SUMMER STUDENT LECTURES ON ACCELERATORS (2, 3 & 4/5)

1 & 5/5
⇒ Simone

Elias Métral (3 × 45 min = 135 min, 92 slides)

+ Discussion Sessions

2
- Introduction and references (4 slides)
- Transverse beam dynamics (27)

3
- Longitudinal beam dynamics (12)
- Figure of merit for a synchrotron/collider = Brightness/Luminosity (6)
- Beam control (8)

4
- Limiting factors for a synchrotron/collider ⇒ Collective effects (34)
  - Space charge (8)
  - Wake field and impedance (12)
  - Beam-beam interaction (8)
  - Electron cloud (6)

Elias.Metral@cern.ch
Tel.: 72560 or 164809

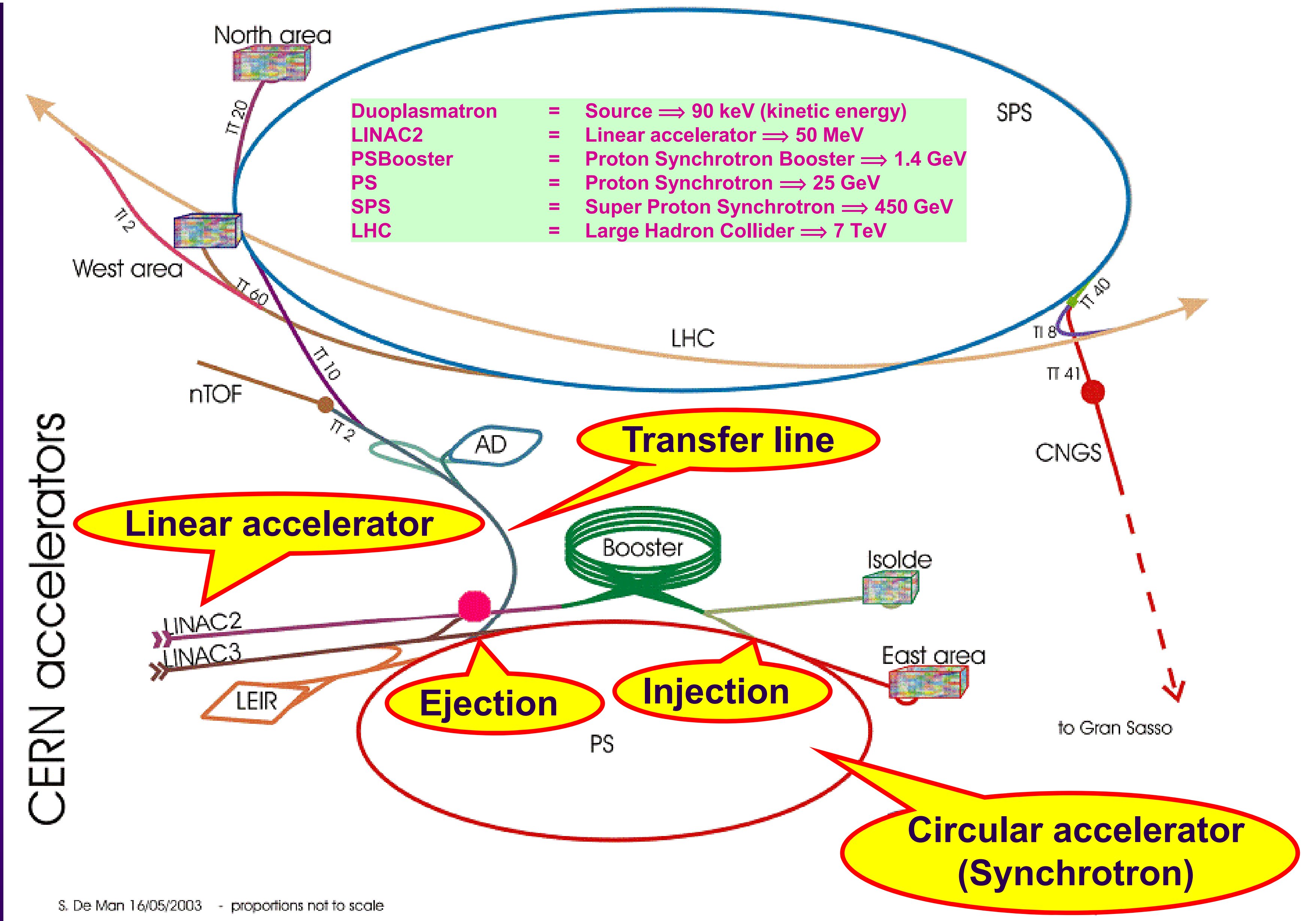
PURPOSE OF THIS COURSE

- **Try to give you an overview of the basic concepts & vocabulary ⇒ No mathematics, just physics**

- **…But I would also like you to catch a glimpse of what accelerator physicists are "really" doing, showing you pictures of some recent/current studies**

LHC beam in the injector chain

Duplasmatron = Source ⟹ 90 keV (kinetic energy)
LINAC2 = Linear accelerator ⟹ 50 MeV
PSBooster = Proton Synchrotron Booster ⟹ 1.4 GeV
PS = Proton Synchrotron ⟹ 25 GeV
SPS = Super Proton Synchrotron ⟹ 450 GeV
LHC = Large Hadron Collider ⟹ 7 TeV



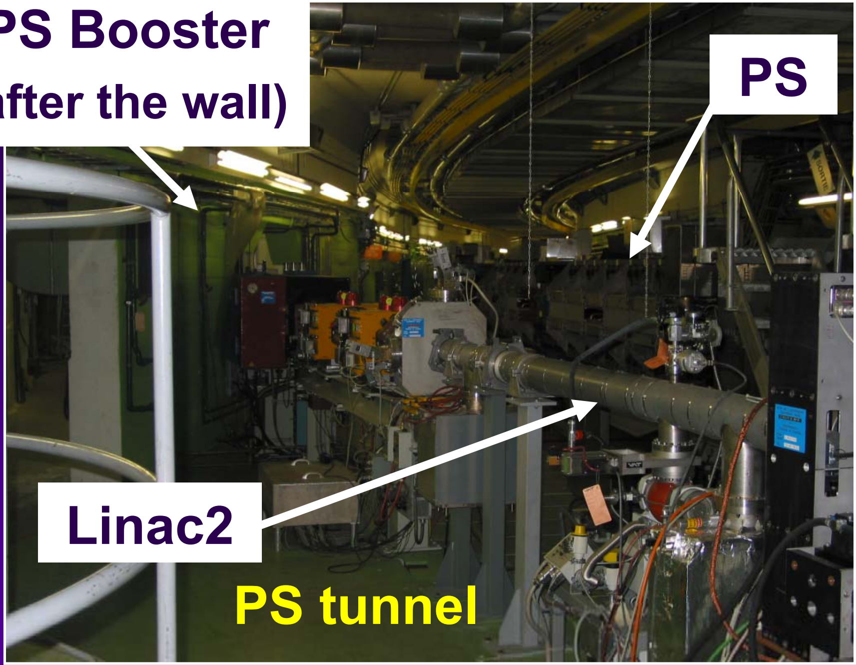
Transfer line

Linear accelerator

Ejection

Injection

Circular accelerator (Synchrotron)



Reminder : 1 atm = 760 Torr and 1 mbar = 0.75 Torr = 100 Pa

REFERENCES

[0] 2005 Summer Student Lectures of O. Bruning, [http://agenda.cern.ch/askArchive.php?base=agenda&categ=a054021&id=a054021/transparencies]

[1] M. Martini, An Introduction to Transverse Beam Dynamics in Accelerators, CERN/PS 96-11 (PA), 1996, [http://doc.cern.ch/archive/electronic/cern/preprints/ps/ps-96-011.pdf]

[2] L. Rinolfi, Longitudinal Beam Dynamics (Application to synchrotron), CERN/PS 2000-008 (LP), 2000, [http://doc.cern.ch/archive/electronic/cern/preprints/ps/ps-2000-008.pdf]

[3] Theoretical Aspects of the Behaviour of Beams in Accelerators and Storage Rings: International School of Particle Accelerators of the 'Ettore Majorana' Centre for Scientific Culture, 10–22 November 1976, Erice, Italy, M.H. Blewett (ed.), CERN report 77-13 (1977) [http://preprints.cern.ch/cgi-bin/setlink?base=cernrep&categ=Yellow_Report&id=77-13]

[4] CERN Accelerator Schools [http://cas.web.cern.ch/cas/]

[5] K. Schindl, Space Charge, CERN-PS-99-012-DI, 1999 [http://doc.cern.ch/archive/electronic/cern/preprints/ps/ps-99-012.pdf]

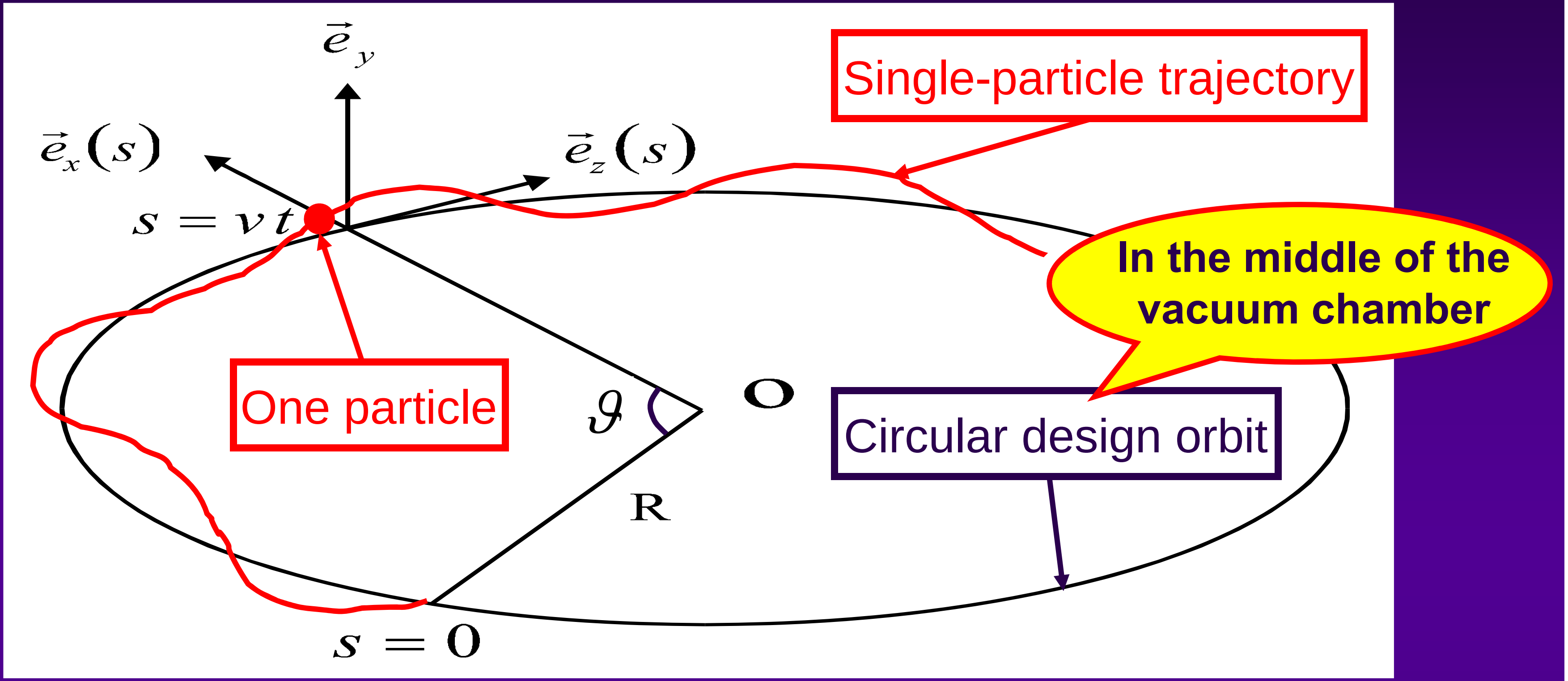
[6] A.W. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators, New York: Wiley, 371 p, 1993 [http://www.slac.stanford.edu/~achao/wileybook.html]

[7] Web site on LHC Beam-Beam Studies [http://wwwslap.cern.ch/collective/zwe/lhcbb/]

[8] Web site on Electron Cloud Effects in the LHC [http://ab-abp-rlc.web.cern.ch/ab-abp-rlc-ecloud/]

[9] LHC Design Report [http://ab-div.web.cern.ch/ab-div/Publications/LHC-DesignReport.html]

TRANSVERSE BEAM DYNAMICS (1/27)



- **The motion of a charged particle (proton) in a beam transport channel or a circular accelerator is governed by the LORENTZ FORCE**

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

- **The motion of particle beams under the influence of the Lorentz force is called BEAM OPTICS**

TRANSVERSE BEAM DYNAMICS (2/27)

- The Lorentz force is applied as a
  - **BENDING FORCE** (using **DIPOLES**) to guide the particles along a predefined ideal path, the **DESIGN ORBIT**, on which – ideally – all particles should move
  - **FOCUSING FORCE** (using **QUADRUPOLES**) to confine the particles in the vicinity of the ideal path, from which most particles will unavoidably deviate

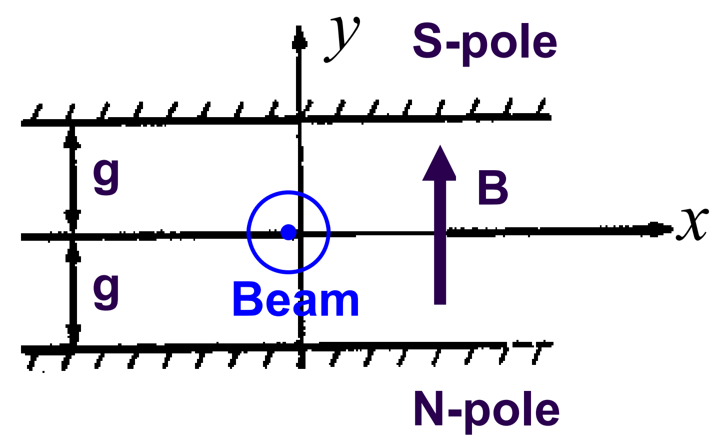
- **LATTICE** = Arrangement of magnets along the design orbit

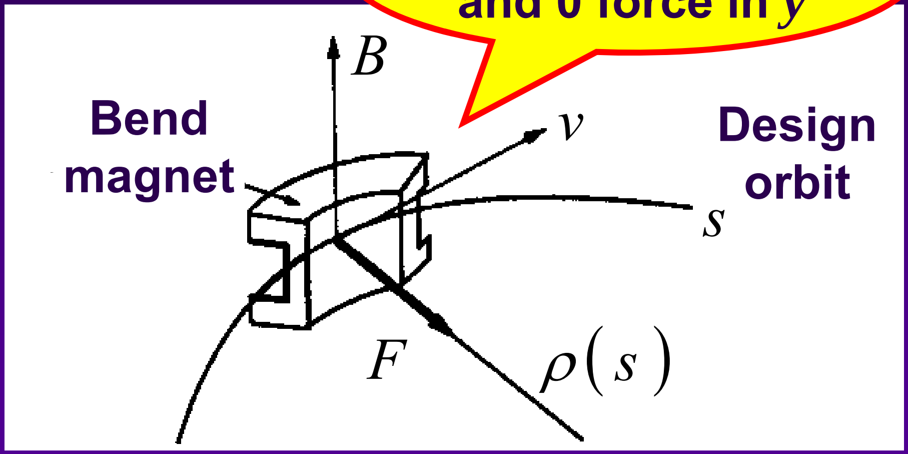
- The **ACCELERATOR DESIGN** is made considering the beam as a collection of non-interacting single particles

TRANSVERSE BEAM DYNAMICS (3/27)

DIPOLE = Bending magnet

Constant force in x and 0 force in y





⇒ A particle, with a constant energy, describes a circle in equilibrium between the centripetal magnetic force and the centrifugal force

- **BEAM RIGIDITY**

$$B\,\rho\,[\mathrm{T\,m}] = 3.3356\; p_0\,[\mathrm{GeV/c}]$$

Magnetic field

Curvature radius of the dipoles

Beam momentum

TRANSVERSE BEAM DYNAMICS (4/27)

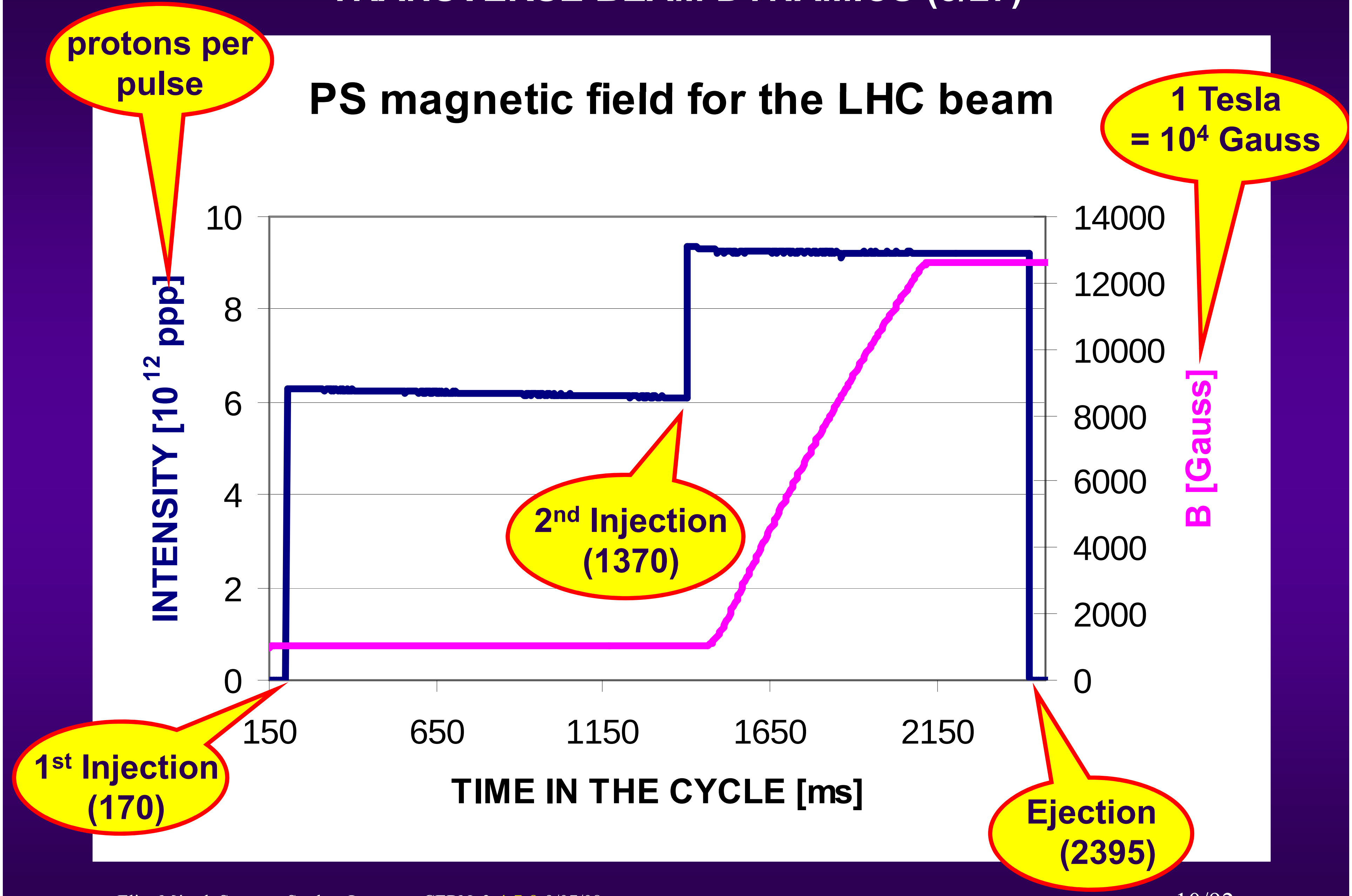
- **LEP vs LHC magnets (in same tunnel) ⟹ A change in technology**

	LEP	LHC
ρ [m]	3096.175	2803.95
p_0 [GeV/c]	104	7000
B [T]	0.11	8.33

Room-temperature coils

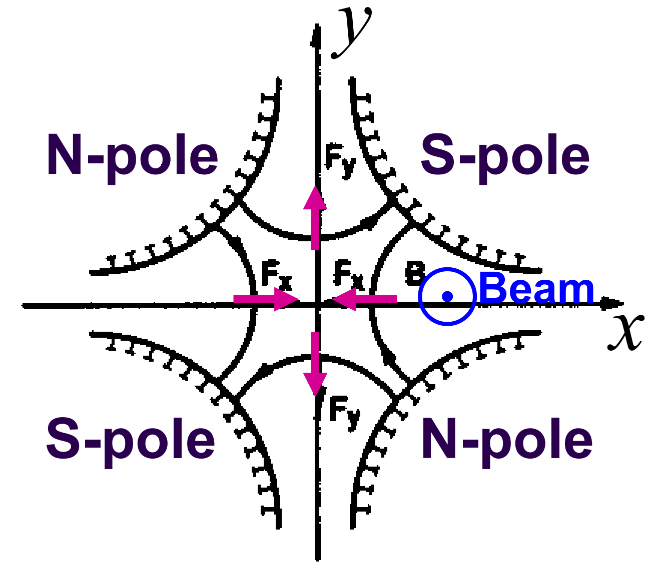
Superconducting coils

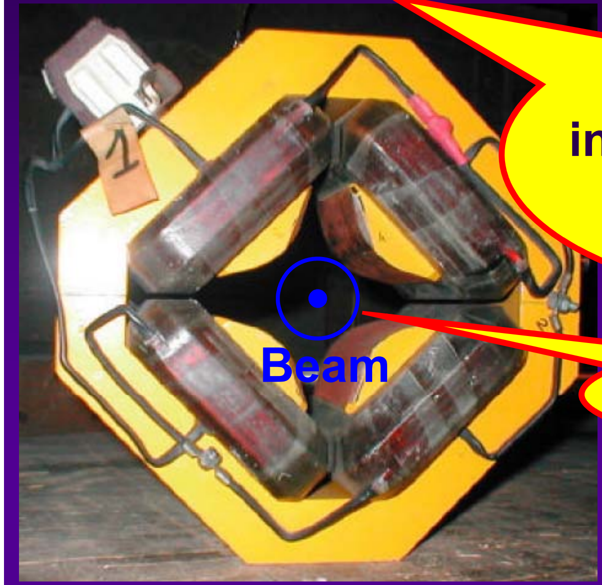
TRANSVERSE BEAM DYNAMICS (5/27)



TRANSVERSE BEAM DYNAMICS (6/27)

QUADRUPOLE = Focusing magnet





In *x* (and Defocusing in *y*) ⇒ F-type. Permutating the N- and S- poles gives a D-type

Linear force in x&y

⇒ $x''(s) + K\,x(s) = 0$: **Equation of a harmonic oscillator**

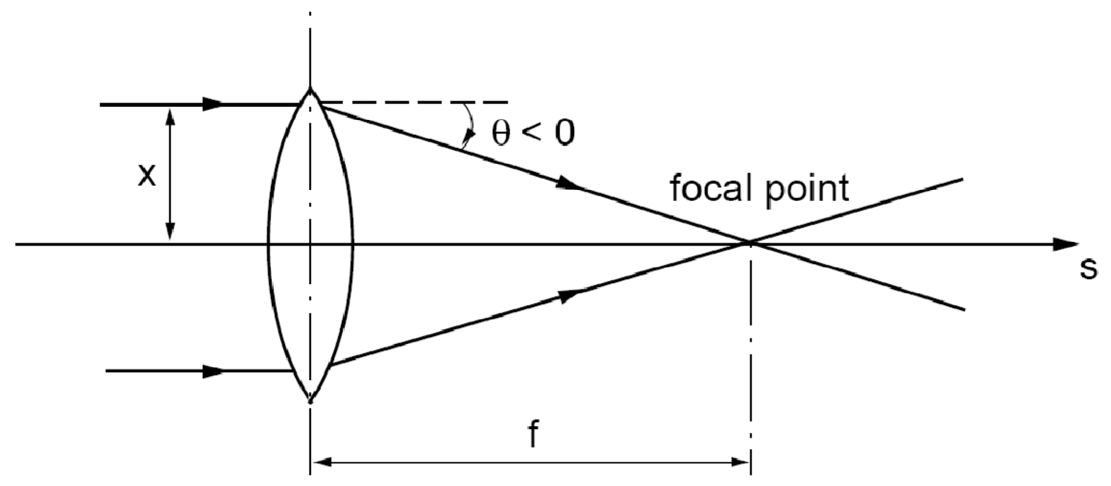
- From this equation, one can already anticipate the elliptical shape of the particle trajectory in the phase space (*x*, *x*’) by integration

$$x'^2(s) + K\,x^2(s) = \text{Constant}$$

TRANSVERSE BEAM DYNAMICS (7/27)

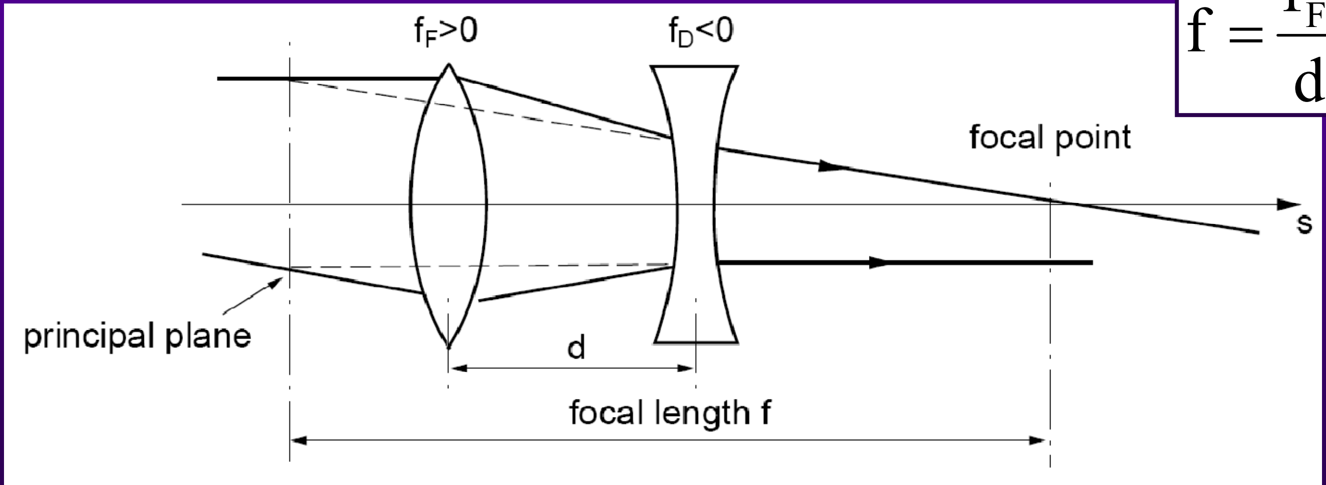
Analogy with light optics

Principle of focusing for light



$$\tan\theta = -\frac{x}{f}$$

Principle of STRONG FOCUSING for light



$$f = \frac{f_F^2}{d} > 0 \left(\text{when } f_D = -f_F \right)$$

$\Longrightarrow$ **Focusing in both planes**

TRANSVERSE BEAM DYNAMICS (8/27)

- Along the accelerator *K* is not constant and depends on *s* (and is periodic) ⇒ The equation of motion is then called **HILL'S EQUATION**
- The solution of the Hill's equation is a pseudo-harmonic oscillation with varying amplitude and frequency called **BETATRON OSCILLATION**

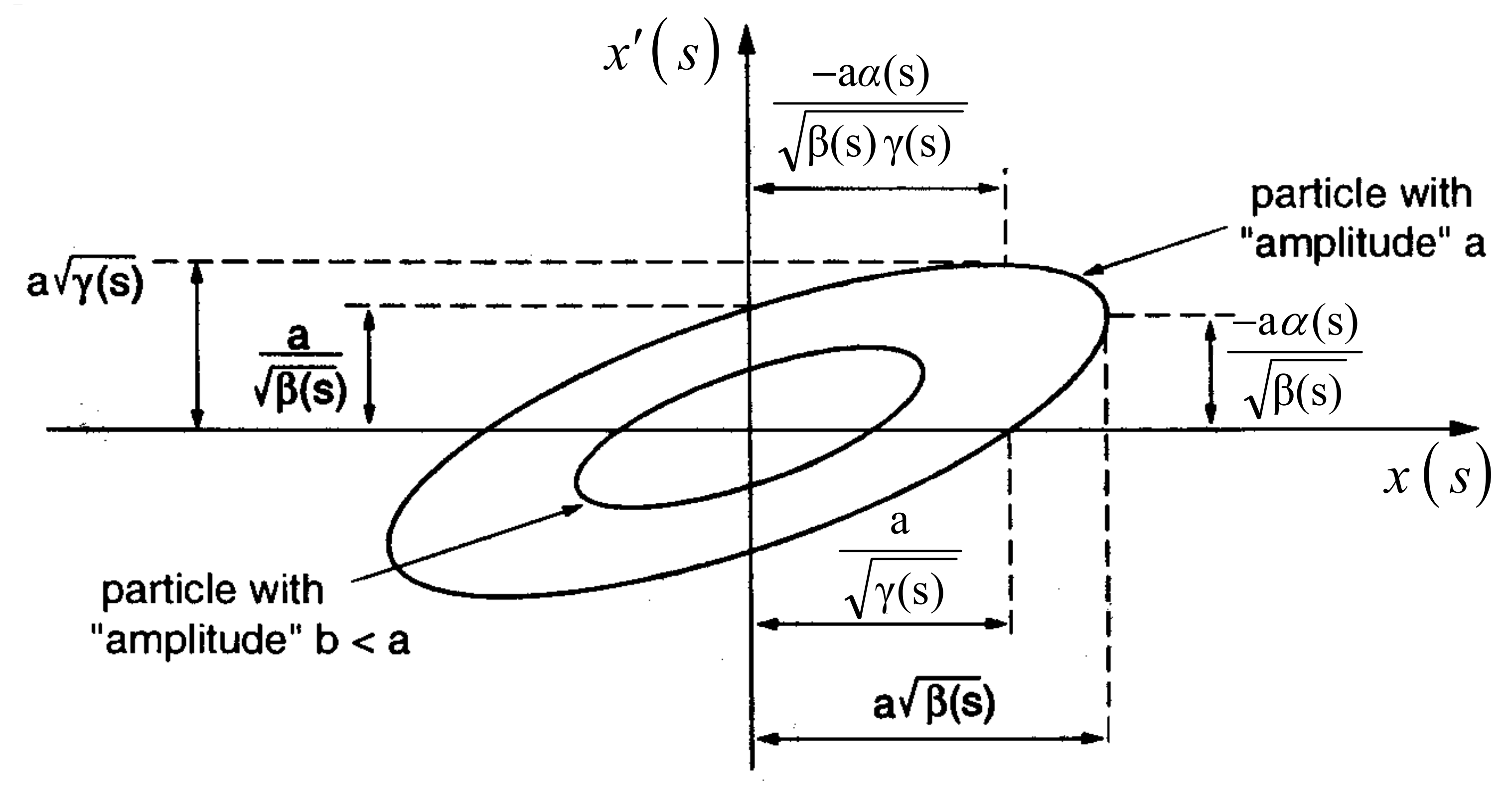
Betatron function

$$x(s) = \mathrm{a}\,\sqrt{\beta(s)}\,\cos\left[\mu(s) + \varphi\right]$$

- An invariant, i.e. a constant of motion, (called **COURANT-SNYDER INVARIANT**) can be found from the solution of the Hill's equation

⇒ Equation of an ellipse (**motion for one particle**) in the phase space plane (x, x'), with area $\pi\,\mathrm{a}^2$

TRANSVERSE BEAM DYNAMICS (9/27)

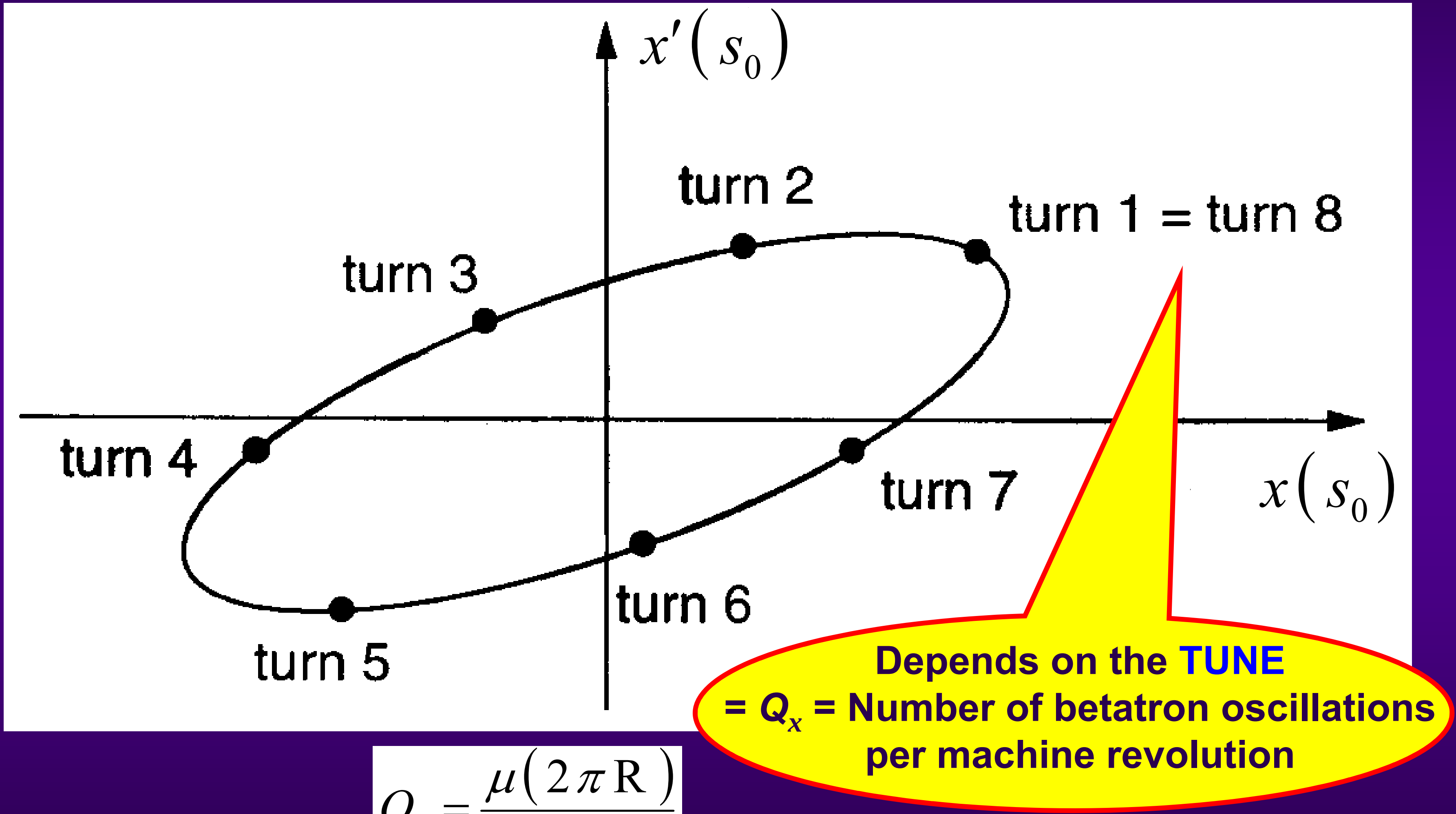


$\beta(s)$ $\alpha(s) = -\frac{\beta'(s)}{2}$ $\gamma(s) = \frac{1+\alpha^2(s)}{\beta(s)}$ **are called TWISS PARAMETERS**

