LONGITUDINAL
beam DYNAMICS
in circular accelerators

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Introduction to Accelerator Physics
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The CERN Accelerator School

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Scope and Summary of the 2 lectures:

The goal of an accelerator is to provide a stable particle beam.

The particles nevertheless perform transverse betatron oscillations.
We will see that they also perform (so-called **synchrotron**) **oscillations** in the longitudinal plane and in energy.

We will look at the stability of these oscillations, their dynamics and derive some basic equations.

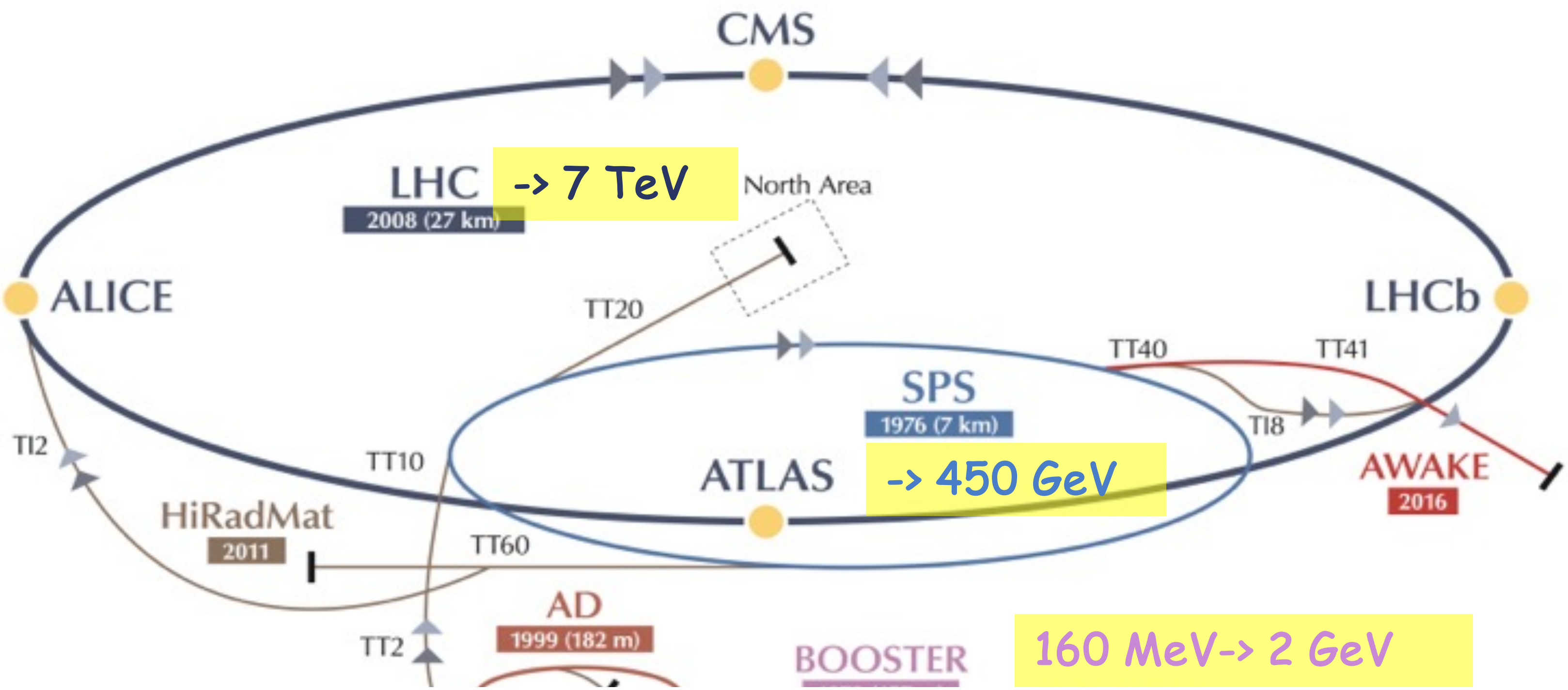
- Introduction
- Circular accelerators: Cyclotron / Synchrotron
- Dispersion Effects in Synchrotron
- Stability and Longitudinal Phase Space Motion
- Hamiltonian
- Stationary Bucket
- Injection Matching

More related lectures:

- Linacs – David Alesini
- RF Systems - Heiko Damerau
- Electron Beam Dynamics - Lenny Rivkin
- Non-Linear longitudinal Beam Dynamics - Heiko Damerau

- **Hands-on calculations** – longitudinal in the second week !!!

Motivation for circular accelerators



- Linear accelerators scale in size and cost(!) ~linearly with the energy.
- Circular accelerators can each turn reuse
  - the **accelerating system**
  - the vacuum chamber
  - the bending/focusing magnets
  - beam instrumentation, …

-> economic solution to reach higher particle energies

But each accelerator has a limited energy range.

Particle types and acceleration

The accelerating system will depend upon the evolution of the particle velocity:

- electrons reach a constant velocity (~speed of light) at relatively low energy
- heavy particles reach a constant velocity only at very high energy

-> need different types of resonators, optimized for different velocities

-> the **revolution frequency will vary**, so the RF frequency will be changing

-> magnetic field needs to follow the momentum increase

Particle rest mass m_0:

electron	0.511 MeV
proton	938 MeV
^{239}U	~220000 MeV

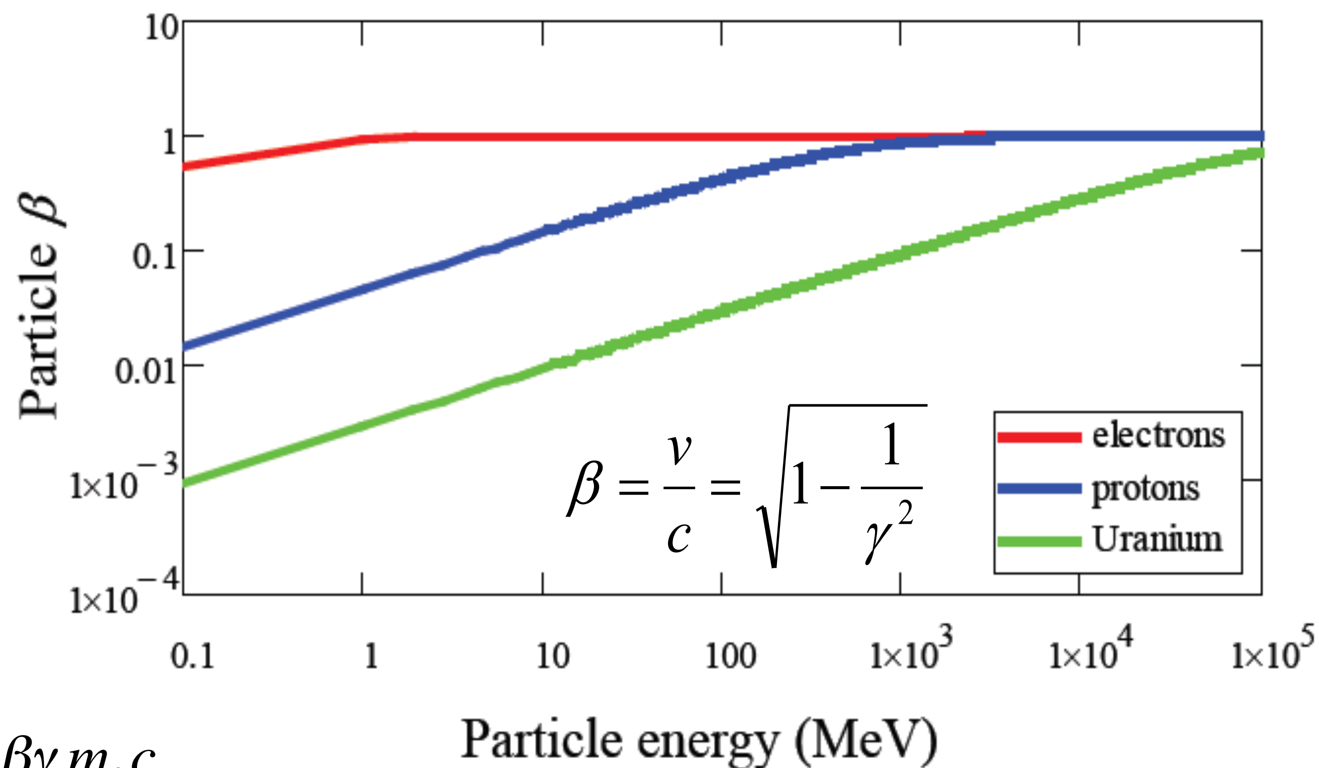
Total Energy: $E = \gamma m_0 c^2$

Relativistic gamma factor:

$$\gamma = \frac{E}{E_0} = \frac{m}{m_0} = \frac{1}{\sqrt{1-\beta^2}}$$

Momentum:

$$p = mv = \frac{E}{c^2}\beta c = \beta \frac{E}{c} = \beta\gamma m_0 c$$



Revolution frequency variation

The revolution and RF frequency will be changing during acceleration
Much more important for lower energies (values are kinetic energy - protons).

PS Booster:	50 MeV (β= 0.314) -> 1.4 GeV (β=0.915)
(pre LS2)	602 kHz -> 1746 kHz => **190% frequency increase**
(post LS2):	160 MeV (β= 0.520) -> 2 GeV (β=0.948) => **95% increase**
PS:	1.4 GeV (β=0.915) -> 25.4 GeV (β =0.9994)
	437 KHz -> 477 kHz => **9% increase**
(post LS2):	2 GeV (β=0.948) -> 25.4 GeV (β =0.9994) => **5% increase**
SPS:	25.4 GeV -> 450 GeV (β=0.999998)
	=> **0.06% frequency increase**
LHC:	450 GeV -> 7 TeV (β= 0.999999991)
	=> only **2 10^{-6} increase**

RF system needs more flexibility in lower energy accelerators.

Question: What about electrons and positrons?

Acceleration + Energy Gain

May the force be with you!

To accelerate, we need a **force in the direction of motion**!

Newton-Lorentz Force on a charged particle:

$$\vec{F} = \frac{d\vec{p}}{dt} = q(\vec{E} + \vec{v} \times \vec{B})$$

2nd term always perpendicular to motion => no acceleration

Hence, it is necessary to have an electric field E (preferably) along the direction of the initial momentum (z), which changes the momentum p of the particle.

$$\frac{dp}{dt} = qE_z$$

In relativistic dynamics, total energy E and momentum p are linked by

$$E^2 = E_0^2 + p^2c^2 \quad \Rightarrow \quad dE = v\,dp \qquad \left(2E\,dE = 2c^2 p\,dp \Leftrightarrow dE = c^2 mv / E\,dp = v\,dp\right)$$

The rate of energy gain per unit length of acceleration (along z) is then:

$$\frac{dE}{dz} = v\frac{dp}{dz} = \frac{dp}{dt} = qE_z$$

and the kinetic energy gained from the field along the z path is:

$$dW = dE = qE_z\,dz \quad \rightarrow \quad W = q\int E_z\,dz = qV$$

- V is a potential
- q the charge

Unit of Energy

Today's accelerators and future projects work/aim at the TeV energy range.

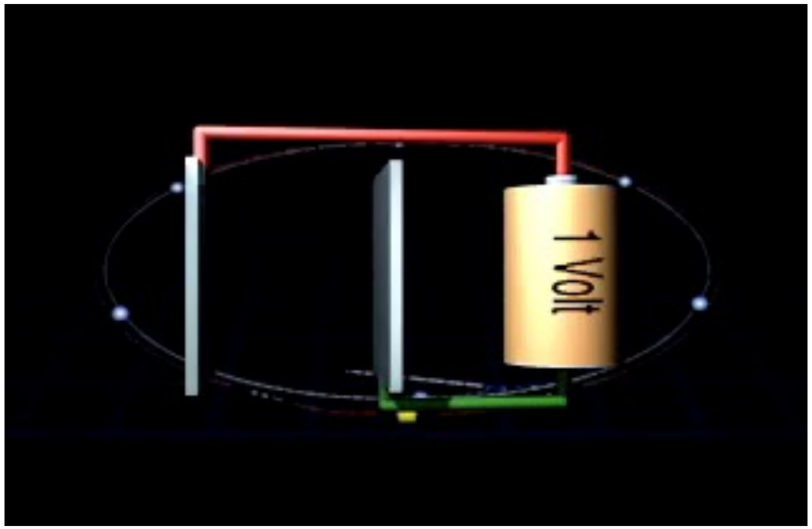
LHC:	7 TeV -> 14 TeV
CLIC:	380 GeV -> 3 TeV
FCC:	100 TeV

In fact, this energy unit comes from acceleration:

1 eV (electron Volt) is the energy that 1 elementary charge e (like one electron or proton) gains when it is accelerated in a potential (voltage) difference of 1 Volt.

Basic Unit: **eV (electron Volt)**

keV = 1000 eV = 10^3 eV
MeV = 10^6 eV
GeV = 10^9 eV
TeV = 10^{12} eV

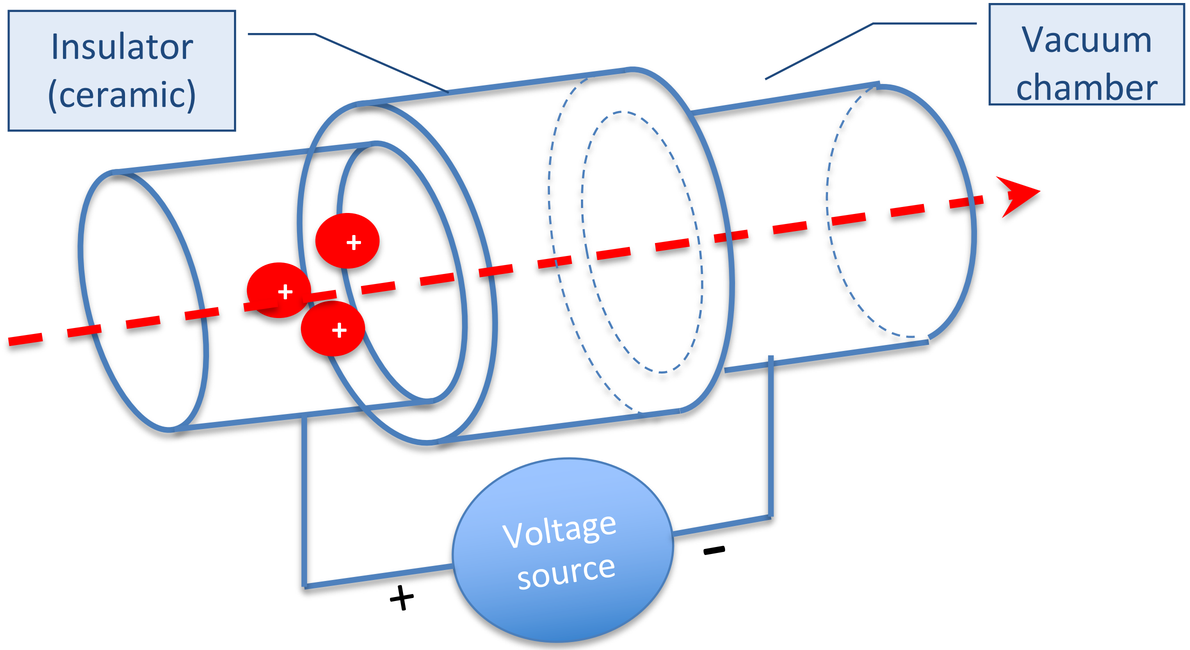


LHC = ~450 Million km of batteries!!!
3x distance Earth-Sun

Methods of Acceleration in circular accelerators

Electrostatic field limited by insulation, magnetic field doesn't accelerate at all.

Circular machine: DC acceleration impossible since $\oint \vec{E} \cdot \mathrm{d}\vec{s} = 0$



→ no Acceleration

The electric field is derived from a scalar potential φ and a vector potential A
The time variation of the magnetic field H generates an electric field E

The solution: => time varying electric fields
- Induction
- RF frequency fields

$$\oint \vec{E} \cdot \mathrm{d}\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} \cdot \mathrm{d}\vec{A}$$

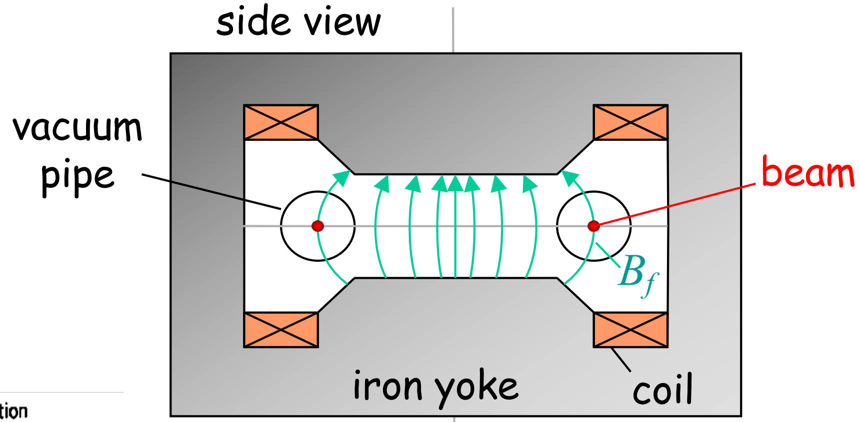
Acceleration by Induction: The Betatron

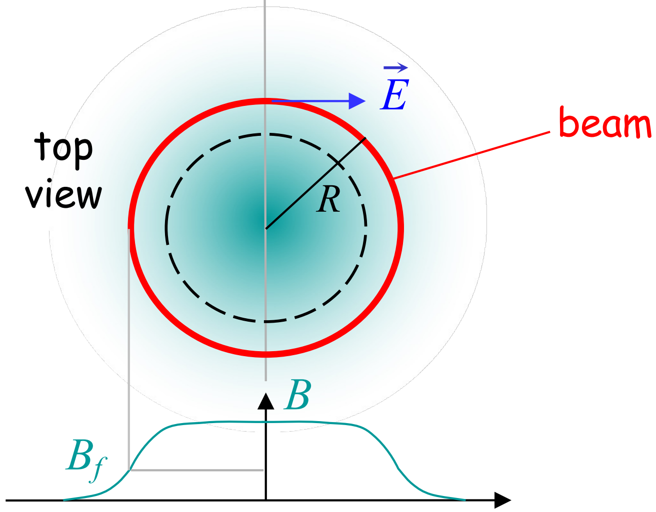
It is based on the principle of a transformer:
- primary side: large electromagnet - secondary side: electron beam.

The ramping magnetic field is used to guide particles on a circular trajectory as well as for acceleration.

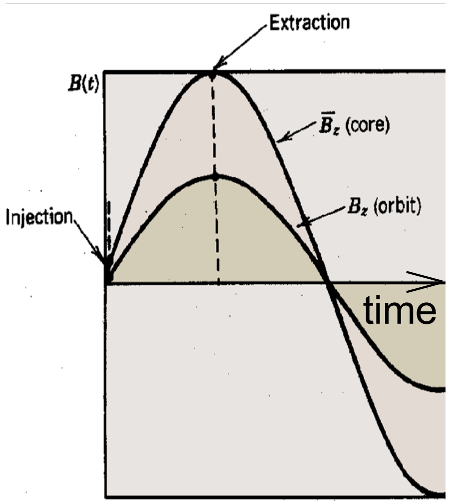
Limited by saturation in iron (~300 MeV e-)

Used in industry and medicine, as they are compact accelerators for electrons





Donald Kerst with the first betatron, invented at the University of Illinois in 1940



Circular accelerators

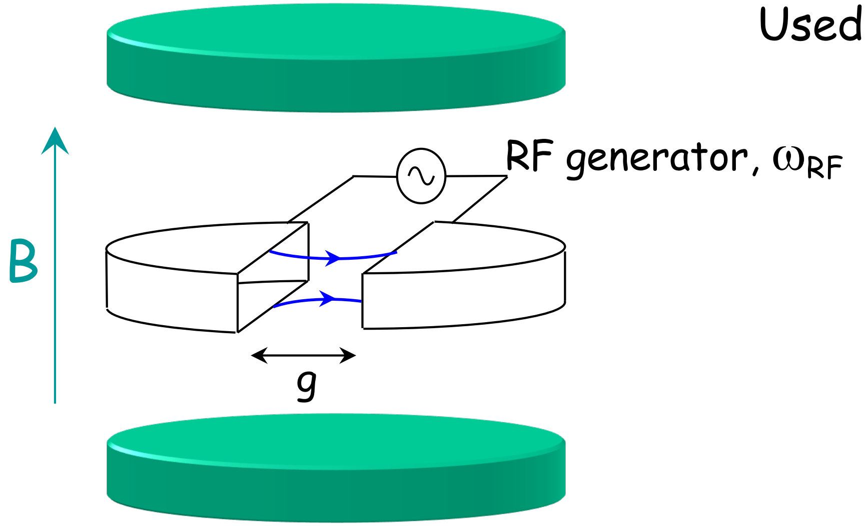
Cyclotron

Synchrotron

Circular accelerators: Cyclotron

Courtesy: EdukiteLearning, https://youtu.be/cNnNM2ZqIsc

Circular accelerators: Cyclotron



Used for protons, ions

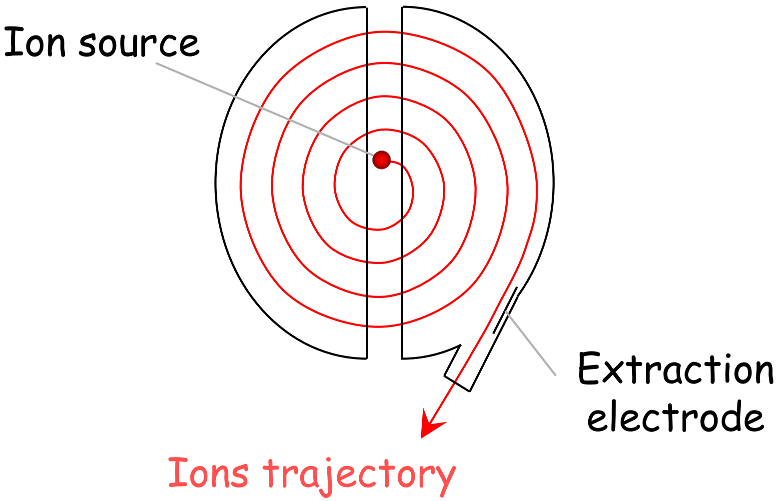
B = constant

ω_{RF} = constant

Synchronism condition

$$\omega_s = \omega_{RF}$$

$$2\pi\ \rho = v_s\ T_{RF}$$



Cyclotron frequency $$\omega = \frac{q\ B}{m_0\ \gamma}$$

1. γ increases with the energy
   ⇒ no exact synchronism
2. if **v << c** ⇒ $\gamma \cong 1$

Animation: https://phyanim.sciences.univ-nantes.fr/Meca/Charges/cyclotron.php

Circular accelerators: Cyclotron

Courtesy Berkeley Lab,
https://www.youtube.com/watch?v=cutKuFxeXmQ

Cyclotron / Synchrocyclotron

TRIUMF 520 MeV cyclotron Vancouver - Canada

CERN 600 MeV synchrocyclotron

Synchrocyclotron: Same as cyclotron, except a modulation of ω_{RF}

B = constant

$\gamma\ \omega_{RF}$ = constant

ω_{RF} decreases with time

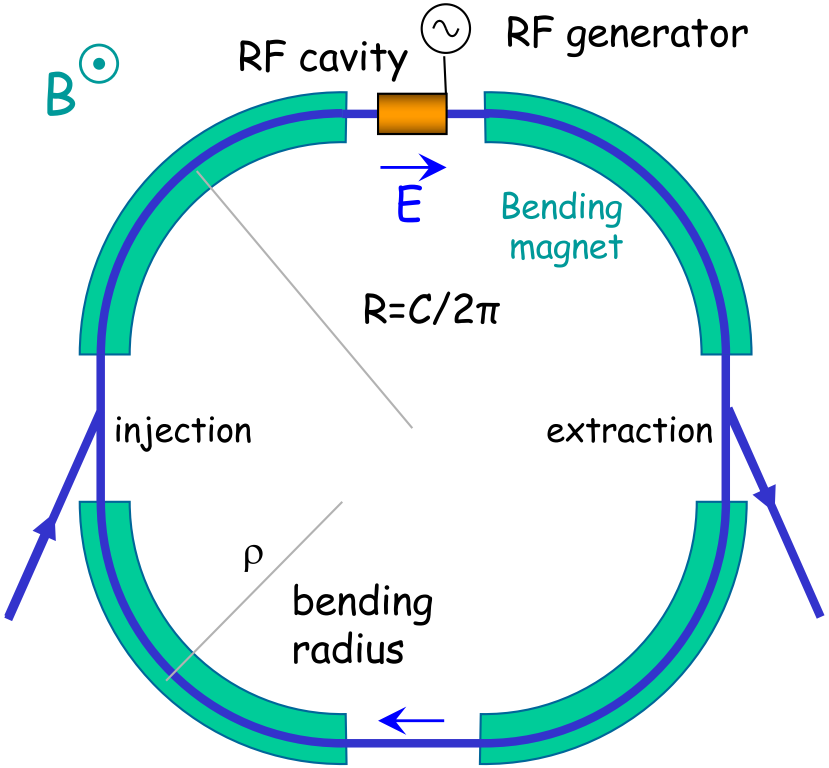
More in lectures by Mike Seidel

The condition:

$$\omega_s(t) = \omega_{RF}(t) = \frac{q\ B}{m_0\ \gamma(t)}$$

Allows to go beyond the non-relativistic energies

Circular accelerators: The Synchrotron



1. Constant orbit during acceleration
2. To keep particles on the closed orbit, B should increase with time
3. ω and ω_{RF} increase with energy

RF frequency can be multiple of revolution frequency

$$\omega_{RF} = h\omega$$

Synchronism condition

$$T_s = h\, T_{RF}$$

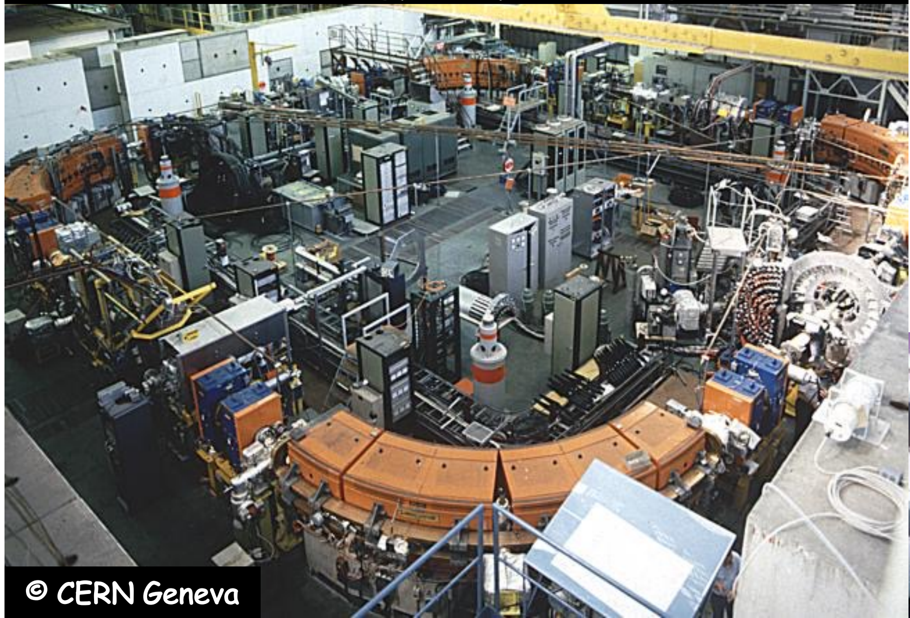
$$\frac{2\pi R}{v_s} = h\, T_{RF}$$

h integer,
harmonic number:
number of RF cycles per revolution

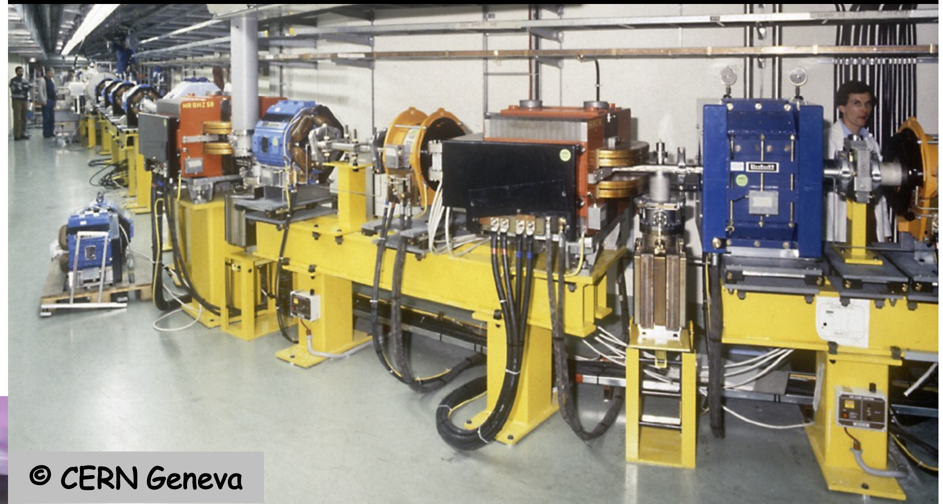
h is the maximum number of bunches in the synchrotron.
Normally less bunches due to gaps for kickers, collision constraints,...

