Future Accelerator Projects

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CERN

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 ???

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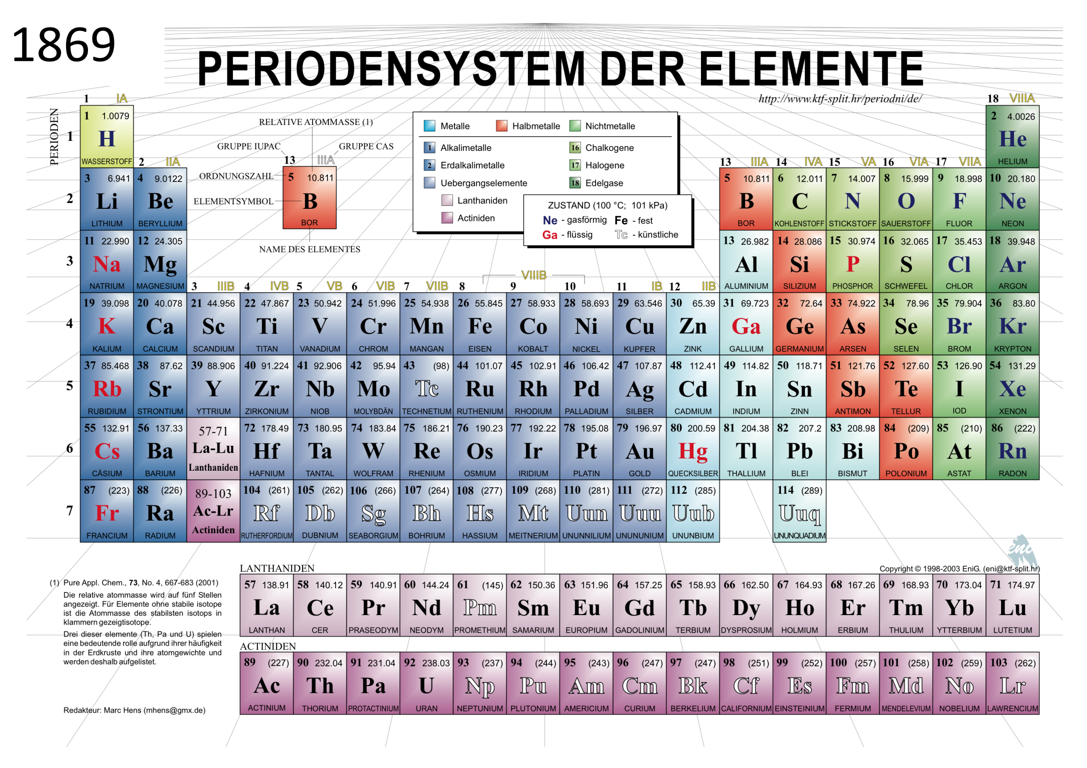


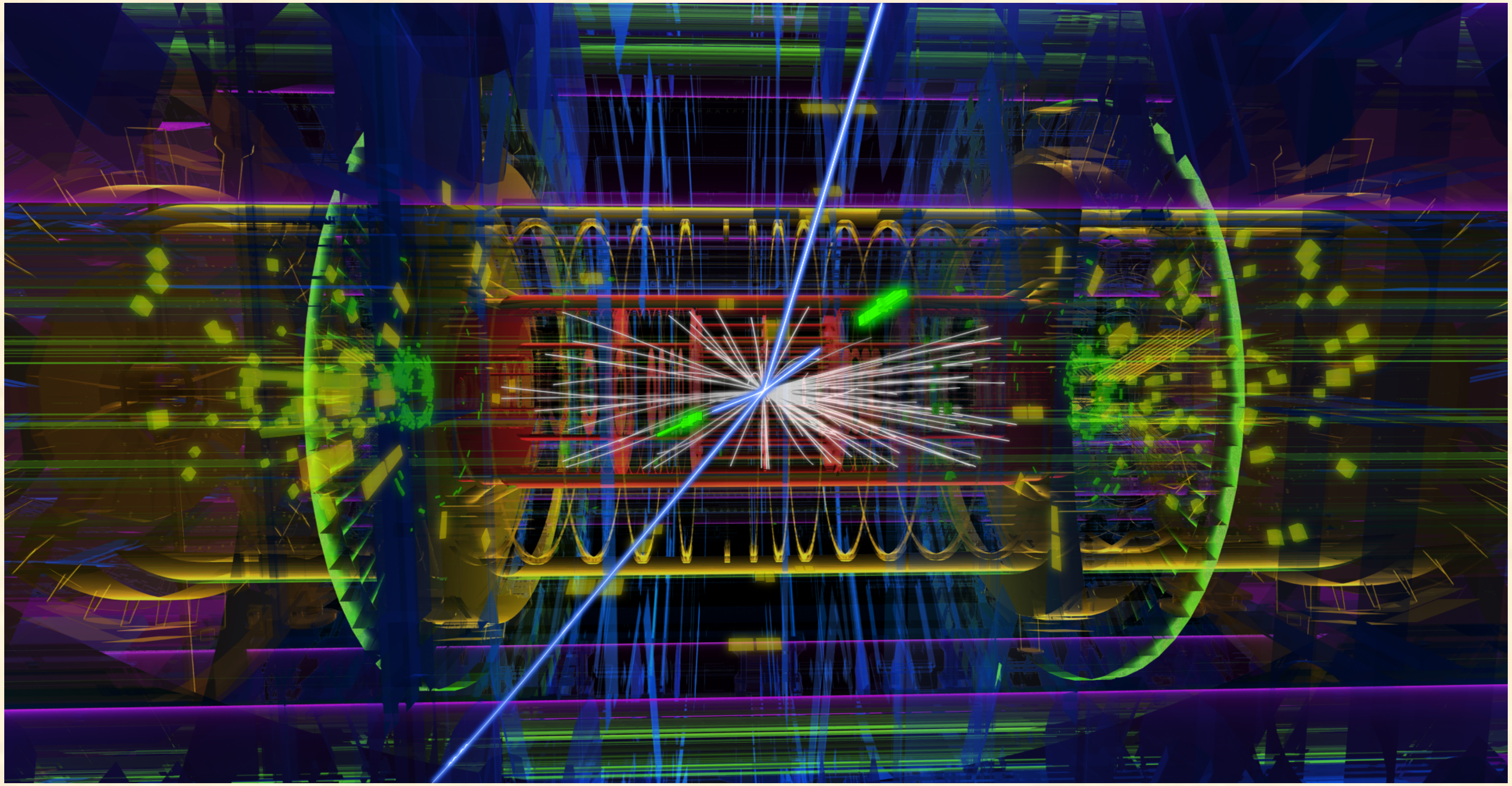
$E=mc^2$, $\lambda=h/p$

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

$$E = m_0 c^2 = m_{e1} + m_{e2} + m_{\mu 1} + m_{\mu 2} = 125.4\ GeV$$

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

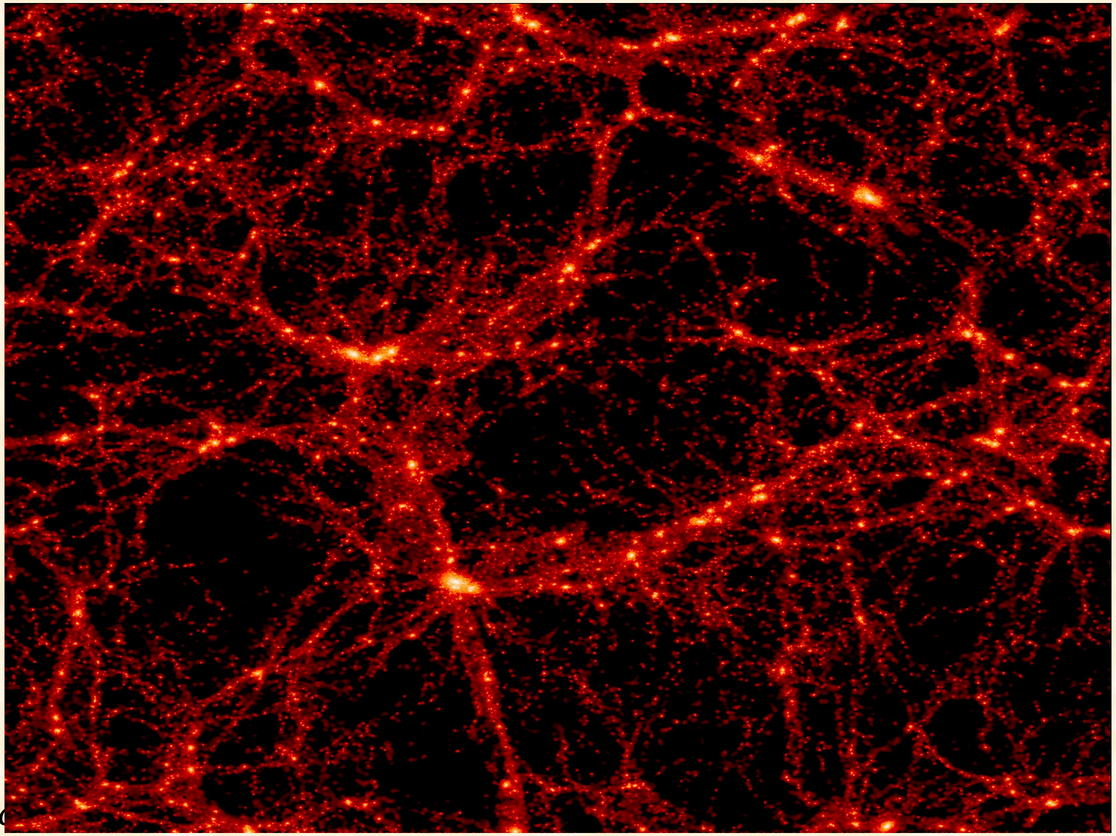
$$\frac{mv^2}{r} = \frac{mMg}{r^2} \quad \rightarrow \quad v_{cric} = \sqrt{\frac{Mg}{r}}$$

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

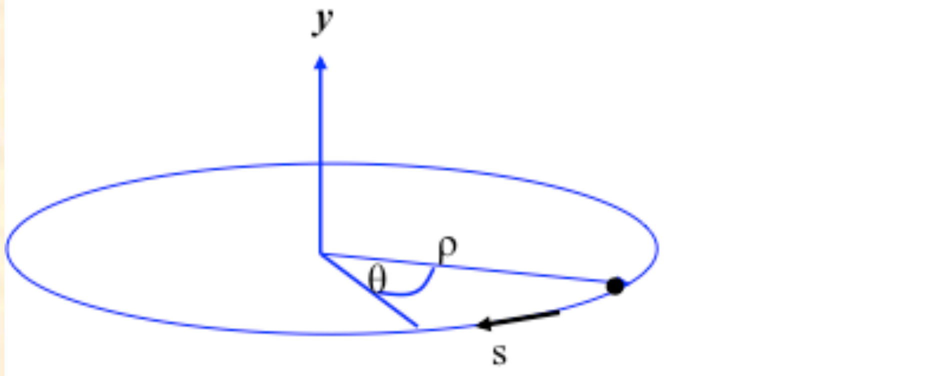
Linear colliders
ILC (International Linear Collider): e^+e^-, 500 GeV cms energy,
CLIC (Compact Linear Collider): e^+e^-, 380GeV - 3TeV cms energy,

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"

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



circular coordinate system

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

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

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

$B\,\rho$ = "beam rigidity"

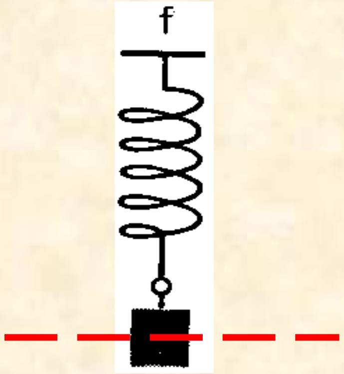
The overall integral of all dipole fields around the ring has to give 2π bending angle

2.)Focusing Forces: Hook's law

... keeping the flocs together:
In addition to the pure bending of the beam
we have to keep 10^{11} particles close together

focusing force

And here we borrow the idea from classical mechanics:
The pendulum



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

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

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

general solution:
free harmonic oscillation

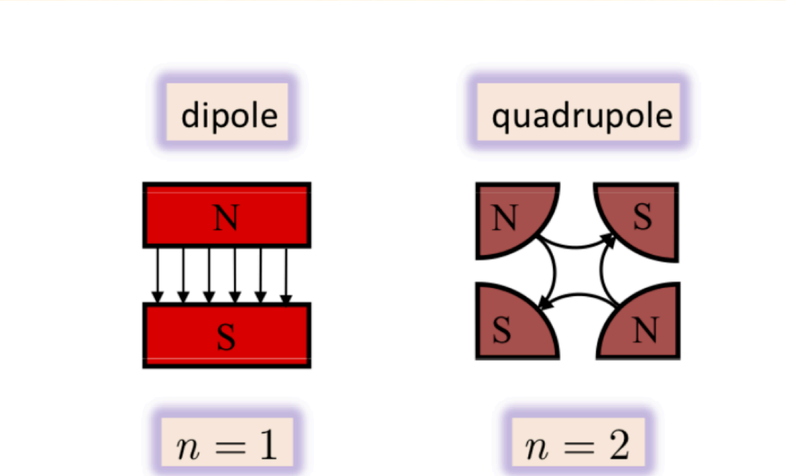
$$x(t) = A * \cos(\omega t + \varphi)$$

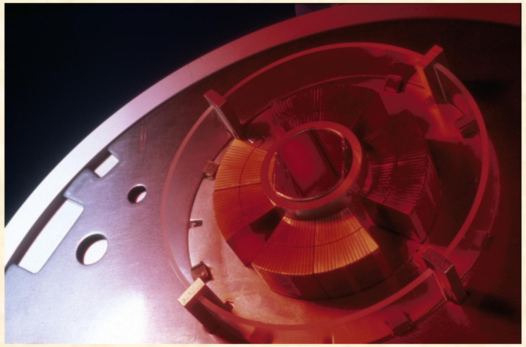
*...**this is how grandma's Kuckuck's clock is working!!!***

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:

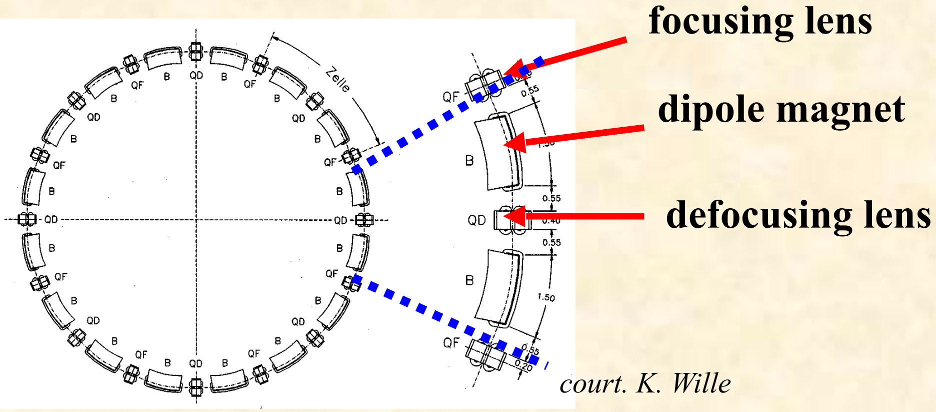
$$B_y = g \cdot x, \quad B_x = g \cdot y$$

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

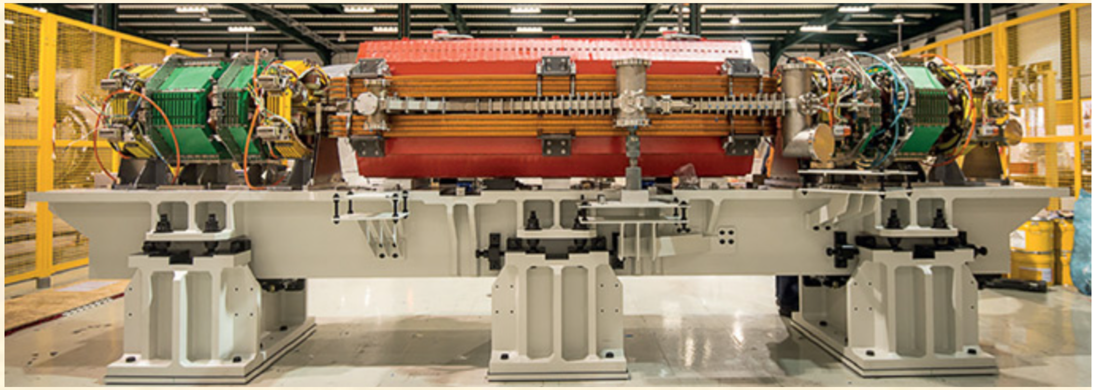
$$B_y = g * x \qquad\qquad B_y = const$$

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.

