Future Accelerator Projects

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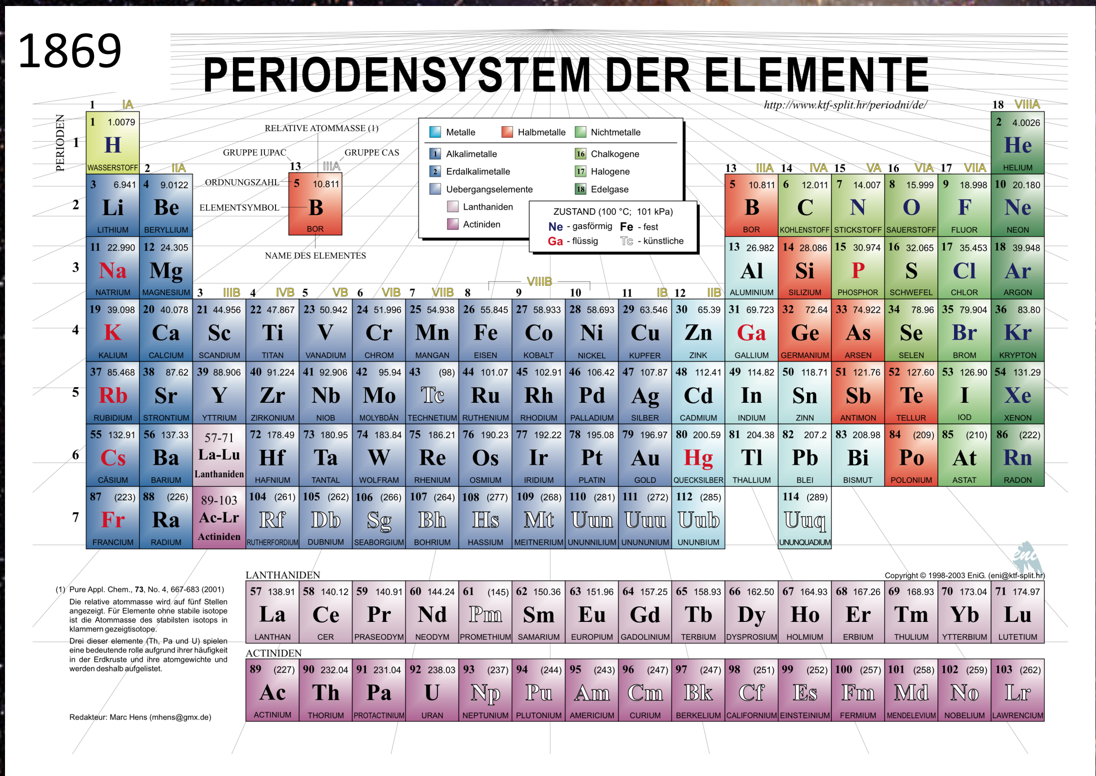
A Short Introduction … LOL

In the end and after all … : We try to explain the structure of the "hadronic matter" in the Universe.
In other words: What is going on up there ???



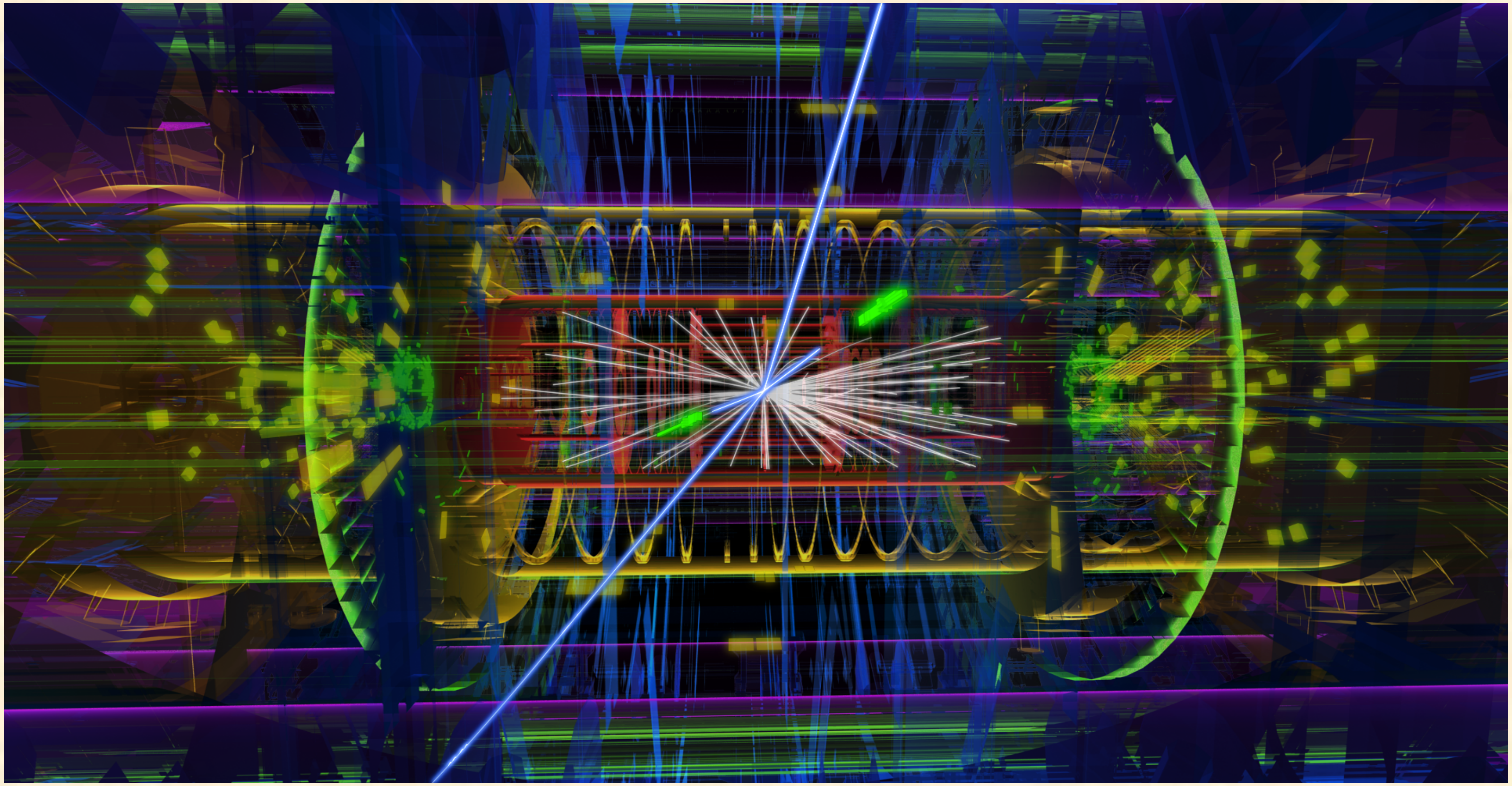
E=mc², λ=h/p

1.) Where are we ?

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

... and why all that ??

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



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

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

2.) Where do we go ?

**** Physics beyond the Standard Model***
**** Dark Matter / Dark Energy***

Physics Beyond the Standard Model (BSM)

Example: Dark Matter

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

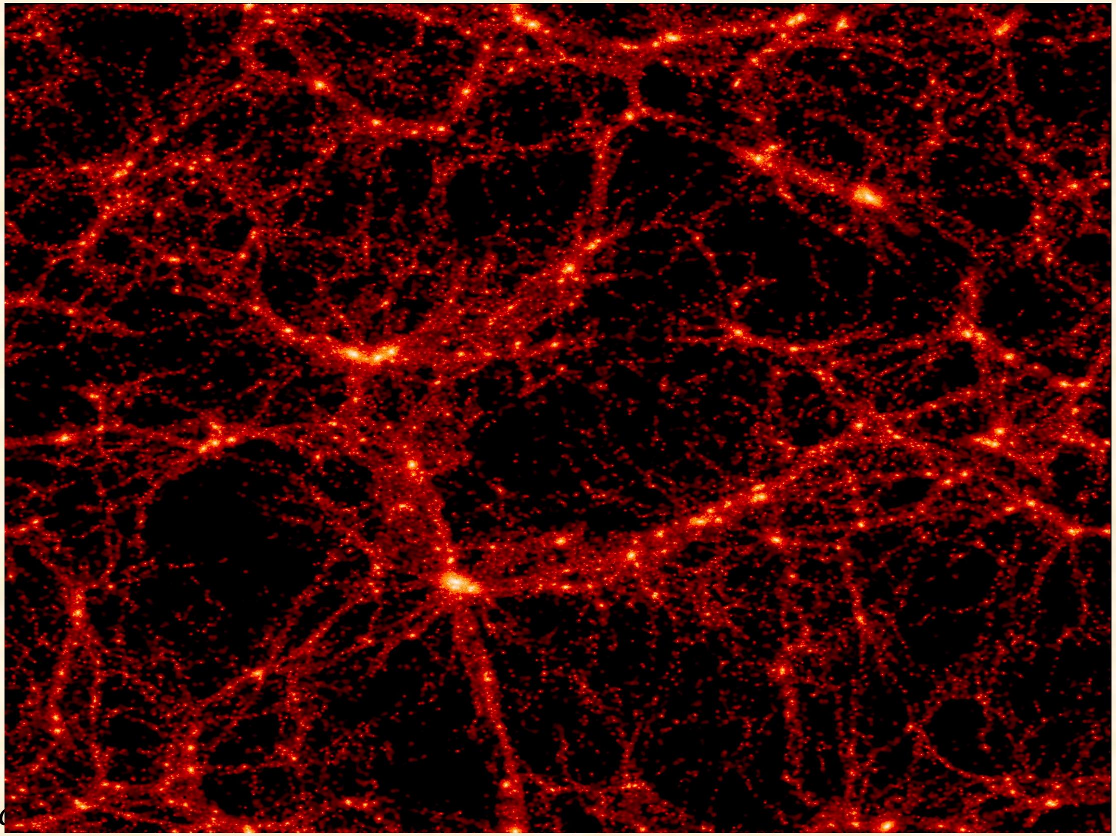
$$\frac{mv^2}{r} = \frac{mMg}{r^2} \longrightarrow v_{cric} = \sqrt{\frac{Mg}{r}}$$

Dark matter would explain this

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

What is it?

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



European Strategy Group
Future High Energy Frontier Colliders

Luminosity Upgrade of LHC:
HL-LHC

Circular colliders:
FCC (Future Circular Collider)
FCC-hh: 100 TeV proton-proton cm energy
FCC-ee: 90-350 GeV lepton collider

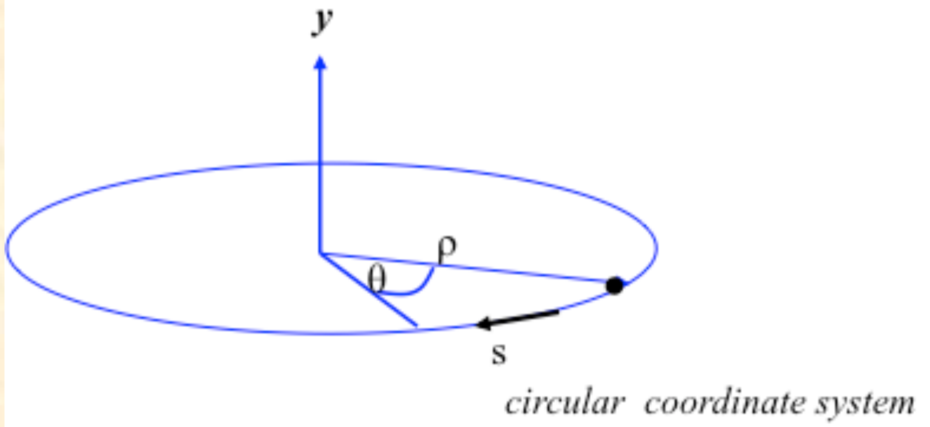
Linear colliders
ILC (International Linear Collider): e^+e^-, 500 GeV cms energy,
CLIC (Compact Linear Collider): e^+e^-, 380GeV - 3TeV cms energy,

Others
ERLs
Muon collider,
Plasma acceleration

1.) Geometry of a Storage Ring:

A charged particle in a magnetic dipole field feels a transverse deflecting force, The „Lorentz force“

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



We have to calculate relativistically, which is not so difficult and leads to E ⟷ p

Condition for an ideal circular orbit:

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

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

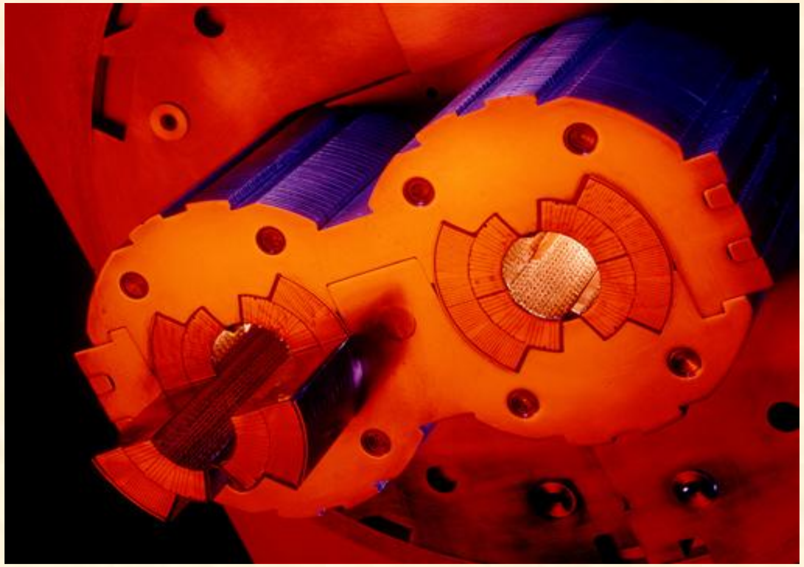
$p = \gamma \cdot m_0 v \qquad \dfrac{\gamma\, m_0\, v^{\cancel{2}}}{\rho} = e\,\cancel{v}\,B$

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

$B\rho$ = "beam rigidity"

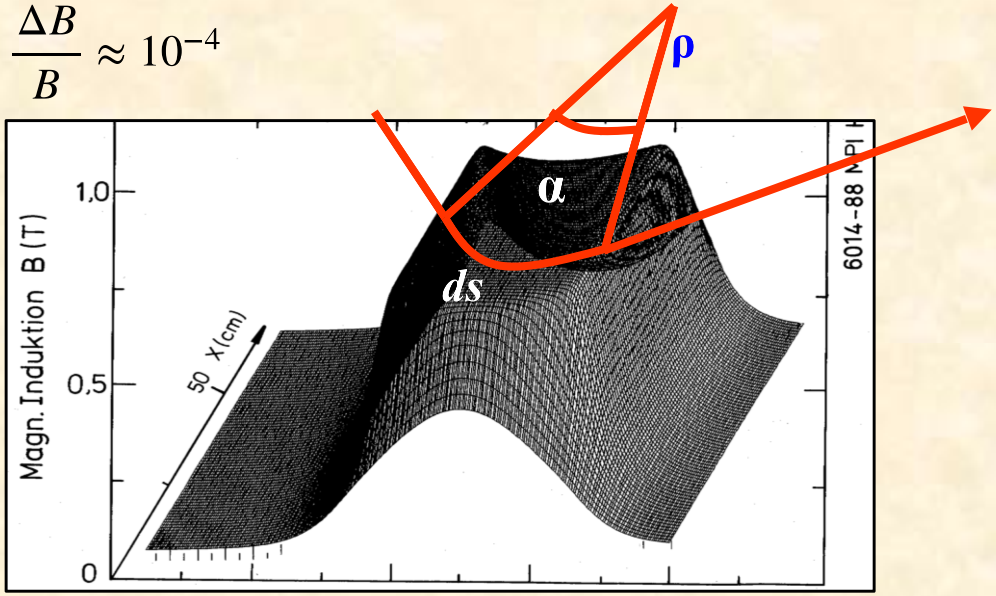
The overall integral of all dipole fields around the ring has to give 2π bending angle

The Magnetic Guide Field



$B \approx 1 \ldots 8\ T$

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



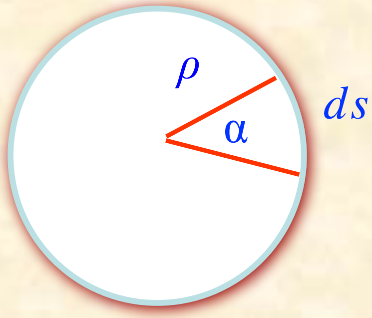
field map of a storage ring dipole magnet

Dipoles produce a constant (!) Magnetfeld

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

nota bene:
for ultra relativistic particles $$p \approx \frac{E}{c}$$

$$\rho = 2.8\ km$$



Bending Abgle of a Dipole: $$\alpha_{dipole} = \frac{ds}{\rho} = \frac{\int B\ ds}{B\ \rho} \approx \frac{B \cdot l_{dipole}}{B\ \rho}$$

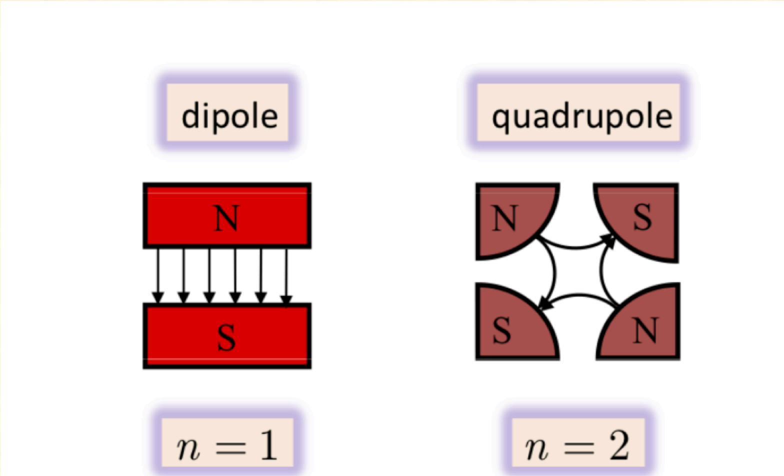
Number of Dipol Magnets: $$N_{dipole} = \frac{2\pi}{\alpha_{dipole}} = 1232\ !!!$$

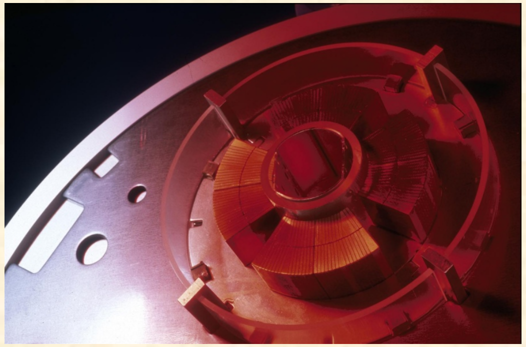
Storage Ring Circumference: $$C_0 = 2\pi \cdot \rho$$

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:

$$B_y = g \cdot x, \quad B_x = g \cdot y$$

Focusing forces and particle trajectories:

A linear increasing restoring force leads always (!) to a harmonic oscillation.
==> quadrupoles do that for us
And dipoles define the particle momentum

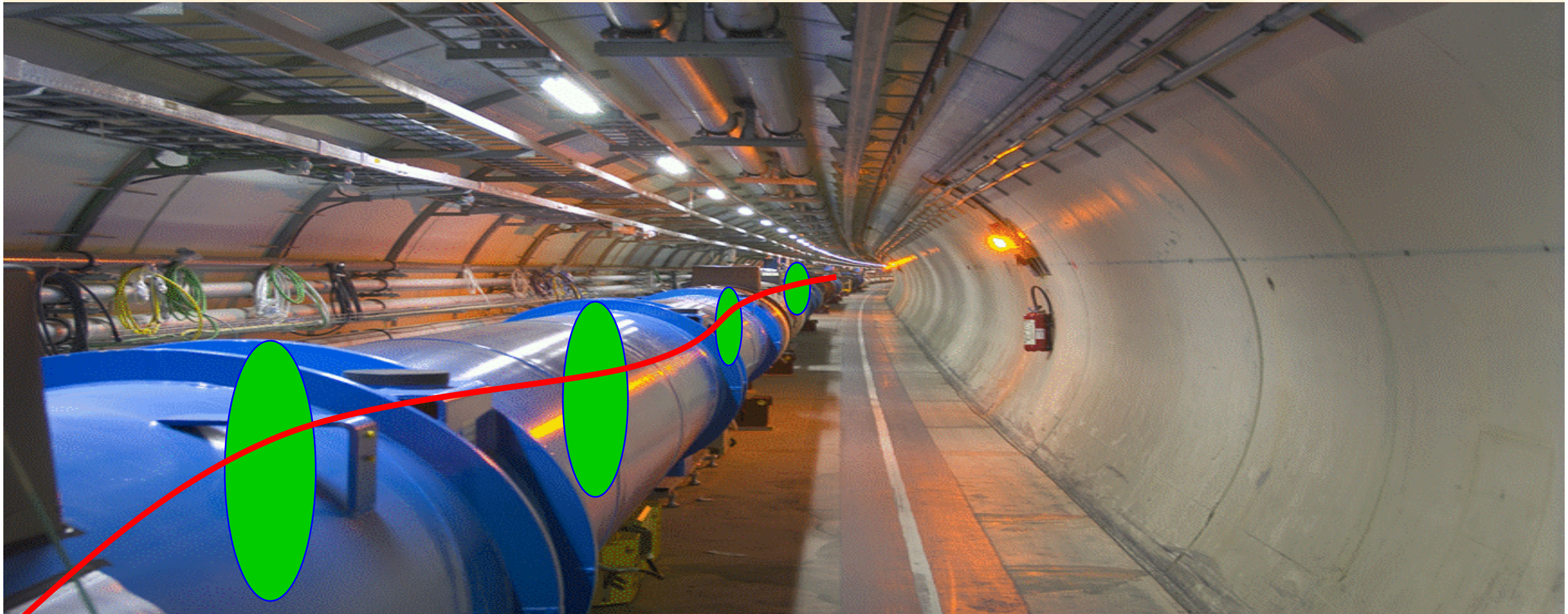
normalise magnet fields to momentum
(remember: ***B*ρ = p / q*** *)*

Dipole Magnet

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

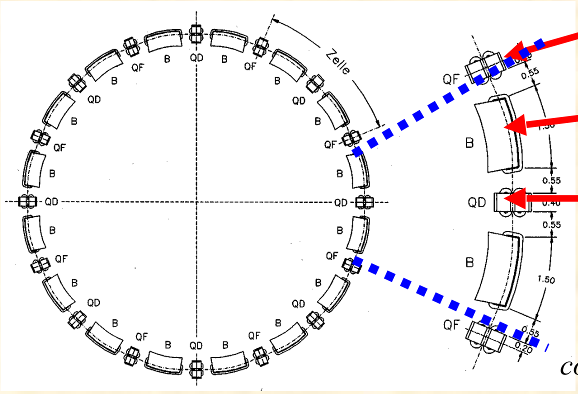
Quadrupole Magnet

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



The movement of a charged particle in the "Lattice" of external magnetic fields can be described analytically.

