Accelerator Physics

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A Short Introduction … LOL

In the end and after all … : We try to explain the structure of "hadronic matter" in the universe.

In short words: "What is going on, up there ???"

Eine der wichtigsten Fragen in der Physik des 20ten Jahrhunderts:

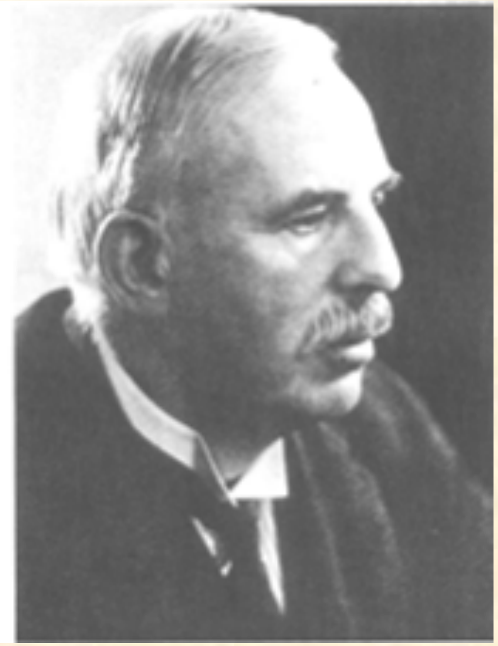
Woraus besteht Goldfolie ?

naja, a bissi mehr wissenschaftlich:

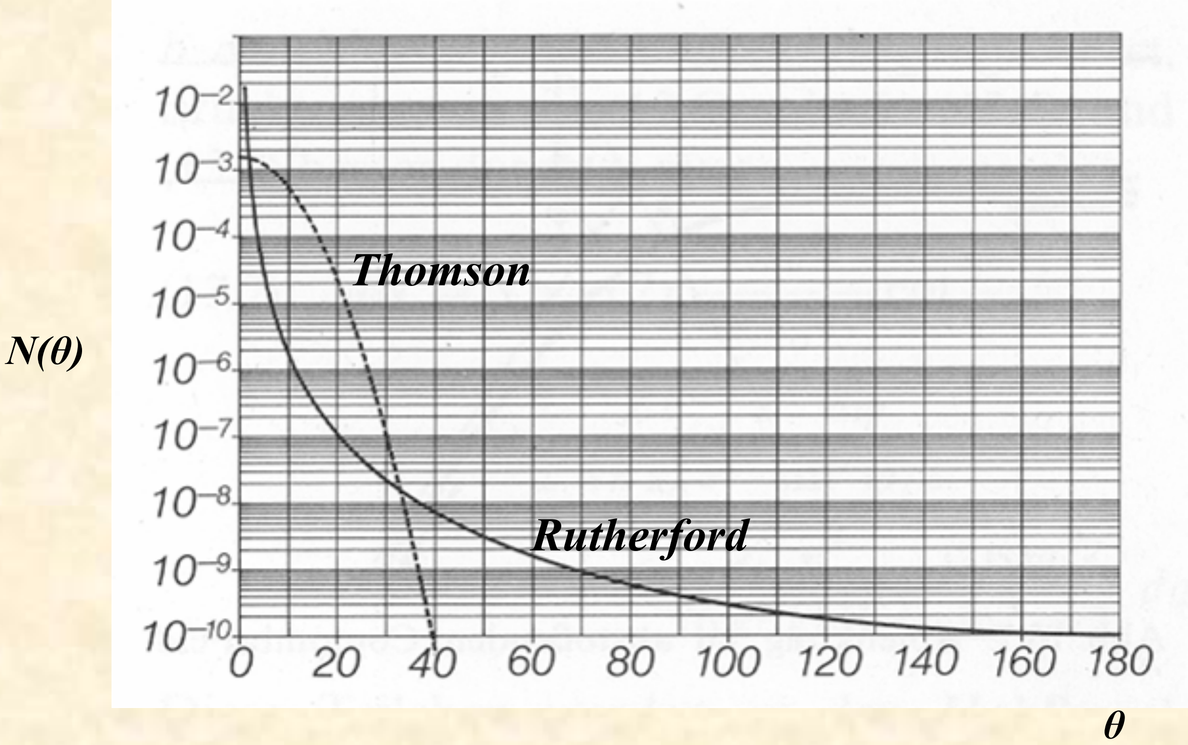
woraus besteht Materie ??

oder noch besser …

wie sind positive und negative Ladungen in der Materie verteilt ???



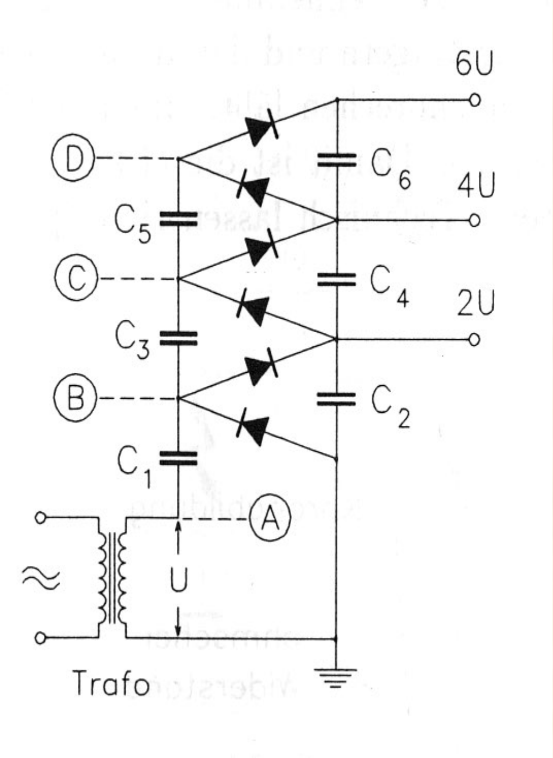
$$N(\theta) = \frac{N_i n t Z^2 e^4}{(8\pi\varepsilon_0)^2 r^2 K^2} * \frac{1}{\sin^4(\theta / 2)}$$



Rutherford Scattering, 1911

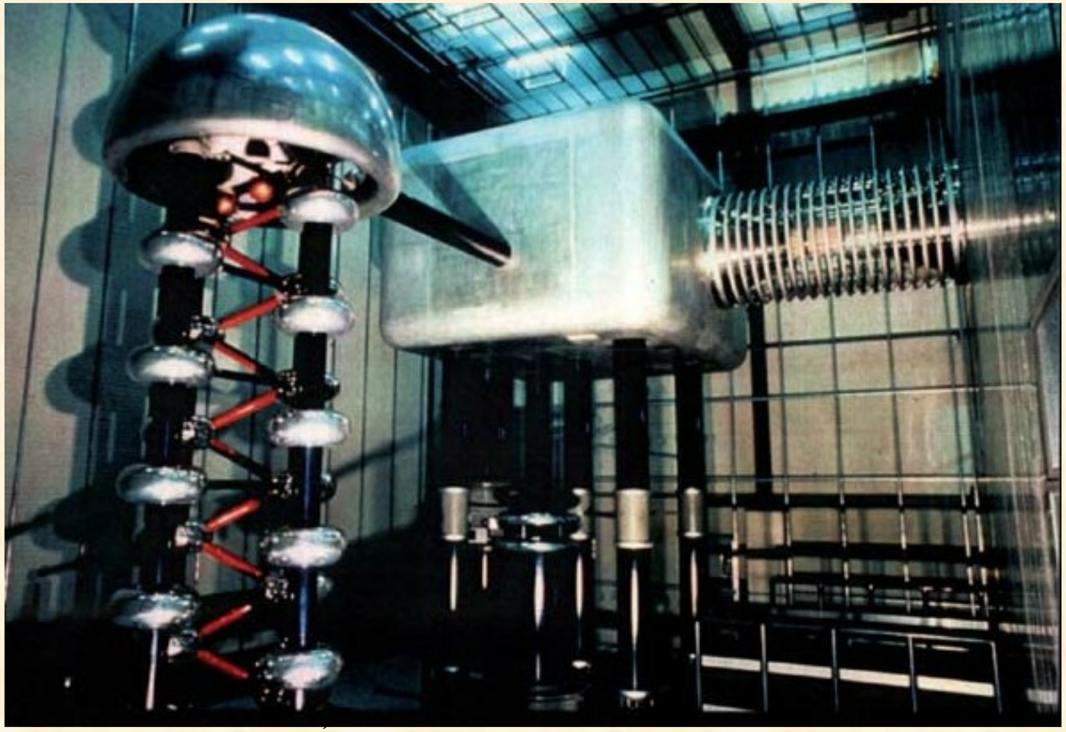
Using radioactive particle sources:
α-particles of some MeV energy

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*

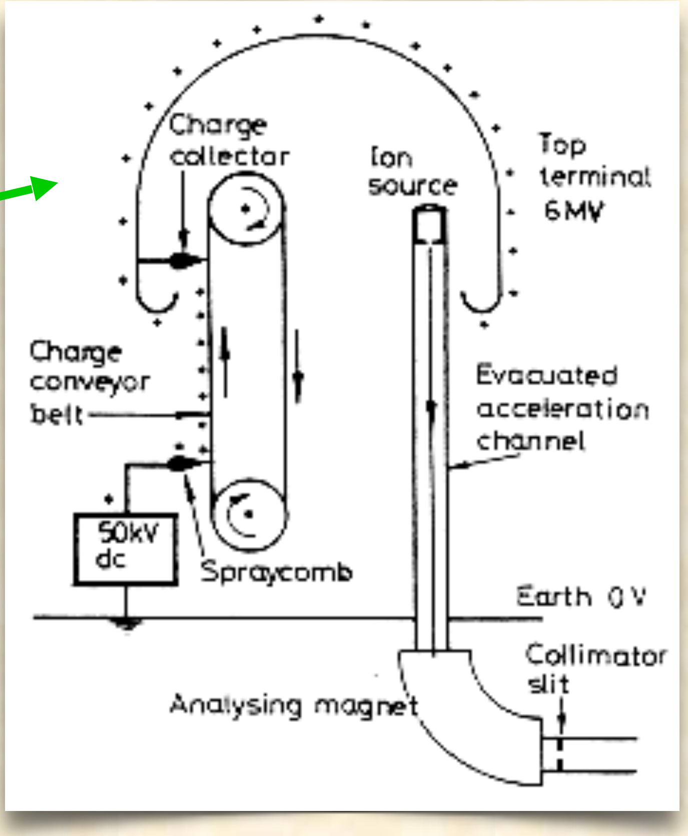
Technically: rectifier circuit, built of capacitors and diodes (Greinacher)

Problem:
DC Voltage can only be used once

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

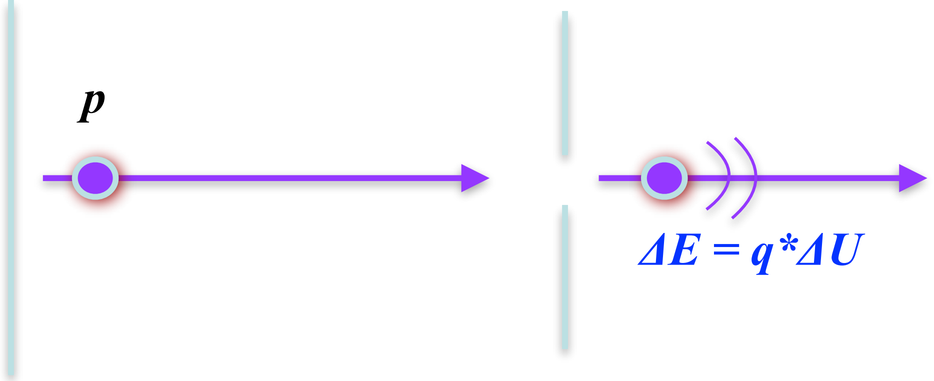
creating high voltages by mechanical transport of charges

* *Terminal Potential: $U \approx 12 \ldots 28$ MV*
using high pressure gas to suppress discharge (SF_6)



*Energie=Ladung * Spannung (Differenz)*

Das Prinzip:



$\Delta E = q * \Delta U$

$U = 12$ MV

$U = 0$

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

Gretchen Frage (J.W. Goethe, Faust)

Fallen die Dinger eigentlich runter ?

$l_{vdG} = 30m$

$v \approx 10\,\%\,c \approx 3 * 10^7 \; m/s$

$\Delta t = 1\mu s$

Free Fall in Vacuum:

$$s = \frac{1}{2} g t^2$$

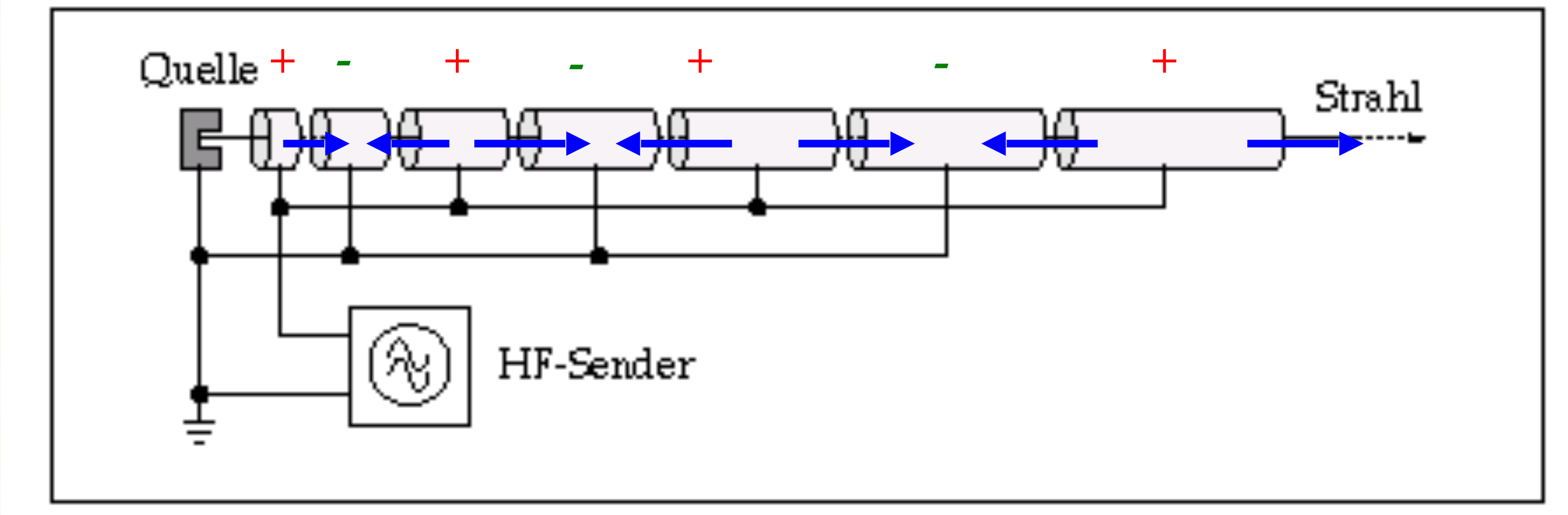
$$s = \frac{1}{2} \cdot 10 \frac{m}{s^2} \cdot (1\mu s)^2$$

$$s = 5 \cdot 10^{-12} m = 5pm$$

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

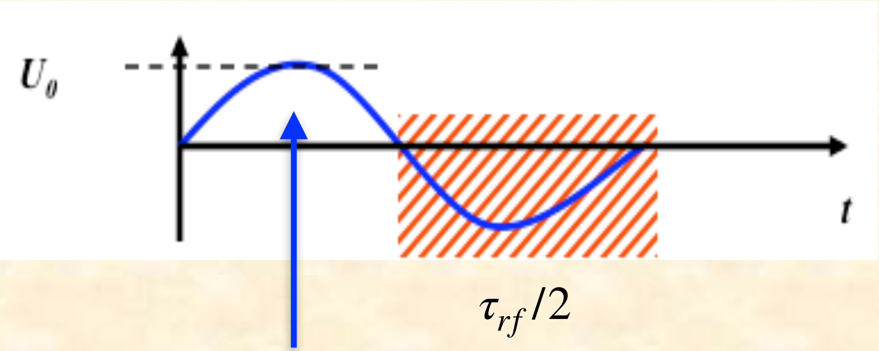
$$E_n = \bigcirc\!\!\!\!\!\!\! n \cdot q \cdot U_0 \cdot \sin \psi_s$$

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



$\tau_{rf}/2$

idealer Zeitpunkt
90 grad —> sin(90⁰)=1

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

Length of the Drift Tube: $l_n = v_n \cdot \frac{\tau_{rf}}{2}$

Kinetic Energy of the Particles $E_n = \frac{1}{2}mv^2 \longrightarrow v_n = \sqrt{2E_n/m}$

mit der kin. Energie $E_n = n \cdot q \cdot U_0 \cdot sin\ \psi_s$

ergibt das $v_n = \sqrt{\frac{2 \cdot n \cdot q \cdot U_0 \cdot sin(\psi_s)}{m}}$

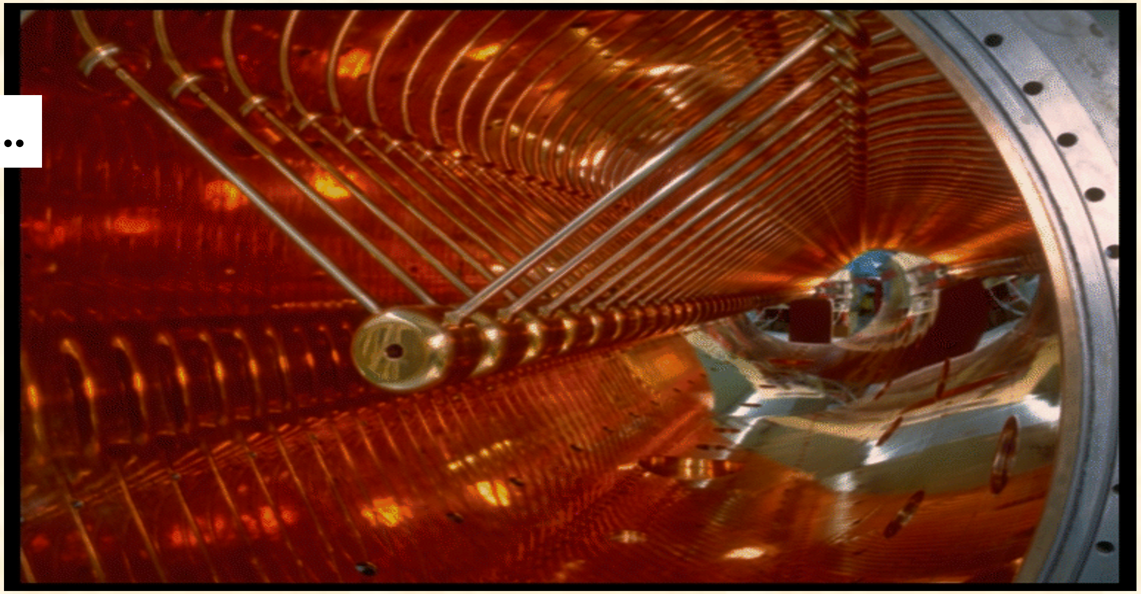
Bauplan fuer einen Wideroe Beschleuniger: $l_n = v_n \cdot \frac{\tau_{rf}}{2} = \frac{1}{f_{rf}} \cdot \sqrt{\frac{n \cdot q \cdot U_0 \cdot sin\psi_s}{2m}}$

Und so sieht das innen drinnen aus:

Achtung !!! valid for non relativistic particles ...