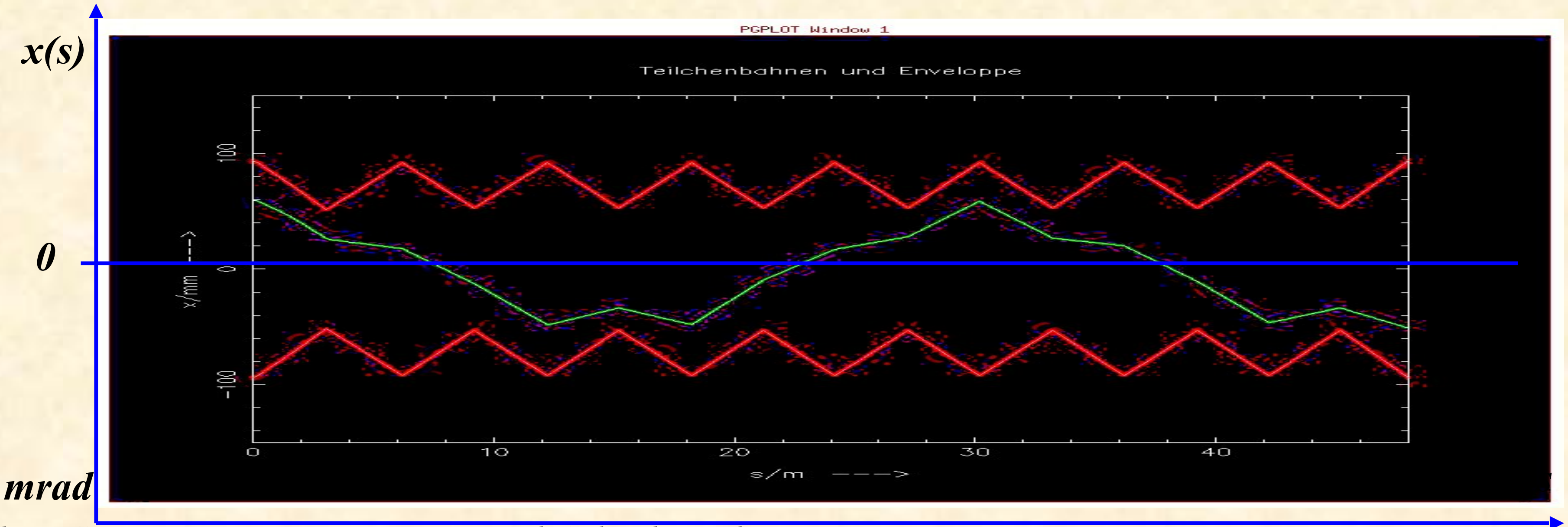


court. K. Wille



Sesame Light Source

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

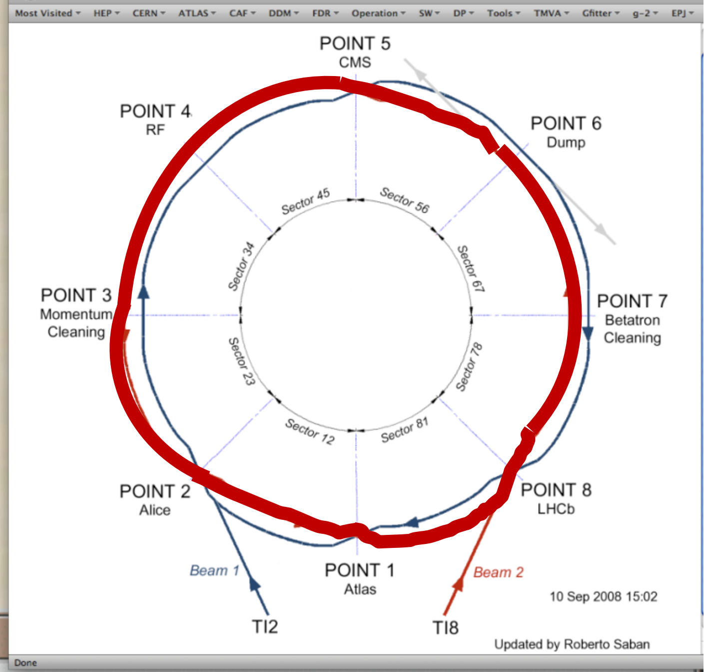


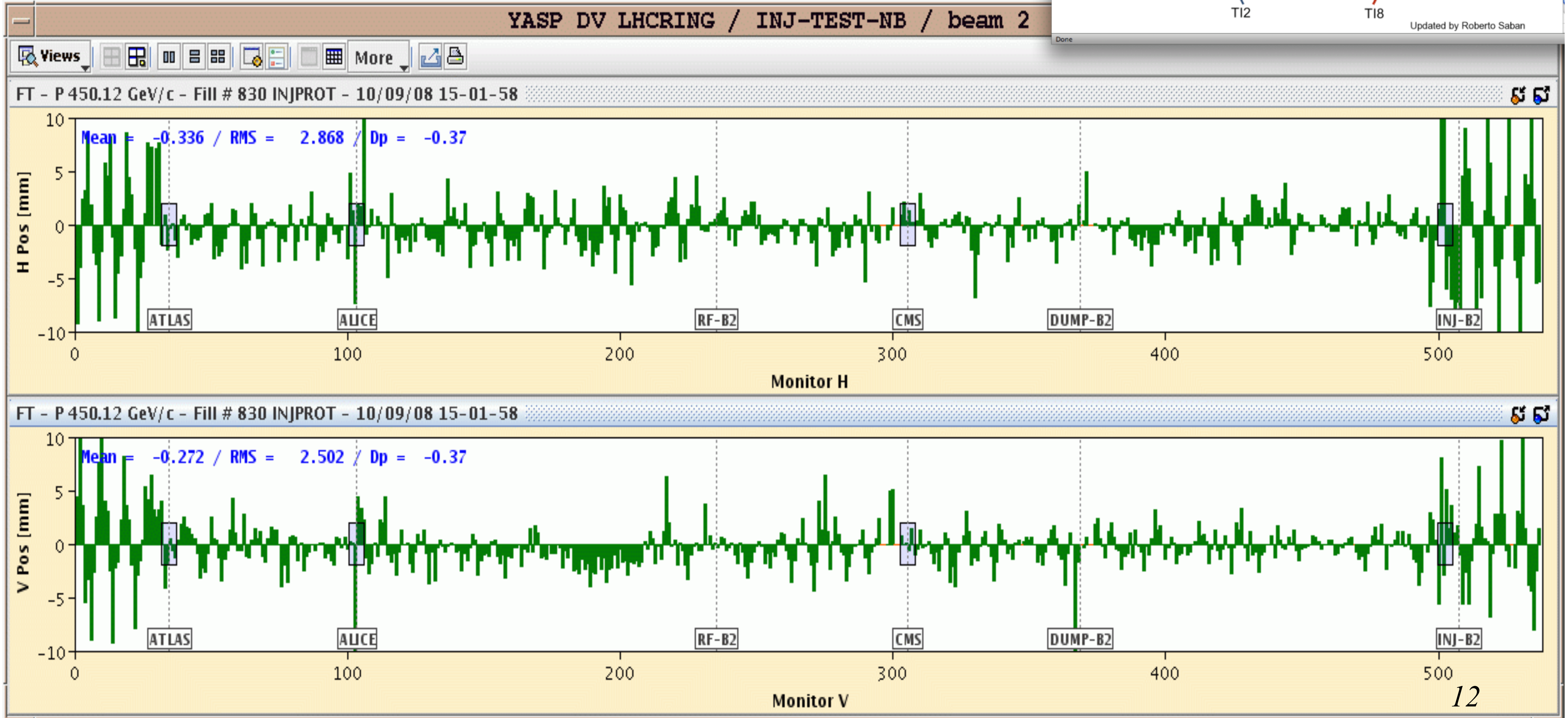
typical values in a strong foc. machine:
$x \approx mm$, $x' \leq mrad$

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.



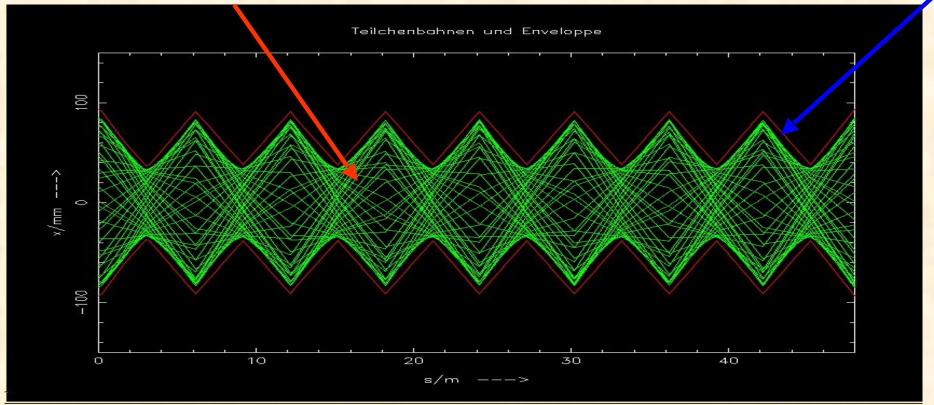


Many particles: The Beam

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

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

Beta-Function describing the size of the Particle Ensemble



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

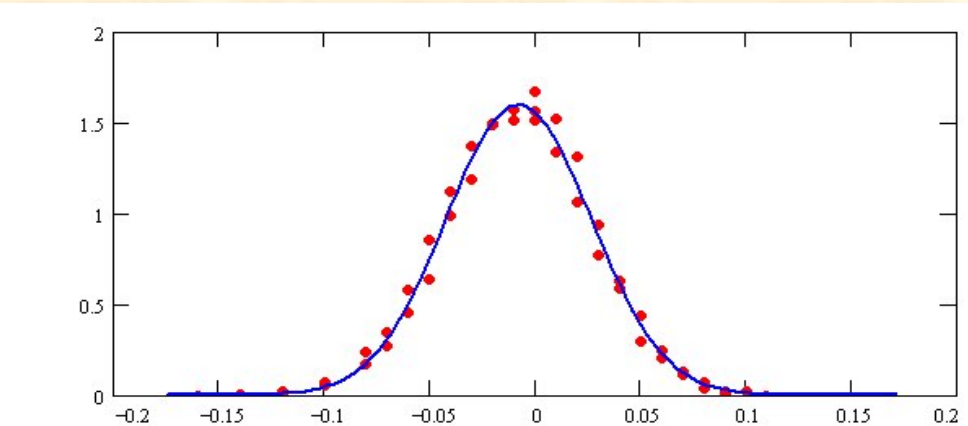
Gauß Particle Distribution:

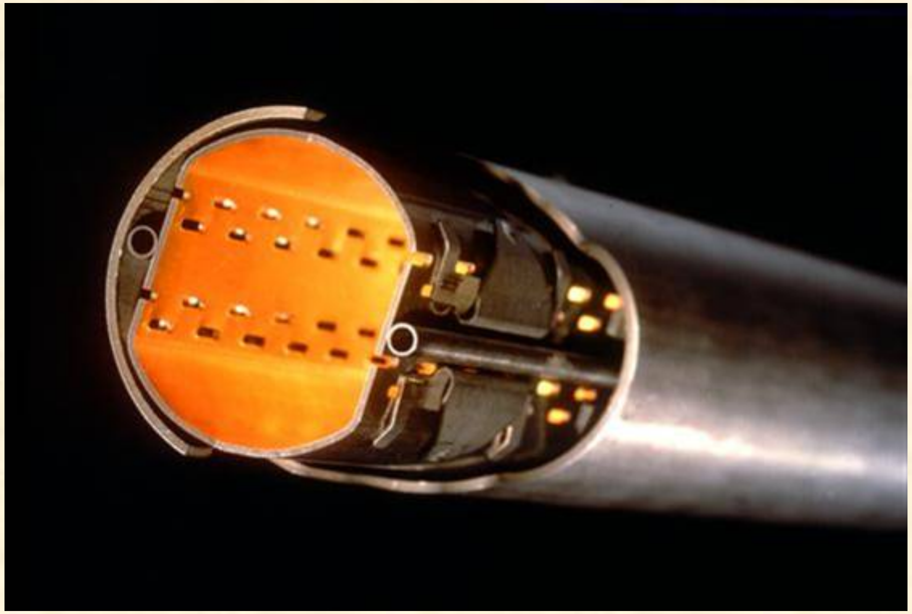
$$\rho(x) = \frac{N\cdot e}{\sqrt{2\pi}\,\sigma_x}\cdot e^{-\frac{1}{2}\frac{x^2}{\sigma_x^2}}$$

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 * σ

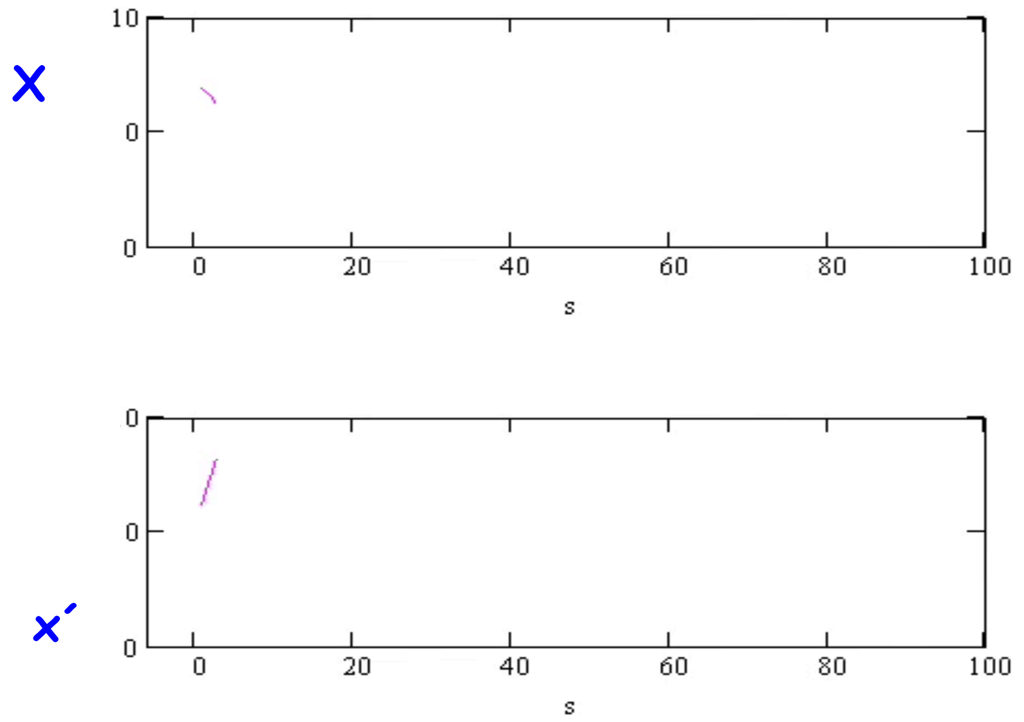
ATTENTION: its classical mechanis

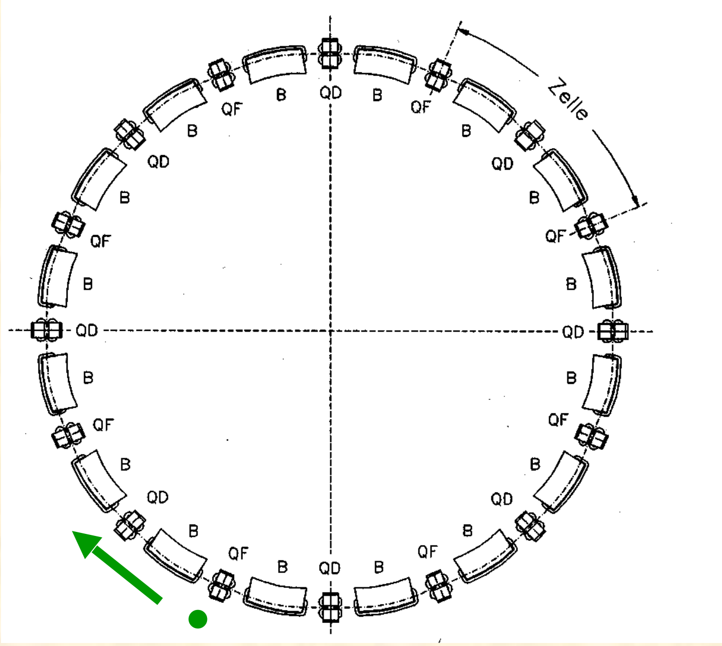
Beam Dynamics in a Storage Ring

The particle movement described in

phase space, x, x'