… and corresponds - in linear fields - to a harmonic transverse oscillation.

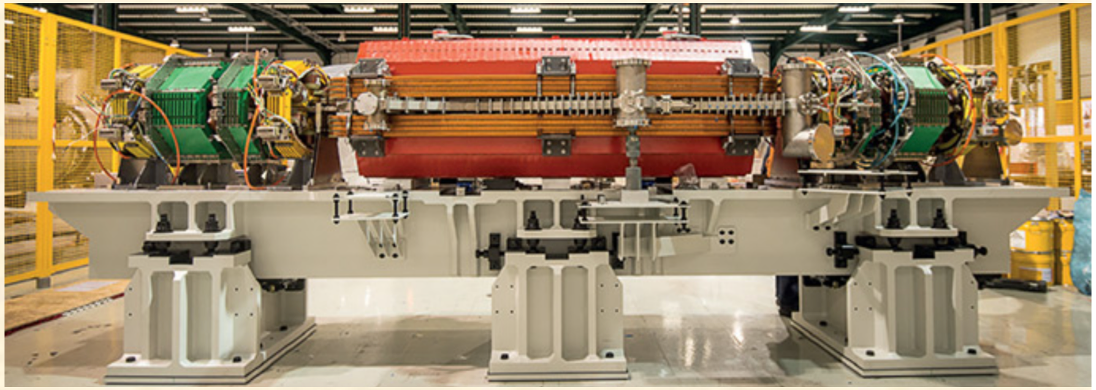


focusing lens

dipole magnet

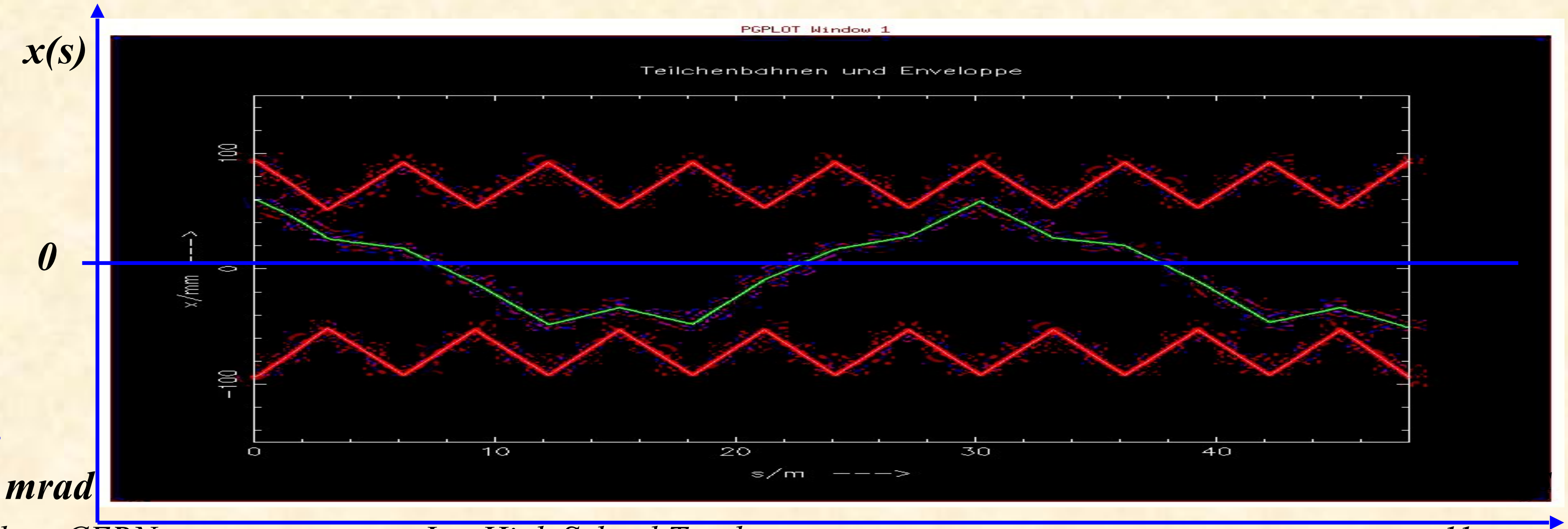
defocusing lens

court. K. Wille



Sesame Light Source

We can calculate the single particle trajectories for an arbitrary number of turns.



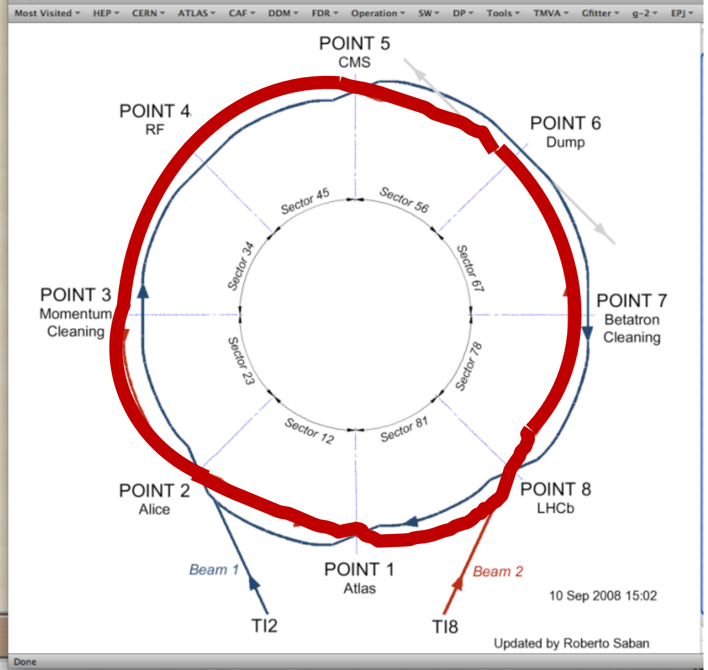
typical values in a strong foc. machine:

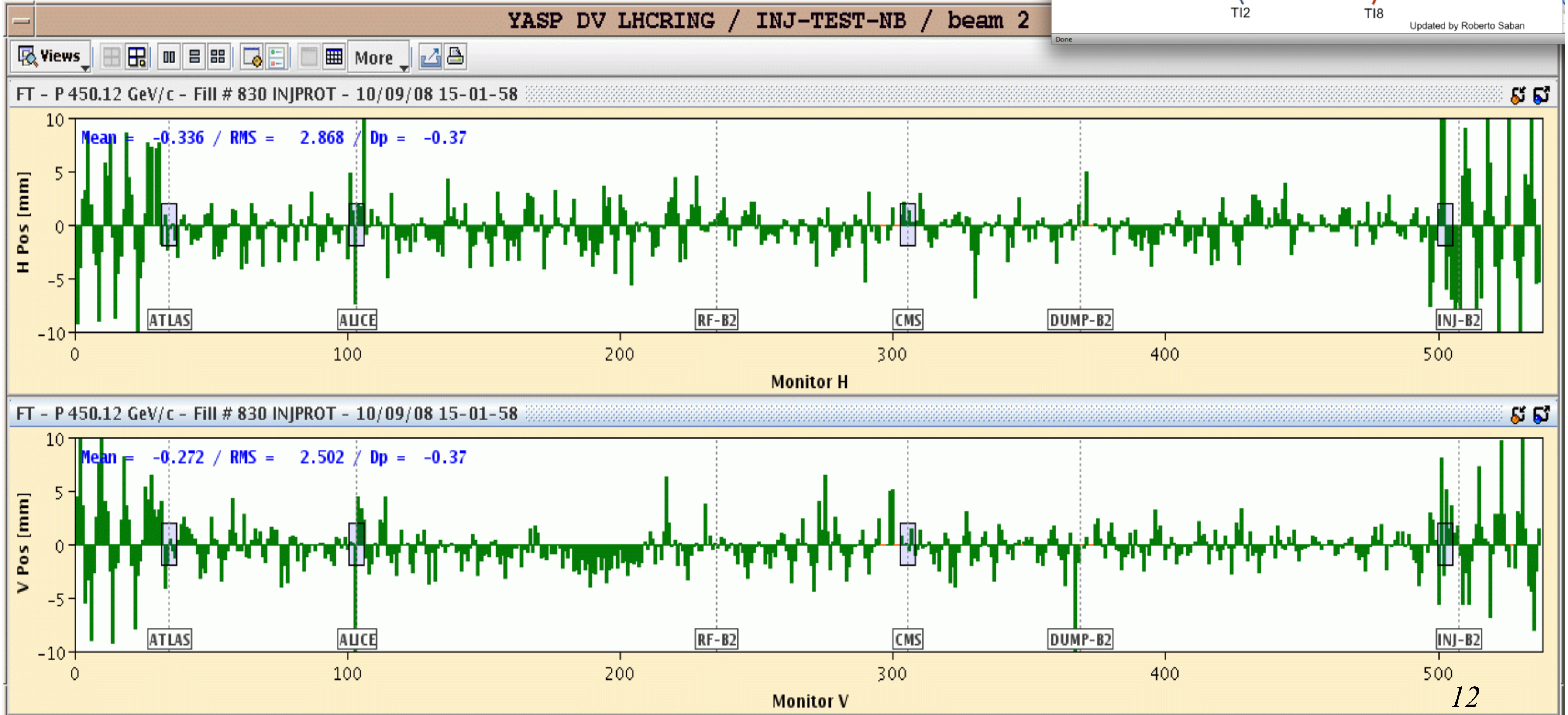
$x \approx mm$, $x' \leq mrad$

LHC Operation: Beam Commissioning

First turn steering "by sector:"

- One beam at the time
- Beam through 1 sector (1/8 ring), correct trajectory, open collimator and move on.



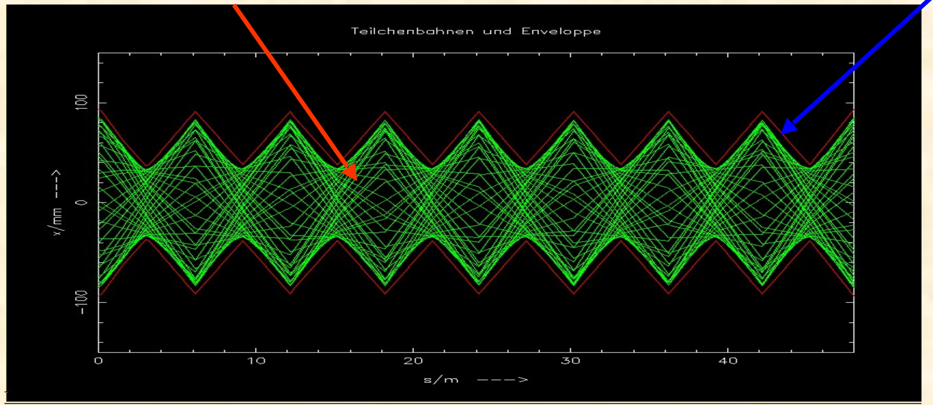


Many particles: The Beam

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

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

Beta-Function describing the size of the Particle Ensemble



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

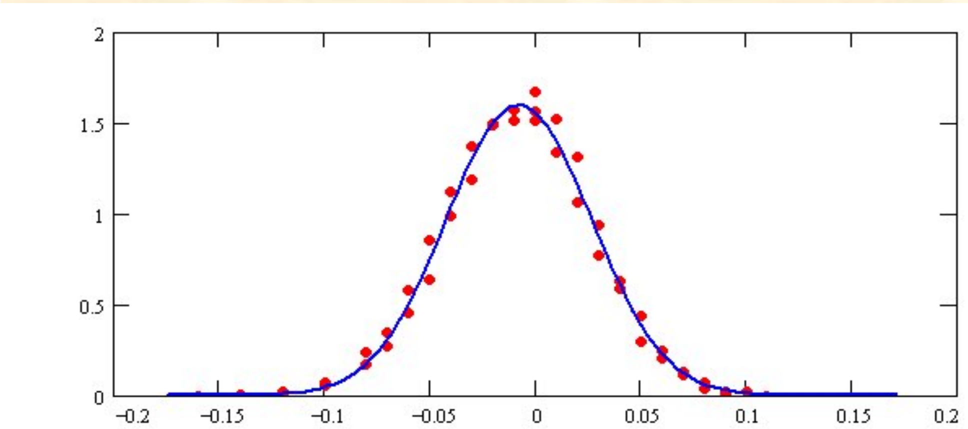
Gauß Particle Distribution:

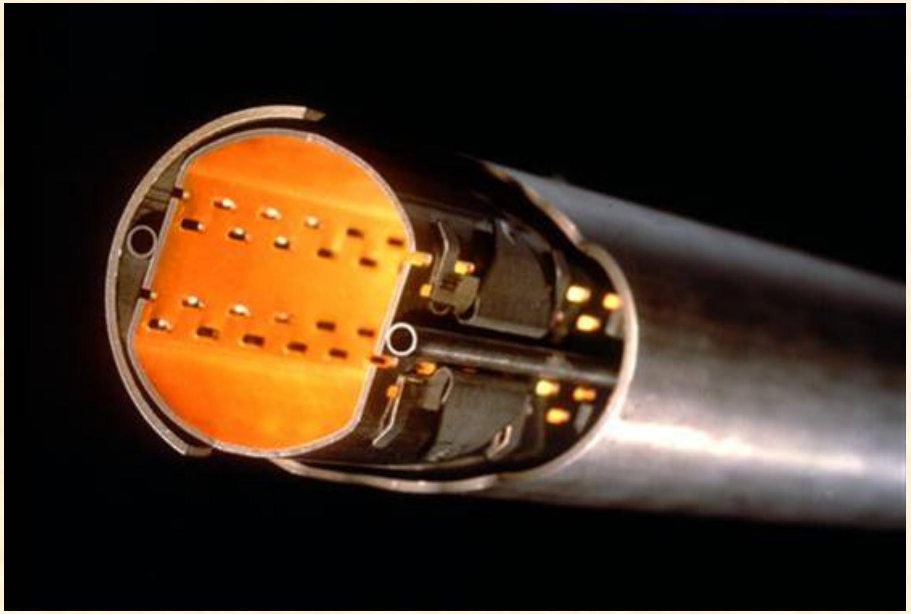
$$\rho(x) = \frac{N\cdot e}{\sqrt{2\pi}\,\sigma_x}\cdot e^{-\frac{1}{2}\frac{x^2}{\sigma_x^2}}$$

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

LHC:

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





aperture requirements: $r_0 = 17 * \sigma$

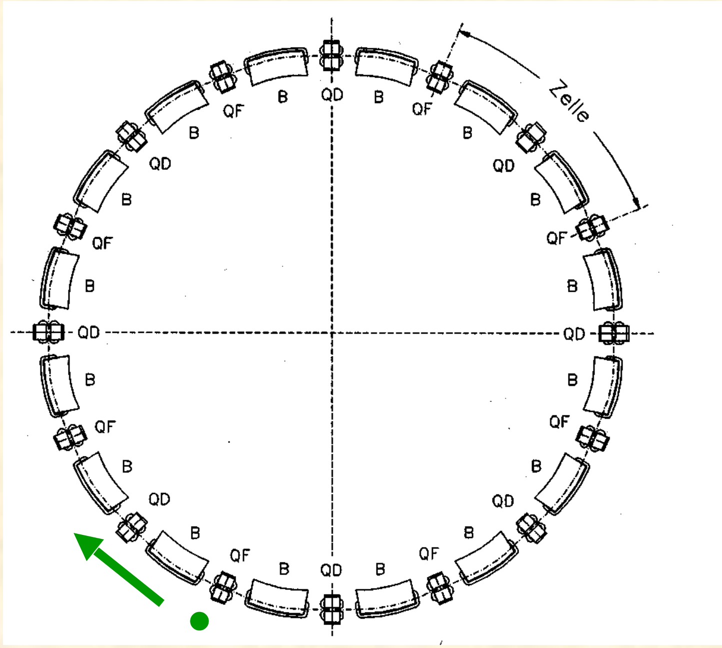
ATTENTION: its classical mechanis

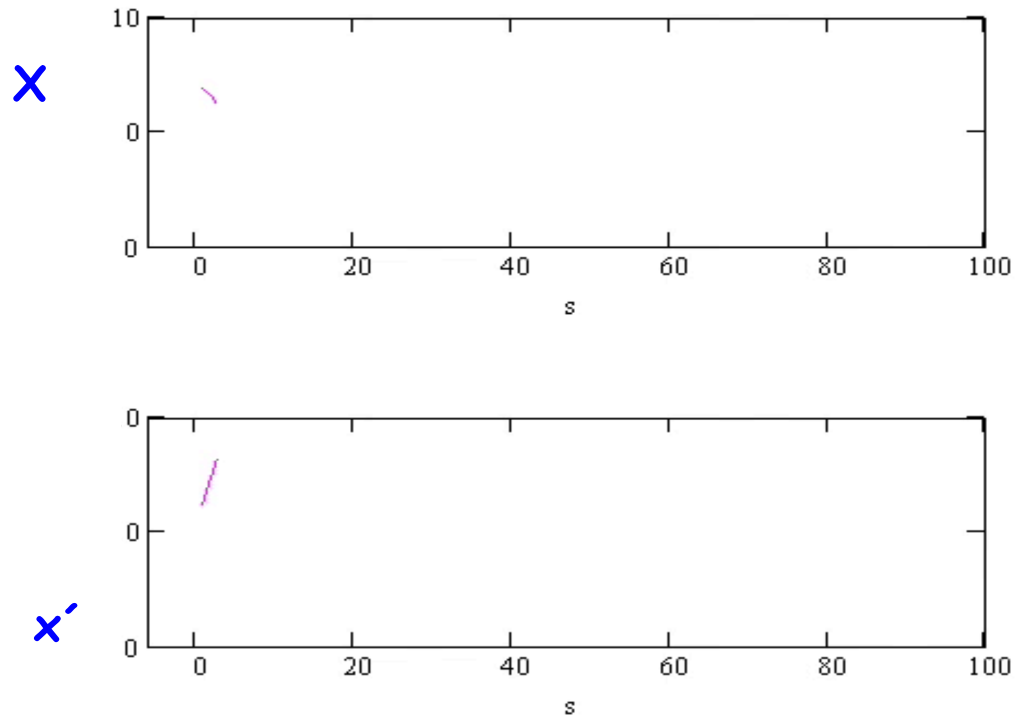
Beam Dynamics in a Storage Ring

The particle movement described in

phase space, x, x'

—> plot x, x´as a function of „s"

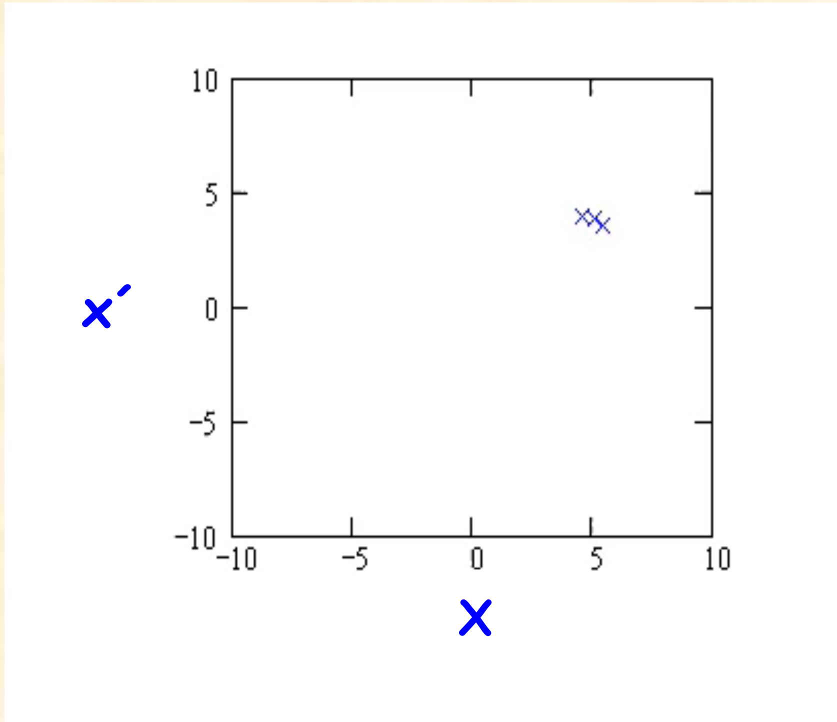




Theorem of Liouville

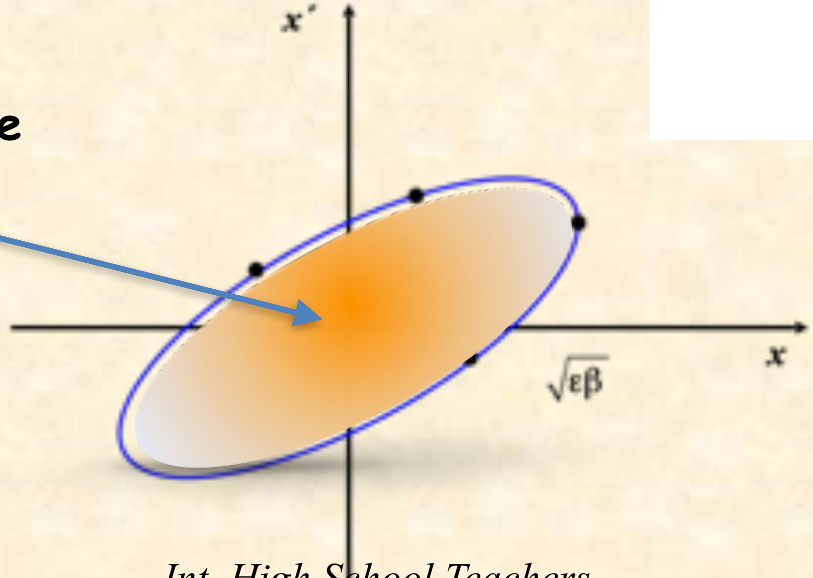
… and now the ellipse:

note for each turn x, x´at a given position „s" and plot in the phase space diagram



under the influence of conservative forces, the particle kinematics will always follow an ellipse in phase space x, x'phase space volume = constant

We use the area of that beam-ellipse as quality attribute for the particle ensemble: $A = \varepsilon\,\pi$



Time for a blue Slide …

Why do we do that ?

