Introduction to Accelerator Physics

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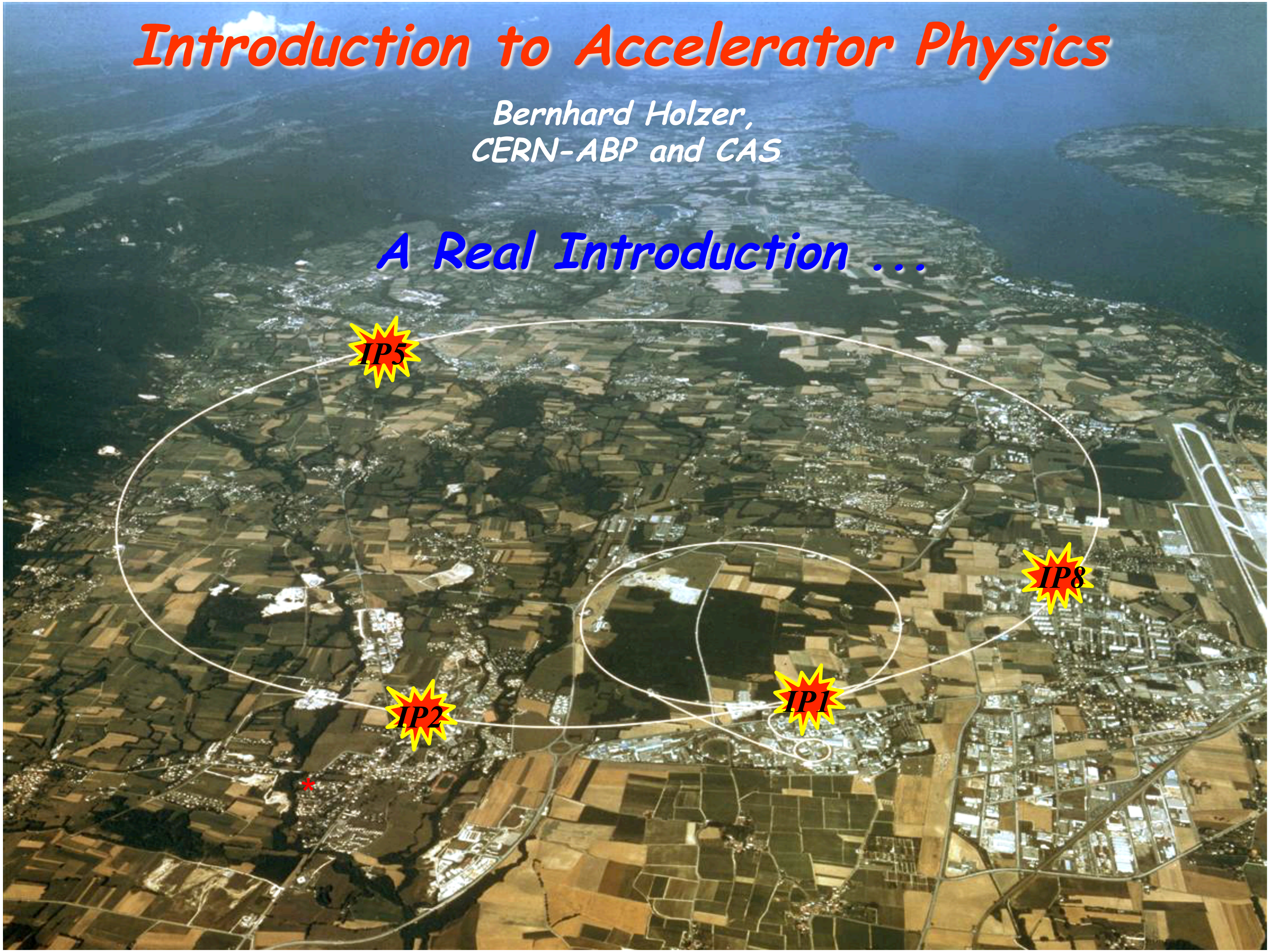
CERN-ABP and CAS

A Real Introduction ...



the beta function is usually obtained via the matrix element „m12“, which is in Twiss form for the undistorted case

$$m_{12} = \beta_0 \sin 2\pi Q$$

$$(1) \quad m_{12}^{*} = \beta_0 \sin 2\pi Q - a_{12} b_{12} \Delta k ds$$

As M is still a matrix for one complete turn we still can express the element* ***m***$_{12}$ *in twiss form:*

$$(2) \quad m_{12}^{*} = (\beta_0 + d\beta) * \sin 2\pi (Q + dQ)$$

Equalising (1) and (2) and assuming a small error

and including the error:

$$\underbrace{m_{12}^{*}} = b_{11} a_{12} + b_{12} a_{22} - \cancel{b_{12} a_{12}} \Delta k ds$$

$$m_{12} = \beta_0 \sin 2\pi Q$$

$$- a_{12} b_{12} \Delta k ds = \beta_0 2\pi dQ \cos 2\pi Q + d\beta_0 \sin 2\pi Q$$

$$dQ = \frac{\Delta k \beta_1 ds}{4\pi}$$

$$\beta_0 \sin 2\pi Q - a_{12} b_{12} \Delta k ds = (\beta_0 + d\beta) * \sin 2\pi (Q + dQ)$$

What we will NOT do .....

$$\beta_0 \sin 2\pi Q - a_{12} b_{12} \Delta k ds = (\beta_0 + d\beta) * \sin 2\pi Q \underbrace{\cos 2\pi dQ}_{\approx 1} + \cos 2\pi Q \underbrace{\sin 2\pi dQ}_{\approx 2\pi dQ}$$

$$- a_{12} b_{12} \Delta k ds = \frac{\beta_0 \Delta k \beta_1 ds}{2} \cos 2\pi Q + d\beta_0 \sin 2\pi Q$$

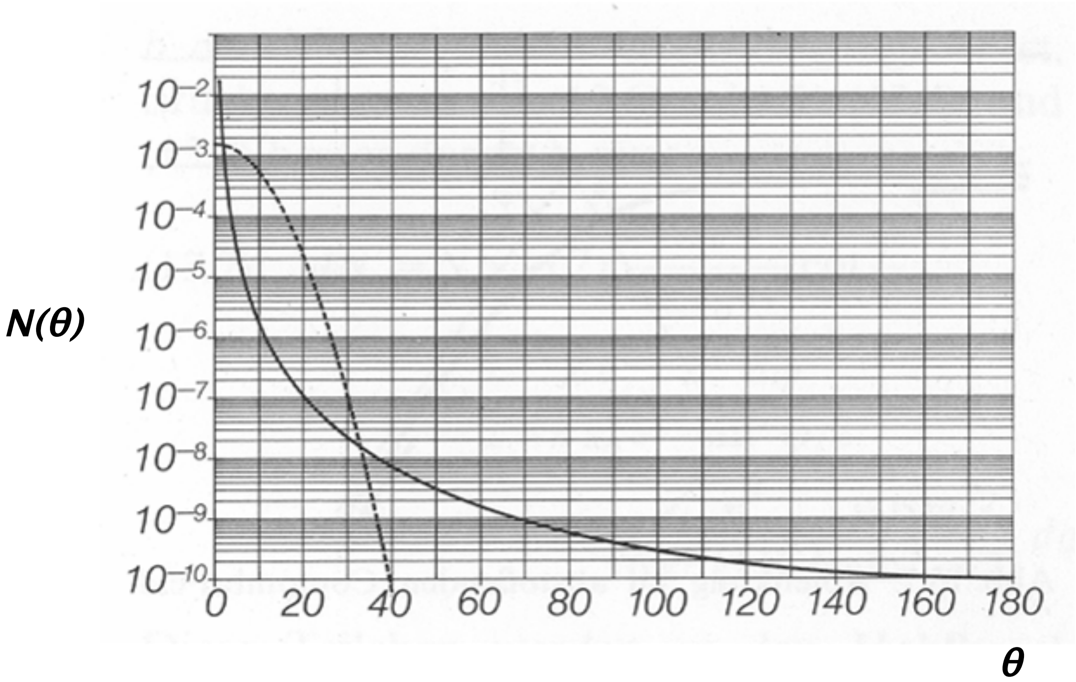
$$\beta_0 \sin 2\pi Q - \cancel{a_{12} b_{12} \Delta k ds} = \beta_0 \sin 2\pi Q + \cancel{\beta_0 2\pi dQ \cos 2\pi Q} + d\beta_0 \sin 2\pi Q + d\beta_0 2\pi dQ \cos 2\pi Q$$

$$d\beta_0 = \frac{-1}{2 \sin 2\pi Q} \left\{ 2 a_{12} b_{12} + \beta_0 \beta_1 \cos 2\pi Q \right\} \Delta k ds$$

$$M = \begin{pmatrix} \sqrt{\frac{\beta_s}{\beta_0}} \left(\cos\psi_s + \alpha_0 \sin\psi_s \right) & \sqrt{\beta_s \beta_0} \sin\psi_s \\ \frac{(\alpha_0 - \alpha_s)\cos\psi_s - (1 + \alpha_0 \alpha_s)\sin\psi_s}{\sqrt{\beta_s \beta_0}} & \sqrt{\frac{\beta_0}{\beta s}} \left(\cos\psi_s - \alpha_s \sin\psi_s \right) \end{pmatrix}$$

I.) A Bit of History

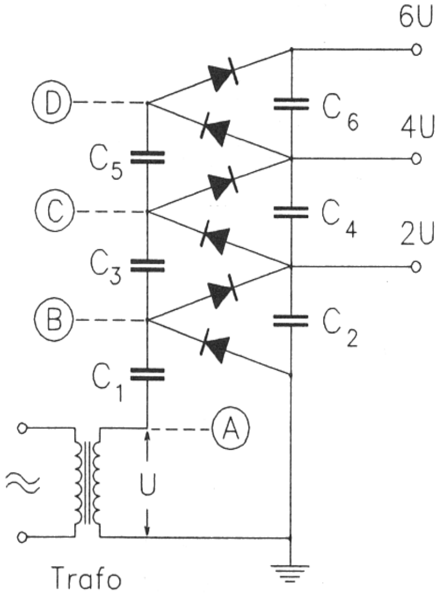
$$N(\theta) = \frac{N_i ntZ^2 e^4}{(8\pi\varepsilon_0)^2 r^2 K^2} * \frac{1}{\sin^4(\theta / 2)}$$



Rutherford Scattering, 1911

Using radioactive particle sources:
α-particles of some MeV energy

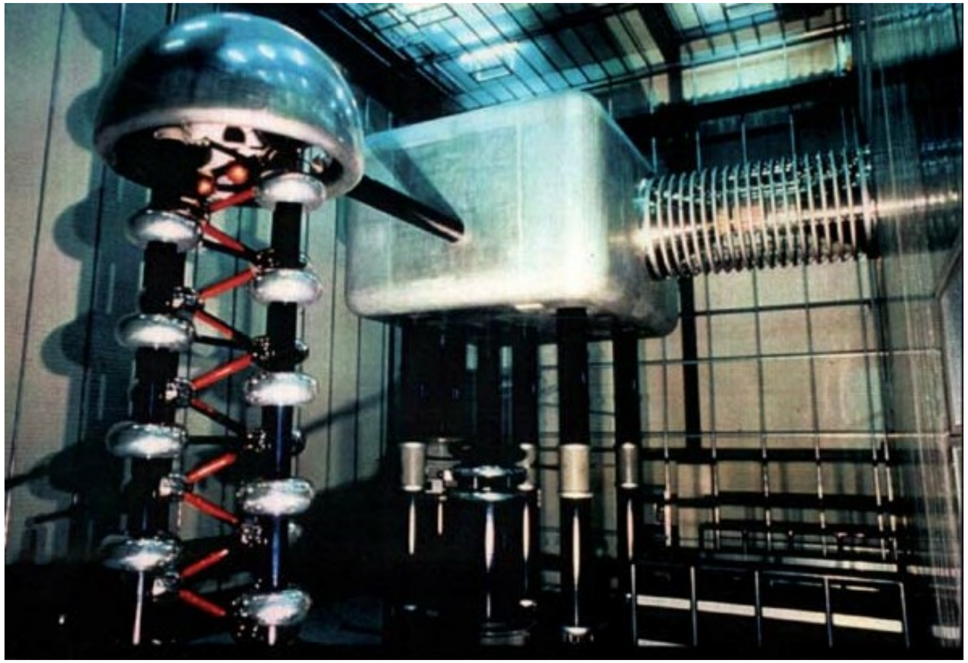
1.) Electrostatic Machines:
The Cockcroft-Walton Generator



1928: Encouraged by Rutherford Cockcroft and Walton start the design & construction of a high voltage generator to accelerate a proton beam

1932: First particle beam (protons) produced for nuclear reactions: splitting of Li-nuclei with a proton beam of 400 keV

Particle source: Hydrogen discharge tube on 400 kV level
Accelerator: evacuated glas tube
Target: Li-Foil on earth potential

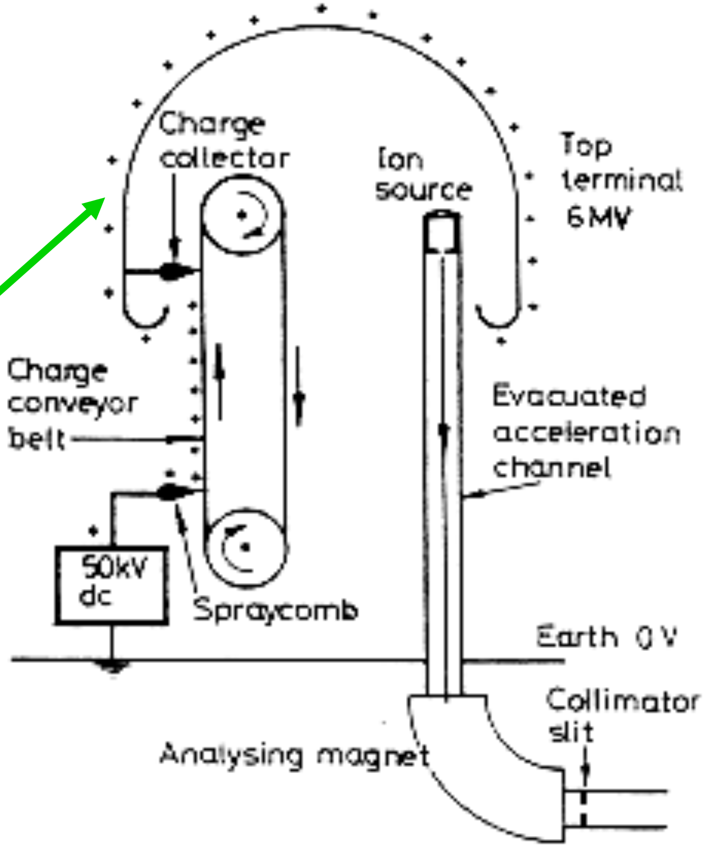


Technically: rectifier circuit, built of capacitors and diodes (Greinacher)

Problem:
DC Voltage can only be used once

2.) Electrostatic Machines:
(Tandem –) van de Graaff Accelerator (1930 ...)

creating high voltages by mechanical transport of charges



** Terminal Potential: U ≈ 12 ...28 MV*
using high pressure gas to suppress discharge (SF_6)

*Problems: * Particle energy limited by high voltage discharges*
** high voltage can only be applied once per particle ...*
... or twice ?

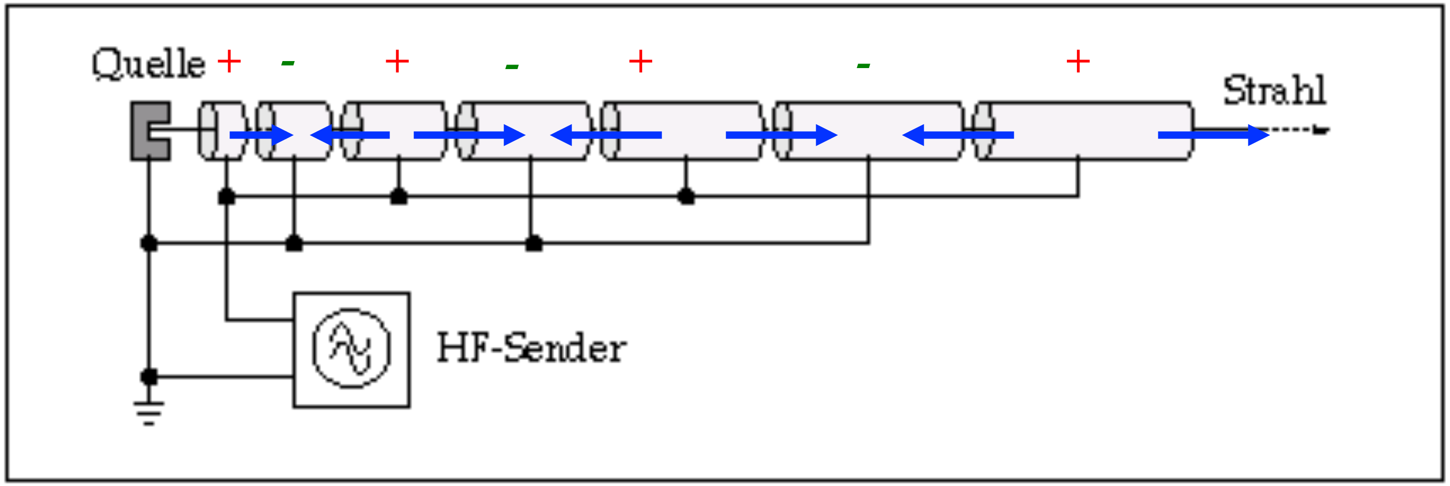
The „Tandem principle“: Apply the accelerating voltage twice ...
... by working with negative ions (e.g. H^-) and
stripping the electrons in the centre of the
structure

Example for such a „steam engine“: 12 MV-Tandem van de Graaff Accelerator at MPI Heidelberg

3.) The first RF-Accelerator: „Linac“

1928, Wideroe: ***how can the acceleration voltage be applied several times to the particle beam***

schematic Layout:



Energy gained after n acceleration gaps

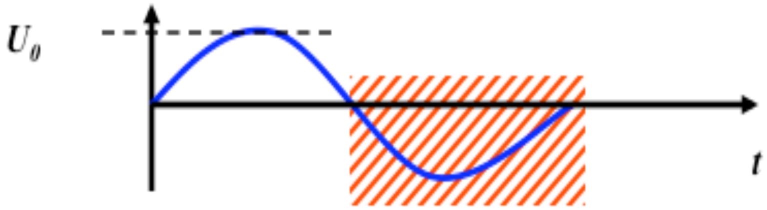
$$E_n = n * q * U_0 * \sin\psi_s$$

n *number of gaps between the drift tubes*
q *charge of the particle*
U_0 *Peak voltage of the RF System*
Ψ_S *synchronous phase of the particle*

**** acceleration of the proton in the first gap***
**** voltage has to be „flipped“ to get the right sign in the second gap → RF voltage***
→ shield the particle in drift tubes during the negative half wave of the RF voltage

Wideroe-Structure: the drift tubes

shielding of the particles during the negative half wave of the RF



Time span of the negative half wave: $\tau_{RF}/2$

Length of the Drift Tube: $l_i = v_i * \frac{\tau_{rf}}{2}$

Kinetic Energy of the Particles $E_i = \frac{1}{2} m v^2$

$$\rightarrow v_i = \sqrt{2E_i/m}$$

$$l_i = \frac{1}{\nu_{rf}} * \sqrt{\frac{i*q*U_{0*\sin\psi_s}}{2m}}$$

valid for non relativistic particles ...

