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.

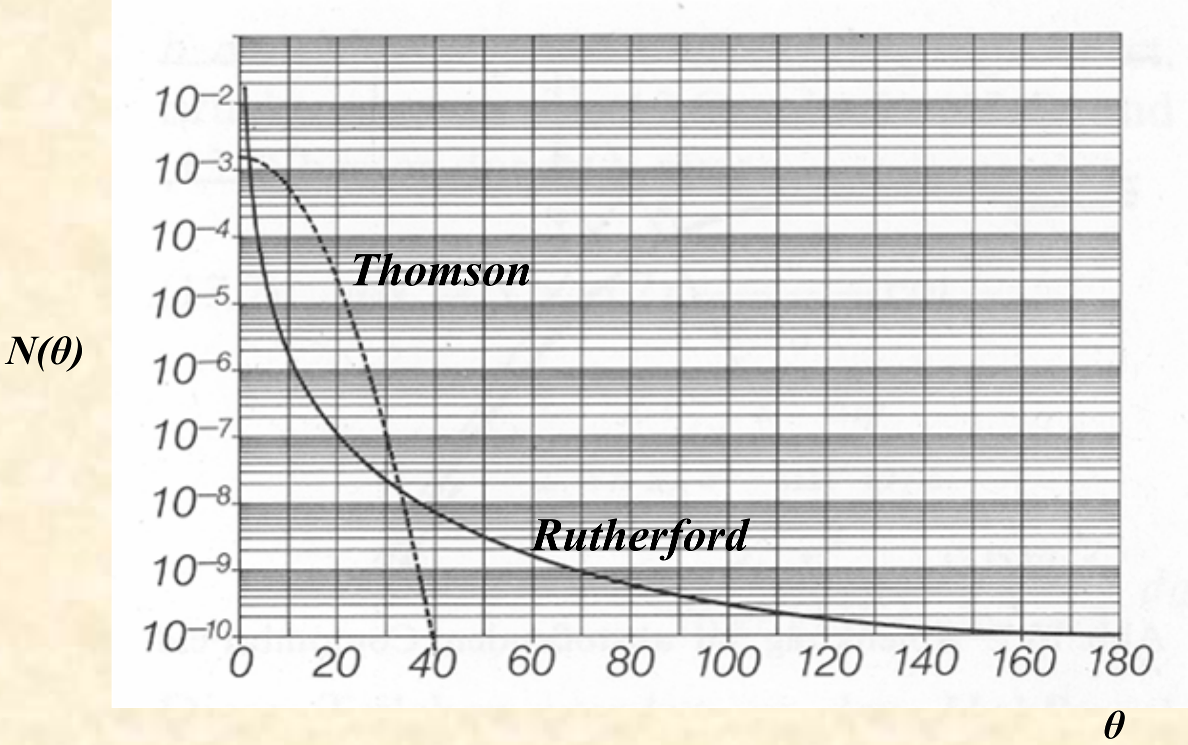
In short words: "What is going on, up there ???"

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

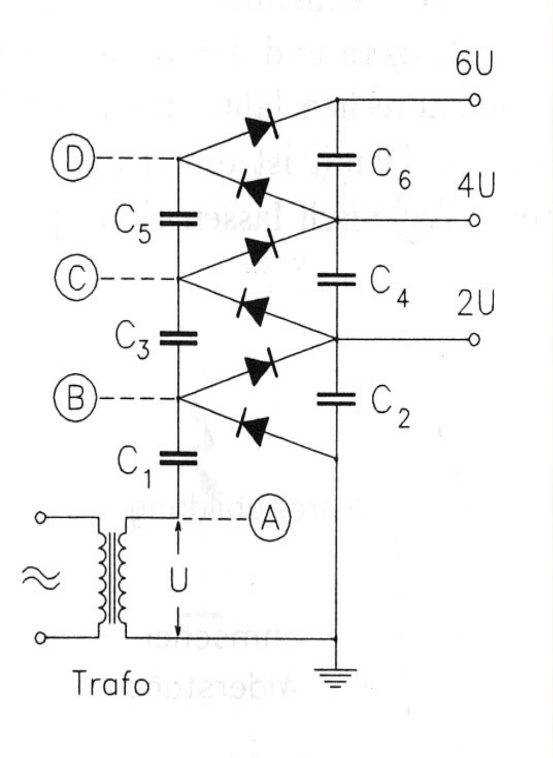
$$N(\theta) = \frac{N_i n t Z^2 e^4}{(8\pi\varepsilon_0)^2 r^2 K^2} * \frac{1}{\sin^4(\theta/2)}$$

Rutherford Scattering, 1911

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

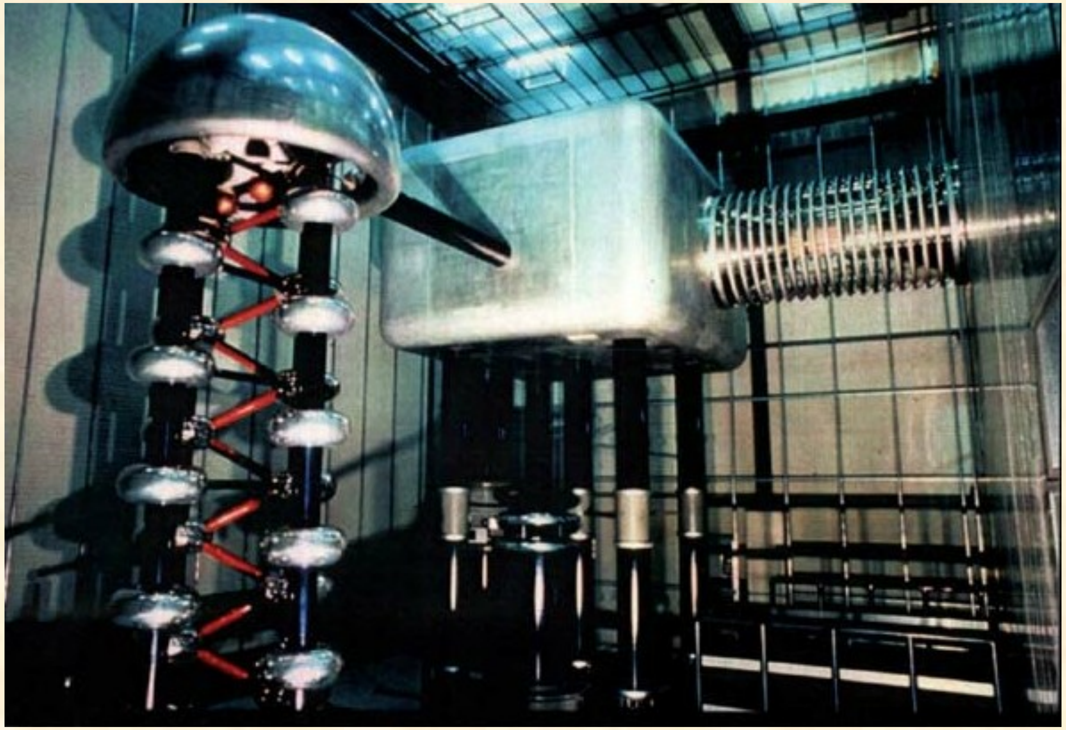


1.) Electrostatic Machines:
The Cockcroft-Walton Generator



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*

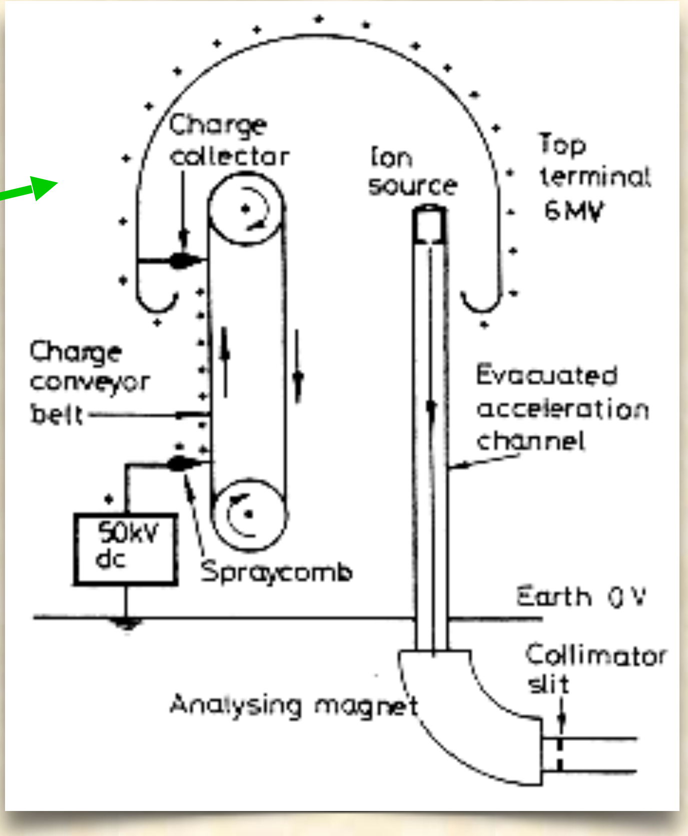
Technically: rectifier circuit, built of capacitors and diodes (Greinacher)

Problem:
DC Voltage can only be used once

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

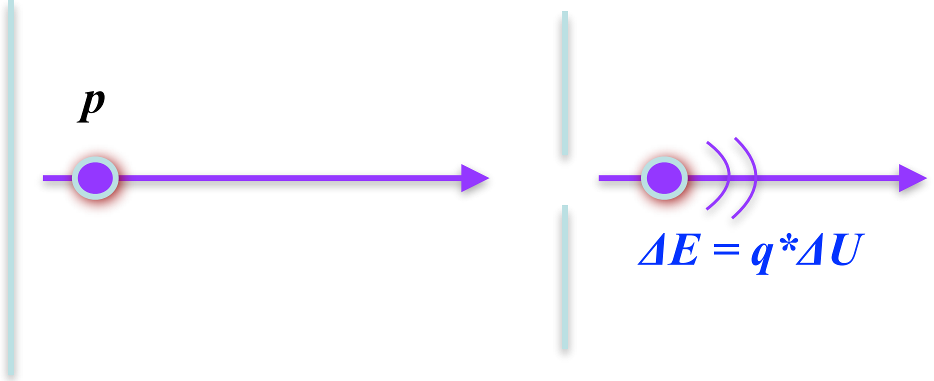
creating high voltages by mechanical transport of charges

* *Terminal Potential: U ≈ 12 ...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 ?

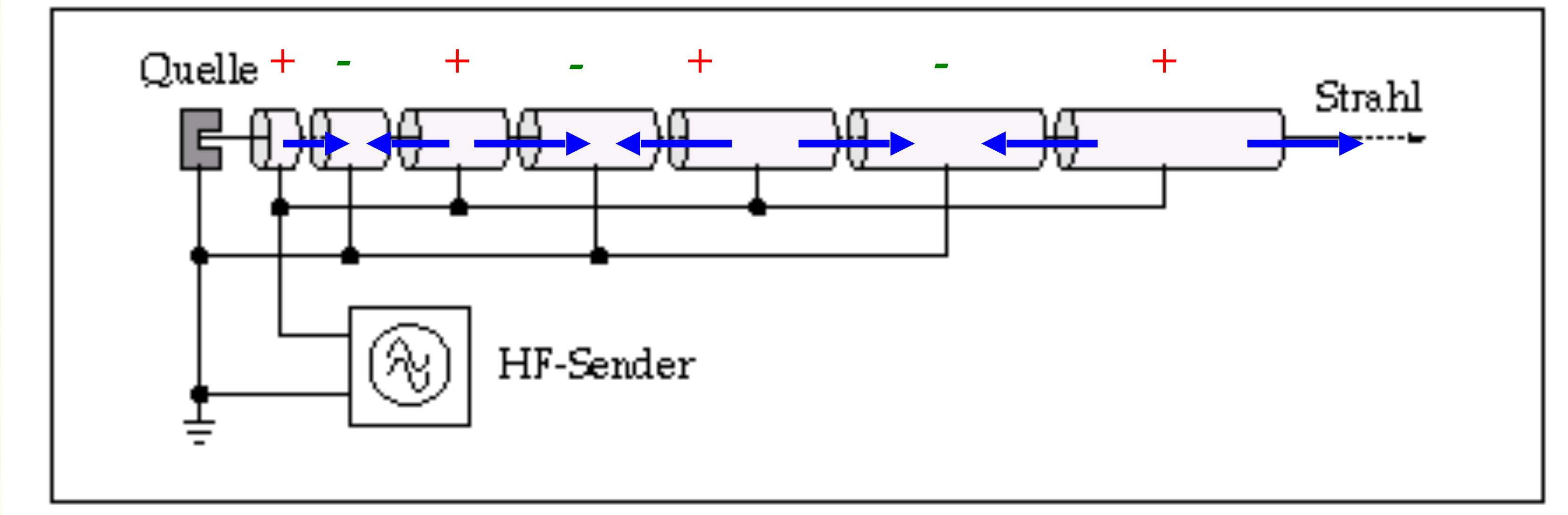
The „Tandem principle“: ***Apply the accelerating voltage twice ...***
... by working with negative ions (e.g. H $^-$) and
stripping the electrons in the centre of the structure

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

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

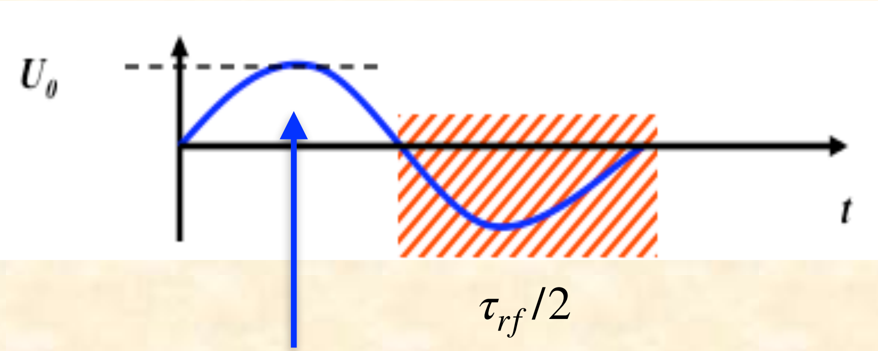
$$E_n = \boxed{n \cdot} q \cdot U_0 \boxed{\cdot \sin \psi_s}$$

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 $E_n = \frac{1}{2}mv^2 \longrightarrow v_n = \sqrt{2E_n/m}$

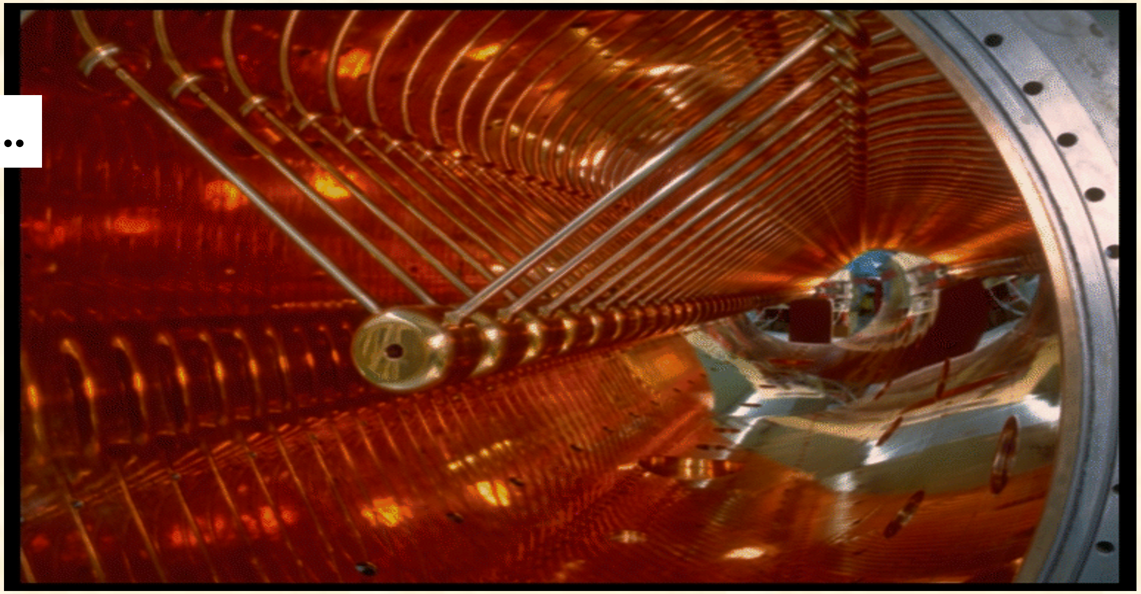
mit der kin. Energie $E_n = n \cdot q \cdot U_0 \cdot sin\ \psi_s$

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 $E_{total} = E_{kin} + m_0 c^2$

kinetic energy $E_{kin} = E_{total} - m_0 c^2$

Ruhe-Energie $E_0 = m_0 c^2$

Linac III:

$$E_{total} = 988\ MeV$$

$$m_0 c^2 = 938\ MeV$$

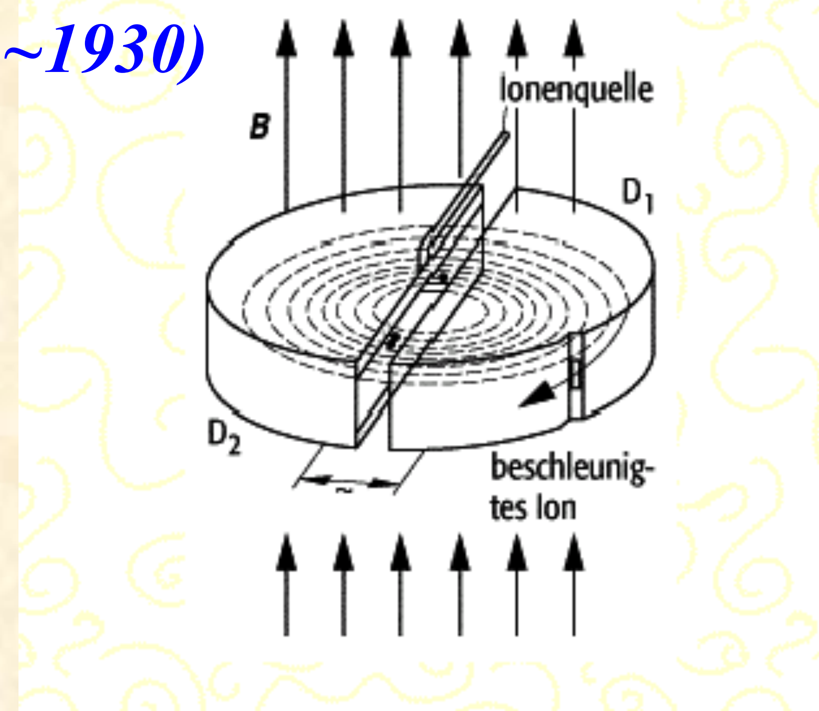
$$E_{kin} = 50\ MeV$$

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

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

—> 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

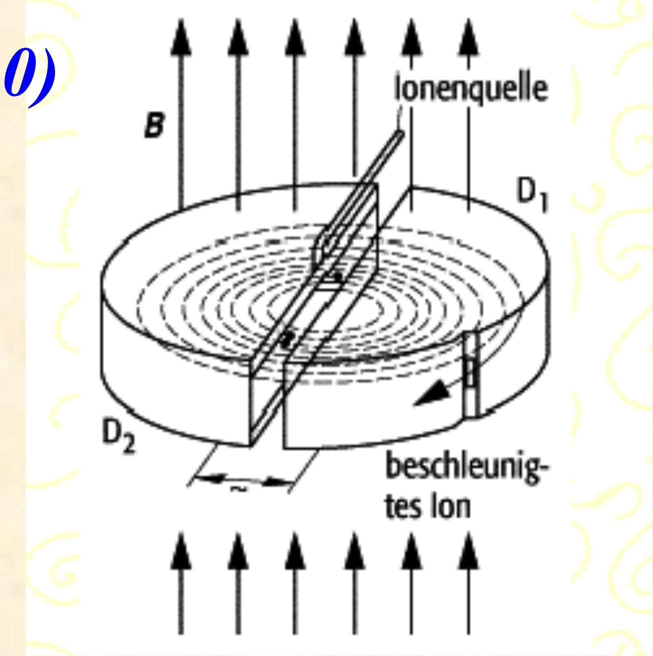
$$F = q \cdot v \cdot B$$

geladene Teilchen in Bewegung werden im Magnetfeld abgelenkt.

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

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

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

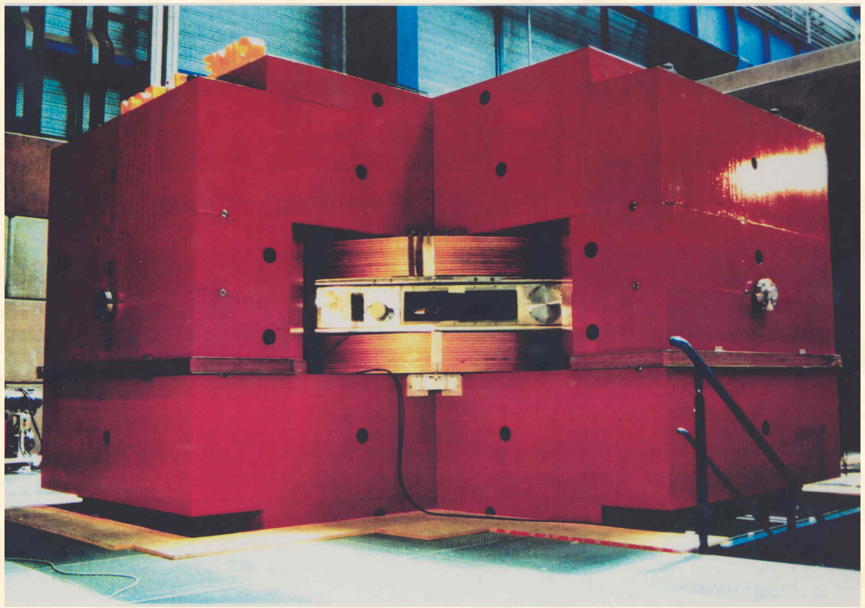
$$\omega_{rf} = \omega_{revolution} \quad \textbf{oder} \quad \omega_{rf} = h \cdot \omega_{revolution}$$

Problem: Albert !!!