—> the beam size is given by two parameters:
β function - focusing properties
ε as intrinsic beam quality

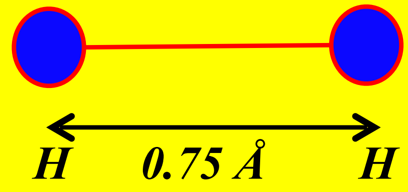
—> beam size: $\sigma = \sqrt{\varepsilon \cdot \beta}$

—> the stability of the phase space ellipse, ε,
tells us about the stability
of the particle oscillation, which is …
… "the lifetime" of the beam.

—> the size of the ellipse tells us about the particle density,
… which is the beam quality in collision.

Particle Density in matter

Hydrogen molecule

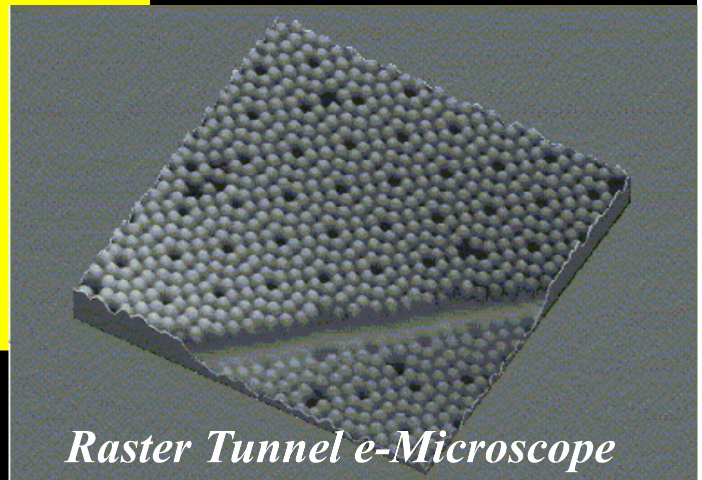


Atomic Distance in Hydrogen Molecule

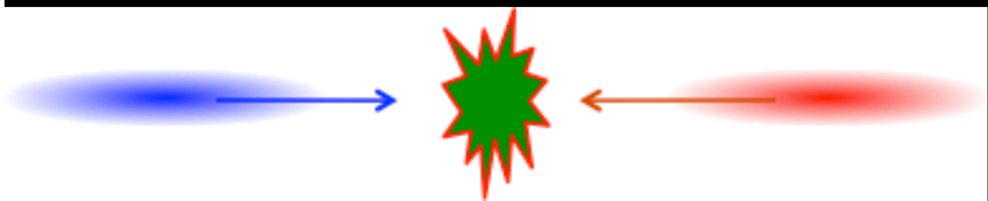
$R_B \approx 0.5$ Å

in solids / fluids $\lambda \approx 2.1 \; \ldots \; 2.9$ Å

in gases $\lambda \approx 33$ Å $= 3.3$ nm

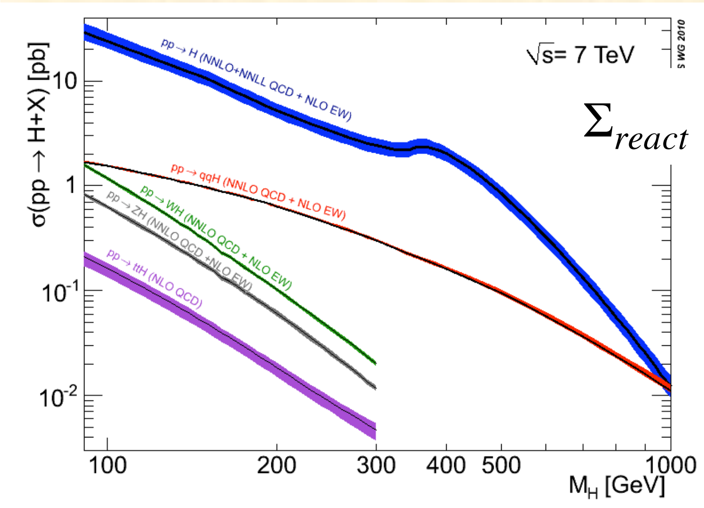

Raster Tunnel e-Microscope

Particle Distance in Accelerators: $\lambda \approx = 6000$ Å $= 600$ nm (Arc LHC)

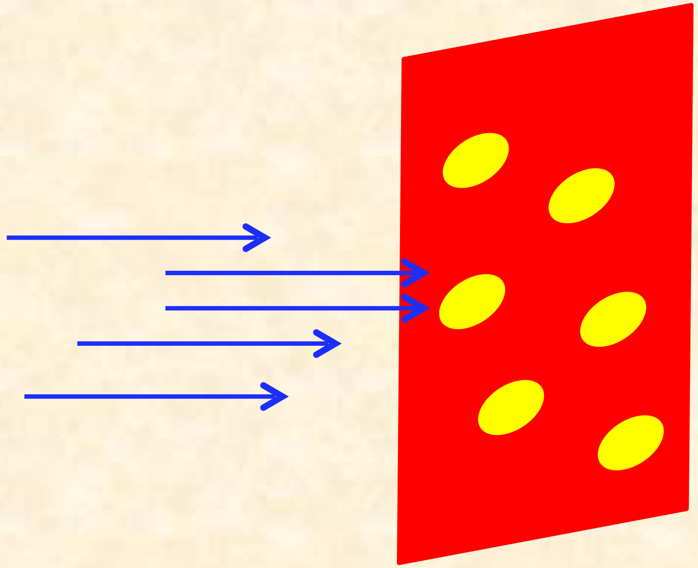


Problem: Our particles are VERY small !!

Overall cross section of the Higgs:



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



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

$$1\ pb = 10^{-12} \cdot 10^{-24} cm^2 = 1/mio \cdot 1/mio \cdot 1/mio \cdot 1/mio \cdot 1/mio \cdot 1/10000\ mm^2$$

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

The particles are "very small"

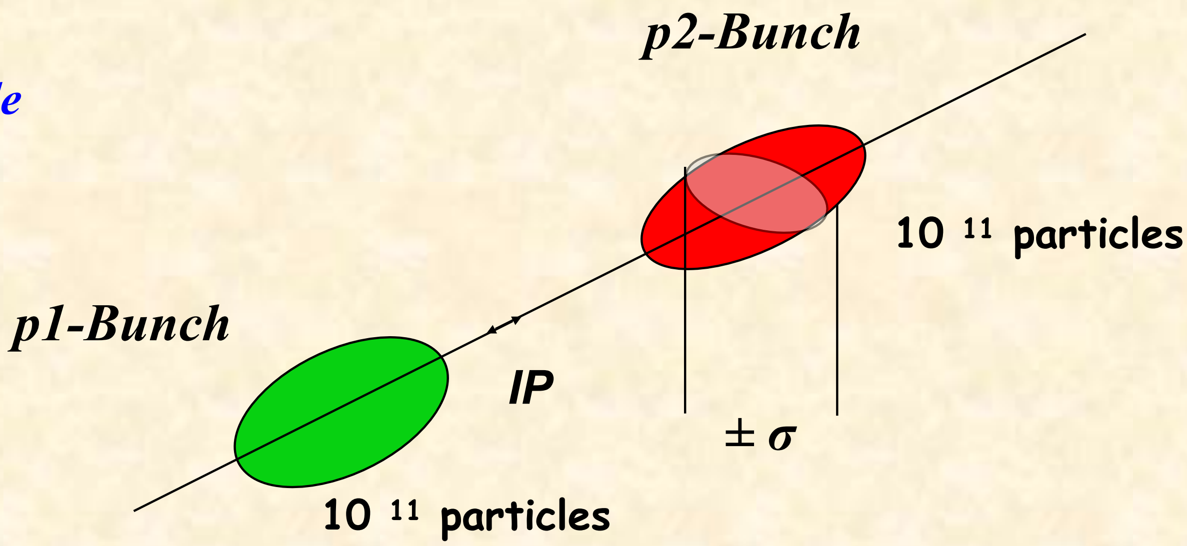
LHC typical:

σ = 0.1 mm → 16 µm

5.) Luminosity

Ereignis Rate: "Physik" pro Sekunde

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

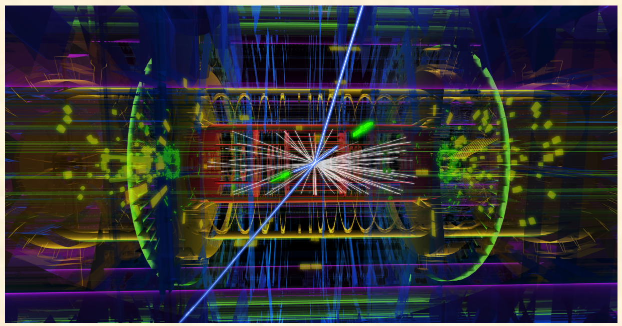


Example: Luminosity run at LHC

$\sigma_x = \sigma_y = 16\mu m$	*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*

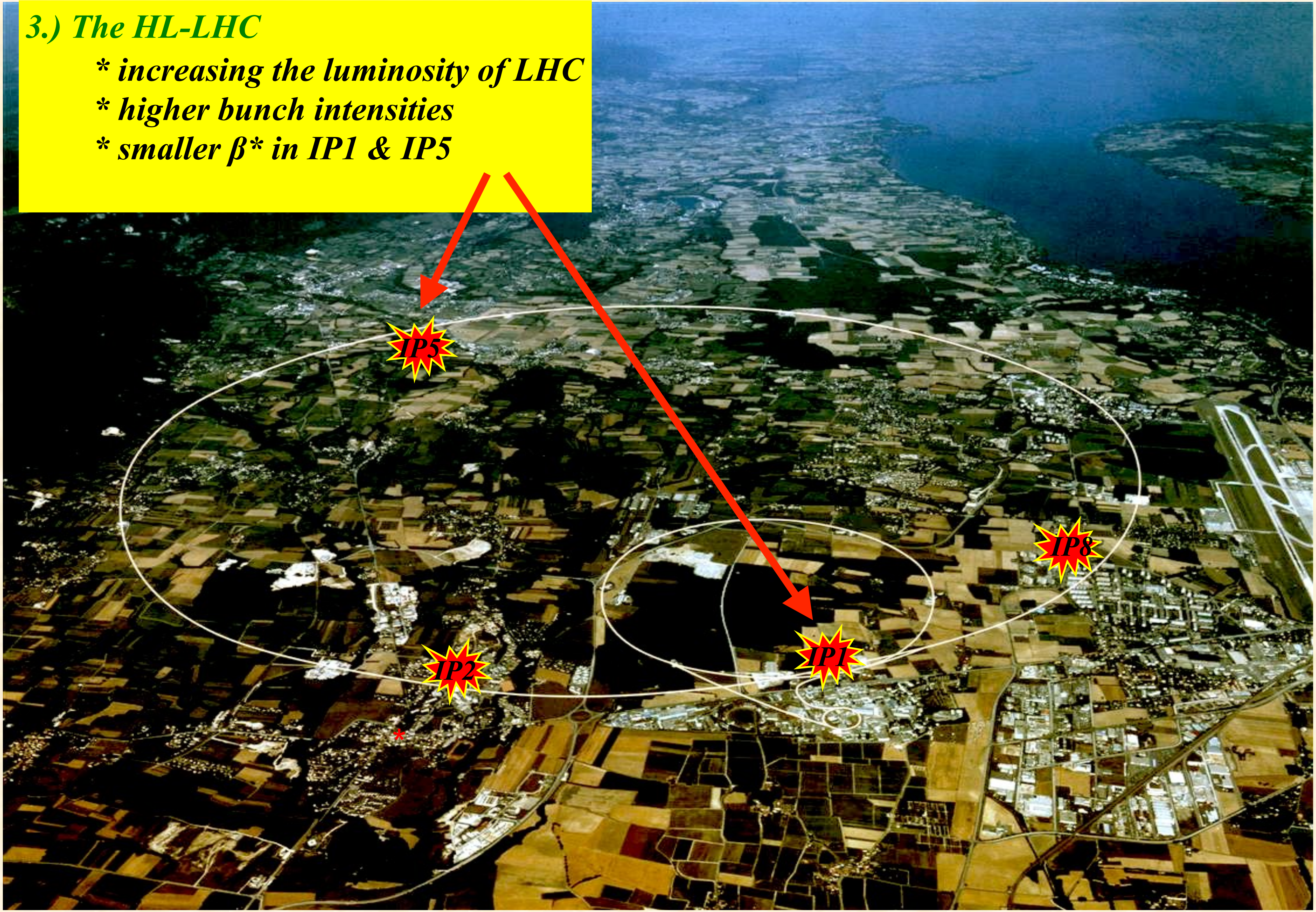
$$L = 1.0 * 10^{34}\ \frac{1}{cm^2 s}$$

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



3.) The HL-LHC

** increasing the luminosity of LHC*
** higher bunch intensities*
** smaller β* in IP1 & IP5*

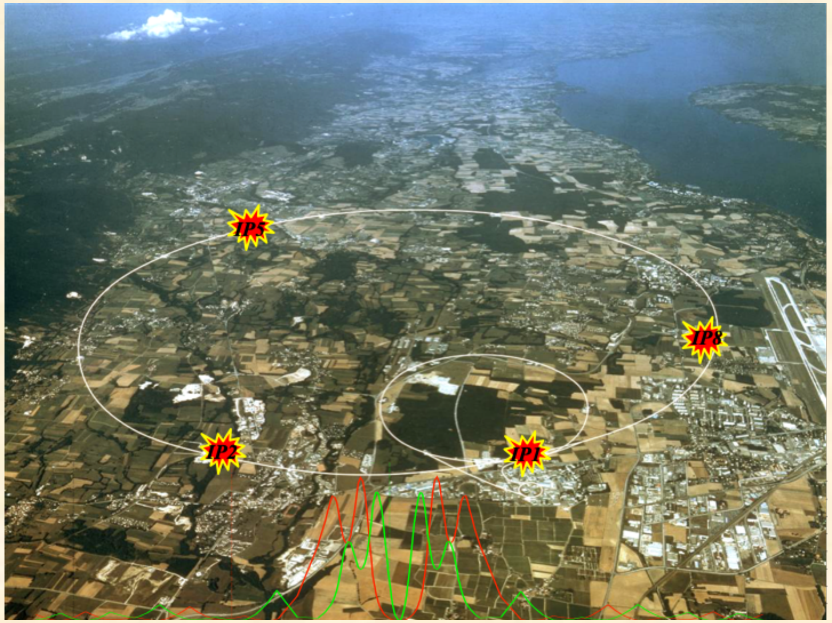


3.) The HL-LHC

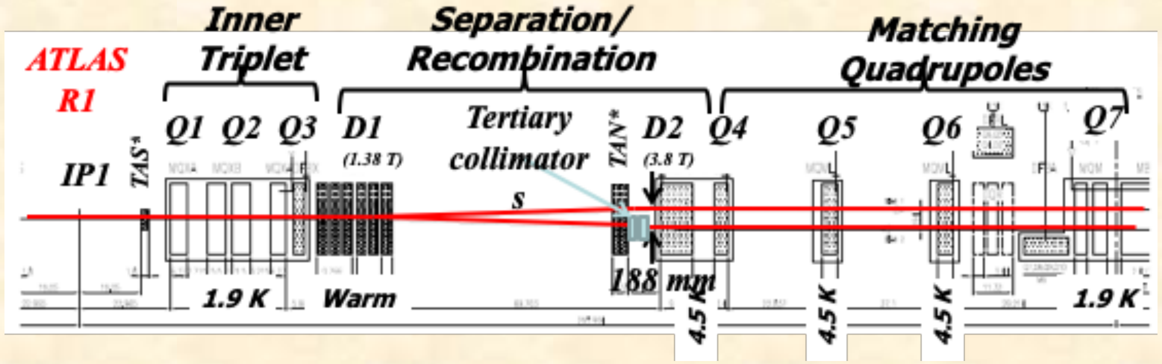
* *increasing the luminosity of LHC*
* *higher bunch intensities*
* *smaller β**

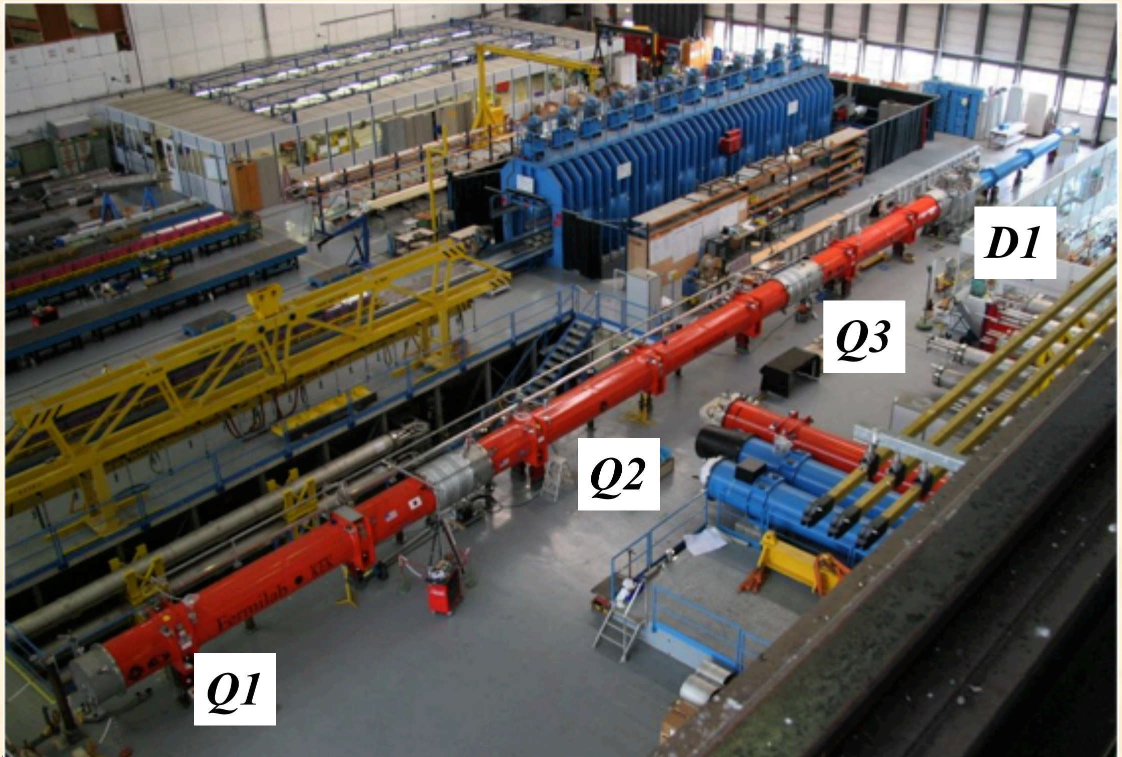
	LHC	HL-LHC
Energy	7 TeV	7 TeV
Particles / bunch	$1.2*10^{11}$	$2.2*10^{11}$
number of bunches	2808	2748
β*	55 cm	15 cm
ε	$5.0*10^{-10}$ m rad	$3.3*10^{-10}$ m rad
σ	16 μm	7 μm
Luminosity	$1.0*10^{34}\ cm^{-2}\ s^{-1}$	$7.0*10^{34}\ cm^{-2}\ s^{-1}$