Energy: ≈ 20 MeV per Nucleon

$\beta = v/c \approx 0.04 \dots 0.6$, *Particles: Protons/Ions*



Zahlenbeispiel:

total energy $E_{total} = E_{kin} + m_0c^2$

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

Ruhe-Energie $E_0 = m_0c^2$

Linac III:

$E_{total} = 988\ MeV$

$m_0c^2 = 938\ MeV$

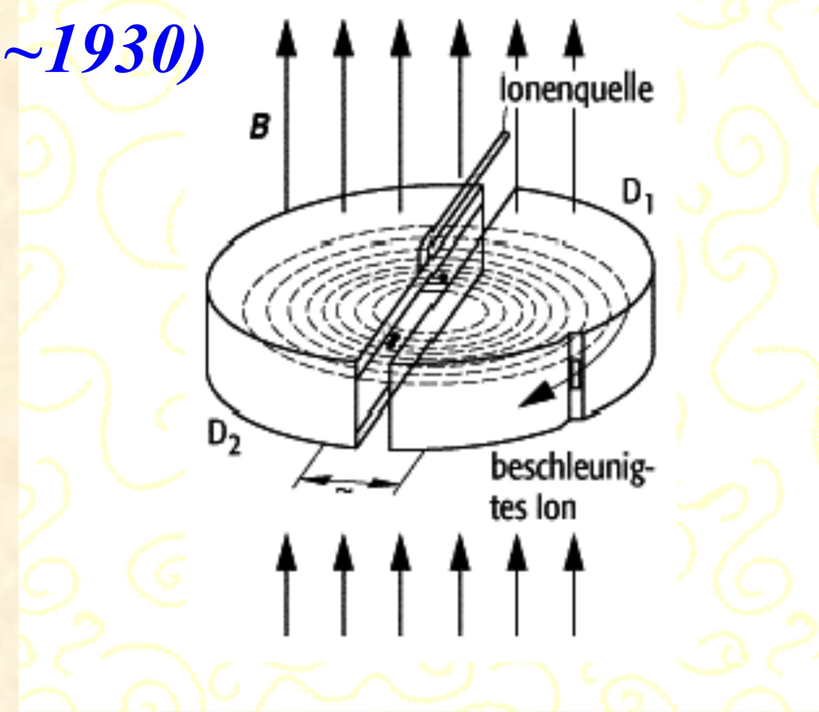
$E_{kin} = 50\ MeV$

man erinnert sich: $m \to \gamma \cdot m_0$

$$\gamma = \frac{E_{ges}}{E_0} = \frac{988}{938} = 1.05$$

—> im klassischen Bereich

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



Problem:
Linacs werden bei v=c sehr schnell sehr lanngggg.

—> Man erhaelt ne kompakte (d.h. billigere) Maschine,
wenn man den Orbit der Teilchen aufwickelt.

Idea: Apply a magnetic field: $B = const$

Lorentzforce

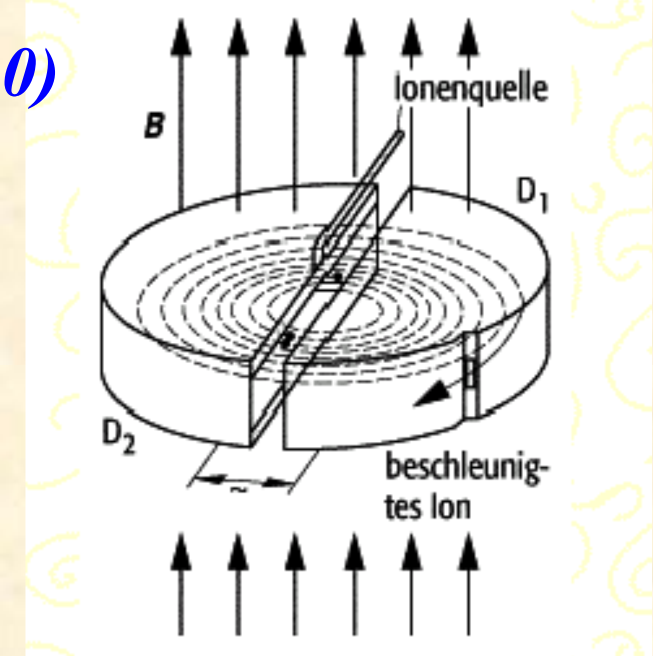
$$F = q \cdot v \cdot B$$

geladene Teilchen in Bewegung werden im Magnetfeld abgelenkt.

Kreisbahn-Bedingung:
Zentrifugalkraft wird durch die entgegengesetzte Lorentz-Kraft aufgehoben.

$$\left.\begin{array}{l} \boxed{F_{Lorentz} = F_{zentrifugal}} \\ q \cdot v \cdot B = \dfrac{mv^2}{r} \end{array}\right\} \quad B \cdot R = \frac{mv}{q} \longrightarrow B \cdot R = \frac{p}{q}$$

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



revolution frequency

$$\omega_{revol} = \frac{v}{r} = \frac{q}{m} \cdot B = \quad const!!!$$

Die Umlaufs-frequenz im Cyclotron ist konstant.
Wir lassen eine gleich-grosse konstante RF frequenz
auf die Teilchen los und die Kiste funktioniert.

increasing radius for increasing momentum ➔ ***Spiral Trajectory***

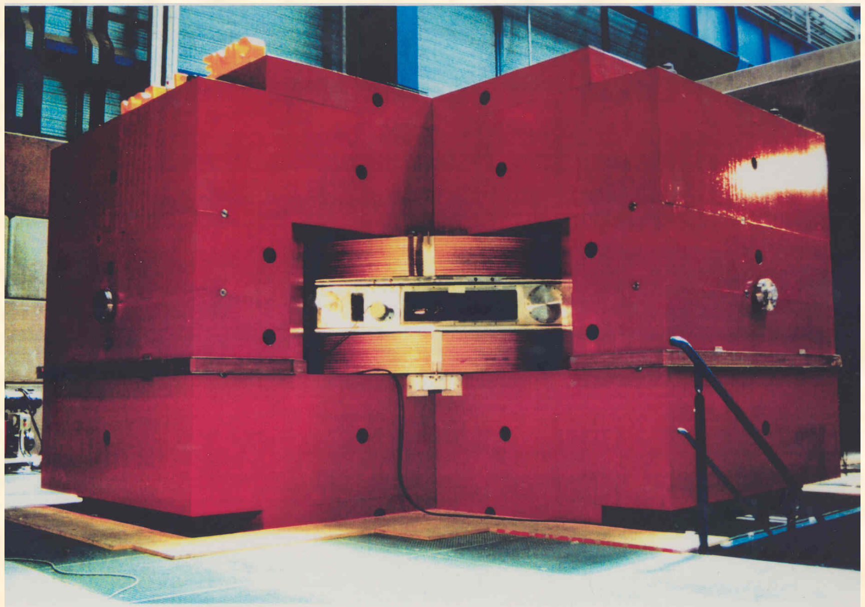
$\omega_{rf} = \omega_{revolution}$ **oder** $\omega_{rf} = h \cdot \omega_{revolution}$

Problem: Albert !!!

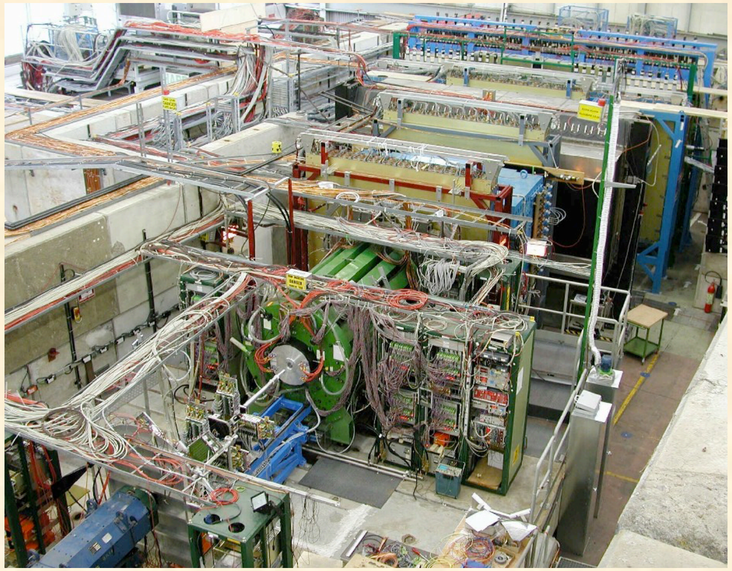
$$m \rightarrow \gamma \cdot m_0$$

$$\omega_{revol} = \frac{q}{\boxed{\gamma \; m}} \neq \; const$$

Synchro-Cyclotron
Korrektur der RF
Frequenz

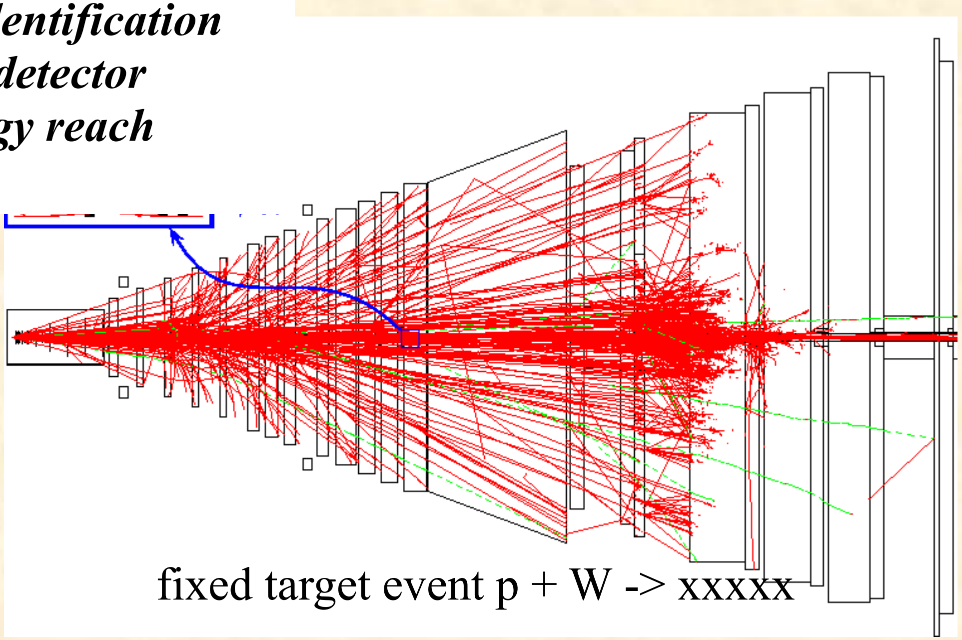


Fixed target experiments:



HARP Detector, CERN

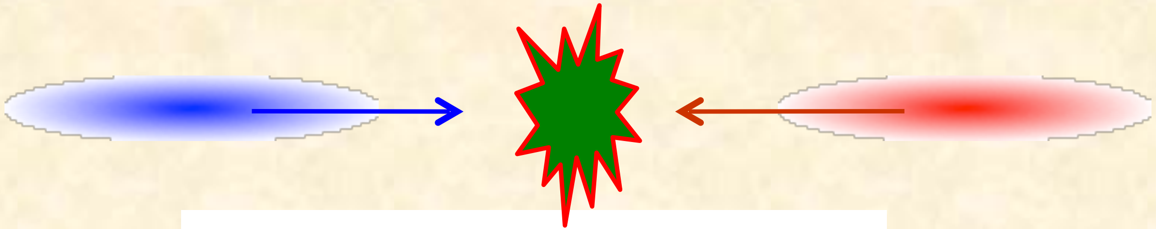
high event rate
easy track identification
asymmetric detector
limited energy reach



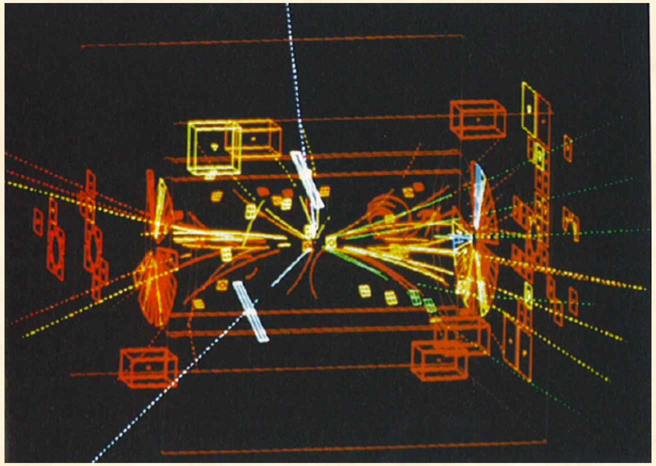
fixed target event p + W -> xxxxx

Collider experiments:

$E=mc^2$

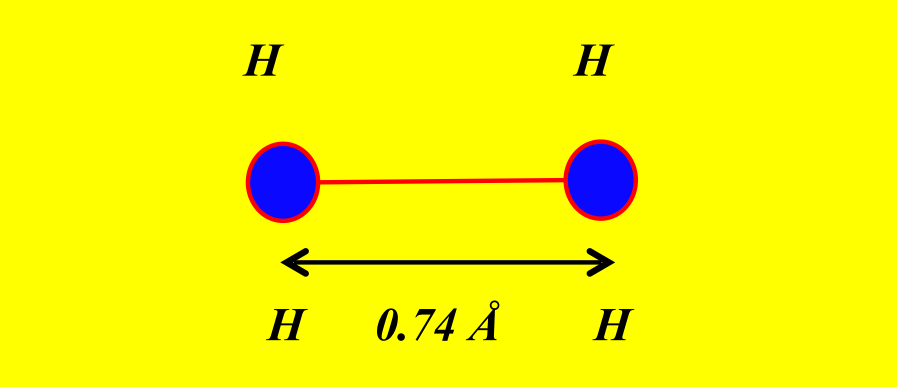


low event rate (luminosity)
challenging track identification
symmetric detector
$E_{lab} = E_{cm}$



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

Particle Density in matter

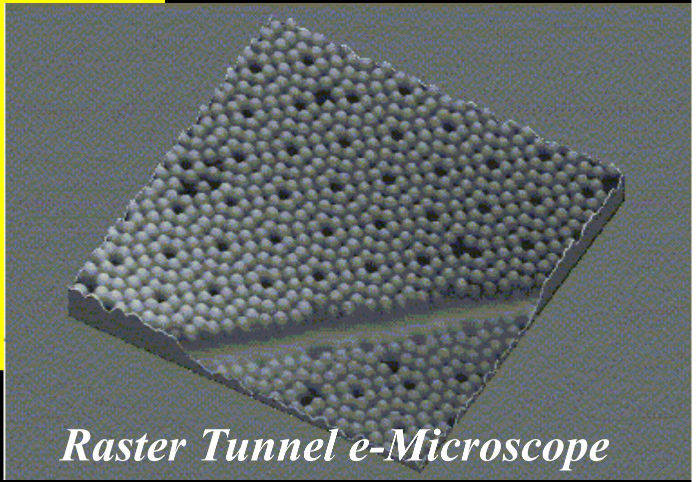


Atomic Distance in Hydrogen Molecule

$R_B \approx 0.5$ Å

in solids / fluids $\lambda \approx 1 \ldots 3$ Å $(1 \ldots 3 * 10^{-10}$ m)

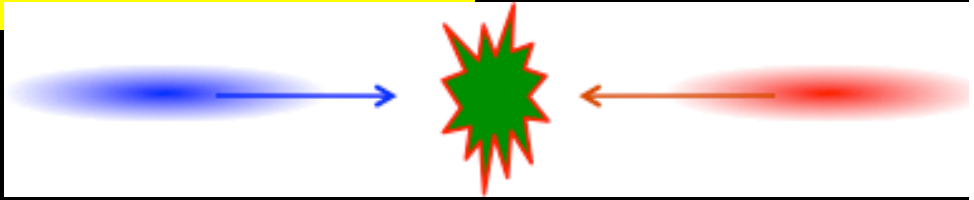
in gases $\lambda \approx 35$ Å $= 3.5$ nm



Raster Tunnel e-Microscope

Particle Distance in Accelerators: $\lambda \approx 600$ nm (Arc) … 300nm (IP LEP)

$= 3000$ Å



II.)