—> plot x, x´as a function of „s"

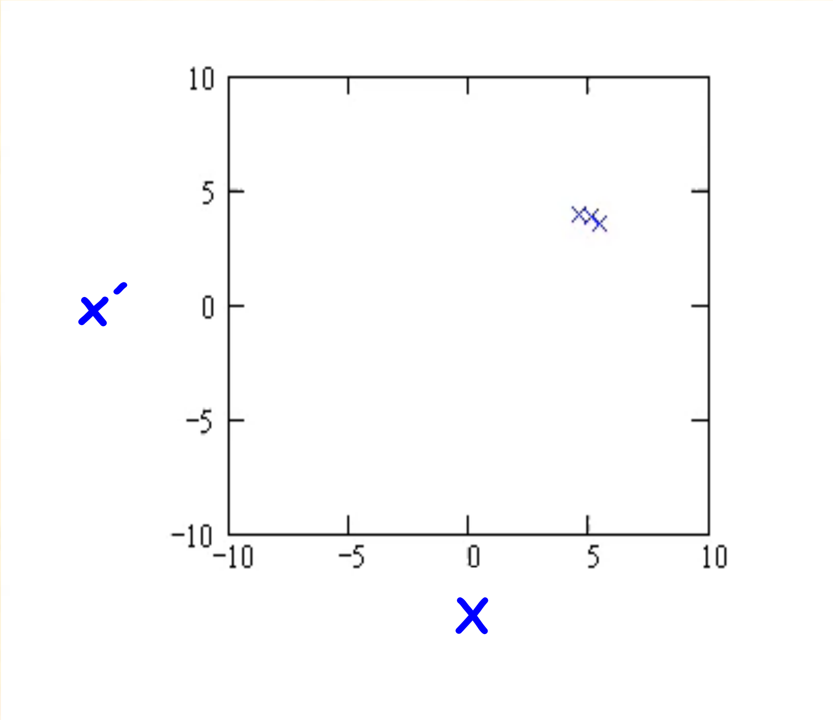




Theorem of Liouville

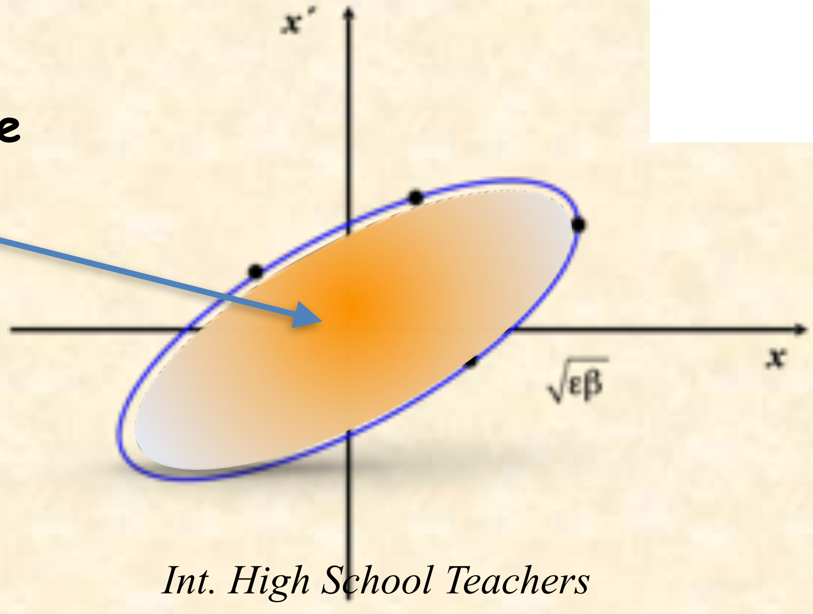
… and now the ellipse:

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

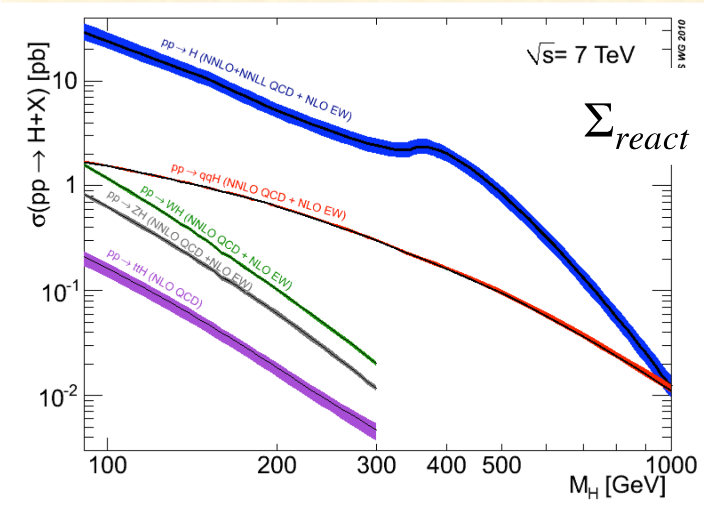
—> beam size: $$\sigma = \sqrt{\varepsilon \cdot \beta}$$

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

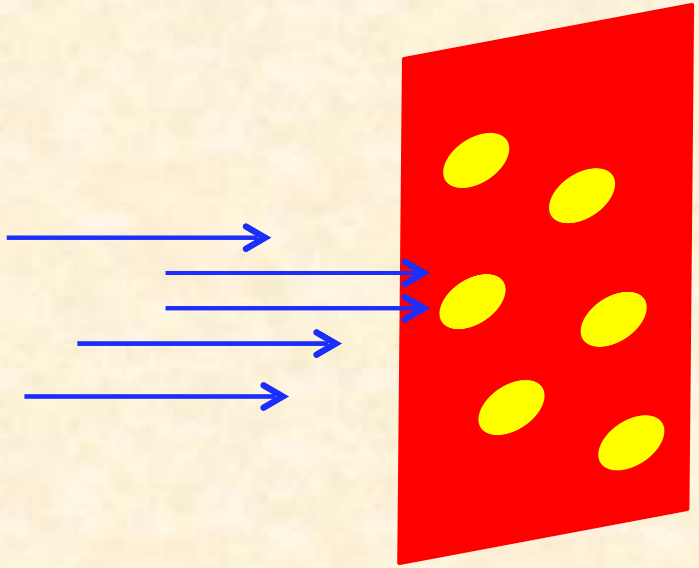
—> the size of the ellipse tells us about the particle density, … which is the beam quality in collision.

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

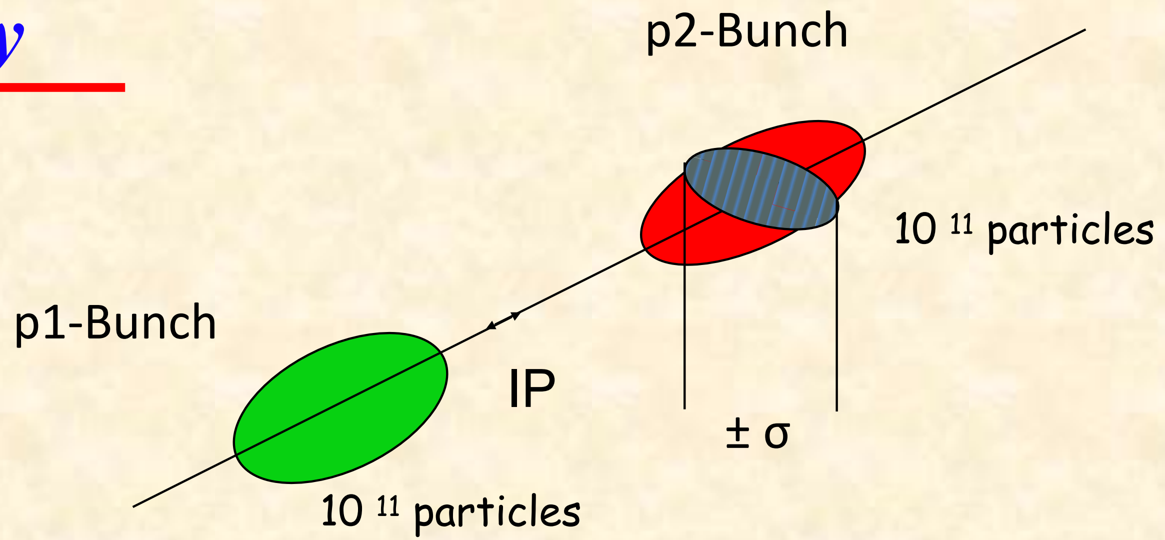
The particles are "very small"

LHC typical:

σ = 0.1 mm → 16 μm

Luminosity

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



Example: Luminosity run at LHC

$$\beta_{x,y} = 0.55\ m \qquad f_0 = 11.245\ kHz$$

$$\varepsilon_{x,y} = 5 * 10^{-10}\ rad\ m \qquad n_b = 2808$$

$$\sigma_{x,y} = 16\ \mu m$$

$$I_p = 584\ mA$$

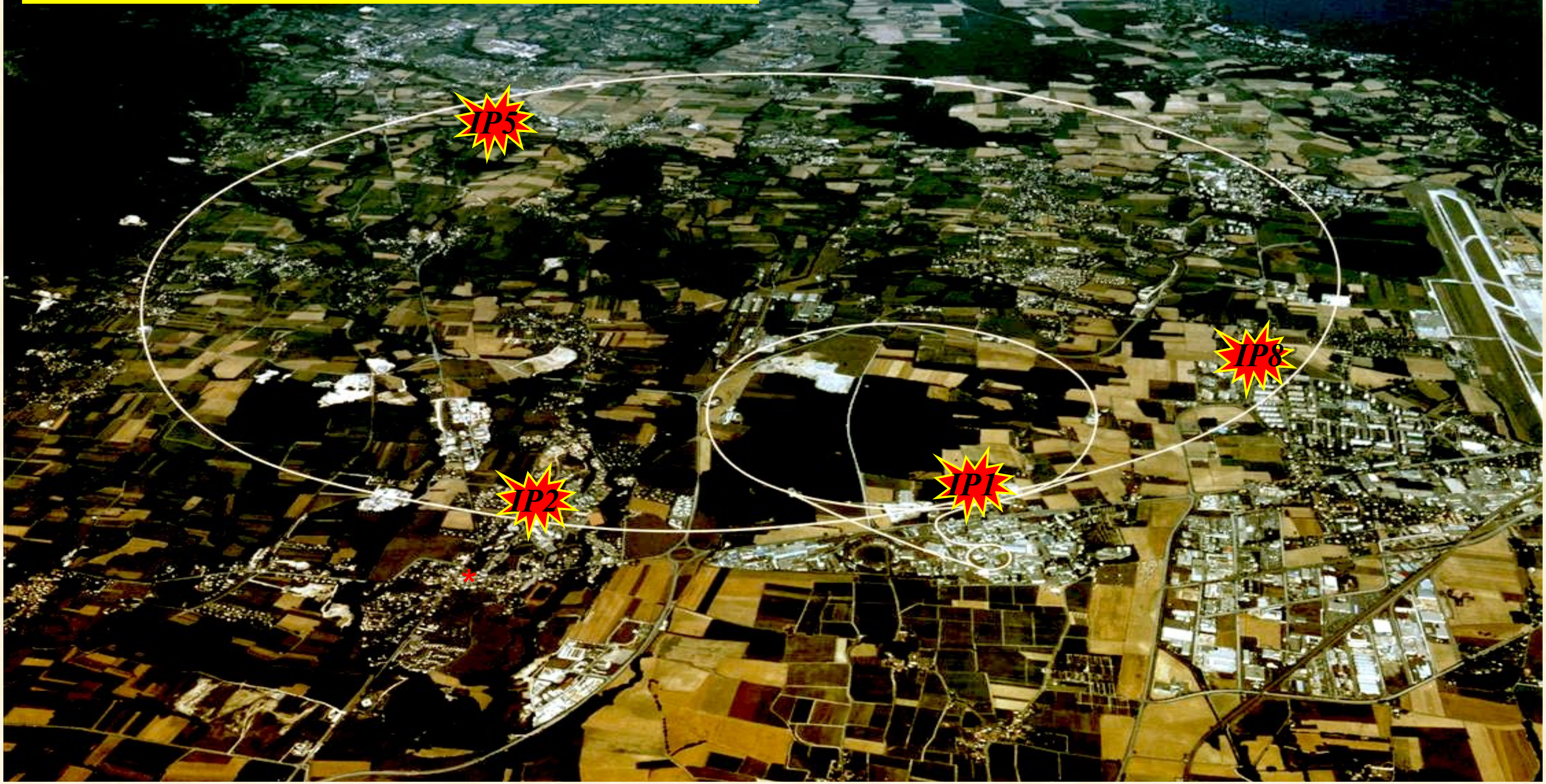
$$L = \frac{1}{4\pi e^2 f_0 n_b} * \frac{I_{p1} I_{p2}}{\sigma_x \sigma_y}$$

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

Every future collider has to push for highest possible luminosity … and energy.

3.) The HL-LHC

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

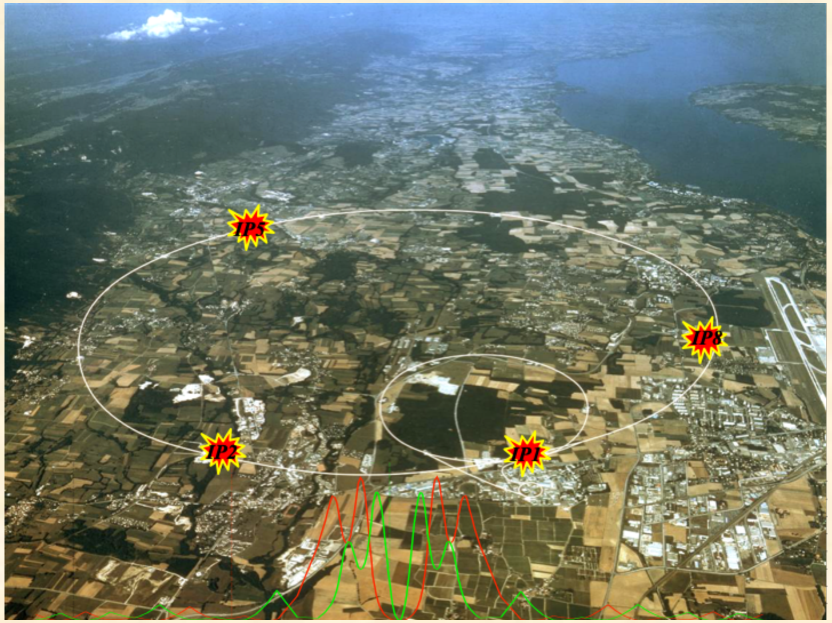


3.) The HL-LHC

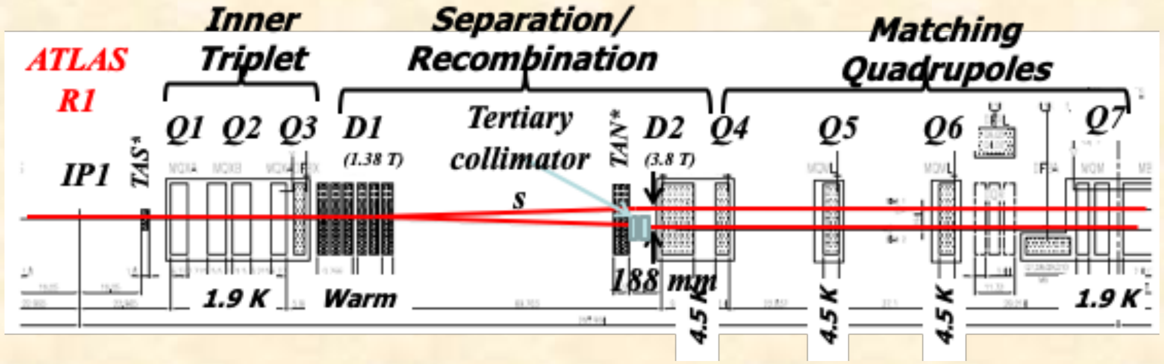
* increasing the luminosity of LHC
* higher bunch intensities
* smaller β*