LHC & HL-LHC



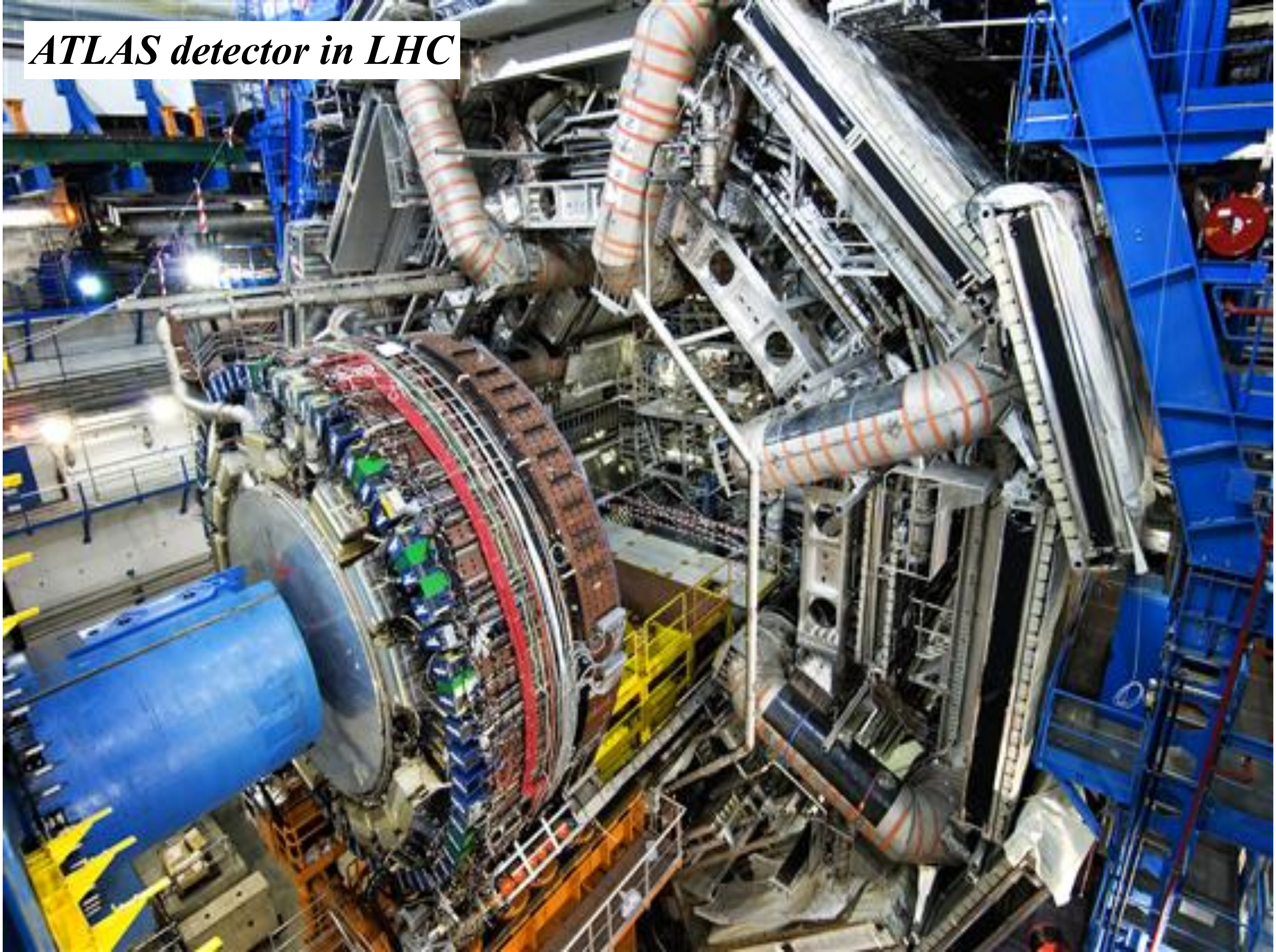
At one (or a very few) points in the accelerator, we make the beams as small as possible, to push for highest particle density.





Mini-Beta Insertion

ATLAS detector in LHC



Theorem of Liouville

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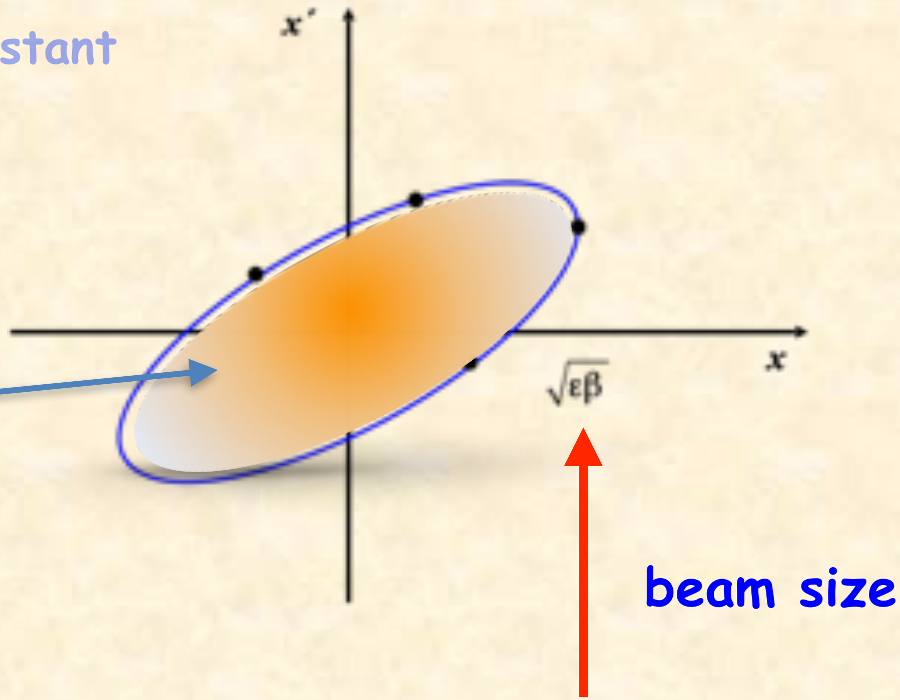


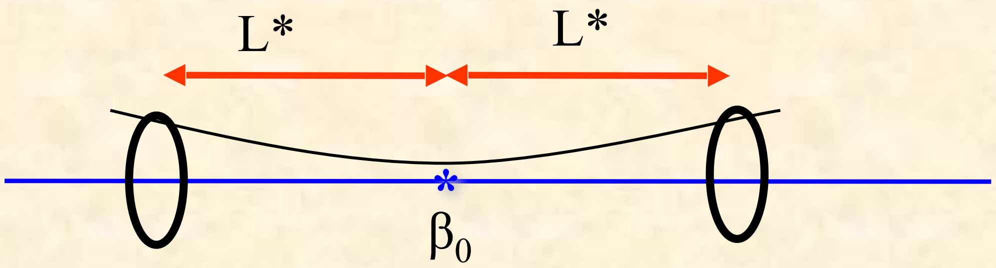
β-Function in a Drift:

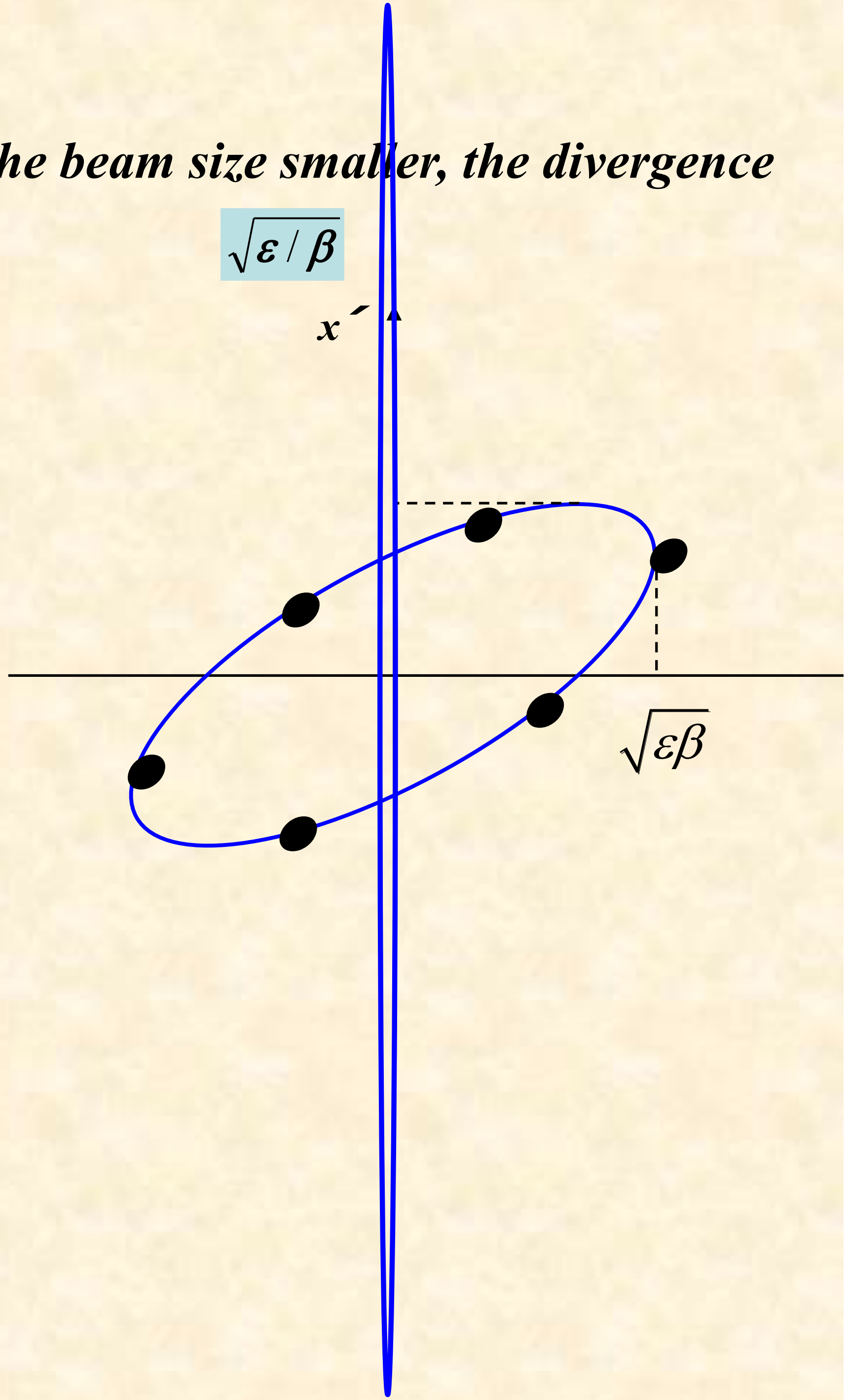
A direct consequence of "Liouville",
i.e. phase space conservation, is that … if we make the beam size smaller, the divergence increases.

in our β-language:

$$\beta(L) = \beta_0 + \frac{L^2}{\beta_0}$$

! ! !





At the end of a long symmetric drift space the beta function reaches its maximum value in the complete lattice.
-> here we get the largest beam dimension.

-> keep L* as small as possible

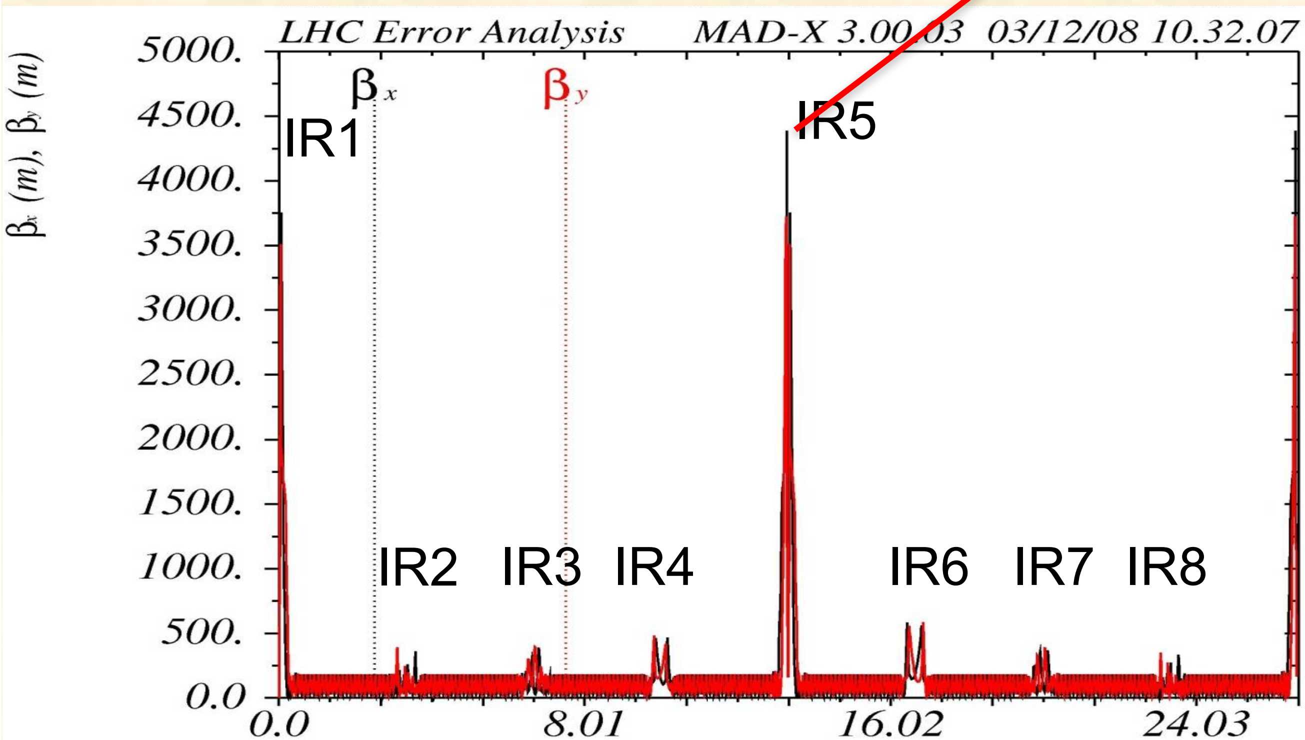
Luminosity Upgrade:

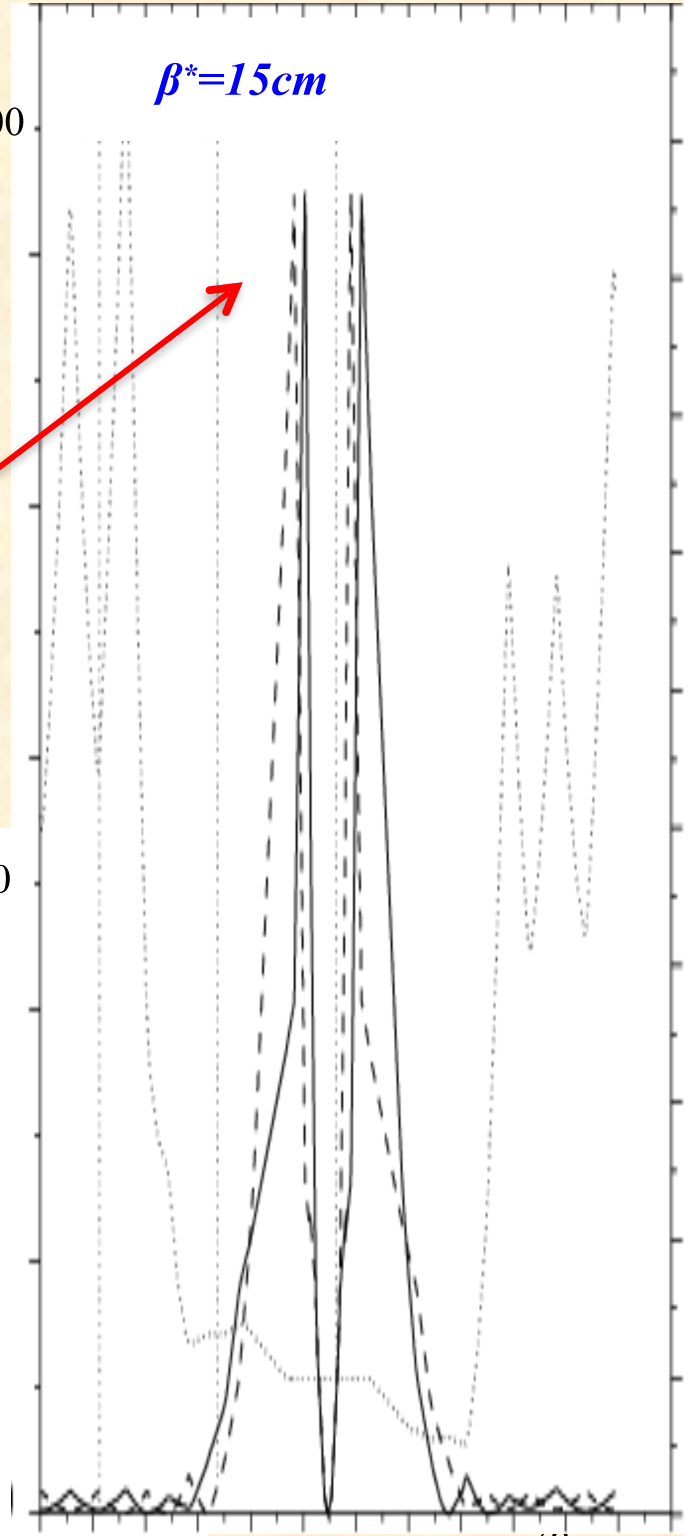
stronger focusing → smaller beam size at the IP

High Gradient / Large Aperture Insertion Quadupole Magnets

l = 8 m, G= 175 T/m, aperture = 120 mm,
(B_{peak}=13 T)

higher gradients & larger aperture
new sc. technology Nb_3Sn

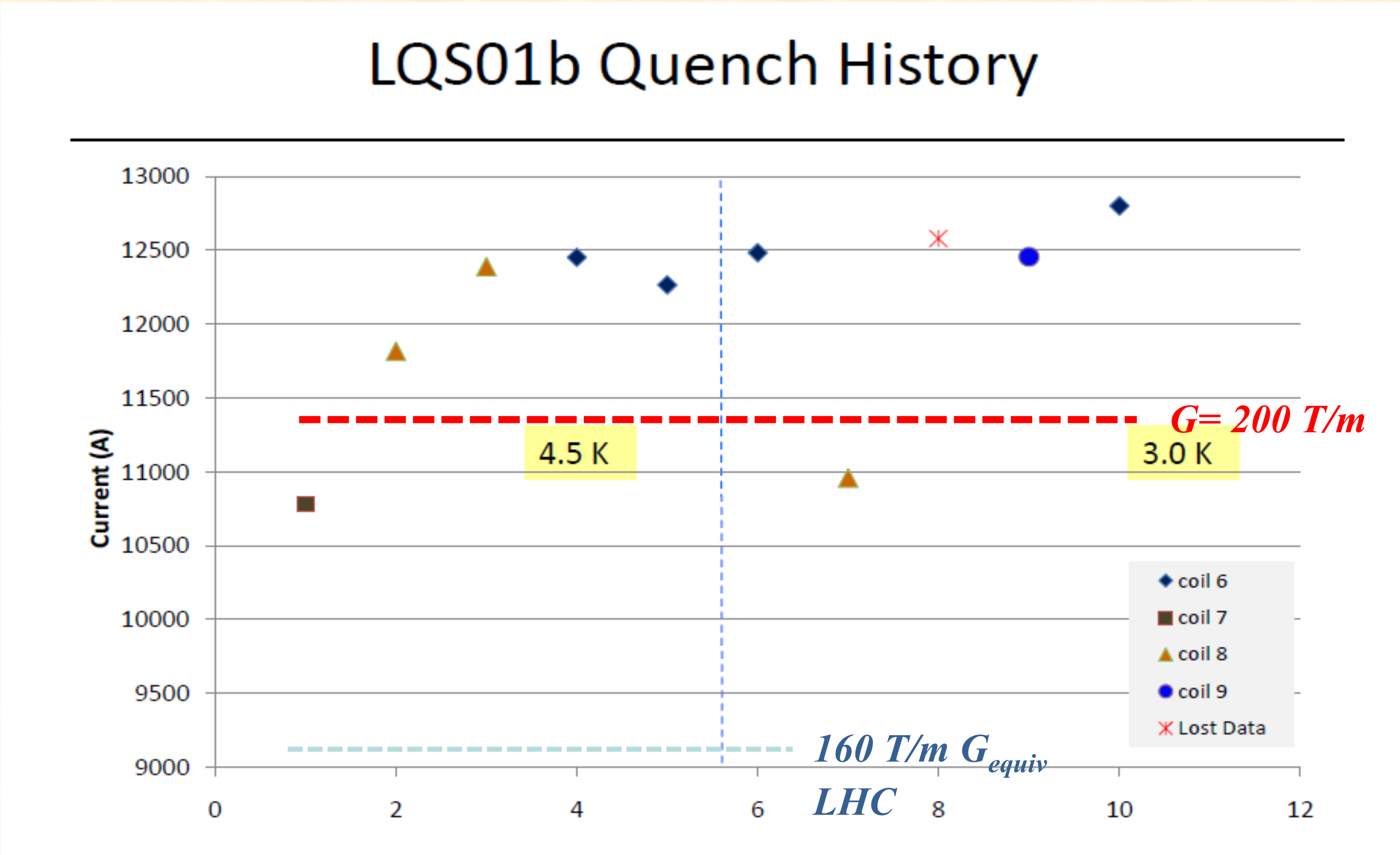




Challenge: High Field Nb_3Sn Quad

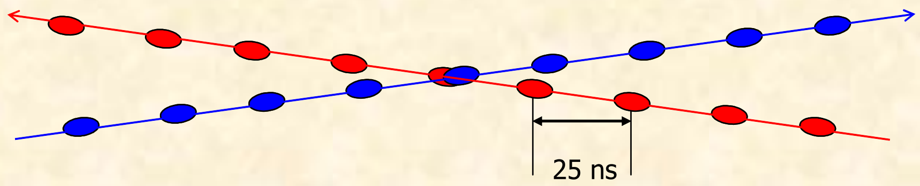
Stronger focusing needs stronger magnets

