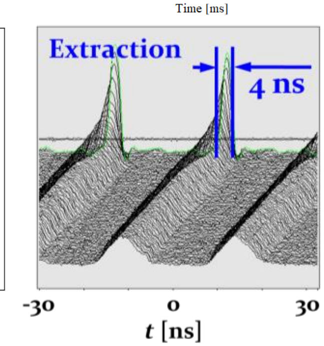
Only acceleration? → RF can do much more!

Control of long. beam parameters

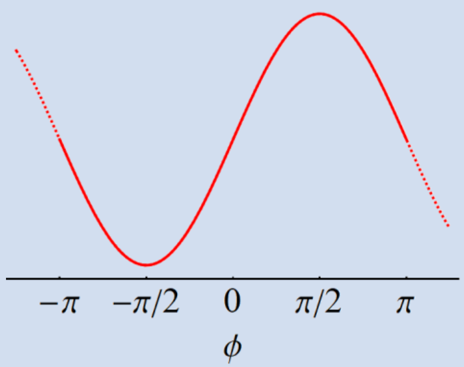








Impact and application of RF

RF parameter	Beam parameter
• Frequency, f_{RF} • Harmonic number, h	→ Bunch spacing: $1/f_{RF}$ and multiples → Bunch length and pattern
	→ Orbit length: $2\pi R$ is multiple of RF wavelength → Radial offset → Beam energy: approximately proportional to orbit length
• Amplitude, V_{RF}	→ Bunch length
• Phase, ϕ	→ Position of beam in time or phase

Beyond acceleration

→ Control over longitudinal beam parameters

→ Impacts some transverse properties

Motivation

- Energy gain per turn in a hadron synchrotron

$$\Delta E_{\text{turn}} = 2\pi q \rho R \dot{B}$$

→ Grows with size of accelerator, $\rho \cdot R$

Low and medium energy < ~50 GeV	High energy synchrotrons and colliders > ~50 GeV
• Moderate RF voltage requirements: < ~ 1 MV • Non-relativistic beam → Revolution frequency sweeps → Tuneable (ferrite) or wideband RF systems	• Large RF voltages for fast acceleration: several MV • Ultra-relativistic beam → Tiny revolution frequency increase → Fixed-frequency RF systems • Short bunches in collision
→ RF frequencies below 50 MHz	→ RF frequencies above 50 MHz

Motivation

Low and medium energy		High energy synchrotrons and colliders	
→ RF frequencies well below 50 MHz		→ RF frequencies above 50 MHz	
CERN PS	2.8…10 MHz	CERN SPS	200 MHz
BNL AGS	1.6…4.5 MHz	BNL RHIC	198 MHz
FNAL Booster	38…53 MHz	LHC	400 MHz

→ Need RF to increase RF frequency in chain of synchrotrons

→ Beam parameters for an experiment, e.g., short bunches

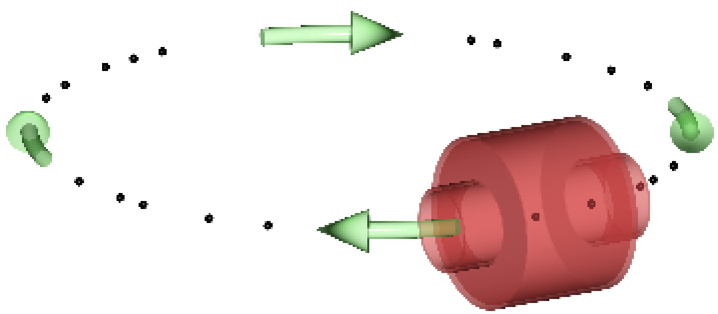
→ Longitudinal stacking and accumulation of beam

RF manipulations

Longitudinal beam dynamics

RF voltage, potential and bucket

Simple accelerator model:

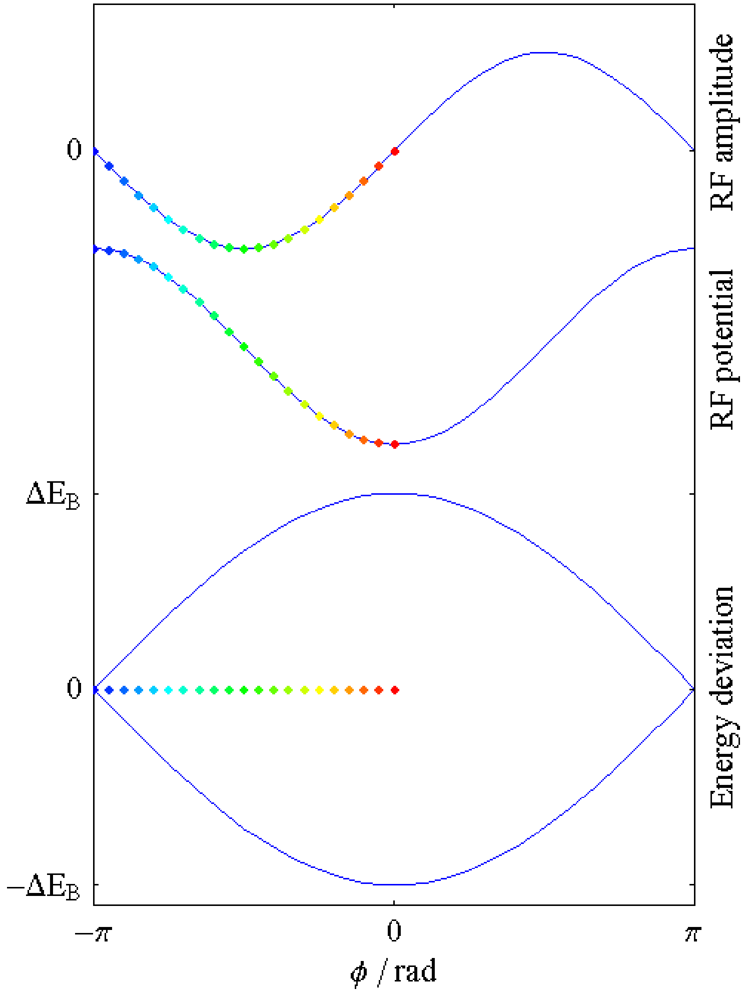


Energy dependent phase advance, ϕ:

$$\phi_{n+1} = \phi_n + 2\pi h\eta \frac{\Delta E_n}{\beta^2 E},\ \eta = \frac{1}{\gamma_{\mathrm{tr}}^2} - \frac{1}{\gamma^2}$$

Phase dependent energy gain, ΔE:

$$\Delta E_{n+1} = \Delta E_n + qVg(\phi_{n+1})$$



Works for arbitrary shape of acceleration amplitude $g(\phi)$

Longitudinal beam dynamics – single RF

- **Construct Hamiltonian from equations of motion**

$$\frac{d}{dt}\phi = \frac{h\eta\omega_{\mathrm{rev}}}{pR}\left(\frac{\Delta E}{\omega_{\mathrm{rev}}}\right)$$

$$\frac{d}{dt}\left(\frac{\Delta E}{\omega_{\mathrm{rev}}}\right) = \frac{qV}{2\pi}(\sin\phi - \sin\phi_S)$$

same structure

$$\frac{dq}{dt} = \frac{\partial H}{\partial p}$$

$$\frac{dp}{dt} = -\frac{\partial H}{\partial q}$$

$$q = \phi \qquad p = \frac{\Delta E}{\omega_{\mathrm{rev}}}$$

$$H(p,q) = T(p) + W(q)$$

- **Hamiltonian constant on trajectory**

$$H(p,q) = H_{\mathrm{trajectory}}$$

→ **'Energy conservation'**

Continuous approximation – single RF

Single-harmonic RF system

$$\frac{d}{dt}\phi = \frac{h\eta\omega_{\mathrm{rev}}}{pR}\left(\frac{\Delta E}{\omega_{\mathrm{rev}}}\right)$$

$$\frac{d}{dt}\left(\frac{\Delta E}{\omega_{\mathrm{rev}}}\right) = \frac{qV}{2\pi}(\sin\phi - \sin\phi_{\mathrm{S}})$$

$$H\left(\phi, \frac{\Delta E}{\omega_{\mathrm{rev}}}\right) = \frac{1}{2}\frac{h\eta\omega_{\mathrm{rev}}}{pR}\left(\frac{\Delta E}{\omega_{\mathrm{rev}}}\right)^2 + \frac{qV}{2\pi}\left[\cos\phi - \cos\phi_{\mathrm{S}} + (\phi - \phi_{\mathrm{S}})\sin\phi_{\mathrm{S}}\right]$$

with $\phi = \phi_{\mathrm{S}} + \Delta\phi$ **this becomes**

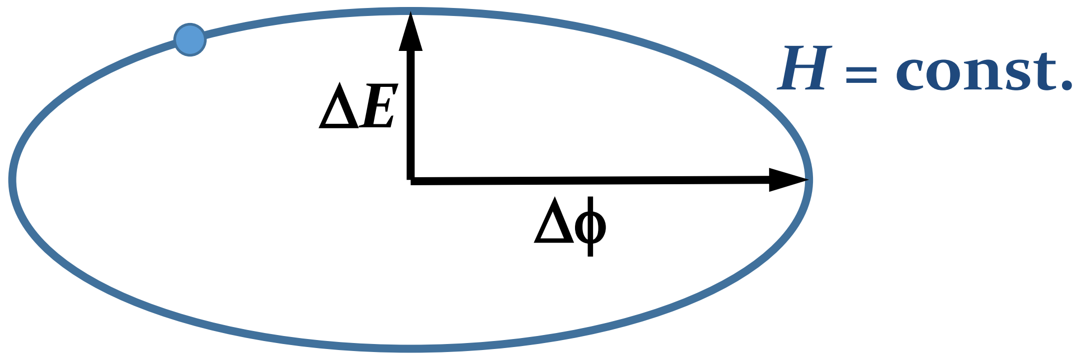
$$H\left(\Delta\phi, \frac{\Delta E}{\omega_{\mathrm{rev}}}\right) = \frac{1}{2}\frac{h\eta\omega_{\mathrm{rev}}}{pR}\left(\frac{\Delta E}{\omega_{\mathrm{rev}}}\right)^2 + \frac{qV}{2\pi}\left[\cos(\phi_{\mathrm{S}} + \Delta\phi) - \cos\phi_{\mathrm{S}} + \Delta\phi\sin\phi_{\mathrm{S}}\right]$$

→ Conventional longitudinal beam dynamics → E. Shaposhnikova

Linear part of non-linear bucket

$$H\left(\Delta\phi, \frac{\Delta E}{\omega_{\mathrm{rev}}}\right) \simeq \frac{1}{2}\frac{h\eta\omega_{\mathrm{rev}}}{pR}\left(\frac{\Delta E}{\omega_{\mathrm{rev}}}\right)^2 - \frac{1}{2}\frac{qV}{2\pi}\cos\phi_S \Delta\phi^2$$

- **In the centre of the bucket, $\Delta\phi \ll 1$ → particles move on elliptical trajectories in $\Delta\phi$-ΔE phase space**
- **Hamiltonian is constant on these trajectories**



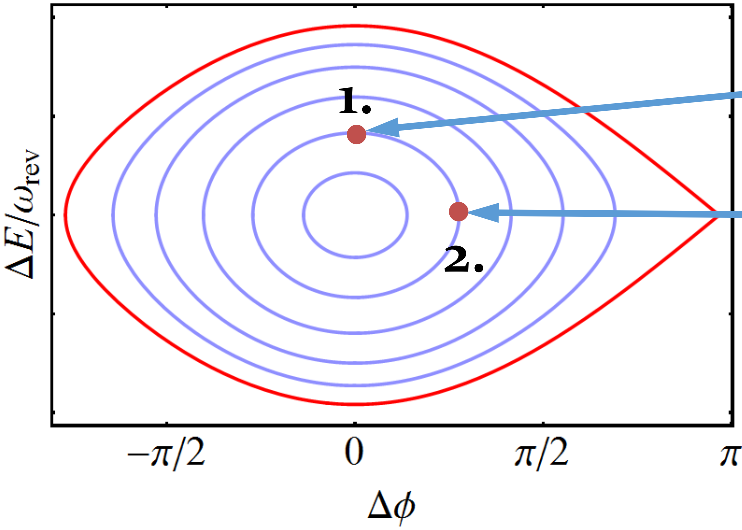
- **In the bucket centre, particles oscillate with the synchrotron frequency, $\omega_S = 2\pi f_S$**

$$\omega_S^2 = -\frac{h\eta\omega_{\mathrm{rev}} qV\cos\phi_S}{2\pi pR}$$

$$\eta = \frac{1}{\gamma_{\mathrm{tr}}^2} - \frac{1}{\gamma^2}$$

Longitudinal emittance

- **Compare two particles on the same trajectory**
  1. **No phase deviation**
  2. **No energy deviation**



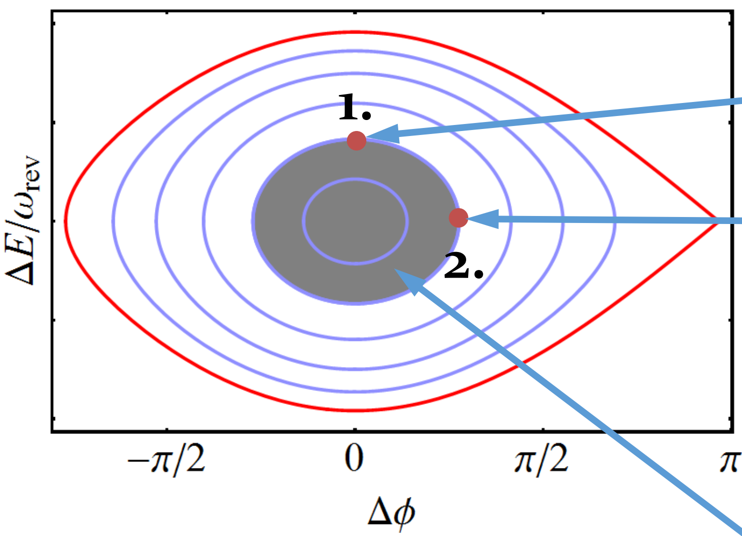
$$H\left(\Delta\phi = 0, \frac{\Delta E}{\omega_{\rm rev}}\right) = \frac{1}{2}\frac{h\eta\omega_{\rm rev}}{pR}\left(\frac{\Delta E}{\omega_{\rm rev}}\right)^2$$

$$H\left(\Delta\phi, \frac{\Delta E}{\omega_{\rm rev}} = 0\right) = -\frac{1}{2}\frac{qV}{2\pi}\cos\phi_S \Delta\,\phi^2$$

Longitudinal emittance

- **Compare two particles on the same trajectory**

1. No phase deviation **2. No energy deviation**



$$H\left(\Delta\phi = 0, \frac{\Delta E}{\omega_{\mathrm{rev}}}\right) = \frac{1}{2}\frac{h\eta\omega_{\mathrm{rev}}}{pR}\left(\frac{\Delta E}{\omega_{\mathrm{rev}}}\right)^2$$

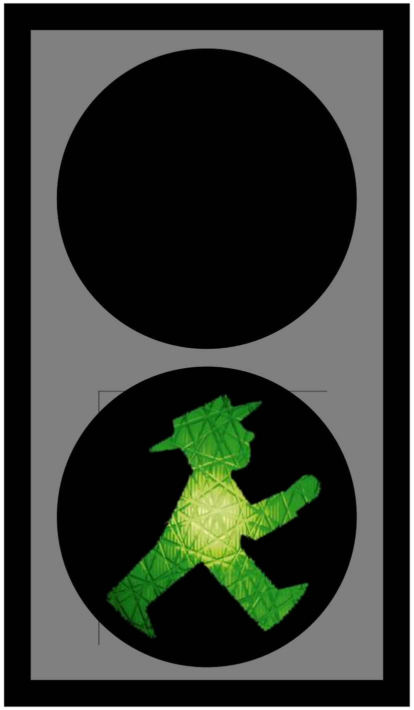
$$H\left(\Delta\phi, \frac{\Delta E}{\omega_{\mathrm{rev}}} = 0\right) = -\frac{1}{2}\frac{qV}{2\pi}\cos\phi_S \Delta\,\phi^2$$

$$\varepsilon_l = \frac{2}{h\omega_{\mathrm{rev}}}\int_{\Delta\phi_i}^{\Delta\phi_f} \Delta E(\Delta\phi)\, d(\Delta\phi)$$

Longitudinal emittance, ε_l

~ **Surface occupied by particles in longitudinal phase space**

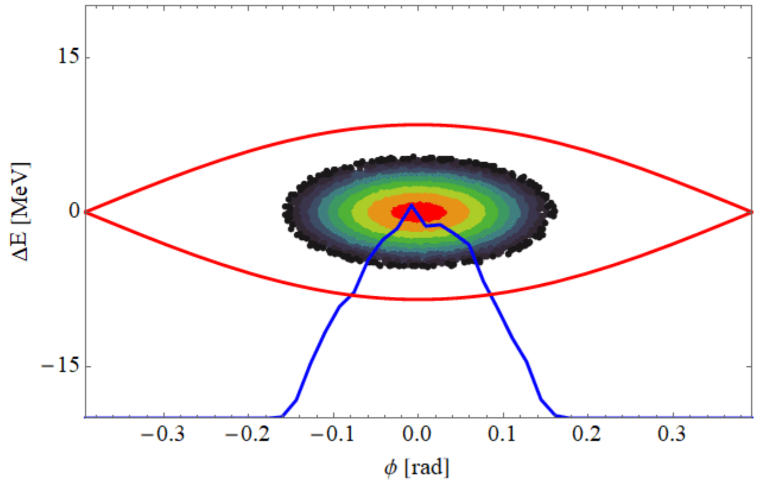
→ **Preserved in physical $[\pi \Delta\tau\, \Delta E]$ = eVs**

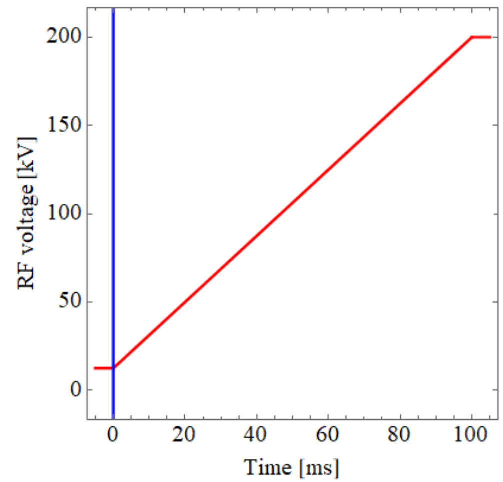


RF voltage variations

Most simple RF manipulation

- Change bunch length by simply changing RF voltage





- Bunches get shorter, but not much
- Which voltage function is optimal to get from V_i to V_f?

Optimum voltage changes

- **Which voltage function is optimal to get from V_i to V_f?**

$\rightarrow$ **Definition adiabaticity parameter**

Relative change of synchrotron frequency $\frac{d\omega_\mathrm{S}/dt}{\omega_\mathrm{S}}$

during one period $T_\mathrm{S} = \frac{2\pi}{\omega_\mathrm{S}}$

$$\alpha = 2\pi \frac{1}{\omega_\mathrm{S}^2} \frac{d\omega_\mathrm{S}}{dt}$$

$\rightarrow$ **Derive voltage functions with constant α**

Optimum voltage changes

- **Which voltage function is optimal to get from V_i to V_f, within the time, τ ?**

→ Synchrotron frequency depends on RF voltage

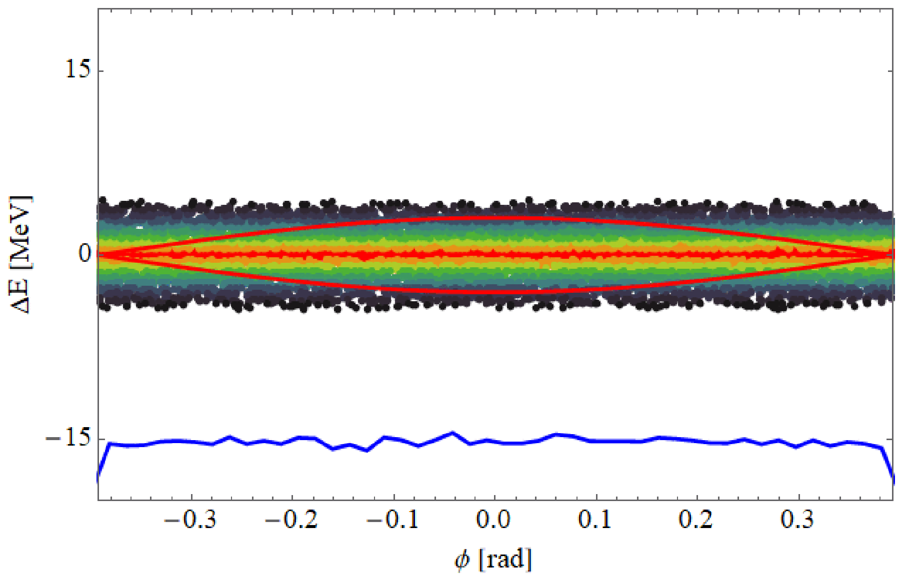
$$\alpha = 2\pi \frac{1}{\omega_\mathrm{S}^2} \frac{d\omega_\mathrm{S}}{dt} \quad \Rightarrow \quad \alpha = \frac{2\pi}{\omega_\mathrm{rev}} \sqrt{\frac{2\pi E \beta^2}{h|\eta|q}} \cdot \frac{1}{2V_\mathrm{RF}(t)^{3/2}} \frac{d}{dt} V_\mathrm{RF}(t)$$

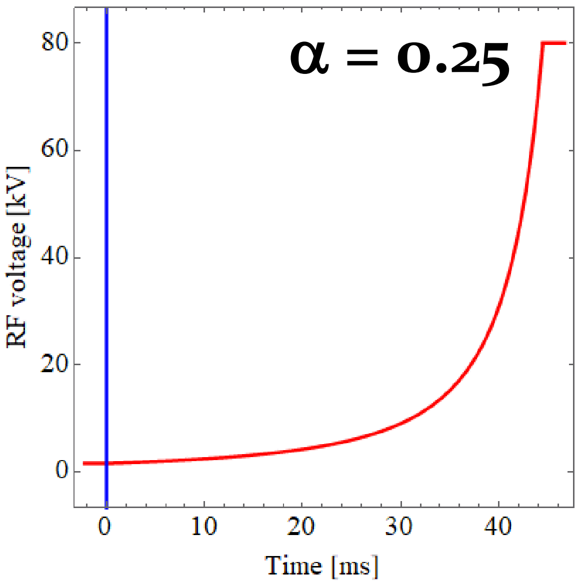
→ Voltage function with constant adiabaticity, α

$$V_\mathrm{RF}(t) = \frac{V_\mathrm{i}}{\left(1 - \frac{t}{\tau} \frac{\sqrt{V_\mathrm{f}} - \sqrt{V_\mathrm{i}}}{\sqrt{V_\mathrm{f}}}\right)^2}$$

RF capture of a coasting beam

1. **Start from coasting beam, for example injected Linac**
2. **Switch RF on at low voltage, V_i**
3. **Raise voltage to the desired level, V_f**



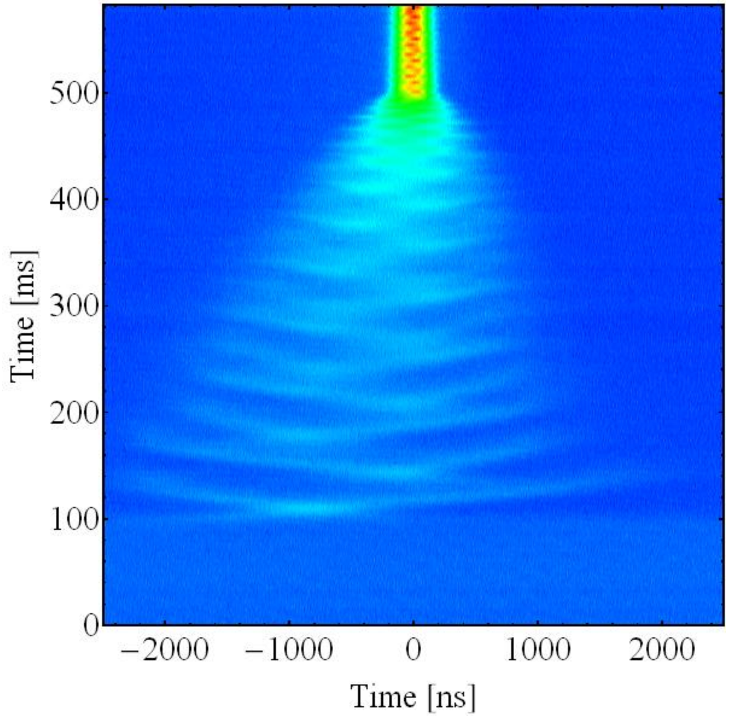


→ **Clean capture**

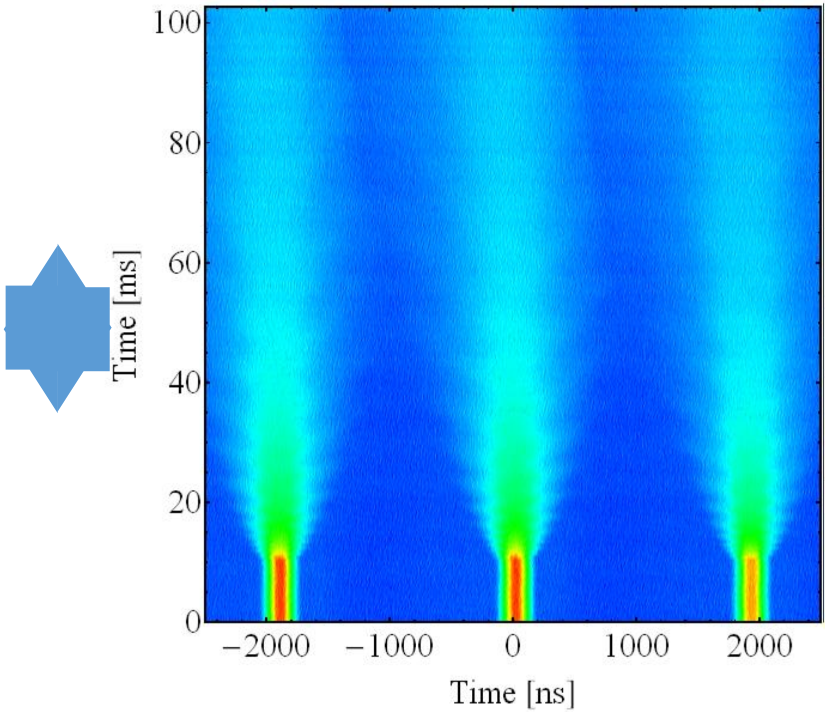
RF capture, debunching and rebunching

- Bunch a beam without RF structure, e.g. after injection
- De-bunching → Rebunching: Change harmonic number

RF capture, bunching (AD)



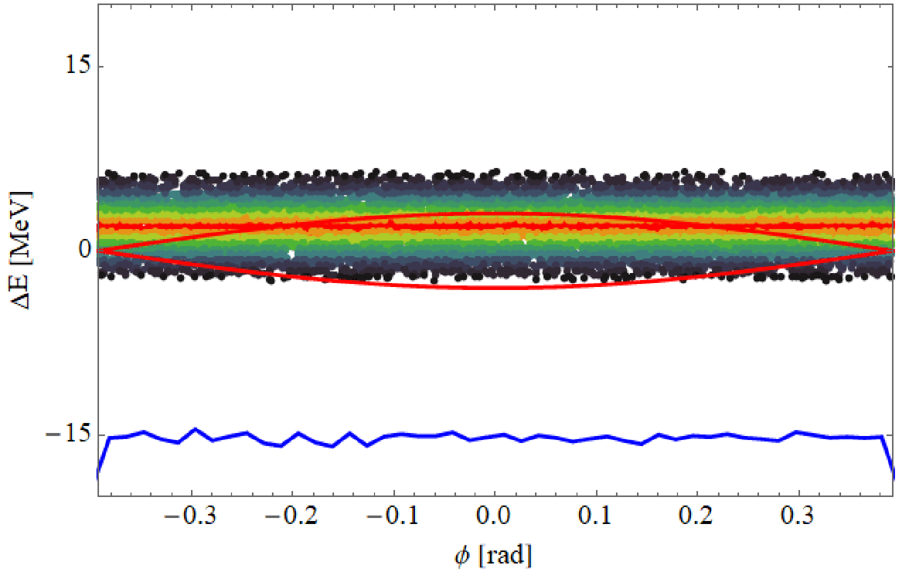
Debunching (CERN AD)

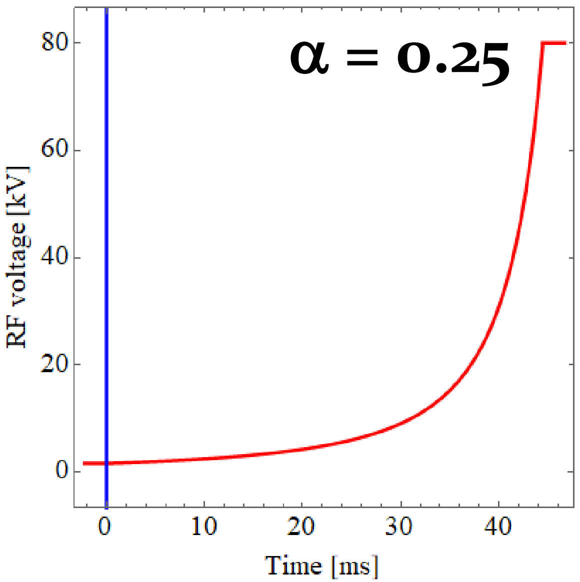


Strengths and weaknesses	
+	Simple manipulation, e.g. to change harmonic number
-	Need the right RF frequency (exactly $n \cdot f_{rev}$) for capture
-	No RF control while beam is debunched

RF capture of a coasting beam

1. **Start from coasting beam, for example injected Linac**
2. **Switch RF on at low voltage, V_i**
3. **Raise voltage to the desired level, V_f**

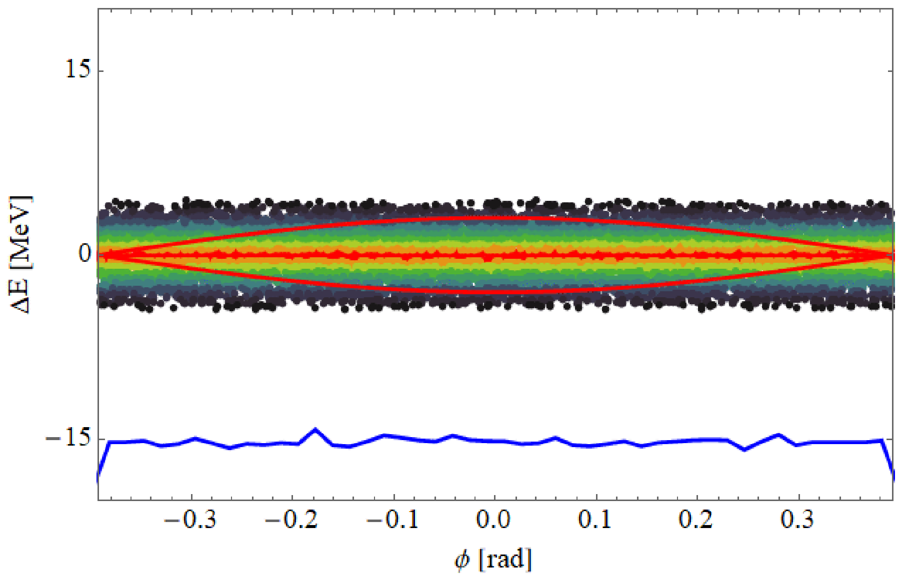


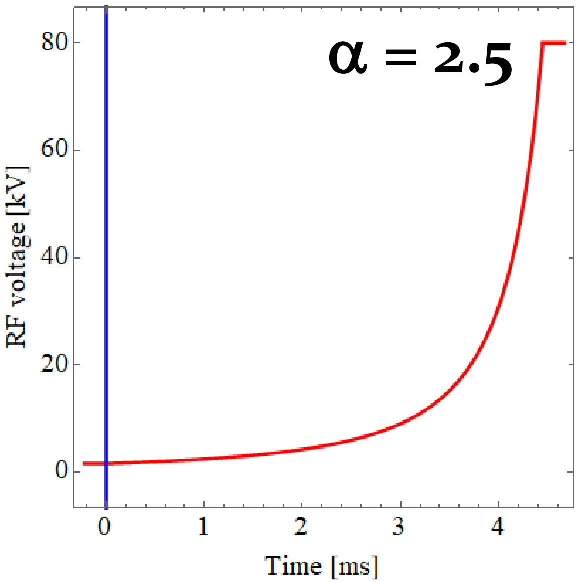


→ **Some filamentation**

RF capture of a coasting beam

1. Start from coasting beam, for example injected Linac
2. Switch RF on at low voltage, V_i
3. Raise voltage to the desired level, V_f

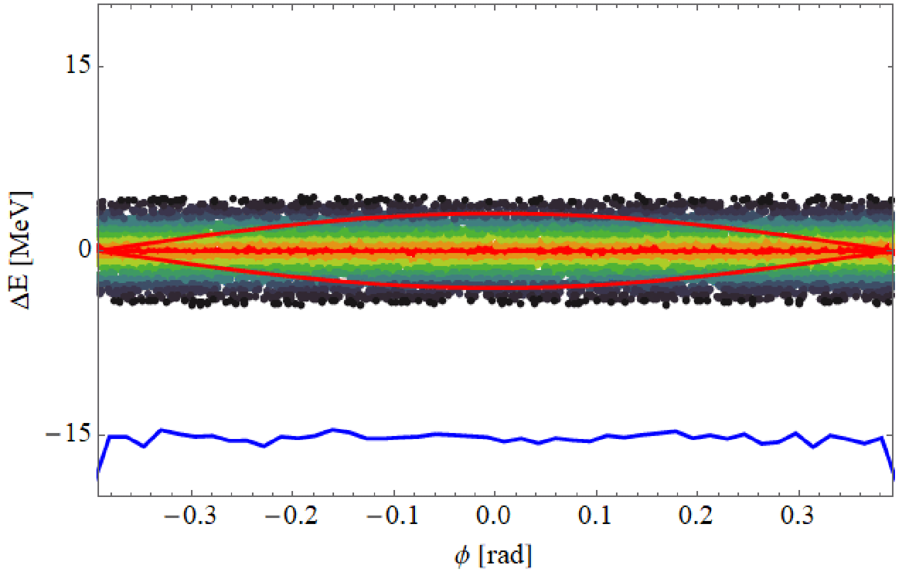


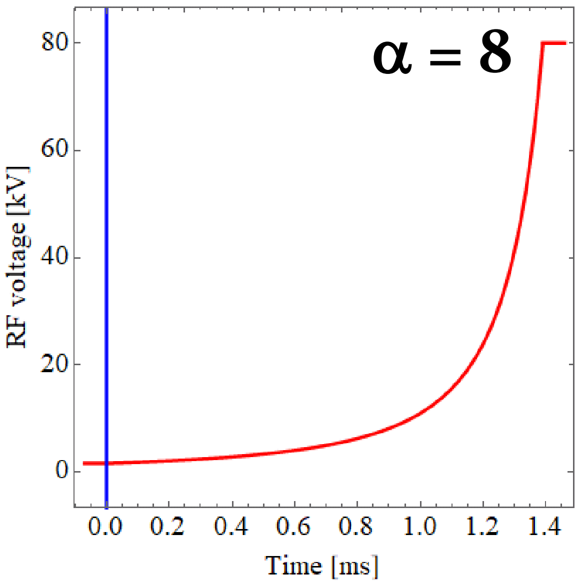


→ Some filamentation

RF capture of a coasting beam

1. Start from coasting beam, for example injected Linac
2. Switch RF on at low voltage, V_i
3. Raise voltage to the desired level, V_f



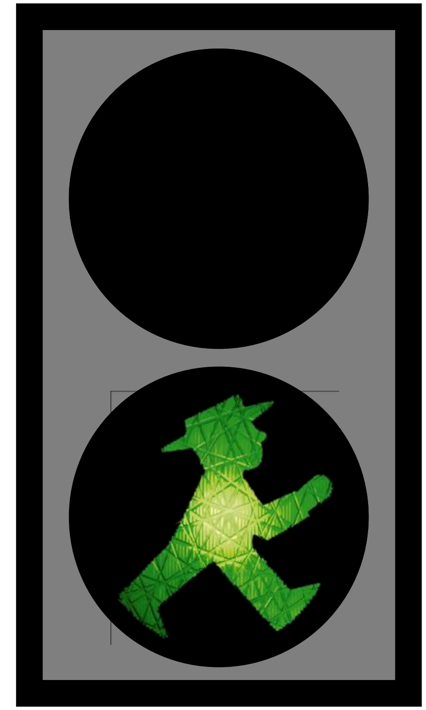


→ Beam more rotating then being captured

→ Slow and fast RF manipulations, depending on α

→ Period of synchrotron frequency is the reference

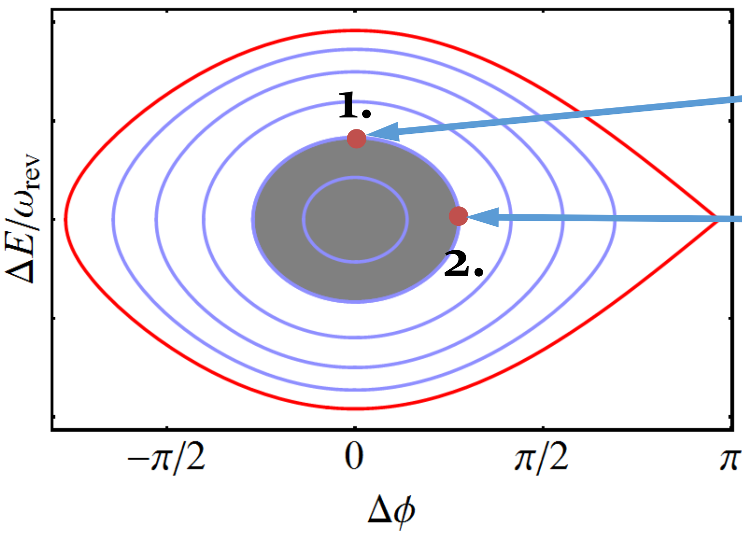
fast variations



Bunch rotation

Change RF voltage to change bunch length?