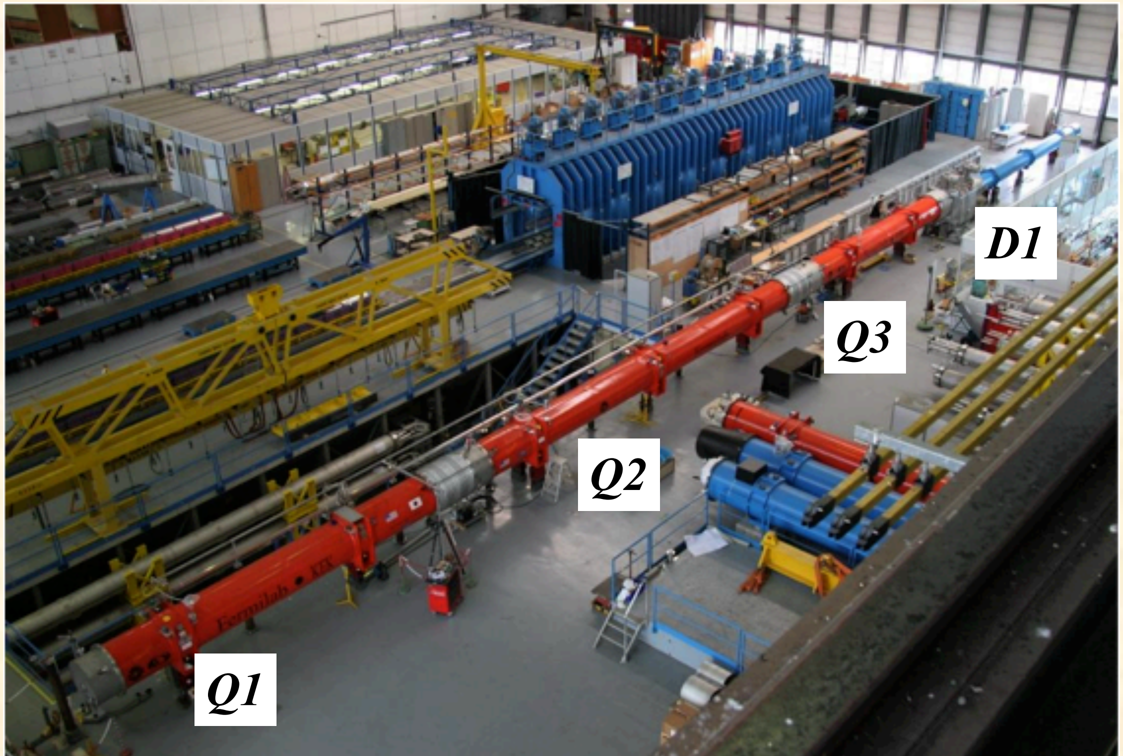
	LHC	HL-LHC
Energy	7 TeV	7 TeV
Particles / bunch	$1.2*10^{11}$	$2.2*10^{11}$
number of bunches	2808	2748
β*	55 cm	15 cm
ε	$5.0*10^{-10}$ m rad	$3.3*10^{-10}$ m rad
σ	16 μm	7 μm
Luminosity	$1.0*10^{34}$ cm^{-2} s^{-1}	$7.0*10^{34}$ cm^{-2} s^{-1}

LHC & HL-LHC



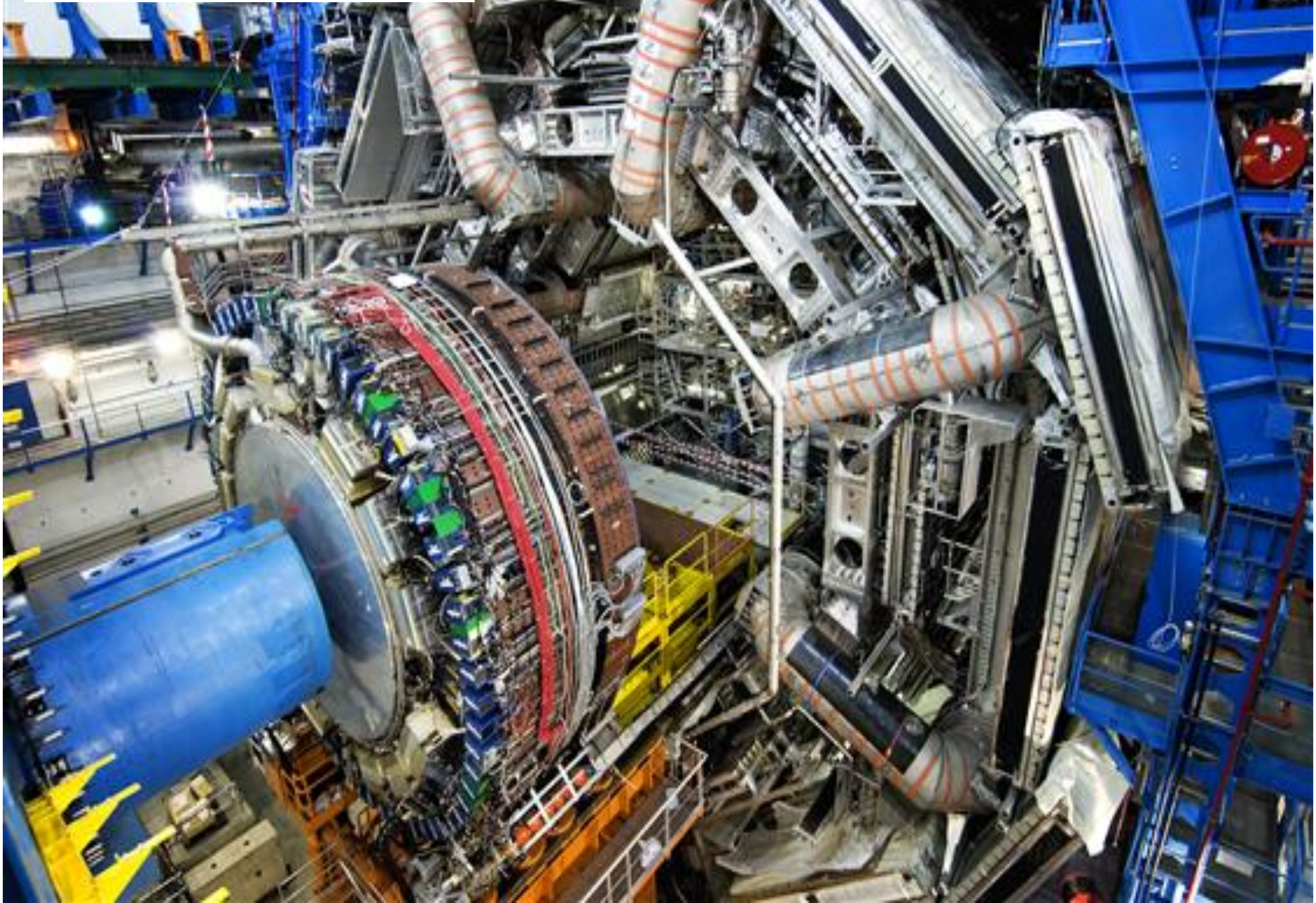
At one (or a very few) points in the accelerator, we make the beams as small as possible, to push for highest particle density.





Mini-Beta Insertion

ATLAS detector in LHC



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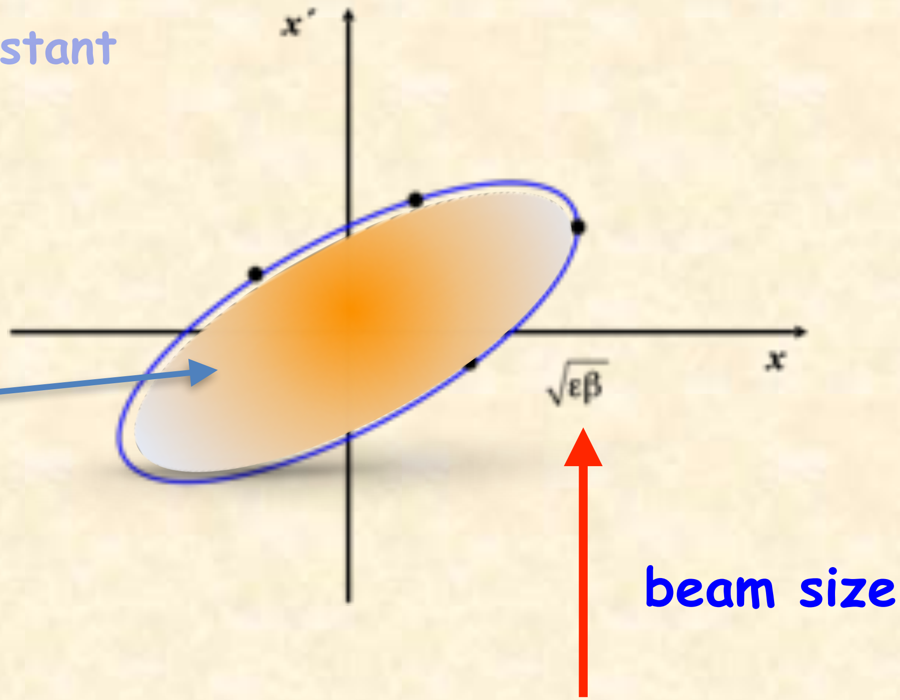


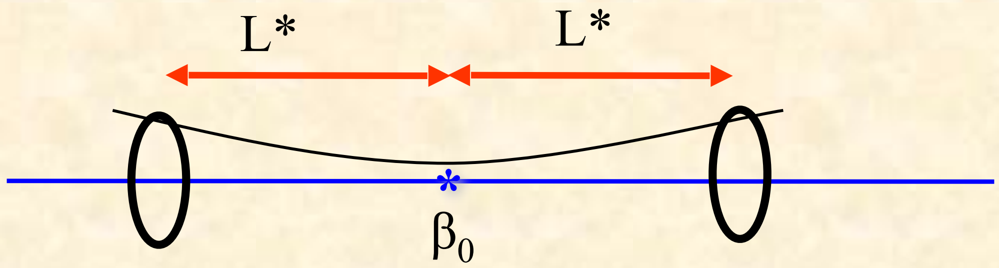
β-Function in a Drift:

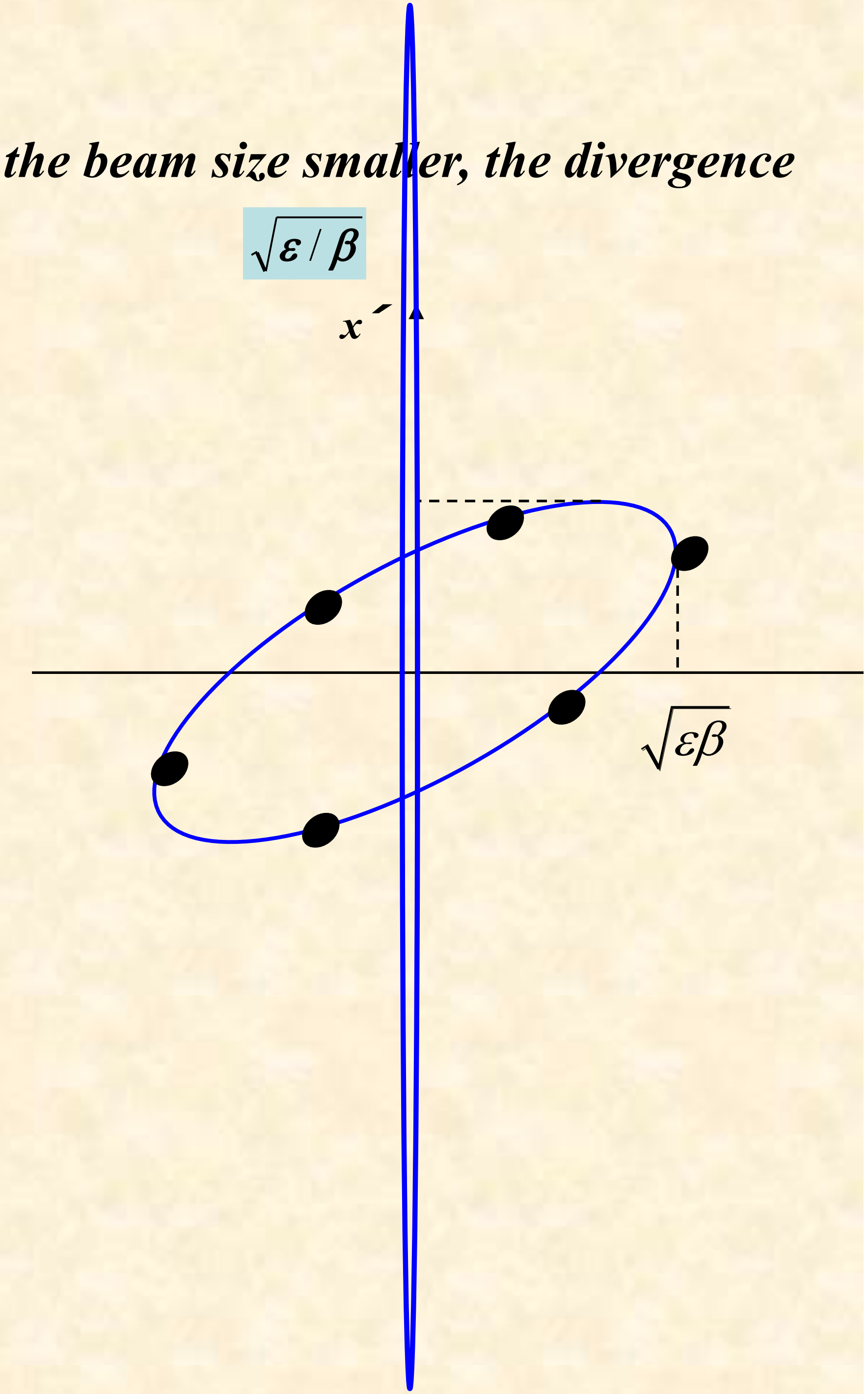
A direct consequence of "Liouville",
i.e. phase space conservation, is that … if we make the beam size smaller, the divergence increases.