We need a material that can withstand this higher field in its super conducting phase !!! Nb_3Sn



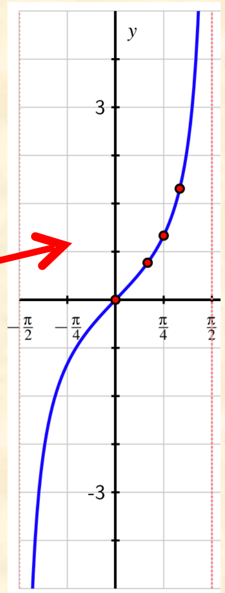
reminder: LHC standard inner triplet NbTi: G=215 T/m, Φ=66 mm

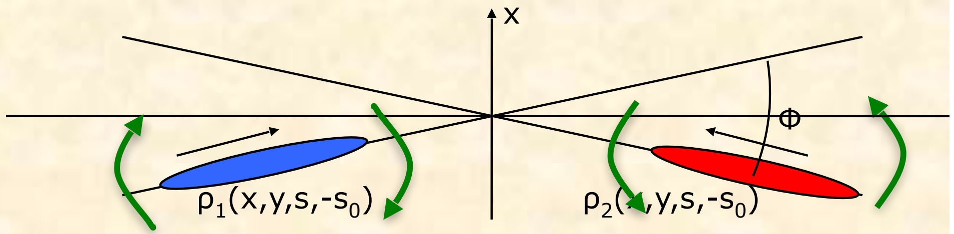
Challenge: HL-LHC Crab Cavities



$$L = L_{ideal} \cdot F$$

$$F = \frac{1}{\sqrt{1 + 2\frac{\sigma_s^2}{\sigma_{1x}^2 + \sigma_{2x}^2}\tan^2\frac{\phi}{2}}}$$



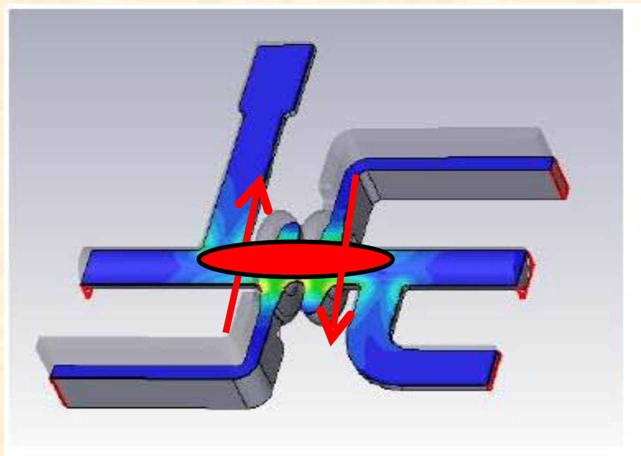


F = Spaghetti-Loss Factor

Transverse deflecting cavity at 800 MHz

Prototype test in SPS … at the moment technical challenge:

fast, precise, compact,
Fail SAFE !!



The Luminosity defines the number of “hits”. It depends on the particle density at the collision point.

The Beta function at the IP “β*” should be made as small as possible to increase the particle density. In a drift β is growing quadratically and proportional to 1/β*, which sets the ultimate limit to the achievable luminosity.

The distance L* of the focusing magnets from the IP should be as small as possible.
… try to avoid detectors like ATLAS or CMS whenever possible.   LOL.

The beam dimensions at the IP are typically a few μm.

What is a μm ?

4.) Push for higher energy: FCC

**** increasing the ring size***
**** stronger magnets***

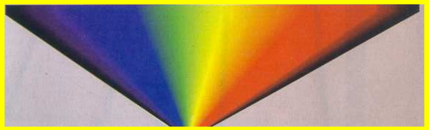
Collisions

de Broglie: ***Particles behave like waves*** *with a well defined wavelength* $\lambda = \frac{h}{p}$

$h = 4.1 \cdot 10^{-21}\ MeV\ s$

Spectrum of visible light:

$\lambda = 400 \ldots 800\ nm$



Resolution of light microscopes: a few μm

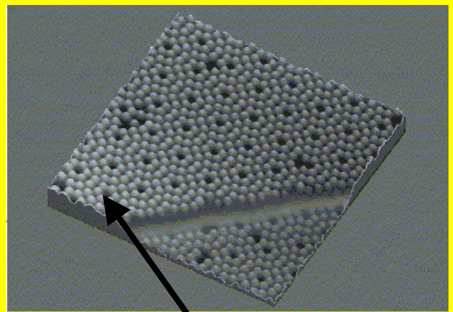
$\longleftrightarrow$ $250\ \mu m$

LHC… as gigantic microscope:

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

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

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



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

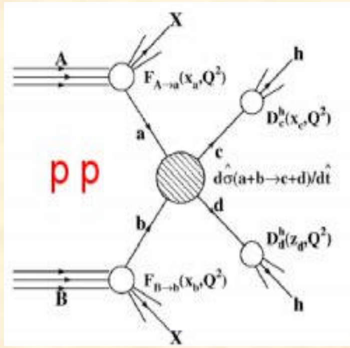
Nuclei: $\approx 10^{-15}\, m$

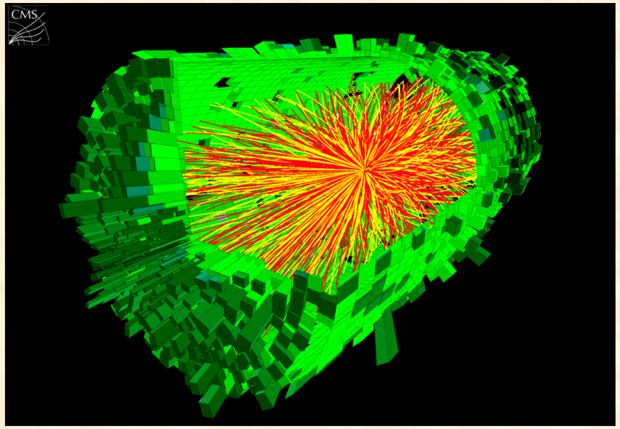
Future Colliders:

Hadrons or Leptons?

***Hadron collisions**: compound particles*

Proton = u+u+d + gluons + sea-quarks
Mix of quarks, anti-quarks and gluons
→ variety of processes
Parton energy spread
Hadron collisions ⇒ large discovery range

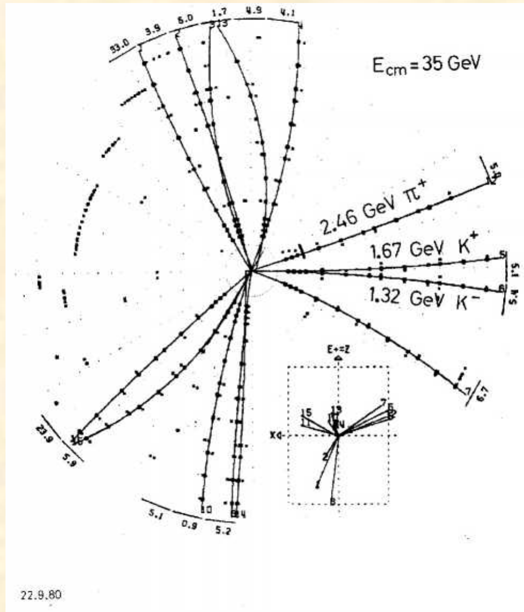




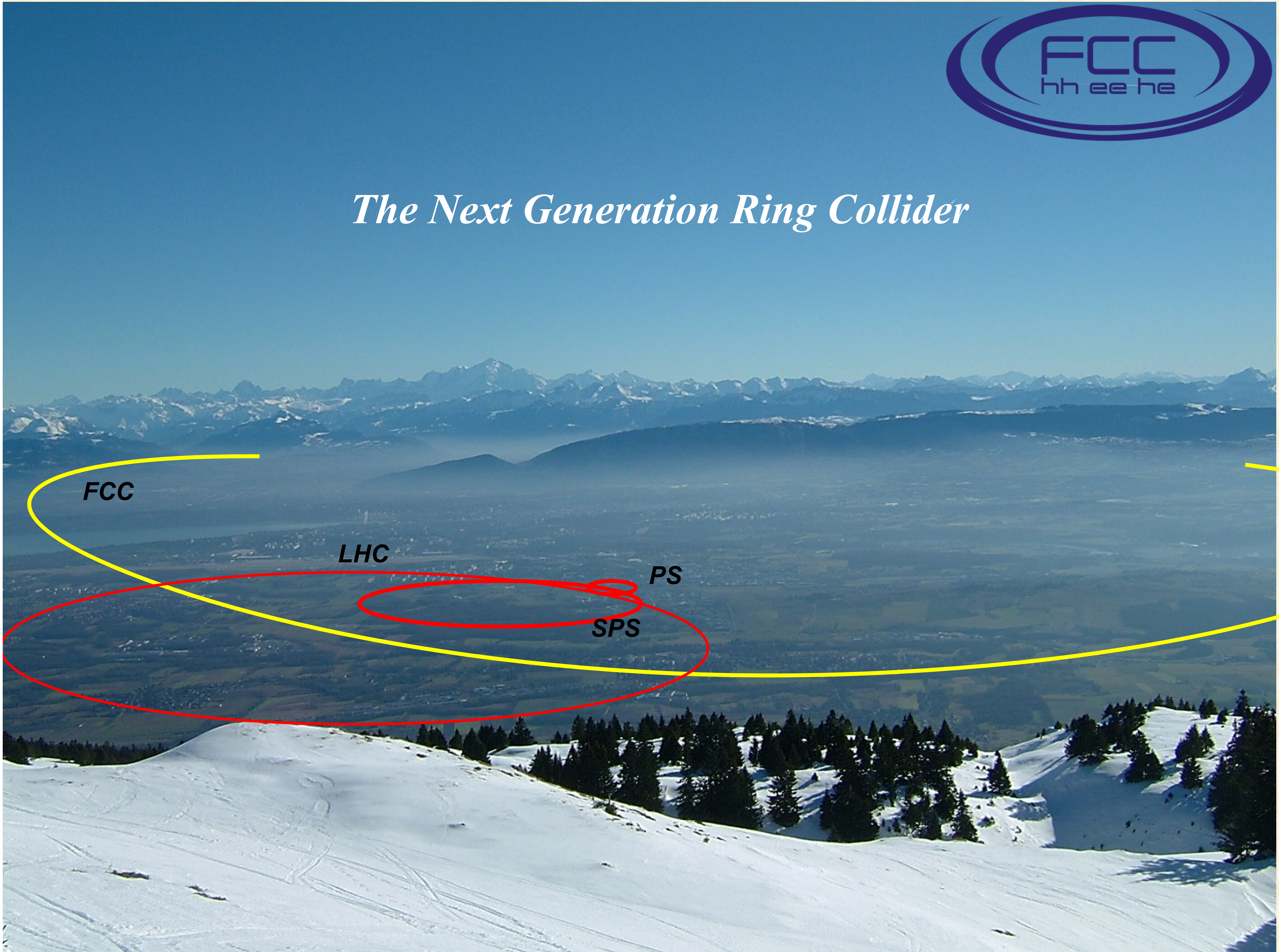
LHC Pb-Pb collision (Atlas)

Lepton collisions: Elementary particles / Anti-particles

Collision process known
Well defined energy
Other physics background limited
Lepton collisions ⇒ precision measurements
in e+ e- collisions quantum numbers disappear

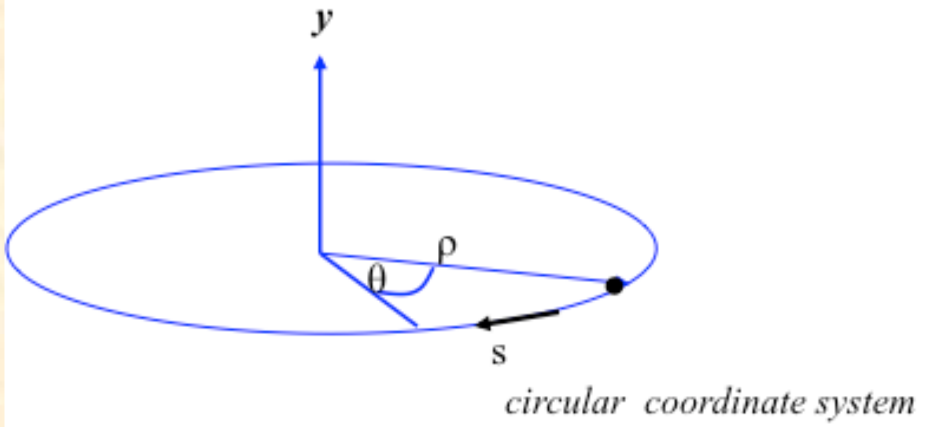


PETRA: gluon discovery


FCC hh ee he
The Next Generation Ring Collider
FCC
LHC
PS
SPS

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



~~$E = mc^2$~~ $E^2 = (pc)^2 + m^2c^4$

Condition for an ideal circular orbit:

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

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

$p = \gamma \cdot m_0 v$ $\dfrac{\gamma\, m_0\, v^2}{\rho} = e\,v\,B$

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

$B\,\rho$ = "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_3Sn

168 5 *Supraleiter im Magnetfeld*

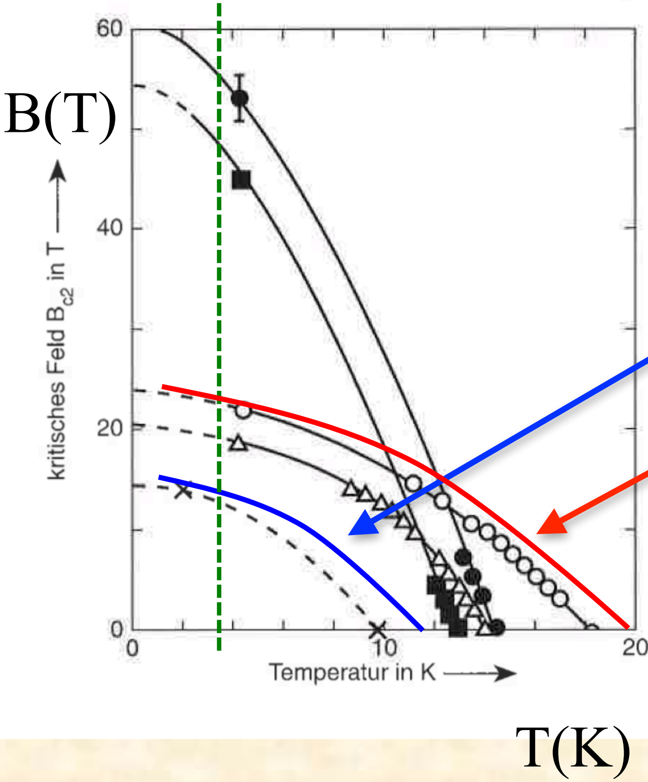
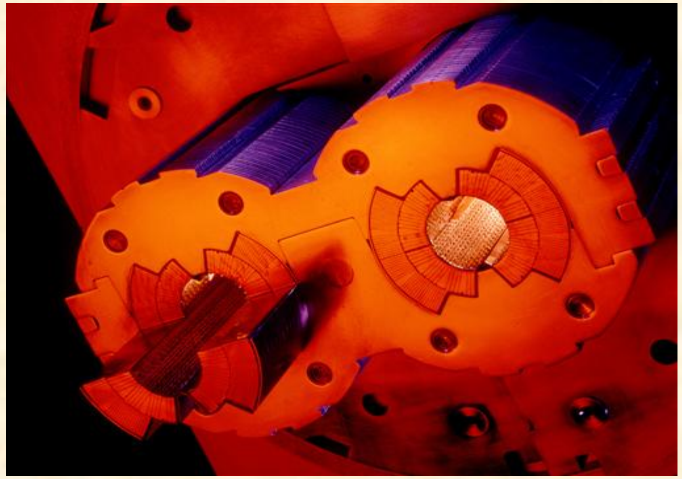


Abb. 77 Oberes kritisches Feld einiger Hochfeldsupraleiter.

–○–○–○–	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).

critical field in NbTi and Nb_3Sn



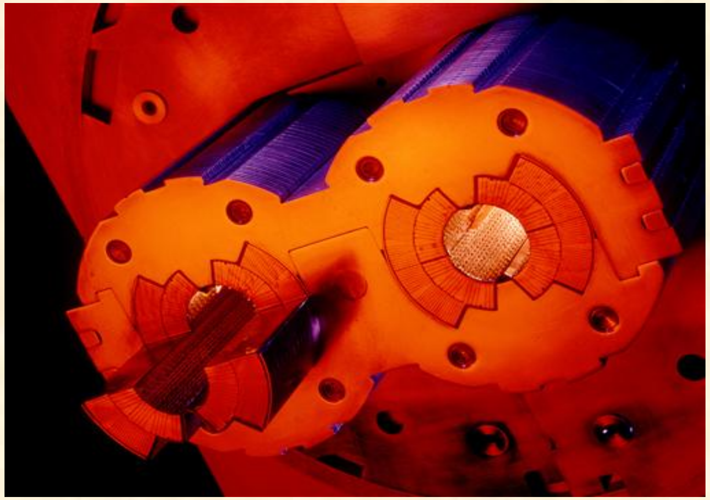
FCC -hh means Nb_3Sn technology for dipoles & quadrupoles

which is equally true in parts for HL-LHC

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

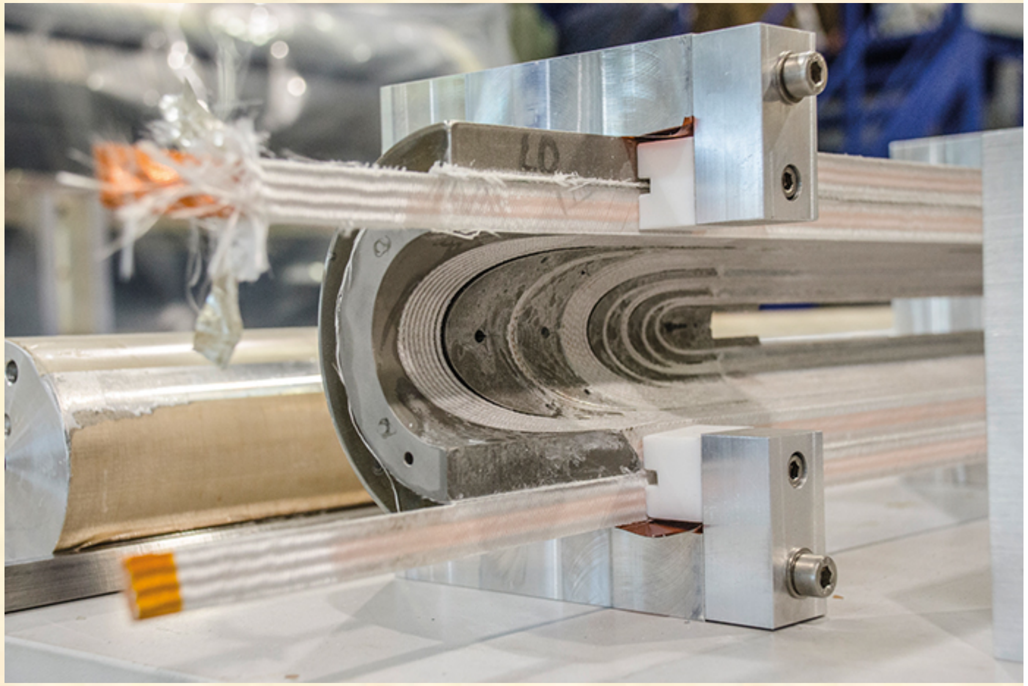
($j_c\perp$ = 100A/mm², $j_c\|$ = 800A/mm²)

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:

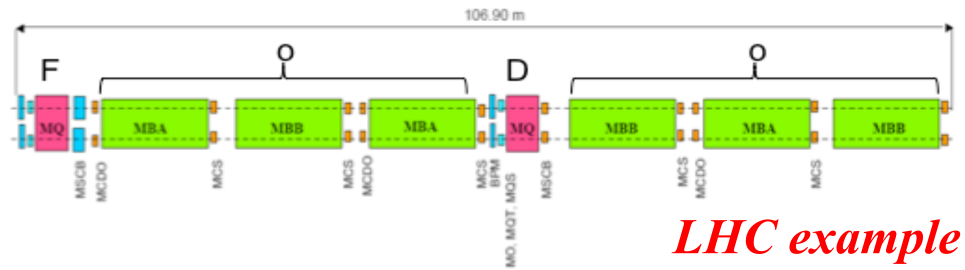
circumference 100km /27km
→ *Factor 3.7*

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*

FCC-hh Parameter List



LHC example

Pushing the limit (Dipole Fill Factor):