Alvarez-Structure: 1946, surround the whole structure by a rf vessel

Energy: ≈ 20 MeV per Nucleon $\beta \approx 0.04$ … 0.6, Particles: Protons/Ions

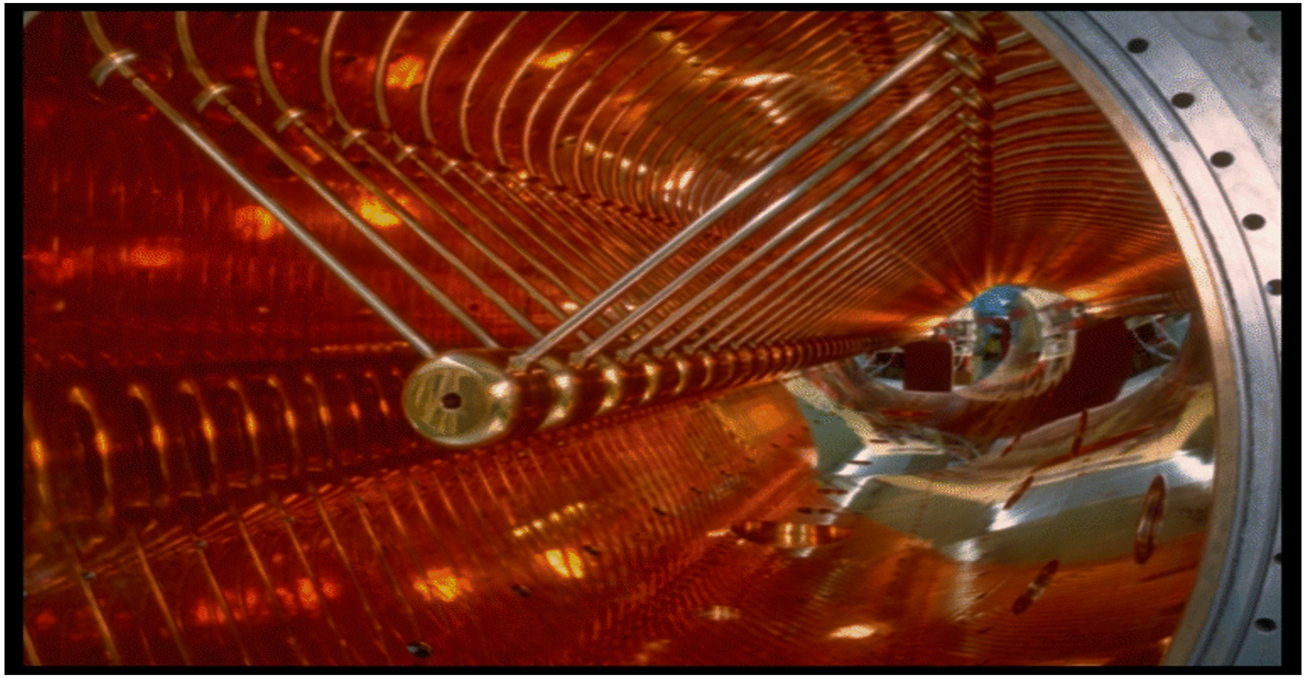
Accelerating structure of a Proton Linac (DESY Linac III)

$E_{total} = 988\, MeV$

$m_0c^2 = 938\, MeV$

$p = 310\, MeV\ / c$

$E_{kin} = 50\, MeV$



Beam energies

Energy Gain per „Gap“: $\boxed{W = q\, U_0 \sin \omega_{RF} t}$

1.) reminder of some relativistic formula

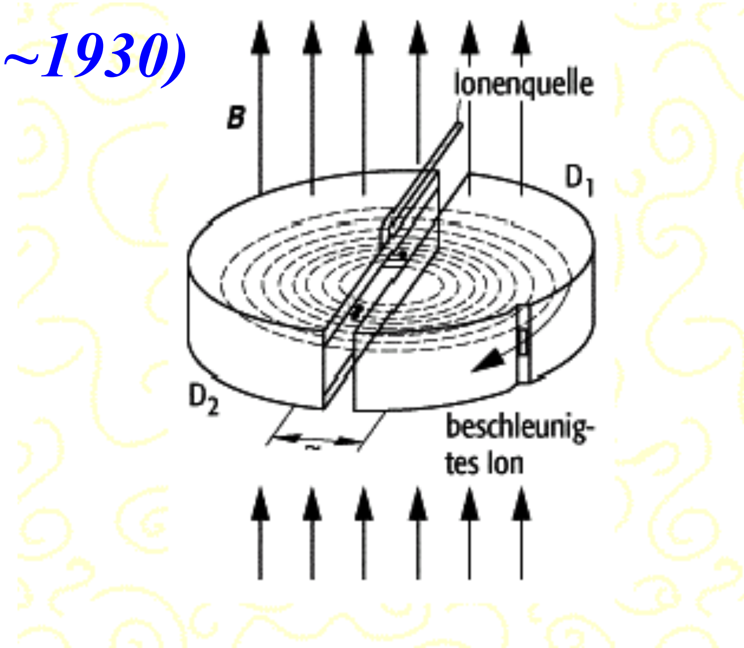
rest energy $E_0 = m_0c^2$

total energy $E = \gamma * E_0 = \gamma * m_0c^2$

kinetic energy $E_{kin} = E_{total} - m_0c^2$

momentum $E^2 = c^2p^2 + m_0^2c^4$

3.) The Cyclotron: (Livingston / Lawrence ~1930)



Idea: B = const, RF = const
Synchronisation particle / RF via orbit

Lorentzforce

$$\vec{F} = q * (\vec{v} \times \vec{B}) = q * v * B$$

circular orbit

$$q * v * B = \frac{m * v^2}{R} \quad \longrightarrow \quad B * R = p/q$$

increasing radius for increasing momentum
➔ *Spiral Trajectory*

revolution frequency

$$\omega_z = \frac{v}{R} = \frac{q}{m} * B_z$$

the cyclotron (rf-) frequency is independent of the momentum

rf-frequency = h* revolution frequency,   h = "harmonic number"

Cyclotron:

exact equation for revolution frequency:

$$\omega_z = \frac{v}{R} = \frac{q}{\boxed{\gamma *} m} * B_z$$

Cyclotron SPIRAL at GANIL

1.) if $v << c \Rightarrow \gamma \cong 1$

2.) γ increases with the energy
$\Rightarrow$ no exact synchronism

"synchronisation" with the acceleration potential is established via the spiraling orbit length

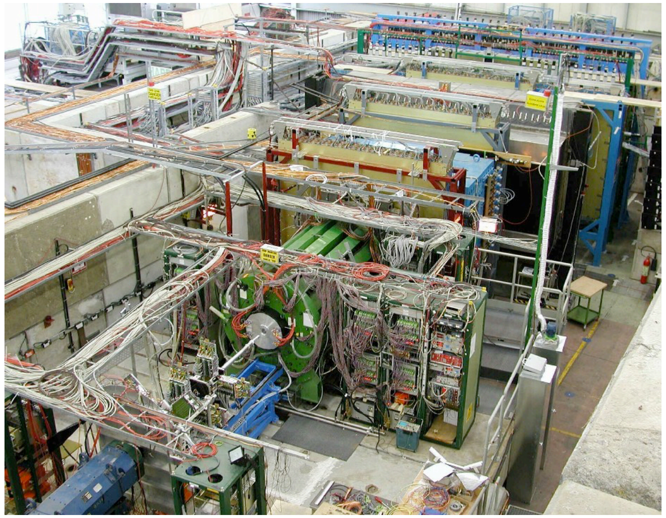
Syn on

B = constant
$\gamma\, \omega_{RF}$ = constant
ω_{RF} decreases with time

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

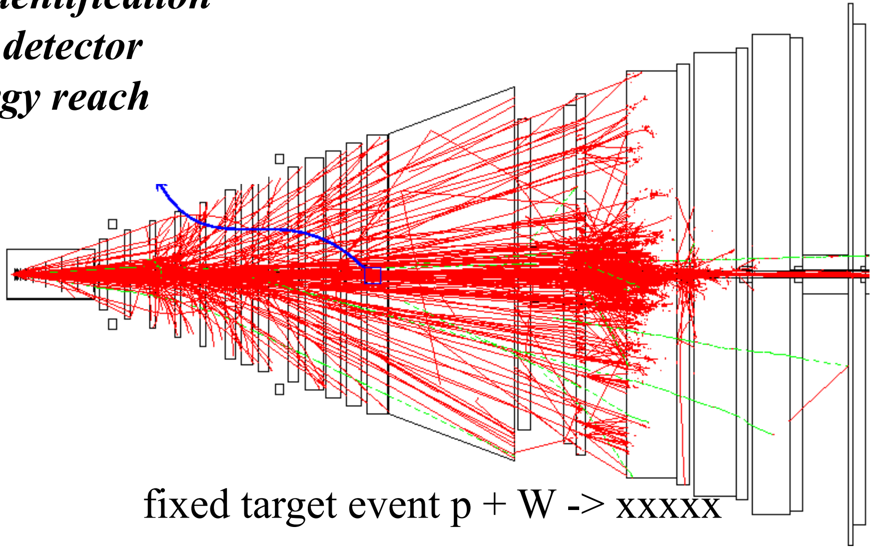
keep the synchronisation condition by varying the rf frequency

Fixed target experiments:



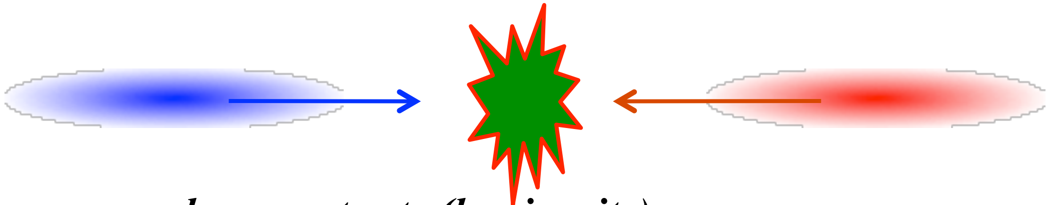
HARP Detector, CERN

high event rate
easy track identification
asymmetric detector
limited energy reach

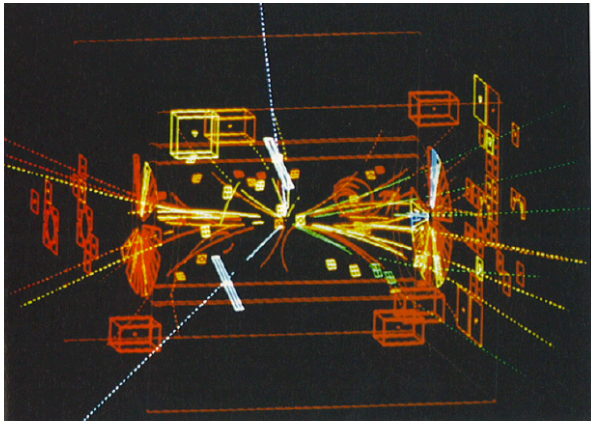


fixed target event p + W -> xxxxx

Collider experiments:



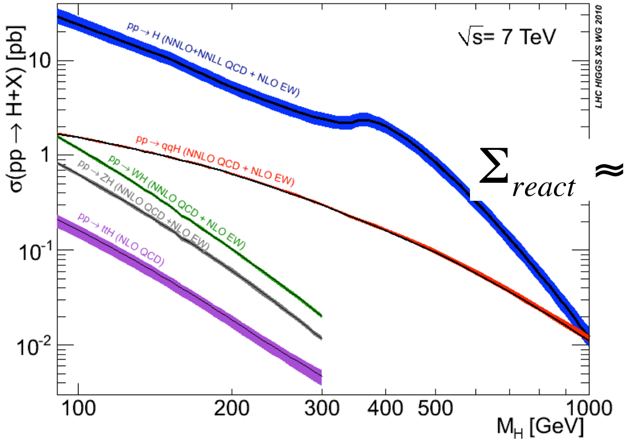
low event rate (luminosity)
challenging track identification
symmetric detector
$E_{lab} = E_{cm}$



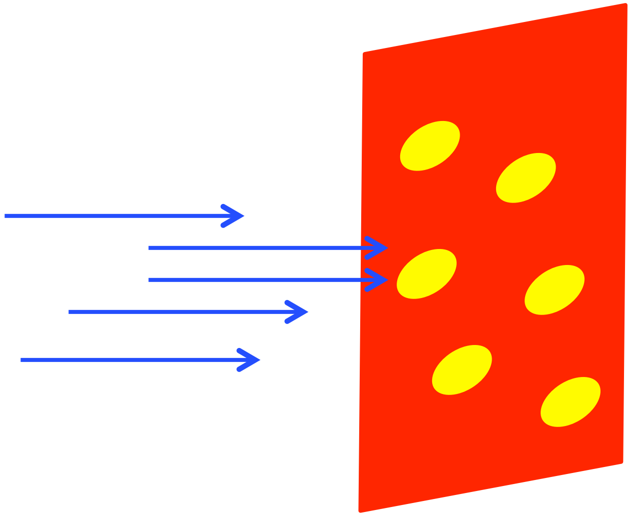
Z_0 boson discovery at the UA2 experiment (CERN).
The Z_0 boson decays
into a e+e− pair, shown as white dashed lines.

Problem: Our particles are VERY small !!

Overall cross section of the Protons:



$$\Sigma_{react} \approx 1\,pb$$

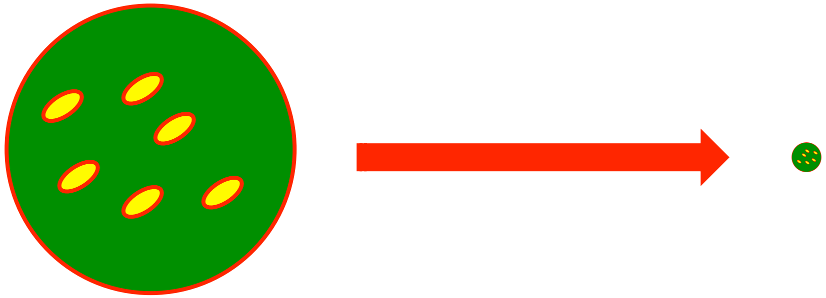


$$1b \;= 10^{-24}\,cm^2$$

$$1pb = \quad 10^{-12} * 10^{-24}\,cm^2 = 1/mio * 1/mio * 1/mio * 1/mio * 1/mio * 1/10000\;mm^2$$

The particles are "very small"

The only chance we have:
compress the transverse beam size … at the IP



LHC typical:

σ = 0.1 mm → 16 µm

II.) A Bit of Theory

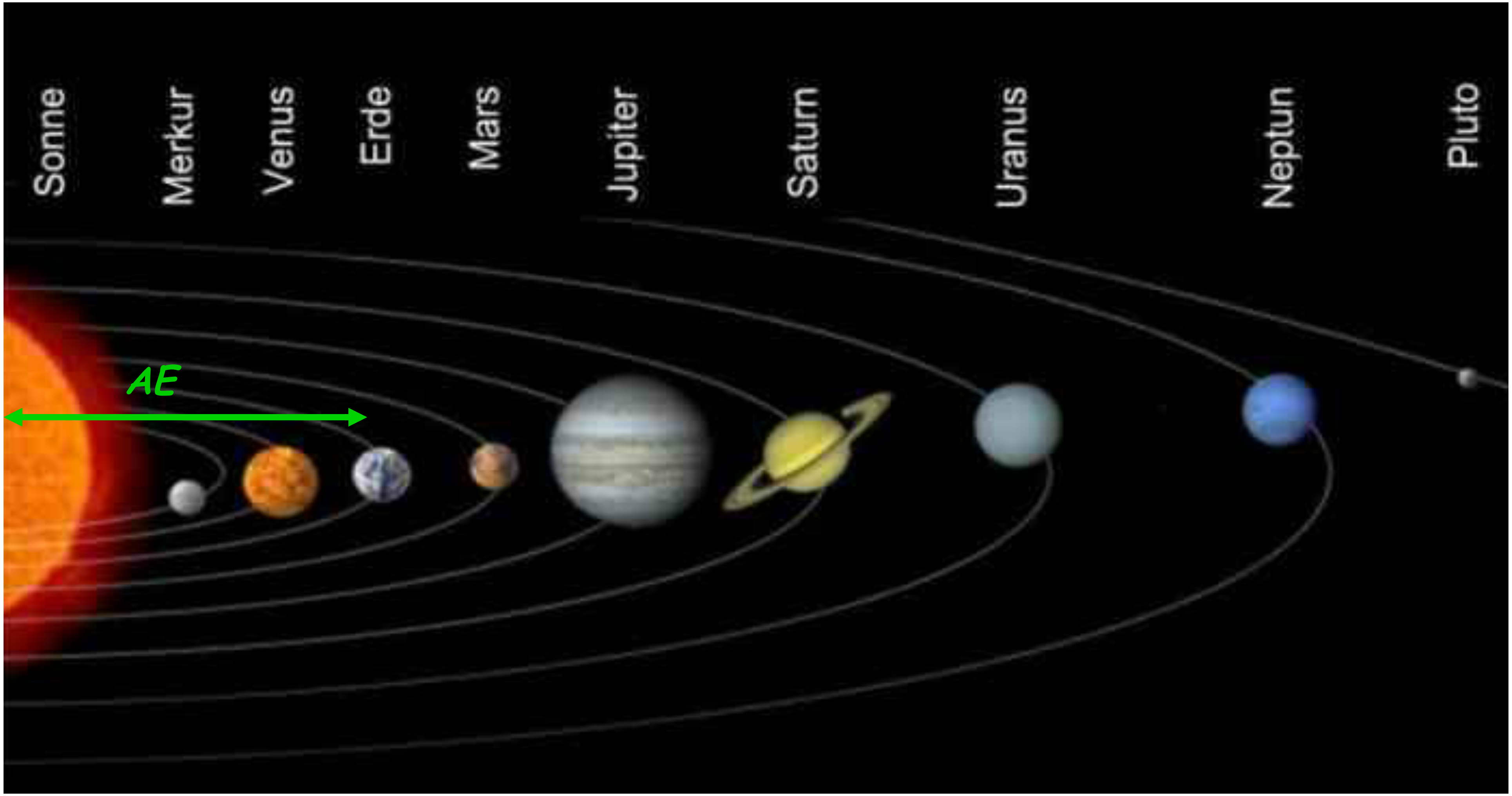
The big storage rings: „Synchrotrons“

Largest storage ring: The Solar System

astronomical unit: average distance earth-sun

$1AE \approx 150 * 10^6$ km

Distance Pluto-Sun ≈ 40 AE



1.) Introduction and Basic Ideas

„ ... in the end and after all it should be a kind of circular machine“

→ need transverse deflecting force

Lorentz force

$$\vec{F} = q * (\cancel{\vec{E}} + \vec{v} \times \vec{B})$$

typical velocity in high energy machines:

$$v \approx c \approx 3 * 10^8 \, {}^{m}\!/\!{}_{s}$$

Example:

$$B = 1\,T \quad \rightarrow \quad F = q * 3 * 10^8 \frac{m}{s} * 1 \frac{Vs}{m^2}$$

$$F = q * \underbrace{300 \frac{MV}{m}}_{E}$$

equivalent electrical field:

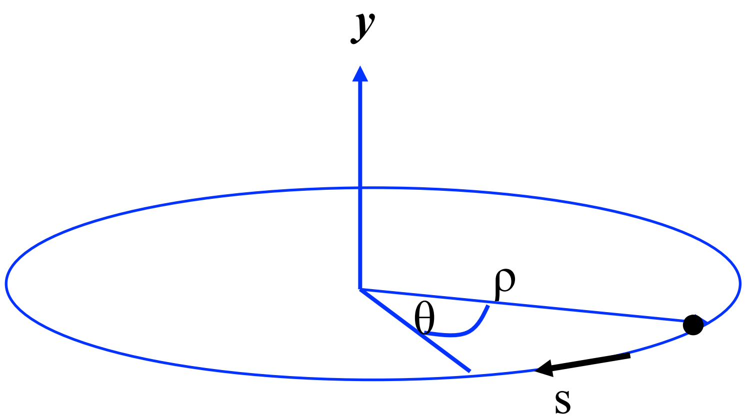
Technical limit for electrical fields:

$$E \leq 1 \frac{MV}{m}$$

old greek dictum of wisdom:

if you are clever, you use magnetic fields in an accelerator wherever it is possible.