→ **Calculate aspect ratio of bucket trajectories**



$$H\left(\Delta\phi = 0, \frac{\Delta E}{\omega_{\text{rev}}}\right) = \frac{1}{2}\frac{h\eta\omega_{\text{rev}}}{pR}\left(\frac{\Delta E}{\omega_{\text{rev}}}\right)^2$$

$$H\left(\Delta\phi, \frac{\Delta E}{\omega_{\text{rev}}} = 0\right) = -\frac{1}{2}\frac{qV}{2\pi}\cos\phi_S \Delta\phi^2$$

Equating both sides gives

$$\left(\frac{\Delta E}{\Delta\tau}\right)^2 = -\frac{qV}{2\pi}E\beta^2 h\omega_{\text{rev}}^2\frac{\cos\phi_S}{\eta}$$

with emittance as $\varepsilon_l = \pi\Delta\tau\Delta E = \text{const.}$ $\longrightarrow$ $\Delta\tau \propto \frac{1}{\sqrt[4]{V}}$

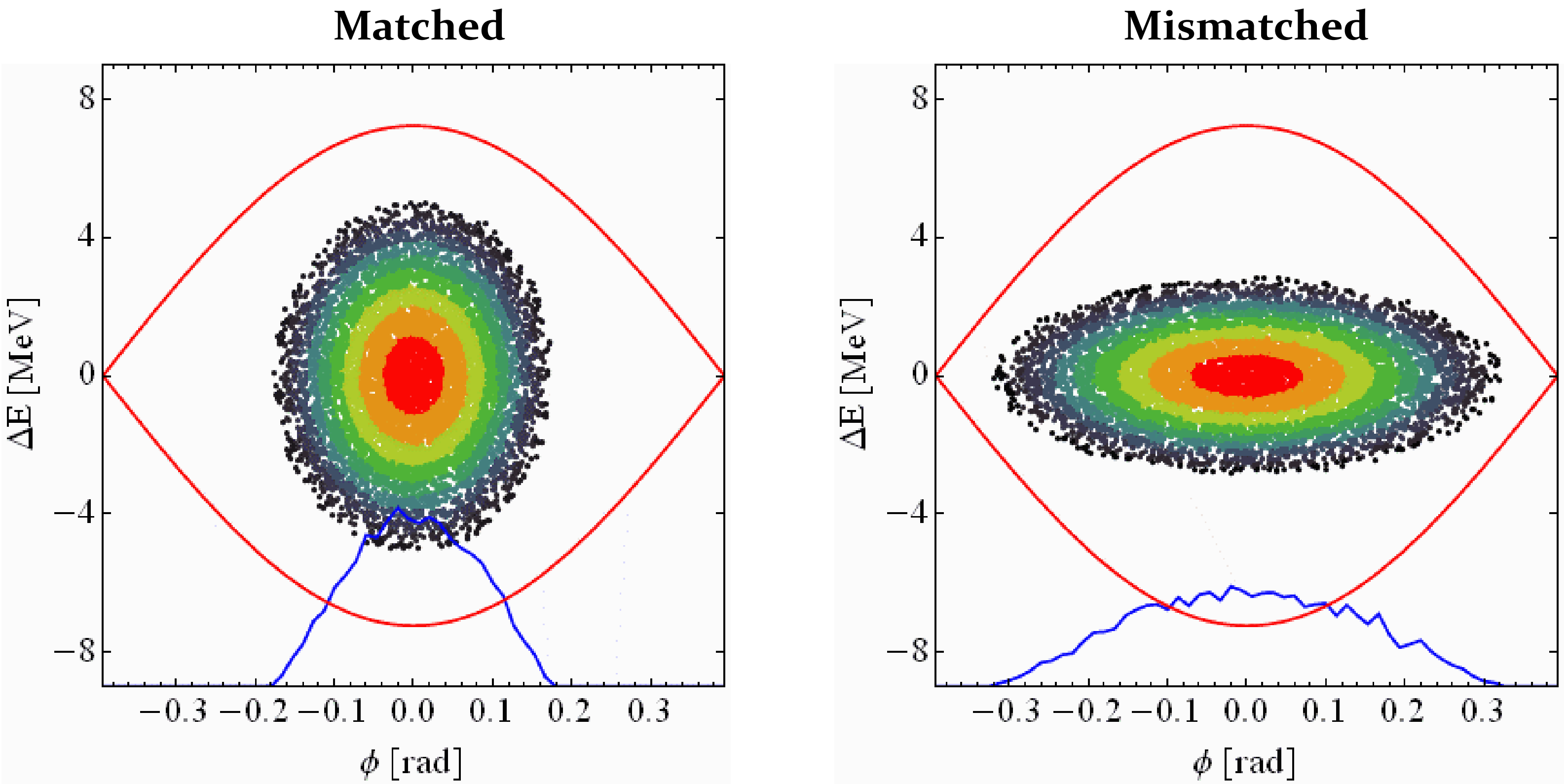
→ **Not efficient at all**

→ **16 times more RF voltage needed to cut bunch length in half**

Abrupt change of RF voltage

→ **Individual particles in matched bunch oscillate but no macroscopic motion**

→ **Abruptly changing the RF voltage flips particles to new trajectories**

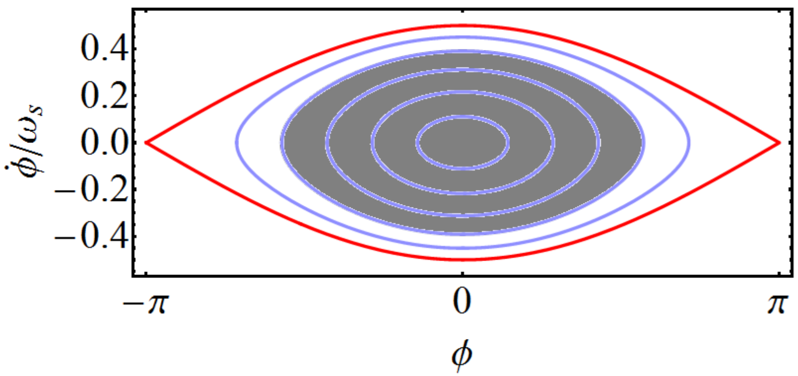


→ **The bunch distribution seems to rotate**

→ **Exchange of bunch length and momentum spread**

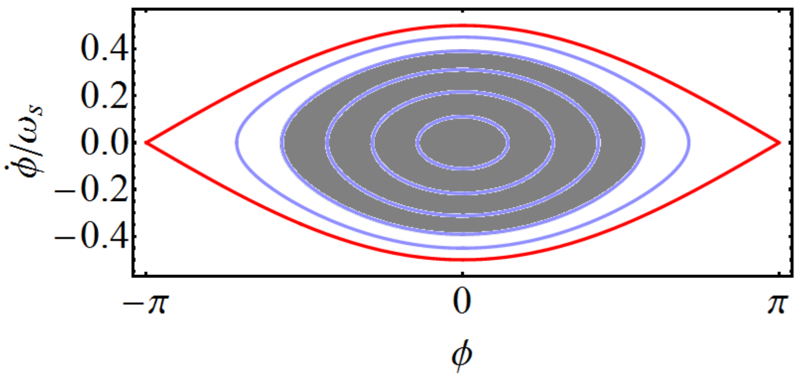
Introduce sudden change: bunch rotation

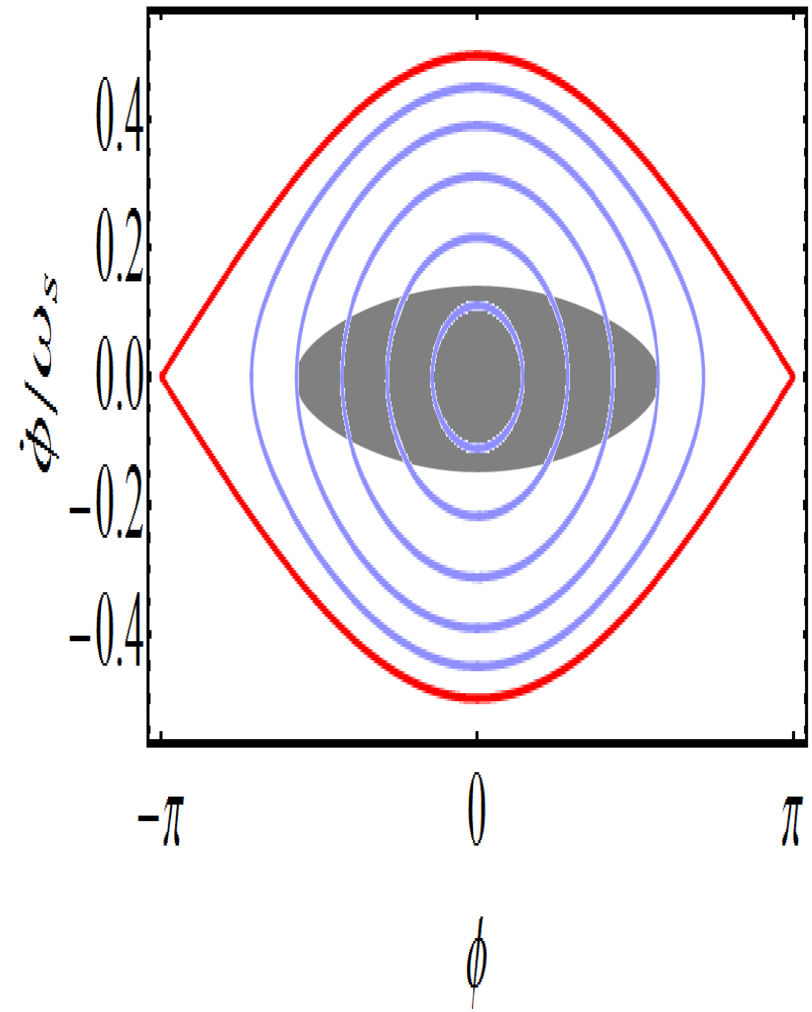
→ **Quickly exchange longitudinal phase space behind bunch**
→ **Increase RF voltage much faster than period of f_S**



Introduce sudden change: bunch rotation

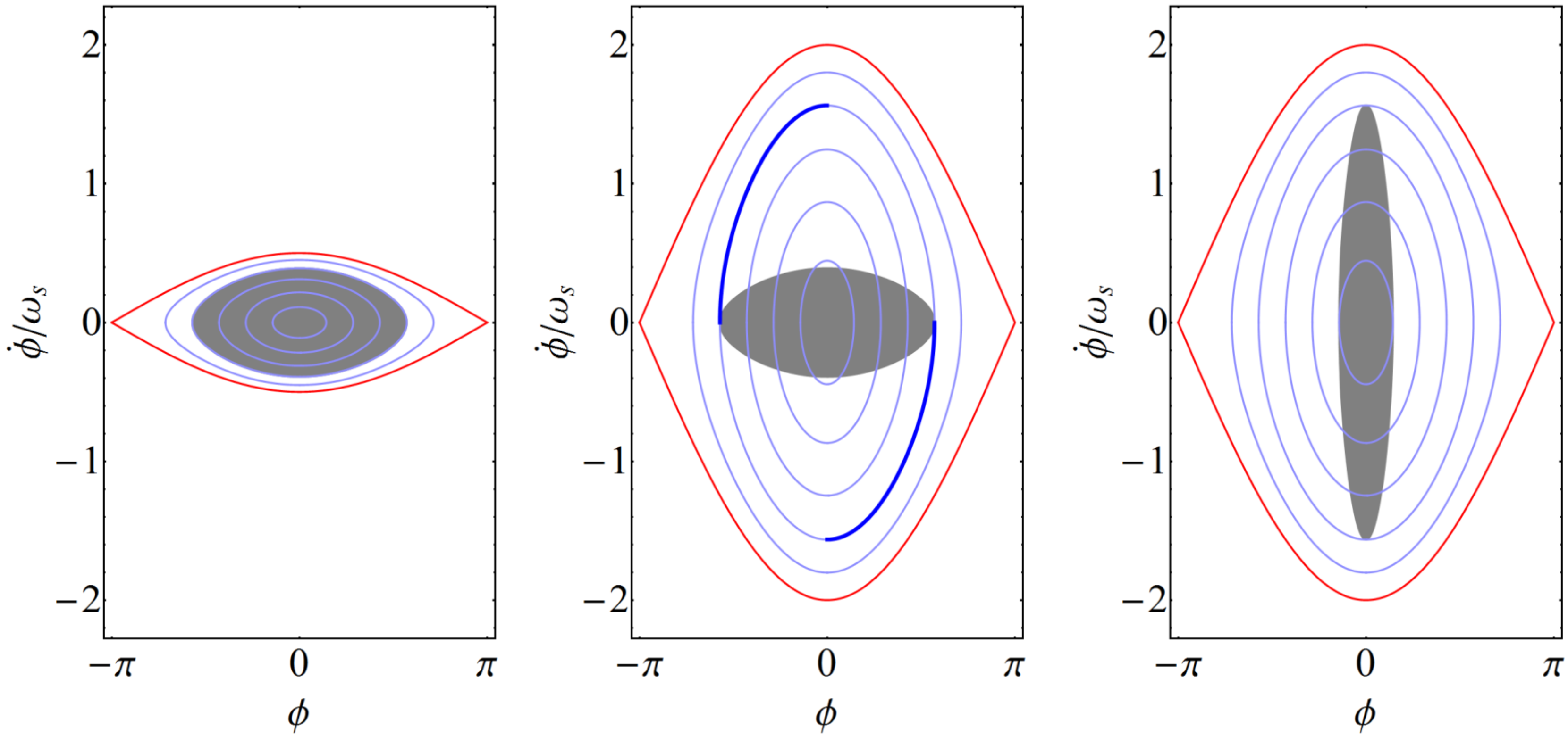
→ **Quickly exchange longitudinal phase space behind bunch**
→ **Increase RF voltage much faster than period of f_s**





Introduce sudden change: bunch rotation

→ **Switch RF voltage much faster than period of f_s**

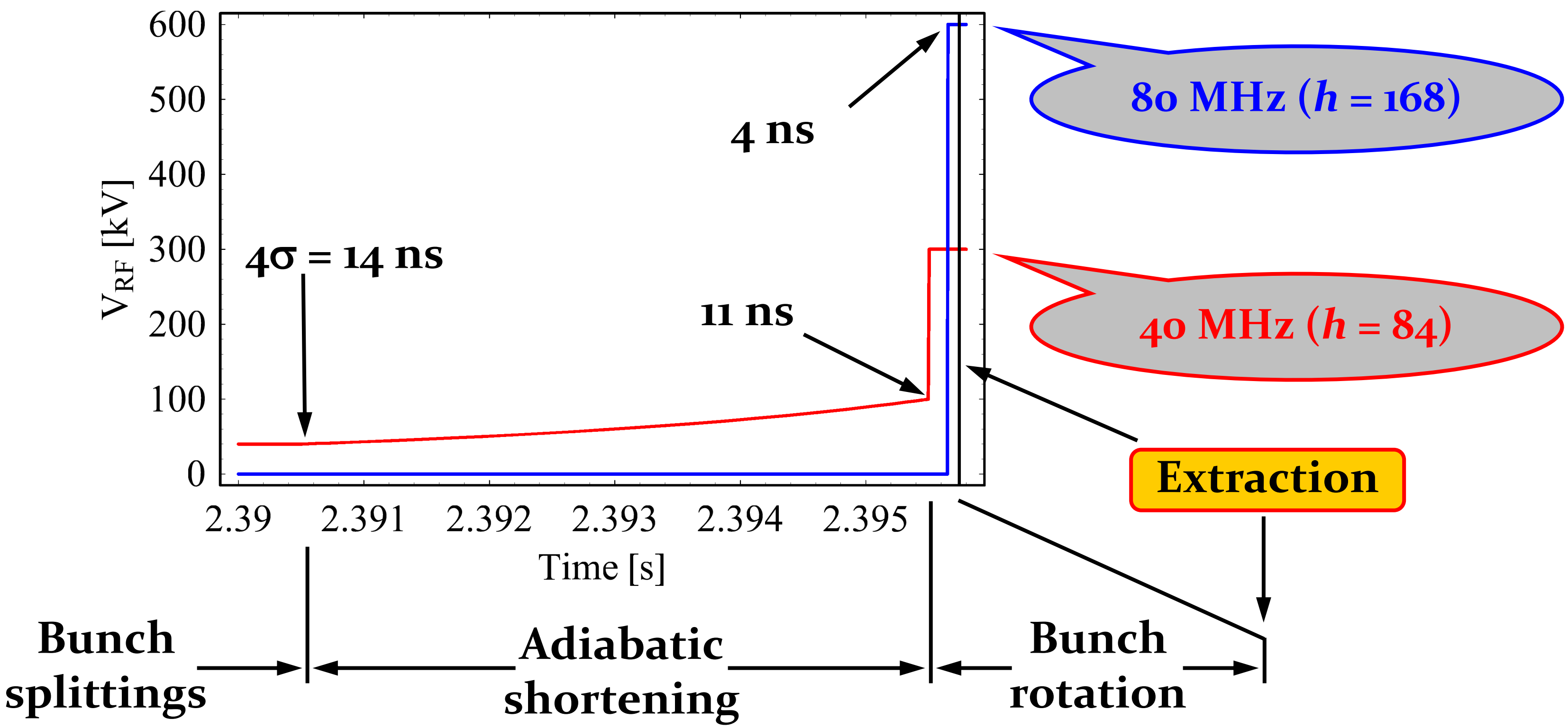


$$V_i \propto \left(\frac{\Delta E_i}{\Delta \tau_i}\right)^2 \qquad V_f \propto \left(\frac{\Delta E_f}{\Delta \tau_i}\right)^2 \qquad \frac{\Delta \tau_f}{\Delta \tau_i} = \frac{\Delta E_i}{\Delta E_f} = \sqrt{\frac{V_i}{V_f}}$$

Example: PS to SPS transfer at CERN

- **Fit 14 ns long bunches into 5 ns long buckets in the SPS**

→ Double-step bunch rotation



Example: rotation at PS-SPS transfer

→ Bunch length now proportional to $\sqrt{V}$ and not $\sqrt[4]{V}$

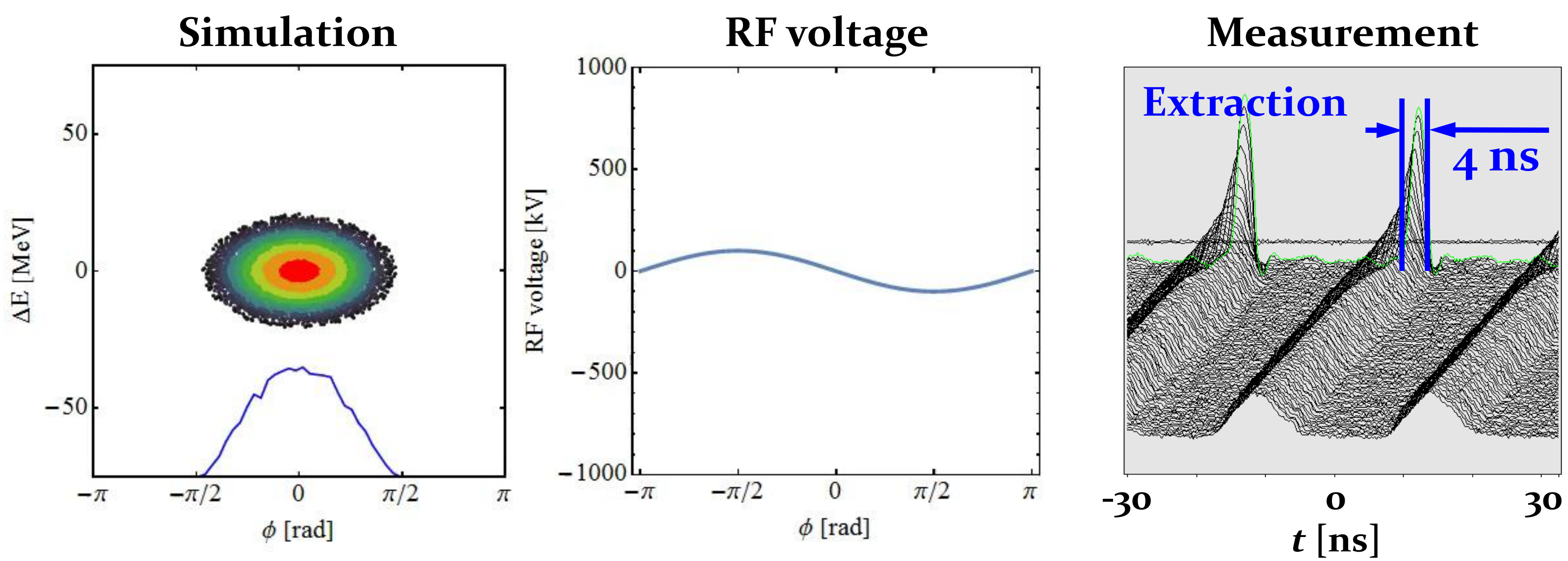
→ Can save enormous RF voltage

→ Bunch shortening from 14 ns to 4 ns (ratio ~3.5)

→ Starting from 100 kV at 40 MHz

→ Slow shortening would require $100\ \mathrm{kV} \cdot 3.5^4 \sim 15\ \mathrm{MV}$

→ Installed RF voltage is only about 1.2 MV

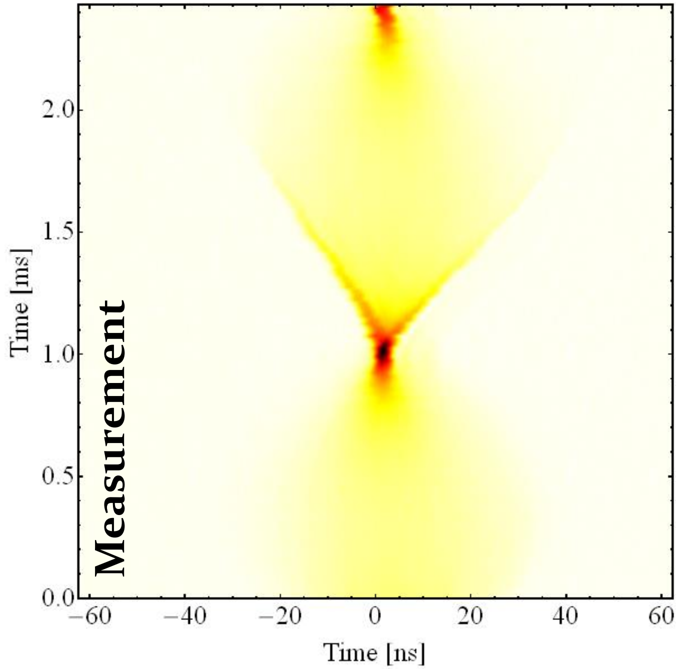


Bunch stretching at unstable fixed point

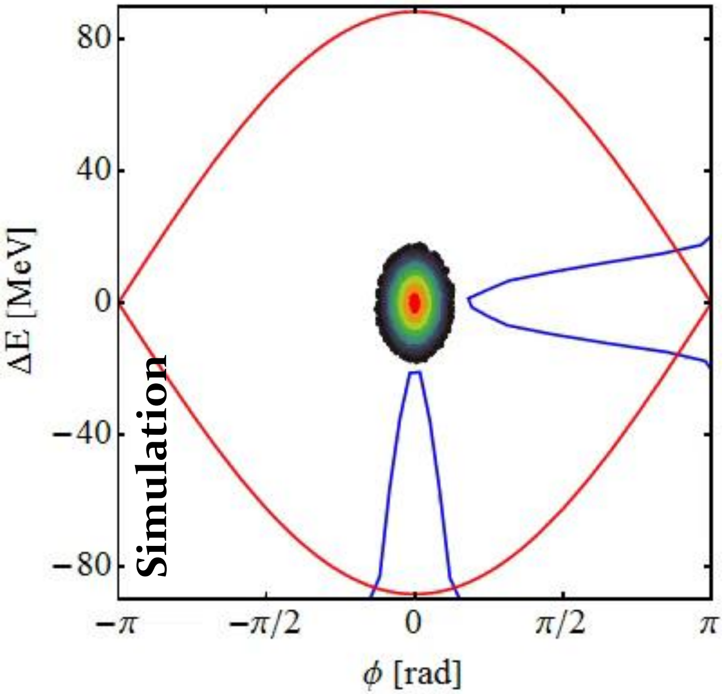
Need large momentum spread for slow extraction

1. **Jump RF phase such that bunch at unstable fixed point**
2. **Jump back**
3. **Let bunch rotate, switch RF off at large momentum spread**

Bunch profile evolution



Longitudinal phase space

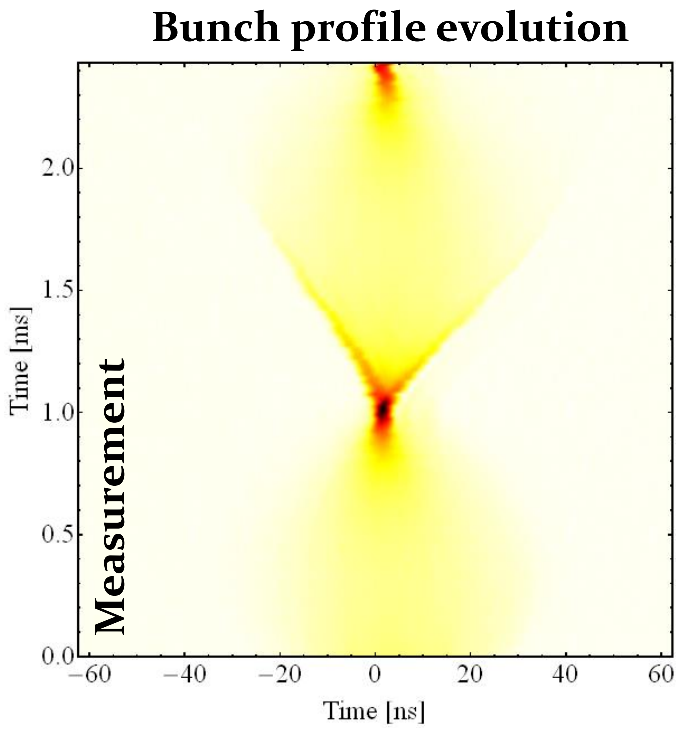


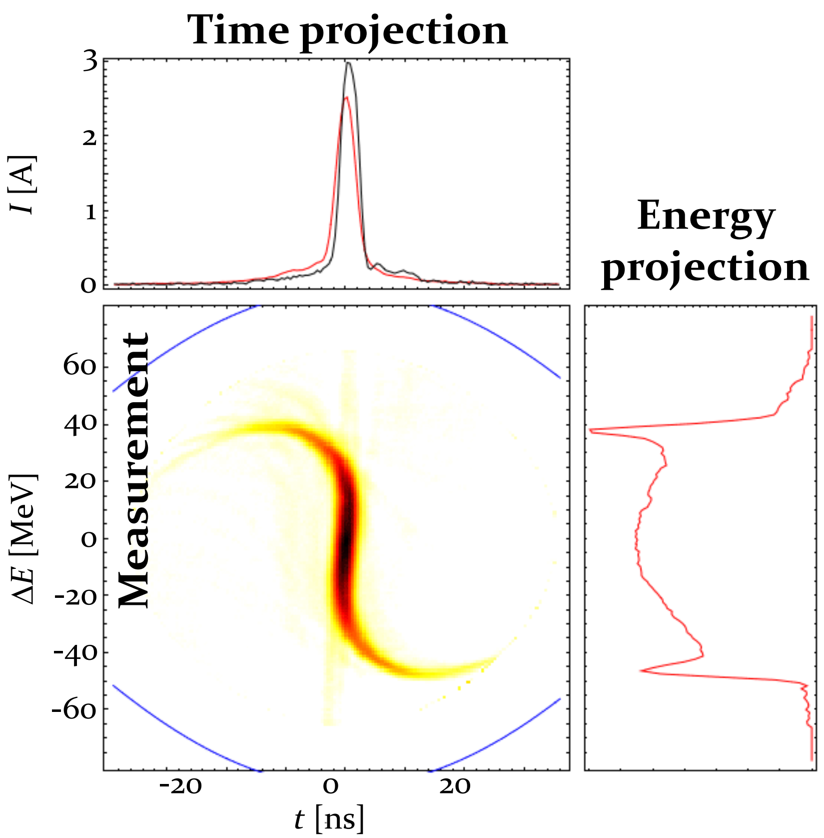
→ Non-linearity of bunch rotation helps

Example: using the non-linearity

Need large momentum spread for slow extraction

1. **Jump RF phase such that bunch at unstable fixed point**
2. **Jump back**
3. **Let bunch rotate, switch RF off at large momentum spread**





→ Almost constant momentum distribution after rotation

Comparison of bunch rotation techniques

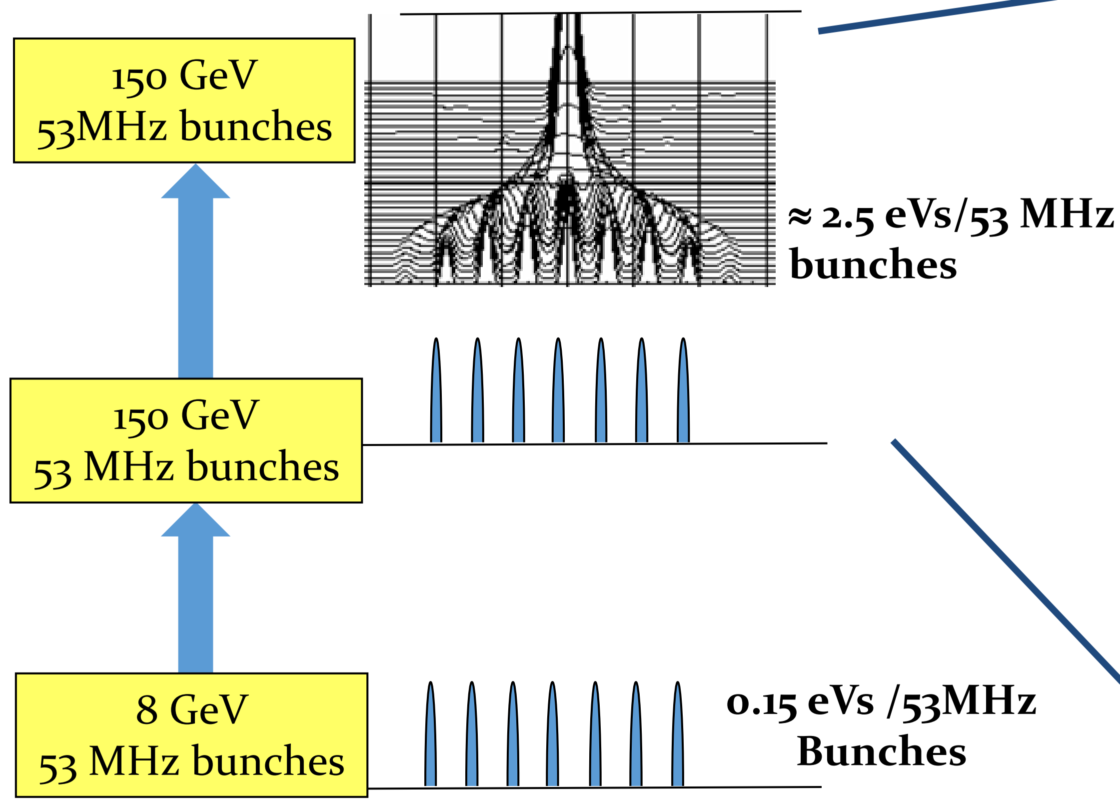
→ Bunch length proportional to $\sqrt{V}$

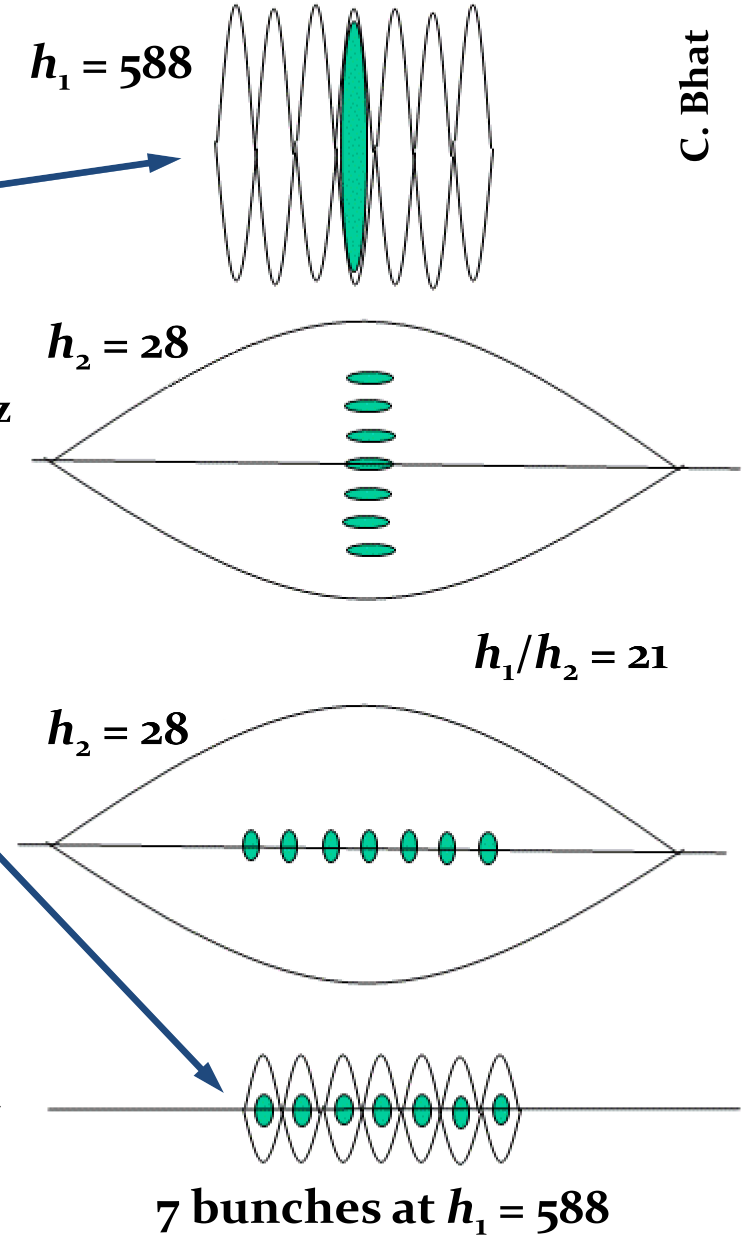
Which one to choose?

RF voltage jump	Jump to unstable fixed-point and back
+ Easy implementation: just raise voltage quickly	+ Bunch always kept in bucket with large RF voltage + Controlled RF phase jumps straightforward with digital RF sources
- Power demand on RF systems during voltage jump - Bunch kept at low RF voltage before	- Non-linearity → rotation of more than π/2 in longitudinal phase space

Multi-bunch rotation at Fermilab: coalescing

- **Proton bunch coalescing in Main Injector at Fermilab**

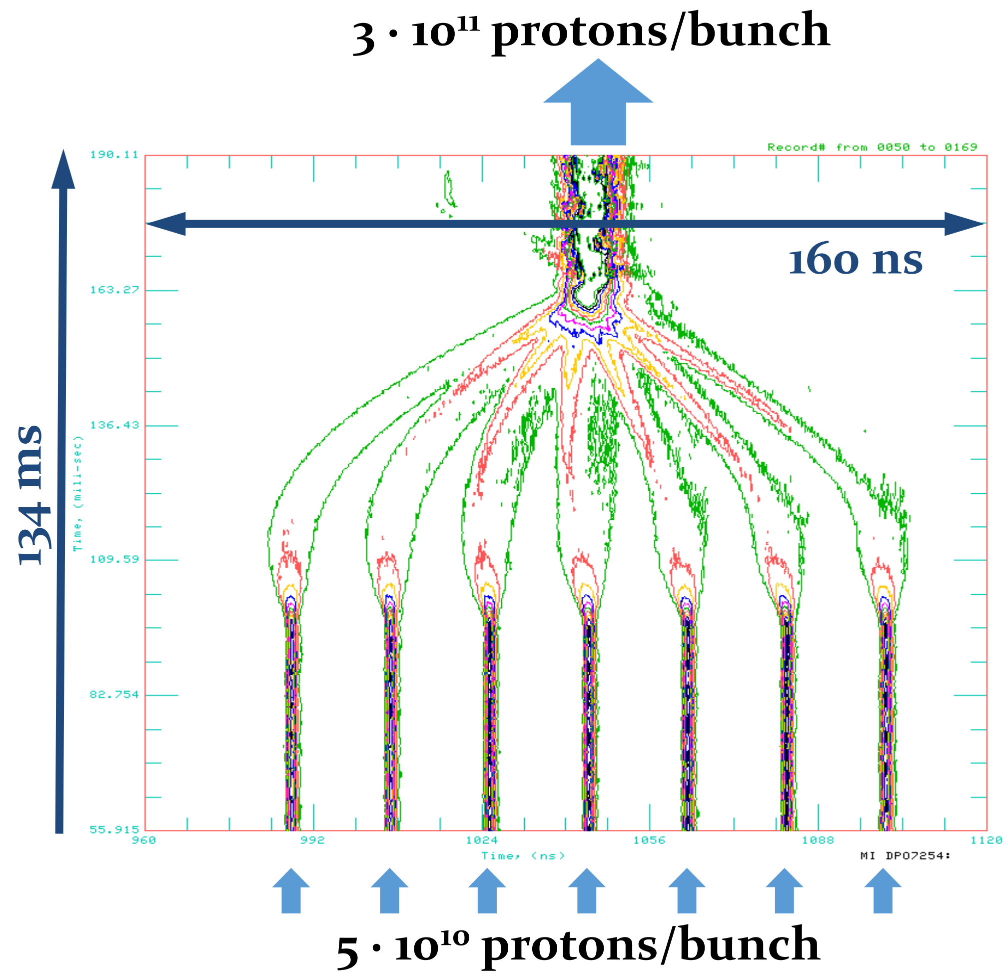




→ **Geometrical minimum longitudinal emittance growth about 27%**

Example: Main ring bunch coalescing

C. Bhat



→ **Clever combination of bunch rotation and subsequent harmonic handover (rebucketing)**

Controlled longitudinal emittance blow-up

Controlled emittance blow-up

- How to reduce longitudinal density and increase bunch length in well-defined way?

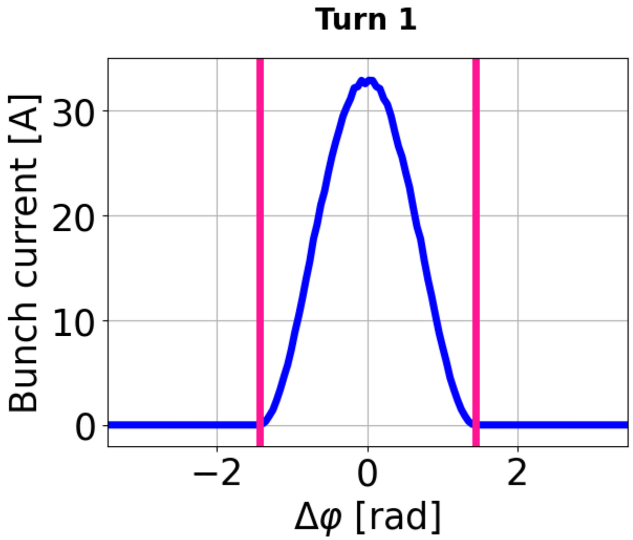
→ Shake the RF bucket

→ Introduce some diffusion

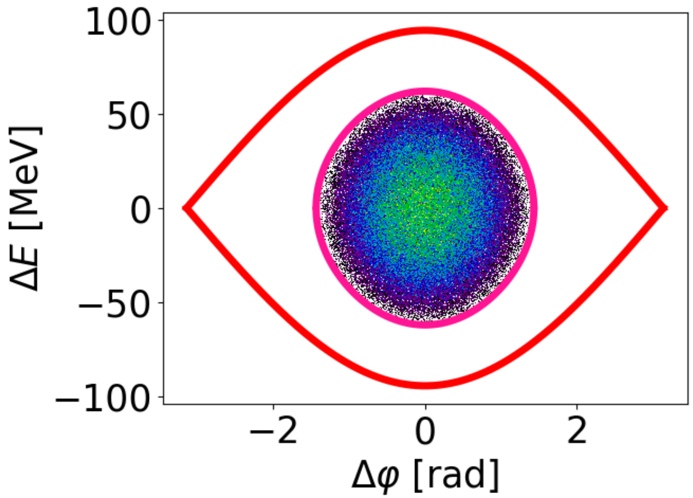
Main RF system only	Higher-harmonic RF
1. Phase noise modulation of main RF in fixed frequency band • Variant: fixed-frequency excitation during acceleration → Bunch Spreader	2. Separate higher-harmonic RF system with periodic phase modulation

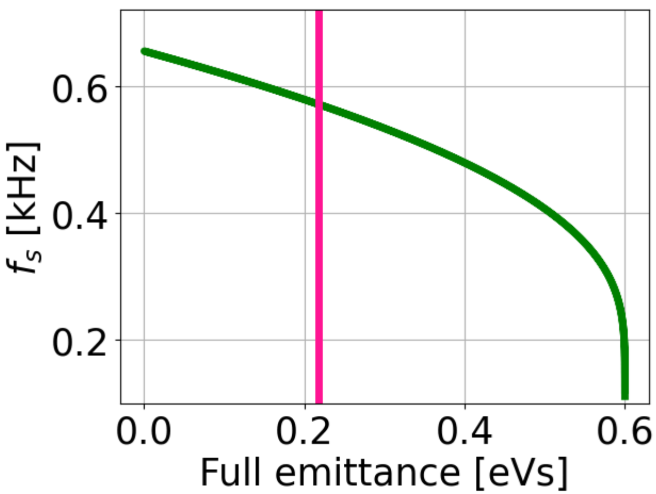
Emittance control with phase noise

2. Phase noise modulation of main RF in fixed frequency band



1. **Choose upper frequency to cover synchrotron frequency at bunch centre**
2. **Choose lower frequency to match target emittance**
3. **Excite**



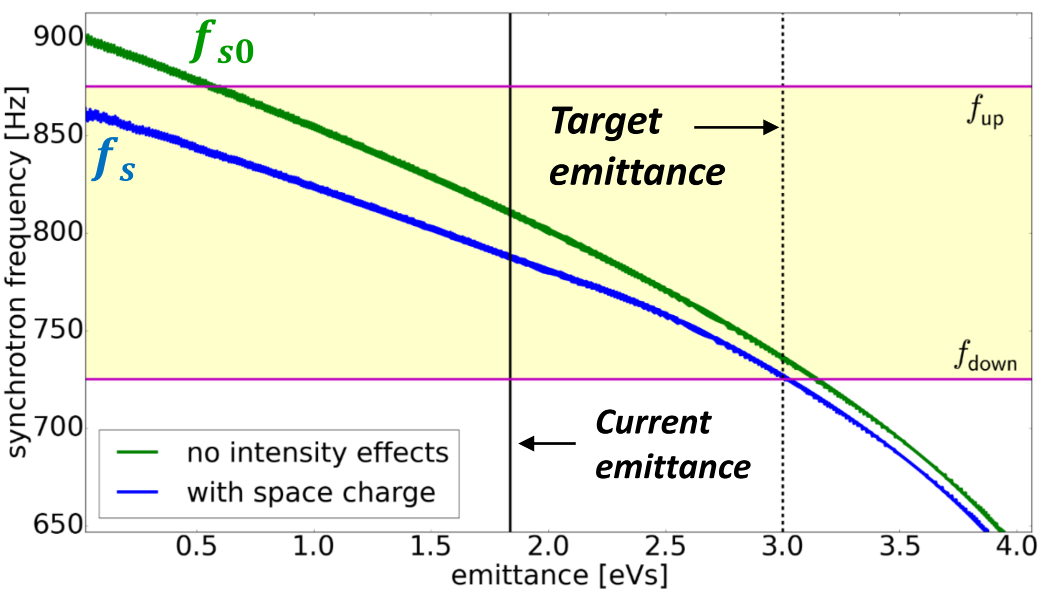


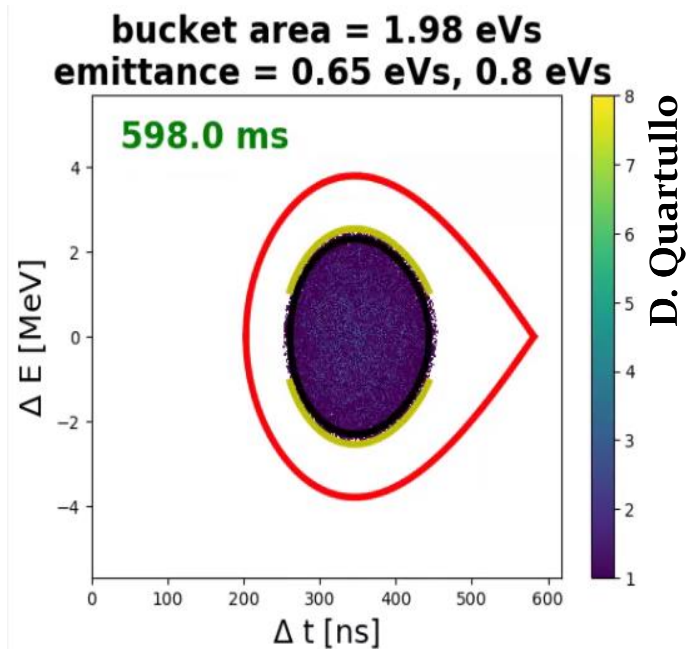
D. Quartullo

Example: Phase noise blow-up in PS Booster

- **Noise excitation of bunch by band-width limited noise**

→ **Controlled longitudinal blow-up in the PSB**





Strengths and weaknesses	
+	Single harmonic, no need for 2[nd] RF system
+	Few parameters: band of excitation, amplitude
-	Difficult to achieve smooth blow-up

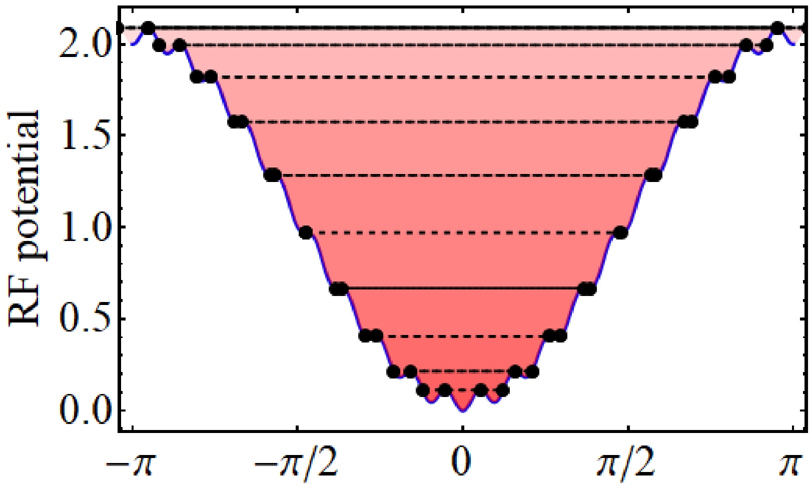
Controlled emittance blow-up

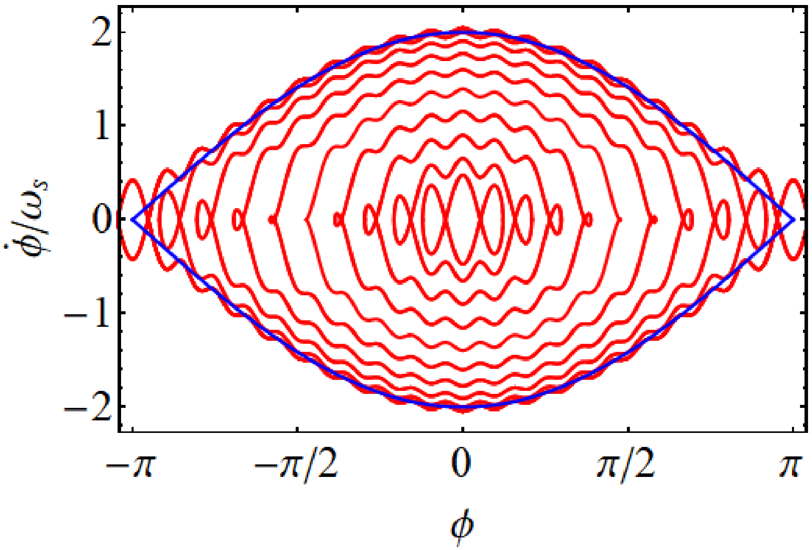
- How to **reduce longitudinal density** and **increase bunch length** in **well-defined** way?