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

} ***5016 dipoles***

	LHC	HL-LHC	FCC-hh Initial	FCC-hh Nominal
Main parameters and geometrical aspects				
c.m. Energy (TeV)	14		100	
Circumference C (km)	26.7		97.75	
Dipole field (T)	8.33		<16	
Physics performance and beam parameters				
Peak luminosity[1] (10^{34} cm^{-2}s^{-1})	1.0	5.0	5.0	<30.0
Beam parameters				
Number of bunches n	2808		10 400	
Bunch spacing (ns)	25	25	25	
Bunch population $N(10^{11})$	1.15	2.2	1.0	
RMS bunch length[2] (cm)	7.55		8	
IP beta function (m)	0.55	0.15 (min)	1.1	0.3
RMS IP spot size (μm)	16.7	7.1 (min)	6.8	3.5
Full crossing angle (μrad)	285	590	104	200[3]
Other beam and machine parameters				
Stored energy per beam (GJ)	0.392	0.694	8.3	
SR power per ring (MW)	0.0036	0.0073	2.4	

5.) High Energy Lepton Colliders

** Limited by Synchrotron Radiation*
** and RF Power*


FCC
hh ee he
The next Generation e+/e- Ring Collider

Synchrotron Radiation

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

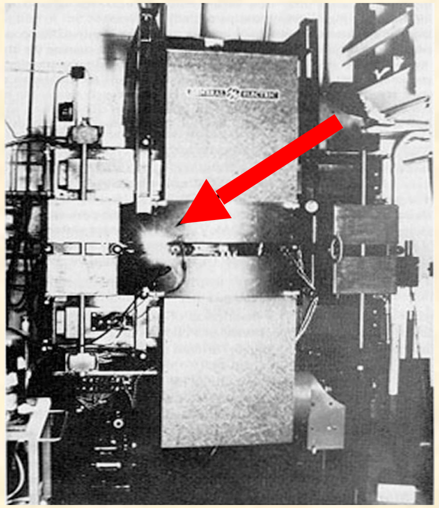
$$P_s = \frac{2}{3}\alpha\hbar c^2 \frac{\gamma^4}{\rho^2}$$ *radiation power*

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

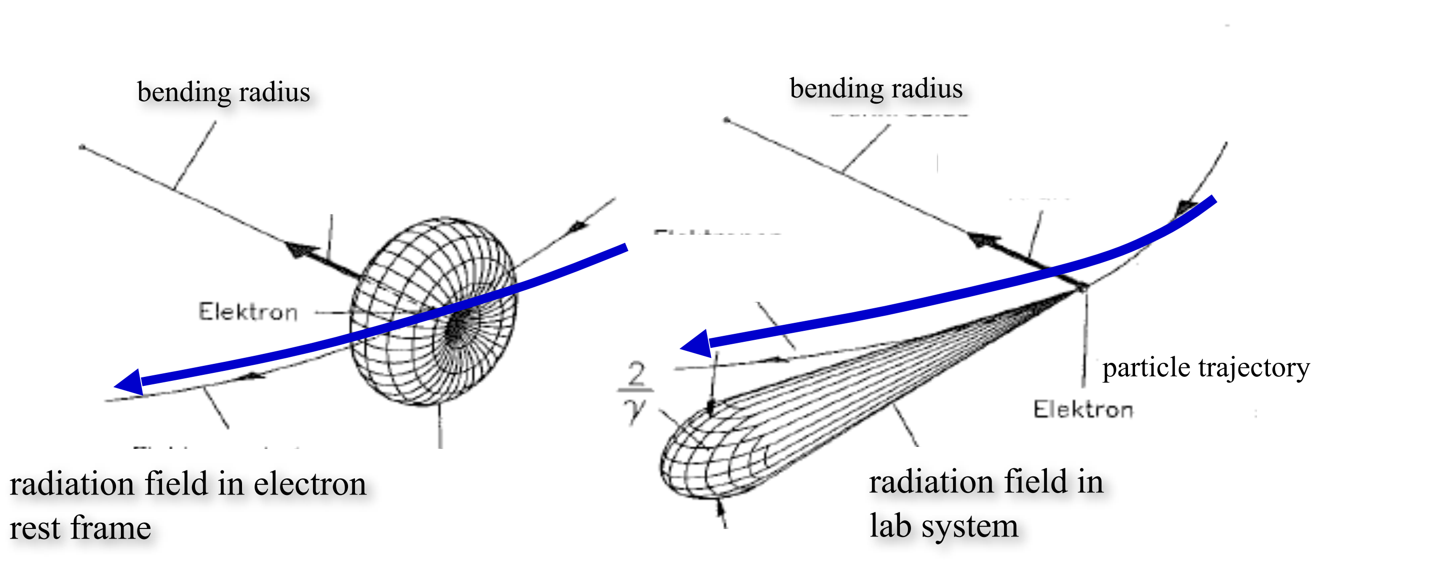
$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}$$ *critical frequency*

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

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



1946 observed for the first time in the General Electric Synchrotron



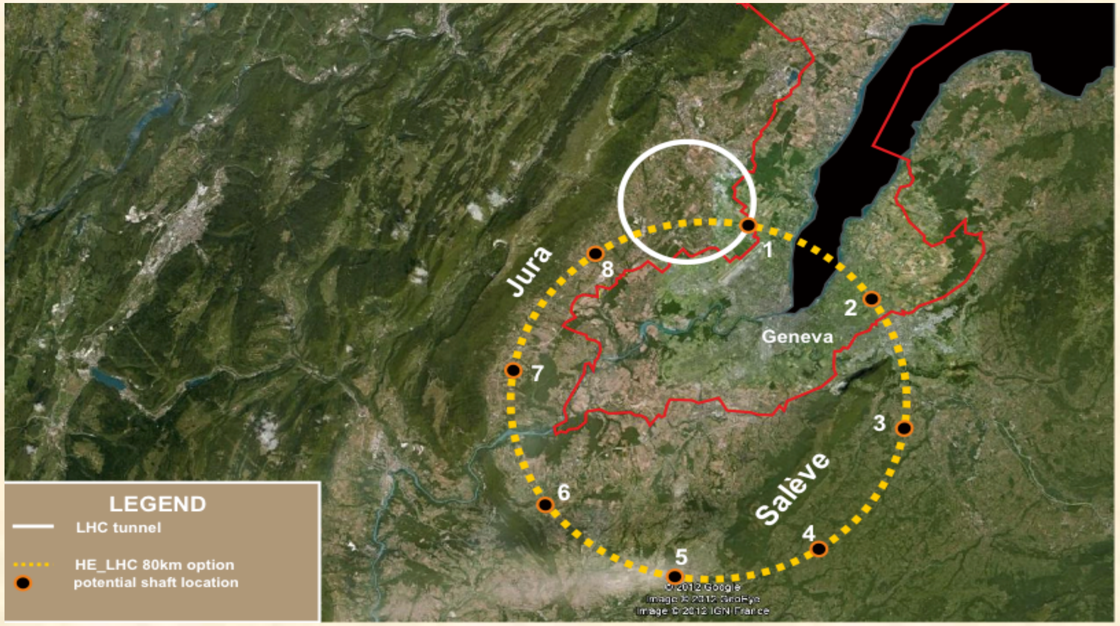
court. K. Wille

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***

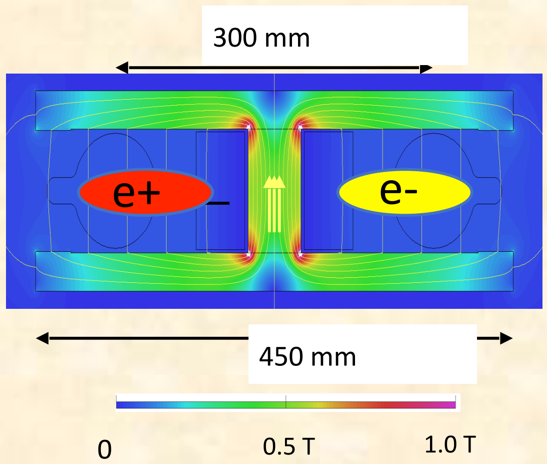
Circular e+ / e- colliders are severely limited by synchrotron radiation losses and have to be replaced for higher energies by linear accelerators

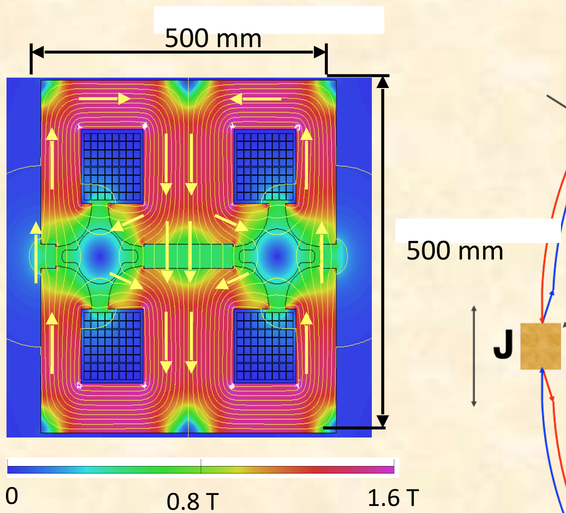
FCC-ee

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

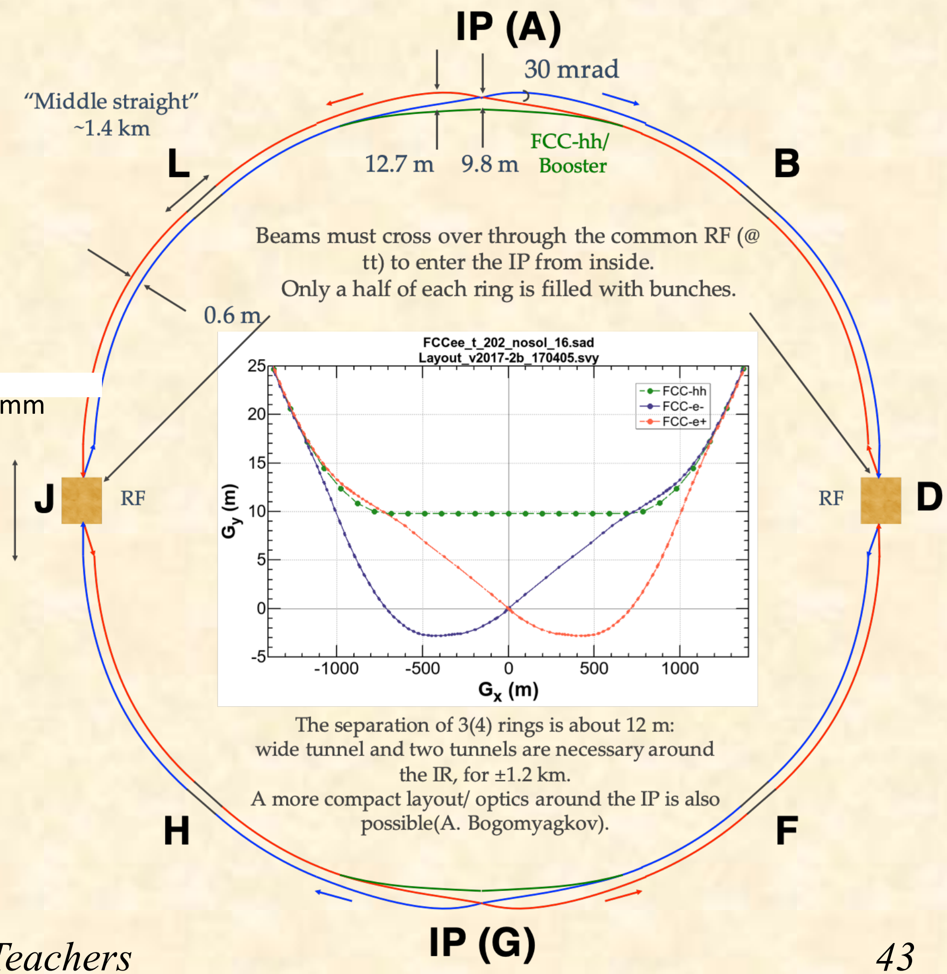
Work supported by the European Commission under 7th Framework Programme project EuCARD--2, and under the Horizon 2020 Programme.

Twin Aperture Magnets





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



FCC-ee Parameters

	Z	WW	ZH	$t\bar{t}$	
Circumference [km]			97.756		
Bending radius [km]			10.760		
Free length to IP l^* [m]			2.2		
Solenoid field at IP [T]			2.0		
Full crossing angle at IP θ [mrad]			30		
SR power / beam [MW]			50		
Beam energy [GeV]	45.6	80	120	175	182.5
Beam current [mA]	1390	147	29	6.4	5.4
Bunches / beam	16640	2000	328	59	48
Bunch population [10^{11}]	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x [nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y [pm]	1.0	1.7	1.3	2.7	2.9
Horizontal β^*_x [m]	0.15	0.2	0.3	1.0	
Vertical β^*_y [mm]	0.8	1.0	1.0	1.6	
Luminosity / IP [10^{34}/cm^{2}s]	230	28	8.5	1.8	1.55

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

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

RF Voltage applied depends on the beam energy as $U \propto \gamma^4$

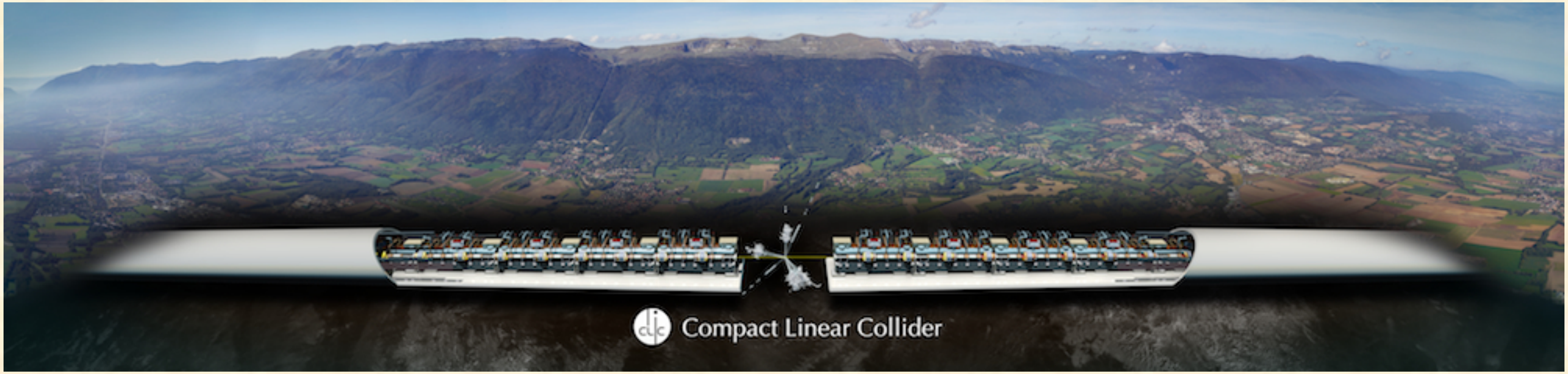
Emittance ratio … in the range of 1-2 per mille !!

6.) Push for higher lepton energy

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

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

„C“-LIC ... = CERN ... or „compact“



50 km

Description [units]	500 GeV	3 TeV
Total (peak 1%) luminosity	$2.3\ (1.4) \times 10^{34}$	$5.9\ (2.0) \times 10^{34}$
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

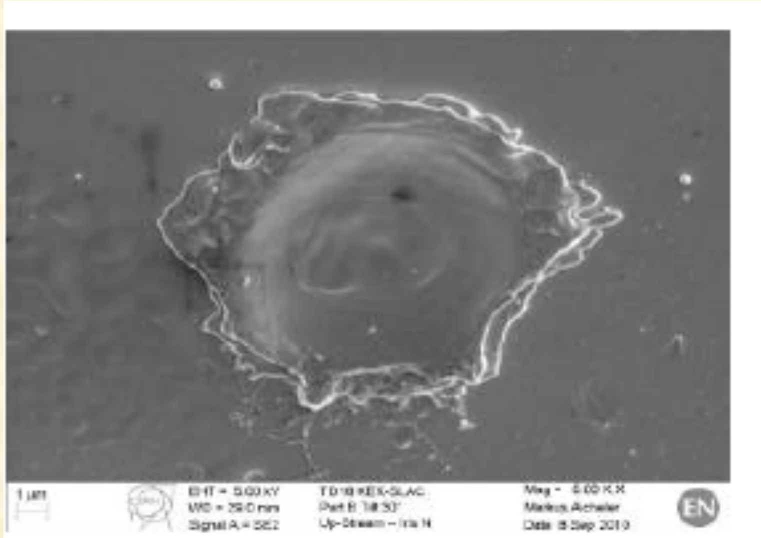
challenge: running at the break down limit

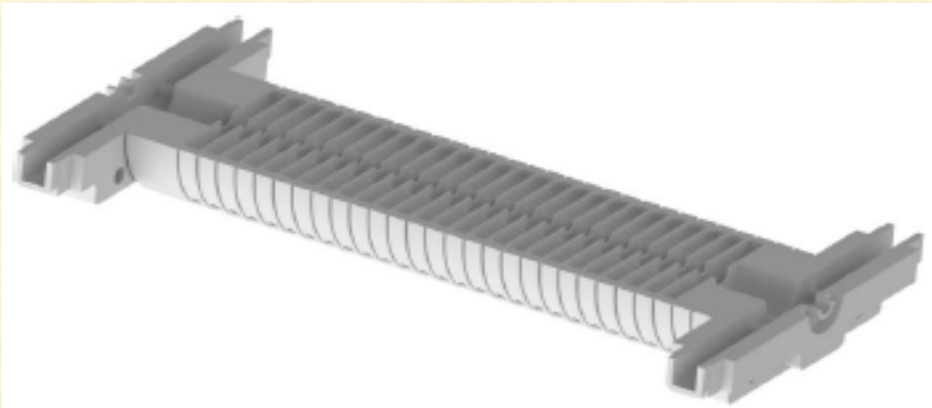
Accereration Gradient 100MV/m studied & optimised since years

" 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 ? "

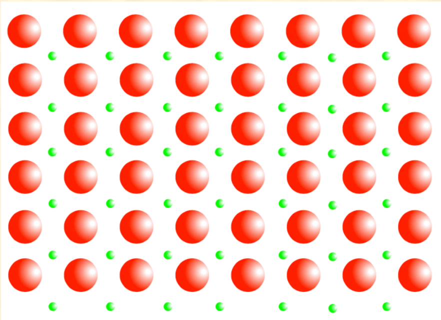
they have impact on

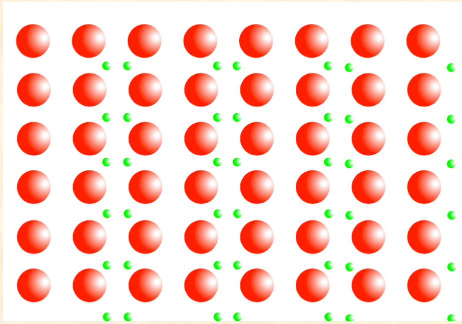
=> the accelerator performance (luminosity)
=> beam quality
=> and the accelerating structure itself