A Bit of Theory

The big storage rings: „Synchrotrons“

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:

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

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

equivalent electrical field: E

Technical limit for electrical fields:

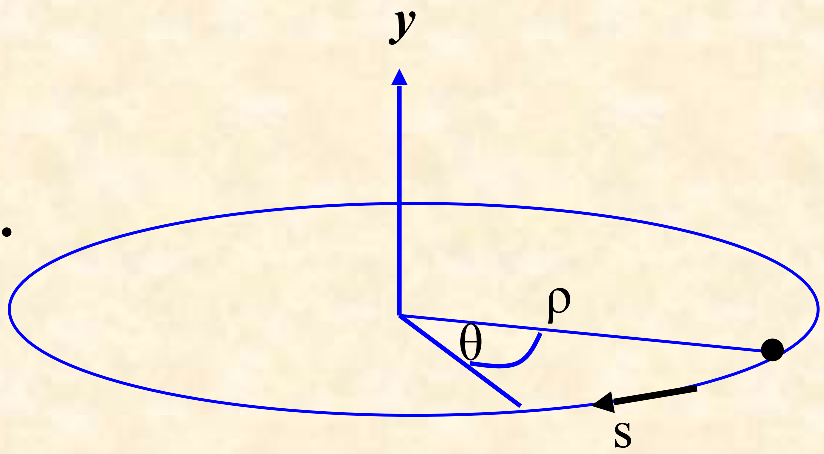
$$E \leq 1 \frac{MV}{m}$$

Ein Speicherring besteht aus
Magneten, Magneten und Magneten

***und ein wenig Vakuum-Kammern, Strahldiagnose,** und RF Systemen*

The ideal circular orbit

… das hatten wir schon.



circular coordinate system

condition for circular orbit:

Lorentz force

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

centrifugal force

$$F_{centr} = \frac{\gamma\, m_0\, v^2}{\rho}$$

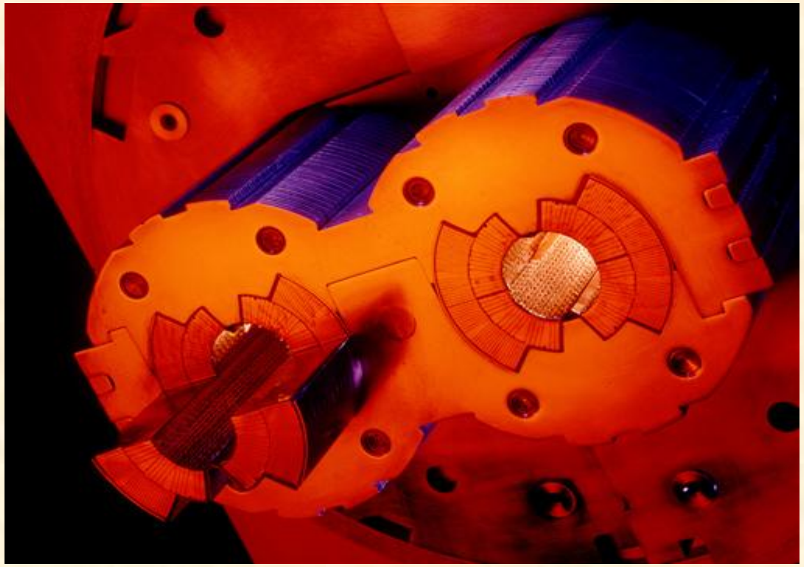
$$\frac{\gamma\, m_0\, v^{\cancel{2}}}{\rho} = e\,\cancel{v}\,B$$

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

B ρ = "beam rigidity"

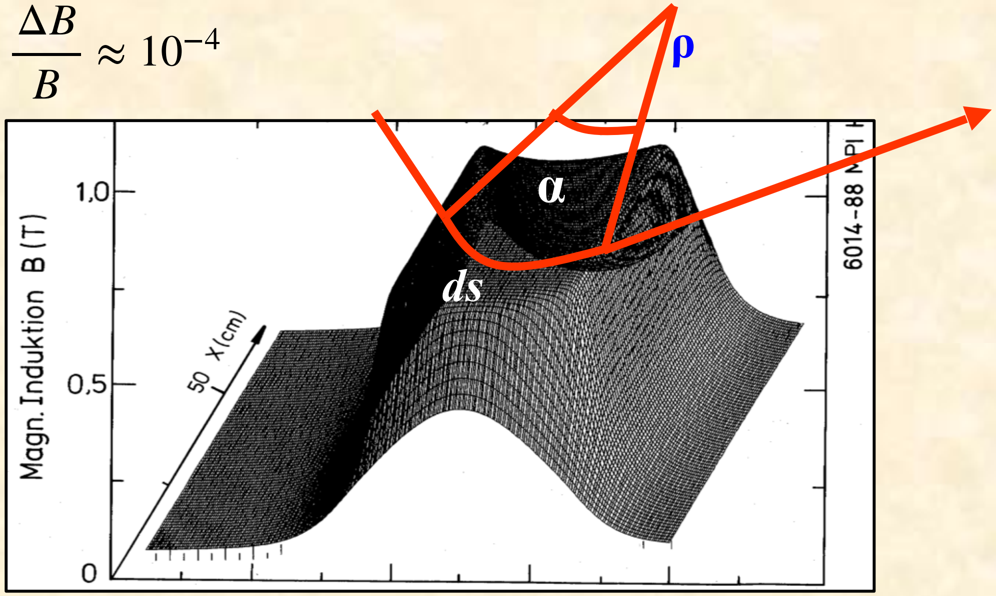
… und jetzt isses sogar relativistisch korrekt.

The Magnetic Guide Field



$B \approx 1 \ldots 8\ T$

$$\frac{\Delta B}{B} \approx 10^{-4}$$



field map of a storage ring dipole magnet

Dipole erzeugen ein konstantes (!) Magnetfeld

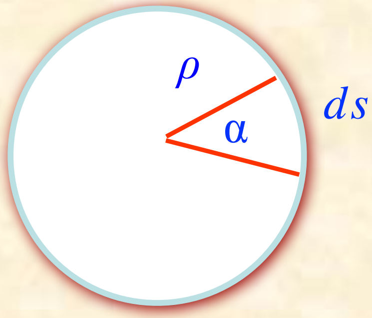
Ablenkradius:

$$\rho = \frac{p}{e\ B} = \frac{7000 \cdot 10^9\ eV}{3 \cdot 10^8 m/s * 8Vs/m^2}$$

nota bene:
fuer ultra relativistische
Teilchen gilt

$$p \approx \frac{E}{c}$$

$$\rho = 2.8\ km$$



Ablenkwinkel eines Dipols:

$$\alpha_{dipol} = \frac{ds}{\rho} = \frac{\int B\ ds}{B\ \rho} \approx \frac{B \cdot l_{dipol}}{B\ \rho}$$

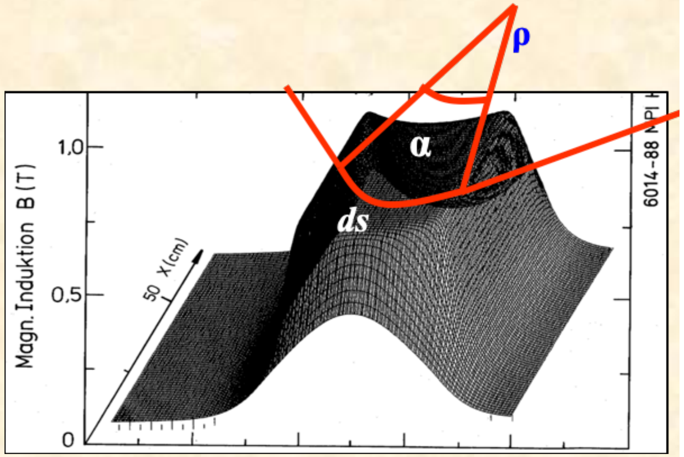
Anzahl Dipol Magnete:

$$N_{dipole} = \frac{2\pi}{\alpha_{dipol}} = \ 1232\ !!!$$

Umfang des Speicherrings:

$$C_0 = 2\pi \cdot \rho$$

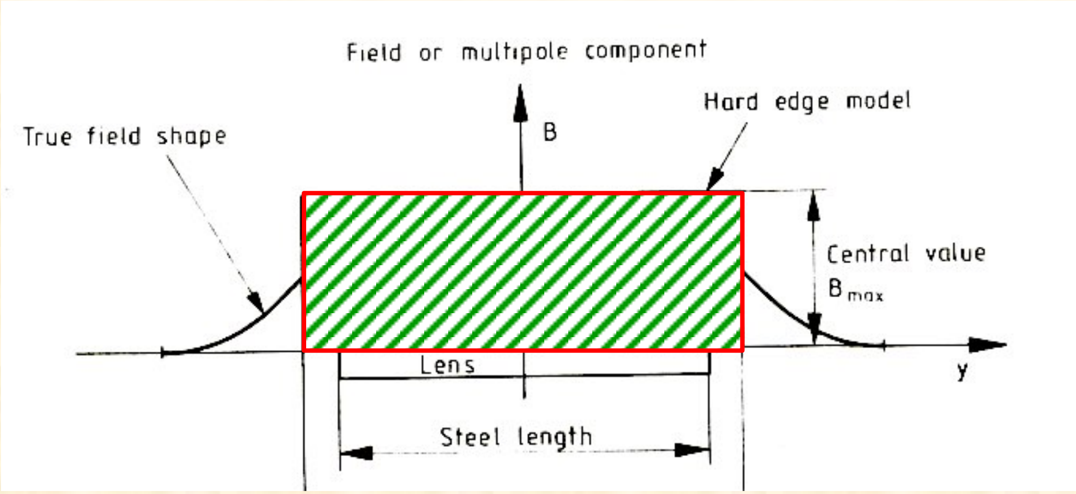
Bending Angle



„wieviele Dipole sollen's denn sein ???

Winkel im Kreis-Segment $$\alpha = \frac{ds}{\rho} = \frac{B \cdot ds}{B \cdot \rho}$$

fuer den ganzen Dipol $$\boxed{\boldsymbol{B\, l_{eff} = \int_0^{l_{mag}} B\, ds}}$$



Und alle Dipole zusammen muessen nen Vollkreis ergeben, also 2 π

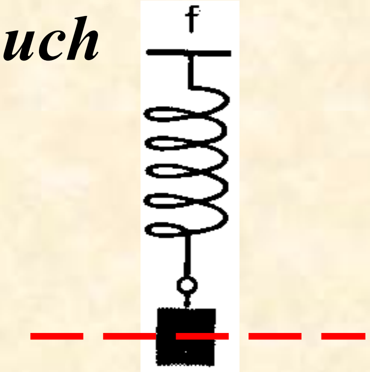
$$\alpha = \frac{\int B\ dl}{B\ \rho} \approx \frac{n \cdot B \cdot l_{dipol}}{B\ \rho} = 2\pi$$

und damit braucht's "n" Dipole mit Feldstaerke "B" und Laenge "l"

$$\boxed{n \cdot B \cdot l_{dipol} = 2\pi \cdot \frac{p}{q}}$$

2.) Focusing Forces: Hook's law

Federpendel im Physik Buch



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

$$F = m * a = -\,const * x$$

$$F = m * \frac{d^2x}{dt^2} = -\,const * x$$

Hook's Federgesetz: $F = -\,k * x$

Integration liefert uns eine cos- artige Lösung $x(t) = A \cdot cos(\omega t)$

oder eine sinus artige $x(t) = B \cdot sin(\omega t)$

oder eine Kombination aus beiden $x_{allg}(t) = A \cdot cos(\omega t) + B \cdot sin(\omega t)$

Vorteil:

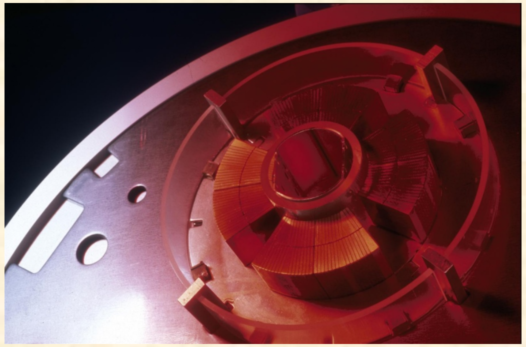
harmonische Schwingungen sind sehr (!!) stabil,
haben eine wohldefinierte Frequenz
sind in der Natur (i.e. Physik) weit verbreitet

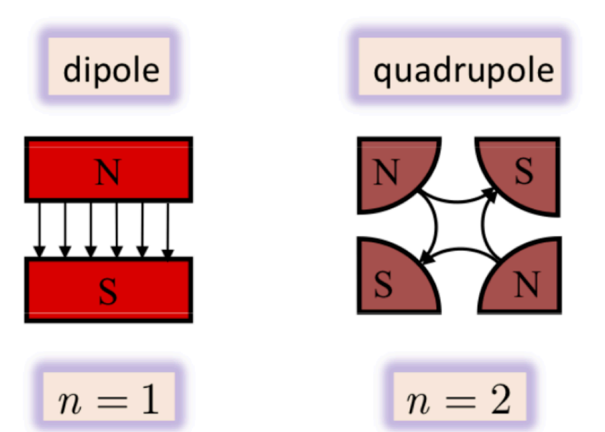
2.)Focusing Forces: Quadrupole Fields

Apply this concept to magnetic forces: we need a Lorentz force that rises as a function of the distance to ...