- **The shape and orientation of the phase plane ellipse evolve along the machine, but not its area**

TRANSVERSE BEAM DYNAMICS (10/27)

Stroboscopic representation or POINCARÉ MAPPING



Depends on the **TUNE**
= Q_x = Number of betatron oscillations per machine revolution

$$Q_x = \frac{\mu(2\pi R)}{2\pi}$$

TRANSVERSE BEAM DYNAMICS (11/27)

- **MATRIX FORMALISM:** The previous (linear) equipments of the accelerator (extending from s_0 to s) can be described by a matrix, $M\,(s\,/\,s_0)$, called **TRANSFER MATRIX**, which relates (x, x') at s_0 and (x, x') at s

$$\begin{bmatrix} x(s) \\ x'(s) \end{bmatrix} = M\left(s/s_0\right)\begin{bmatrix} x(s_0) \\ x'(s_0) \end{bmatrix}$$

- The transfer matrix over one revolution period is then the product of the individual matrices composing the machine

- The transfer matrix over one period is called the **TWISS MATRIX**

- **Once the Twiss matrix has been derived the Twiss parameters can be obtained at any point along the machine**

TRANSVERSE BEAM DYNAMICS (12/27)

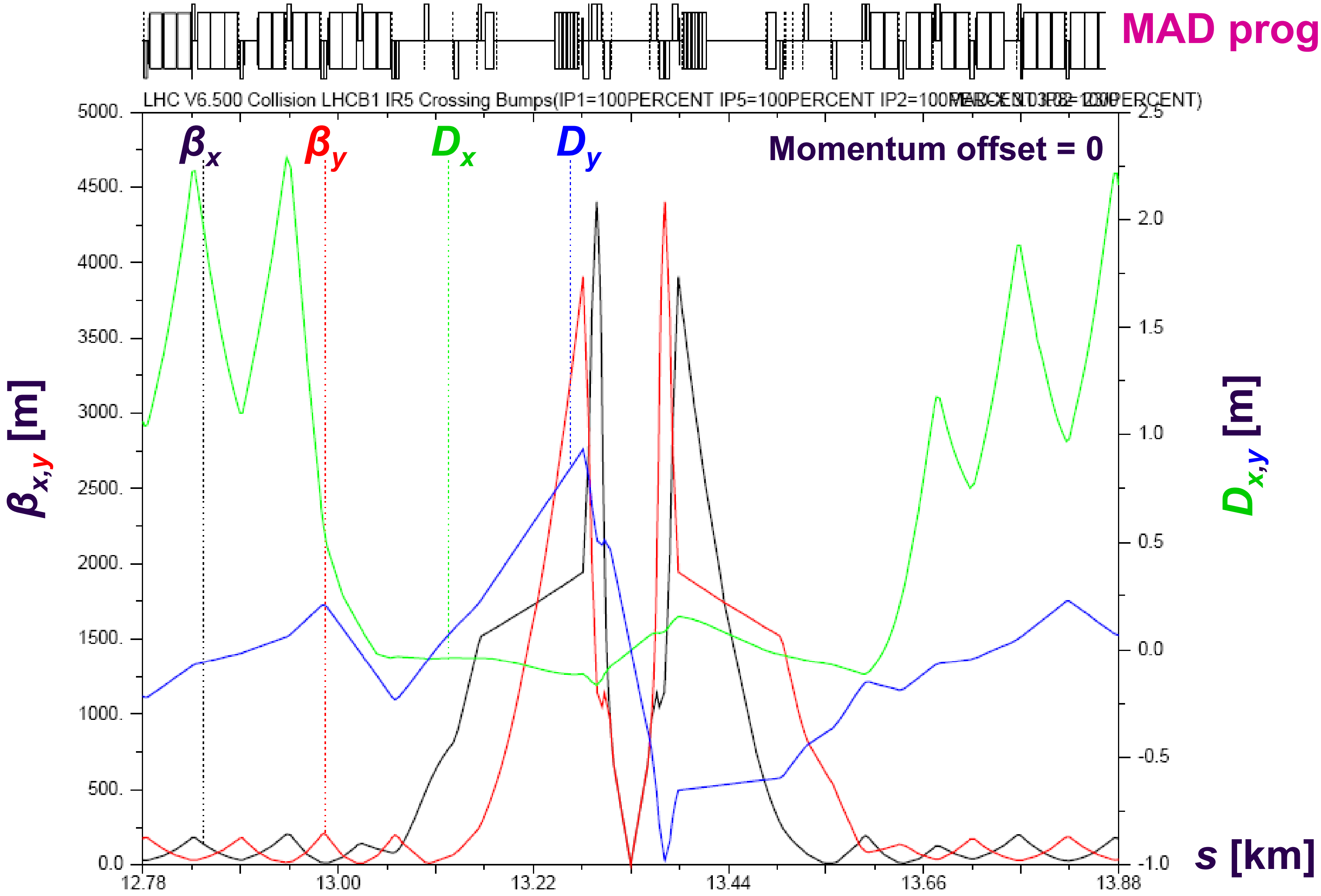
- In practice, particle beams have a finite dispersion of momenta about the ideal momentum p_0. A particle with momentum $p \neq p_0$ will perform betatron oscillations around A DIFFERENT CLOSED ORBIT from that of the reference particle

⇒ Displacement of $$\boxed{x_\Delta(s) = D_x(s)\frac{p - p_0}{p_0} = D_x(s)\frac{\Delta p}{p_0}}$$

$\boxed{D_x(s)}$ is called the DISPERSION FUNCTION

TRANSVERSE BEAM DYNAMICS (13/27)

- **LHC optics for the Interaction Point (IP) 5 (CMS) in collision**



MAD program

TRANSVERSE BEAM DYNAMICS (14/27)

- **BEAM EMITTANCE = Measure of the spread in phase space of the points representing beam particles ⇒ 3 definitions**

1) In terms of the phase plane "amplitude" a_q enclosing *q* % of the particles

$$\iint\limits_{\substack{\text{ellipse of} \\ \text{"amplitude" } a_q}} dx\,dx' = \pi\,\varepsilon_x^{(q\%)}$$

[mm mrad] or [µm]

2) In terms of the 2nd moments of the particle distribution

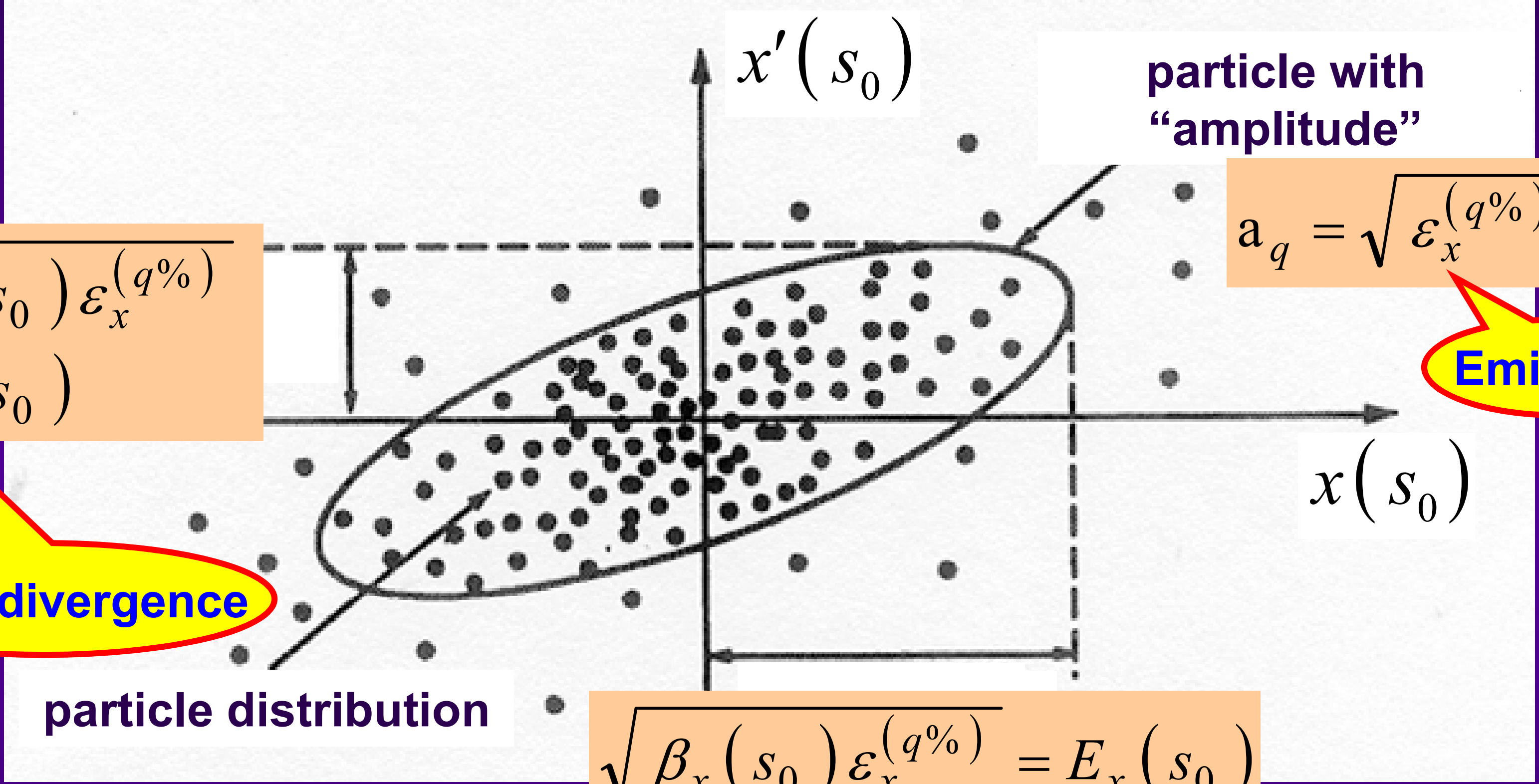
$$\varepsilon_x^{(\text{stat})} \equiv \sqrt{<x^2><x'^2> - <x\,x'>^2}$$

Determinant of the covariance matrix

3) In terms of σ_x the standard deviation of the particle distribution in real space (= projection onto the x-axis)

$$\varepsilon_x^{(\sigma_x)} \equiv \frac{\sigma_x^2}{\beta_x}$$

TRANSVERSE BEAM DYNAMICS (15/27)



particle with "amplitude"

$a_q = \sqrt{\varepsilon_x^{(q\%)}}$

Emittance

$\sqrt{\gamma_x(s_0)\,\varepsilon_x^{(q\%)}} = A_x(s_0)$

Beam divergence

particle distribution

$\sqrt{\beta_x(s_0)\,\varepsilon_x^{(q\%)}} = E_x(s_0)$

Beam envelope

The *β*-function reflects the size of the beam and depends only on the lattice

TRANSVERSE BEAM DYNAMICS (16/27)

- MACHINE mechanical (i.e. from the vacuum chamber) ACCEPTANCE or APERTURE = Maximum beam emittance

- NORMALIZED BEAM EMITTANCE

Relativistic factors

$$\varepsilon_{x,norm}^{(\sigma_x)} = \beta_r \, \gamma_r \, \varepsilon_x^{(\sigma_x)}$$

$\Rightarrow$ The normalized emittance is conserved during acceleration (in the absence of collective effects…)

- ADIABATIC DAMPING: As $\beta_r \gamma_r$ increases proportionally to the particle momentum *p*, the (physical) emittance decreases as 1 / *p*

- However, many phenomena may affect (increase) the emittance

- An important challenge in accelerator technology is to preserve beam emittance and even to reduce it (by COOLING)

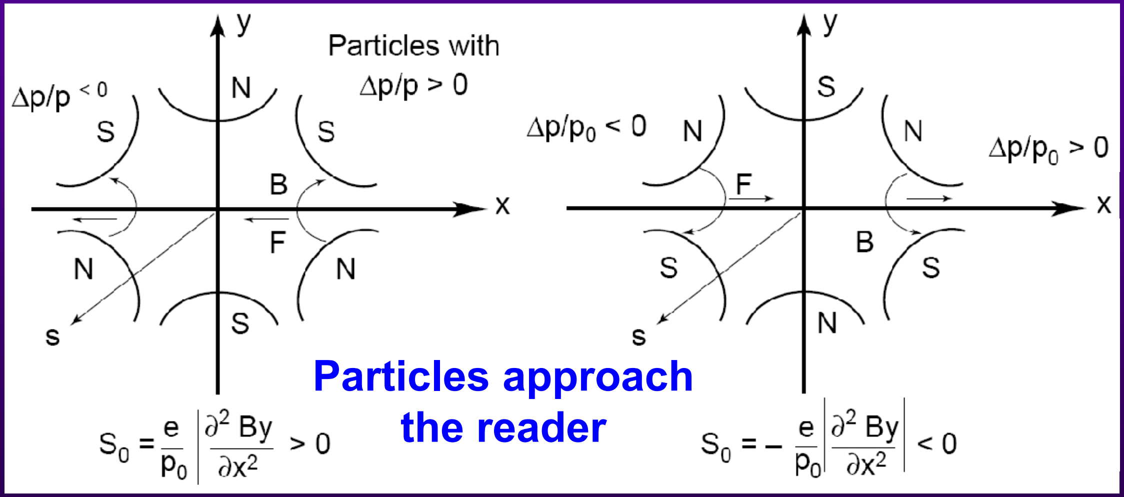
TRANSVERSE BEAM DYNAMICS (17/27)

- CHROMATICITY = Variation of the tune with the momentum

$$Q'_x = \frac{\Delta Q_x}{\Delta p / p_0}$$

- The control of the chromaticity (using a SEXTUPOLE magnet) is very important for 2 reasons
  - Avoid shifting the beam on resonances due to changes induced by chromatic effects (see later)
  - Prevent some transverse coherent (head-tail) instabilities (see also later)

SEXTUPOLE =
1st nonlinear magnet



Particles approach the reader

$$S_0 = \frac{e}{p_0}\left|\frac{\partial^2 B_y}{\partial x^2}\right. > 0 \qquad S_0 = -\frac{e}{p_0}\left|\frac{\partial^2 B_y}{\partial x^2}\right| < 0$$

TRANSVERSE BEAM DYNAMICS (18/27)

- Multipole magnetic FIELD EXPANSION (used for the LHC magnets)

$$B_y + j\,B_x = B_{ref} \sum_{n=1}^{\infty} \left[b_n + j\,a_n \right] \left(\frac{x + j\,y}{R_r} \right)^{n-1}$$

  - B_{ref} = magnetic field at the reference radius R_r = 17 mm
  - $n = 1 \Longrightarrow$ dipole; $n = 2 \Longrightarrow$ quadrupole; $n = 3 \Longrightarrow$ sextupole…
  - $b_n \Longrightarrow$ normal harmonics
  - $a_n \Longrightarrow$ skew harmonics (the skew magnets differ from the regular magnets only by a rotation about the s-axis by an angle $\pi / 2n$, where n is the order of the multipole)

TRANSVERSE BEAM DYNAMICS (19/27)

- In the presence of extra (NONLINEAR) FORCES, the Hill's equation takes the general form

$$x''(s) + K_x(s)\,x(s) = P_x(x, y, s)$$

Any perturbation

- Perturbation terms in the equation of motion may lead to UNSTABLE motion, called RESONANCES, when the perturbating field acts in synchronism with the particle oscillations

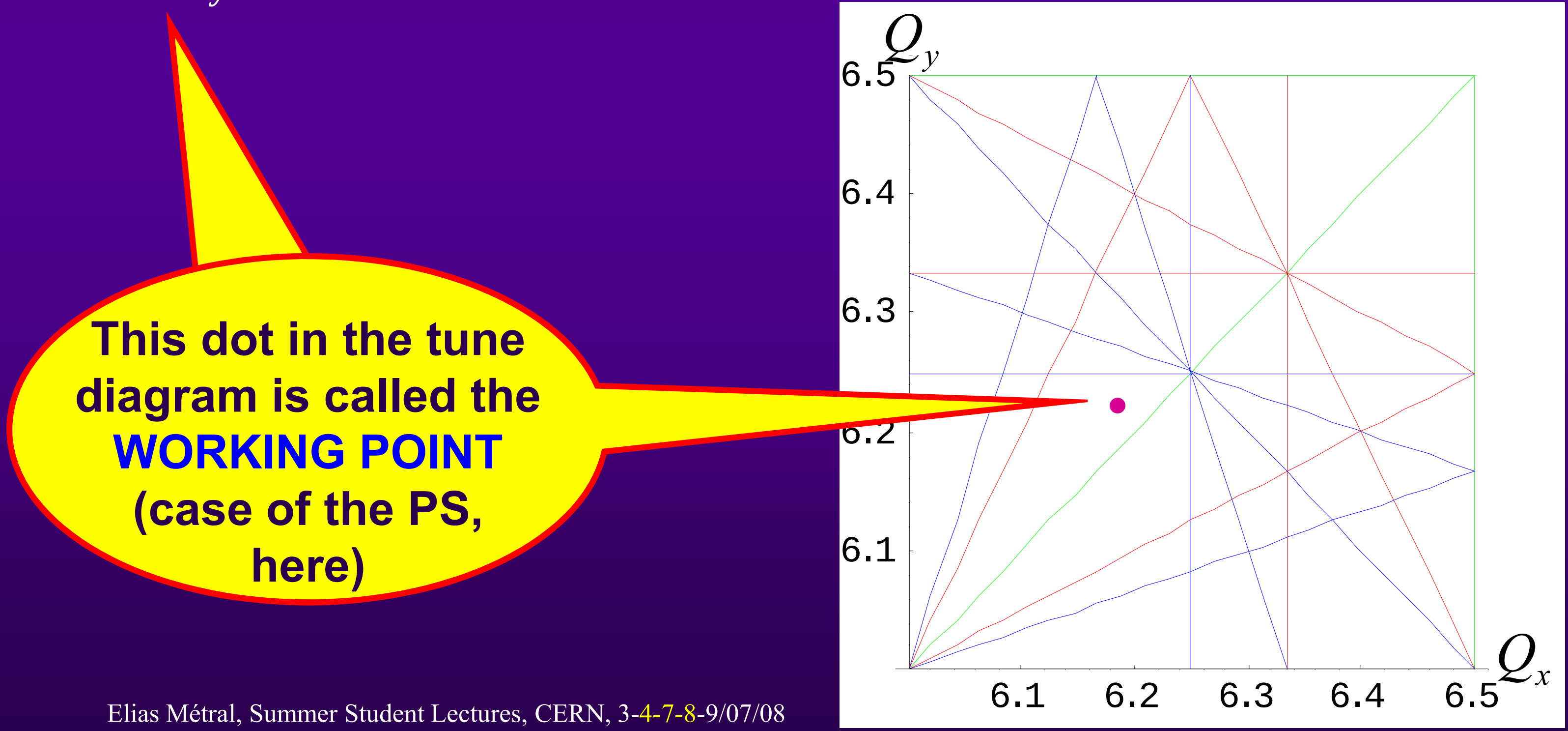
- A multipole of *n*th order is said to generate resonances of order *n*. Resonances below the 3rd order (i.e. due to dipole and quadrupole field errors for instance) are called LINEAR RESONANCES. The NONLINEAR RESONANCES are those of 3rd order and above

TRANSVERSE BEAM DYNAMICS (20/27)

- General **RESONANCE CONDITIONS** $\boxed{M\,Q_x + N\,Q_y = P}$

  where *M*, *N* and *P* are integers, *P* being non-negative, |M| + |N| is the order of the resonance and *P* is the order of the perturbation harmonic

- Plotting the resonance lines for different values of *M*, *N*, and *P* in the (Q_x, Q_y) plane yields the so-called **RESONANCE or TUNE DIAGRAM**



This dot in the tune diagram is called the **WORKING POINT** (case of the PS, here)

TRANSVERSE BEAM DYNAMICS (21/27)

- **RESONANCE WIDTH =** Band with some thickness around every resonance line in the resonance diagram, in which the motion may be unstable, depending on the oscillation amplitude

- **STOPBAND =** Resonance width when the resonance is linear (i.e. below the 3rd order), because the entire beam becomes unstable if the operating point (Q_x, Q_y) reaches this region of tune values

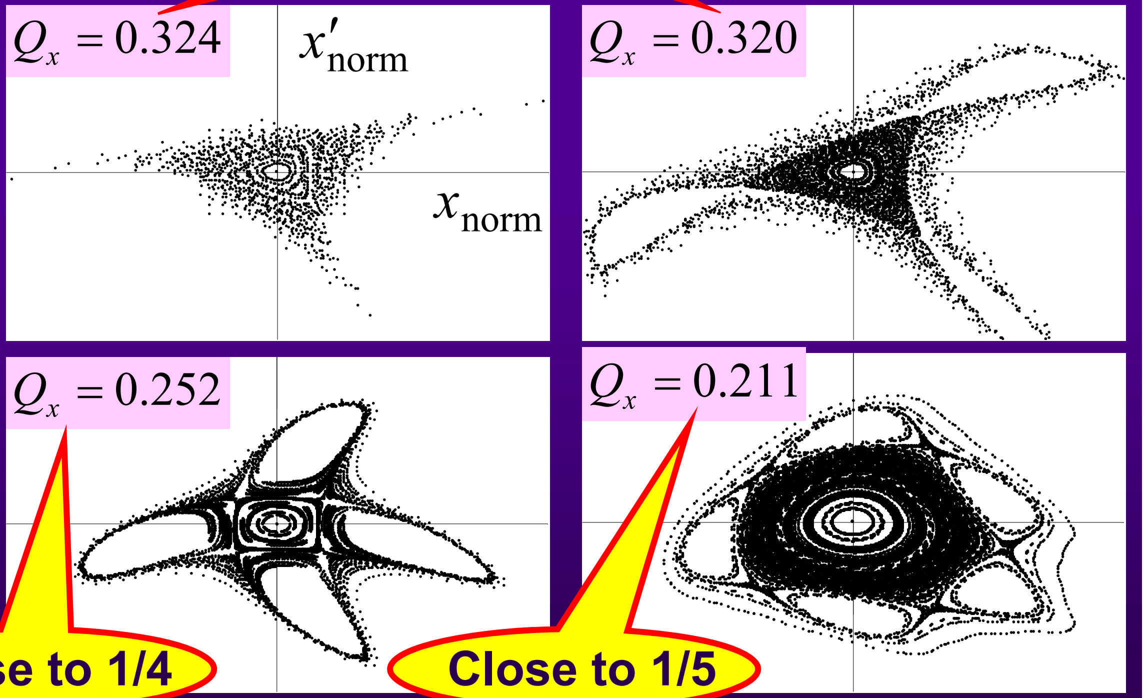
- **DYNAMIC APERTURE =** Largest oscillation amplitude which is stable in the presence of nonlinearities

- **TRACKING:** In general, the equations of motion in the presence of nonlinear fields are untractable for any but the simplest situations. Tracking consists to simulate (user computer programs such as **MAD**) particle motion in circular accelerators in the presence of nonlinear fields

TRANSVERSE BEAM DYNAMICS (22/27)

- **KICK MODEL:** Any nonlinear magnet is treated in the “point-like” approximation (i.e. the particle position is assumed not to vary as the particle traverses the field), the motion in all other elements of the lattice is assumed to be linear. Thus, at each turn the local magnetic field gives a “kick” to the particle, deflecting it from its unperturbed trajectory

- **HENON MAPPING** = Stroboscopic representation of phase-space trajectories (normalised $\Rightarrow$ circles instead of ellipses for linear motion) on every machine turn at the fixed azimuthal position of the perturbation



Close to 1/3

Close to 1/4

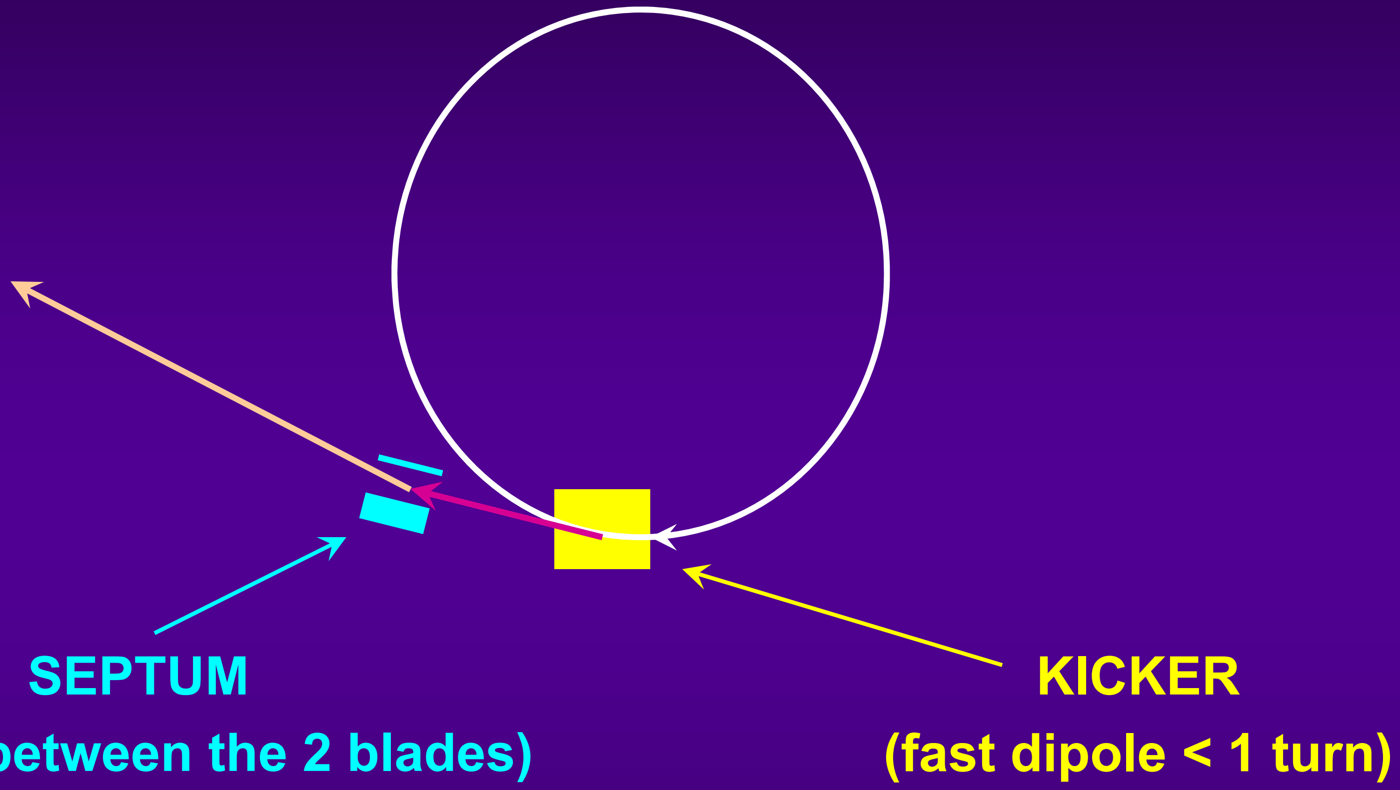
Close to 1/5

TRANSVERSE BEAM DYNAMICS (23/27)

- SEPARATRICES define boundaries between stable motion (bounded oscillations) and unstable motion (expanding oscillations)
- The 3rd order resonance is a drastic (unstable) one because the particles which go onto this resonance are lost
- (STABLE) ISLANDS: For the higher order resonances (e.g. 4th and 5th) stable motions are also possible in (stable) islands. There are 4 stable islands when the tune is closed to a 4th order resonance and 5 when it is closed to a 5th order resonance

TRANSVERSE BEAM DYNAMICS (24/27)

- (fast) EXTRACTION from a ring



SEPTUM

(field ≠ 0 between the 2 blades)

KICKER

(fast dipole < 1 turn)

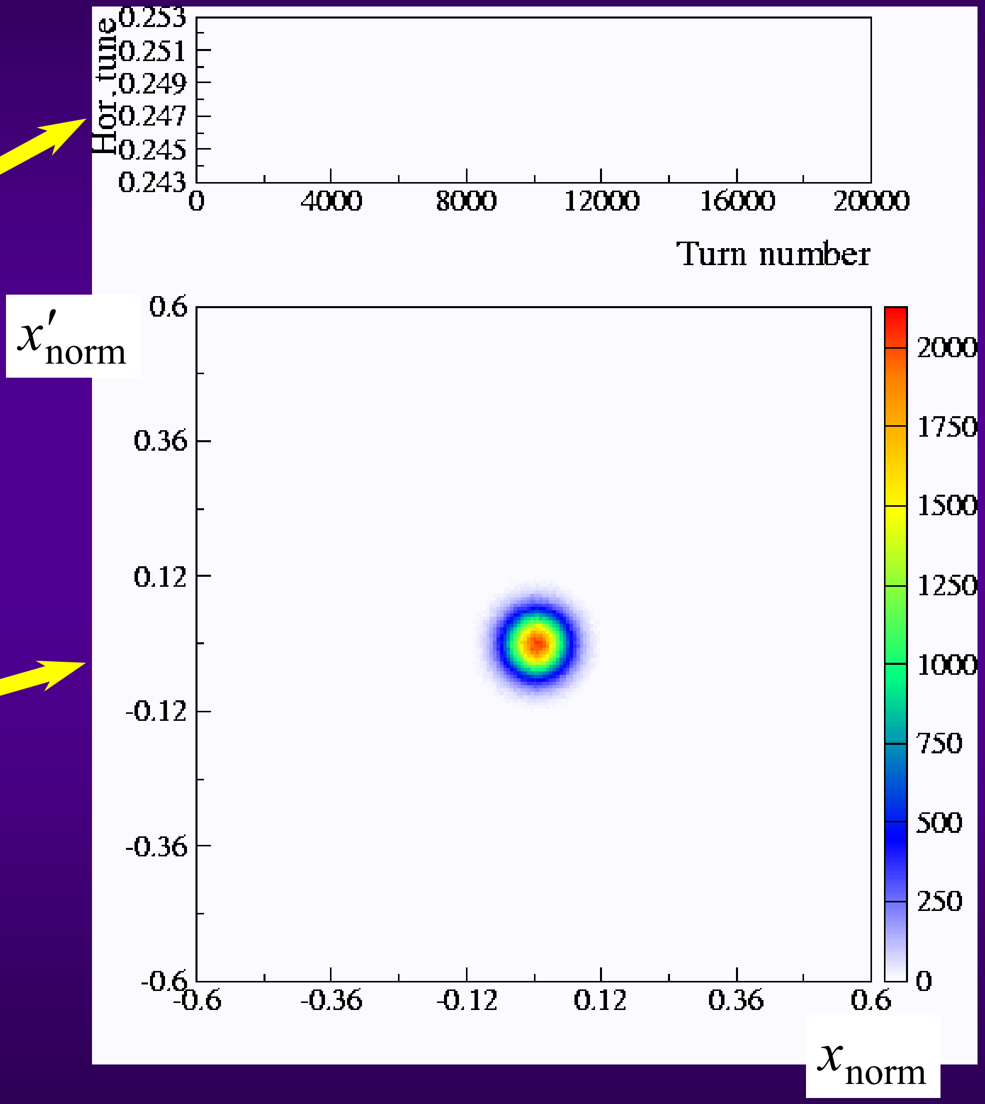
- (fast) INJECTION into a ring ⟹ Reverse process

TRANSVERSE BEAM DYNAMICS (25/27)

Many other injection & ejection schemes ⟹ Example of another extraction

Tune variation

Phase space portrait



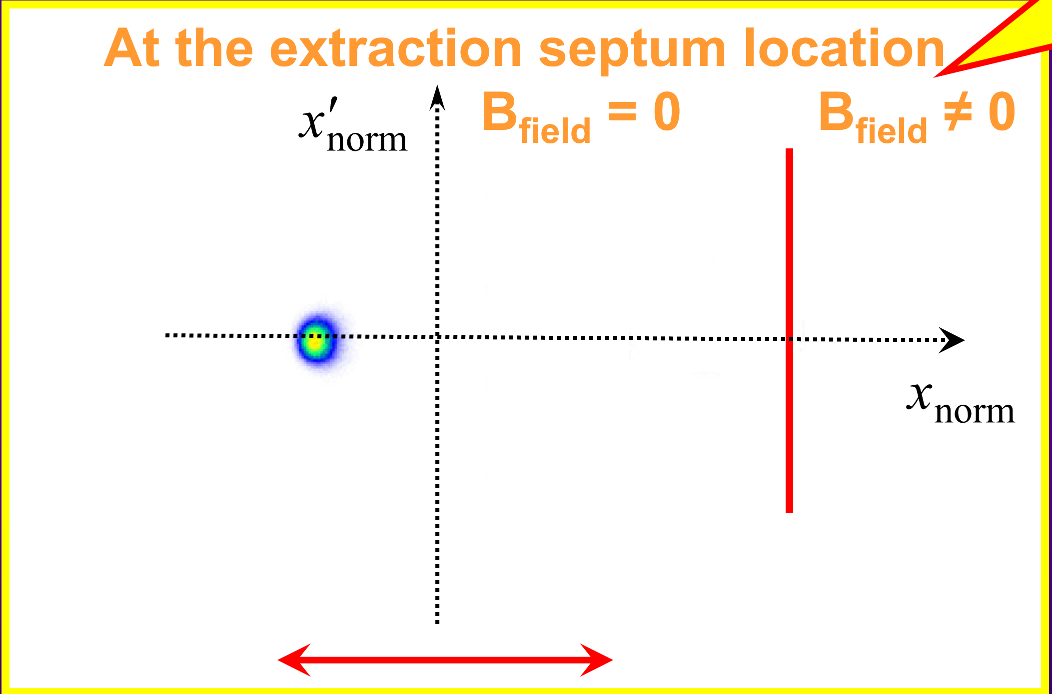
Simulation for the NEW PS MULTI-TURN EXTRACTION (in commissioning)