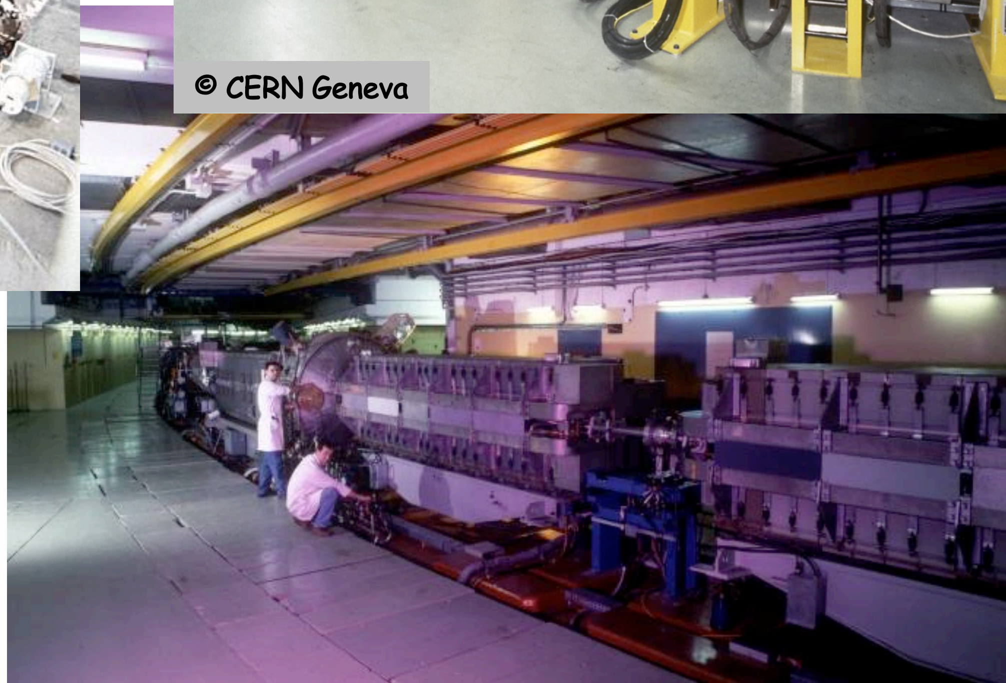
Circular accelerators: The Synchrotron

LEAR (CERN)
Low Energy Antiproton Ring



EPA (CERN)
Electron Positron Accumulator





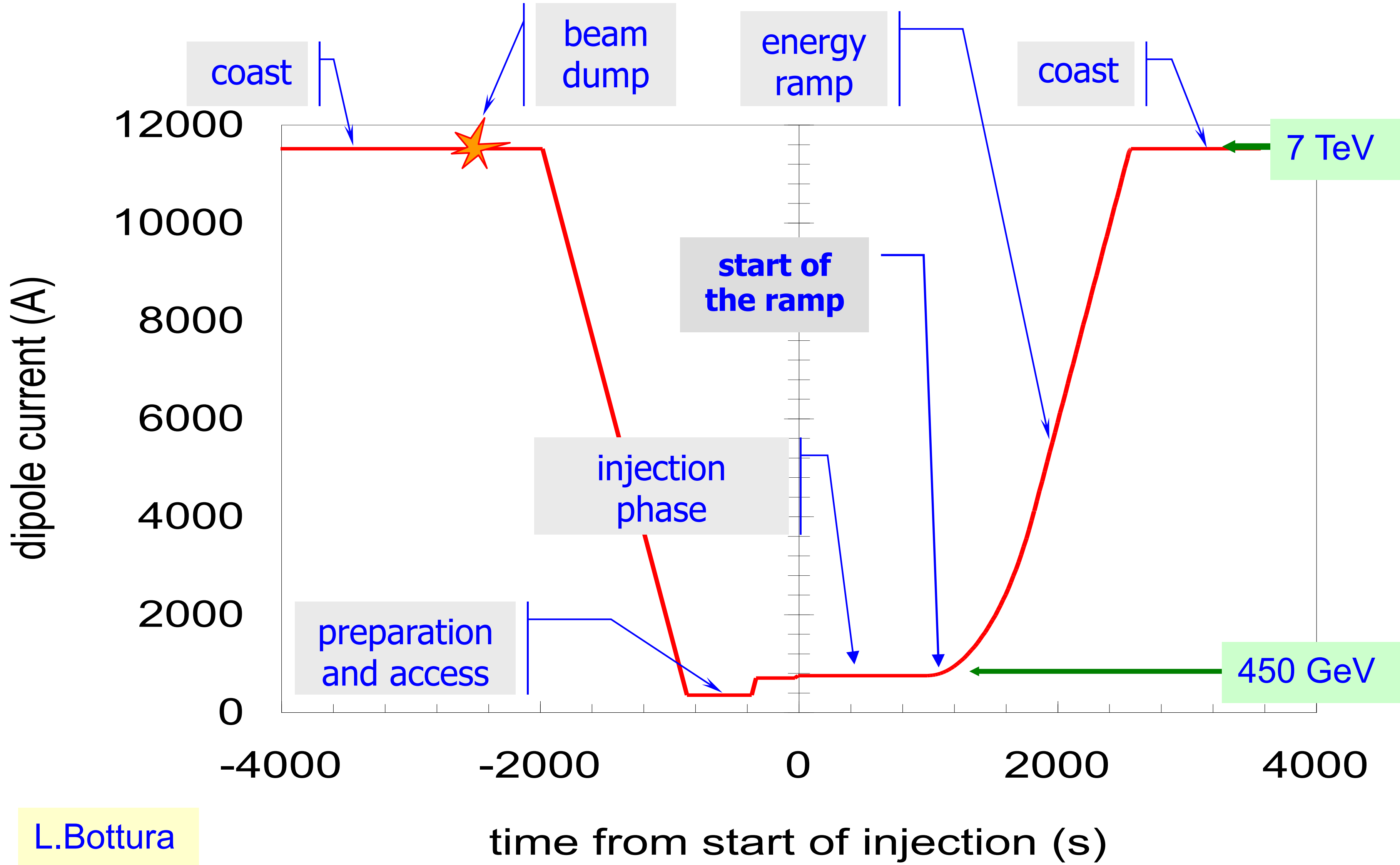
PS (CERN)
Proton Synchrotron © CERN Geneva

Examples of different proton and electron synchrotrons at CERN

+ LHC (of course!)

The Synchrotron – LHC Operation Cycle

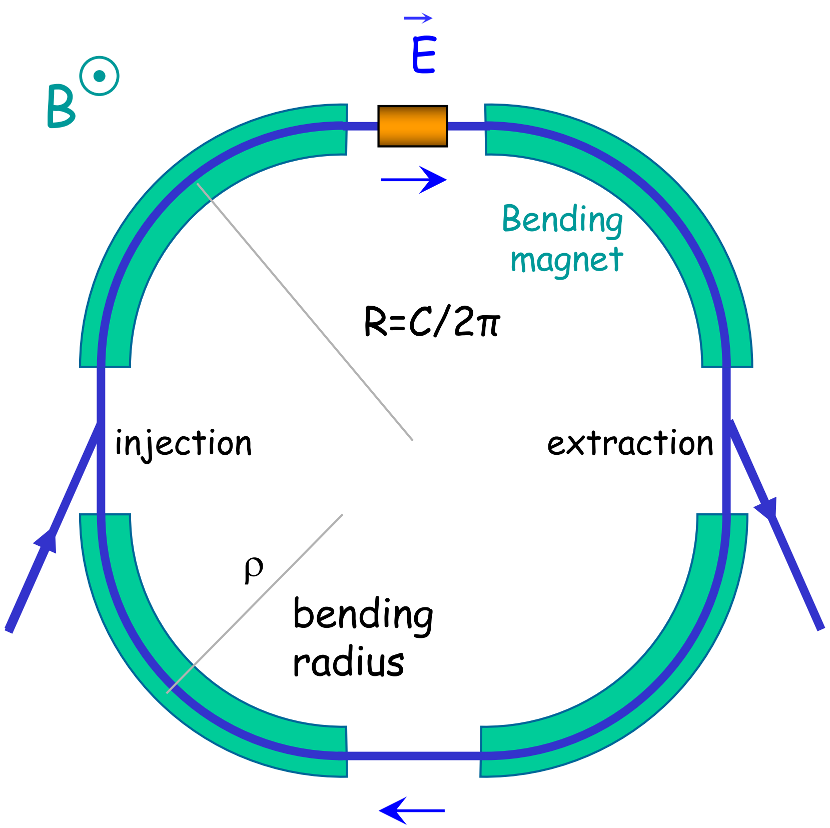
The magnetic field (dipole current) is increased during the acceleration.



L.Bottura

The Synchrotron

The synchrotron is a synchronous accelerator since there is a synchronous RF phase for which the energy gain fits the increase of the magnetic field at each turn. That implies the following operating conditions:



$e\hat{V}\sin\phi$ ⟶ Energy gain per turn

$\phi = \phi_s$ ⟶ Synchronous particle

$\omega_{RF} = h\omega$ ⟶ RF synchronism (h - harmonic number)

$\rho = cte \quad R = cte$ ⟶ Constant orbit

$B\rho = P/e \Rightarrow B$ ⟶ Variable magnetic field

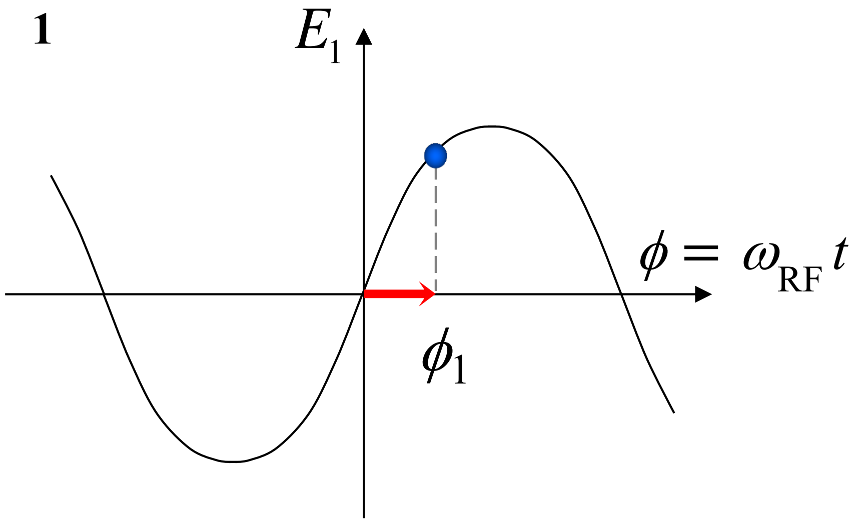
If v≈c, ω hence ω_{RF} remain constant (ultra-relativistic e^-)

Common Phase Conventions

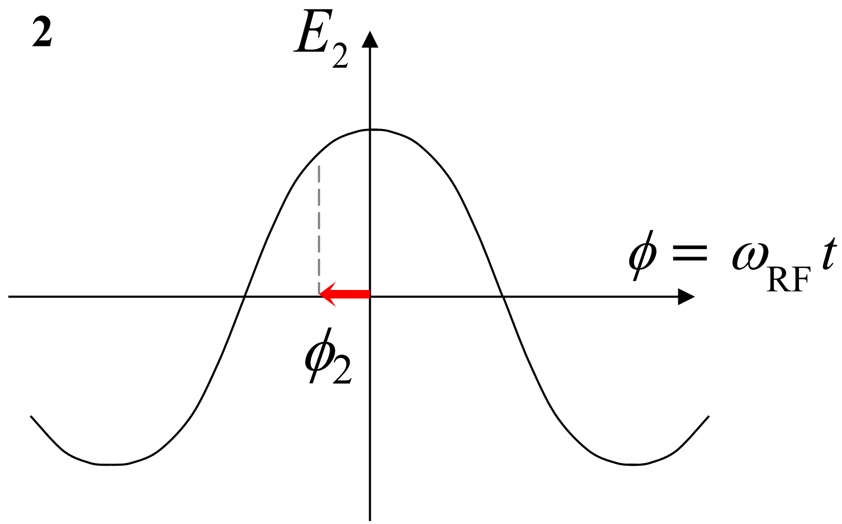
1. For circular accelerators, the origin of time is taken at the zero crossing of the RF voltage with positive slope

2. For linear accelerators, the origin of time is taken at the positive crest of the RF voltage

Time t= 0 chosen such that:



$$E_1(t) = E_0 \sin(\omega_{RF} t)$$



$$E_2(t) = E_0 \cos(\omega_{RF} t)$$

3. I will stick to **convention 1** in the following to avoid confusion

The Synchrotron – Energy ramping

Energy ramping by increasing the B field (frequency has to follow v):

$$p = eB\rho \underset{\rho\ \text{const.}}{\Rightarrow} \frac{dp}{dt} = e\rho \dot{B} \Rightarrow (\Delta p)_{turn} = e\rho \dot{B} T_r = \frac{2\pi e\rho R\dot{B}}{v}$$

With

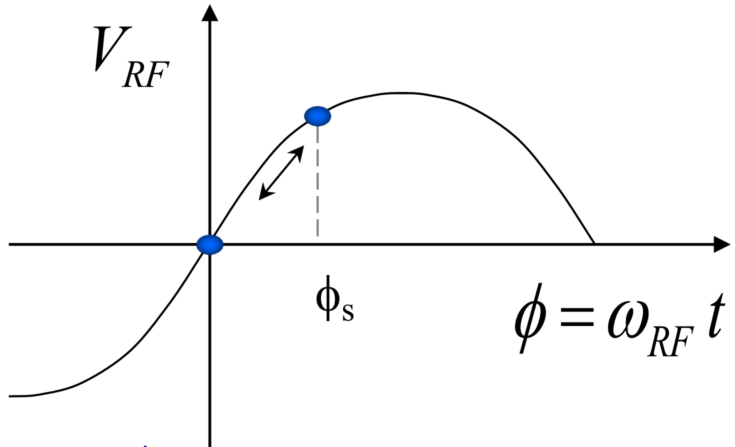
$$E^2 = E_0^2 + p^2c^2 \Rightarrow \Delta E = v\Delta p$$

$$\left(\Delta E\right)_{turn} = \left(\Delta W\right)_s = 2\pi e\rho R\dot{B} = e\hat{V}\sin\phi_s$$

Synchronous phase φ_s changes during energy ramping

$$\sin\phi_s = 2\pi\rho R\frac{\dot{B}}{\hat{V}_{RF}} \Rightarrow \phi_s = \arcsin\left(2\pi\rho R\frac{\dot{B}}{\hat{V}_{RF}}\right)$$

- The synchronous phase depends on
  - the change of the magnetic field
  - and the RF voltage



The Synchrotron – Frequency change

During the energy ramping, the RF frequency increases to follow the increase of the revolution frequency :

$$\omega = \frac{\omega_{RF}}{h} = \omega(B, R_s)$$

Hence: $\frac{f_{RF}(t)}{h} = \frac{v(t)}{2\pi R_s} = \frac{1}{2\pi} \frac{ec^2}{E_s(t)} \frac{\rho}{R_s} B(t)$ (using $p(t) = eB(t)\rho, \quad E = mc^2$)

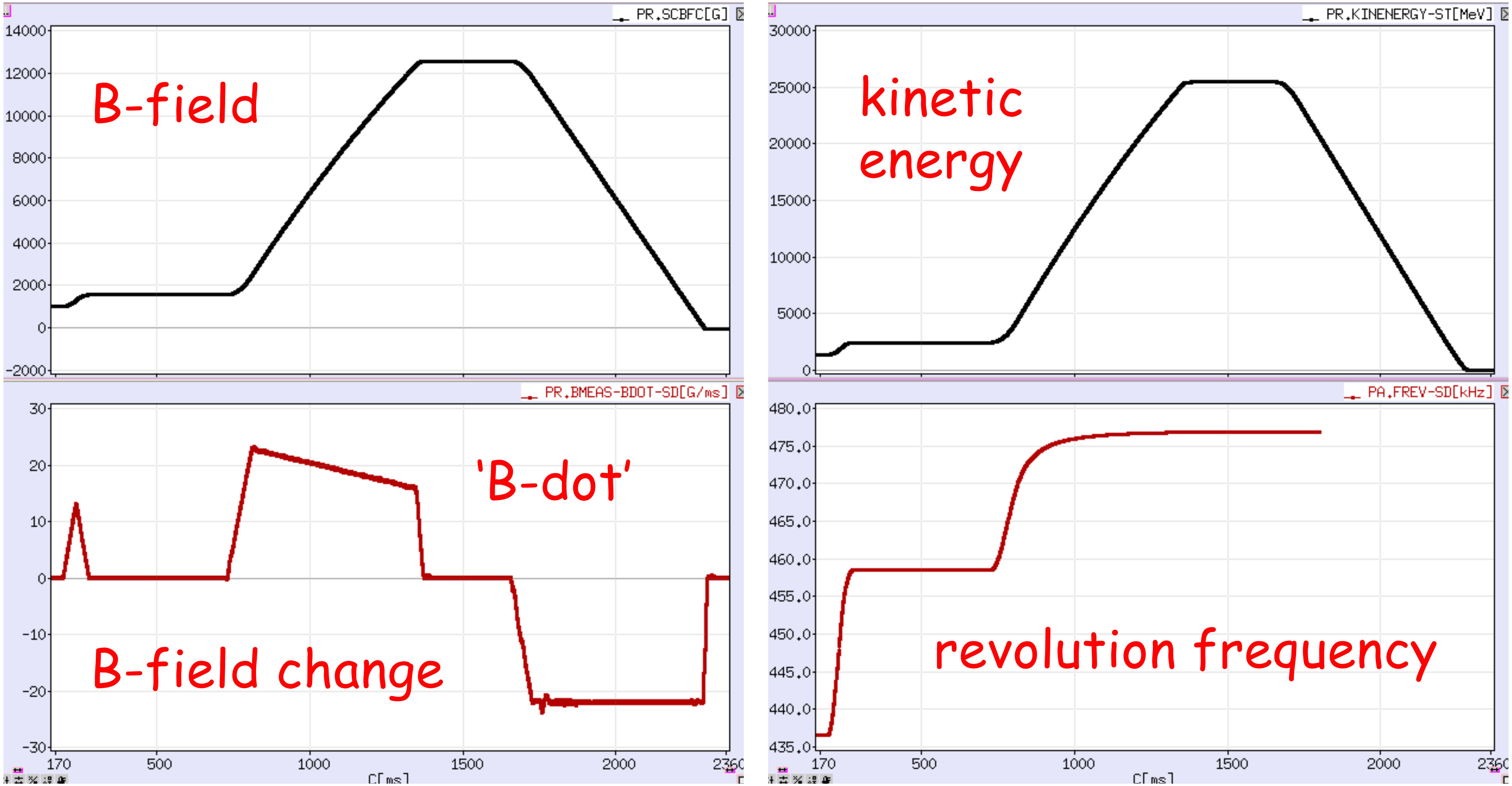
Since $E^2 = (m_0 c^2)^2 + p^2 c^2$ the RF frequency must follow the variation of the B field with the law

$$\frac{f_{RF}(t)}{h} = \frac{c}{2\pi R_s} \left\{ \frac{B(t)^2}{(m_0 c^2 / ec\rho)^2 + B(t)^2} \right\}^{1/2}$$

RF frequency program during acceleration determined by B-field !

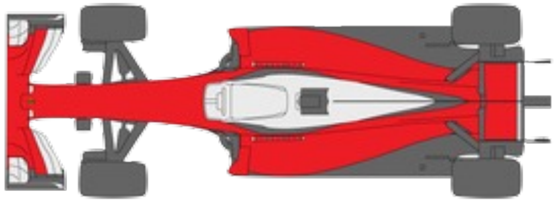
Example: PS - Field / Frequency change

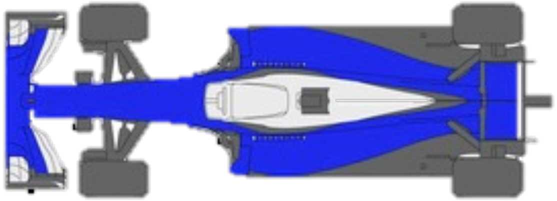
During the energy ramping, the B-field and the revolution frequency increase



time (ms) → time (ms) →

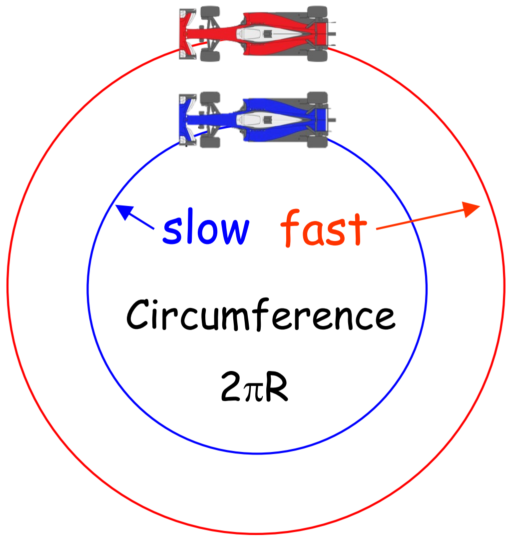
Overtaking in a Formula 1 Race





Overtaking in a Formula 1 Race

Overtaking in a Formula 1 Race



A F1 car wants to overtake another car! It will have a

- a different track length due to a 'dispersion orbit'
- and a different velocity.

$$T = \frac{L}{v} = \frac{2\pi R}{v} \quad \text{and} \quad f_r = \frac{1}{T} = \frac{v}{2\pi R}$$

$$\Rightarrow \frac{\Delta T}{T} = \frac{\Delta R}{R} - \frac{\Delta v}{v}$$

The winner depends on the relative change in speed compared to the relative change in track length!

v=speed of the car

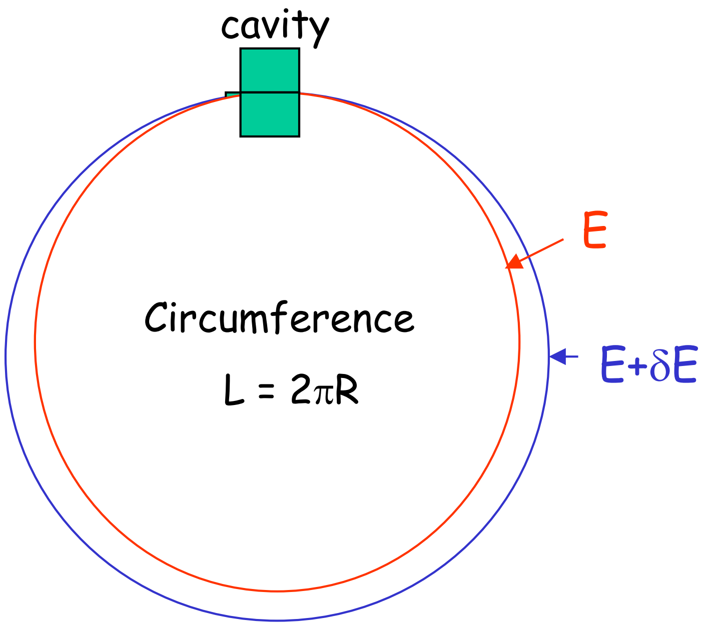
R=track physical radius

T=revolution period

f_r=revolution frequency

If the relative change in speed is larger than the relative change in track length => the red car will win!

Overtaking in a Synchrotron



p=particle momentum

R=synchrotron physical radius

T=revolution period

A particle slightly shifted in momentum will have a

- dispersion orbit and a different orbit length
- a different velocity.

As a result of both effects the revolution period T changes with a "slip factor" η :

$$\eta = \frac{dT/T}{dp/p}$$

Note: you also find η defined with a minus sign!