The ideal circular orbit



circular coordinate system

condition for circular orbit:

Lorentz force $F_L = e\,v\,B$

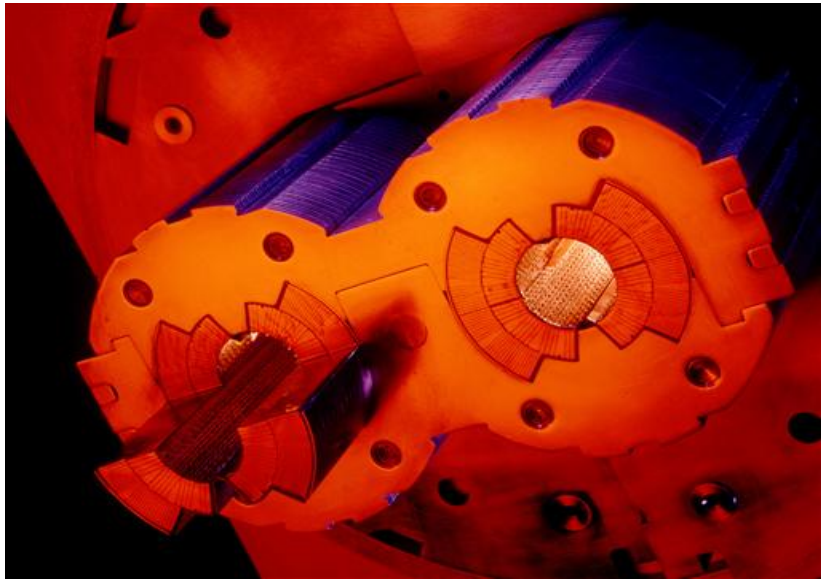
centrifugal force $F_{centr} = \dfrac{\gamma\, m_0\, v^2}{\rho}$

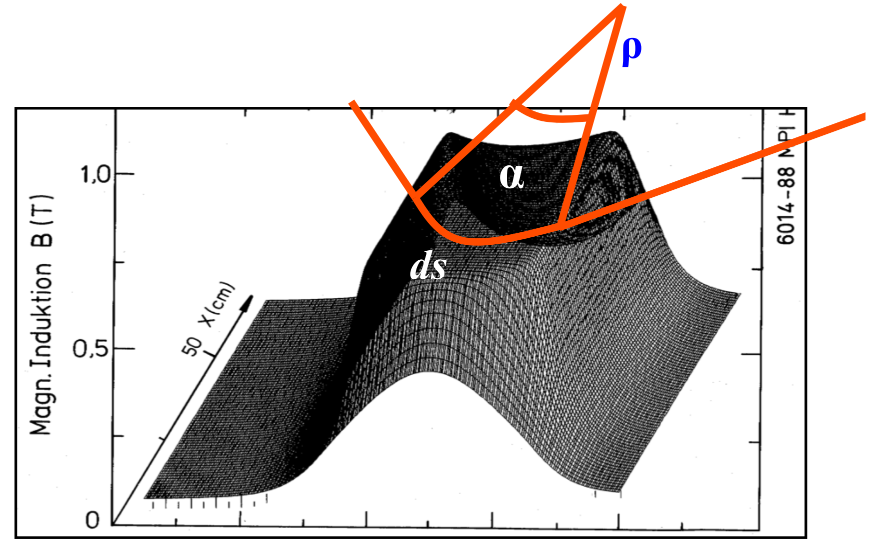
$$\frac{\gamma\, m_0\, \cancel{v^2}}{\rho} = e\,\cancel{v}\,B$$

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

$B\rho$ = "beam rigidity"

The Magnetic Guide Field





field map of a storage ring dipole magnet

$\rho = 2.8\ km$ → $2\pi\rho = 17.6\ km$

$\approx 66\%$

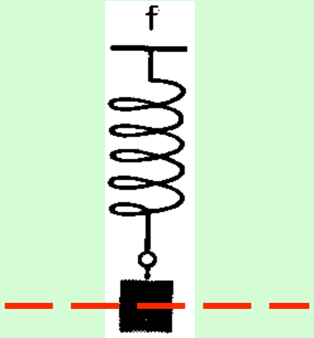
$B \approx 1 \ldots 8\ T$

rule of thumb: $$\boxed{\frac{1}{\rho} \approx 0.3\,\frac{B\left[T\right]}{p\left[GeV/c\right]}}$$

„normalised bending strength“

Focusing Properties and Quadrupole Magnets

classical mechanics:
pendulum



there is a restoring force, proportional to the elongation x:

$$m*\frac{d^2x}{dt^2}=-c*x$$

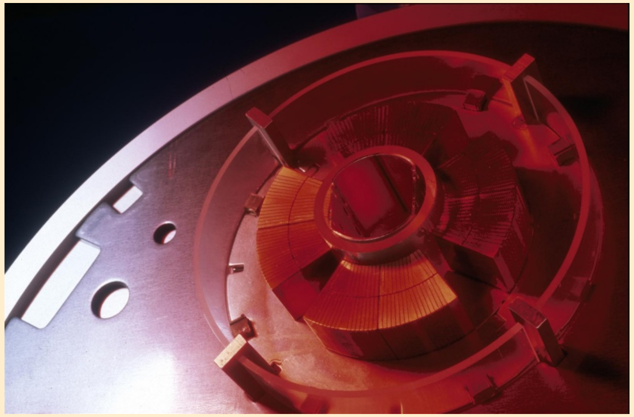
general solution: free harmonic oszillation $x(t)=A*\cos(\omega t+\varphi)$

this is how grandma's Kuckuck's clock is working!!!

Storage Rings: ***linear increasing Lorentz force to keep trajectories in vicinity of the ideal orbit***

linear increasing magnetic field $B_y = g\,x \qquad B_x = g\;y$

$$F(x)=q*v*B(x)$$



LHC main quadrupole magnet $g \approx 25\,...\,220\;\;T/m$

Focusing forces and particle trajectories:

normalise magnet fields to momentum
(remember: $\mathbf{B}^*\boldsymbol{\rho} = \mathbf{p} / \mathbf{q}$ *)*

Dipole Magnet

$$\frac{B}{p/q} = \frac{B}{B\rho} = \frac{1}{\rho}$$

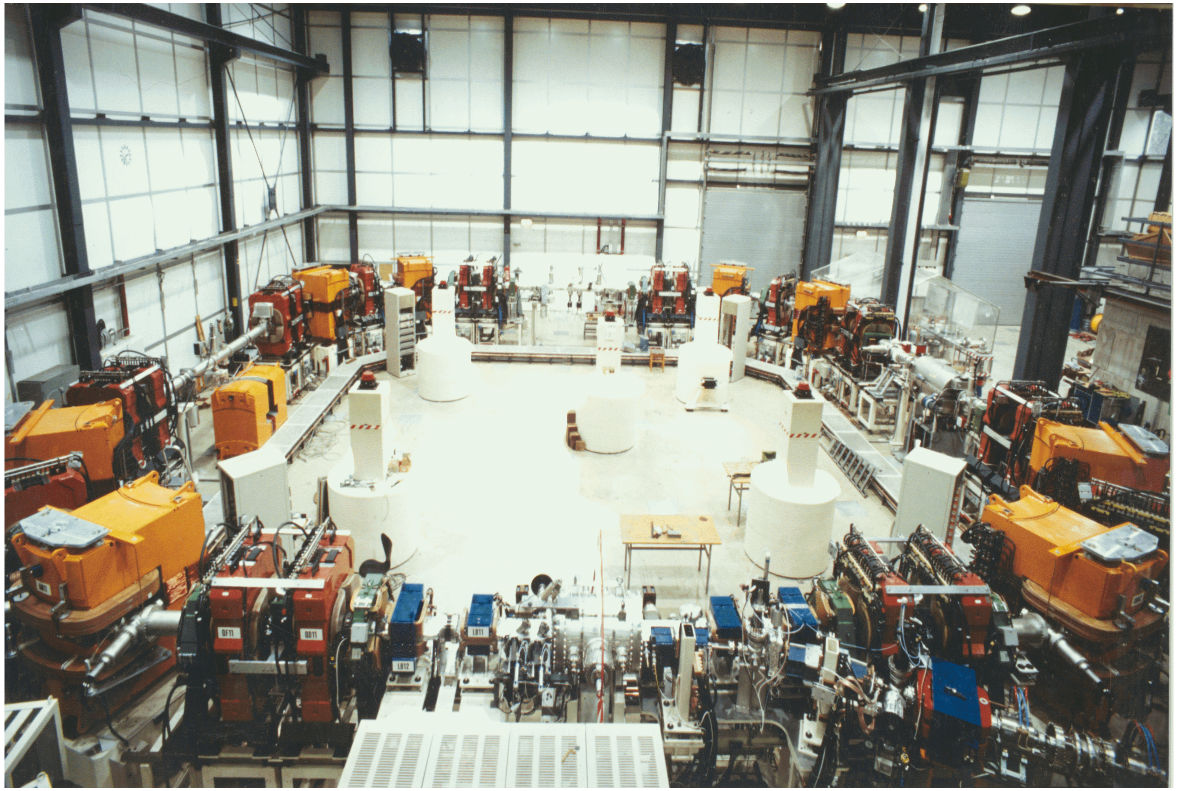
Quadrupole Magnet

$$k := \frac{g}{p/q}$$

3.) The Equation of Motion:

$$\frac{B(x)}{p/e} = \frac{1}{\rho} + k\,x + \cancel{\frac{1}{2!}m\,x^2} + \cancel{\frac{1}{3!}n\,x^3} + \ldots$$

only terms linear in x, y taken into account *dipole fields*
quadrupole fields



Separate Function Machines:

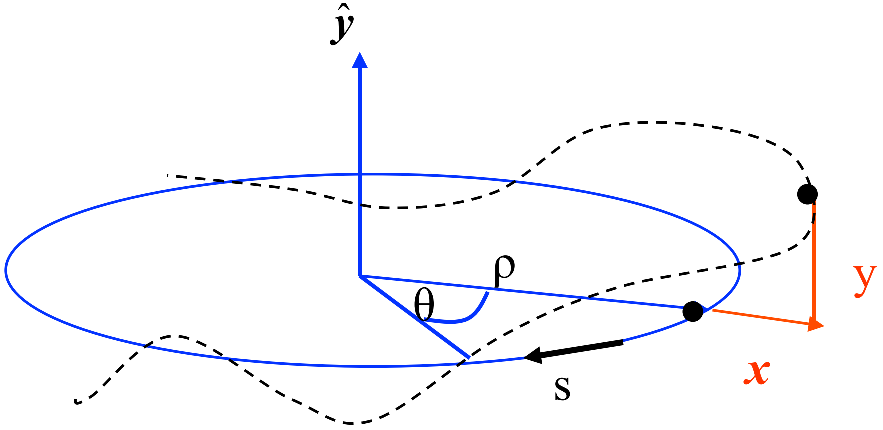
Split the magnets and optimise them according to their job:

bending, focusing etc

Example:
heavy ion storage ring TSR

*
man sieht nur
dipole und quads → linear

The Equation of Motion:



* *Equation for the* ***horizontal motion:***

$$x'' + x\,(\frac{1}{\rho^2} + k) = 0$$

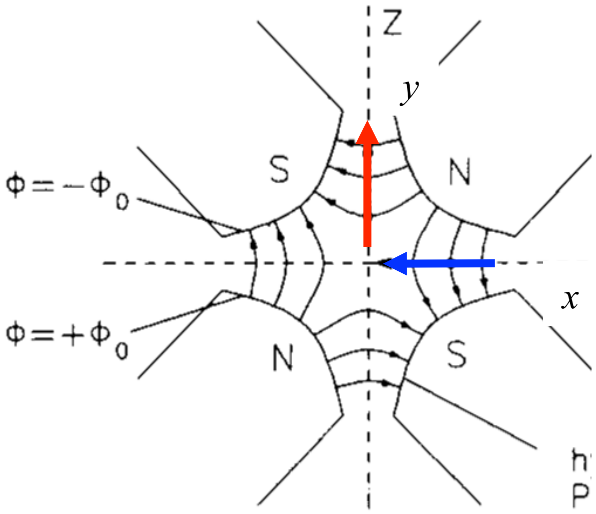
x = particle amplitude
x' = angle of particle trajectory (wrt ideal path line)

* *Equation for the* ***vertical motion:***

$$\frac{1}{\rho^2} = 0$$ ***no dipoles … in general …***

$$k \leftrightarrow -k$$ ***quadrupole field changes sign***

$$y'' - k\ y = 0$$



4.) Solution of Trajectory Equations

Define … hor. plane: $K = 1/\rho^2 + k$

… vert. Plane: $K = - k$

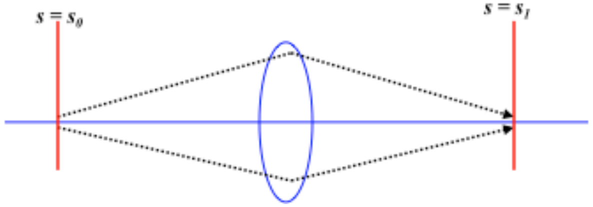
$$x'' + K\,x = 0$$

Differential Equation of harmonic oscillator … with spring constant K

Ansatz: ***Hor. Focusing Quadrupole K > 0:***

$$x(s) = x_0 \cdot \cos(\sqrt{|K|}s) + x_0' \cdot \frac{1}{\sqrt{|K|}} \sin(\sqrt{|K|}s)$$

$$x'(s) = -x_0 \cdot \sqrt{|K|} \cdot \sin(\sqrt{|K|}s) + x_0' \cdot \cos(\sqrt{|K|}s)$$



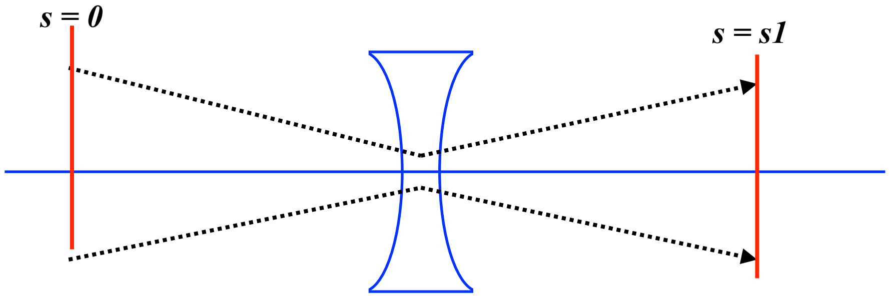
For convenience expressed in matrix formalism:

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{s1} = M_{foc} * \begin{pmatrix} x \\ x' \end{pmatrix}_{s0}$$

$$\boldsymbol{M}_{foc} = \begin{pmatrix} \cos\left(\sqrt{|\boldsymbol{K}|}\boldsymbol{l}\right) & \frac{1}{\sqrt{|\boldsymbol{K}|}} \sin\left(\sqrt{|\boldsymbol{K}|}\boldsymbol{l}\right) \\ -\sqrt{|\boldsymbol{K}|}\sin\left(\sqrt{|\boldsymbol{K}|}\boldsymbol{l}\right) & \cos\left(\sqrt{|\boldsymbol{K}|}\boldsymbol{l}\right) \end{pmatrix}$$

hor. defocusing quadrupole:

$$x'' - K\,x = 0$$



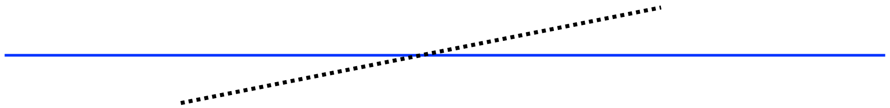
Ansatz: ***Remember from school***

$$x(s) = a_1 \cdot \cosh(\omega s) + a_2 \cdot \sinh(\omega s)$$

$$M_{defoc} = \begin{pmatrix} \cosh\sqrt{|K|}l & \frac{1}{\sqrt{|K|}}\sinh\sqrt{|K|}l \\ \sqrt{|K|}\sinh\sqrt{|K|}l & \cosh\sqrt{|K|}l \end{pmatrix}$$

drift space:

$$K = 0$$



$$x(s) = x'_0 * s$$

$$M_{drift} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}$$

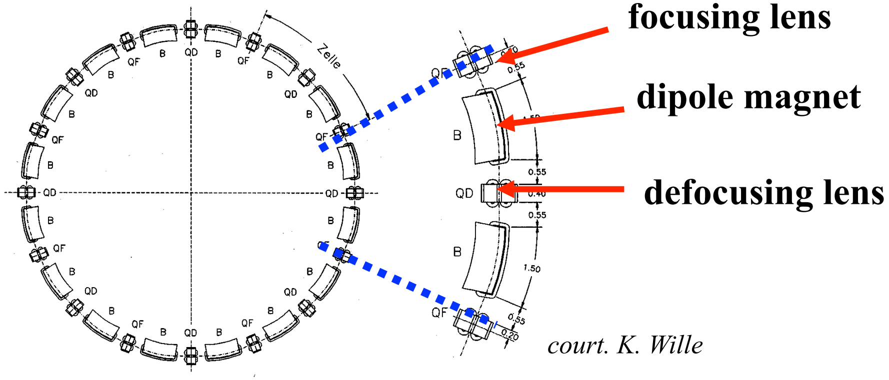
! with the assumptions made, the motion in the horizontal and vertical planes are independent „ ... the particle motion in x & y is uncoupled“

