LONGITUDINAL DYNAMICS

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Basics of Accelerator Physics and Technology
ESI, Archamps, 25-29 June 2018

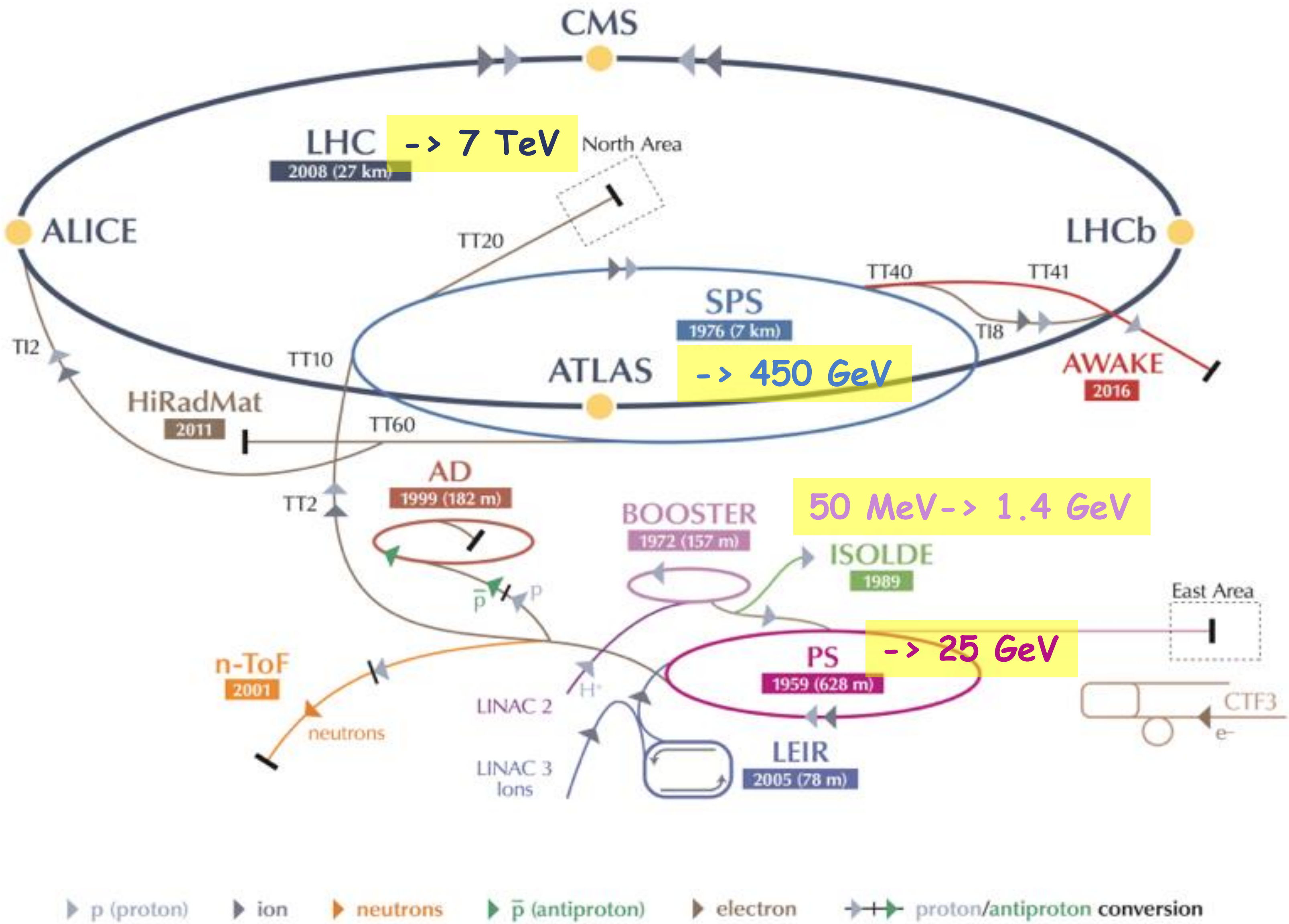
Summary of the 2 lectures:

- Acceleration methods
- Accelerating structures
- Linac: Phase Stability + Energy-Phase oscillations
- Circular accelerators: Cyclotron / Synchrotron
- Dispersion Effects in Synchrotron
- Stability and Longitudinal Phase Space Motion
- Injection Matching
- RF manipulations in the PS

Two more related lectures:

- Linacs – Alessandra Lombardi
- RF Systems - myself

The CERN Accelerator Complex



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

  -> we 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

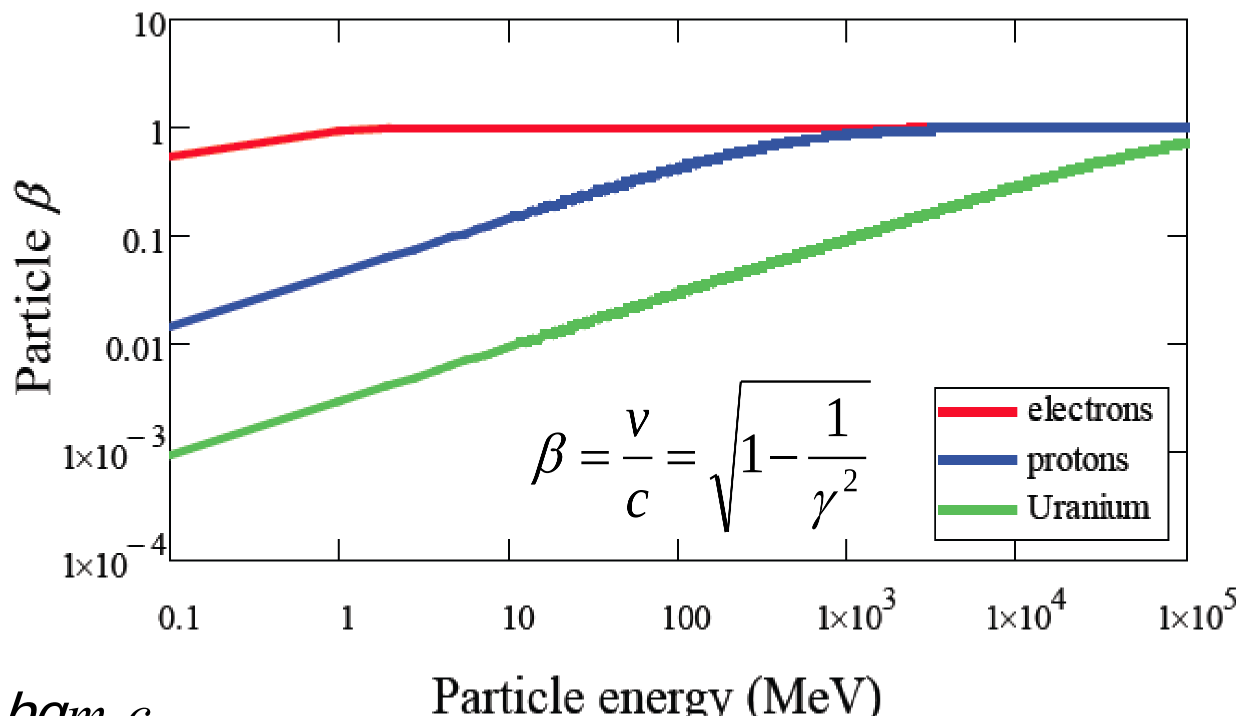
Total Energy: $E = gm_0c^2$

Relativistic gamma factor:

$$g = \frac{E}{E_0} = \frac{m}{m_0} = \frac{1}{\sqrt{1 - b^2}}$$

Momentum:

$$p = mv = \frac{E}{c^2} bc = b\frac{E}{c} = bgm_0c$$



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)
602 kHz -> 1746 kHz => **190% increase**

PS: 1.4 GeV (β=0.915) -> 25.4 GeV (β =0.9994)
437 KHz -> 477 kHz => **9% increase**

SPS: 25.4 GeV -> 450 GeV (β=0.999998)
=> **0.06% increase**

LHC: 450 GeV -> 7 TeV (β= 0.999999991)
=> **$2\ 10^{-6}$ increase**

RF system needs more flexibility in lower energy accelerators.

Acceleration: May the force be with you

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

Newton-Lorentz Force on a charged particle:

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

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 of the particle.

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

The 2nd term - larger at high velocities – is used for:

- BENDING: generated by a magnetic field perpendicular to the plane of the particle trajectory. The bending radius ρ obeys to the relation :

$$\frac{p}{e} = B\rho$$

in practical units: $B\ r\ [\mathrm{Tm}]\ \text{»}\ \frac{p\ [\mathrm{GeV/c}]}{0.3}$

- FOCUSING: the bending effect is used to bring the particles trajectory closer to the axis, hence to increase the beam density.

Energy Gain

The acceleration increases the **momentum**, providing **kinetic energy** to the charged particles.

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

$$E^2 = E_0^2 + p^2c^2 \qquad (E = E_0 + W) \qquad W \text{ kinetic energy}$$

Hence: $dE = v\,dp$ $\qquad \left(2E\,dE = 2c^2 p\,dp \Leftrightarrow dE = c^2 mv / E\; dp = v\,dp\right)$

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

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

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

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

where V is just a potential.

Unit of Energy

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

LHC: 7 TeV -> 14 TeV
CLIC: 3 TeV
HE/VHE-LHC: 33/100 TeV

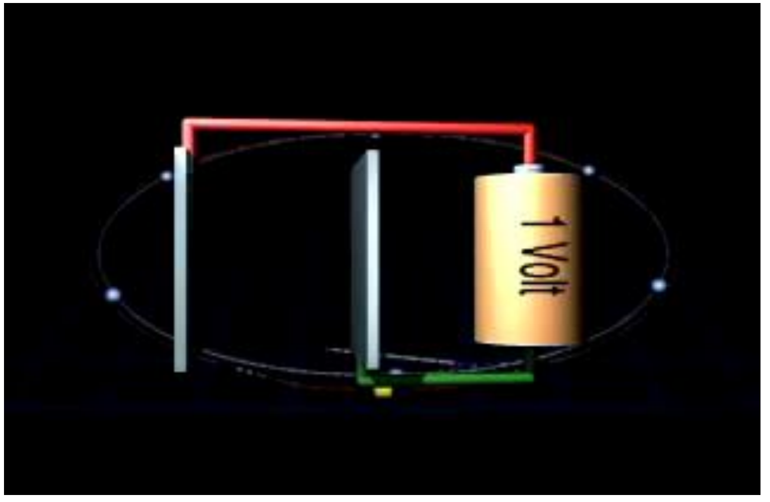
In fact, this energy unit comes from acceleration:

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.

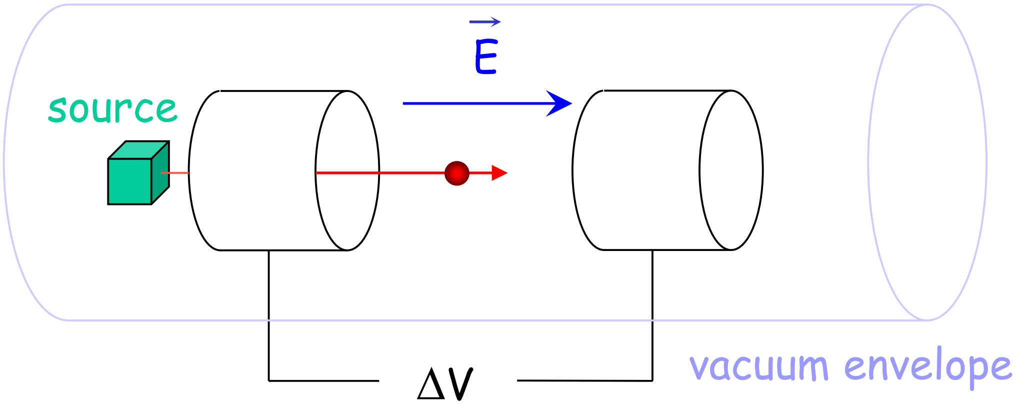
Basic Unit: **eV (electron Volt)**

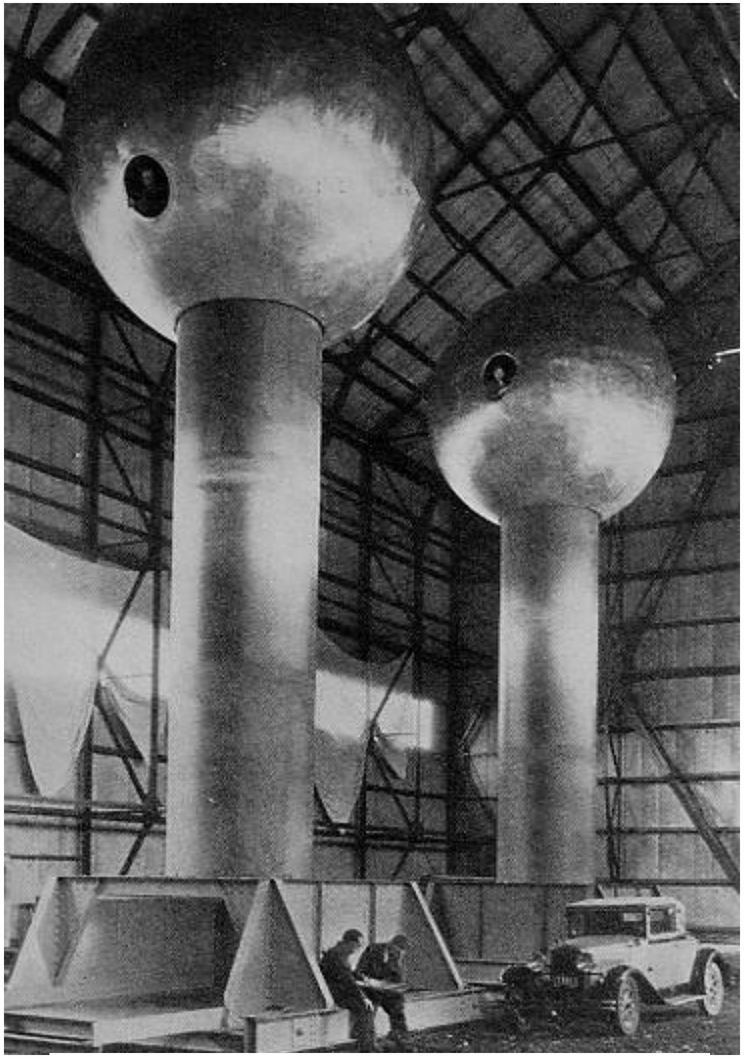
keV = 1000 eV = 10^3 eV
MeV = 10^6 eV
GeV = 10^9 eV
TeV = 10^{12} eV

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



Electrostatic Acceleration





Van-de-Graaf generator at MIT

Electrostatic Field:

Force: $\vec{F} = \frac{d\vec{p}}{dt} = e\,\vec{E}$

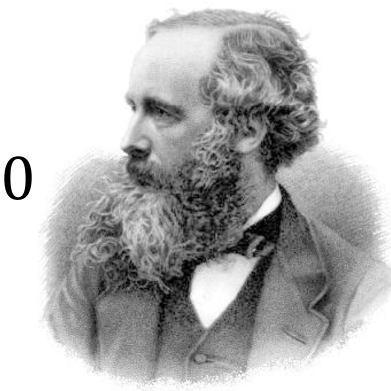
Energy gain: W = e ΔV

used for first stage of acceleration:
particle sources, electron guns,
x-ray tubes

Limitation: insulation problems
maximum high voltage (~ 10 MV)

Methods of Acceleration: Time varying fields

Electrostatic field is limited by insulation problems,
the magnetic field does not accelerate at all.



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

From Maxwell's Equations:

$$\vec{E} = -\vec{\nabla} f - \frac{\partial \vec{A}}{\partial t}$$

$$\vec{B} = m\vec{H} = \vec{\nabla} \times \vec{A} \qquad \text{or} \qquad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

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

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

Consequence: We can only accelerate bunched beam!

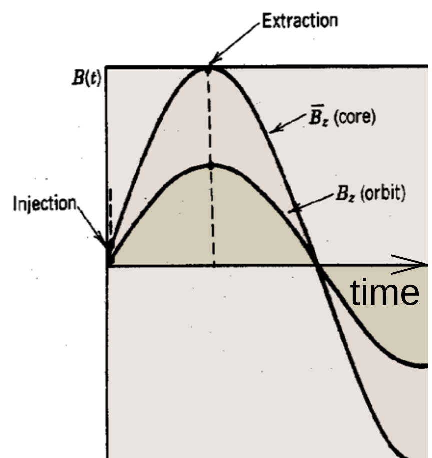
Acceleration by Induction: The Betatron

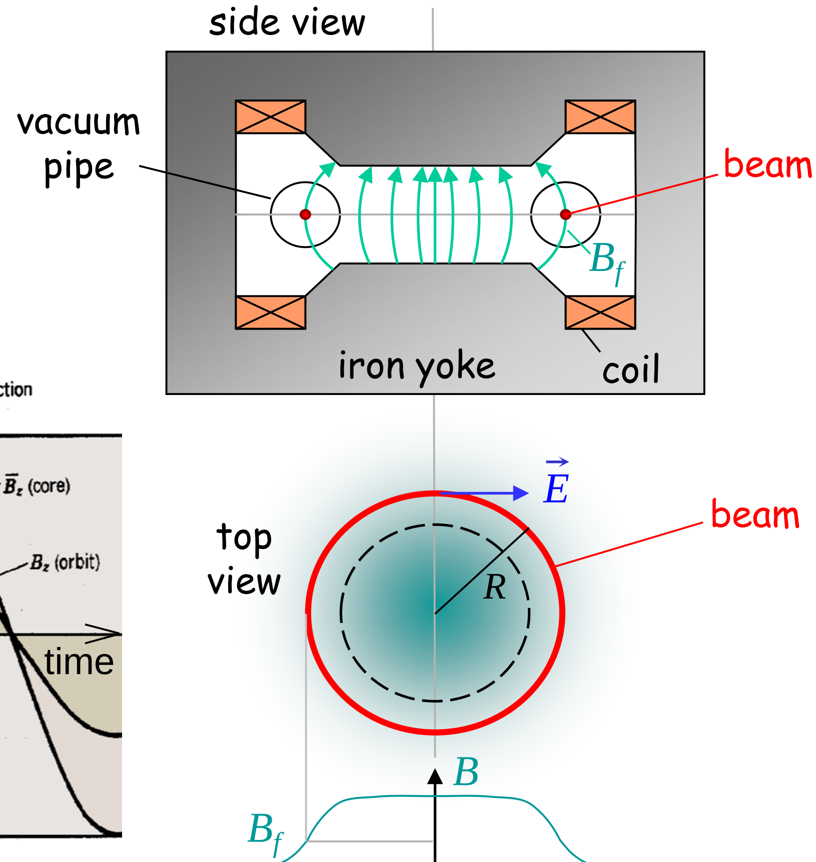
It is based on the principle of a transformer:
- primary side: large electromagnet - secondary side: electron beam.

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

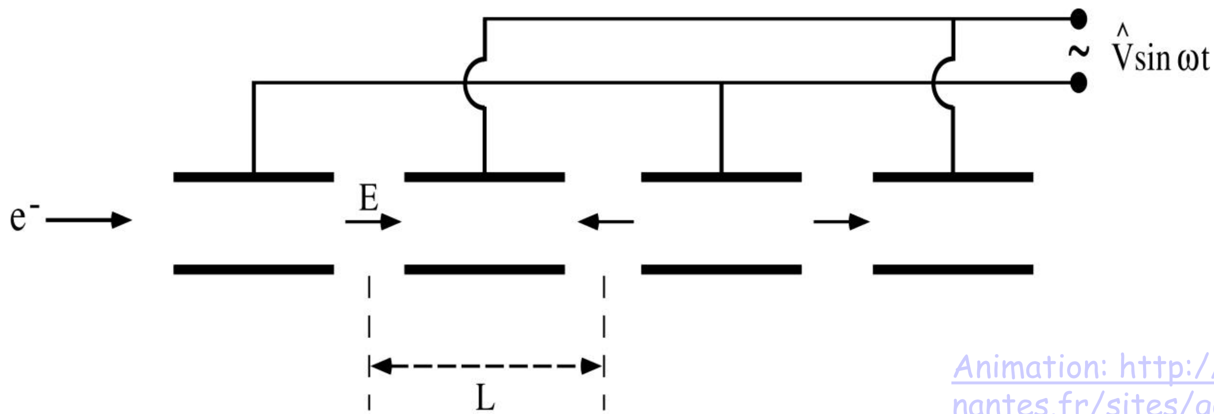




Donald Kerst with the first betatron, invented at the University of Illinois in 1940

Radio-Frequency (RF) Acceleration

Electrostatic acceleration limited by isolation possibilities => use RF fields



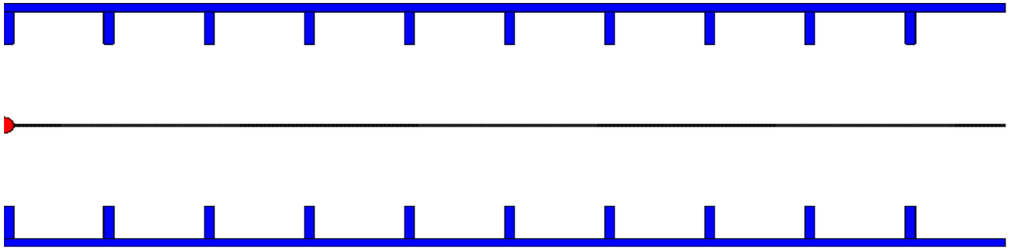
Widerøe-type structure

Animation: http://www.sciences.univ-nantes.fr/sites/genevieve_tulloue/Meca/Charges/linac.html

Cylindrical electrodes (drift tubes) separated by gaps and fed by a RF generator, as shown above, lead to an alternating electric field polarity

Synchronism condition ⟶ $L = v\,T/2$

v = particle velocity
T = RF period



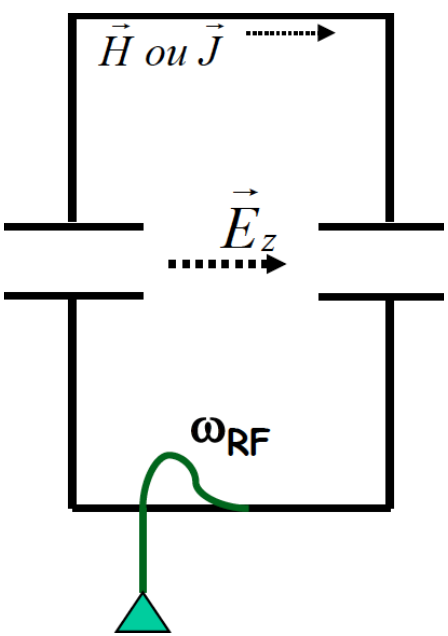
Similar for standing wave cavity as shown (with v≈c)

D.Schulte

Resonant RF Cavities

- Considering RF acceleration, it is obvious that when particles get high velocities the drift spaces get longer and one looses on the efficiency.
  => The solution consists of using a higher operating frequency.