Courtesy
M. Giovannozzi

TRANSVERSE BEAM DYNAMICS (26/27)

Final stage after 20000 turns (about 42 ms for the PS)

The particles here are extracted through the TT2 transfer line



About 6 cm in physical space

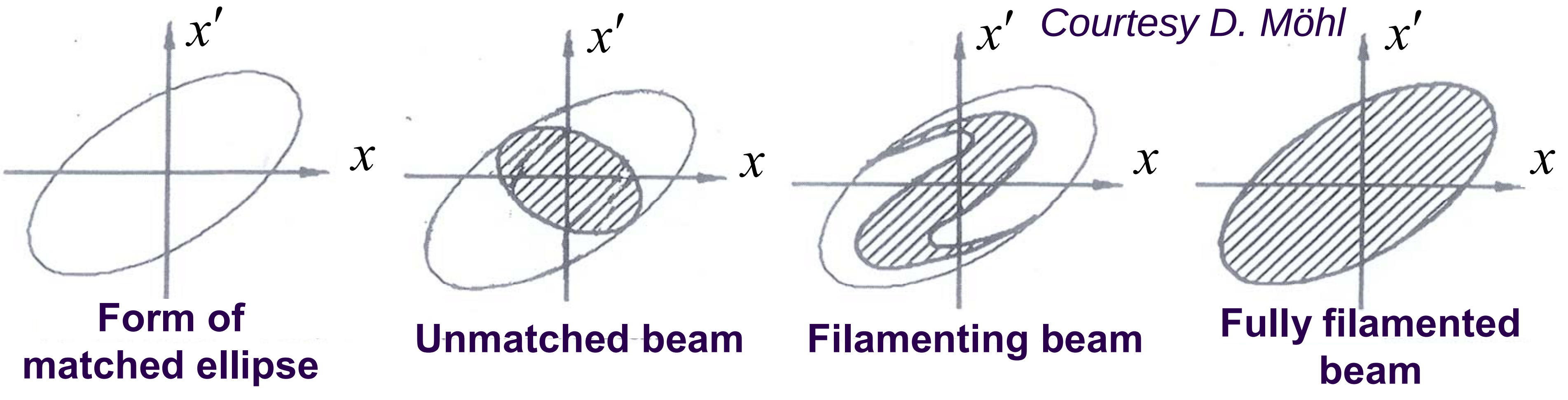
Slow (few thousand turns) bump first (closed distortion of the periodic orbit)

Fast (less than one turn) bump afterwards (closed distortion of the periodic orbit)

Courtesy
M. Giovannozzi

TRANSVERSE BEAM DYNAMICS (27/27)

- **BETATRON MATCHING = The phase space ellipses at the injection (ejection) point of the circular machine, and the exit (entrance) of the beam transport line, should be homothetic. To do this, the Twiss parameters are modified using quadrupoles. If the ellipses are not homothetic, there will be a dilution (i.e. a BLOW-UP) of the emittance**

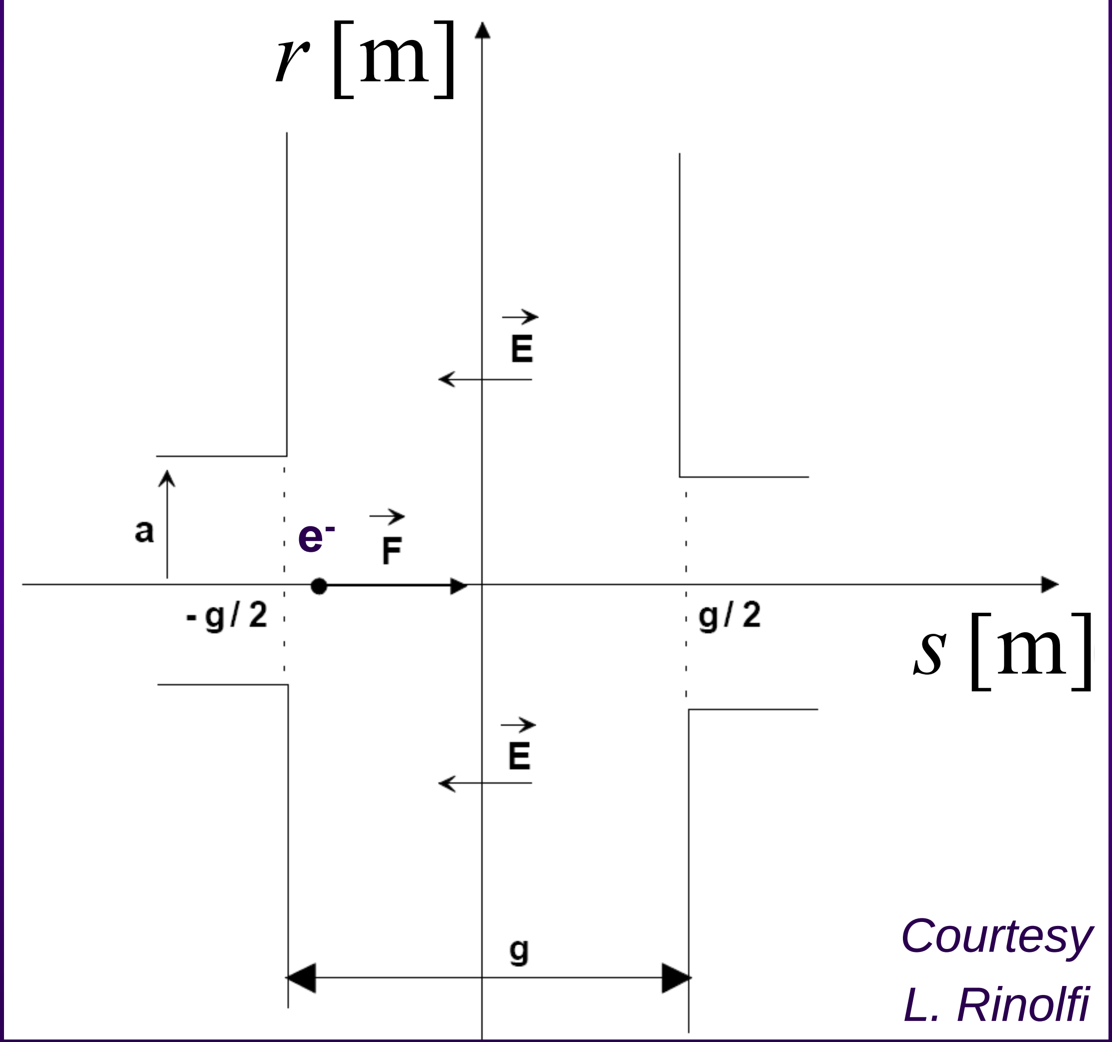


Courtesy D. Möhl

- **DISPERSION MATCHING = D_x and D'_x should be the same at the injection (ejection) point of the circular machine, and the exit (entrance) of the beam transport line. If there are different, there will be also a BLOW-UP, but due to a missteering (because the beam is not injected on the right orbit)**

LONGITUDINAL BEAM DYNAMICS (1/12)

- The electric field is used to accelerate or decelerate the particles, and is produced by one or more RF (Radio-Frequency) CAVITIES



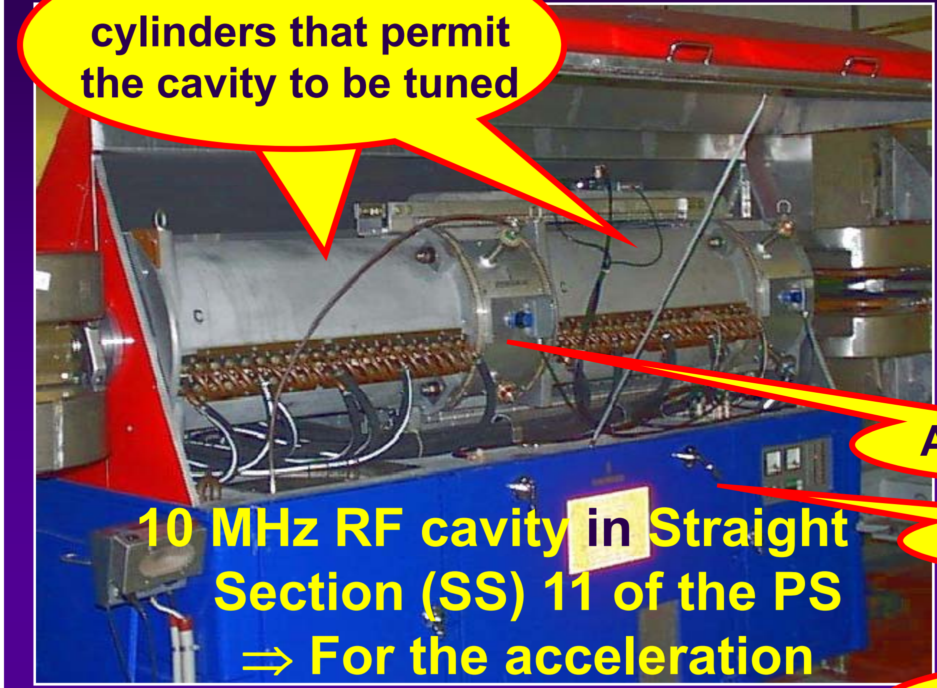
Courtesy L. Rinolfi

$$\Delta E = e \int_{-g/2}^{g/2} E_s(s, t)\, ds$$

[eV]

[V/m]

LONGITUDINAL BEAM DYNAMICS (2/12)



2 ferrite loaded cylinders that permit the cavity to be tuned

Accelerating gap

Final power amplifier

10 MHz RF cavity in Straight Section (SS) 11 of the PS

⇒ For the acceleration

Six 200 MHz in SS6

RF gymnastics

13 MHz in SS92

40 MHz in SS78

80 MHz in SS13

World Radio Geneva: 88.4 MHz

LONGITUDINAL BEAM DYNAMICS (3/12)

- **TRANSITION ENERGY:** The increase of energy has 2 contradictory effects
  - An increase of the particle's velocity
  - An increase of the length of the particle's trajectory

According to the variations of these 2 parameters, the revolution frequency evolves differently

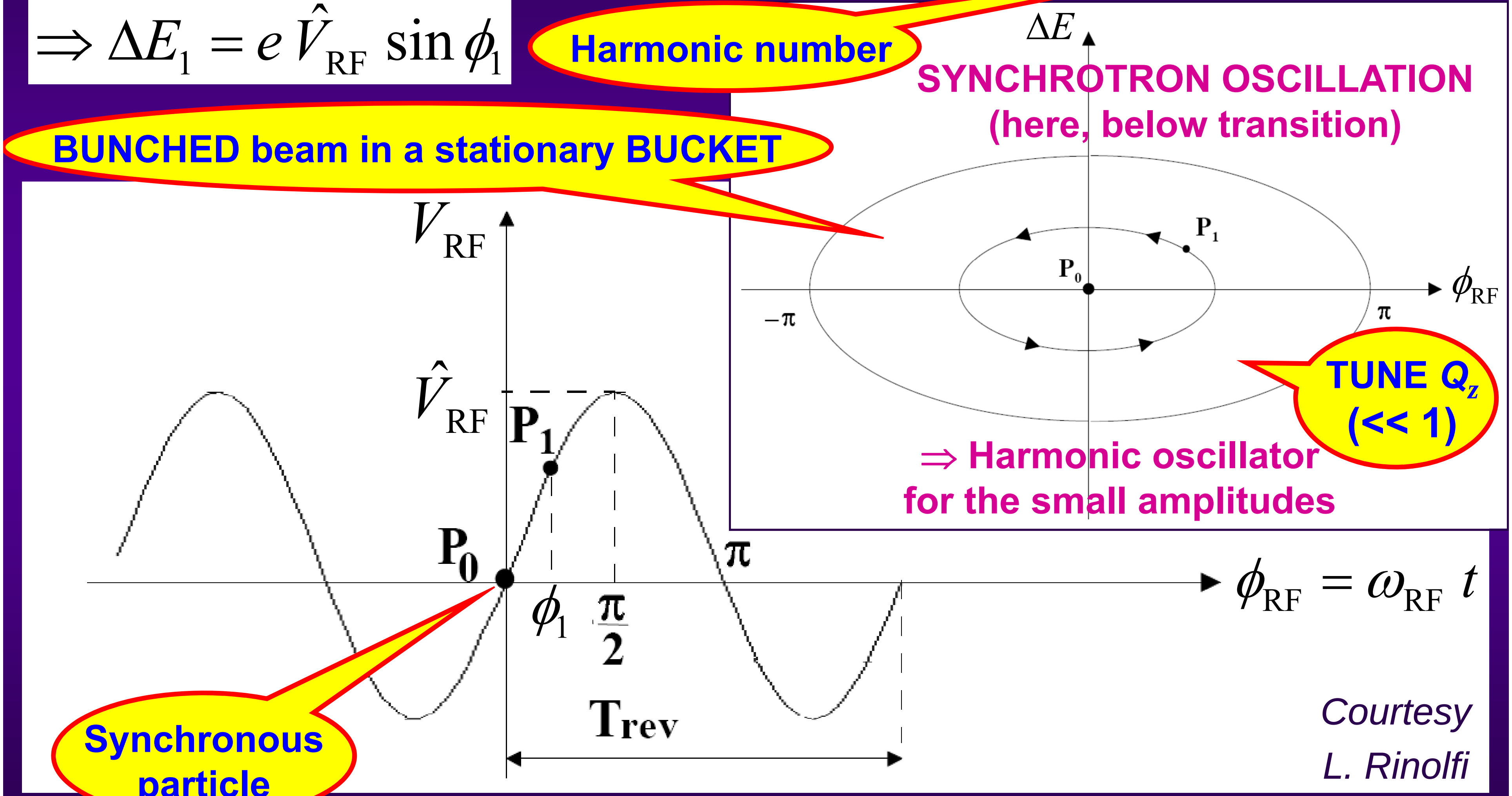
  - Below transition energy: The velocity increases faster than the length ⇒ The revolution frequency increases
  - Above transition energy: It is the opposite case ⇒ The revolution frequency decreases
  - At transition energy: The variation of the velocity is compensated by the variation of the trajectory ⇒ A variation of energy does not modify the frequency

LONGITUDINAL BEAM DYNAMICS (4/12)

- Sinusoidal voltage applied $V_{\mathrm{RF}} = \hat{V}_{\mathrm{RF}} \sin \phi_{\mathrm{RF}}\left(t\right)$ $\omega_{\mathrm{RF}} = h\,\omega_{\mathrm{rev}}$

$$\Rightarrow \Delta E_1 = e\,\hat{V}_{\mathrm{RF}} \sin \phi_1$$

Harmonic number



SYNCHROTRON OSCILLATION (here, below transition)

BUNCHED beam in a stationary BUCKET

TUNE Q_z (<< 1)

⇒ Harmonic oscillator for the small amplitudes

Synchronous particle

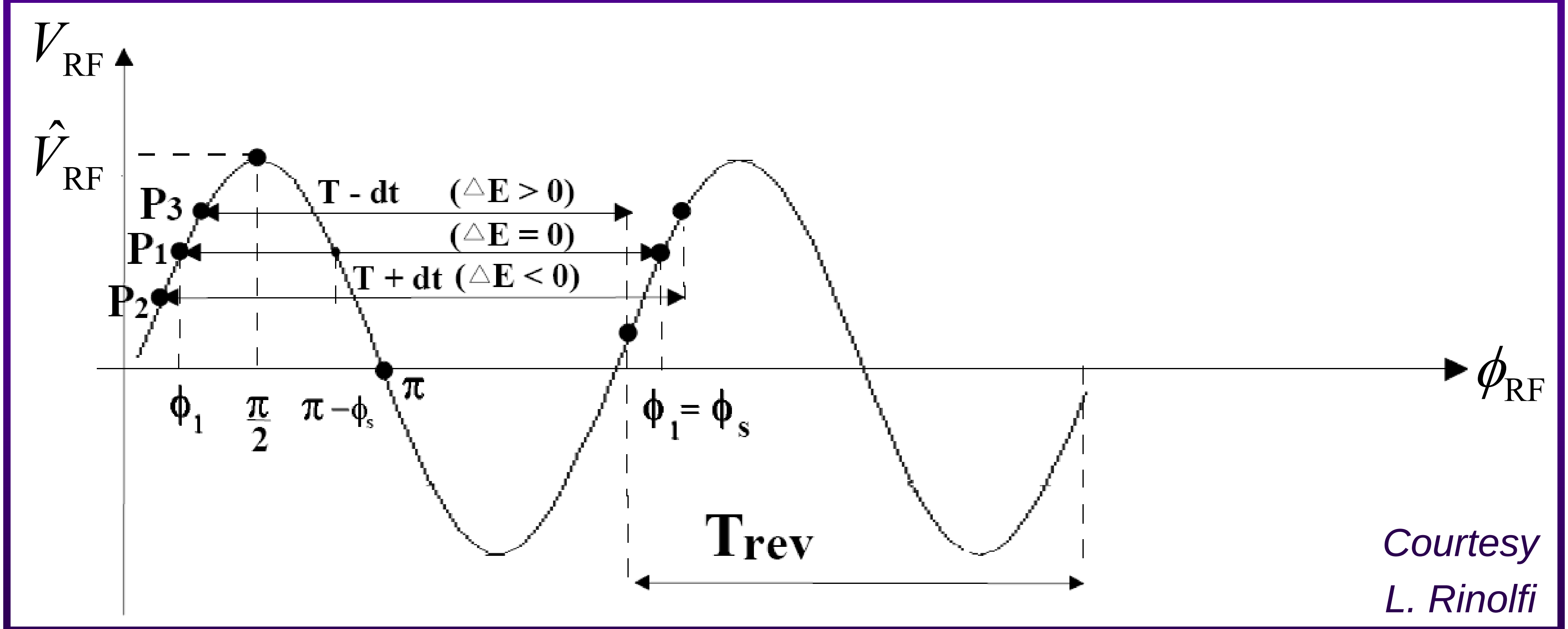
Courtesy L. Rinolfi

LONGITUDINAL BEAM DYNAMICS (5/12)

Synchronous phase

- **Synchrotron oscillation during acceleration (below transition)** $\phi_1 = \phi_s \neq 0$

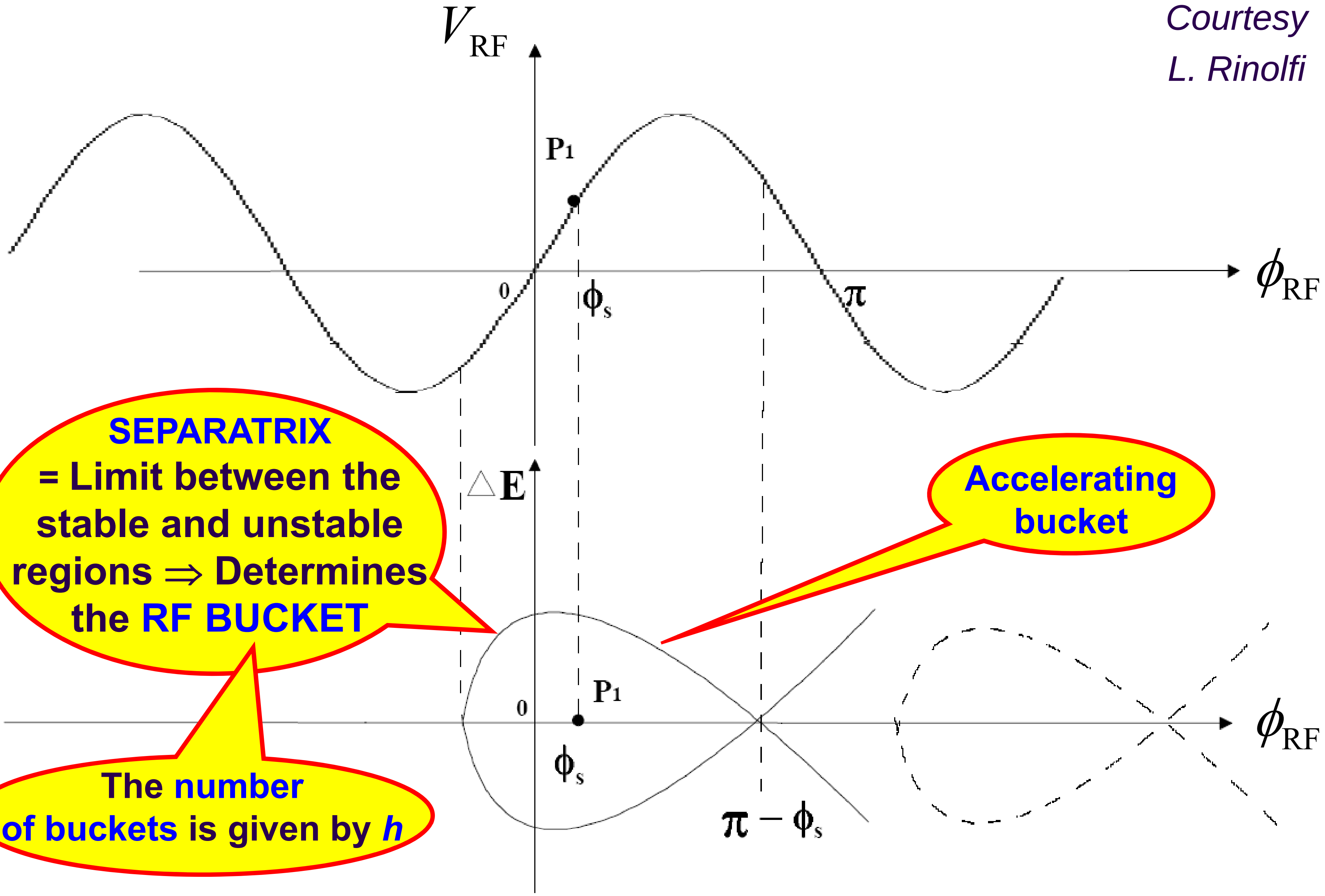
Above transition, the stable phase is $\pi - \phi_s$



Courtesy L. Rinolfi

LONGITUDINAL BEAM DYNAMICS (6/12)

Courtesy
L. Rinolfi



SEPARATRIX
= Limit between the stable and unstable regions ⇒ Determines the RF BUCKET

Accelerating bucket

The number of buckets is given by *h*

LONGITUDINAL BEAM DYNAMICS (7/12)

⇒ $$\ddot{\tau}(t) + \omega_s^2 \, \tau(t) = 0$$: **Equation of a harmonic oscillator**

τ = Time interval between the passage of the synchronous particle and the particle under consideration

$$\omega_s = \sqrt{\frac{\left|\eta \cos \phi_s\right| \hat{V}_{\mathrm{RF}} \, h}{2 \pi \, \beta_r^2 \left(E / e\right)}} \; \omega_{\mathrm{rev}}$$

$$\eta = \gamma_{tr}^{-2} - \gamma_r^{-2} = (\Delta T / T_0) / (\Delta p / p_0)$$

= Momentum compaction factor α_{p}

Slip factor (sometimes defined with a negative sign…)

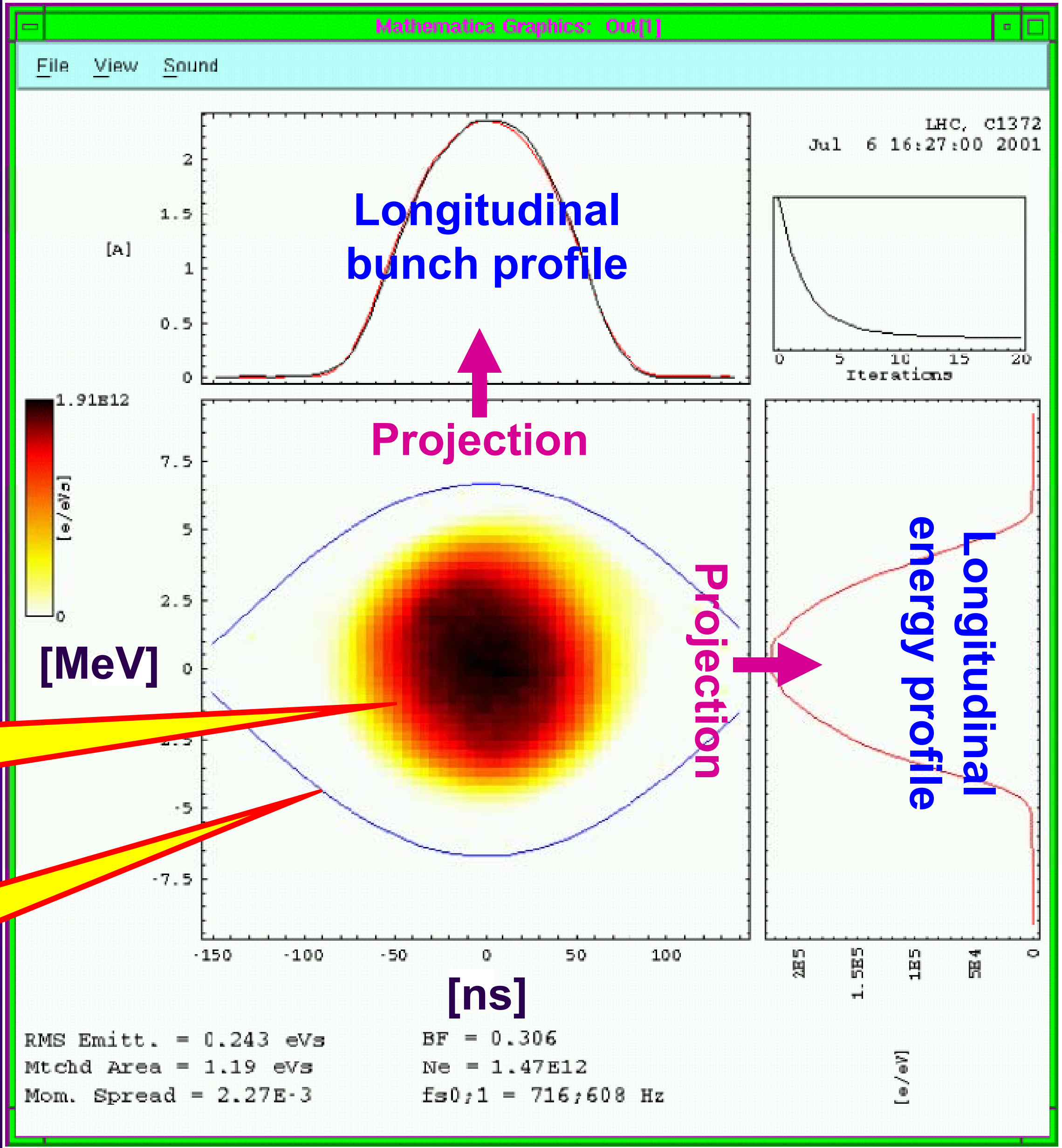
⇒ $$Q_z = \frac{\omega_s}{\omega_{\mathrm{rev}}}$$: **Synchrotron tune**

Number of synchrotron oscillations per machine revolution

LONGITUDINAL BEAM DYNAMICS (8/12)

TOMOSCOPE (developed by S. Hancock, CERN/AB/RF)

The aim of TOMOGRAPHY is to estimate an unknown distribution (here the 2D longitudinal distribution) using only the information in the bunch profiles (see Beam control)



```
RMS Emitt. = 0.243 eVs          BF = 0.306
Mtchd Area = 1.19 eVs           Ne = 1.47E12
Mom. Spread = 2.27E-3           fs0;1 = 716;608 Hz
```

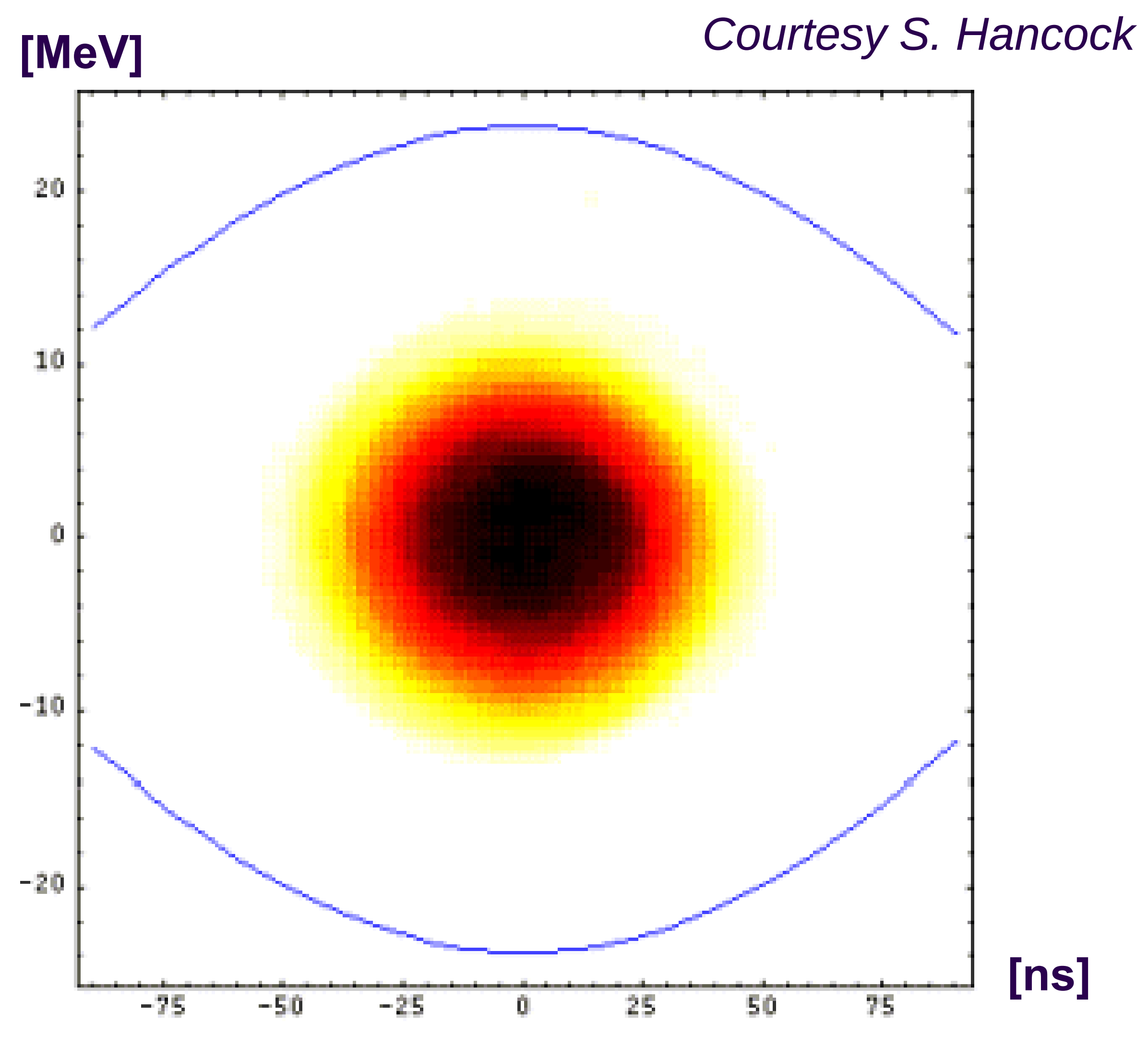
Surface = Longitudinal EMITTANCE of the bunch = ε_L [eV.s]

Surface = Longitudinal ACCEPTANCE of the bucket

LONGITUDINAL BEAM DYNAMICS (9/12)