Plasma Wake Acceleration

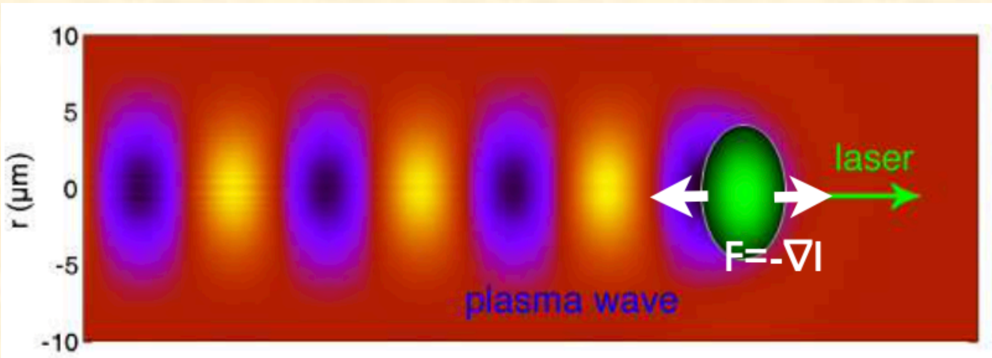


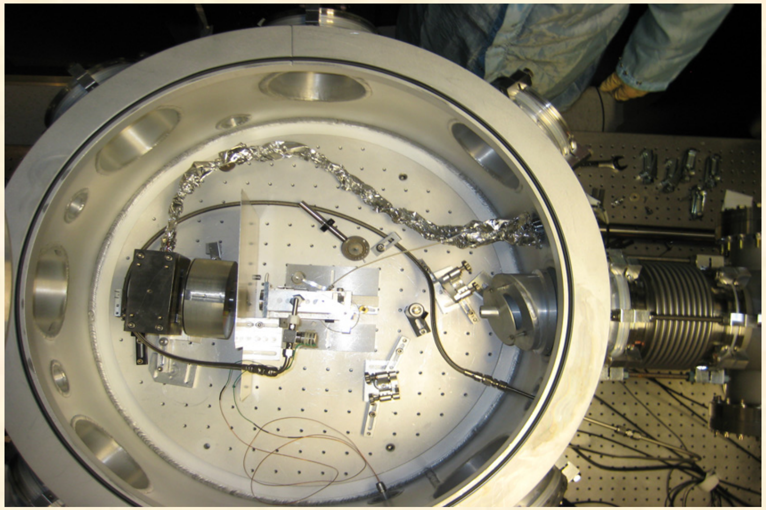


Excite a plasma wave with an intense LASER or proton pulse

—> create acc. fields

Field Gradients up to 100 GeV /m observed

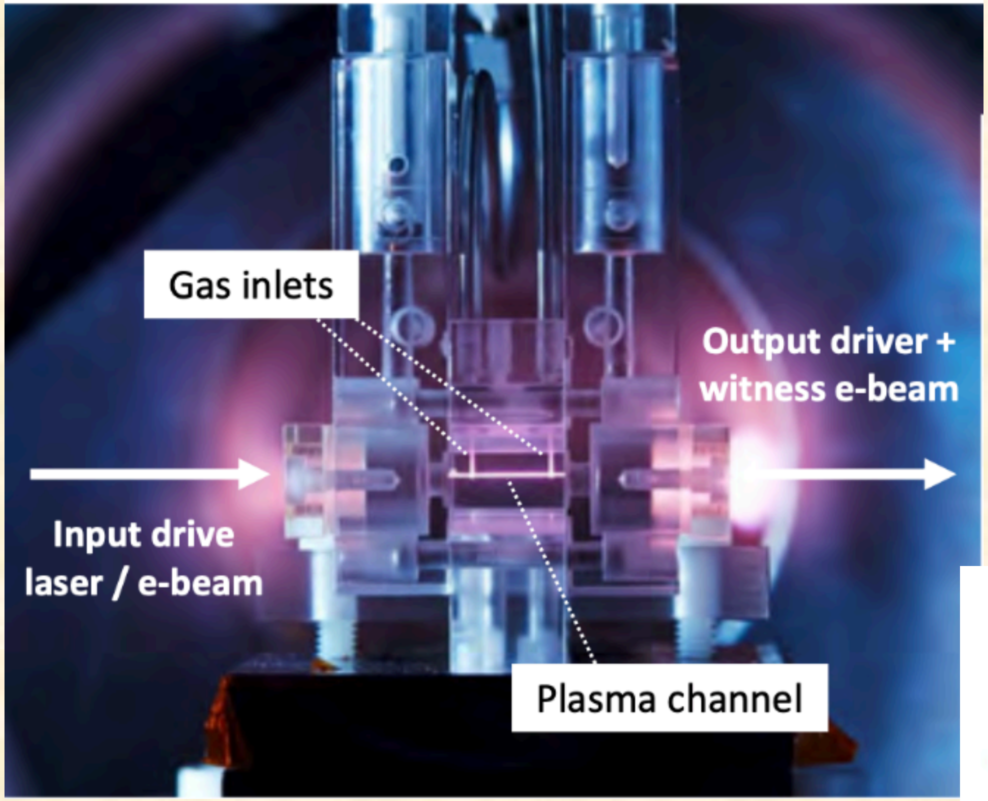




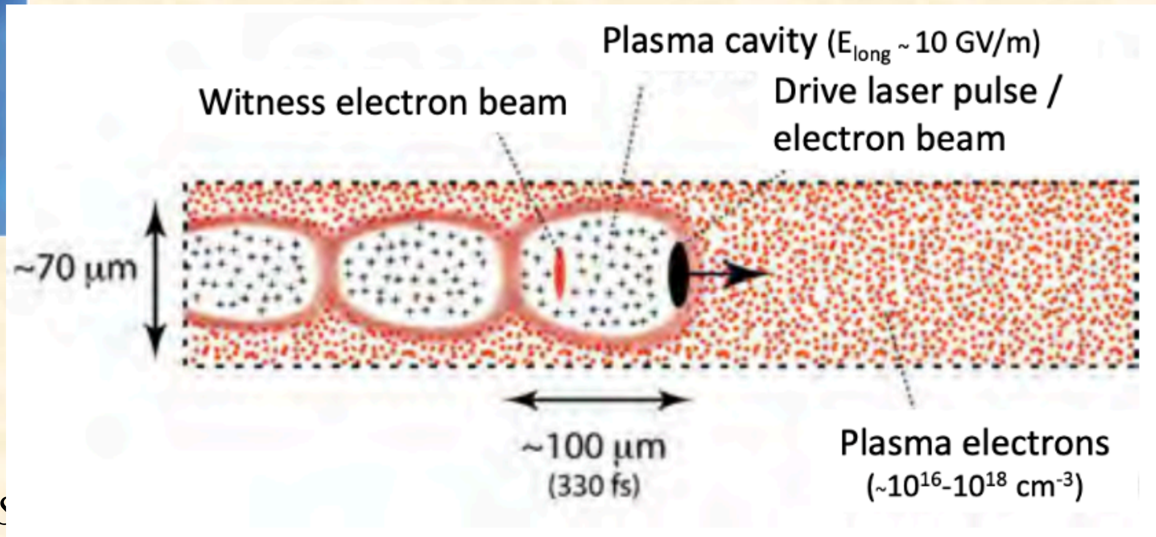
Plasma cell Univ. Texas, Austin
E_e =2 GeV

AWAKE:
Proton driven Wake Acceleration Experiment at CERN

Prototype: 1m long Rb Plasma Cell



Eupraxia: European PWA accelerator
INFN, Frascati



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

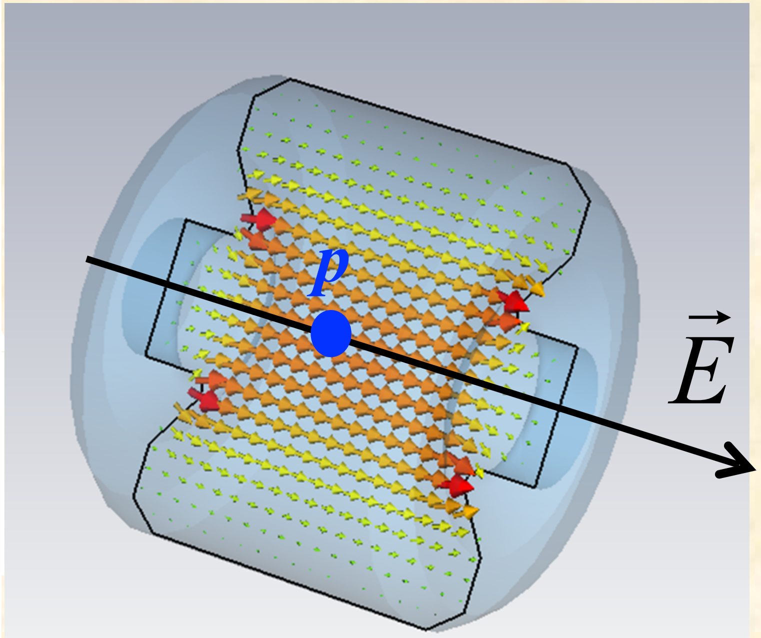
... Traditional, sc / nc or PWA ?

Merci

Acceleration

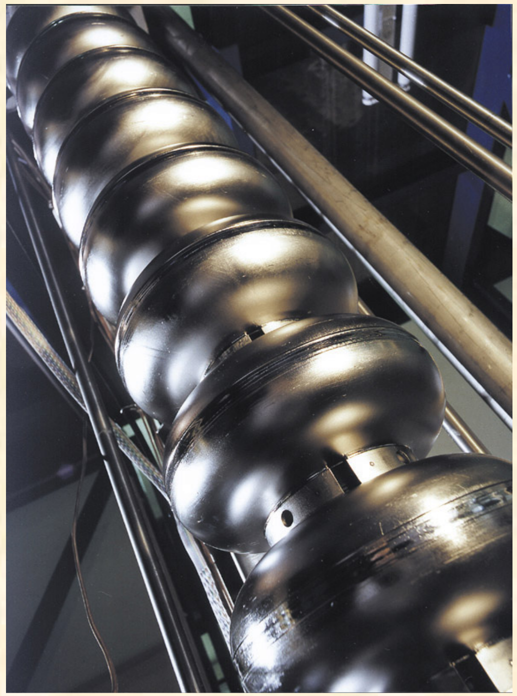
Finally we need the electric Field $\vec{E}$

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



Create in a resonant structure a standing electro-magnetic wave and synchronise the timing between bunch and resonator.

LHC standard RF system:
sc cavity, 400MHz, 7cell



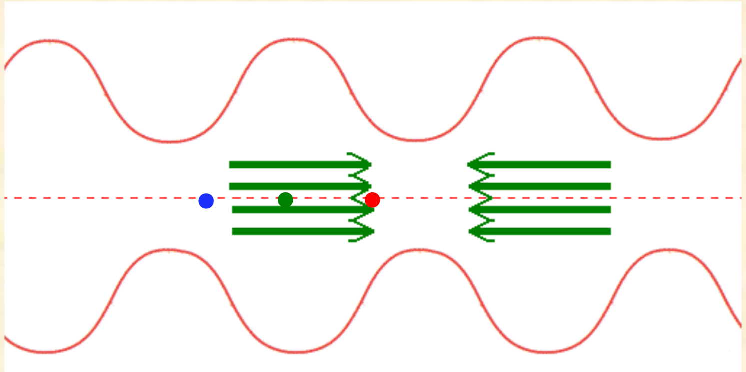
Longitudinal Beam Dynamics & "Phase Focusing"

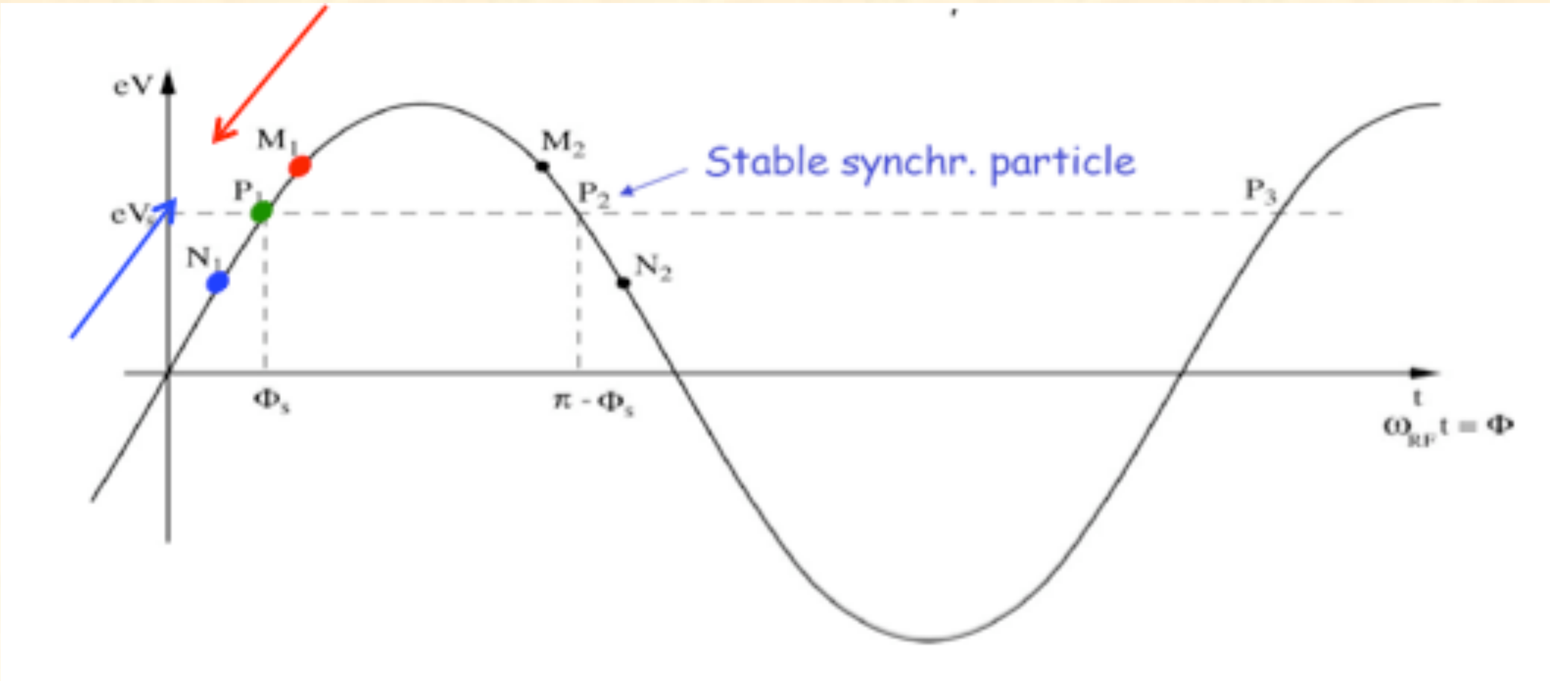
$\Delta p/p \neq 0$ below transition

ideal particle •

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

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





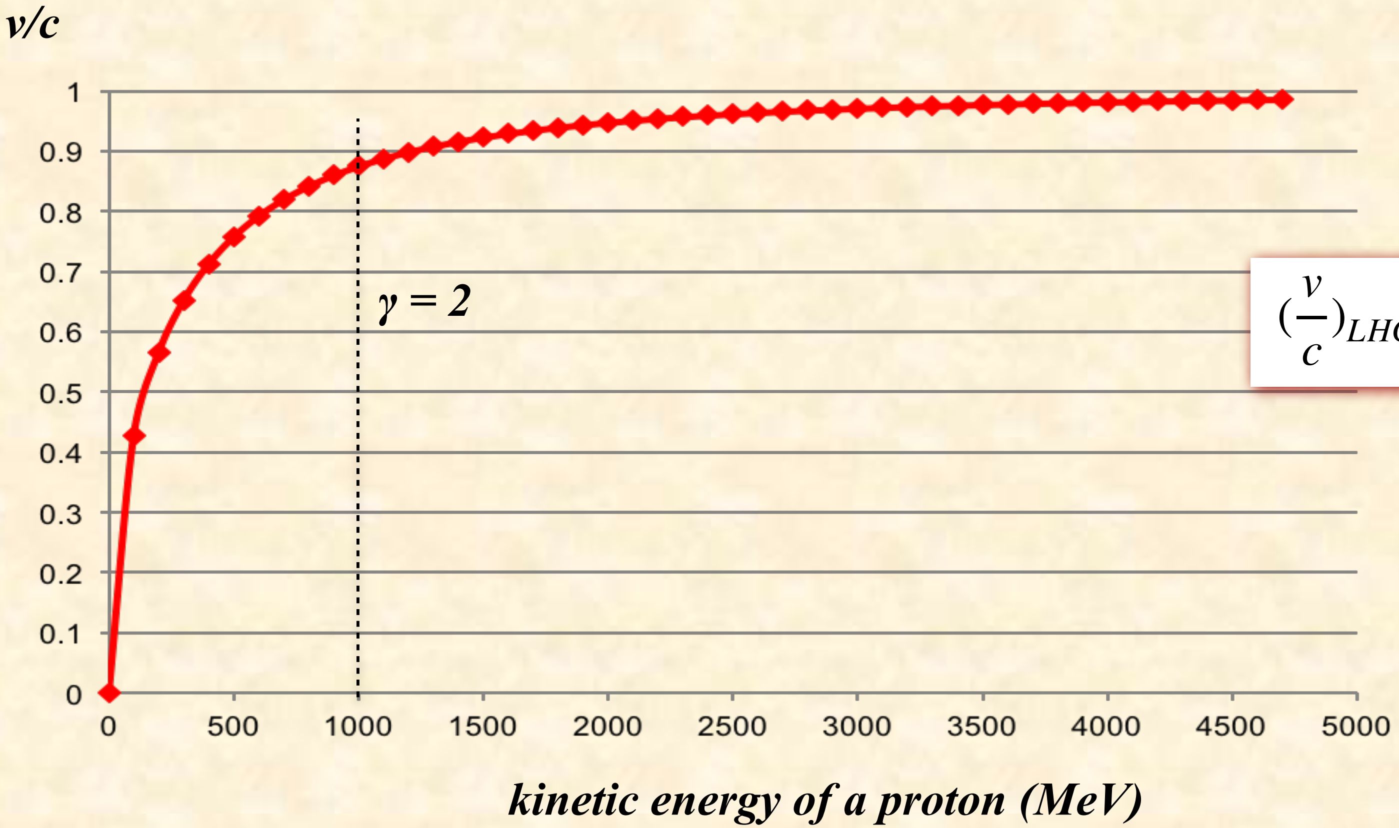
Focussing effect in the longitudinal direction keeping the particles close together ... forming a "bunch"

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

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

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

die Teilchen werden irgendwann nicht mehr schneller !

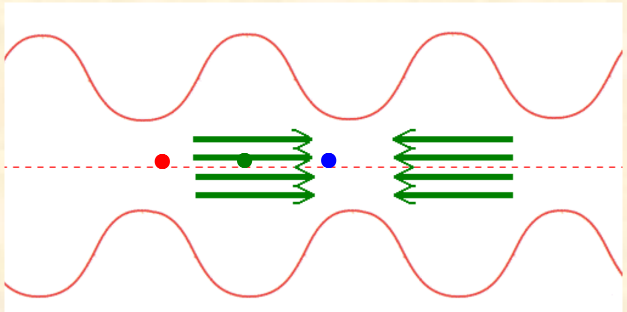


$$\left(\frac{v}{c}\right)_{LHC} = 0.999999991$$

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

.... but heavier !

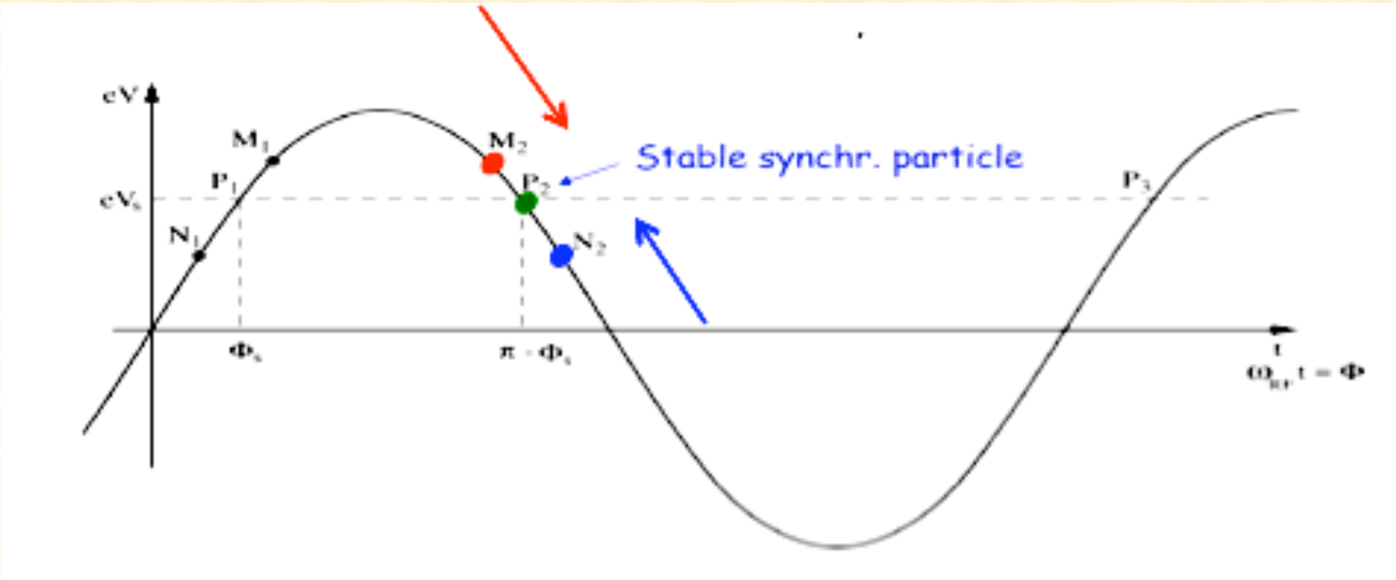
The Acceleration above transition



ideal particle •

particle with Δp/p > 0 • *heavier*

particle with Δp/p < 0 • *lighter*

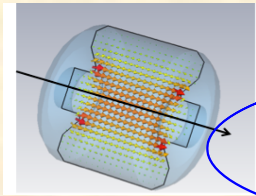


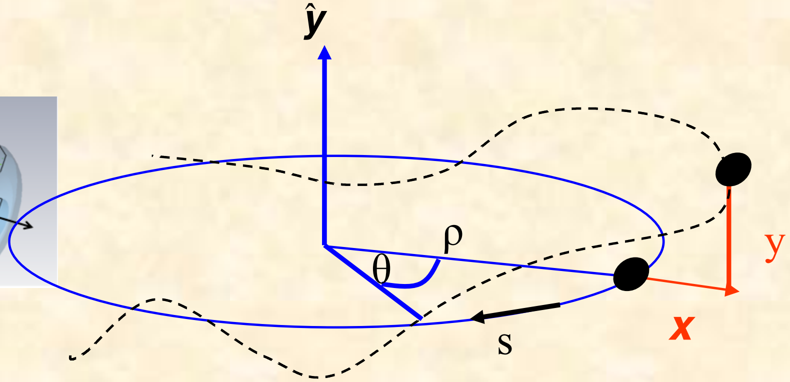
Focussing effect in the longitudinal direction
keeping the particles close together ... forming a "bunch"

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

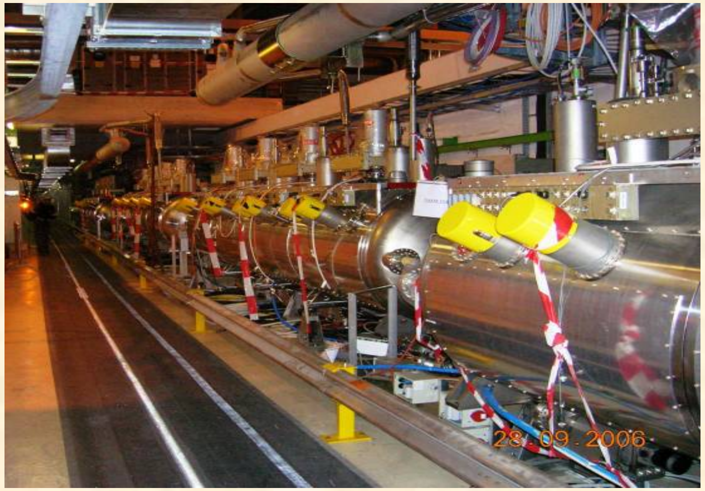
with the dipole magnets !