The "momentum compaction factor" is defined as relative orbit length change with momentum:

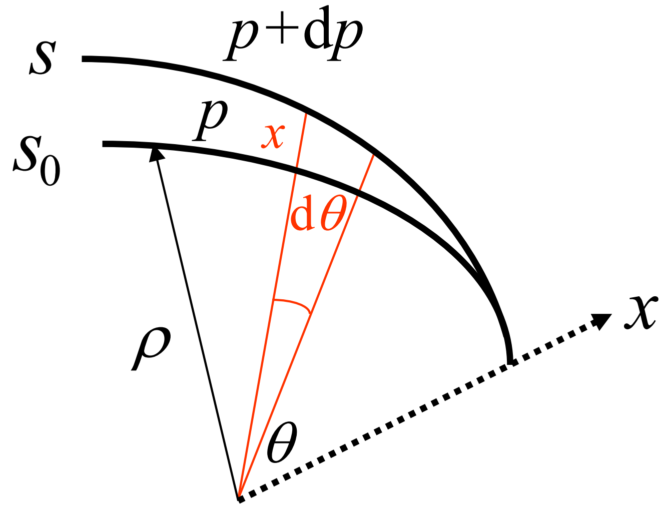
$$\alpha_c = \frac{dL/_L}{dp/_p} \qquad \alpha_c = \frac{p}{L}\frac{dL}{dp}$$

Momentum Compaction Factor

$$\alpha_c = \frac{p}{L}\frac{dL}{dp}$$

$$ds_0 = \rho d\theta$$

$$ds = (\rho + x)d\theta$$



The elementary path difference from the two orbits is:

definition of dispersion D_x

$$\frac{dl}{ds_0} = \frac{ds - ds_0}{ds_0} = \frac{x}{\rho} = \frac{D_x}{\rho}\frac{dp}{p}$$

$$x = x_0 + D_x \frac{\Delta p}{p}$$

leading to the total change in the circumference:

$$dL = \int_C dl = \int \frac{x}{\rho} ds_0 = \int \frac{D_x}{\rho}\frac{dp}{p} ds_0$$

$$\alpha_c = \frac{1}{L}\int_C \frac{D_x(s)}{\rho(s)} ds_0$$

With ρ=∞ in straight sections we get:

$$\alpha_c = \frac{\langle D_x \rangle_m}{R}$$

$\langle\ \rangle_m$ means that the average is considered over the bending magnet only

Property of the **transverse** beam optics!

Dispersion Effects – Revolution Period

The two effects of the orbit length and the particle velocity change the revolution period as:

$$T = \frac{L}{\beta c} \quad \Rightarrow \quad \frac{dT}{T} = \frac{dL}{L} - \frac{d\beta}{\beta} = \alpha_c \frac{dp}{p} - \frac{d\beta}{\beta}$$

↑ definition of momentum compaction factor

$$\frac{dT}{T} = \left(\alpha_c - \frac{1}{\gamma^2}\right)\frac{dp}{p}$$

$$p = mv = \beta\gamma \frac{E_0}{c} \quad \Rightarrow \quad \frac{dp}{p} = \frac{d\beta}{\beta} + \frac{d\left(1-\beta^2\right)^{-1/2}}{\left(1-\beta^2\right)^{-1/2}} = \underbrace{\left(1-\beta^2\right)^{-1}}_{\gamma^2} \frac{d\beta}{\beta}$$

Slip factor: $\eta = \alpha_c - \frac{1}{\gamma^2}$ or $\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$ with $\gamma_t = \frac{1}{\sqrt{\alpha_c}}$

Note: you also find η defined with a minus sign!

At transition energy, $\eta = 0$, the velocity change and the path length change with momentum compensate each other. So the revolution frequency there is independent from the momentum deviation.

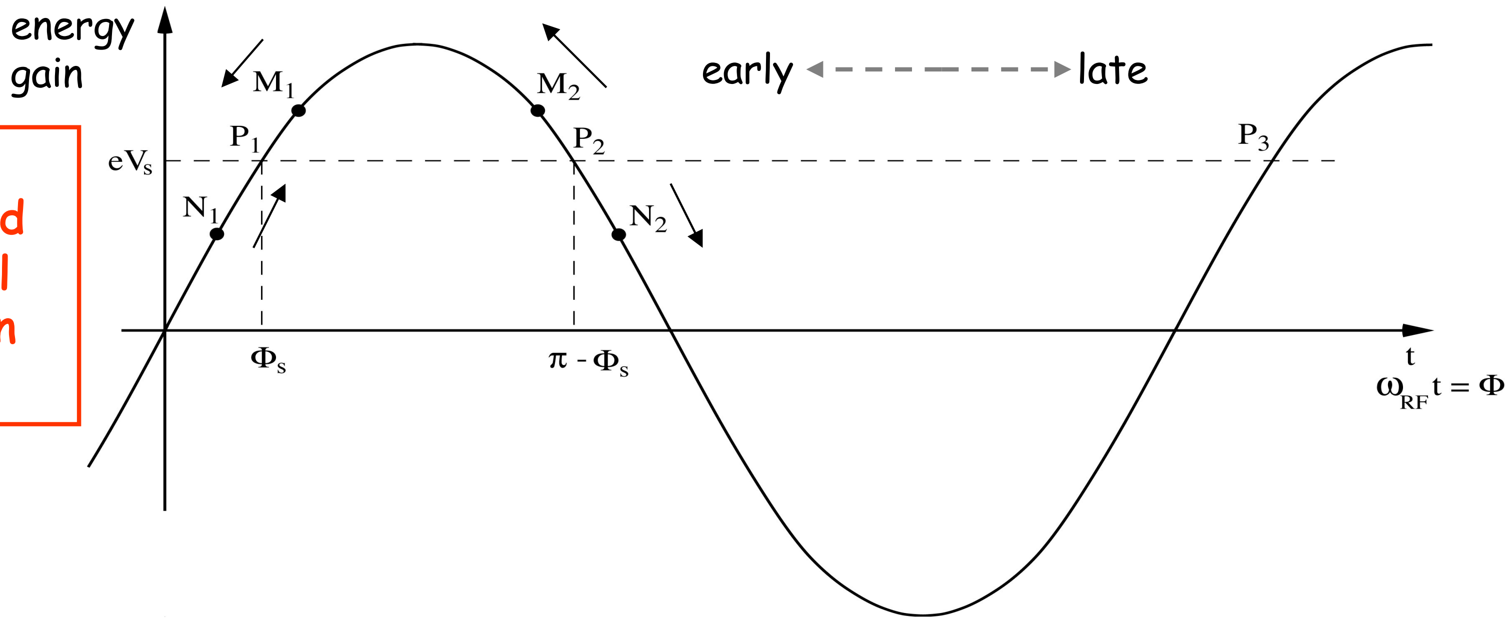
RECAP: Principle of Phase Stability (Linac)

Let's consider a succession of accelerating gaps, operating in the 2π mode, for which the synchronism condition is fulfilled for a phase Φ_s.

$$eV_s = e\hat{V}\sin\Phi_s$$

is the energy gain in one gap for the particle to reach the next gap with the same RF phase: P_1, P_2, …… are fixed points.

For a 2π mode, the electric field is the same in all gaps at any given time.



If an energy increase is transferred into a velocity increase =>

M_1 & N_1 will move towards P_1 => stable

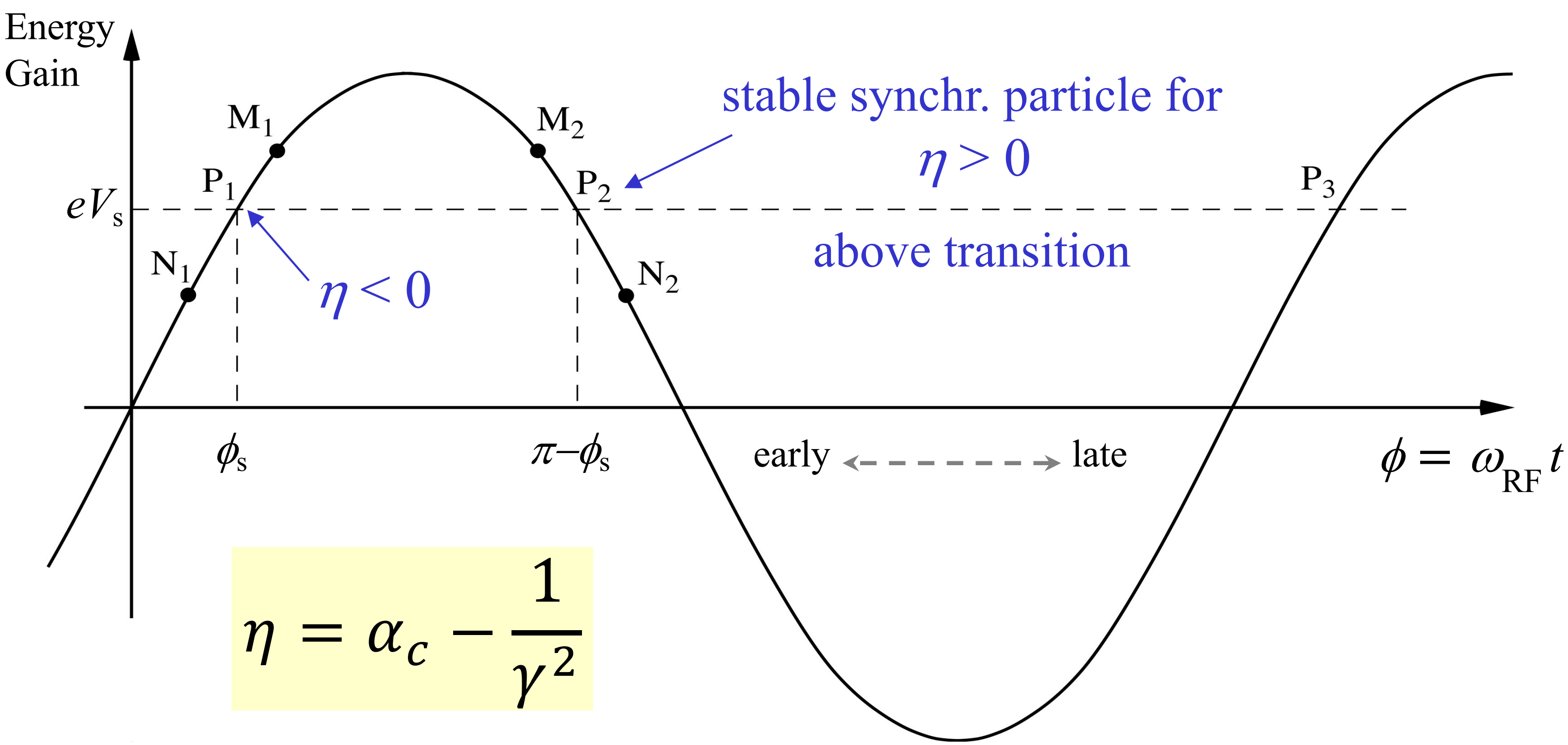
M_2 & N_2 will go away from P_2 => unstable

(Highly relativistic particles have no significant velocity change)

Phase Stability in a Synchrotron

From the definition of η it is clear that an increase in momentum gives
- below transition ($\eta < 0$) a higher revolution frequency (increase in velocity dominates) while

- above transition ($\eta > 0$) a lower revolution frequency ($v \approx c$ and longer path) where the momentum compaction (generally > 0) dominates.



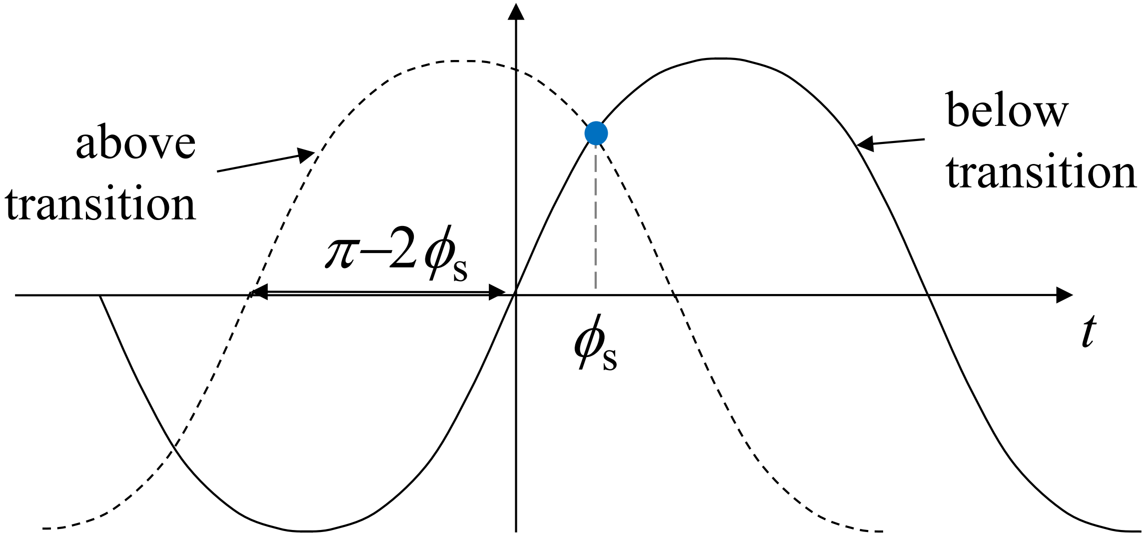
$$\eta = \alpha_c - \frac{1}{\gamma^2}$$

Crossing Transition

At transition, the velocity change and the path length change with momentum compensate each other. So the revolution frequency there is independent from the momentum deviation.

Crossing transition during acceleration makes the previous stable synchronous phase unstable. The RF system needs to make a rapid change of the RF phase, a 'phase jump'.

$$\alpha_c \sim \frac{1}{Q_x^2} \qquad \gamma_t = \frac{1}{\sqrt{\alpha_c}} \sim Q_x$$



In the PS: γ_t is at ~6 GeV

In the SPS: γ_t= 22.8, injection at γ=27.7

=> no transition crossing!

In the LHC: γ_t is at ~55 GeV, also far below injection energy

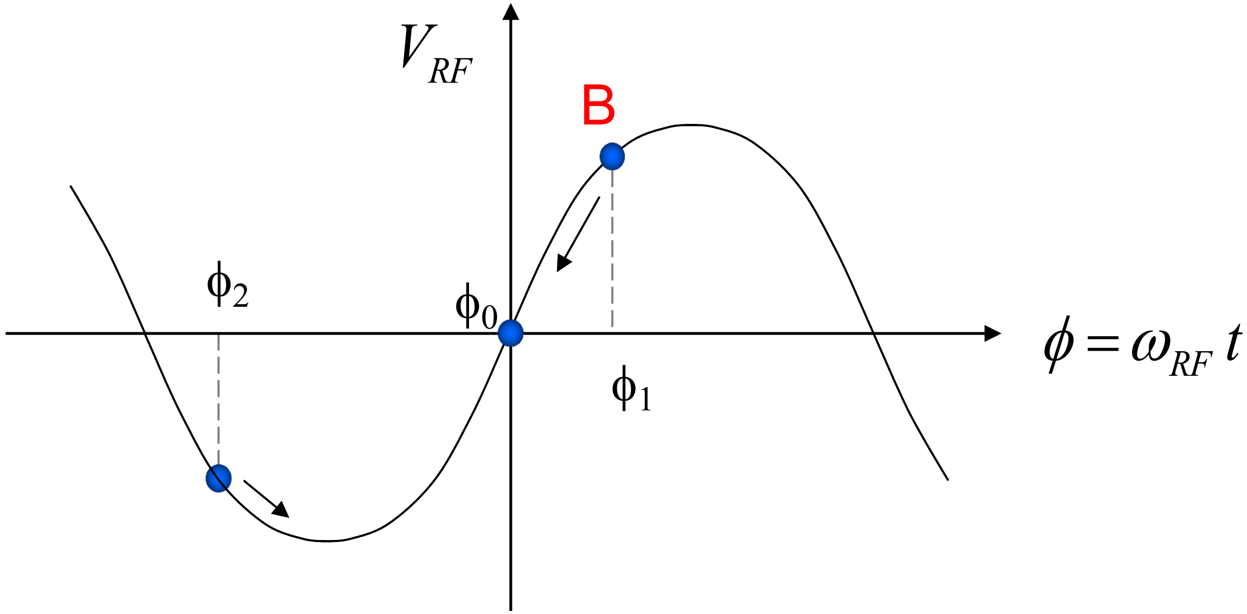
Transition crossing not needed in leptons machines, why?

Dynamics: Synchrotron oscillations

Simple case (no accel.): B = const., below transition $\gamma < \gamma_t$

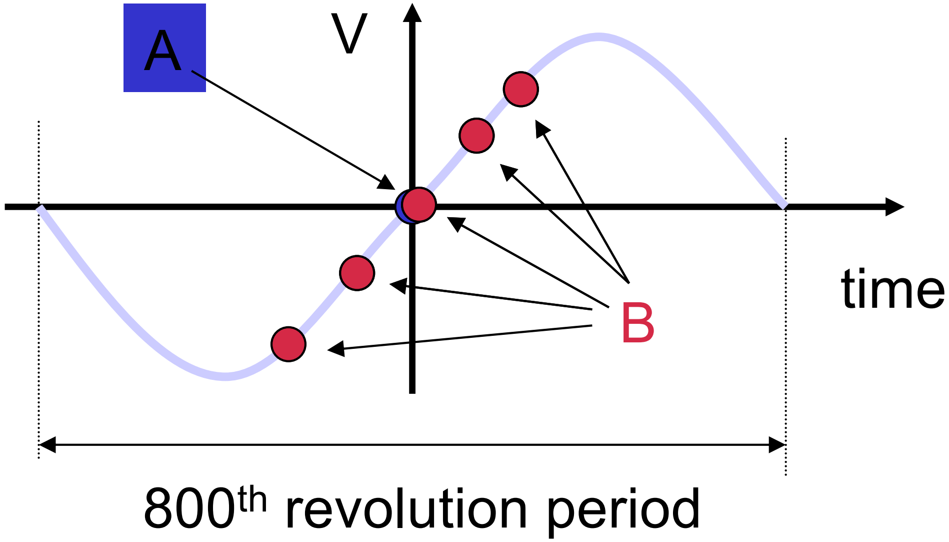
The phase of the synchronous particle must therefore be $\phi_0 = 0$.

Φ_1 - The particle B is accelerated
- Below transition, an energy increase means an increase in revolution frequency
- The particle arrives earlier – tends toward ϕ_0



ϕ_2 - The particle is decelerated
- decrease in energy - decrease in revolution frequency
- The particle arrives later – tends toward ϕ_0

Synchrotron oscillations

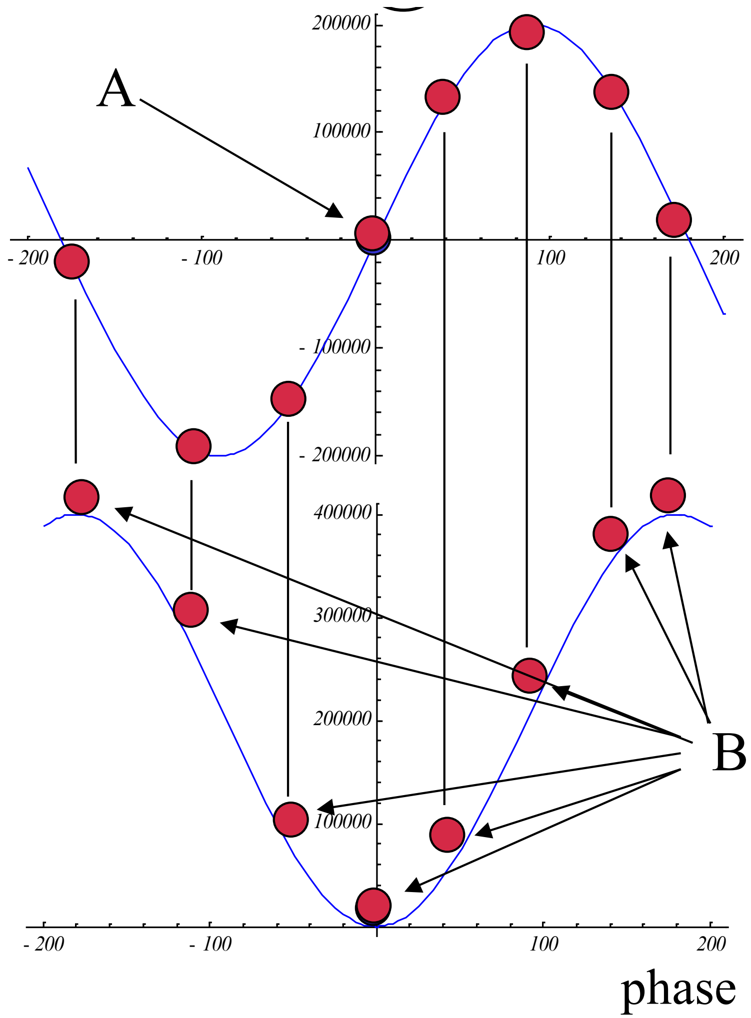


Particle B is performing Synchrotron Oscillations around synchronous particle A.

The amplitude depends on the initial phase and energy.

The oscillation frequency is much slower than in the transverse plane. It takes a large number of revolutions for one complete oscillation. Restoring electric force smaller than magnetic force.

The Potential Well

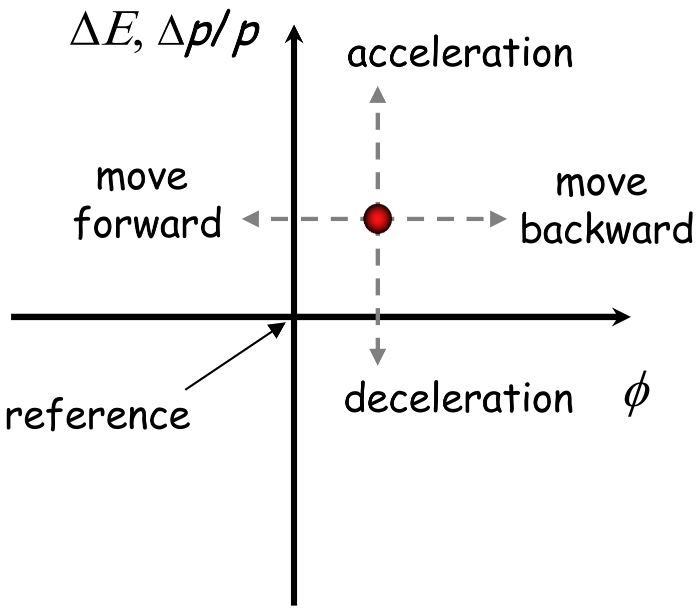


Cavity voltage

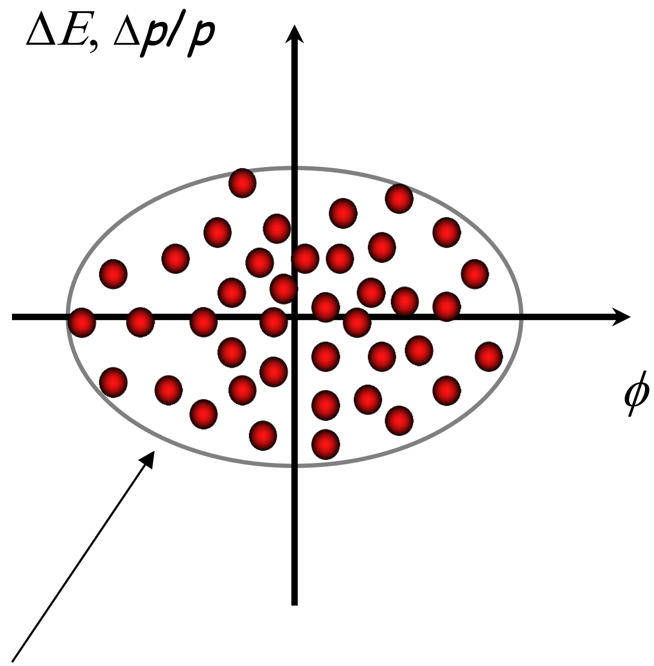
Potential well

Longitudinal phase space

The energy – phase oscillations can be drawn in phase space:



The particle trajectory in the phase space ($\Delta p/p$, ϕ) describes its longitudinal motion.