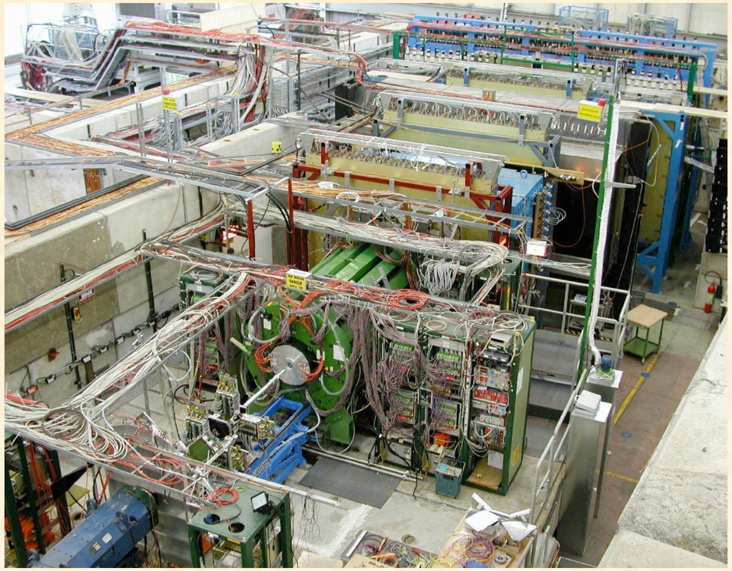
$$m \rightarrow \gamma \cdot m_0$$

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

Synchro-Cyclotron
Korrektur der RF
Frequenz

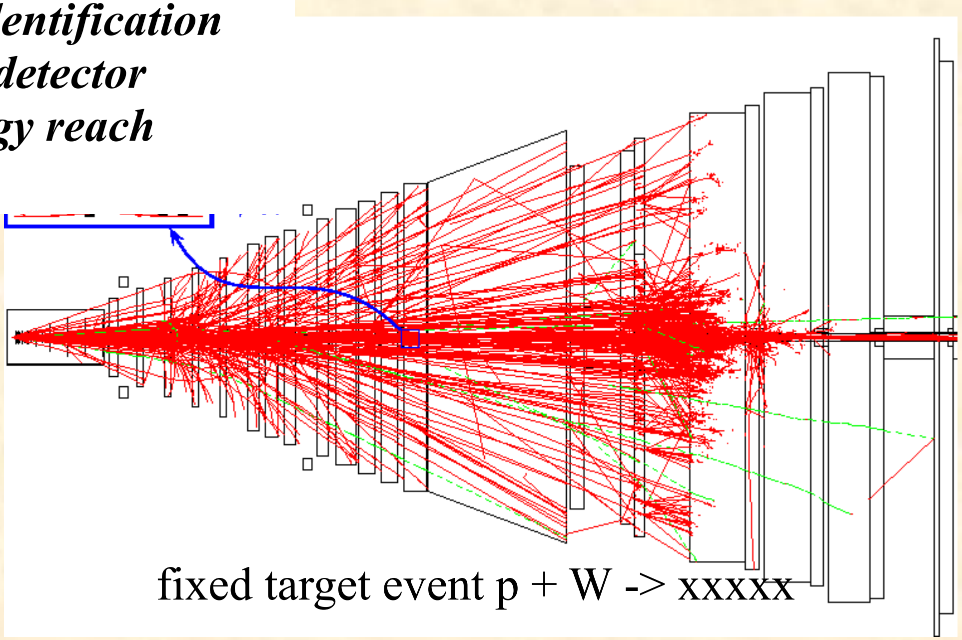


Fixed target experiments:



HARP Detector, CERN

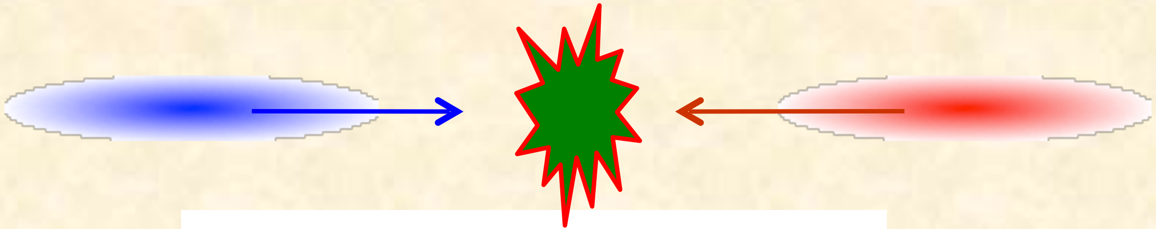
high event rate
easy track identification
asymmetric detector
limited energy reach



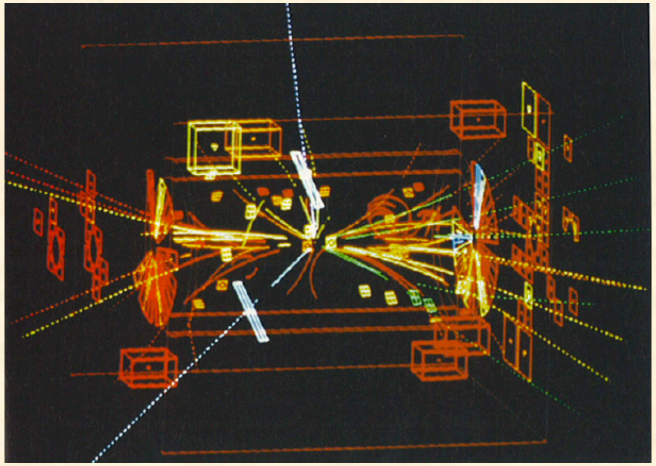
fixed target event p + W -> xxxxx

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.

Theory of 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:

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

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

equivalent electrical field:

Technical limit for electrical fields:

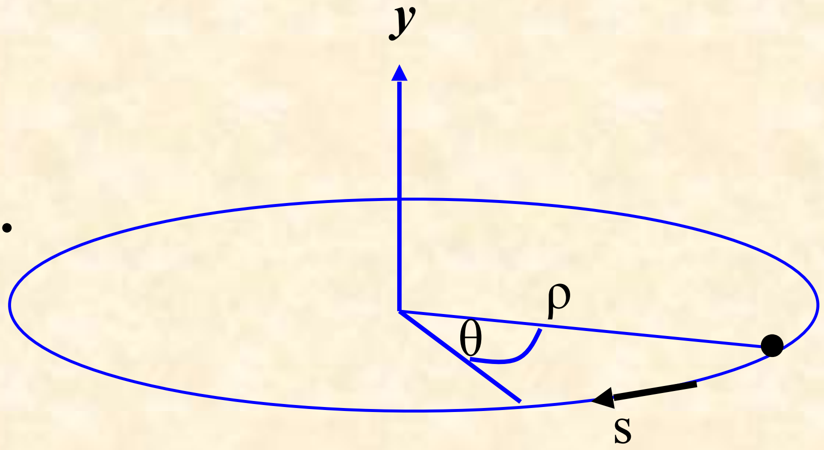
$$E \leq 1 \frac{MV}{m}$$

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

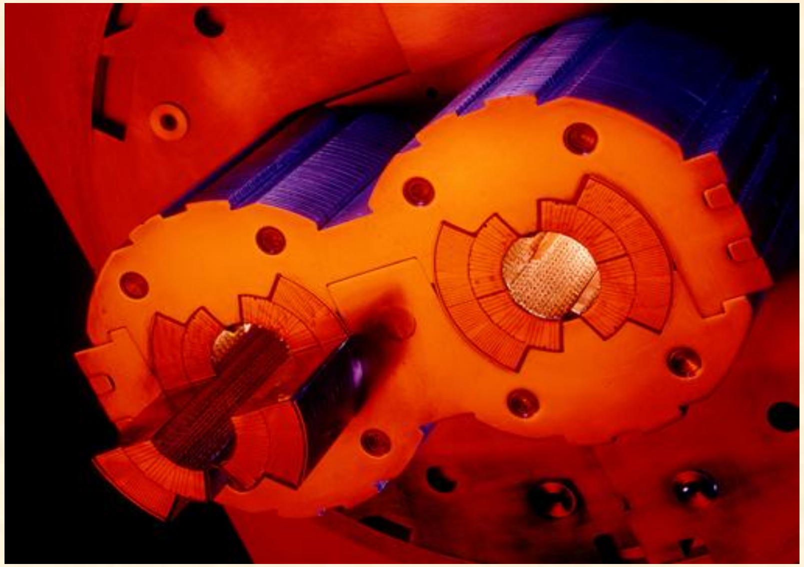
$$\frac{\gamma\, m_0\, v^{\cancel{2}}}{\rho} = e\,\cancel{v}\,B$$

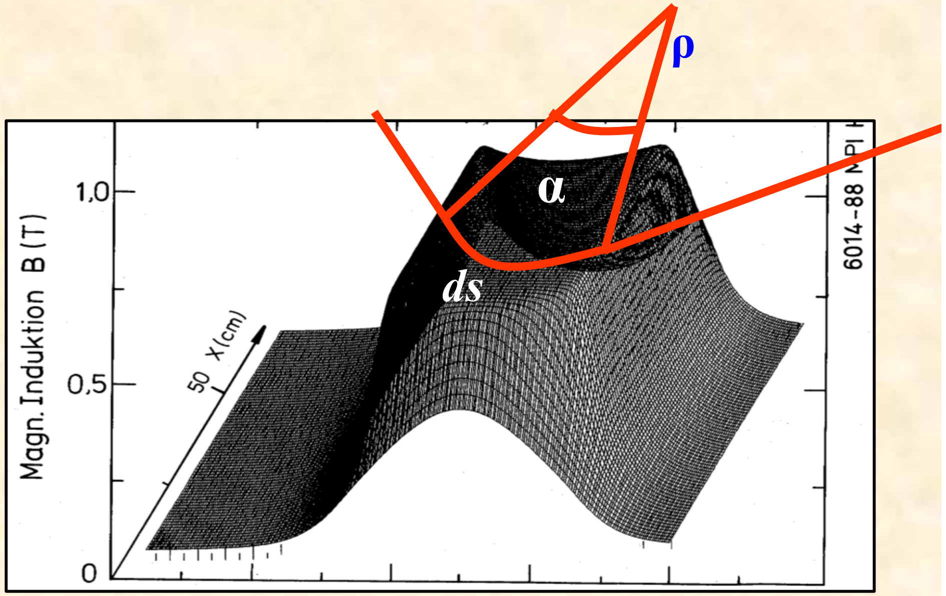
$$\boxed{\frac{p}{e} = B\,\rho}$$

B ρ = "beam rigidity"

… und jetzt isses sogar relativistisch korrekt.

The Magnetic Guide Field





field map of a storage ring dipole magnet

Dipole erzeugen mit zwei parallelen Polschuhen ein konstantes (!) Magnetfeld

$B \approx 1 \dots 8\ T$

Achtung: um zum Pluto zu kommen muessen wir höchste Präzision fordern.

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

Ablenkradius:

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

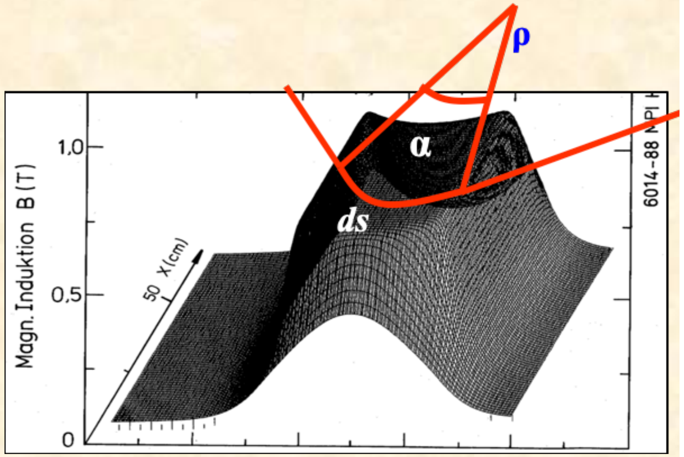
nota bene:
die allgemeinste Ausdruck fuer die Energie ist

$$\rho = 2.8\ km$$

$$E^2 = p^2c^2 + m^2c^4 \quad \rightarrow \quad p \approx \frac{E}{c}$$

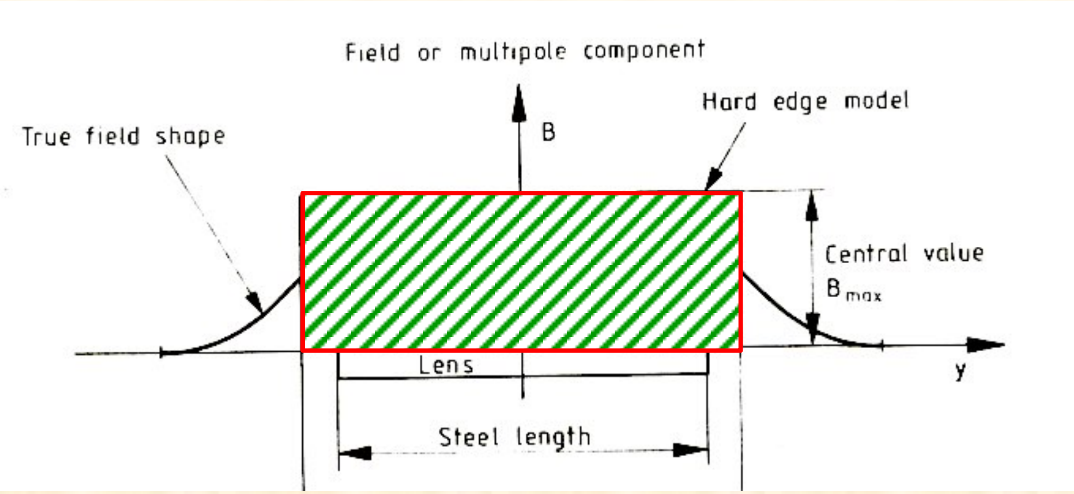
Bending Angle

„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 $$\boldsymbol{B\, l_{eff} = \int_0^{l_{mag}} B\, ds}$$



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"

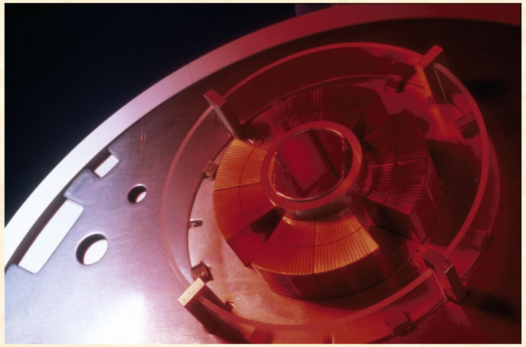
$$n \cdot B \cdot l_{dipol} = 2\pi \cdot \frac{p}{q}$$

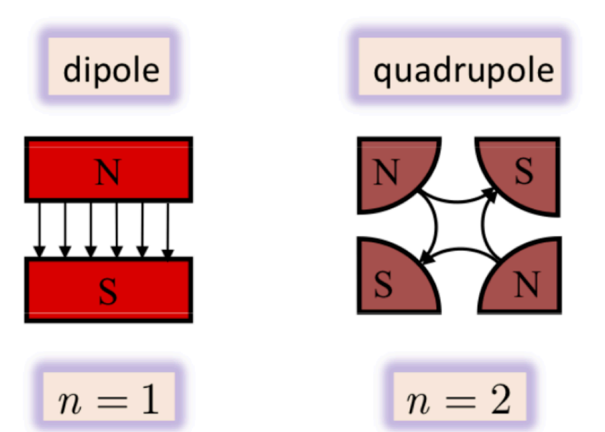
2.)Focusing Forces: Quadrupole Fields

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: $B*\rho = p / q$)

Dipole Magnet

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

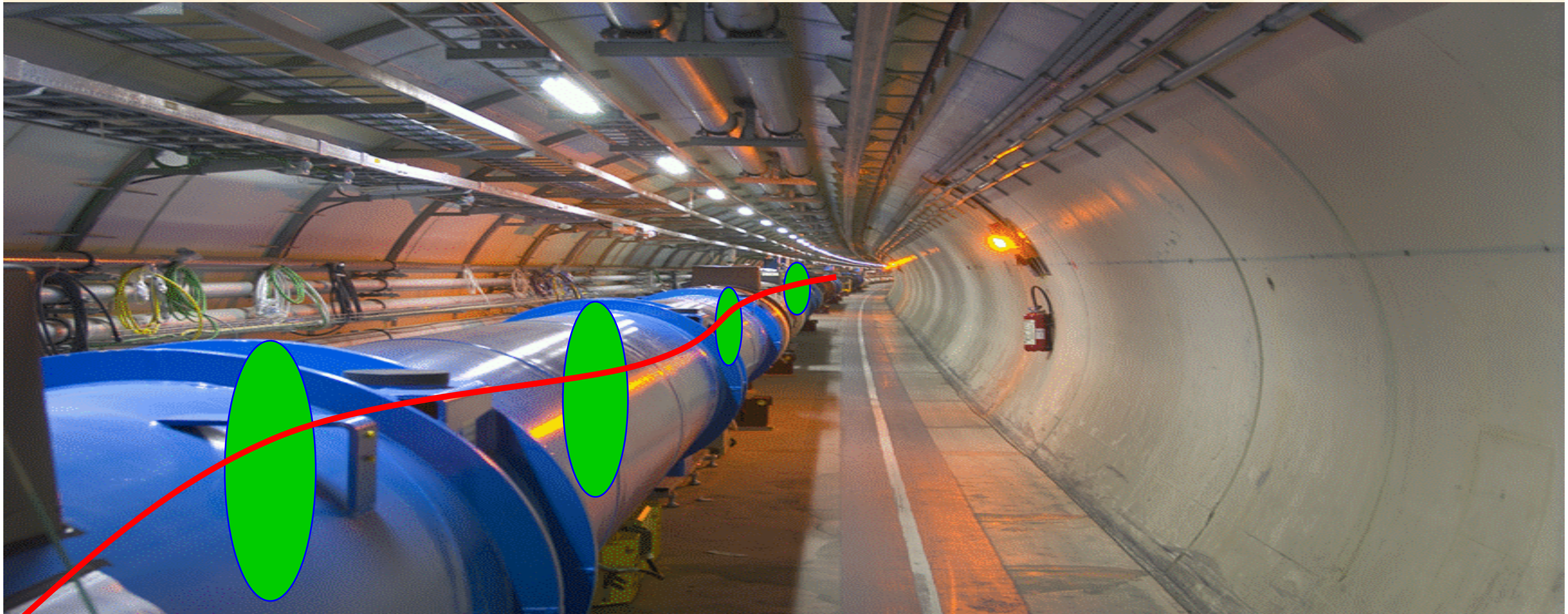
Quadrupole Magnet

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

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

„normalised bending strength“

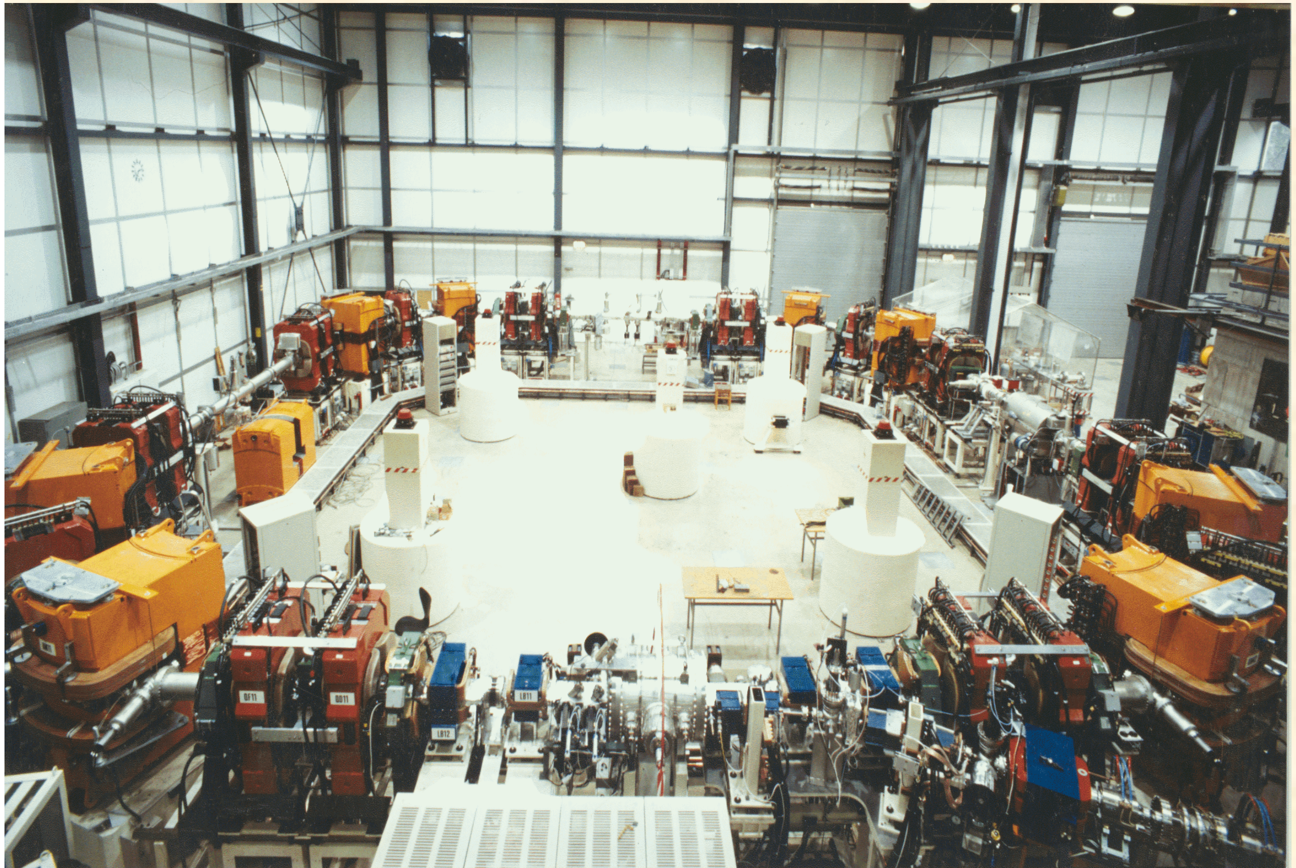
$$1/\rho = \frac{B}{p/e}$$



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:

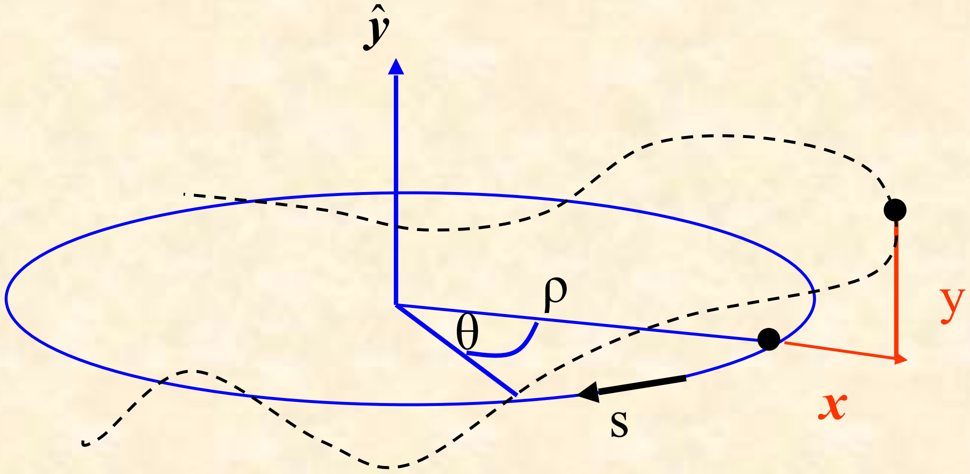
Split the magnets and optimise them according to their job:

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:*

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

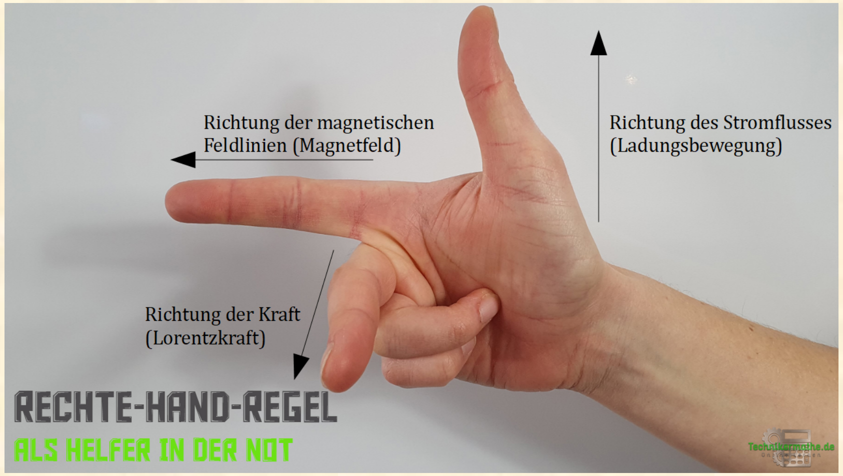
x = particle amplitude
x' = angle of particle trajectory (wrt ideal path line)

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

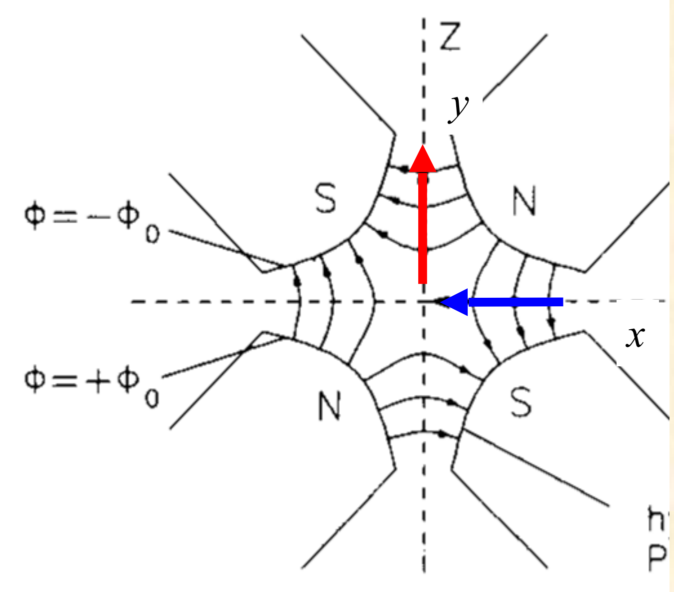
$$x'' = \quad -K \cdot \; x$$

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

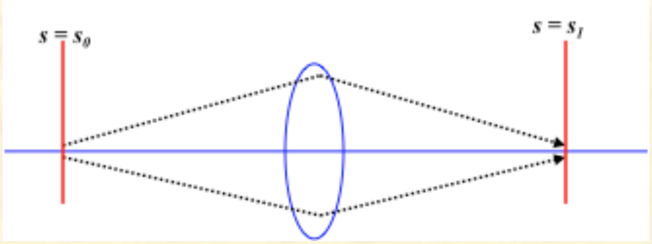
$$x'' + K\ x = 0$$

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.