- The power lost by radiation, due to circulating currents on the electrodes, is proportional to the RF frequency.
  => The solution consists of enclosing the system in a cavity which resonant frequency matches the RF generator frequency.



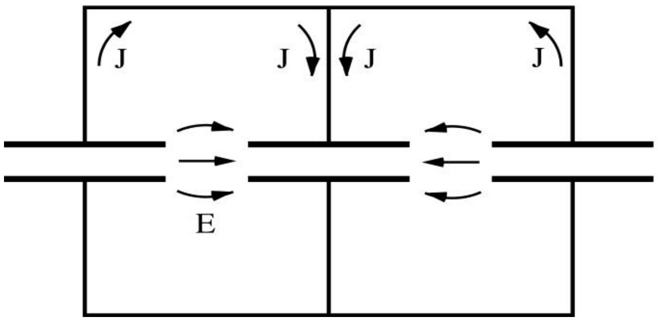
- The electromagnetic power is now constrained in the resonant volume

- Each such cavity can be independently powered from the RF generator

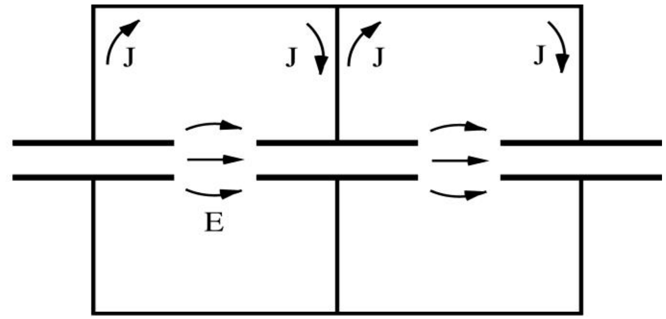
- Note however that joule losses will occur in the cavity walls (unless made of superconducting materials)

Some RF Cavity Examples

$L = vT/2$ (π mode)



$L = vT$ (2π mode)



Single Ga

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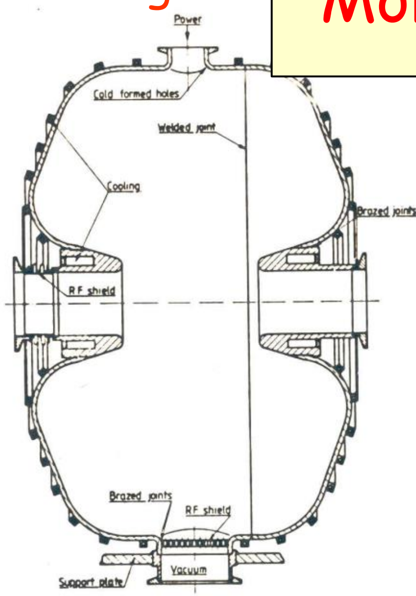
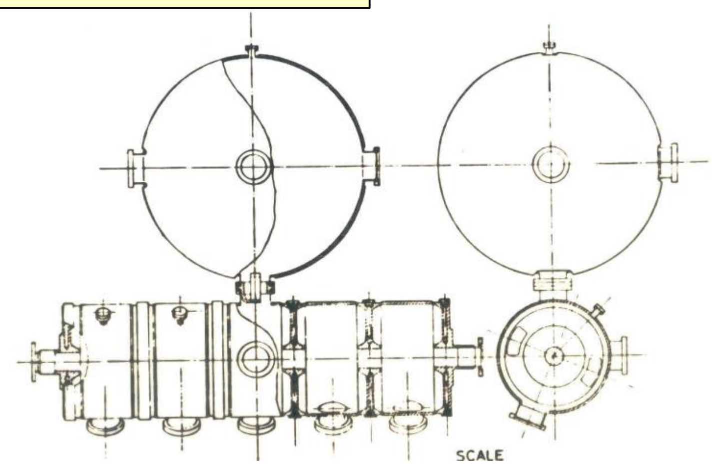
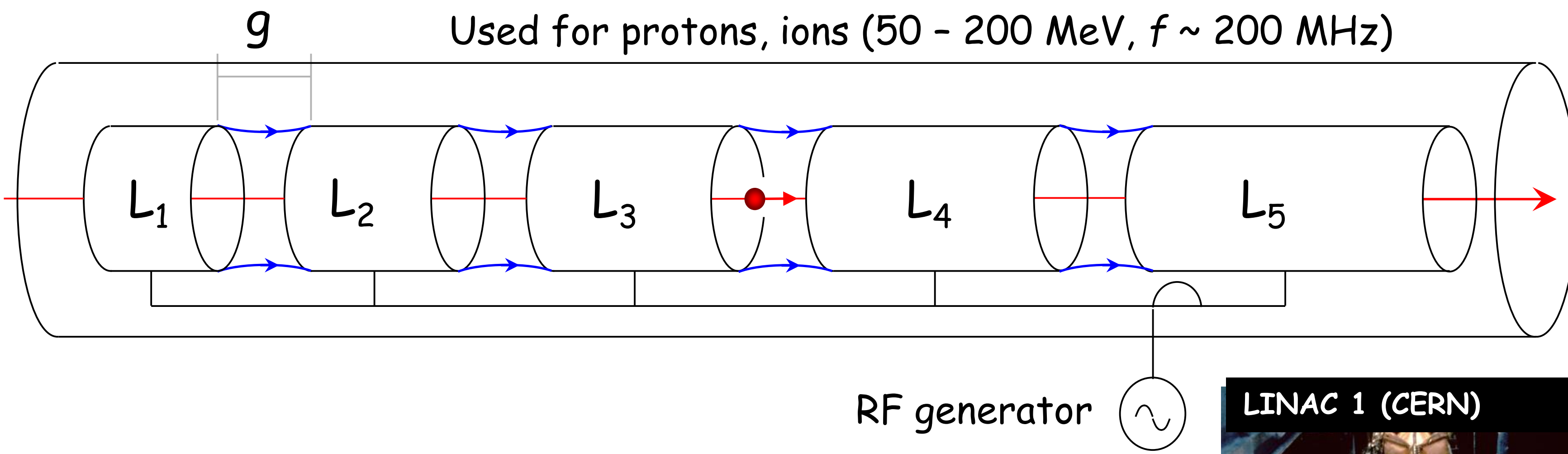
More in RF Systems

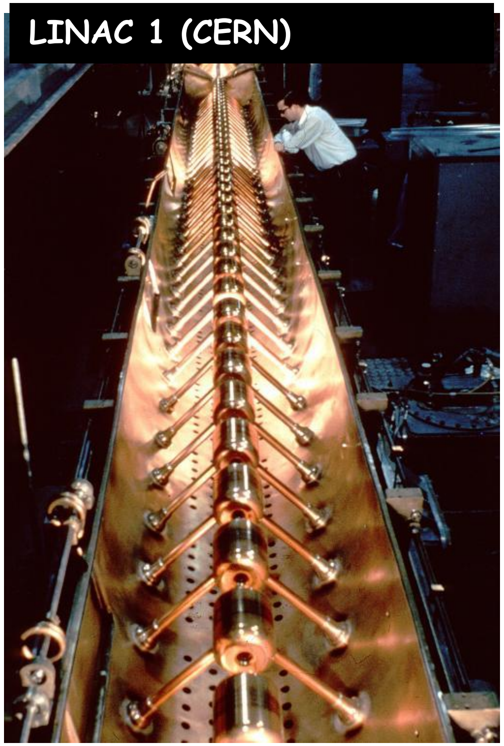




RF acceleration: Alvarez Structure

Used for protons, ions (50 – 200 MeV, f ~ 200 MHz)





Synchronism condition $(g << L)$

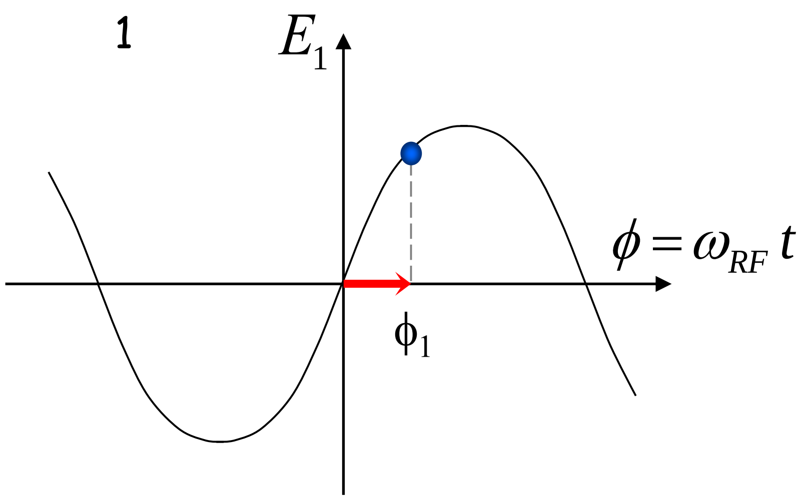
$$L = v_s T_{RF} = \beta_s \lambda_{RF}$$

$$\omega_{RF} = 2\pi f_{RF} = 2\pi \frac{v_s}{L}$$

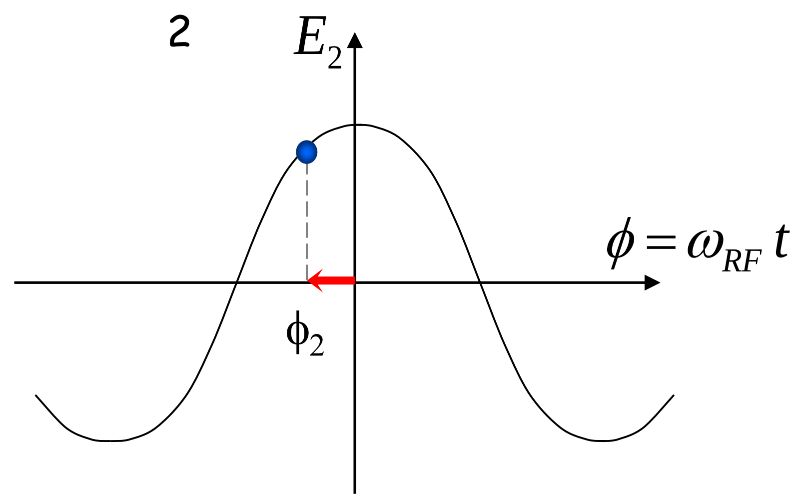
Common Phase Conventions

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:



$$E_1(t) = E_0 \sin\left(w_{RF}\, t\right)$$



$$E_2(t) = E_0 \cos\left(w_{RF}\, t\right)$$

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

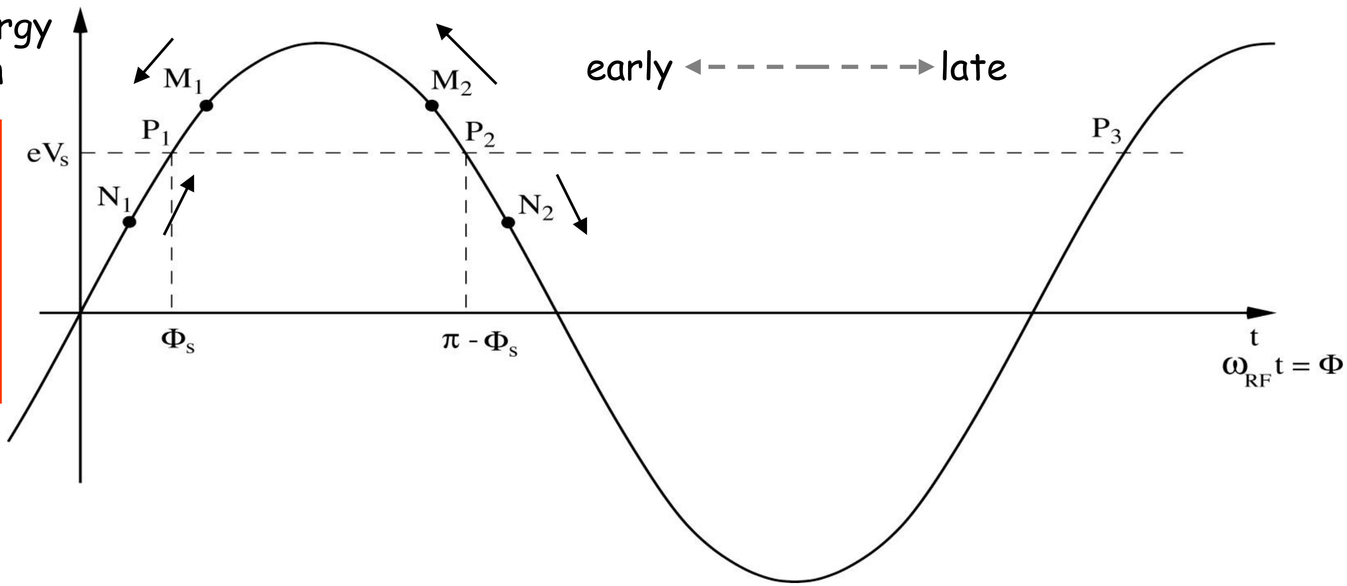
Principle of Phase Stability (Linac)

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.



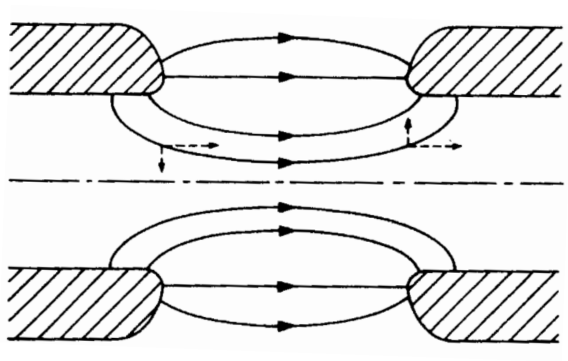
If an energy increase is transferred into a velocity increase =>

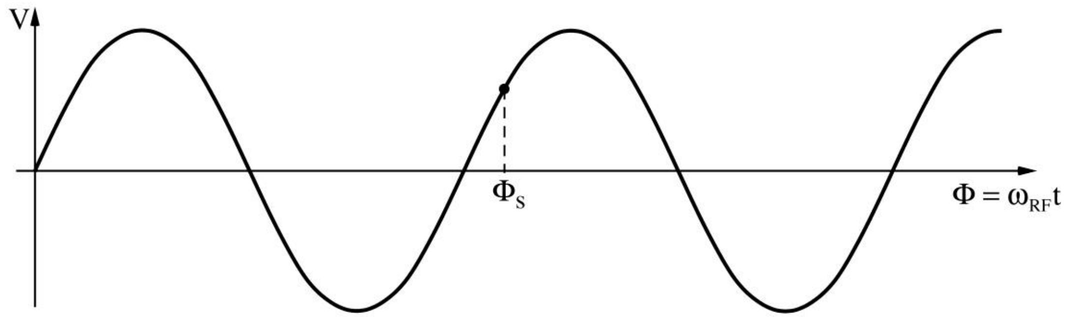
M_1 & N_1 will move towards P_1 => stable

M_2 & N_2 will go away from P_2 => unstable

(Highly relativistic particles have no significant velocity change)

A Consequence of Phase Stability





The divergence of the field is zero according to Maxwell :

$$\nabla \vec{E} = 0 \quad \Rightarrow \quad \frac{\partial E_x}{\partial x} + \frac{\partial E_z}{\partial z} = 0 \quad \Rightarrow \quad \frac{\partial E_x}{\partial x} = - \frac{\partial E_z}{\partial z}$$

Transverse fields

- focusing at the entrance and
- defocusing at the exit of the cavity.

Electrostatic case: Energy gain inside the cavity leads to focusing
RF case: Field increases during passage => transverse defocusing!

External focusing (solenoid, quadrupole) is then necessary

Energy-phase Oscillations (Small Amplitude) (1)

- Rate of energy gain for the synchronous particle:

$$\frac{dE_s}{dz} = \frac{dp_s}{dt} = eE_0 \sin f_s$$

- Use **reduced variables** with respect to synchronous particle

$$w = W - W_s = E - E_s \qquad \varphi = \phi - \phi_s$$

Energy gain:
$$\frac{dw}{dz} = eE_0 \left[\sin\left(\phi_s + \varphi\right) - \sin\phi_s\right] \approx eE_0 \cos\phi_s . \varphi \quad \left(small\ \varphi\right)$$

- Rate of **phase change** with respect to the synchronous one:

$$\frac{d\varphi}{dz} = \omega_{RF}\left(\frac{dt}{dz} - \left(\frac{dt}{dz}\right)_s\right) = \omega_{RF}\left(\frac{1}{v} - \frac{1}{v_s}\right) \cong -\frac{\omega_{RF}}{v_s^2}\left(v - v_s\right)$$

Leads finally to:
$$\frac{d\varphi}{dz} = -\frac{\omega_{RF}}{m_0 v_s^3 \gamma_s^3} w$$

Energy-phase Oscillations (Small Amplitude) (2)

Combining the two 1st order equations into a 2nd order equation gives the equation of a harmonic oscillator:

$$\frac{d^2\varphi}{dz^2} + \Omega_s^2 \varphi = 0$$

with

$$\Omega_s^2 = \frac{eE_0 \omega_{RF} \cos\phi_s}{m_0 v_s^3 \gamma_s^3}$$

Slower for higher energy!

Stable harmonic oscillations imply: $W_s^2 > 0$ and real

hence: $\cos\phi_s > 0$

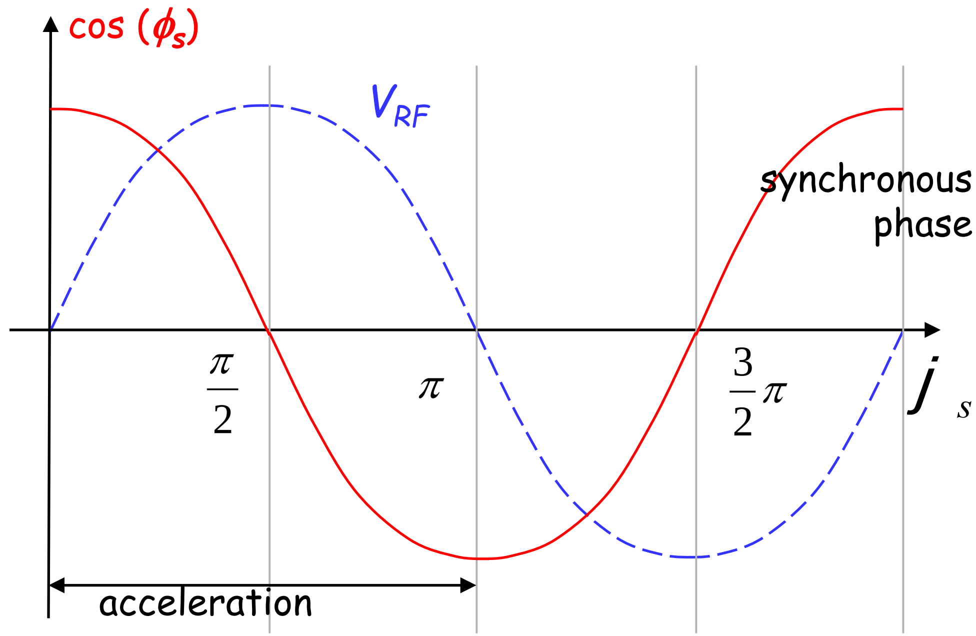
And since acceleration also means:

$$\sin\phi_s > 0$$

You finally get the result for the stable phase range:

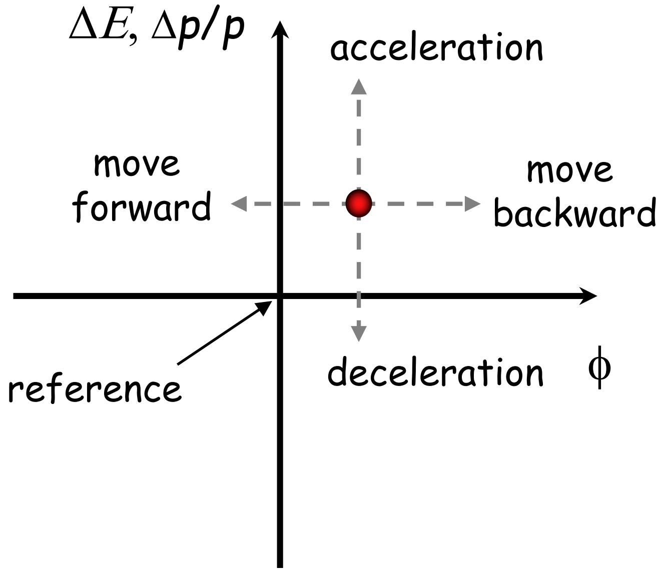
$$0 < \phi_s < \frac{\pi}{2}$$

Positive rising RF slope!