→ Shake the RF bucket

→ Introduce some diffusion

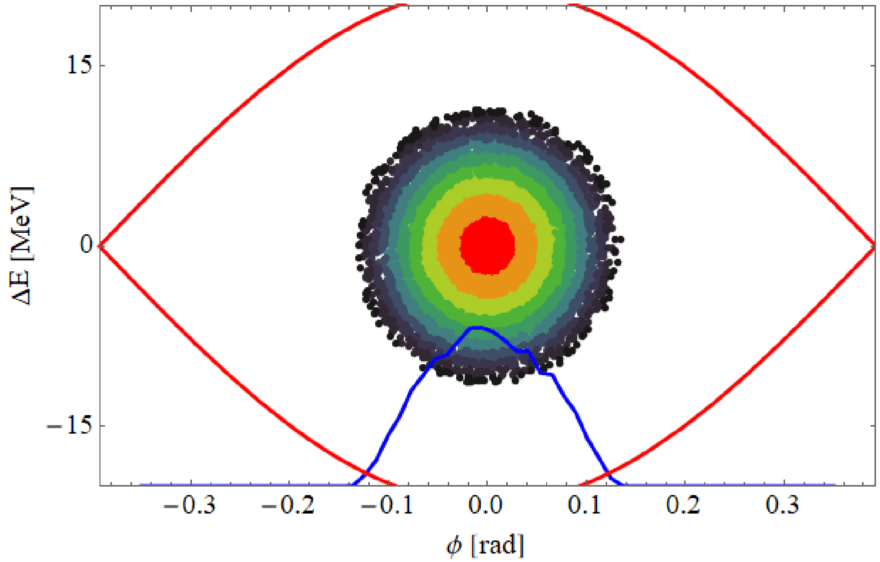
1. **Higher-harmonic RF with periodic phase modulation**

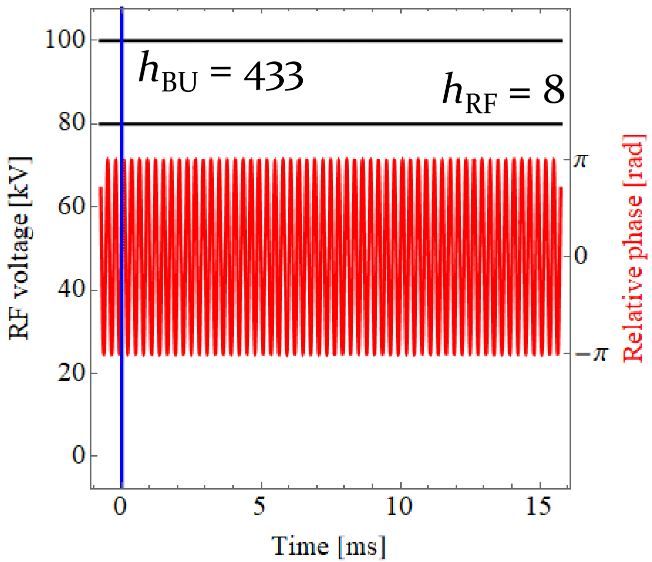




Higher-harmonic RF system

- **Prefer high harmonic ratios, ideally > ~20**
- **Voltage ratios of the order of ~1**



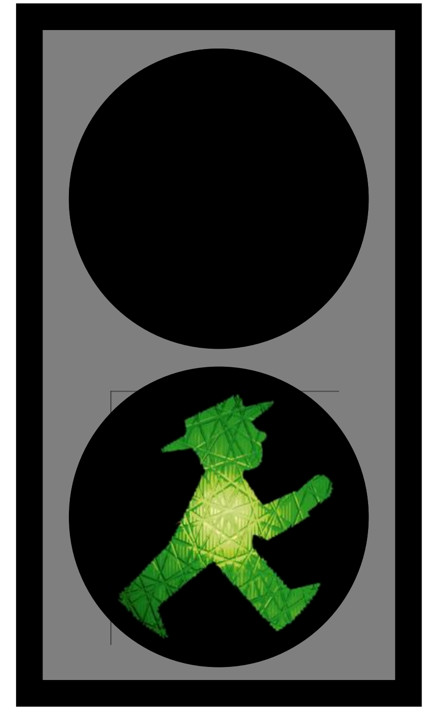


Strengths and weaknesses

+ **Blow-up easily controllable: RF voltage and duration (h_{BU}/h_{RF}>20)**
+ **Equalizes bunch-by-bunch parameters differences**
+ **Control of longitudinal distribution**

- **Requires additional RF system**
- **Difficult to adjust for smaller ratios h_{BU}/h_{RF}**

h* and *n* · *h



Arbitrary RF waveform

Replace $V \sin\phi \rightarrow V g(\phi) \rightarrow$ **arbitrary amplitude**

Equations of motion

$$\frac{d}{dt}\phi = \frac{h\eta\omega_{\text{rev}}}{pR}\left(\frac{\Delta E}{\omega_{\text{rev}}}\right)$$

$$\frac{d}{dt}\left(\frac{\Delta E}{\omega_{\text{rev}}}\right) = \frac{qV}{2\pi}\left[g(\phi) - g(\phi_{\text{S}})\right]$$

same structure

$$\frac{dq}{dt} = \frac{\partial H}{\partial p}$$

$$\frac{dp}{dt} = -\frac{\partial H}{\partial q}$$

The Hamiltonian describing the system becomes

$$H\left(\phi, \frac{\Delta E}{\omega_{\text{rev}}}\right) = \frac{1}{2}\frac{h\eta\omega_{\text{rev}}}{pR}\left(\frac{\Delta E}{\omega_{\text{rev}}}\right)^2 - \frac{qV}{2\pi}\left[\int g(\phi)d\phi - g(\phi_{\text{S}})\phi\right]$$

$$\eta = \frac{1}{\gamma_{\text{tr}}^2} - \frac{1}{\gamma^2}$$

Arbitrary RF waveform

$$H\left(\phi, \frac{\Delta E}{\omega_{\text{rev}}}\right) = \frac{1}{2}\frac{h\eta\omega_{\text{rev}}}{pR}\left(\frac{\Delta E}{\omega_{\text{rev}}}\right)^2 - \frac{qV}{2\pi}\underbrace{\left[\int g(\phi)d\phi - g(\phi_S)\phi\right]}_{\propto W(\phi)}$$

→ **RF potential**

$$W(\phi) = \frac{1}{\cos\phi_S}\left[\int g(\phi)\, d\phi - g(\phi_S)\phi\right]$$

→ **and without acceleration**

$$W(\phi, \phi_S = 0) = \int g(\phi)\, d\phi$$

Integral of RF voltage → RF potential

Two sinusoidal RF voltages

Sinusoidal double-harmonic RF

- **Double-harmonic sum voltage**

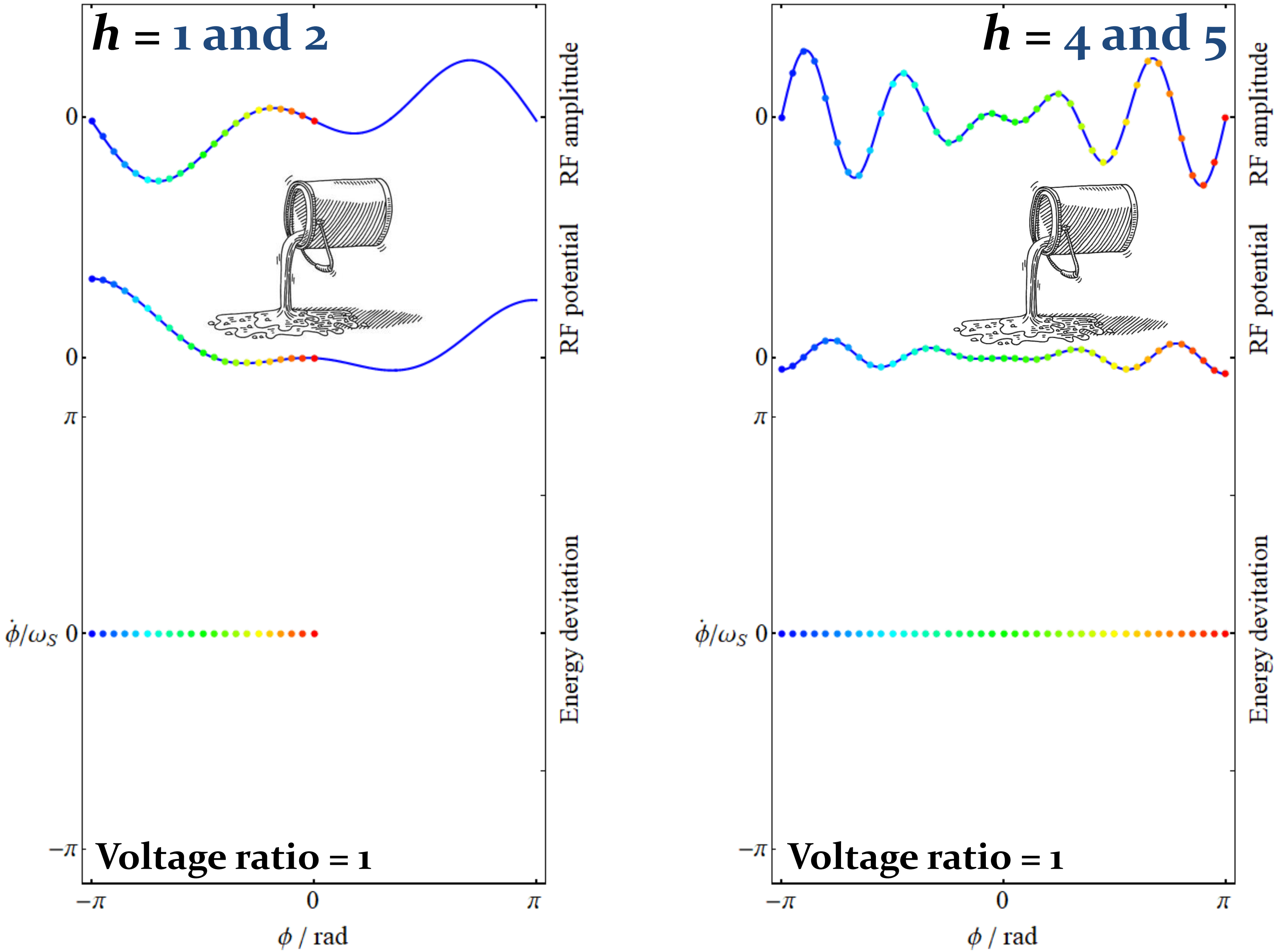
$$V_{\mathrm{RF}}(\phi) = V_1 \sin(h_1\phi + \phi_1) + V_2 \sin(h_2\phi + \phi_2)$$

- **Corresponding RF potential**

$$\begin{aligned} W(\phi) =& \frac{V_1}{h_1}\left[\cos\phi_1 - \cos(h_1\phi + \phi_1)\right] \\ &+ \frac{V_2}{h_2}\left[\cos\phi_2 - \cos(h_2\phi + \phi_2)\right] \end{aligned}$$

$\rightarrow$ **Actually one relative phase between both RF systems**

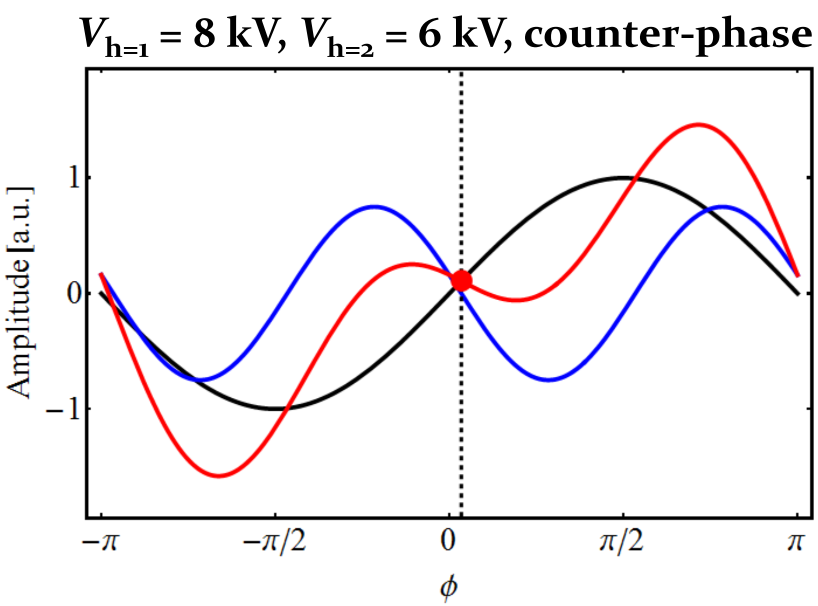
Examples of double-harmonic RF voltage

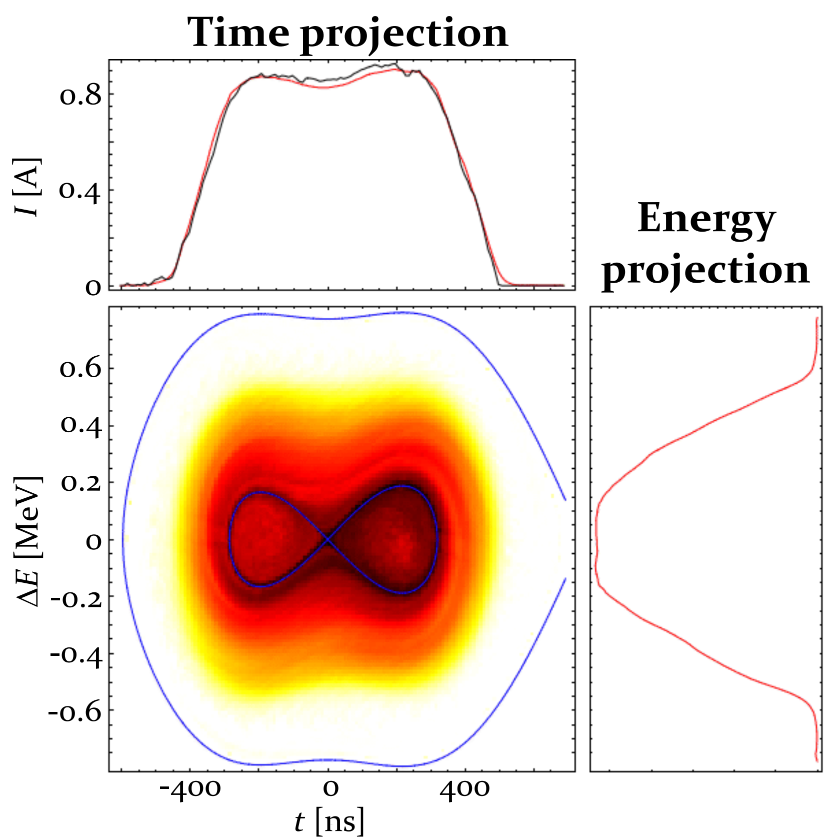


Example application: space charge in PSB

RF amplitude $V_{\mathrm{RF}}(\phi) = V_1 \sin(h_1\phi + \phi_1) + V_2 \sin(h_2\phi + \phi_2)$

→ Space charge ∝ instantaneous current





- **Inverted gradient at bucket centre**
- **Flattened bunch with reduced peak current** → Space charge reduction at low energy

Rebucketing

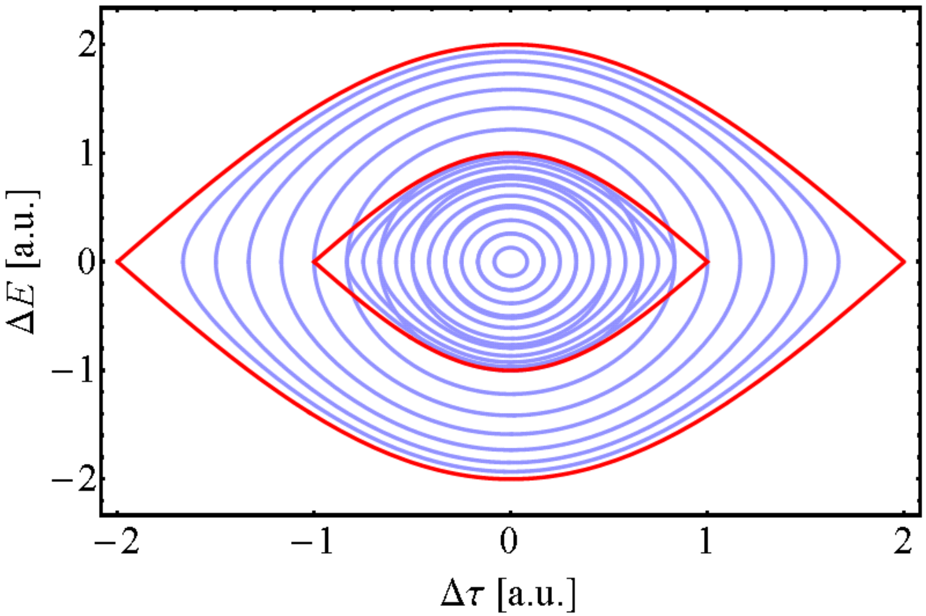
Both RF systems in phase: rebucketing

- **Change of harmonic number from bucket centre to centre**

→ **Phase space aspect ratio:**

$$\Delta E = \beta \omega_{\mathrm{rev}} \sqrt{\frac{qV}{2\pi} E h \left| \frac{\cos \phi_0}{\eta} \right|} \cdot \Delta \tau$$

RF buckets with $h_2 = 2h_1$ and $V_{RF2} = V_{RF1}/2$

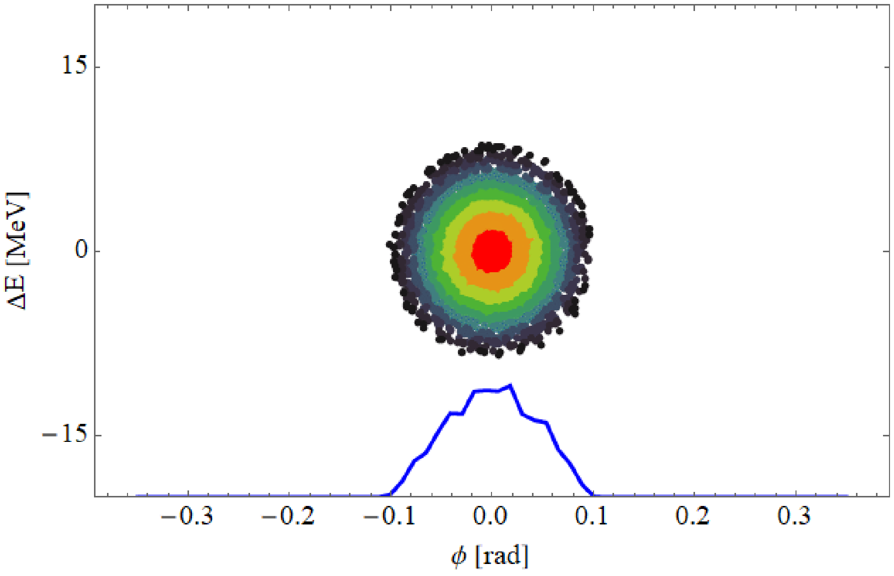


Both RF systems in phase: rebucketing

- **Change of harmonic number from bucket centre to centre**

→ **Phase space aspect ratio:**

$$\Delta E = \beta \omega_{\mathrm{rev}} \sqrt{\frac{qV}{2\pi} E h \left| \frac{\cos \phi_0}{\eta} \right|} \cdot \Delta\tau$$

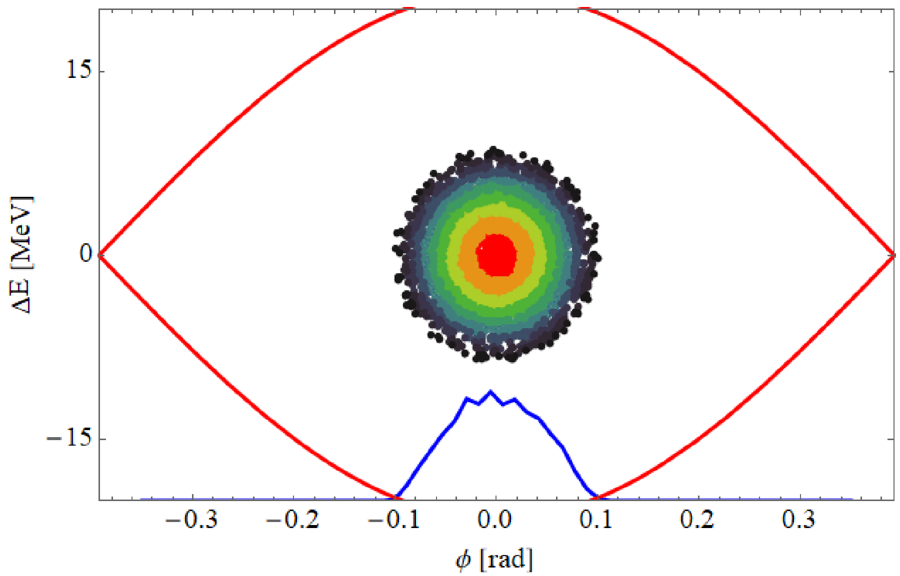


Both RF systems in phase: rebucketing

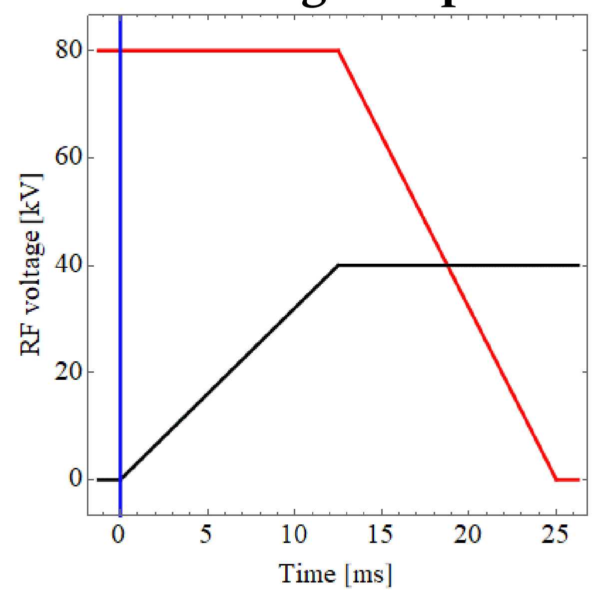
- **Change of harmonic number from bucket centre to centre**

→ **Phase space aspect ratio:**

$$\Delta E = \beta \omega_{\mathrm{rev}} \sqrt{\frac{qV}{2\pi} E h \left| \frac{\cos \phi_0}{\eta} \right|} \cdot \Delta \tau$$



RF voltages in phase

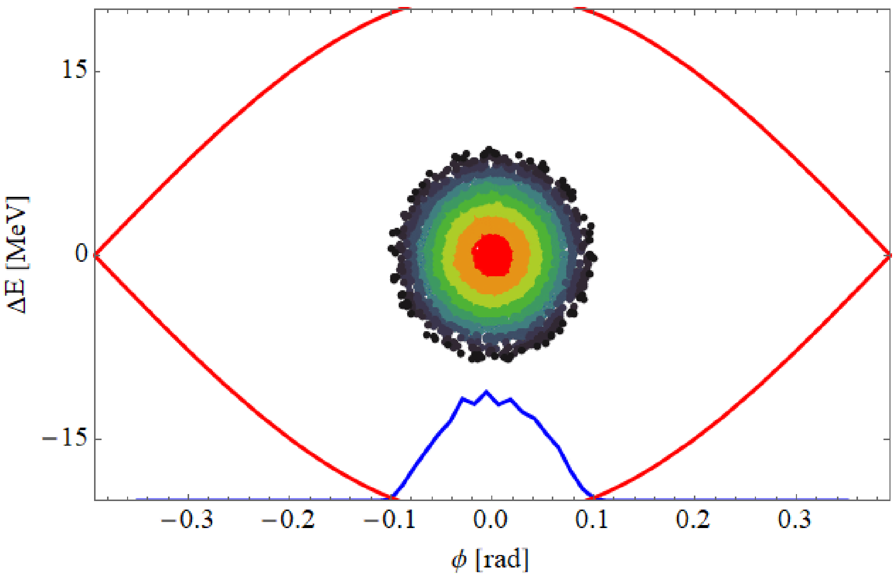


Both RF systems in phase: rebucketing

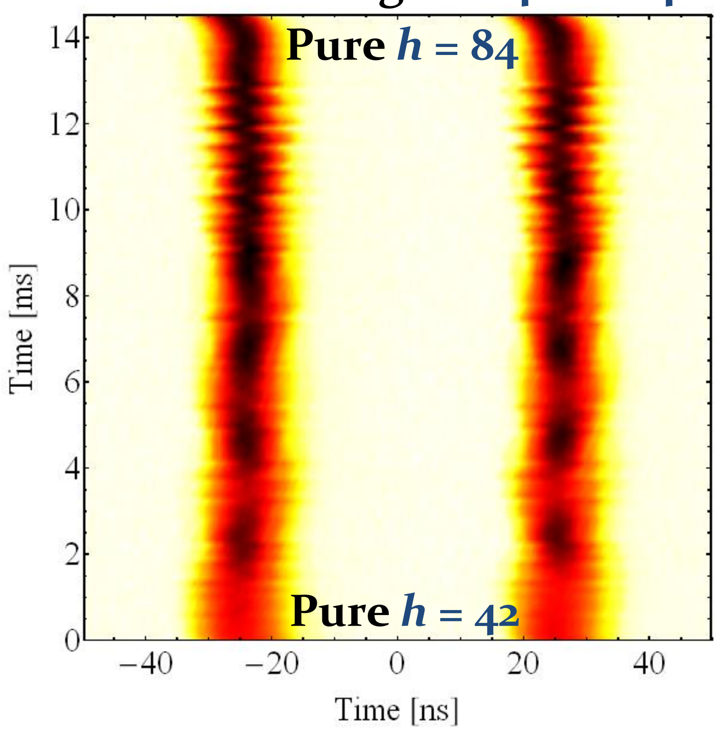
- **Change of harmonic number from bucket centre to centre**

→ **Phase space aspect ratio:**

$$\Delta E = \beta \omega_{\mathrm{rev}} \sqrt{\frac{qV}{2\pi} E h \left| \frac{\cos \phi_0}{\eta} \right|} \cdot \Delta\tau$$



Rebucketing: *h* = 42 → 84



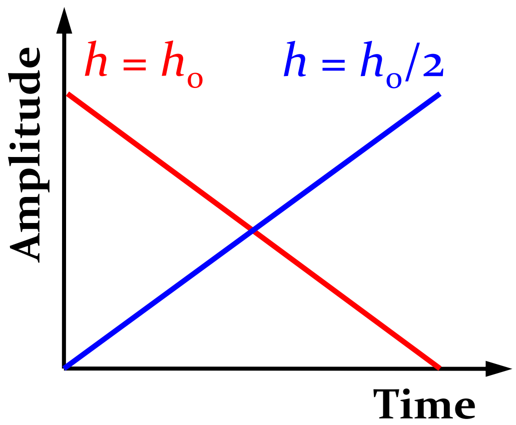
→ **Not much happens during well adjusted rebucketing**

Bunch merging and splitting

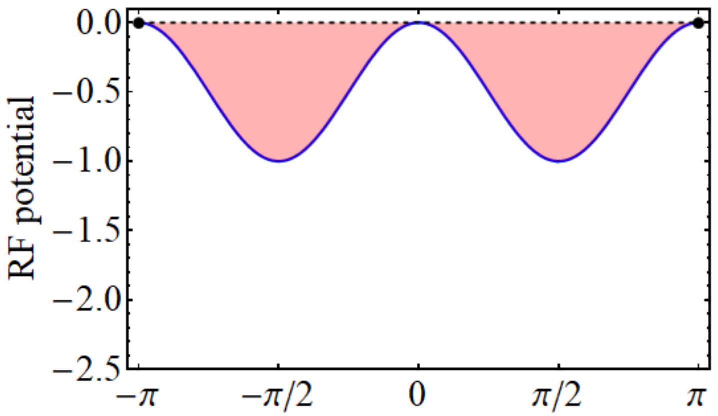
Merging two bunches into one

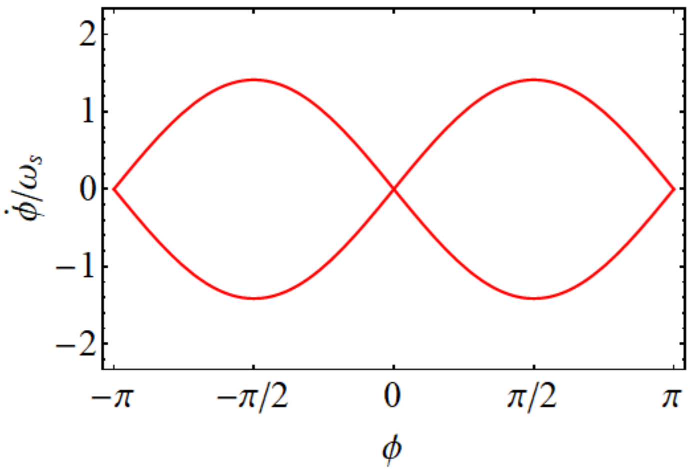
- **Double intensity per bunch**
- **No change of transverse beam parameters → more brightness**

→ **Increase RF voltage on $h = h_0/2$ while decrease on h_0**



Voltages in counter-phase



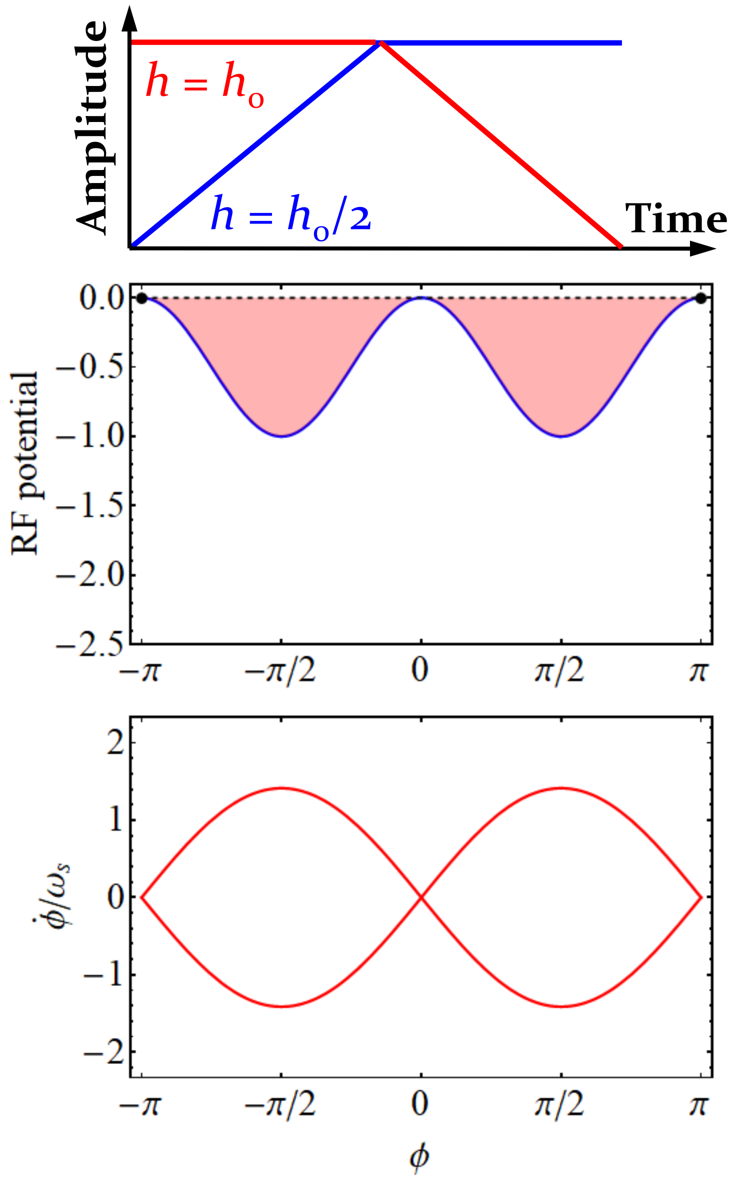


→ **Particles are squeezed out of sub-buckets**

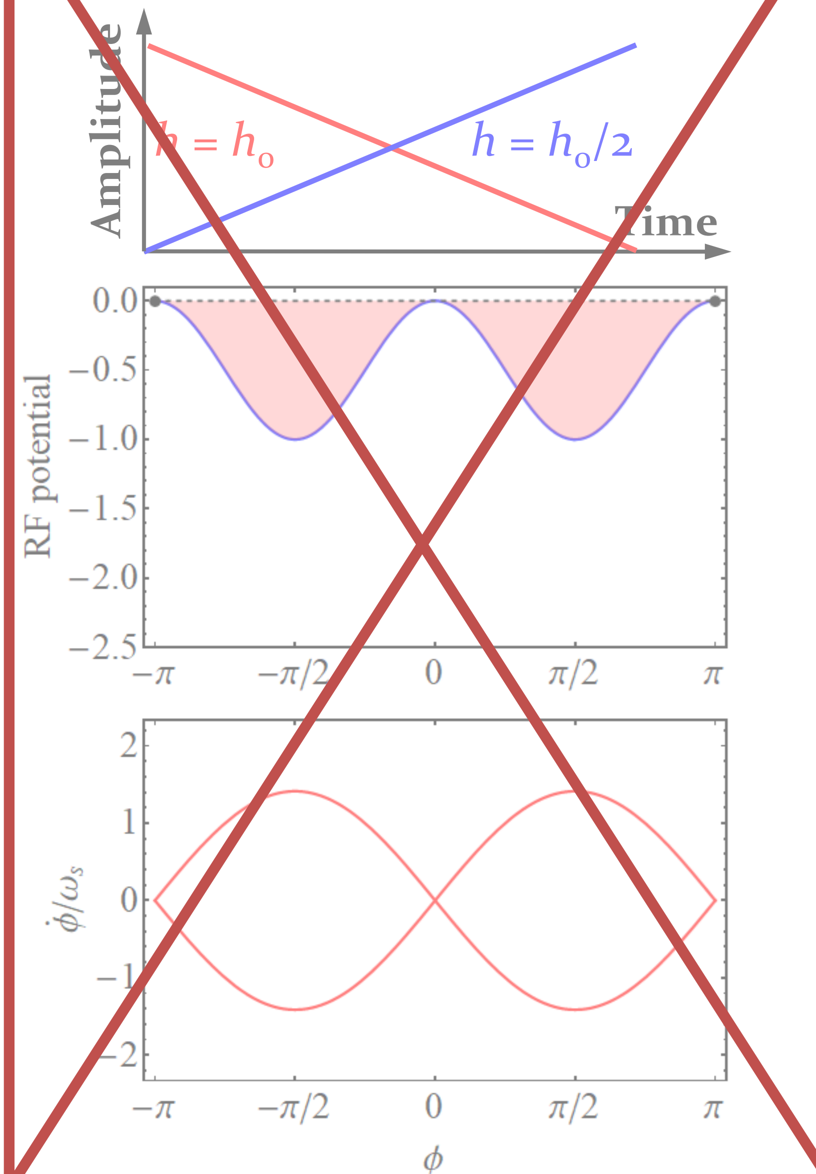
→ **Not fully profiting from available RF voltage at both harmonics**

Bunch splitting and merging

Overlapping crossing

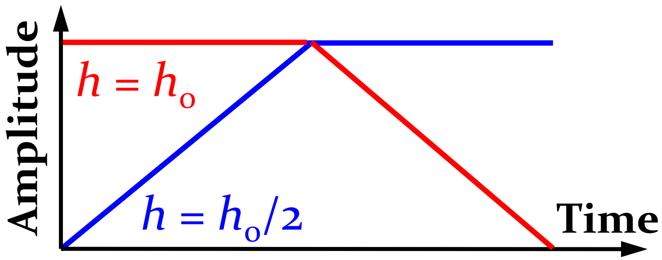


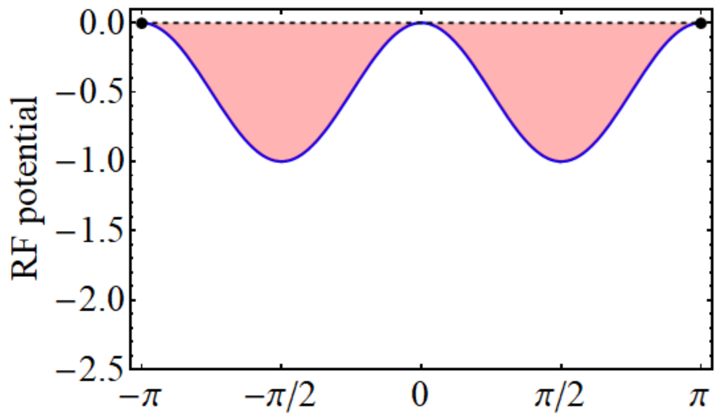
X-crossing

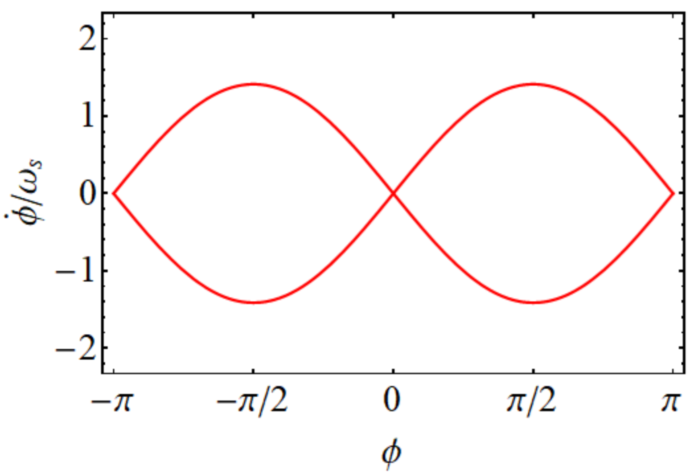


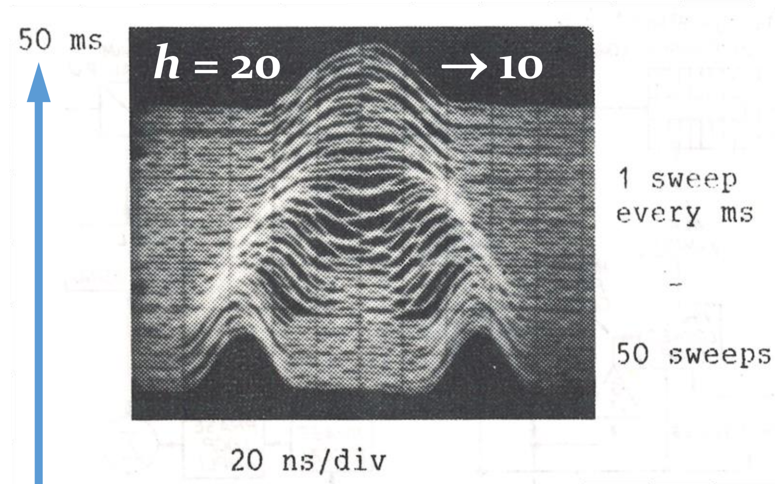
Bunch merging

Overlapping crossing

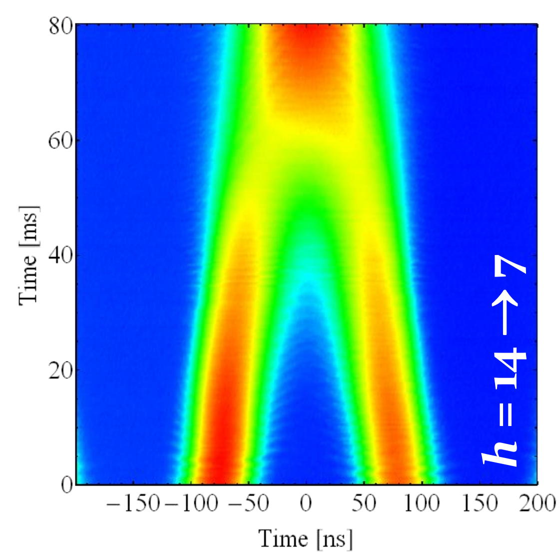






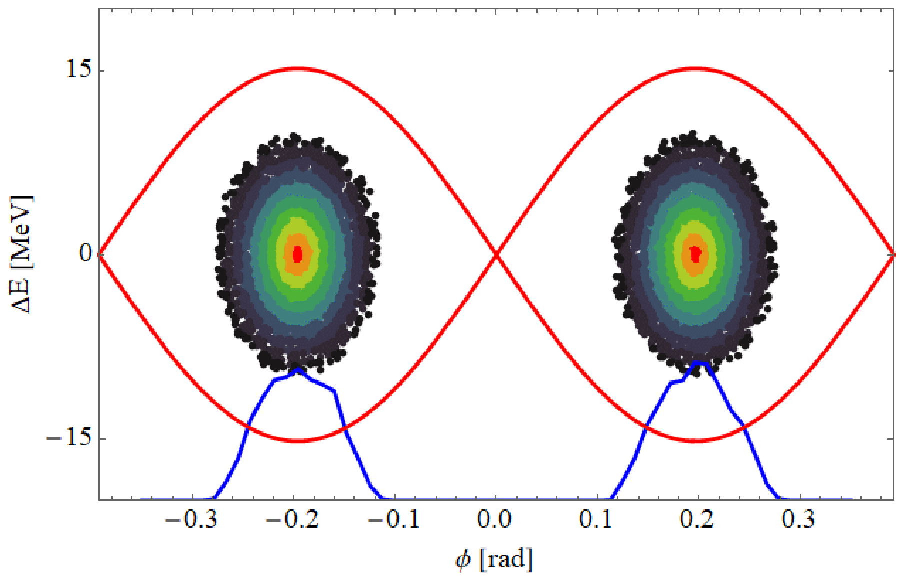


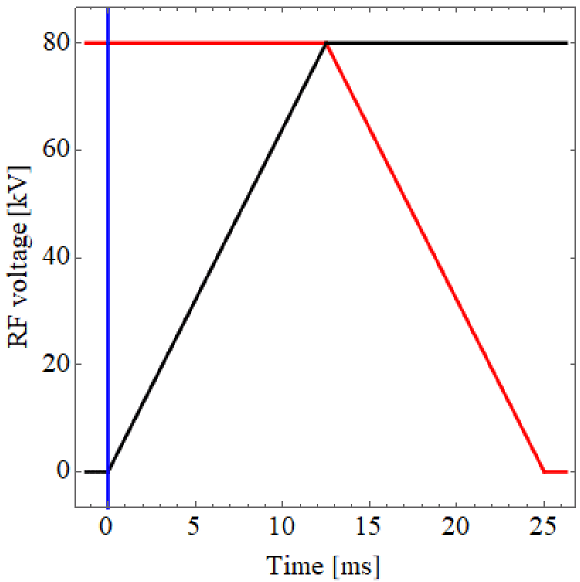
B. J. Evans, R. Garoby, et al. *The Antiproton Production Beam for the Antiproton Collector ("A.C.")*, PAC'87, p. 1925



Bunch merging

→ **Simulation of an adiabatic manipulation**





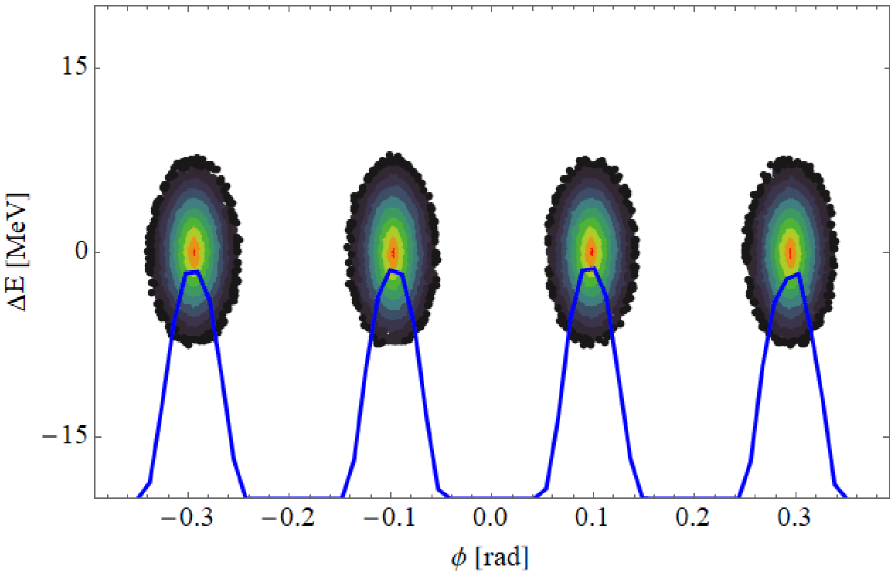
- **Longitudinal distribution ideally unchanged**
  → **Central part of the bunch remains in the centre**

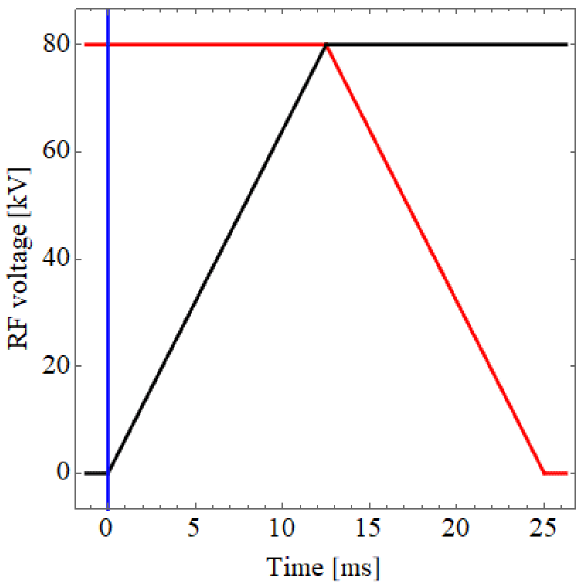
Strengths and weaknesses	
+	Simple manipulation to increase intensity per bunch
-	Initial bunches must have identical longitudinal emittance
-	Relative RF phase critical to avoid blow-up