Examples of RF gymnastics

Longitudinal BUNCH SPLITTING

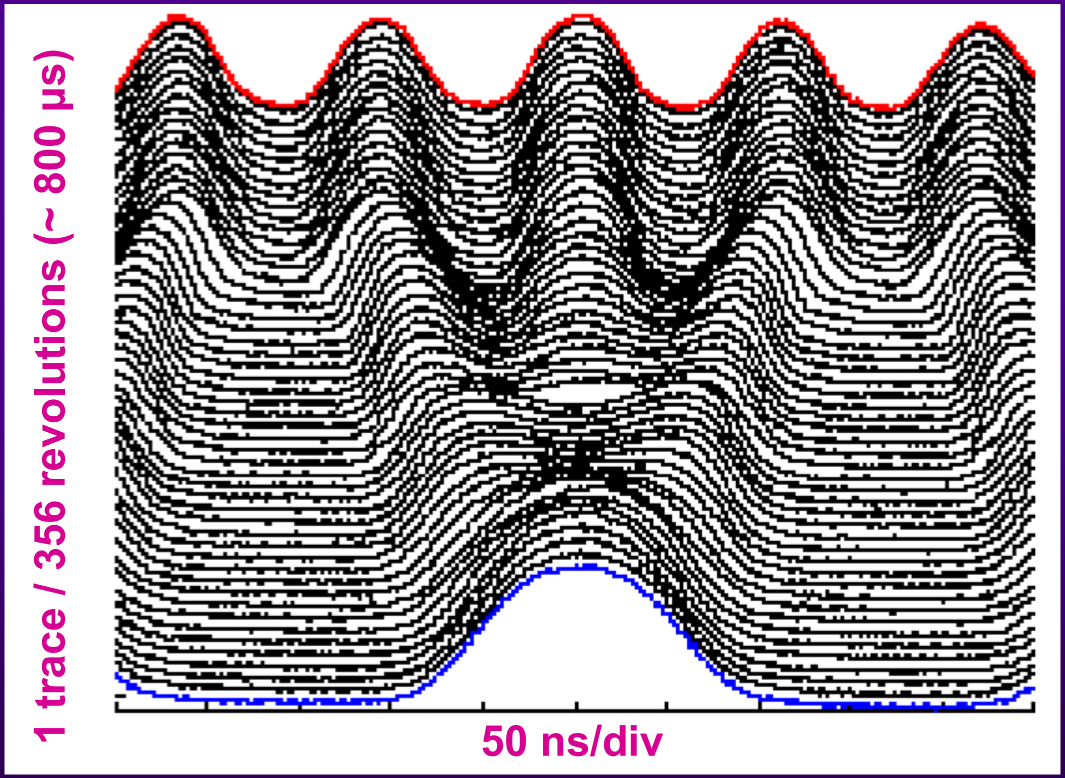


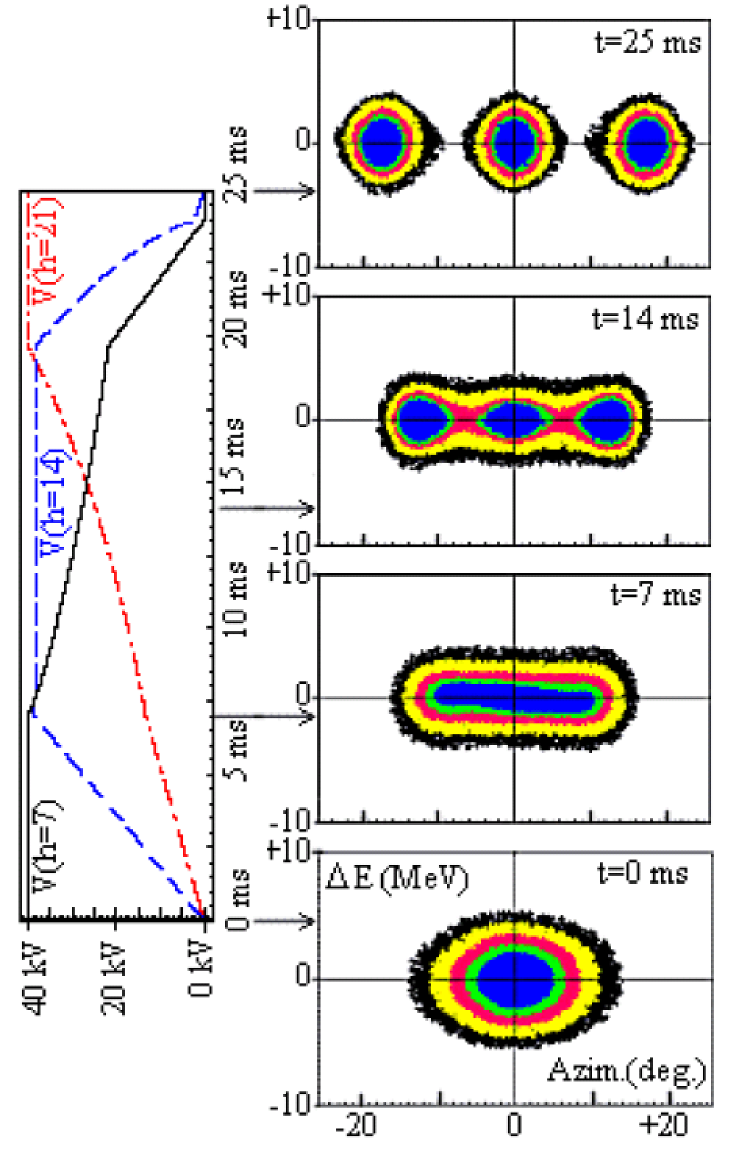
Courtesy S. Hancock

LONGITUDINAL BEAM DYNAMICS (10/12)

Triple bunch splitting

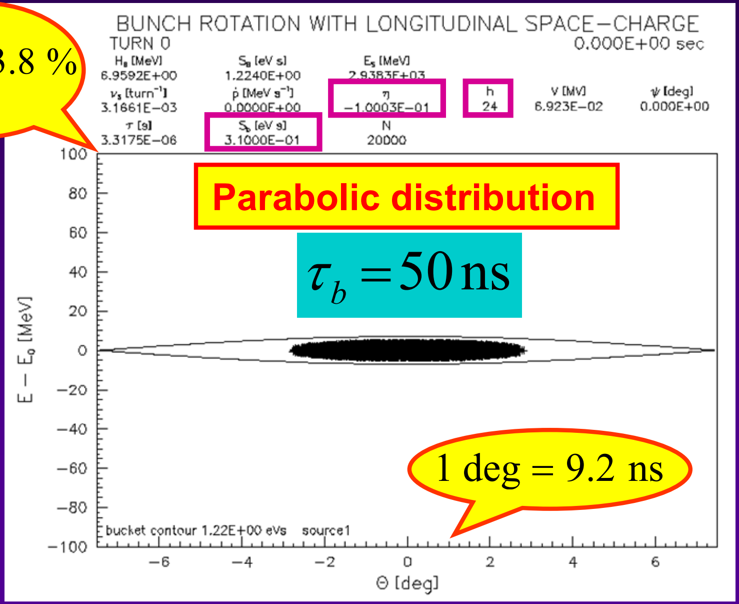
Courtesy R. Garoby





LONGITUDINAL BEAM DYNAMICS (11/12)

BUNCH ROTATION (with ESME)

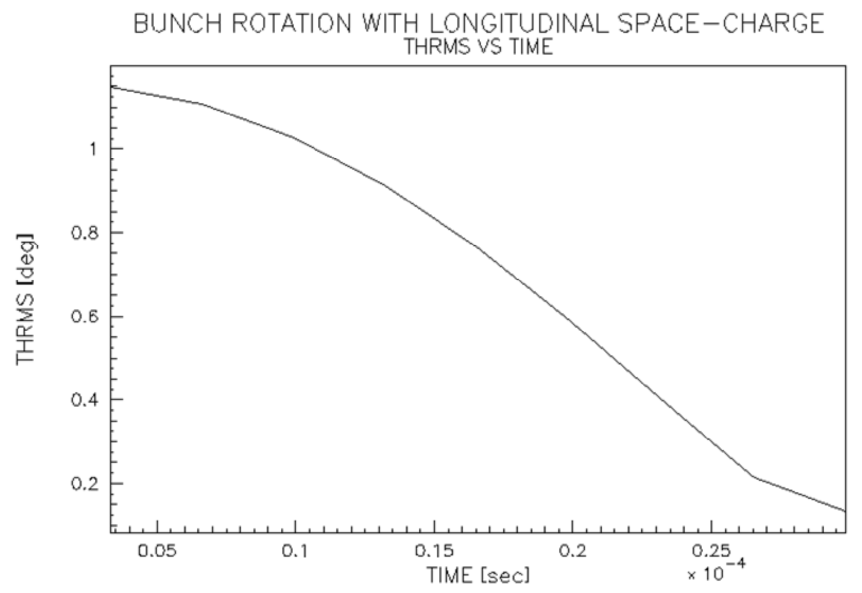


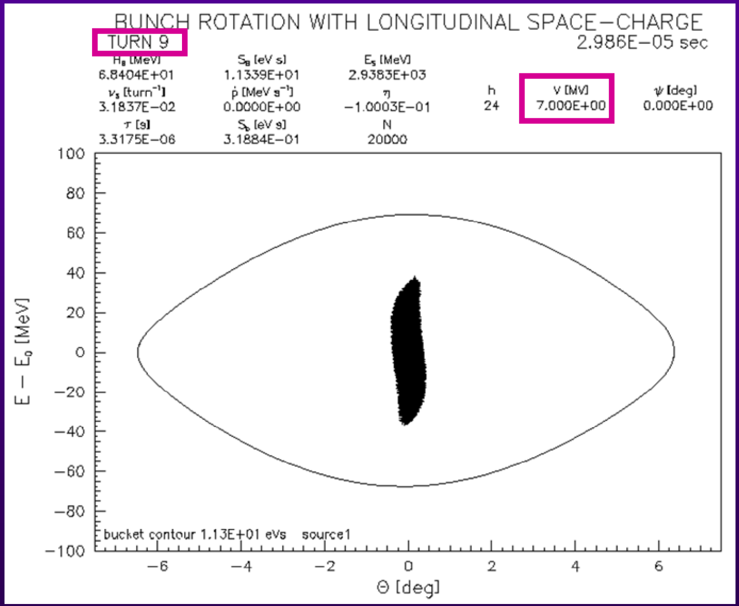
$$\frac{\Delta p}{p_0} = 3.8\ \%$$

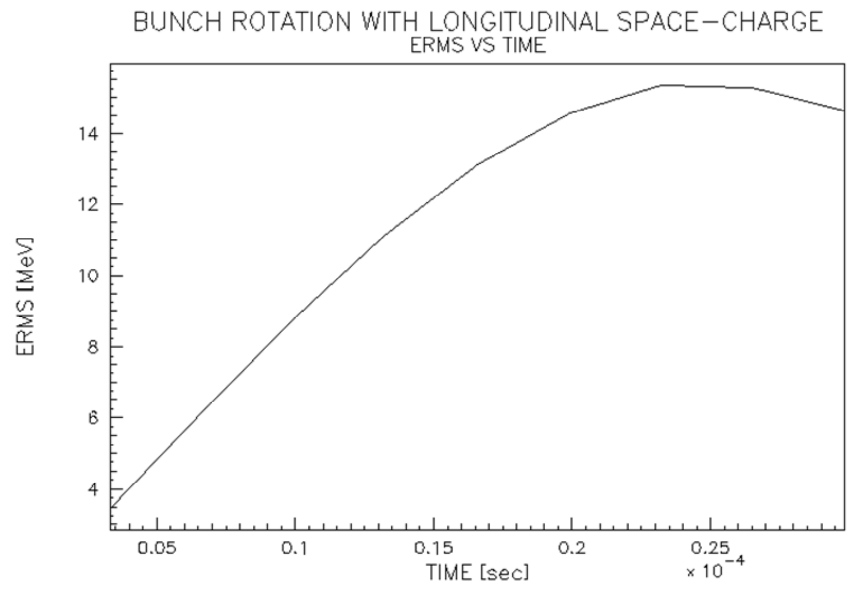
Parabolic distribution

$$\tau_b = 50\,\text{ns}$$

1 deg = 9.2 ns







LONGITUDINAL BEAM DYNAMICS (12/12)

- **EXTRACTION AND LONGITUDINAL MATCHING**

⟹ **The RF buckets (expressed in energy vs. time) of the 2 rings should be homothetic (ΔE / Δt conserved), otherwise longitudinal BLOW-UP**

FIGURE OF MERIT FOR A SYNCHROTRON / COLLIDER: BRIGHTNESS / LUMINOSITY (1/6)

- **(2D) BEAM BRIGHTNESS**

$$B = \frac{I}{\pi^2 \; \varepsilon_x \; \varepsilon_y}$$

Beam current

Transverse emittances

- **MACHINE LUMINOSITY**

$$L = \frac{N_{events / second}}{\sigma_{event}}$$

Number of events per second generated in the collisions

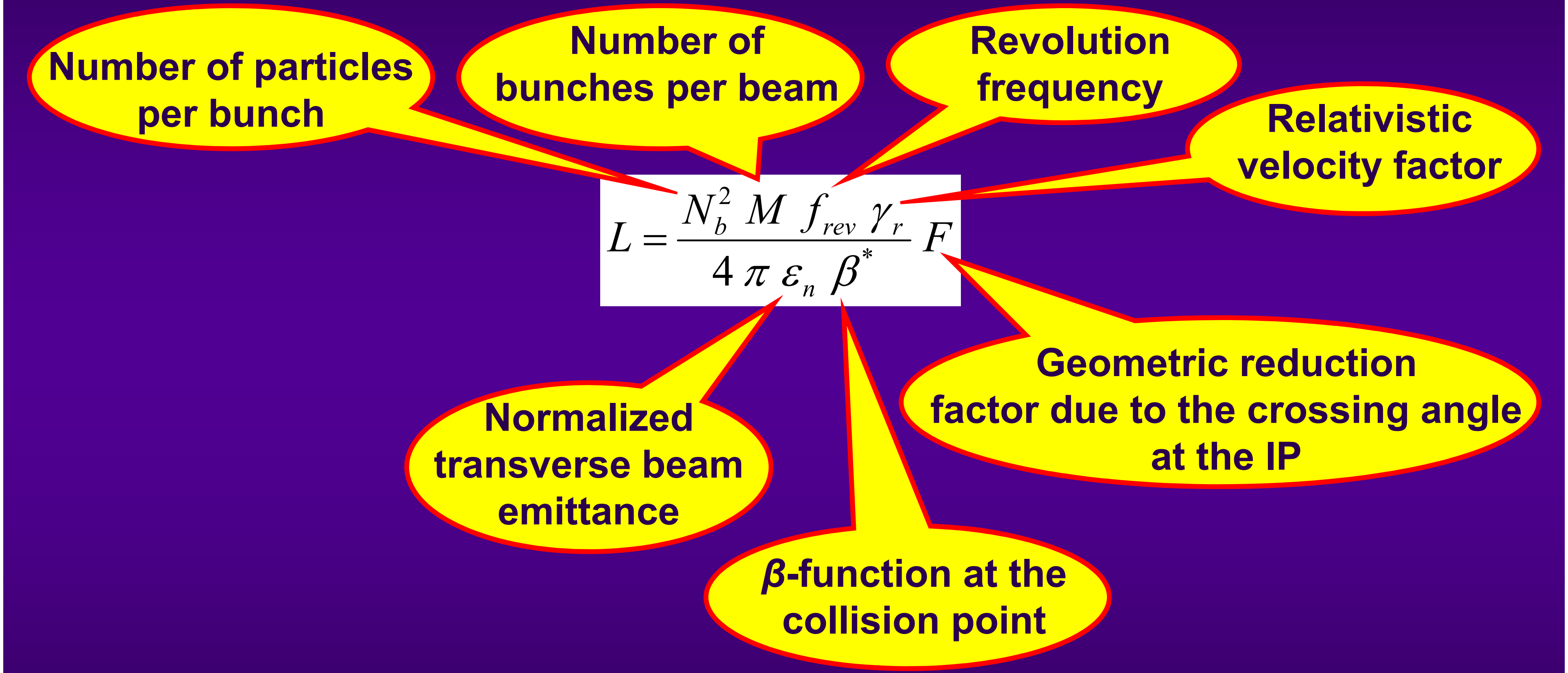
Cross-section for the event under study

[cm^{-2} s^{-1}]

- **The Luminosity depends only on the beam parameters ⇒ It is independent of the physical reaction**
- **Reliable procedures to compute and measure**

FIGURE OF MERIT FOR A SYNCHROTRON / COLLIDER: BRIGHTNESS / LUMINOSITY (2/6)

⇒ For a Gaussian (round) beam distribution



$$L = \frac{N_b^2 \; M \; f_{rev} \; \gamma_r}{4 \, \pi \, \varepsilon_n \; \beta^*} \; F$$

Number of particles per bunch

Number of bunches per beam

Revolution frequency

Relativistic velocity factor

Normalized transverse beam emittance

β-function at the collision point

Geometric reduction factor due to the crossing angle at the IP

- **PEAK LUMINOSITY** for ATLAS&CMS in the LHC = $L_{peak} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

FIGURE OF MERIT FOR A SYNCHROTRON / COLLIDER: BRIGHTNESS / LUMINOSITY (3/6)

Number of particles per bunch	N_b	1.15×10^{11}
Number of bunches per beam	M	2808
Revolution frequency	f_{rev}	11245 Hz
Relativistic velocity factor	γ_r	7461 ($\Longrightarrow$ E = 7 TeV)
β-function at the collision point	β^*	55 cm
Normalised rms transverse beam emittance	ϵ_n	3.75×10^{-4} cm
Geometric reduction factor	F	0.84

$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

Full crossing angle at the IP	θ_c	285 μrad
Rms bunch length	σ_z	7.55 cm
Transverse rms beam size at the IP	σ^*	16.7 μm

FIGURE OF MERIT FOR A SYNCHROTRON / COLLIDER: BRIGHTNESS / LUMINOSITY (4/6)

- **INTEGRATED LUMINOSITY** $L_{\text{int}} = \int_0^T L(t)\, dt$

$\Rightarrow$ **The real figure of merit =** $L_{\text{int}}\, \sigma_{event} = \text{number of events}$

- **LHC integrated Luminosity expected per year: [80-120] fb^{-1}**

Reminder: 1 barn = 10^{-24} cm^{2}
and femto = 10^{-15}

FIGURE OF MERIT FOR A SYNCHROTRON / COLLIDER: BRIGHTNESS / LUMINOSITY (5/6)

- The total proton-proton cross section at 7 TeV is ~ 110 mbarns:
  - Inelastic $\Longrightarrow \sigma_{\text{in}}$ = 60 mbarns
  - Single diffractive $\Longrightarrow \sigma_{\text{sd}}$ = 12 mbarns
  - Elastic $\Longrightarrow \sigma_{\text{el}}$ = 40 mbarns

- The cross section from elastic scattering of the protons and diffractive events will not be seen by the detectors as it is only the inelastic scatterings that give rise to particles at sufficient high angles with respect to the beam axis

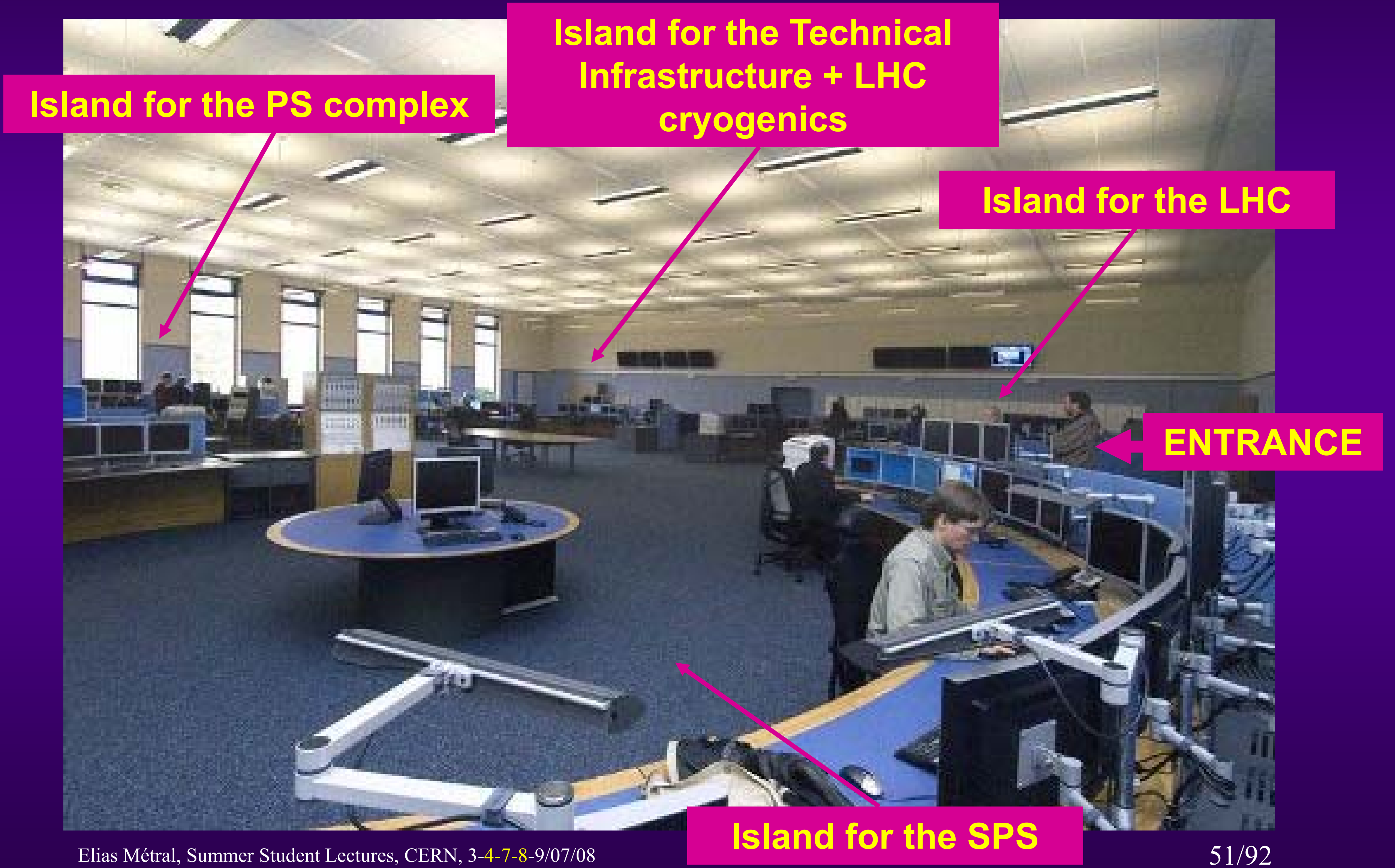
- Inelastic event rate at nominal luminosity = $10^{34} \times 60 \times 10^{-3} \times 10^{-24}$ = 600 millions / second per high-luminosity experiment

FIGURE OF MERIT FOR A SYNCHROTRON / COLLIDER: BRIGHTNESS / LUMINOSITY (6/6)

- The bunch spacing in the LHC is 25 ns ⟹ Crossing rate of 40 MHz
- However, there are bigger gaps (for the kickers) ⟹ Average crossing rate = number of bunches × revolution frequency = 2808 × 11245 = 31.6 MHz
- (600 millions inelastic events / second) / (31.6 × 10^6) = 19 inelastic events per crossing
- Total inelastic events per year (~10^7 s) = 600 millions × 10^7 = 6 × 10^{15} ~ 10^{16}
- The LHC experimental challenge is to find rare events at levels of 1 in 10^{13} or more ⟹ ~ 1000 Higgs events in each of the ATLAS and CMS experiments expected per year

BEAM CONTROL (1/8)

- New CERN Control Centre (CCC) at Prevessin since March 2006



Island for the PS complex

Island for the Technical Infrastructure + LHC cryogenics

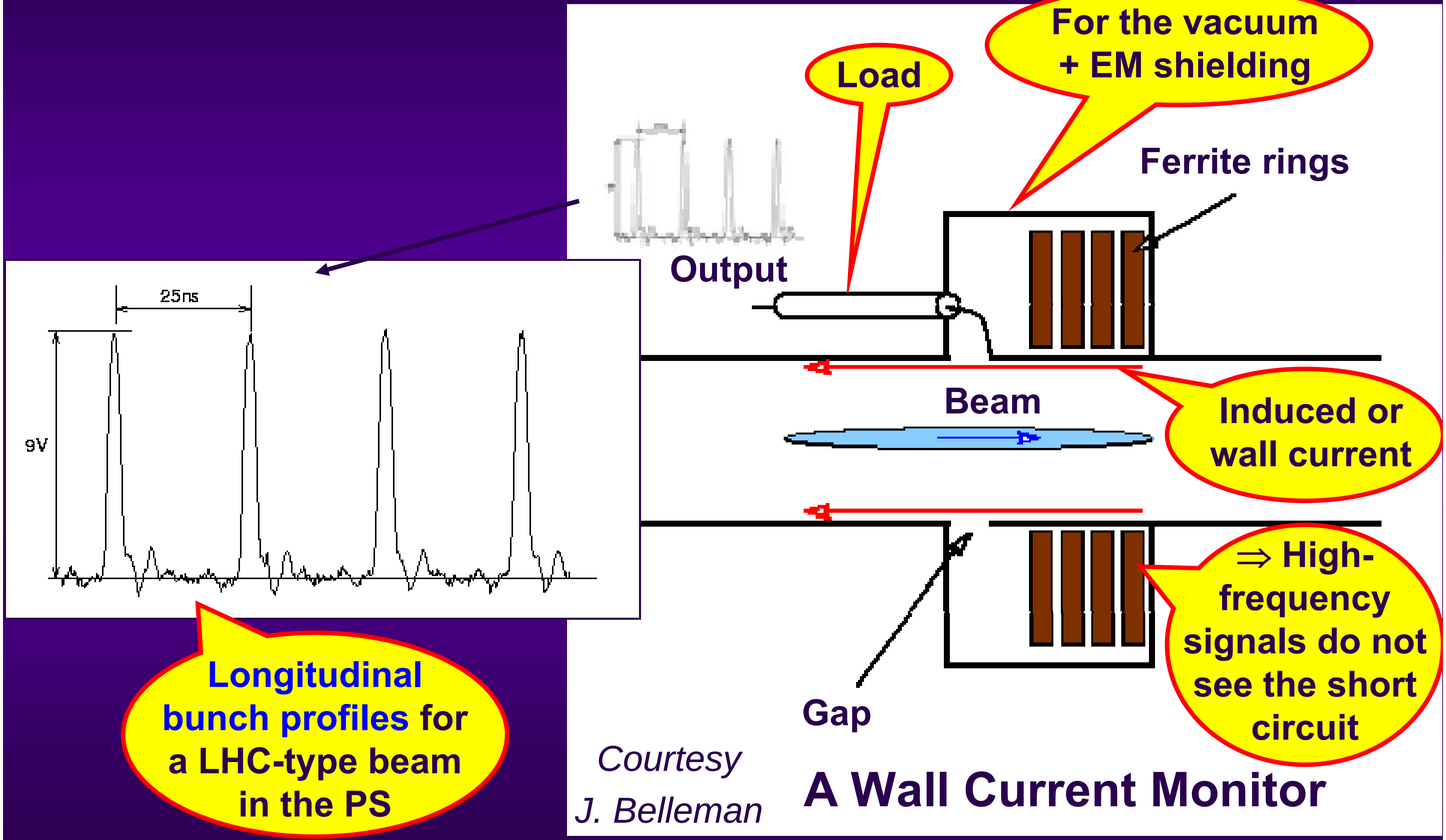
Island for the LHC

ENTRANCE

Island for the SPS

BEAM CONTROL (2/8)

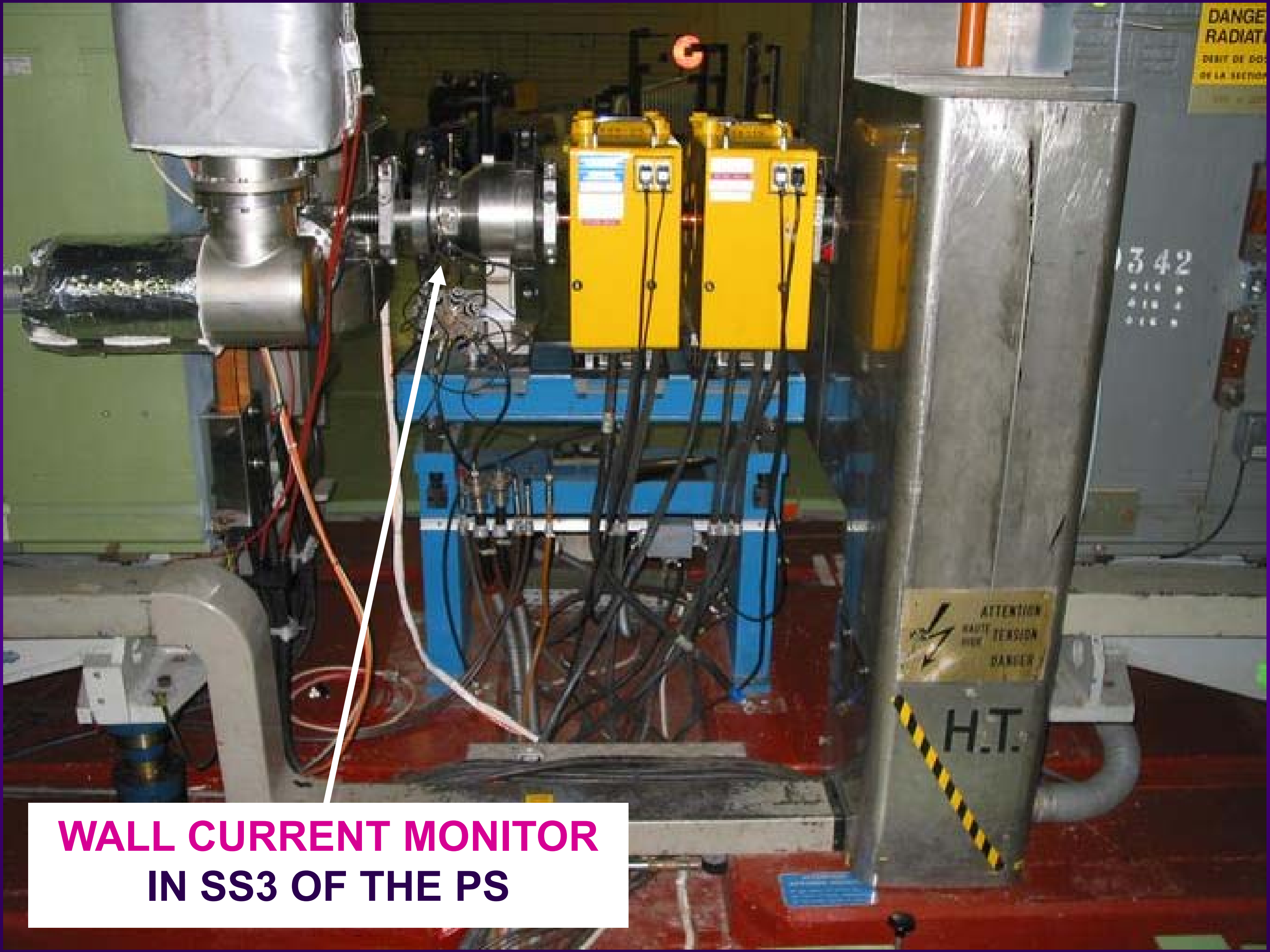
◆ **WALL CURRENT MONITOR** = Device used to measure the instantaneous value of the beam current



Courtesy J. Belleman

A Wall Current Monitor

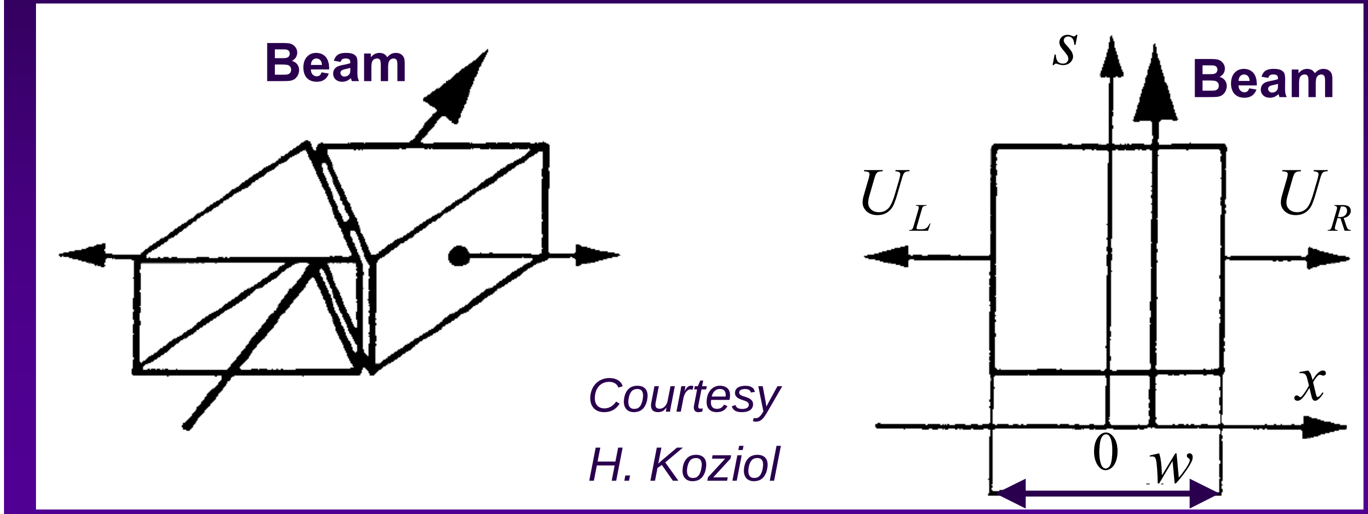
BEAM CONTROL (3/8)



WALL CURRENT MONITOR
IN SS3 OF THE PS

BEAM CONTROL (4/8)

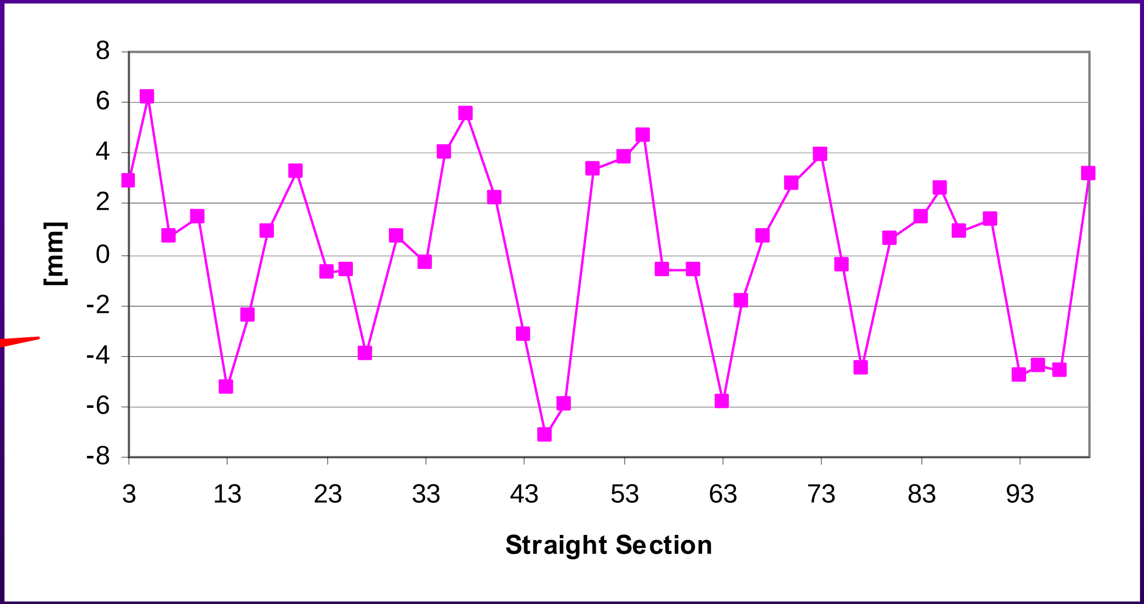
- (Transverse) beam POSITION PICK-UP MONITOR