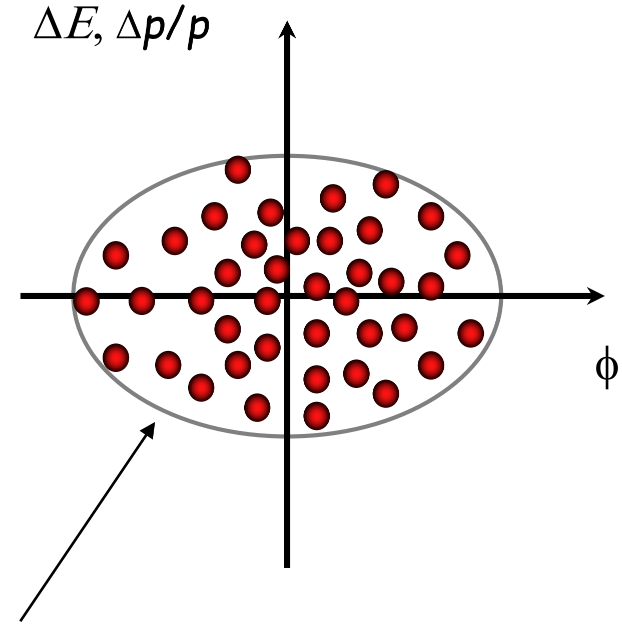


Longitudinal phase space

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)

Summary up to here…

- Acceleration by electric fields, static fields limited
  => time-varying fields
- Synchronous condition needs to be fulfilled for acceleration
- Particles perform oscillation around synchronous phase
- visualize oscillations in phase space

- Electrons are quickly relativistic, speed does not change
  use traveling wave structures for acceleration
- Protons and ions need changing structure geometry

Circular accelerators

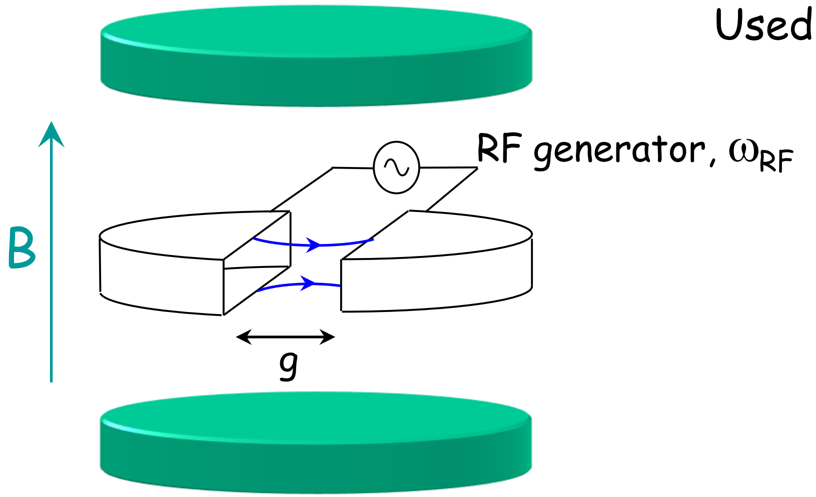
Cyclotron

Synchrotron

Circular accelerators: Cyclotron

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

Circular accelerators: Cyclotron



Used for protons, ions

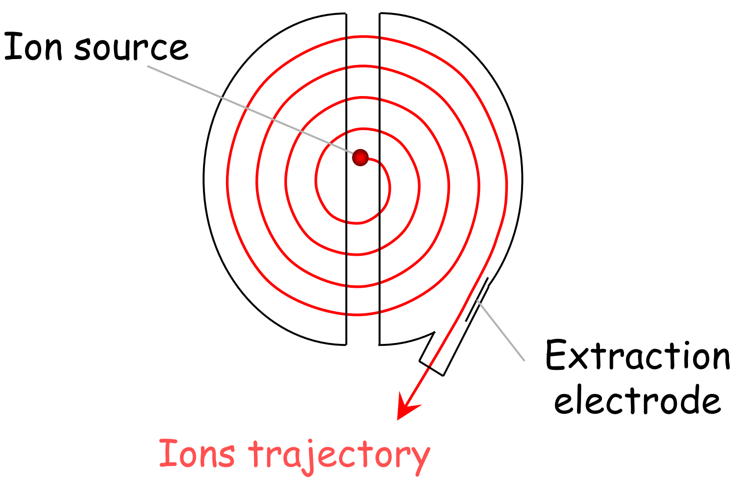
B = constant

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** ⇒ $\gamma \cong 1$

Cyclotron Animation

Animation: http://www.sciences.univ-nantes.fr/sites/genevieve_tulloue/Meca/Charges/cyclotron.html

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

The condition:

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

Allows to go beyond the non-relativistic energies

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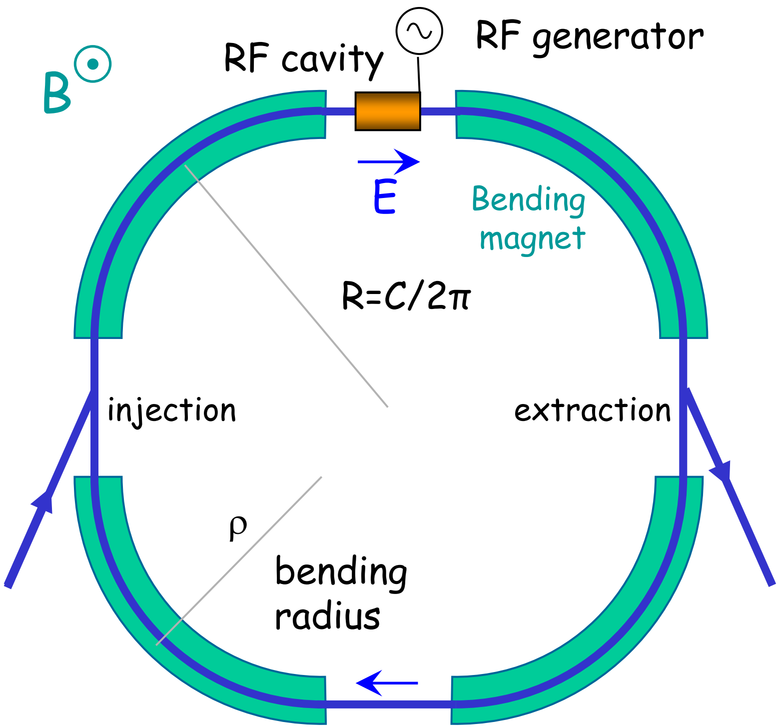
Circular accelerators: The Synchrotron



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

Circular accelerators: The Synchrotron

LEAR (CERN)
Low Energy Antiproton Ring

EPA (CERN)
Electron Positron Accumulator

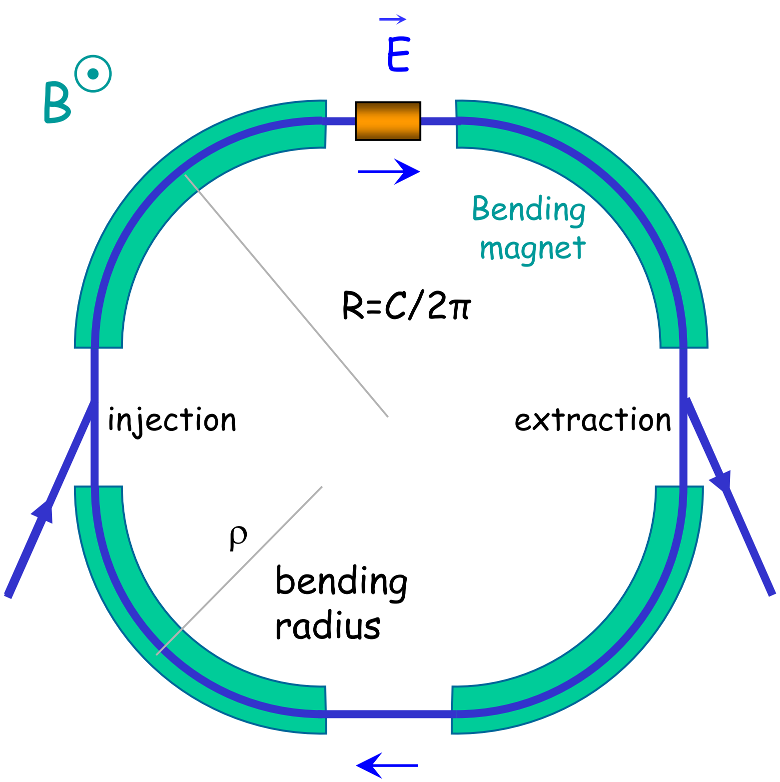
PS (CERN)
Proton Synchrotron
© CERN Geneva

Examples of different proton and electron synchrotrons at CERN

+ LHC (of course!)

The Synchrotron

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:



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

$f = f_s = cte$ ⟶ **Synchronous particle**

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

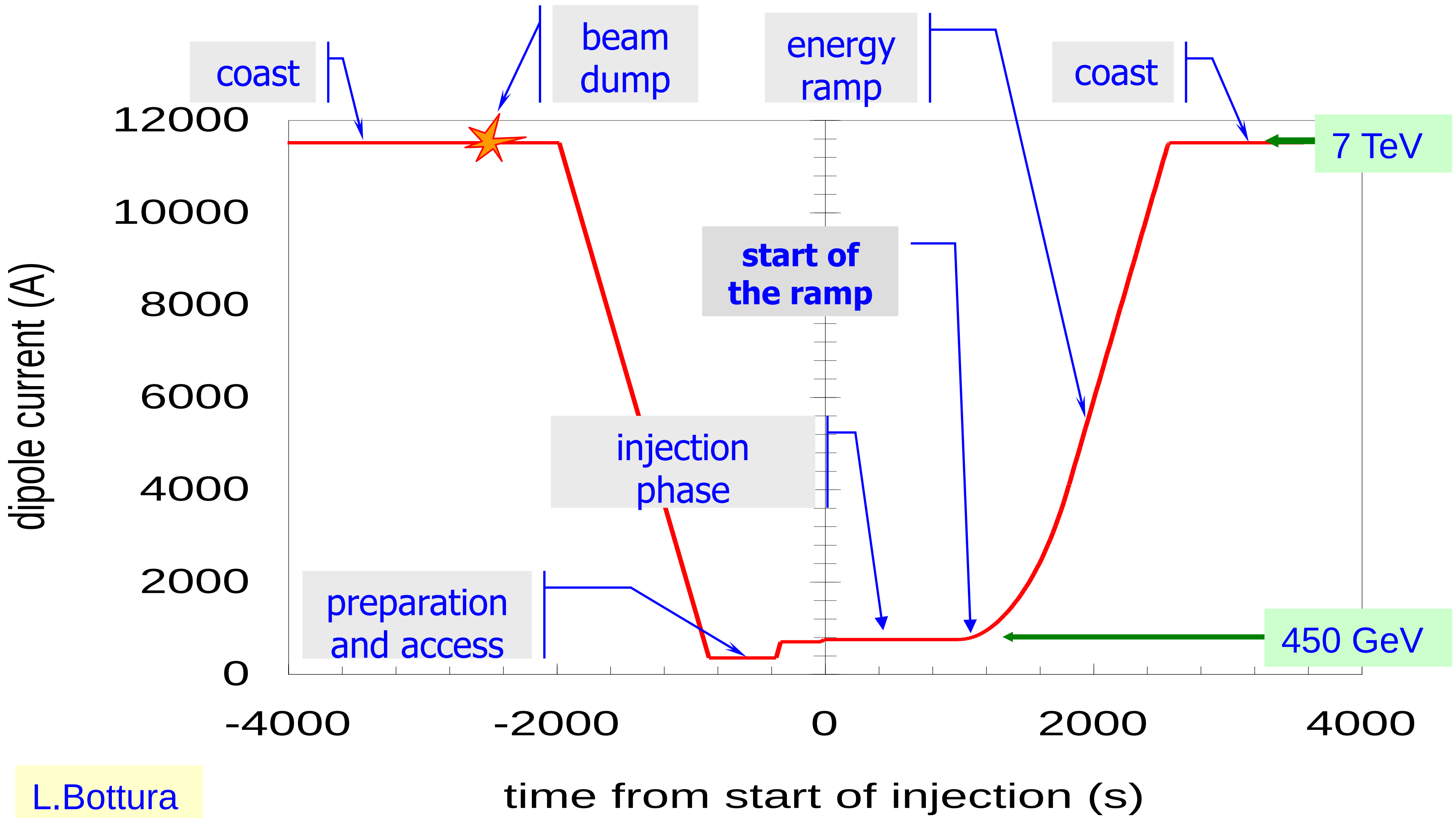
$r = cte \quad R = cte$ ⟶ **Constant orbit**

$B r = P/e$ Þ B ⟶ **Variable magnetic field**

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

The Synchrotron – LHC Operation Cycle

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



L.Bottura

The Synchrotron – Energy ramping

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

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

Since:

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

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

Stable phase φ_s changes during energy ramping

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

- The number of stable synchronous particles is equal to the harmonic number h. They are equally spaced along the circumference.
- Each synchronous particle satisfies the relation p=eBρ. They have the nominal energy and follow the nominal trajectory.

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 $p(t) = eB(t)\rho, \quad E = mc^2$)

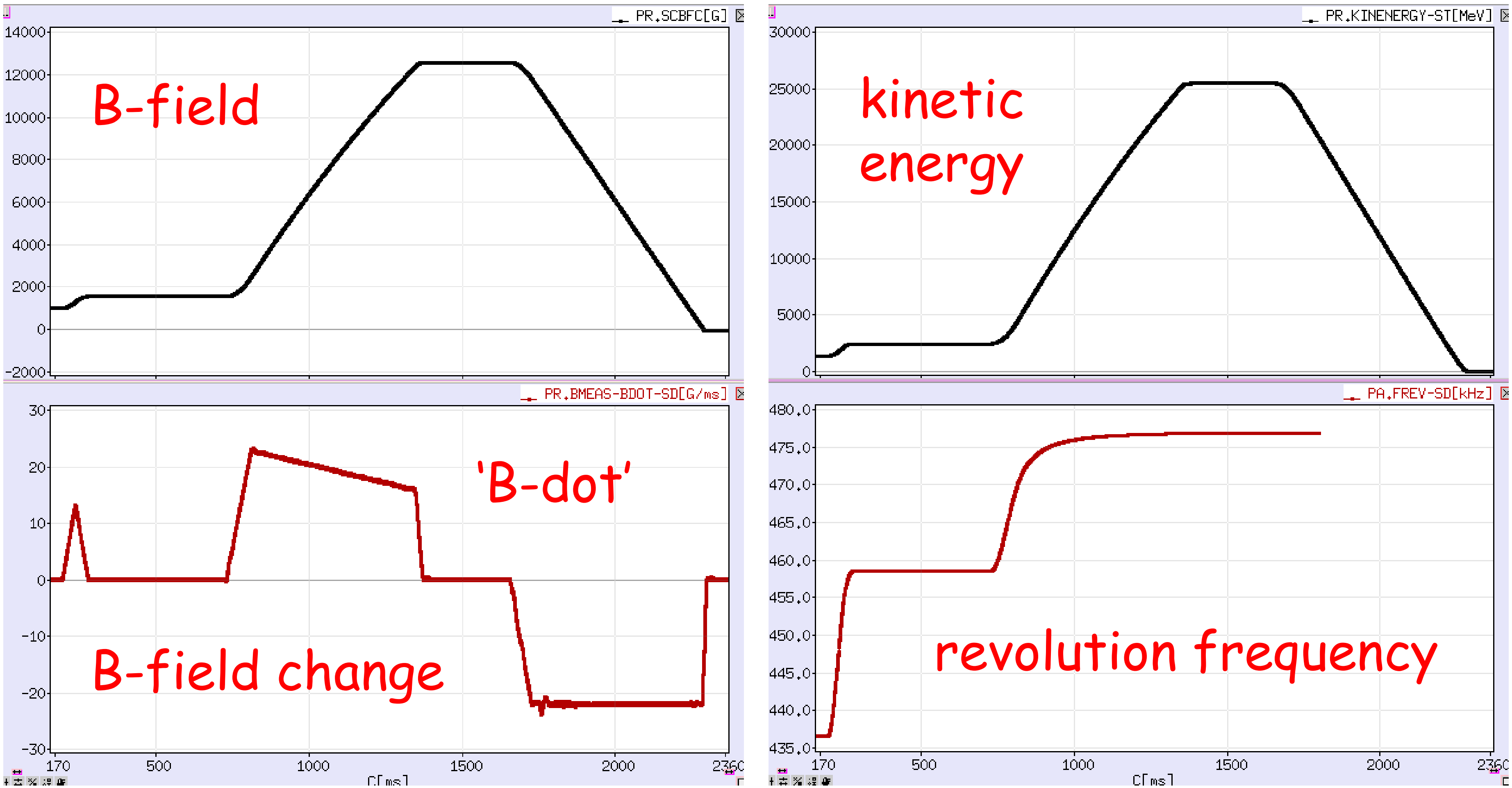
Since $E^2 = (m_0c^2)^2 + p^2c^2$ the RF frequency must follow the variation of the B field with the law

$$\frac{f_{RF}(t)}{h} = \frac{c}{2\pi R_s}\left\{\frac{B(t)^2}{(m_0c^2/ec\rho)^2 + B(t)^2}\right\}^{1/2}$$

This asymptotically tends towards $f_r \to \frac{c}{2\pi R_s}$ when B becomes large compared to $m_0c^2/(ec\rho)$ which corresponds to $v \to c$

Example: PS - Field / Frequency change

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



time (ms) →

time (ms) →

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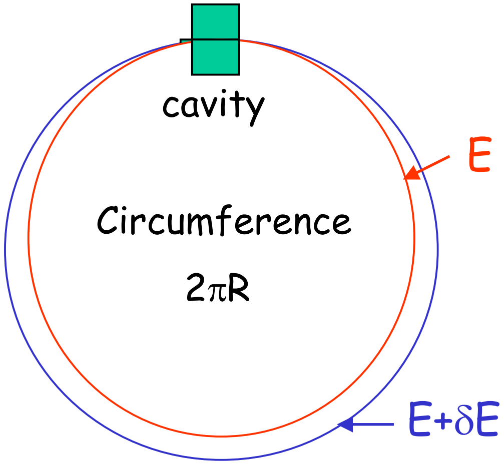
Dispersion Effects in a Synchrotron



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 frequency changes with a "slip factor η":

$$\eta = \frac{\mathrm{d}f_r / f_r}{\mathrm{d}p / p} \Rightarrow \eta = \frac{p}{f_r}\frac{df_r}{dp}$$

p=particle momentum

R=synchrotron physical radius

f_r=revolution frequency

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

Effect from orbit defined by Momentum compaction factor: $\alpha_c = \frac{dL/L}{dp/p}$

Property of the beam optics: (derivation in Appendix)

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

Dispersion Effects – Revolution Frequency

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

$$f_r = \frac{bc}{2pR} \quad \text{Þ} \quad \frac{df_r}{f_r} = \frac{db}{b} - \frac{dR}{R} = \frac{db}{b} - a_c\frac{dp}{p}$$

definition of momentum compaction factor

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

$$p = mv = bg\frac{E_0}{c} \quad \text{Þ} \quad \frac{dp}{p} = \frac{db}{b} + \frac{d\left(1-b^2\right)^{-½}}{\left(1-b^2\right)^{-½}} = \underbrace{\left(1-b^2\right)^{-1}}_{g^2}\frac{db}{b}$$

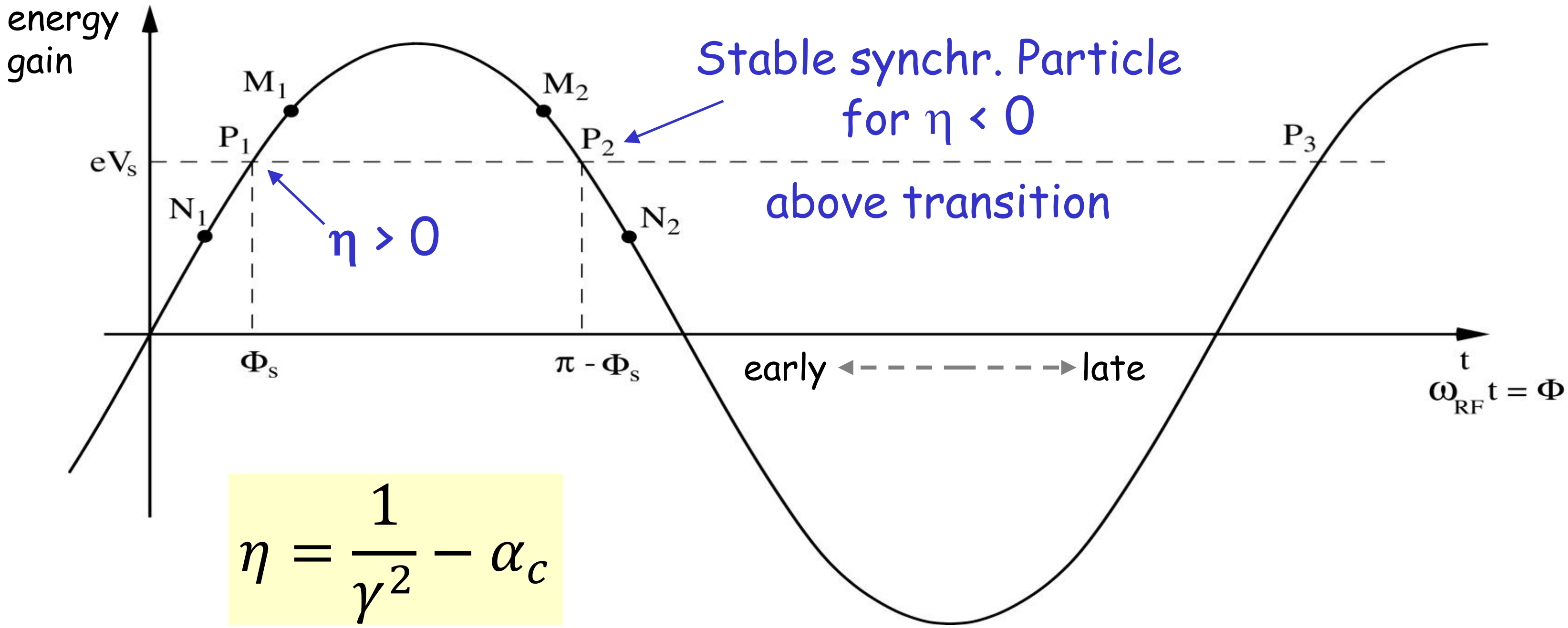
Slip factor: $\eta = \frac{1}{\gamma^2} - \alpha_c$ or $\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}$ with $\gamma_t = \frac{1}{\sqrt{\alpha_c}}$

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.

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.