Emittance: phase space area including all the particles

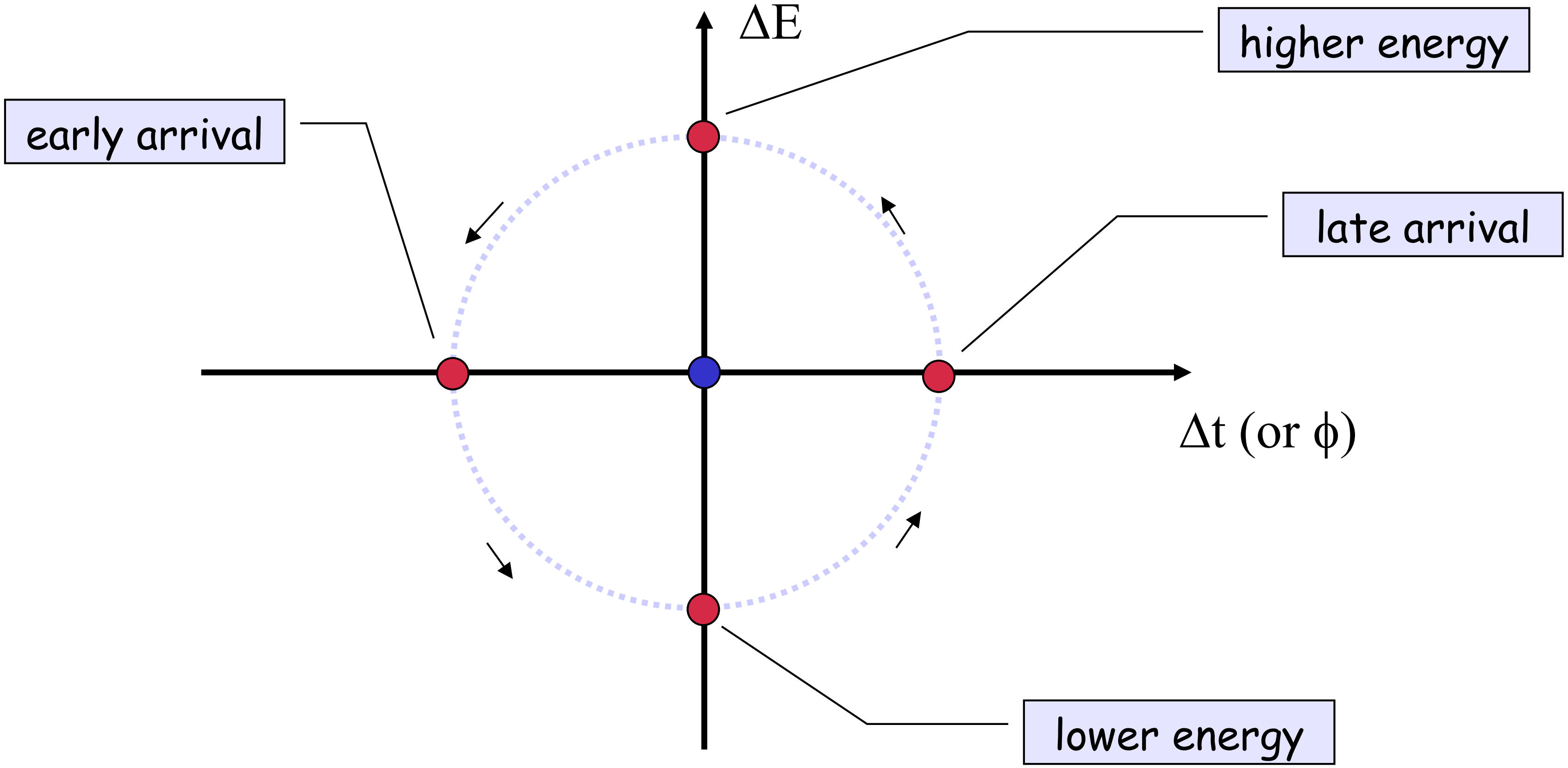
NB: if the emittance contour correspond to a possible orbit in phase space, its shape does not change with time (matched beam)

Longitudinal Phase Space Motion

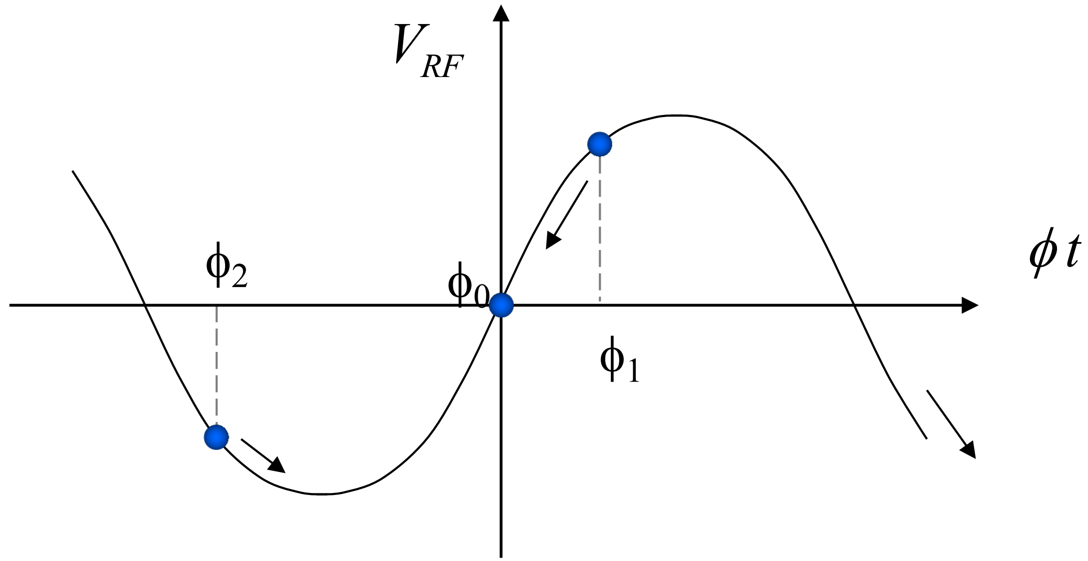
Particle B oscillates around particle A

This is a synchrotron oscillation

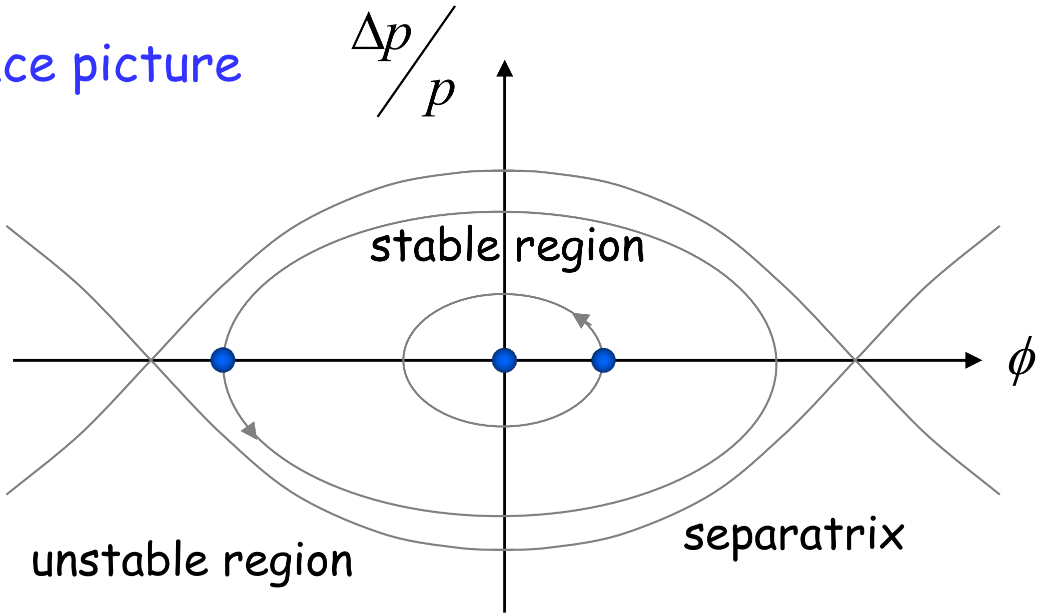
Plotting this motion in longitudinal phase space gives:



Synchrotron oscillations – No acceleration



Phase space picture

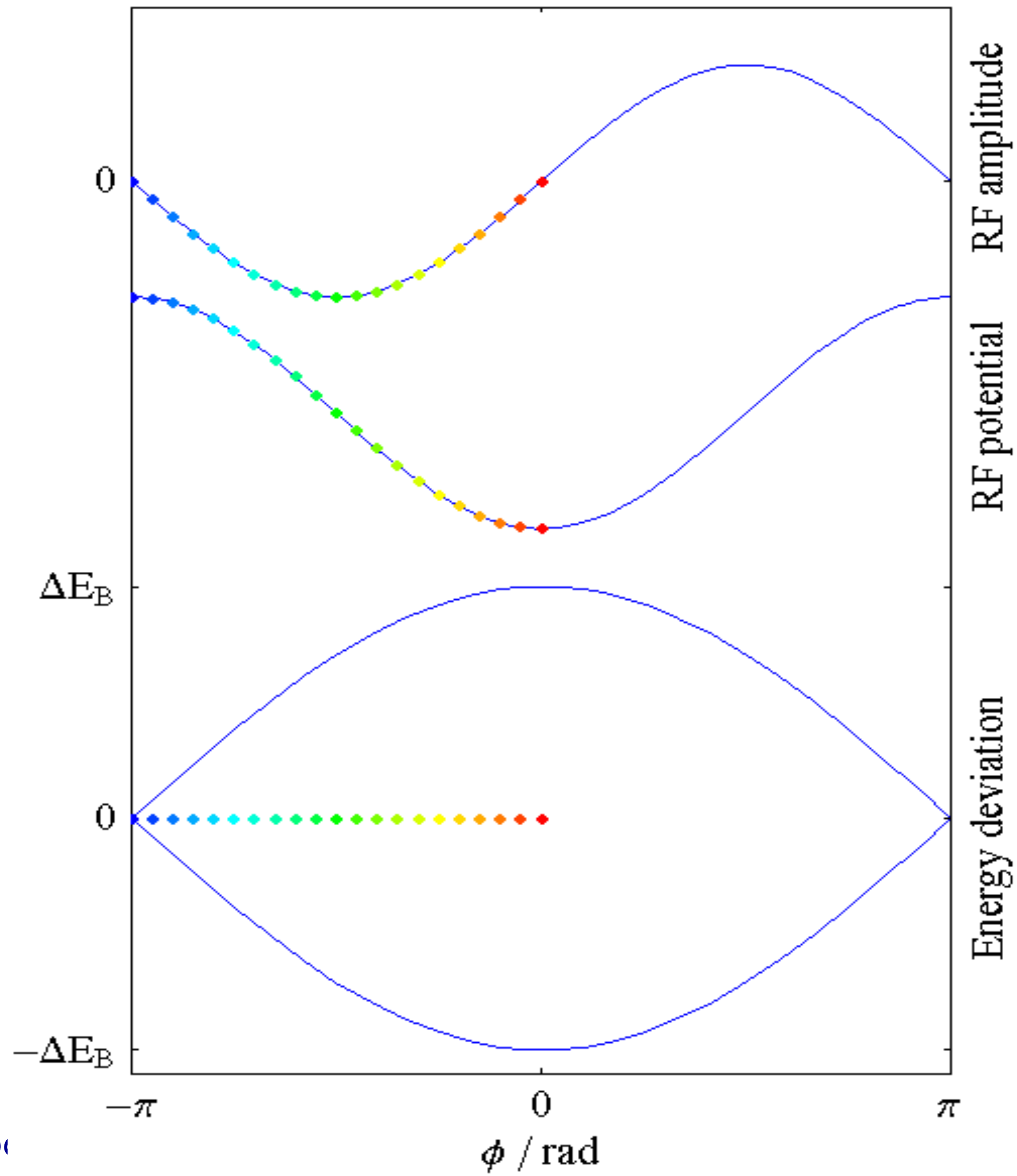


Synchrotron motion in phase space

The restoring force is non-linear.
⇒ speed of motion depends on position in phase-space

(here shown for a stationary bucket)

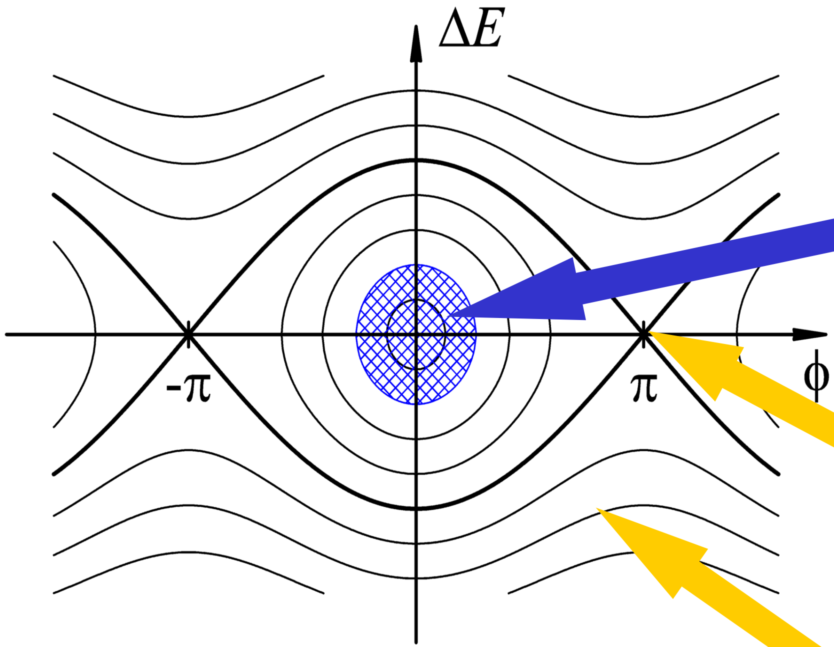
Remark:
Synchrotron frequency much smaller than betatron frequency.



Synchrotron motion in phase space

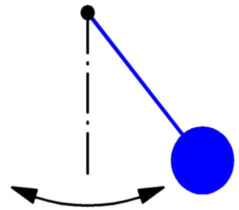
Dynamics of a particle
Non-linear, conservative oscillator → e.g. pendulum

ΔE-ϕ **phase space** of a stationary bucket
(when there is no acceleration)



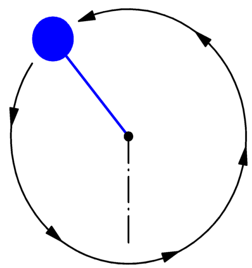
Bucket area: area enclosed by the separatrix
The area covered by particles is the longitudinal emittance

Particle **inside the separatrix:**



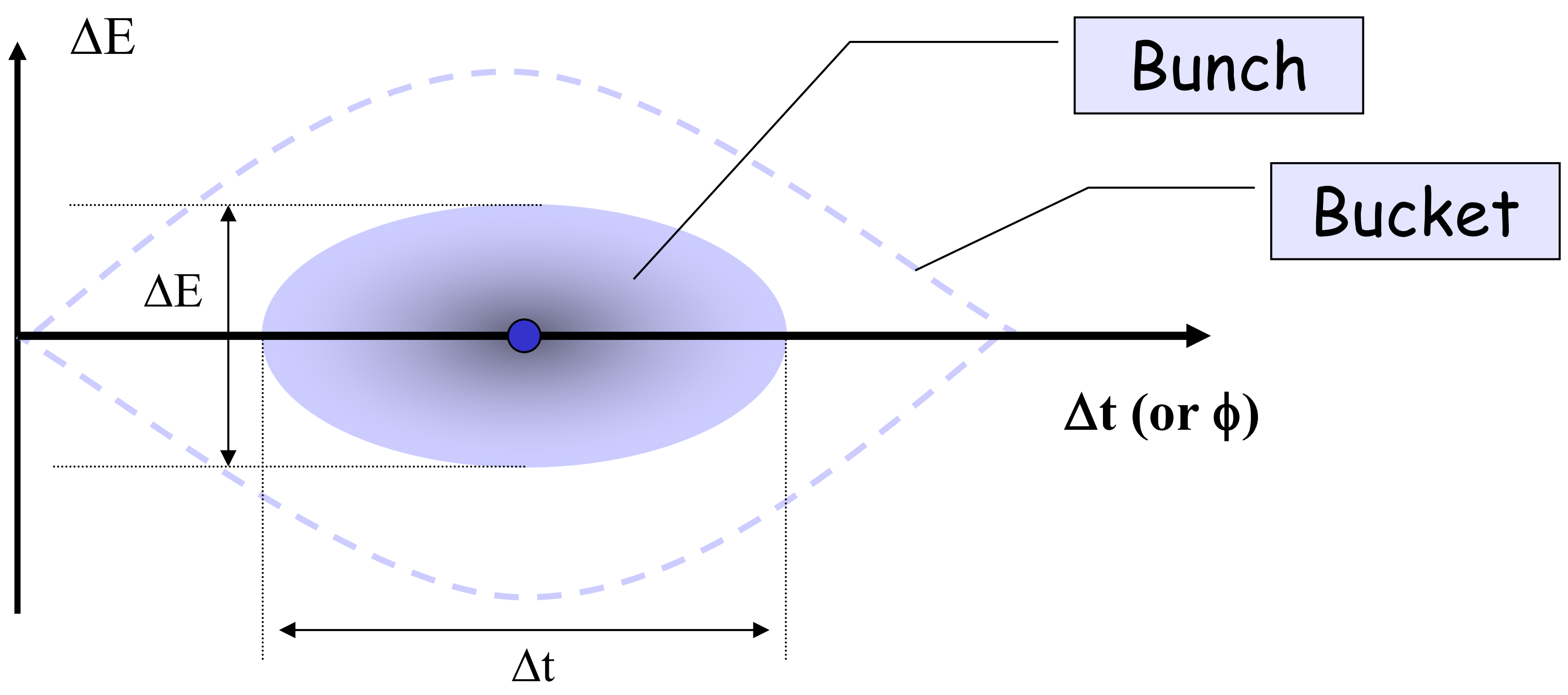
Particle at the **unstable fix-point**

Particle **outside the separatrix:**



(Stationary) Bunch & Bucket

The bunches of the beam fill usually a part of the bucket area.



Bucket area = <u>longitudinal Acceptance</u> [eVs]

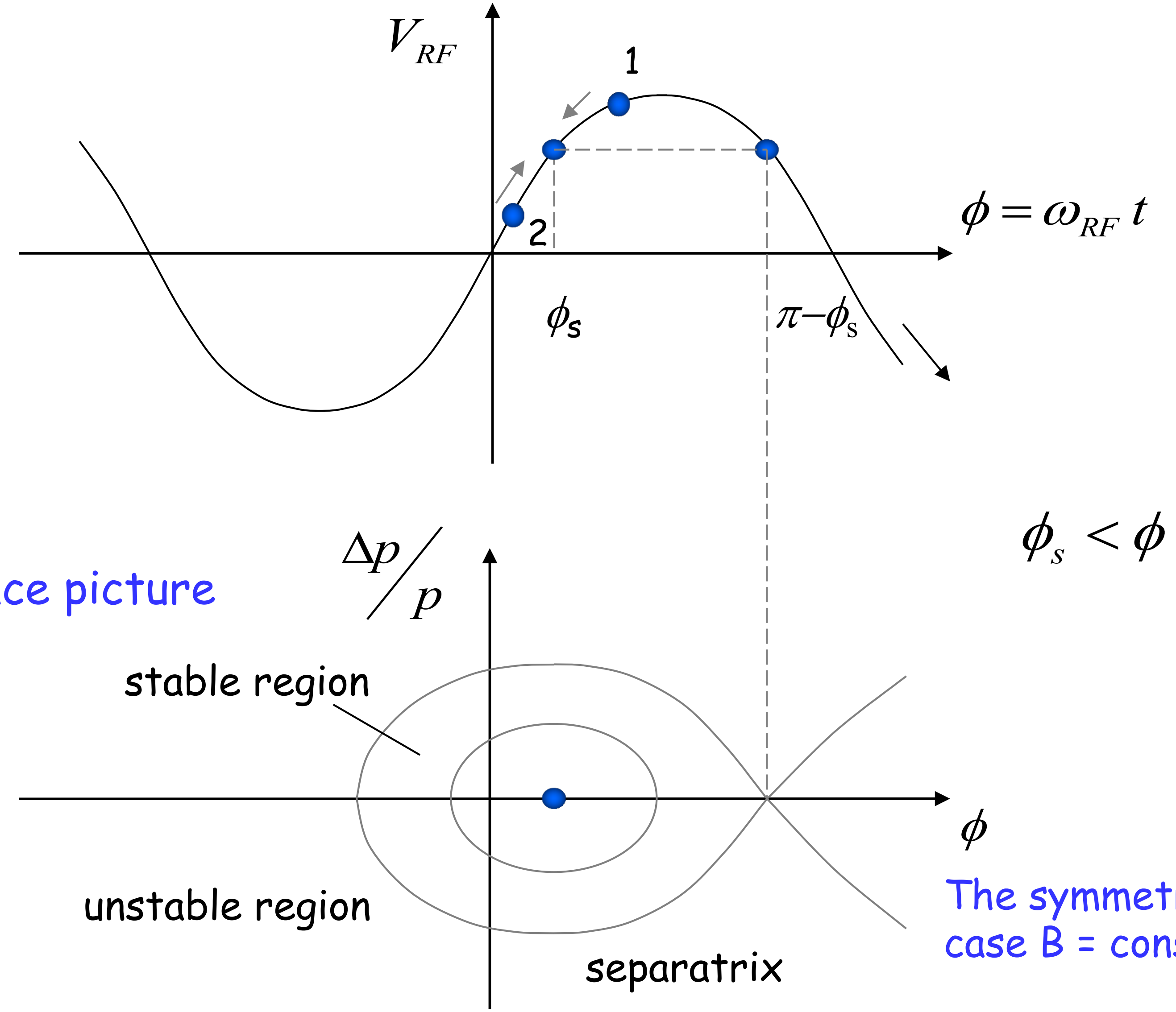
Bunch area = <u>longitudinal beam emittance</u> (rms) = $\pi \, \sigma_E \, \sigma_t$ [eVs]

Attention: Different definitions are used!

Synchrotron oscillations (with acceleration)

Case with acceleration *B* increasing

$\gamma < \gamma_t$

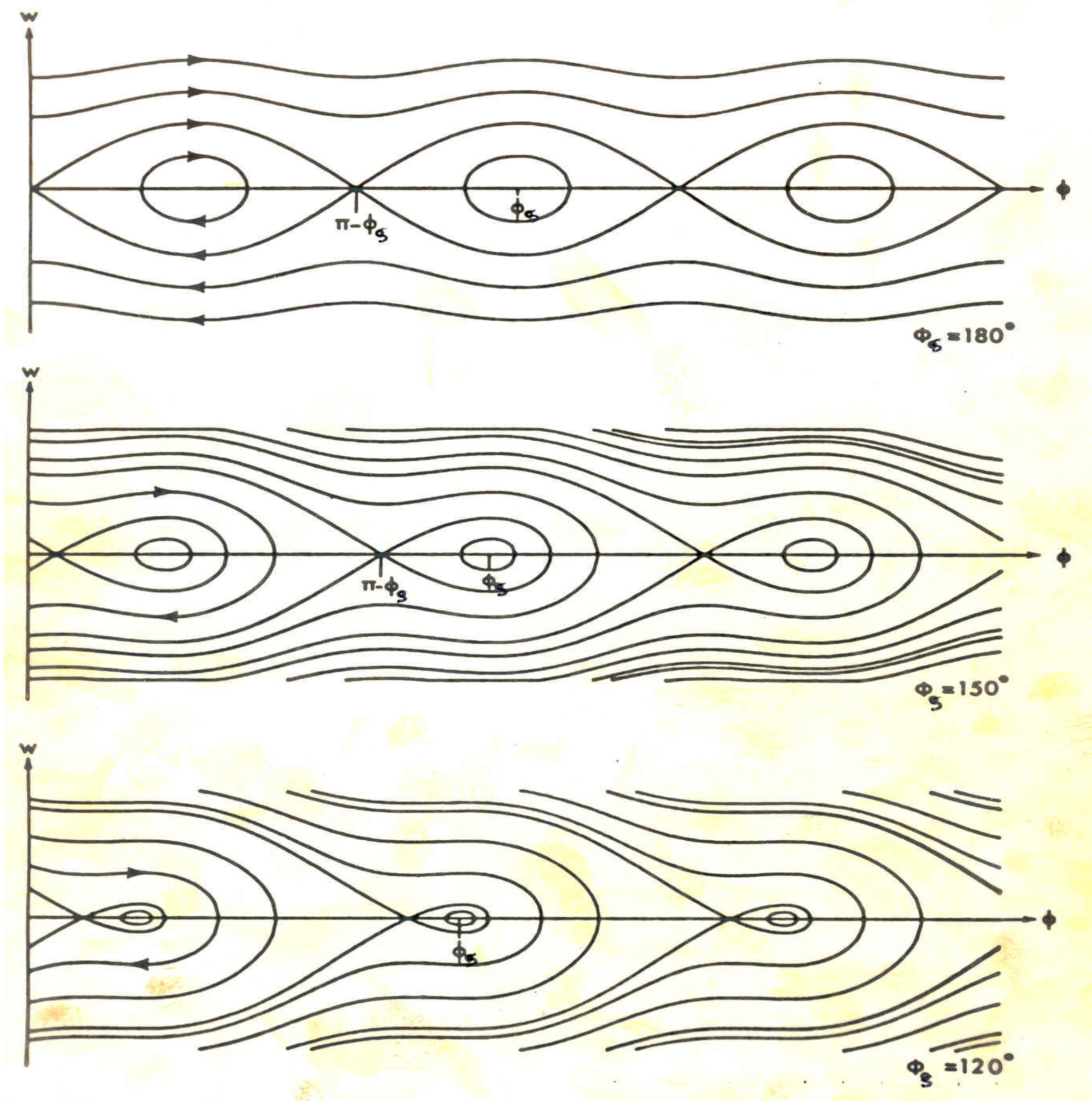


$$\phi_s < \phi < \pi - \phi_s$$

Phase space picture

The symmetry of the case B = const. is lost

RF Acceptance versus Synchronous Phase



The areas of stable motion (closed trajectories) are called "BUCKET". The number of circulating buckets is equal to "h".

The phase extension of the bucket is maximum for ϕ_s =180° (or 0°) which means no acceleration.

During acceleration, the buckets get smaller, both in length and energy acceptance.

=> Injection preferably without acceleration.

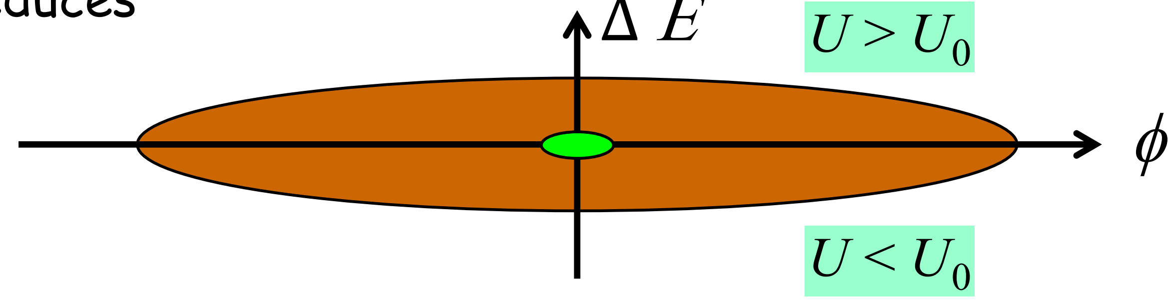
Longitudinal Motion with Synchrotron Radiation

Synchrotron radiation energy-loss energy dependant:

$$U_0 = \frac{4}{3}\pi \frac{r_{e,p}}{(m_0 c^2)^3}\frac{E^4}{\rho}$$

During one period of synchrotron oscillation:

- when the particle is in the upper half-plane, it loses more energy per turn, its energy gradually reduces



- when the particle is in the lower half-plane, it loses less energy per turn, but receives U_0 on the average, so its energy deviation gradually reduces

The phase space trajectory spirals towards the origin (limited by quantum excitations)

=> The synchrotron motion is damped toward an equilibrium bunch length and energy spread.

$$\sigma_\tau = \frac{\alpha}{\Omega_s}\left(\frac{\sigma_\varepsilon}{E}\right)$$

More details in the lectures on *Electron Beam Dynamics*

Longitudinal Dynamics in Synchrotrons

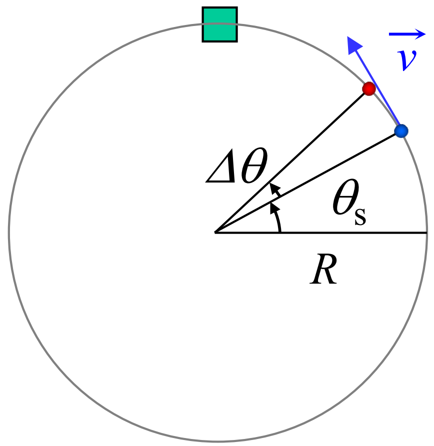
Now we will look more quantitatively at the "synchrotron motion".