Courtesy
H. Koziol

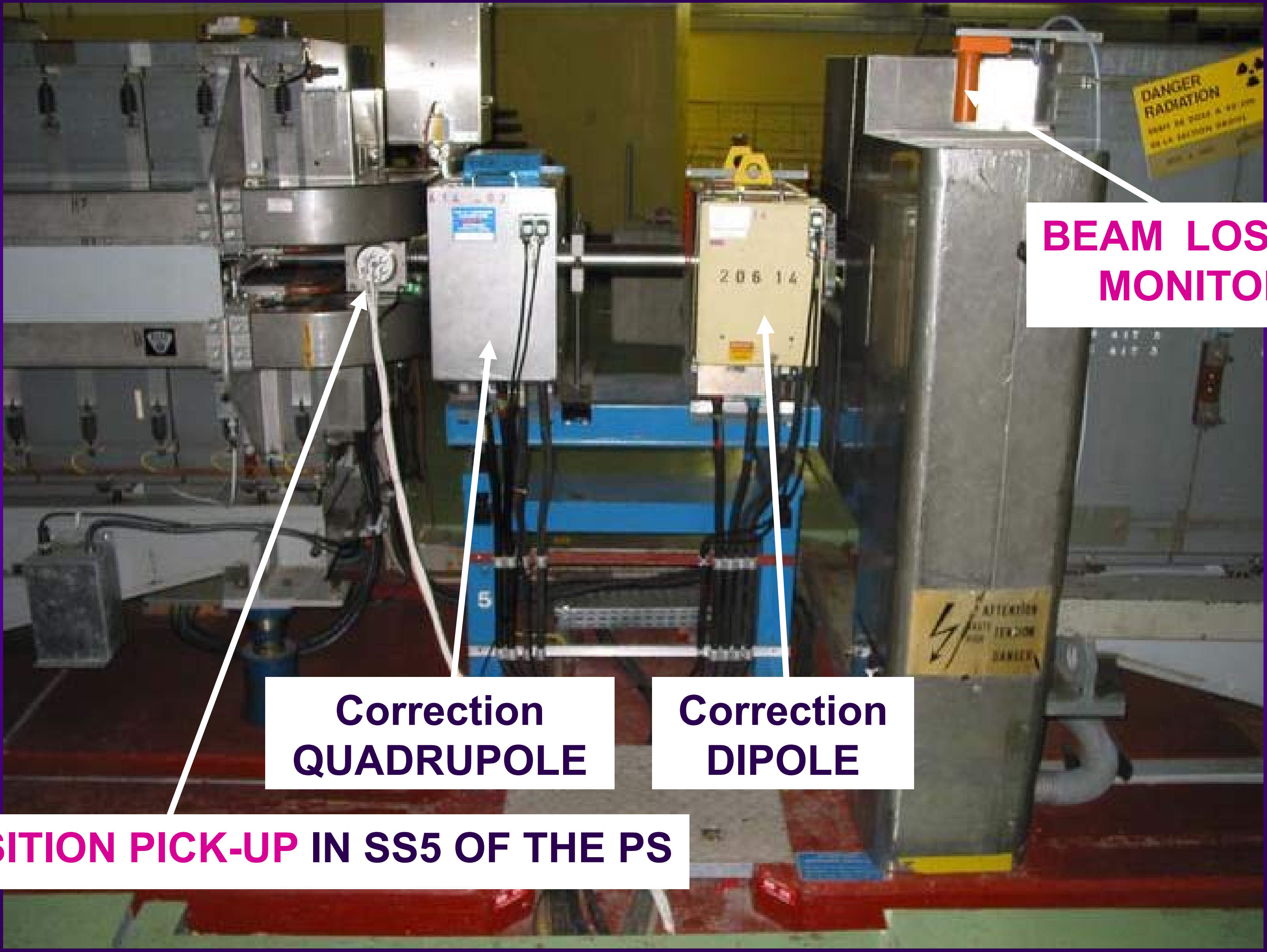
$$x = \frac{w}{2} \frac{U_R - U_L}{U_R + U_L}$$

⇒ **Horizontal beam orbit measurement in the PS**



6 spikes observed as $Q_x \approx 6.25$

BEAM CONTROL (5/8)



BEAM LOSS MONITOR

Correction QUADRUPOLE

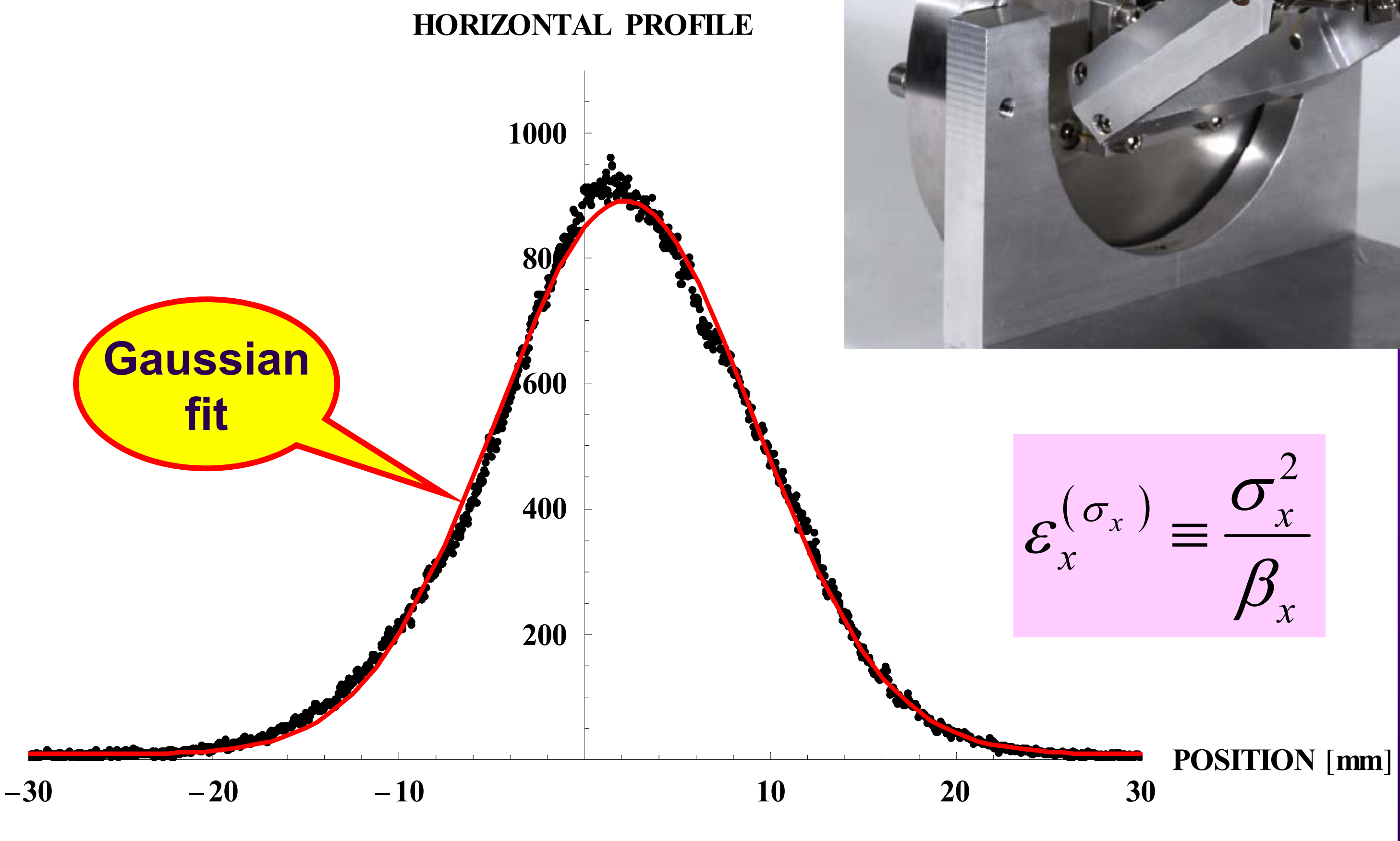
Correction DIPOLE

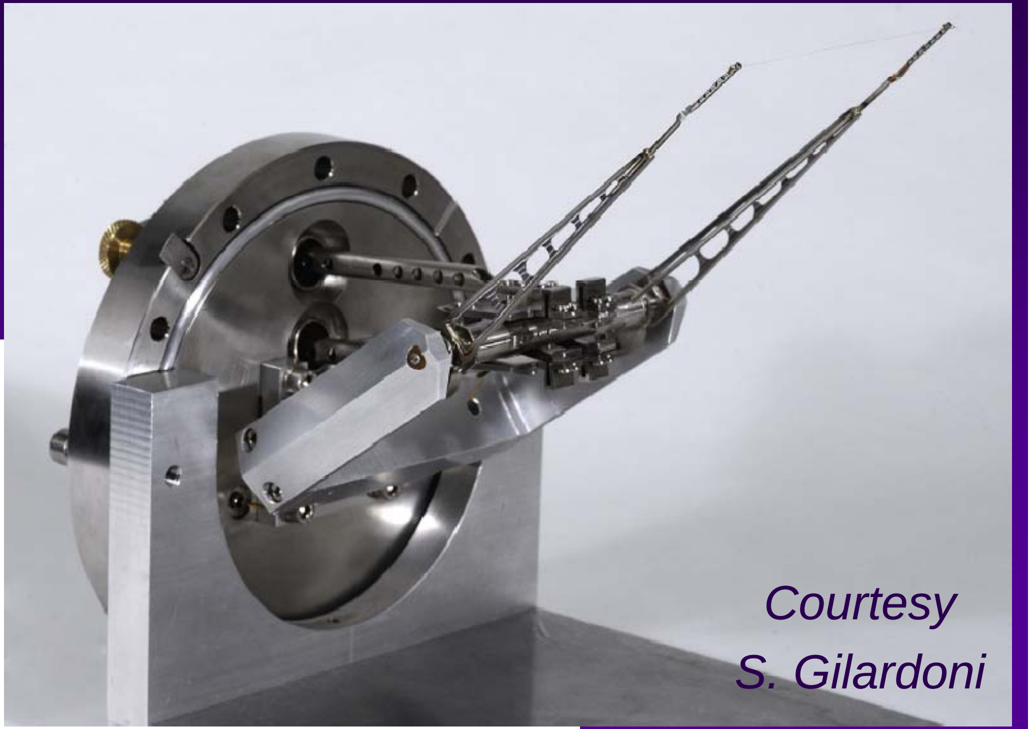
POSITION PICK-UP IN SS5 OF THE PS

BEAM CONTROL (6/8)

- **FAST WIRE SCANNER**

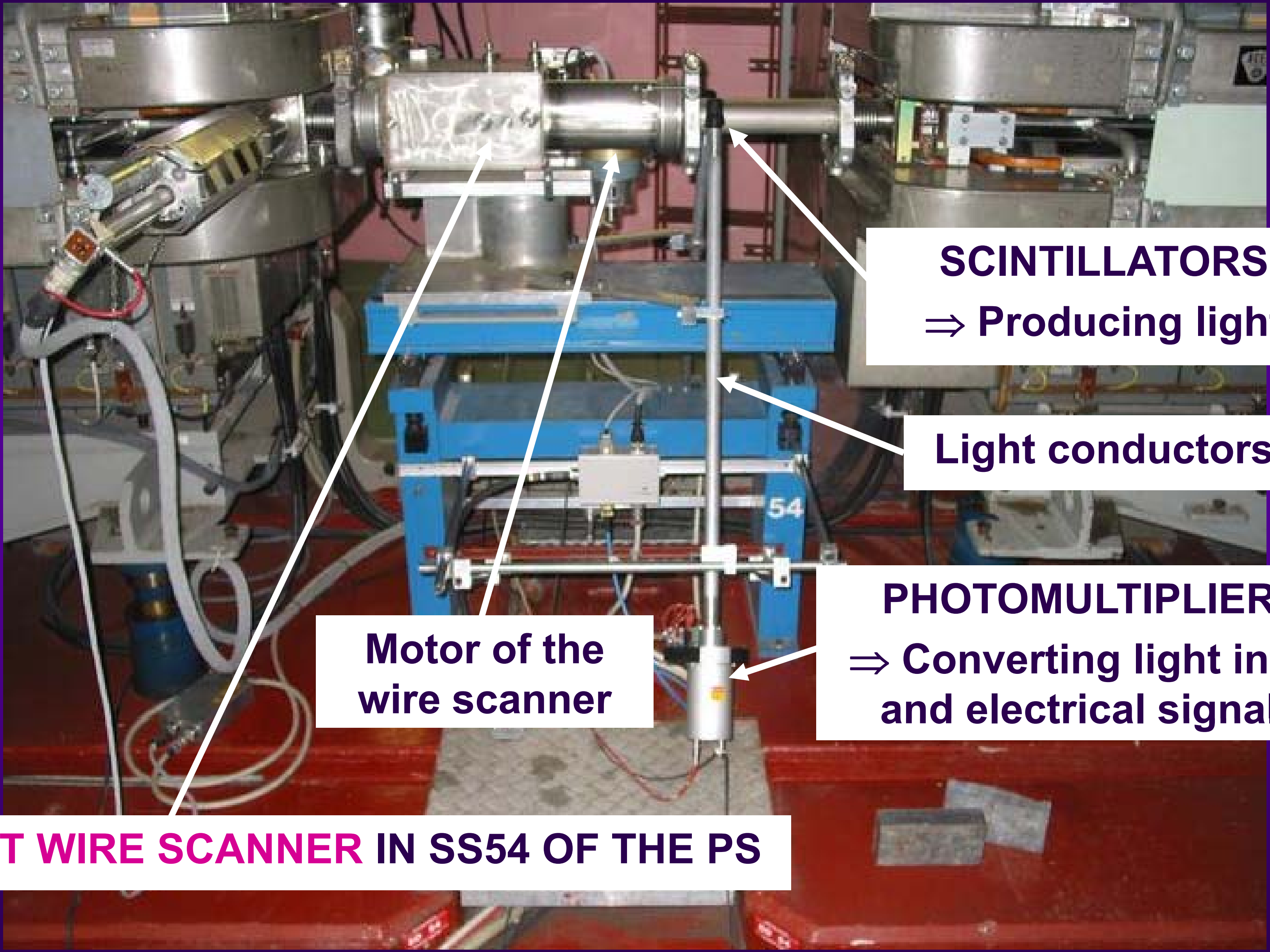
⇒ Measures the transverse beam profiles by detecting the particles scattered from a thin wire swept rapidly through the beam




Courtesy
S. Gilardoni

$$\varepsilon_x^{(\sigma_x)} \equiv \frac{\sigma_x^{2}}{\beta_x}$$

BEAM CONTROL (7/8)



SCINTILLATORS

⇒ Producing light

Light conductors

PHOTOMULTIPLIER

⇒ Converting light into and electrical signal

Motor of the wire scanner

FAST WIRE SCANNER IN SS54 OF THE PS

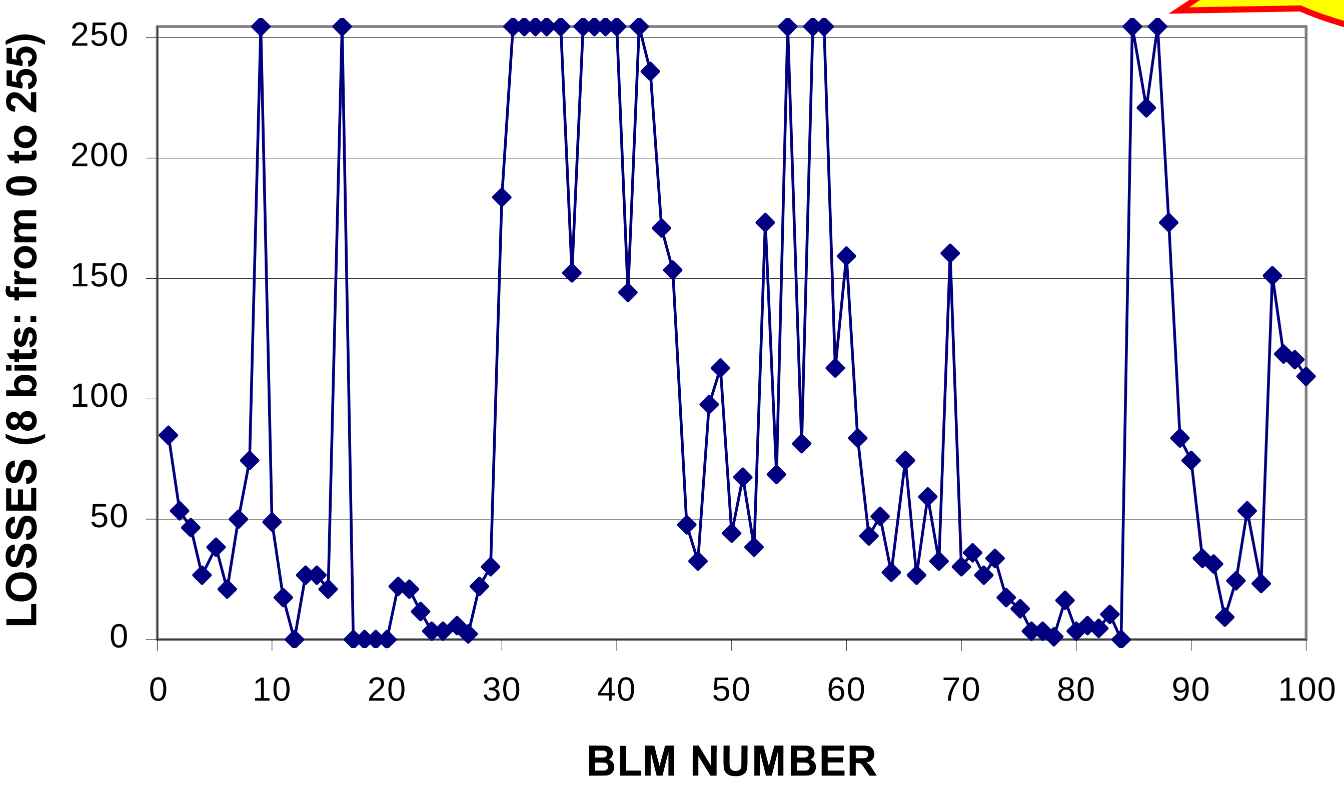
BEAM CONTROL (8/8)

- **BEAM LOSS MONITOR**

PS record intensity (CNGS beam)

3.42 10^{13} ppp @ 14 GeV/c
(Monday 27/09/04 12:47)

Saturation at 255 ⟹ Could be much higher

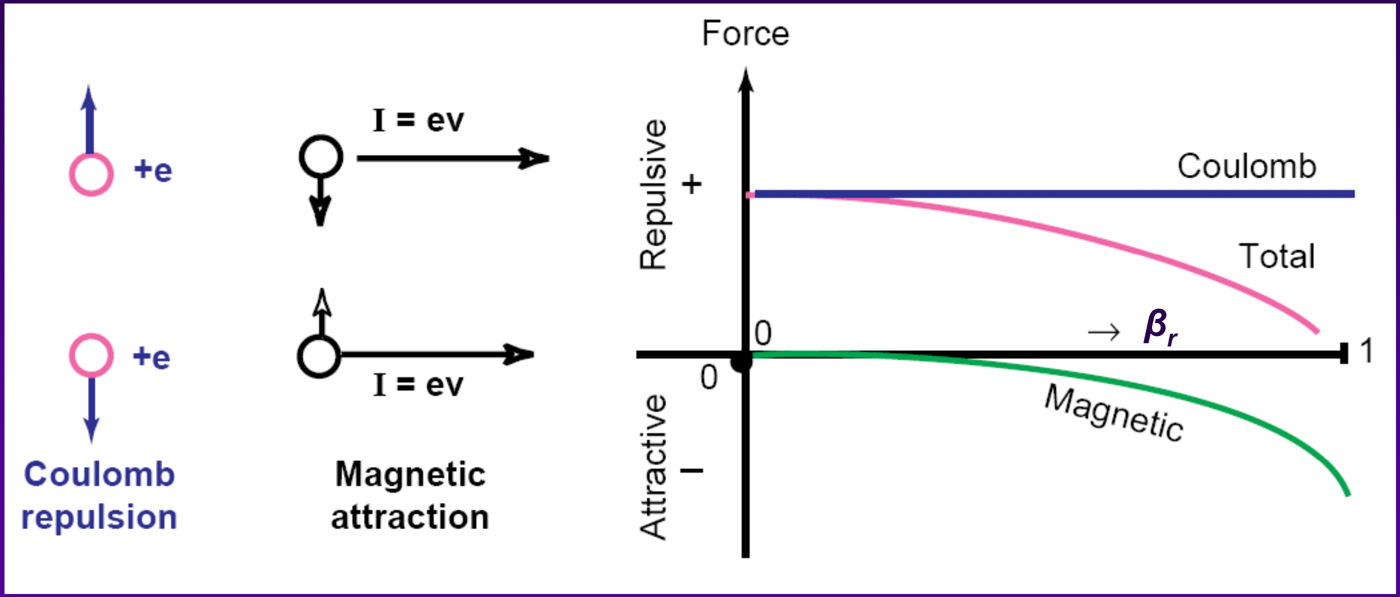


Detector = ACEM (Aluminum Cathod Electron Multiplier), placed at the beginning of the SS ⇒ Similar to a Photomultiplier and it is cheap, robust and radiation resistant

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER ⇒ COLLECTIVE EFFECTS (1/34)

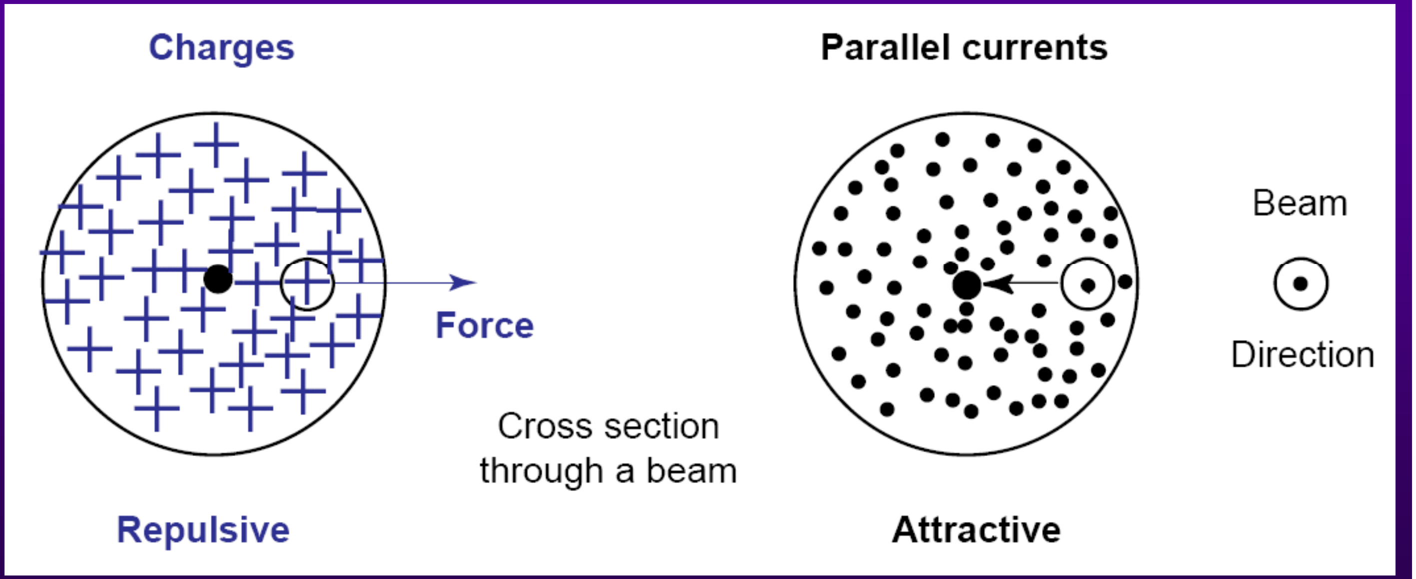
Space charge

2 particles at rest or travelling



Courtesy K. Schindl

Many charged particles travelling in an unbunched beam with circular cross-section

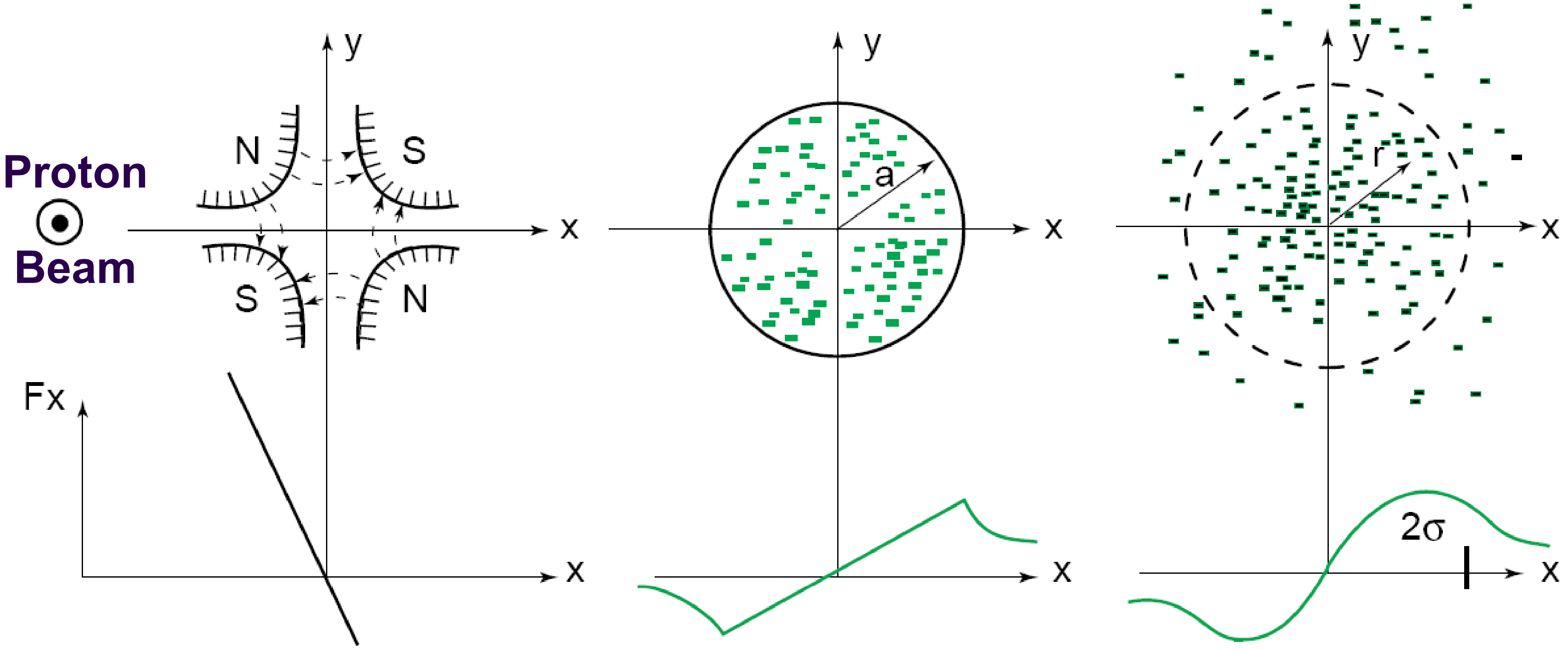


LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER ⇒ COLLECTIVE EFFECTS (2/34)

Quadrupole (F-type)

Uniform

Gaussian



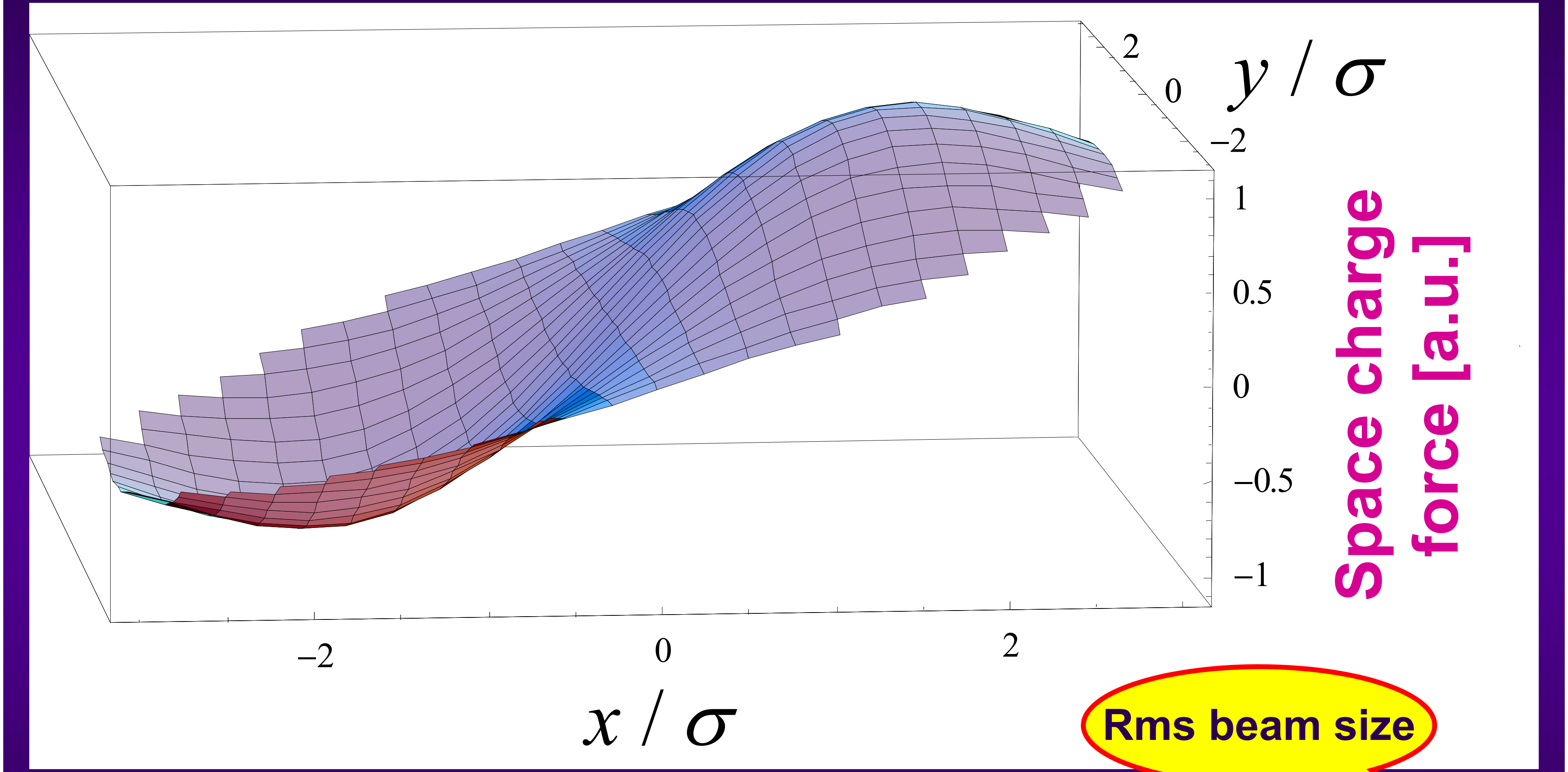
Focusing
Linear

Defocusing
Linear

Defocusing
Non-Linear

Courtesy K. Schindl

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER $\Rightarrow$ COLLECTIVE EFFECTS (3/34)



Rms beam size

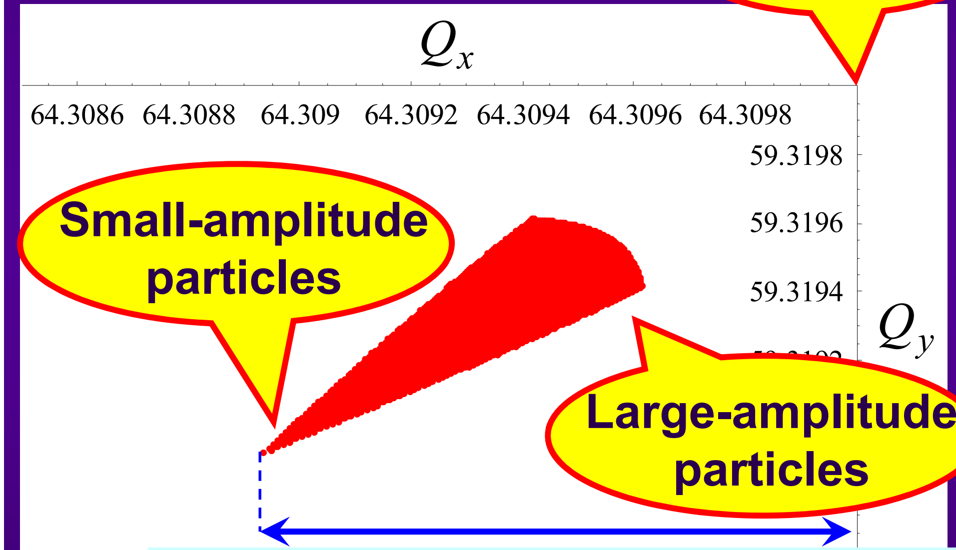
Case of a bunch with a transverse beam profile extending up to 3.2 σ

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER ⇒ COLLECTIVE EFFECTS (4/34)