… the design orbit

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





Dipoles: Create a constant field $B_y = const$

Quadrupoles: Create a linear increasing magnetic field: $B_y(x) = g \cdot x, \quad B_x(y) = g \cdot y$

Focusing forces and particle trajectories:

normalise magnet fields to momentum
(remember: ***B*ρ = p / q*** *)*

Achtung:
um Energie unabhängige Gleichungen zu erhalten teilen wir die Felder durch “p”

„normalised
bending strength“

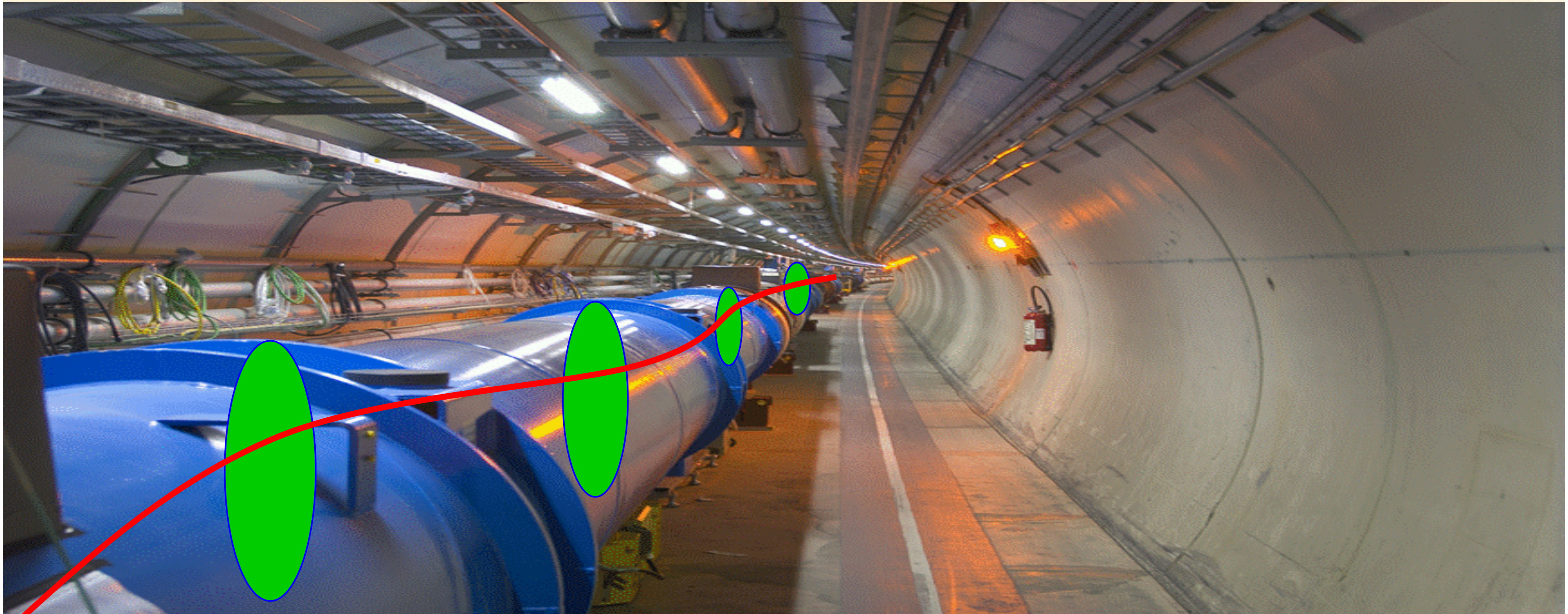
$$1/\rho = \frac{B}{p/e}$$

Dipole Magnet

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

Quadrupole Magnet

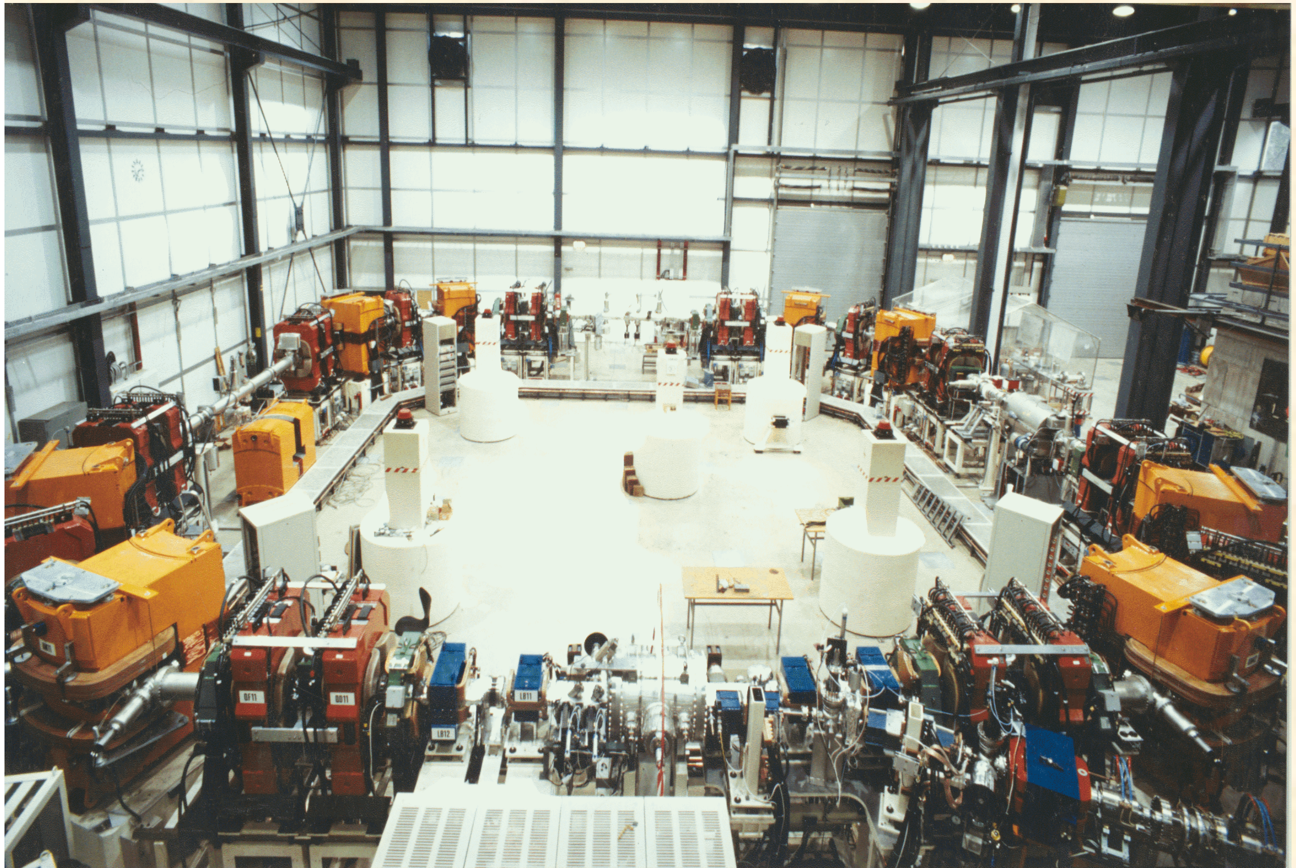
$$k := \frac{g}{p/q}$$



3.) The Equation of Motion:

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

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:

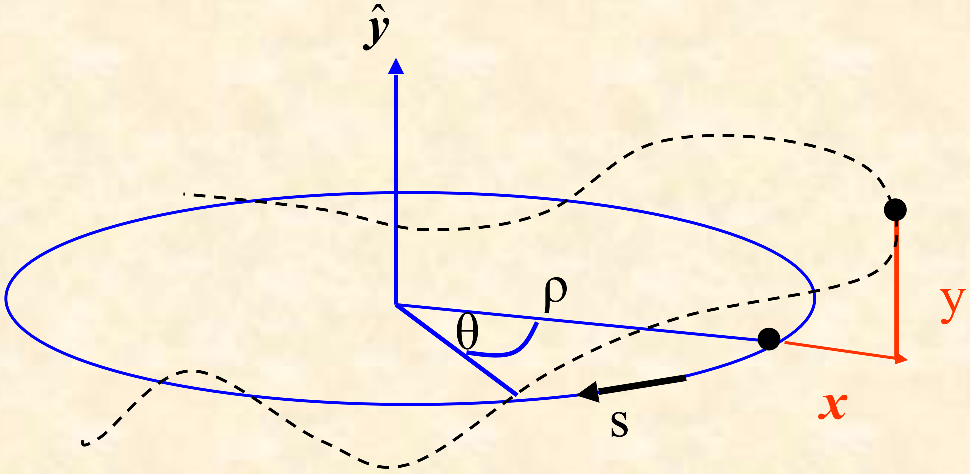
bending, focusing etc

Example:
heavy ion storage ring TSR

*

man sieht nur dipole und quads → linear

The Equation of Motion:



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

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

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

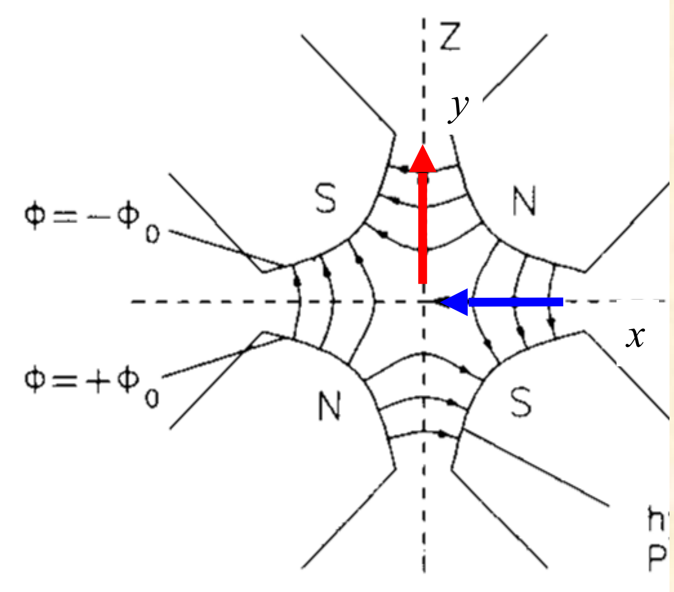
$$x'' = -x \cdot \underbrace{(\frac{1}{\rho^2} + k)}$$

$$x'' = \quad -K \cdot \; x$$

Hook's Gesetz fuer Speicherringe

… es gibt da nur ein kleines Problem:

In der vertikalen Ebene drehen sich die Magnetfeld-Linien um



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

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

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

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

… und Teilchen,
die in der horizontalen Ebene fokussiert werden,
werden im gleichen Atemzug in der vertikalen Ebene
aus der Maschine befördert.

!

4.) Solution of Trajectory Equations

Define … hor. plane: K= 1/ρ² + k

… vert. Plane: K = - k

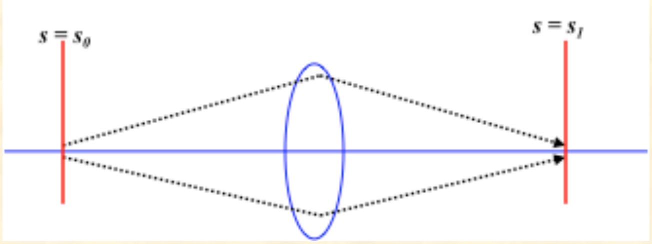
$$x'' + K\ x = 0$$

Differential Equation of harmonic oscillator … with spring constant K

Ansatz: Hor. Focusing Quadrupole K > 0:

$$x(s) = x_0 \cdot \cos(\sqrt{|K|}s) + x'_0 \cdot \frac{1}{\sqrt{|K|}} \sin(\sqrt{|K|}s)$$

$$x'(s) = -x_0 \cdot \sqrt{|K|} \cdot \sin(\sqrt{|K|}s) + x'_0 \cdot \cos(\sqrt{|K|}s)$$



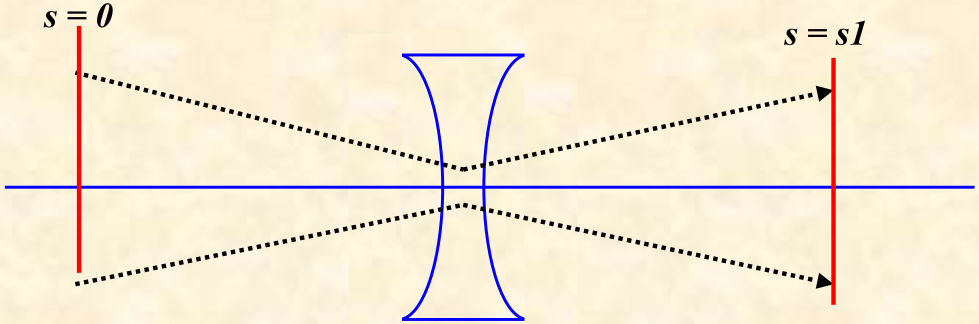
… da ist wieder unsere Kuckucksuhr.

For convenience expressed in matrix formalism:

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

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

hor. defocusing quadrupole:



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

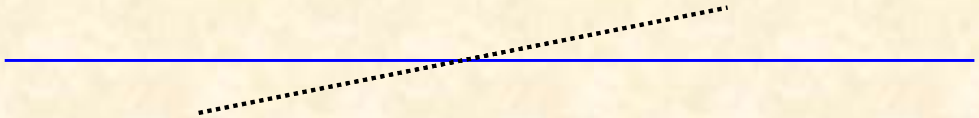
Ansatz: ***Remember from school***

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

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

drift space:

$K = 0$



$$x(s) = x_0' \cdot s$$

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

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

… zur Erinnerung:
hyperbolische Funktionen führen leicht zu Panik Attacken !

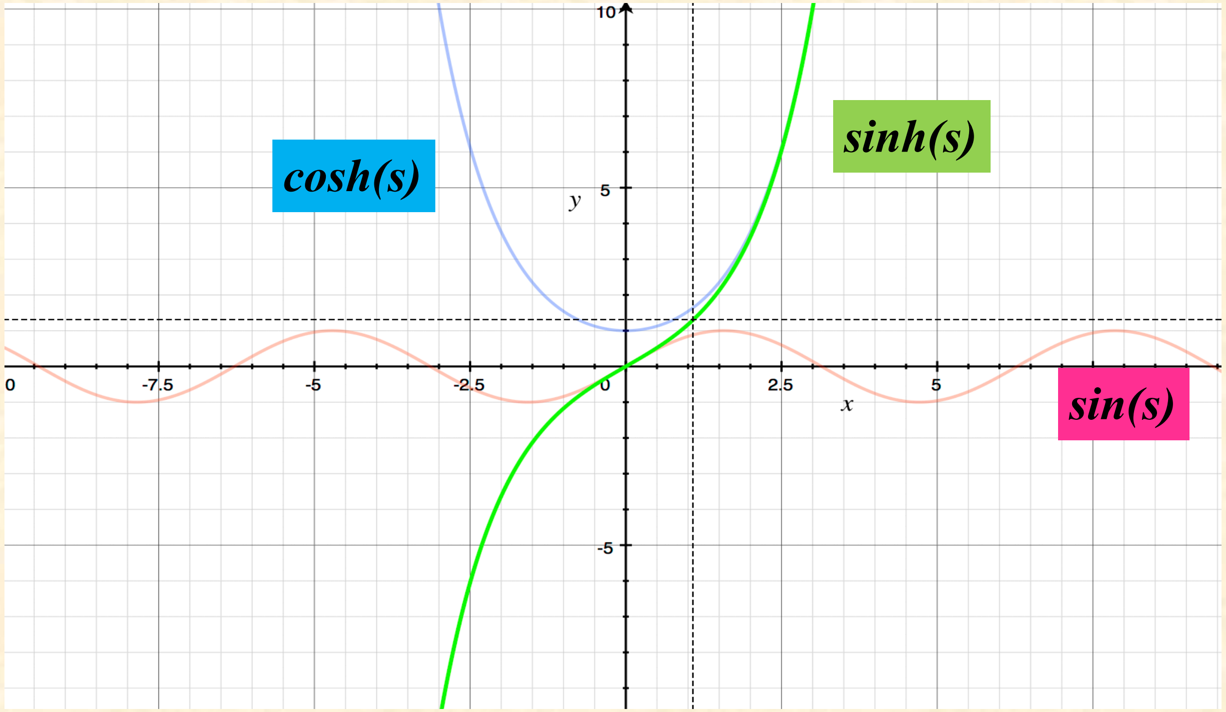
$$M_{defoc} = \begin{pmatrix} \cosh\sqrt{|K|}l & \frac{1}{\sqrt{|K|}}\sinh\sqrt{|K|}l \\ \sqrt{|K|}\sinh\sqrt{|K|}l & \cosh\sqrt{|K|}l \end{pmatrix}$$

$f(s) = sin(s)$ $\quad$ $f(s) = cos(s)$

$f(s) = sinh(s)$ $\quad$ $f(s) = cosh(s)$

Ansatz für die Teilchenbewegung im defokusierenden Fall:

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

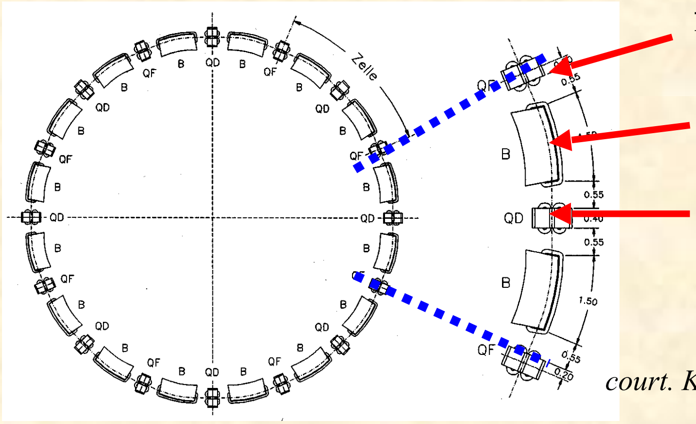


Transformation through a system of lattice elements

combine the single element solutions by multiplication of the matrices

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

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



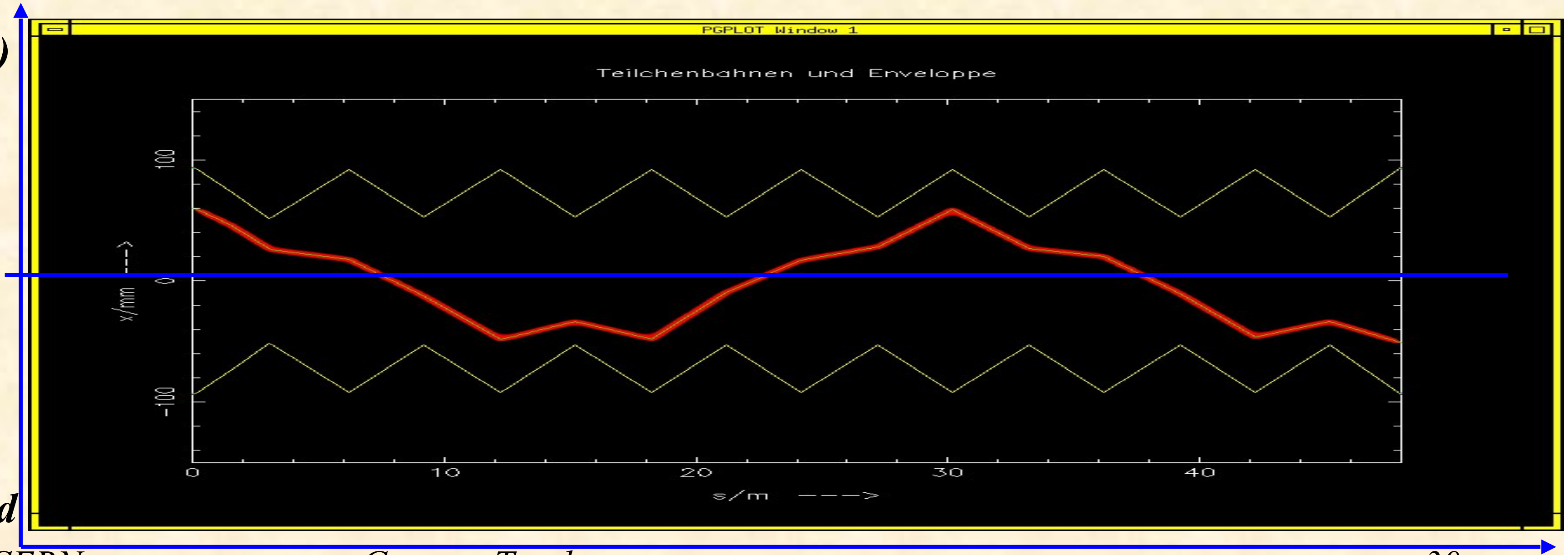
focusing lens

dipole magnet

defocusing lens

court. K. Wille

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

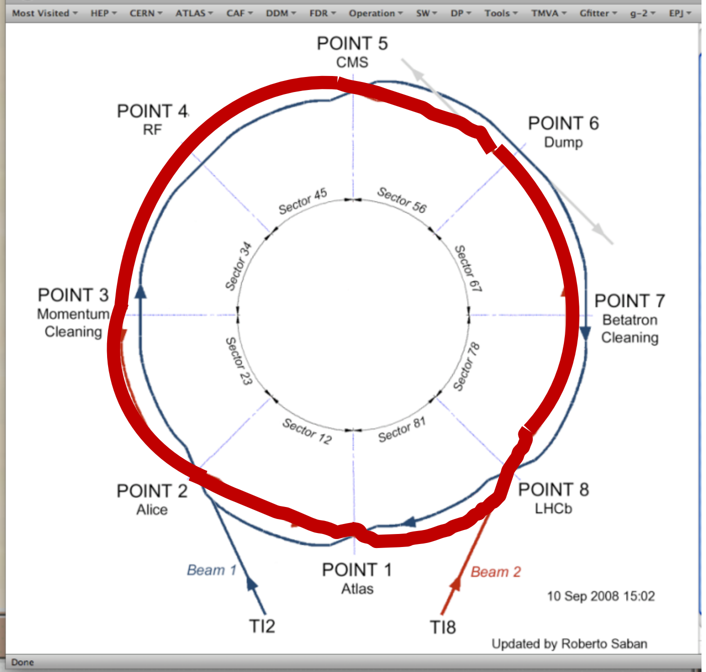


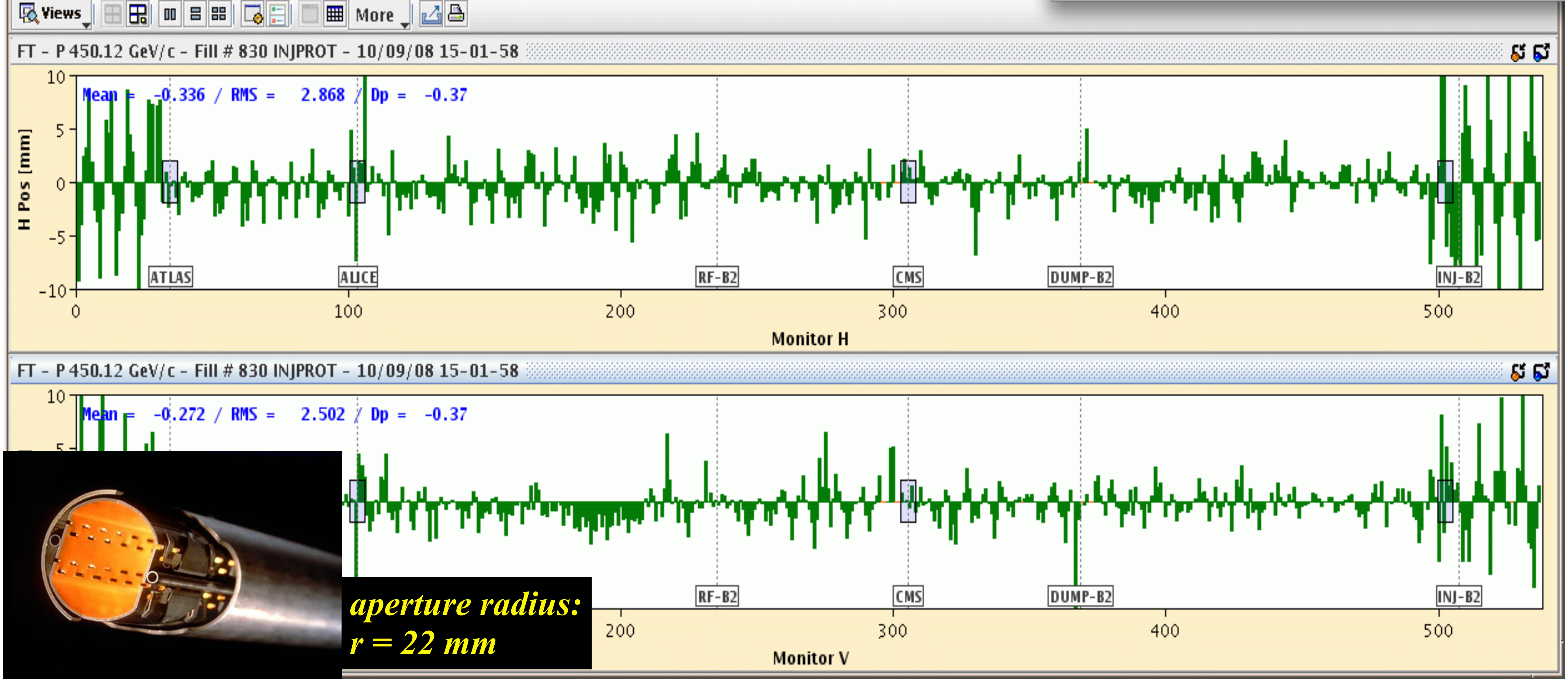
typical values in a strong foc. machine:
$x \approx$ mm, $x' \leq$ mrad

LHC Operation: Beam Commissioning

*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

aperture radius:
r = 22 mm

"Once more unto the breach, dear friends, once more"
(W. Shakespeare, Henry 5)

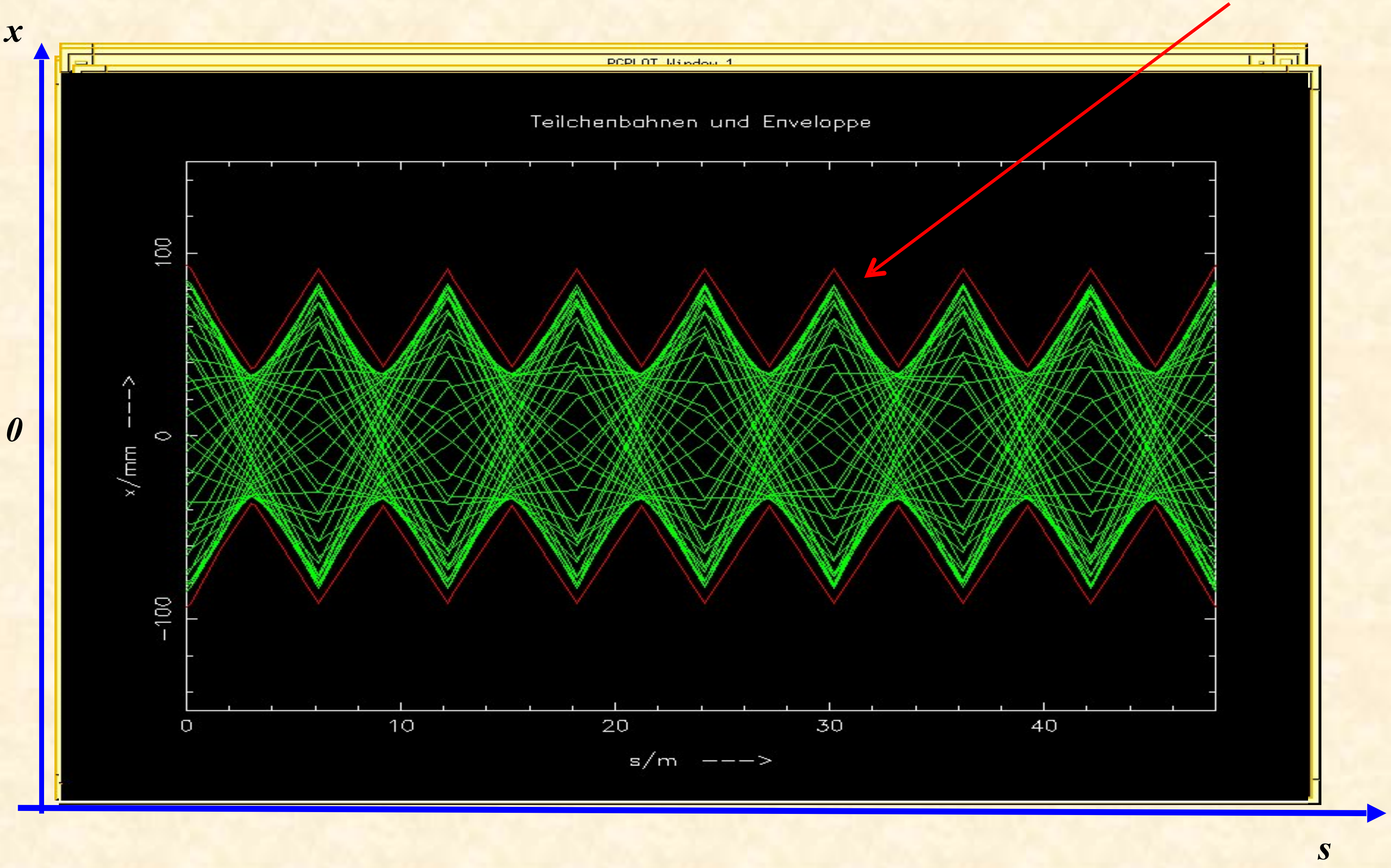
"Do they actually drop ?"

Answer: No

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

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

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



Collisions

Die zwei wichtigsten Formeln fuer uns ...

$$E = mc^2$$

die Energie unserer Strahlen kann in ***Masse neuer Teilchen*** *umgewandelt werden.*

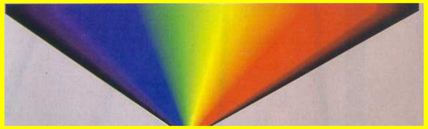
$$\lambda = \frac{h}{p}$$

Teilchen verhalten sich wie Wellen *mit einer wohl definierten Wellenlaenge;* $h = 4.1 \cdot 10^{-21}$ *MeV s*

Collisions

Lichtspektrum:

$\lambda = 400 \ldots 800\ nm$



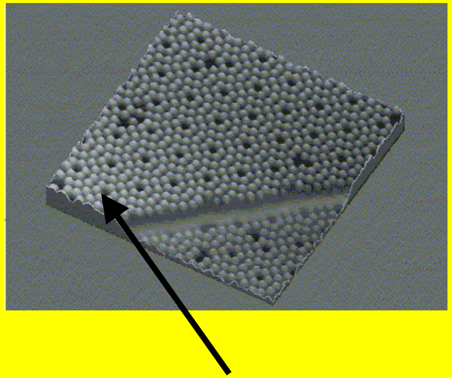
Lichtmikroskope haben damit eine Auflösung von etwas besser als µm

LHC:

$$E = p \cdot c \quad \rightarrow \quad p = \frac{E}{c} \qquad\qquad p = \frac{7 \cdot 10^{12}\, eV}{3 \cdot 10^{8}\, m/s}$$

$$\lambda = \frac{h}{p} \quad = 4.1 \cdot 10^{-21}\, MeV\, s \cdot \frac{3 * 10^{8} m/s}{7 \cdot 10^{12}\, eV}$$

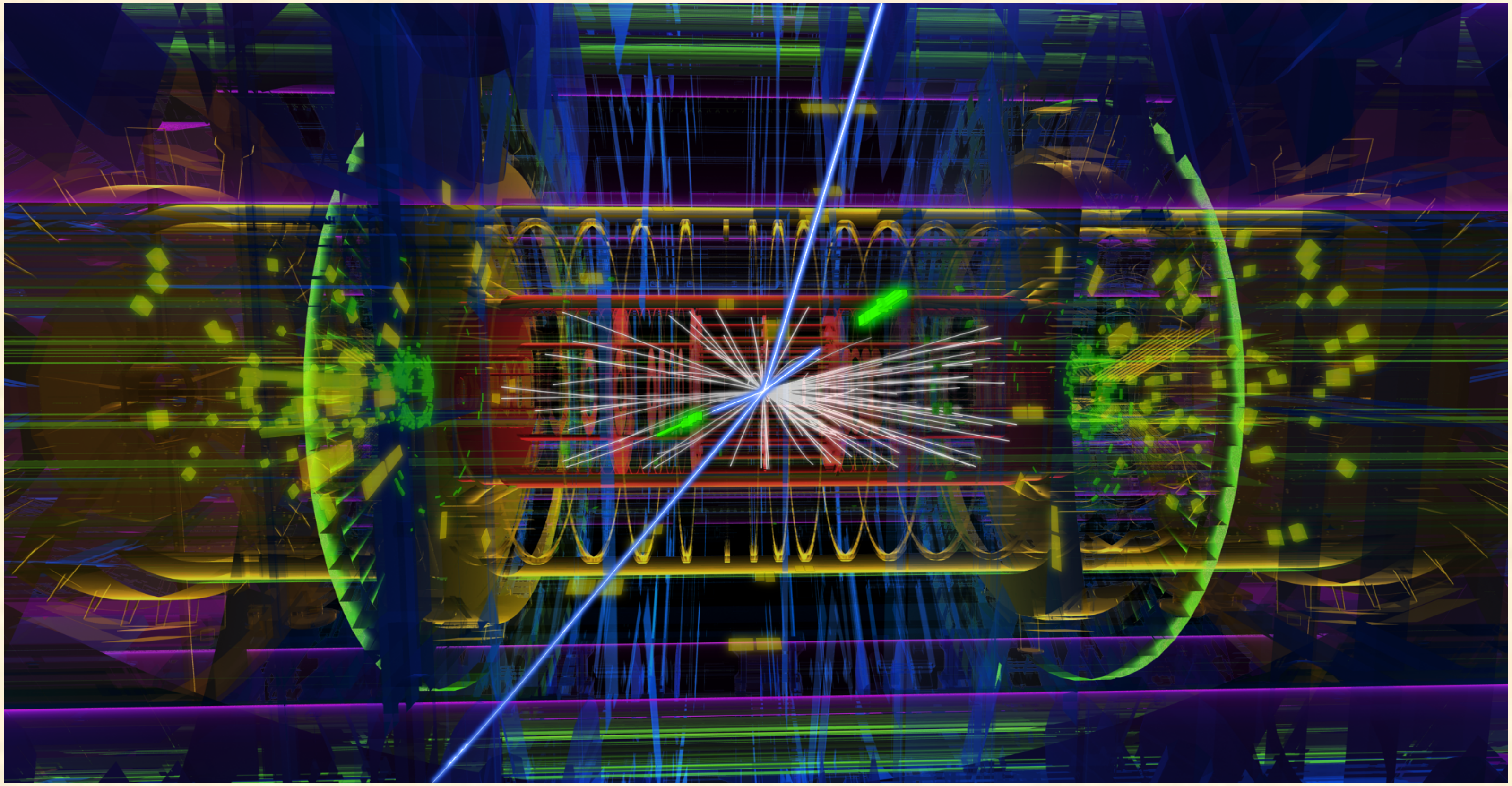
$$\lambda \approx 2 \cdot 10^{-19}\, m$$



Atome: $\approx 10^{-10}\, m$

Kerne: $\approx 10^{-15}\, m$

Collisions



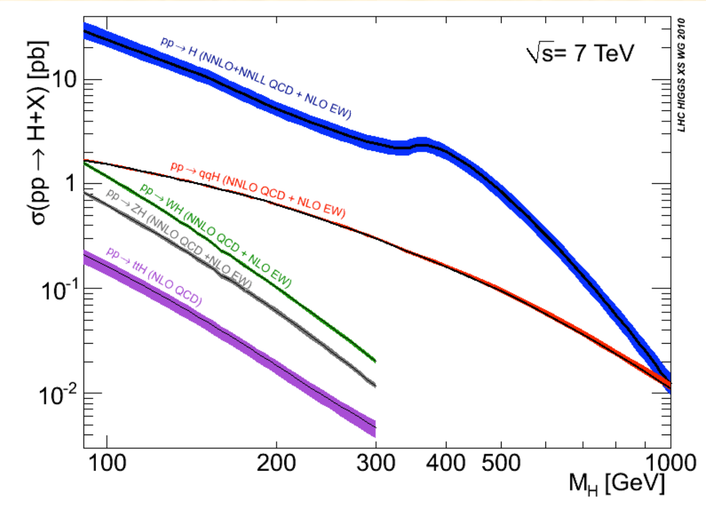
ATLAS event display: Higgs => two electrons & two muons

$$E = m_0c^2 = m_{e1} + m_{e2} + m_{\mu 1} + m_{\mu 2} = 125.4\ GeV$$

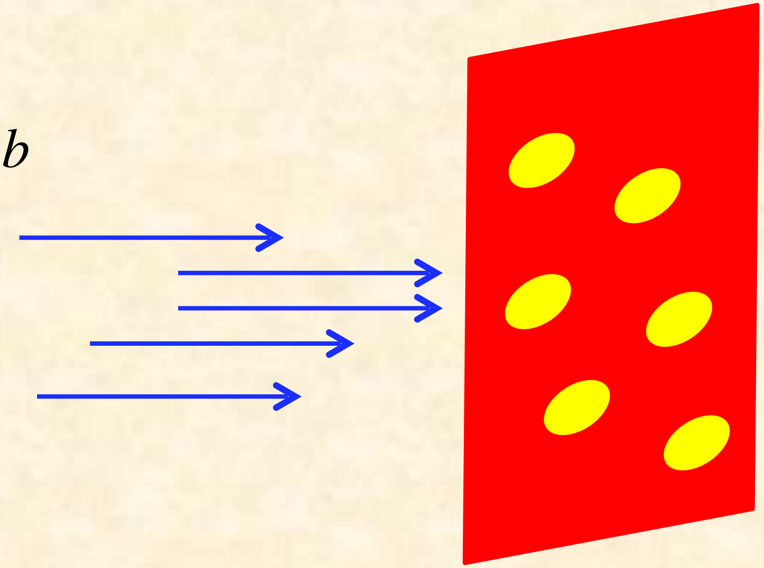
Problem: Our particles are VERY small !!

man trifft nicht so häufig.