The RF acceleration process clearly emphasizes two coupled variables, the energy gained by the particle and the RF phase experienced by the same particle.
Since there is a well defined synchronous particle which has always the same phase ϕ_s, and the nominal energy E_0, it is sufficient to follow other particles with respect to that particle.
So let's introduce the following **reduced variables**:

particle RF phase :	$\Delta\phi = \phi - \phi_s$
particle momentum :	$\Delta p = p - p_0$
particle energy :	$\Delta E = E - E_0$
angular frequency :	$\Delta\omega = \omega - \omega_0$
azimuth orbital angle:	$\Delta\theta = \theta - \theta_s$

Look at difference from synchronous particle

First Energy-Phase Equation



$$f_{RF} = h f_r \quad \Rightarrow \quad \Delta\phi = -h\,\Delta\theta \quad with \quad \theta = \int \omega \; dt$$

particle ahead arrives earlier
=> smaller RF phase

For a given particle with respect to the reference one:

$$\Delta\omega = \frac{d}{dt}(\Delta\theta) = -\frac{1}{h}\frac{d}{dt}(\Delta\phi) = -\frac{1}{h}\frac{d\phi}{dt}$$

Since: $\eta = -\frac{p_0}{\omega_0}\left(\frac{d\omega}{dp}\right)_s$ and $E^2 = E_0^2 + p^2c^2$

$$\Delta E = v_s \Delta p = \omega_0 R \Delta p$$

one gets:

$$\frac{\Delta E}{\omega_0} = \frac{p_0 R}{h\eta\omega_0}\frac{d(\Delta\phi)}{dt} = \frac{p_0 R}{h\eta\omega_0}\dot{\phi}$$

Second Energy-Phase Equation

The rate of energy gained by a particle is: $\frac{dE}{dt} = e\hat{V}\sin\phi \frac{\omega_r}{2\pi}$

The rate of relative energy gain with respect to the reference particle is then:

$$2\pi\Delta\left(\frac{\dot{E}}{\omega_0}\right) = e\,\hat{V}(\sin\phi - \sin\phi_s)$$

Expanding the left-hand side to first order:

$$\Delta\left(\dot{E}T_r\right) \cong \dot{E}\Delta T_r + T_{rs}\Delta\dot{E} = \Delta E\,\dot{T}_r + T_{rs}\Delta\dot{E} = \frac{d}{dt}\left(T_{rs}\Delta E\right)$$

leads to the second energy-phase equation:

$$2\pi\frac{d}{dt}\left(\frac{\Delta E}{\omega_0}\right) = e\,\hat{V}(\sin\phi - \sin\phi_s)$$

Equations of Longitudinal Motion

$$\frac{\Delta E}{\omega_0} = \frac{p_0 R}{h\eta\omega_0}\dot{\phi}$$

$$2\pi \frac{d}{dt}\left(\frac{\Delta E}{\omega_0}\right) = e\,\hat{V}(\sin\phi - \sin\phi_s)$$

deriving and combining

$$\frac{d}{dt}\left[\frac{-p_0 R}{h\eta\omega_0}\frac{d\phi}{dt}\right] + \frac{e\,\hat{V}}{2\pi}(\sin\phi - \sin\phi_s) = 0$$

This second order equation is non linear. Moreover the parameters within the bracket are in general slowly varying with time.

We will study some cases in the following…

Small Amplitude Oscillations

Let's assume constant parameters R, p_0, ω_0 and η:

$$\ddot{\phi} + \frac{\Omega_s^2}{\cos\phi_s}(\sin\phi - \sin\phi_s) = 0$$

with

$$\Omega_s^2 = \frac{-q\hat{V}_{RF}\eta h\omega_0}{2\pi R p_0}\cos\phi_s$$

Consider now small phase deviations from the reference particle:

$$\sin\phi - \sin\phi_s = \sin(\phi_s + \Delta\phi) - \sin\phi_s \cong \cos\phi_s \Delta\phi$$

(for small $\Delta\phi$)

and the corresponding linearized motion reduces to a harmonic oscillation:

$$\ddot{\phi} + \Omega_s^2 \Delta\phi = 0$$

where Ω_s is the synchrotron angular frequency.

The **synchrotron tune ν_s** is the number of synchrotron oscillations per revolution:

$$\nu_s = \Omega_s / \omega_0$$

Typical values are <<1, as it takes several 10 - 1000 turns per oscillation.

- proton synchrotrons of the order 10^{-3}
- electron storage rings of the order 10^{-1}

Stability condition for ϕ_s

$$\Omega_s^2 = \frac{-q\hat{V}_{RF}\eta h\omega_0}{2\pi R p_0}\cos\phi_s \Leftrightarrow \Omega_s^2 = \omega_0^2\frac{-q\hat{V}_{RF}\eta h}{2\pi\beta^2 E}\cos\phi_s$$

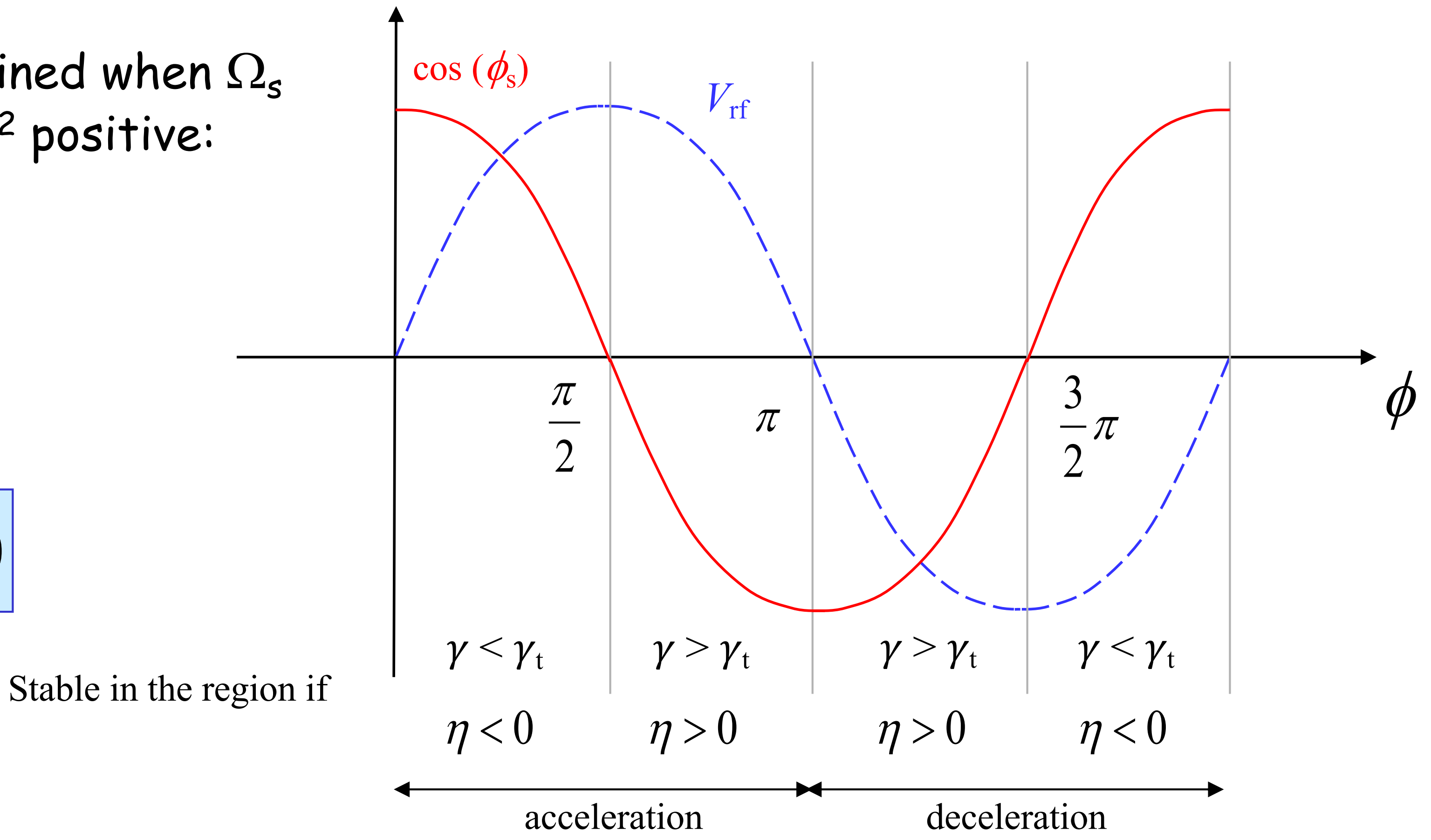
with $Rp = \dfrac{\beta^2 E}{\omega}$

Stability is obtained when Ω_s is real and so Ω_s^2 positive:

$$\Omega_s^2 > 0$$

$$\Updownarrow$$

$$\eta\cos\phi_s < 0$$



Large Amplitude Oscillations

For larger phase (or energy) deviations from the reference the second order differential equation is non-linear:

$$\ddot{\phi} + \frac{\Omega_s^2}{\cos\phi_s}\left(\sin\phi - \sin\phi_s\right) = 0$$

(Ω_s as previously defined)

Multiplying by $\dot{\phi}$ and integrating gives an invariant of the motion:

$$\frac{\dot{\phi}^2}{2} - \frac{\Omega_s^2}{\cos\phi_s}\left(\cos\phi + \phi\sin\phi_s\right) = I$$

which for small amplitudes reduces to:

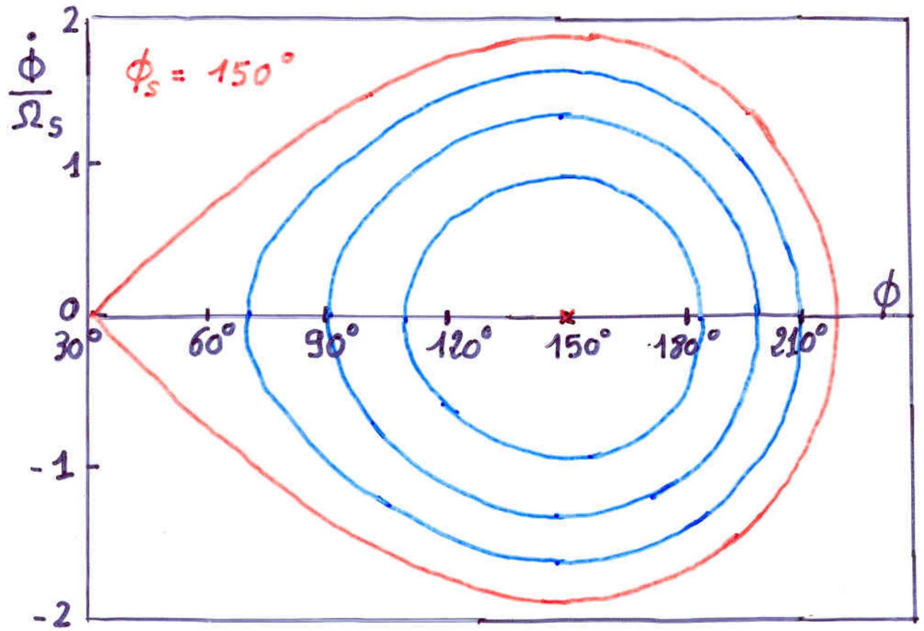
$$\frac{\dot{\phi}^2}{2} + \Omega_s^2\frac{(\Delta\phi)^2}{2} = I'$$

(the variable is $\Delta\phi$, and ϕ_s is constant)

Similar equations exist for the second variable : $\Delta E \propto d\phi/dt$

Large Amplitude Oscillations (2)

When ϕ reaches π-ϕ_s the force goes to zero and beyond it becomes non restoring.
Hence π-ϕ_s is an extreme amplitude for a stable motion which in the phase space($\frac{\dot{\phi}}{\Omega_s}, \Delta\phi$) is shown as closed trajectories.



Equation of the separatrix:

$$\frac{\dot{\phi}^2}{2} - \frac{\Omega_s^2}{\cos\phi_s}\left(\cos\phi + \phi\sin\phi_s\right) = -\frac{\Omega_s^2}{\cos\phi_s}\left(\cos(\pi - \phi_s) + (\pi - \phi_s)\sin\phi_s\right)$$

Second value ϕ_m where the separatrix crosses the horizontal axis:

$$\cos\phi_m + \phi_m\sin\phi_s = \cos(\pi - \phi_s) + (\pi - \phi_s)\sin\phi_s$$

Energy Acceptance

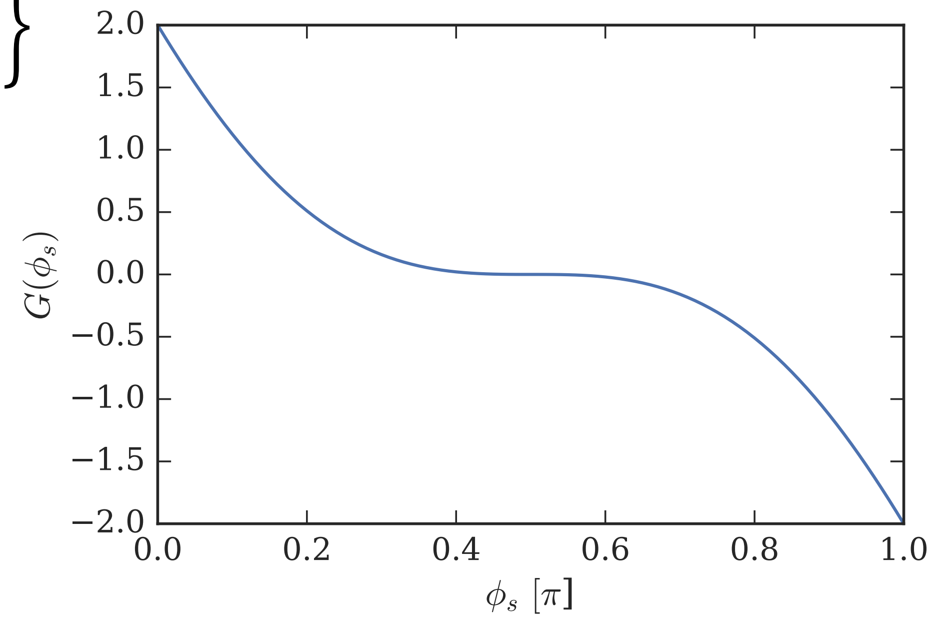
From the equation of motion it is seen that $\dot{\phi}$ reaches an extreme at $\phi = \phi_s$.
Introducing this value into the equation of the separatrix gives:

$$\dot{\phi}^2_{max} = 2\Omega_s^2 \left\{ 2 + \left(2\phi_s - \pi\right)\tan\phi_s \right\}$$

That translates into an energy acceptance:

$$\left(\frac{\Delta E}{E_0}\right)_{max} = \pm\beta\sqrt{\frac{-q\hat{V}}{\pi h \eta E_0} G(\phi_s)}$$

$$G(\phi_s) = \left[2\cos\phi_s + \left(2\phi_s - \pi\right)\sin\phi_s\right]$$



This "RF acceptance" depends strongly on ϕ_s and plays an important role for the capture at injection, and the stored beam lifetime.

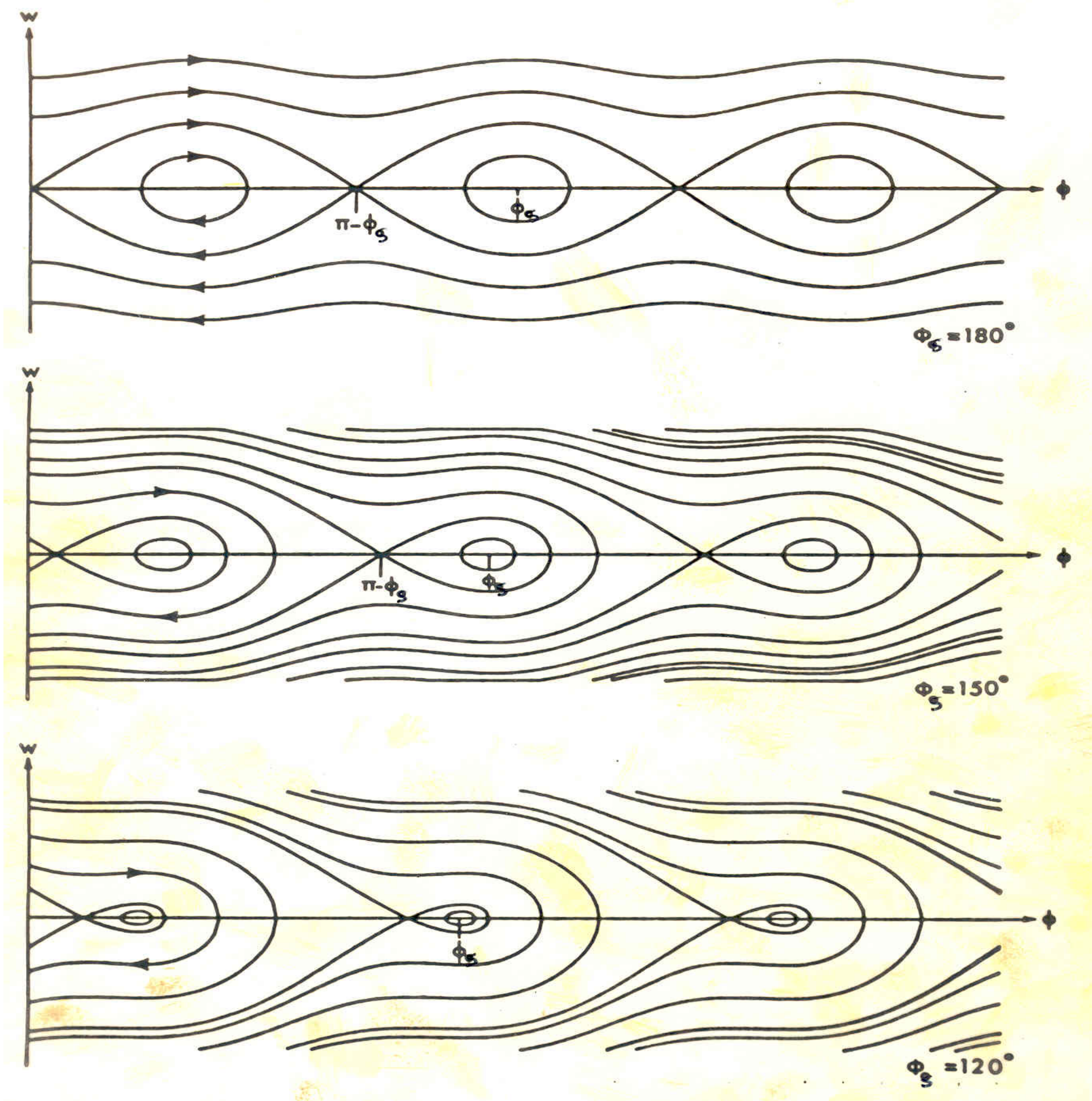
It's largest for ϕ_s=0 and ϕ_s=π (no acceleration, depending on η).

It becomes smaller during acceleration, when ϕ_s is changing

Need a higher RF voltage for higher acceptance.

For the same RF voltage it is smaller for higher harmonics h.

RF Acceptance versus Synchronous Phase



The areas of stable motion (closed trajectories) are called "BUCKET". The number of circulating buckets is equal to "h".

The phase extension of the bucket is maximum for ϕ_s =180° (or 0°) which means no acceleration.

During acceleration, the buckets get smaller, both in length and energy acceptance.

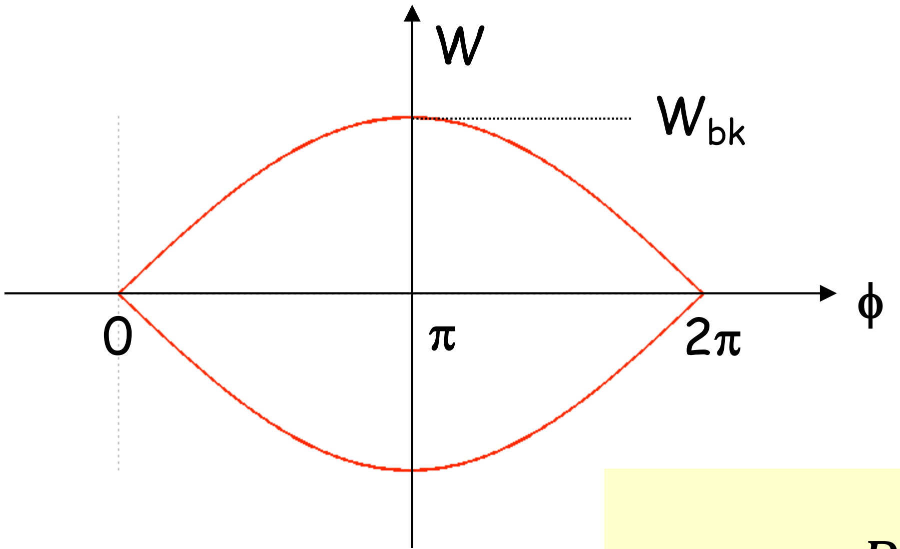
=> Injection preferably without acceleration.

Stationnary Bucket - Separatrix

This is the case $\sin\phi_s=0$ (no acceleration) which means $\phi_s=0$ or π . The equation of the separatrix for $\phi_s=\pi$ (above transition) becomes:

$$\frac{\dot{\phi}^2}{2}+\Omega_s^2\cos\phi=\Omega_s^2 \qquad \frac{\dot{\phi}^2}{2}=2\Omega_s^2\sin^2\frac{\phi}{2}$$

Replacing the phase derivative by the (canonical) variable W:



$$W=\frac{\Delta E}{\omega_0}=\frac{p_0 R}{h\eta\omega_0}\dot{\phi}$$

and introducing the expression for Ω_s leads to the following equation for the separatrix:

with $C=2\pi R$

$$W=\pm\frac{R}{c}\sqrt{\frac{2q\hat{V}E_0}{\pi h\eta}}\sin\frac{\phi}{2}=\pm W_{bk}\sin\frac{\phi}{2}$$

Bucket height – bucket area

Setting $\phi=\pi$ in the previous equation gives the height of the stationary bucket:

$$W_{bk} = \frac{R}{c}\sqrt{\frac{2q\hat{V}E_0}{\pi h|\eta|}}$$

The bucket area is: $$A_{bk} = 2\int_0^{2\pi} W\, d\phi$$

Since: $$\int_0^{2\pi} \sin\frac{\phi}{2}\, d\phi = 4$$

one gets: $$A_{bk} = 8\, W_{bk} = \frac{8R}{c}\sqrt{\frac{2q\hat{V}E_0}{\pi h|\eta|}}$$ → $$W_{bk} = \frac{A_{bk}}{8}$$

For an accelerating bucket, this area gets reduced by a factor depending on Φ_s:

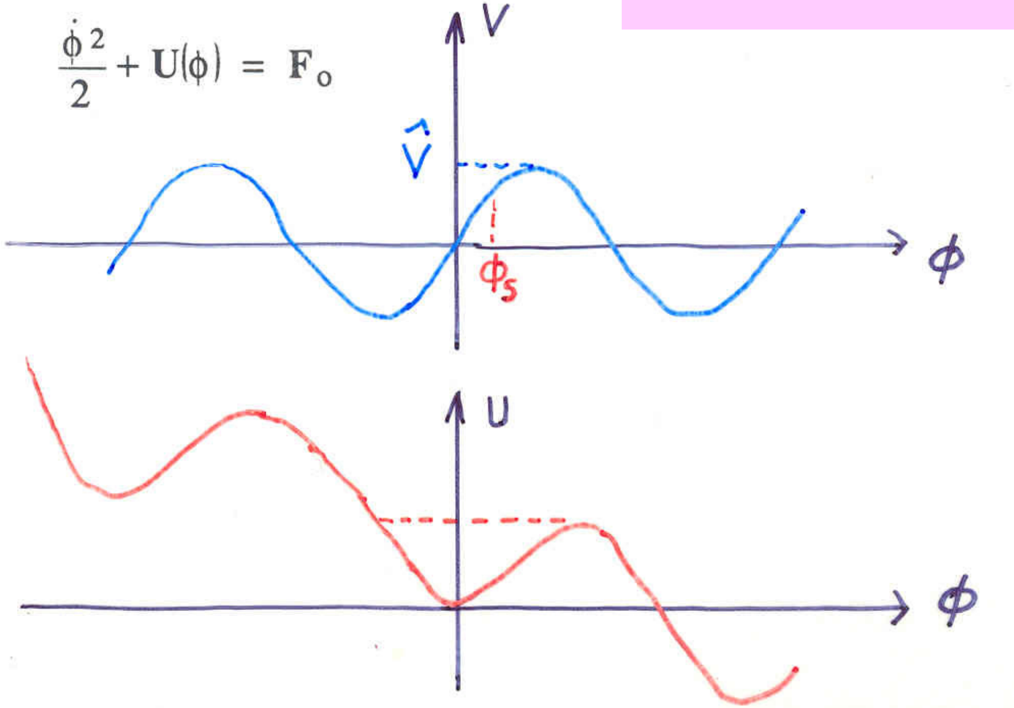
$$\alpha(\phi_s) \approx \frac{1 - \sin\phi_s}{1 + \sin\phi_s}$$

Potential Energy Function

The longitudinal motion is produced by a force that can be derived from a scalar potential:

$$\frac{d^2\phi}{dt^2} = F(\phi) \qquad F(\phi) = -\frac{\partial U}{\partial \phi}$$

$$U = -\int_0^{\phi} F(\phi)\, d\phi = -\frac{\Omega_s^2}{\cos\phi_s}\left(\cos\phi + \phi\sin\phi_s\right) - F_0$$



The sum of the potential energy and kinetic energy is constant and by analogy represents the total energy of a non-dissipative system.