Transformation through a system of lattice elements

combine the single element solutions by multiplication of the matrices

$$M_{total} = M_{QF} * M_{D} * M_{QD} * M_{Bend} * M_{D*}.....$$

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{s2} = M(s_2,s_1) * \begin{pmatrix} x \\ x' \end{pmatrix}_{s1}$$



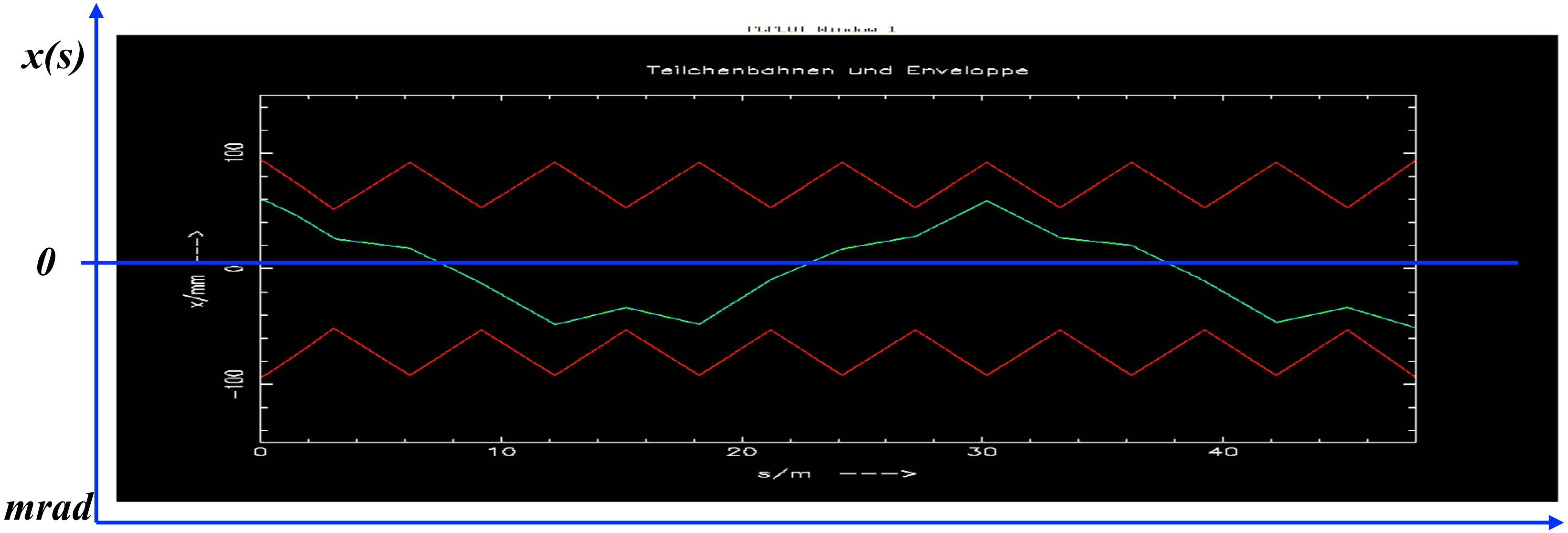
focusing lens

dipole magnet

defocusing lens

court. K. Wille

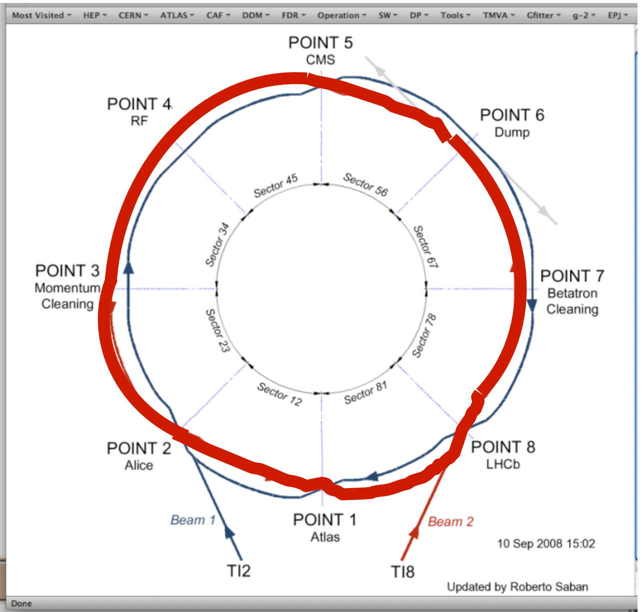
in each accelerator element the particle trajectory corresponds to the movement of a harmonic oscillator „



typical values in a strong foc. machine:

x ≈ mm, x´ ≤ mrad

LHC Operation: Beam Commissioning

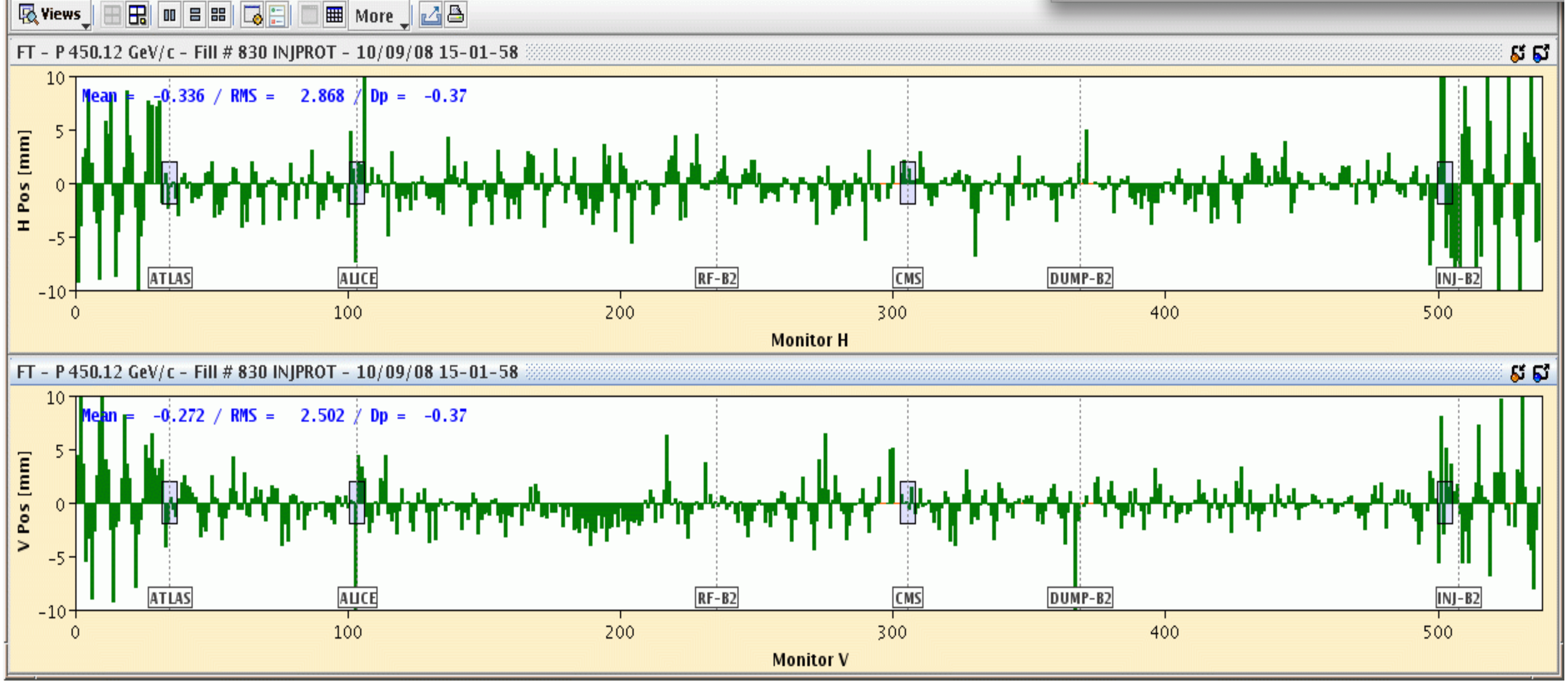


10 Sep 2008 15:02

Updated by Roberto Saban

*The **transverse focusing fields** create a **harmonic oscillation of the particles** with a well defined "Eigenfrequency" which is called **tune***

First turn steering "by sector:"



YASP DV LHCRING / INJ-TEST-NB / beam 2

FT - P 450.12 GeV/c - Fill # 830 INJPROT - 10/09/08 15-01-58

Mean = -0.336 / RMS = 2.868 / Dp = -0.37

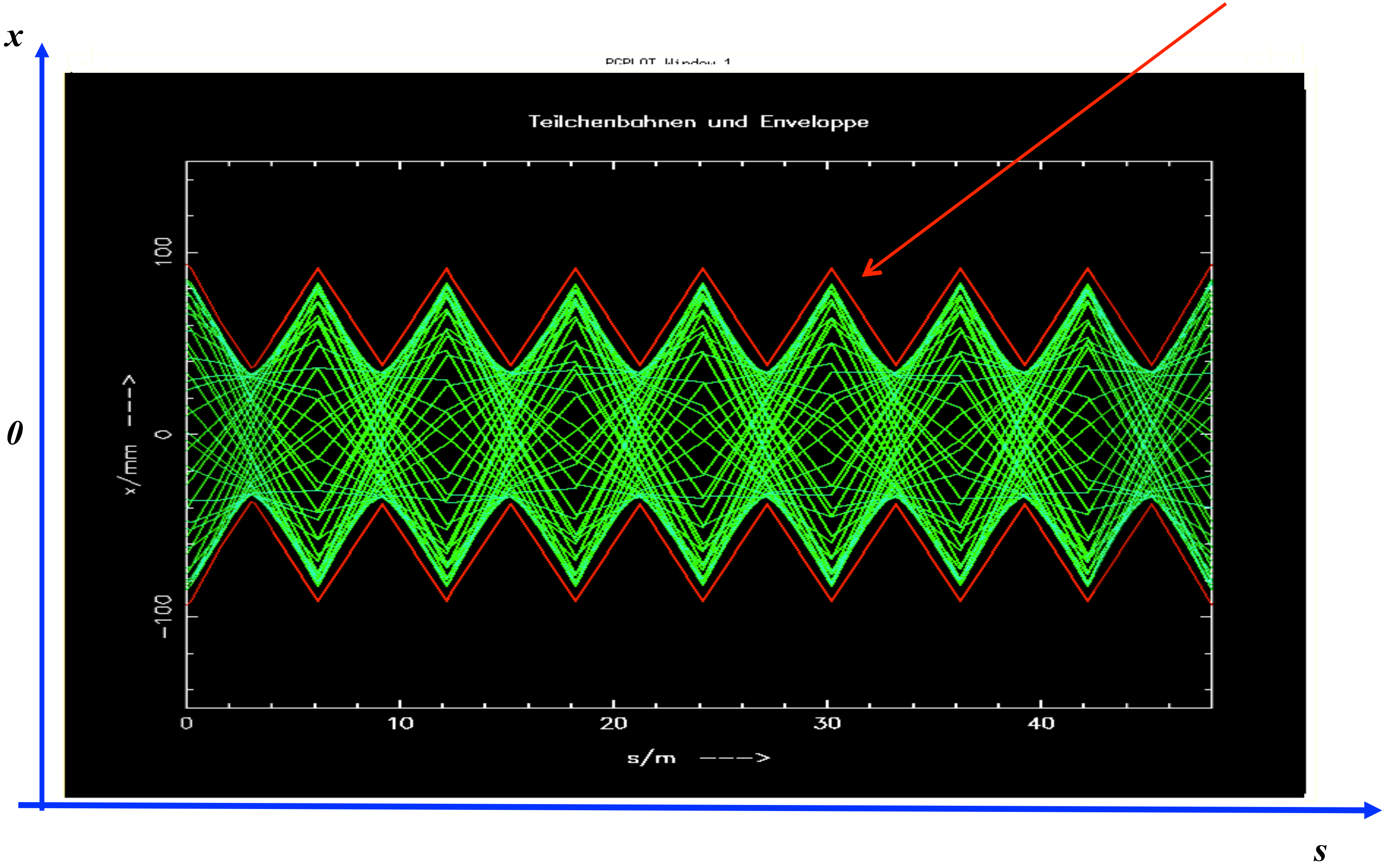
FT - P 450.12 GeV/c - Fill # 830 INJPROT - 10/09/08 15-01-58

Mean = -0.272 / RMS = 2.502 / Dp = -0.37

Question: what will happen, if the particle performs a second turn ?

... or a third one or ... 10^{10} turns

$$\sigma = \sqrt{\varepsilon\beta}$$



Astronomer Hill:

differential equation for motions with periodic focusing properties
„Hill 's equation"

Example: particle motion with periodic coefficient

equation of motion: $x''(s) - k(s)x(s) = 0$

restoring force ≠ const,
k(s) = depending on the position s
k(s+L) = k(s), periodic function

we expect a kind of quasi harmonic oscillation: amplitude & phase will depend on the position s in the ring.

Amplitude of a particle trajectory:

$$x(s) = \sqrt{\varepsilon} * \sqrt{\beta(s)} * \cos(\psi(s) + \varphi)$$

Maximum size of a particle amplitude

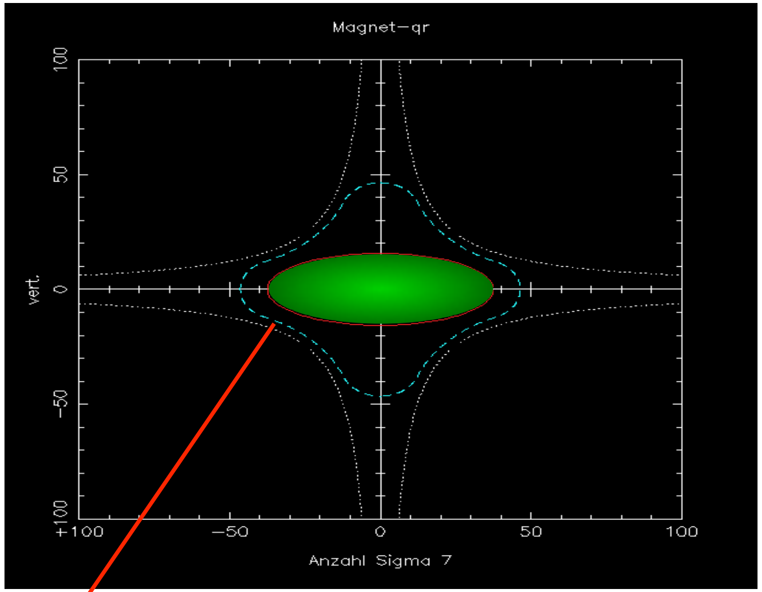
$$\hat{x}(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}$$

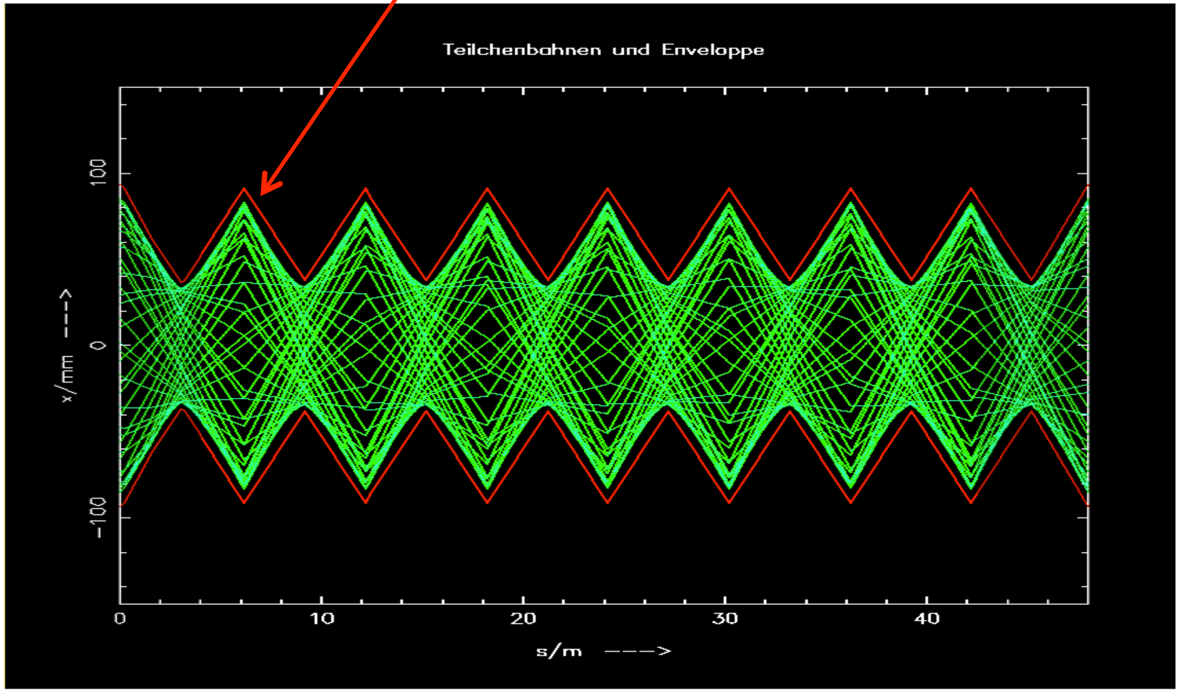
The Beta Function

β determines the beam size

... the envelope of all particle trajectories at a given position "s" in the storage ring under the influence of all (!) focusing fields.