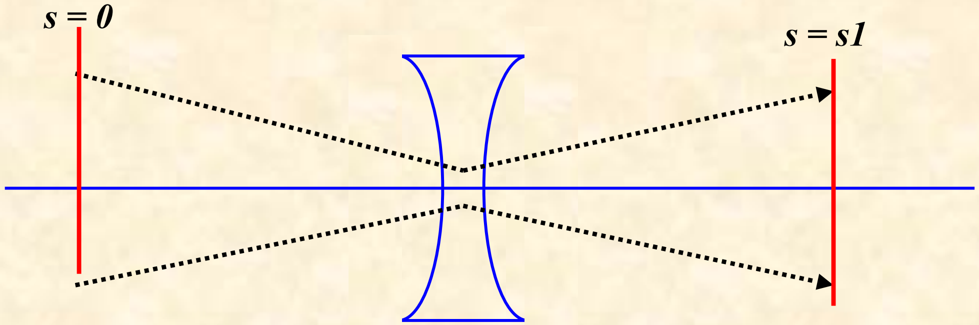
For convenience expressed in matrix formalism:

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

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

hor. defocusing quadrupole:

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



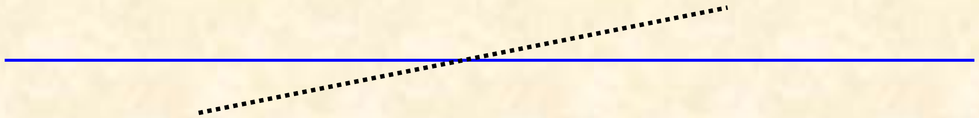
Ansatz: ***Remember from school***

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

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

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 !

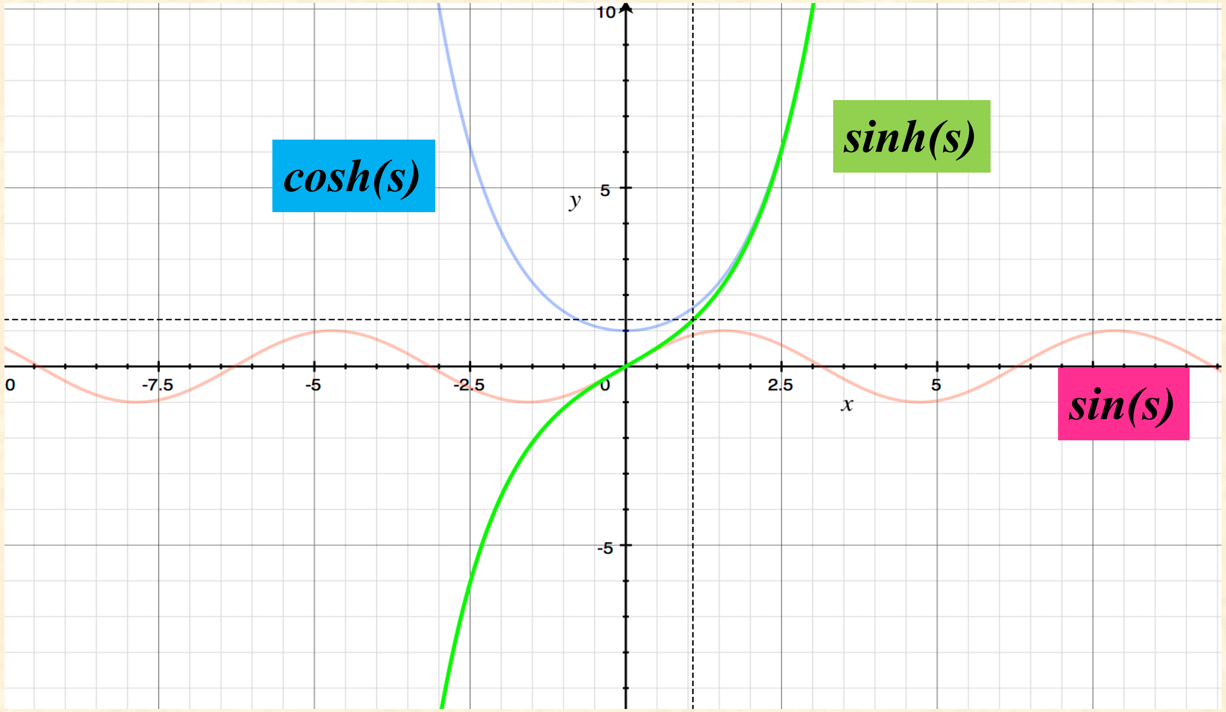
$$M_{defoc} = \begin{pmatrix} \cosh \sqrt{|K|}l & \frac{1}{\sqrt{|K|}} \sinh \sqrt{|K|}l \\ \sqrt{|K|} \sinh \sqrt{|K|}l & \cosh \sqrt{|K|}l \end{pmatrix}$$

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

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

Ansatz für die Teilchenbewegung im defokusierenden Fall:

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

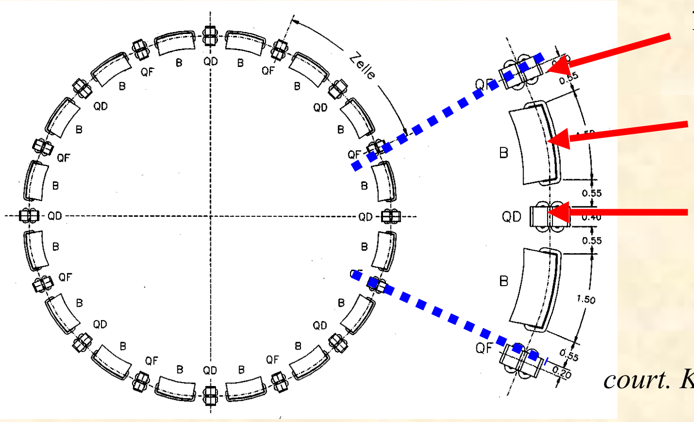


Transformation through a system of lattice elements

combine the single element solutions by multiplication of the matrices

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

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



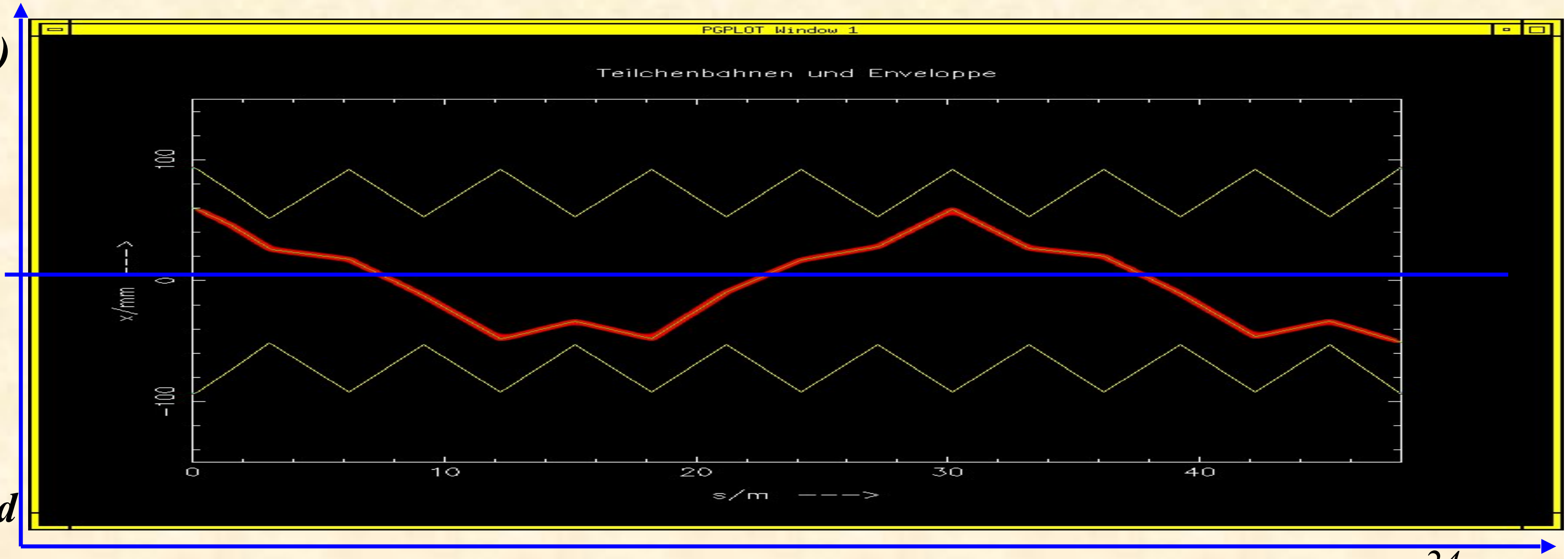
focusing lens

dipole magnet

defocusing lens

court. K. Wille

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



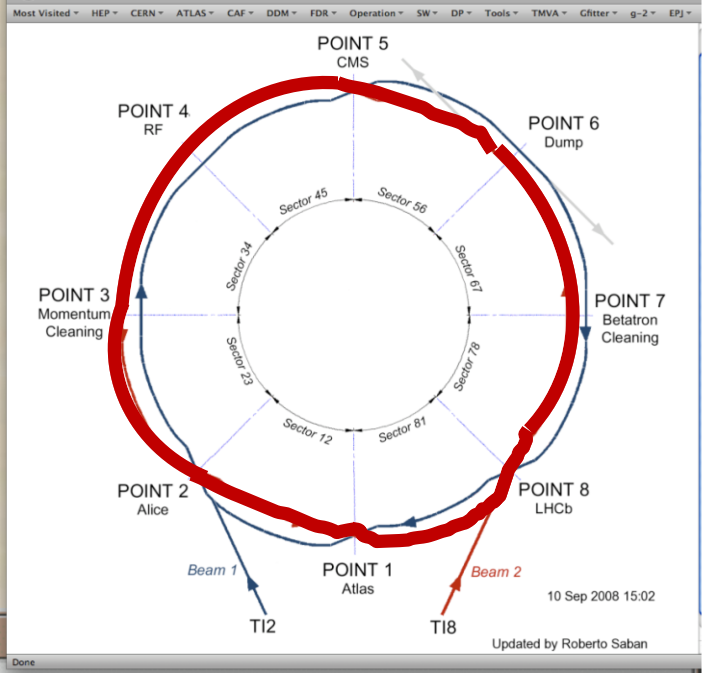
typical values in a strong foc. machine:

x ≈ mm, x´ ≤ 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:"



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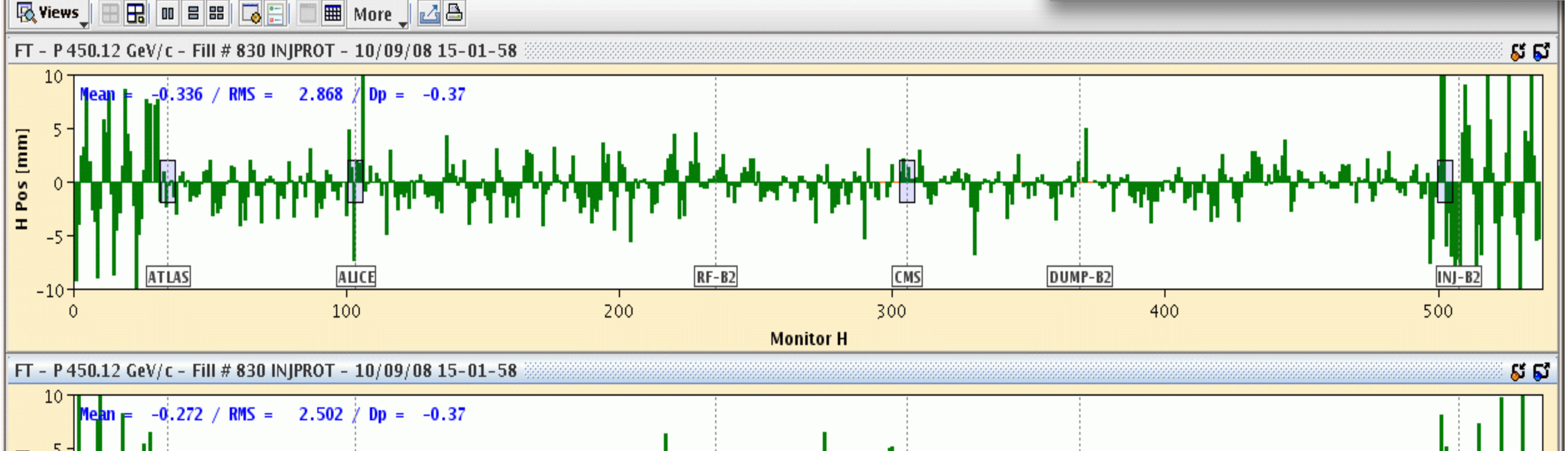
Updated by Roberto Saban

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

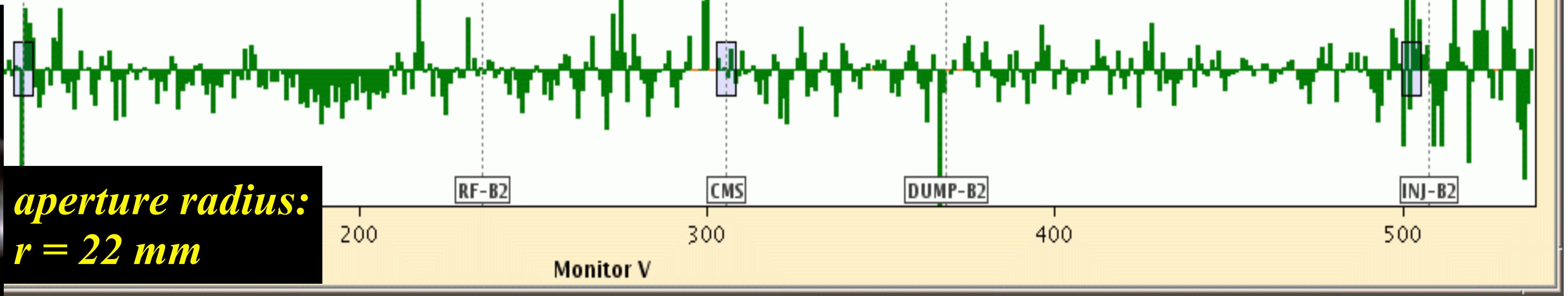


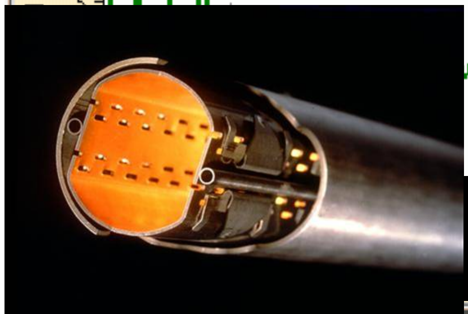
FT - P 450.12 GeV/c - Fill # 830 INJPROT - 10/09/08 15-01-58

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



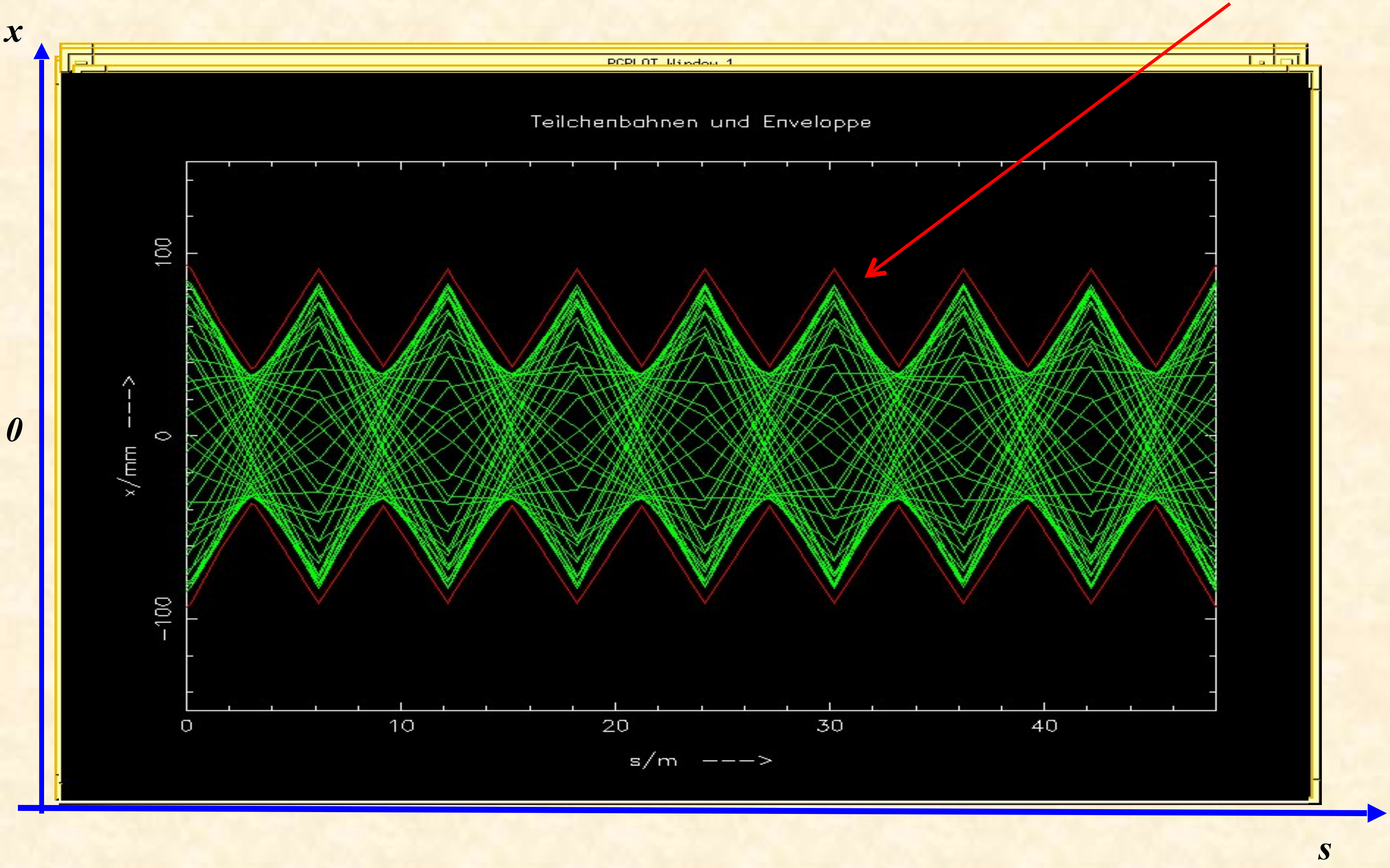


aperture radius:
r = 22 mm

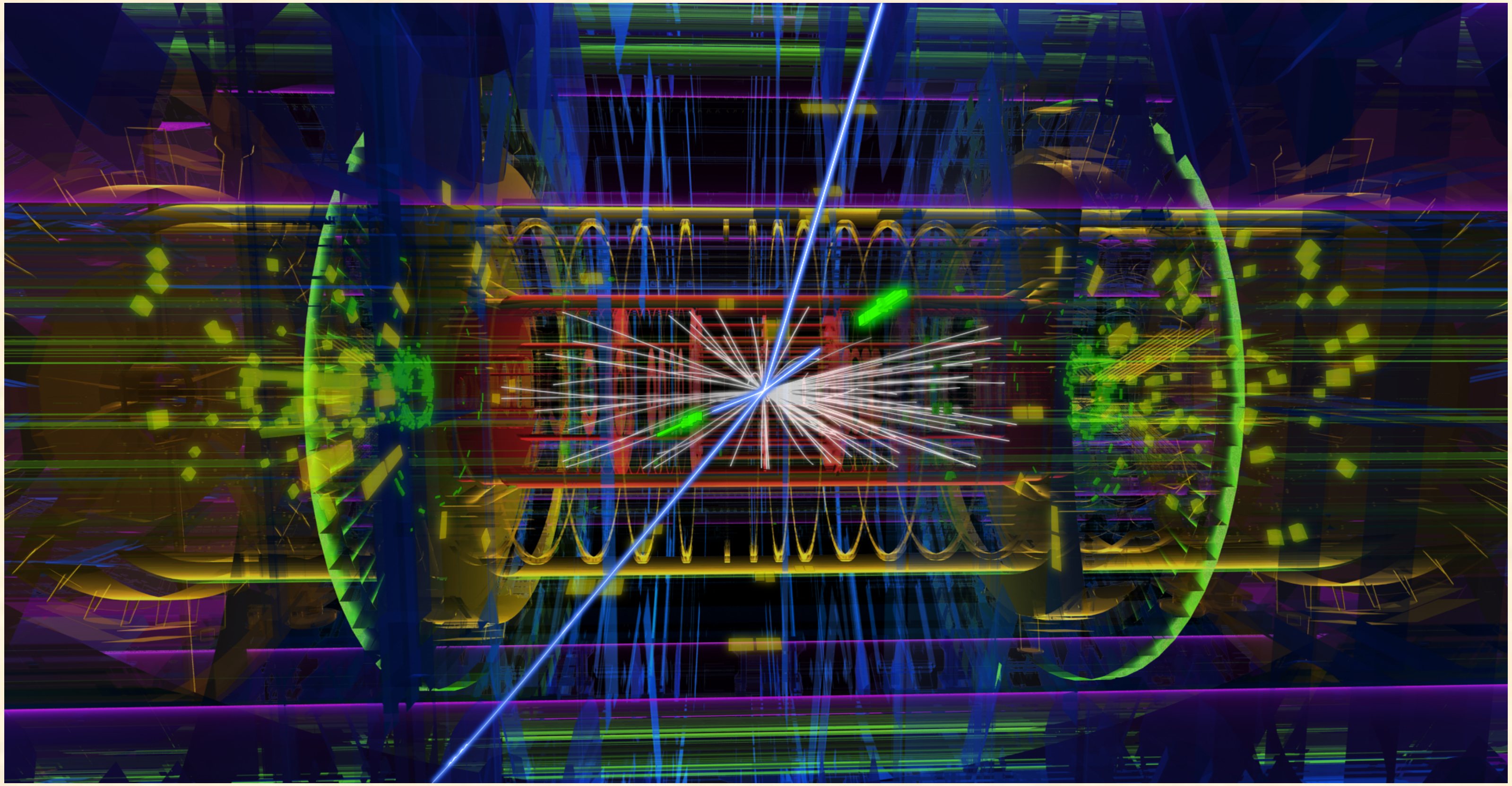
***Question:* what will happen, if the particle performs a second turn ?**