Hamiltonian of Longitudinal Motion

Introducing a new convenient variable, W, leads to the 1st order equations:

$$W = \frac{\Delta E}{\omega_0} \longrightarrow \quad \frac{d\phi}{dt} = \frac{h\eta\omega_0}{p_0 R} W$$

$$\frac{dW}{dt} = \frac{e\hat{V}}{2\pi}(\sin\phi - \sin\phi_s)$$

The two variables ϕ,W are canonical since these equations of motion can be derived from a Hamiltonian H(ϕ,W,t):

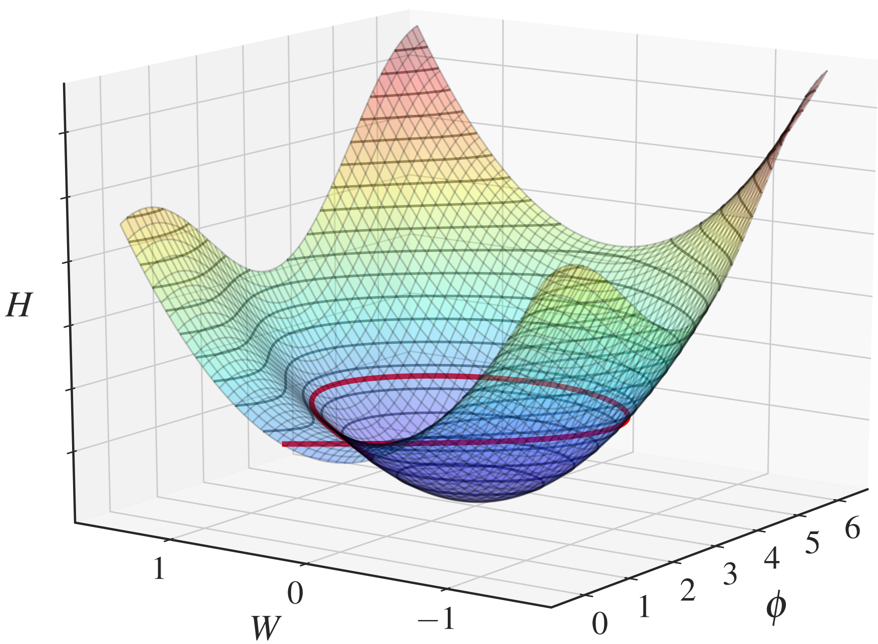
$$\frac{d\phi}{dt} = \frac{\partial H}{\partial W} \qquad \frac{dW}{dt} = -\frac{\partial H}{\partial \phi}$$

$$H(\phi, W) = \frac{1}{2}\frac{h\eta\omega_0}{p_0 R} W^2 + \frac{e\hat{V}}{2\pi}[\cos\phi - \cos\phi_s + (\phi - \phi_s)\sin\phi_s]$$

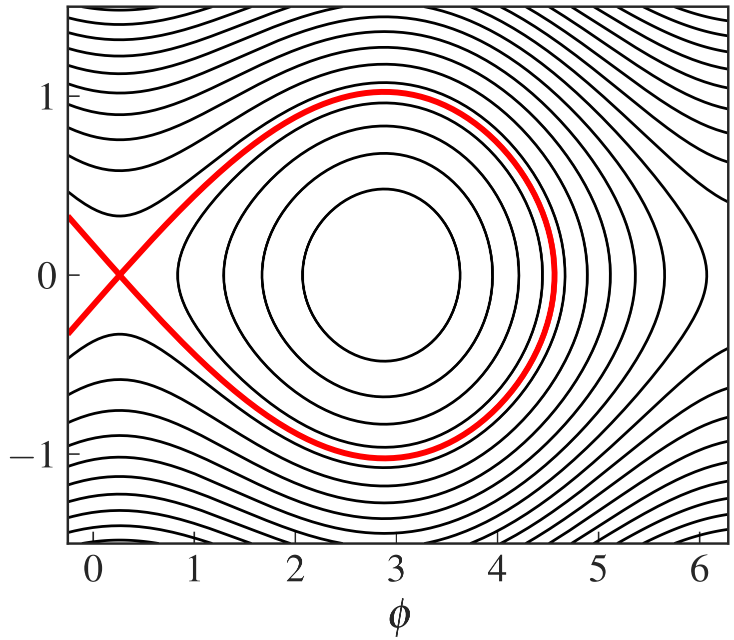
Hamiltonian of Longitudinal Motion

What does it represent? The total energy of the system!

Surface of H (φ,W)



Contours of H (φ,W)

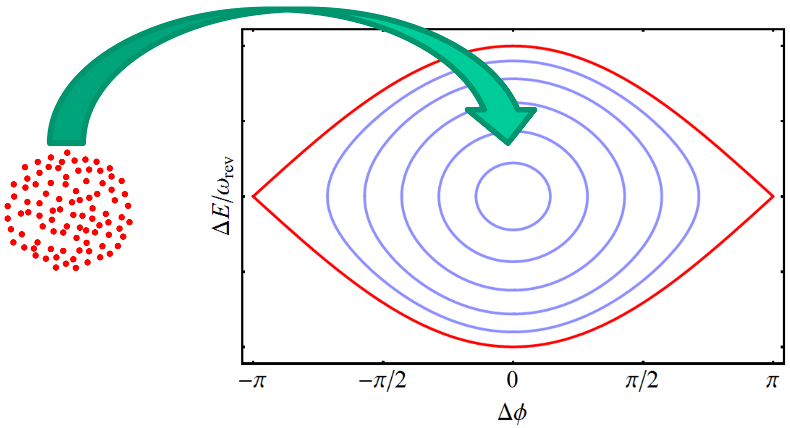


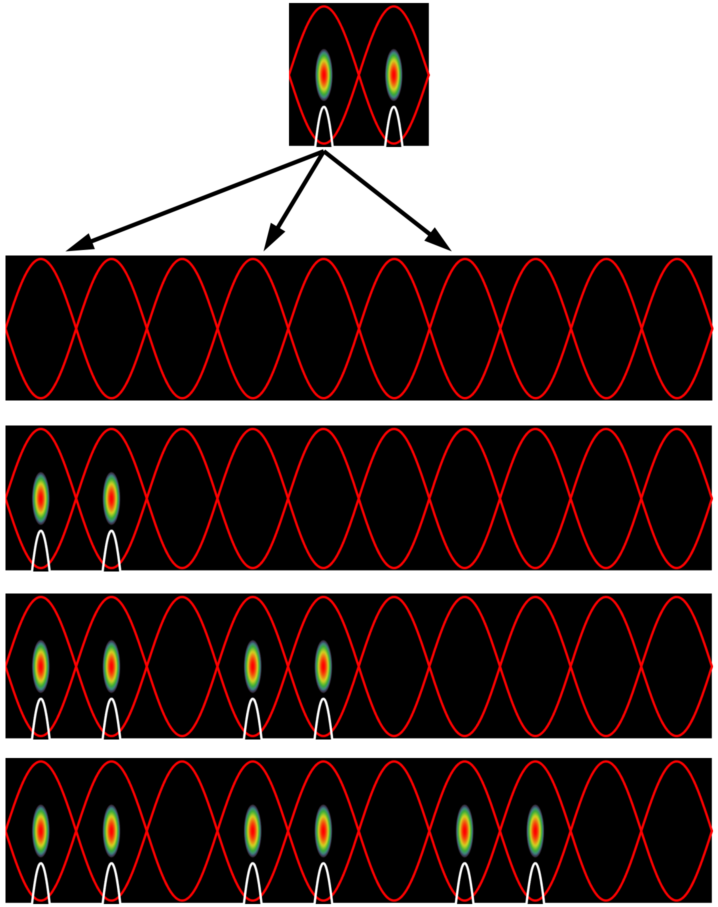
Contours of constant H are particle trajectories in phase space!
(H is conserved)

Hamiltonian Mechanics can help us understand some fairly complicated dynamics (multiple harmonics, bunch splitting, …)

Injection: Bunch-to-bucket transfer

- Bunch from sending accelerator into the bucket of receiving





Advantages:

→ Particles always subject to longitudinal focusing

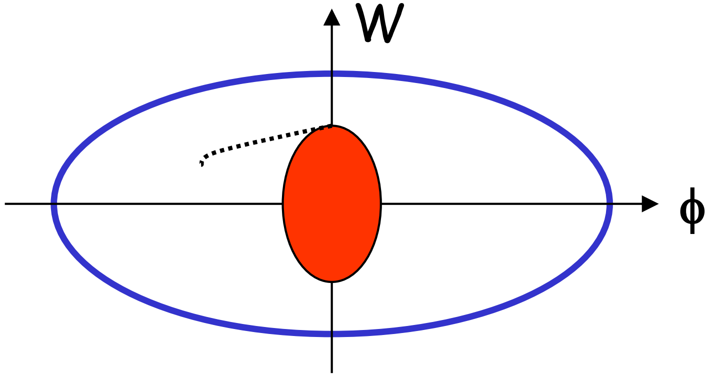
→ No need for RF capture of de-bunched beam in receiving accelerator

→ No particles at unstable fixed point

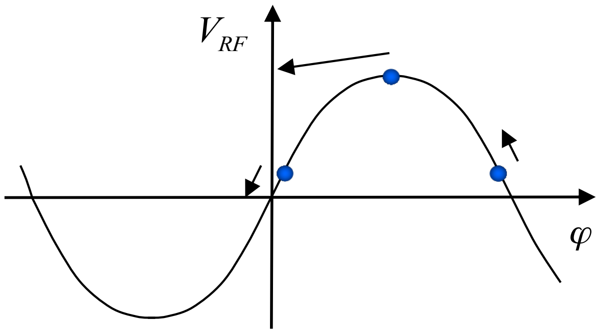
→ Time structure of beam preserved during transfer

Effect of a Mismatch

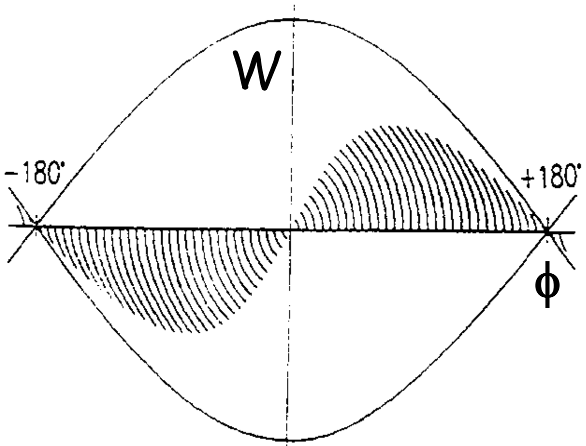
Injected bunch: short length and large energy spread
after 1/4 synchrotron period: longer bunch with a smaller energy spread.



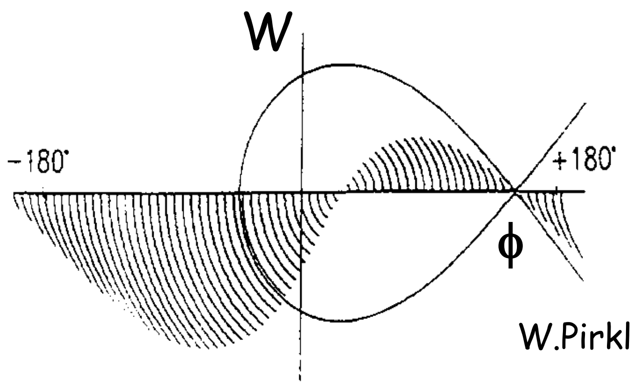
For larger amplitudes, the angular phase space motion is slower
(1/8 period shown below) => can lead to filamentation and emittance growth



restoring force is non-linear



stationary bucket

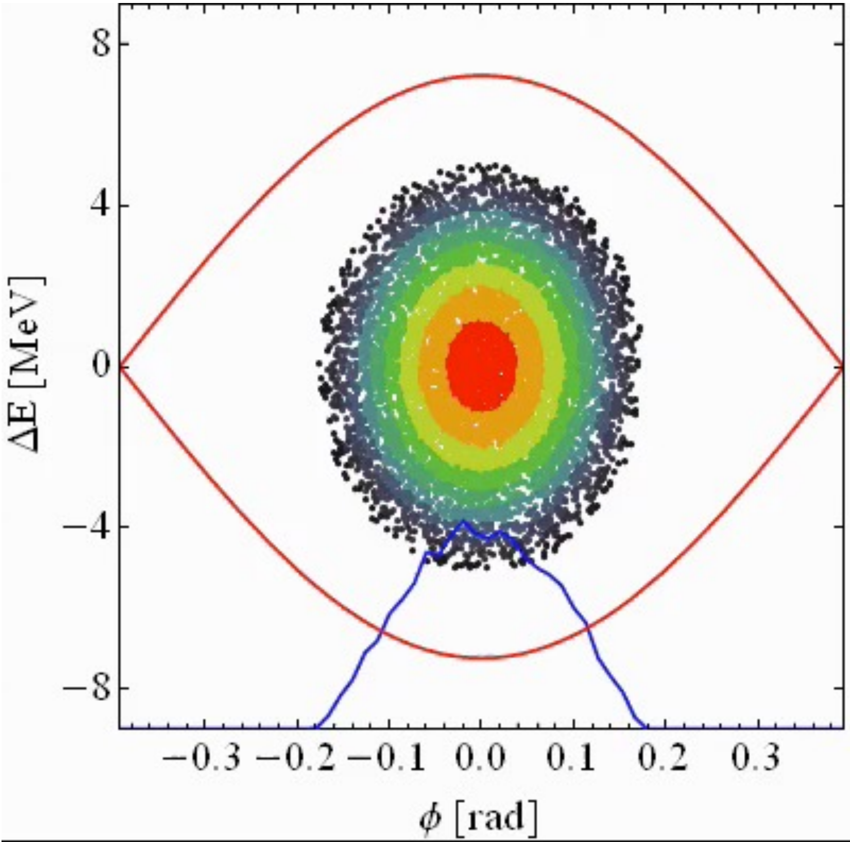


accelerating bucket

Effect of a Mismatch (2)

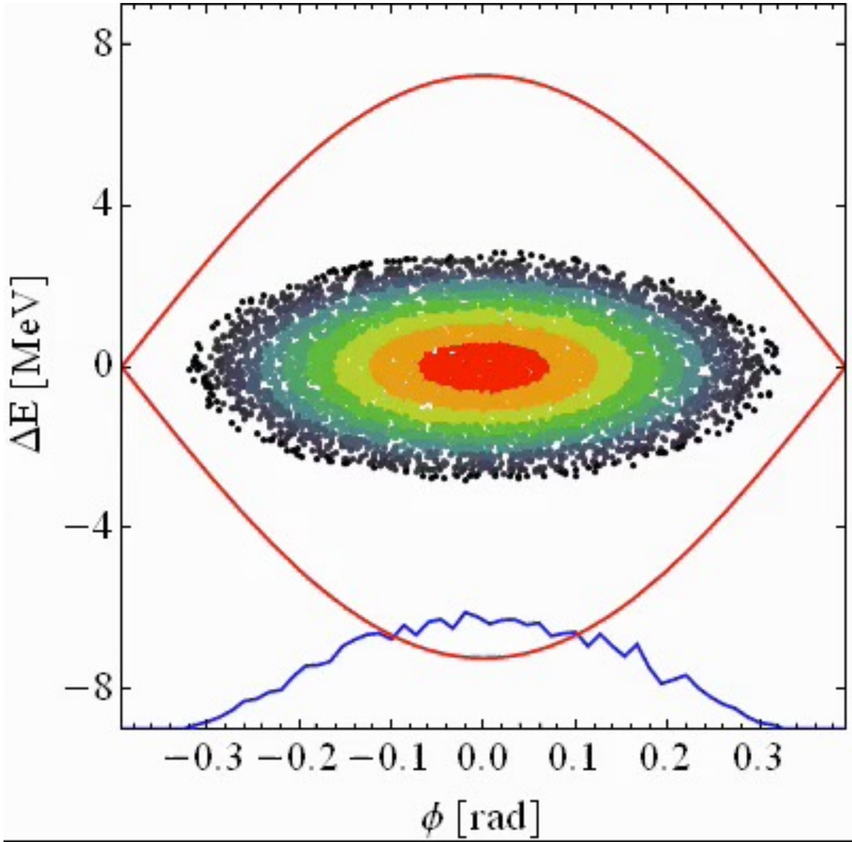
- Long. emittance is only preserved for correct RF voltage

Matched case



→ Bunch is fine, longitudinal emittance remains constant

Longitudinal mismatch

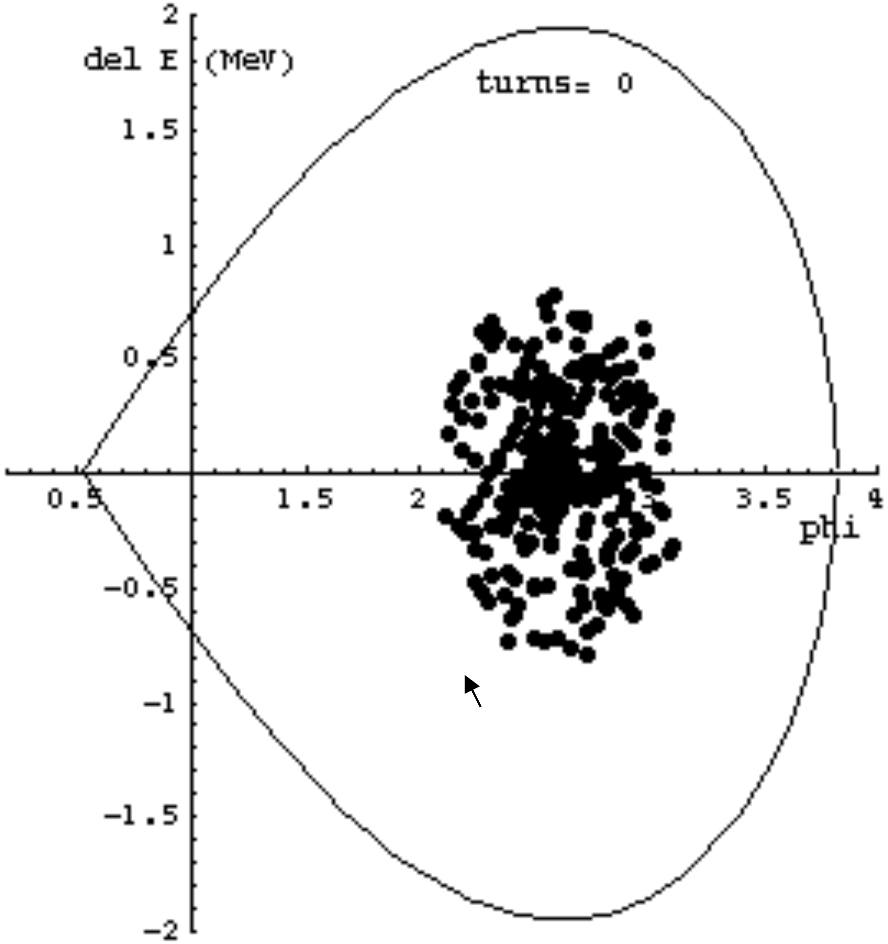


→ Dilution of bunch results in increase of long. emittance

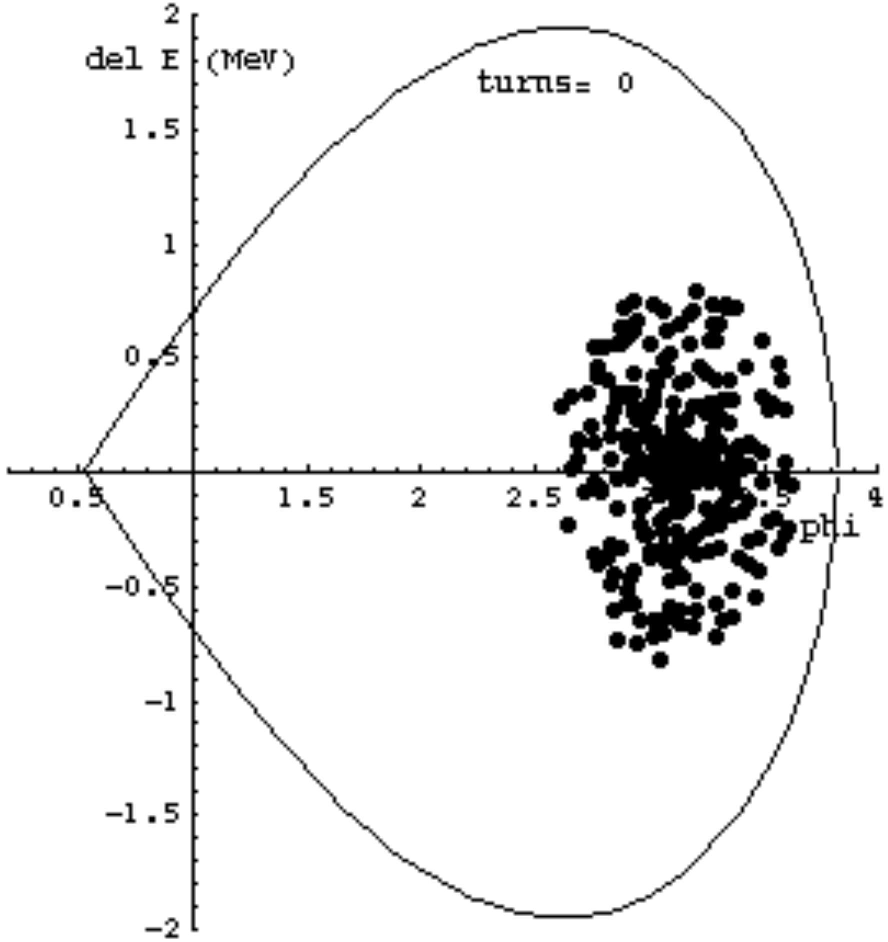
Effect of a Mismatch (3)

Evolution of an injected beam for the first 100 turns.

For a mismatched transfer, the emittance increases (right).



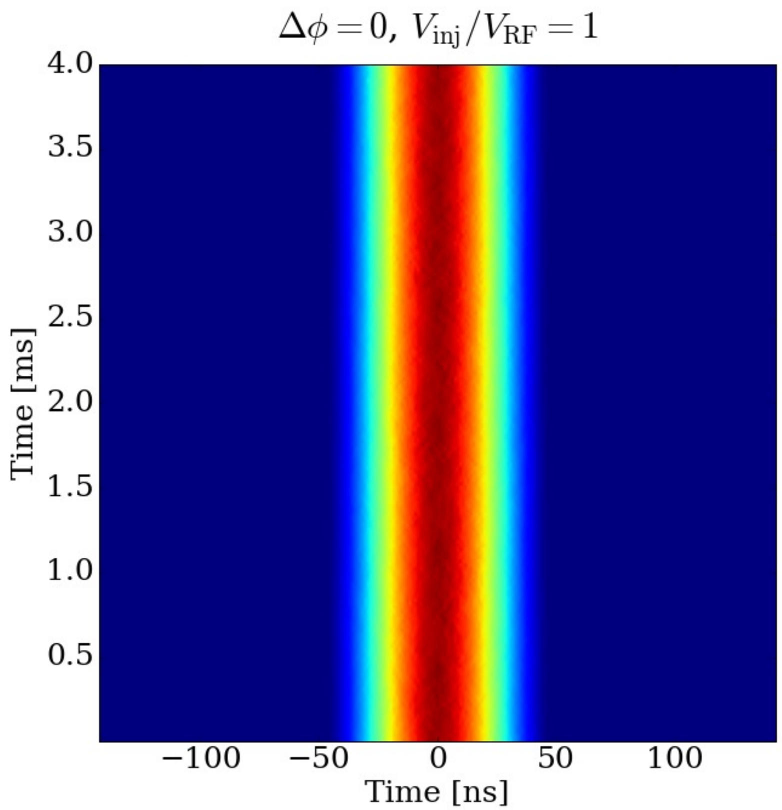
matched beam



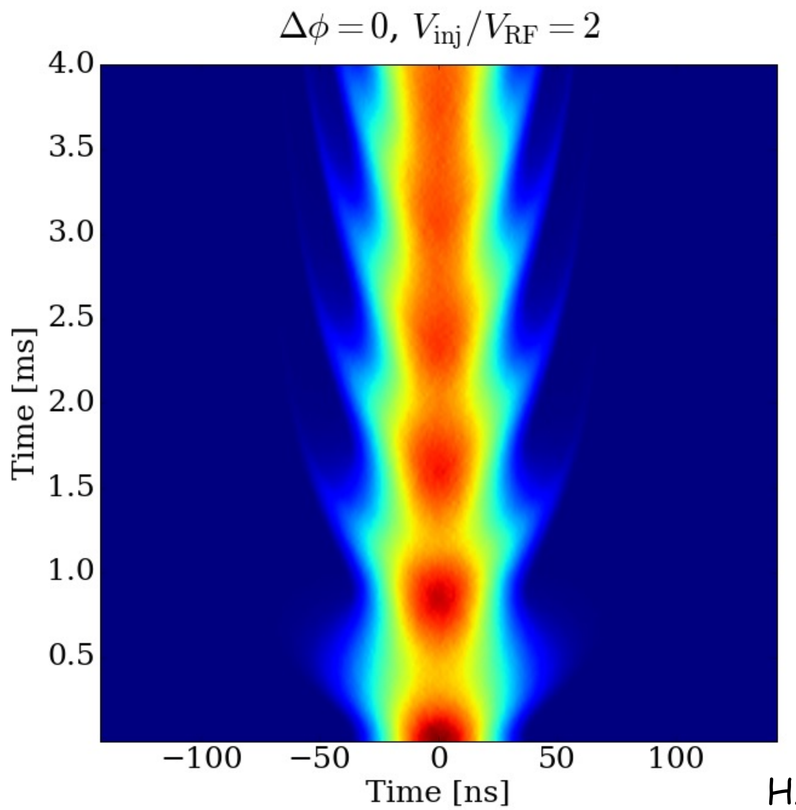
mismatched beam – phase error

Longitudinal matching - Beam profile

Matched case



Longitudinal mismatch



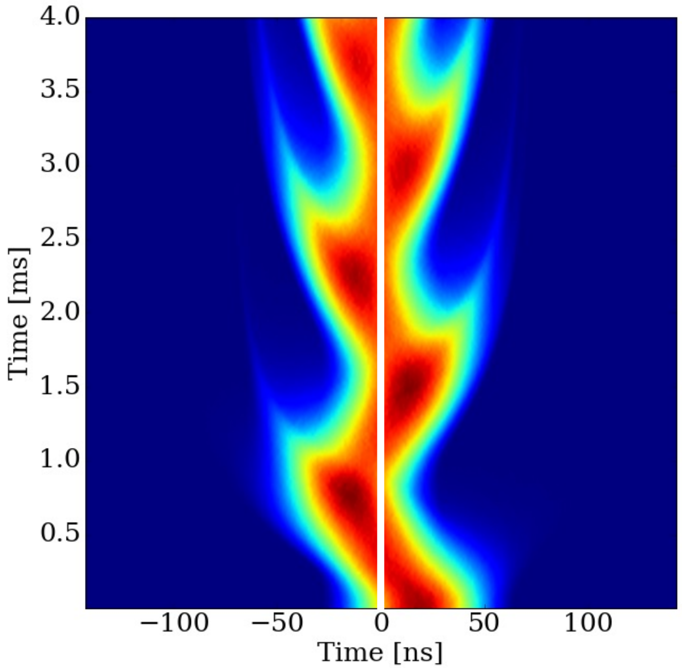
H.Damerau

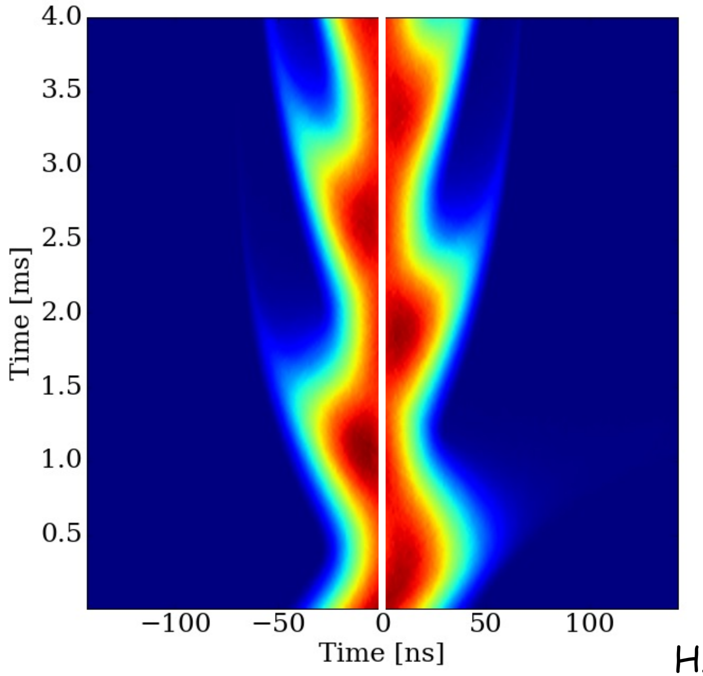
→ Bunch is fine, longitudinal emittance remains constant

→ Dilution of bunch results in increase of long. emittance

Matching quiz!