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

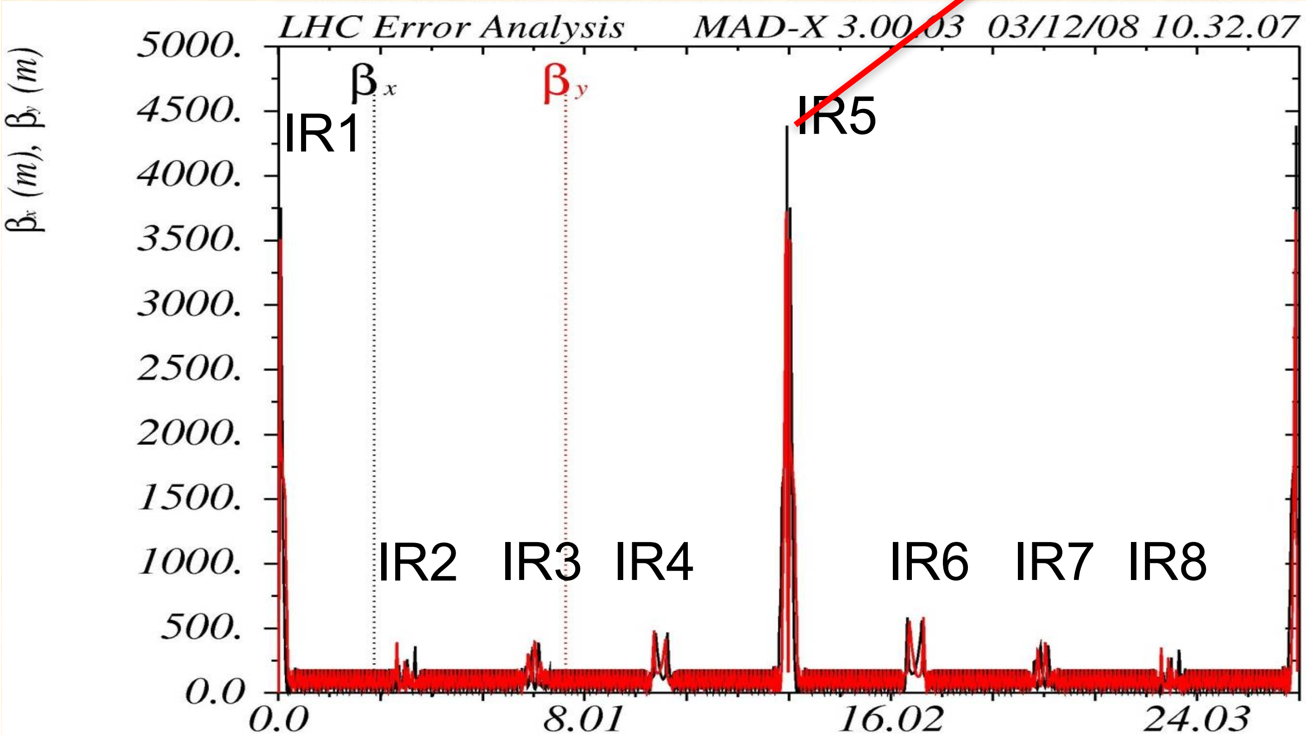
Luminosity Upgrade:

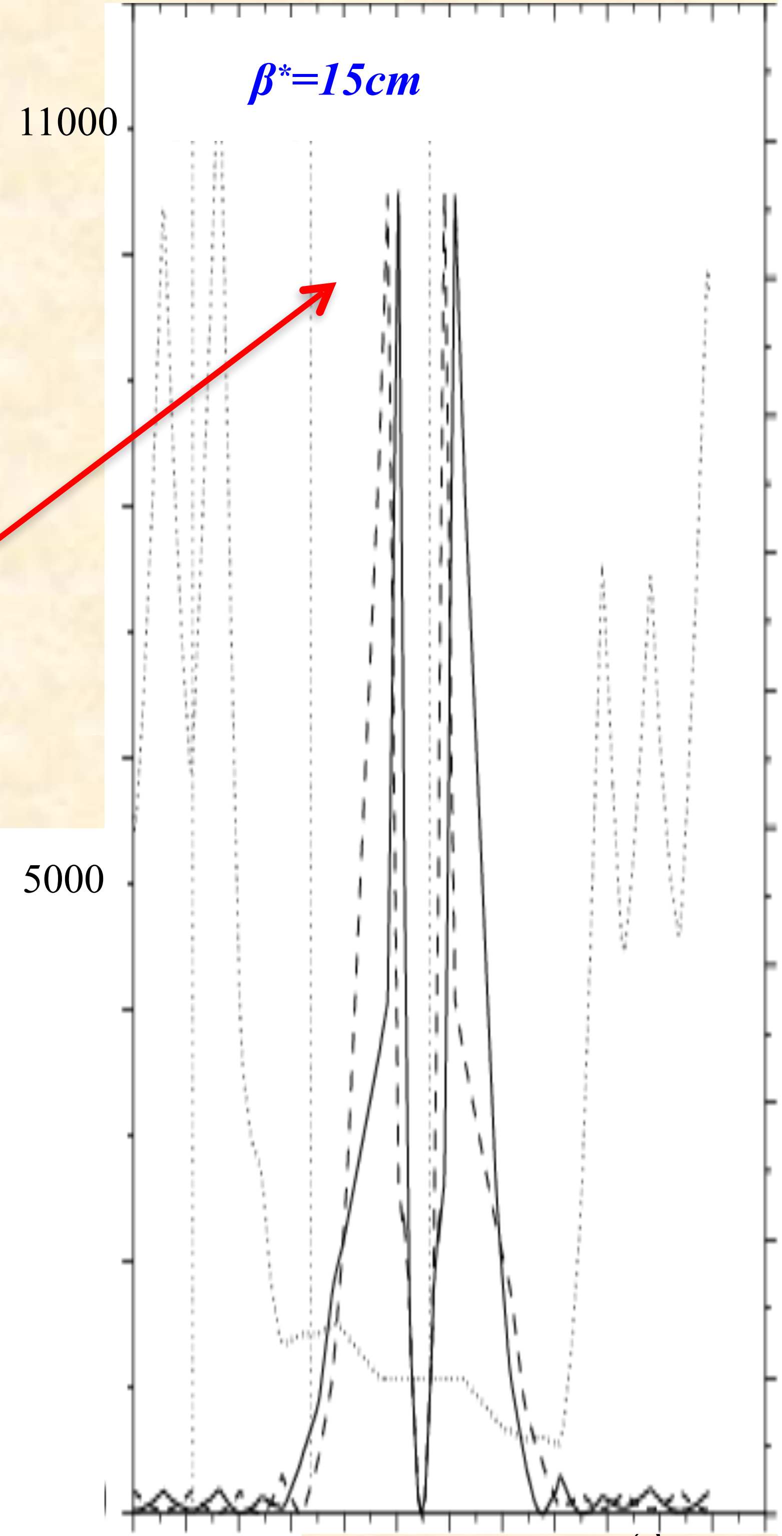
stronger focusing → smaller beam size at the IP

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

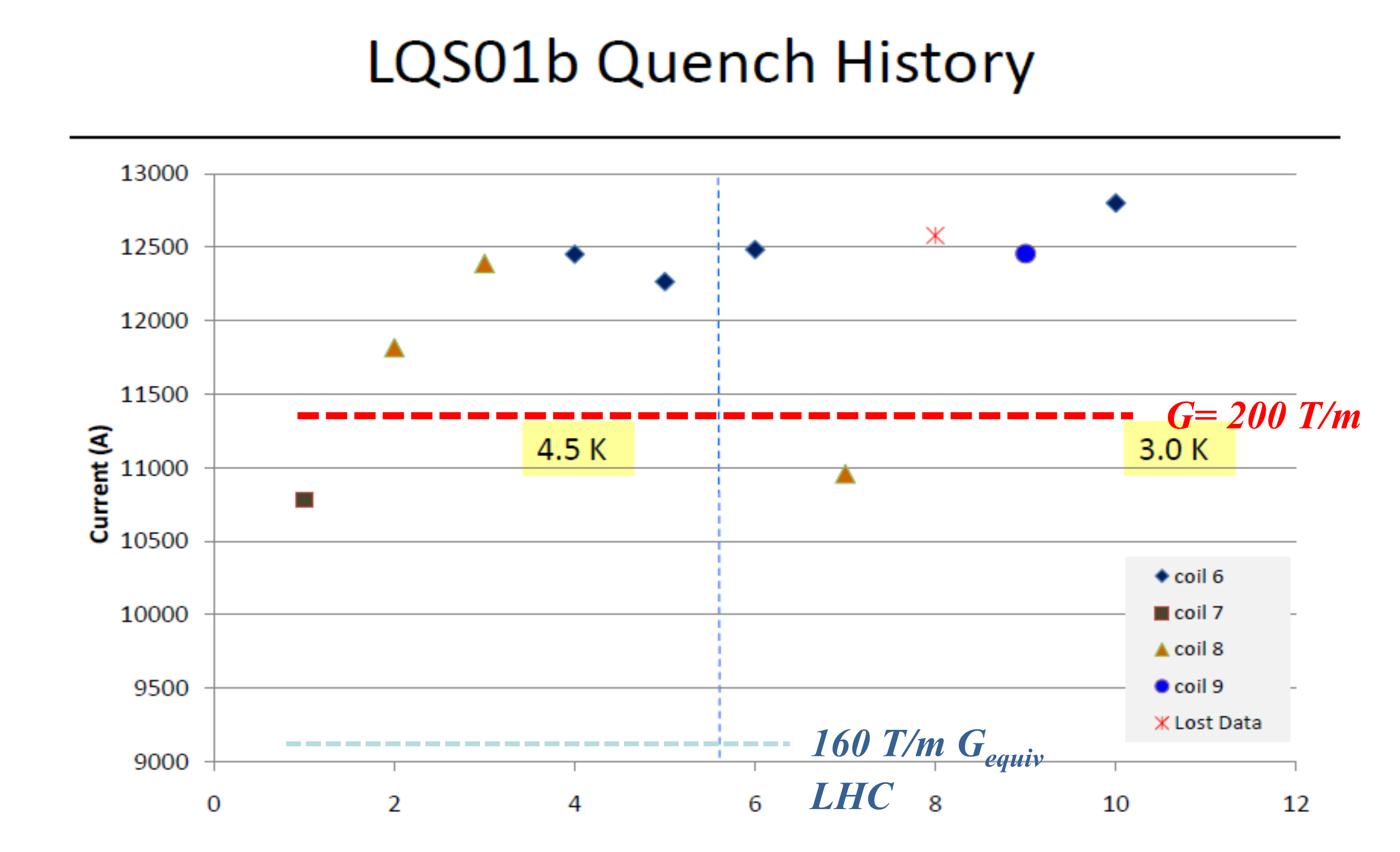




Challenge: High Field Nb_3Sn Quad

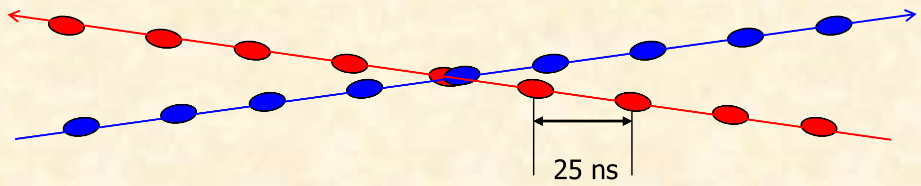
Stronger focusing needs stronger magnets

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



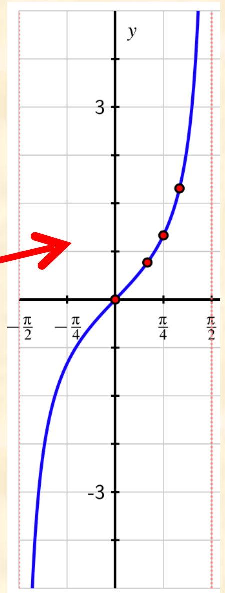
reminder: LHC standard inner triplet NbTi: G=215 T/m, Φ=66 mm

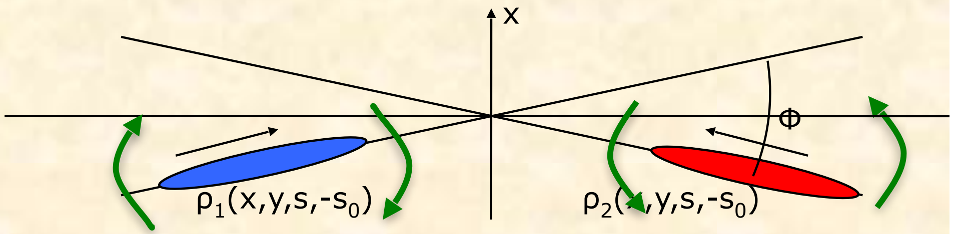
Challenge: HL-LHC Crab Cavities



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

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



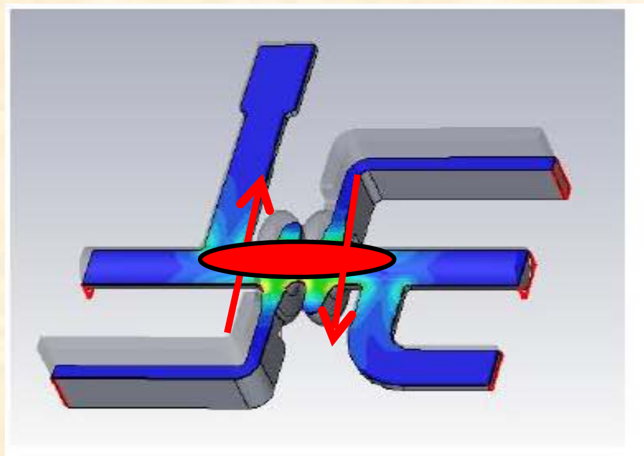


F = Spaghetti-Loss Factor

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 $1/\beta^*$, 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***

Future Colliders:
Hadrons or Leptons?

***Hadron collisions**: compound particles*

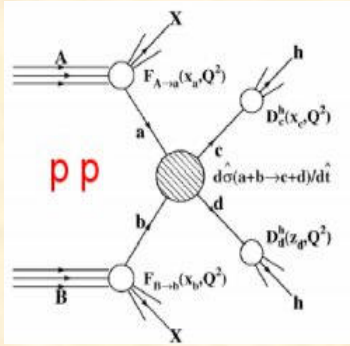
Proton = u+u+d + gluons + sea-quarks

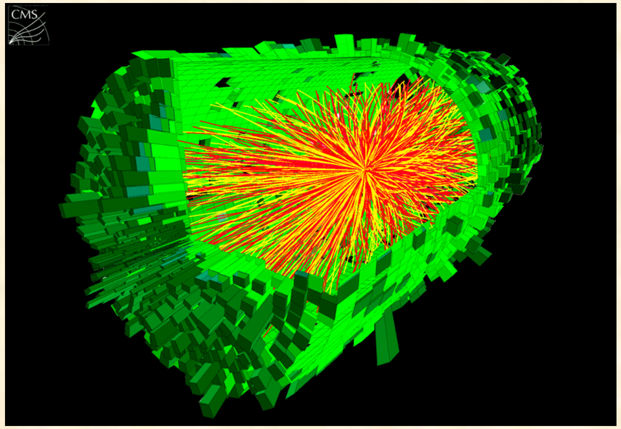
Mix of quarks, anti-quarks and gluons

→ variety of processes

Parton energy spread

Hadron collisions ⇒ large discovery range





LHC Pb-Pb collision (Atlas)