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

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



Collisions



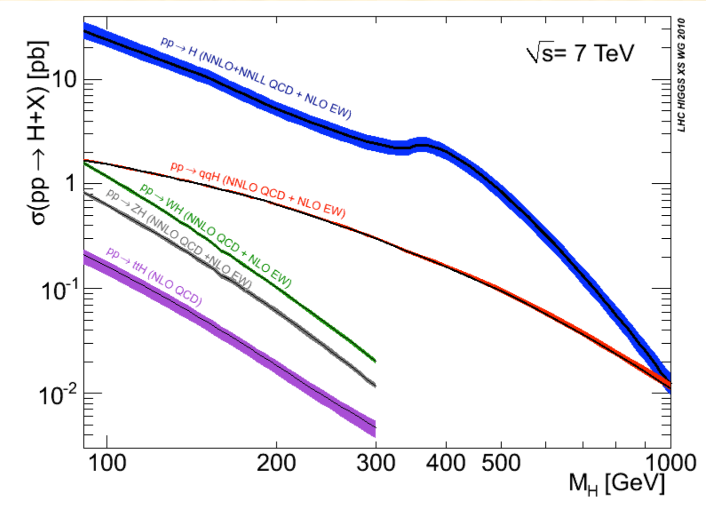
ATLAS event display: Higgs => two electrons & two muons

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

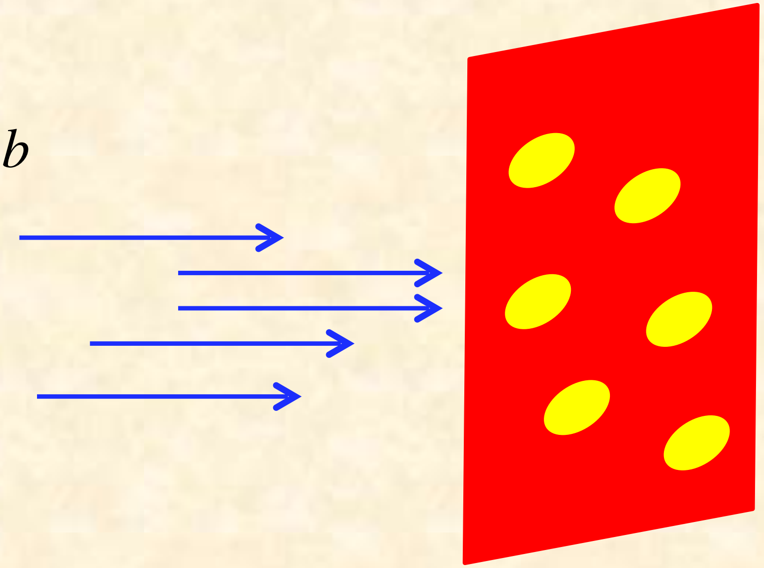
Problem: Our particles are VERY small !!

man trifft nicht so häufig.

Overall cross section of the Higgs:



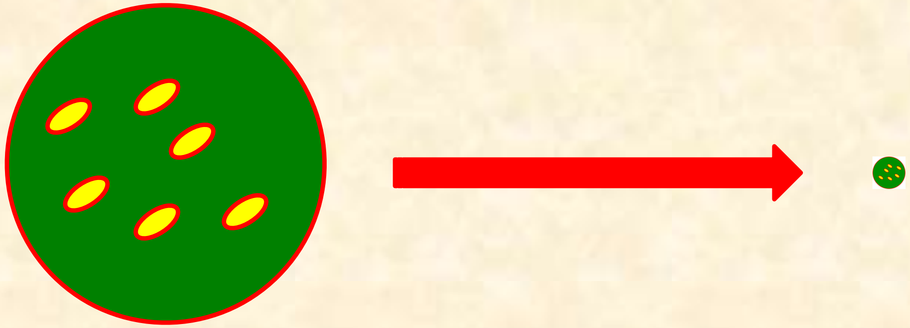
$$\Sigma_{react} \approx 1pb$$



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

The particles are "very small"

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

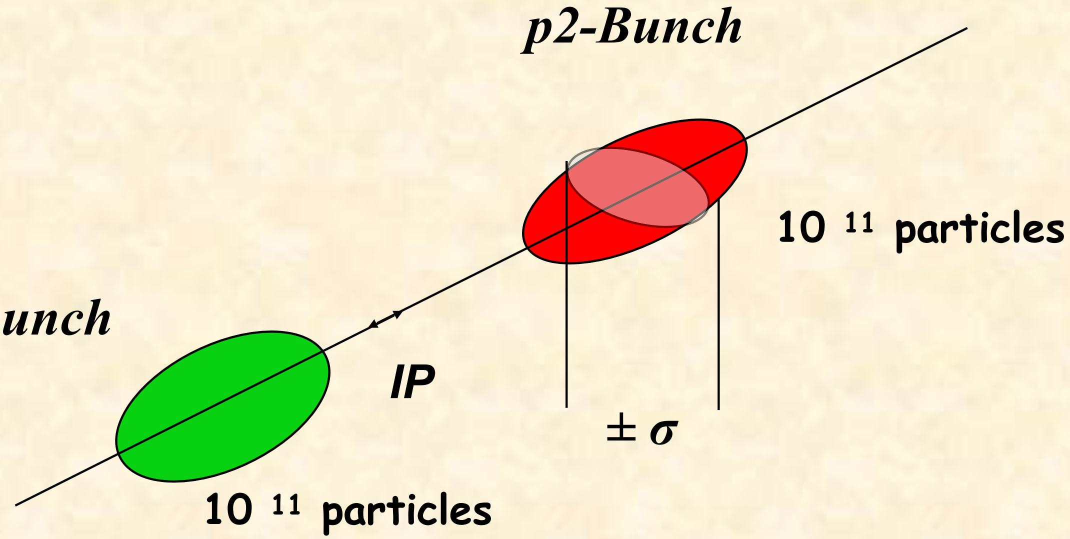


LHC typical → 16 μm

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*

$\boldsymbol{f}_0 = 11.245\ \boldsymbol{kHz}$ *Umlaufs-Frequenz*

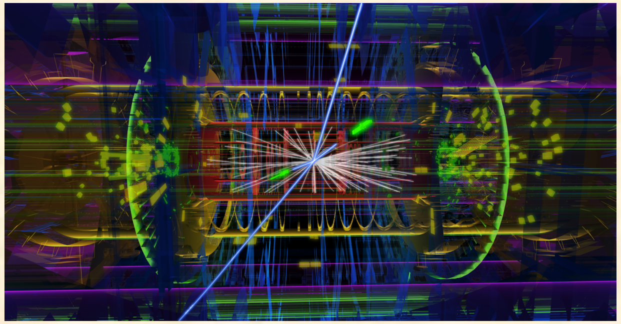
$\boldsymbol{n}_b = 2808$ *Zahl der Bunche*

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

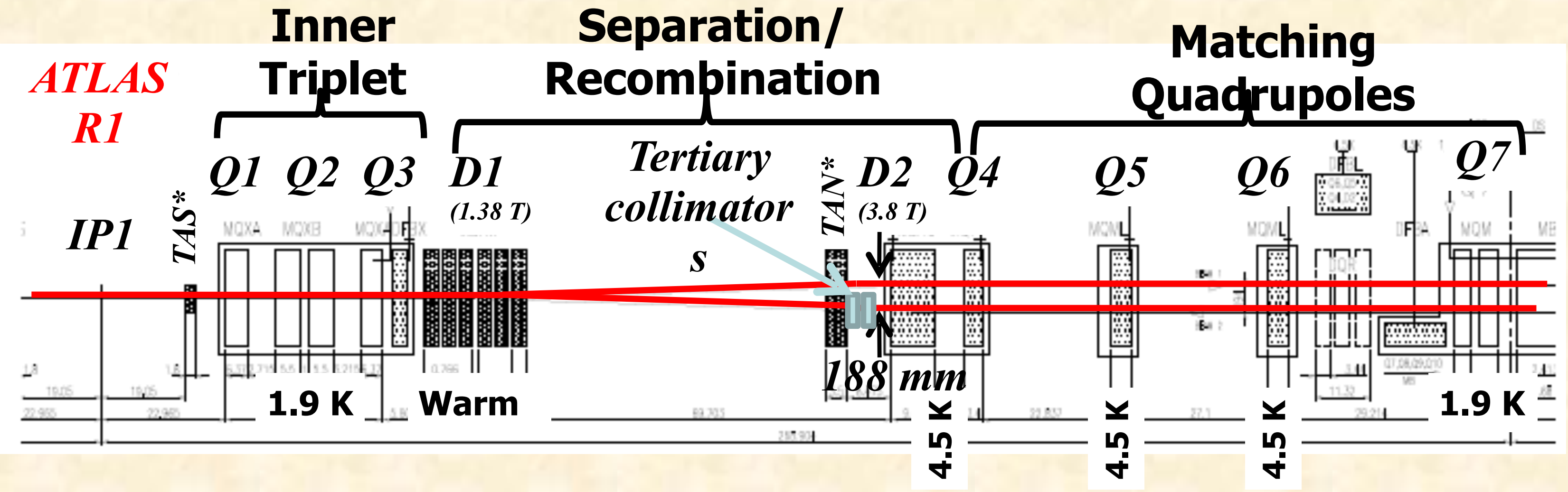
$\boldsymbol{I}_p = 584\ \boldsymbol{mA}$ *Strahlstrom*

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

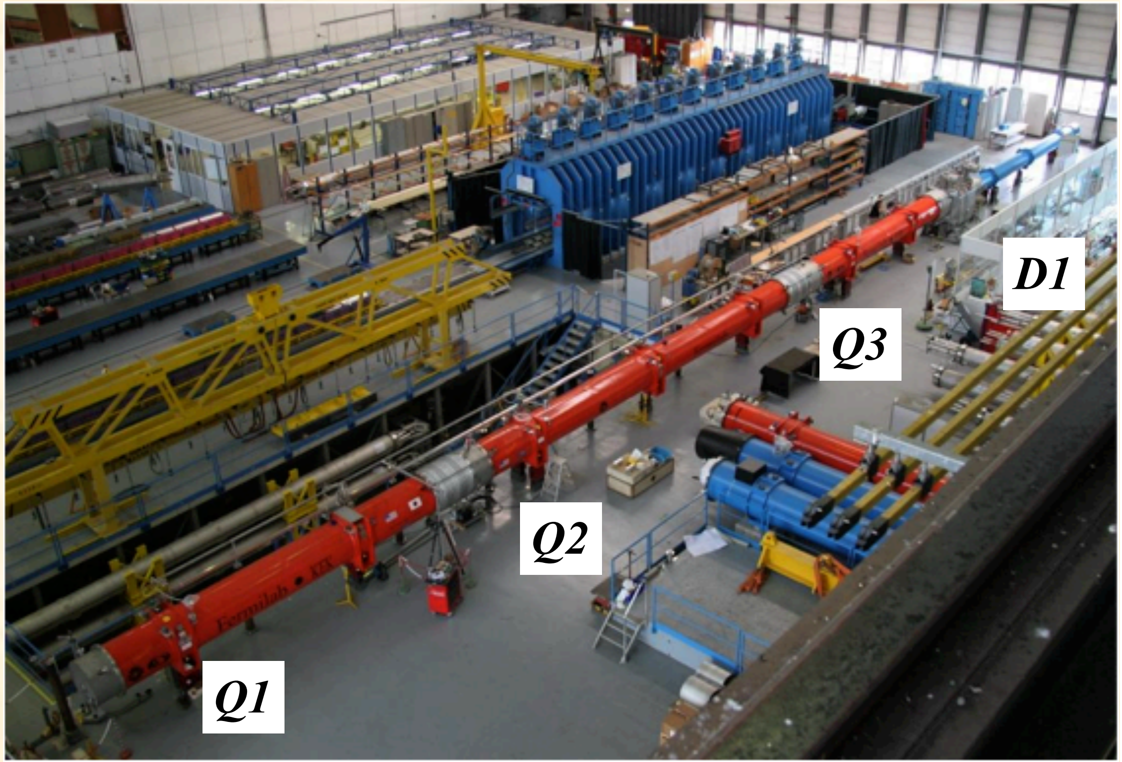
$$L = \frac{1}{4\pi} \cdot N_{p1} \cdot \frac{N_{p2}}{\sigma_x \sigma_y} \cdot (n_b \cdot f_0)$$



The LHC Mini-Beta-Insertions

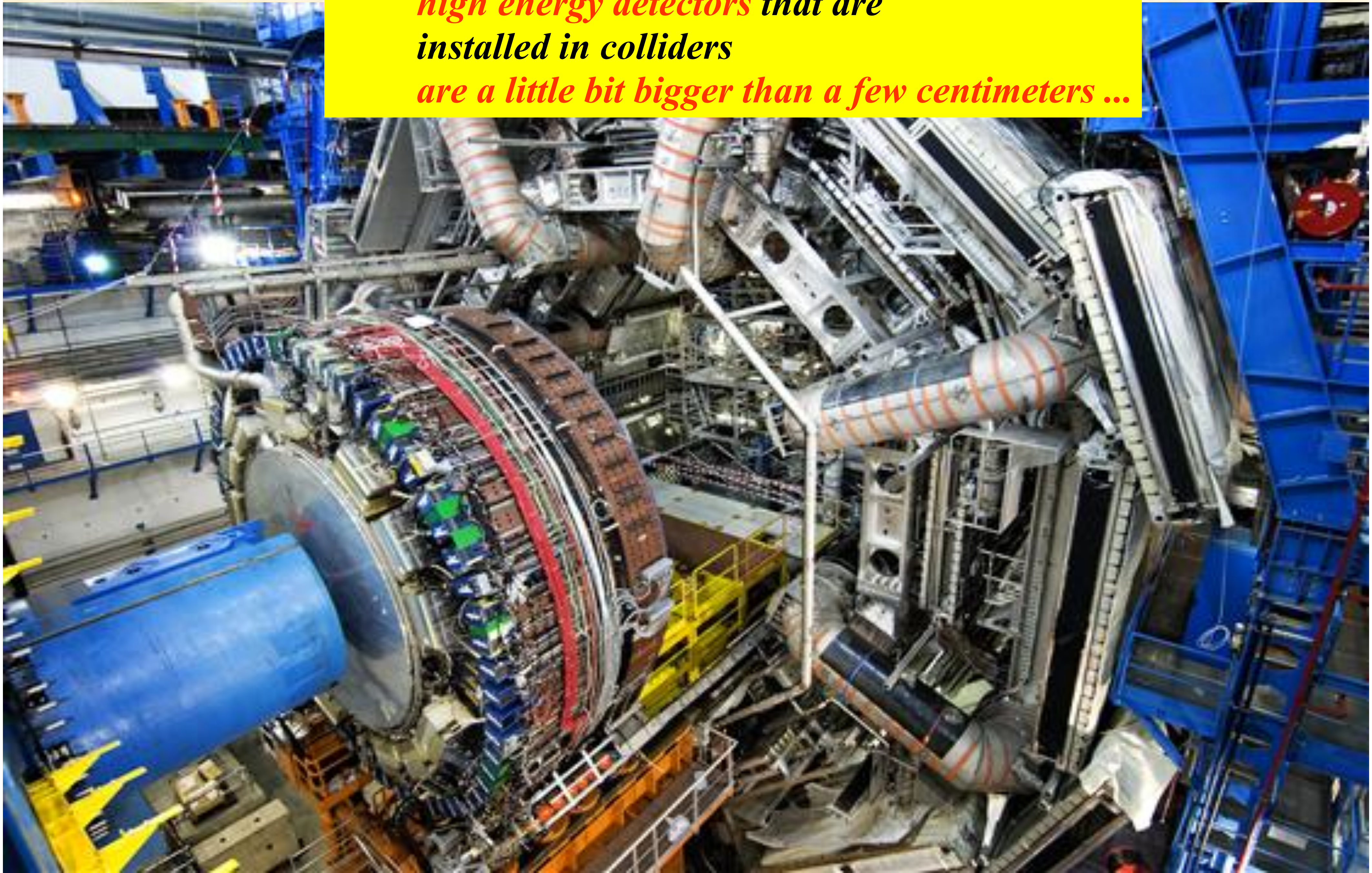


Extrem starke Fokussierung (in beiden Ebenen) für beide Strahlen, um die Trajektorien der 10^{11} Teilchen auf micro Meter zu komprimieren.



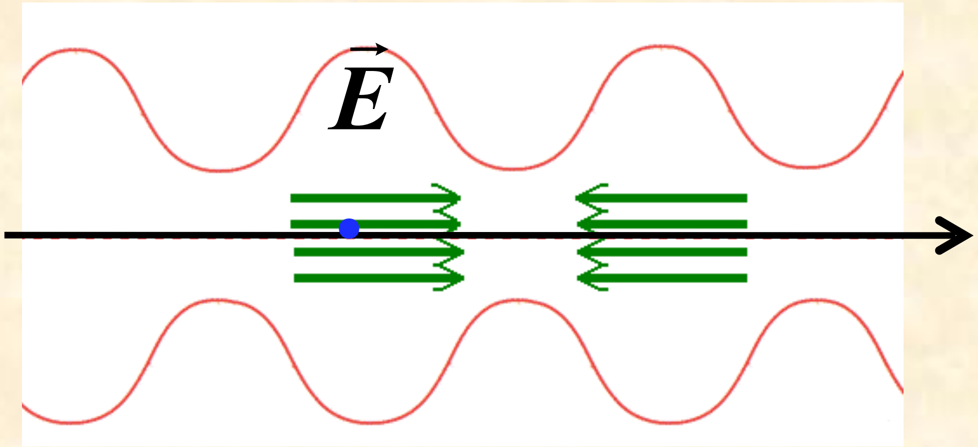
... clearly there is another problem !!!

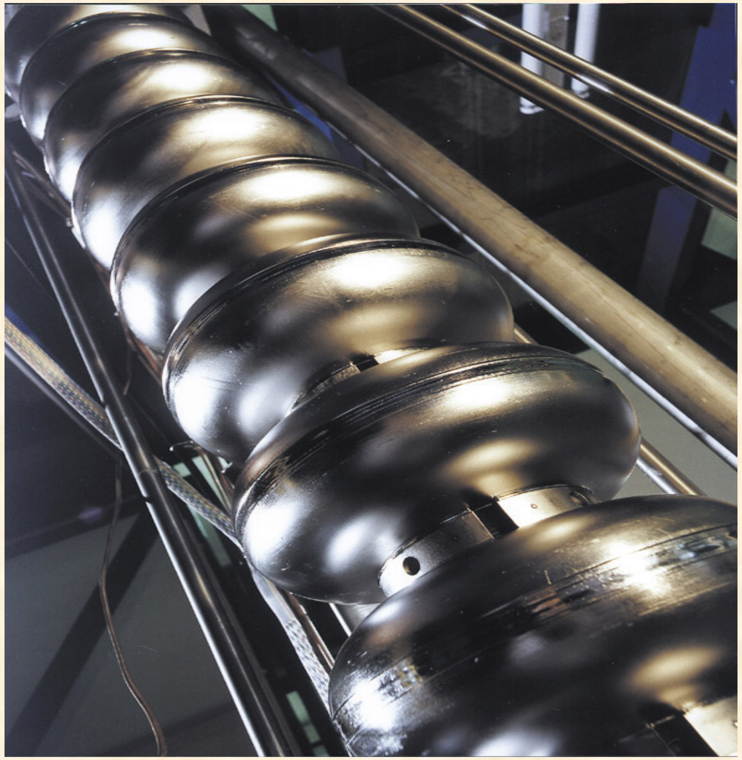
... unfortunately ... in general
high energy detectors that are
installed in colliders
are a little bit bigger than a few centimeters ...