Overall cross section of the Higgs:



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



$$1b = 10^{-24} cm^2 = \frac{1}{mio} \cdot \frac{1}{mio} \cdot \frac{1}{mio} \cdot \frac{1}{10000} \quad mm^2 \longrightarrow \boxed{1pb = 10^{-12} b \approx ZERO}$$

The particles are "very small"

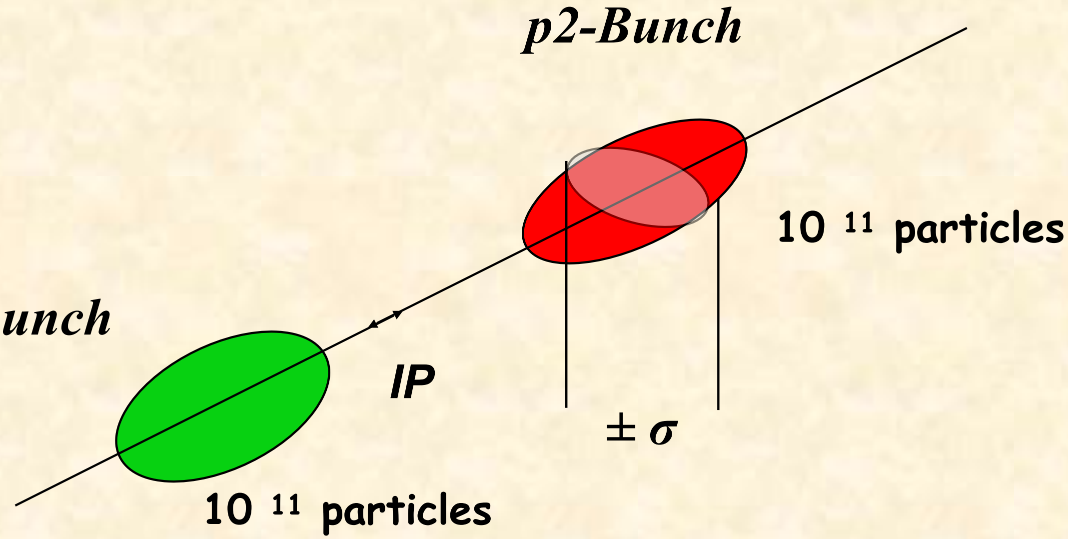
The only chance we have:
compress the transverse beam size … at the IP

LHC typical → 16 μm

5.) Luminosity

Ereignis Rate: "Physik" pro Sekunde

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



Example: Luminosity run at LHC

$\sigma_x = \sigma_y = 16 \mu m$ *Strahlgröße am IP*

$f_0 = 11.245\ kHz$ *Umlaufs-Frequenz*

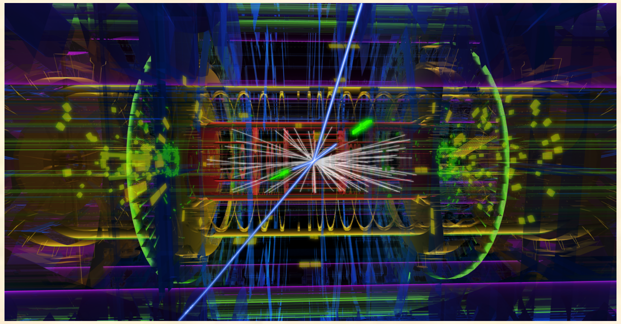
$n_b = 2808$ *Zahl der Bunche*

$N_p = 1.2 \cdot 10^{11}$ *Teilchen in einem Bunch*

$I_p = 584\ mA$ *Strahlstrom*

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

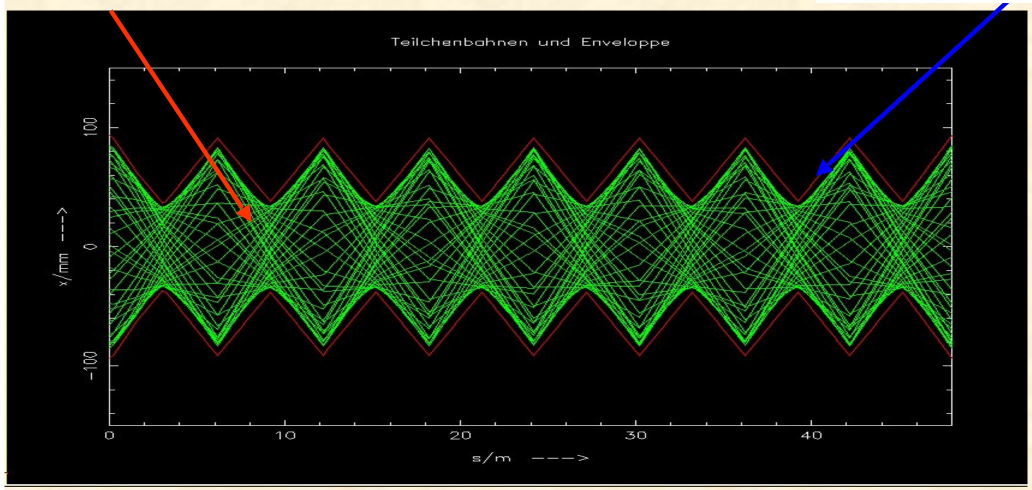
$$L = \frac{1}{4\pi} \cdot N_{p1} \cdot \frac{N_{p2}}{\sigma_x \sigma_y} \cdot (n_b \cdot f_0)$$



Emittance of the Particle Ensemble:

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

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



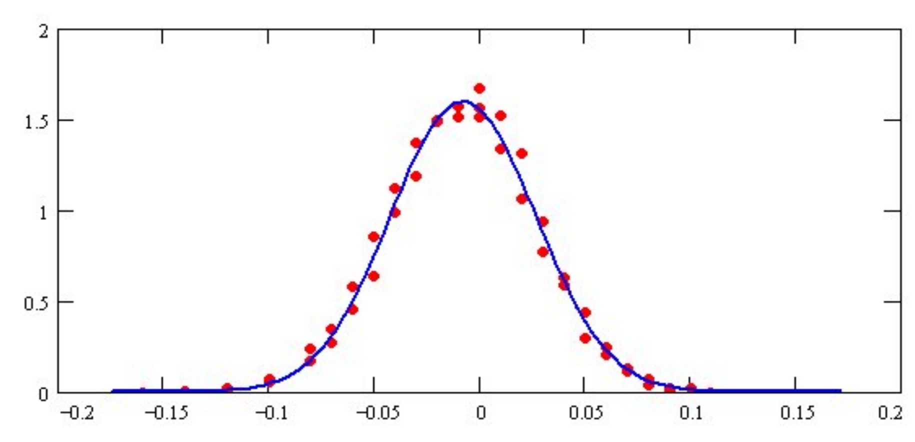
single particle trajectories, N ≈ 10 ^{11} per bunch

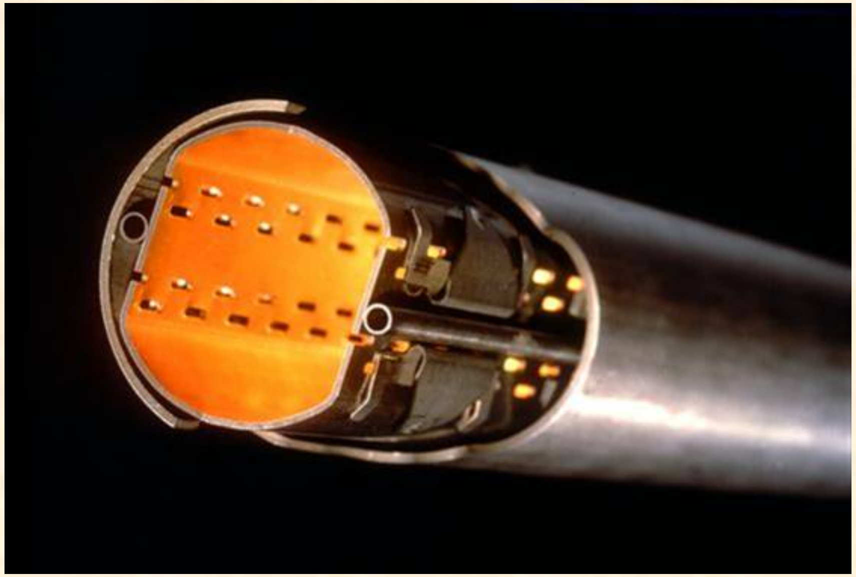
Gauß
Particle Distribution:

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

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

LHC: Strahlgroesse = σ ≃ 0.3 mm

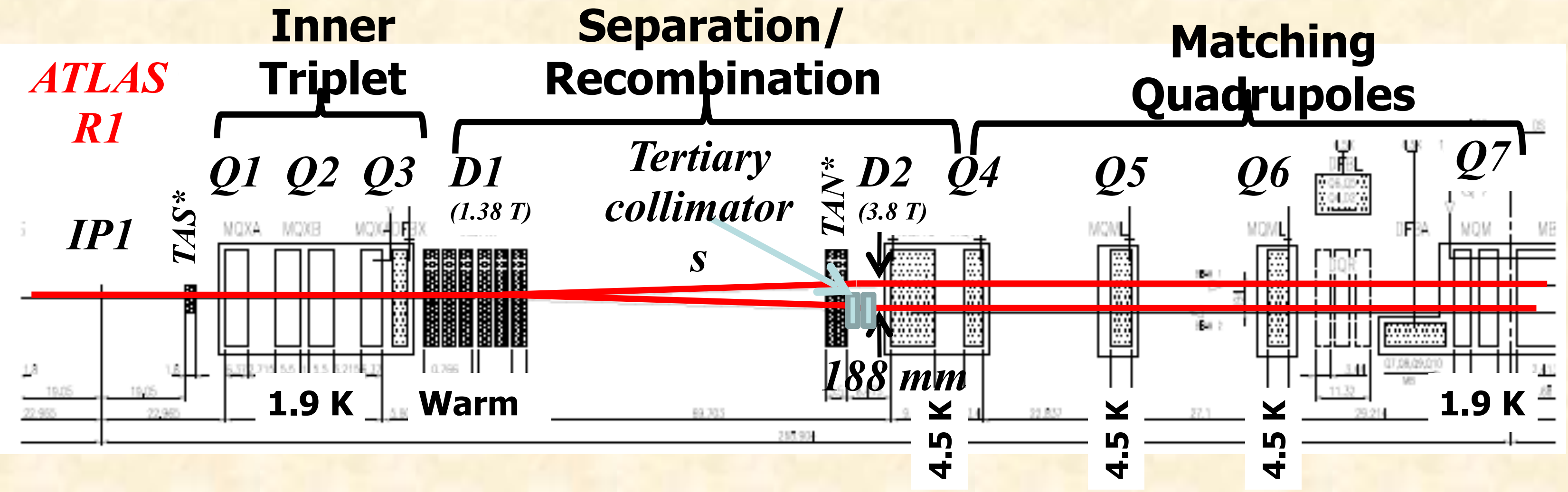




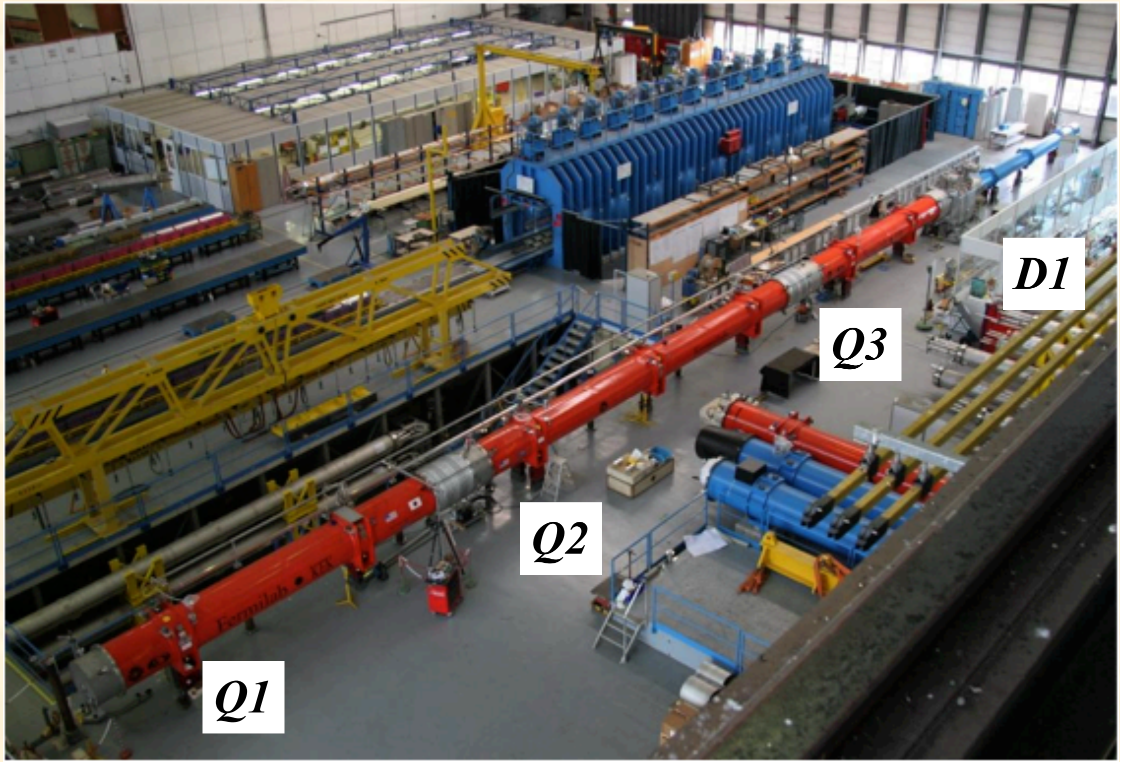
aperture requirements: $r_0 = 17 * \sigma$

beam sizes in the order of my cat’s hair !!