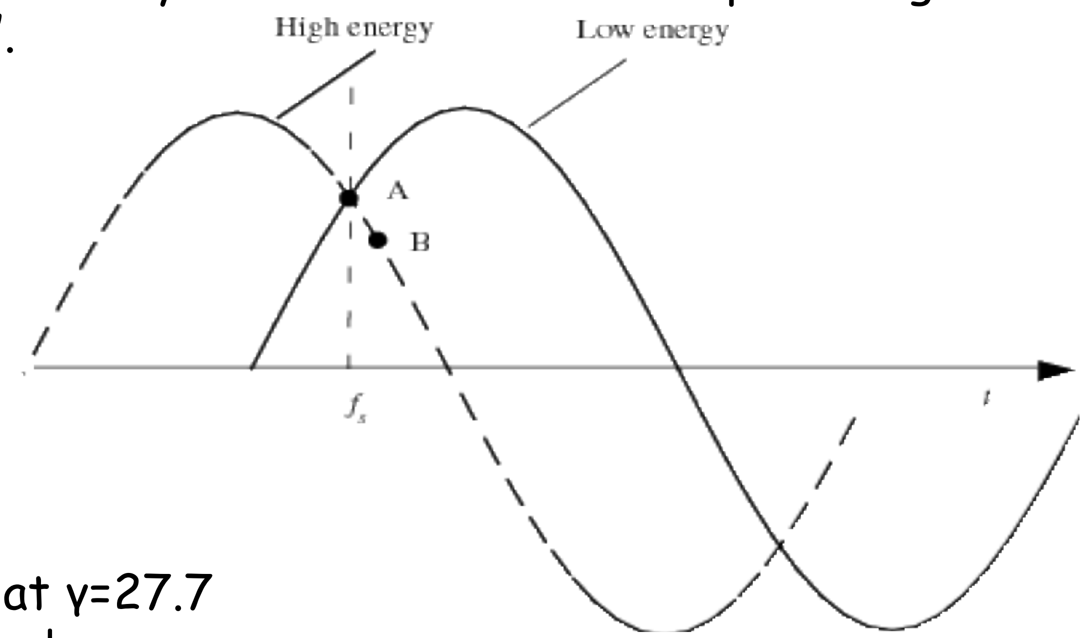


$$\eta = \frac{1}{\gamma^2} - \alpha_c$$

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

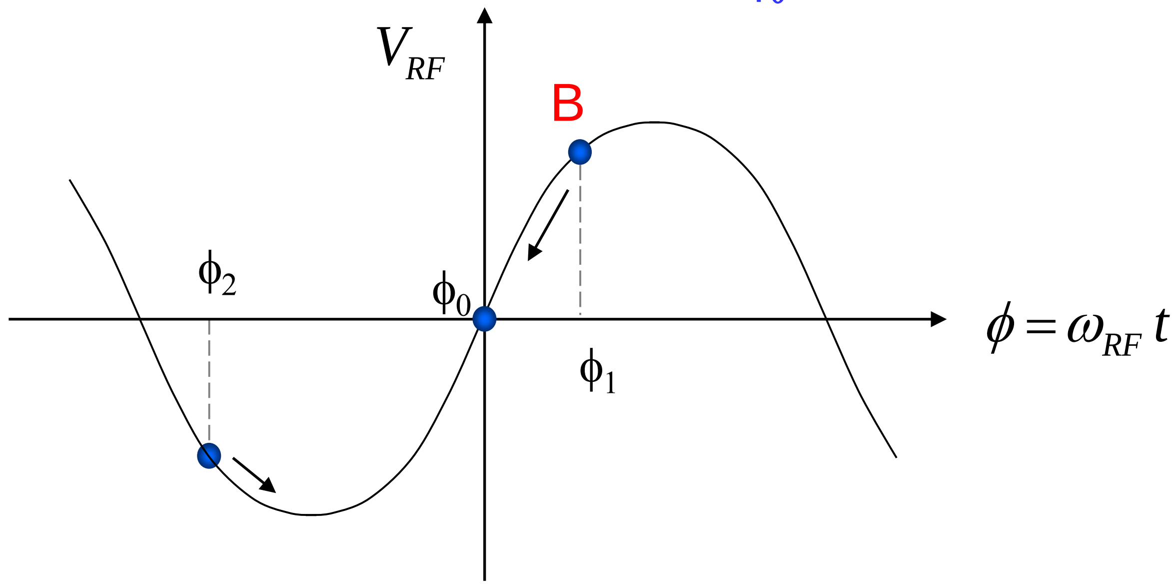
Transition crossing not needed in leptons machines, why?

Dynamics: Synchrotron oscillations

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

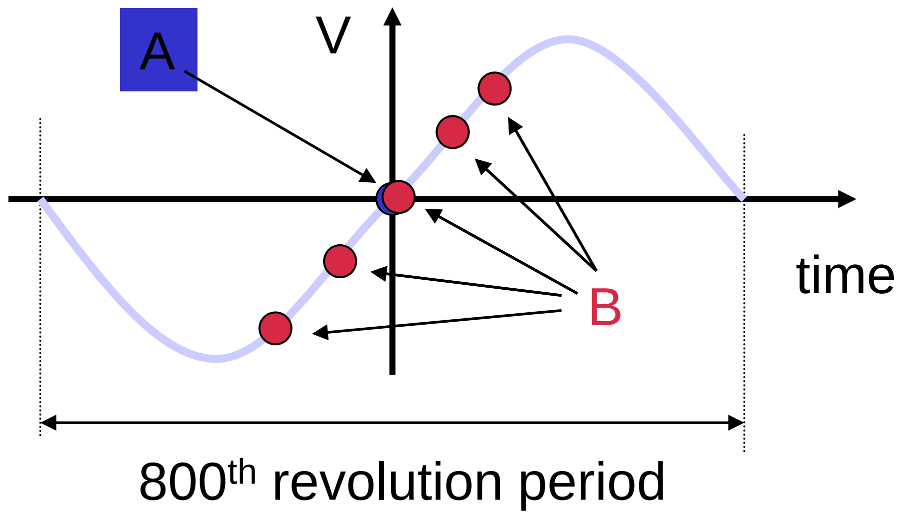
The phase of the synchronous particle must therefore be $\phi_0 = 0$.

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

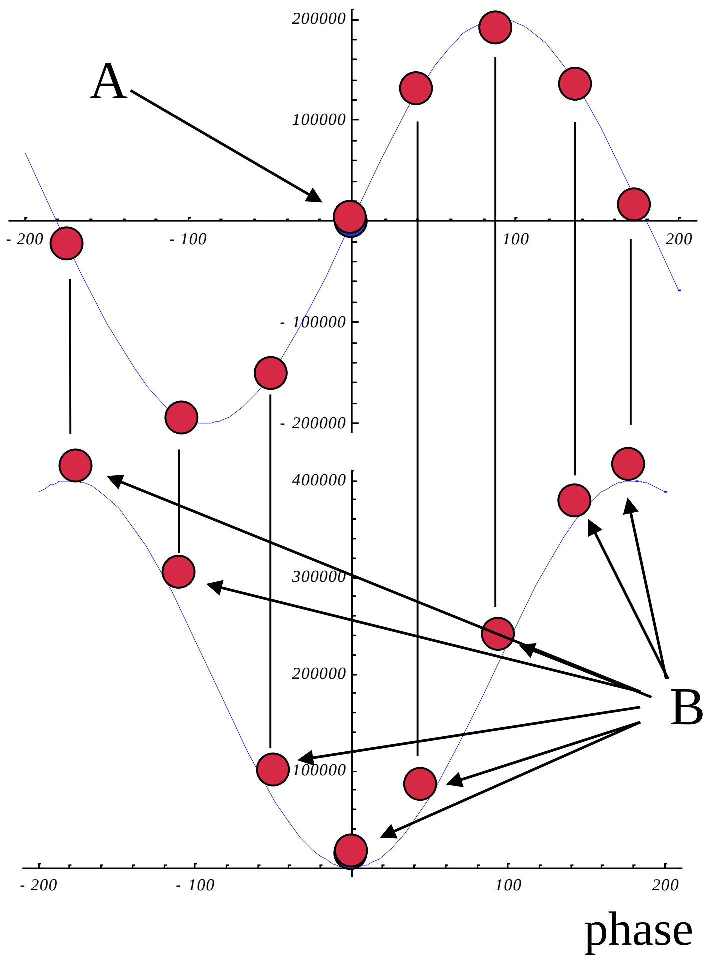


Particle B is performing Synchrotron Oscillations around synchronous particle A.

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

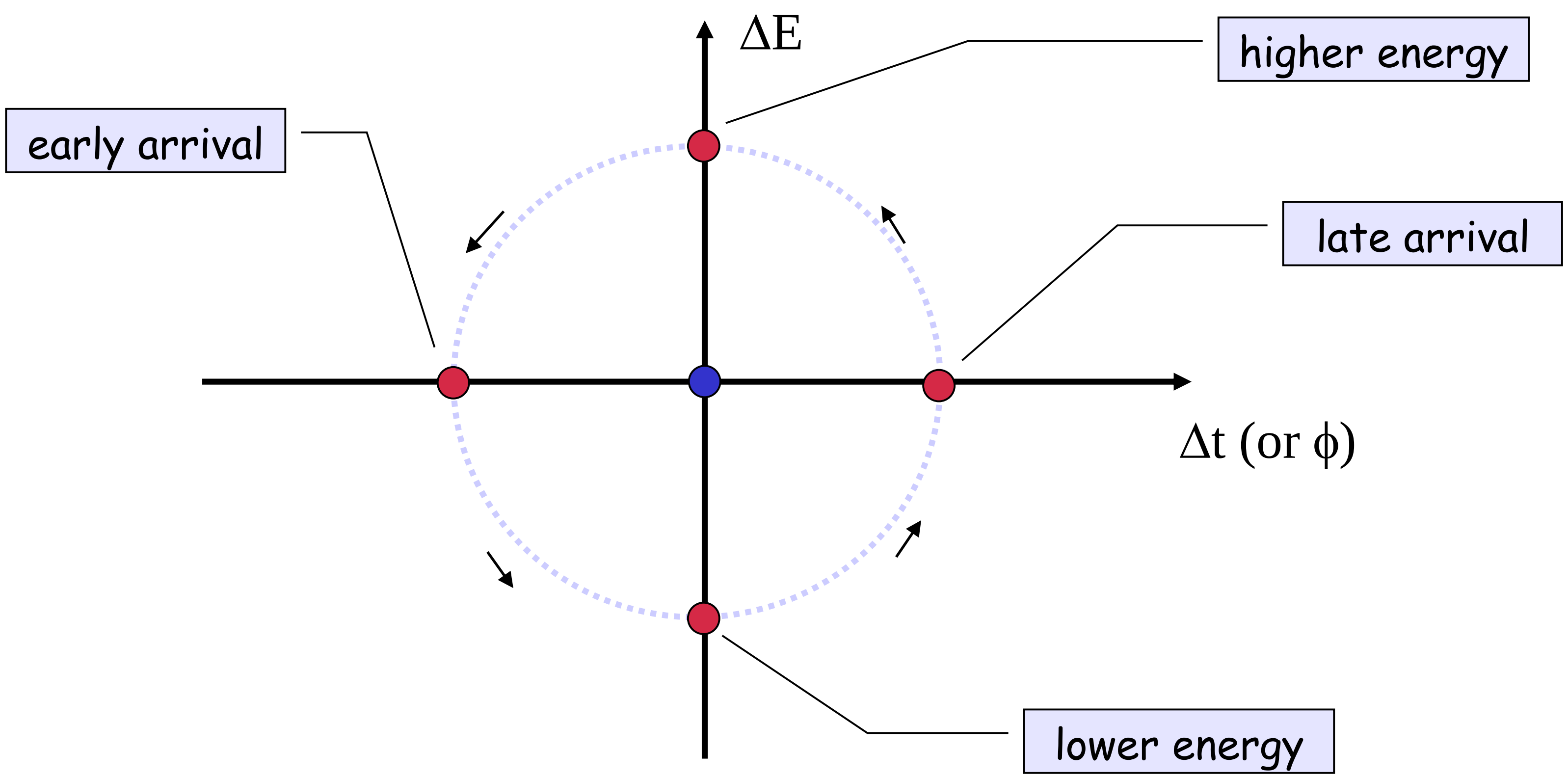
Potential well

Longitudinal Phase Space Motion

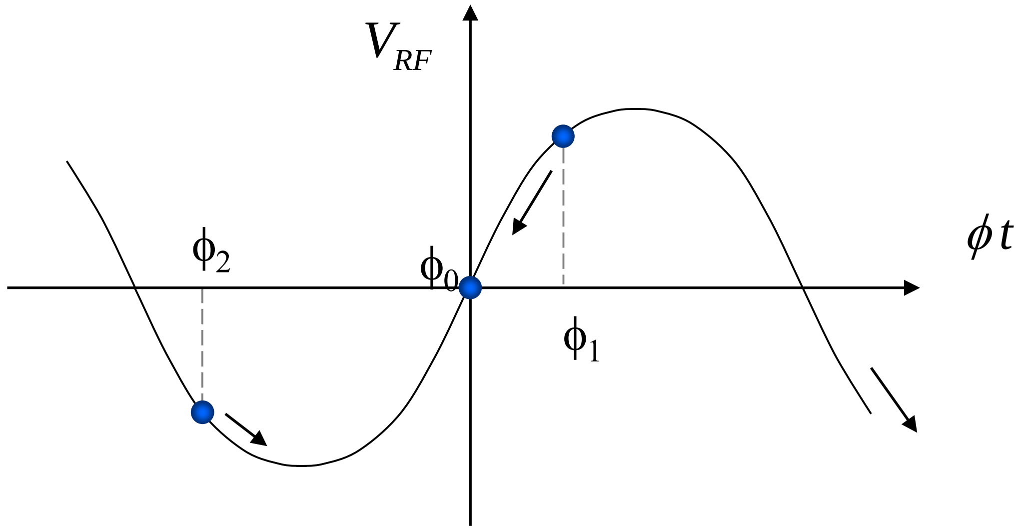
Particle B oscillates around particle A

This is a synchrotron oscillation

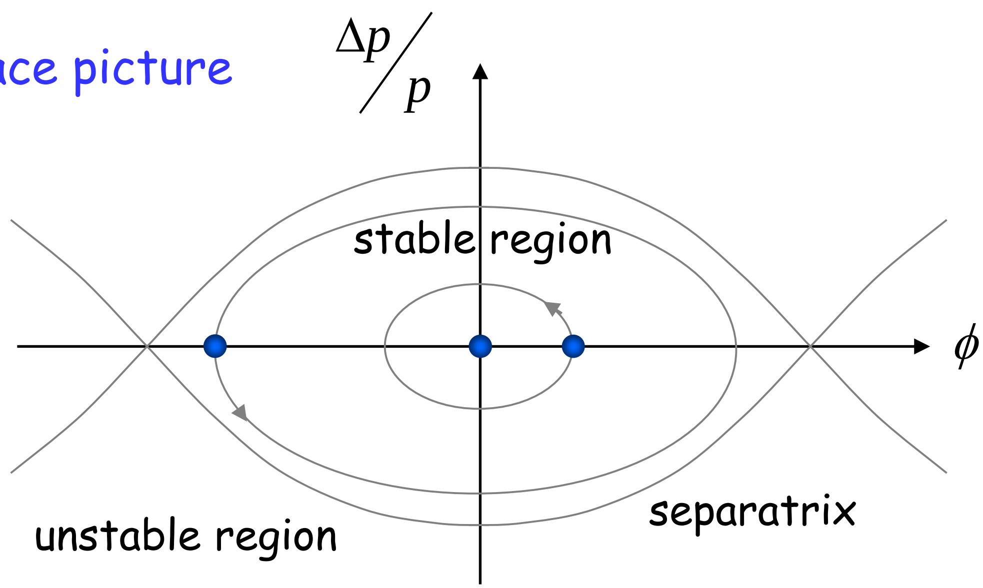
Plotting this motion in longitudinal phase space gives:



Synchrotron oscillations – No acceleration



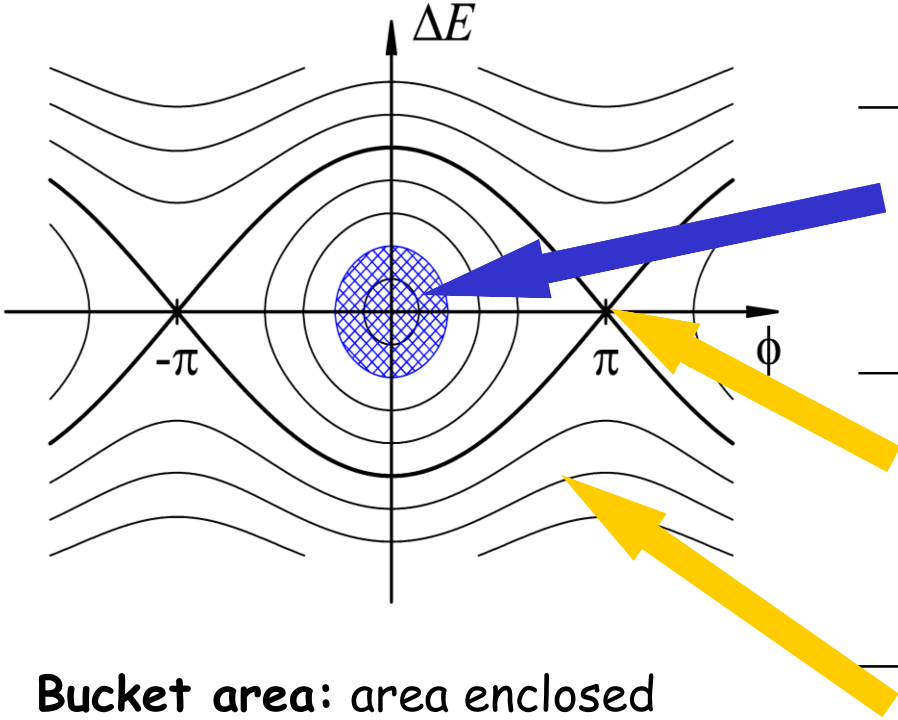
Phase space picture



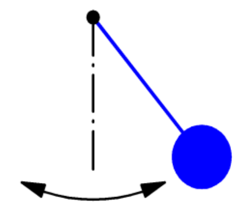
Synchrotron motion in phase space

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

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

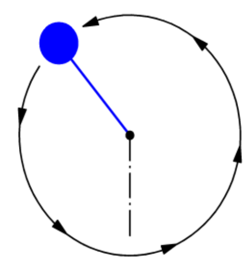


Particle **inside the separatrix**:



Particle at the **unstable fix-point**

Particle **outside the separatrix**:

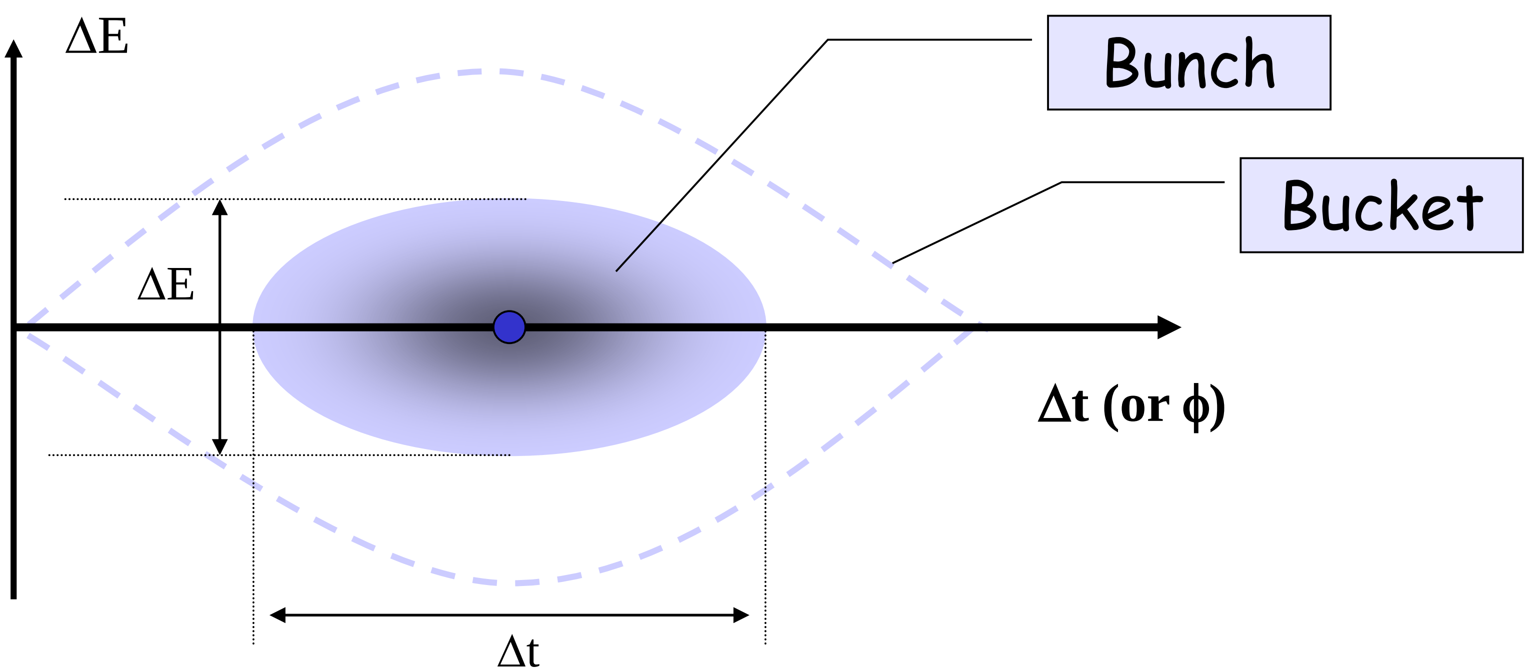


Bucket area: area enclosed by the separatrix

The area covered by particles is the longitudinal emittance

(Stationary) Bunch & Bucket

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



Bucket area = **longitudinal Acceptance** [eVs]

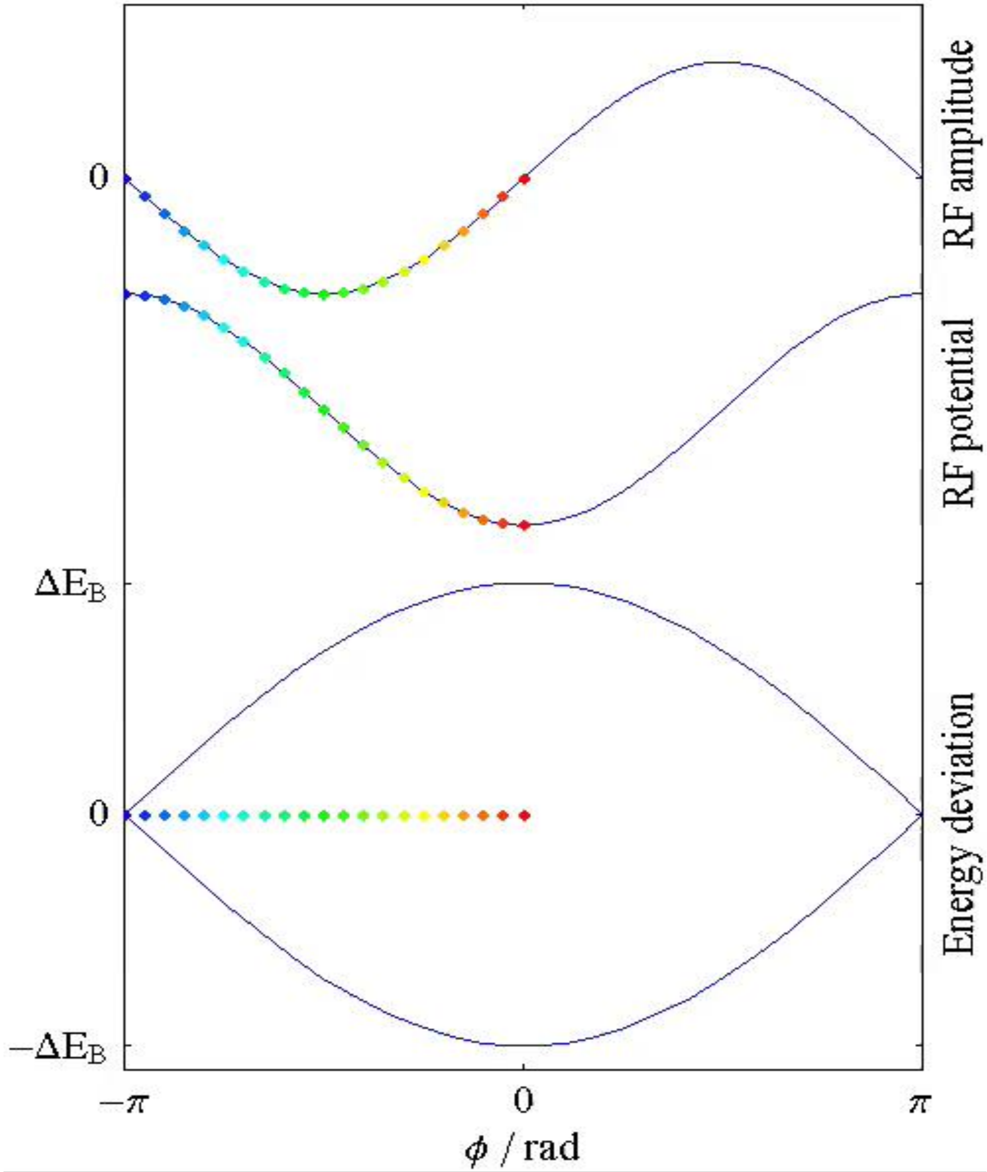
Bunch area = **longitudinal beam emittance** = $4\pi\, \sigma_E\, \sigma_t$ **[eVs]**

Attention: Different definitions are used!