Bunch merging

- **Generalization of bunch merging for multiple bunches?**

→ **Direct hand-over from $h \rightarrow h/n$**



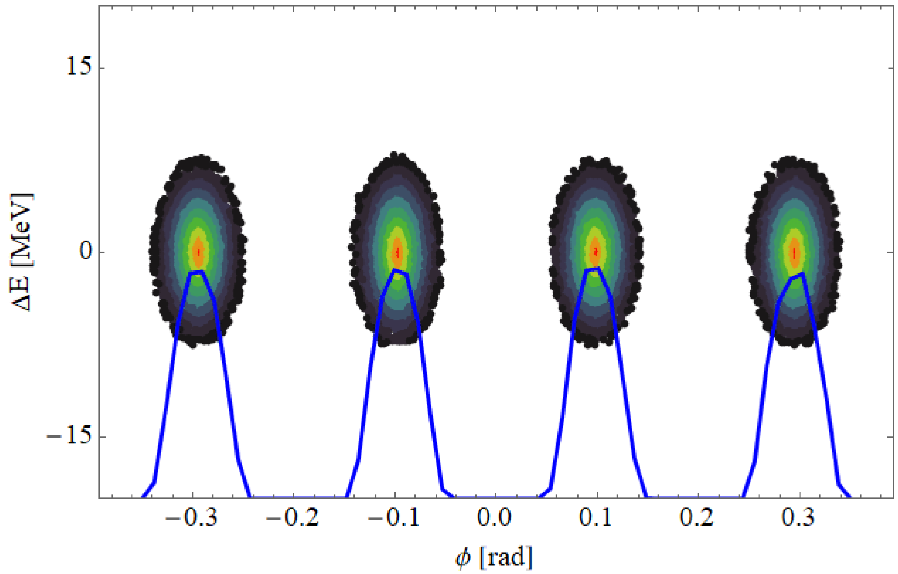


→ **Impossible in one single step!**

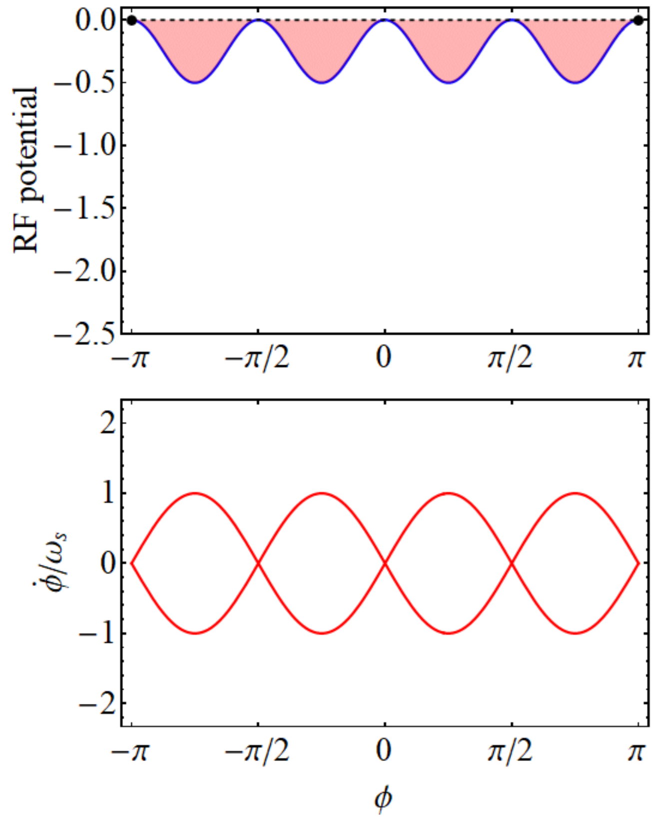
Bunch merging

- **Generalization of bunch merging for multiple bunches?**

→ **Direct hand-over from $h \to h/n$**



Voltages in counter-phase



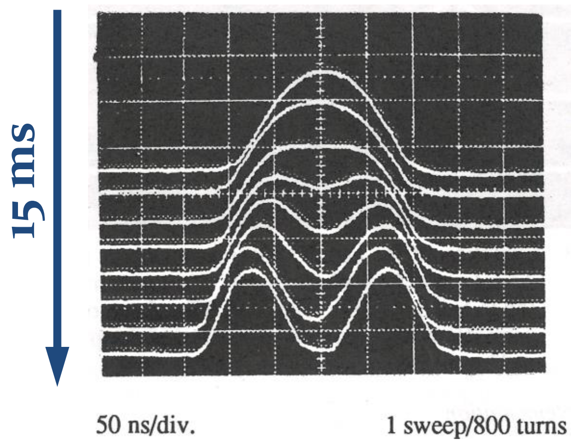
→ **Impossible in one single step!**

→ **Sub-buckets do not fill simultaneously**

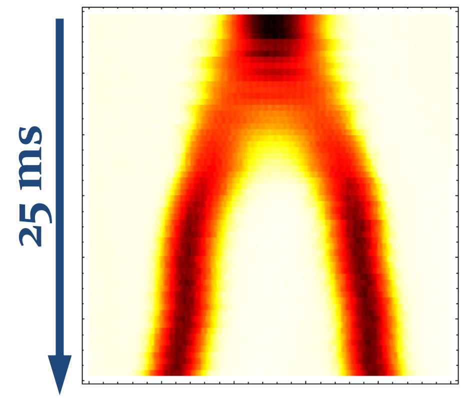
→ **Sequential manipulation of two mergings instead: $h \to h/2 \to h/4$**

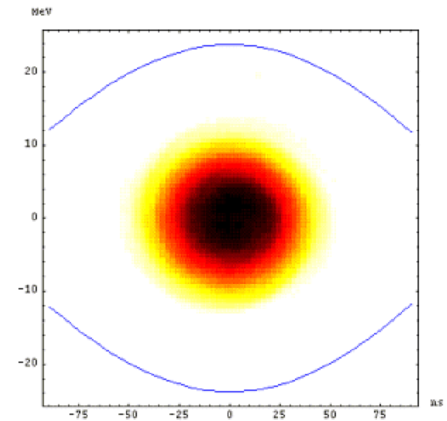
Bunch splitting

- **Inverse bunch merging → Bunch Splitting**



R. Garoby, S. Hancock, *New Techniques for Tailoring Longitudinal Density in a Proton Synchrotron*, EPAC'94, p. 282





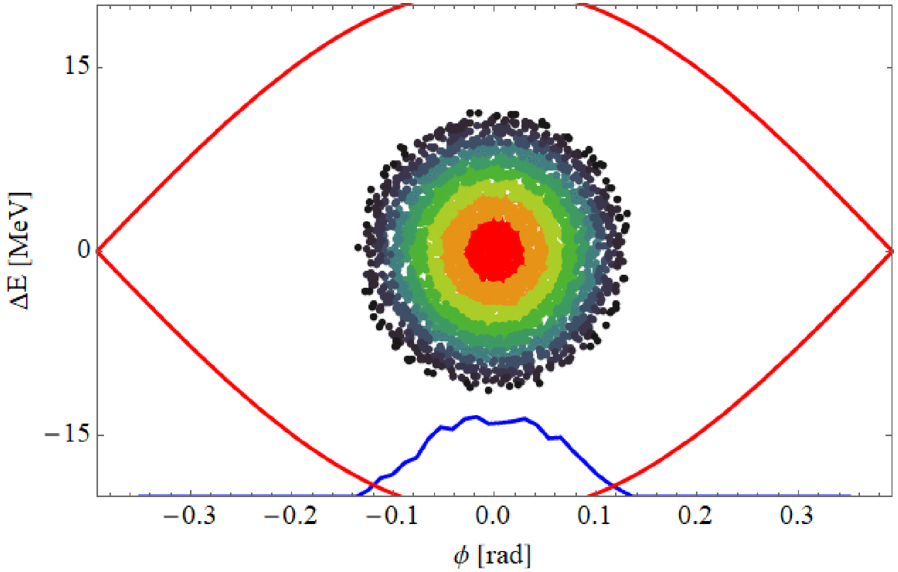
→ **Increase number of bunches and RF frequency**

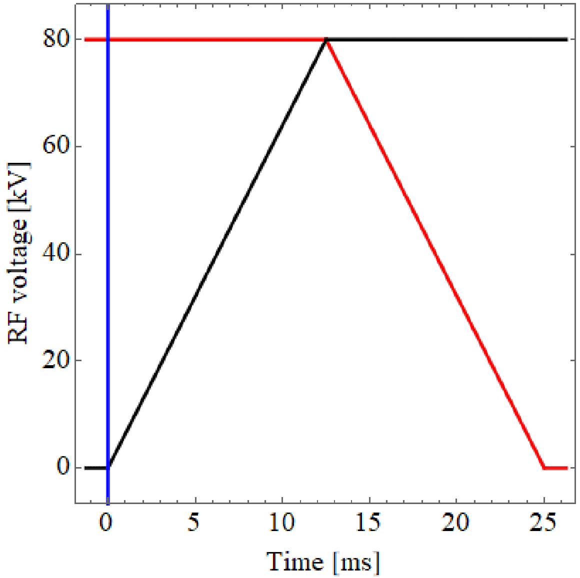
→ **Reduce bunch spacing**

→ **Distribute intensity more equally around circumference**

Bunch splitting

- **Inverse bunch merging → Bunch Splitting**





→ **Increase number of bunches and RF frequency**

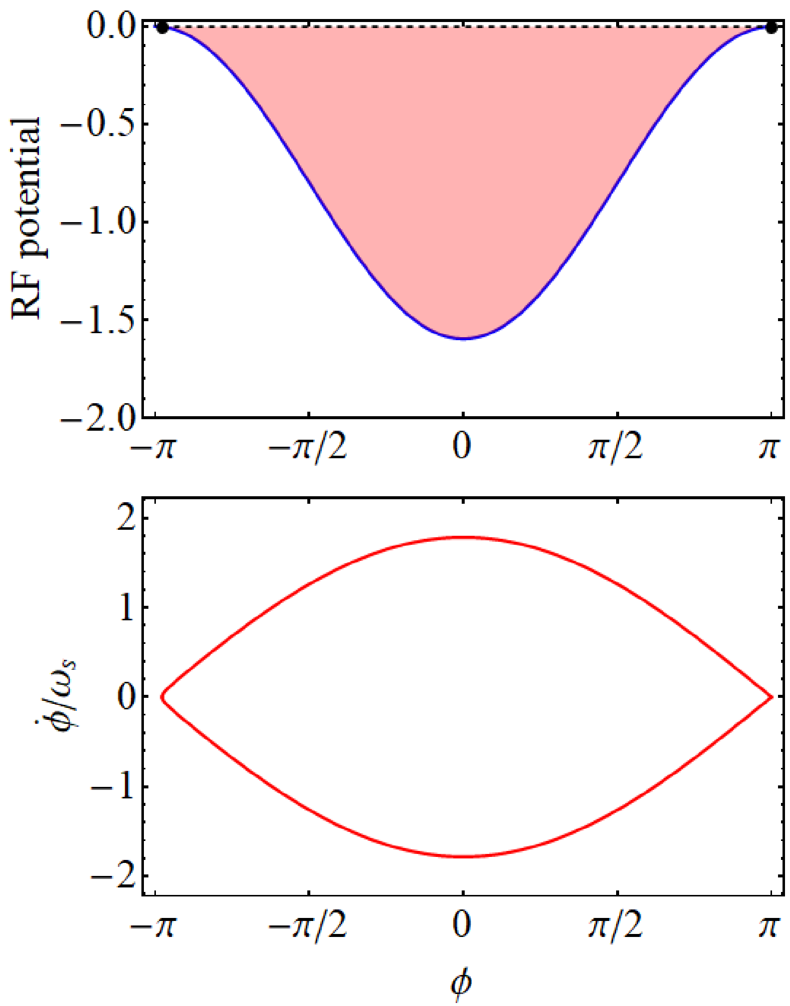
→ **Reduce bunch spacing**

Strengths and weaknesses	
+	**Simple manipulation, to increase intensity per bunch**
-	**Relative RF phase critical to avoid blow-up, especially for small bucket filling factors**

Extension of bunch splitting → Triple split

→ **Apply RF voltage at 3 harmonics h, $2h$ and $3h$ at the same time**

→ **Form sub-buckets of equal size during process**



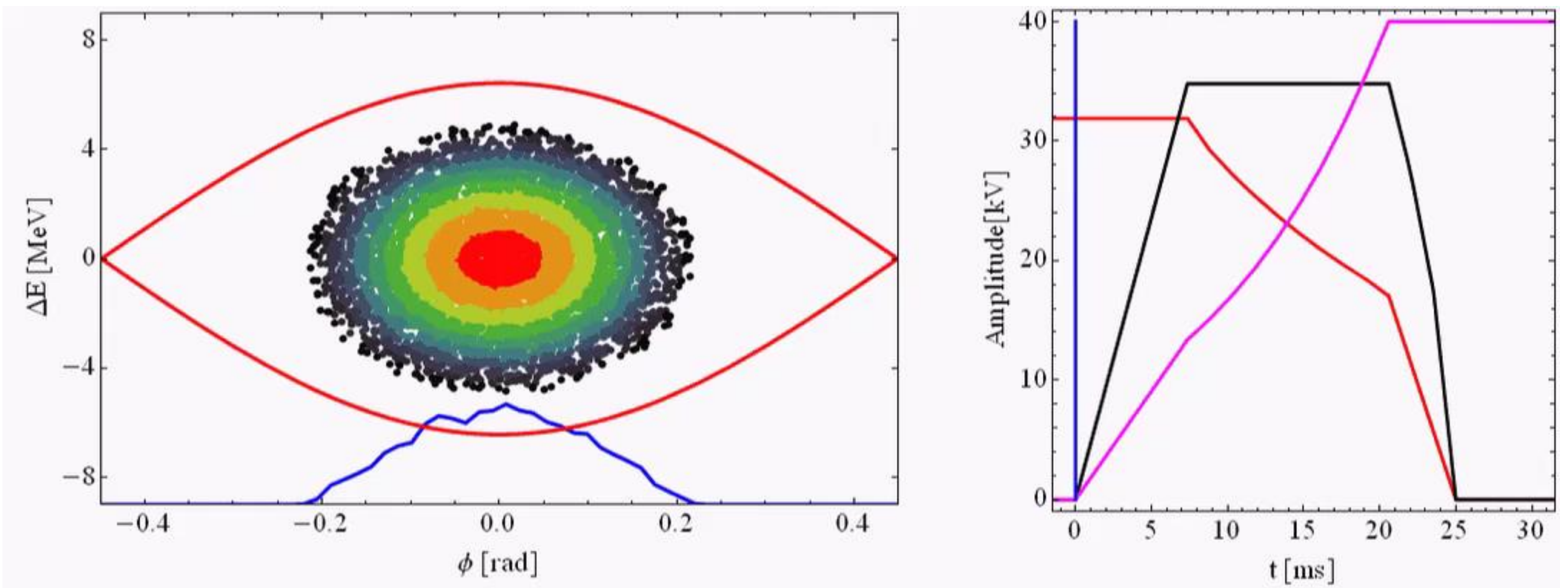
1. **RF voltages at h and $3h$ in phase**
2. **Voltage at $2h$ in counter-phase to bucket particles outside**

→ **Defines voltage programs during the process**

Bunch splitting and merging

→ **Apply RF voltage at 3 harmonics *h*, 2*h* and 3*h* at the same time**

→ **Form sub-buckets of equal size during process**



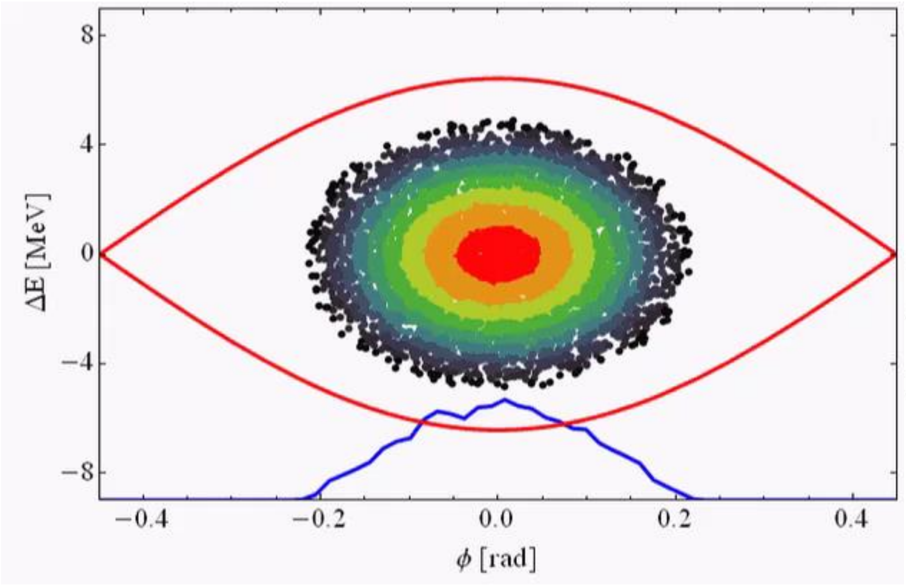
→ **Triple-harmonic RF manipulation**

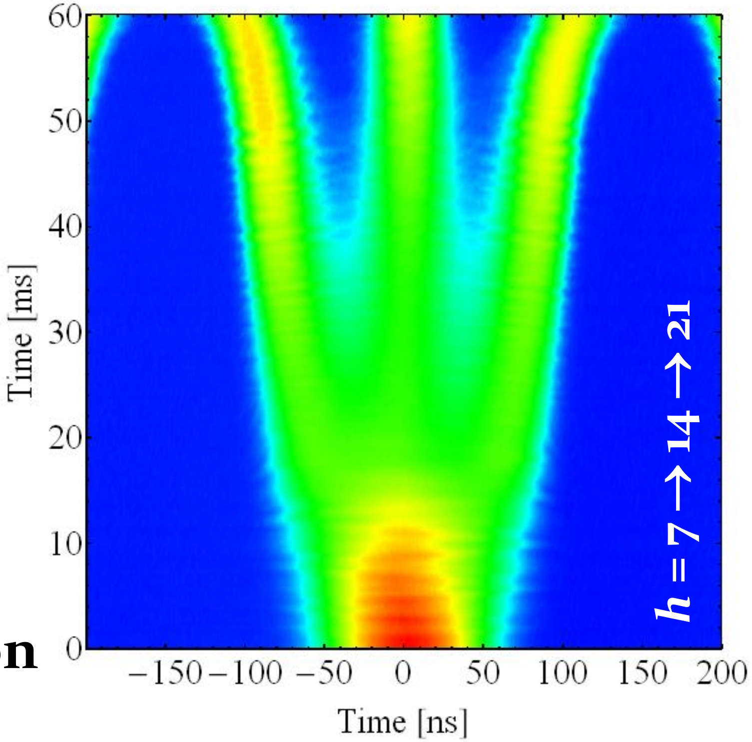
✓ **Works on paper**

Bunch splitting and merging

→ **Apply RF voltage at 3 harmonics *h*, 2*h* and 3*h* at the same time**

→ **Form sub-buckets of equal size during process**





→ **Triple-harmonic RF manipulation**

✓ **… and with beam as well!**

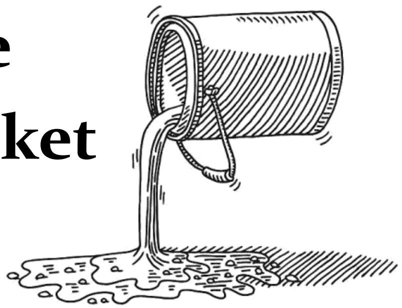
Summary

- RF can do so much more than just acceleration

→ Adiabaticity and synchrotron frequency decide whether a manipulation is slow or fast

- The RF potential is the integral of voltage

  → Fill occupied phase space into the bucket



→ Change bunch length and harmonic number

→ Merge and split bunches

Thank you very much for your attention!

RF Manipulations II

H. Dameraü
CERN

RF for Accelerators

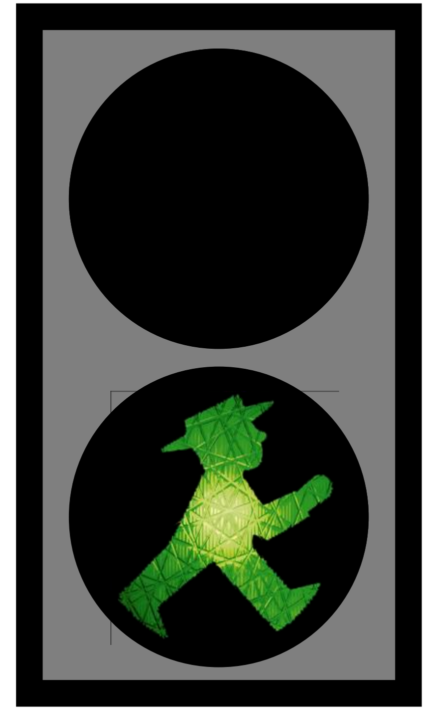
30 June 2023

The CERN Accelerator School

Copyright statement and speaker's release for video publishing

Outline

- Introduction
- Single-harmonic RF
- Double-harmonic RF
  - Rebucketing, bunch merging and splitting
  - Batch compression
- Double RF system
  - Slip stacking
- Non-sinusoidal RF voltages
  - Barrier bucket manipulations
- Sequences, design and implementation
  - Batch compression, merging and splitting
  - A real world example
- Summary



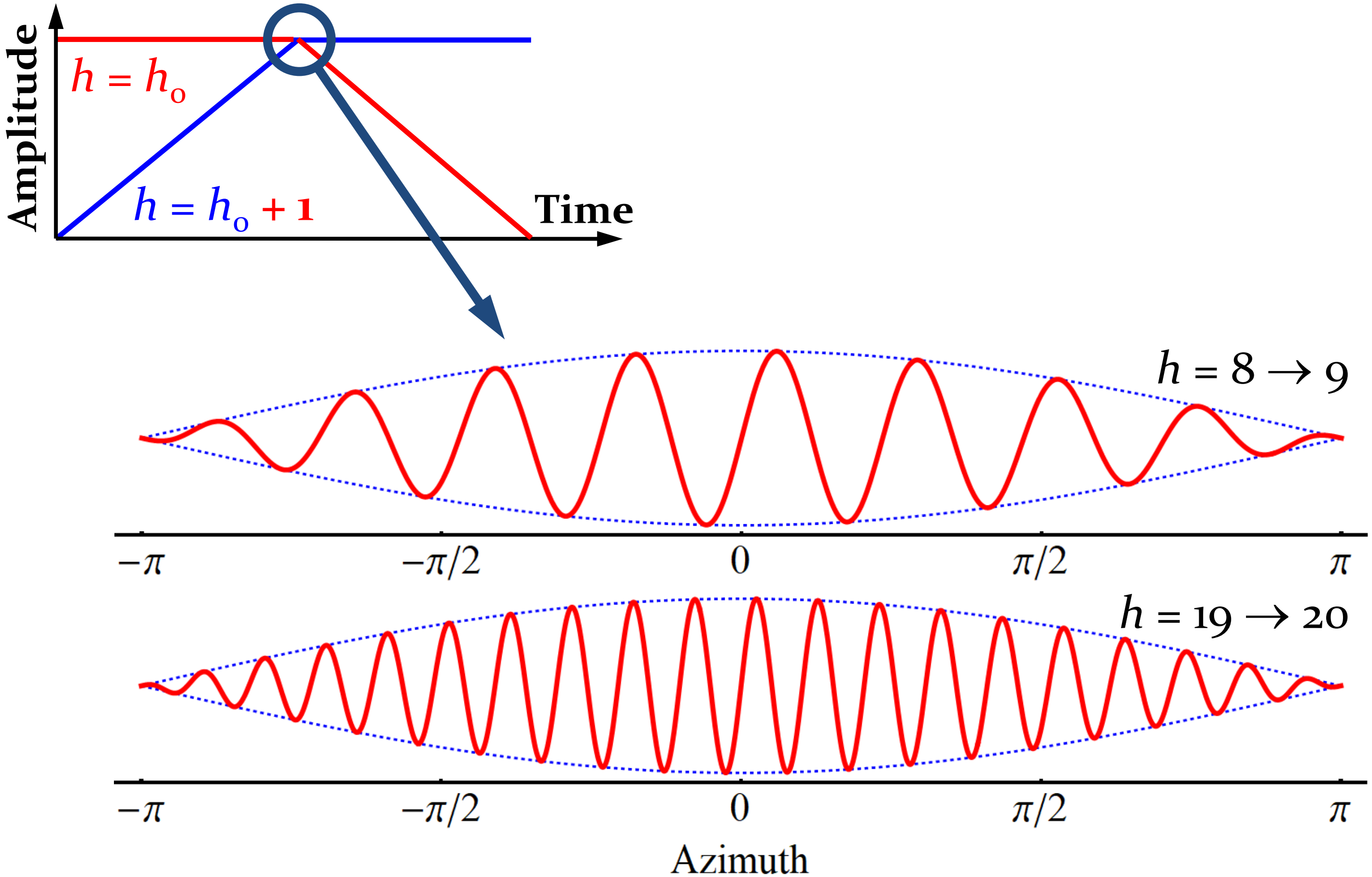
h_1 and h_2

Batch compression

Change harmonic in small steps

→ **Control spacing between bunches → proportional to T_{rev}/h**

→ **Slowly change harmonic: $h \rightarrow h + n$ with $n = 1, 2, 3, \ldots$**

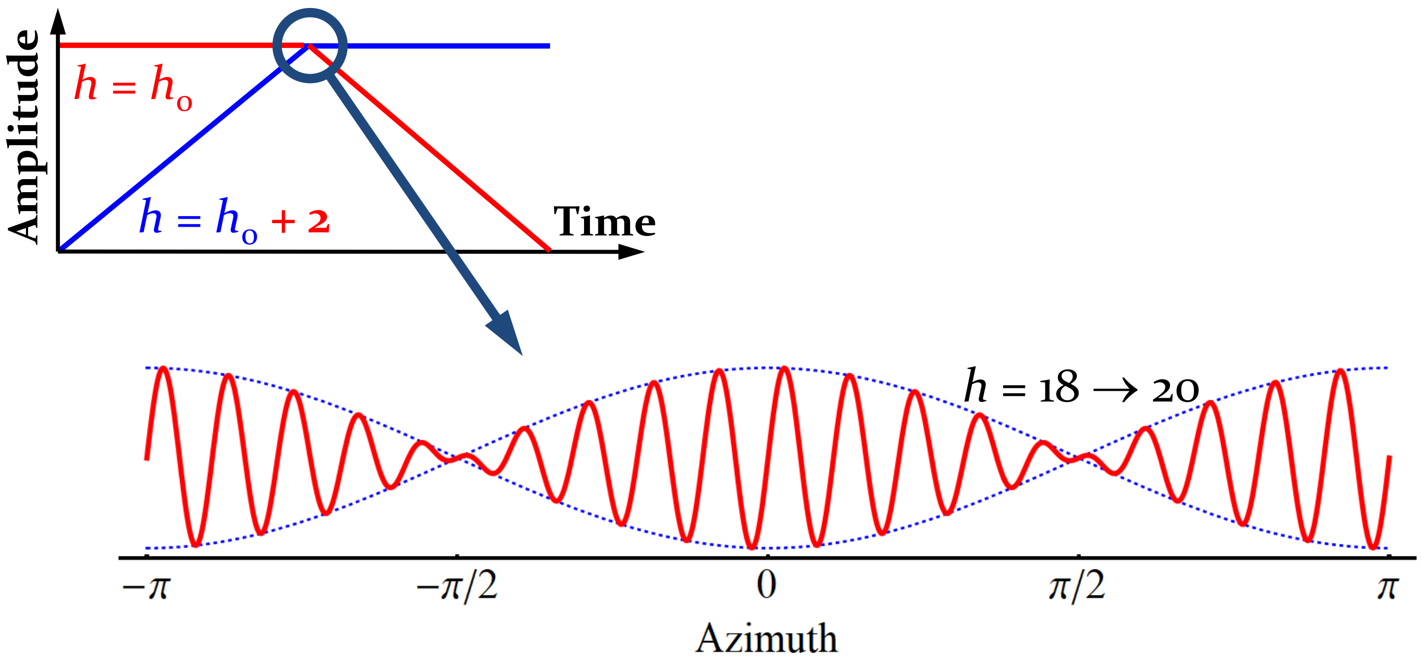


→ **Amplitude modulation for RF voltage envelope**

Change harmonic in small steps

→ **Control spacing between bunches → proportional to T_{rev}/h**

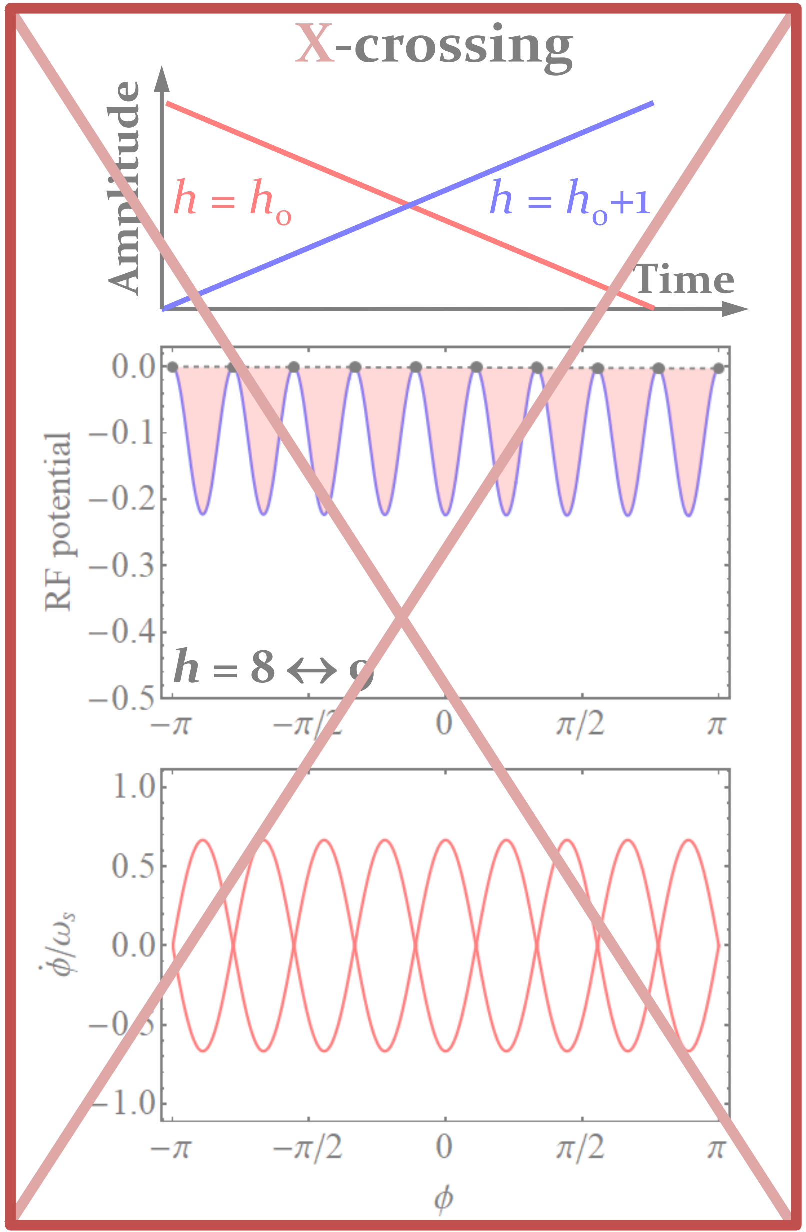
→ **Slowly change harmonic: $h \to h + n$ with $n = 1, 2, 3, \ldots$**

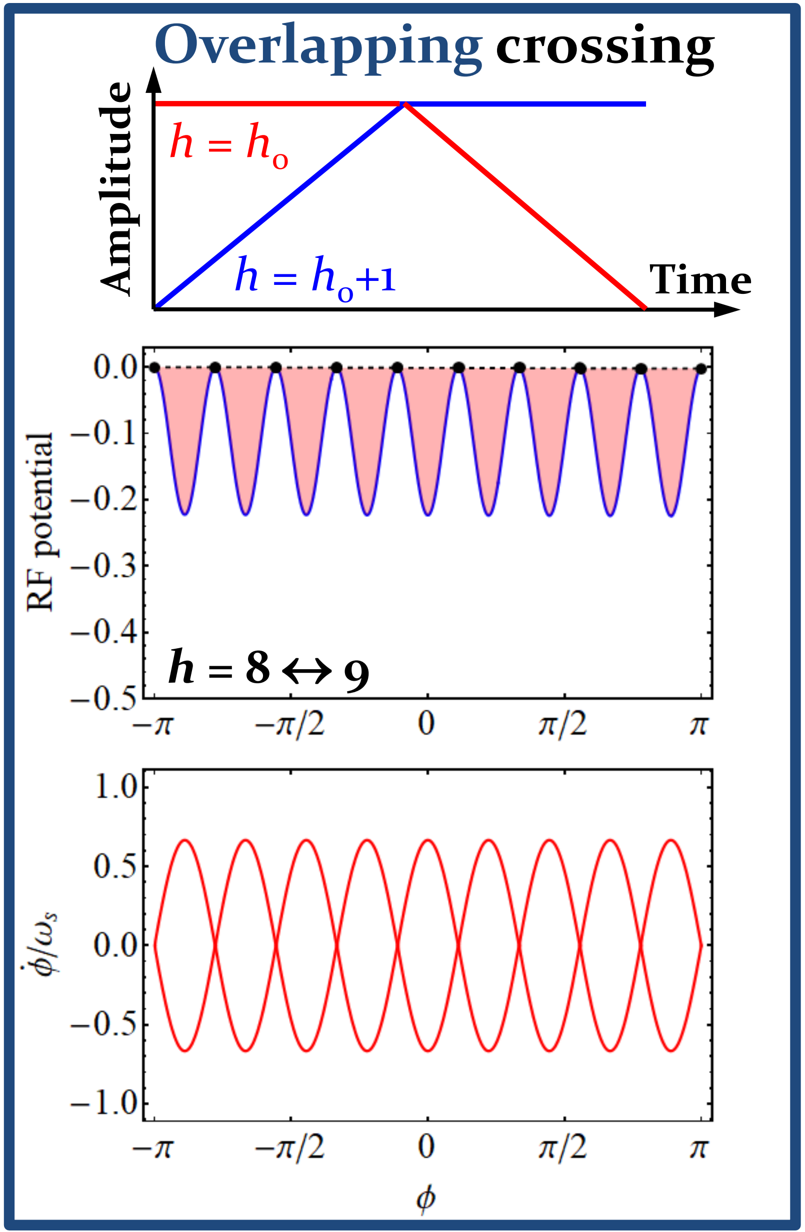


→ **Maximum length of bunch train limited to $2\pi/\Delta h$ to avoid azimuth regions with no RF**

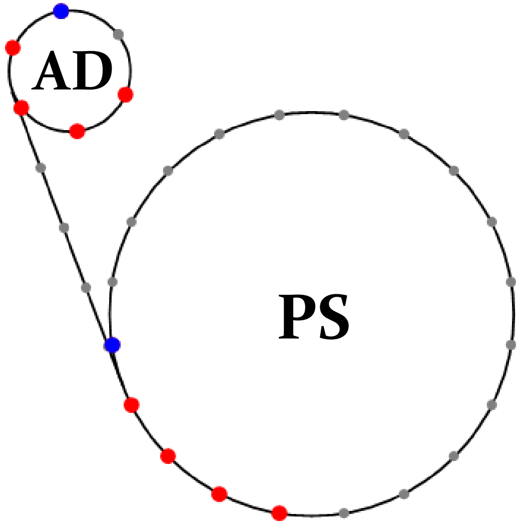
RF potential and buckets during handover

- **Example: hand-over from $h = 8$ to $h = 9$ (and back)**





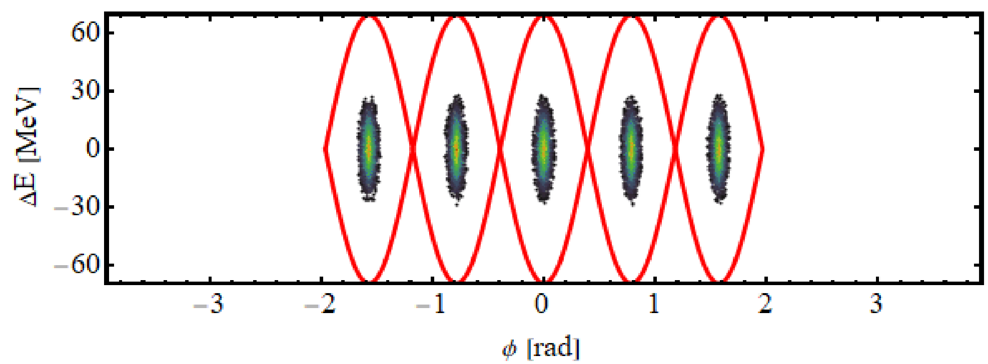
Example batch compression for AD

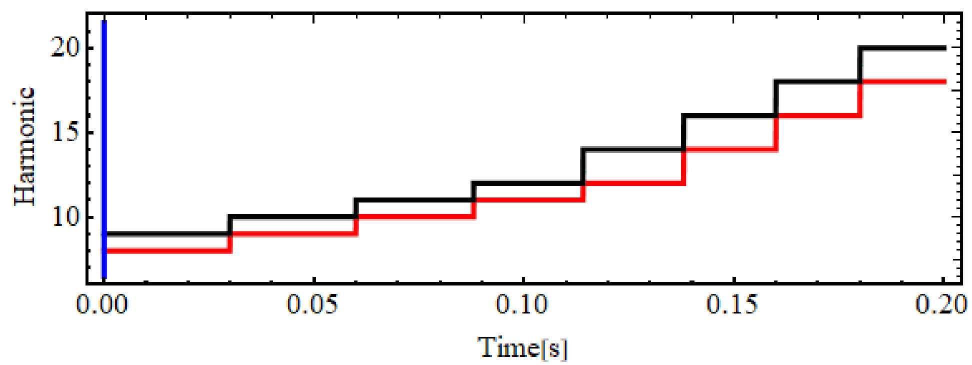


- **Antiproton decelerator (AD) much smaller than Proton Synchrotron (PS)**

→ $T_{\mathrm{rev,AD}} = T_{\mathrm{rev,PS}}/(10/3) \approx T_{\mathrm{rev,PS}}/3.33$

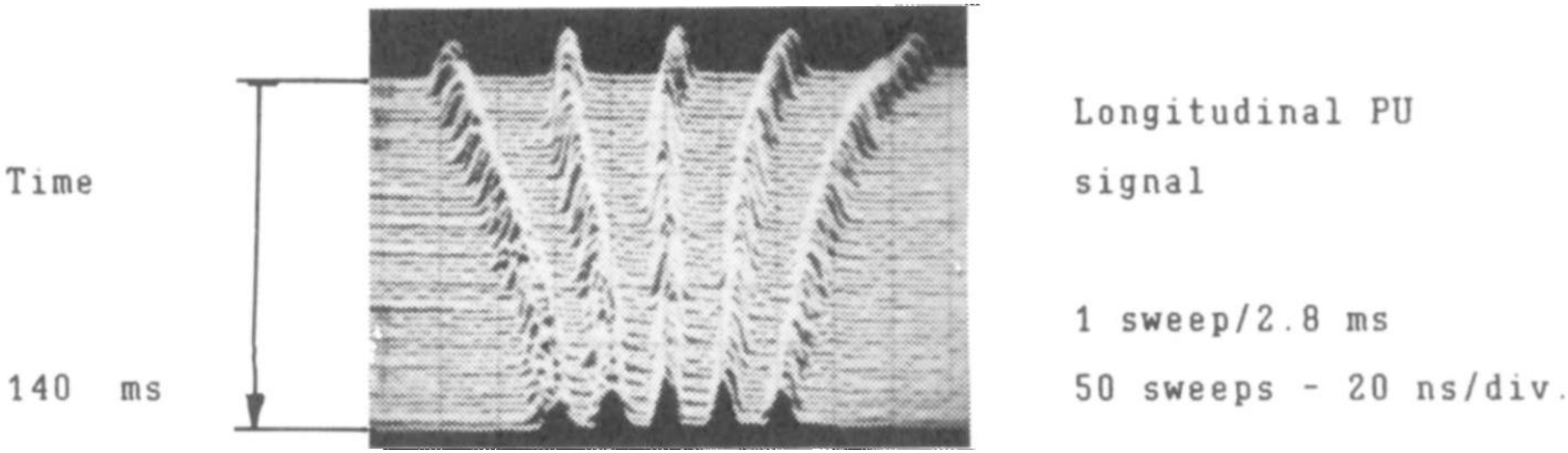
→ **Batch compression to make it fit**





Example batch compression for AD

h = 10 → 12 → 14 → 16 → 18 → 20



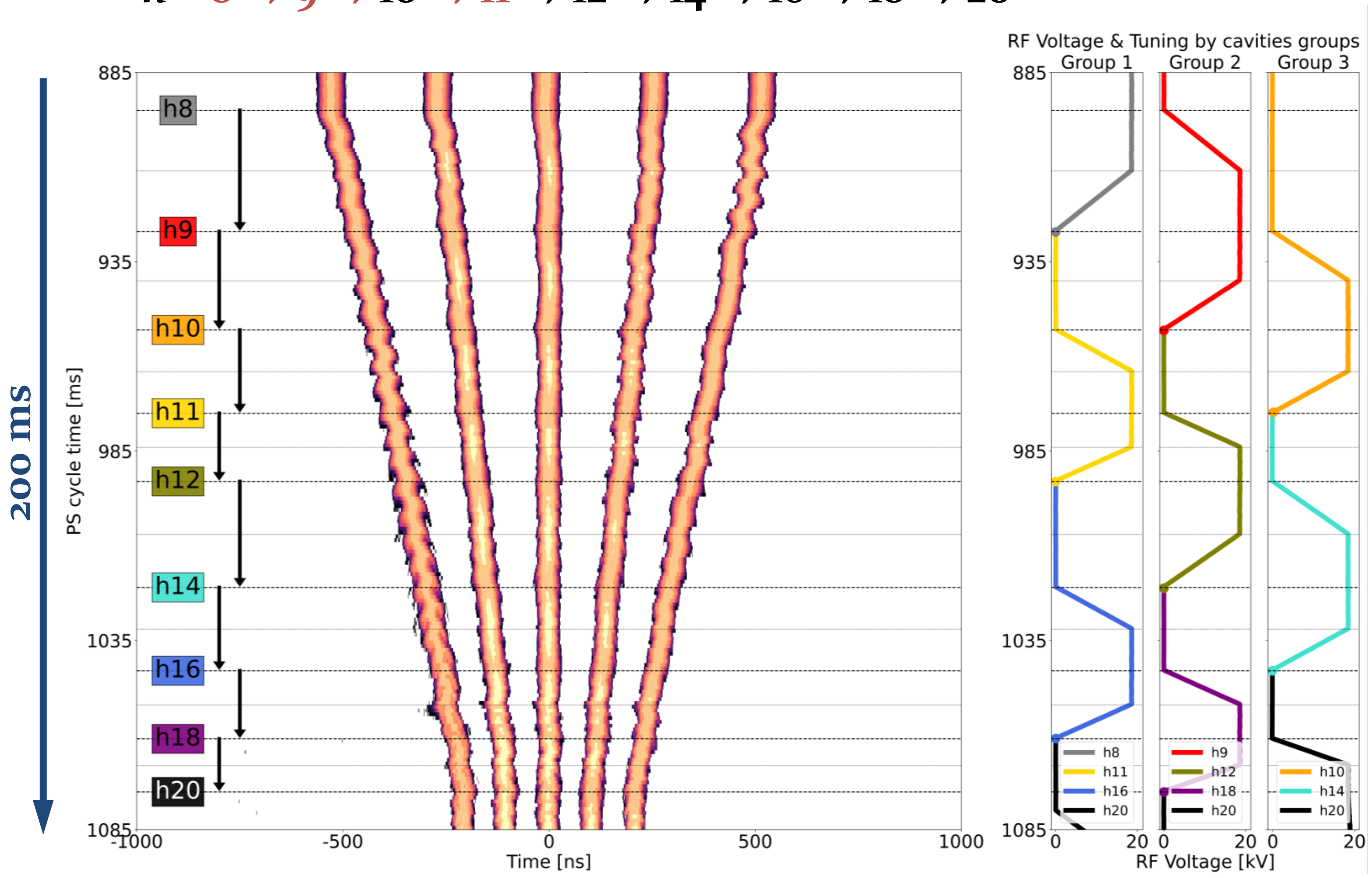
R. Cappi, B. J. Evans, R. Garoby, *Status of the anti-proton production beam in the CERN PS*, Part. Accel. 26 (1990), p. 217