It reflects the periodicity of the magnet structure.

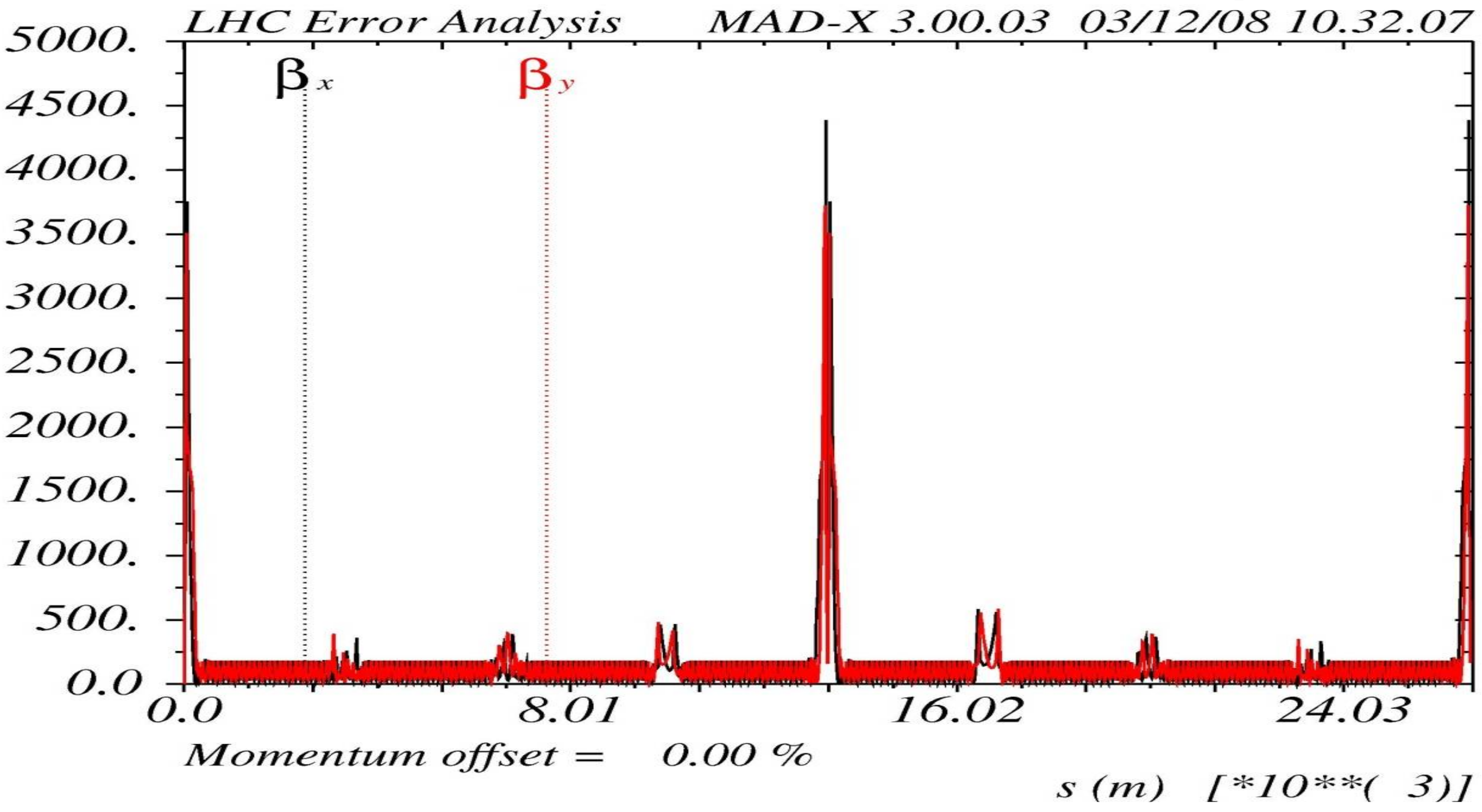




The Beta Function: Lattice Design & Beam Optics

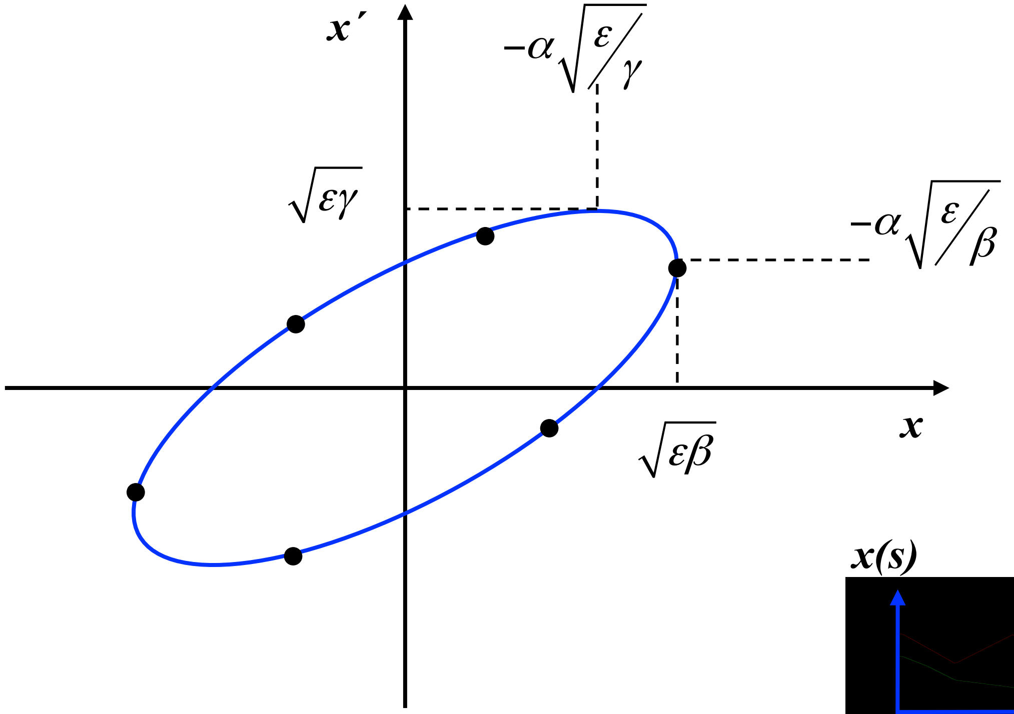
The beta function determines the maximum amplitude a single particle trajectory can reach at a given position in the ring.
It is determined by the focusing properties of the lattice and follows the periodicity of the machine.

optics at 7000 GeV



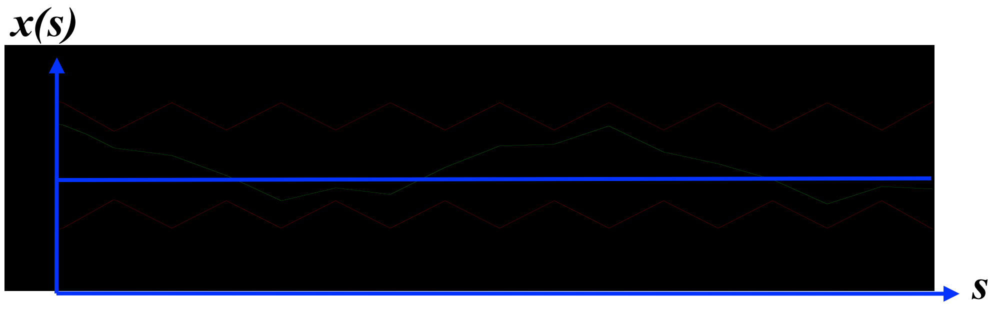
Beam Emittance and Phase Space Ellipse

$$\varepsilon = \gamma(s) * x^2(s) + 2\alpha(s)x(s)x'(s) + \beta(s)x'(s)^2$$



***Liouville:* in reasonable storage rings**
area in phase space is constant.

A = π*ε=const

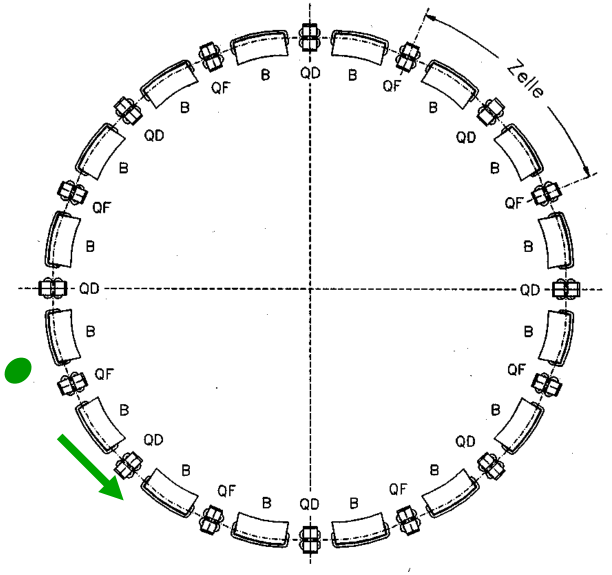


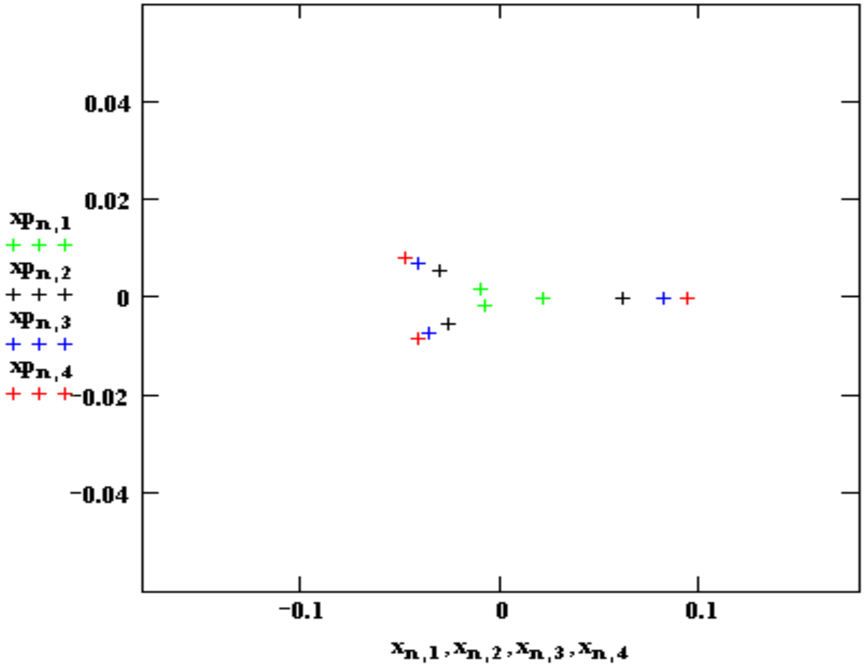
ε beam emittance = woozilycity of the particle ensemble, intrinsic beam parameter,
cannot be changed by the foc. properties.
Scientifiquely spoken: area covered in transverse x, x´ phase space … and it is constant !!!

Particle Tracking in a Storage Ring

Calculate x, x´ for each accelerator element according to matrix formalism and plot x, x´at a given position „s“ in the phase space diagram

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{s1} = M_{turn} * \begin{pmatrix} x \\ x' \end{pmatrix}_{s0}$$





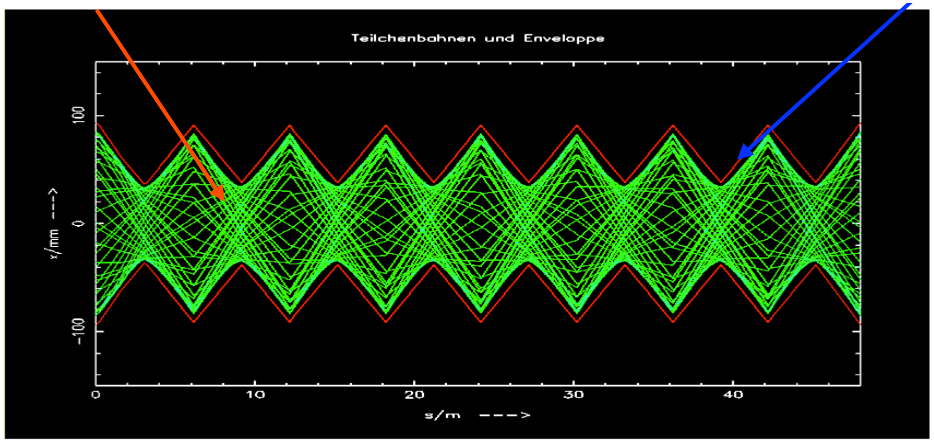
A beam of 4 particles

– each having a slightly different emittance:

Emittance of the Particle Ensemble:

$$x(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}\cdot\cos(\Psi(s)+\phi)$$

$$\hat{x}(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}$$



single particle trajectories, $N \approx 10^{11}$ per bunch

Gauß
Particle Distribution:

$$\rho(x) = \frac{N\cdot e}{\sqrt{2\pi}\sigma_x}\cdot e^{-\frac{1}{2}\frac{x^2}{\sigma_x{}^2}}$$

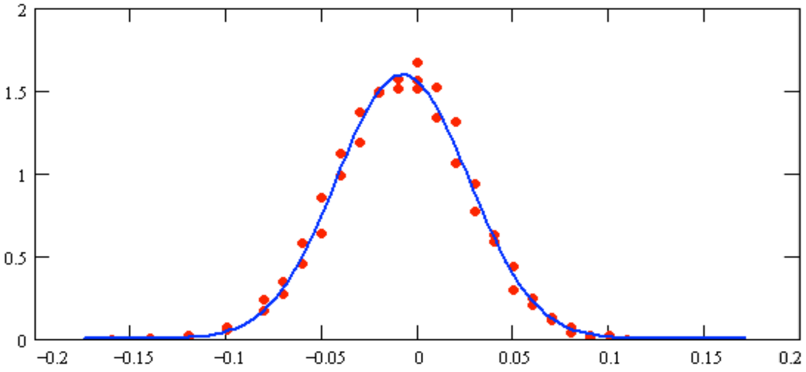
particle at distance 1 σ from centre
↔ 68.3 % of all beam particles

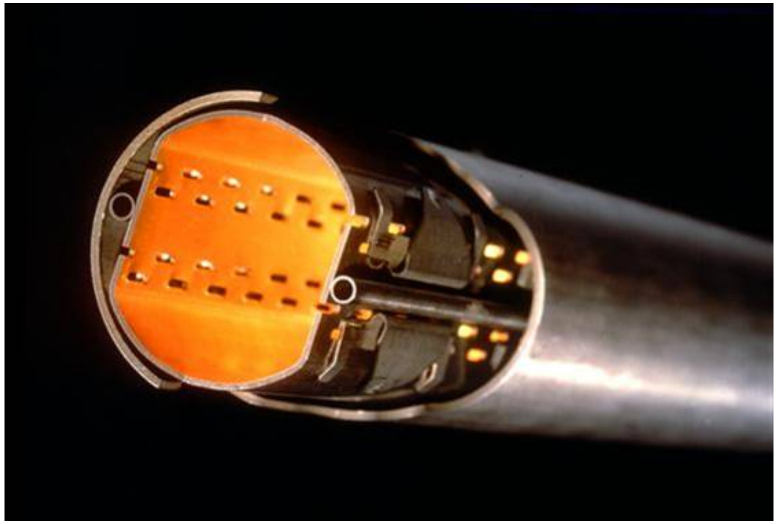
LHC:

$$\beta = 180\,m$$

$$\varepsilon = 5*10^{-10}\,m\,rad$$

$$\sigma = \sqrt{\varepsilon*\beta} = \sqrt{5*10^{-10}m*180m} = 0.3\,mm$$

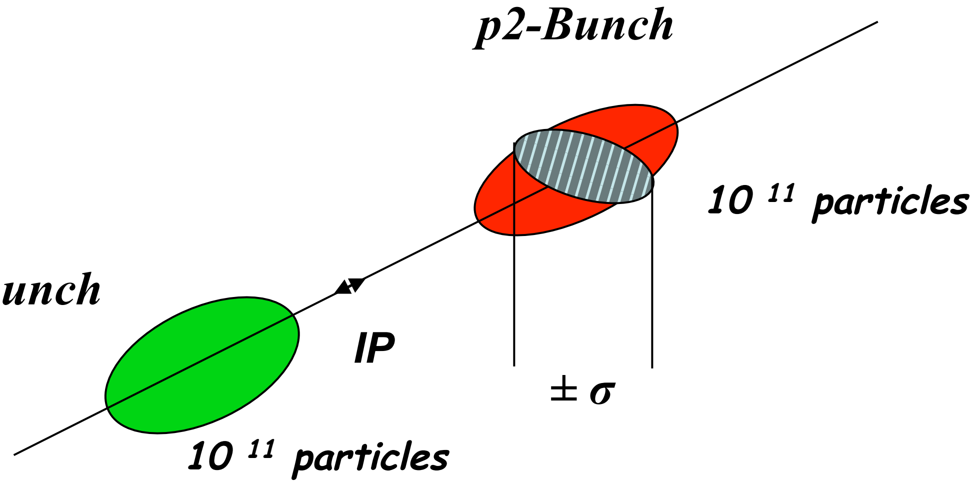




aperture requirements: $r_0 = 17 * \sigma$

5.) Luminosity

$$R = L * \Sigma_{react}$$



Example: Luminosity run at LHC

$$\beta_{x,y} = 0.55\ m$$

$$\varepsilon_{x,y} = 5 * 10^{-10}\ rad\ m$$

$$\sigma_{x,y} = 17\ \mu m$$

$$f_0 = 11.245\ kHz$$

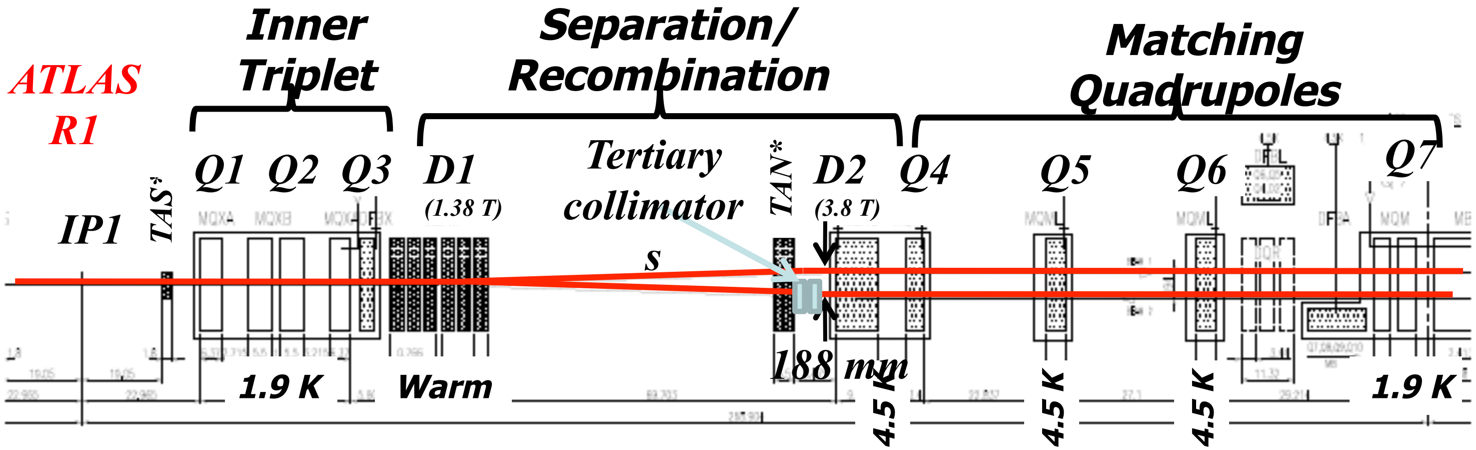
$$n_b = 2808$$

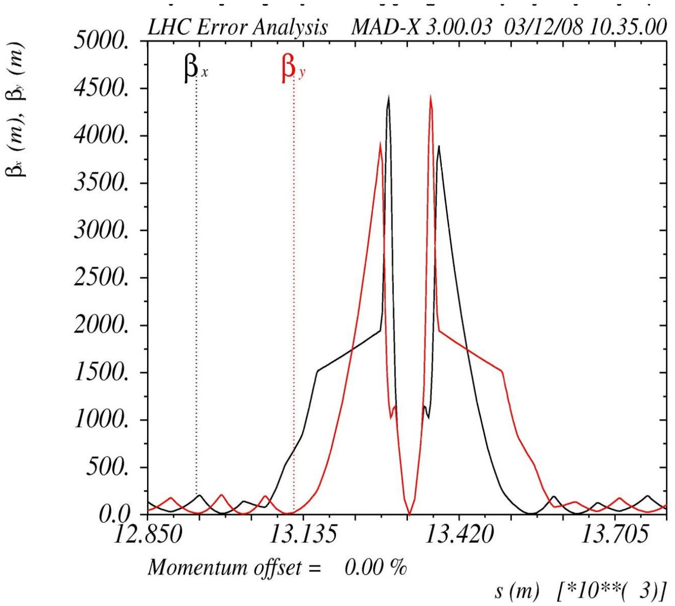
$$I_p = 584\ mA$$

$$L = \frac{1}{4\pi e^2 f_0 n_b} * \frac{I_{p1} I_{p2}}{\sigma_x \sigma_y}$$

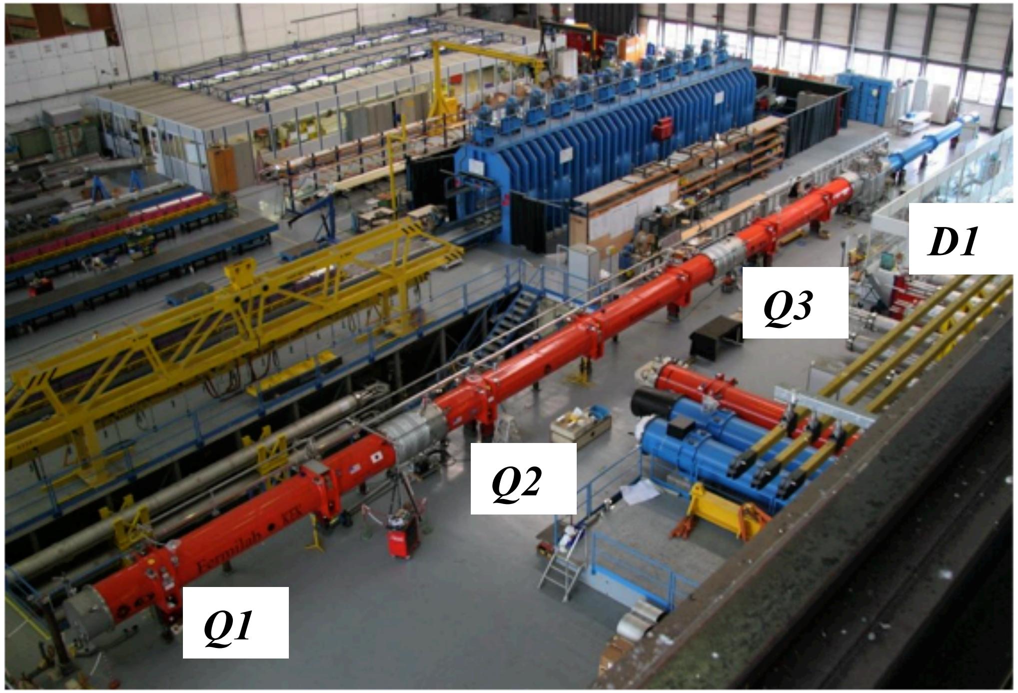
$$L = 1.0 * 10^{34}\ {}^{1}\!/_{cm^2 s}$$

The LHC Mini-Beta-Insertions





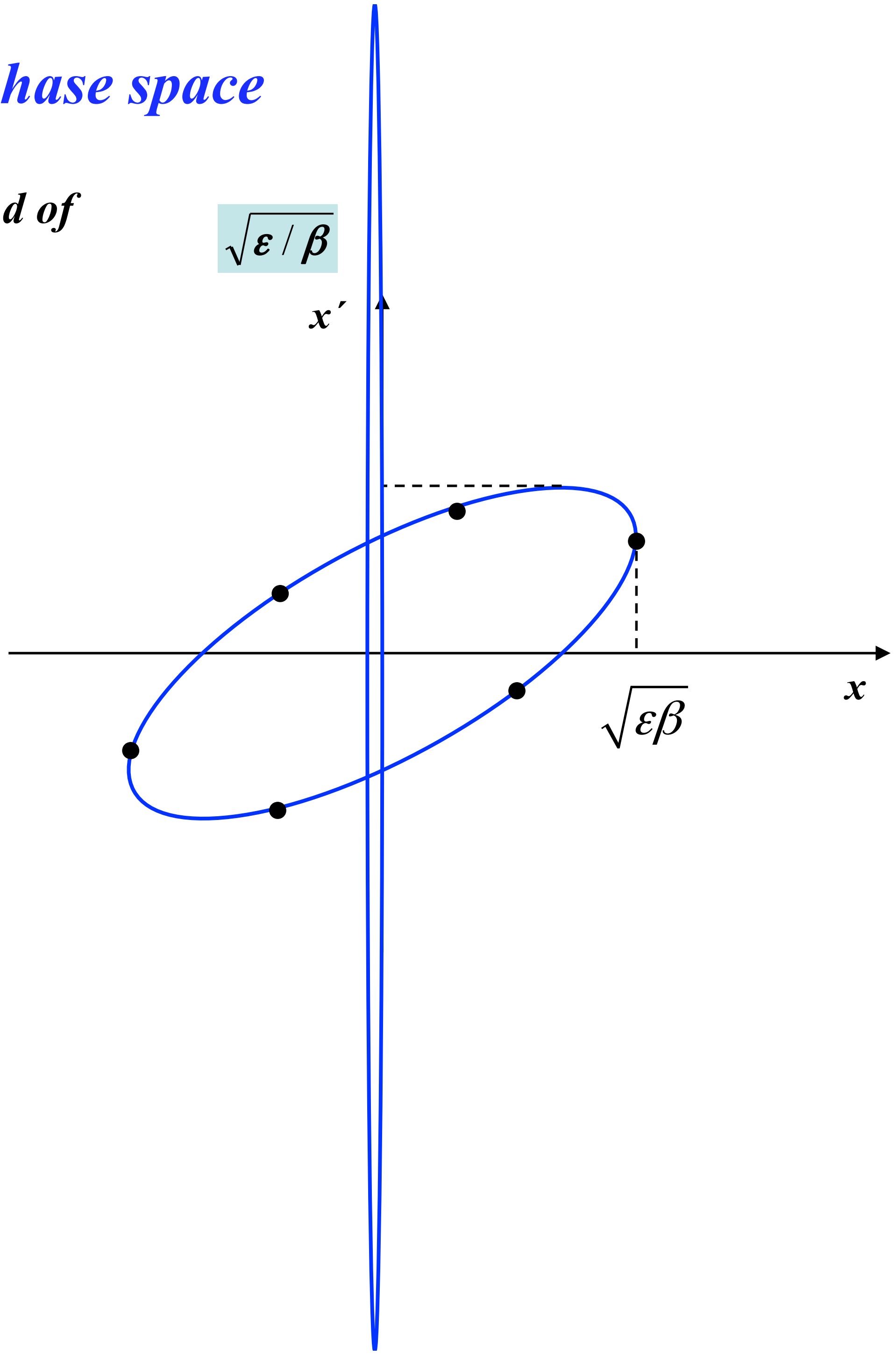
mini β optics



Mini-Beta-Insertions in phase space

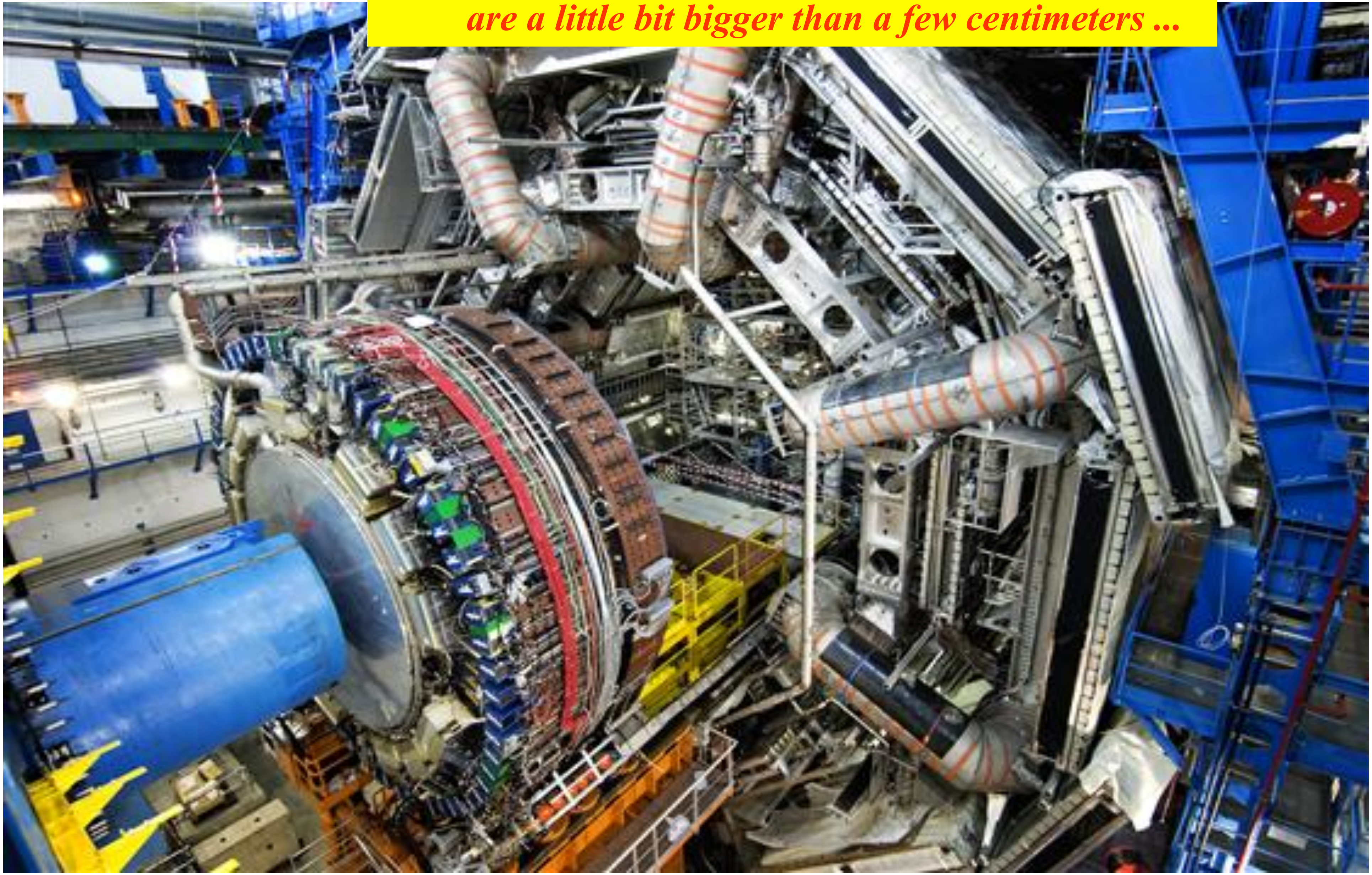
A mini-β insertion is always a kind of
special symmetric drift space.
→ greetings from Liouville

the smaller the beam size
the larger the bam divergence



... clearly there is an

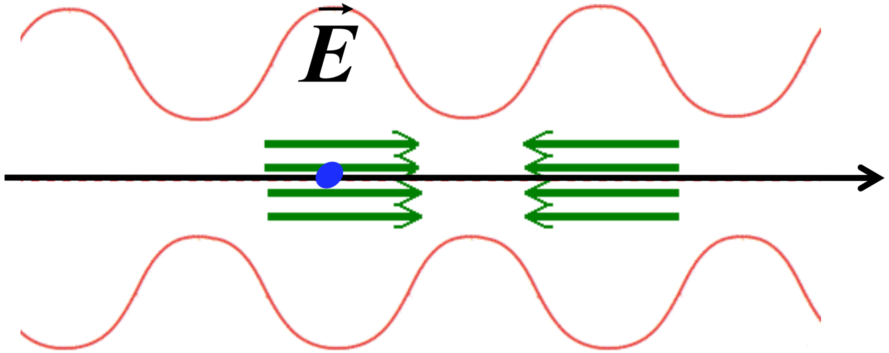
... unfortunately ... in general
high energy detectors that are
installed in that drift spaces
are a little bit bigger than a few centimeters ...

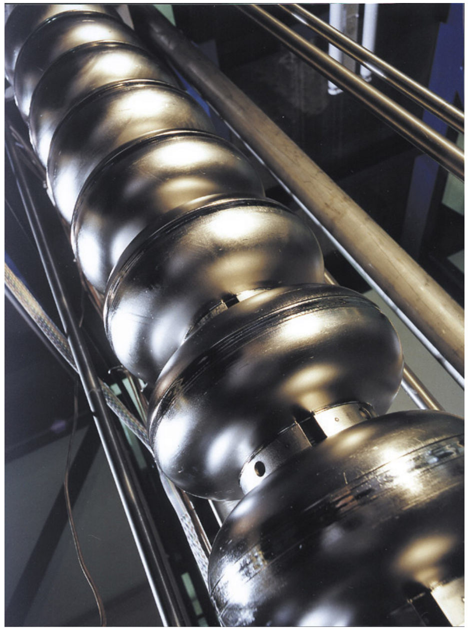


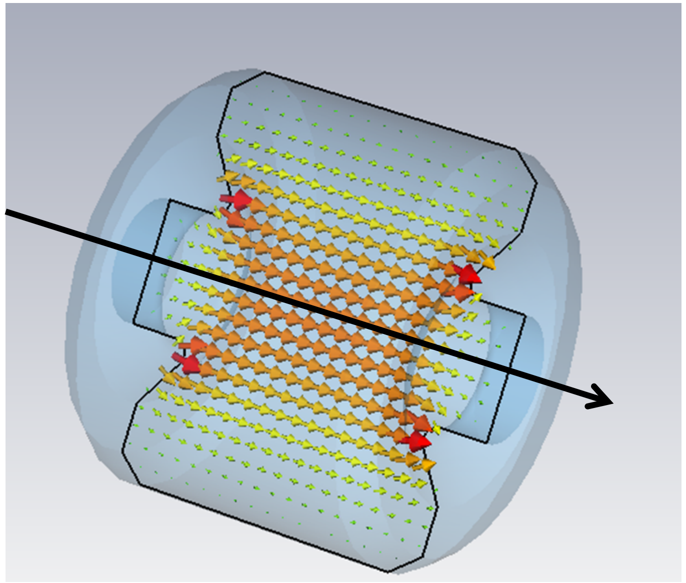
III. The Acceleration

Where is the acceleration?