The Acceleration

Install an RF accelerating structure in the ring:





z

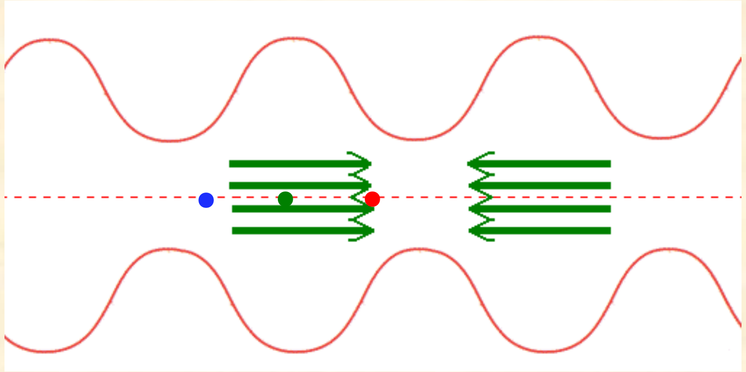
The Acceleration & "Phase Focusing"

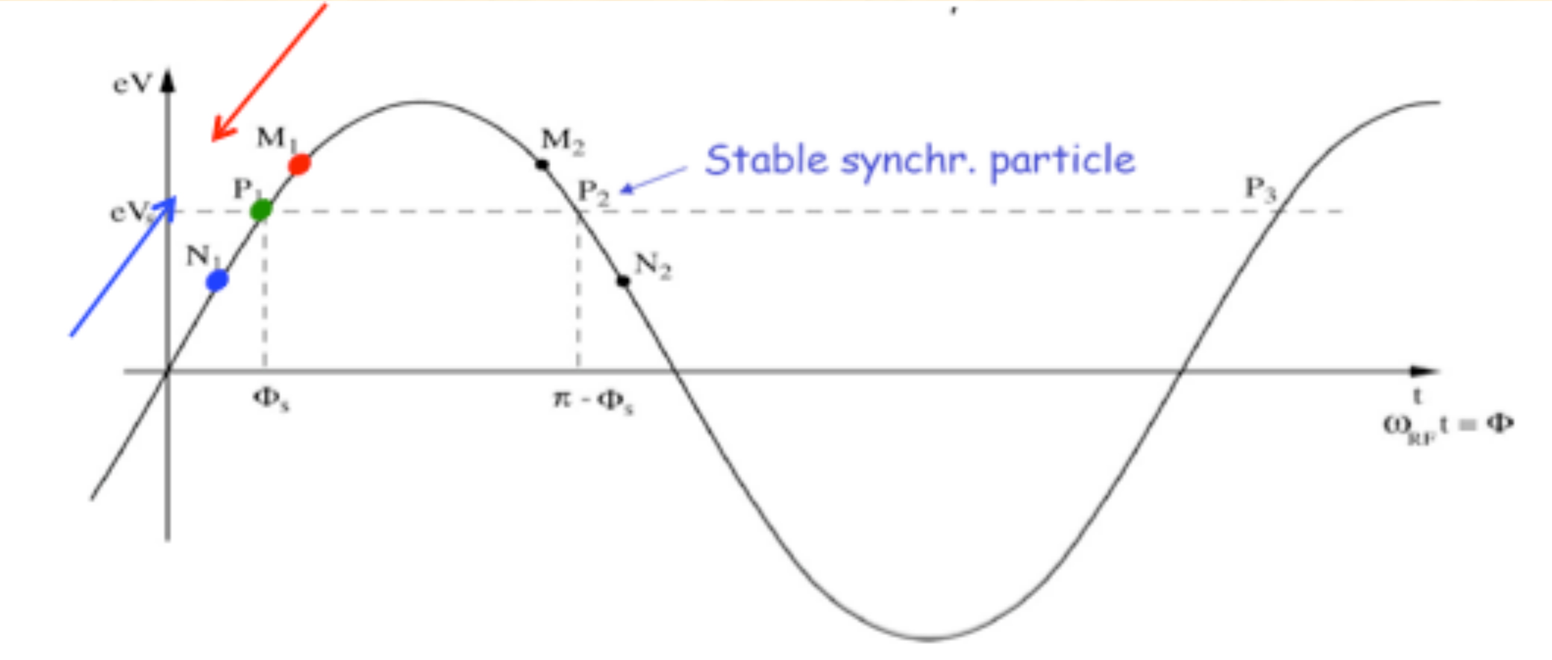
$\Delta p/p \neq 0$ below transition

ideal particle ●

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

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





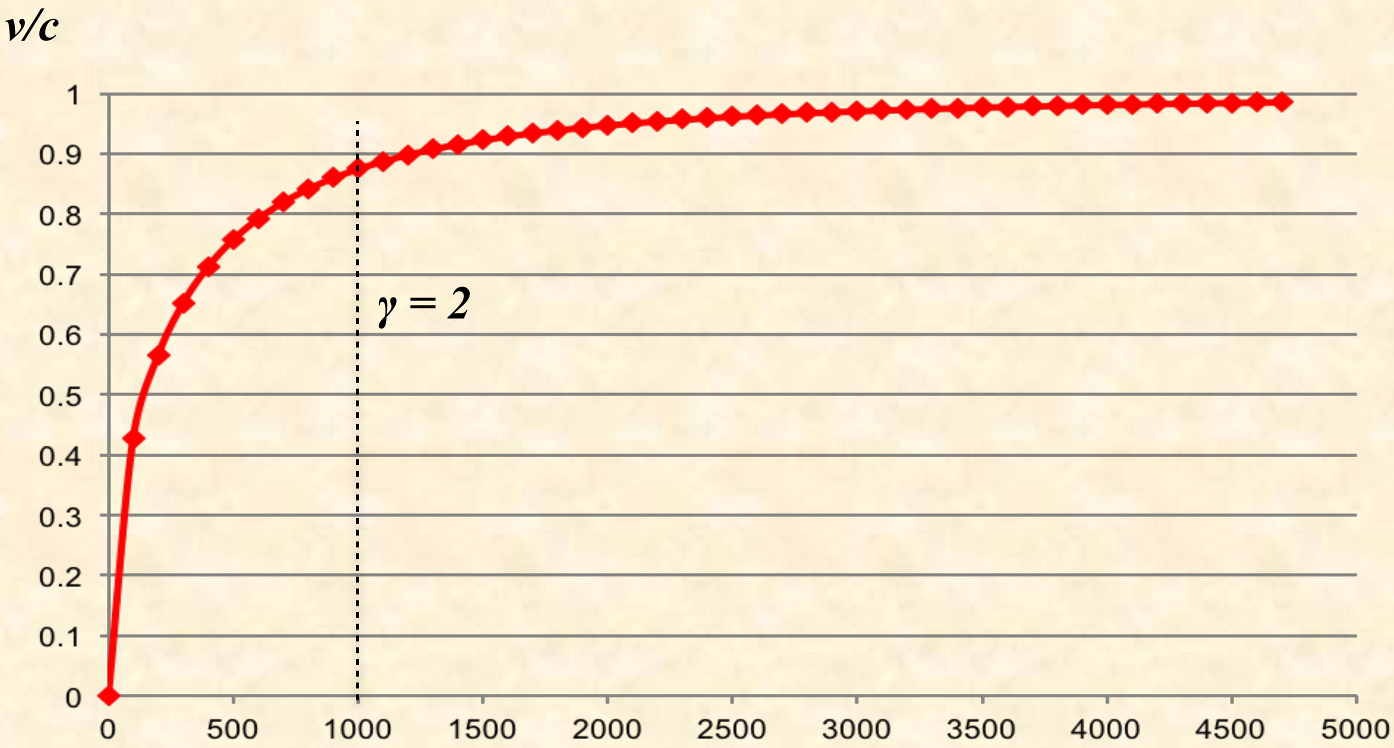
Focussing effect in the longitudinal direction keeping the particles close together ... forming a "bunch"

... 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 !



kinetic energy of a proton (MeV)

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

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

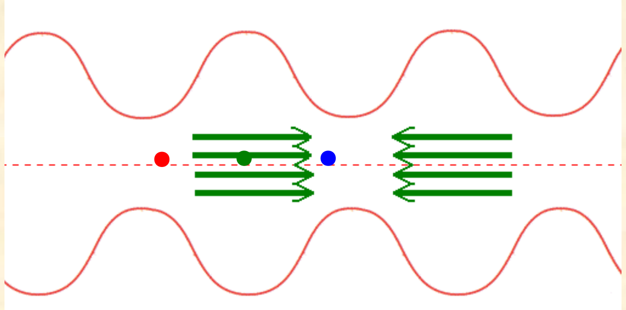
.... but heavier !

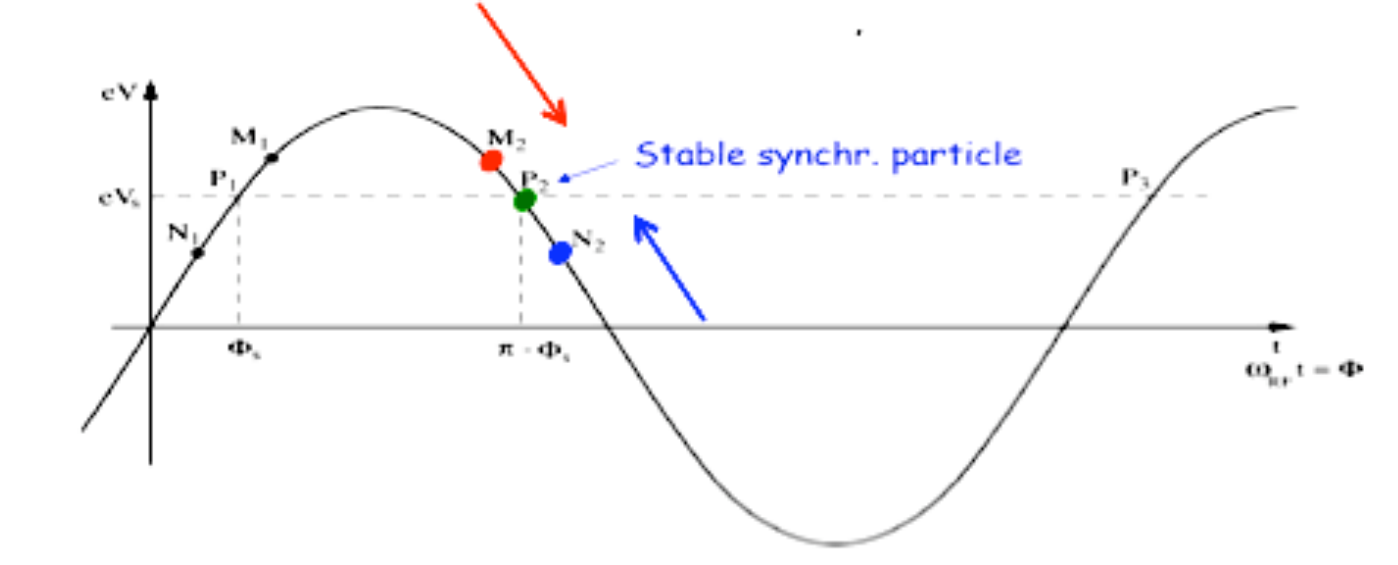
The Acceleration above transition

ideal particle ●

particle with Δp/p > 0 ● *heavier*

particle with Δp/p < 0 ● *lighter*





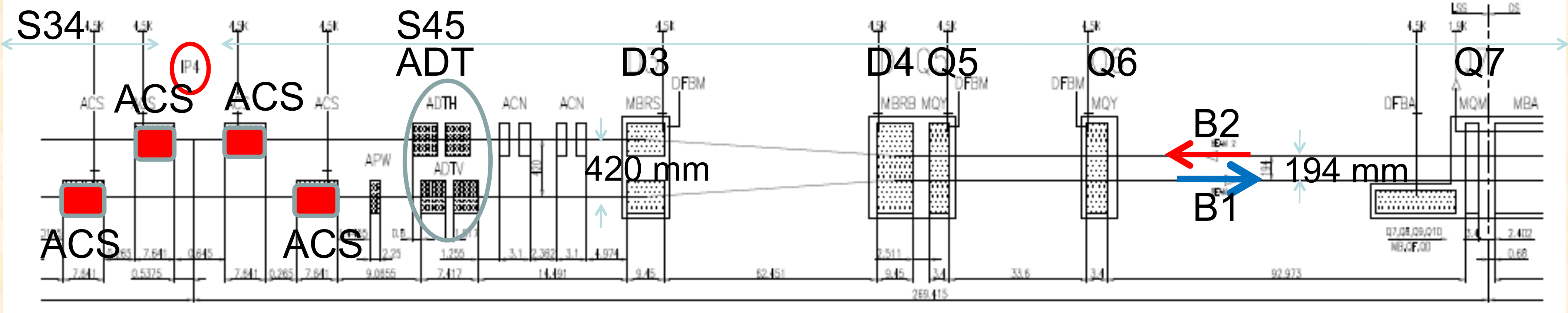
Stable synchr. particle

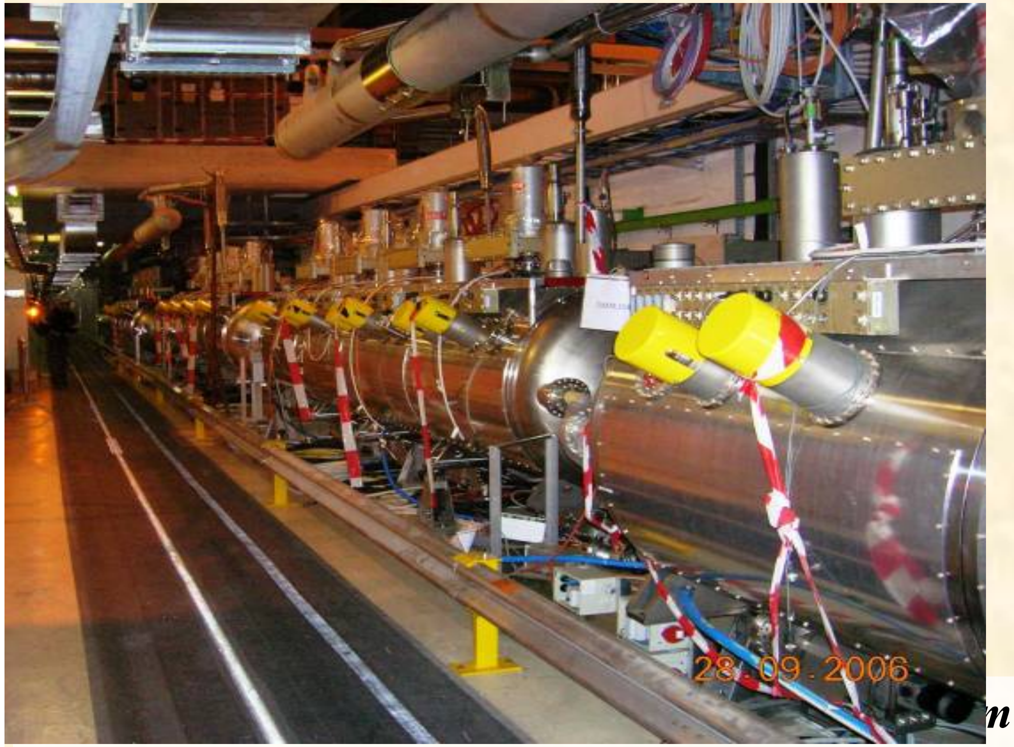
Focussing effect in the longitudinal direction
keeping the particles close together ... forming a "bunch"

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

with the dipole magnets !

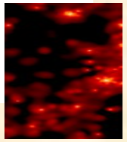
The RF system: IR4





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



Operational Safety & Machine Protection

Boooooom

LHC Design Parameters

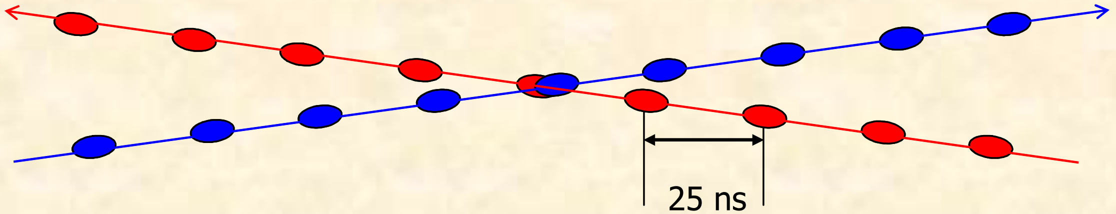
	Design	Achieved
Momentum at collision	7 TeV /c	6.8 TeV/c
Luminosity	10^{34} cm $^{-2}$ s^{-1}	10^{34} cm $^{-2}$ s^{-1}
Protons per bunch	1.15×10^{11}	1.50×10^{11}
Number of bunches/beam	2808	2808
Nominal bunch spacing	25 ns	25ns
beta *	55 cm	35 cm
rms beam size IP	17 µm	13 µm

Protect components (Experiment & Accelerator) … from beam impact

LHC Operation: Machine Protection & Safety

Energy stored in magnet system	10	GJ
Energy stored in one main dipole circuit	1.1	GJ
Energy stored in one beam	362	MJ

Enough to melt 500 kg of copper



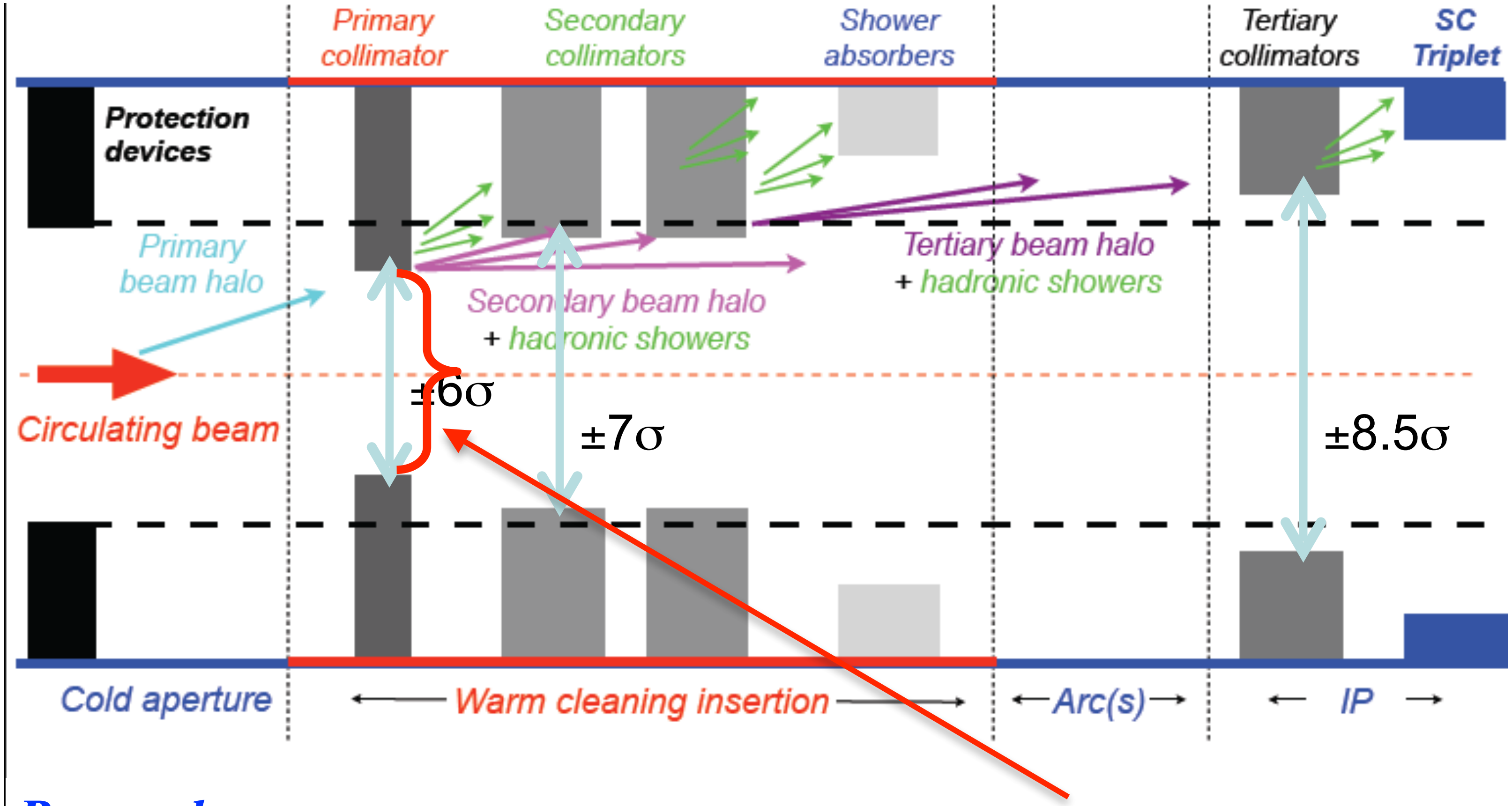
$2\cdot10^{12}$ $4\cdot10^{12}$ $8\cdot10^{12}$ $6\cdot10^{12}$ 450 GeV p Strahl

remember:

$$N_{ges} = 2808 \cdot 1.2 \cdot 10^{11}$$

$$N_{ges} = 2.4 \cdot 10^{17} \quad \textit{Teilchen}$$

LHC Aperture and Collimation



Remember:

Beam size (σ) = 300 μm (@arc)
Beam size (σ) = 17 μm (@IR1, IR5)