Strengths and weaknesses

- \+ Hand-over from bucket centre to bucket centre
  → Robust RF manipulation
- \+ No particles at unstable fixed point
- \- Requires two groups of active RF cavities, ideally with a 3rd preparing for subsequent harmonic
- \- Complex RF voltage programmes

Example batch compression for AD

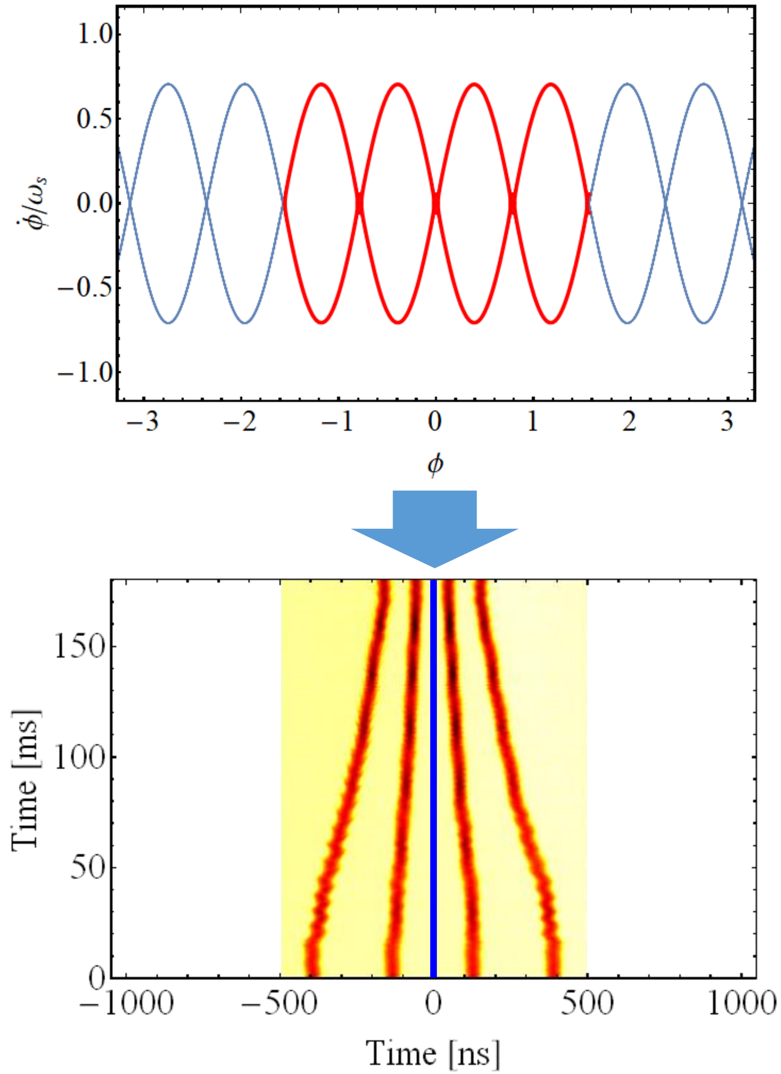
$h = 8 \rightarrow 9 \rightarrow 10 \rightarrow 11 \rightarrow 12 \rightarrow 14 \rightarrow 16 \rightarrow 18 \rightarrow 20$



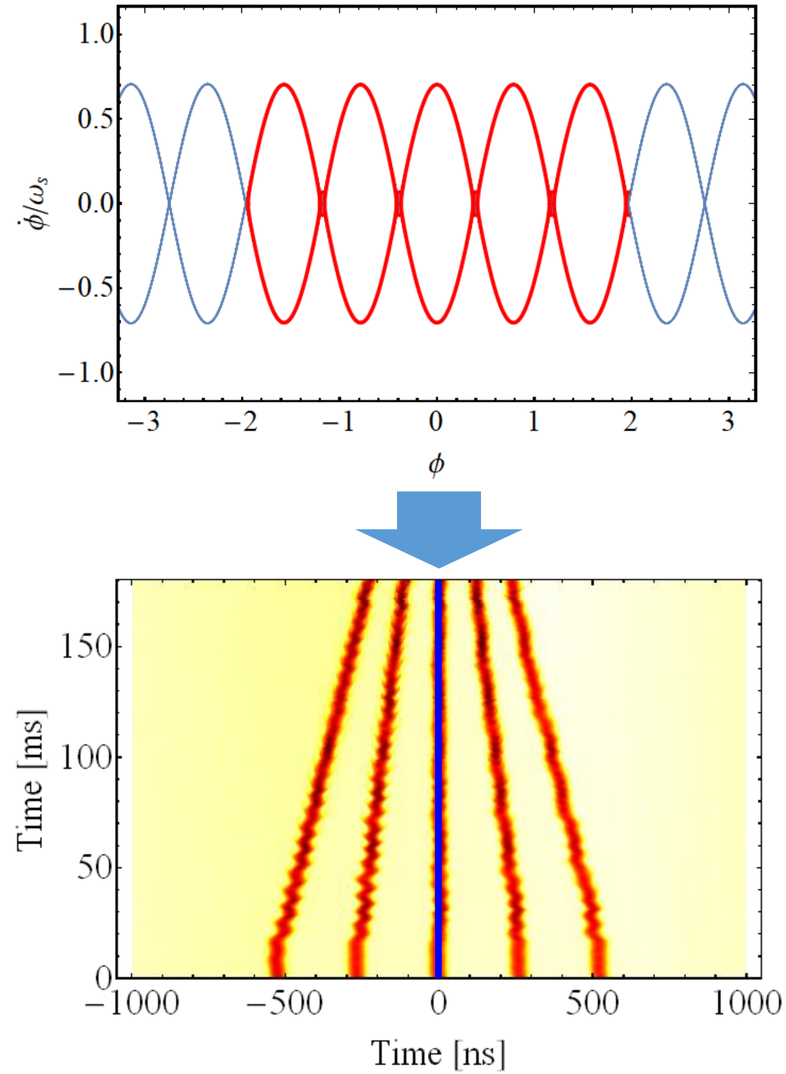
C. Lombard et al., *Improved antiproton production beam at CERN*, PAC2023

Symmetry of batch compression

Even number of bunches

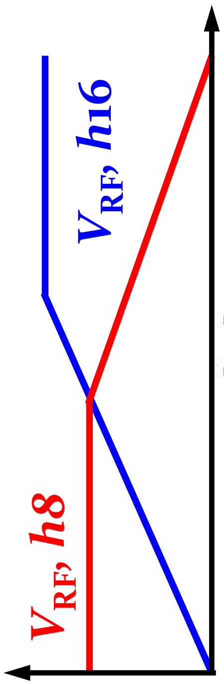


Odd number of bunches

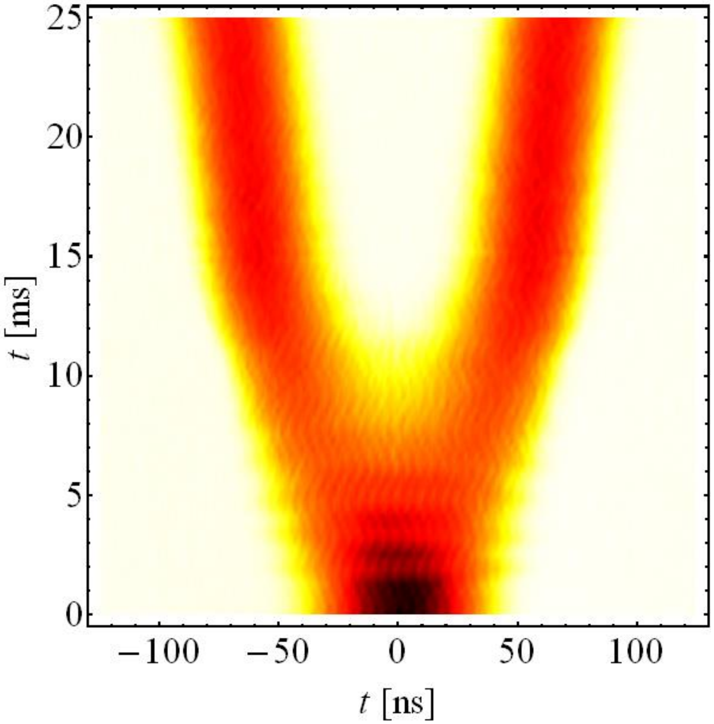


→ **Just RF phases decide whether a bucket forms in the center**

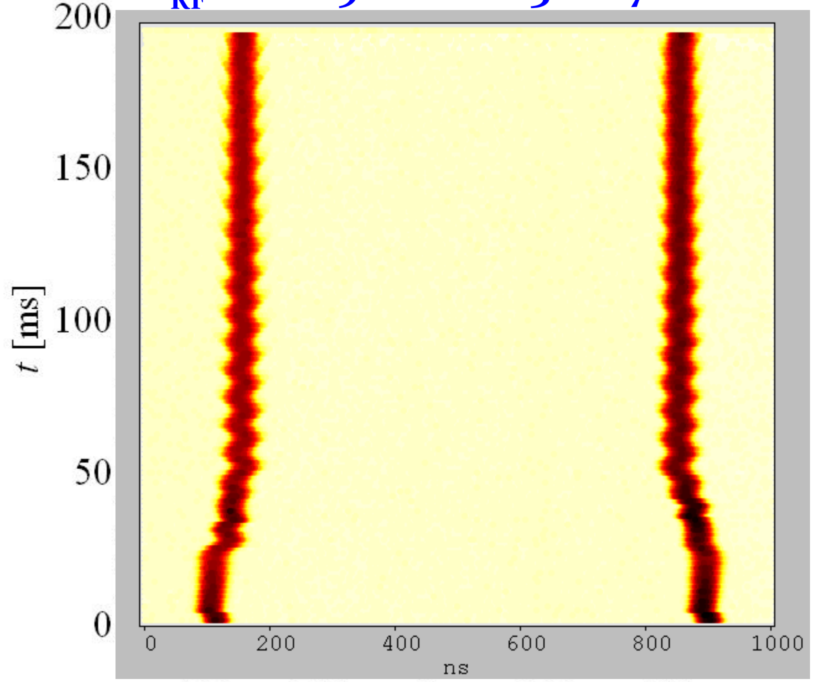
Symmetry of RF manipulations



Splitting: $h_{RF} = 8 \rightarrow 16$



Batch compression:
$h_{RF} = 8 \rightarrow 9 \rightarrow 11 \rightarrow 13 \rightarrow 17 \rightarrow 20$



- **Works in every bucket**

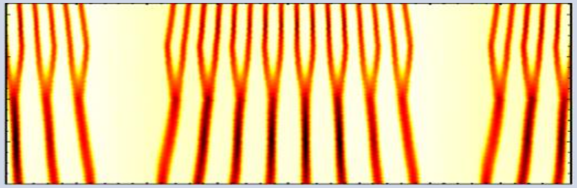
$\rightarrow$ **Periodicity: $h = 8$**

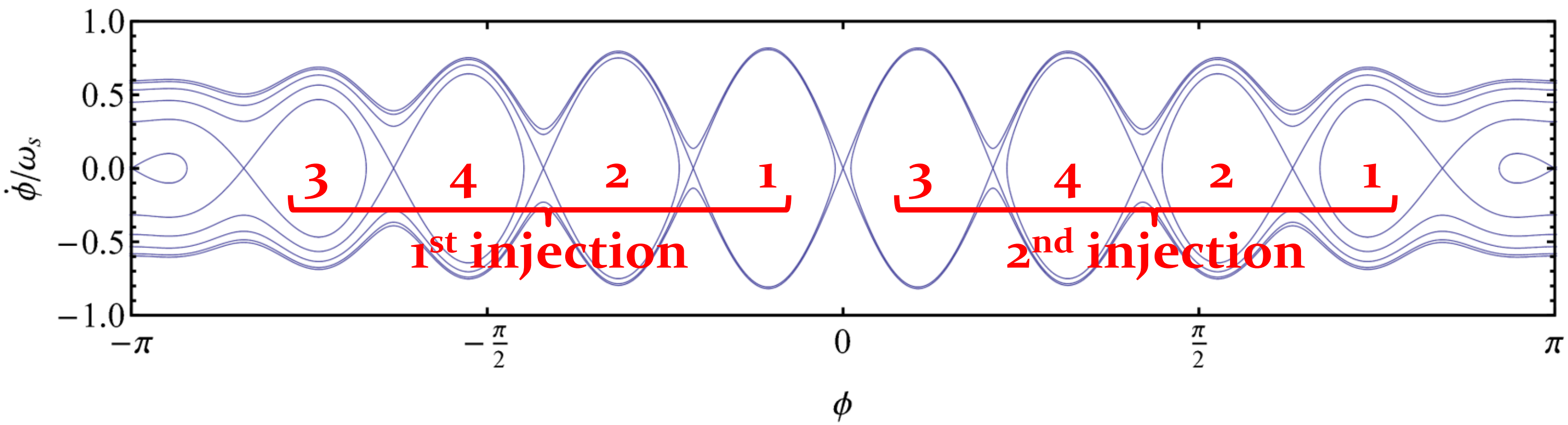
- **All buckets different (even and odd harm.)**

$\rightarrow$ **Periodicity: $h = 1$**

$\rightarrow$ **All RF sources must be synchronous with respect to f_{rev} at any harmonic**

Bucket numbering for RF manipulations

	Triple splitting	Batch compression
Injection harmonic		
Periodicity of RF manipulation	**Every bucket**	**Only one beating along circumference**
Injection bucket selection	**4 buckets difference between both injections**	**Both injections into independently defined buckets**

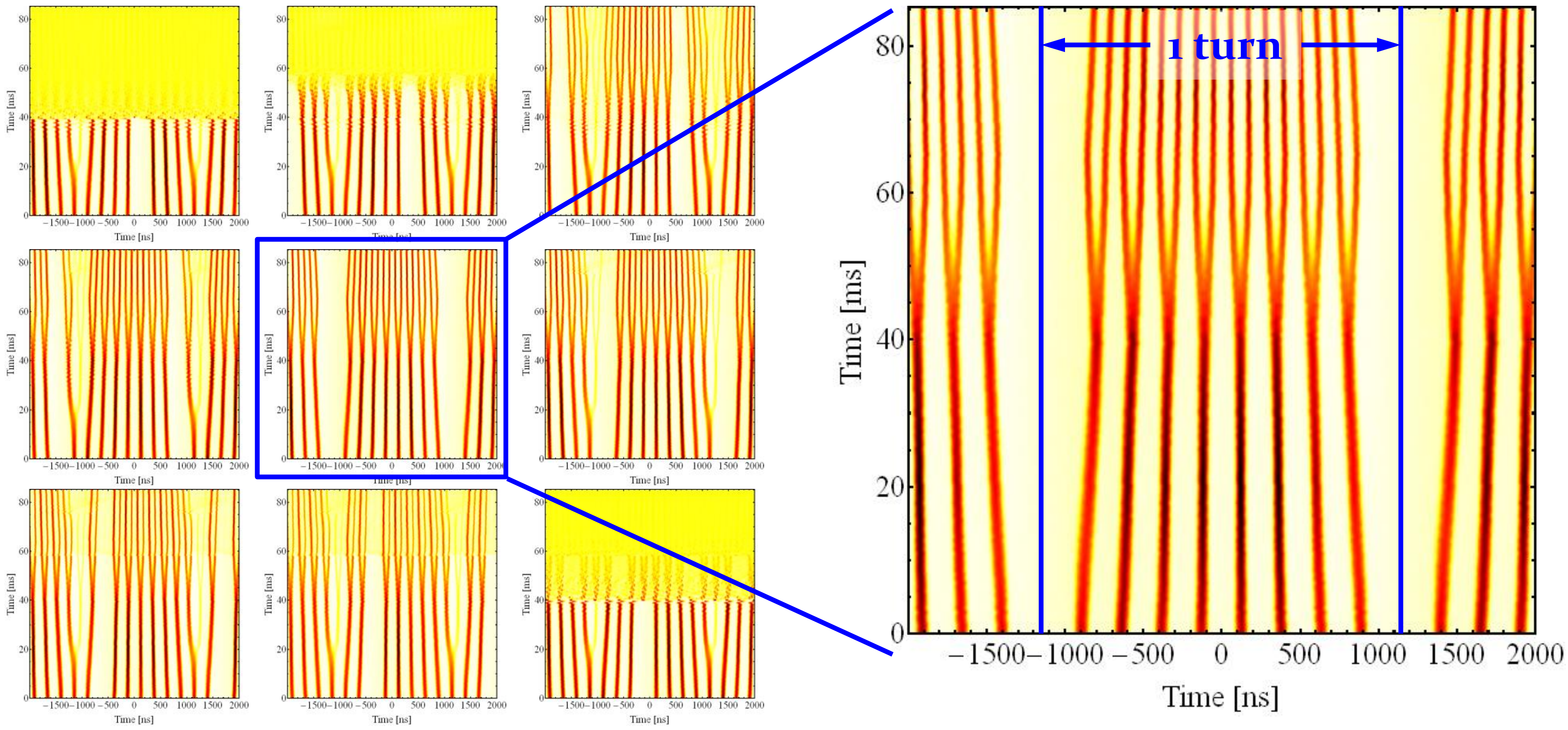


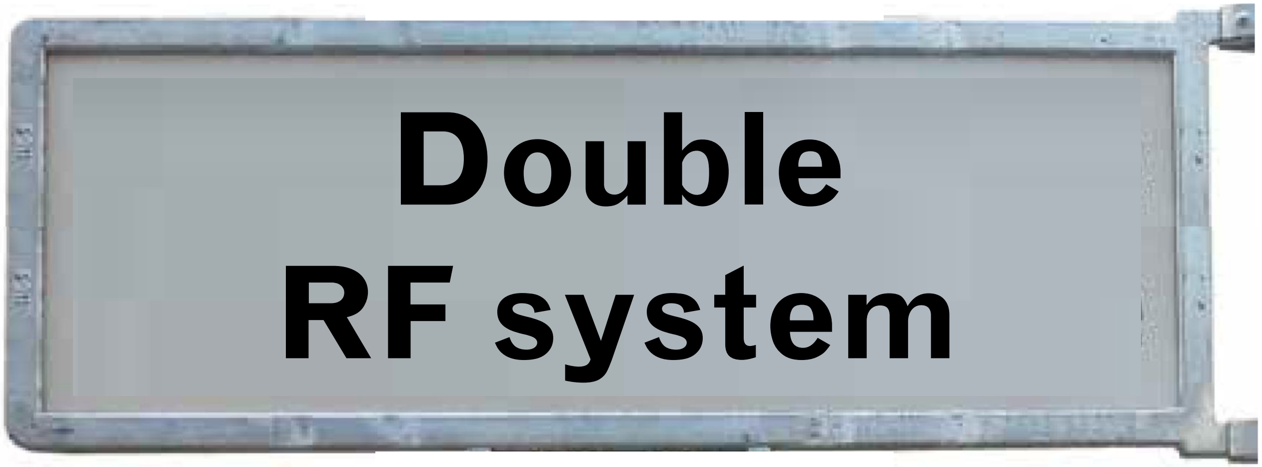
→Must inject into the correct bucket numbers

Bucket numbering

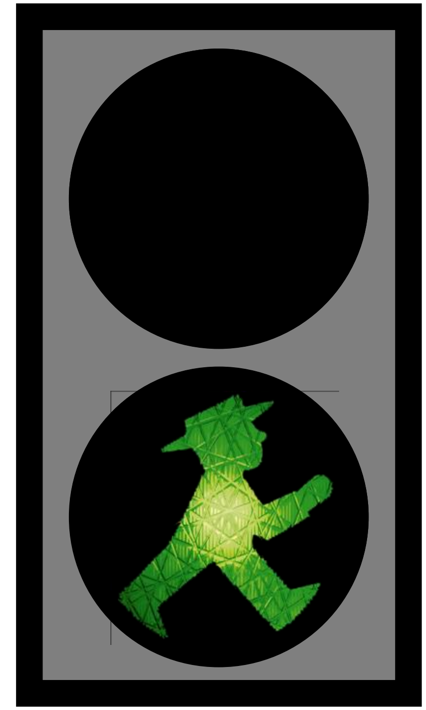
- Bunches must be placed into the correct buckets

→ Must respect bucket number → azimuth relative to phase of $h = 1$





Two beams



Slip stacking

Momentum, radial position and frequency

- **Ideal beam circulates with the expected revolution frequency (Δf = 0) on the central orbit (ΔR = 0) → Δp = 0**
- **Real beam behaviour is calculated using**

Variables	Equations
$B,\ p,\ R$	$\frac{dp}{p} = \gamma_{\mathrm{tr}}^2 \frac{dR}{R} + \frac{dB}{B}$
$f,\ p,\ R$	$\frac{dp}{p} = \gamma^2 \frac{df}{f} + \gamma^2 \frac{dR}{R}$
$B,\ f,\ p$	$\frac{dB}{B} = \gamma_{\mathrm{tr}}^2 \frac{df}{f} + \frac{\gamma^2 - \gamma_{\mathrm{tr}}^2}{\gamma^2} \frac{dp}{p}$
$B,\ f,\ R$	$\frac{dB}{B} = \gamma^2 \frac{df}{f} + (\gamma^2 - \gamma_{\mathrm{tr}}^2) \frac{dR}{R}$

C. Bovet, R. Gouiran, I. Gumowski, K. H. Reich, *A selection of formulae and data useful for the design of A.G. synchrotrons*, CERN-MPS-SI-Int-DL-70-4

Momentum, radial position and frequency

- **Ideal beam circulates with the expected revolution frequency (Δf = 0) on the central orbit (ΔR = 0) → Δp = 0**
- **Real beam behaviour is calculated using**

Variables	Equations
$B,\ p,\ R$	$\frac{dp}{p} = \gamma_{tr}^2 \frac{dR}{R} + \cancel{\frac{dB}{B}}^{\,0}$
$f,\ p,\ R$	$\frac{dp}{p} = \gamma^2 \frac{df}{f} + \gamma^2 \frac{dR}{R}$
$B,\ f,\ p$	$\cancel{\frac{dB}{B}}^{\,0} = \gamma_{tr}^2 \frac{df}{f} + \frac{\gamma^2 - \gamma_{tr}^2}{\gamma^2} \frac{dp}{p}$
$B,\ f,\ R$	$\cancel{\frac{dB}{B}}^{\,0} = \gamma^2 \frac{df}{f} + (\gamma^2 - \gamma_{tr}^2) \frac{dR}{R}$

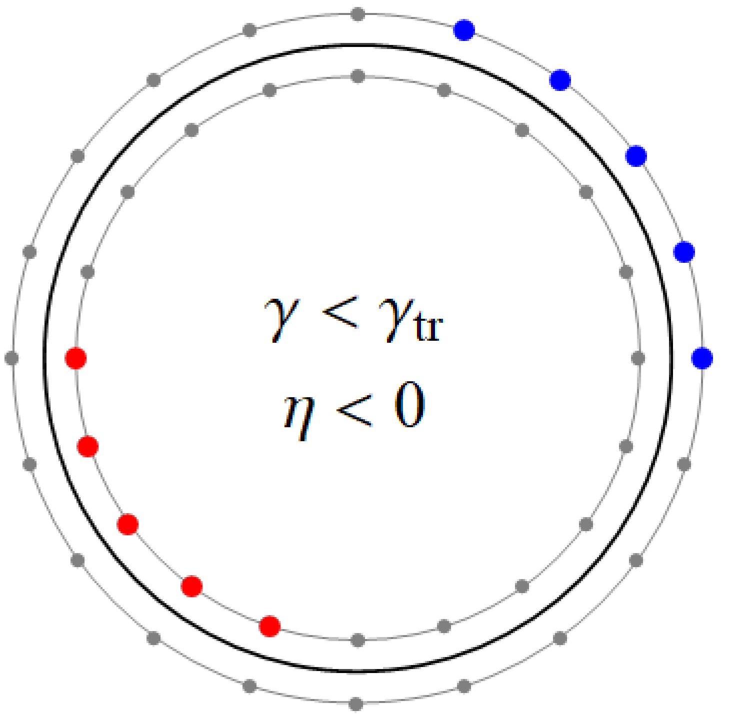
C. Bovet, R. Gouiran, I. Gumowski, K. H. Reich, *A selection of formulae and data useful for the design of A.G. synchrotrons*, CERN-MPS-SI-Int-DL-70-4

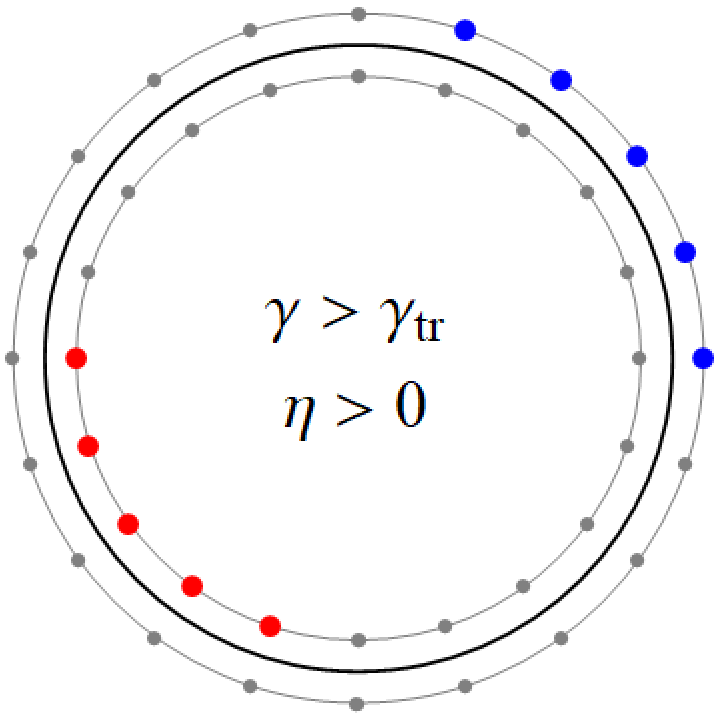
At constant bending field *f*, *p* and *R* are equivalent

→ RF frequency controls beam momentum and radial position
…when the beampipe is wide enough

Two co-rotating beams simultaneously?

- **Difference in revolution frequencies causes phase slip**

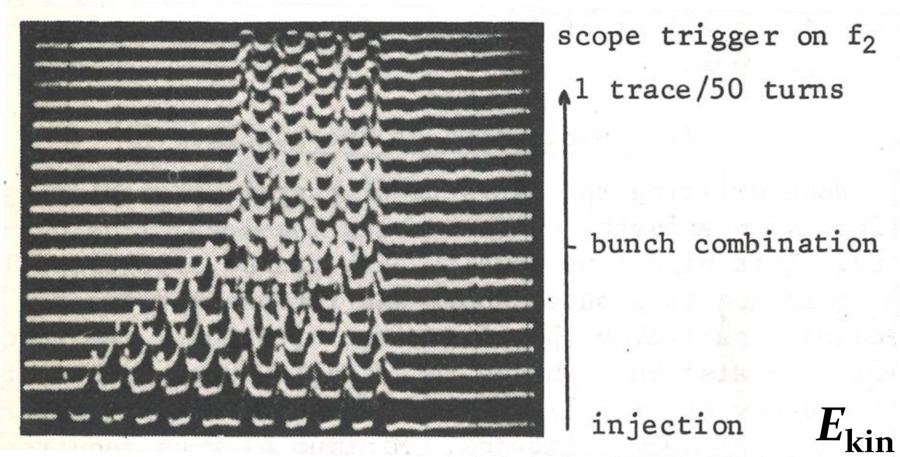


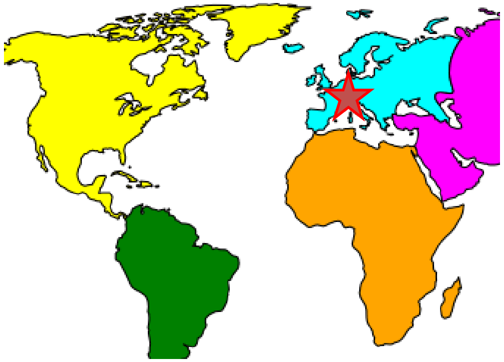


1. **Increase intensity by slip-stacking of bunches**
2. **Reduce bunch spacing → Interleaved slip-stacking**

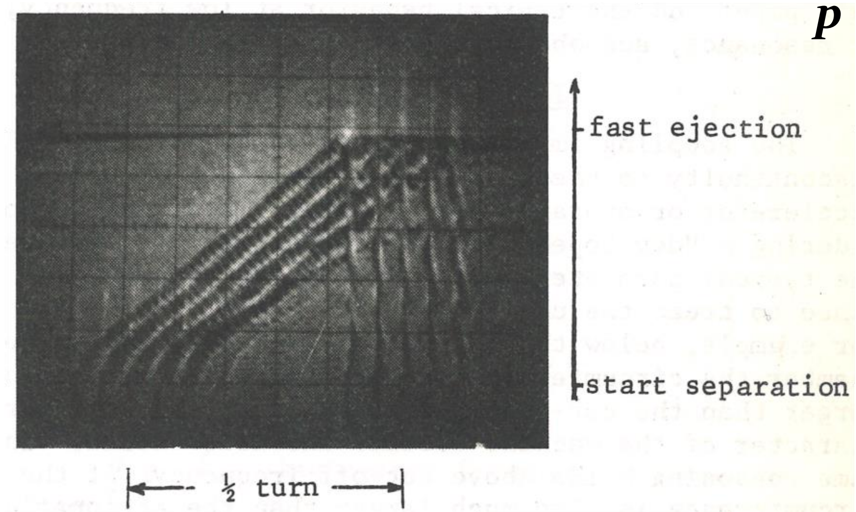
Two co-rotating beams simultaneously

- **First slip-stacking ('azimuthal combination') in CERN PS**





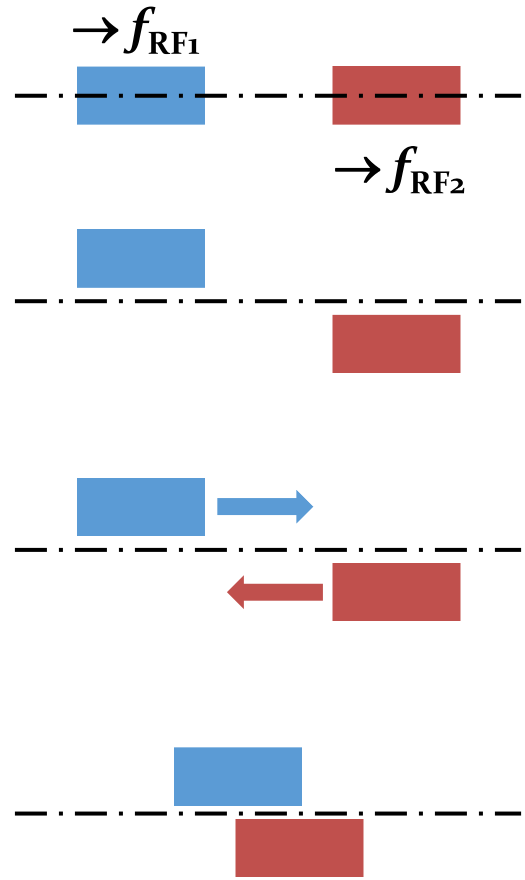
E_{kin} = 800 MeV



p = 26 GeV

D. Boussard,Y. Mizumachi, *Production of beams with high line-density by azimuthal combination of bunches in a synchrotron*, PAC'79, p. 3623

Slip stacking procedure



1. Separate RF for two beams to split RF

- Inject with momentum offset
- RF frequency modulation for bunches separated in time
  - Sufficient RF system bandwidth for modulation at f_{rev}

2. Drift/slippage with $\Delta f_{RF} = f_{RF1} - f_{RF2}$

- Both RF frequencies active simultaneously
- Only minor perturbations of buckets with sufficient Δf_{RF}

3. Approach of f_{RF1} and f_{RF2}

- Carefully optimized compromise between adiabaticity and bucket perturbations

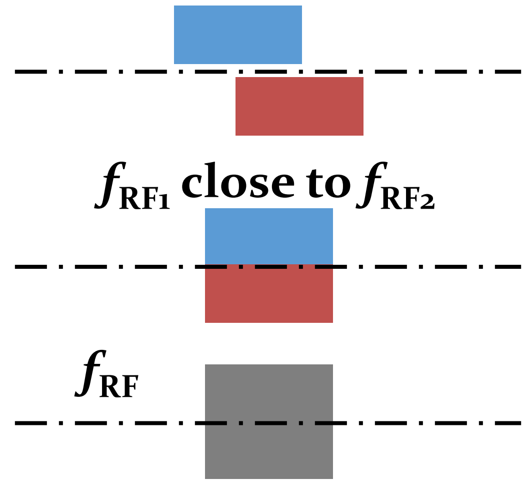
Slip stacking procedure

3. Approach of f_{RF1} and f_{RF2}

- Carefully optimized **compromise** between adiabaticity and bucket perturbations

4. Recapture to common RF frequency: $f_{RF1} = f_{RF1} + f_{RF2}/2$

- Carefully optimized **compromise** between adiabaticity and bucket perturbations



Restaurant RF

Menu à 15€
Entrée + plat/plat + dessert

Menu à 20€
Entrée + plat + dessert

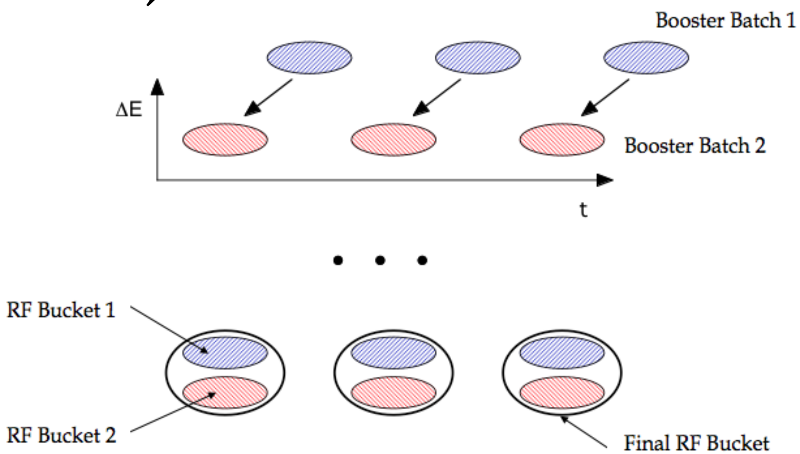
Fromage: supplement 5 €

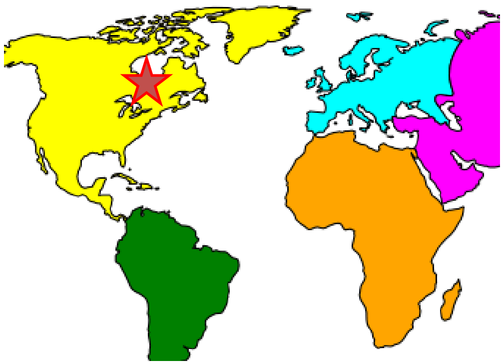
Choose only what is required

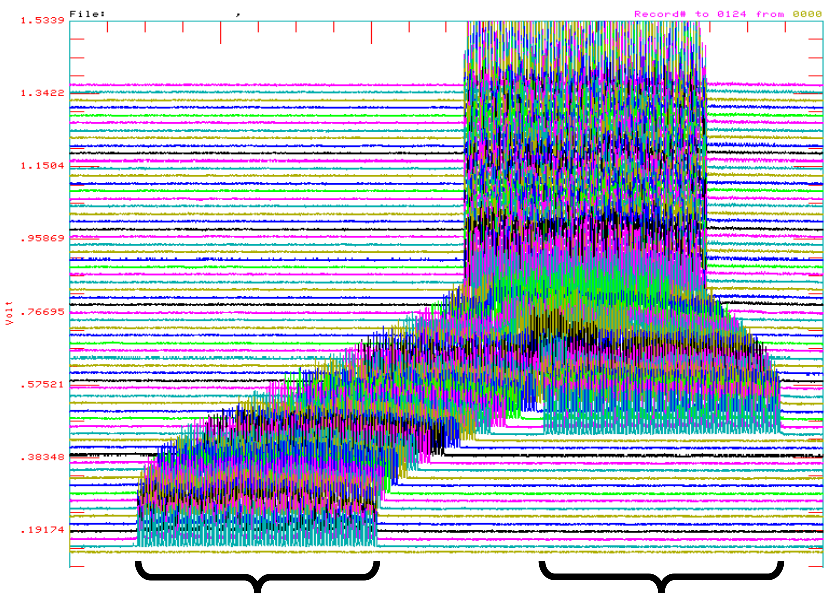
Slip stacking

- **Brought to perfection of stacking long batches in Main Injector at Fermilab**

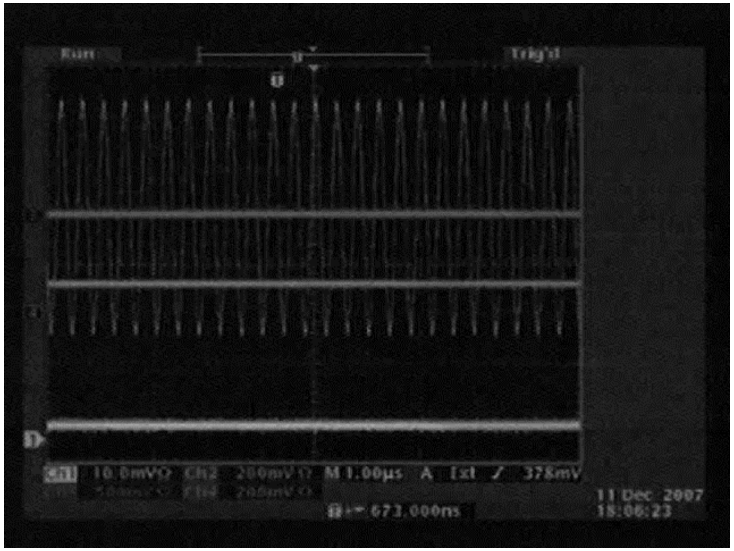
C. Bhat





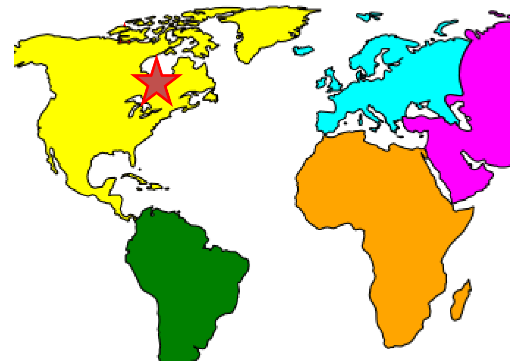


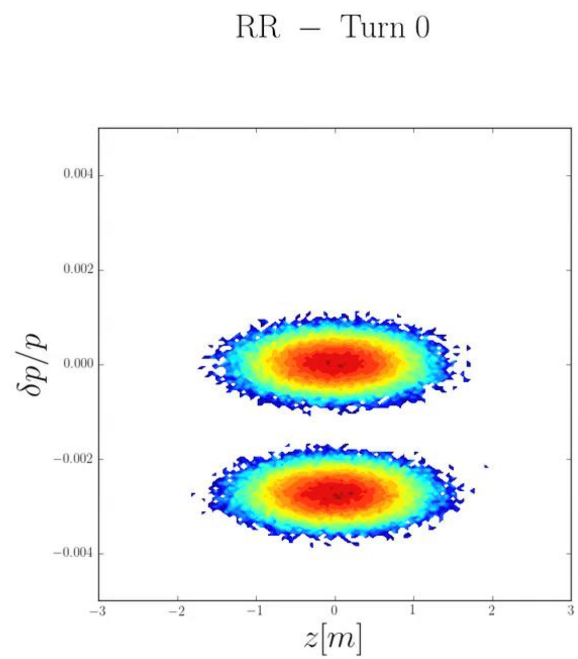
Batch #1 **Batch #2**

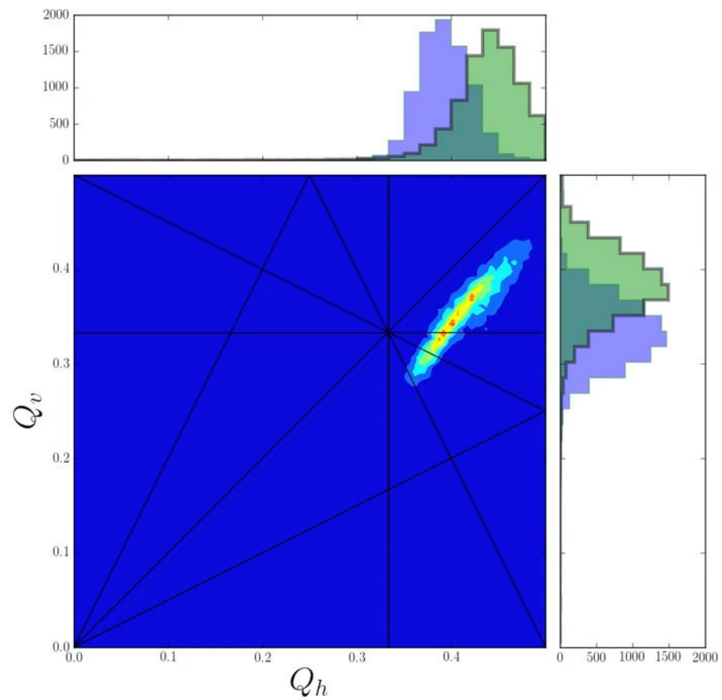


Slip stacking

- **Brought to perfection of stacking long batches in Main Injector at Fermilab**