Install an RF accelerating structure in the ring:







B. Salvant
N. Biancacci

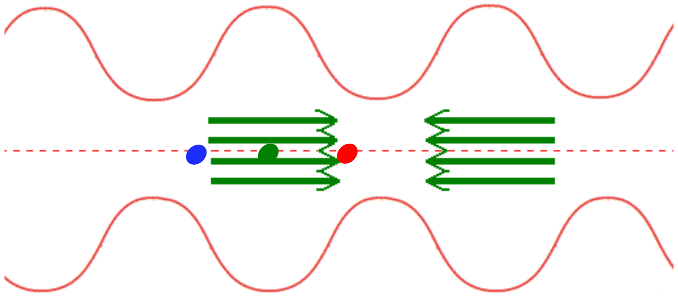
The Acceleration & "Phase Focusing"

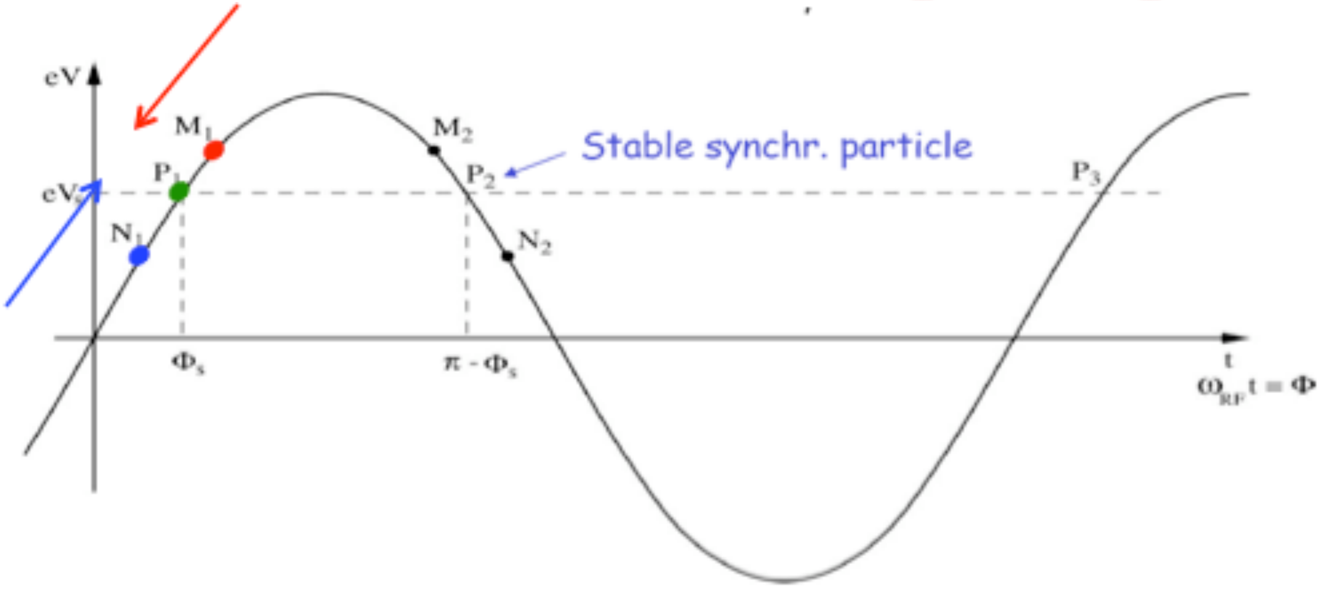
$\Delta p/p \neq 0$ below transition

ideal particle ●

particle with $\Delta p/p > 0$ ● *faster*

particle with $\Delta p/p < 0$ ● *slower*



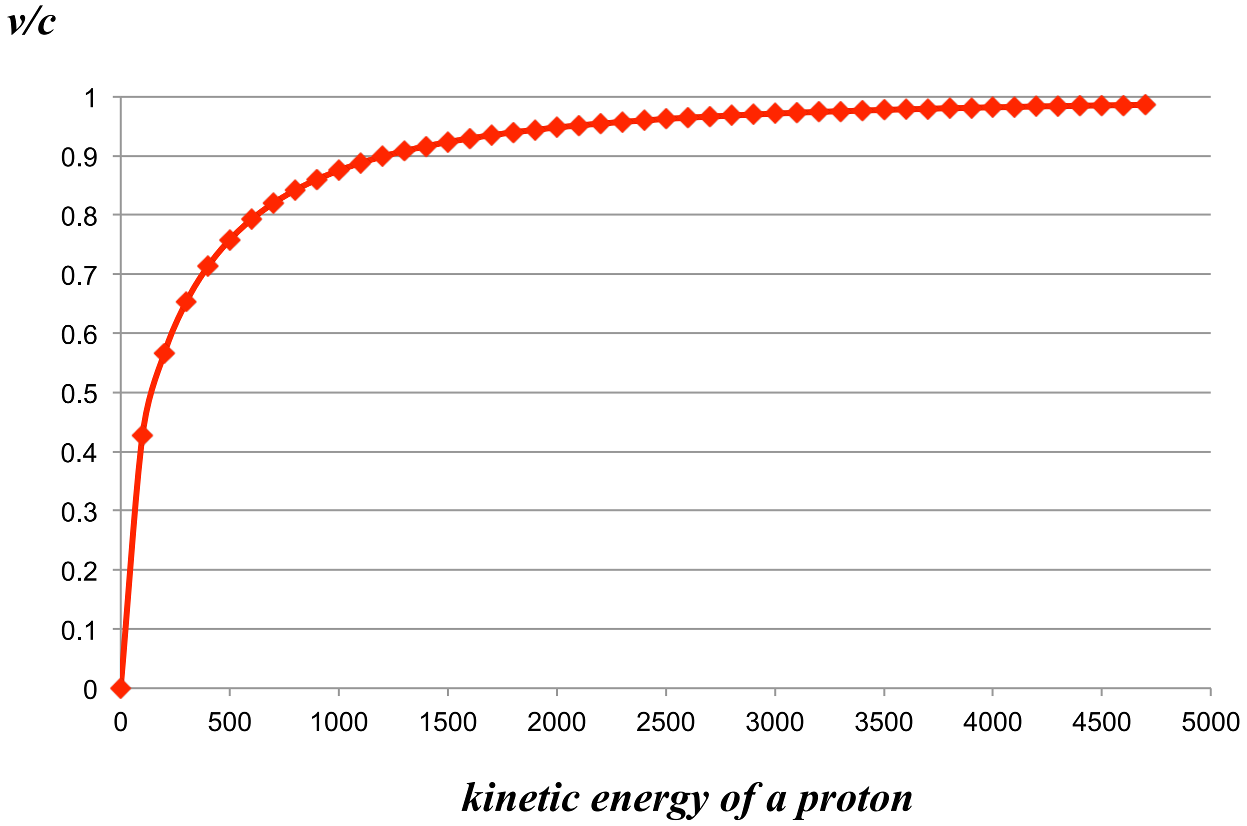


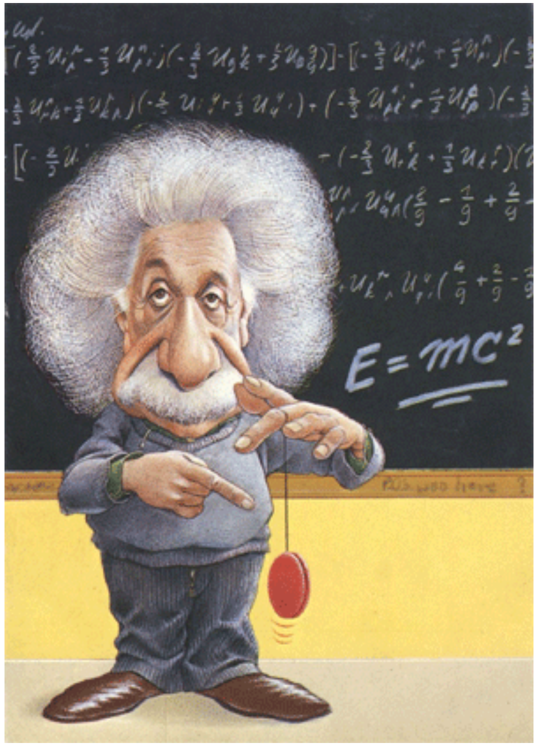
Focussing effect in the longitudinal direction keeping the particles close together
... forming a "bunch"

oscillation frequency: $f_s = f_{rev}\sqrt{-\frac{h\alpha_s}{2\pi} * \frac{qU_0\cos\phi_s}{E_s}}$ *≈ some Hz*

... so sorry, here we need help from Albert:

$$\gamma = \frac{E_{total}}{mc^2} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \longrightarrow \frac{v}{c} = \sqrt{1-\frac{mc^2}{E^2}}$$





... some when the particles do not get faster anymore

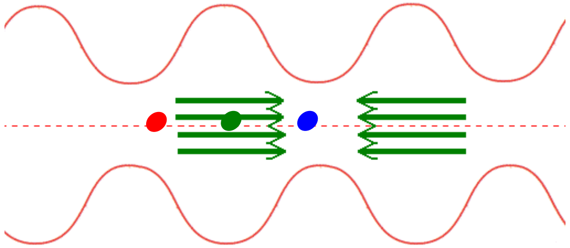
.... but heavier !

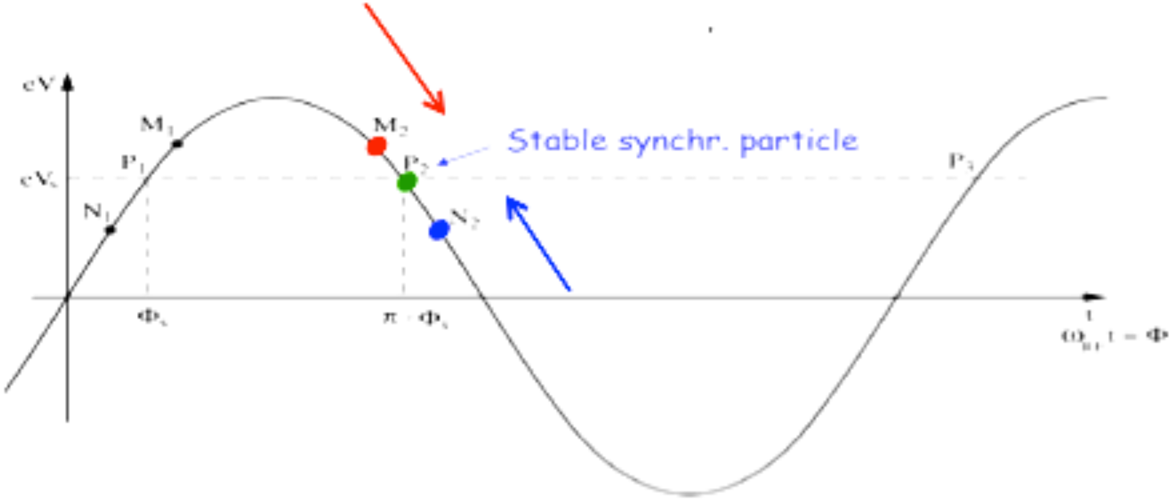
The Acceleration above transition

ideal particle ●

particle with $\Delta p/p > 0$ ● *heavier*

particle with $\Delta p/p < 0$ ● *lighter*



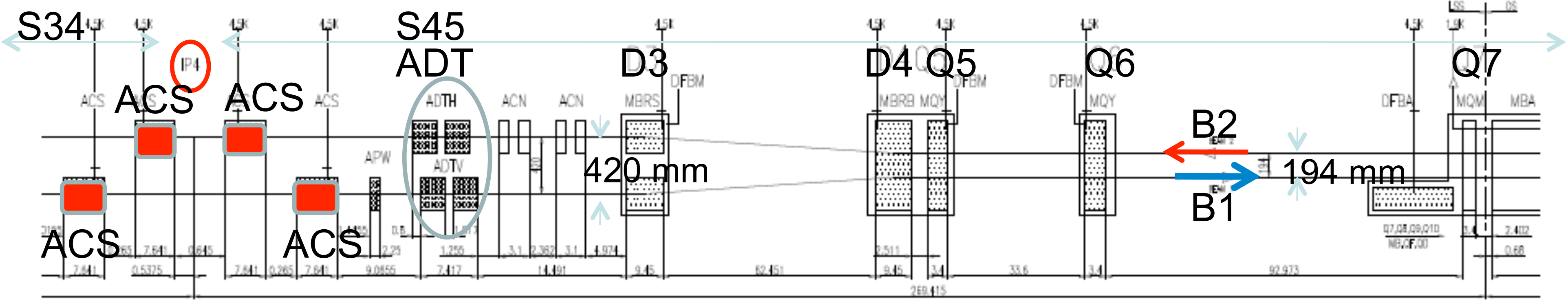


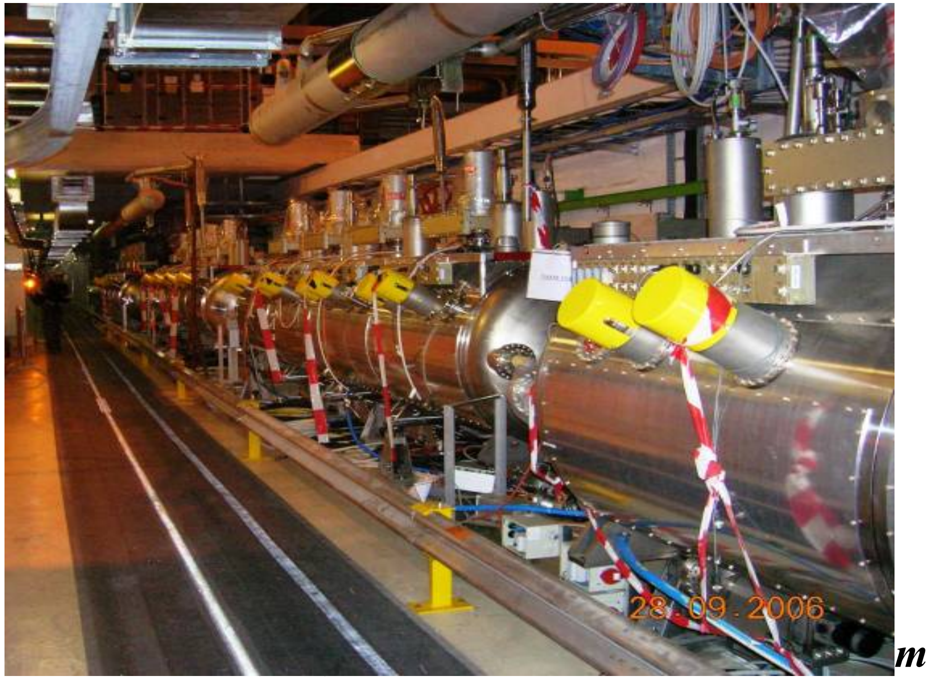
Focussing effect in the longitudinal direction keeping the particles close together ... forming a "bunch"

... and how do we accelerate now ???

with the dipole magnets !

The RF system: IR4



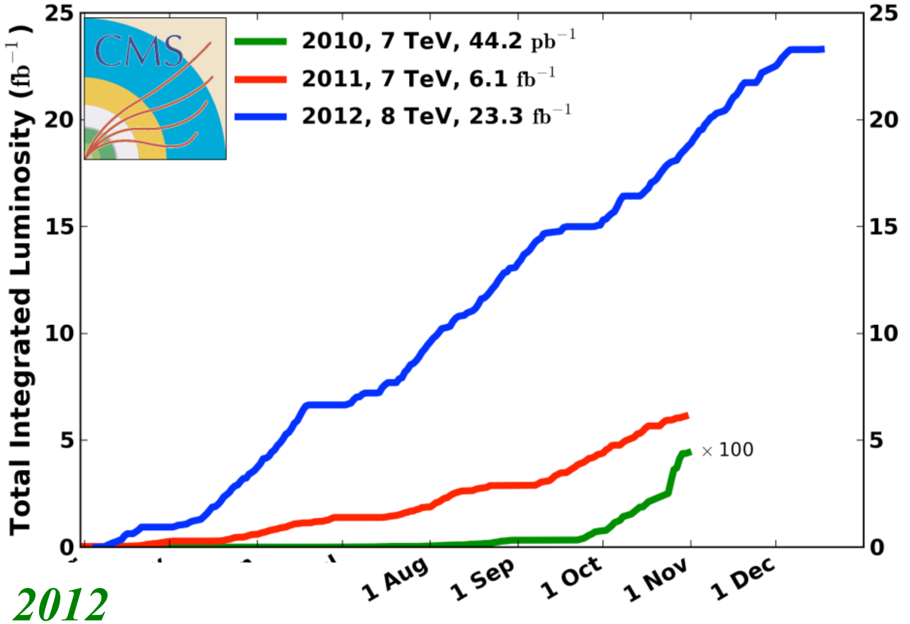


m

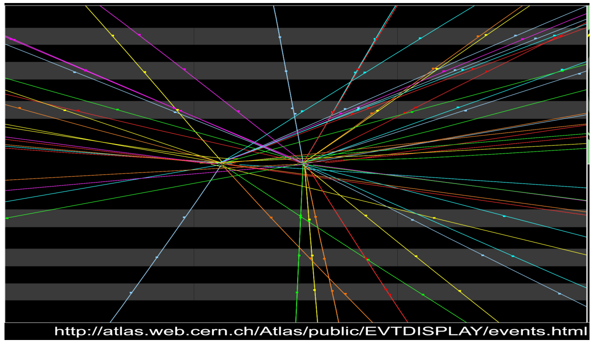
Nb on Cu cavities @4.5 K (=LEP2)
Beam pipe diam.=300mm

Bunch length (4σ)	*ns*	*1.06*
Energy spread (2σ)	*10^{-3}*	*0.22*
Synchr. rad. loss/turn	*keV*	*7*
Synchr. rad. power	*kW*	*3.6*
RF frequency	*MHz*	*400*
Harmonic number		*35640*
RF voltage/beam	*MV*	*16*
Energy gain/turn	*keV*	*485*
Synchrotron frequency	*Hz*	*23.0*

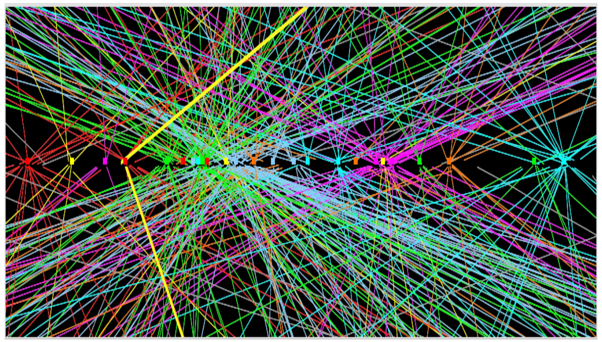
And still...
The LHC Performance in Run 1



	Design	*2012*
Momentum at collision	*7 TeV /c*	*4 TeV/c*
Luminosity	*10^{34} cm $^{-2}$ s^{-1}*	*$7.7 * 10^{33}$ cm $^{-2}$ s^{-1}*
Protons per bunch	*1.15×10^{11}*	*1.50×10^{11}*
Number of bunches/beam	*2808*	*1380*
Nominal bunch spacing	*25 ns*	*50ns*
Normalized emittance	*3.75 μm*	*2.5μm*
*beta **	*55 cm*	*60 cm*
rms beam size (arc)	*300 μm*	*350 μm*
rms beam size IP	*17 μm*	*20 μm*


http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

2 vertices

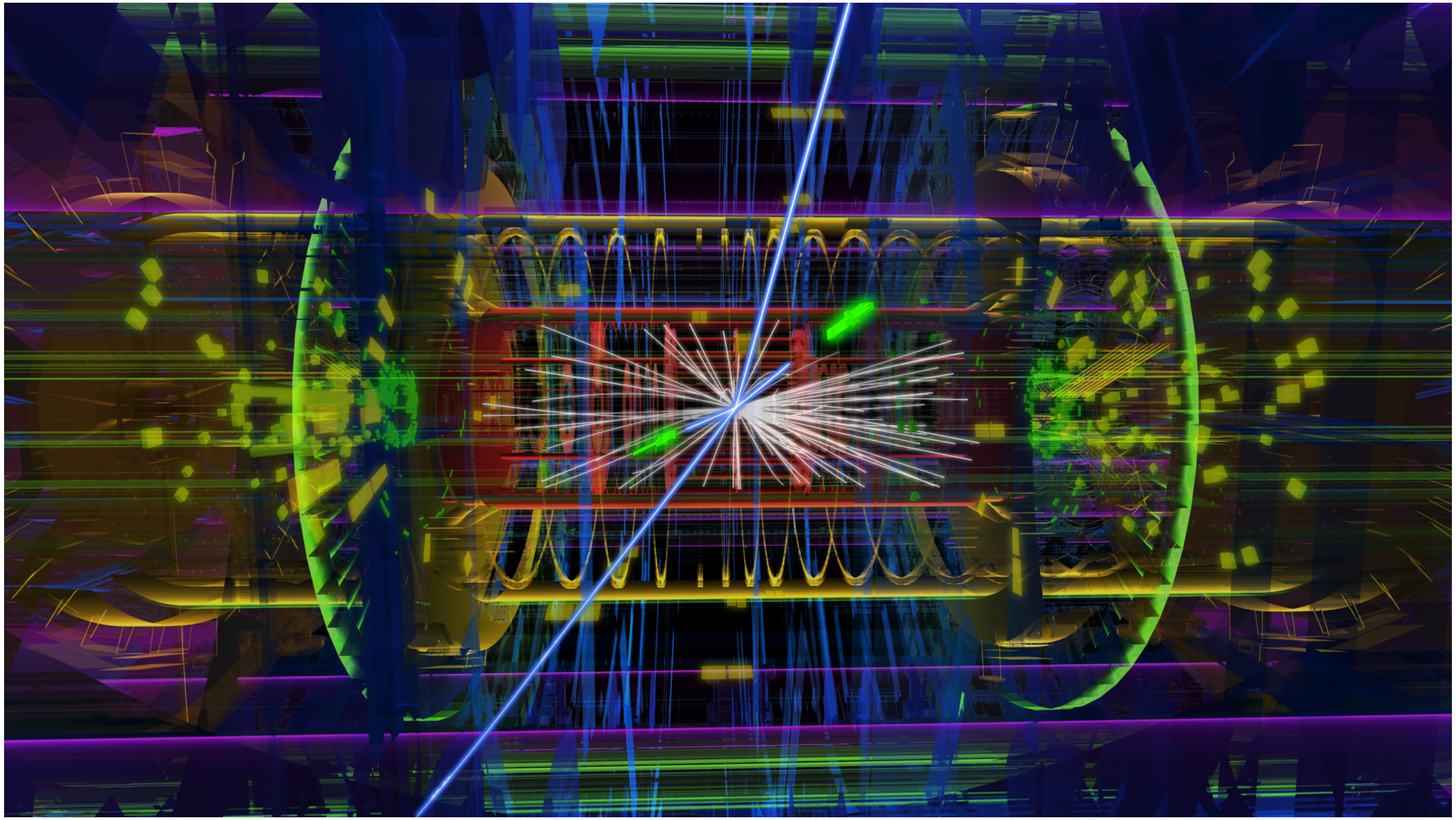


20 vertices

1.) Where are we ?