- Find the difference!





H.Damerau

→ -45° phase error at injection

→ Can be easily corrected by bucket phase

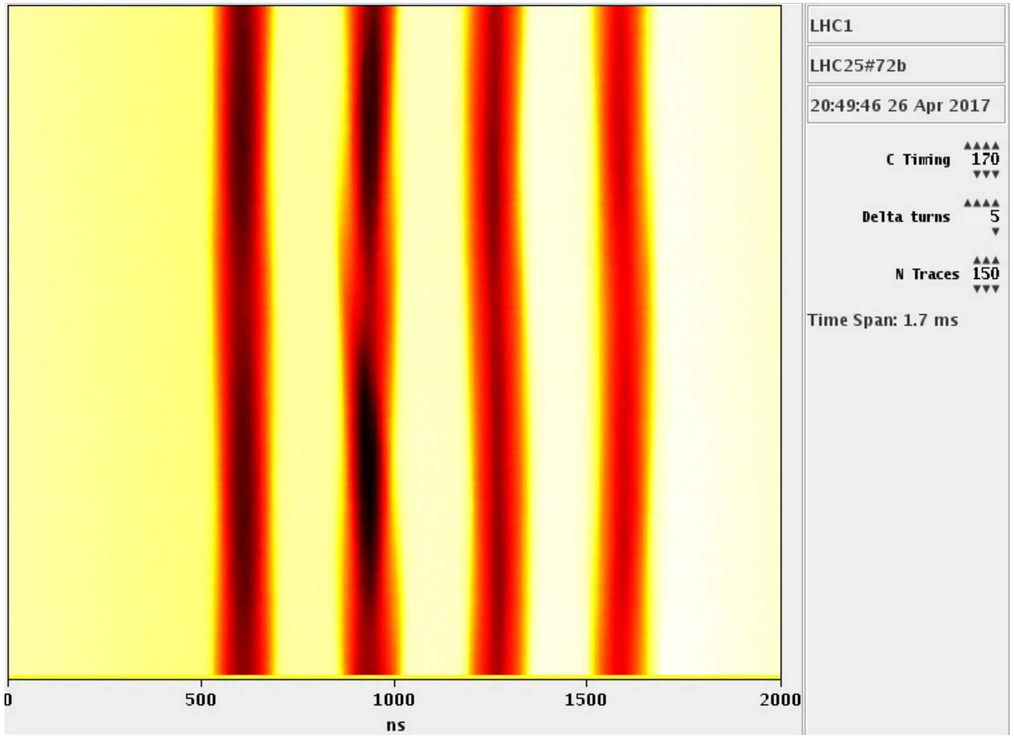
→ Equivalent energy error

→ Phase does not help: requires beam energy change

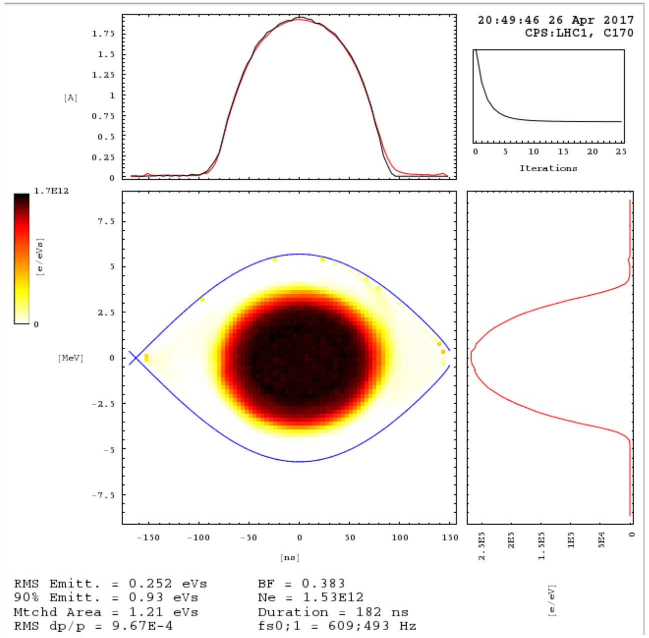
Phase Space Tomography

We can reconstruct the phase space distribution of the beam.

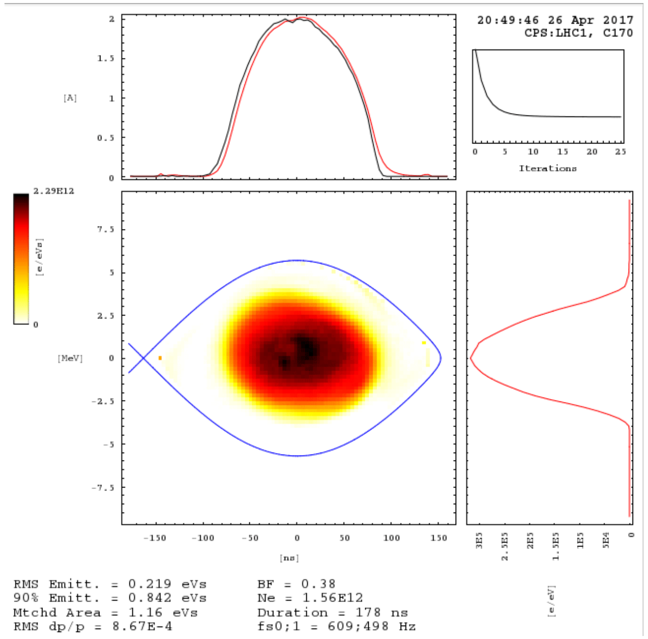
- Longitudinal bunch profiles over a number of turns
- Parameters determining Ω_s



1st bunch



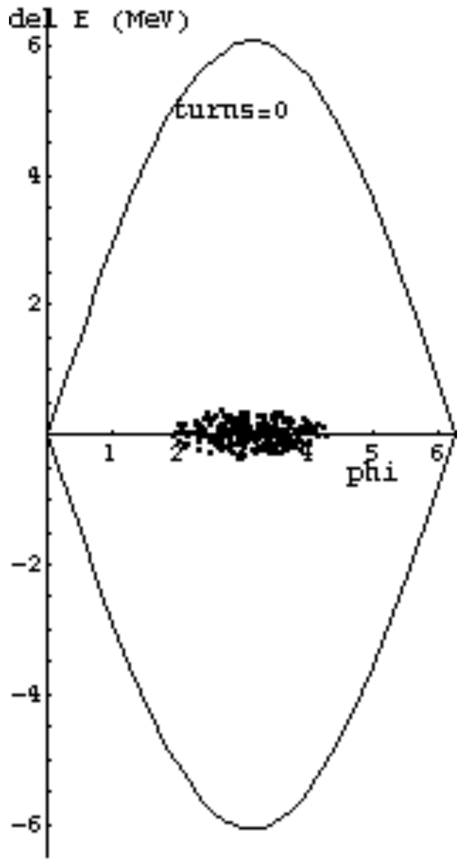
2nd bunch

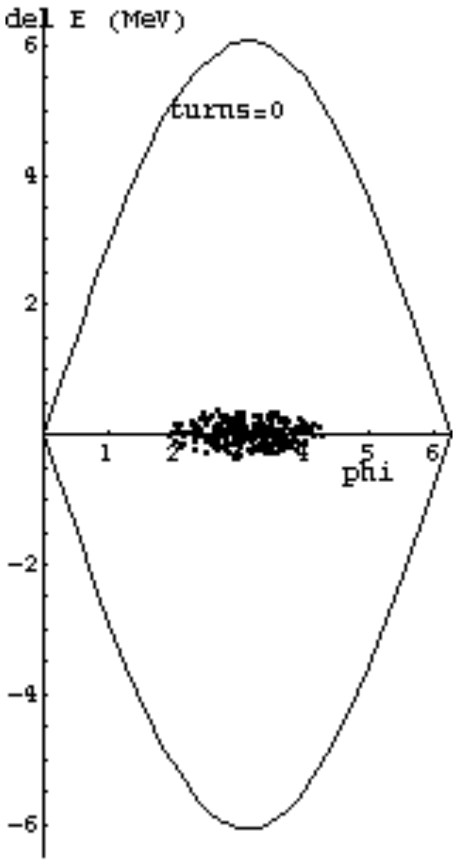


Bunch Rotation

Phase space motion can be used to make short bunches.

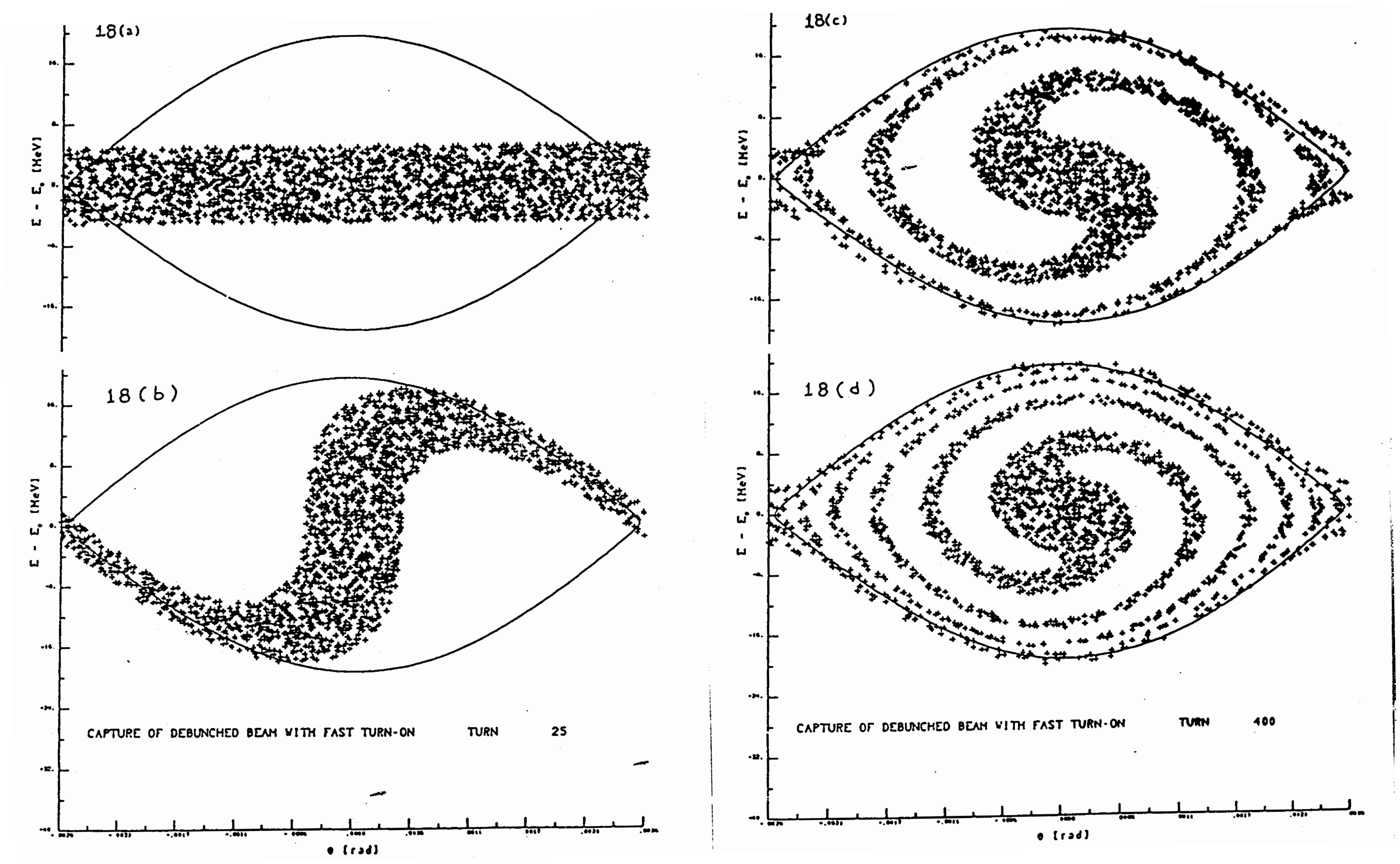
Start with a long bunch and extract or recapture when it's short.



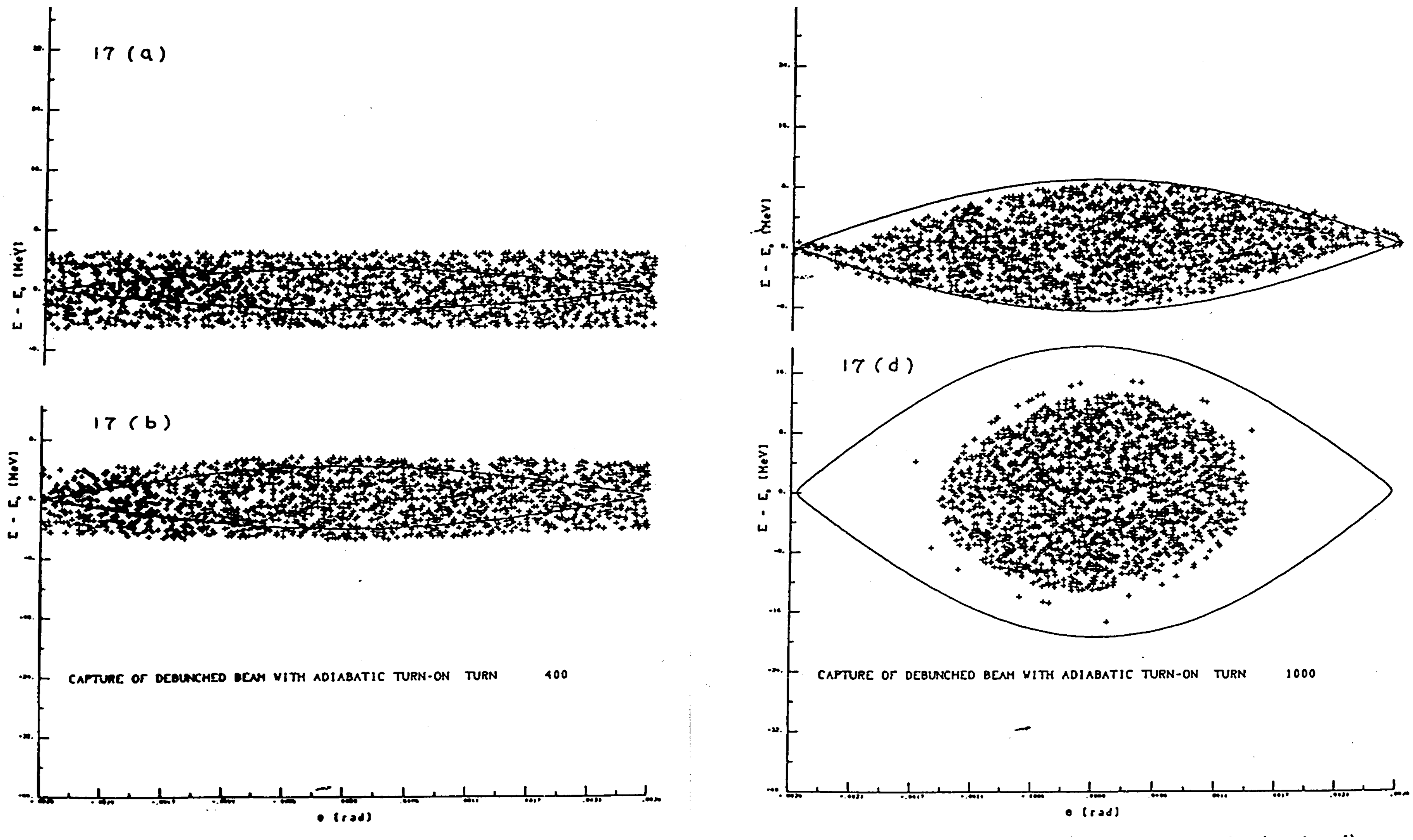


initial beam

Capture of a Debunched Beam with Fast Turn-On

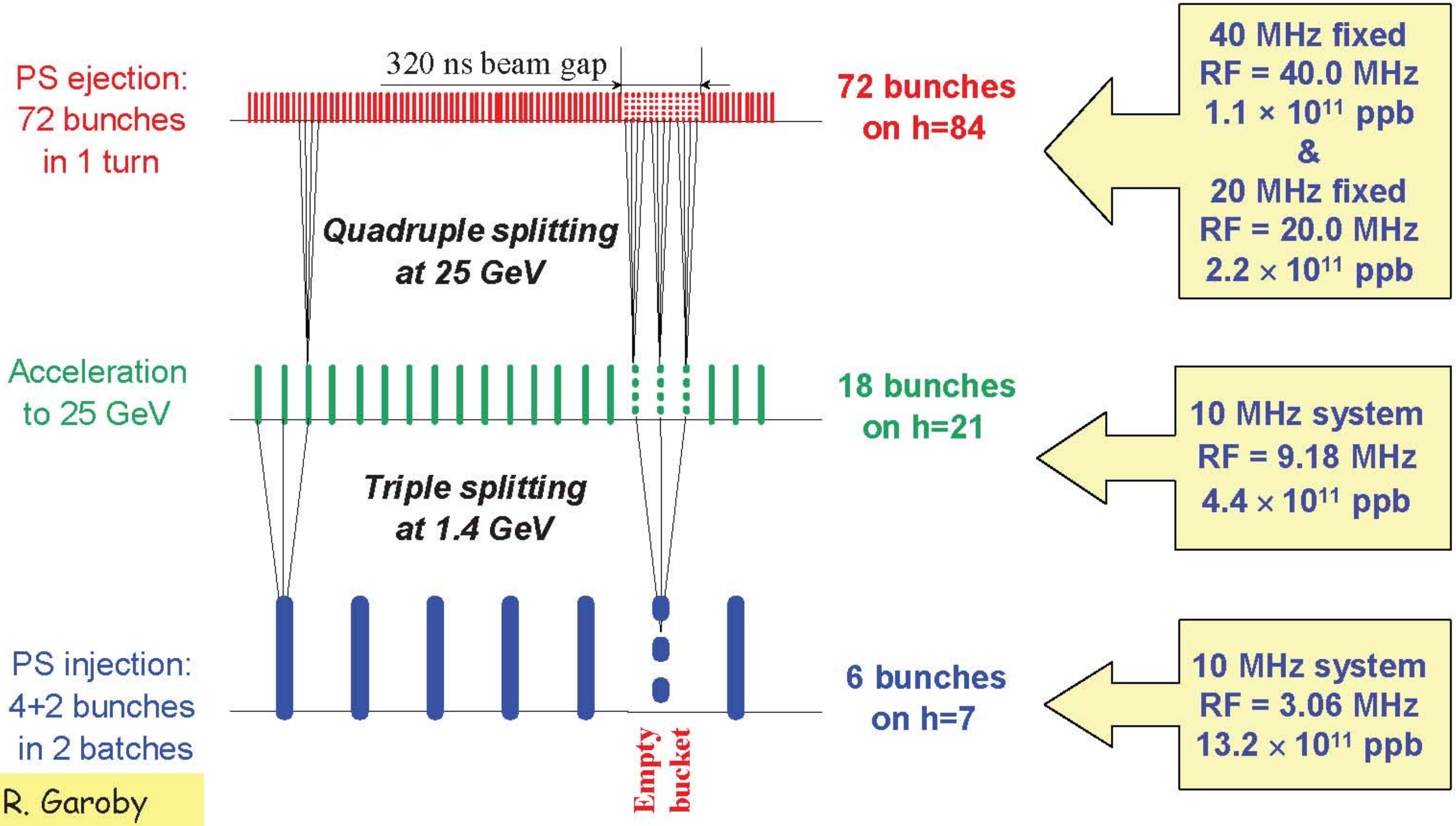


Capture of a Debunched Beam with Adiabatic Turn-On



Generating a 25ns LHC Bunch Train in the PS

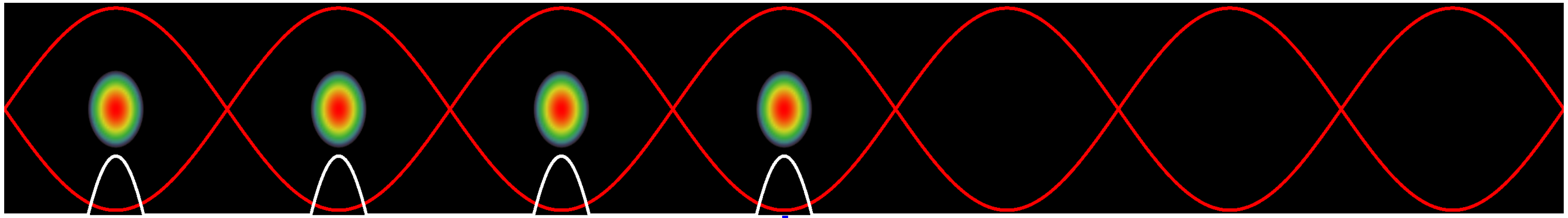
- **Longitudinal bunch splitting (basic principle)**
  - Reduce voltage on principal RF harmonic and simultaneously rise voltage on multiple harmonics (adiabatically with correct phase, etc.)



R. Garoby

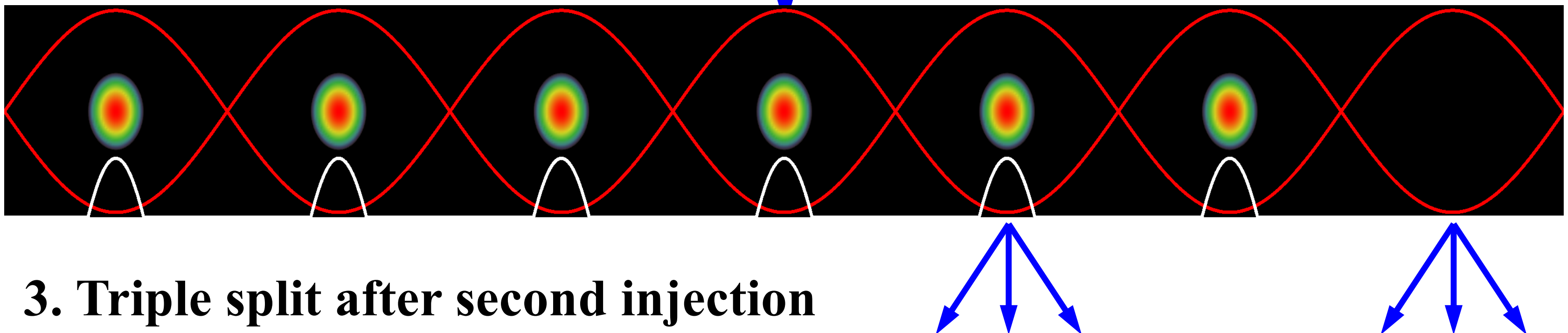
Production of the LHC 25 ns beam

1. Inject four bunches **~ 180 ns, 1.3 eVs**

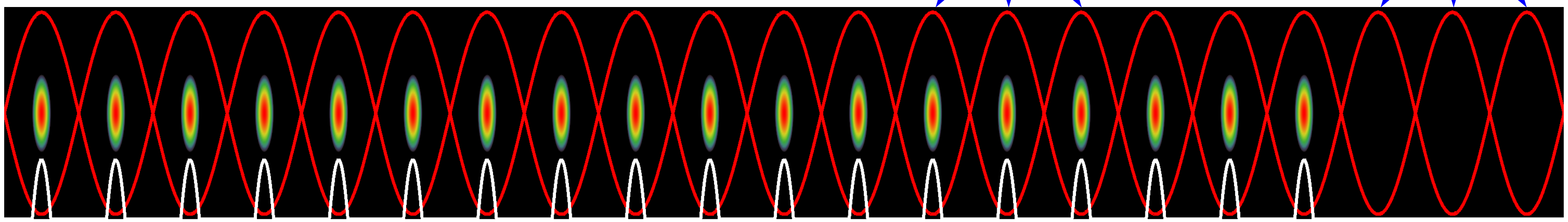


Wait 1.2 s for second injection

2. Inject two bunches



3. Triple split after second injection

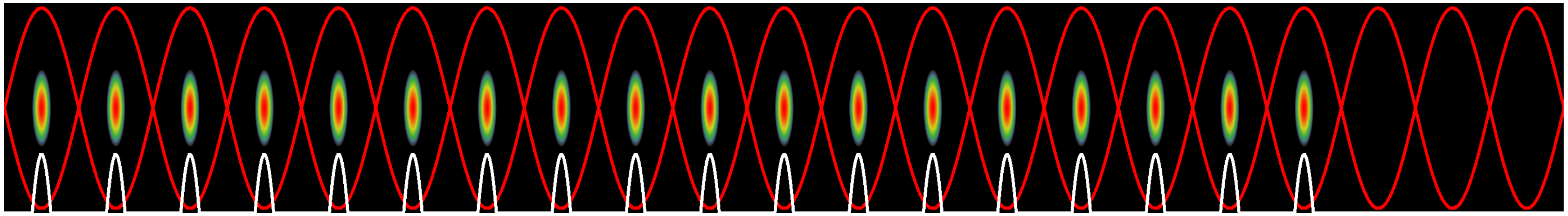


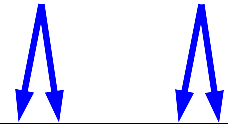
~ 0.7 eVs

4. Accelerate from 1.4 GeV (E_{kin}) to 26 GeV

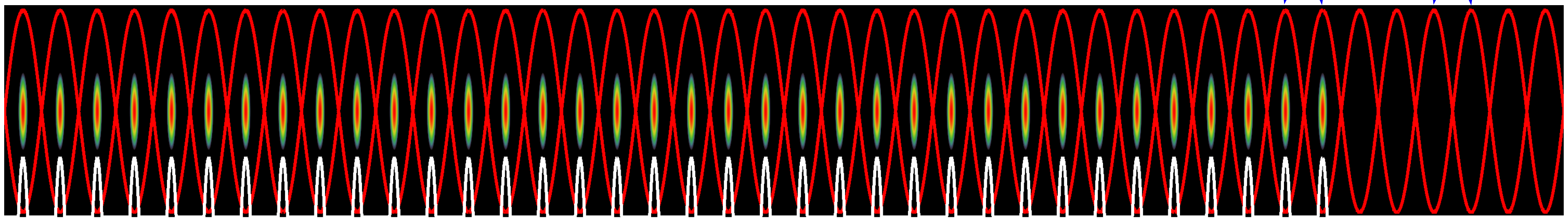
Production of the LHC 25 ns beam

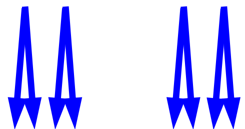
5. During acceleration: longitudinal emittance blow-up: 0.7 – 1.3 eVs