- **2D TUNE FOOTPRINT**

⇒ INCOHERENT

(single-particle) tunes



Low-intensity working point

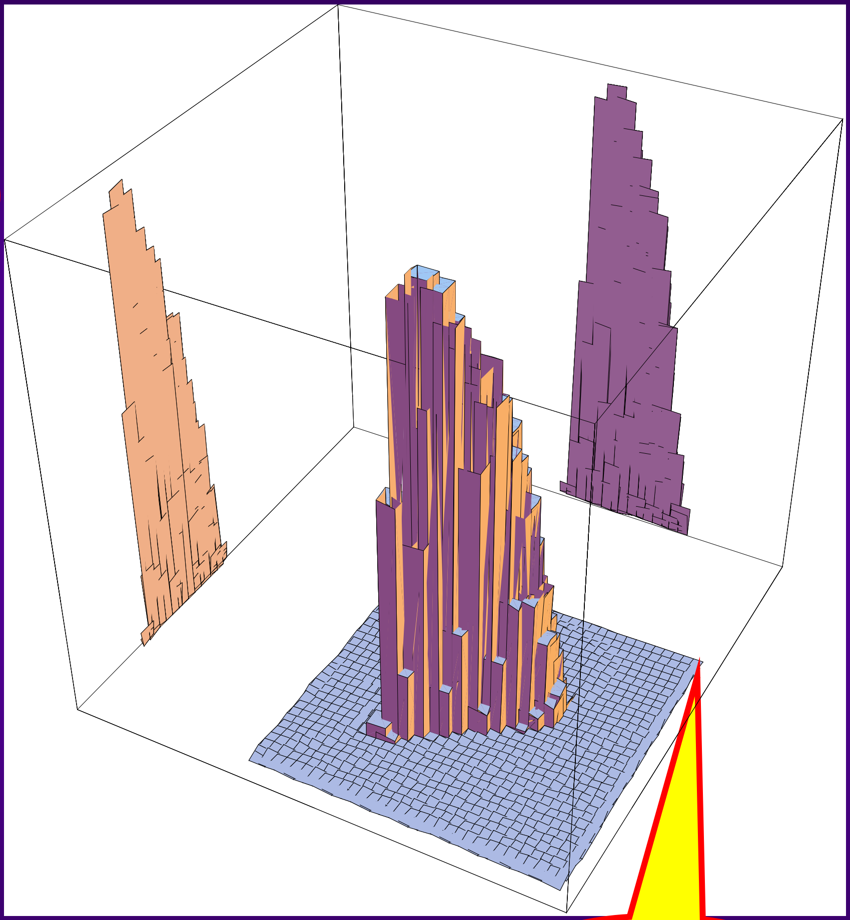
Small-amplitude particles

Large-amplitude particles

$$\Delta_0 \propto -\frac{N_b}{\beta_r\,\gamma_r^2\,\varepsilon_{rms}^{norm}}$$

$$= \text{Linear space - charge tune shift}$$

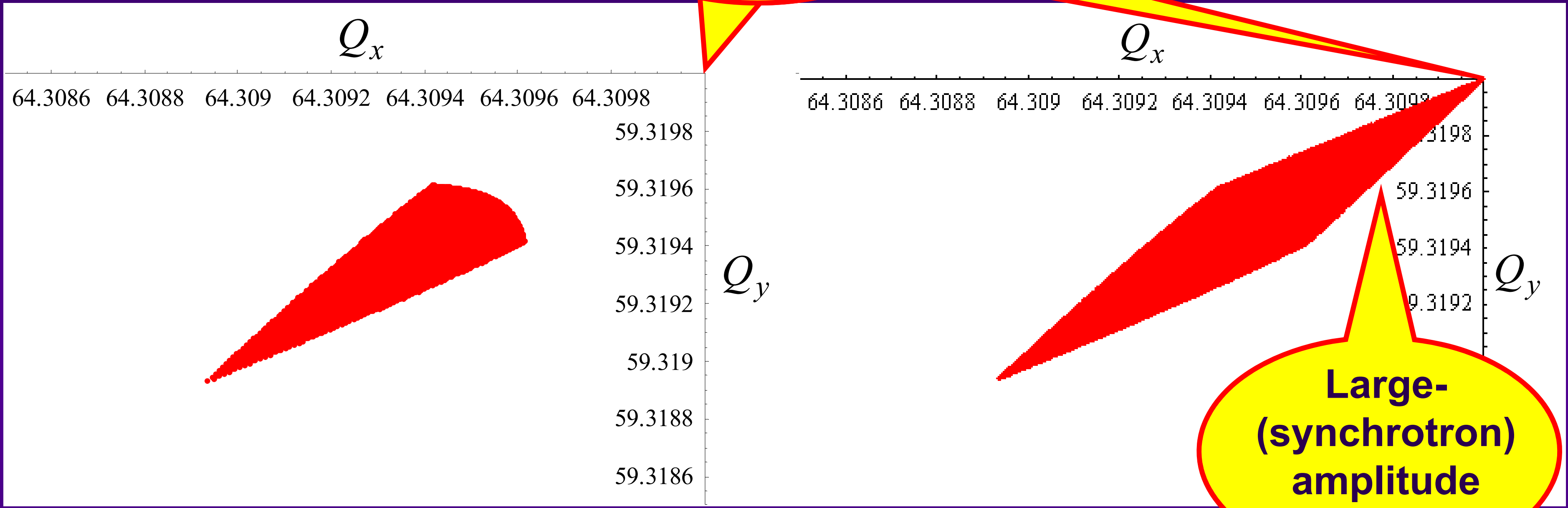
- **3D view of the 2D tune footprint**



Low-intensity working point

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (5/34)

- 2D tune footprint
- 3D tune footprint



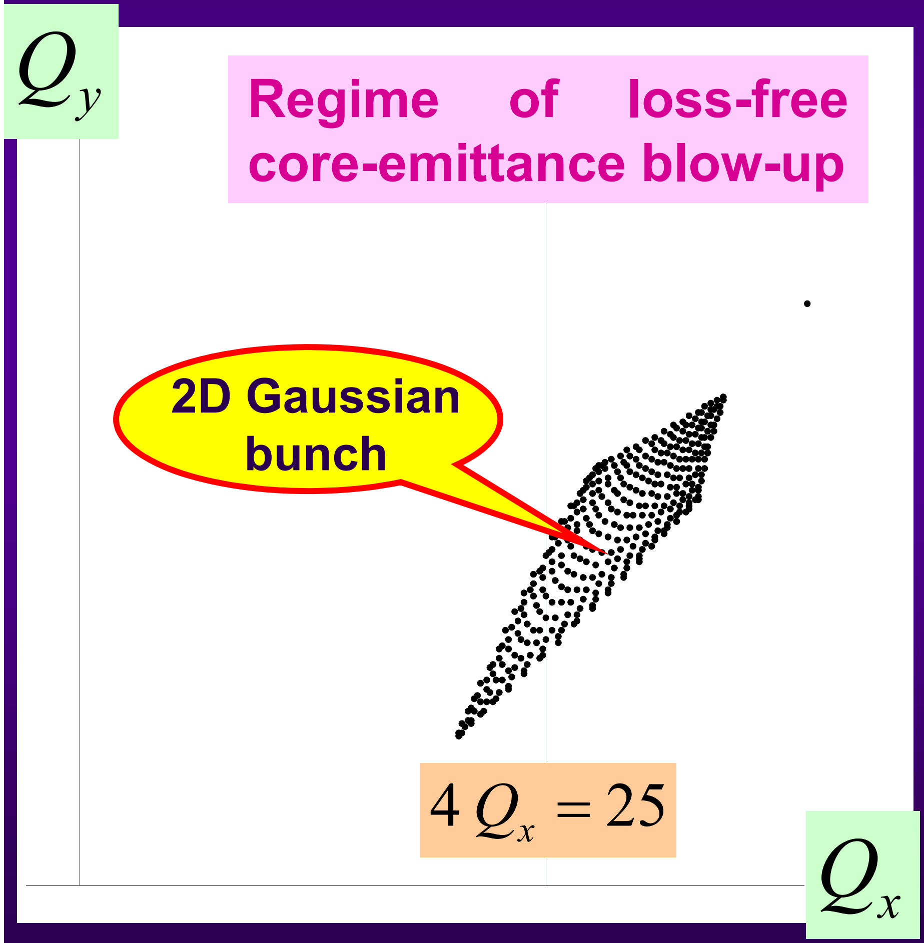
Low-intensity working point

Large- (synchrotron) amplitude particles

⇒ The longitudinal variation (due to synchrotron oscillations) of the transverse space-charge force fills the gap until the low-intensity working point

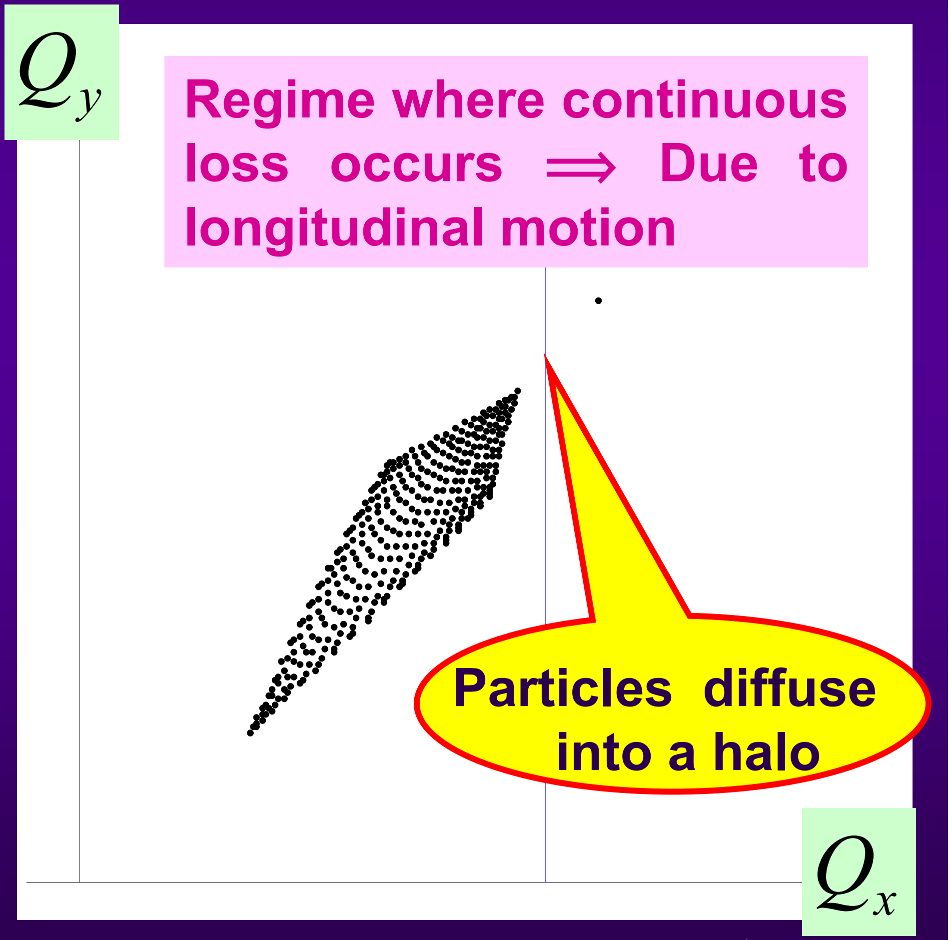
LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (6/34)

Interaction with a resonance



Regime of loss-free core-emittance blow-up

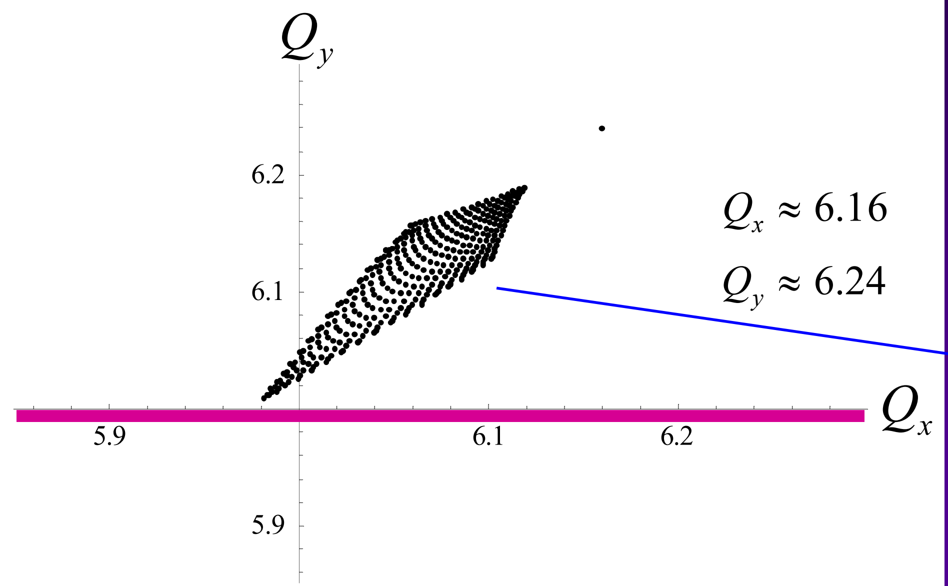
2D Gaussian bunch

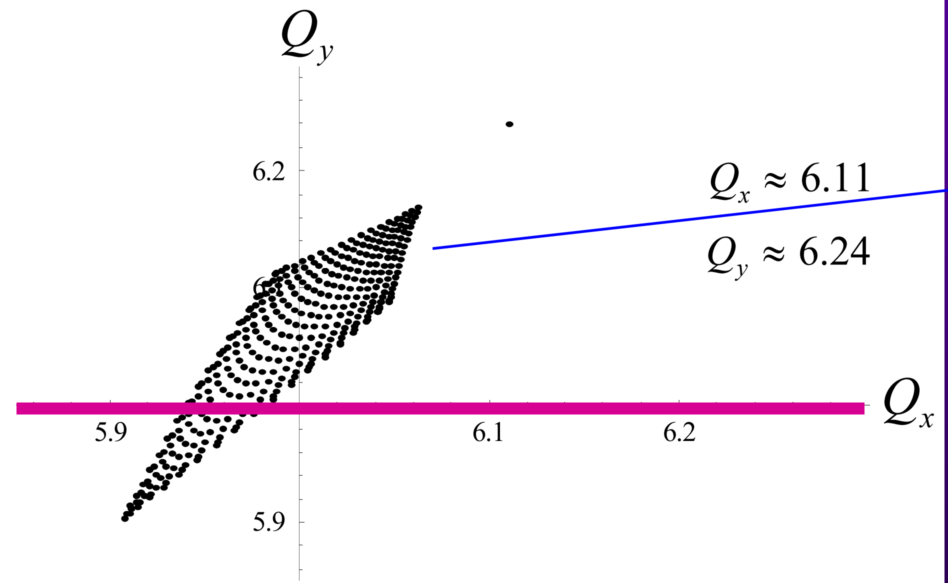


Regime where continuous loss occurs ⟹ Due to longitudinal motion

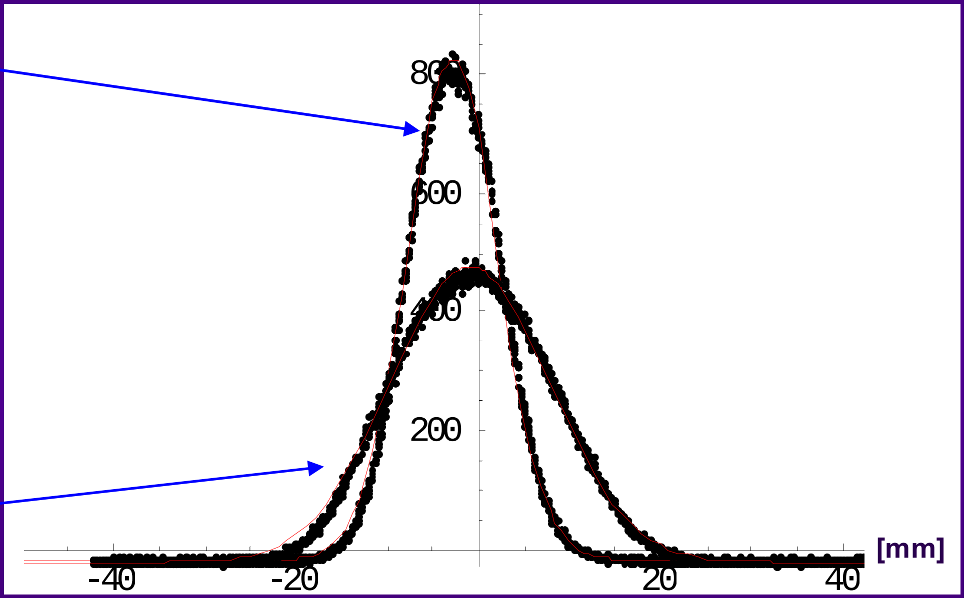
Particles diffuse into a halo

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (7/34)





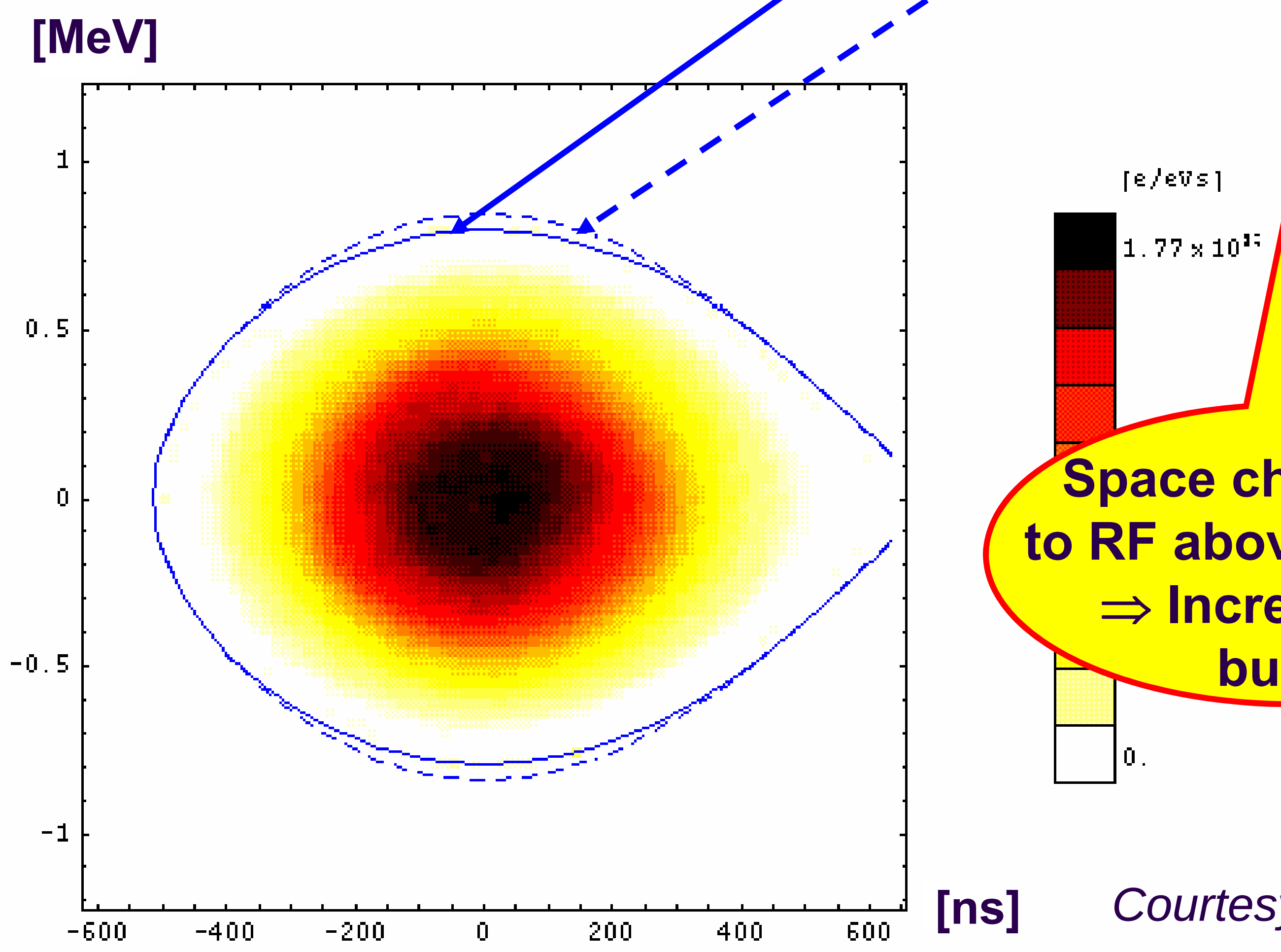
Horizontal bunch profile
+ Gaussian fit



Regime of loss-free core-emittance blow-up

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (8/34)

"High-intensity" bunch ⇒ Bucket separatrix with/without space charge below transition



Space charge adds to RF above transition ⇒ Increases the bucket

Courtesy S. Hancock

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (9/34)

Wake field and impedance

- Wake fields = Electromagnetic fields generated by the beam interacting with its surroundings (vacuum pipe, etc.)
  - Energy loss
  - Beam instabilities
  - Excessive heating
- For a collective instability to occur, the beam environment must not be a perfectly conducting smooth pipe
- Impedance (Sessler&Vaccaro) = Fourier transform of the wake field
- As the conductivity, permittivity and permeability of a material depend in general on frequency, it is usually better (or easier) to treat the problem in the frequency domain

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (10/34)

- Case of the transverse Resistive Wall (usually made of stainless steel or copper) wake field with $\gamma_r \rightarrow \infty$ (i.e. no space charge effects) and in the "classical thick-wall regime"

$$W_t^{RW} \propto F_t^{RW} \propto \frac{\sqrt{\rho}}{b^3 \sqrt{|z|}}$$

Resistivity:
$\rho_{SS} = 10^{-6}$ Ωm and
$\rho_{Cu} = 1.5 \times 10^{-8}$ Ωm
at room
temperature

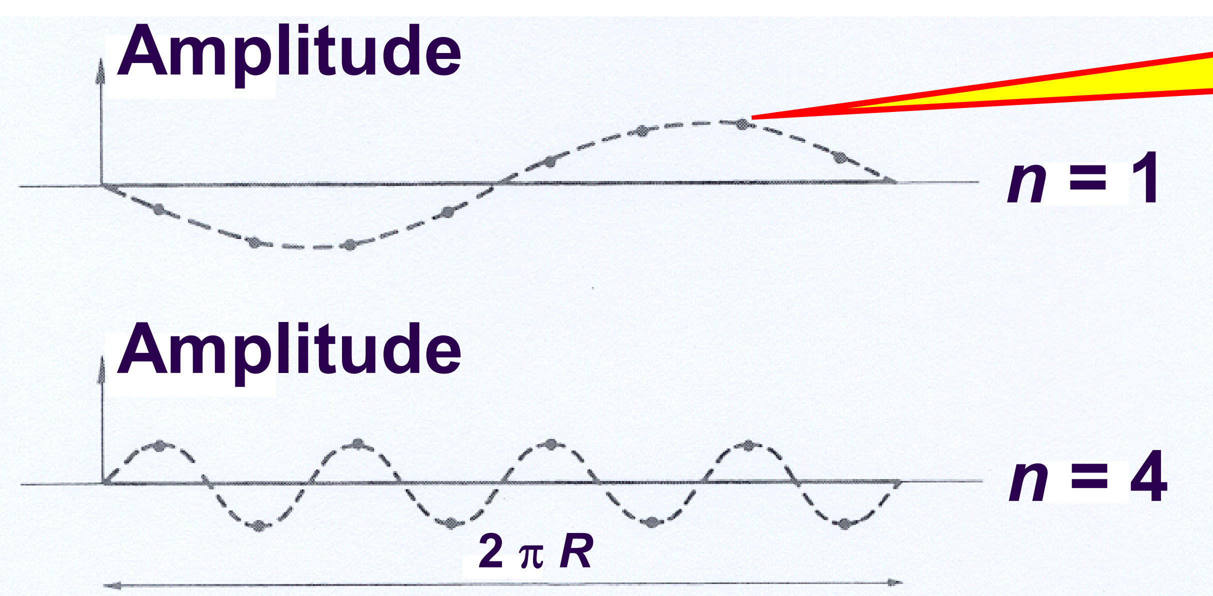
Distance behind
the bunch

Beam pipe radius
⟹ Usually few cm
(< 2 mm for some
LHC collimators!)

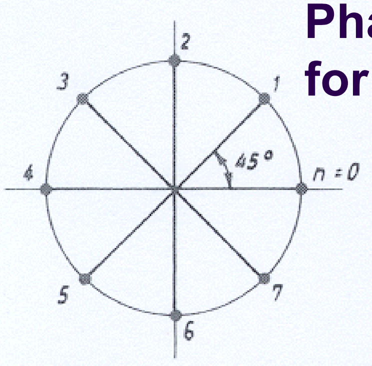
LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (11/34)

BUNCHED-BEAM COHERENT INSTABILITIES

COUPLED-BUNCH MODES



Bunch treated as a Macro-Particle



Phase shift between adjacent bunches for the different coupled-bunch modes

$$\Delta\phi = 2\,\pi\,n\,/\,M$$

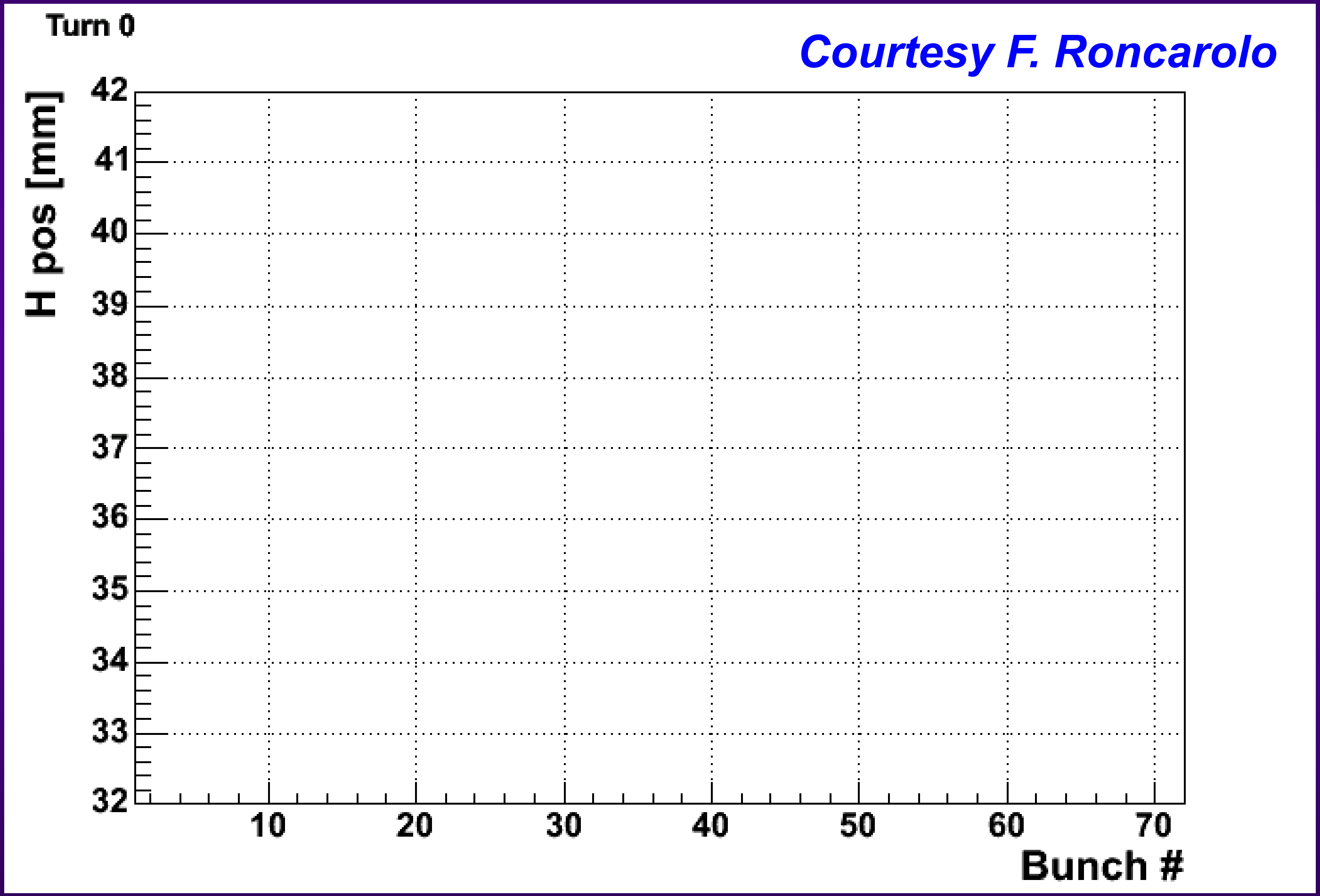
F. Sacherer

M = 8 bunches ⇒ 8 modes n (0 to 7) possible

Reminder: 2 possible modes with 2 bunches (in phase or out of phase)

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER ⇒ COLLECTIVE EFFECTS (12/34)

Observations with 72 bunches in the SPS in 2006



LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (13/34)

COHERENT frequency (or tune) and INSTABILITY RISE-TIME

- We are looking for coherent motions proportional to $e^{j \omega t}$

$$\omega = \omega_R + j \, \omega_i \quad \Rightarrow \quad e^{j \omega t} = e^{j \left(\omega_R + j \, \omega_i \right) t} = e^{j \omega_R t} \, e^{\frac{t}{\tau}}$$

Coherent (angular) frequency

$$Q_{y,coh} = \frac{\omega_R}{\omega_{\text{rev}}}$$

Coherent tune

where τ is the instability rise time [in s]: $$\tau = - \frac{1}{\omega_i}$$

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (14/34)

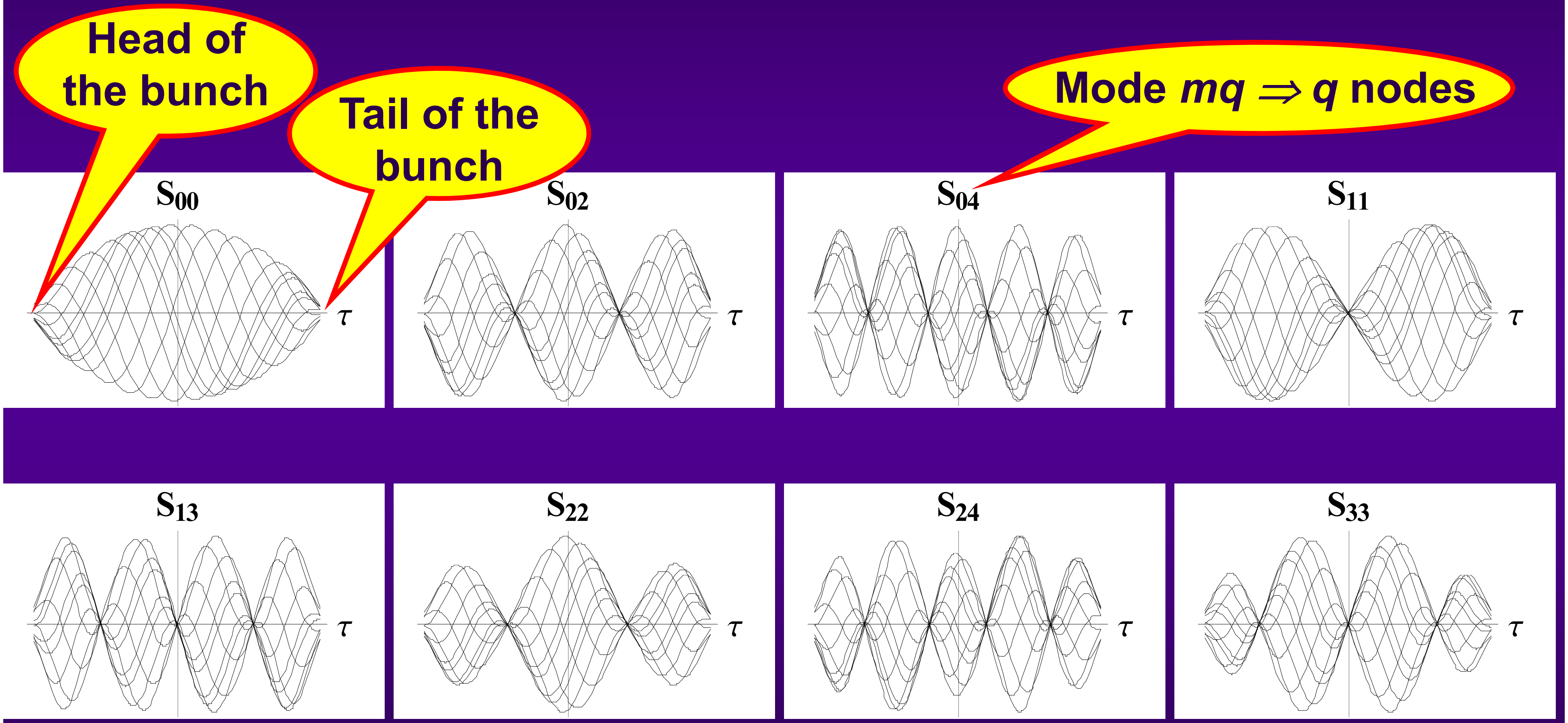
HEAD-TAIL (Single-bunch) MODES: Low intensity

- Defined by 2 modes (as there are 2 degrees of freedom, amplitude and phase) ⇒ Azimuthal mode *m* and radial mode *q*
- The basic mathematical tool used for the mode representation of the beam motion is the VLASOV EQUATION, using a distribution of particles instead of the single-particle formalism
- The Vlasov equation (in its most simple form) is nothing else but a collisionless Boltzmann equation, or an expression for the LIOUVILLE'S CONSERVATION OF PHASE SPACE DENSITY*

*According to the Liouville's theorem, the particles, in a non-dissipative system of forces, move like an incompressible fluid in phase space

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (15/34)

Signal at position Pick-Up predicted by Theory (several turns superimposed)



Head of the bunch

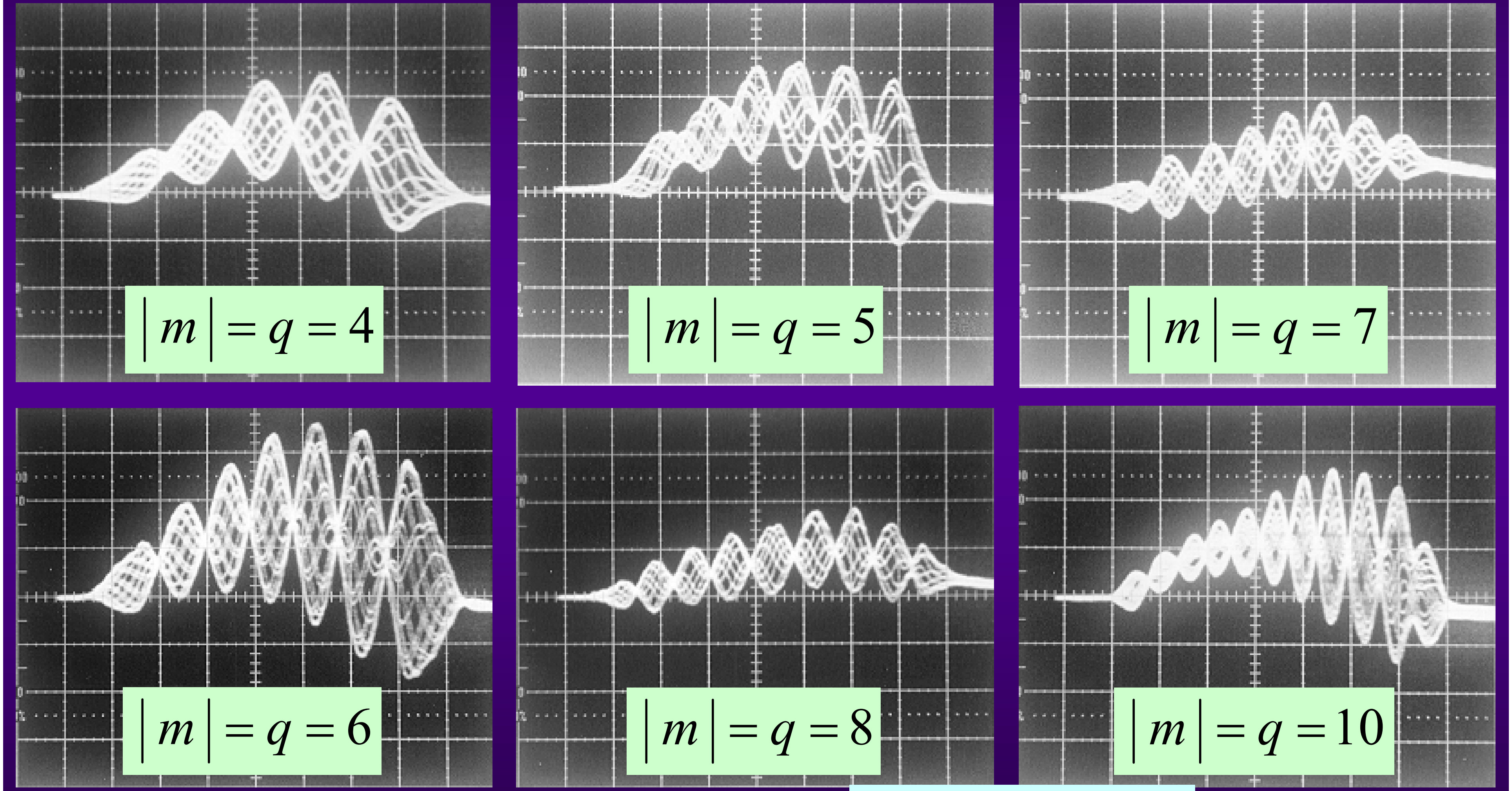
Tail of the bunch

Mode *mq* ⇒ *q* nodes

⇒ Standing-wave pattern along the bunch

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (16/34)