- ***Standard Model of HEP***
- ***Higgs discovery***

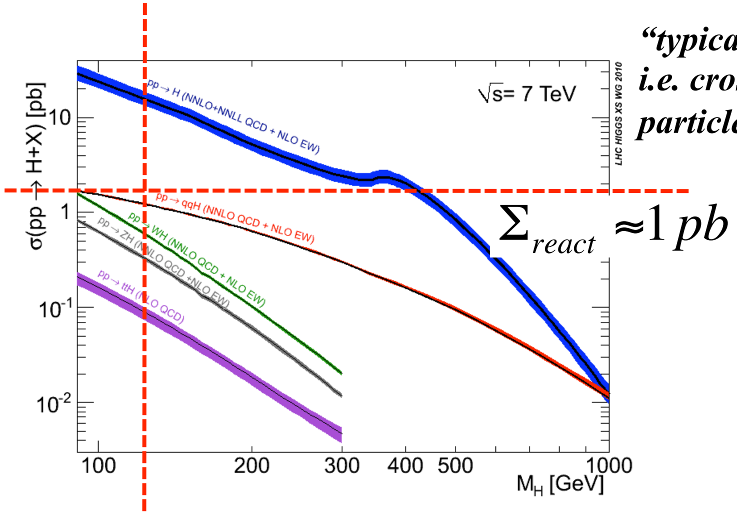
High Light of the HEP-Year 2012 / 13 naturally the HIGGS



ATLAS event display: Higgs => two electrons & two muons

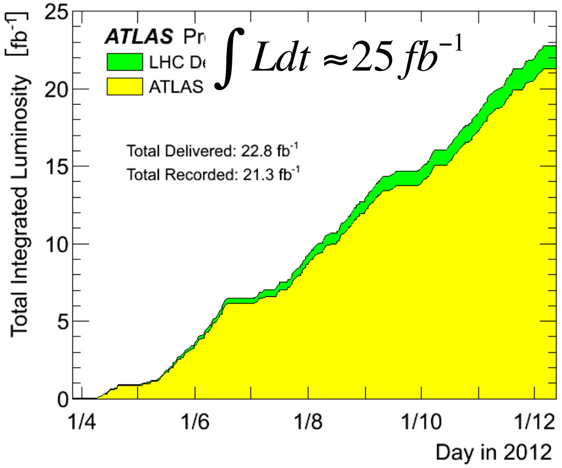
The High light of the year

***production rate of events* is *determined by* the *cross section* Σ_{react}**
and a parameter L that is given by the design of the accelerator:
… the luminosity



$$\Sigma_{react} \approx 1\,pb$$

"typical particle size"
i.e. cross section for
particle production



$$\int Ldt \approx 25\,fb^{-1}$$

accumulated
collision rate
in LHC run 1

$$1b = 10^{-24}\,cm^2 \quad = \quad 1/mio * 1/mio * 1/mio * \frac{1}{100}\,mm^2$$

The particles are "very small"

$$R = L * \Sigma_{react} \quad \approx 10^{-12}\,b \cdot 25\,\frac{1}{10^{-15}\,b} = some\,1000\,H$$

During collider run we had in Run 1 …
1400 bunches circulating,
with 800 Mio proton collisions per second in the experiments
and collected only 450 Higgs particles in three years.

2.) Where do we go ?

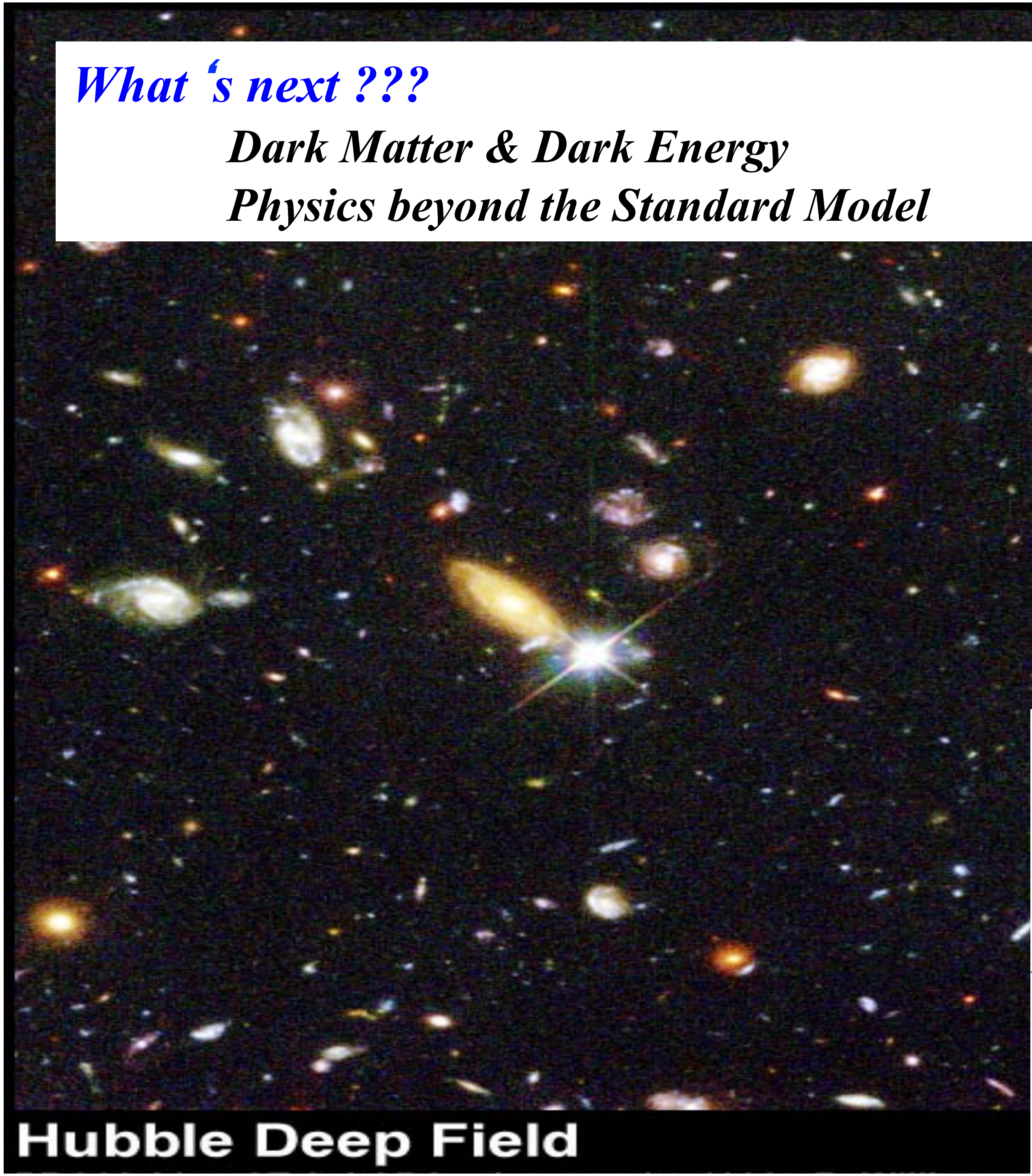
**** Physics beyond the Standard Model***

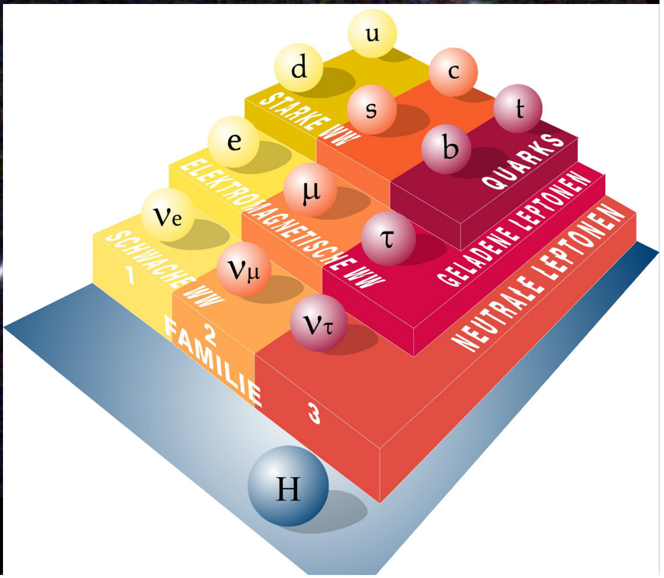
**** Dark Matter / Dark Energy***

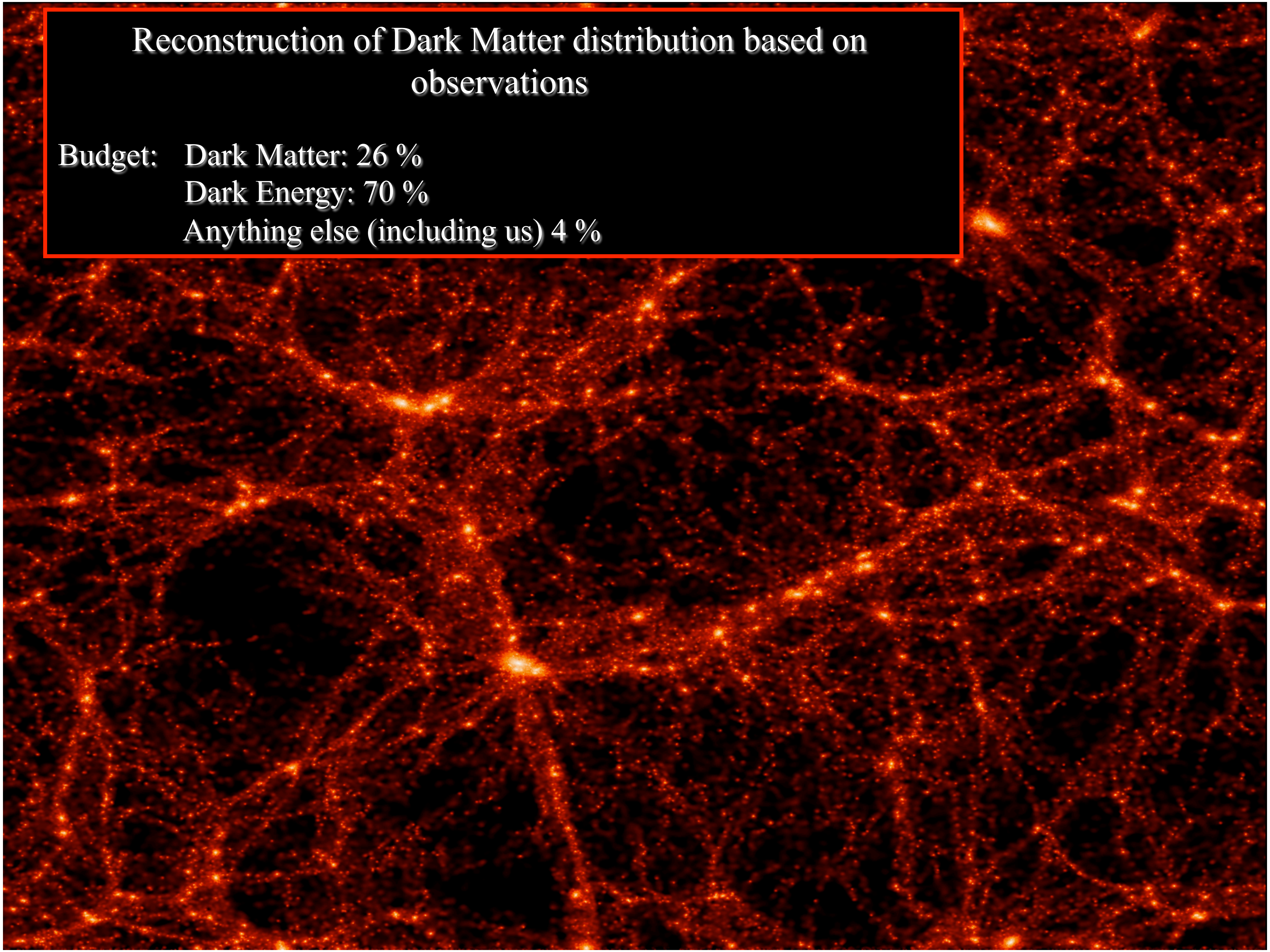
What ‘s next ???

Dark Matter & Dark Energy

Physics beyond the Standard Model







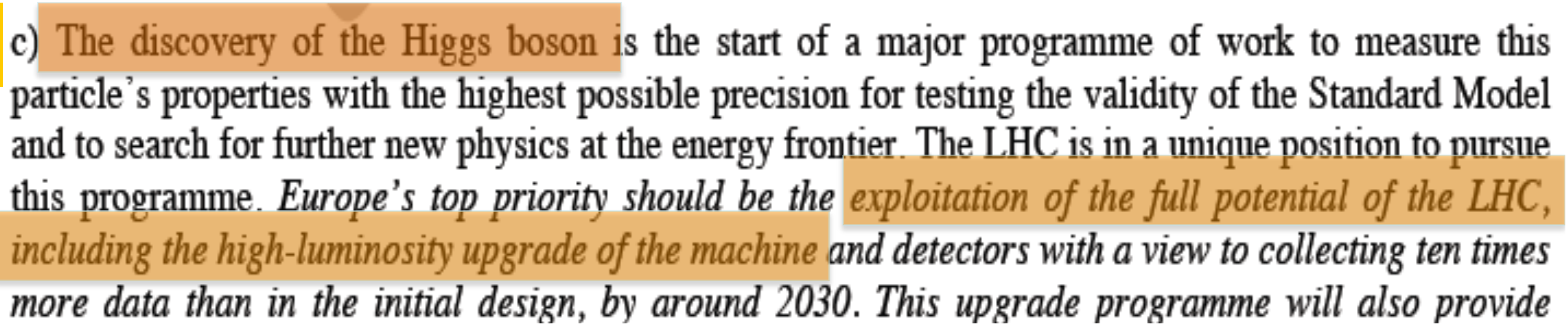
Reconstruction of Dark Matter distribution based on observations

Budget: Dark Matter: 26 %
Dark Energy: 70 %
Anything else (including us) 4 %

Future Projects

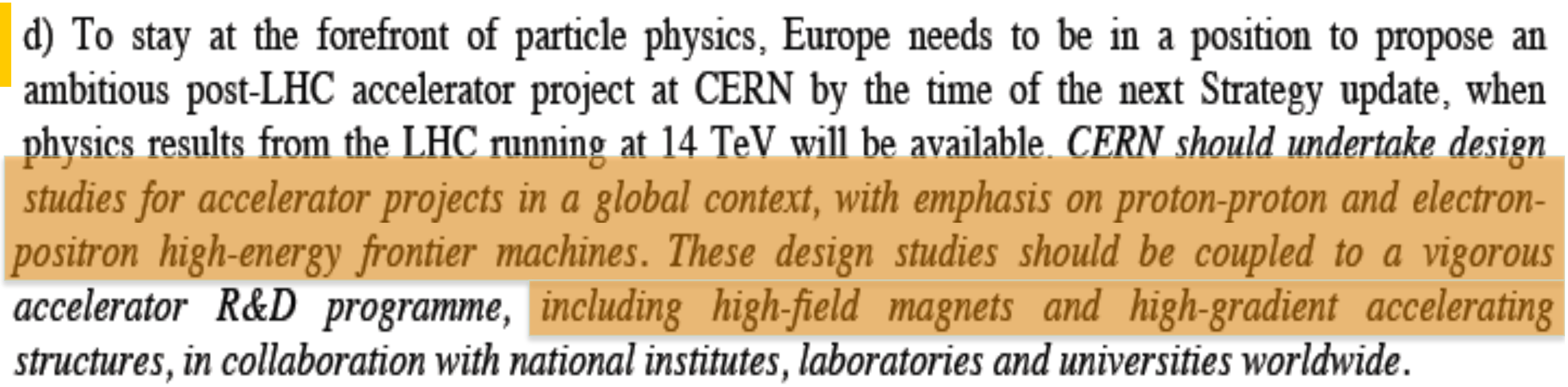
Recommendations from European Strategy Group

#1



c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide*

#2



d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

→Proton –Proton Colliders ***=> e+/e- colliders***

LHC / HL-LHC, HE-LHC ***TLEP, CLIC***

4.) Push for higher energy: FCC

* increasing the ring size
* stronger magnets

FCC-pp - Collider

The Next Generation Ring Collider

$B=16$ T

$C_0=100$ km

$E_{cm}=100$ TeV