Synchrotron motion in phase space

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

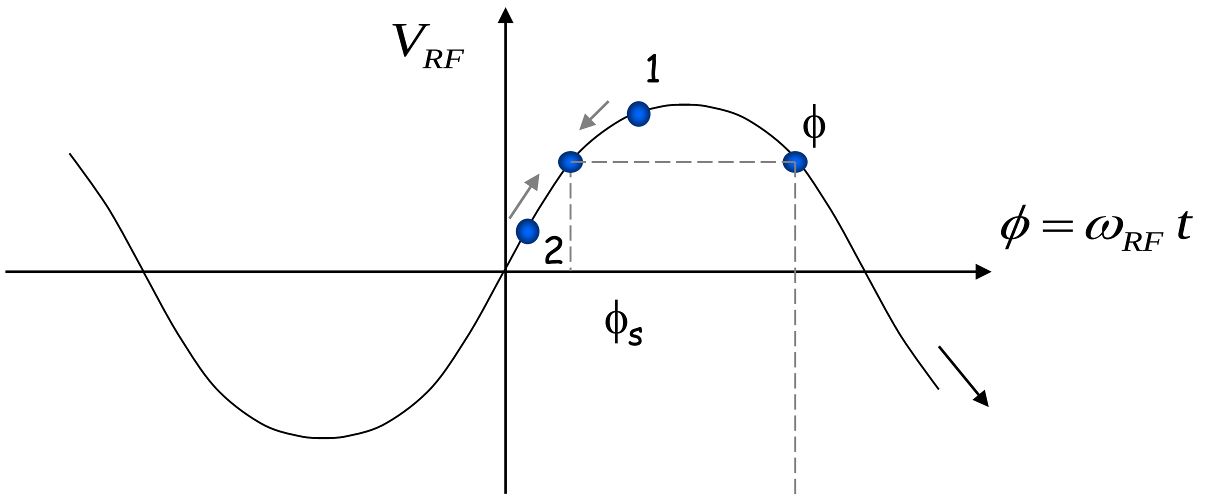
(here shown for a stationary bucket)



Synchrotron oscillations (with acceleration)

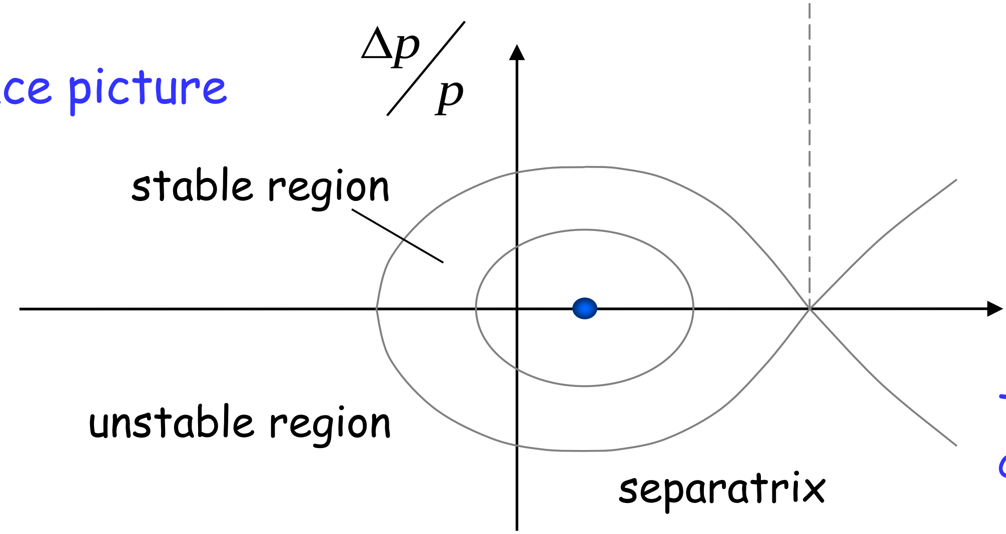
Case with acceleration *B increasing*

$\gamma < \gamma_t$



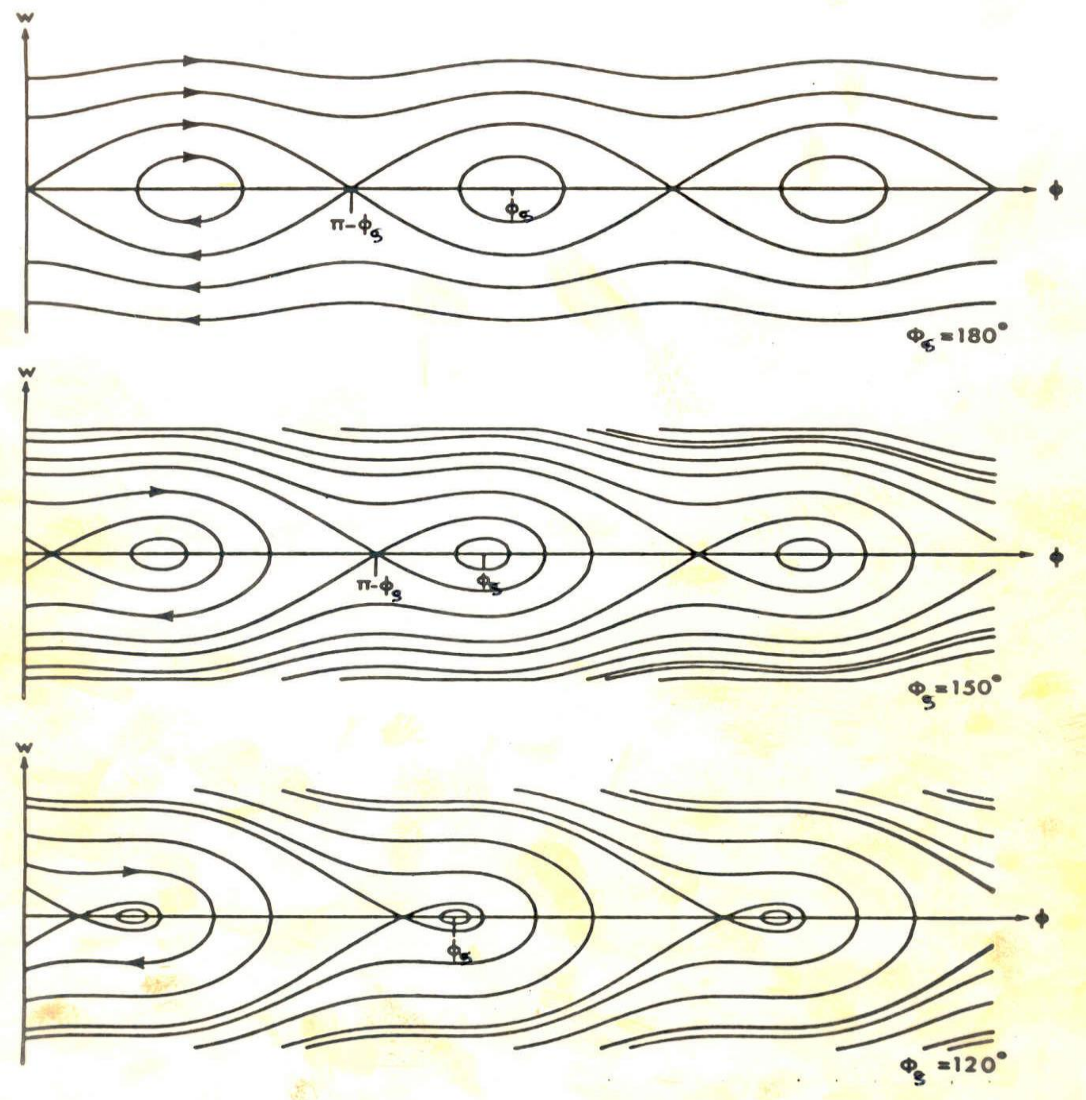
$$\phi_s < \phi < \pi - \phi_s$$

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 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_s, it is sufficient to follow other particles with respect to that particle.
So let's introduce the following **reduced variables**:

revolution frequency :	$\Delta f_r = f_r - f_{rs}$
particle RF phase :	$\Delta\phi = \phi - \phi_s$
particle momentum :	$\Delta p = p - p_s$
particle energy :	$\Delta E = E - E_s$
azimuth angle :	$\Delta\theta = \theta - \theta_s$

Equations of Longitudinal Motion

In these reduced variables, the equations of motion are (see Appendix):

$$\frac{\Delta E}{\omega_{rs}} = -\frac{p_s R_s}{h\eta\omega_{rs}} \frac{d(\Delta\phi)}{dt} = -\frac{p_s R_s}{h\eta\omega_{rs}} \dot{\phi}$$

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

deriving and combining

$$\frac{d}{dt}\left[\frac{R_s p_s}{h\eta\omega_{rs}} \frac{d\phi}{dt}\right] + \frac{e\hat{V}}{2\pi}(\sin\phi - \sin\phi_s) = 0$$

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

We will simplify in the following…

Small Amplitude Oscillations

Let's assume constant parameters R_s, p_s, ω_s and η:

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

with

$$\Omega_s^2 = \frac{h\eta\omega_{rs} e\hat{V}\cos\phi_s}{2\pi R_s p_s}$$

Consider now small phase deviations from the reference particle:

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

(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:

$$\nu_s = \Omega_s / \omega_r$$

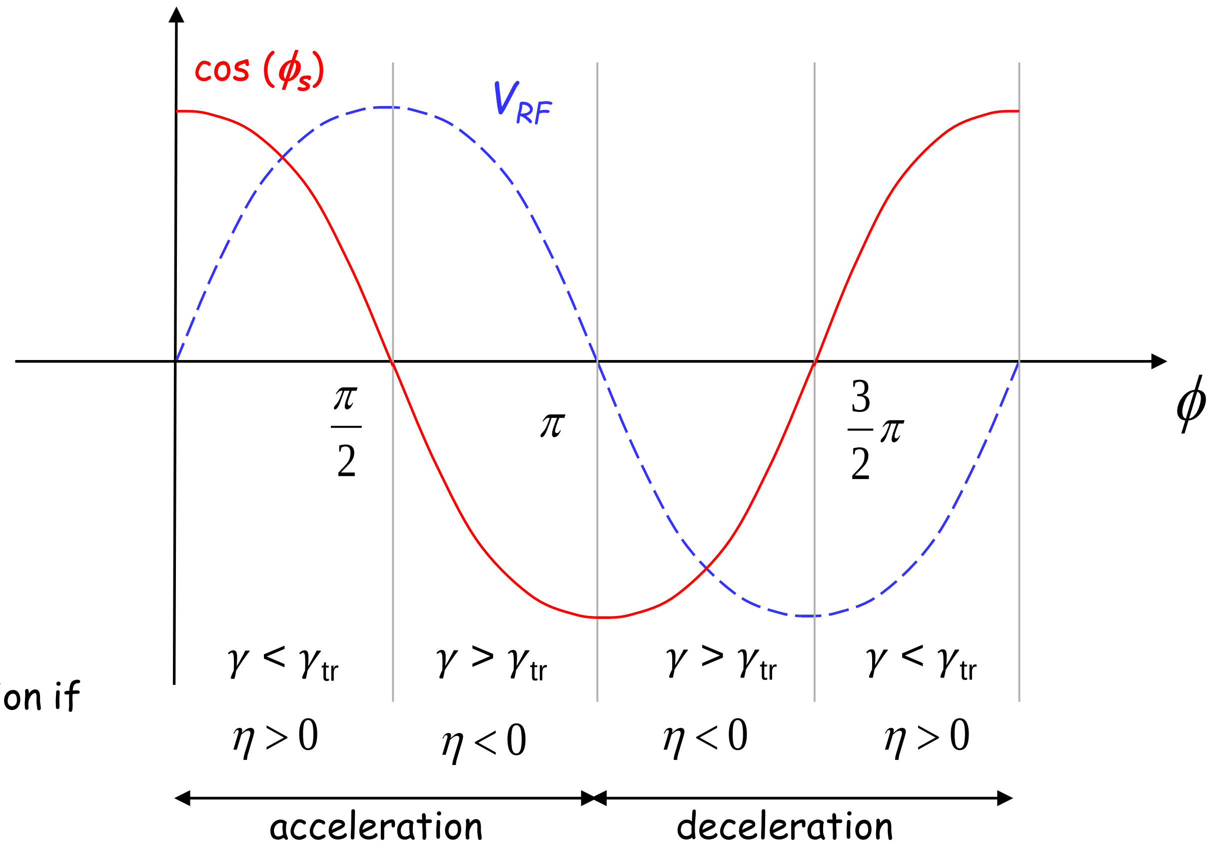
See Appendix for large amplitude treatment and further details.

Stability condition for ϕ_s

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

$$\Omega_s^2 = \frac{e\hat{V}_{RF}\,\eta\, h\,\omega_s}{2\pi R_s p_s}\cos\phi_s \quad\Rightarrow\quad \Omega_s^2 > 0 \quad\Leftrightarrow\quad \eta\cos\phi_s > 0$$

Stable in the region if

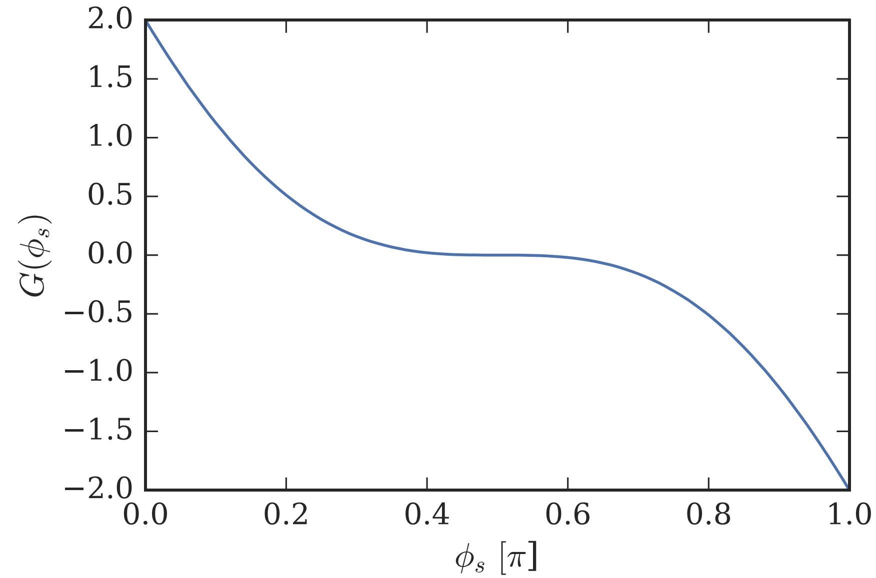


Energy Acceptance

From the equation of the separatrix, we can calculate (see appendix) the acceptance in energy:

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

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



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

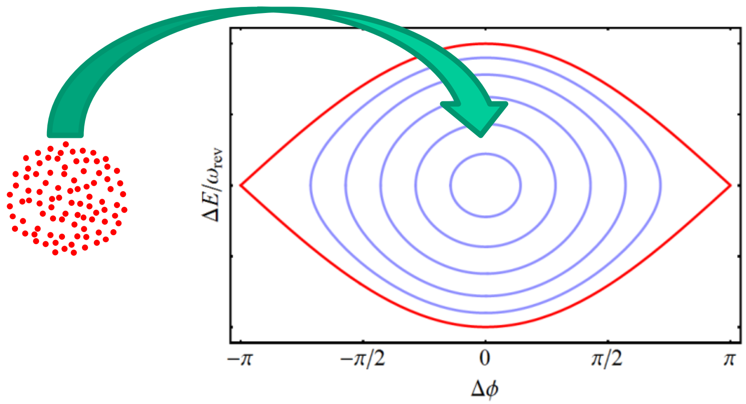
It's largest for $\phi_s=0$ and $\phi_s=\pi$ (no acceleration, depending on η).

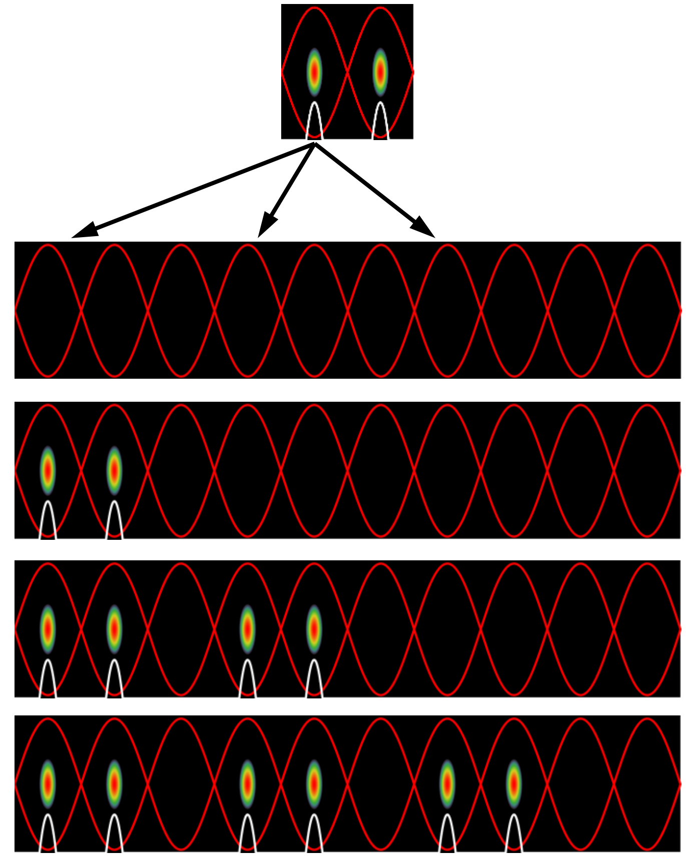
It becomes smaller during acceleration, when ϕ_s is changing

Need a higher RF voltage for higher acceptance.