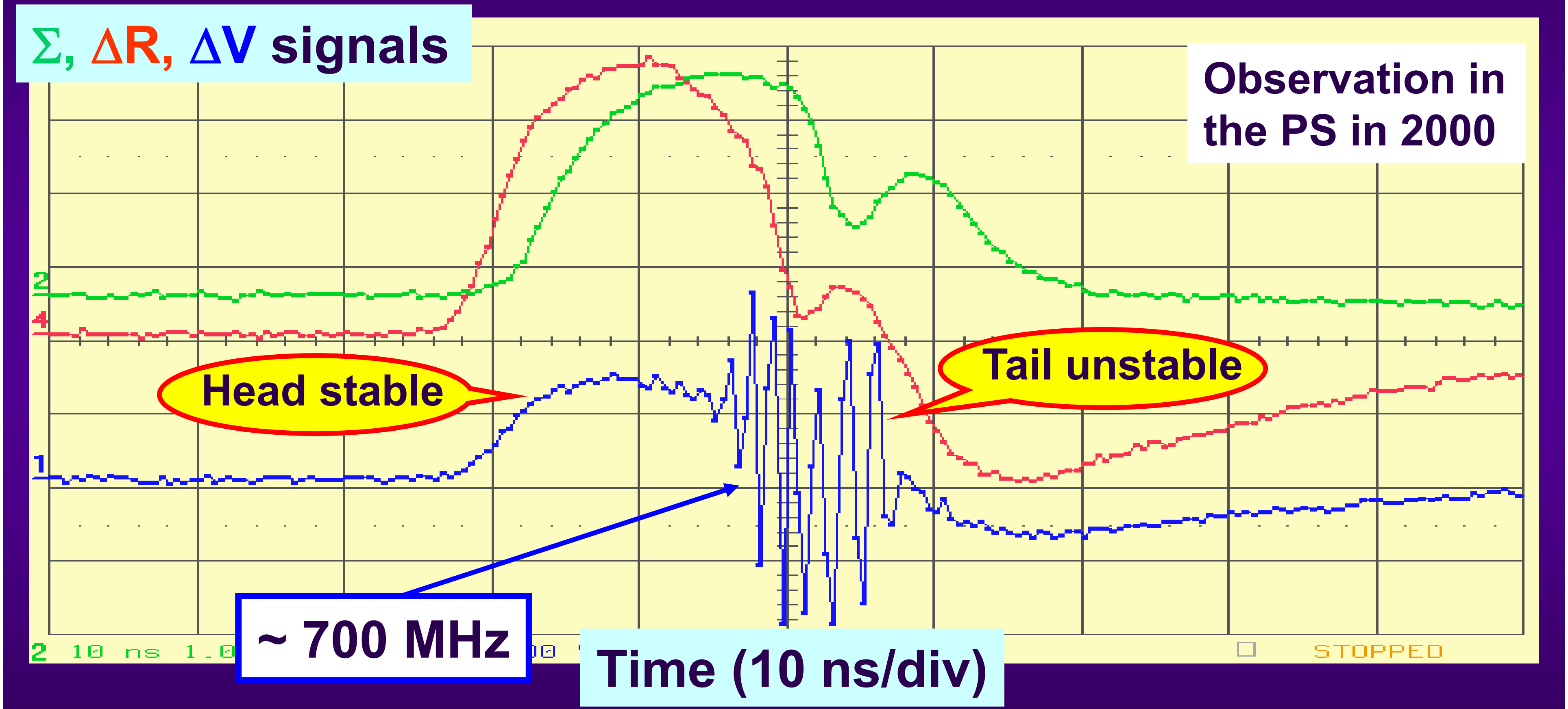
Observations in the PS in 1999 (20 revolutions superimposed)



Time (20 ns/div)

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER ⇒ COLLECTIVE EFFECTS (17/34)

HEAD-TAIL (Single-bunch) MODES: High intensity ⇒ Transverse Mode-Coupling instability



Σ, ΔR, ΔV signals

Observation in the PS in 2000

Head stable

Tail unstable

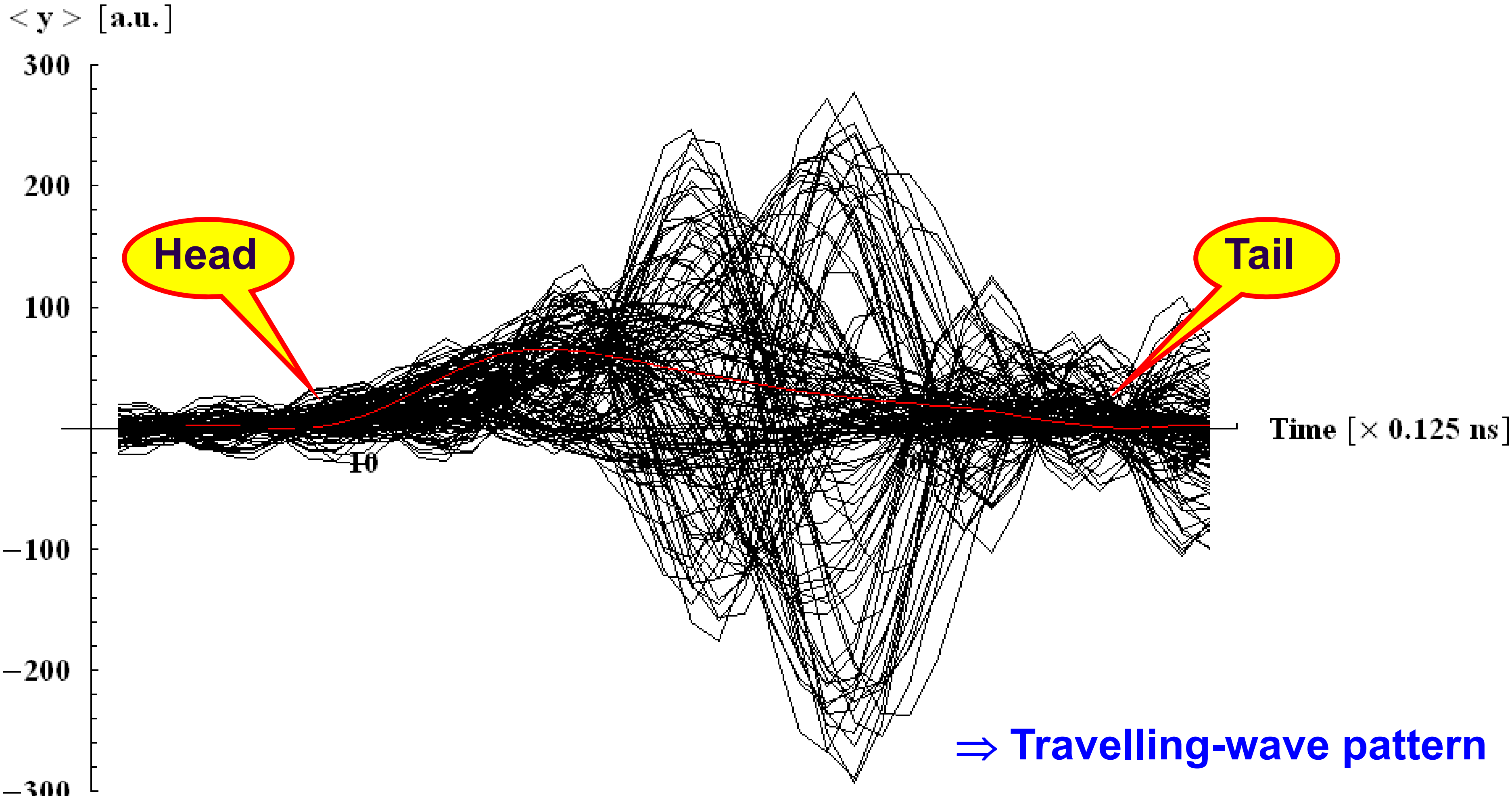
~ 700 MHz

Time (10 ns/div)

⇒ Travelling-wave pattern along the bunch

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (18/34)

Observation in the SPS in 2003



⇒ Travelling-wave pattern

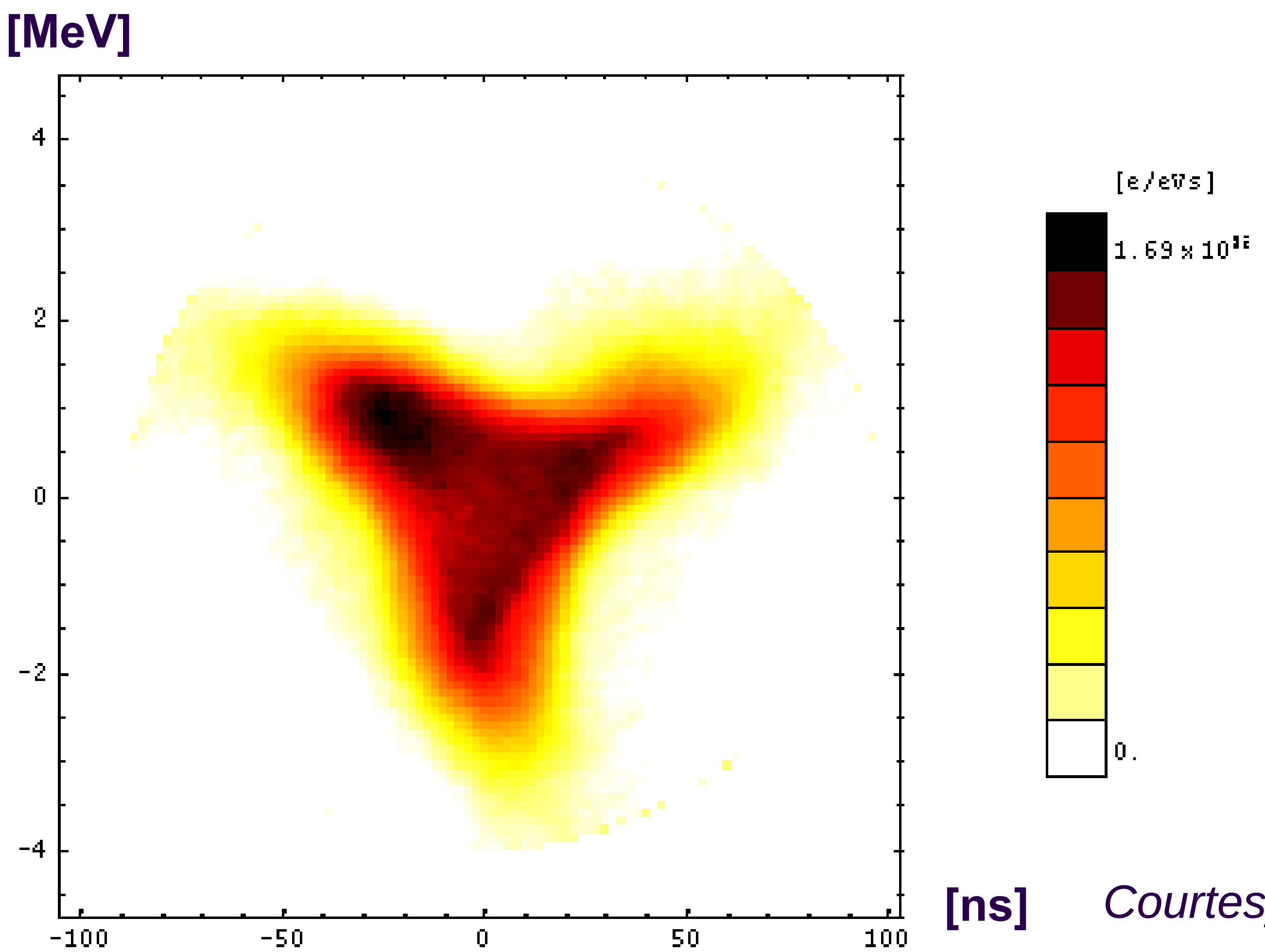
1st trace (in red) = turn 2

Last trace = turn 150

Every turn shown

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER ⇒ COLLECTIVE EFFECTS (19/34)

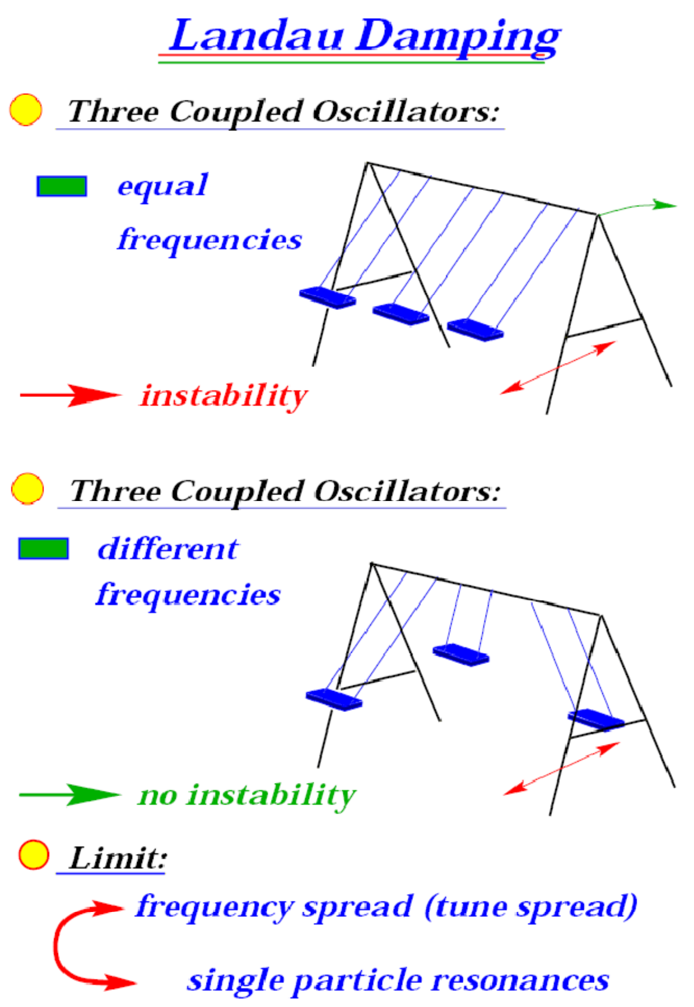
Similar phenomena in the longitudinal plane ⇒ Observation of an unstable bunch (sextupolar instability) in the PS Booster in 2000



Courtesy S. Hancock

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (20/34)

Courtesy O. Bruning



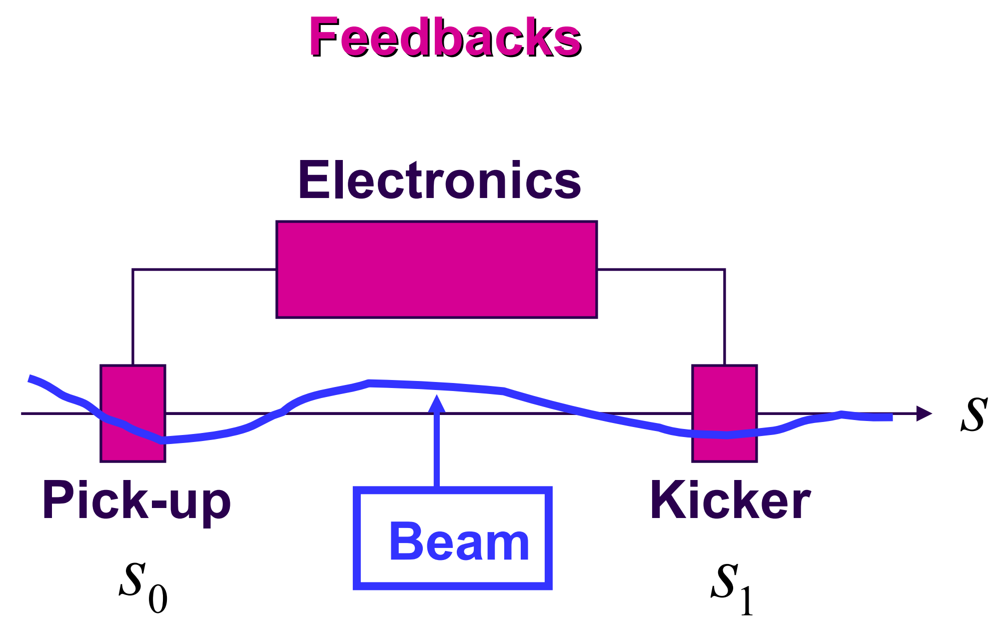
Landau Damping

- *Three Coupled Oscillators:*
  - *equal frequencies*
  - *→ instability*
- *Three Coupled Oscillators:*
  - *different frequencies*
  - *→ no instability*
- *Limit:*
  - *frequency spread (tune spread)*
  - *single particle resonances*

◆ **Stabilization methods**

- Landau damping
- Feedbacks

Stabilization when the coherent tune is inside the incoherent tune spread (due to octupoles….)



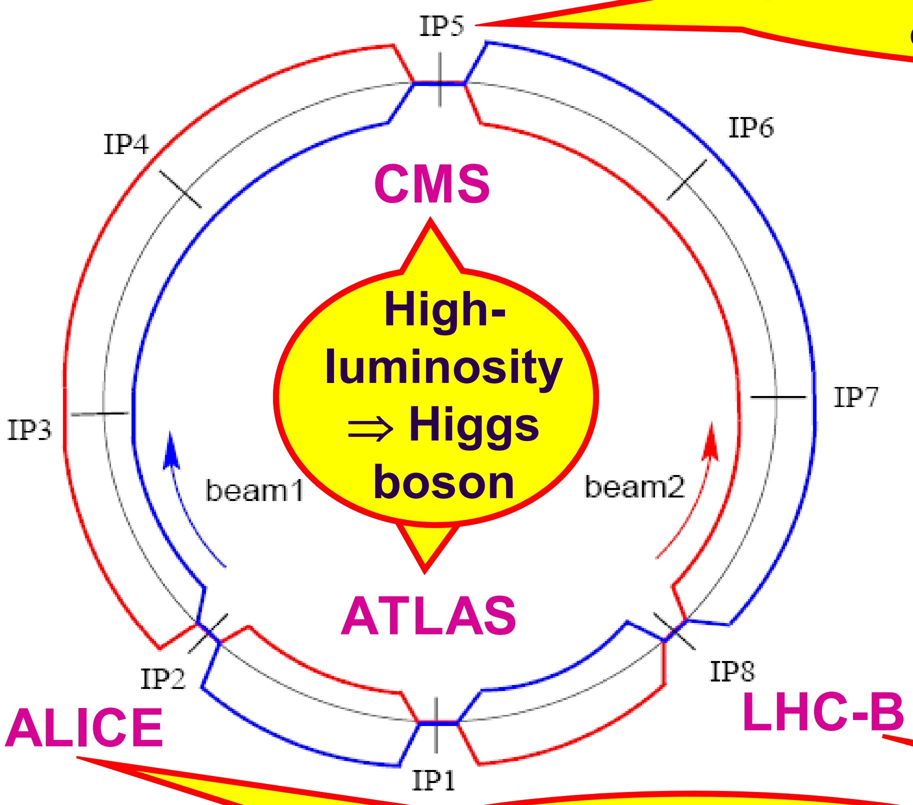
Feedbacks

- Linear coupling between the transverse planes (from skew quadrupoles)

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (21/34)

LAYOUT OF THE LHC

Courtesy W. Herr



High-luminosity ⇒ Higgs boson

+ TOTEM

⇒ Measure the total proton-proton cross-section and study elastic scattering and diffractive physics

Ions ⇒ New phase of matter expected: Quark-Gluon Plasma (QGP)

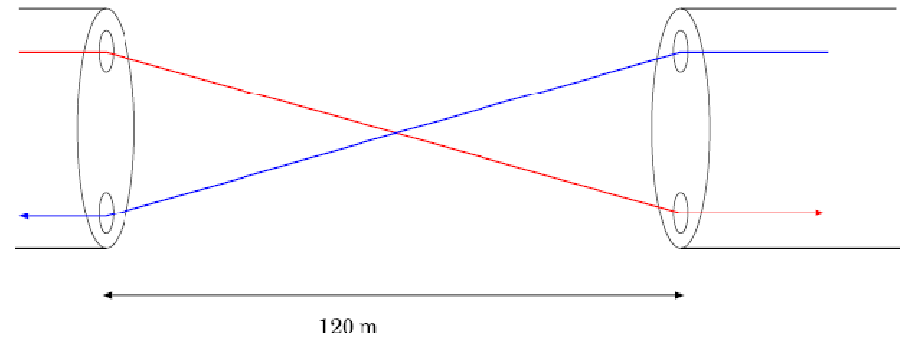
Beauty quark physics

Beam-beam interaction

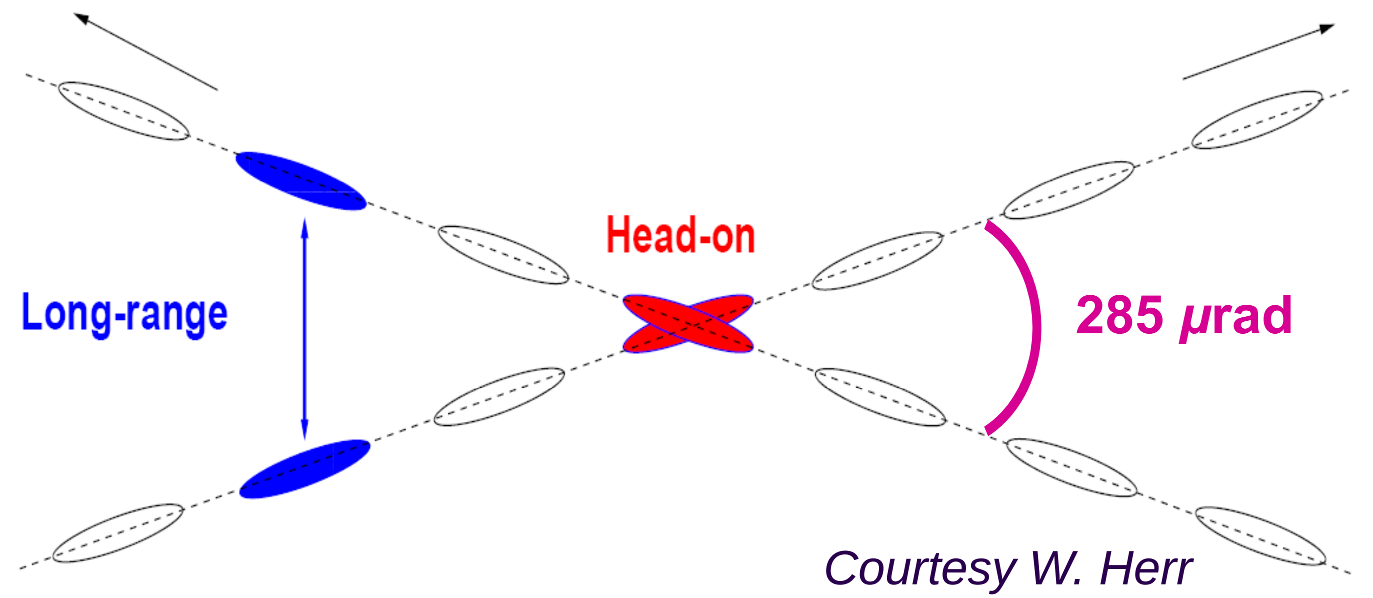
- **Incoherent beam-beam effects ⇒ Lifetime + dynamic aperture**
- **PACMAN effects ⇒ Bunch to bunch variation**
- **Coherent beam-beam effects ⇒ Beam oscillations and instabilities**

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (22/34)

CROSSING ANGLE ⇒ To avoid unwanted collisions, a crossing angle is needed to separate the 2 beams in the part of the machine where they share a vacuum chamber



Courtesy W. Herr

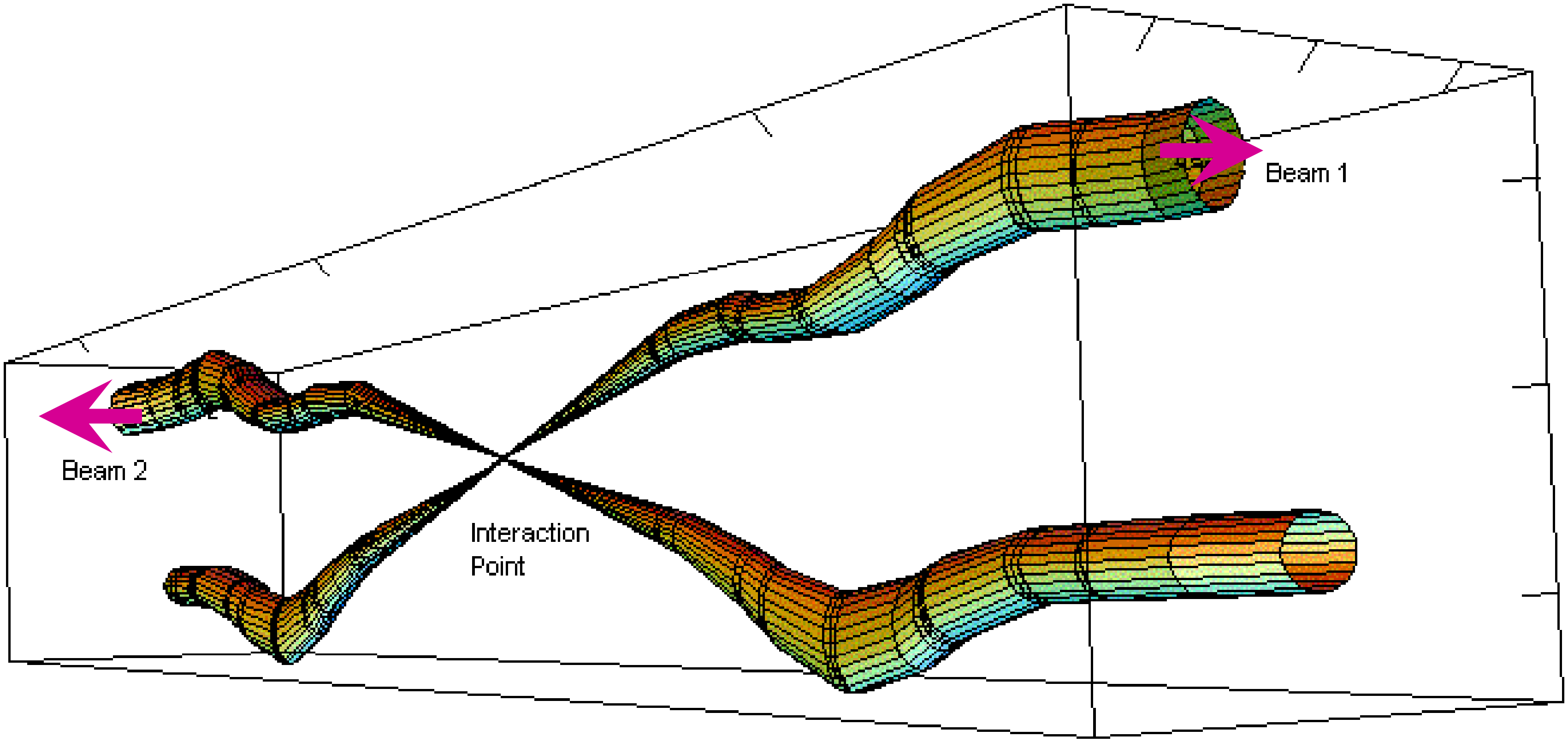


Courtesy W. Herr

- **30 long-range interactions around each IP ⇒ 120 in total**
- **Separation: 9 σ**

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (23/34)

◆ COLLISION in IP1 (ATLAS)

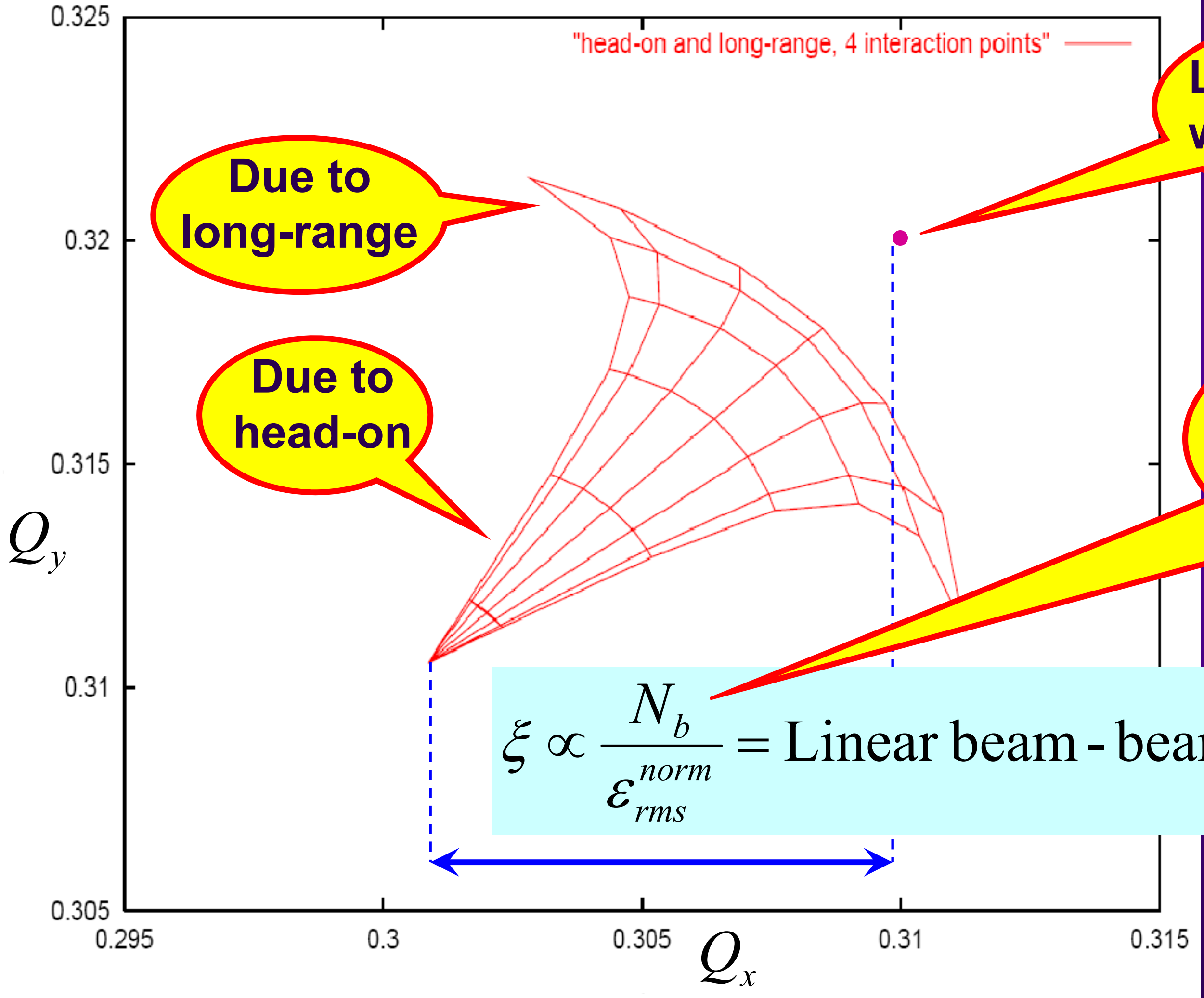


Relative beam sizes around IP1 (Atlas) in collision

⇒ **Vertical crossing angle in IP1 (ATLAS) and horizontal one in IP5 (CMS)**

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER ⇒ COLLECTIVE EFFECTS (24/34)

- **2D tune footprint for nominal LHC parameters in collision. Particles up to amplitudes of 6 σ are included**