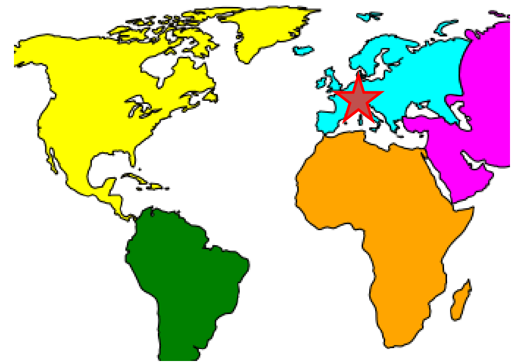


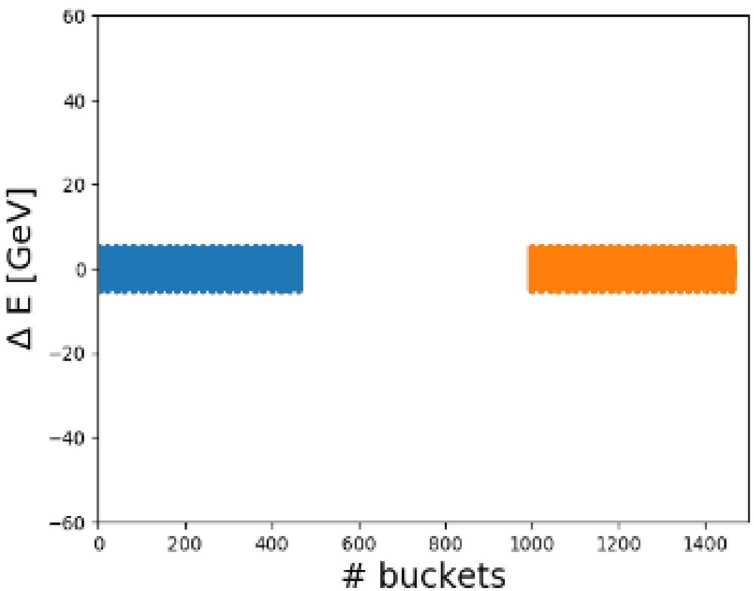


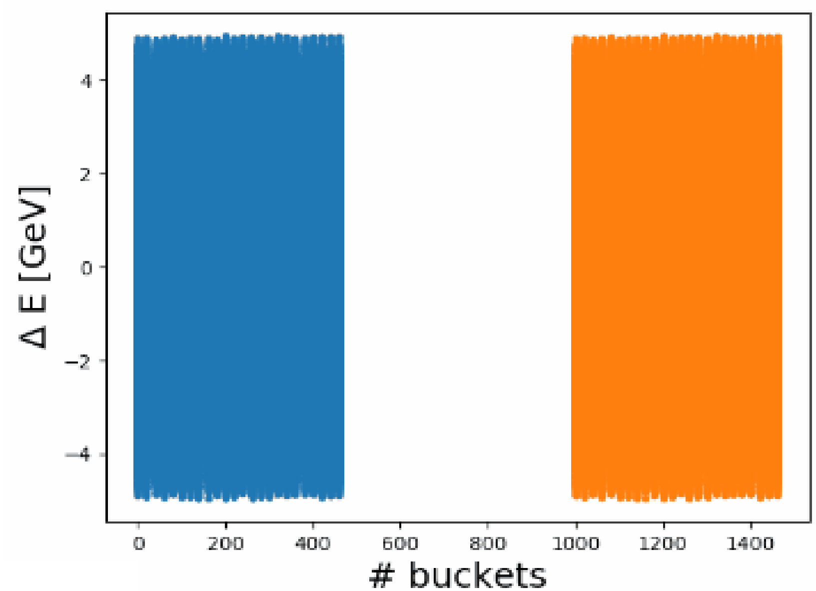
R. Ainsworth

Example: interleaved slip-stacking

- **Reduce bunch spacing by interleaved slip-stacking**







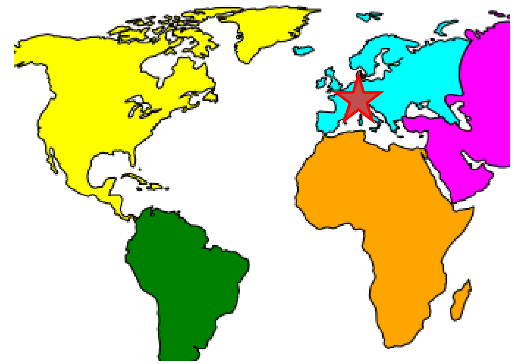
D. Quartullo

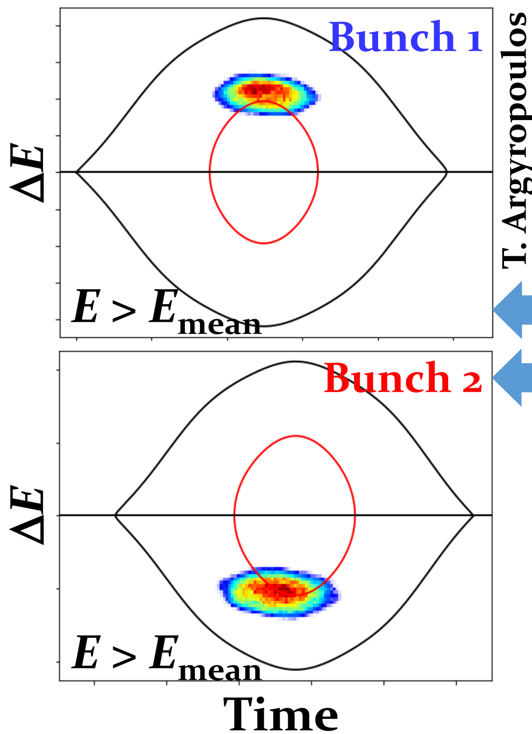
→ **Reduce bunch spacing from 100 ns to 50 ns**

→ **Ion beams for LHC in the SPS at CERN**

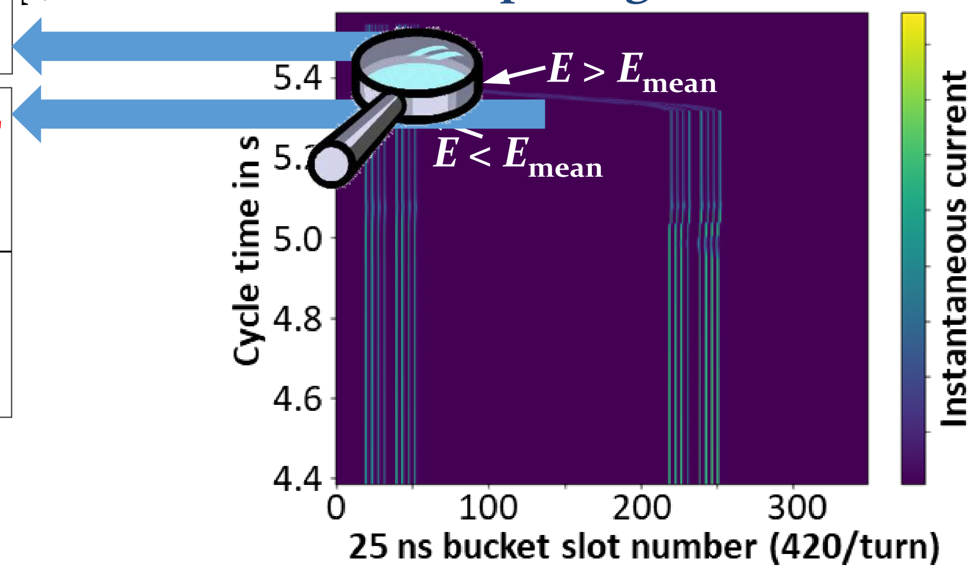
Example: interleaved slip-stacking

- **Reduce bunch spacing by interleaved slip-stacking: SPS**

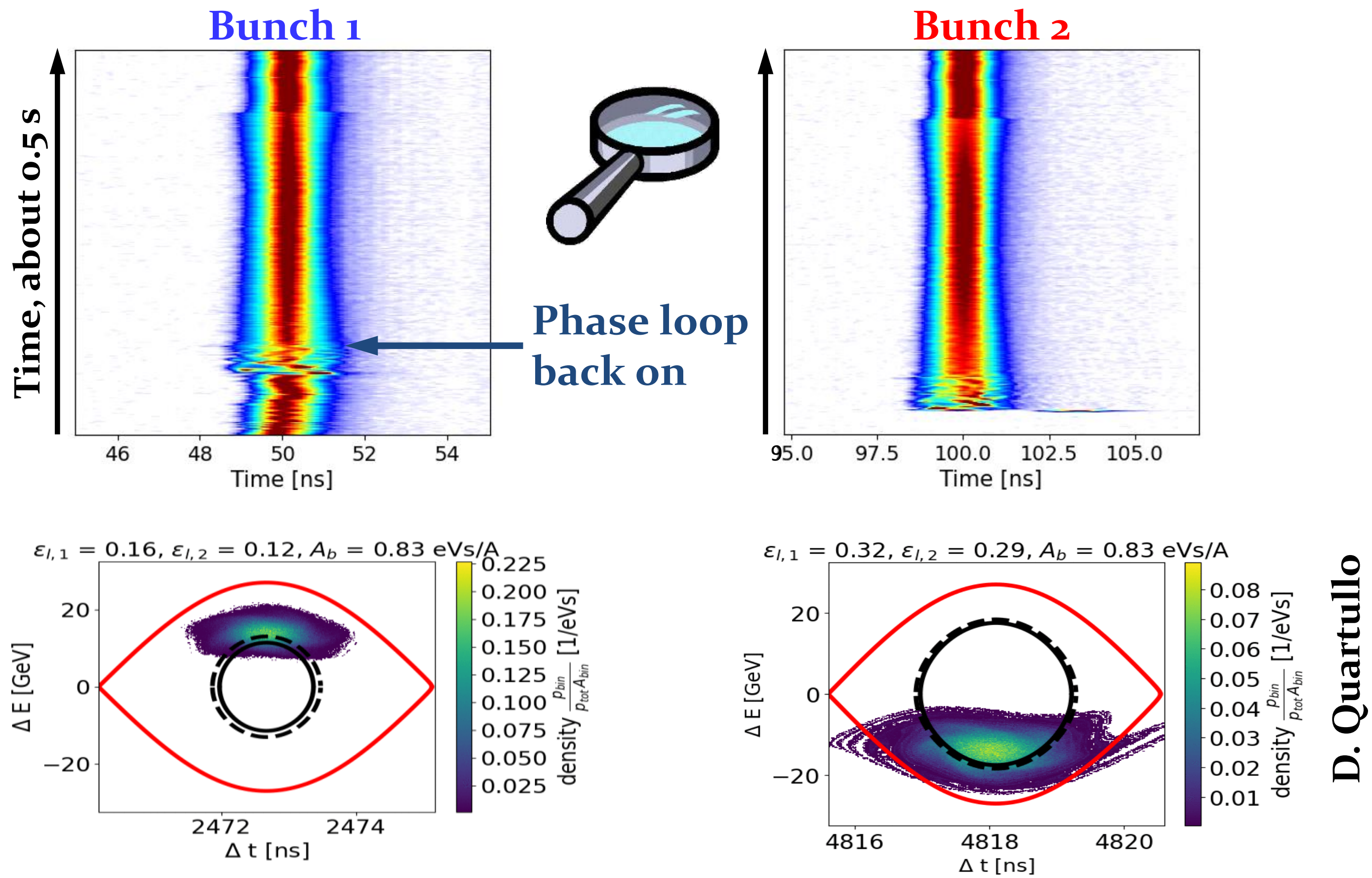




100 ns → 50 ns bunch spacing reduction



Example: interleaved slip-stacking



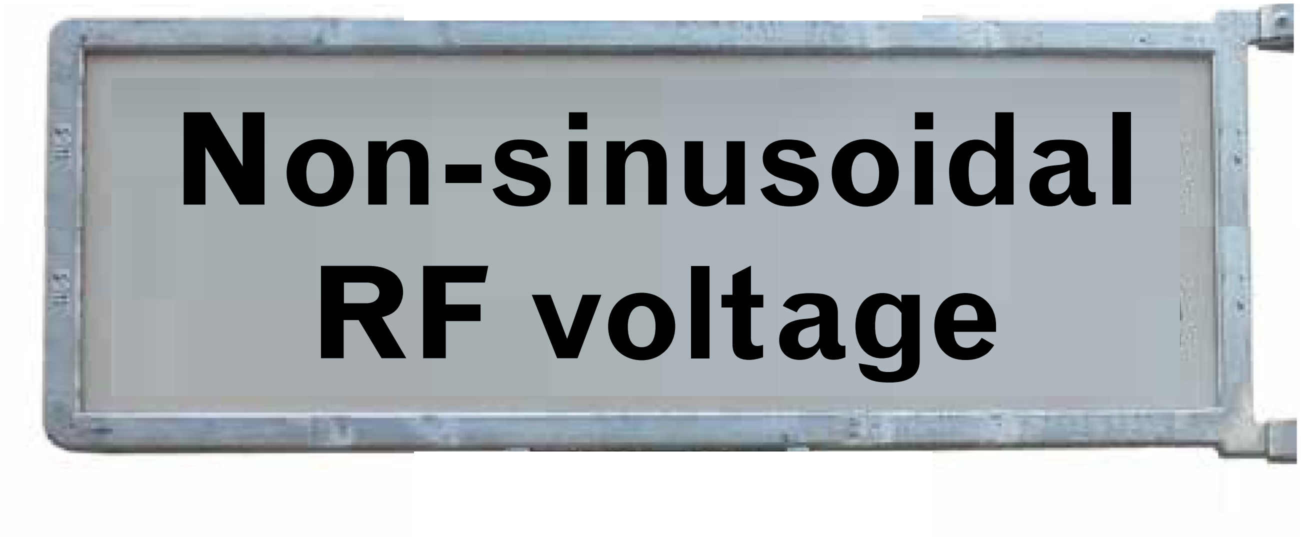
Strengths and weaknesses

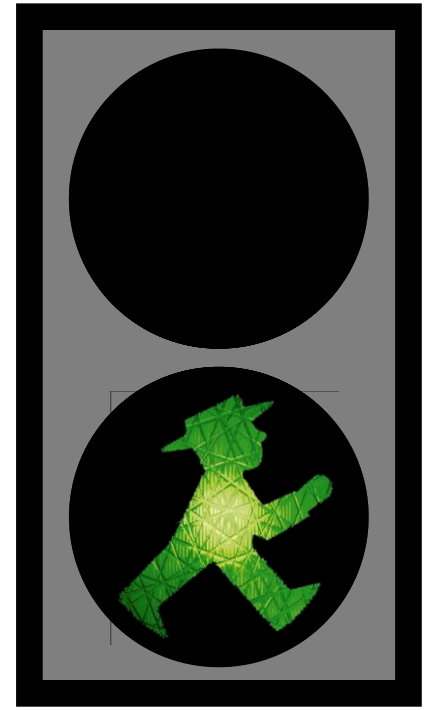
\+ Powerful stacking scheme

\+ Partial scheme combined with injection and extraction

\- Large emittance growth at recapture

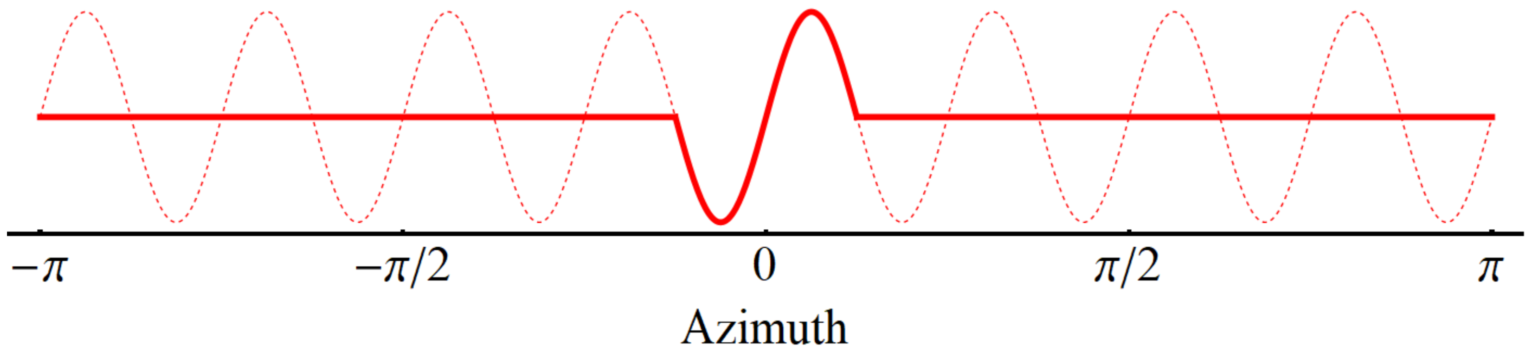
\- Complex implementation: modulation, two RF frequencies





Isolated and barrier bucket

Non-sinusoidal RF voltage



- Active RF for one only one period
- One RF bucket per pulse

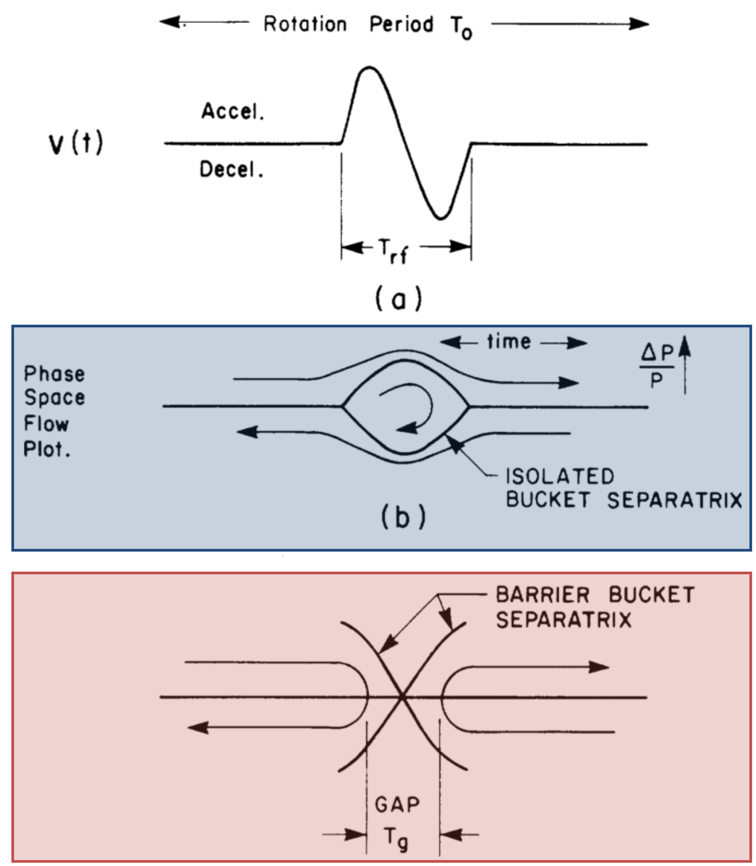
→ Isolated bucket

- Switch polarity of RF

→ Barrier bucket

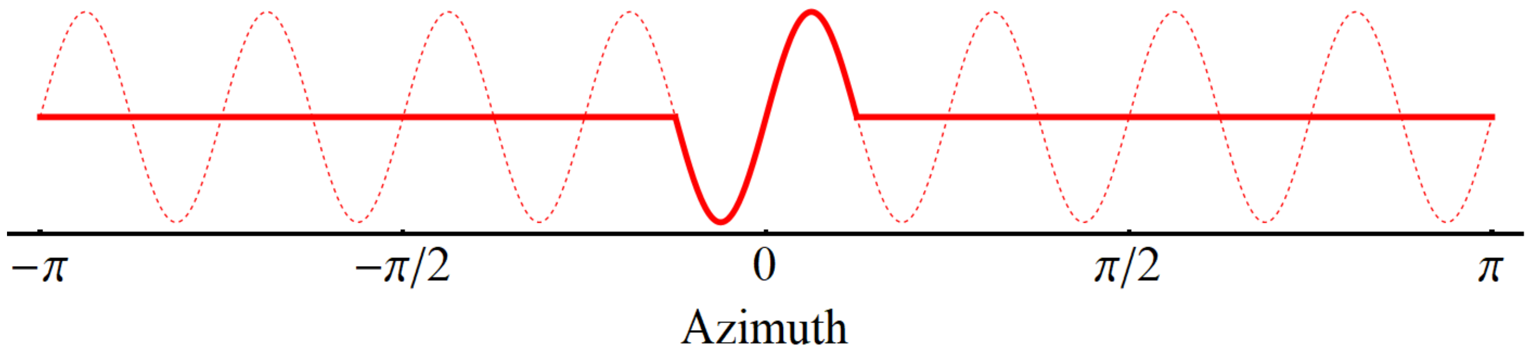
→ No RF between pulses: coasting beam in a bucket

→ Enormous flexibility to move barriers in phase

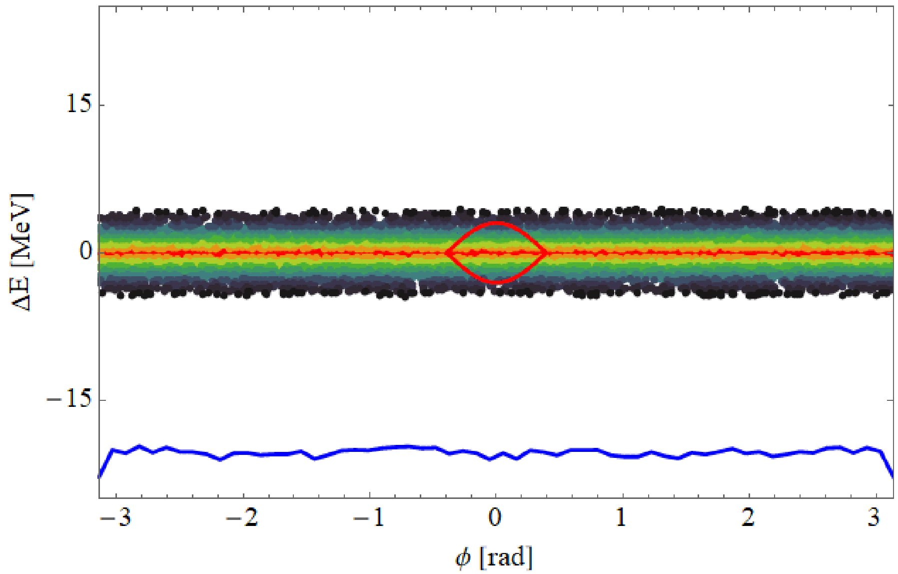


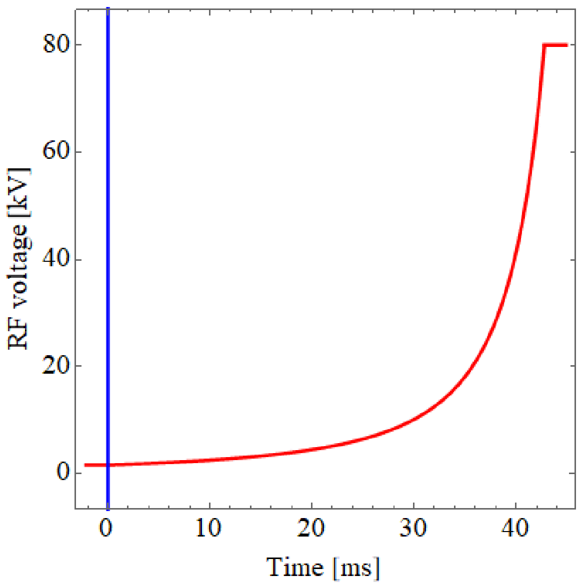
J. E. Griffin et al., PAC'83
A. G. Ruggiero, CERN-68-22

Isolated bucket



→ **RF capture into an isolated bucket**



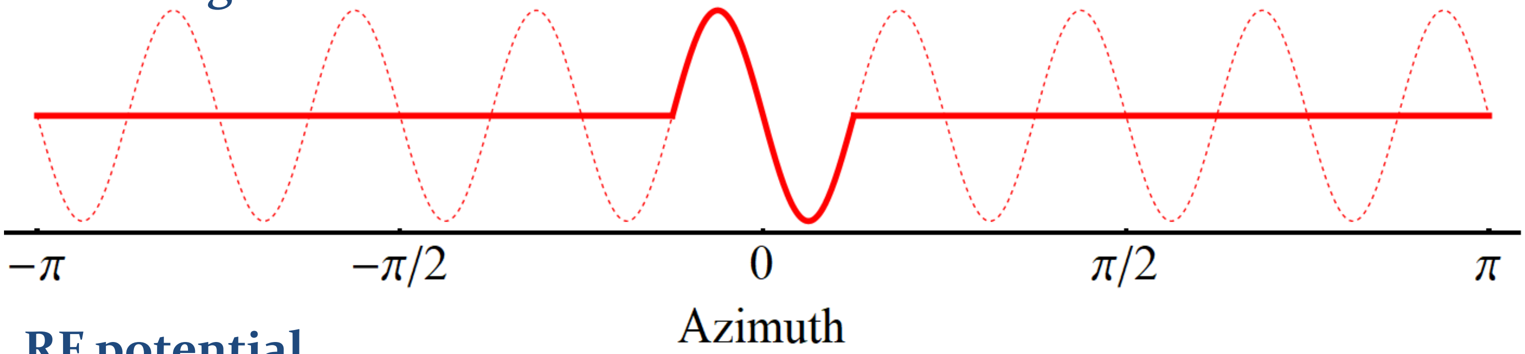


→ **Continuous capture from coasting beam**

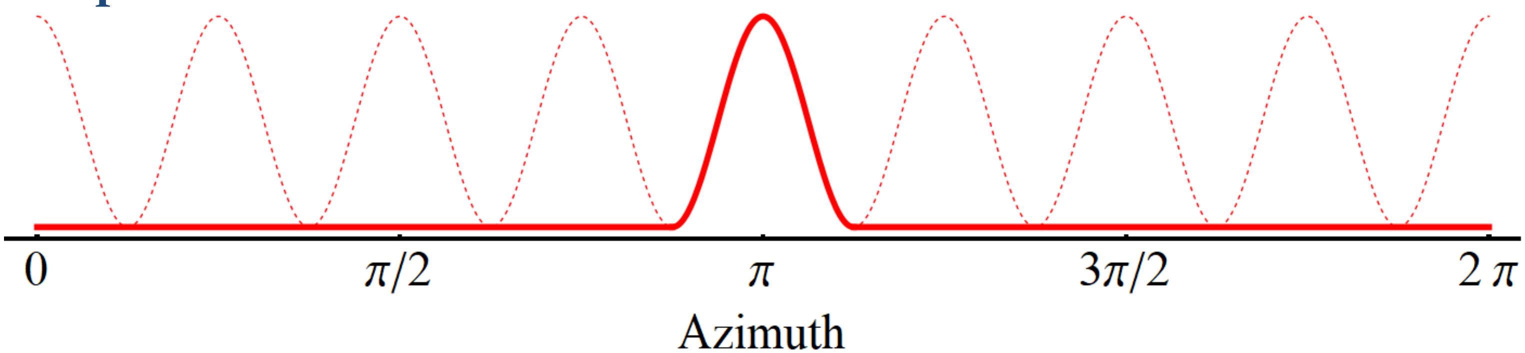
→ **Little practical application until today**

Barrier bucket

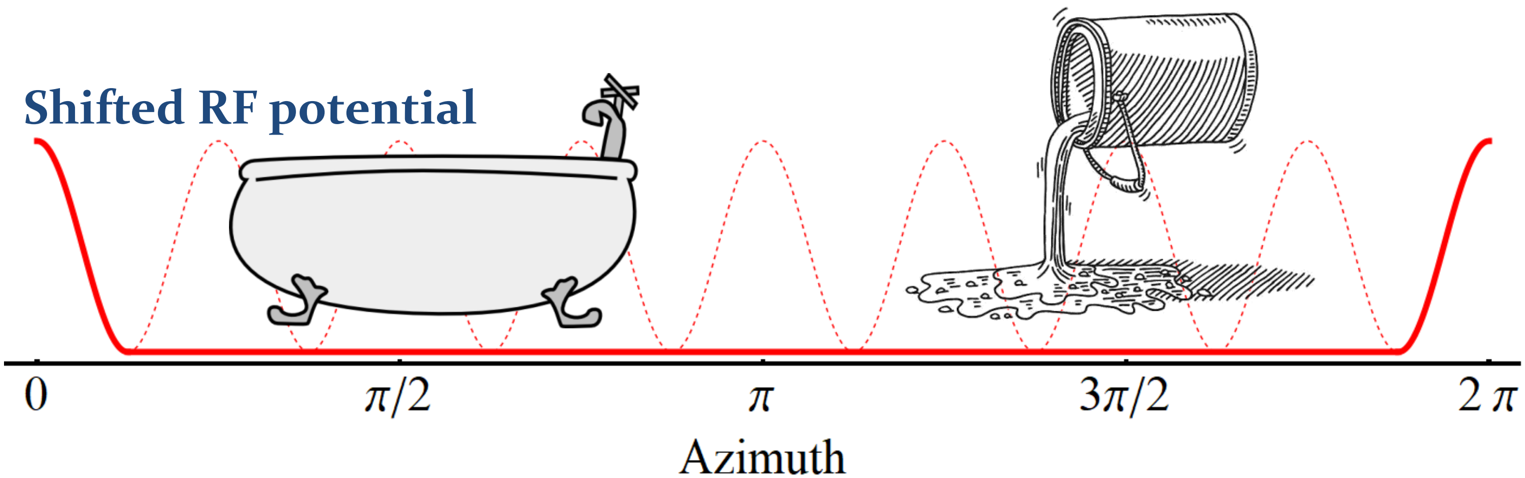
RF voltage



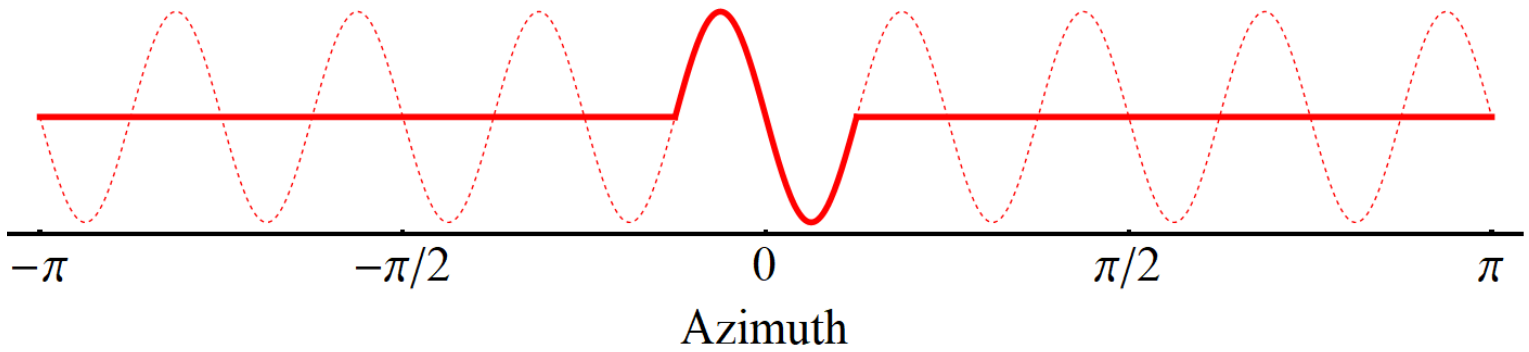
RF potential



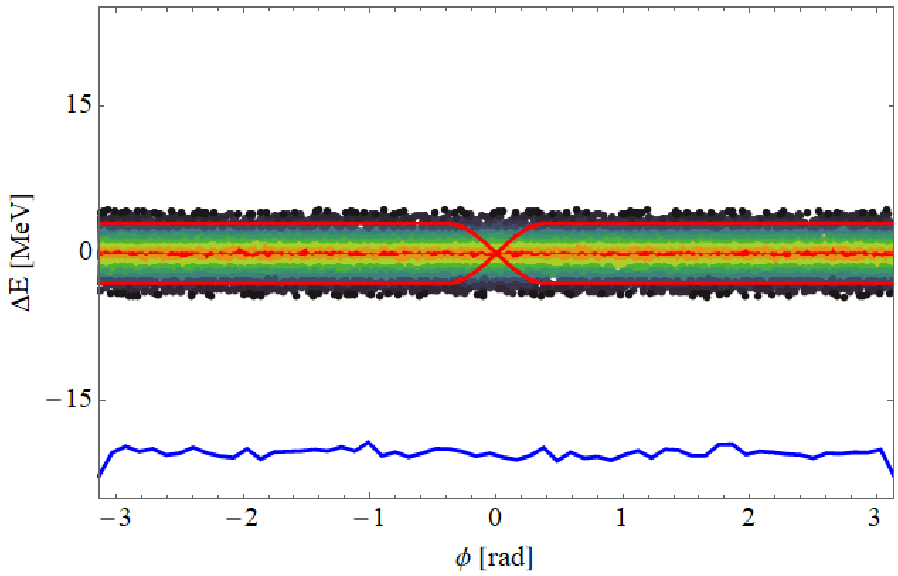
Shifted RF potential

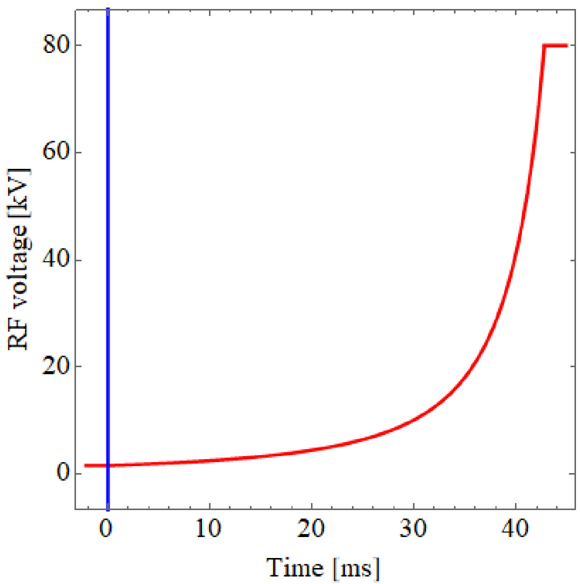


Barrier bucket



→ **RF capture into a barrier bucket**



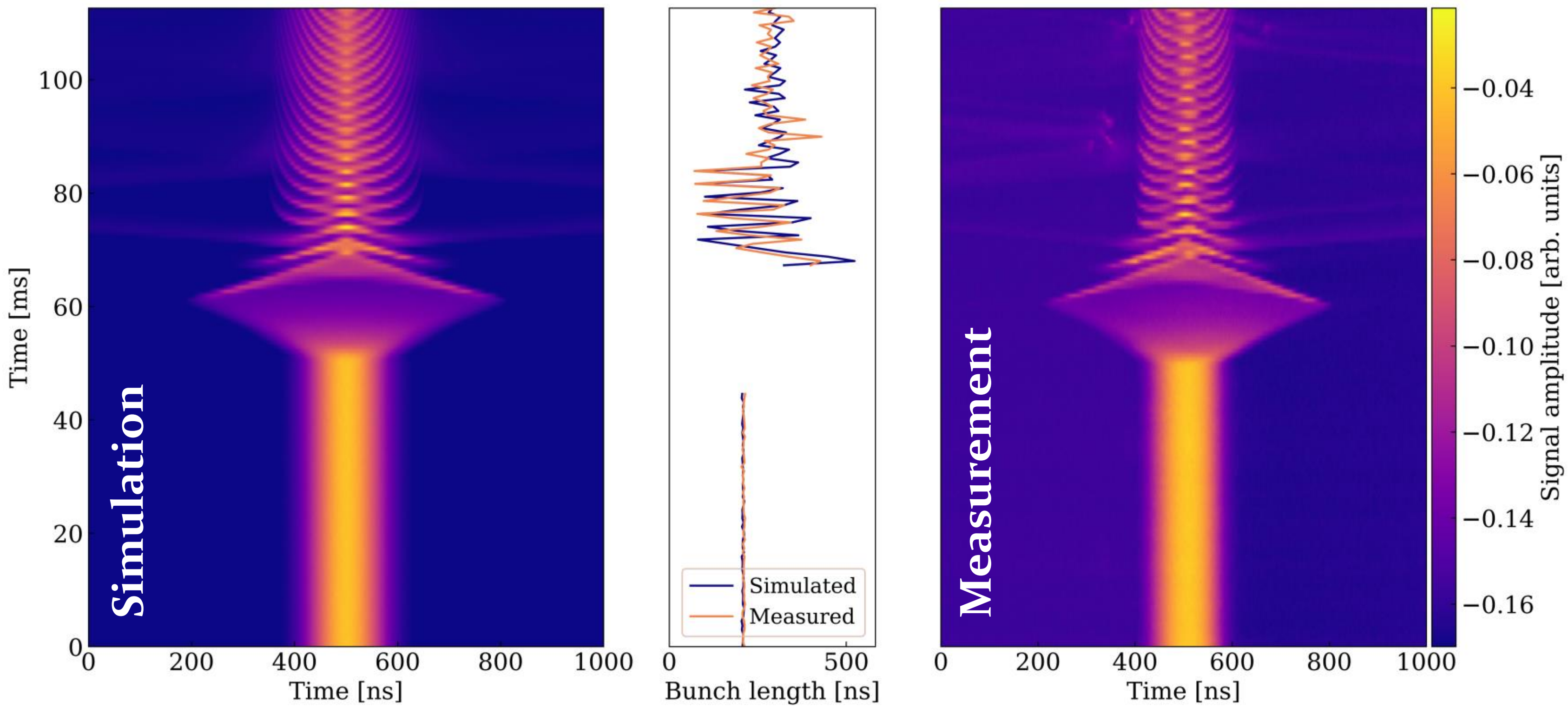


→ **Combine advantages of continuous and bunched beam**

→ **Most simple application: Generate particle free gap**

Barrier-bucket application in CERN PS

- Compress or stretch bunch by moving phase of RF barriers



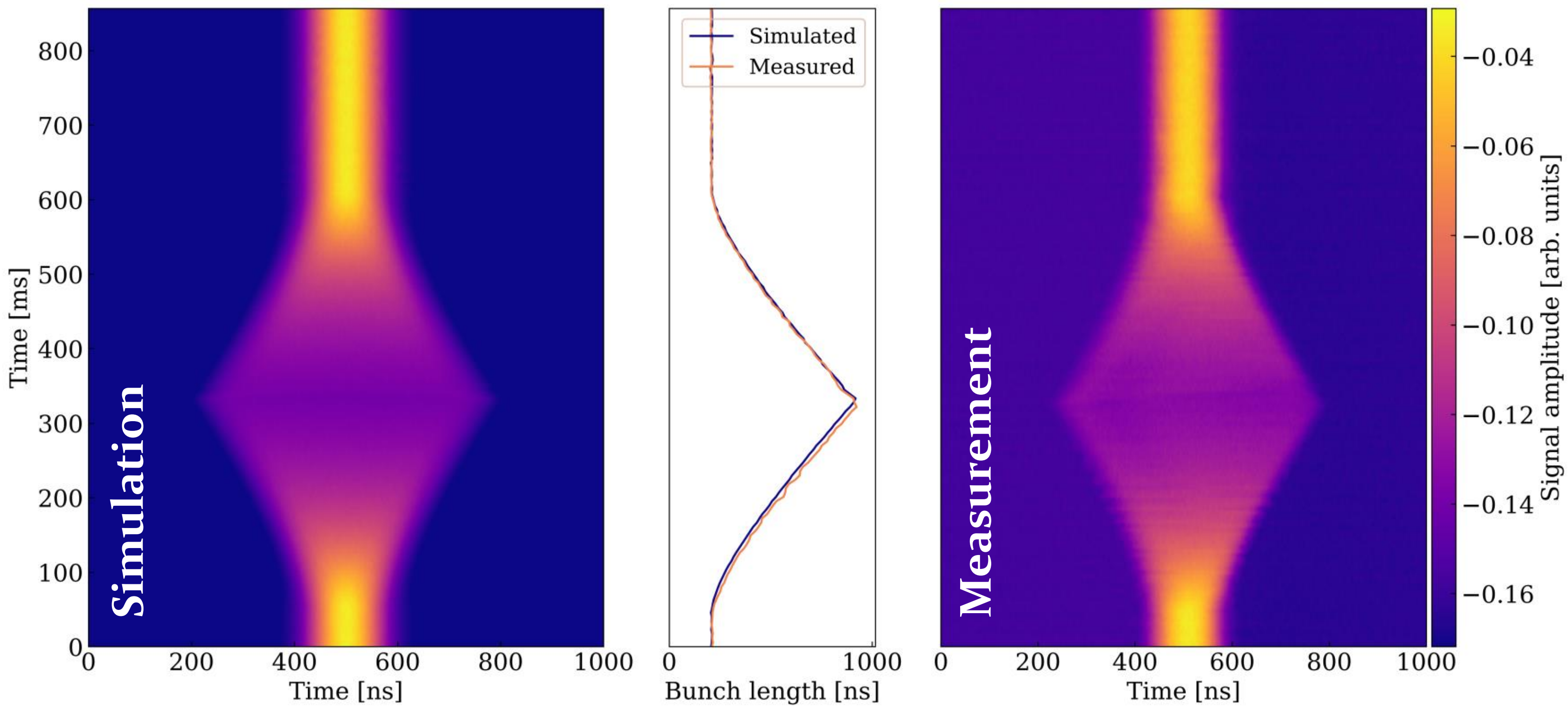
→ Perfect bunch length manipulation, but slow

→ Bunch oscillations very well predicted by simulations

M. Vadai

Barrier-bucket application in CERN PS

- Compress or stretch bunch by moving phase of RF barriers

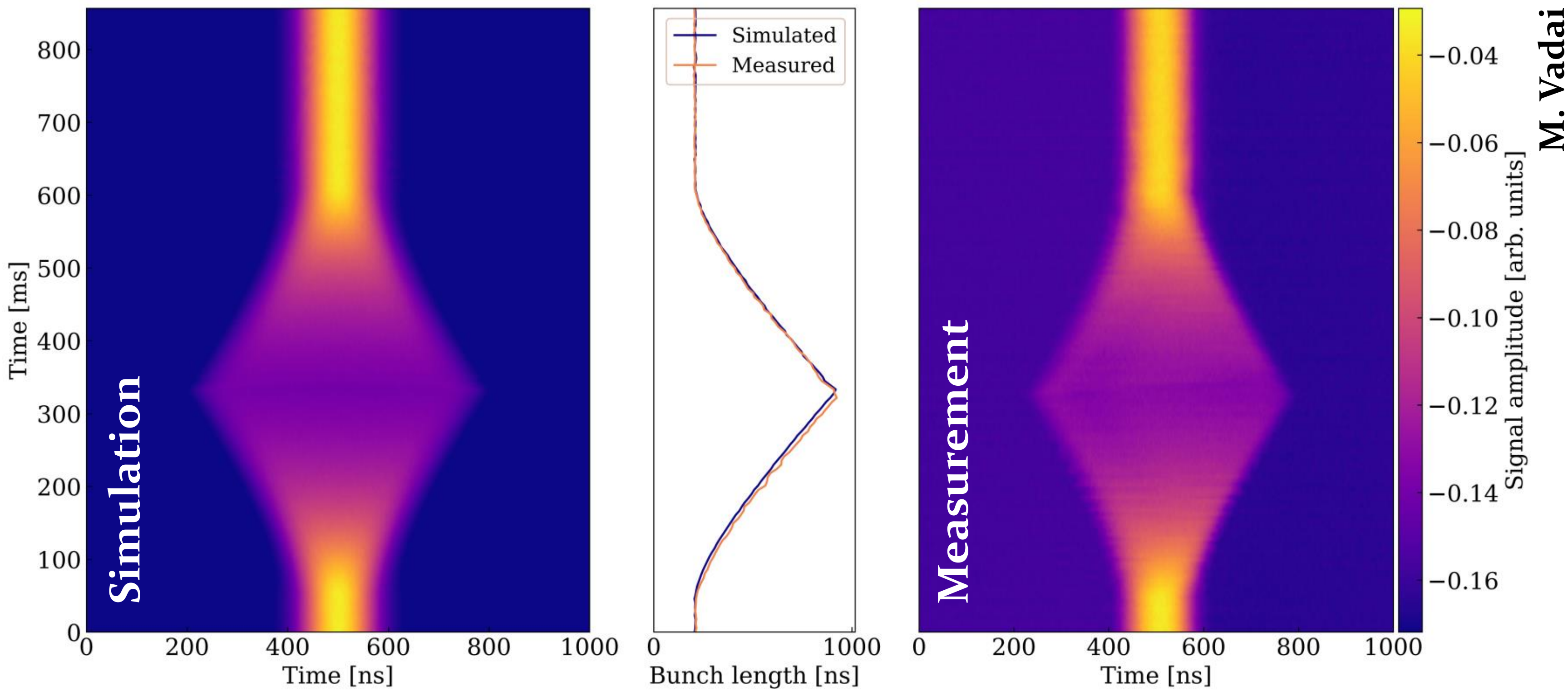


→ **Perfect bunch length manipulation**

M. Vadai

Barrier-bucket application in CERN PS

- Compress or stretch bunch by moving phase of RF barriers



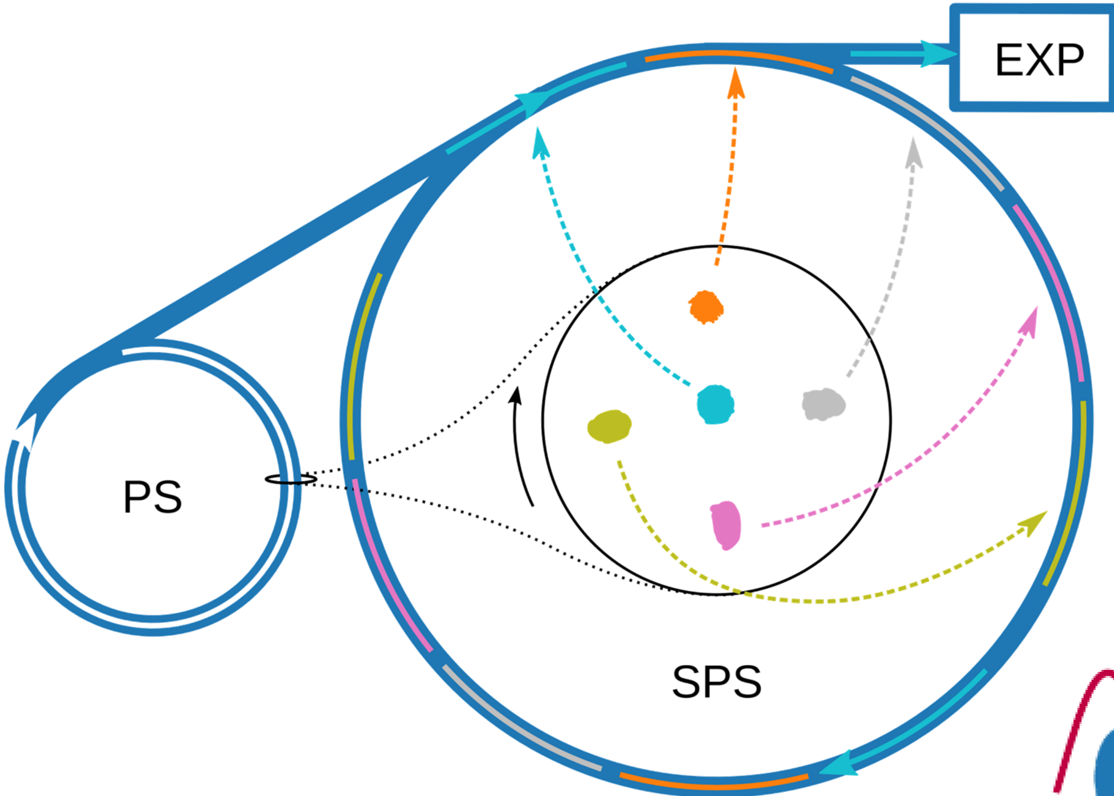
→ **Strengths and weaknesses**

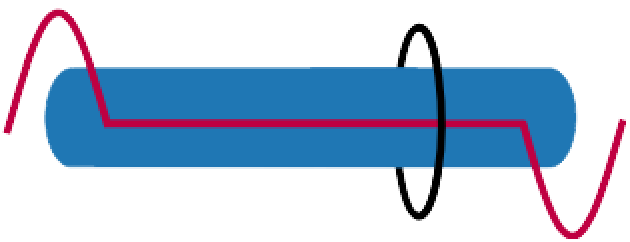
+ Very flexible, control of bunch length and peak current