The LHC RF System





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"



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

Nb on Cu cavities @4.5 K

It takes 14 Mio turns to get to full LHC energies
T_{acc} ≈ 30 min … but we HAVE TIME.

Operational Safety & Machine Protection

Boooooom

LHC Design Parameters

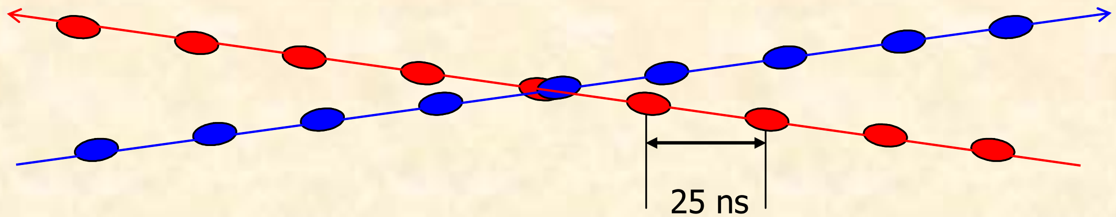
	Design	Achieved
Momentum at collision	7 TeV /c	6.8 TeV/c
Luminosity	10^{34} cm $^{-2}$ s^{-1}	10^{34} cm $^{-2}$ s^{-1}
Protons per bunch	1.15×10^{11}	1.50×10^{11}
Number of bunches/beam	2808	2808
Nominal bunch spacing	25 ns	25ns
beta *	55 cm	35 cm
rms beam size IP	17 µm	13 µm

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

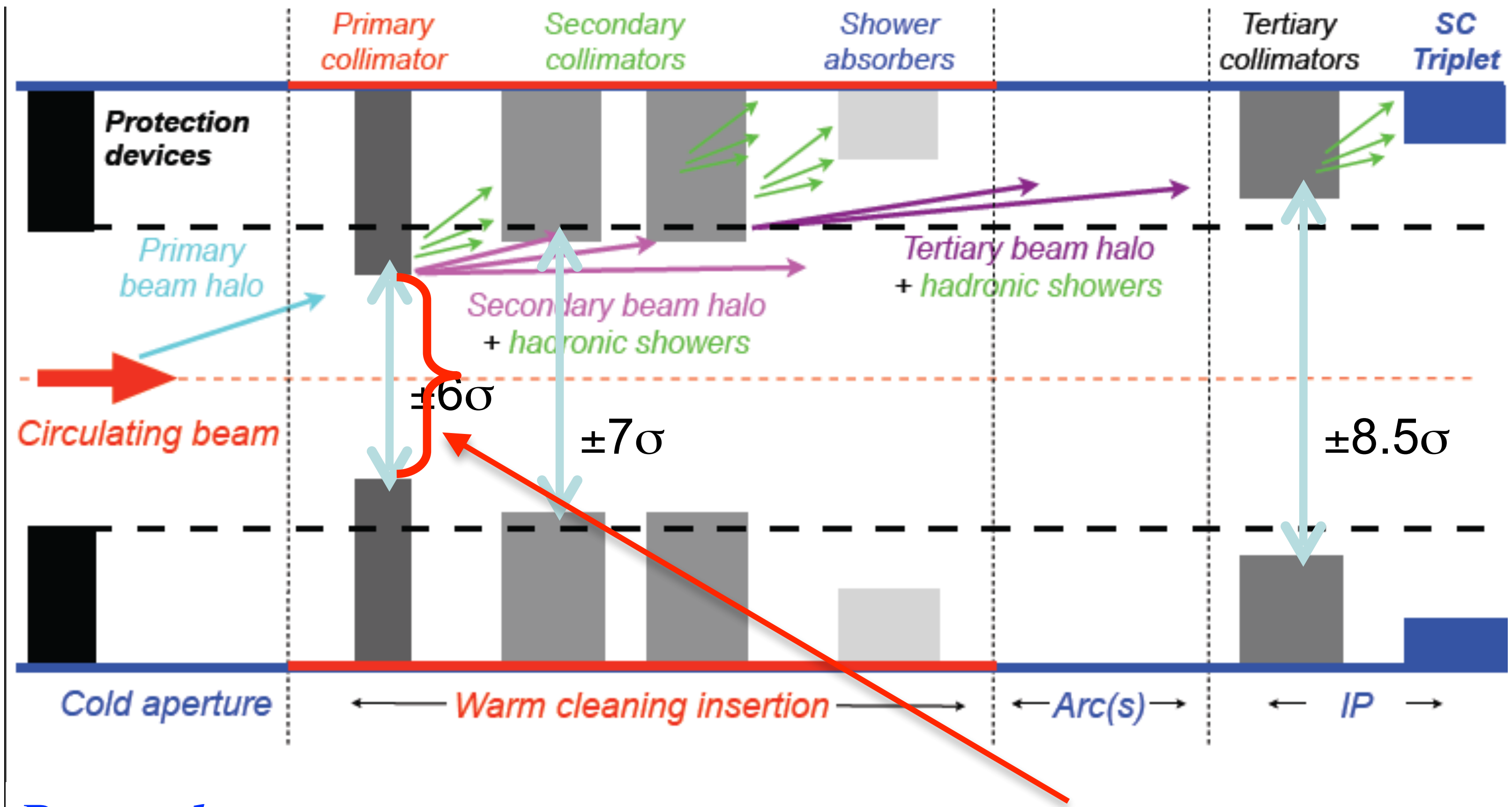


remember:

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

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

LHC Aperture and Collimation



Remember:

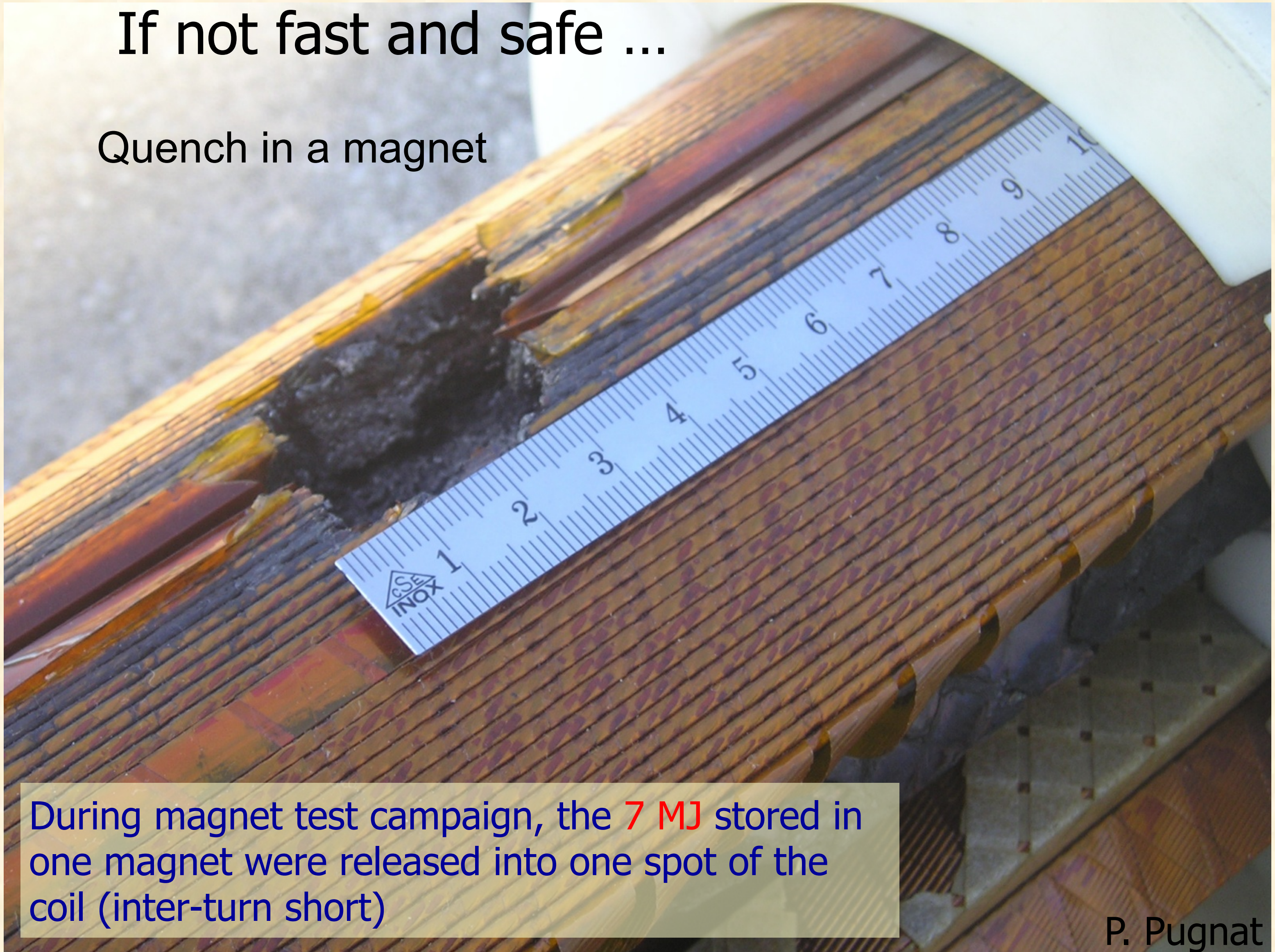
Beam size (σ) = 300 μm (@arc)

Beam size (σ) = 17 μm (@IR1, IR5)

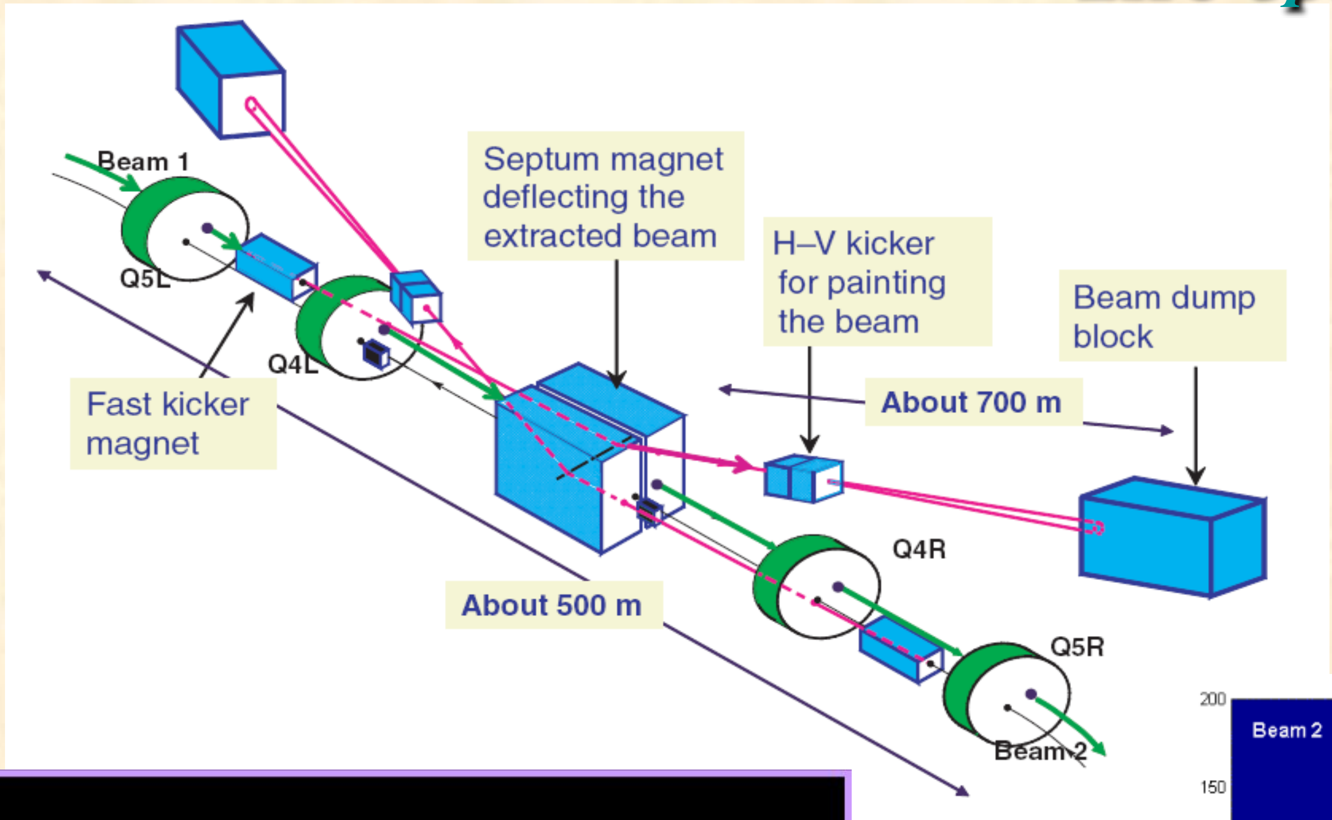
Free Aperture = +/- 1.5 mm

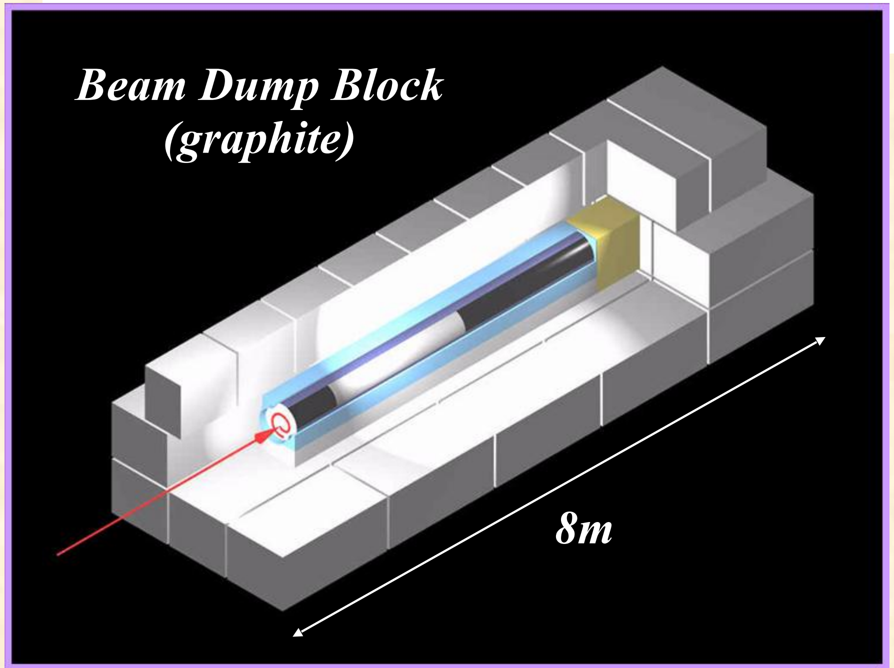
… protect from energy stored in the magnets

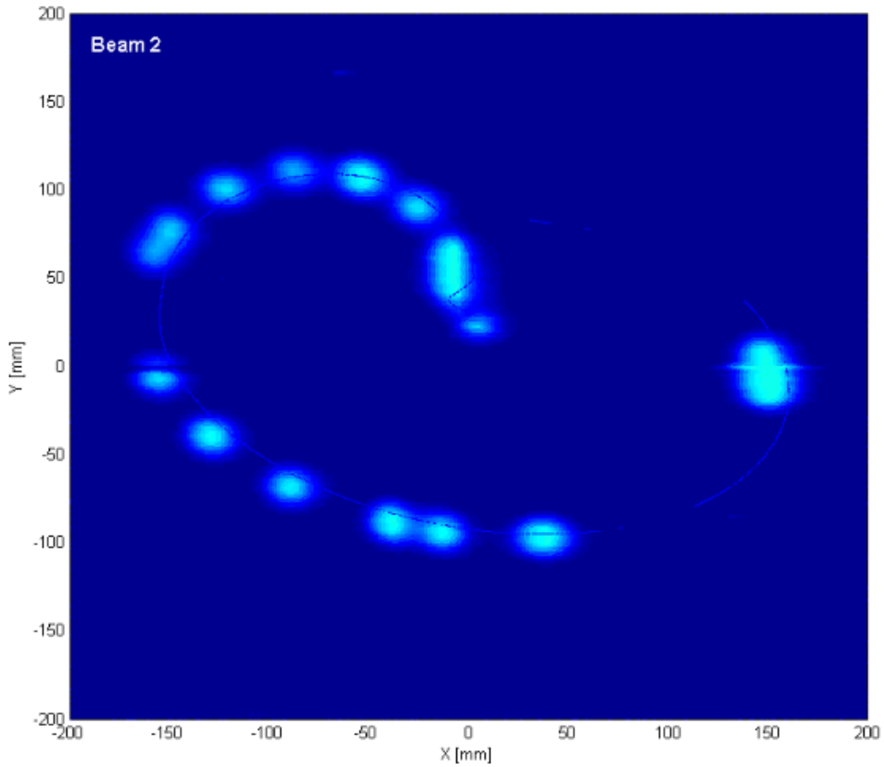
Energy stored in the magnets —> quench



LHC Operation: Dump System





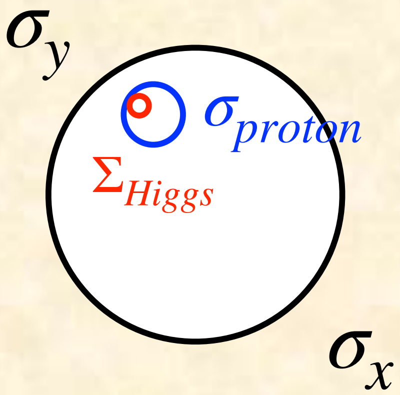


Luminosity ... made crystal clear

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

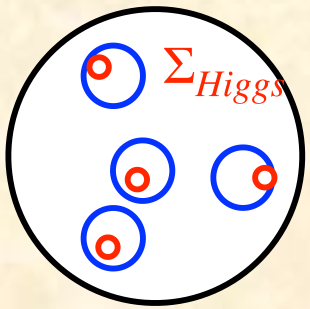
We express the probability for a physics event as

$$\text{hit-probability} = \frac{\text{“target size”}}{\text{beam size}} \qquad R \propto \Sigma_{Higgs} \cdot \frac{1}{\sigma_x\sigma_y}$$



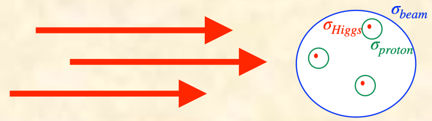
The more targets we have the better —>

$$R \propto \Sigma_{Higgs} \cdot \frac{N_{p2}}{\sigma_x\sigma_y}$$



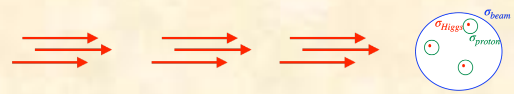
Shoot as many particles as possible —>

$$R \propto \Sigma_{Higgs} \cdot n_b \cdot N_{p1} \cdot \frac{N_{p2}}{\sigma_x\sigma_y}$$



Shoot as often as possible —>

$$R \propto \Sigma_{Higgs} \cdot f_0 \cdot \frac{n_b \cdot N_{p1} \cdot N_{p2}}{\sigma_x\sigma_y}$$

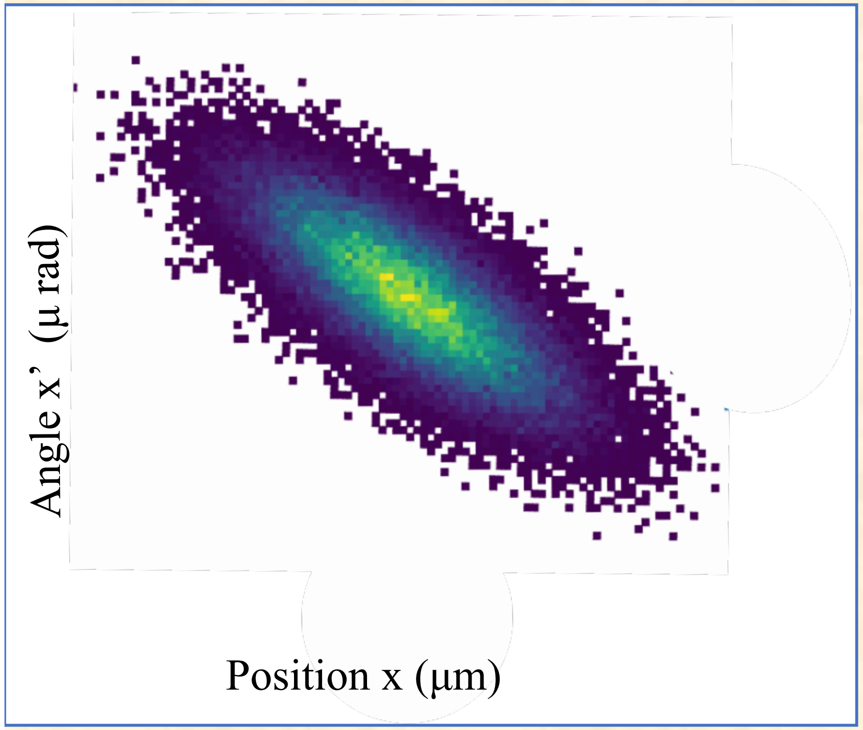


bunches

L

Beam Beam Effect

strong non-linear fields impact the particle distribution



ideal situation, no collisions

collisions - > beam-beam effect
non-linear fields destroy the particle distribution