***Lepton collisions:** Elementary particles / Anti-particles*

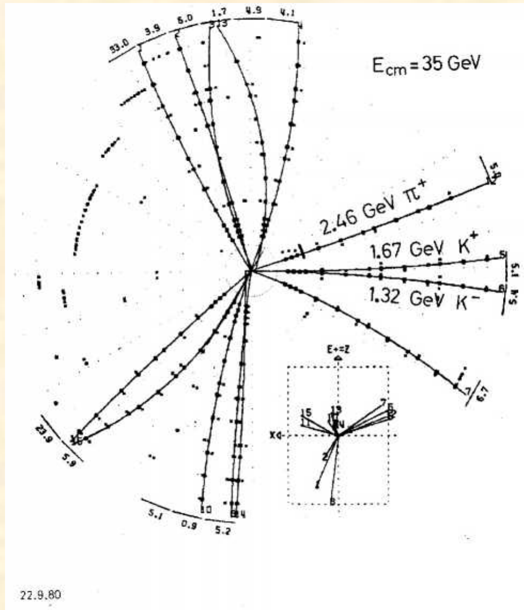
Collision process known

Well defined energy

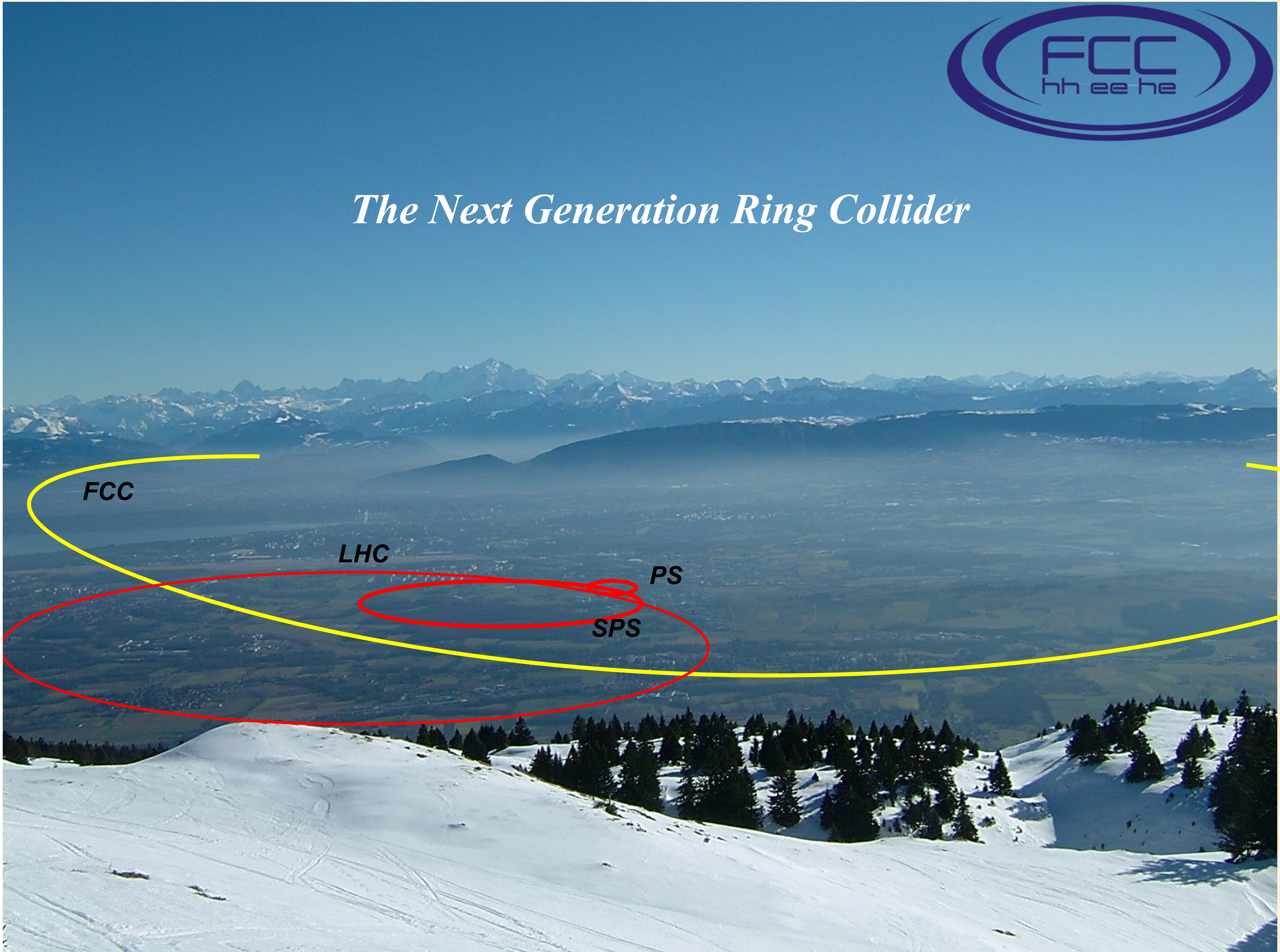
Other physics background limited

Lepton collisions ⇒ precision measurements

in e+ e- collisions quantum numbers disappear

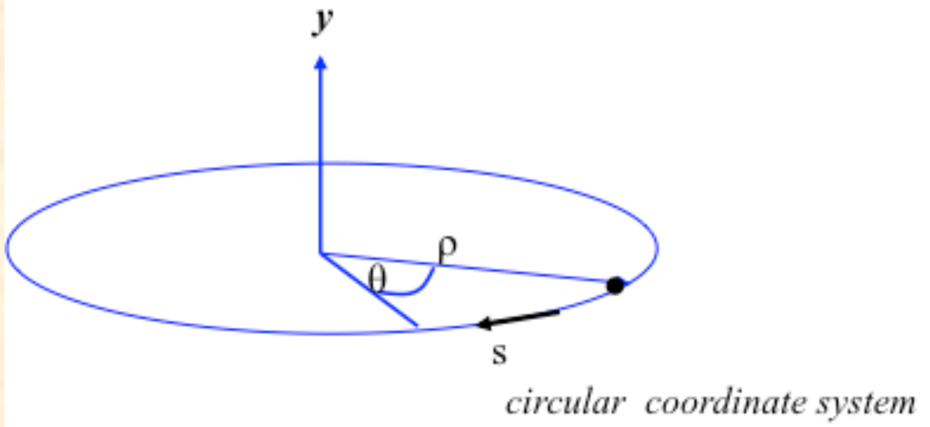


PETRA: gluon discovery


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



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

Condition for an ideal circular orbit:

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

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

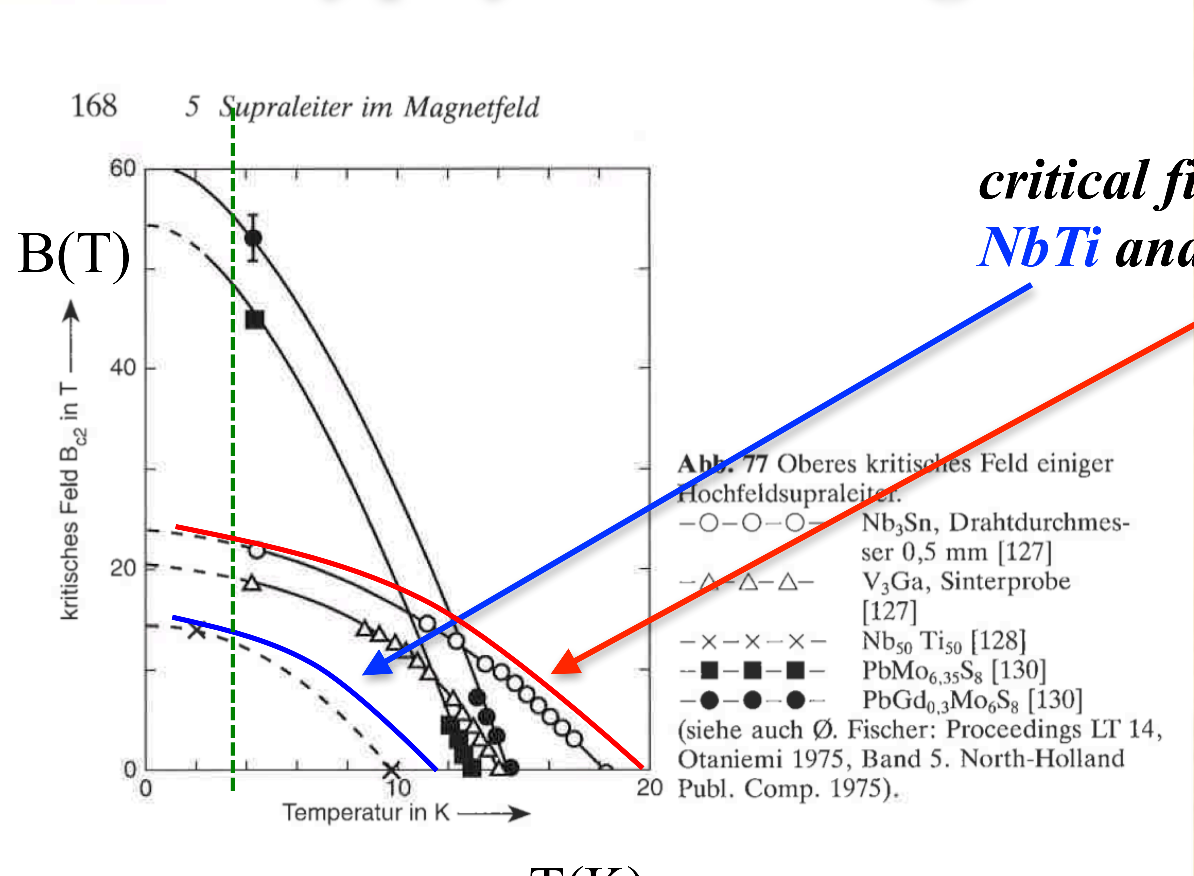
$p = \gamma \cdot m_0 v \qquad \dfrac{\gamma\, m_0\, v^2}{\rho} = e\,v\,B$

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

$B\rho$ = "beam rigidity"

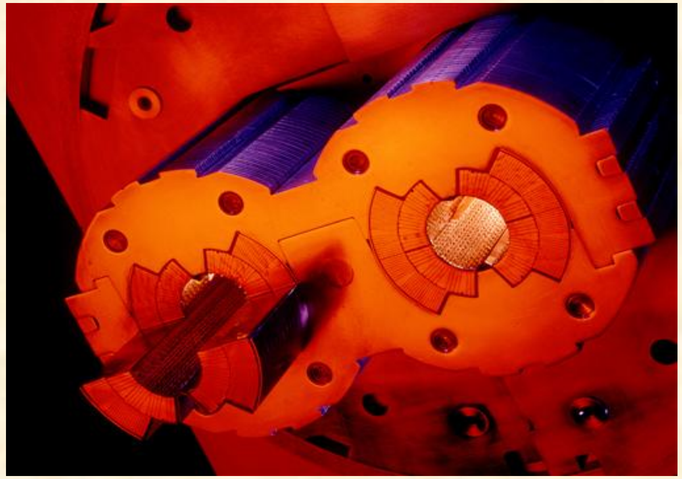
The maximum particle momentum is given by the field strength B and the storage ring size 2πρ

Highest B-field technology:
Two key players in sc magnet technology: NbTi and Nb_3Sn



T(K)

critical field in
NbTi and Nb_3Sn



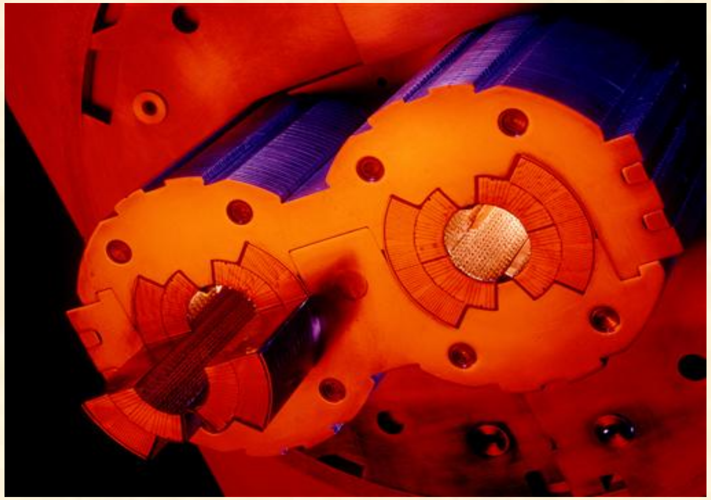
FCC -hh
means Nb_3Sn technology
for dipoles & quadrupoles

which is equally true in parts
for HL-LHC

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

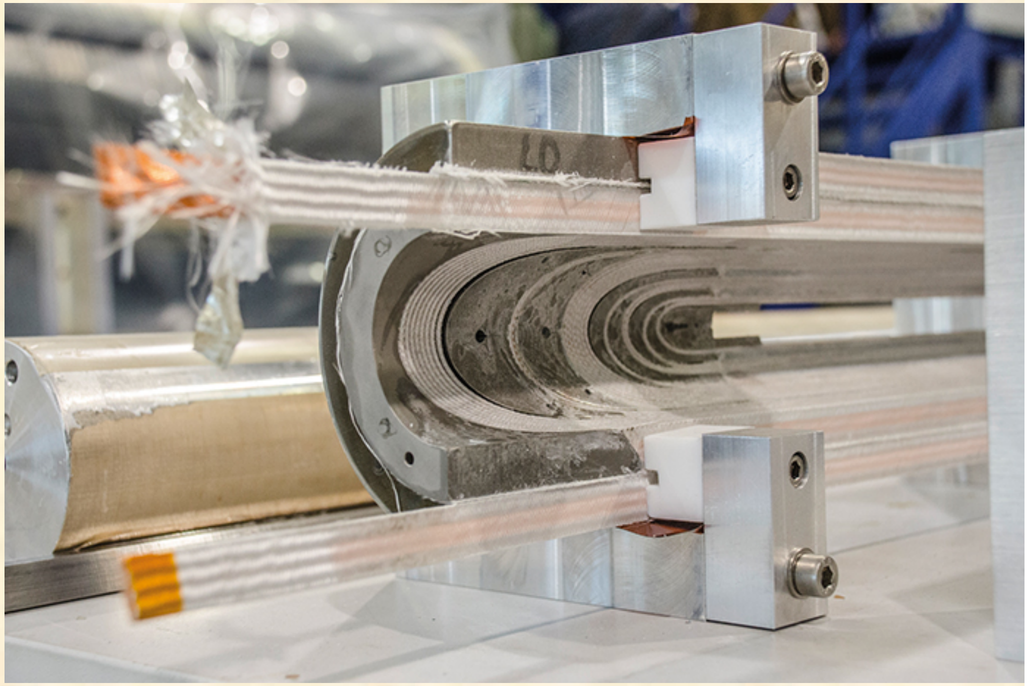
($j_c\perp$ = 100A/mm², $j_c||$ = 800A/mm²)

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:

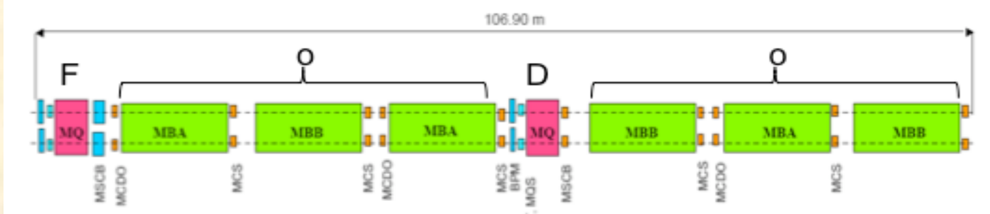
circumference 100km /27km
→ *Factor 3.7*

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*

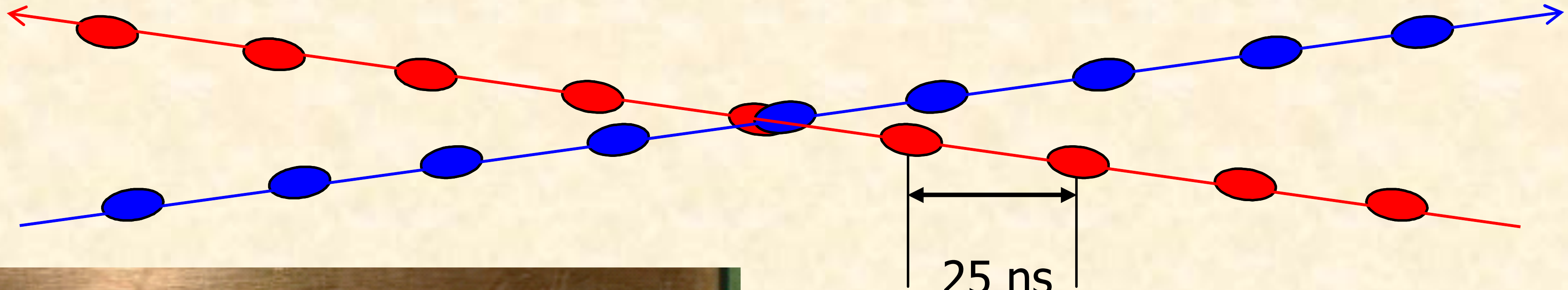
	LHC	HL-LHC	FCC-hh Initial	FCC-hh Nominal
Main parameters and geometrical aspects				
c.m. Energy (TeV)	14		100	
Circumference C (km)	26.7		97.75	
Dipole field (T)	8.33		<16	
Physics performance and beam parameters				
Peak luminosity[1] (10^{34} cm^{-2}s^{-1})	1.0	5.0	5.0	<30.0
Beam parameters				
Number 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	

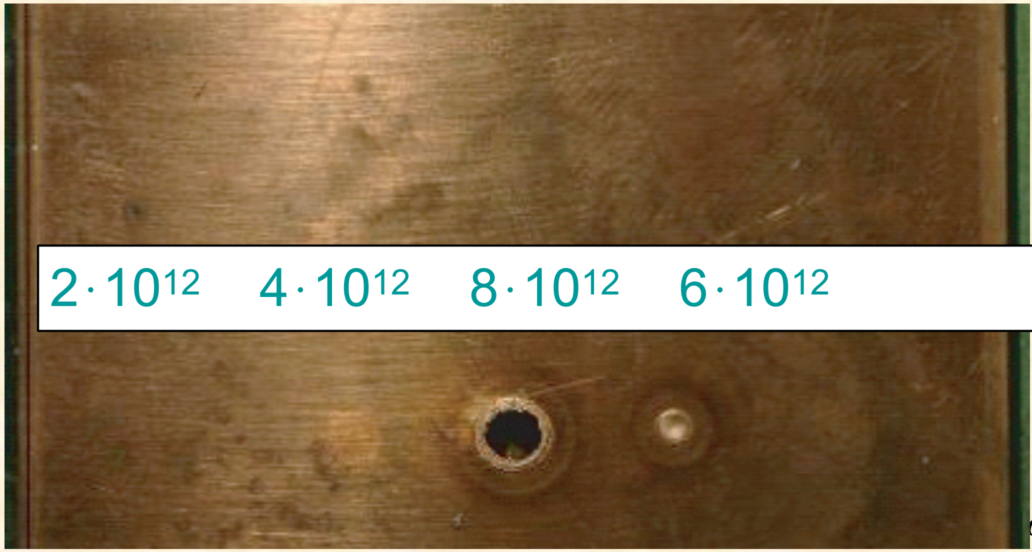
LHC Operation:

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

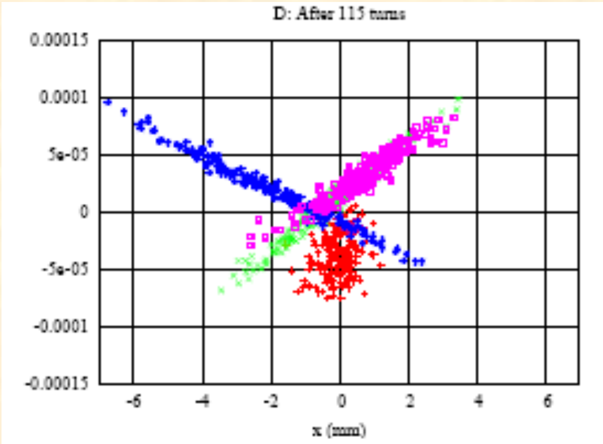




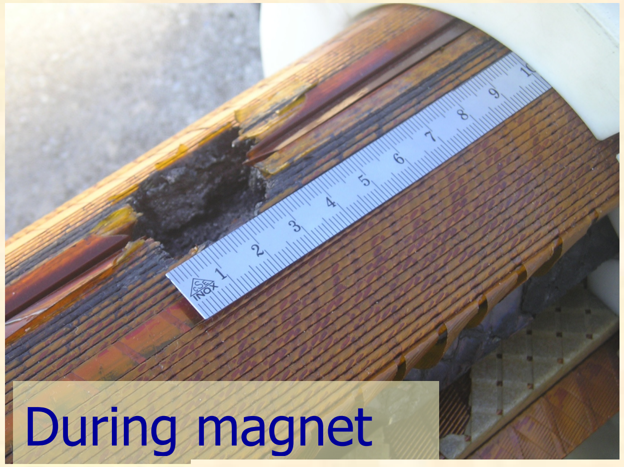
$2\cdot10^{12}$ $4\cdot10^{12}$ $8\cdot10^{12}$ $6\cdot10^{12}$ 450 GeV p Beam

Energy stored in the magnet

in case of problems …
react fast and safe !!