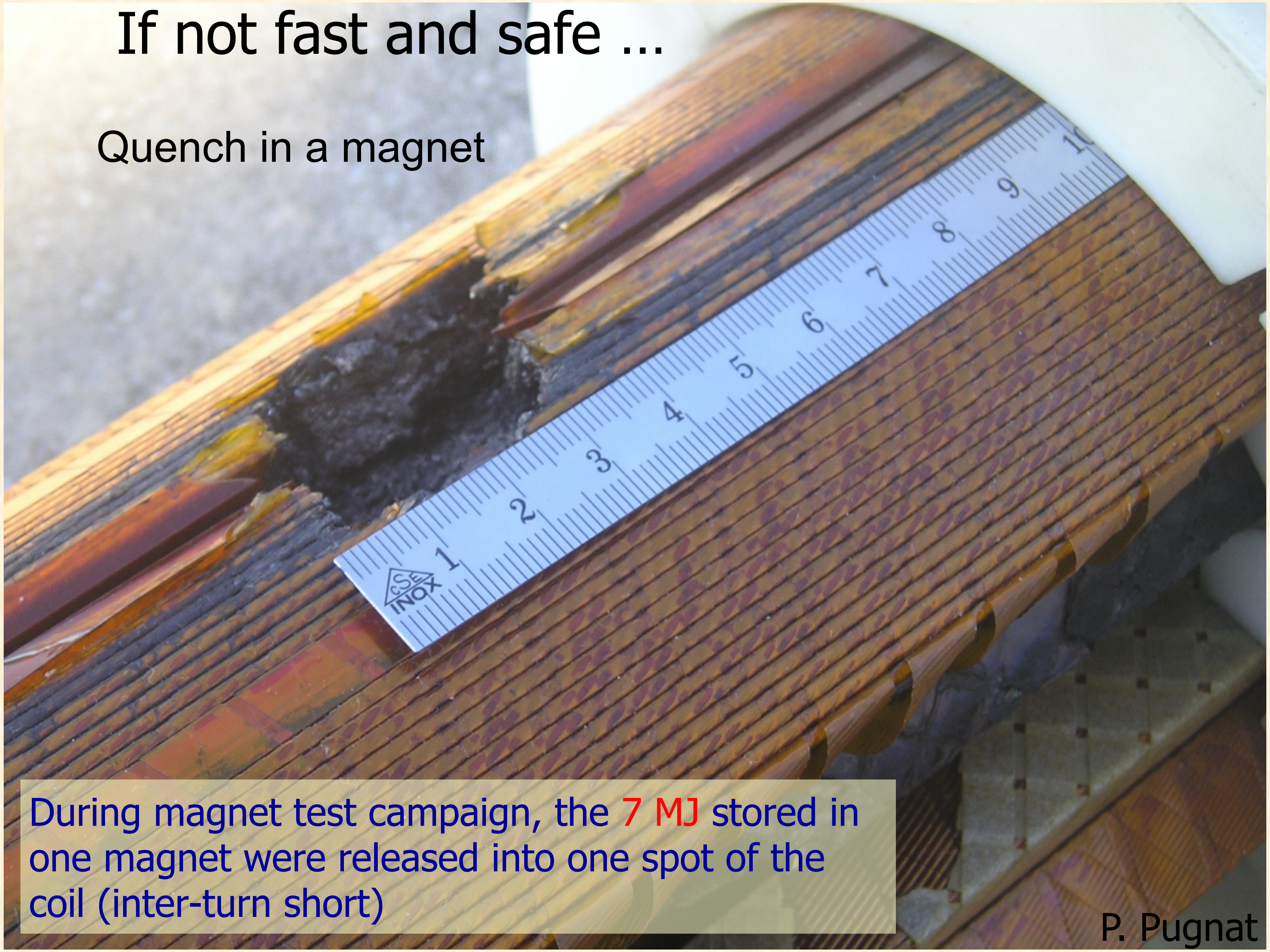
Free Aperture = +/- 1.5 mm

… protect from energy stored in the magnets

Energy stored in the magnets —> quench

If not fast and safe …

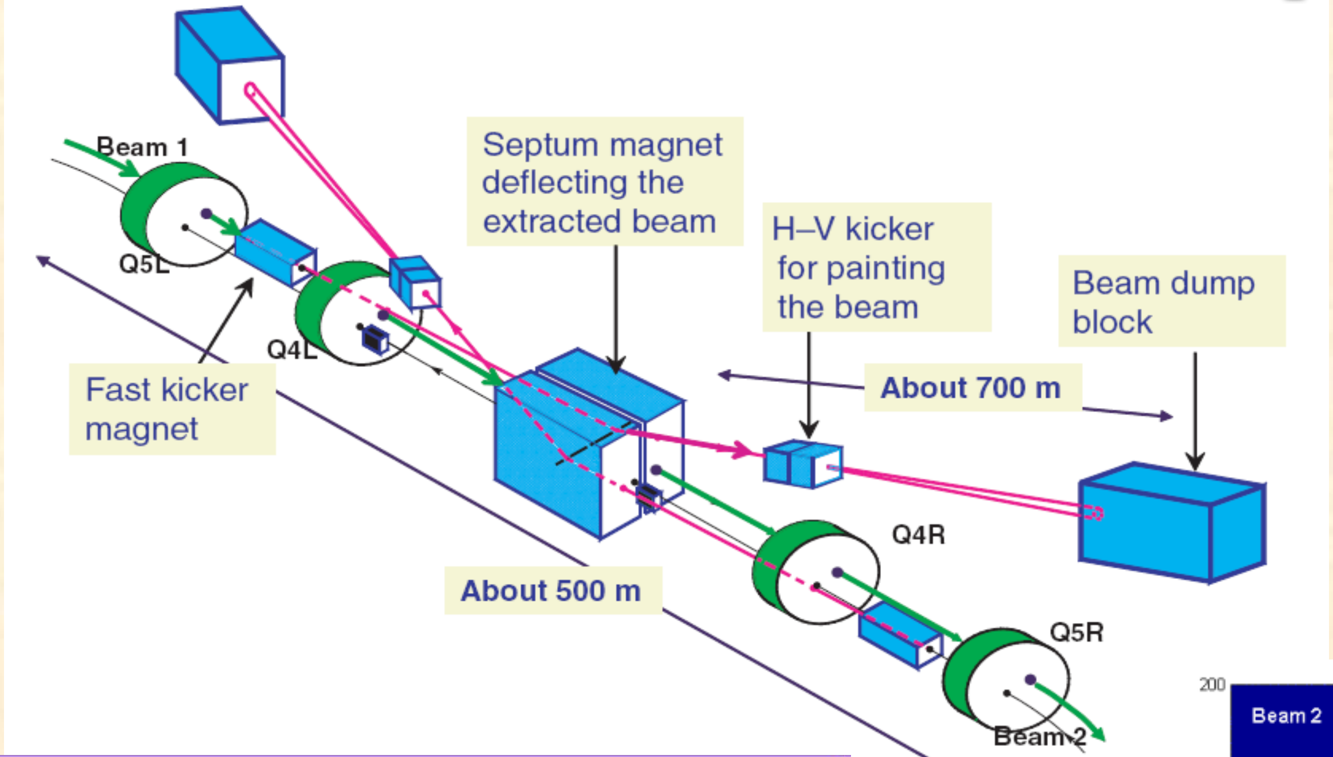
Quench in a magnet

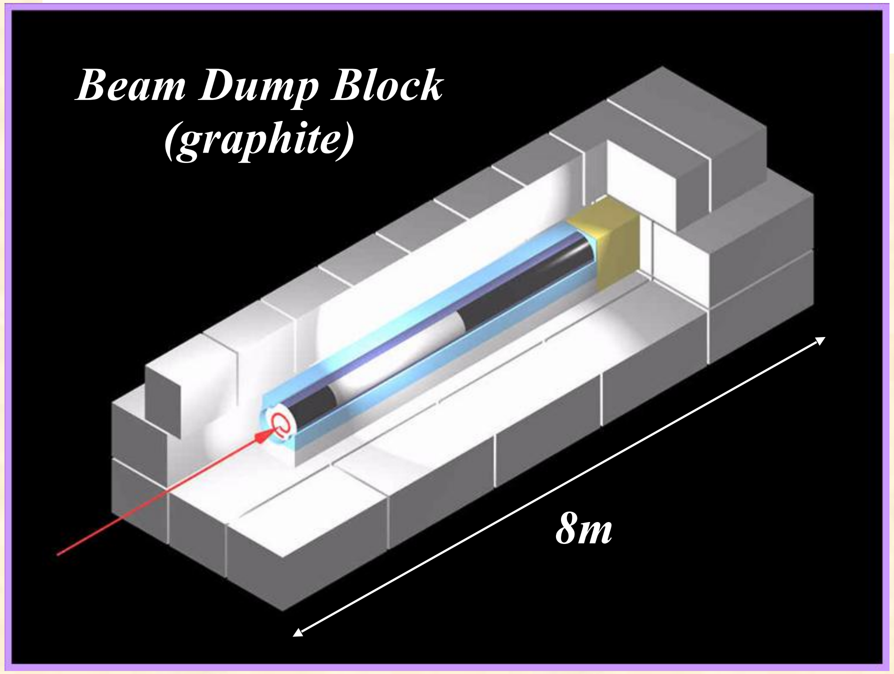


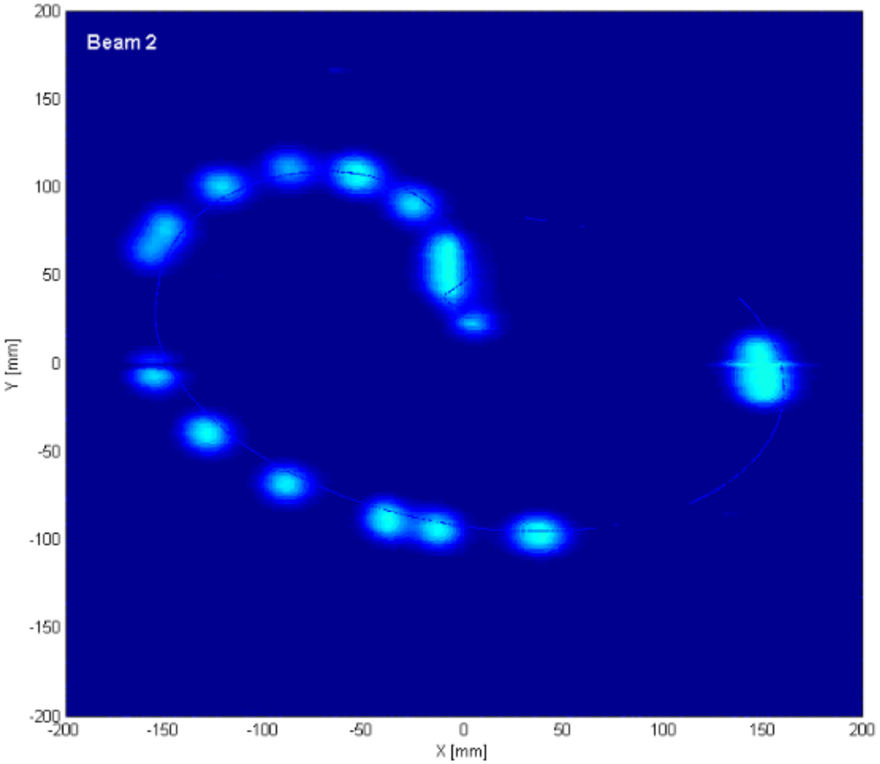
During magnet test campaign, the 7 MJ stored in one magnet were released into one spot of the coil (inter-turn short)

P. Pugnat

LHC Operation:
Dump System







1.) Where are we ?

* Standard Model of HEP
* Higgs discovery

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

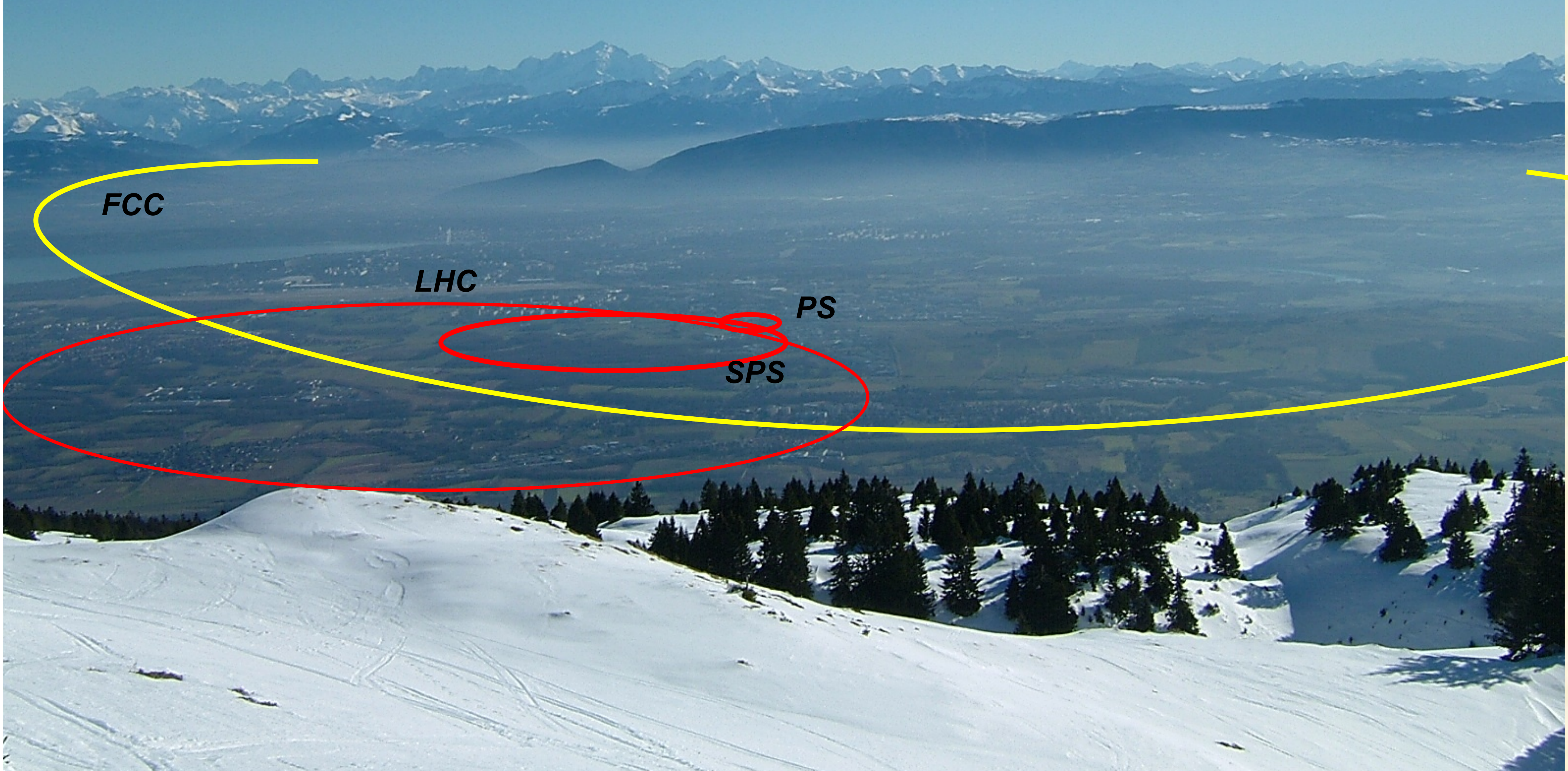
Others

Plasma acceleration

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

Photon-photon collider

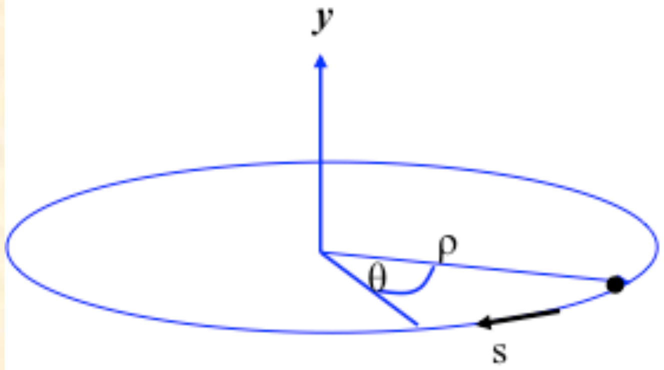
The Next Generation Ring Collider



Maximum Beam Energy in a Storage Ring:

For a given magnet technology it is the size of the machine that defines the maximum particle momentum ... and so the energy

$$\xcancel{E = mc^2} \qquad E^2 = (pc)^2 + m^2c^4$$



circular coordinate system

Condition for an ideal circular orbit:

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

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

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

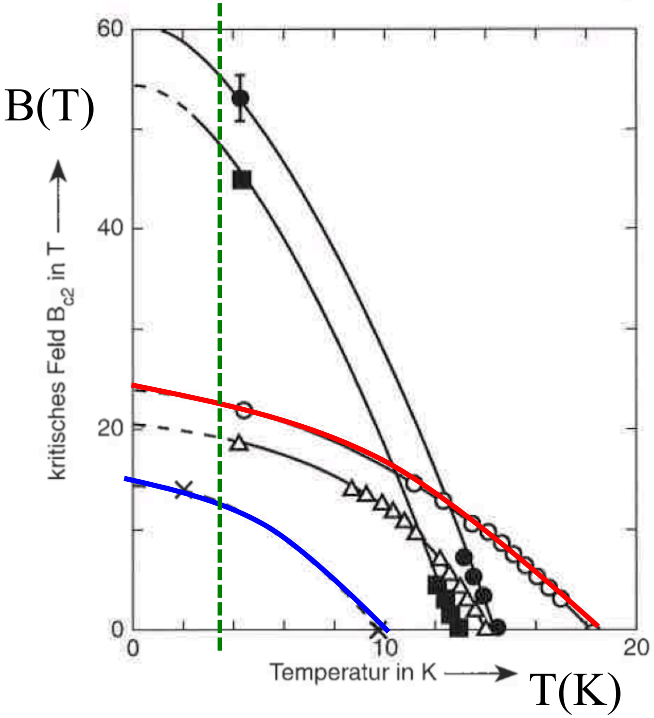
$$\frac{p}{e} = \boxed{B\,\rho}$$

B ρ = "beam rigidity"

The maximum particle momentum is given by the field strength B and the storage ring size 2πρ

Highest B-field technology:
Two key players in sc magnet technology: NbTi and Nb$_3$Sn

168 *5 Supraleiter im Magnetfeld*



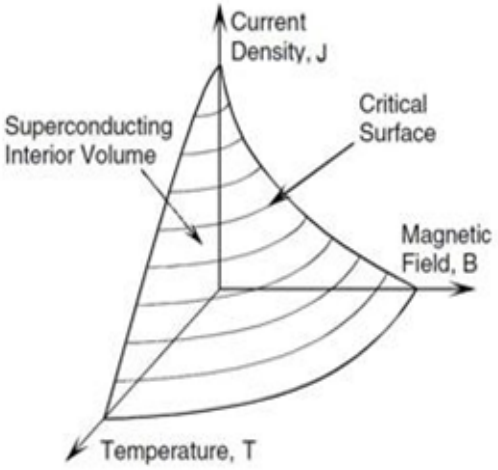
critical field in NbTi and Nb$_3$Sn

Abb. 77 Oberes kritisches Feld einiger Hochfeldsupraleiter.

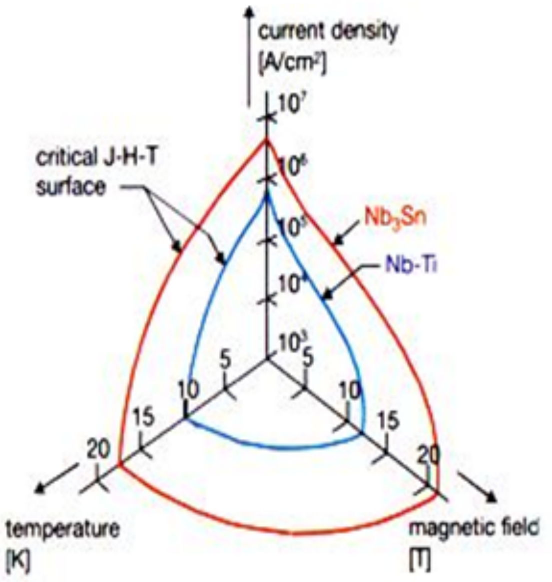
−○−○−○−	Nb_3Sn, Drahtdurchmesser 0,5 mm [127]
−△−△−△−	V_3Ga, Sinterprobe [127]
−×−×−×−	Nb_{50} Ti_{50} [128]
−■−■−■−	$PbMo_{6,35}S_8$ [130]
−●−●−●−	$PbGd_{0,3}Mo_6S_8$ [130]

(siehe auch Ø. Fischer: Proceedings LT 14, Otaniemi 1975, Band 5. North-Holland Publ. Comp. 1975).

General



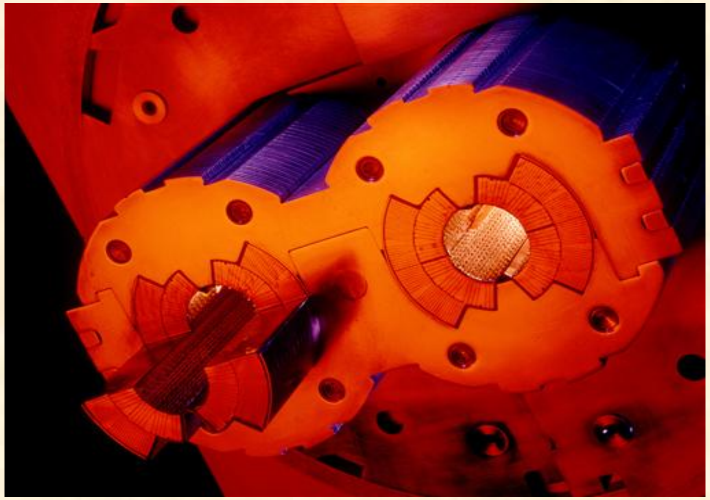
NbTi and Nb$_3$Sn



… and we do NOT talk about
$YBa_2Cu_3O_7$ and friends

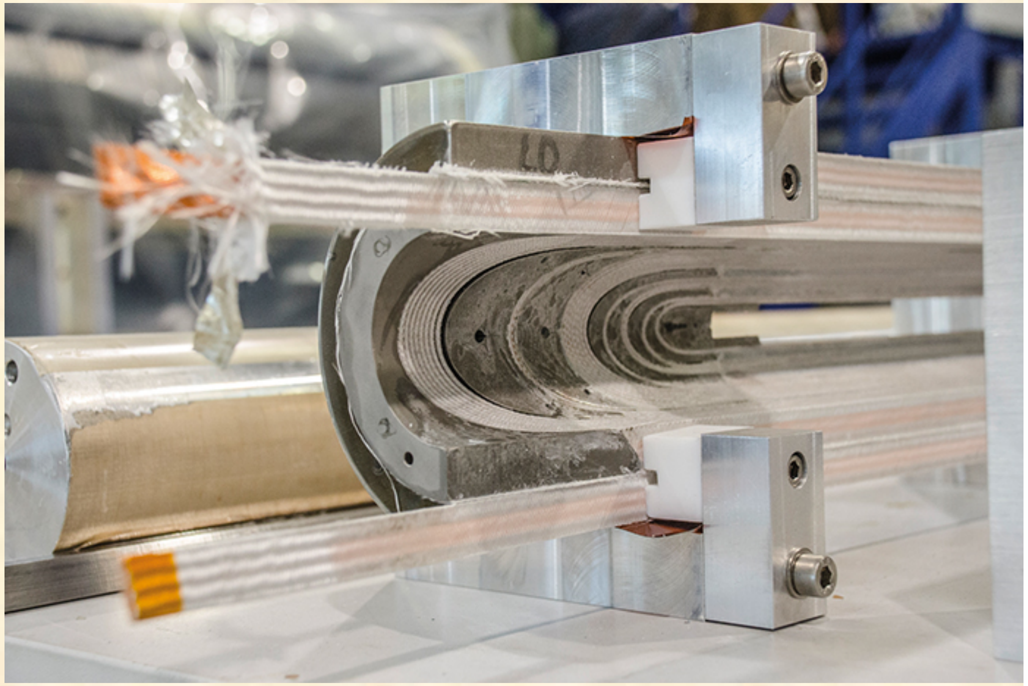
($j_c\perp$ = 100A/mm², $j_c||$ = 800A/mm²)

The Push for Higher Beam Energy



NbTi LHC standard dipoles,
8.3 T

Nb$_3$Sn FCC type dipole coils,
11 T – 16 T



FCC energy reach:

it is a simple scaling wrt LHC:

circumference 100km /27km
→ *Factor 3.7*

dipole field: 16 T / 8.3 T
→ *Factor 1.93*

LHC: E_{cm} *= 2* 7 TeV =14 TeV*

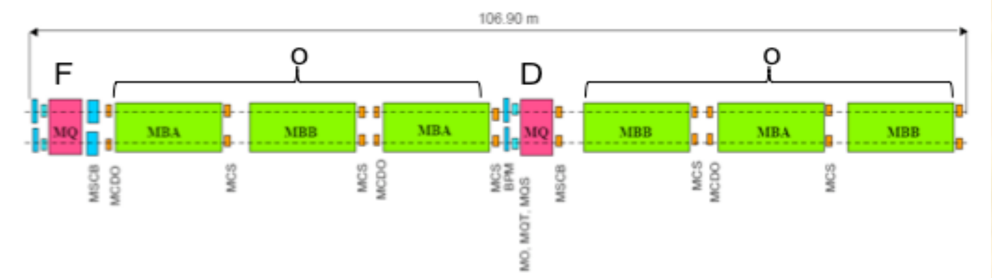
FCC: E_{cm} *= 100 TeV centre of mass*

Scaling for FCCpp: Dipole Fill Factor for present Version V3:

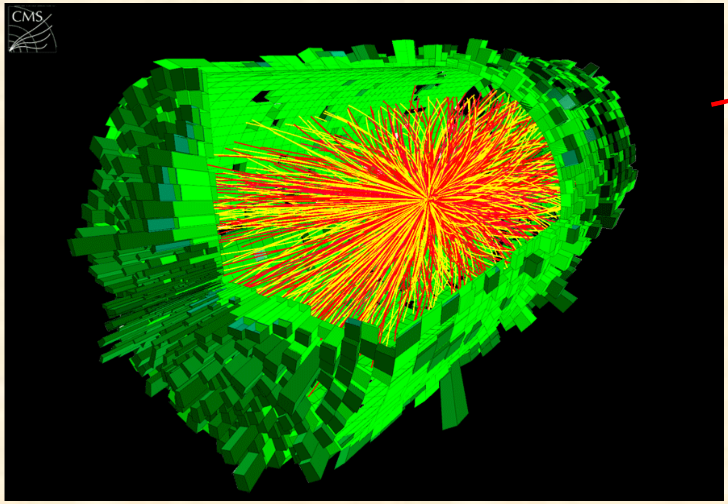
Pushing the limit (Dipole Fill Factor):

12 dipoles per cell, l_{dipole}=14.2m
34 cells per arc
12 arcs
dipole field = 15T <--> 50TeV
or 16T

LHC example



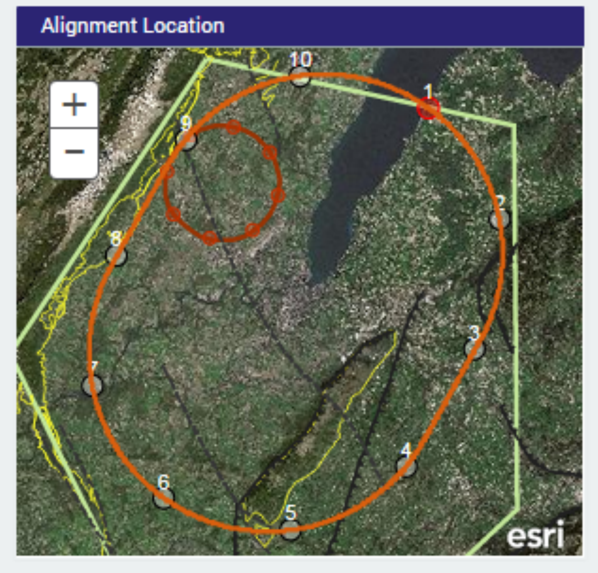
FCC: 5016 dipoles
drifts a la LHC: dipole-quad=3.6m
dipole-dipole=1.3m
Double cell length = 200m

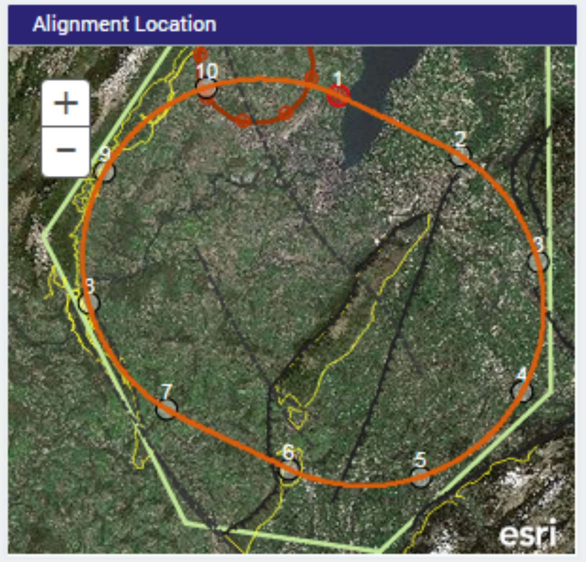


	FCC-hh Baseline	**FCC-hh Ultimate**
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ']	12	Crab. Cav.
Turn-around time [h]	5	4

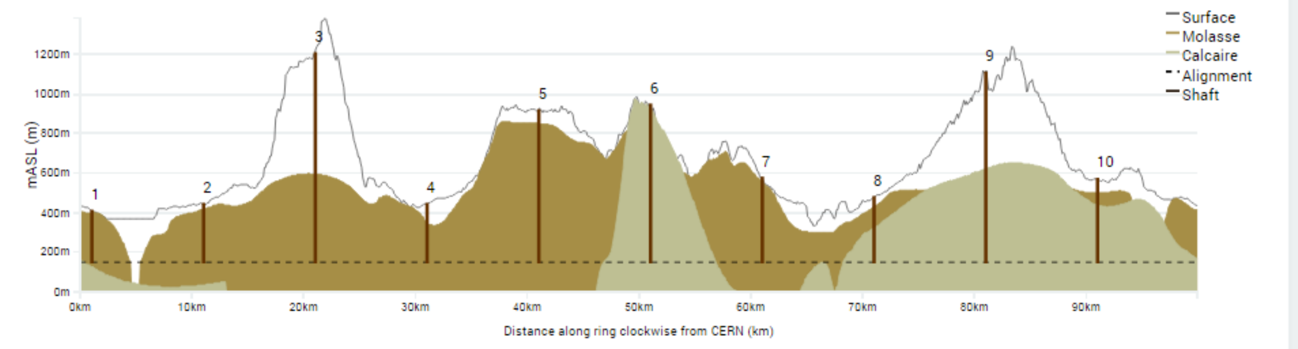
Latest News: Geographical / Geological Considerations

J. Osborne and Family



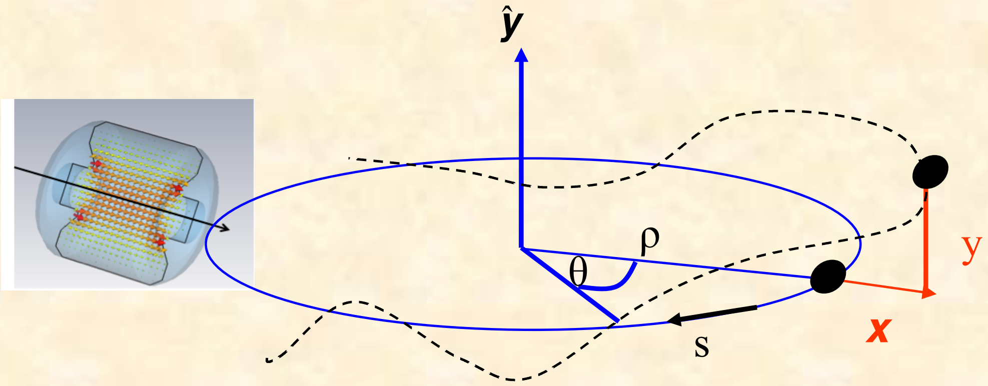


parameter	**FCC-hh**	**(HL) LHC**
collision energy cms [TeV]	**100**	14
dipole field [T]	**16**	8.3
circumference [km]	**100**	27
peak events/bunch crossing	**1020**	27
stored energy/beam	**8.4 GJ**	362 MJ

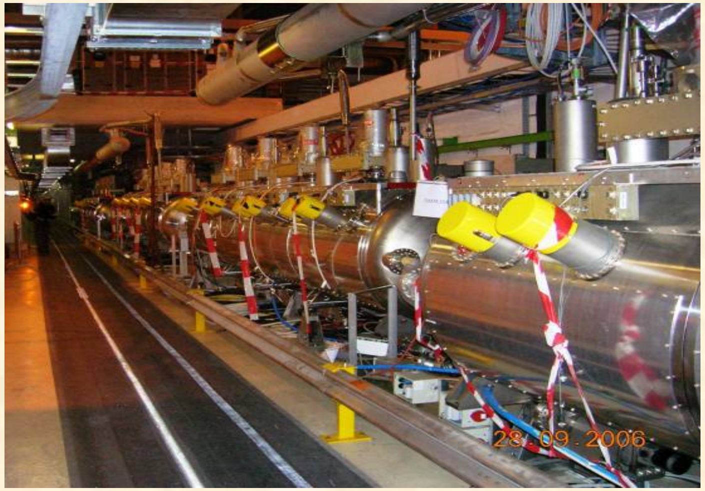


Beside the beam dynamics problems (that are moderate) there is a Considerable technological & logistical & geological problem

The next Generation e+/e- Ring Collider



Install an RF accelerating structure in the ring:
It creates longitudinal electric fields and so
turn by turn the particles will receive a kick and "speed up"



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
RF frequency	MHz	400
RF voltage/beam	MV	16
Energy gain/turn	keV	485

It takes 14 Mio turns to get to full LHC energies
$T_{acc} \approx$ 30 min … but we HAVE time

Synchrotron Radiation

In a circular accelerator charged particles loose energy via emission of intense light.

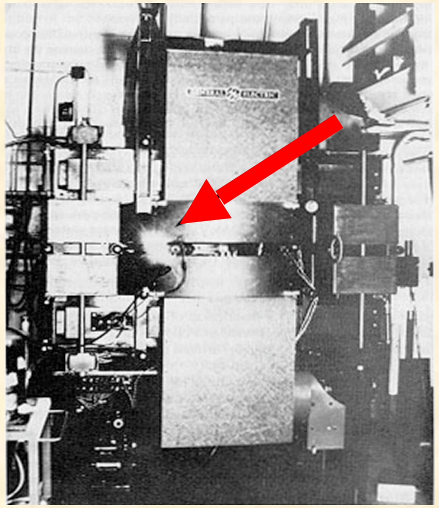
$$P_s = \frac{2}{3}\alpha\hbar c^2 \frac{\gamma^4}{\rho^2}$$ ***radiation power***

$$\Delta E = \frac{4}{3}\pi\alpha\hbar c \frac{\gamma^4}{\rho}$$ ***energy loss***

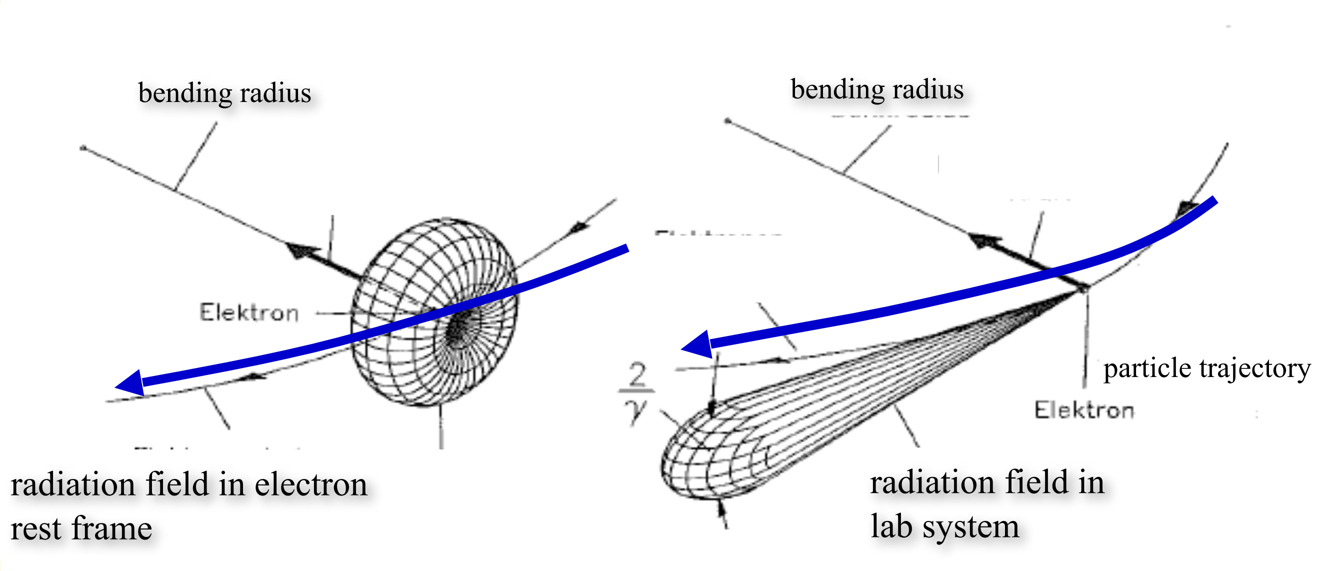
$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}$$ ***critical frequency***

$$\alpha \approx \frac{1}{137}$$

$$\hbar c \approx 197\ MeV\ fm$$



1946 observed for the first time in the General Electric Synchrotron



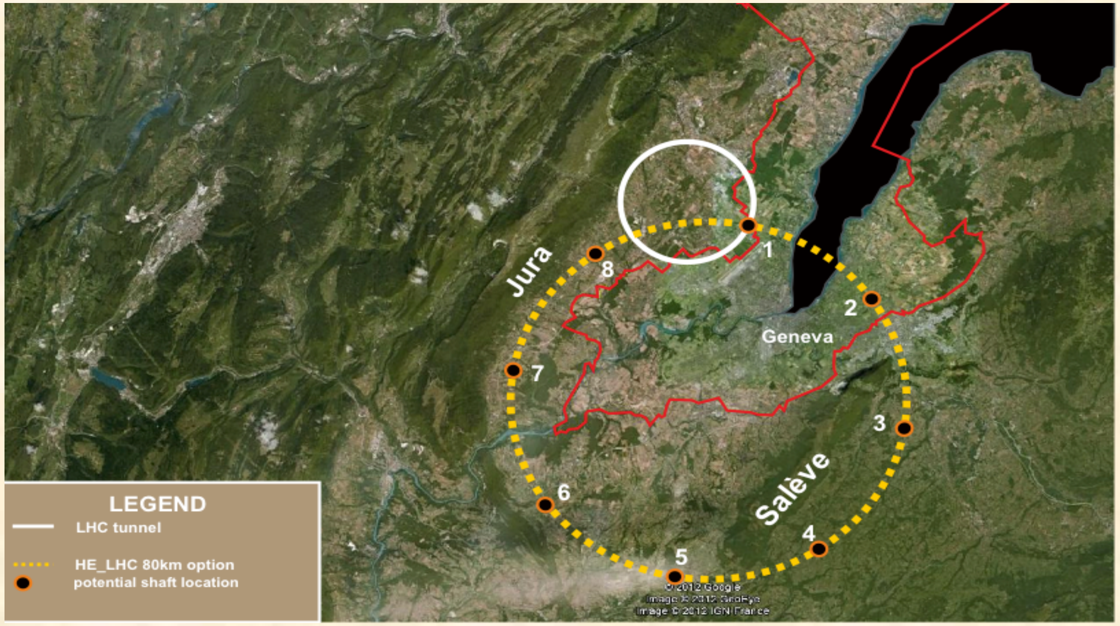
court. K. Wille

FCC-ee: a collider that is dominanted by synchrotron light losses.

→ *Planning the next generation e+ / e- Ring Colliders means build it LARGE.*

Design Parameters FCC-ee

E = 175 GeV / beam
L = 100 km



$$\Delta U_0(keV) \approx \frac{89 * E^4(GeV)}{\rho}$$

$$\Delta U_0 \approx 8.62\ GeV$$

$$\Delta P_{sy} \approx \frac{\Delta U_0}{T_0} * N_p = \frac{10.4 * 10^6 eV * 1.6 * 10^{-19} Cb}{263 * 10^{-6} s} * 9 * 10^{12}$$

$\Delta P_{sy} \approx 47\ MW$ ***... per beam***

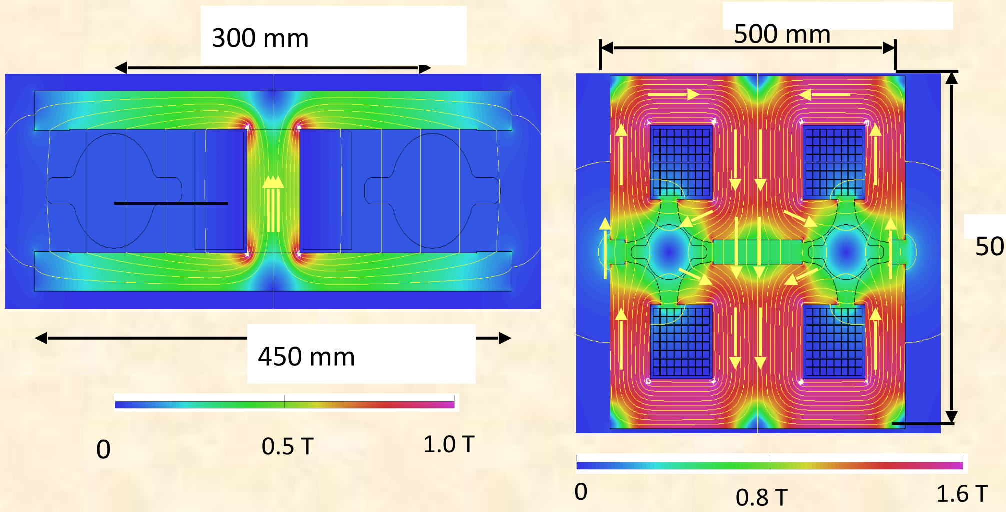
Circular e+ / e- colliders are severely limited by synchrotron radiation losses and have to be replaced for higher energies by linear accelerators

FCC-ee

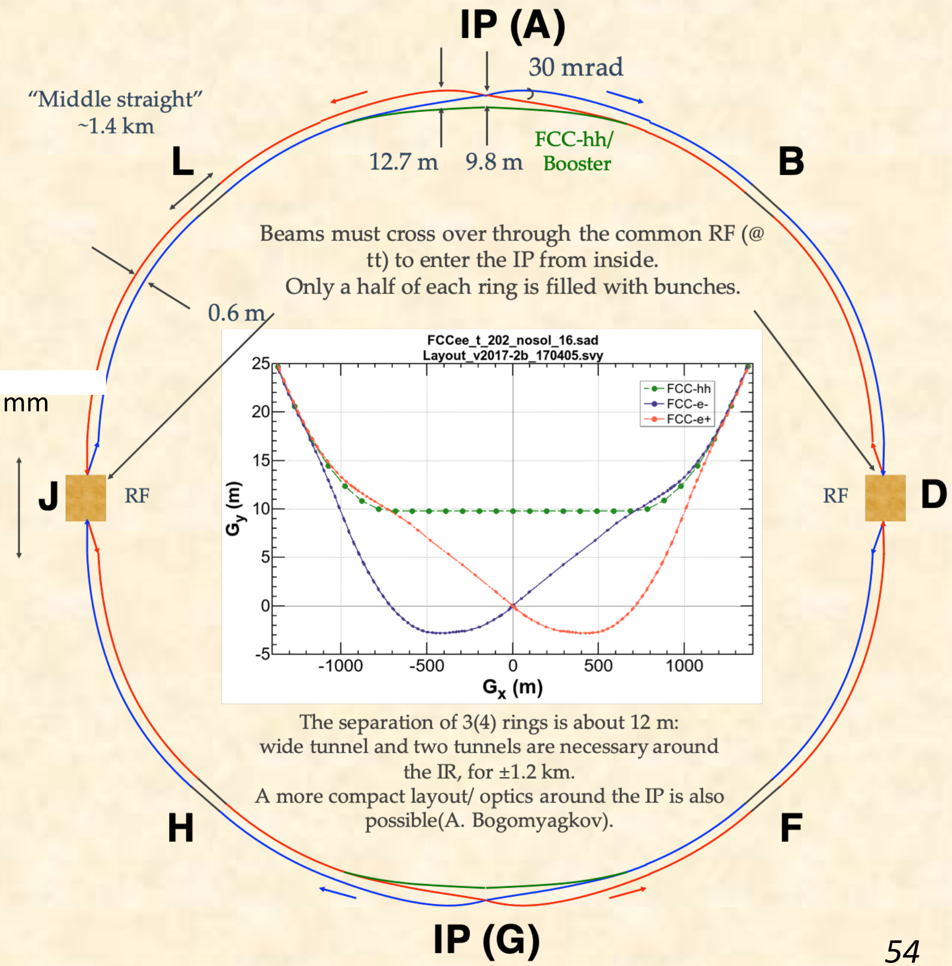
M. Aiba, S. Aumon, E. Belli, M. Benedikt, A. Blondel, A. Bogomyagkov, M. Boscolo, H. Burkhardt,
D. El-Khechen, B. Harer, B. Holzer, P. Janot, M. Koratzinos, E. Levichev, A. Milanese,
A. Novokhatski, S. Ogur, K. Ohmi, K. Oide, D. Shatilov, J. Seeman, S. Sinyatkin, H. Sugimoto, M. Sullivan,
T. Tydecks,
J. Wenninger, D. Zhou, F. Zimmermann

Work supported by the European Commission under 7th Framework Programme
project EuCARD--2, and under the Horizon 2020 Programme.

Twin Aperture Magnets



220 A × 64 turns
2.2 A/mm² on Cu
9.9 T/m



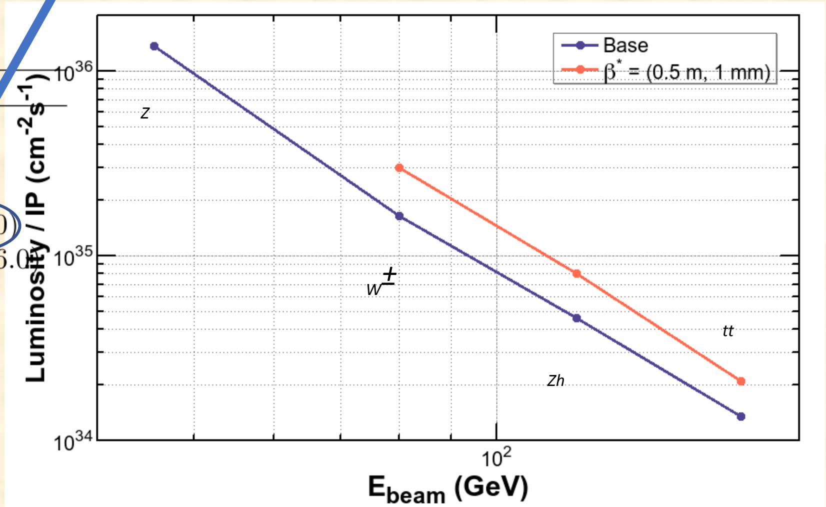
Beams must cross over through the common RF (@ tt) to enter the IP from inside.
Only a half of each ring is filled with bunches.

The separation of 3(4) rings is about 12 m:
wide tunnel and two tunnels are necessary around the IR, for ±1.2 km.
A more compact layout/ optics around the IP is also possible(A. Bogomyagkov).