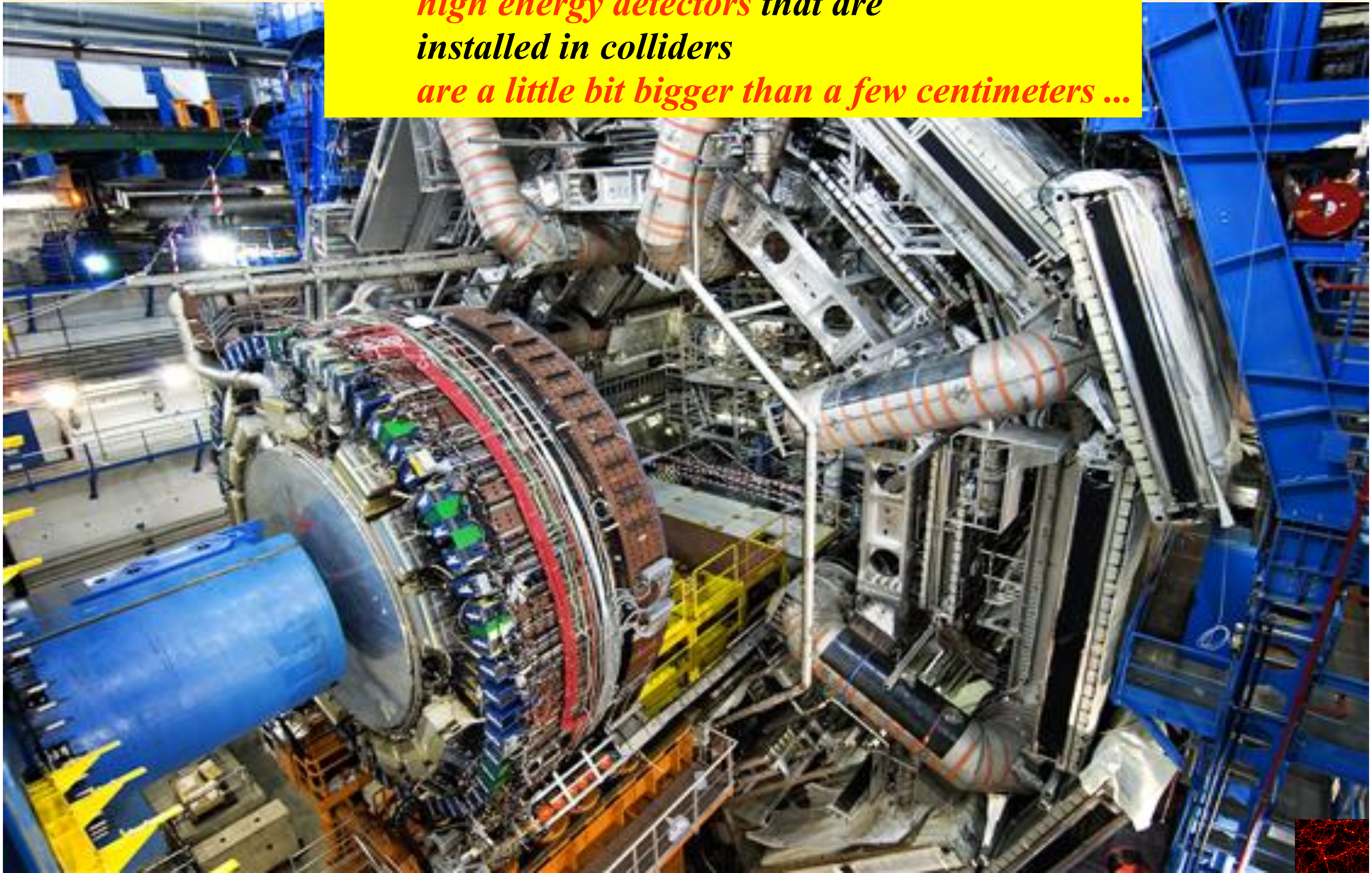
The LHC Mini-Beta-Insertions



Extrem starke Fokussierung (in beiden Ebenen) für beide Strahlen, um die Trajektorien der 10^{11} Teilchen auf micro Meter zu komprimieren.



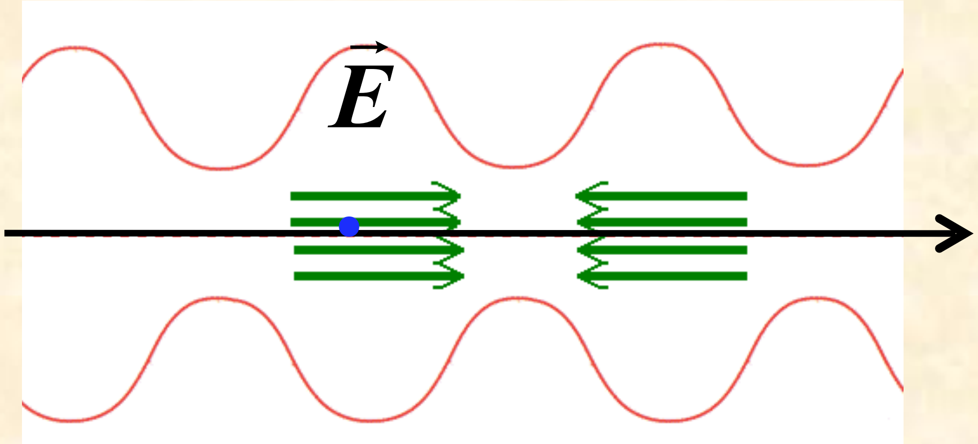
... clearly there is another problem !!!



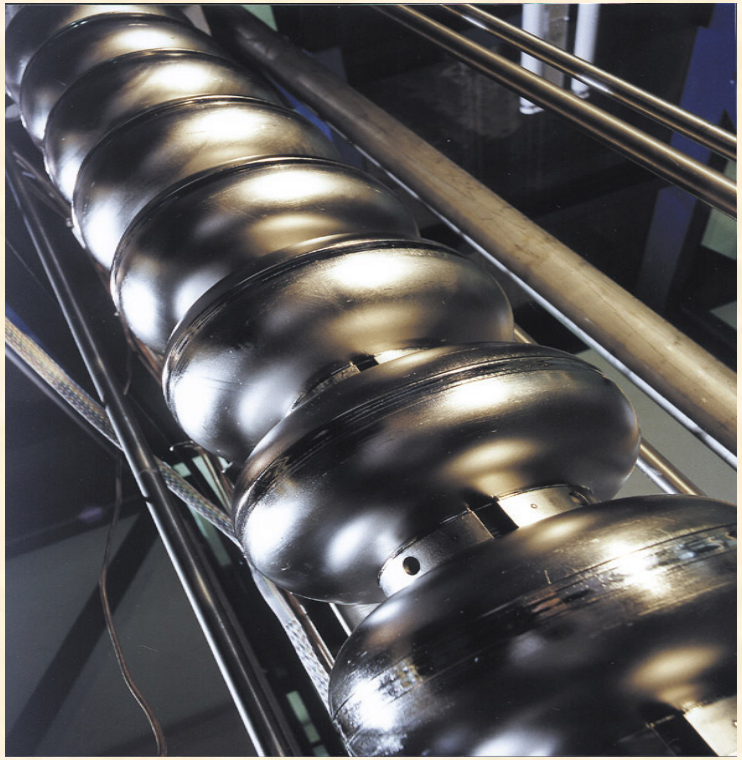
... unfortunately ... in general
high energy detectors that are
installed in colliders
are a little bit bigger than a few centimeters ...

The Acceleration

Install an RF accelerating structure in the ring:



z



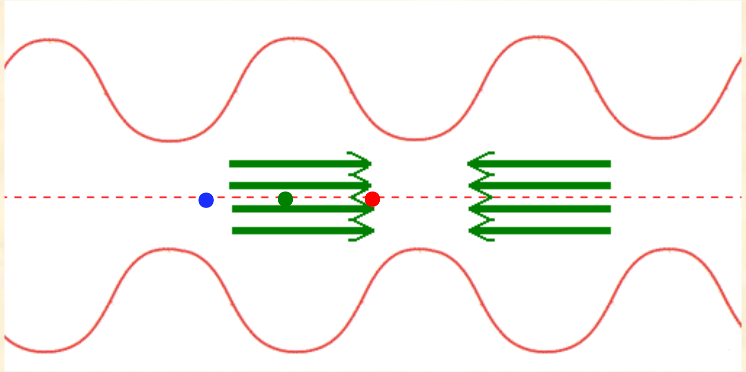
The Acceleration & "Phase Focusing"

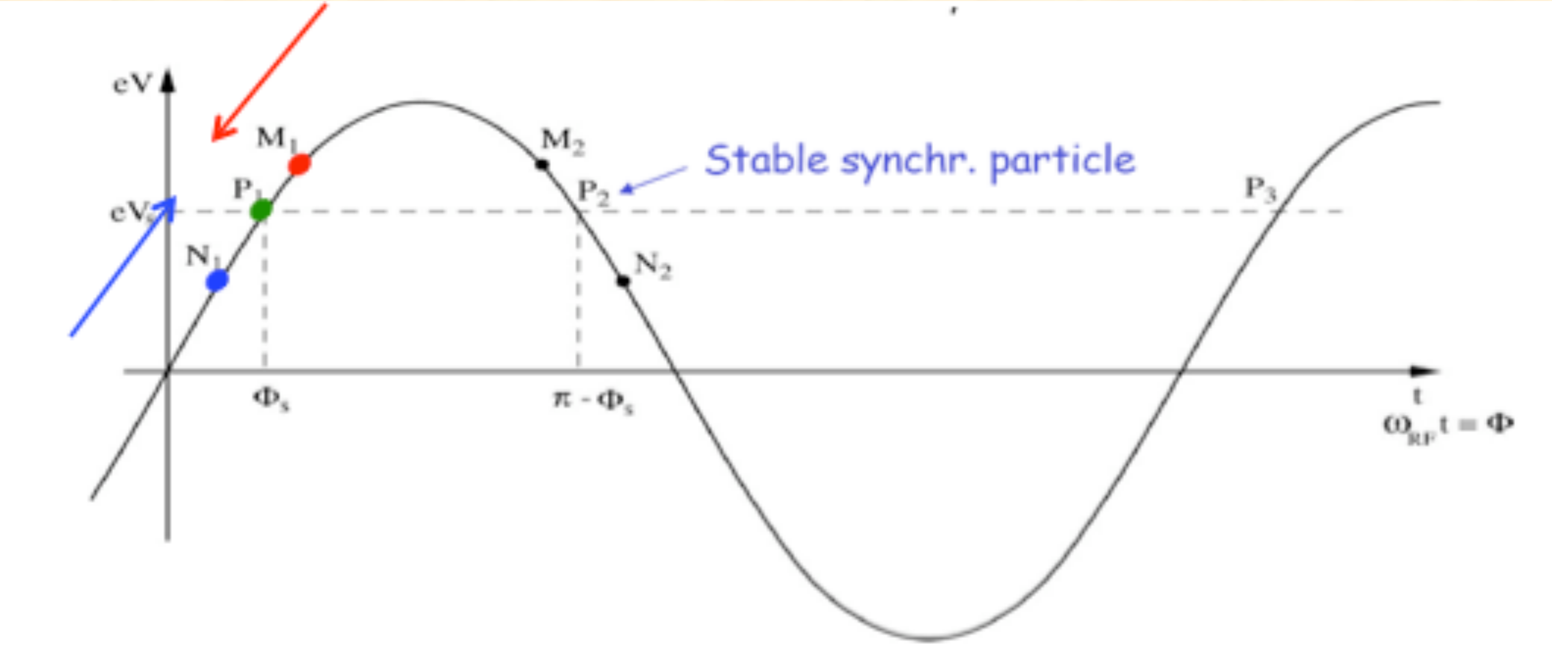
$\Delta p/p \neq 0$ below transition

ideal particle ●

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

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





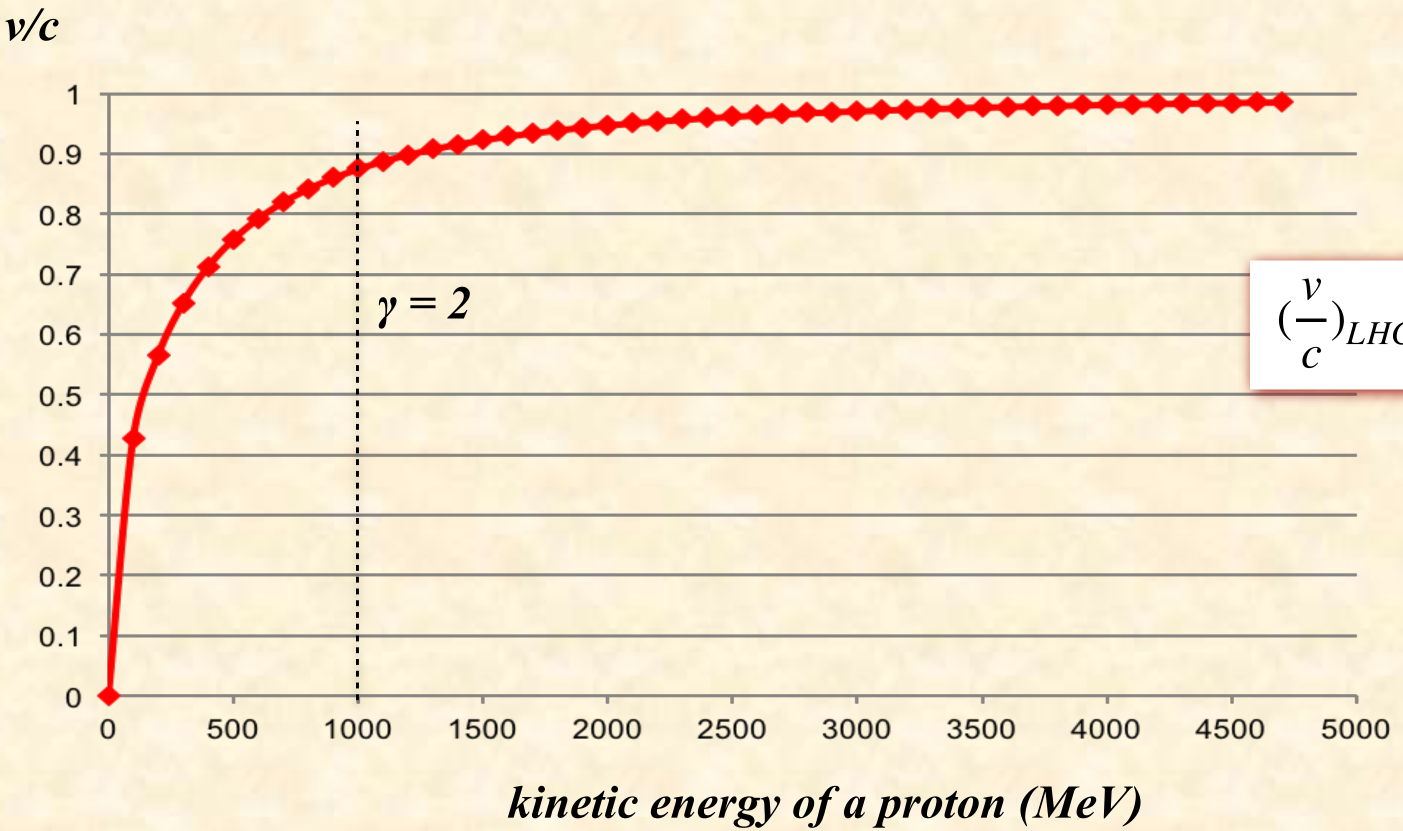
Focussing effect in the longitudinal direction keeping the particles close together ... forming a "bunch"

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

was passiert, wenn wir die Teilchen immer "schneller" machen ?

$$\gamma = \frac{E_{total}}{m_0 c^2} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \quad \longrightarrow \quad \frac{v}{c} = \sqrt{1-\frac{mc^2}{E_{total}^2}}$$

die Teilchen werden irgendwann nicht mehr schneller !



$$\left(\frac{v}{c}\right)_{LHC} = 0.999999991$$

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

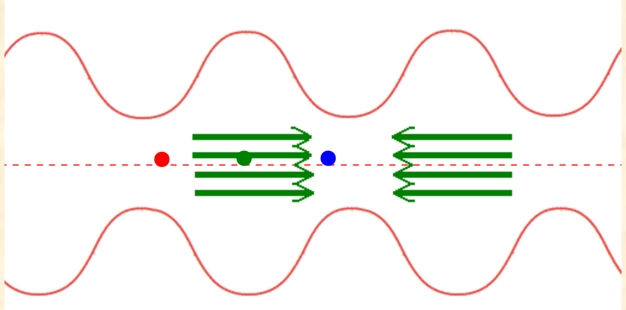
.... but heavier !