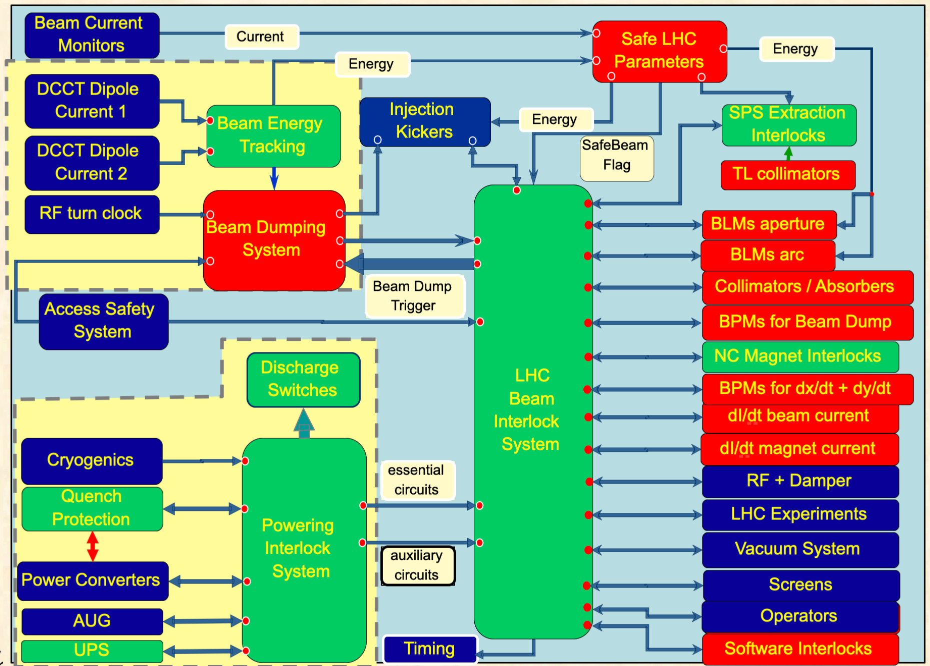
(A. Gómez)



Quench in a LHC magnet

failure of nc. dipole D1: $\tau_{damage} = 6.4$ ms

damage level after 20 turns !!



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

ca 400 000 v. Chr.: Mankind discovers the Fire

Synchrotron Radiation

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

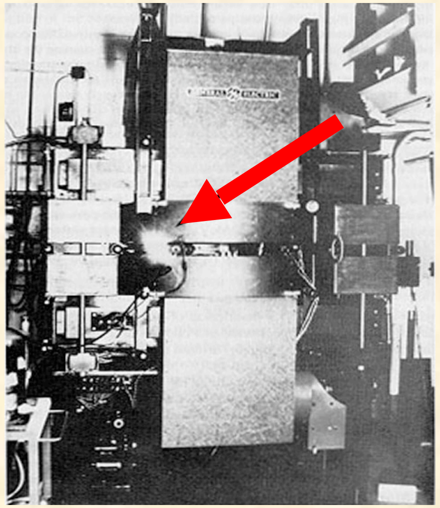
$$P_s = \frac{2}{3}\alpha\hbar c^2 \frac{\gamma^4}{\rho^2}$$ *radiation power*

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

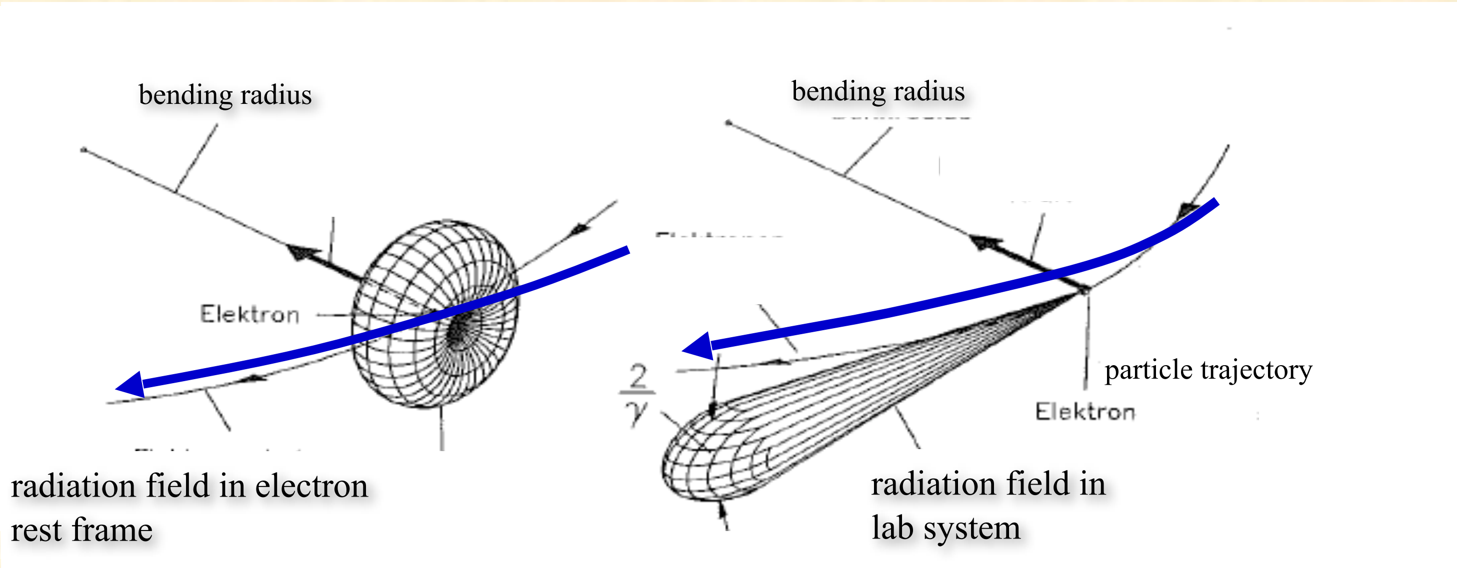
$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}$$ *critical frequency*

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

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



1946 observed for the first time in the General Electric Synchrotron



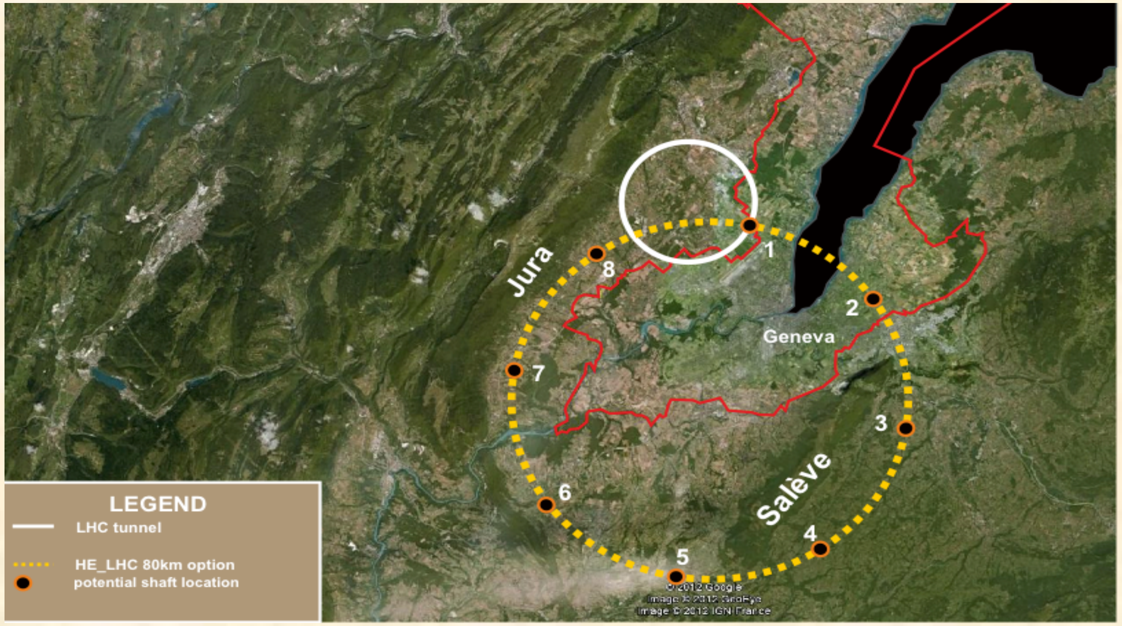
court. K. Wille

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***

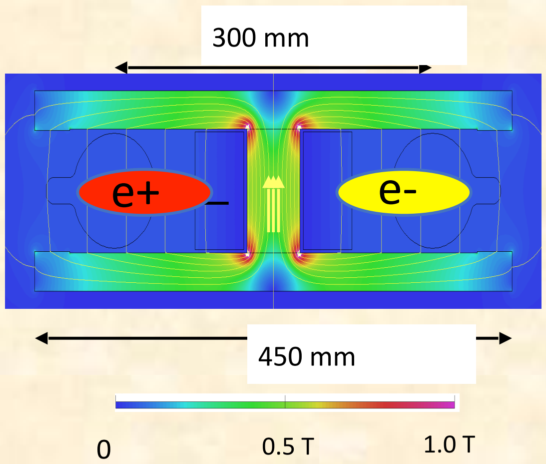
Circular e+ / e- colliders are severely limited by synchrotron radiation losses and have to be replaced for higher energies by linear accelerators

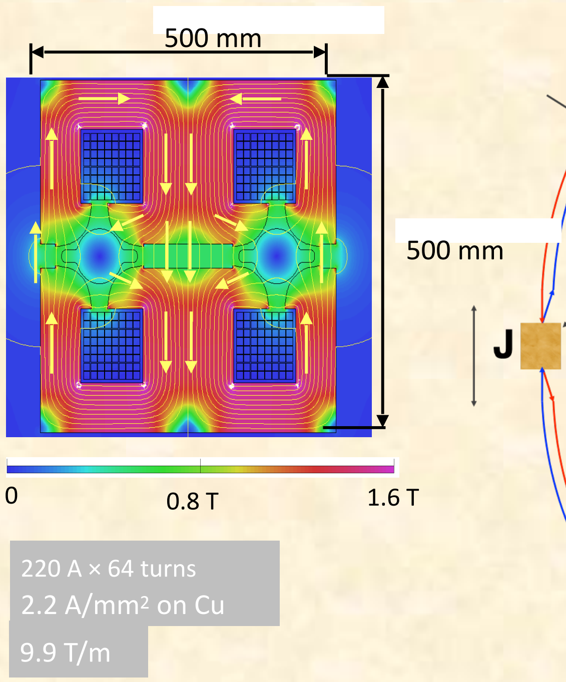
FCC-ee

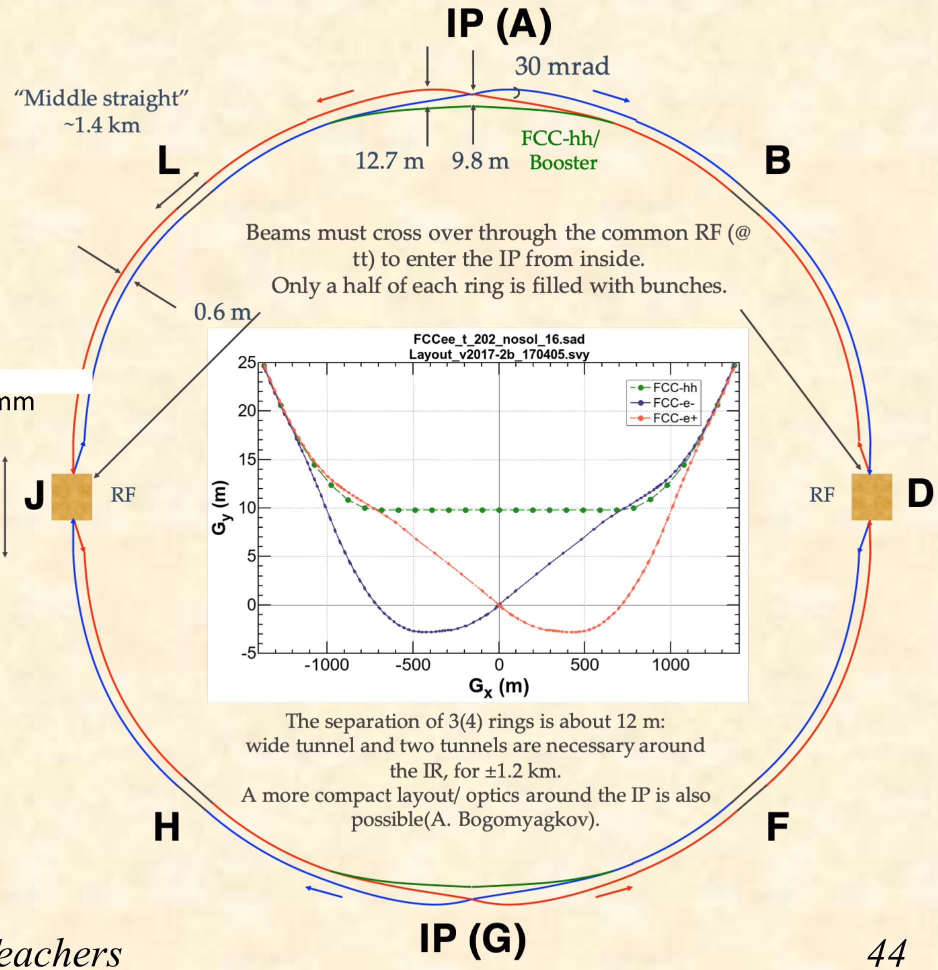
M. Aiba, S. Aumon, E. Belli, M. Benedikt, A. Blondel, A. Bogomyagkov, M. Boscolo, H. Burkhardt, D. El-Khechen, B. Harer, B. Holzer, P. Janot, M. Koratzinos, E. Levichev, A. Milanese, A. Novokhatski, S. Ogur, K. Ohmi, K. Oide, D. Shatilov, J. Seeman, S. Sinyatkin, H. Sugimoto, M. Sullivan, T. Tydecks,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







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 !!