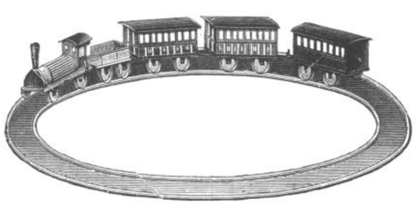
- Difficult to generate large RF voltage with wide-band RF system
- Compensation of beam loading at high intensity

Loss reduction with barrier-bucket transfer

- RF manipulation allows generating a gap for extraction kicker





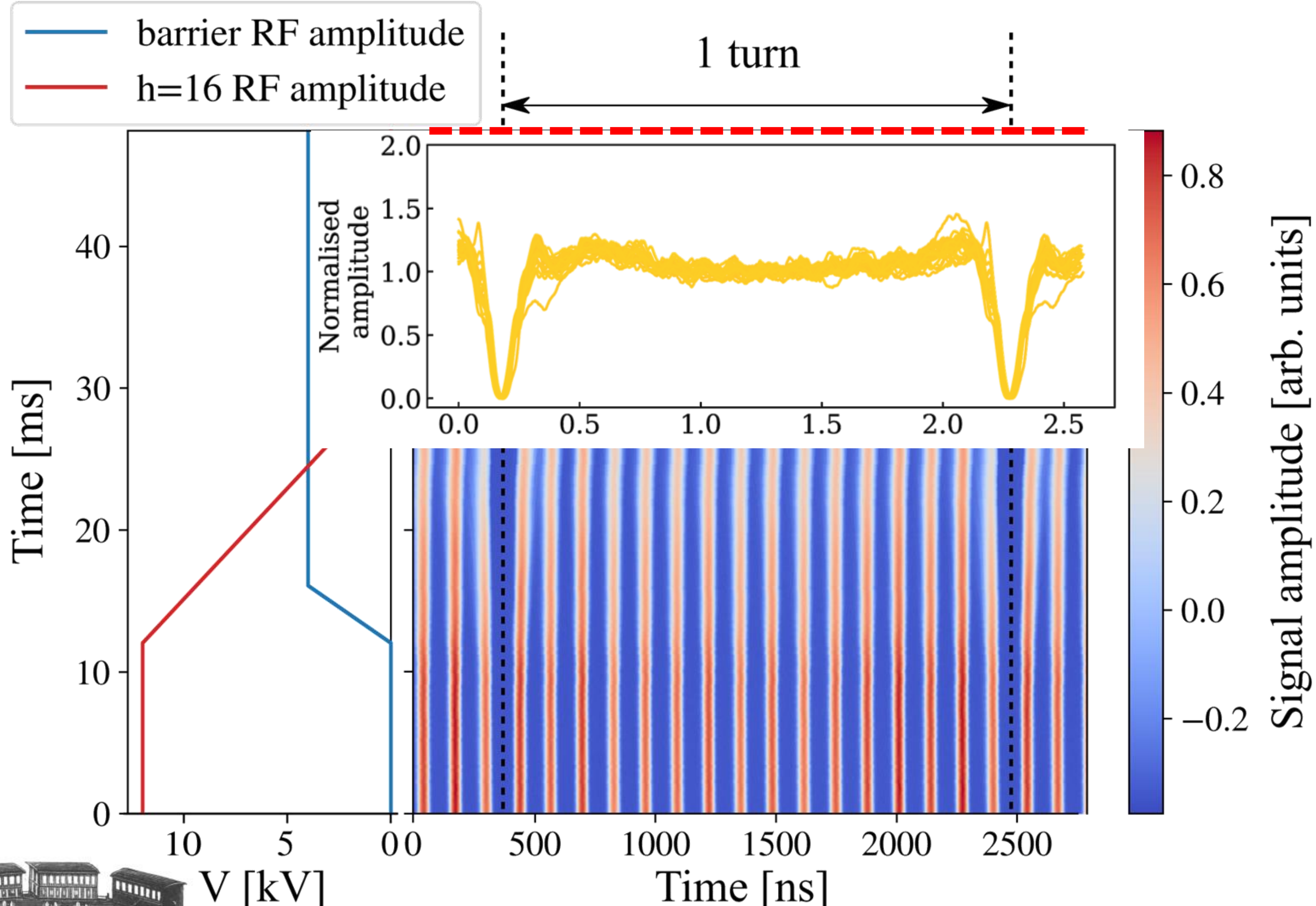


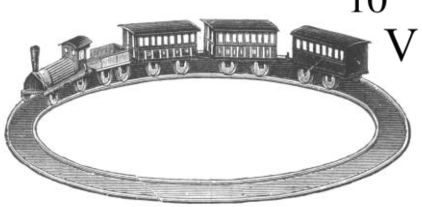
→ **Barrier-bucket to slightly compress bunch train**

M. Vadai

Loss reduction with barrier-bucket transfer

- **RF manipulation to extract (almost) un-bunched beam**





→ **Reduced beam loss during kicker rise**

→ **In operation for SPS fixed-target beam**

M. Vadai

Momentum mining at Fermilab

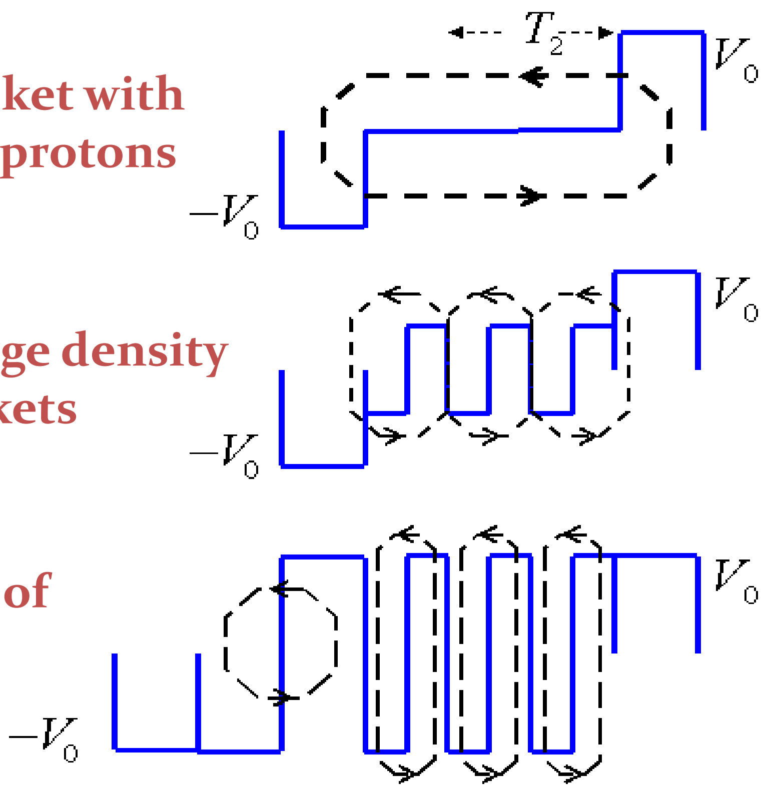
- **Mining of antiprotons at large longitudinal phase space density**

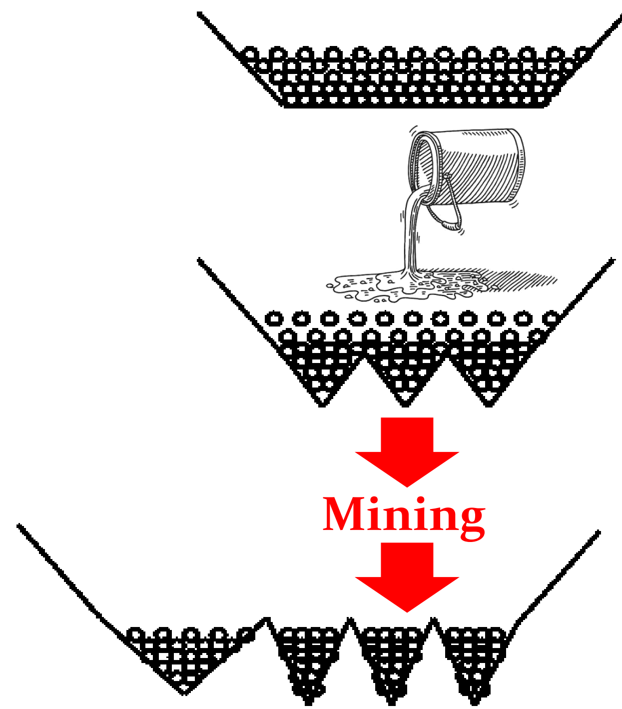
→ **Developed at Fermilab for proton-antiproton collider Tevatron**

RF voltage and separatrices of buckets

RF potential: $\int V_{RF} dt$ and Occupied phase space

1. **Barrier bucket with cooled antiprotons**
2. **Capture large density in sub-buckets**
3. **Separation of low energy spread**





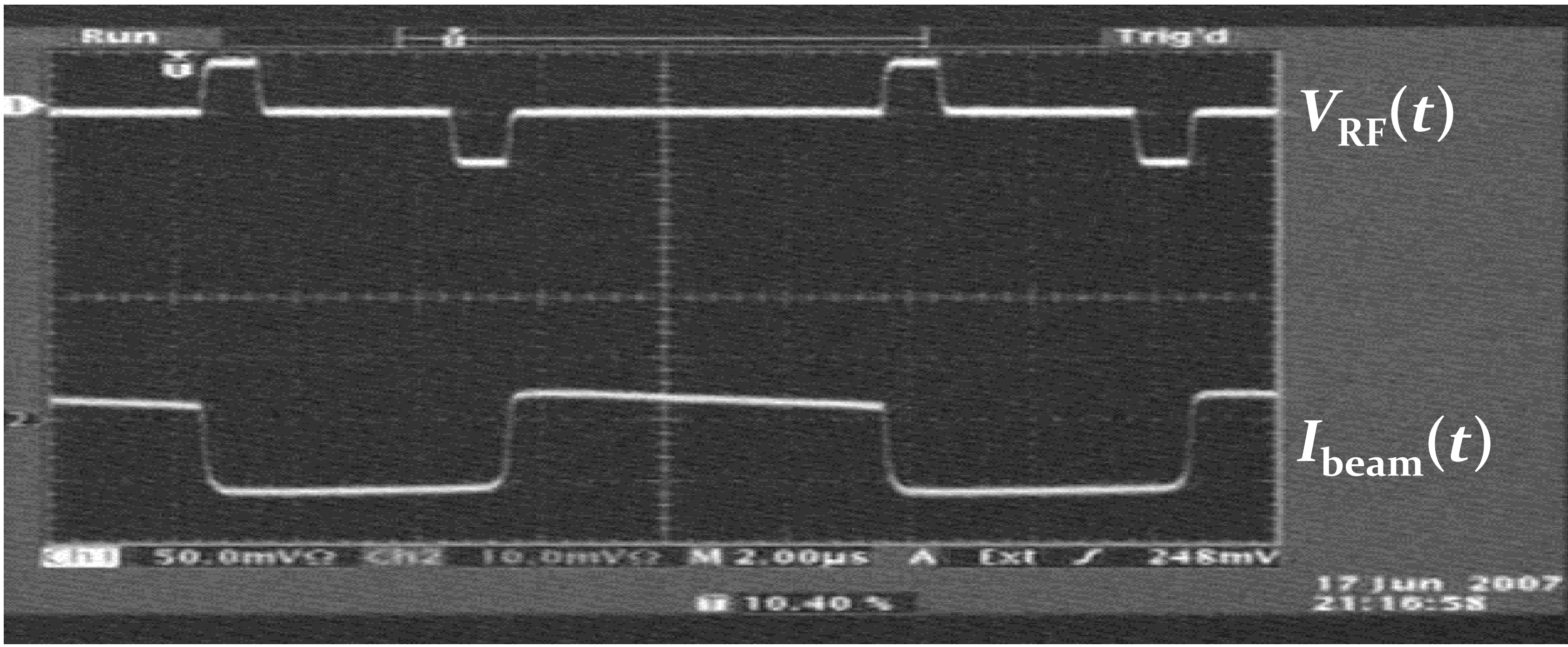
C. Bhat

Momentum mining Fermilab

- **Mining of antiprotons at large longitudinal phase space density**

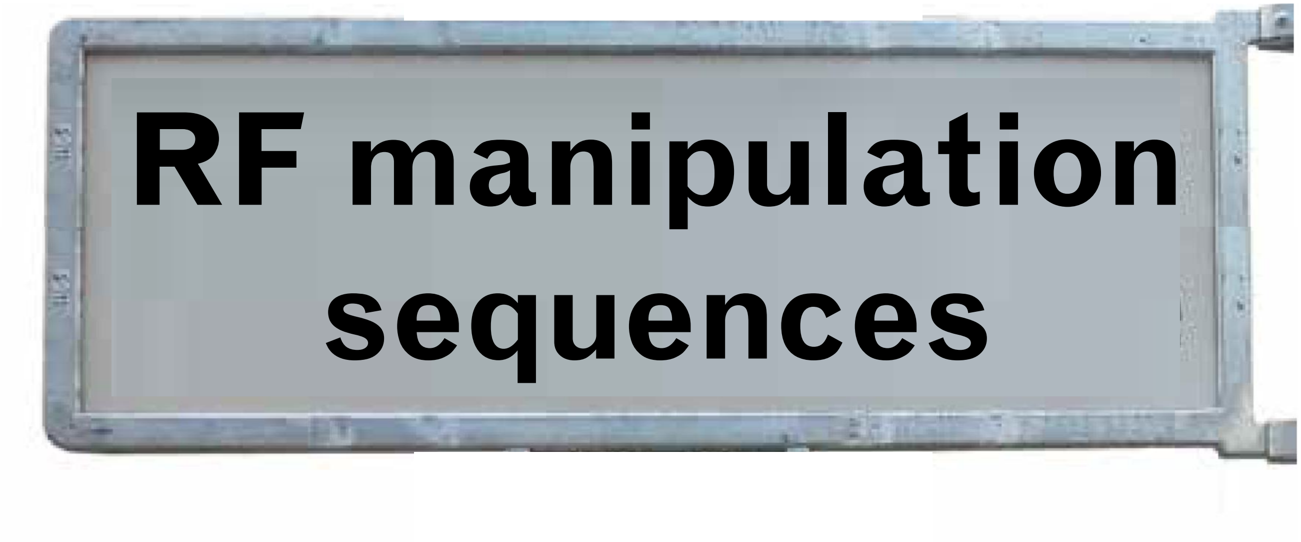
→ Developed at Fermilab for proton-antiproton collider Tevatron

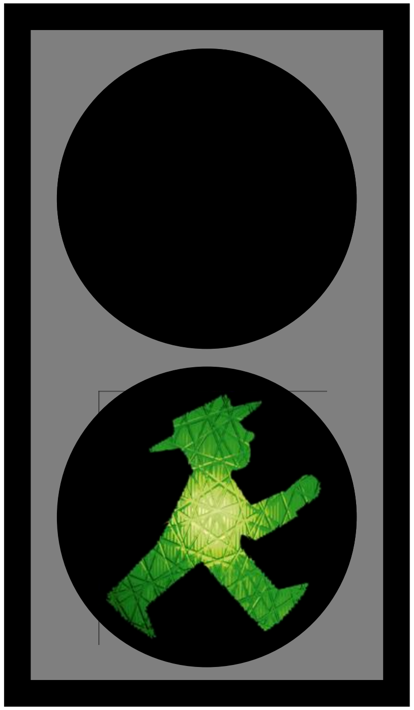
Momentum mining in action in the Fermilab Recycler



C. Bhat

→ One of the most evolved RF manipulation ever performed!

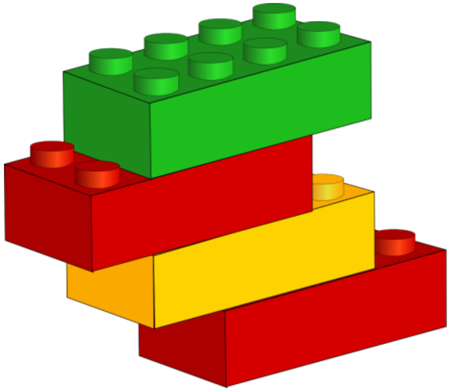


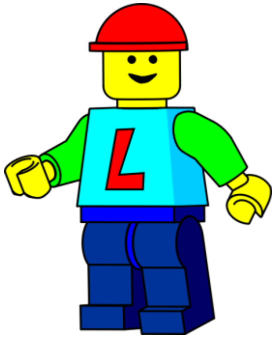


Example: BCMS beam at CERN

RF manipulation sequences

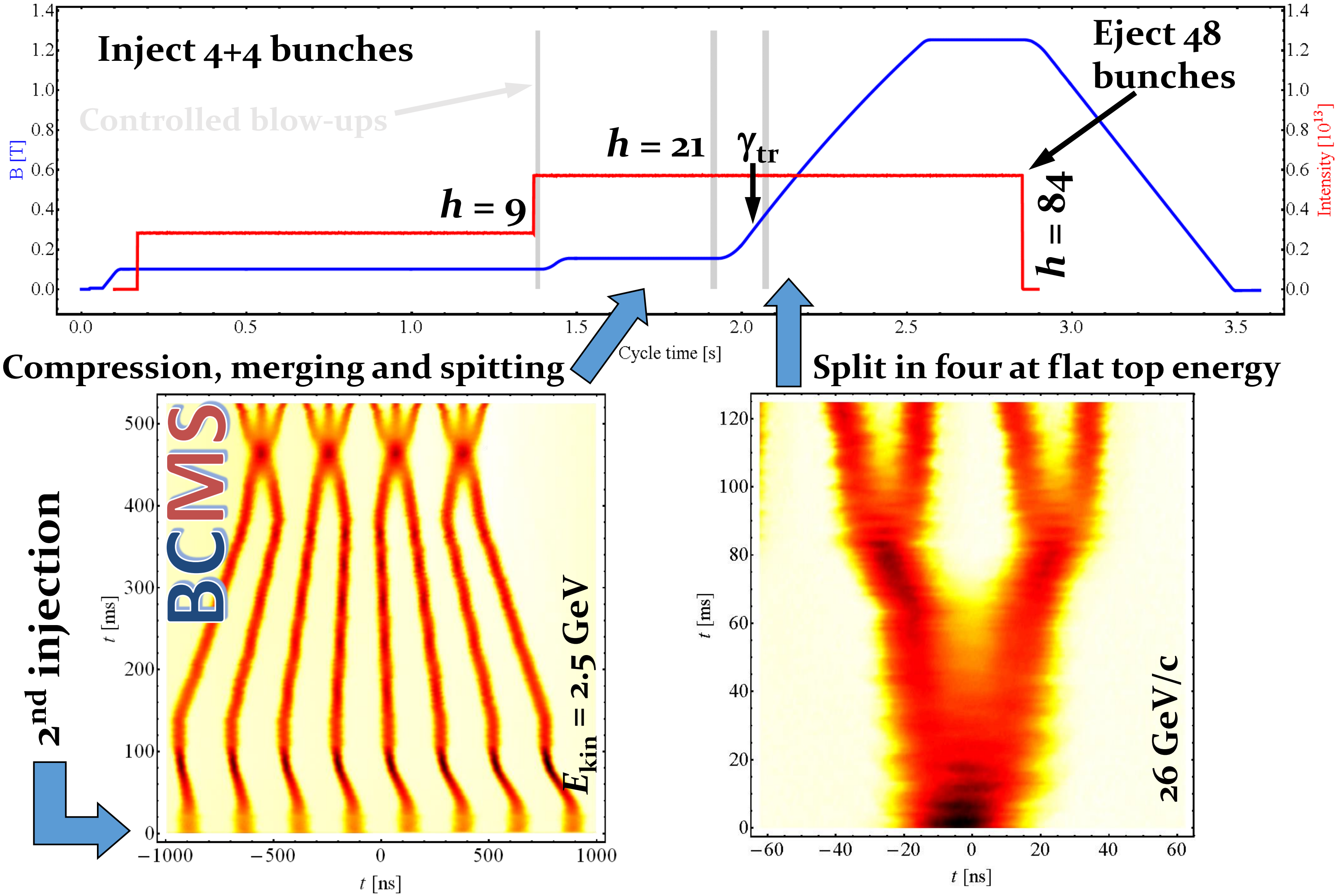
- **Single RF manipulation often not sufficient to make a beam**





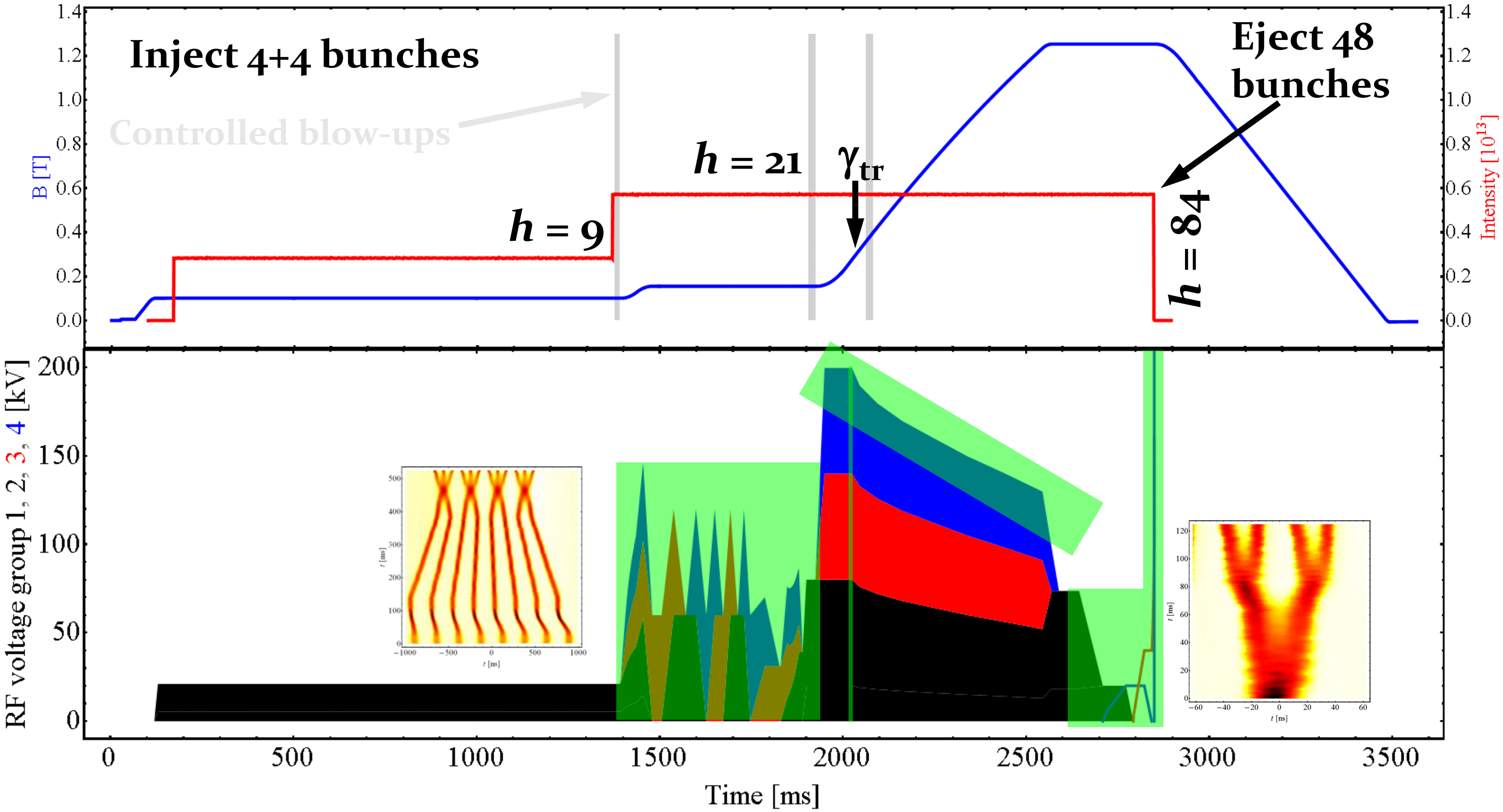
→ Real-life RF manipulations sequence of basic building blocks

Example: LHC-type beam in the CERN PS



- RF manipulations control all longitudinal parameters

Example: LHC-type beam in the CERN PS



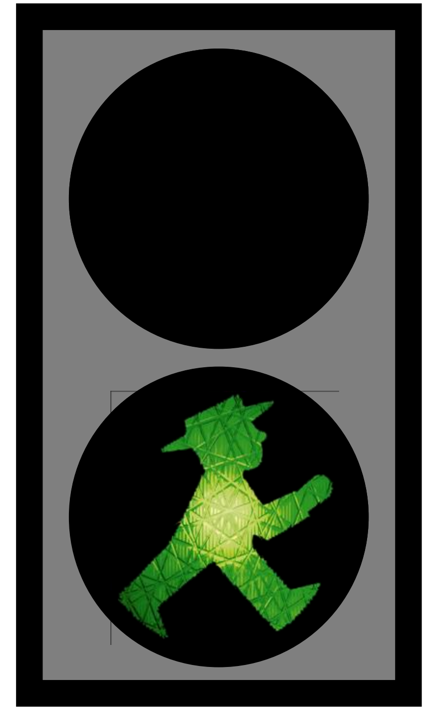
→ RF manipulation from 8 bunches in *h* = 9 to 12 in *h* = 21

→ Transition crossing

→ RF voltage reduction during acceleration

→ Splitting at the flat-top

→ Bunch shortening (rotation) before extraction



Design and implementation

Example: Ions with 75 ns bunch spacing

Question: Can the Proton Synchrotron produce ion bunches with a spacing of 75 ns for LHC?

$^{139}Xe^{39+}$ → $^{208}Pb^{54+}$

→ **Needs an RF manipulation!**

Step 1: Check frequency ranges of existing RF systems

- **75 ns corresponds to h = 28 (13.25 MHz)**
  - ✓ **Within range of existing 13.3/20 MHz cavities**
- **Ions for PS injected from Low Energy Ion Ring (LEIR)**

  → $2\pi R_{LEIR} = 2\pi R_{PS}/8 \rightarrow 8 \times h_{LEIR} = 2\pi R_{PS}$

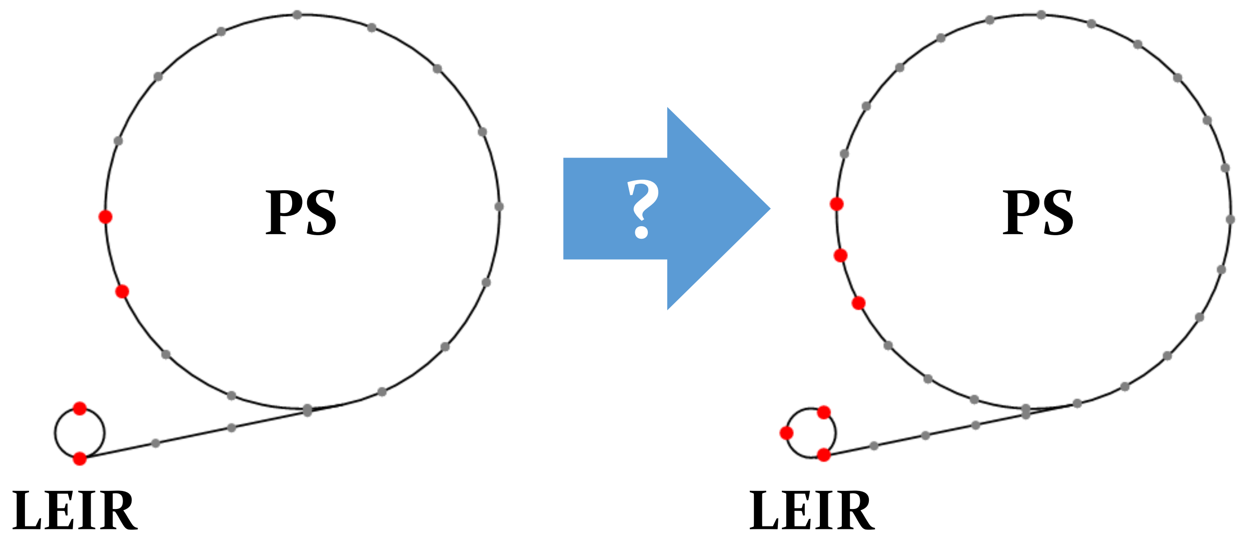
  → **Standard transfer of two bunches:** $h_{LEIR} = 2 \rightarrow h_{PS} = 16$

Step 1: Check of frequencies for 3 bunches

- Ions for PS injected from Low Energy Ion Ring (LEIR)

  → $2\pi R_{\mathrm{LEIR}} = 2\pi R_{\mathrm{PS}}/8 \rightarrow 8 \times h_{\mathrm{LEIR}} = 2\pi R_{\mathrm{PS}}$

  → Standard transfer of two bunches: $h_{\mathrm{LEIR}} = 2 \rightarrow h_{\mathrm{PS}} = 16$



- LEIR: $h_{\mathrm{LEIR}} = 2 \rightarrow 3$
- PS: $h_{\mathrm{PS}} = 16 \rightarrow 24$

} $f_{\mathrm{RF}} = 3.2$ MHz → 4.8 MHz

✓ Within frequency range of LEIR and PS main RF systems

Step 1: Harmonic number sequence

- **Injection:** $h = 24$, $f_{rev} = 202$ kHz, $f_{RF} = 4.8$ MHz

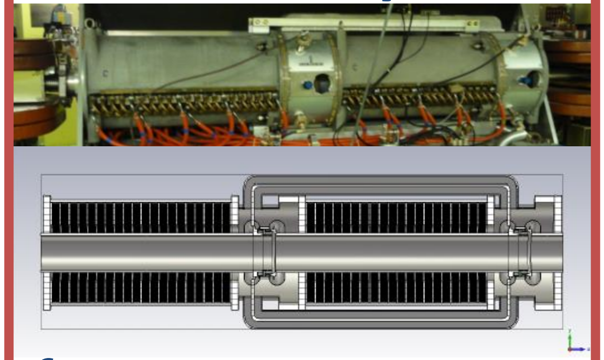
RF manipulation?

- **Flat-top:** $h = 28$, $f_{rev} = 473$ kHz , $f_{RF} = 13.25$ MHz

Step 1: Harmonic number sequence

- **Injection:** $h = 24, f_{rev} = 202$ kHz, $f_{RF} = 4.8$ MHz

PS main RF system



f_{RF} = 2.8 MHz to 10 MHz

~~Batch compression $h = 24 \rightarrow 28$?~~

- **Flat-top:** $h = 28$, $f_{rev} = 473$ kHz , $f_{RF} = 13.25$ MHz

→ Upper frequency too high: 24 · 473 kHz = 11.4 MHz > 10 MHz

→ Maximum harmonic up to flat-top: $h = 21$

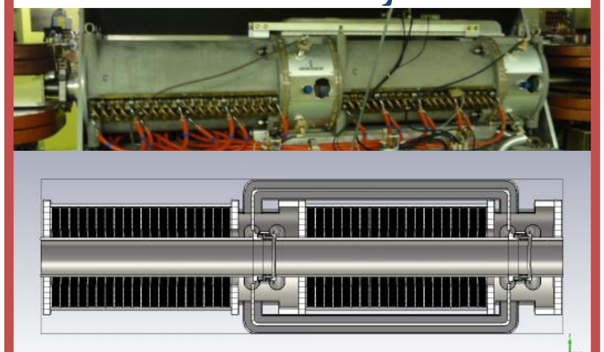
→ Introduce batch expansion h = 24 → 21 at intermediate energy

Step 1: Harmonic number sequence

- **Injection:**

h = 24, f_{rev} = 202 kHz, f_{RF} = 4.8 MHz

PS main RF system



f_{RF} = 2.8 MHz to 10 MHz

1. **Acceleration to intermediate plateau energy at $h = 24$**
2. **Batch expansion $h = 24 \rightarrow 21$**
3. **Acceleration to flat-top at $h = 21$**
4. **Batch compression $h = 21 \rightarrow 28$**

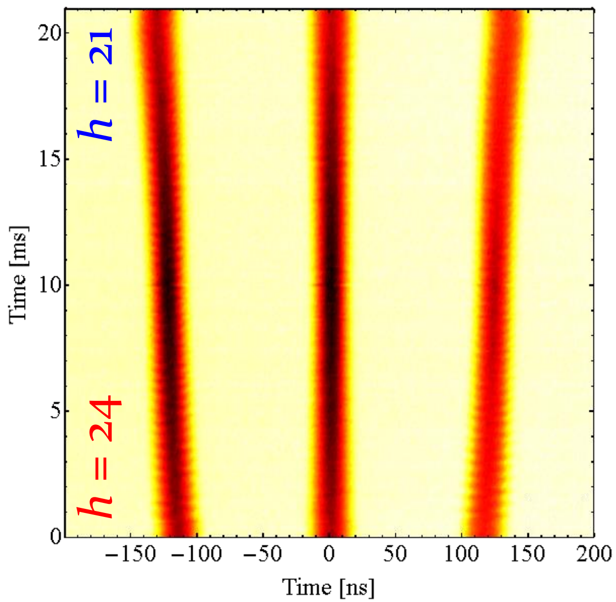
- **Flat-top:**

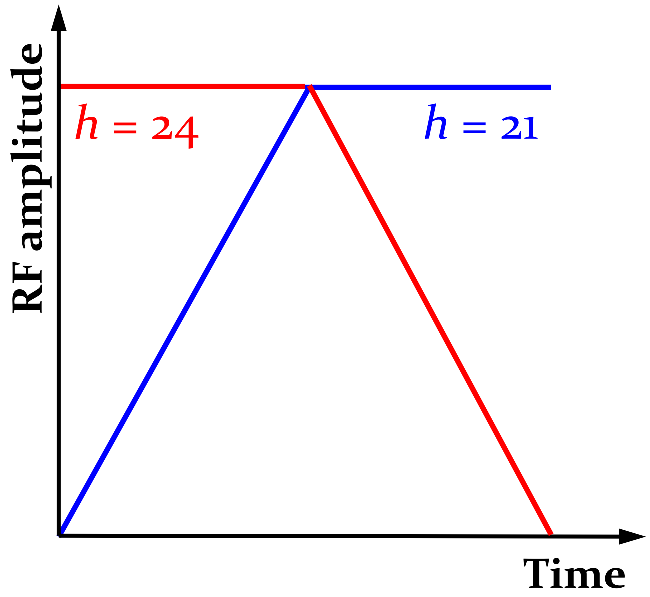
h = 28 , f_{rev} = 473 kHz , f_{RF} = 13.25 MHz

✓ **Sequence respects all frequency limitations of RF systems**

Step 2: Check bucket evolution

2. **Batch expansion** $h = 24 \rightarrow 21$
   - ✓ **Large voltage of main RF system:** $\Sigma V_{RF} = 200$ **kV**





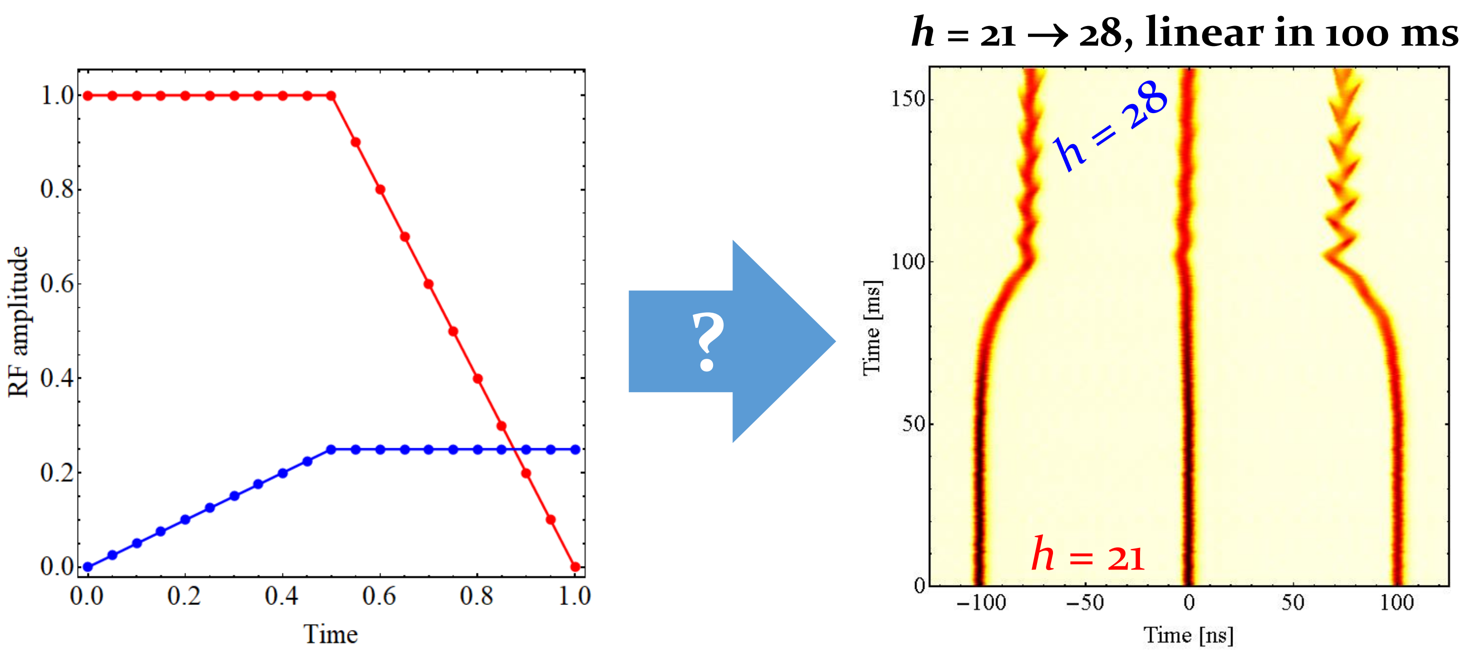
→ **Huge bucket areas**

→ **Simple linear voltage functions are sufficient**

Step 2: Check bucket evolution

4. **Batch compression** ***h*** **= 21 → 28**
   - **Asymmetric voltage capabilities:** ***h*** **= 21 up to 200 kV**
     h **= 28 only 20 kV**

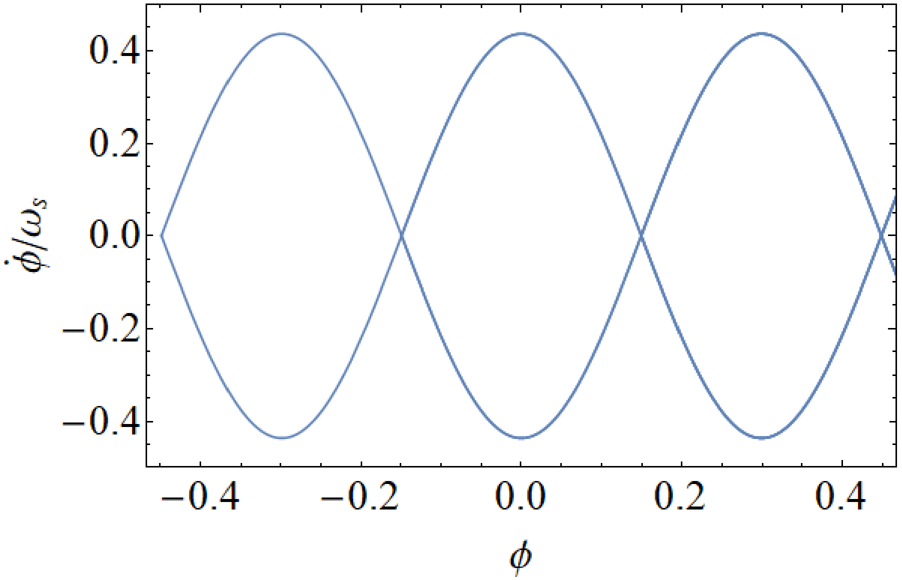
→ Compromise: handover 80 kV → 20 kV



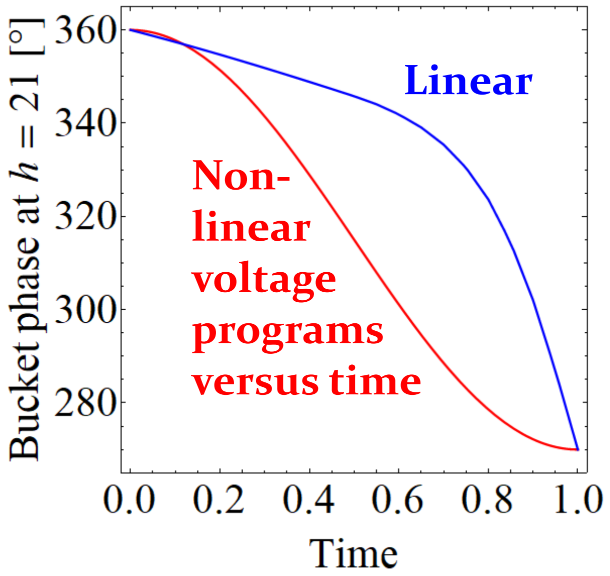
Step 2: Check bucket evolution

4. **Batch compression $h = 21 \rightarrow 28$**
   - **Asymmetric voltage capabilities:** $h = 21$ up to 200 kV
     $h = 28$ only 20 kV