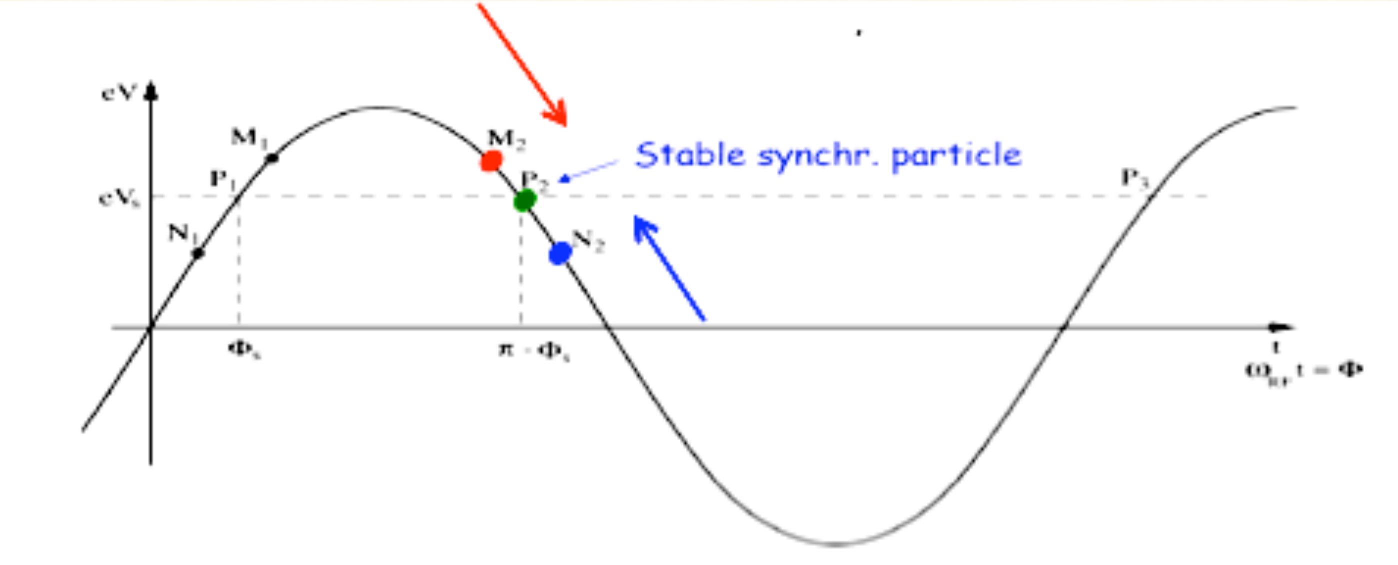
The Acceleration above transition

ideal particle •

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

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



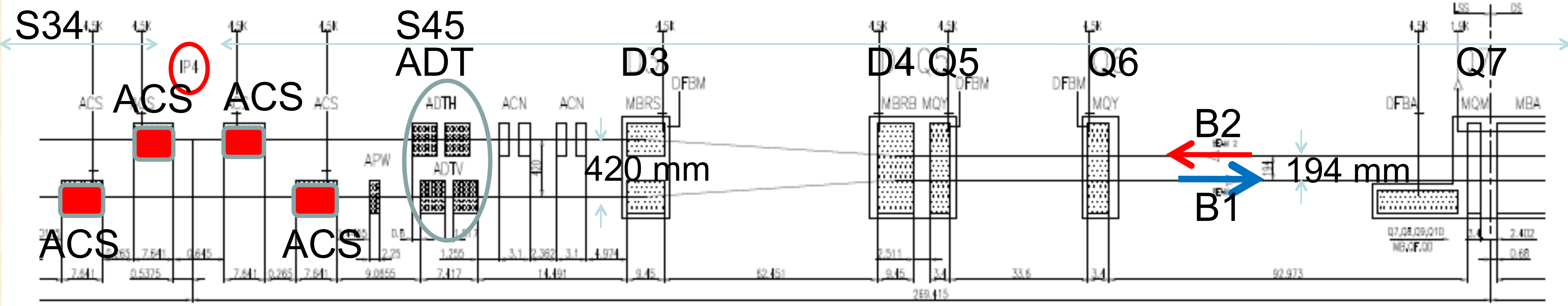


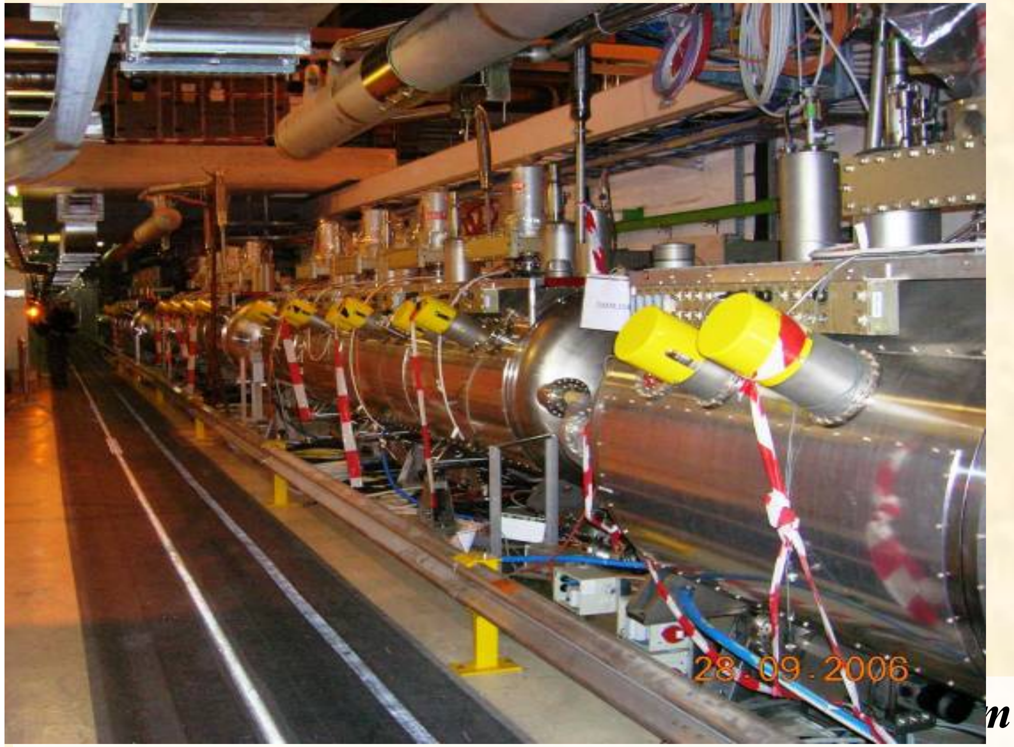
Focussing effect in the longitudinal direction
keeping the particles close together ... forming a "bunch"

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

with the dipole magnets !

The RF system: IR4





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

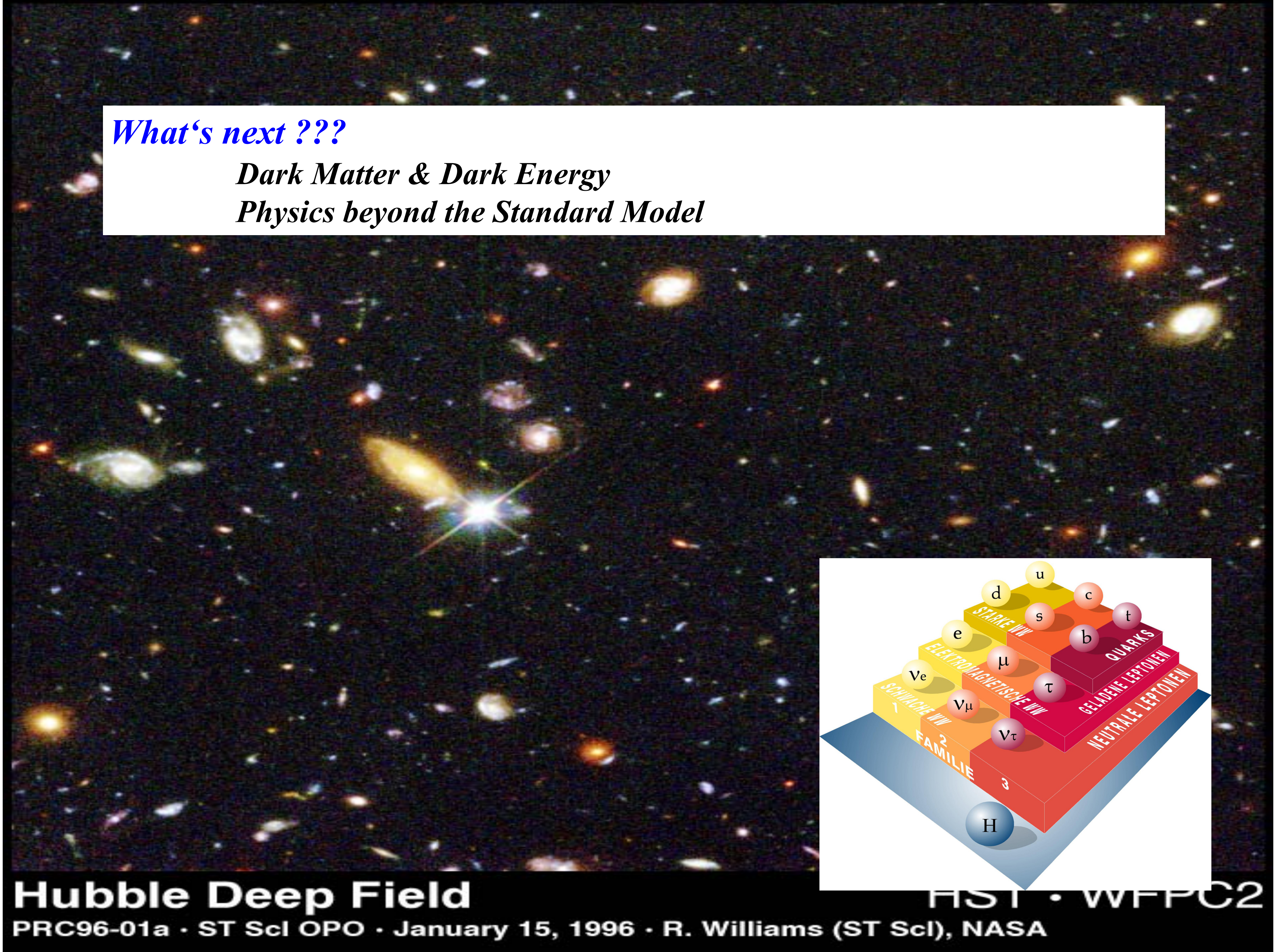
Bunch length (4σ)	ns	1.06
Energy spread (2σ)	10^{-3}	0.22
Synchr. rad. loss/turn	keV	7
Synchr. rad. power	kW	3.6
RF frequency	MHz	400
Harmonic number		35640
RF voltage/beam	MV	16
Energy gain/turn	keV	485
Synchrotron frequency	Hz	23.0

1.) Where are we ?

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

What‘s next ???

Dark Matter & Dark Energy
Physics beyond the Standard Model



What‘s next ???

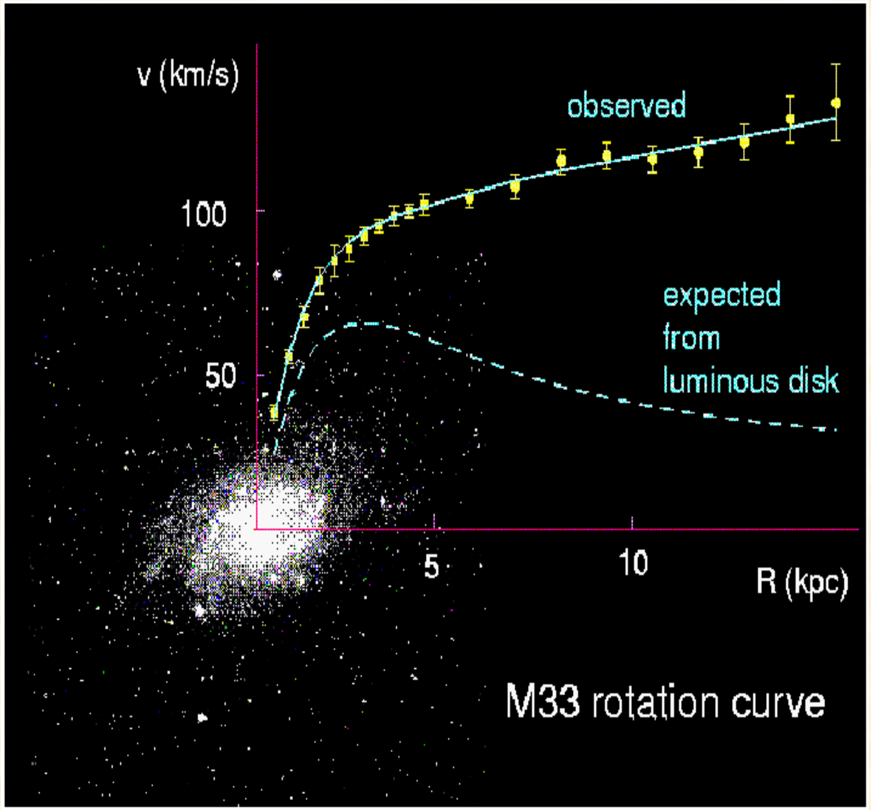
Dark Matter

The outer region of galaxies rotate faster than expected from visible matter

Corbelli & Salucci (2000);
Bergstrom (2000)

$$\frac{m \cdot v^2}{r} = \frac{m_1 \cdot M_2 \cdot G}{r^2}$$

$$v_{circ} = \sqrt{\frac{M_2(r) \cdot G}{r}}$$

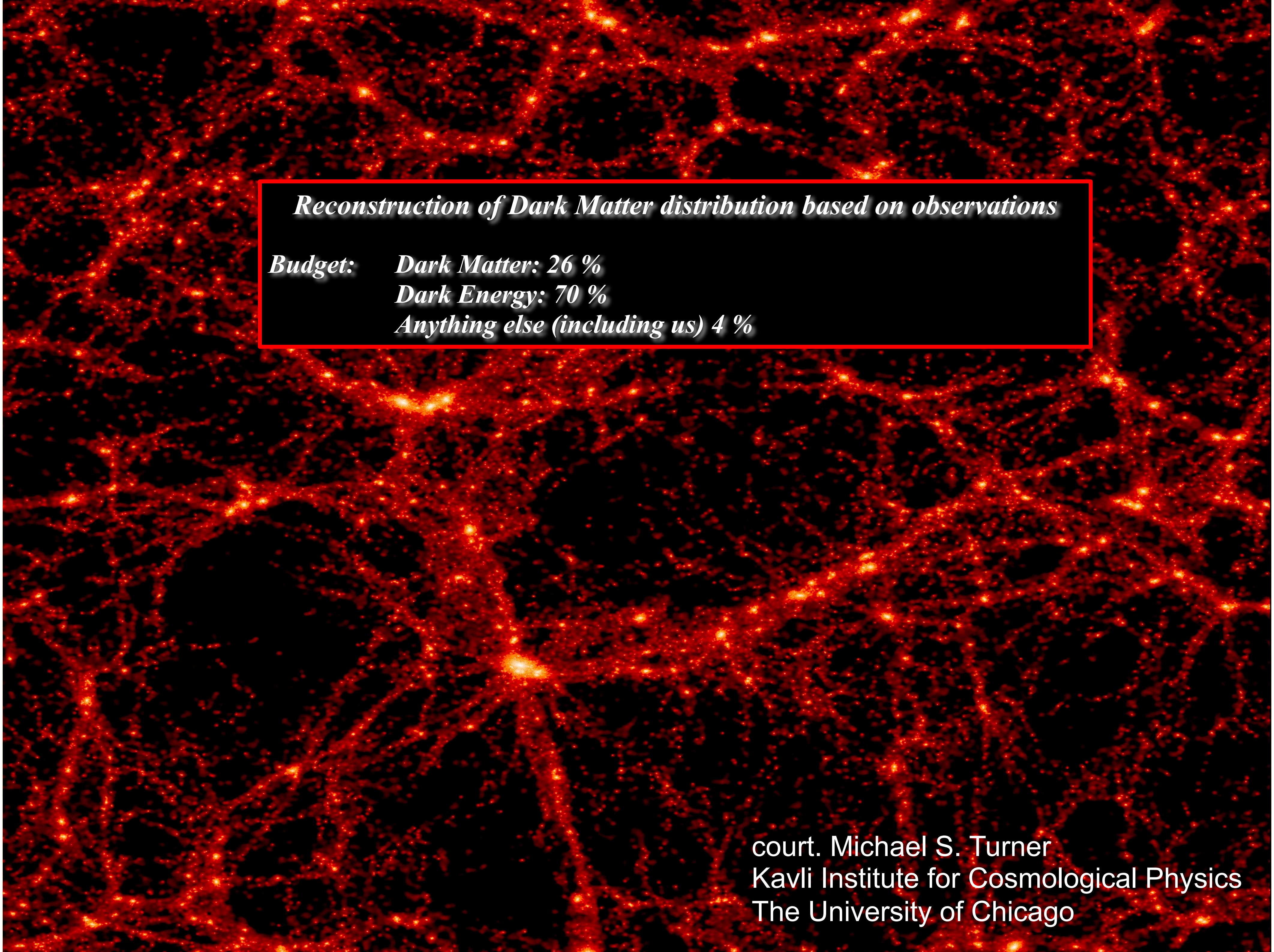


Dark matter would explain this

Other observations exist … (grav. lens effects)
but all through gravity

What is it?

(One explanation is super-symmetry)



Reconstruction of Dark Matter distribution based on observations

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

court. Michael S. Turner
Kavli Institute for Cosmological Physics
The University of Chicago

Considered Future High Energy Frontier Colliders

Circular colliders:

FCC (Future Circular Collider … Euro-Circol)

- *FCC-hh: 100 TeV proton-proton cm energy*
- *FCC-ee: Potential intermediate step 90-350 GeV lepton collider*

Linear colliders

- *ILC (International Linear Collider): e^+e^-, 500 GeV cms energy, Japan considers hosting project*
- *CLIC (Compact Linear Collider): e^+e^-, 380GeV - 3TeV cms energy, CERN hosts collaboration*

Others

Plasma acceleration

Muon collider, has been supported in the US but effort has stopped

Photon-photon collider

FCC
hh ee he

The Next Generation Ring Collider