FCC-ee

Design		2017			
Circumference	[km]	97.750			
Arc quadrupole scheme		**twin aperture**			
Bend. rad. of arc dipoles	[km]	10.747			
Number of IPs / ring		2			
Crossing angle at IP	[mrad]	30			
Solenoid field at IP	[T]	±2			
ℓ^*	[m]	2.2			
Local chrom. correction		y-plane with crab-sext. effect			
RF frequency	[MHz]	400			
Total SR power	[MW]	100			
Beam energy	[GeV]	45.6	80	120	175
SR energy loss/turn	[GeV]	0.036	0.34	1.72	7.80
Long. damping time	[ms]	414	76.8	22.9	7.49
Current/beam	[mA]	1390	147	29.0	6.4
Bunches/ring		70760	7280 (4540)	826 (614)	64 (50)
Particles/bunch	[10^{10}]	4.0	4.1 (6.6)	7.1 (9.6)	20.4 (26.0
Arc cell		60°/60°	90°/90°		
Mom. compaction α_p	[10^{-6}]	**14.79**	7.31		
β-tron tunes ν_x / ν_y		269.14 /267.22	389.08 / 389.18		
Arc sext. families		208	292		
Horizontal emittance ε_x	[nm]	**0.267**	0.28	0.63	1.34
$\varepsilon_y/\varepsilon_x$ at collision	[%]	0.38	0.36	0.2	0.2
β_x^* / β_y^*	[m / mm]	**0.15** / **1**	1 / 2 (0.5 / 1)		
Energy spread by SR	[%]	0.038	0.066	0.099	0.147
Energy spread SR+BS	[%]	0.073	0.072 (0.091)	0.106 (0.122)	0.193 (0.212)
Hor. beam-beam ξ_x		0.008	0.080 (0.046)	0.081 (0.053)	0.082 (0.049)
Ver. beam-beam ξ_y		0.106	0.141 (0.141)	0.140 (0.140)	0.140 (0.138)
RF Voltage	[MV]	**255**	696	2620	9500
Bunch length by SR	[mm]	2.1	2.1	2.0	2.4
Bunch length SR+BS	[mm]	4.1	2.3 (2.9)	2.2 (2.5)	2.9 (3.5)
Synchrotron tune ν_z		−0.0413	−0.0340	−0.0499	−0.0684
RF bucket height	[%]	3.8	3.7	2.2	10.3
Luminosity/IP	[10^{34}/cm^{2}s]	**137**	16.4 (30.0)	4.6 (8.0)	1.35 (2.09)

For a given particle energy the beam Intensity will be limited by the maximum tolerable Synchrotron radiation power loss



The RF Voltage applied depends on the beam energy as U ∝γ⁴

$$\Delta U(keV) = 89 * \frac{E^4/(mc^2)^4}{\rho}$$

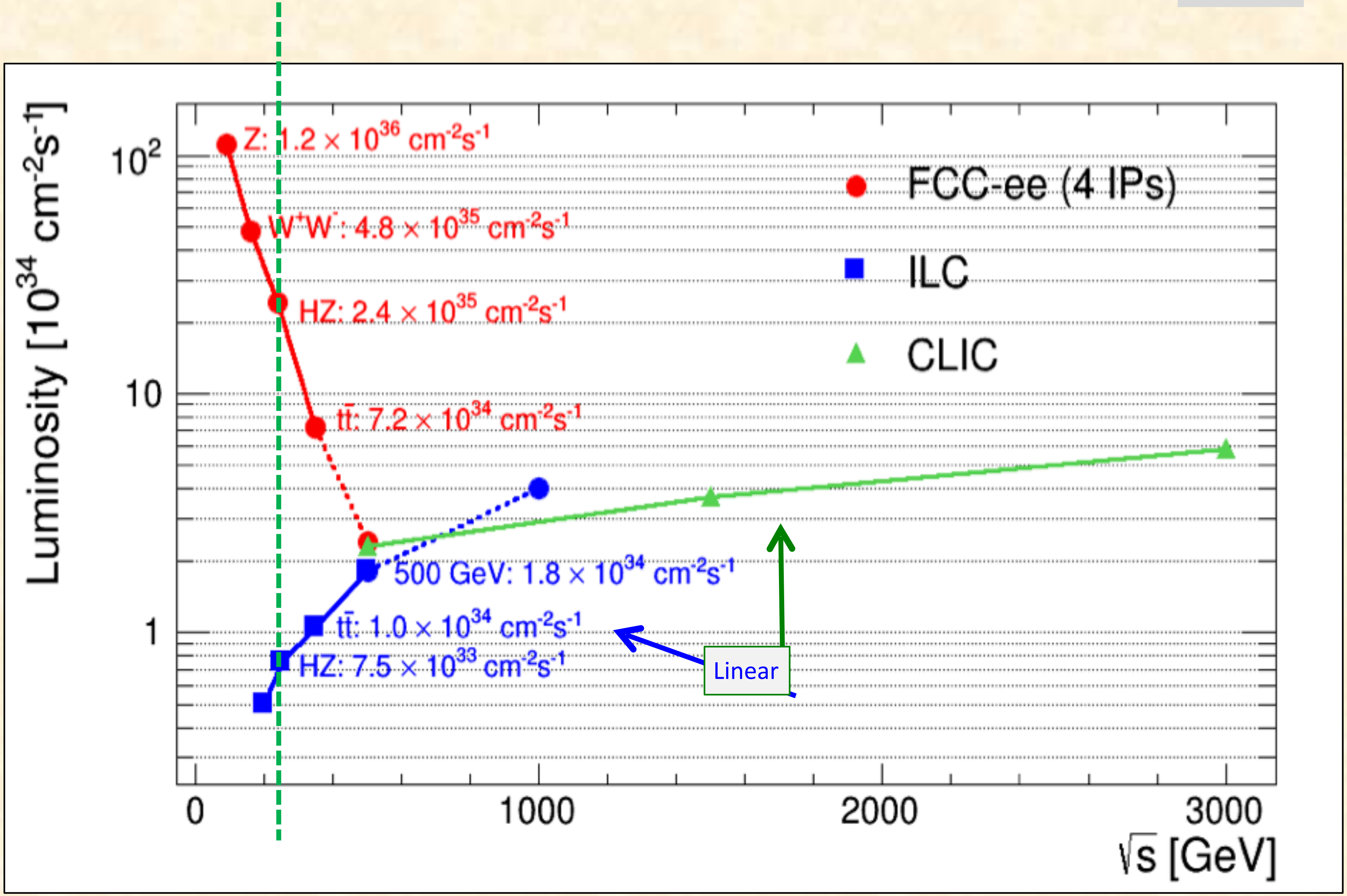
6.) Push for higher lepton energy

- ***go linear***
- ***higher acceleration gradients***

Circular vs. Linear Colliders

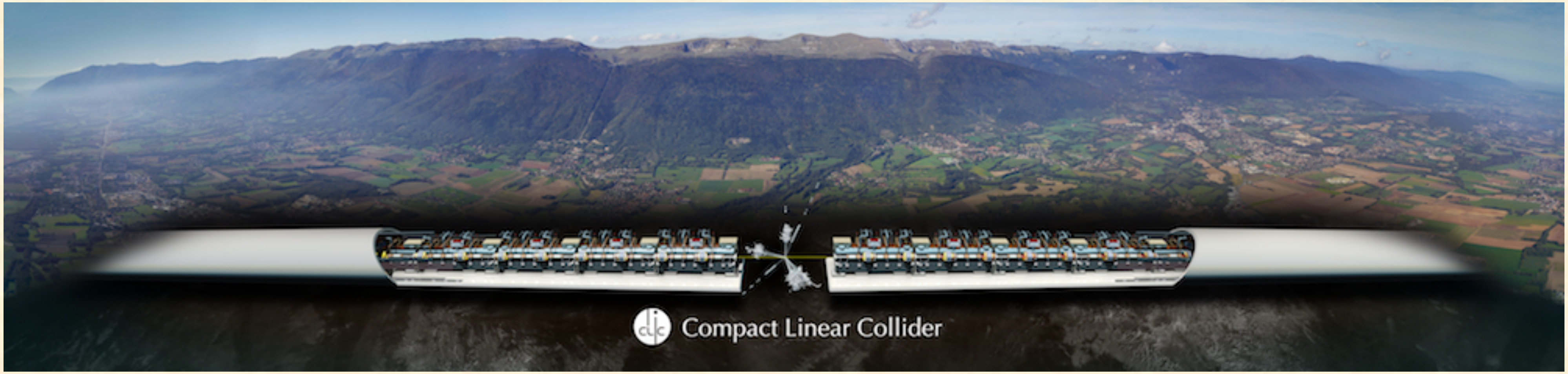
… the light problem

F. Gianotti

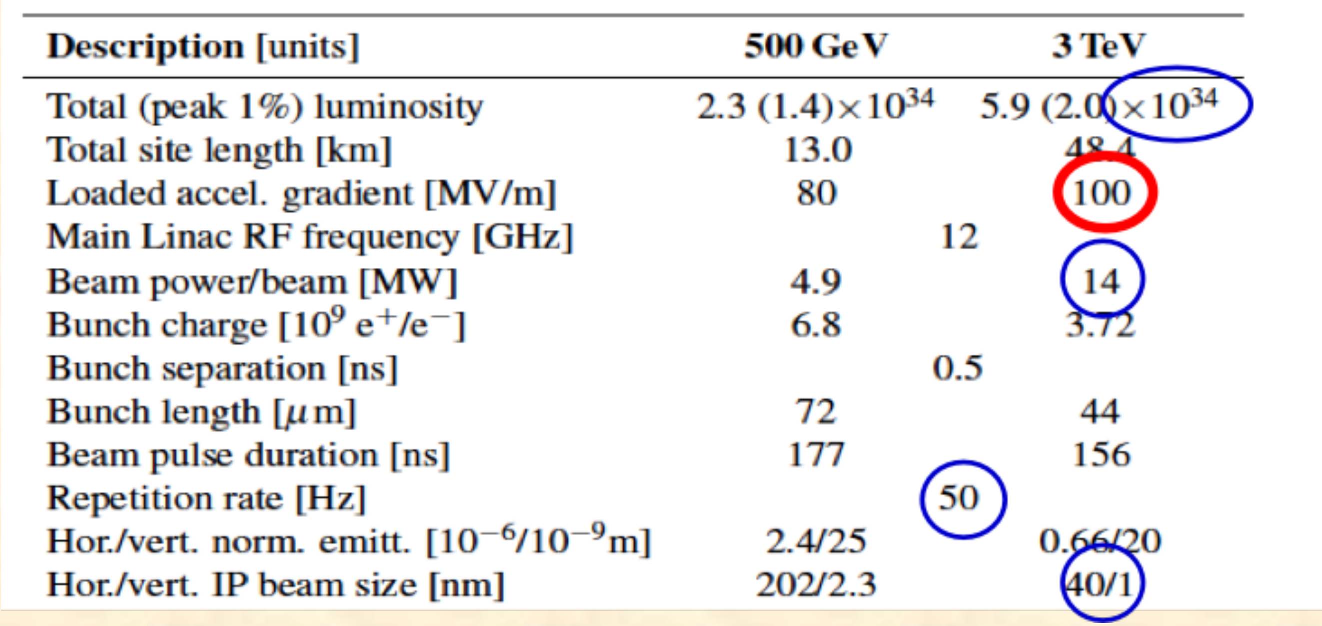


CLIC ... a future Linear e+/ e- Accelerator

„C“-LIC ... = CERN ... or „compact“



50 km



Description [units]	500 GeV	3 TeV
Total (peak 1%) luminosity	2.3 (1.4)×10^{34}	5.9 (2.0)×10^{34}
Total site length [km]	13.0	48.4
Loaded accel. gradient [MV/m]	80	100
Main Linac RF frequency [GHz]	12	
Beam power/beam [MW]	4.9	14
Bunch charge [10^9 e^+/e^-]	6.8	3.72
Bunch separation [ns]	0.5	
Bunch length [μm]	72	44
Beam pulse duration [ns]	177	156
Repetition rate [Hz]	50	
Hor./vert. norm. emitt. [$10^{-6}/10^{-9}$m]	2.4/25	0.66/20
Hor./vert. IP beam size [nm]	202/2.3	40/1

CLIC parameter list

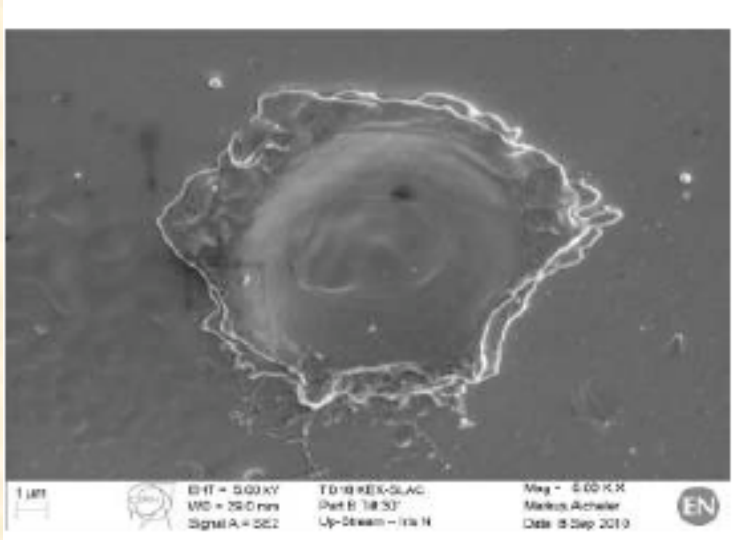
CLIC: Normal conducting RF system
challenge: running at the break down limit

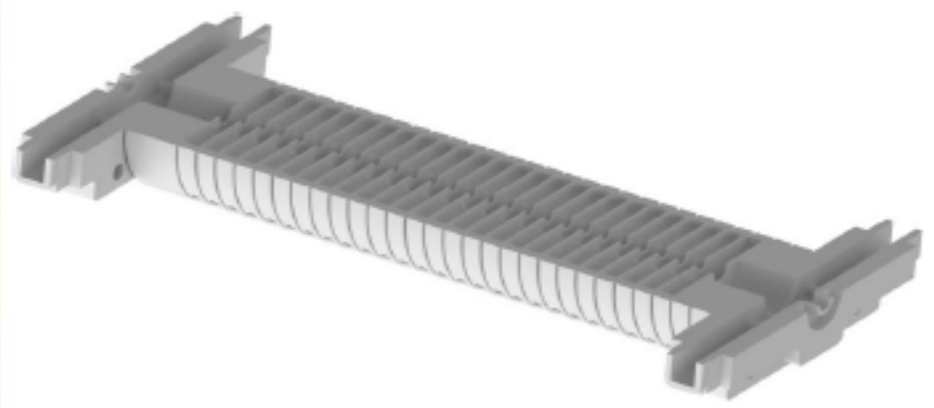
Accereration Gradient 100MV/m studied & optimised since years

" how far can we go and how much can we optimise such a future accelerator before we reach technical limits and how can we push these limits ? "

they have impact on

- *=> the accelerator performance (luminosity)*
- *=> beam quality*
- *=> and the accelerating structure itself*



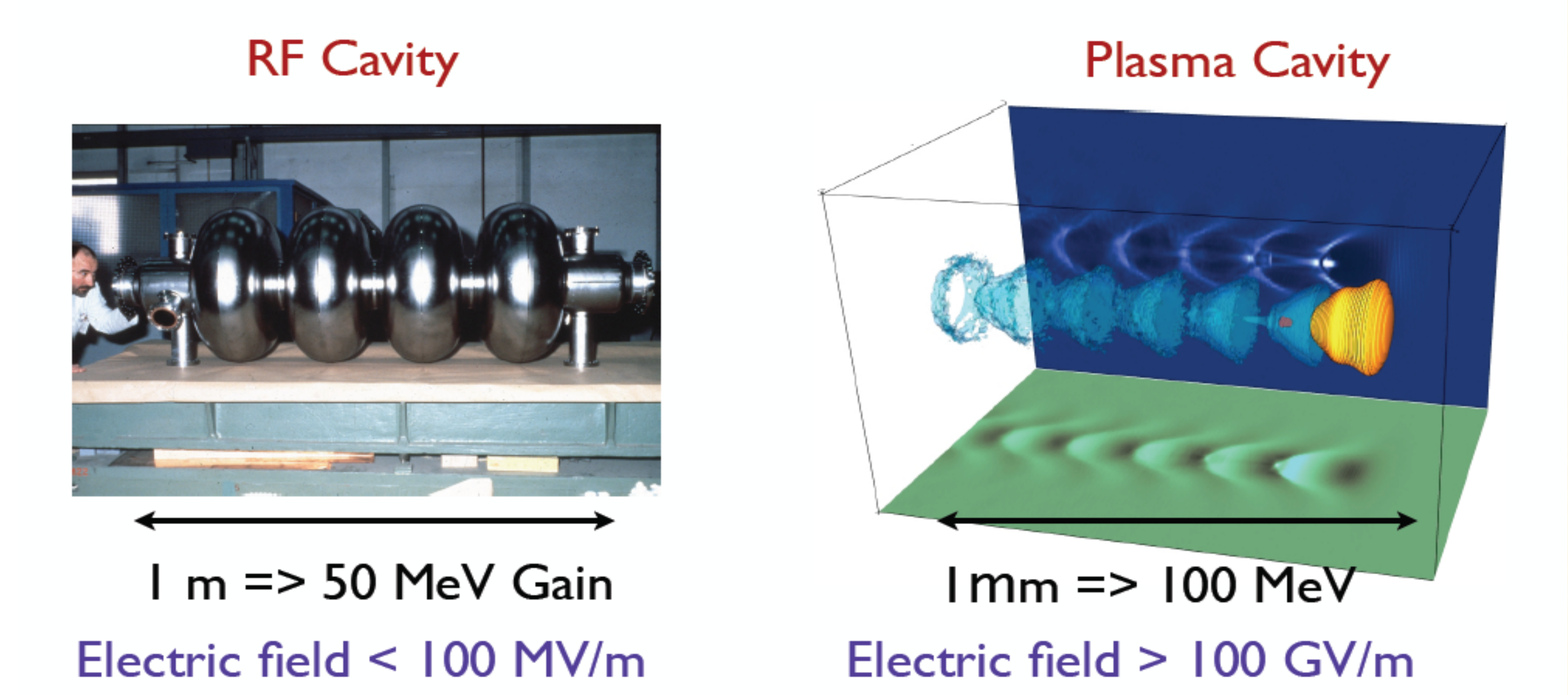


7.) Push for higher energy

**** higher acceleration gradients***

**** new acceleration techniques***

Plasma Wake Acceleration



RF Cavity

Plasma Cavity

1 m => 50 MeV Gain

1mm => 100 MeV

Electric field < 100 MV/m

Electric field > 100 GV/m

Study of High Gradient Acceleration Techniques

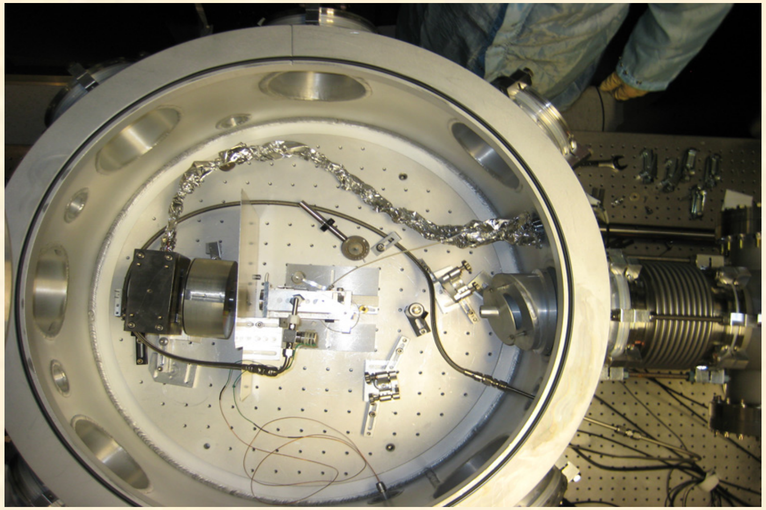
Plasma Wake Acceleration

particle beam driven / LASER driven

Incoming laser pulse (or pulse of particles) creates a travelling plasma wave in a low-pressure gas

Plasma wake field gradient accelerates electrons that 'surf' on the plasma wave

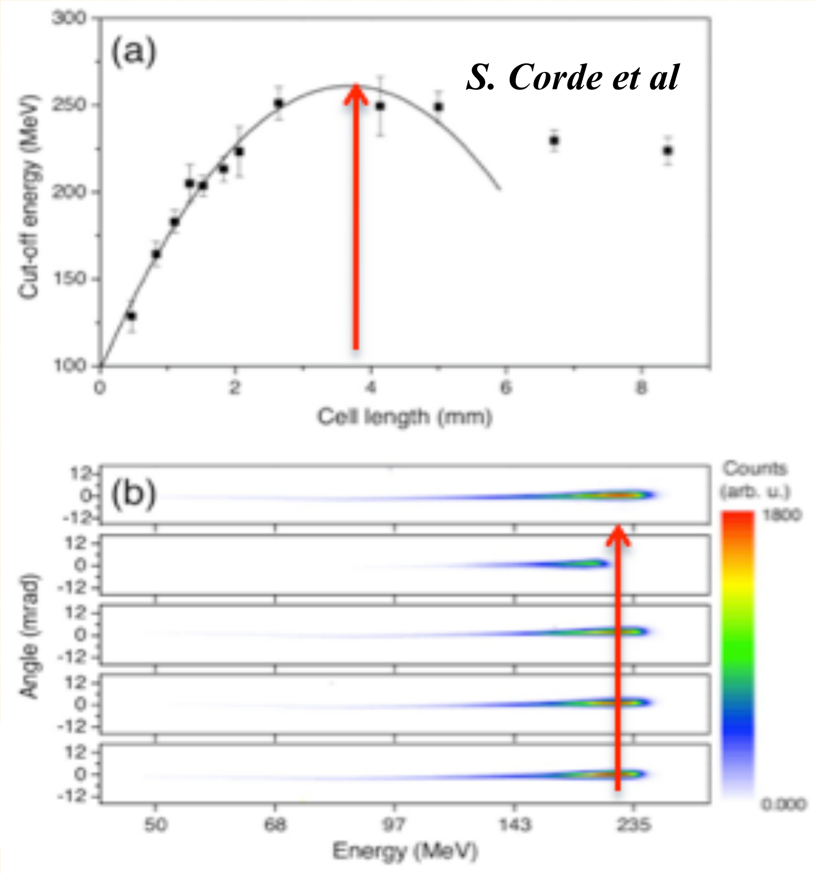
Field Gradients up to 100 GeV /m observed



Plasma cell Univ. Texas, Austin

E_e =2 GeV

$$\Delta E / \Delta s = 200\, MeV / 4mm$$
$$= 50\, GeV / m$$



S. Corde et al

AWAKE:
Proton driven Wake Acceleration Experiment at CERN

AWAKE

John Adams Institute for Accelerator Science,
Budker Institute of Nuclear Physics & Novosibirsk State University
CERN
Cockroft Institute
DESY
Heinrich Heine University, Düsseldorf
Instituto Superior Tecnico
Imperial College
Ludwig Maximilian University
Max Planck Institute for Physics
Max Planck Institute for Plasma Physics
Rutherford Appleton Laboratory
TRIUMF
University College London
Univesity of Oslo
University of Strathclyde

The Collaboration is strong and growing.
16 institutes participating + several requests under consideration.

Prototype: 1m long Rb Plasma Cell

Open questions in particle physics

Dark matter & Energy

… on which energy scale to look for it ?

Physics beyond the standard model

... Lepton or Proton colliders ?

Beam dynamics aspects

... Circular or linear ?

Technical aspects

... Traditional, sc / nc or PWA ?