Injection: Bunch-to-bucket transfer

- Bunch from sending accelerator into the bucket of receiving





Advantages:

→ Particles always subject to longitudinal focusing

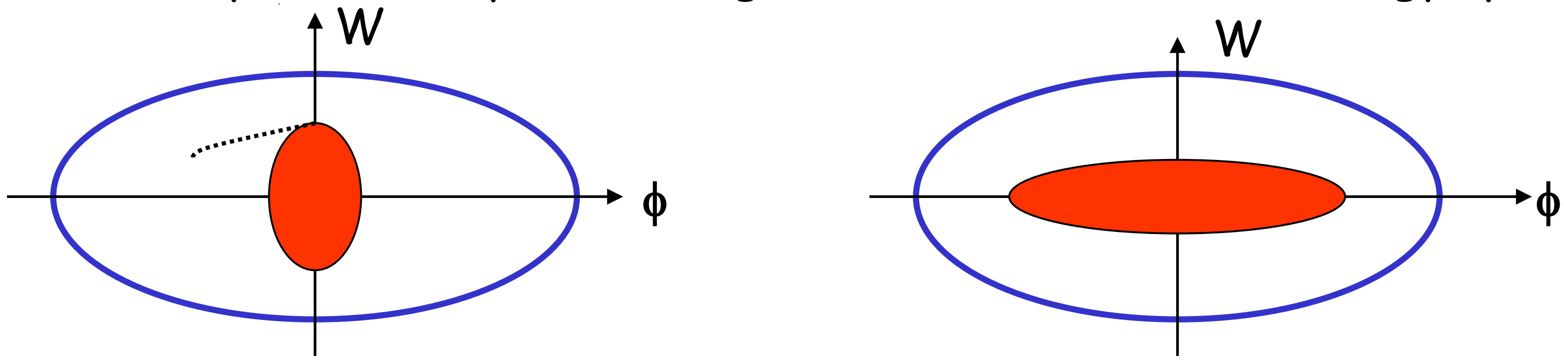
→ No need for RF capture of de-bunched beam in receiving accelerator

→ No particles at unstable fixed point

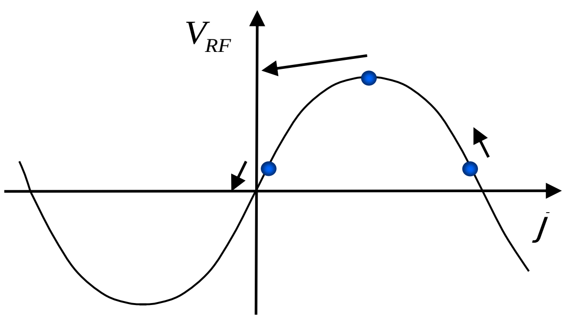
→ Time structure of beam preserved during transfer

Effect of a Mismatch

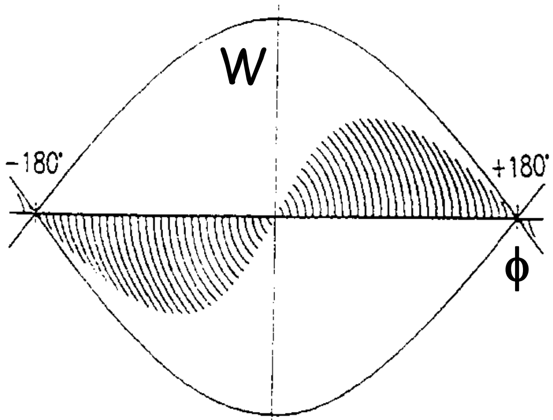
Injected bunch: short length and large energy spread
after 1/4 synchrotron period: longer bunch with a smaller energy spread.



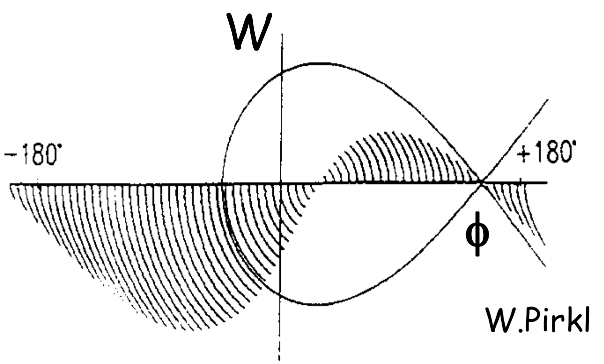
For larger amplitudes, the angular phase space motion is slower
(1/8 period shown below) => can lead to filamentation and emittance growth



restoring force is non-linear



stationary bucket

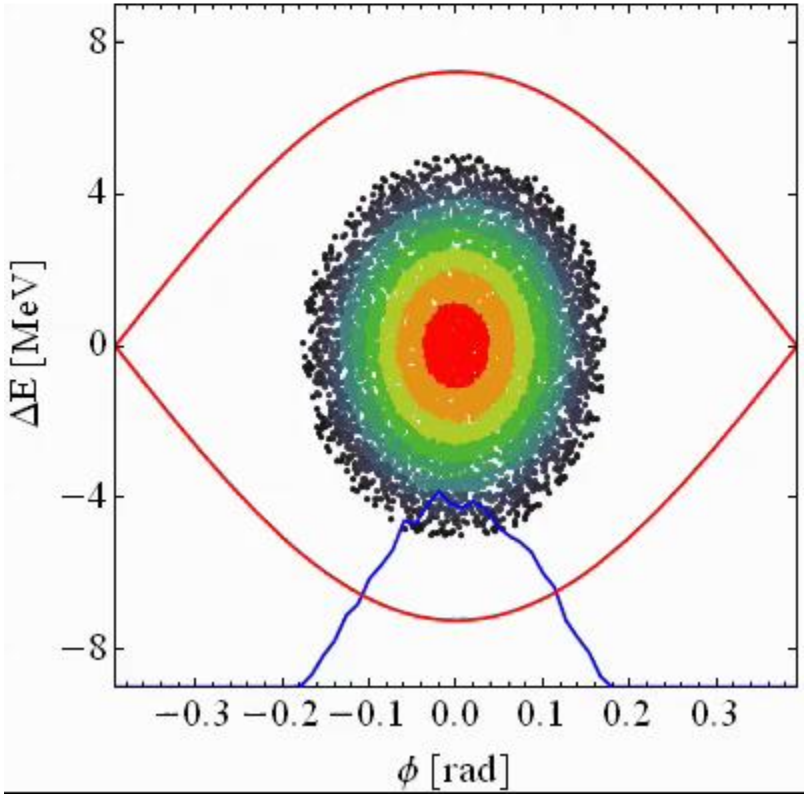


accelerating bucket

Effect of a Mismatch (2)

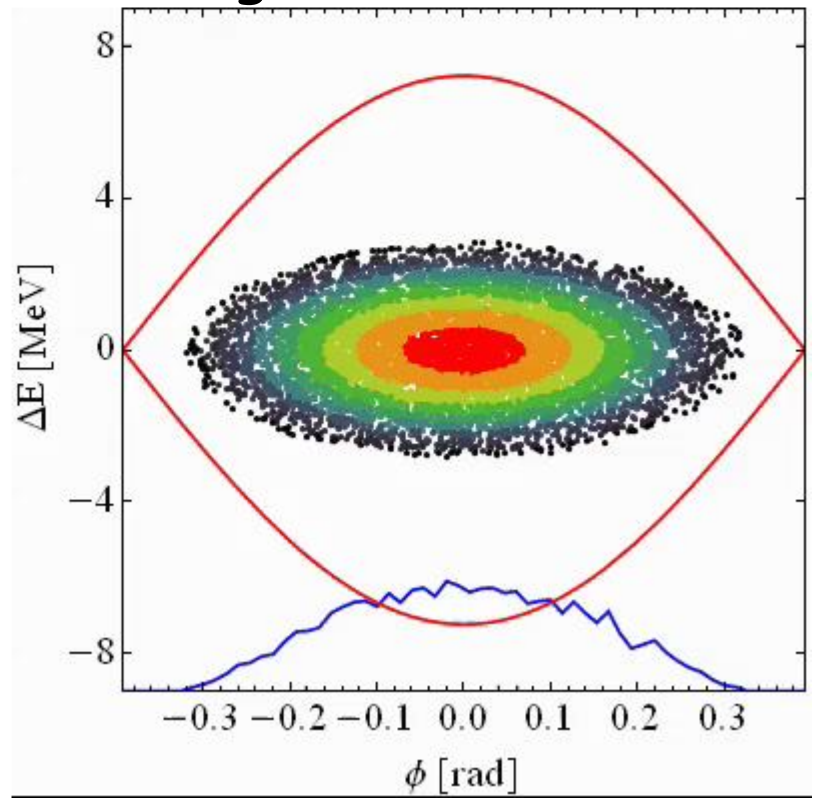
- Long. emittance is only preserved for correct RF voltage

Matched case



→ Bunch is fine, longitudinal emittance remains constant

Longitudinal mismatch

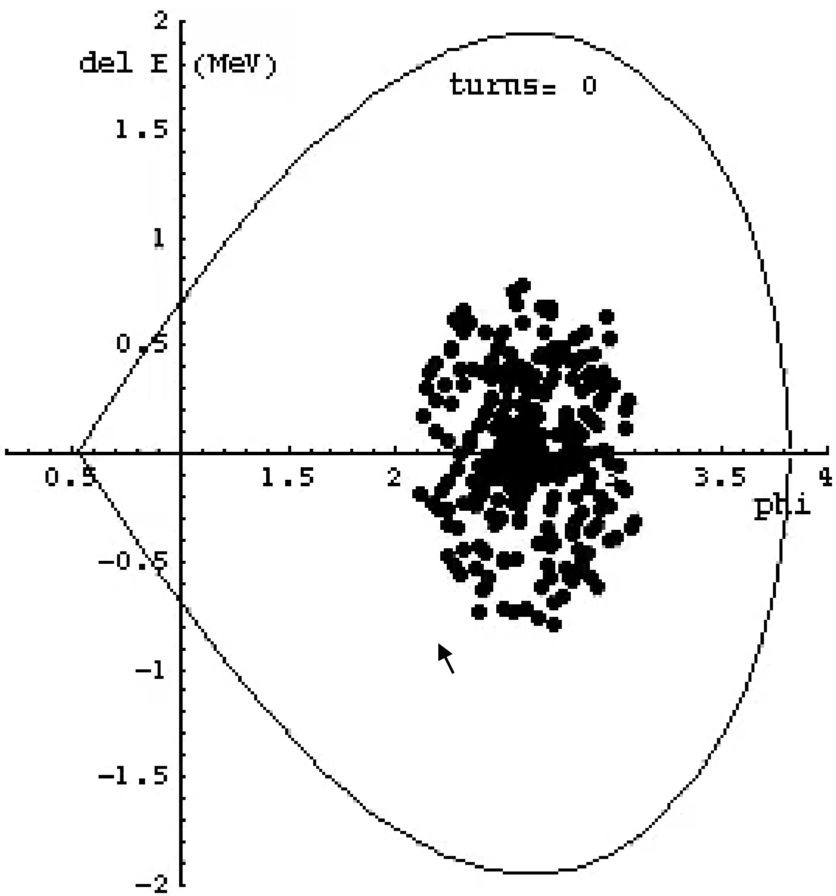


→ Dilution of bunch results in increase of long. emittance

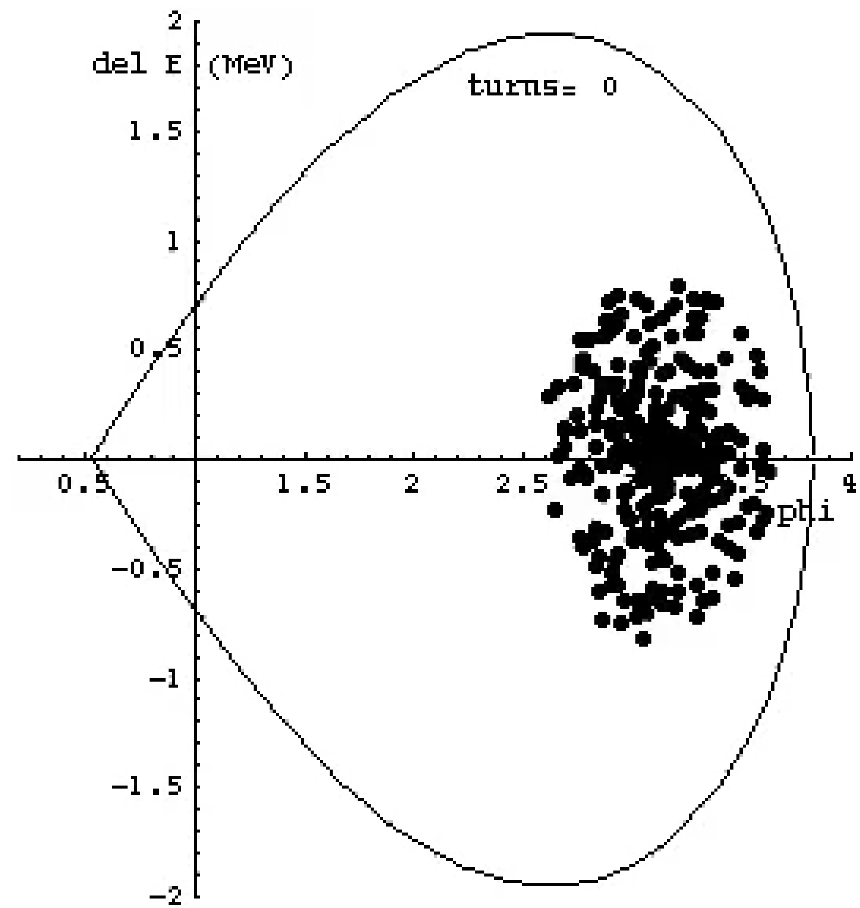
Effect of a Mismatch (3)

Evolution of an injected beam for the first 100 turns.

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



matched beam

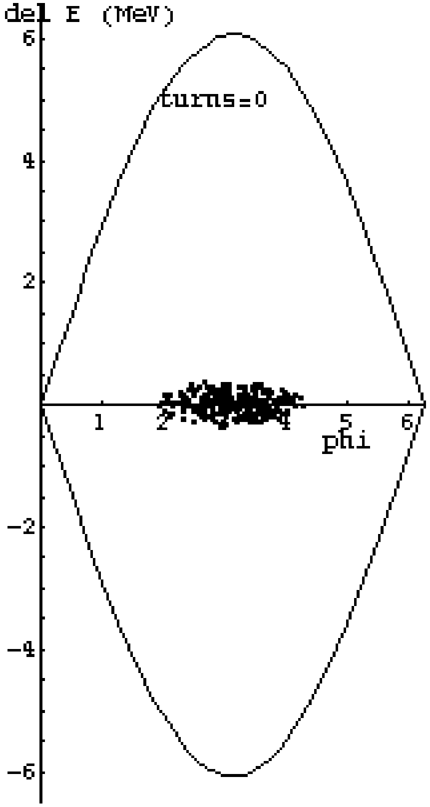


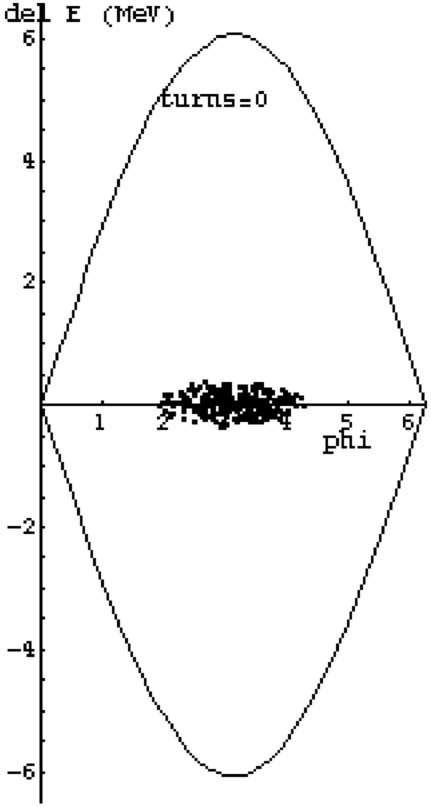
mismatched beam – phase error

Bunch Rotation

Phase space motion can be used to make short bunches.

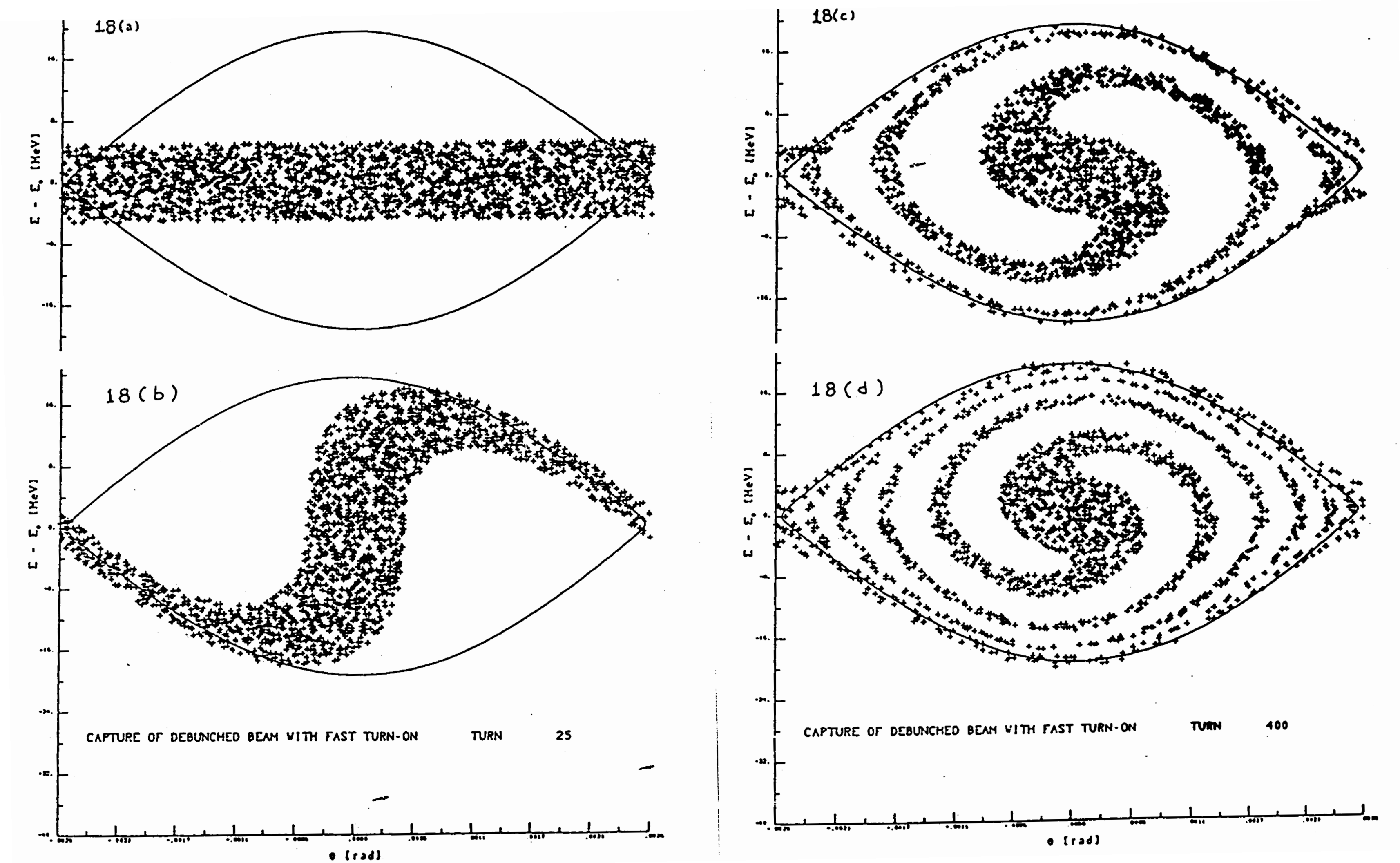
Start with a long bunch and extract or recapture when it's short.