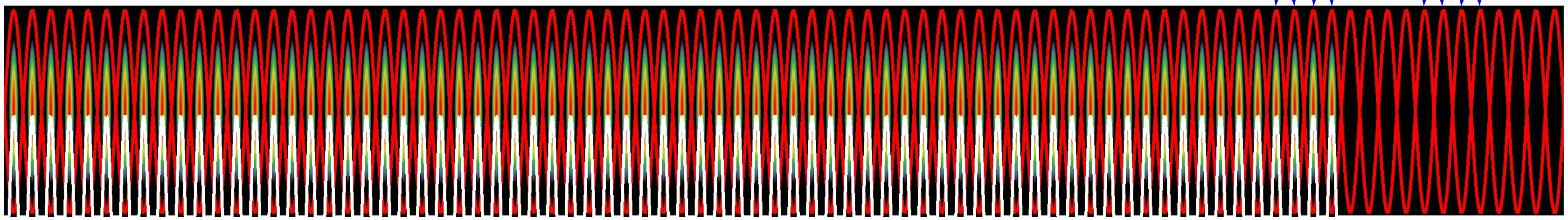


6. Double split ($h21 \rightarrow h42$)



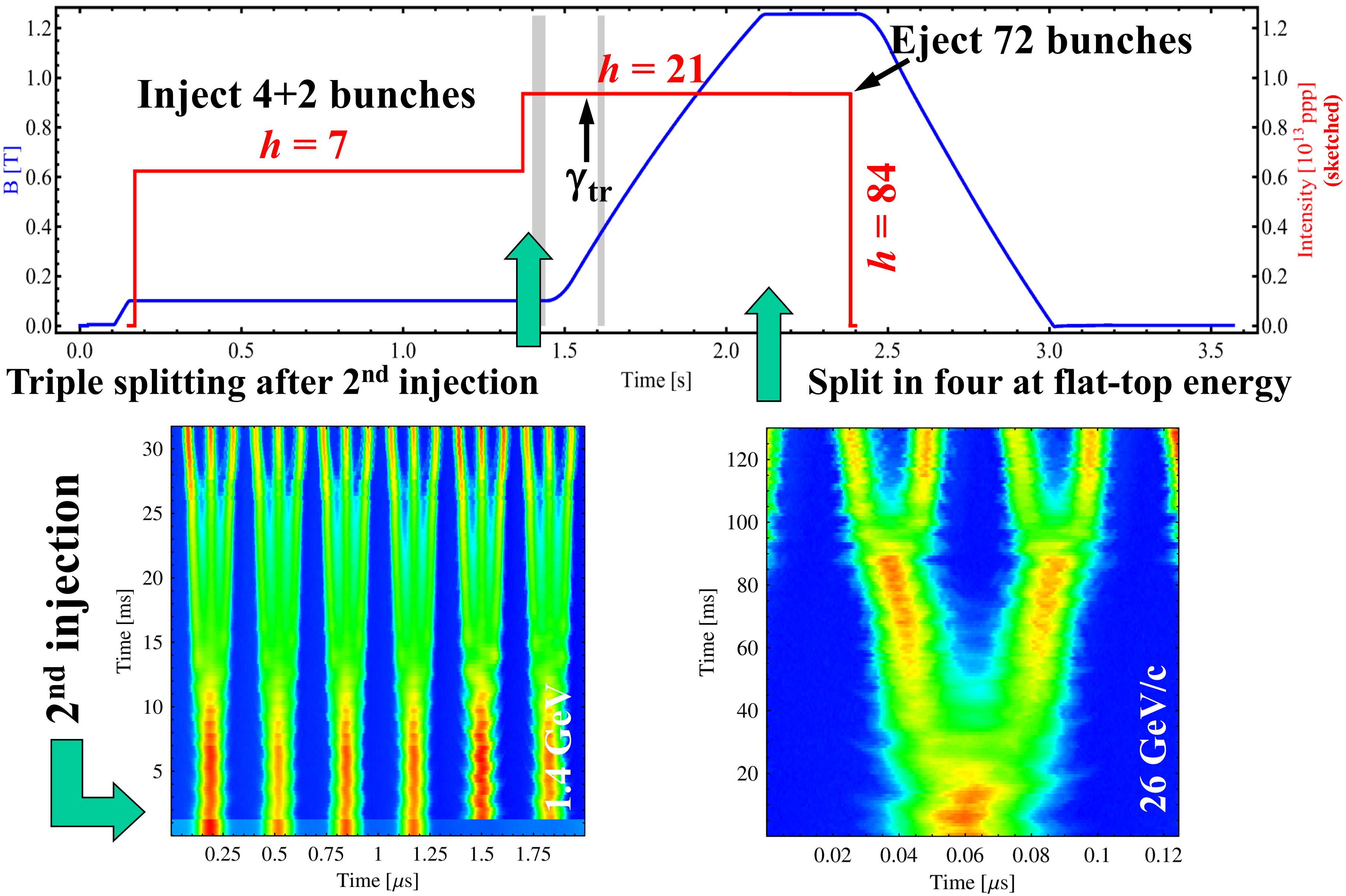


7. Double split ($h42 \rightarrow h84$) **~ 0.35 eVs, 4 ns**



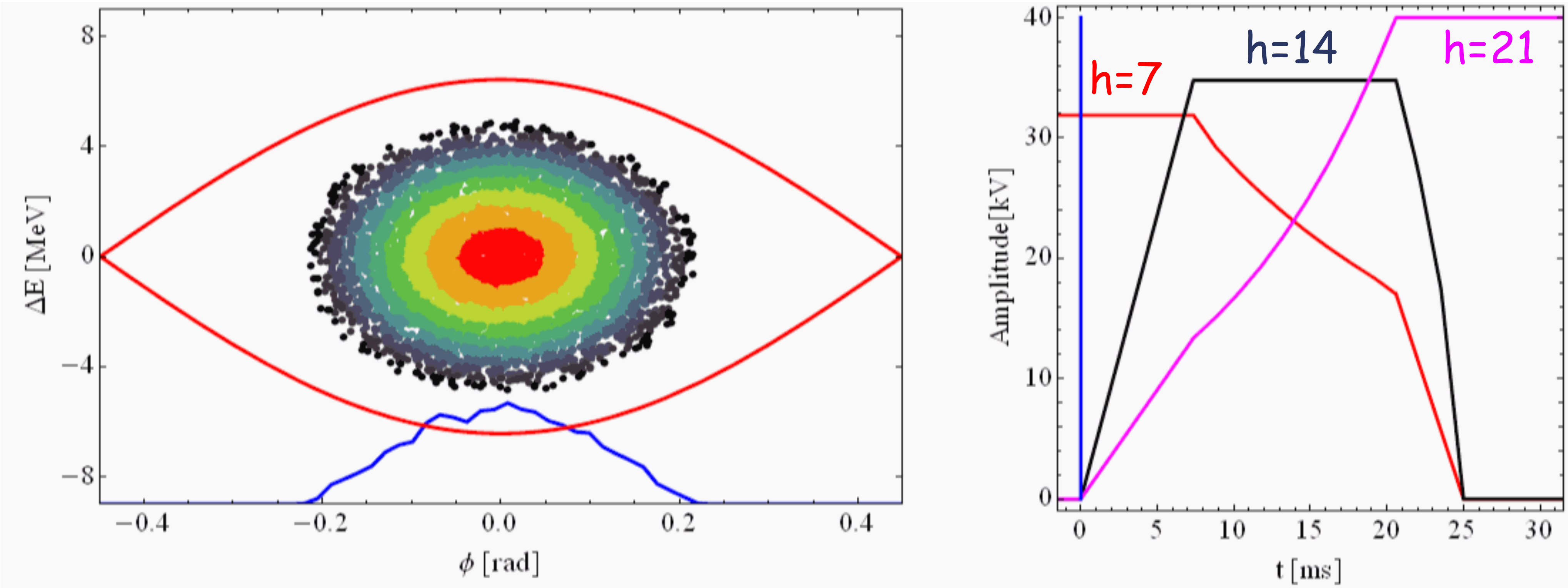
10. Fine synchronization, bunch rotation → Extraction!

The LHC25 (ns) cycle in the PS



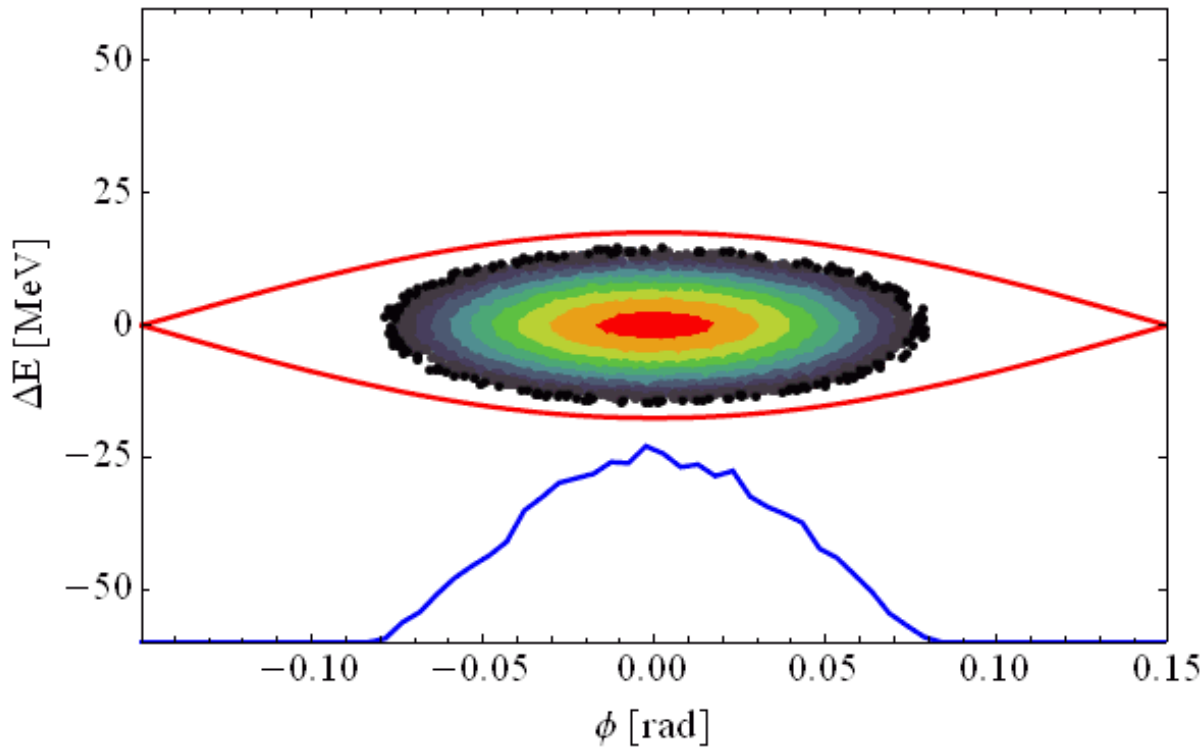
→ Each bunch from the Booster divided by 12 → 6 × 3 × 2 × 2 = 72

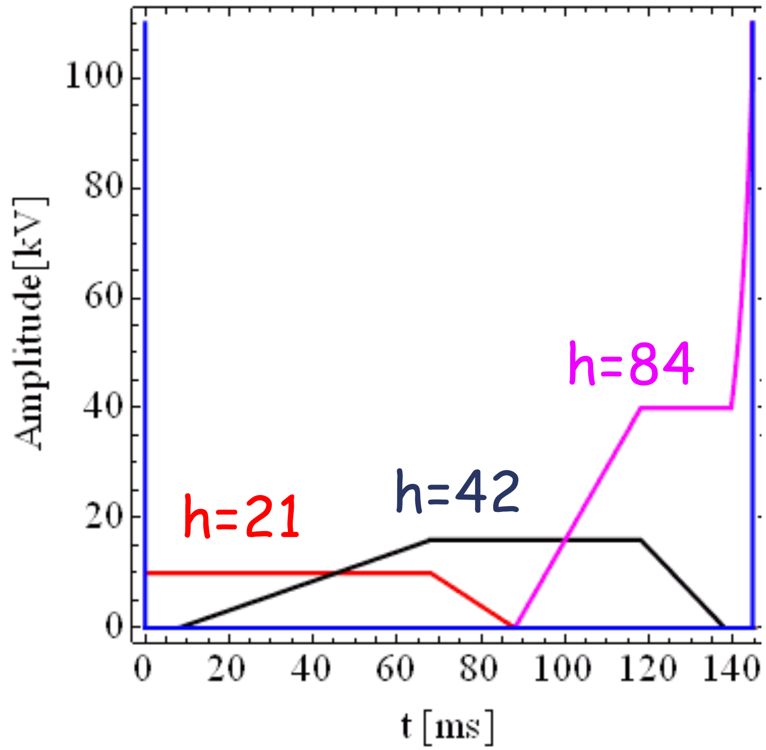
Triple splitting in the PS



Two times double splitting in the PS

Two times double splitting and bunch rotation:





- Bunch is divided twice using RF systems at *h* = 21/42 (10/20 MHz) and *h* = 42/84 (20/40 MHz)
- Bunch rotation: first part *h*84 only + *h*168 (80 MHz) for final part

Summary

- Cyclotrons/Synchrocylotrons for low energy
- Synchrotrons for high energies, constant orbit, synchronously rising field and frequency
- Particles with higher energy have a longer orbit (normally) but a higher velocity
  - at low energies (below transition) velocity increase dominates
  - at high energies (above transition) velocity almost constant
- Particles perform oscillations around synchronous phase
  - synchronous phase depending on acceleration
  - below or above transition
- Hamiltonian approach can deal with fairly complicated dynamics
- Bucket is the stable region in phase space inside the separatrix
- Matching the shape of the bunch to the bucket is essential

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And CERN Accelerator Schools (CAS) Proceedings
In particular: https://arxiv.org/abs/2011.02932
Longitudinal Beam Dynamics in Circular Accelerators

Acknowledgements

Appendix: Relativity + Energy Gain

Newton-Lorentz Force $\vec{F} = \frac{\mathrm{d}\vec{p}}{\mathrm{dt}} = e\left(\vec{E} + \vec{v} \times \vec{B}\right)$

2nd term always perpendicular to motion => no acceleration

Relativistics Dynamics

$$\beta = \frac{v}{c} = \sqrt{1 - \frac{1}{\gamma^2}} \qquad \gamma = \frac{E}{E_0} = \frac{m}{m_0} = \frac{1}{\sqrt{1-\beta^2}}$$

$$p = mv = \frac{E}{c^2}\beta c = \beta\frac{E}{c} = \beta\gamma\, m_0 c$$

$$E^2 = E_0^2 + p^2c^2 \longrightarrow dE = v\,dp$$

$$\frac{dE}{dz} = v\frac{dp}{dz} = \frac{dp}{dt} = eE_z$$

$$dE = dW = eE_z\,dz \rightarrow W = e\int E_z\,dz$$

RF Acceleration

$$E_z = \hat{E}_z \sin\omega_{RF} t = \hat{E}_z \sin\phi(t)$$

$$\int \hat{E}_z\,dz = \hat{V}$$

$$W = e\hat{V}\sin\phi$$

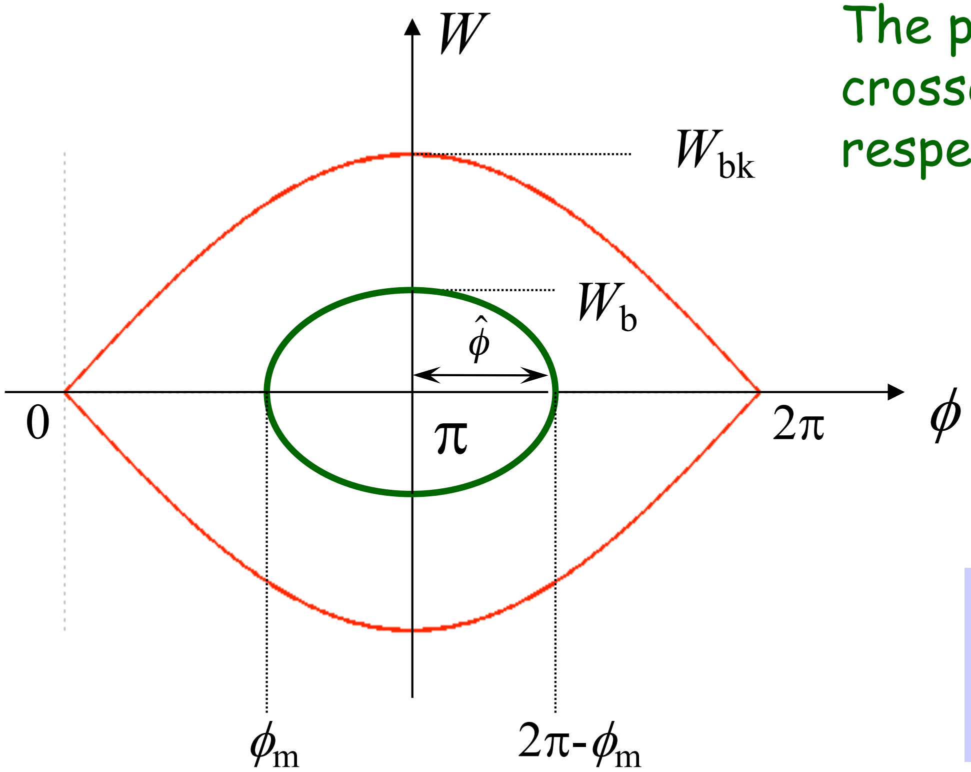
(neglecting transit time factor)

The field will change during the passage of the particle through the cavity
=> effective energy gain is lower

Phase Space Trajectories inside Stationary Bucket

A particle trajectory inside the separatrix is described by the equation:

$$\frac{\dot{\phi}^2}{2} - \frac{\Omega_s^2}{\cos\phi_s}\left(\cos\phi + \phi\sin\phi_s\right) = I \quad \xrightarrow{\phi_s = \pi} \quad \frac{\dot{\phi}^2}{2} + \Omega_s^2\cos\phi = I$$



The points where the trajectory crosses the axis are symmetric with respect to $\phi_s = \pi$

$$\frac{\dot{\phi}^2}{2} + \Omega_s^2\cos\phi = \Omega_s^2\cos\phi_m$$

$$\dot{\phi} = \pm\Omega_s\sqrt{2\left(\cos\phi_m - \cos\phi\right)}$$

$$W = \pm W_{bk}\sqrt{\cos^2\frac{\varphi_m}{2} - \cos^2\frac{\varphi}{2}}$$

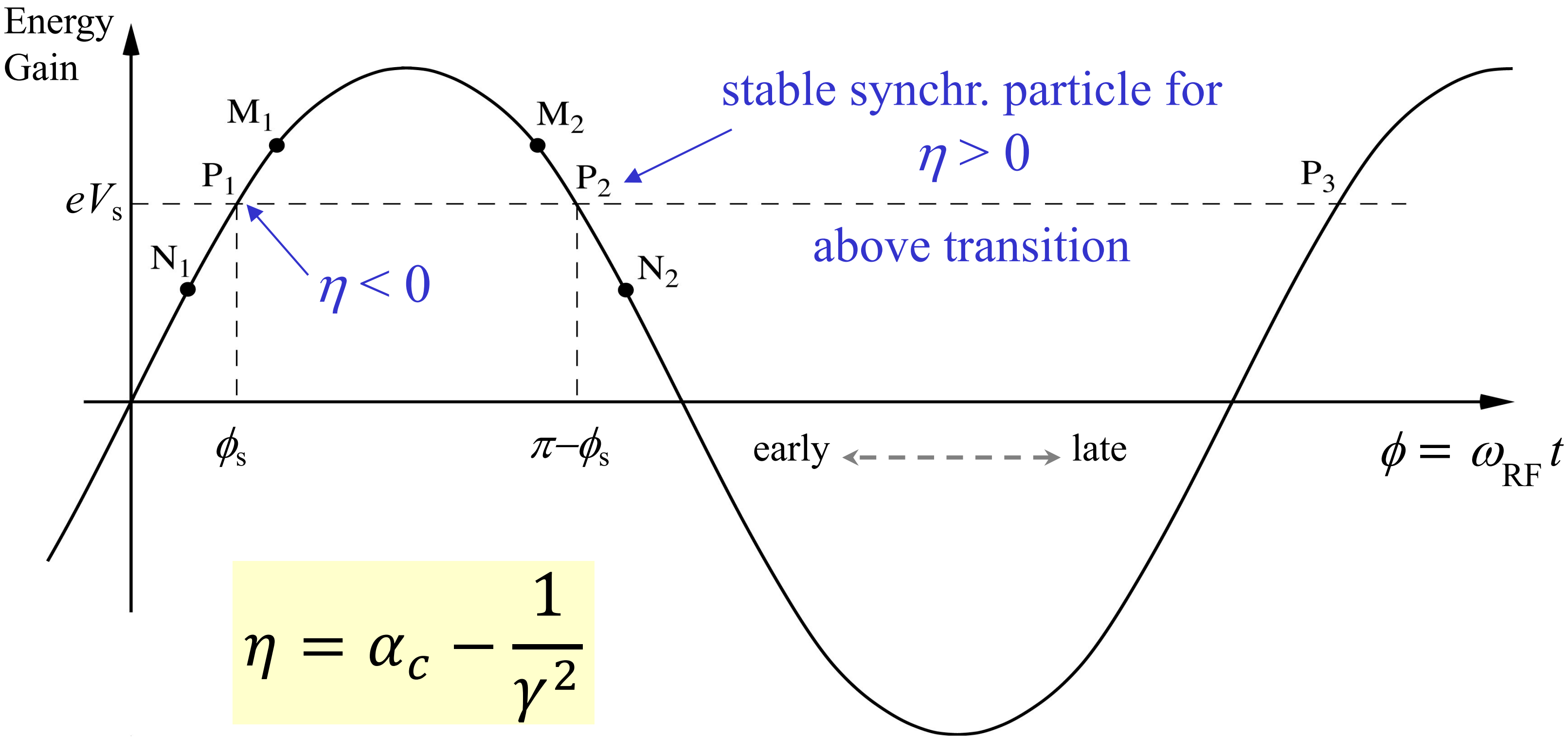
$$\cos(\phi) = 2\cos^2\frac{\phi}{2} - 1$$

The Synchrotron – Energy ramping

Energy ramping by increasing the B field (frequency has to follow v).

Stable phase φ_s changes during energy ramping

$$\sin\phi_s = 2\pi\rho R\,\frac{\dot{B}}{\hat{V}_{RF}} \quad \Rightarrow \quad \phi_s = \arcsin\left(2\pi\rho R\,\frac{\dot{B}}{\hat{V}_{RF}}\right)$$

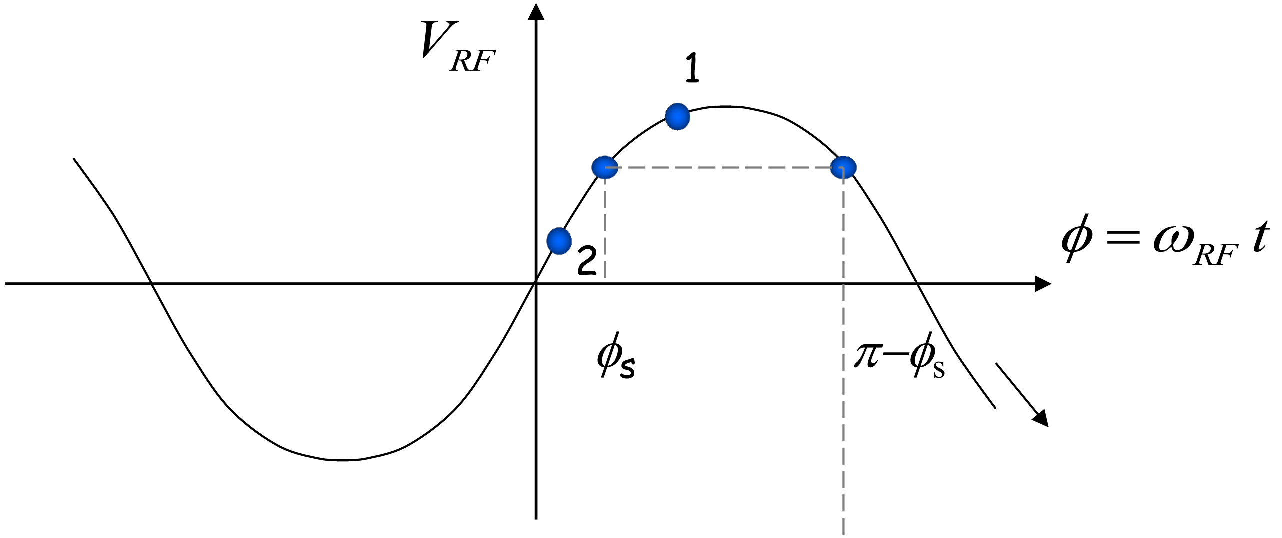


$$\eta = \alpha_c - \frac{1}{\gamma^2}$$

Transition

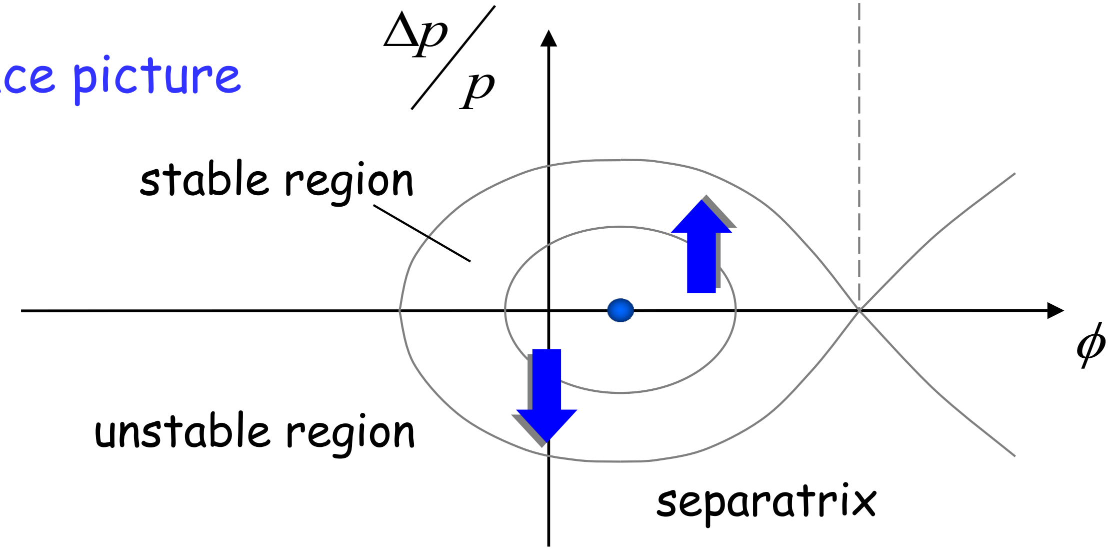
Case with acceleration *B* increasing

$$\gamma < \gamma_t$$



$$\phi_s < \phi < \pi - \phi_s$$

Phase space picture



Particles will accumulate energy difference each turn