Low-intensity working point

Due to long-range

Due to head-on

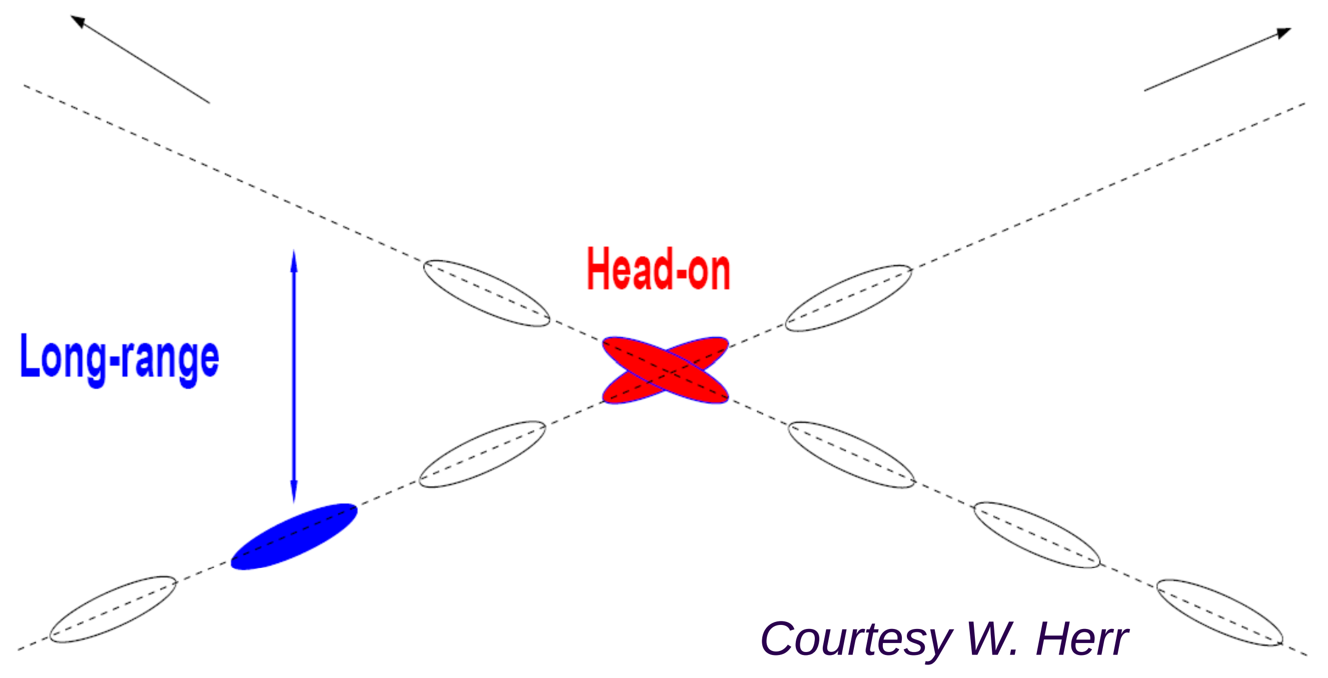
No 1 / γ_r^2 term as for space charge, as the 2 beams are moving in opposite direction

$$\xi \propto \frac{N_b}{\varepsilon_{rms}^{norm}} = \text{Linear beam - beam tune shift}$$

Courtesy W. Herr

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (25/34)

- **PACMAN BUNCHES**
  - LHC bunch filling not continuous: Holes for injection, extraction, dump…
  - 2808 bunches out of 3564 possible bunches ⇒ 1756 holes
  - Holes will meet holes at the IPs
  - But not always… a bunch can meet a hole at the beginning and end of a bunch train



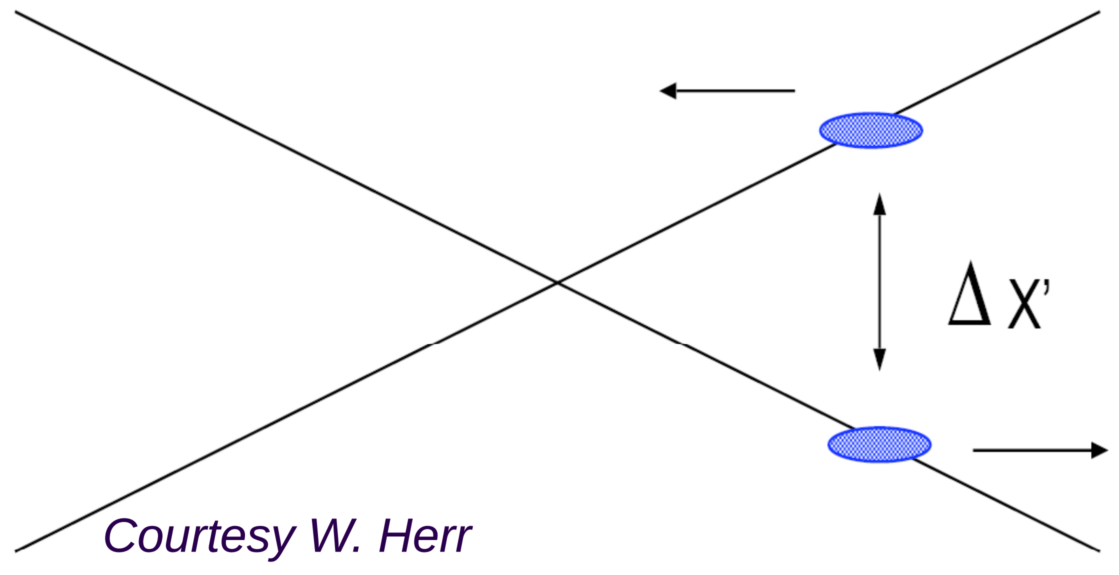
Courtesy W. Herr

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER ⇒ COLLECTIVE EFFECTS (26/34)

- Bunches which do not have the regular collision pattern have been named PACMAN bunches ⇒ ≠ integrated beam-beam effect
- Only 1443 bunches are regular bunches with 4 head-on and 120 long range interactions, i.e. about half of the bunches are not regular
- The identification of regular bunches is important since measurements such as tune, orbit or chromaticity should be selectively performed on them
- SUPERPACMAN bunches are those who will miss head-on interactions
  - 252 bunches will miss 1 head-on interaction
  - 3 will miss 2 head-on interactions
- ALTERNATE CROSSING SCHEME: Crossing angle in the vertical plane for IP1 and in the horizontal plane for IP5 ⇒ The purpose is to compensate the tune shift for the Pacman bunches

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (27/34)

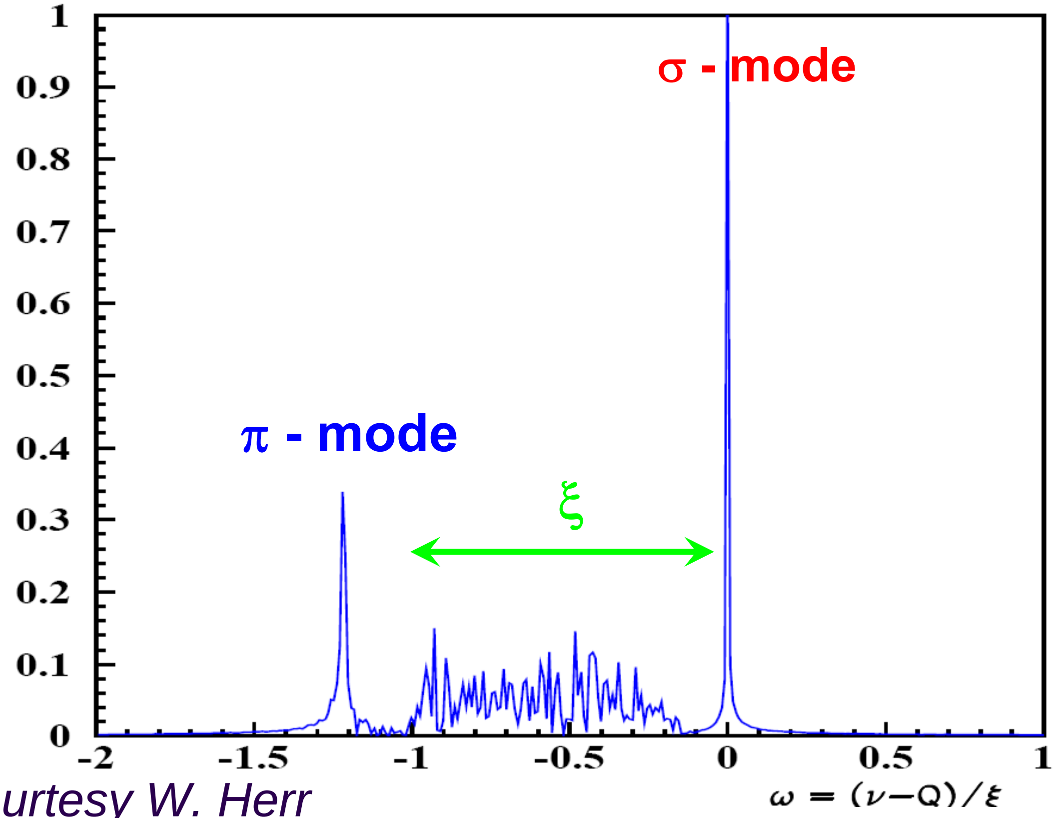
◆ COHERENT BEAM-BEAM EFFECT



Courtesy W. Herr

- A whole bunch sees a (coherent) kick from the other (separated) beam ⇒ Can excite coherent oscillations
- All bunches couple together because each bunch "sees" many opposing bunches ⇒ Many coherent modes possible!

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (28/34)



Beam-beam modes and tune spread

Courtesy W. Herr

For 2 colliding bunches

- **σ-mode (in phase) is at unperturbed tune**
- **π-mode (out of phase) is shifted by 1.1 – 1.3 ξ**
- **Incoherent spread between [0.0,1.0] ξ**

It can be restored when the symmetry between the 2 beams is broken

⇒ Landau damping is lost

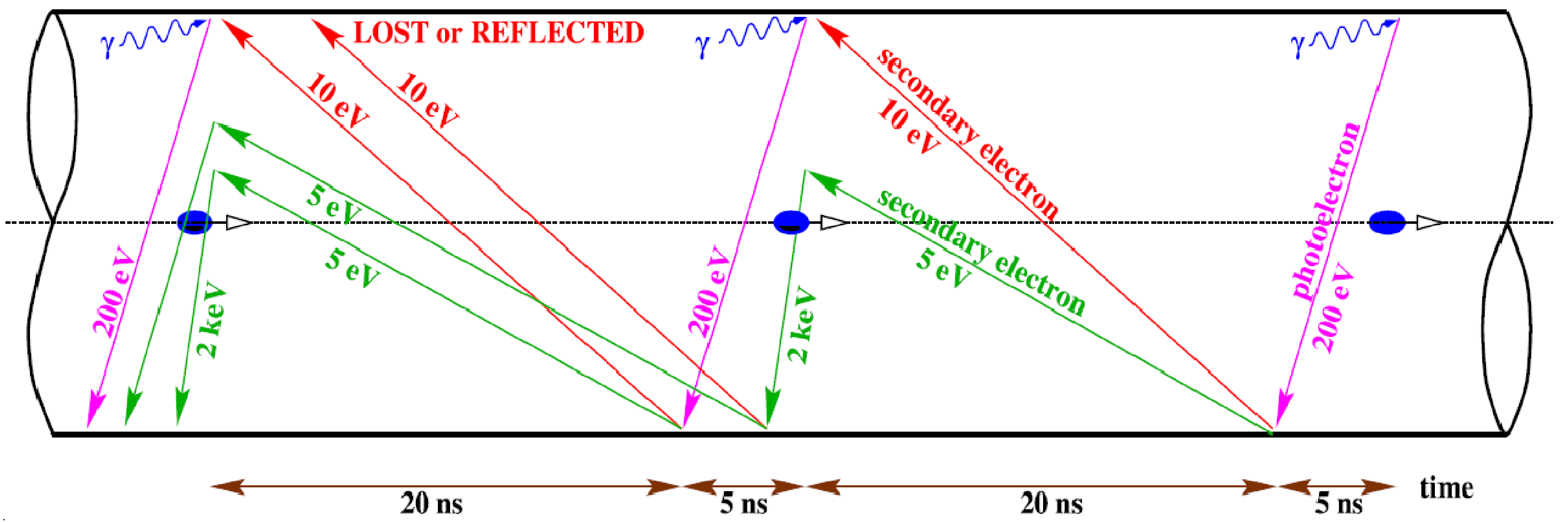
(coherent tune of the π-mode not inside the incoherent tune spread)

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER ⇒ COLLECTIVE EFFECTS (29/34)

Electron cloud

- **Schematic of electron-cloud build up in the LHC beam pipe during multiple bunch passages, via photo-emission (due to synchrotron radiation) and secondary emission**

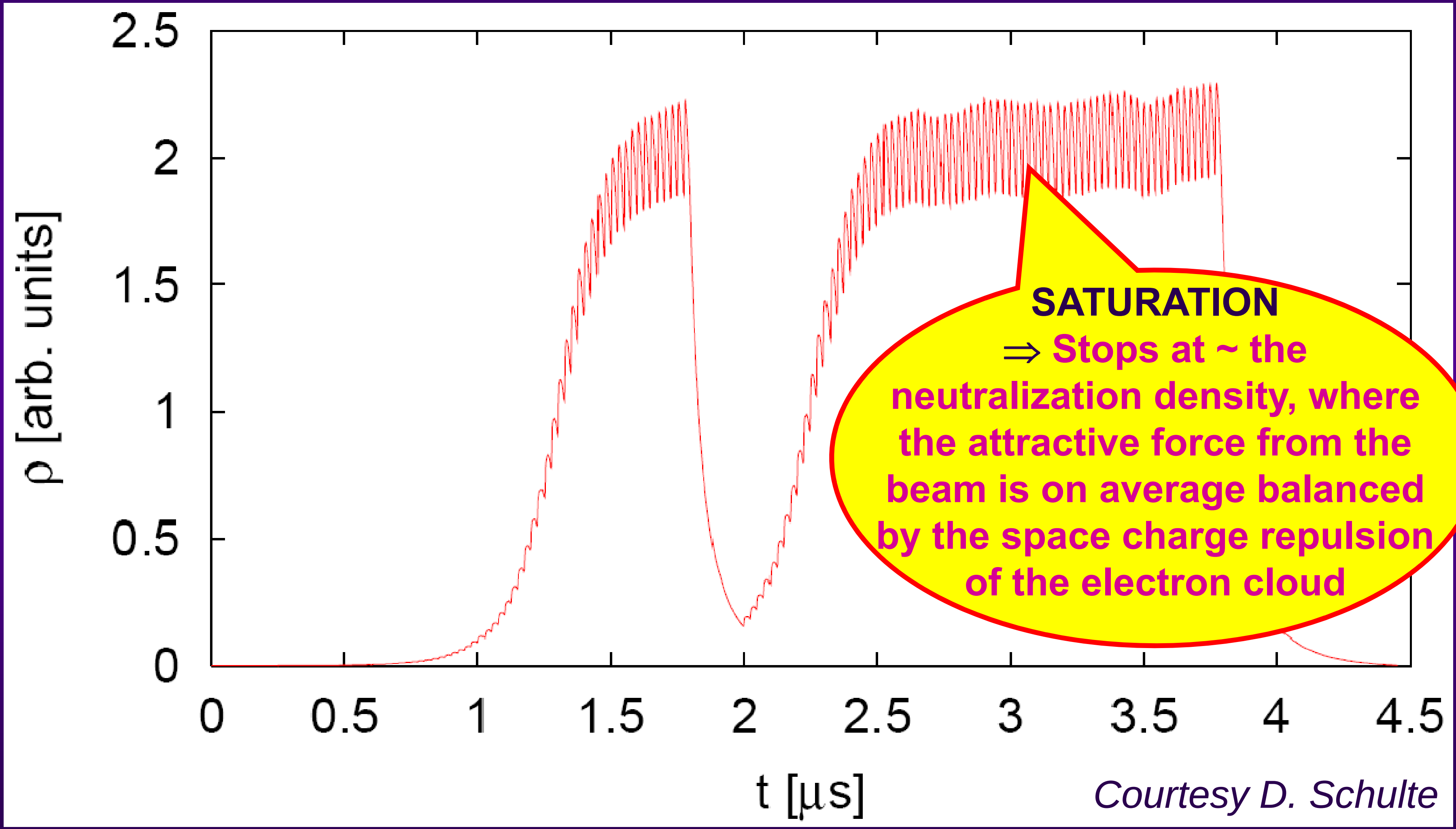
The LHC is the 1st proton storage ring for which synchrotron radiation becomes a noticeable effect



Courtesy F. Ruggiero

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER ⇒ COLLECTIVE EFFECTS (30/34)

- **Simulations of electron-cloud build-up along 2 bunch trains (= 2 batches of 72 bunches) of LHC beam in SPS dipole regions**

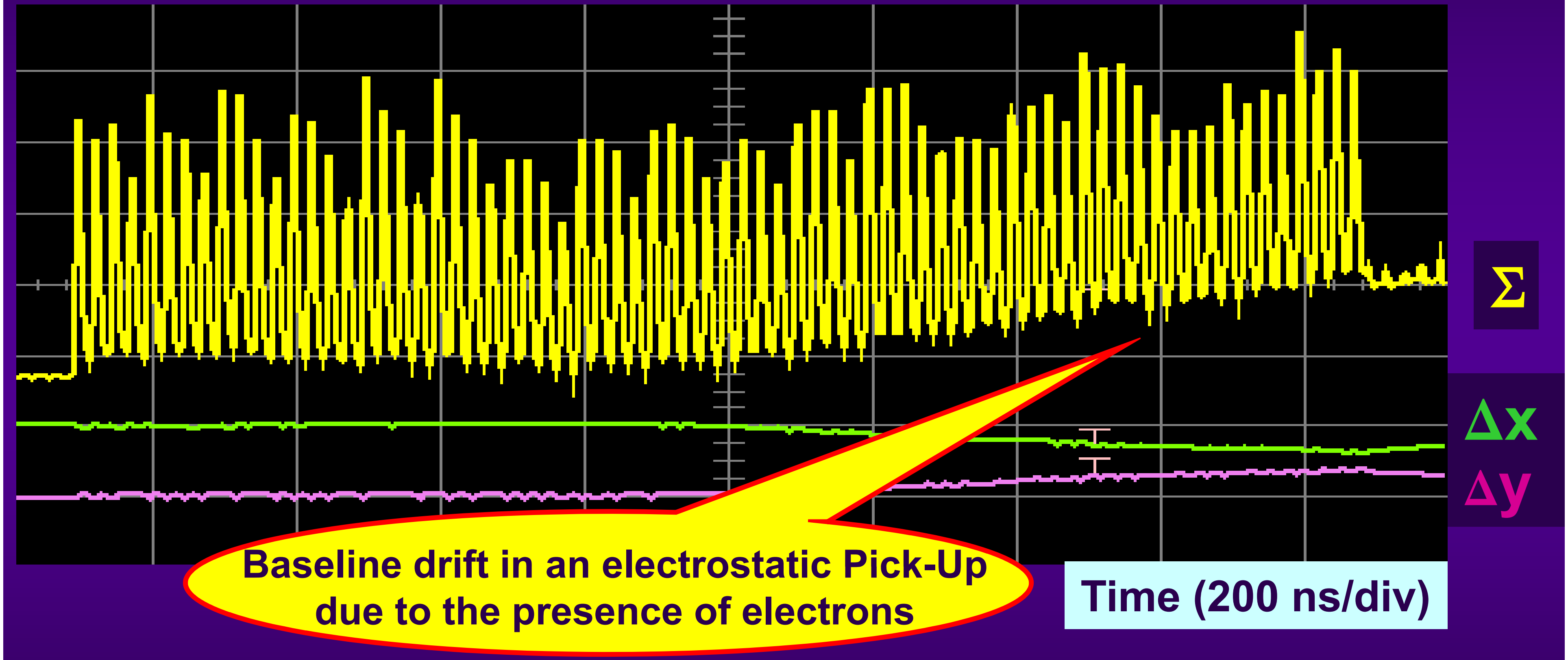


SATURATION
⇒ Stops at ~ the neutralization density, where the attractive force from the beam is on average balanced by the space charge repulsion of the electron cloud

Courtesy D. Schulte

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (31/34)

- **Nominal beam for LHC seen on a Pick-Up in the TT2 transfer line**

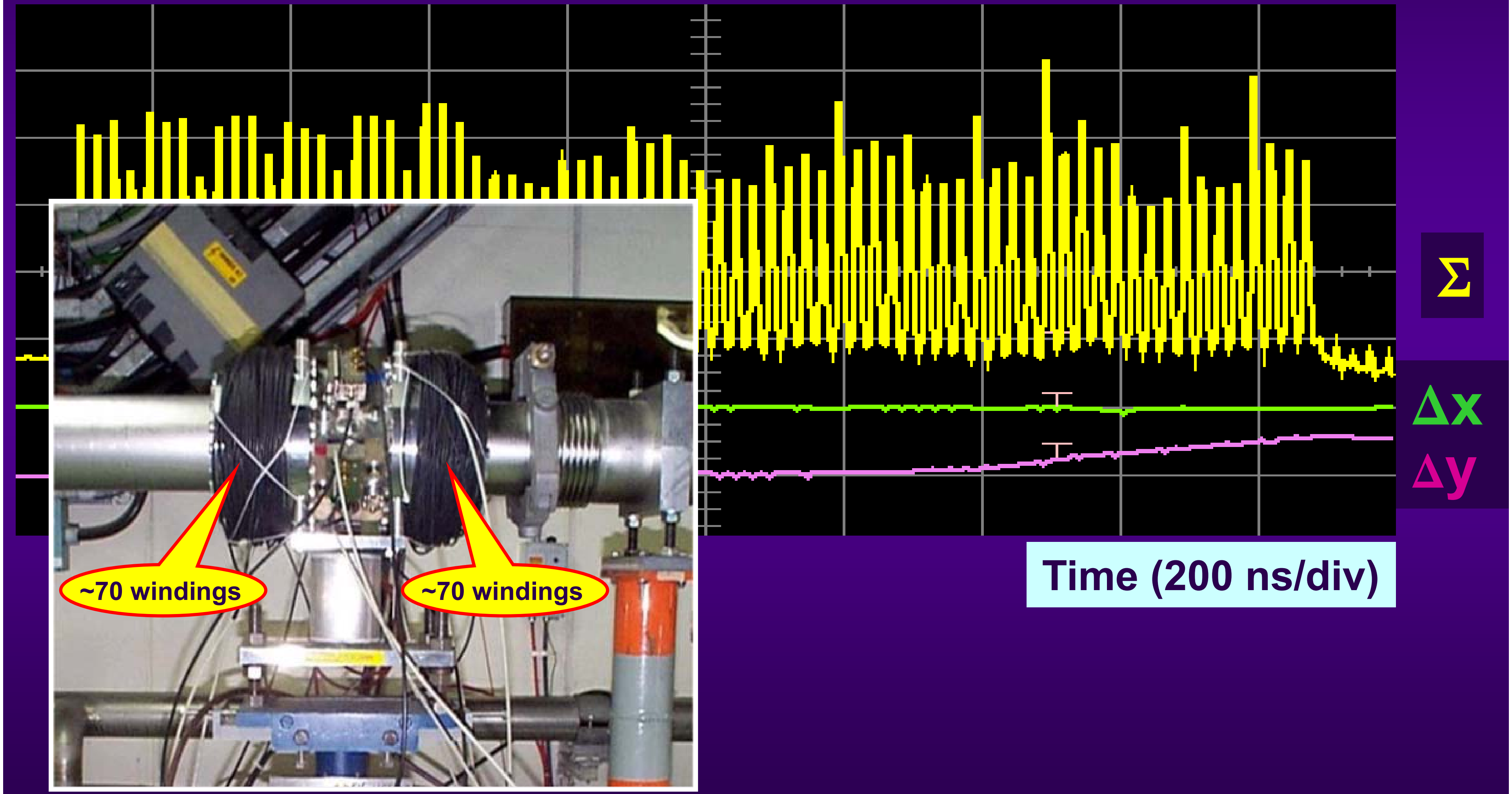


Baseline drift in an electrostatic Pick-Up due to the presence of electrons

⇒ **Confirmation that the electron cloud build-up is a single-pass effect**

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (32/34)

- **Same as before but with a solenoidal field (~ 50-100 G) due to ~70 windings before and after the 25 cm long Pick-Up device**

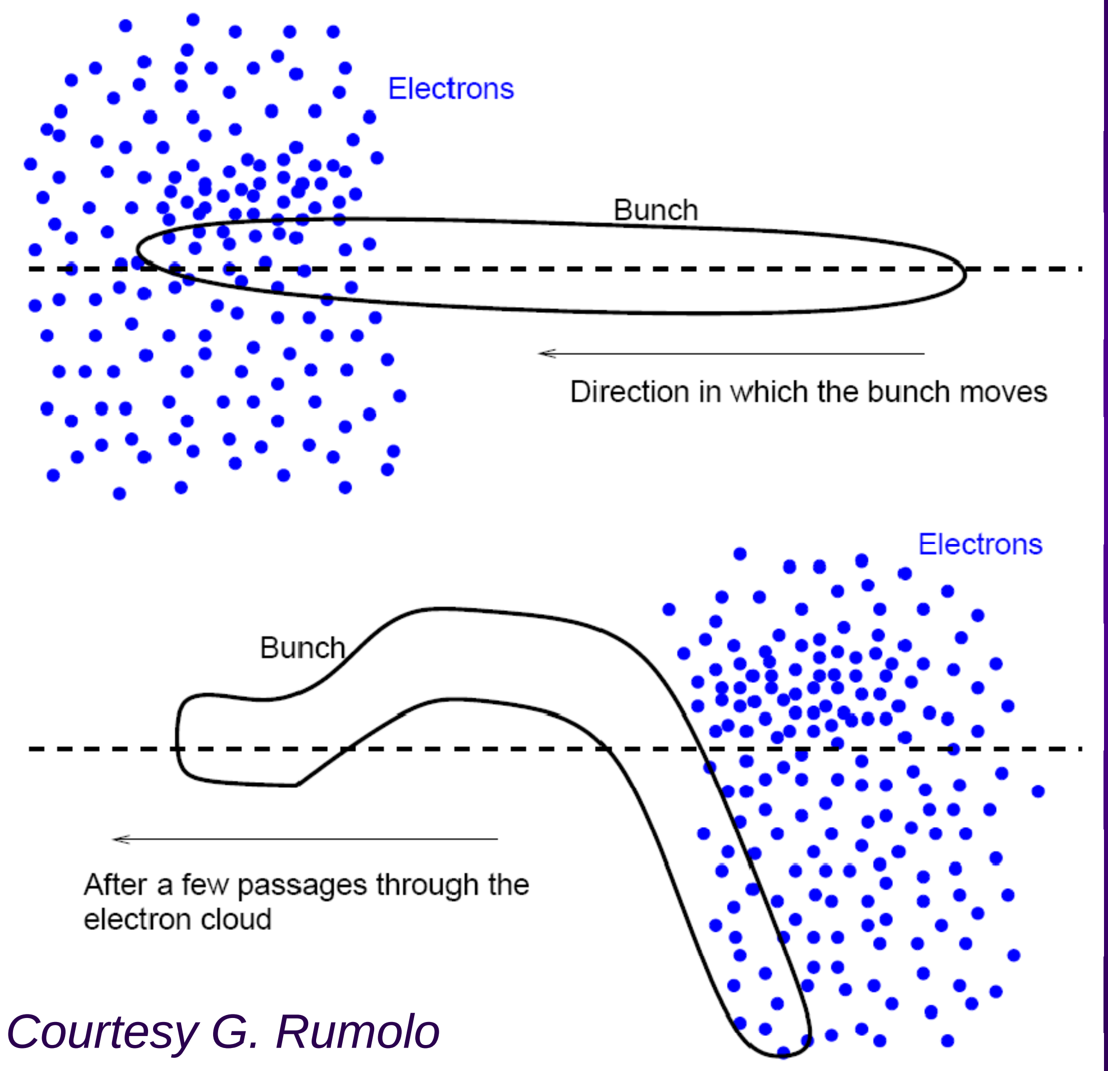


LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (33/34)

- **Schematic of the single-bunch (coherent) instability induced by an electron cloud**

MOVIE
Single-Bunch Instability From ECloud.mpeg

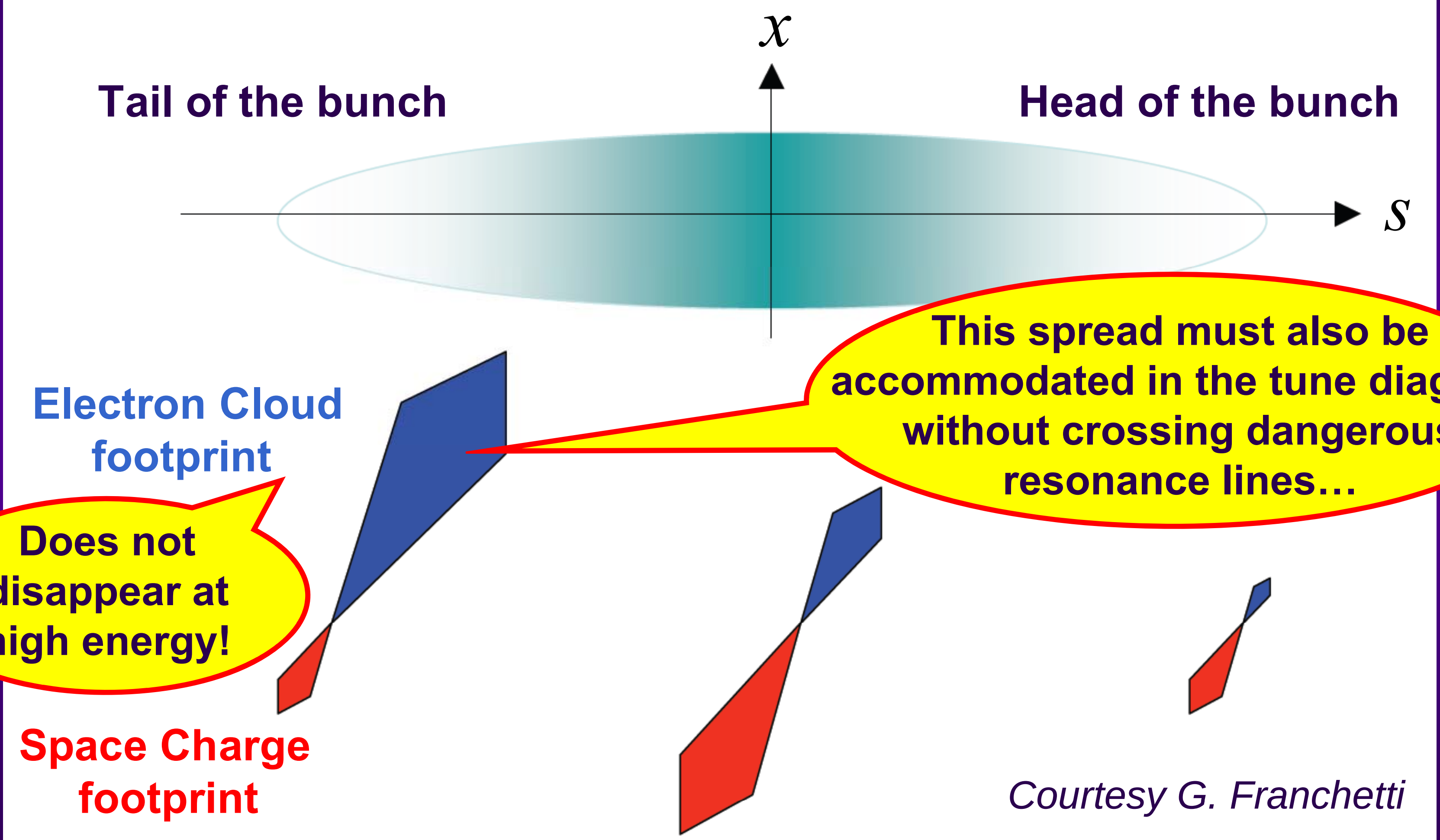
Courtesy G. Rumolo and F. Zimmermann



Courtesy G. Rumolo

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (34/34)

- **Incoherent effects induced by an electron cloud**



Does not disappear at high energy!

This spread must also be accommodated in the tune diagram without crossing dangerous resonance lines…

Courtesy G. Franchetti

APPENDIX A: SUMMARY OF LECTURE 2

- Design orbit in the centre of the vacuum chamber
- Lorentz force $\vec{F} = e\left(\cancel{\vec{E}} + \vec{v} \times \vec{B}\right)$
- Dipoles (constant force) ⇒ Guide the particles along the design orbit
- Quadrupoles (linear force) ⇒ Confine the particles in the vicinity of the design orbit
- Betatron oscillation in x (and in y) ⇒ Tune Q_x (and Q_y) >> 1
- Twiss parameters define the ellipse in phase space (x, $x' = d\,x\,/\,d\,s$)
- β-function reflects the size of the beam and depends only on the lattice
- Beam emittance must be smaller than the mechanical acceptance
- Higher order multipoles from imperfections (nonlinear force) ⇒ Resonances excited in the tune diagram and the working point (Q_x, Q_y) should not be close to most of the resonances
- Nonlinearities reduce the acceptance ⇒ Dynamic aperture
- Injection and extraction
- Betatron and dispersion matching (between a circular accelerator and a transfer line)

APPENDIX B: SUMMARY OF LECTURE 3

- RF cavities are used to accelerate (or decelerate) the particles
- Transition energy and sinusoidal voltage ⇒ $\vec{F} = e\left(\vec{E} + \vec{v} \times \cancel{\vec{B}}\right)$
- Harmonic number = Number of RF buckets (stationary or accelerating)
- Bunched beam (instead of an unbunched or continuous beam)
- Synchrotron oscillation around the synchronous particle in z ⇒ Tune $Q_z << 1$
- Stable phase ϕ_s below transiton and $\pi - \phi_s$ above transition
- Ellipse in phase space (Δt, ΔE)
- Beam emittance must be smaller than the bucket acceptance
- Bunch splittings and rotation very often used
- Figure of merit for a synchrotron/collider = Brightness/Luminosity
- Longitudinal bunch profile from a wall current monitor
- Transverse beam orbit from beam position pick-up monitors
- Transverse beam profile from a fast wire scanner
- Beam losses around the accelerator from beam loss monitors

APPENDIX C: SUMMARY OF LECTURE 4 (1/2)

- (Direct) space charge = Interaction between the particles (without the vacuum chamber) ⇒ Coulomb repulsion + magnetic attraction
    - Tune footprint in the tune diagram ⇒ Interaction with resonances
    - Disappears at high energy
    - Reduces the RF bucket below transition and increases it above

- Wake fields = Electromagnetic fields generated by the beam interacting with its surroundings (vacuum pipe, etc.) ⇒ Impedance = Fourier transform of the wake field
    - Bunched-beam coherent instabilities
        - Coupled-bunch modes
        - Single-bunch or Head-Tail modes (low and high intensity)
    - Beam stabilization
        - Landau damping
        - Feedbacks
        - Linear coupling between the transverse planes

APPENDIX C: SUMMARY OF LECTURE 4 (2/2)

- Beam-Beam = Interaction between the 2 counter-rotating beams ⇒ Coulomb repulsion + magnetic repulsion
  - Crossing angle, head-on and long-range interactions
  - Tune footprint in the tune diagram ⇒ Interaction with resonances
  - Does not disappear at high energy
  - PACMAN effects ⇒ Alternate crossing scheme
  - Coherent modes ⇒ Possible loss of Landau damping

- Electron cloud
  - Electron cloud build-up ⇒ Multi-bunch single-pass effect
  - Coherent instabilities induced by the electron cloud
    - Coupled-bunch
    - Single-bunch
  - Tune footprint in the tune diagram ⇒ Interaction with resonances
  - Does not disappear at high energy