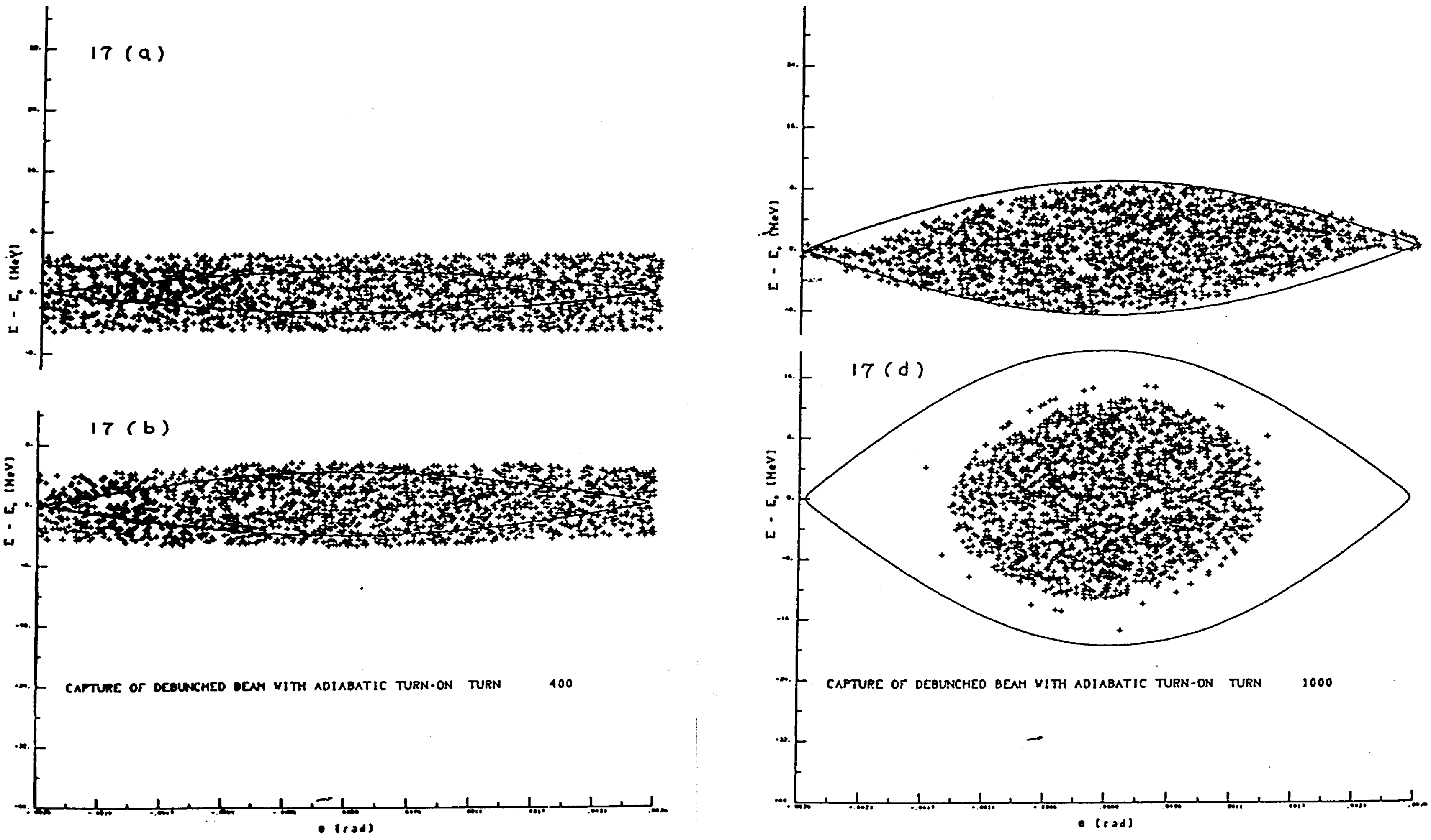


initial beam

Capture of a Debunched Beam with Fast Turn-On

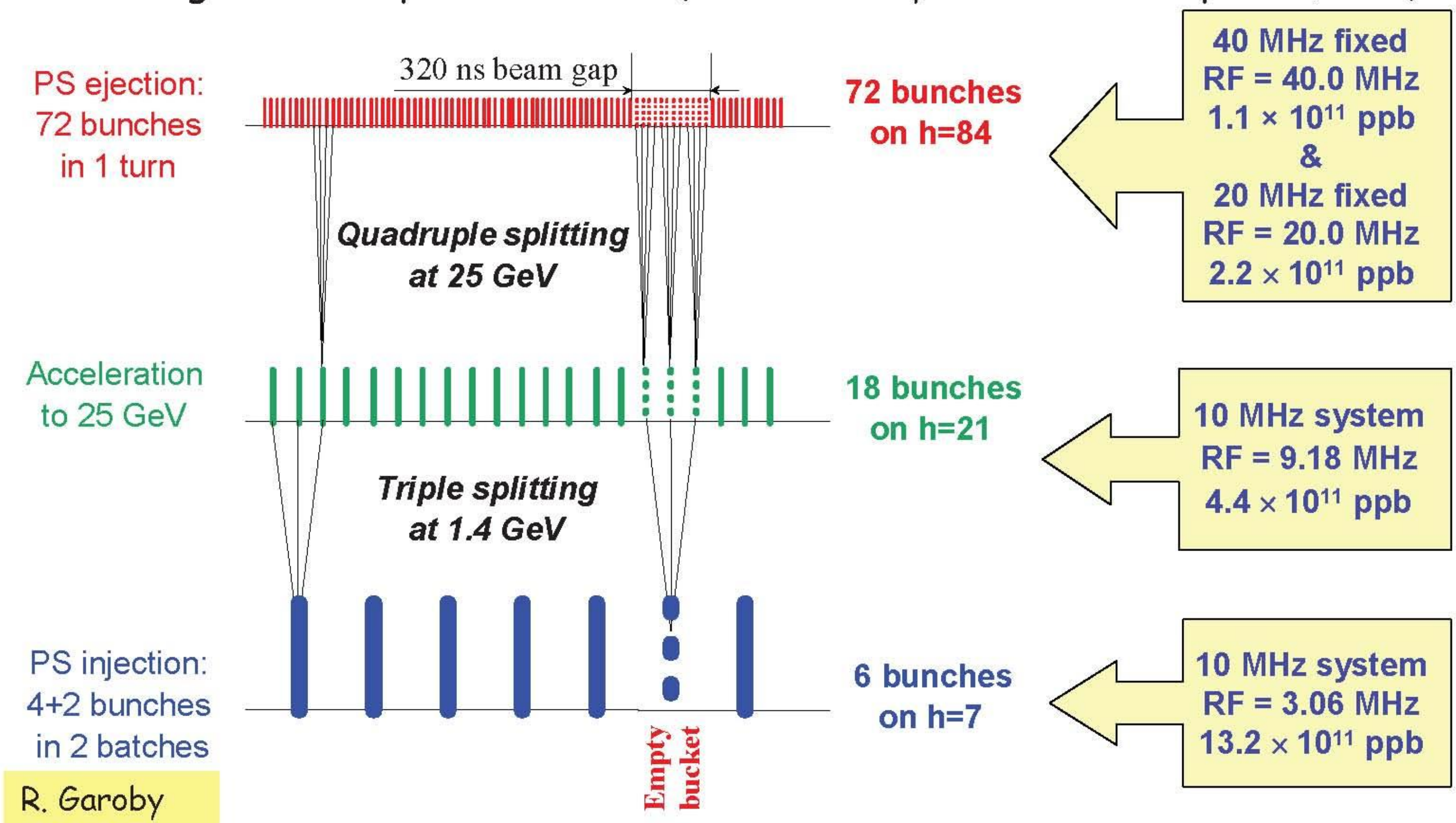


Capture of a Debunched Beam with Adiabatic Turn-On



Generating a 25ns Bunch Train in the PS

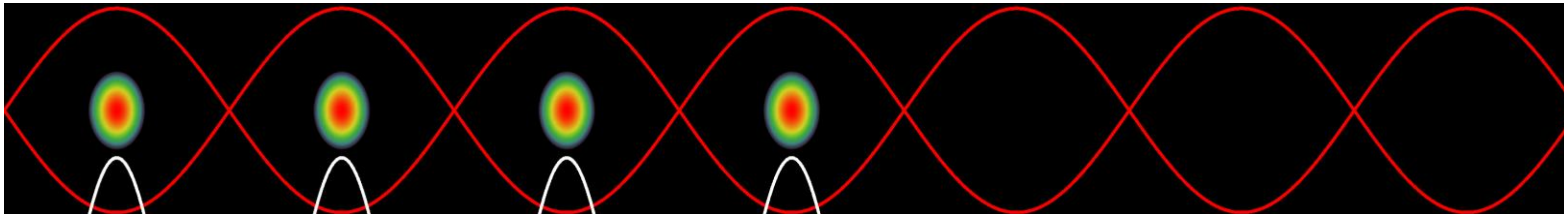
- **Longitudinal bunch splitting (basic principle)**
  - Reduce voltage on principal RF harmonic and simultaneously rise voltage on multiple harmonics (adiabatically with correct phase, etc.)



Use double splitting at 25 GeV to generate 50ns bunch trains instead

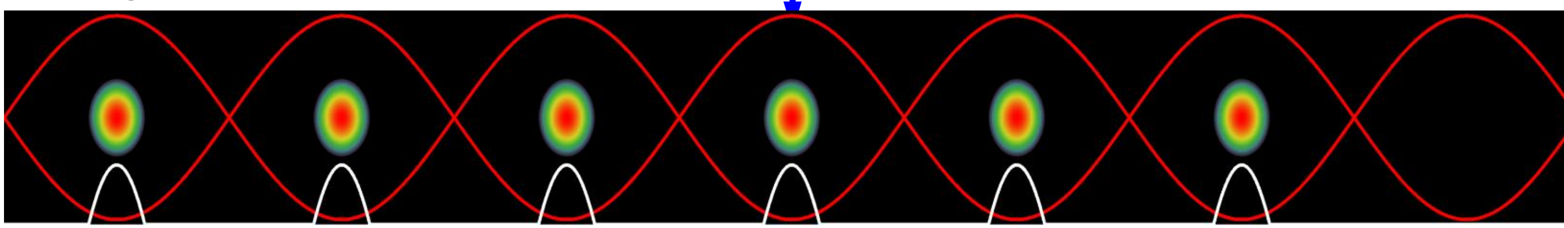
Production of the LHC 25 ns beam

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

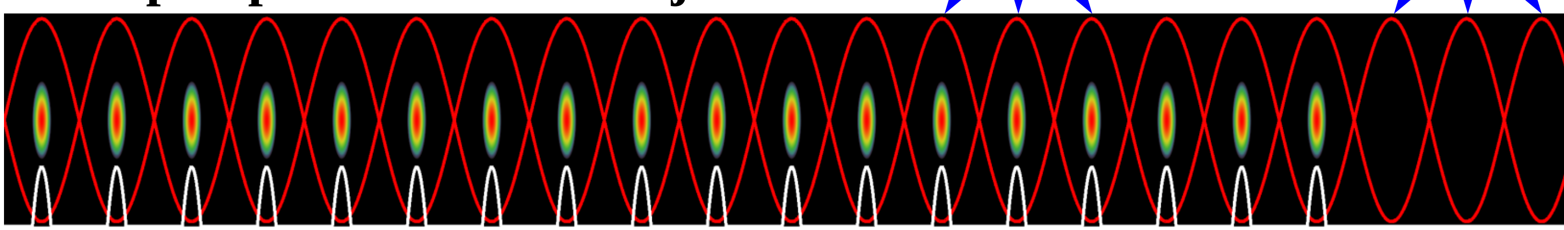


Wait 1.2 s for second injection

2. Inject two bunches



3. Triple split after second injection

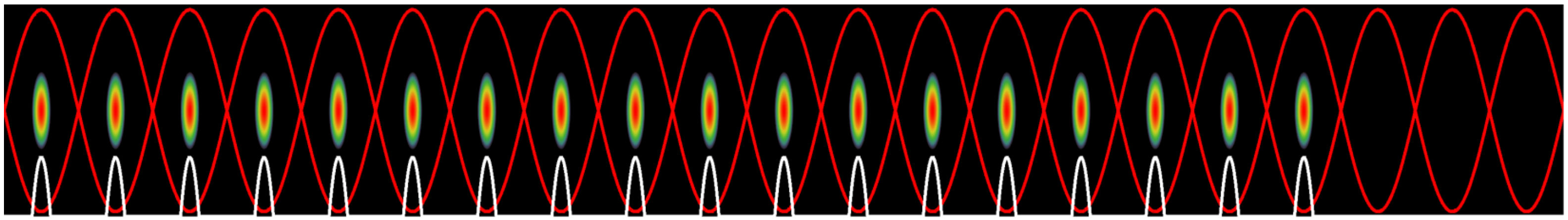


~ 0.7 eVs

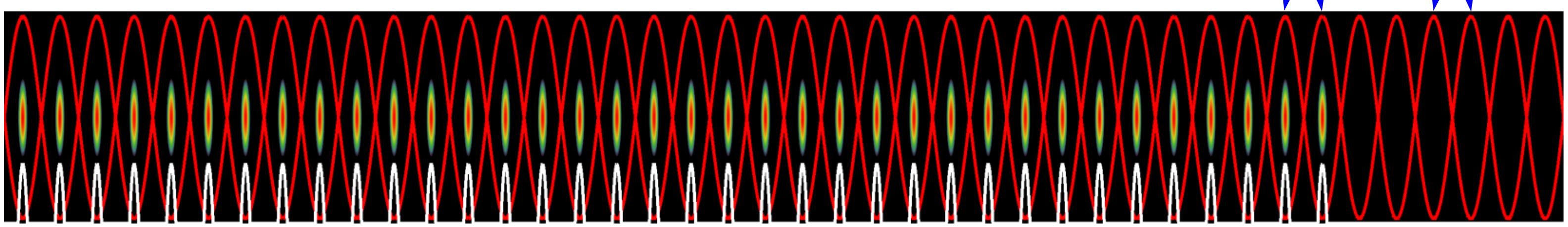
4. Accelerate from 1.4 GeV (E_{kin}) to 26 GeV

Production of the LHC 25 ns beam

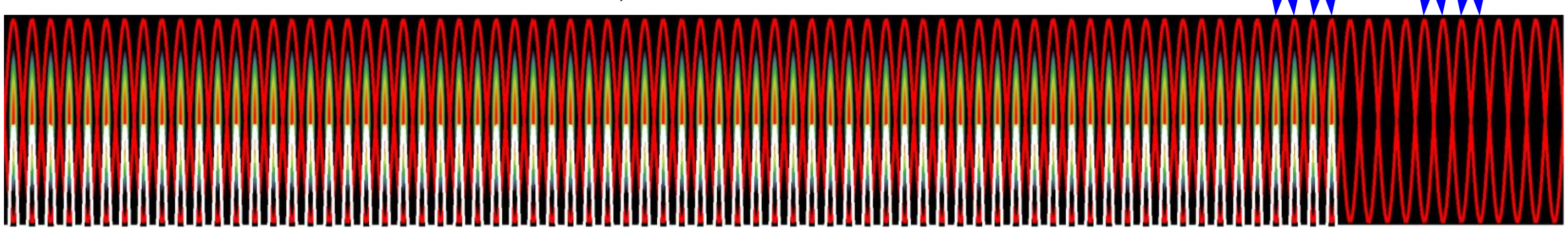
5. During acceleration: longitudinal emittance blow-up: 0.7 – 1.3 eVs



6. Double split (*h*21 → *h*42)

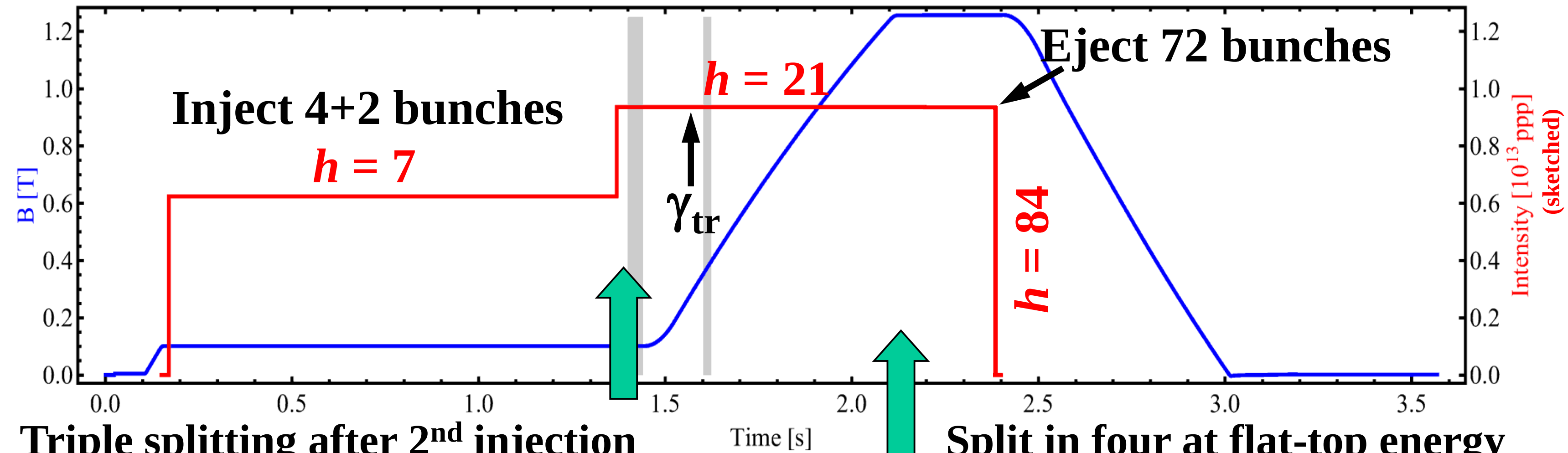


7. Double split (*h*42 → *h*84) **~ 0.35 eVs, 4 ns**



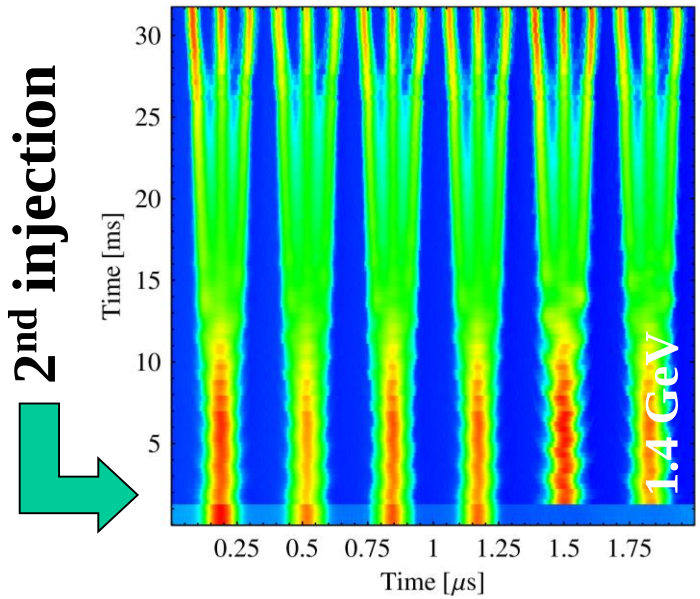
10. Fine synchronization, bunch rotation → Extraction!