$\rightarrow$ Compromise: handover 80 kV $\rightarrow$ 20 kV



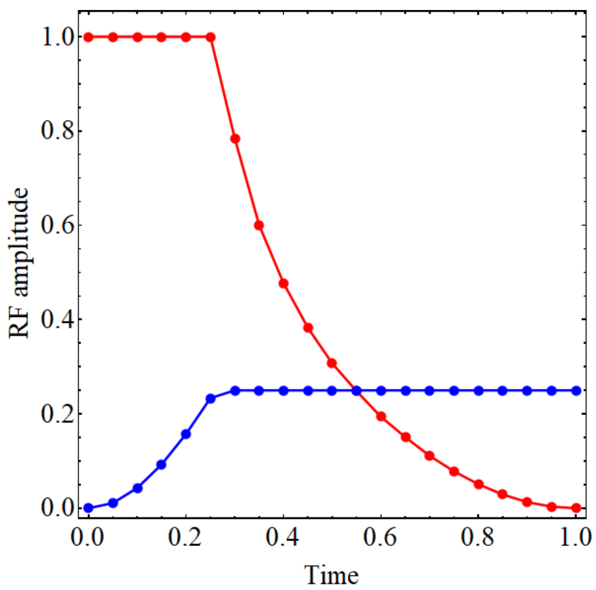
Phase of outer buckets



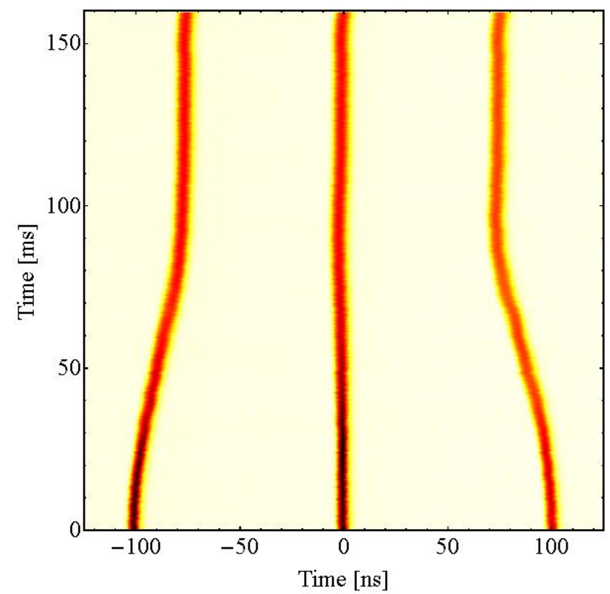
Step 2: Check bucket evolution

4. **Batch compression $h = 21 \rightarrow 28$**
   - **Different voltage capabilities:** $h = 21$ **up to 200 kV**; $h = 28$ **only 20 kV**

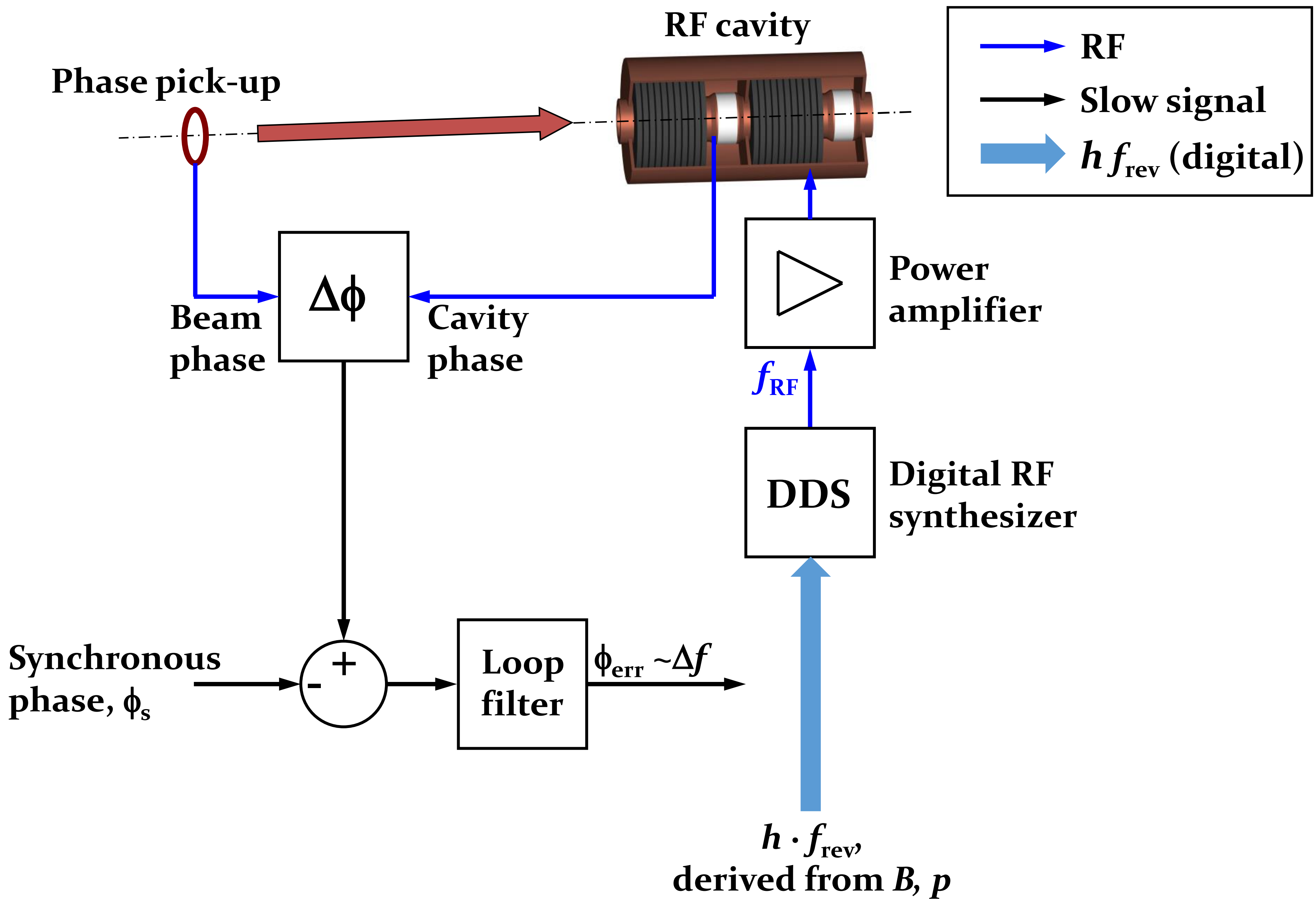
$\rightarrow$ Compromise: handover 80 kV $\rightarrow$ 20 kV



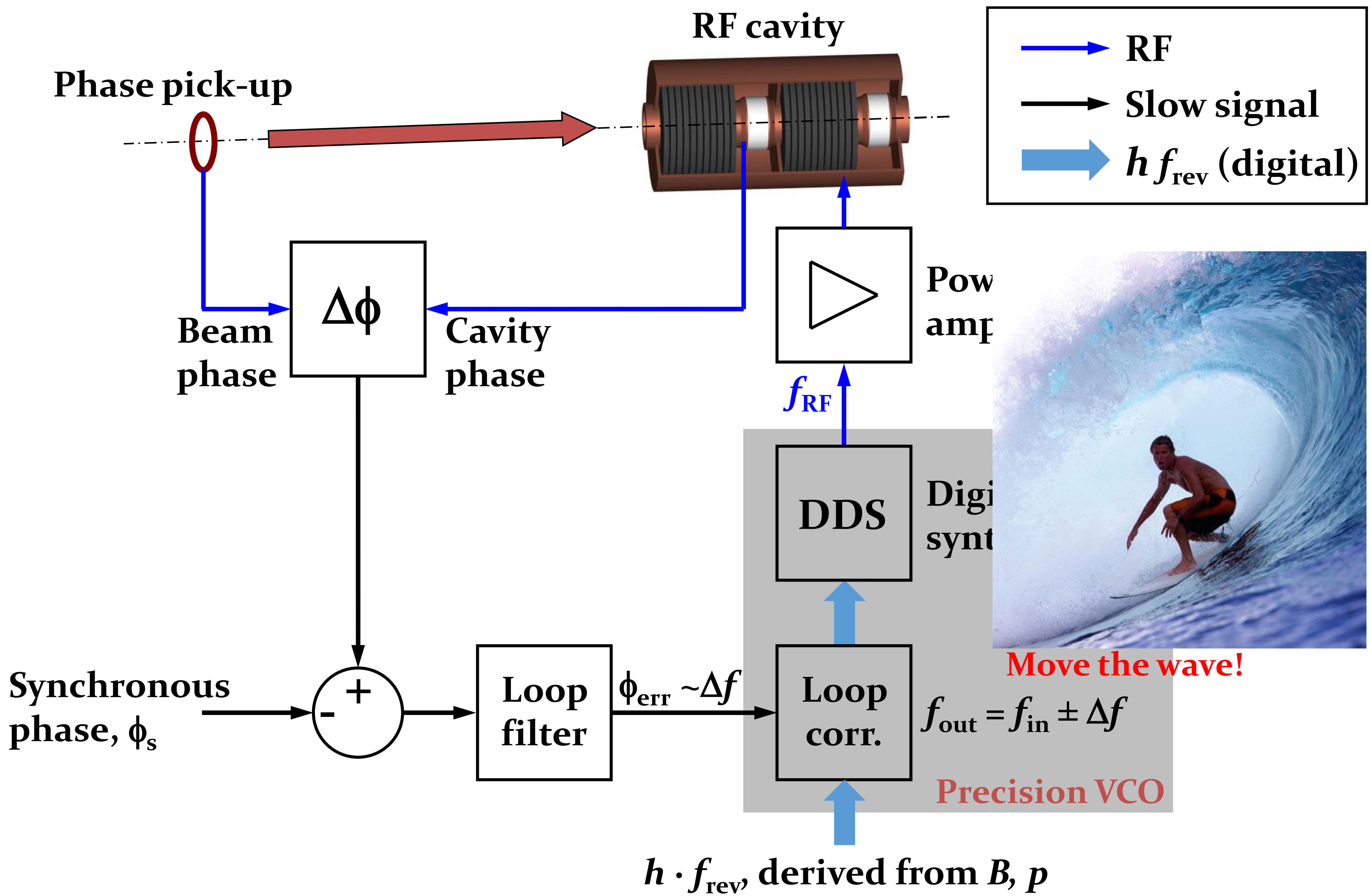
$h = 21 \rightarrow 28$, non-linear in 100 ms



Step 3: Implementation with beam phase loop



Step 3: Implementation with beam phase loop



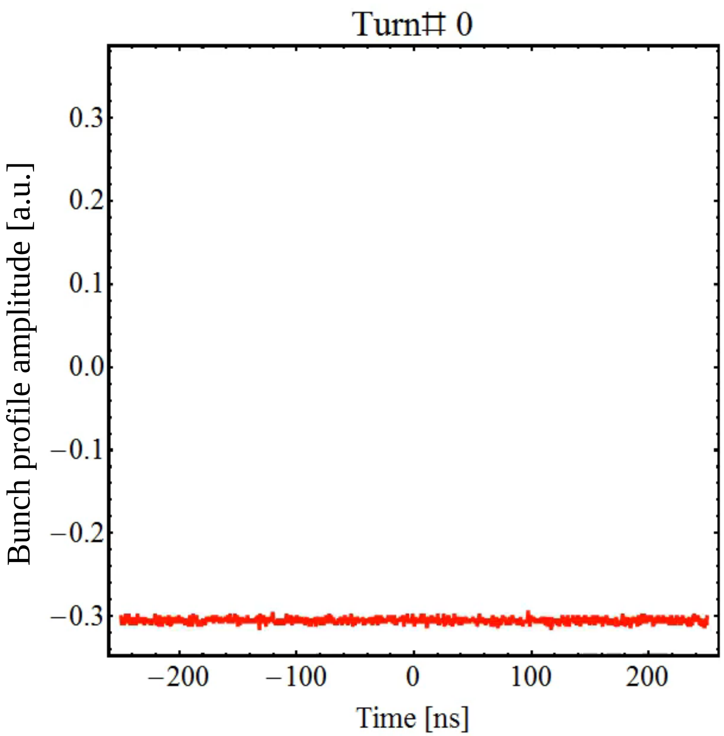
Move the wave!

→ Phase-locked loop with beam phase as reference for RF system

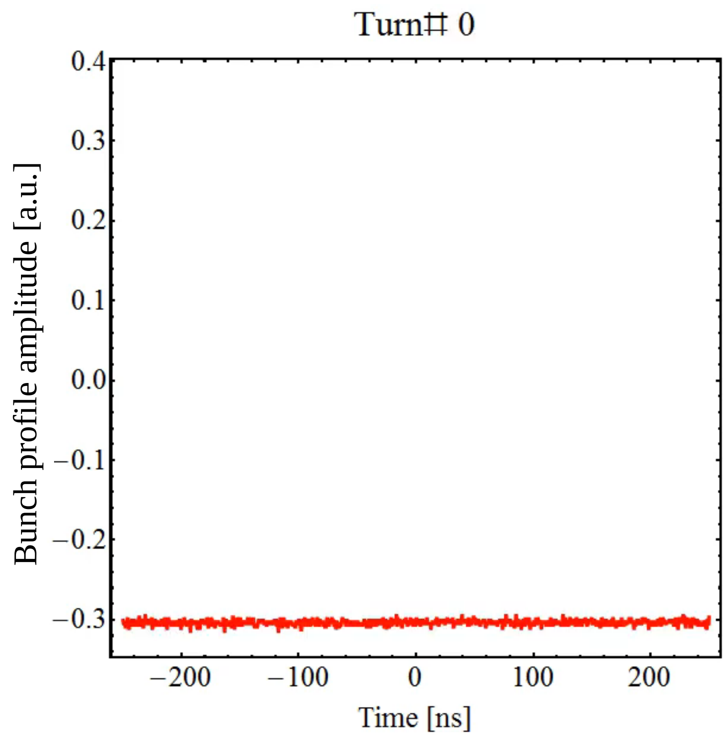
Step 3: Effect of beam phase loop at injection

- **Example: Injection of a bunch from PS Booster into PS**

90° error, phase loop off



90° error, phase loop on



→ **Essential in hadron accelerators to keep RF locked to beam**

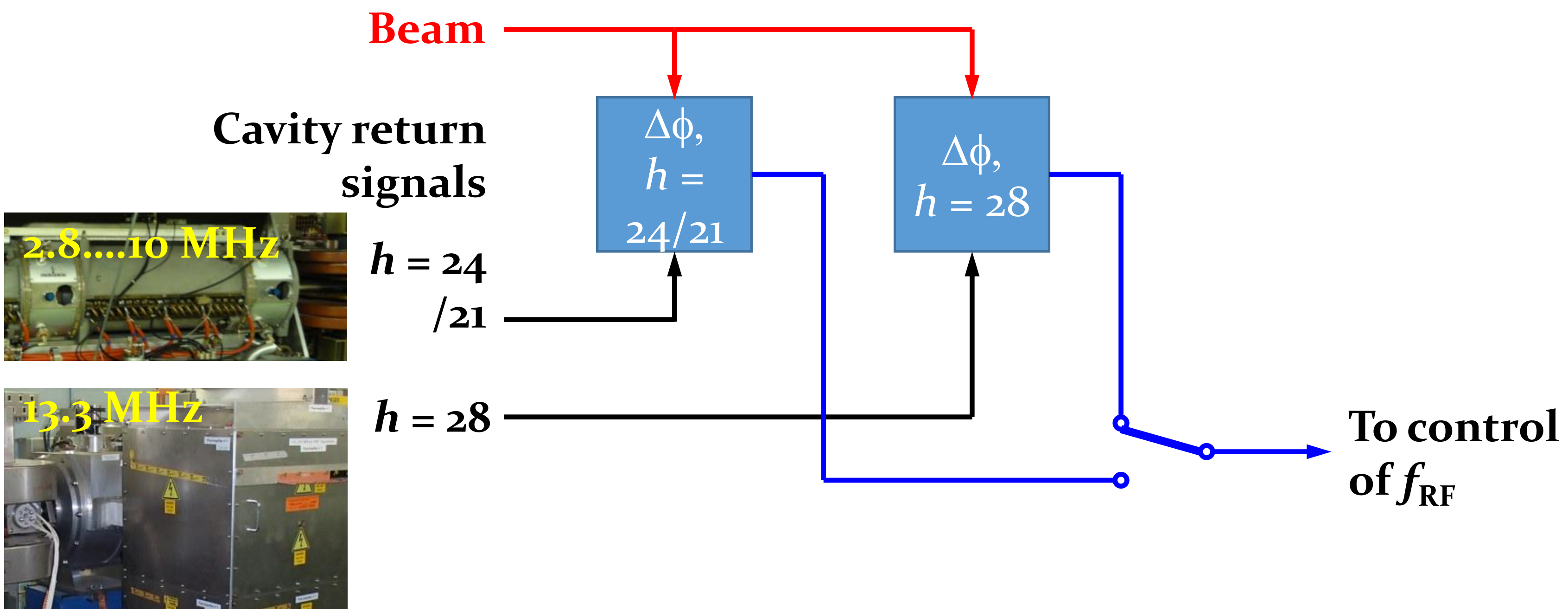
→ **Mitigates common-mode dipole oscillations**

Step 3: Implementation with beam phase loop

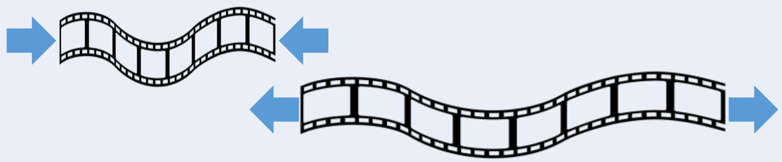
- **Need beam phase loop closed during RF manipulations**
  → Prevent excitation of dipole oscillations during process

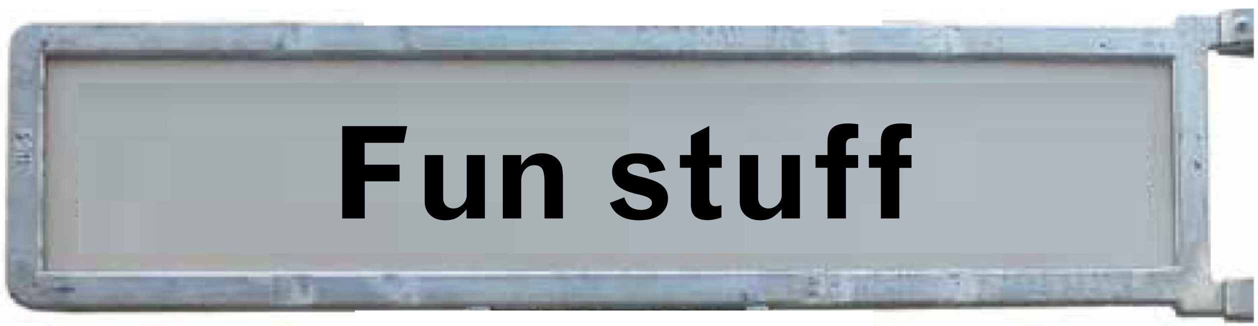
→ Harmonic number sequence of beam phase loop

$$h_{\mathrm{PL}} = 24 \rightarrow 21 \rightarrow 28$$

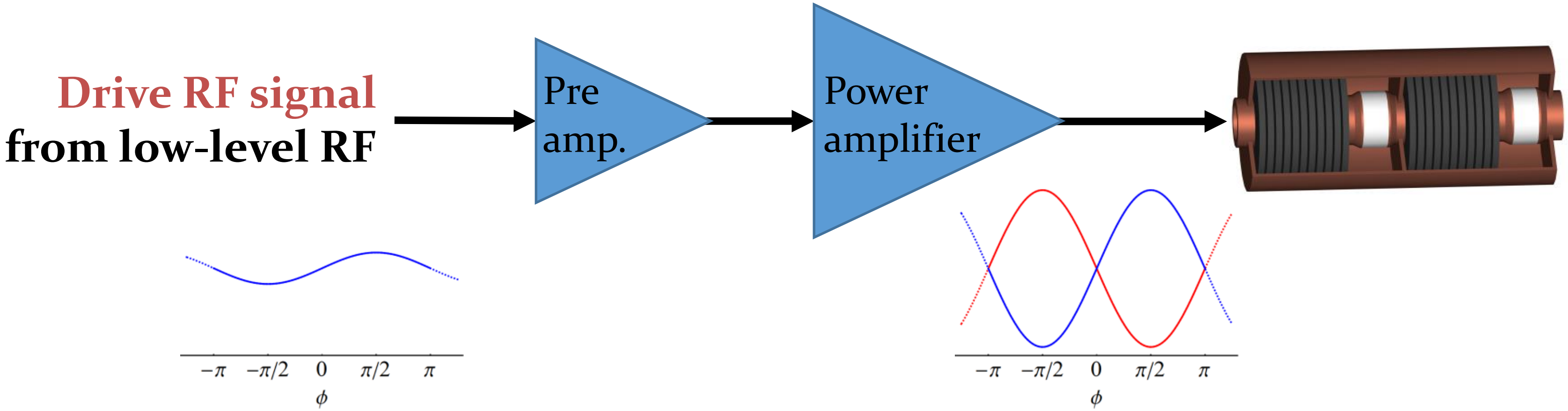


Recipe for RF manipulation design

Item	Remark
1. Define sequence of harmonic numbers	→ Constrained by RF frequencies of existing systems → Propose minimal extension
2. (a) Assume simple (or time-normalized) voltage programs and check evolution of bucket position and area (b) Optimize voltage functions versus time	→ Avoid abrupt changes of bunch phases → Respect adiabaticity 
3. Design phase loop harmonic sequence	→ As few harmonic number changes as possible


Fun stuff

Polarity of RF systems



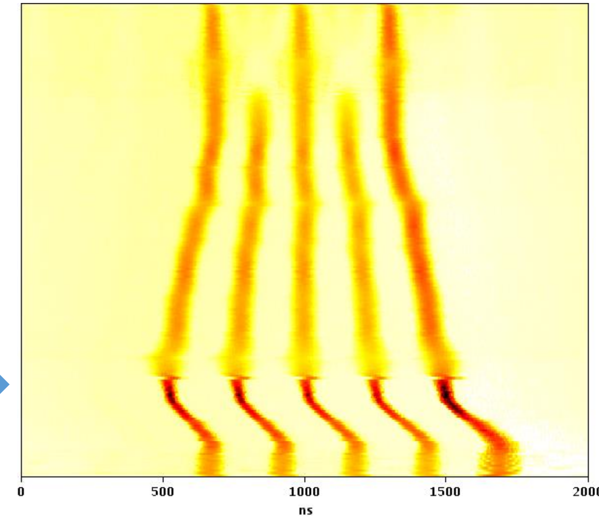
- **What is the polarity of your RF system?**
- **Is your amplifier straight-through or inverting?**

- **Why bother? → Irrelevant for most accelerators**

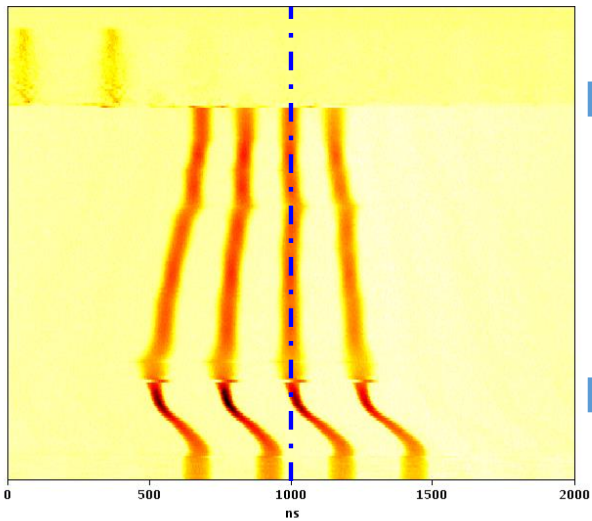
‘First’ beam in Proton Synchrotron (2018)

- **Impossible to establish symmetric batch compression of four bunches**

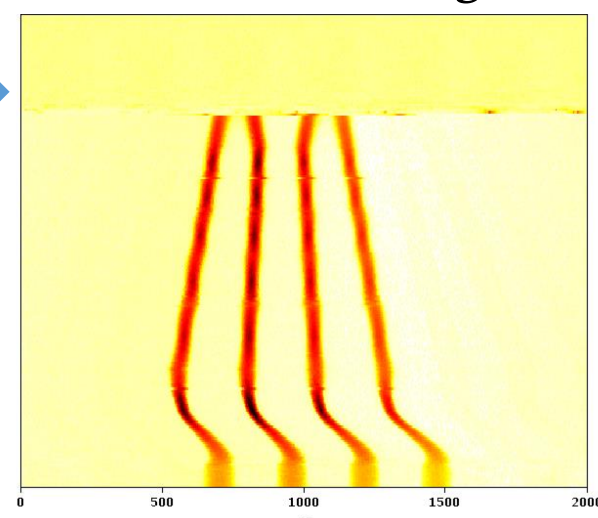
One more bunch would do



The problem

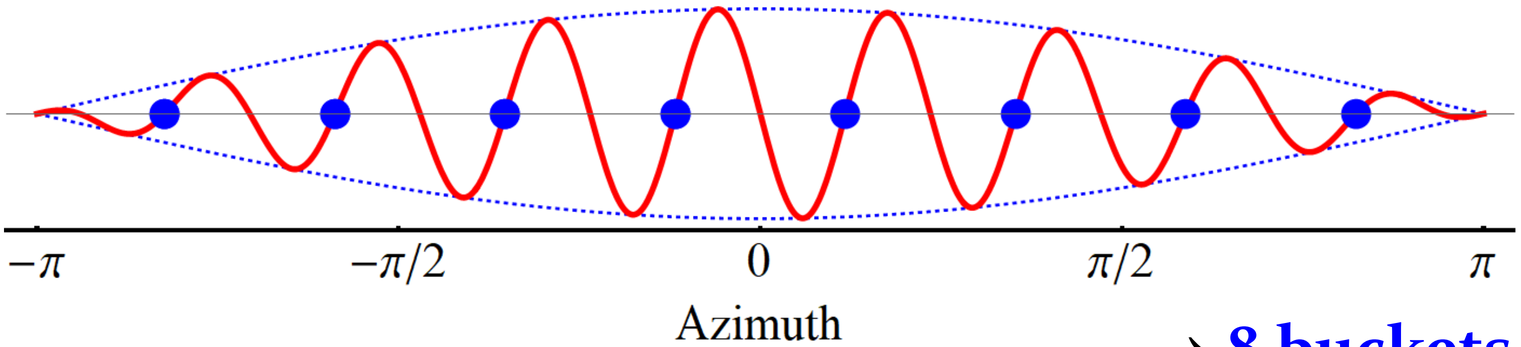


As well as inverting RF

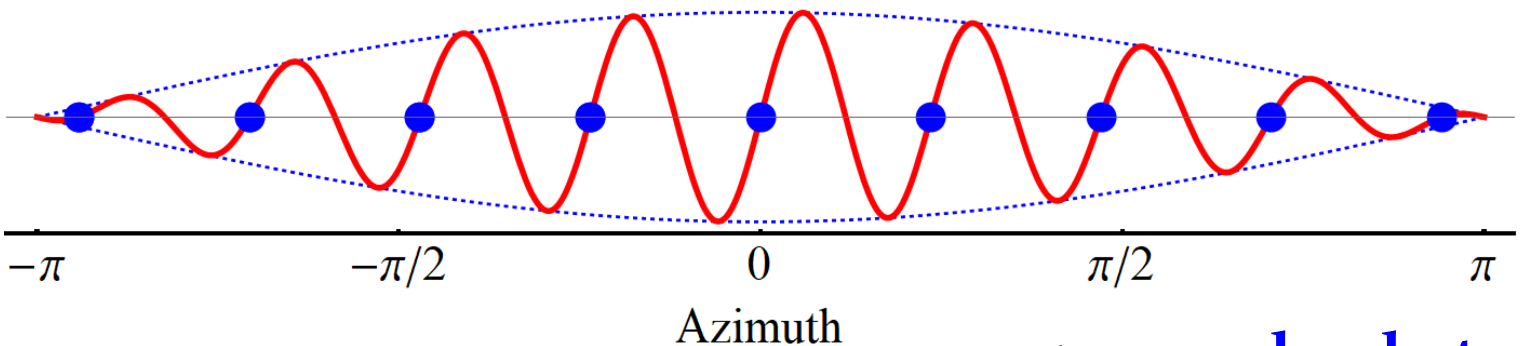


‘First’ beam in Proton Synchrotron (2018)

→ A small preamplifier upgrade had unintentionally and unexpectedly changed the polarity of the gain!



→ 8 buckets



→ 7 or 9 buckets

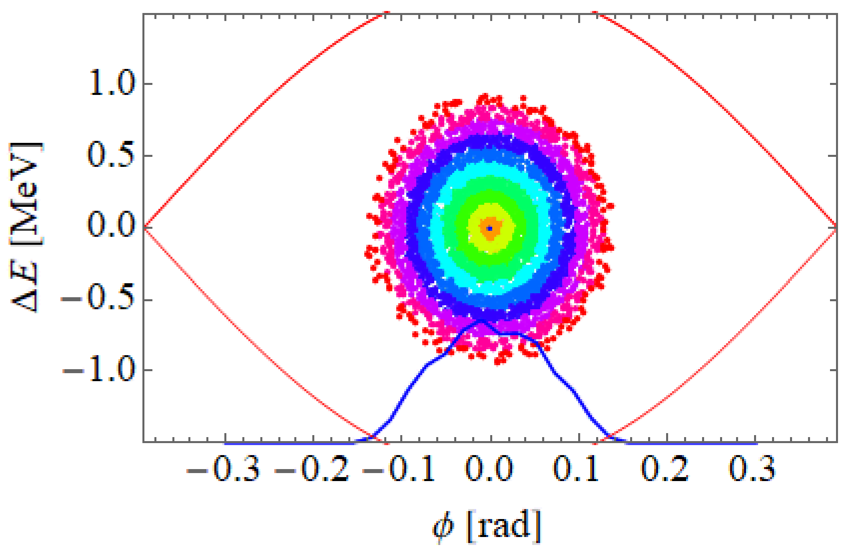
→ Gain polarity of amplifiers becomes relevant with RF voltage at multiple harmonics

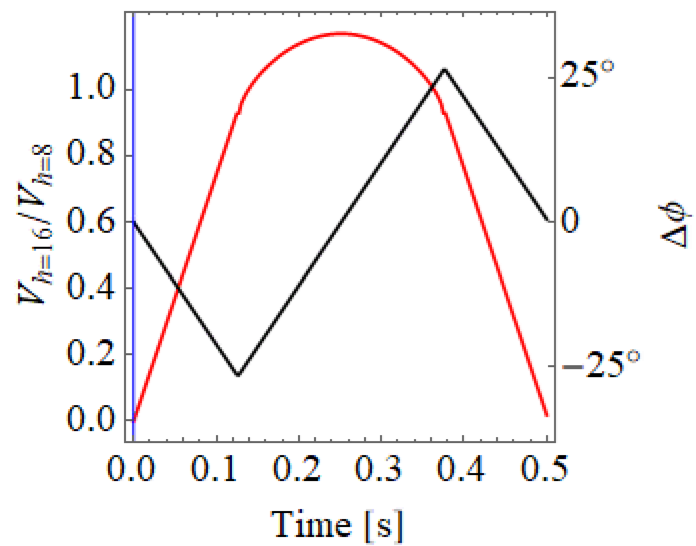
Turn a bunch inside out

- **Bunch core denser that tails**

→ Can core and tails be exchanged to flatten a bunch?

→ Voltage and phase programs calculates to suck bunch into emerging bucket next to it



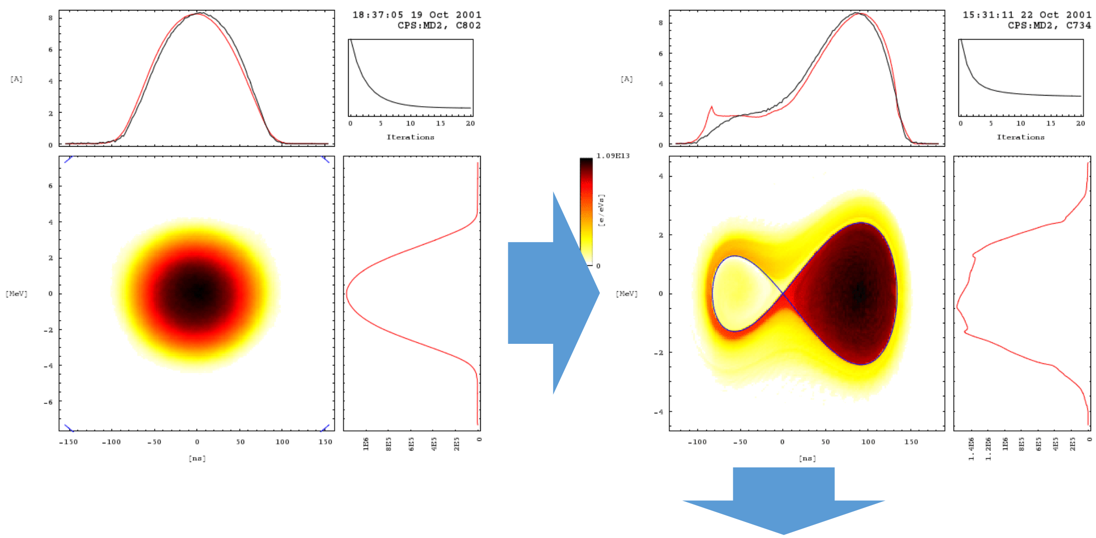


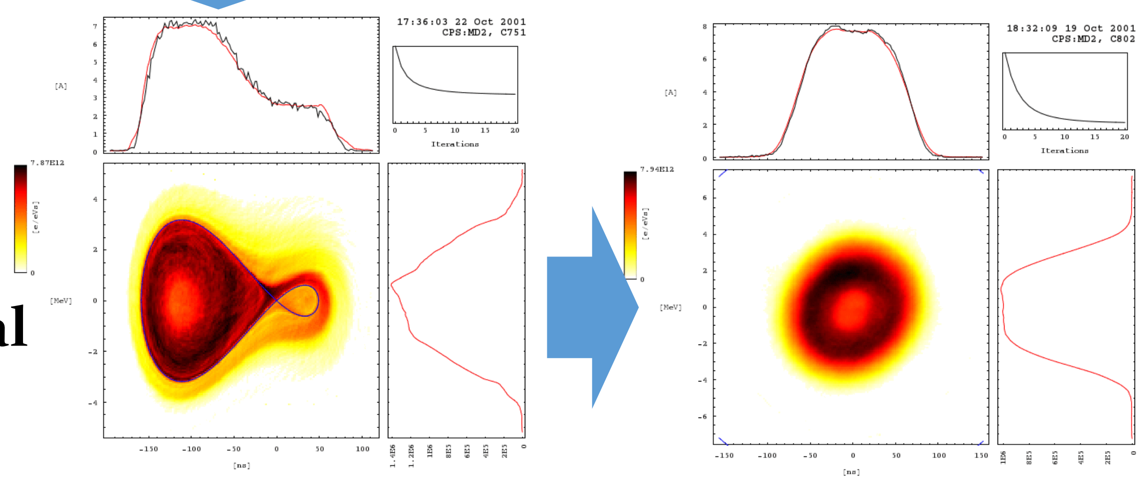
→ Asymmetric merging with an empty bucket

Turn a bunch inside out: hollow bunch

- **Beam test in the CERN PS Booster**

C. Carli, *Creation of hollow bunches using a double-harmonic RF system*, CERN/PS2001-073(AE)



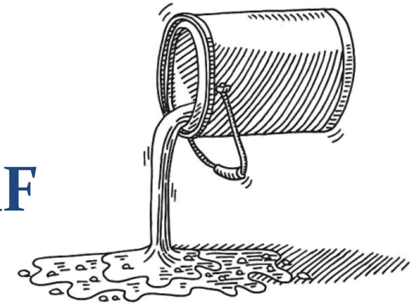


→ **Waiting for practical application**

Summary

- RF can do so much more than just acceleration
- The RF potential is the integral of voltage

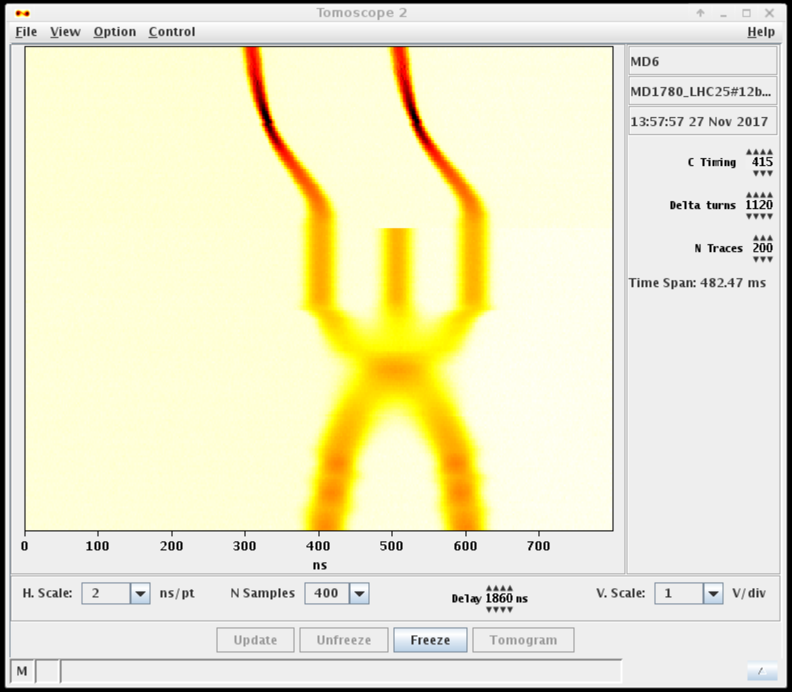
  → Fill occupied phase space into the bucket
- Adiabaticity and synchrotron frequency decide whether a manipulation is slow or fast



→ You will define the next generation of RF manipulations to come

→ Looking forward to seeing your new, unimageable RF manipulations


©Aaron Logan


Tomoscope 2
File
View
Option
Control
Help
MD6
MD1780_LHC25#12b...
13:57:57 27 Nov 2017
C Timing 415
Delta turns 1120
N Traces 200
Time Span: 482.47 ms
0
100
200
300
400
500
600
700
ns
H. Scale: 2 ns/pt
N Samples 400
Delay 1860 ns
V. Scale: 1 V/div
Update
Unfreeze
Freeze
Tomogram
M

A big Thank You

to all colleagues providing support, material and feedback

**Rob Ainsworth, Simon Albright, Chandra Bhat, Thomas Bohl,
Christian Carli, Roland Garoby, Wolfgang Höfle,
Alexandre Lasheen, Cédric Lombard, David McGinnis,
Chihiro Ohmori, Danilo Quartullo, Fumihiko Tamura
and many more…**


Thank you very much
for your attention!

References – general

- D. Boussard, RF techniques for $p\bar{p}$, CERN-84-15, https://cds.cern.ch/record/149856
- M. G. Minty, F. Zimmermann, Longitudinal phase space manipulation, USPAS'99, https://uspas.fnal.gov/materials/99UChicago/beam-tech.pdf
- R. Garoby, RF gymnastics in synchrotrons, CERN-2005-003, https://cds.cern.ch/record/2837684, https://cds.cern.ch/record/2835655
- R. Garoby, RF gymnastics in synchrotrons, CERN-2011-007, https://cds.cern.ch/record/1407406
- H. Klingbeil, U. Laier, D. Lens, Theoretical foundations of synchrotron and storage ring RF systems, Springer, 2015, https://link.springer.com/book/10.1007/978-3-319-07188-6

References – merging/splitting

- I. Bozsik et al., Numerical investigation of bunch-merging in a heavy-ion-synchrotron, https://doi.org/10.1007/3540139095_95
- B.J. Evans, R. Garoby et al., The antiproton production beam for the antiproton collector ("A.C."): beam experiments and RF developments, PAC'87, https://accelconf.web.cern.ch/p87/PDF/PAC1987_1925.PDF
- R. Cappi, B. J. Evans, R. Garoby, Status of the anti-proton production beam in the CERN PS, Part. Accel. 26 (1990), https://cds.cern.ch/record/200151
- R. Garoby, S. Hancock, New techniques for tailoring longitudinal density in a Proton Synchrotron, EPAC'94, https://accelconf.web.cern.ch/e94/PDF/EPAC1994_0282.PDF
- R. Garoby, Bunch merging and splitting techniques in the injectors for high energy hadron colliders, HEACC'98, https://cds.cern.ch/record/2831169
- R. Garoby et al., Demonstration of bunch triple splitting in the CERN PS, EPAC'00, https://accelconf.web.cern.ch/e00/PAPERS/WEOAF102.pdf
- R. Garoby, Multiple bunch-splitting in the PS : results and plans, 11th Workshop of the LHC, https://cds.cern.ch/record/488252
- Y.-S. Yuan et al., RF manipulations of high-intensity hadron beams in SIS-100, https://wiki.gsi.de/pub/SIS100BD/BeamDynamicsReports/Bunch_manipulation_report.pdf

References – batch compression

- R. Garoby, Proposal for a new process realizig longitudinal merging of bunches in the CPS, while conserving the total longitudinal emittance of the beam, https://cds.cern.ch/record/2840498/
- R. Garoby, New rf exercises envisaged in the CERN-PS for the antiprotons production beam of the ACOL machine, PAC'85, https://accelconf.web.cern.ch/p85/PDF/PAC1985_2332.PDF
- R. Cappi, B. J. Evans, R. Garoby, Status of the anti-proton production beam in the CERN PS, Part. Accel. 26 (1990), https://cds.cern.ch/record/200151
- H. Damerau et al., RF Manipulations for Higher Brightness LHC-type Beams, IPAC'13, https://accelconf.web.cern.ch/IPAC2013/papers/wepea044.pdf
- C. Lombard, Improved antiproton production beam at CERN, https://www.ipac23.org/preproc/pdf/TUPM075.pdf

References – longitudinal blow-up

- **V. V. Balandin et al., The resonant theory of longitudinal Emittance blowup by phase modulated high harmonic cavities, https://cds.cern.ch/record/1108240**
- **E. Shaposhnikova et al., Experimental study of controlled longitudinal blow-up, https://cds.cern.ch/record/2844449**
- **T. Toyama, Uniform bunch formation by RF voltage mod-ulation with a band-limited white signal, NIM A 447 (2000), https://www.sciencedirect.com/science/article/pii/S0168900299013121**
- **D. Quartullo et al., Controlled longitudinal emittance blow-up using band-limited phase noise in CERN PSB,IPAC'17 https://accelconf.web.cern.ch/ipac2017/papers/thpva024.pdf**
- **D. Quartullo et al., Controlled longitudinal emittance blow-up for high intensity beams in the CERN SPS, HB2021, https://cds.cern.ch/record/2841808**

References – slip stacking

- **D. Boussard, Y. Mizumachi, Production of bunches with high line density in a synchrotron, PAC'79, https://accelconf.web.cern.ch/p79/PDF/PAC1979_3623.PDF**
- **D. Boussard, Y. Mizumachi, Numercial computation of the behaviour of bunches in the azimuthal combination process, SPS/ARF/YM/gs/Int. Note/79-12**
- **R. Garoby, La recombinaison longitudinale dans le PS principe et mise en oeuvre pratique, CERN-PS-LR-Note-80-9, http://cds.cern.ch/record/2849841/files/CERN-PS-LR-Note-80-9.pdf**
- **C. Ankenbrandt, A New Method of Momentum Stacking, FERMILAB-FN-0352, https://inspirehep.net/files/e7c6c4c5debcf7ec9743c9e811ae659d**
- **K. Koba, J. Steimel, Slip stacking, ICFA-HB2002, https://pubs.aip.org/aip/acp/article-pdf/642/1/223/12021030/223_1_online.pdf**

References – isolated/barrier bucket

- **L. L. Foldy, A method for expanding the phase-stable regime in synchronous accelerators, Il Nuovo Cimento 19 (1961), https://link.springer.com/content/pdf/10.1007/BF02731387.pdf**
- **A. G. Ruggiero, Beam stacking with suppressed buckets in the ISR, CERN-68-22, http://cds.cern.ch/record/275752/files/CERN-68-22.pdf**
- **J. E. Griffin et al., Isolated bucket RF systems in the Fermilab antiproton facility, https://accelconf.web.cern.ch/p83/PDF/PAC1983_3502.pdf**
- **S. Y. Lee, K. Y. Ng. Particle dynamics in storage rings with barrier rf systems, Phys. Rev. E 55 (1997), https://doi.org/10.1103/PhysRevE.55.5992**