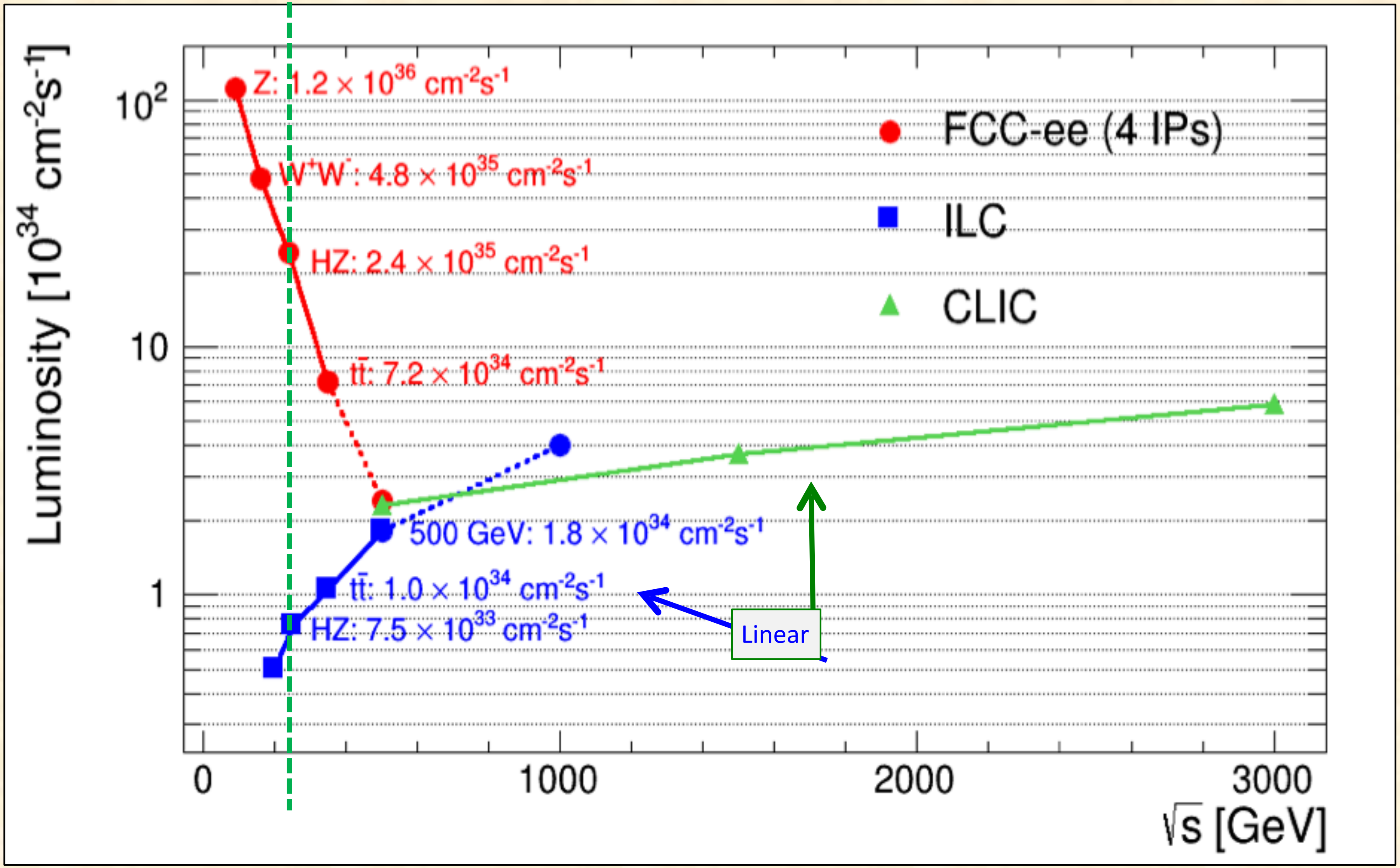
6.) Push for higher lepton energy

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

Circular vs. Linear Colliders

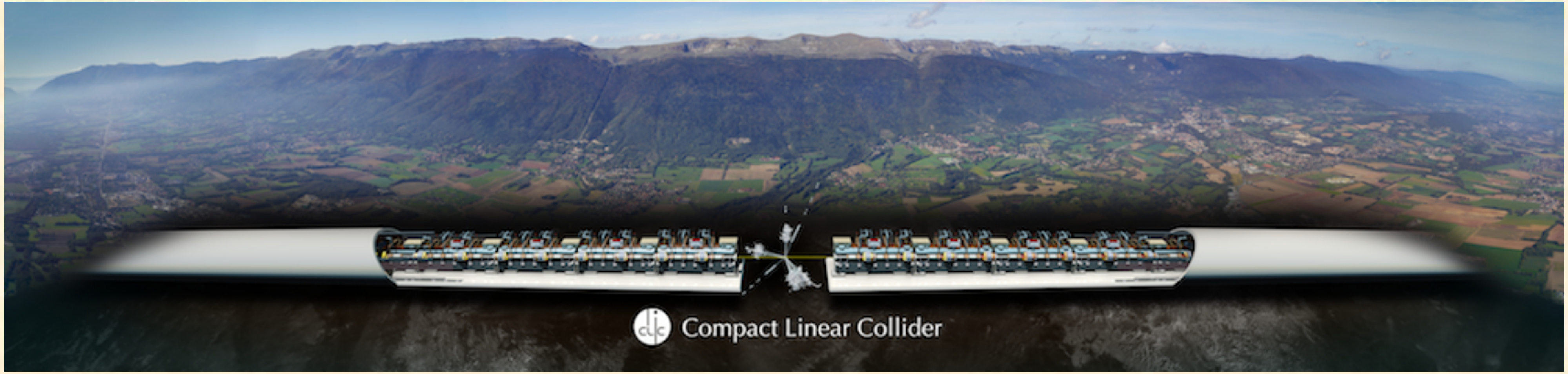
… the light problem

F. Gianotti



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

„C"-LIC ... = CERN ... or „compact"



50 km

CLIC parameter list

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	12
Beam power/beam [MW]	4.9	14
Bunch charge [10^9 e^+/e^-]	6.8	3.72
Bunch separation [ns]	0.5	0.5
Bunch length [μm]	72	44
Beam pulse duration [ns]	177	156
Repetition rate [Hz]	50	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

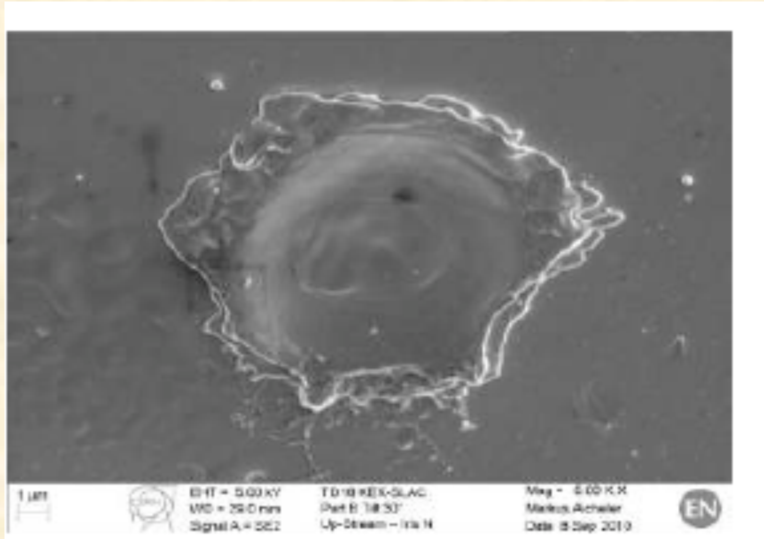
CLIC: Normal conducting RF system
challenge: running at the break down limit

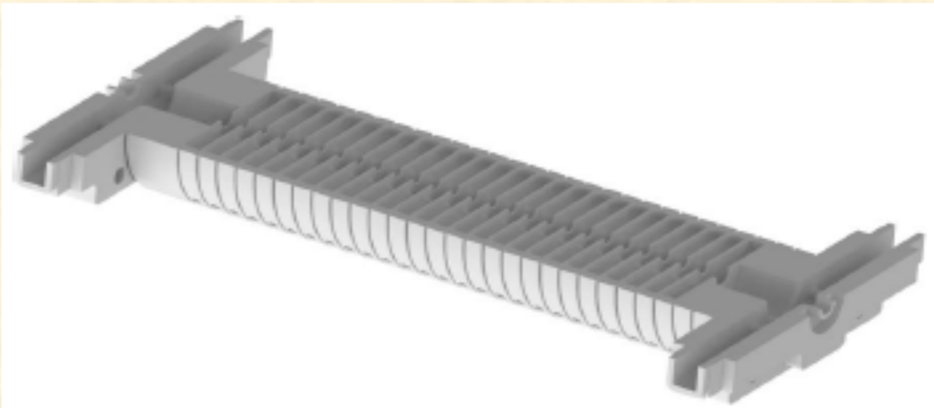
Accereration Gradient 100MV/m studied & optimised since years

" 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 ? "

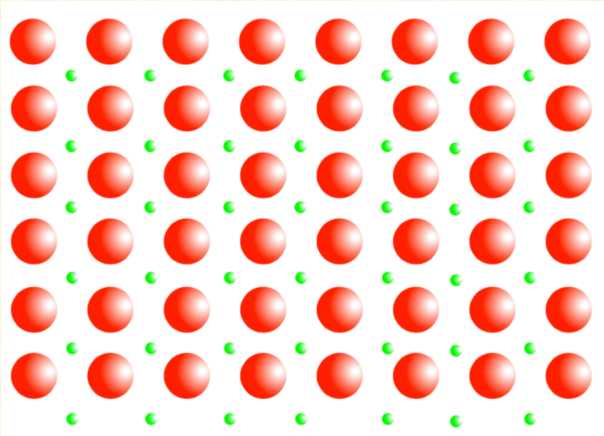
they have impact on

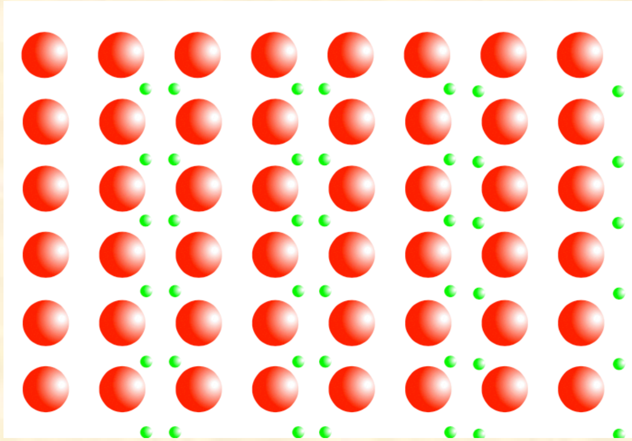
=> the accelerator performance (luminosity)
=> beam quality
=> and the accelerating structure itself

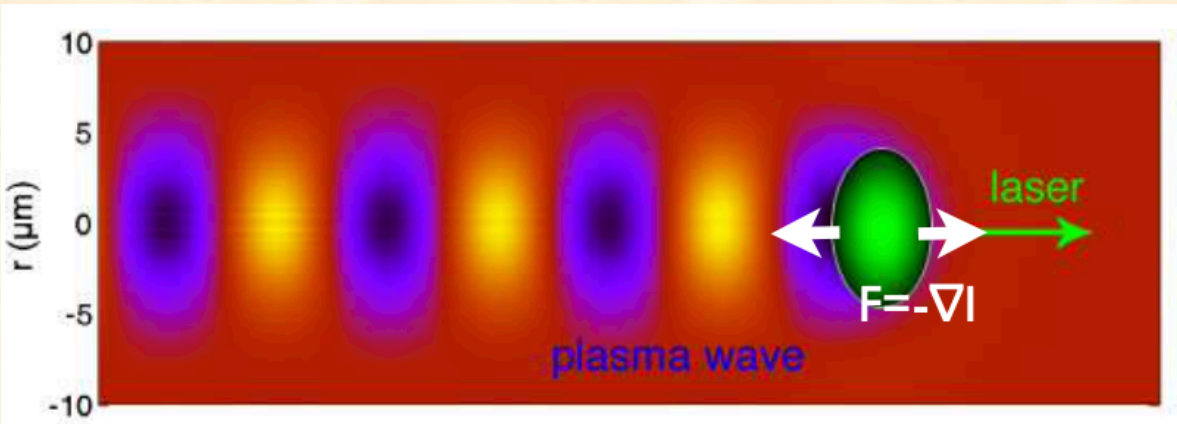




Plasma Wake Acceleration







Excite a plasma wave
with an intense LASER pulse

—> create acc. fields of
E> GV/m

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

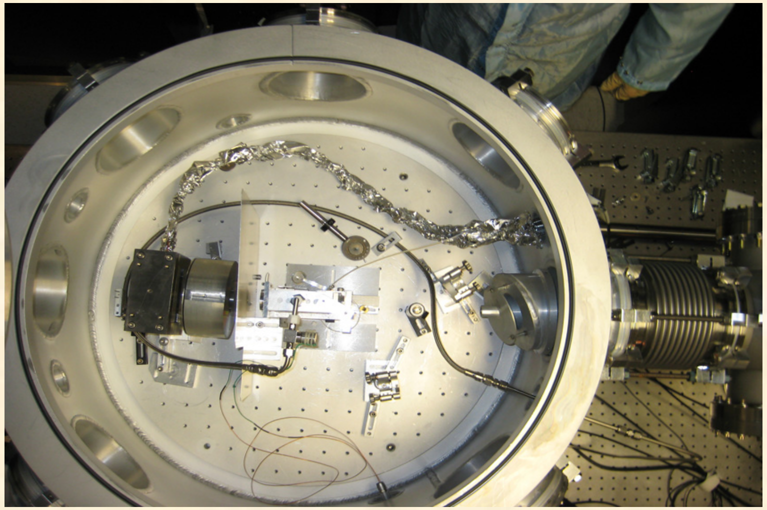
Study of High Gradient Acceleration Techniques

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

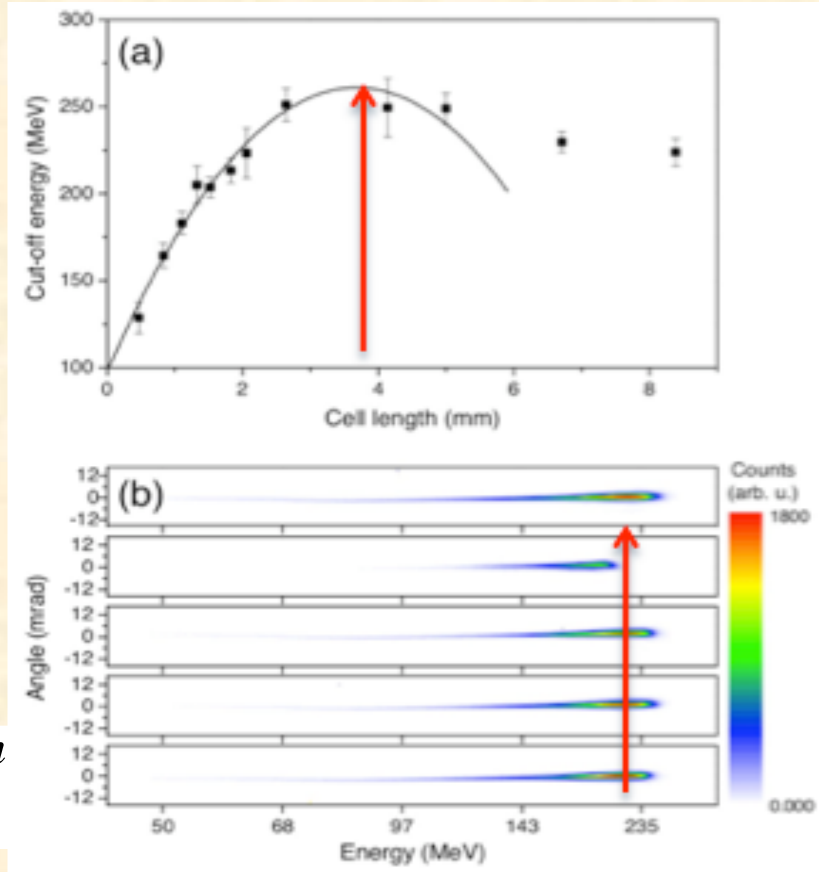
S. Corde et al

Field Gradients up to 100 GeV /m observed



Plasma cell Univ. Texas, Austin
E_e =2 GeV

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



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