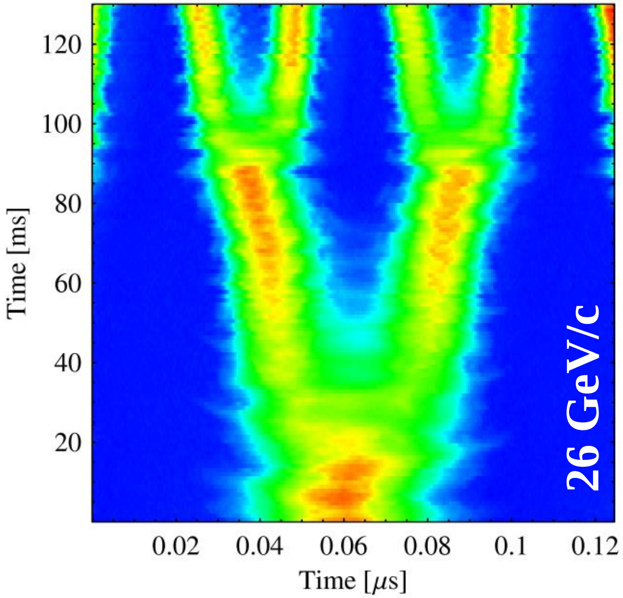
The LHC25 (ns) cycle in the PS



Triple splitting after 2nd injection

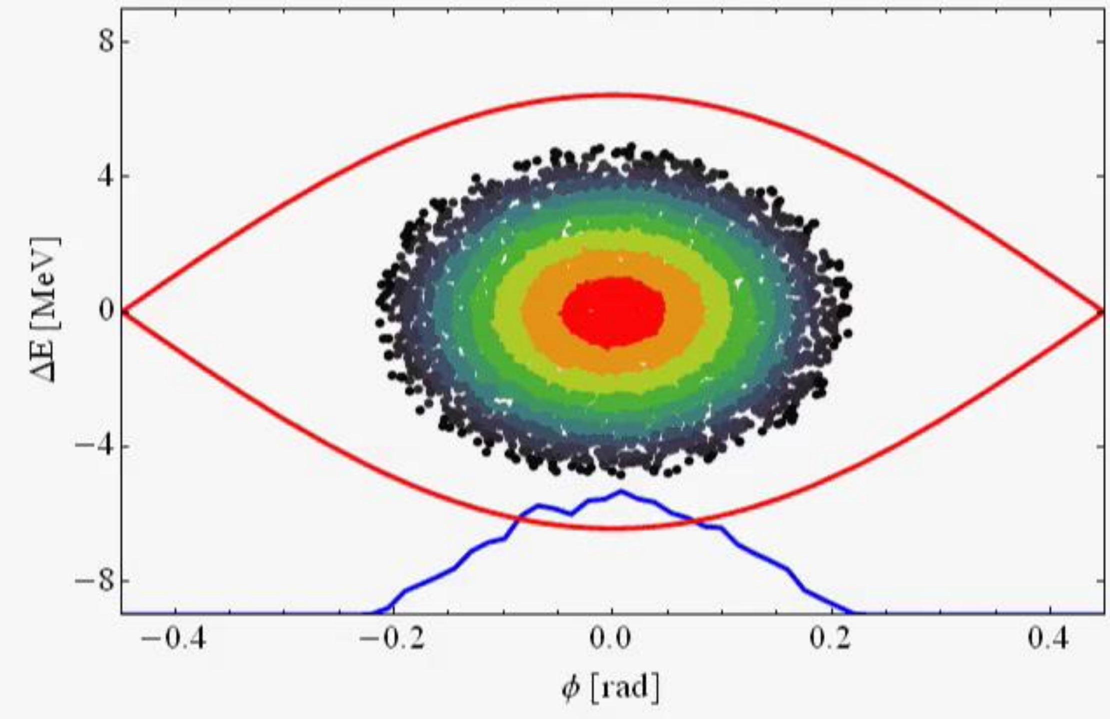
Split in four at flat-top energy

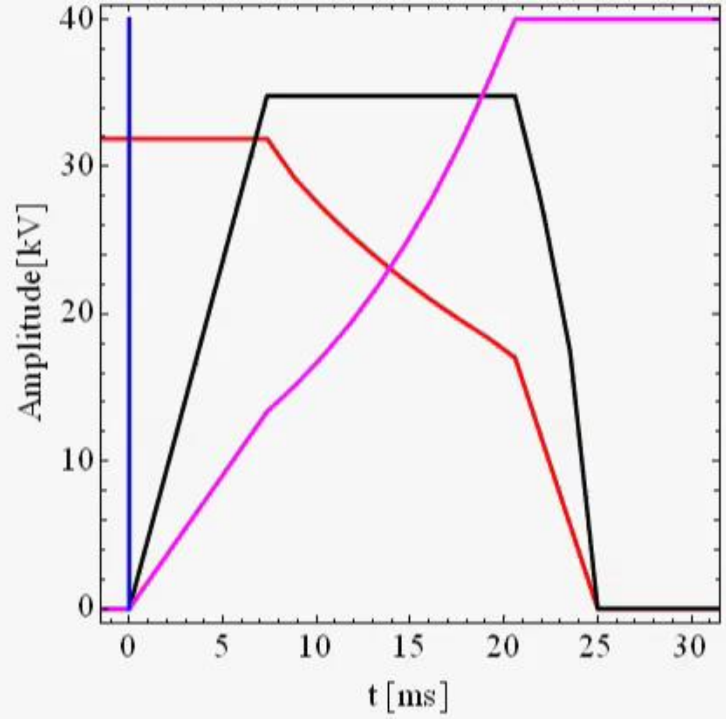




→ Each bunch from the Booster divided by 12 → 6 × 3 × 2 × 2 = 72

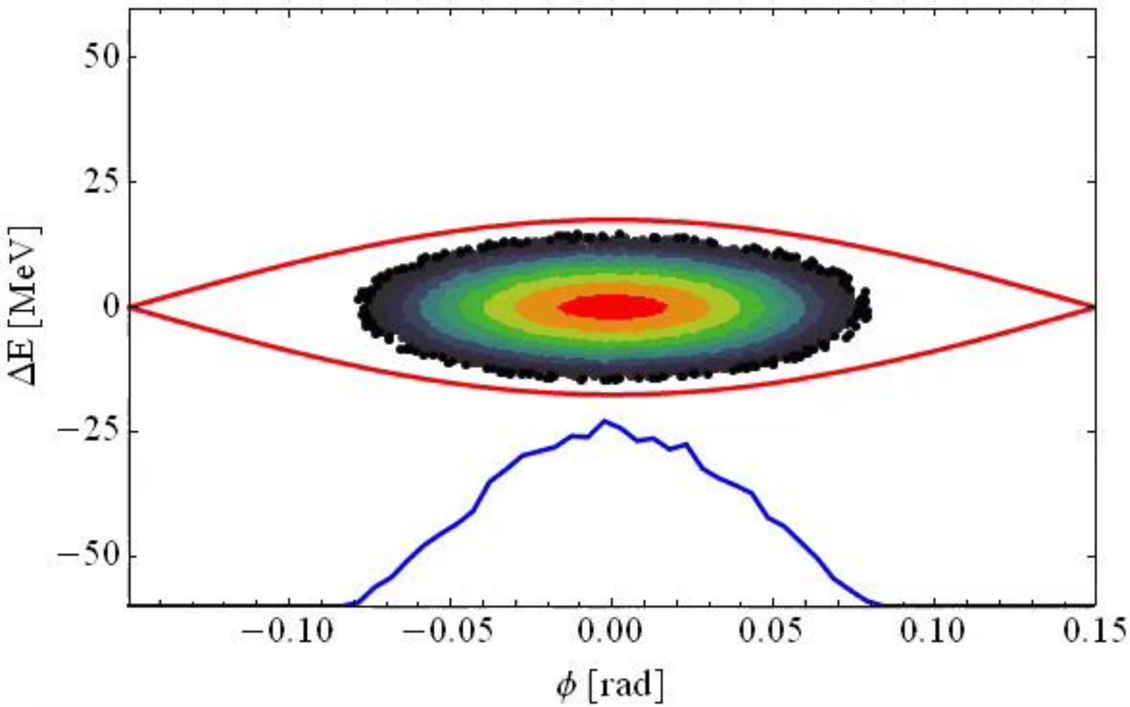
Triple splitting in the PS

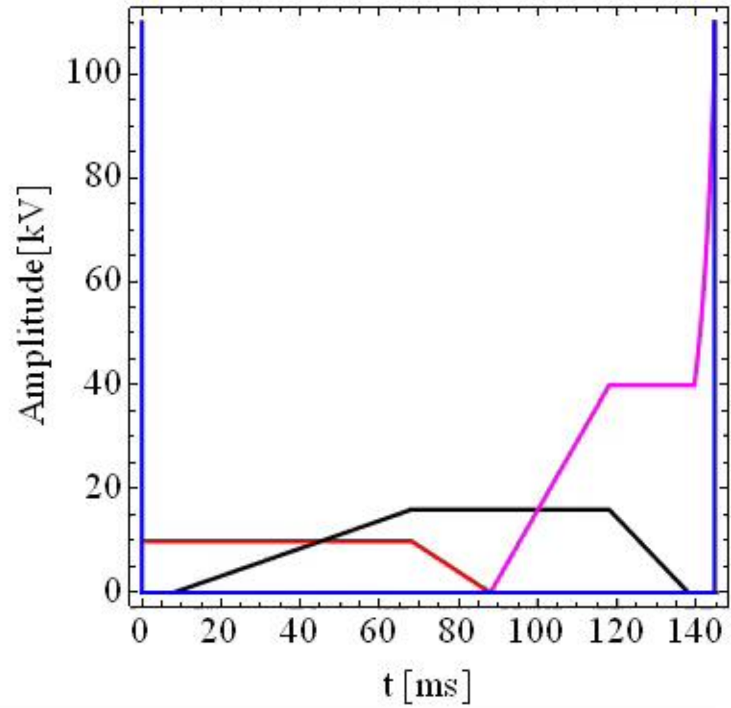




Two times double splitting in the PS

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)
- Rotation: first part h84 only + h168 (80 MHz) for final part

Summary

- Cyclotrons/Synchrocylotrons for low energy
- Synchrotrons for high energies, constant orbit, 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
- 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: CERN-2014-009
Advanced Accelerator Physics - CAS

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Appendix

- Summary Relativity and Energy Gain
- Velocity, Energy, and Momentum
- Momentum compaction factor
- Synchrotron energy-phase oscillations
- Stability condition
- Separatrix stationary bucket
- Large amplitude oscillations
- Bunch matching into stationary bucket

Appendix: Relativity + Energy Gain

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

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

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

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

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

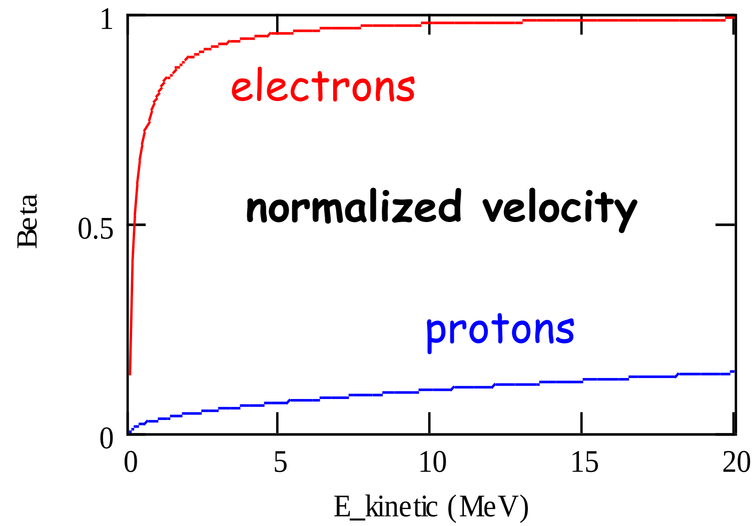
(neglecting transit time factor)

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

Appendix: Velocity, Energy and Momentum

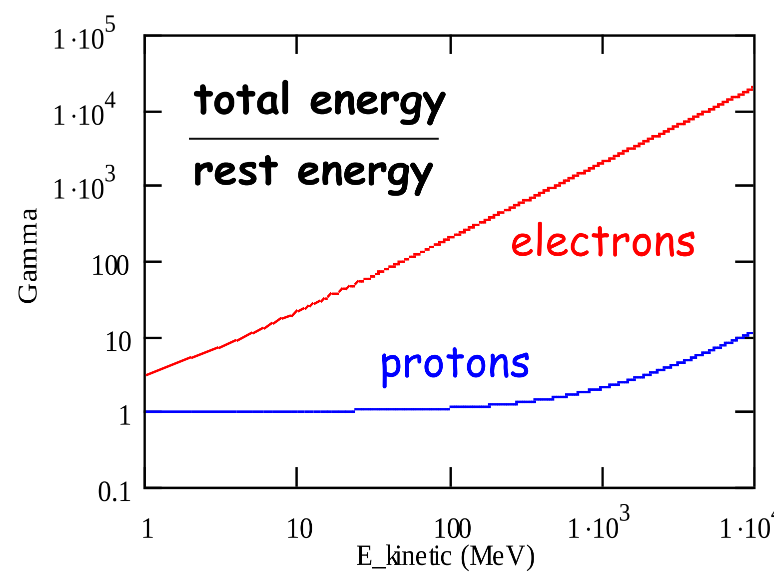
normalized velocity $$\beta = \frac{v}{c} = \sqrt{1 - \frac{1}{\gamma^2}}$$

=> electrons almost reach the speed of light very quickly (few MeV range)



total energy / rest energy $$E = g m_0 c^2$$

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



Momentum $$p = mv = \frac{E}{c^2} bc = b\frac{E}{c} = bg m_0 c$$

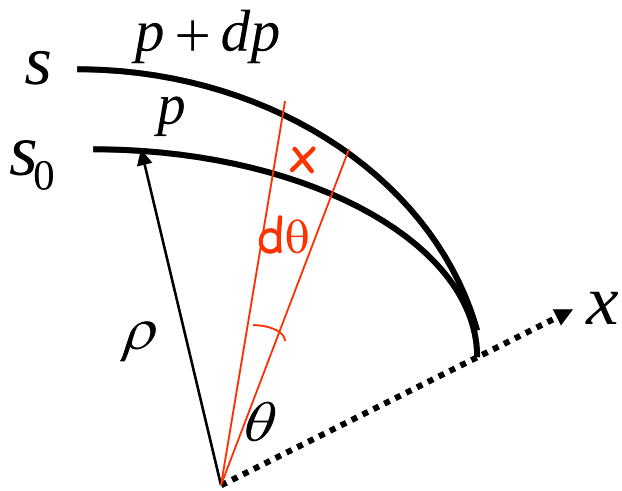
=> Magnetic field needs to follow the momentum increase

Appendix: 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

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

leading to the total change in the circumference:

$$dL = \oint_C dl = \oint \frac{x}{\rho} ds_0 = \oint \frac{D_x}{\rho}\frac{dp}{p} ds_0$$

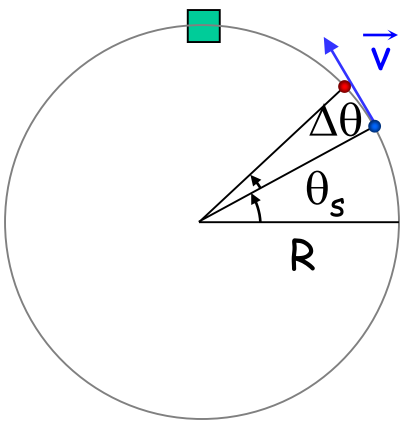
$$\alpha_c = \frac{1}{L}\int_C \frac{D_x(s)}{\rho(s)} ds_0$$

With ρ=∞ in straight sections we get:

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

$< >_m$ means that the average is considered over the bending magnet only

Appendix: 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:

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

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

$$\Delta E = v_s \Delta p = \omega_{rs} R_s \Delta p$$

one gets:

$$\frac{\Delta E}{\omega_{rs}} = -\frac{p_s R_s}{h\eta\omega_{rs}}\frac{d(\Delta\phi)}{dt} = -\frac{p_s R_s}{h\eta\omega_{rs}}\dot{\phi}$$

Appendix: 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:

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

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:

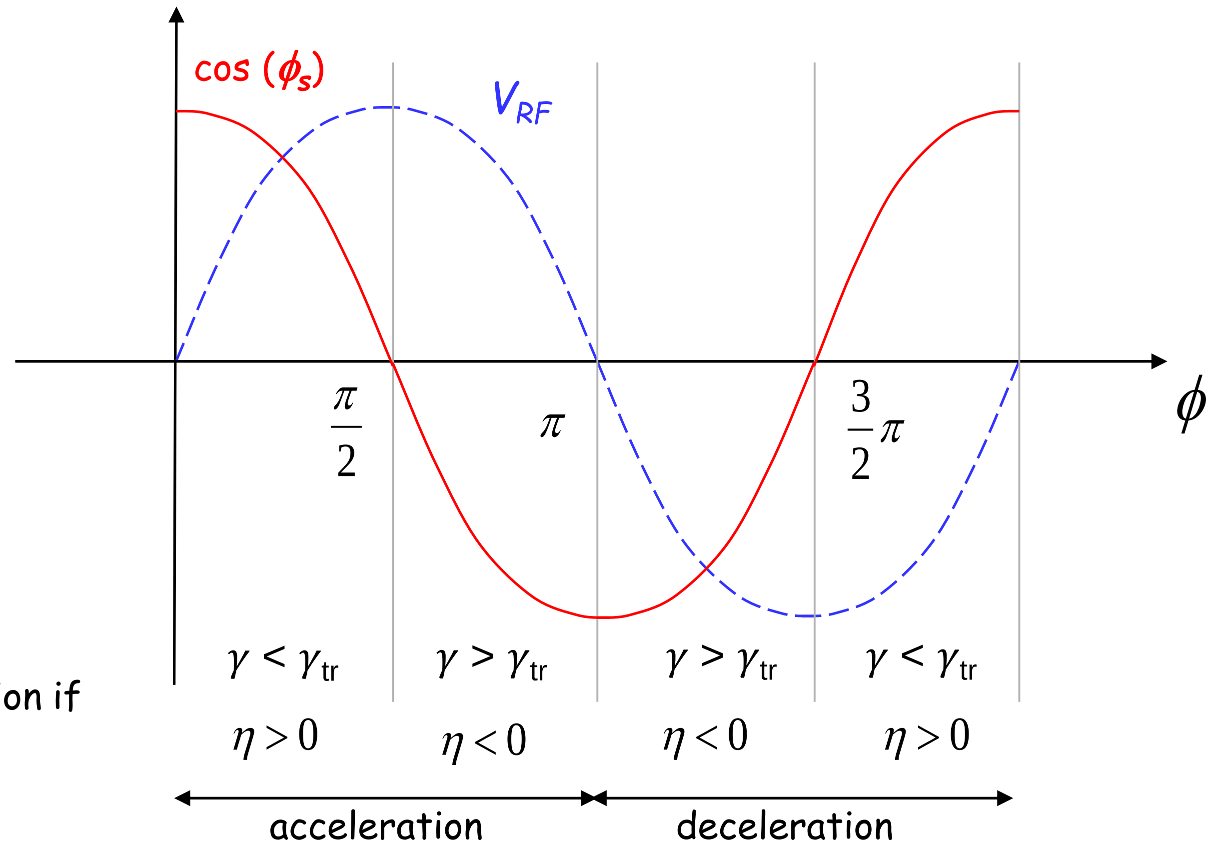
$$2\pi \frac{d}{dt}\left(\frac{\Delta E}{\omega_{rs}}\right) = e\hat{V}\left(\sin\phi - \sin\phi_s\right)$$

Appendix: Stability condition for ϕ_s

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

$$\Omega_s^2 = \frac{e \hat{V}_{RF} \eta h \omega_s}{2\pi R_s p_s} \cos\phi_s \quad \Rightarrow \quad \Omega_s^2 > 0 \quad \Leftrightarrow \quad \eta \cos\phi_s > 0$$

Stable in the region if



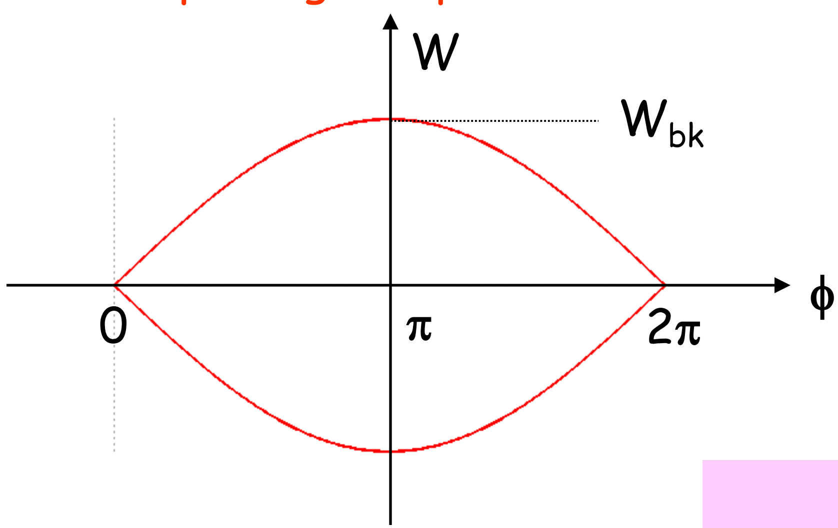
Appendix: Stationary Bucket - Separatrix

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:

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

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

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



$$W=\frac{\Delta E}{\omega_{rf}}=-\frac{p_s R_s}{h\eta\omega_{rf}}\dot\phi$$

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

$$W=\pm\frac{C}{\pi h c}\sqrt{\frac{-e\hat V E_s}{2\pi h\eta}}\sin\frac{\phi}{2}=\pm W_{bk}\sin\frac{\phi}{2}$$

with $C=2\pi R_s$

Stationary Bucket (2)

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

$$W_{bk} = \frac{C}{\pi h c}\sqrt{\frac{-e\hat{V} E_s}{2\pi h \eta}}$$

This results in the maximum energy acceptance:

$$\Delta E_{max} = \omega_{rf} W_{bk} = \beta_s \sqrt{2\frac{-e\hat{V}_{RF} E_s}{\pi h \eta}}$$

The area of the bucket 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: $$A_{bk} = 8 W_{bk} = 8\frac{C}{\pi h c}\sqrt{\frac{-e\hat{V} E_s}{2\pi h \eta}}$$ → $$W_{bk} = \frac{A_{bk}}{8}$$

Appendix: 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:

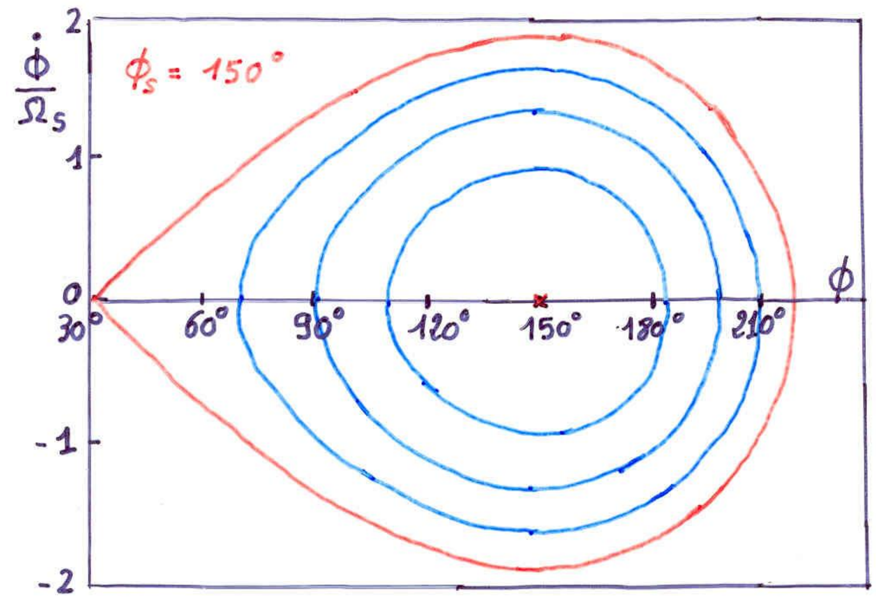
$$\frac{\dot{\phi}^2}{2} + \Omega_s^2\frac{\left(\Delta\phi\right)^2}{2} = I'$$

(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 $\pi-\phi_s$ the force goes to zero and beyond it becomes non restoring.
Hence $\pi-\phi_s$ 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 when $\ddot{\phi} = 0$, hence corresponding to $\phi = \phi_s$.
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 acceptance in energy:

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

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

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

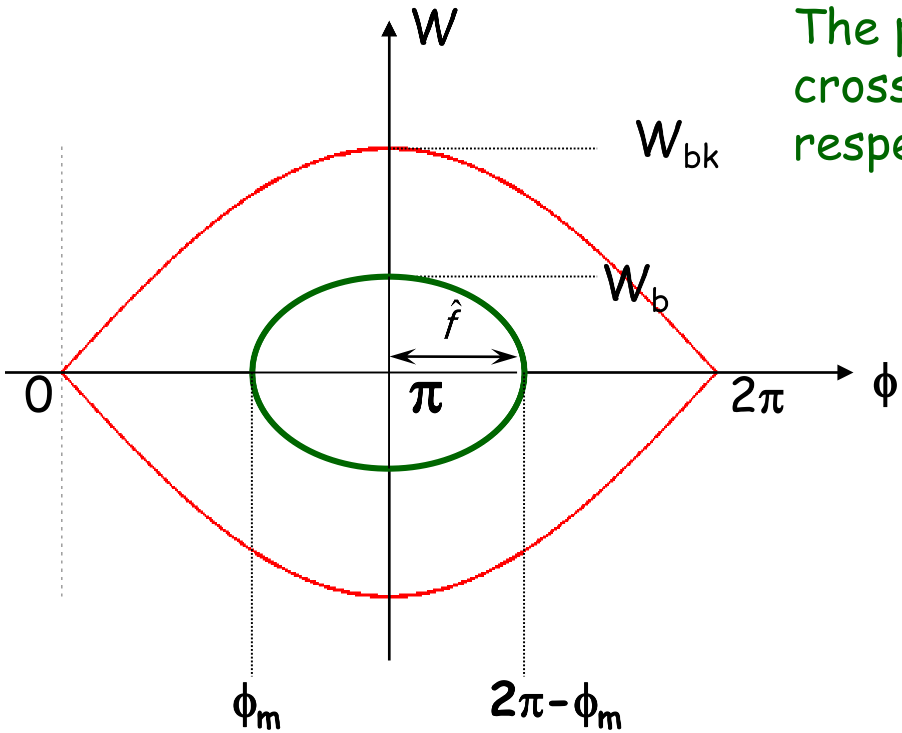
It's largest for $\phi_s = 0$ and $\phi_s = \pi$ (no acceleration, depending on η).

Need a higher RF voltage for higher acceptance.

Bunch Matching into a 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 $\phi_s = \pi$

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

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

$$W = \pm W_{bk}\sqrt{\cos^2\frac{\phi_m}{2} - \cos^2\frac{\phi}{2}}$$

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

Bunch Matching into a Stationary Bucket (2)

Setting $\phi = \pi$ in the previous formula allows to calculate the bunch height:

$$W_b = W_{bk} \cos\frac{\phi_m}{2} = W_{bk} \sin\frac{\hat{\phi}}{2}$$

or:

$$W_b = \frac{A_{bk}}{8} \cos\frac{\phi_m}{2}$$

$$\longrightarrow \quad \left(\frac{\Delta E}{E_s}\right)_b = \left(\frac{\Delta E}{E_s}\right)_{RF} \cos\frac{\phi_m}{2} = \left(\frac{\Delta E}{E_s}\right)_{RF} \sin\frac{\hat{\phi}}{2}$$

This formula shows that for a given bunch energy spread the proper matching of a shorter bunch (ϕ_m close to π, $\hat{\phi}$ small) will require a bigger RF acceptance, hence a higher voltage

For small oscillation amplitudes the equation of the ellipse reduces to:

$$W = \frac{A_{bk}}{16}\sqrt{\hat{\phi}^2 - (\Delta\phi)^2} \quad \longrightarrow \quad \left(\frac{16\,W}{A_{bk}\hat{\phi}}\right)^2 + \left(\frac{\Delta\phi}{\hat{\phi}}\right)^2 = 1$$

Ellipse area is called longitudinal emittance

$$A_b = \frac{\pi}{16} A_{bk} \hat{\phi}^2$$