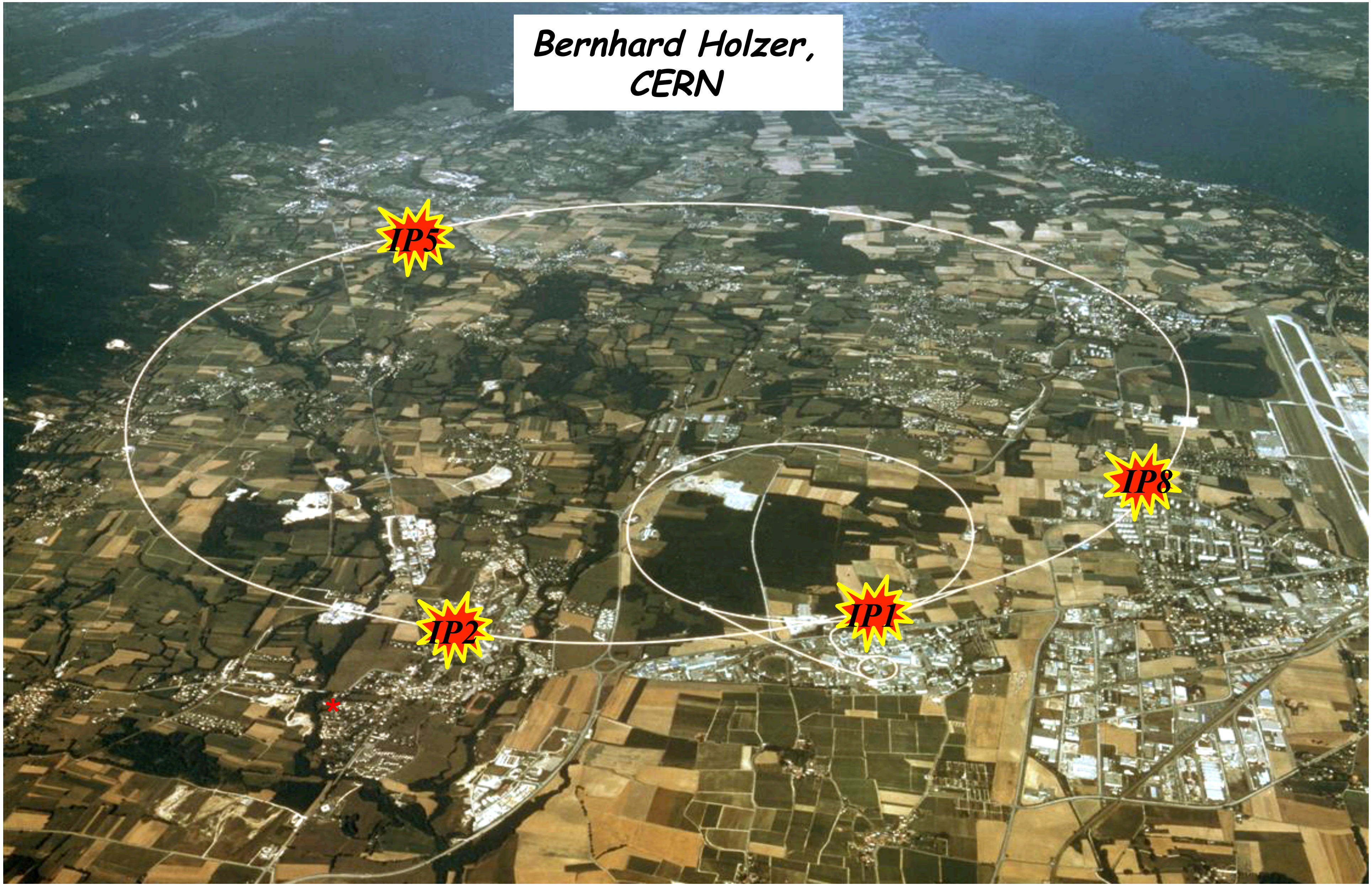
"Future Strategy and Technologies in Particle Acceleration"

Bernhard Holzer,
CERN

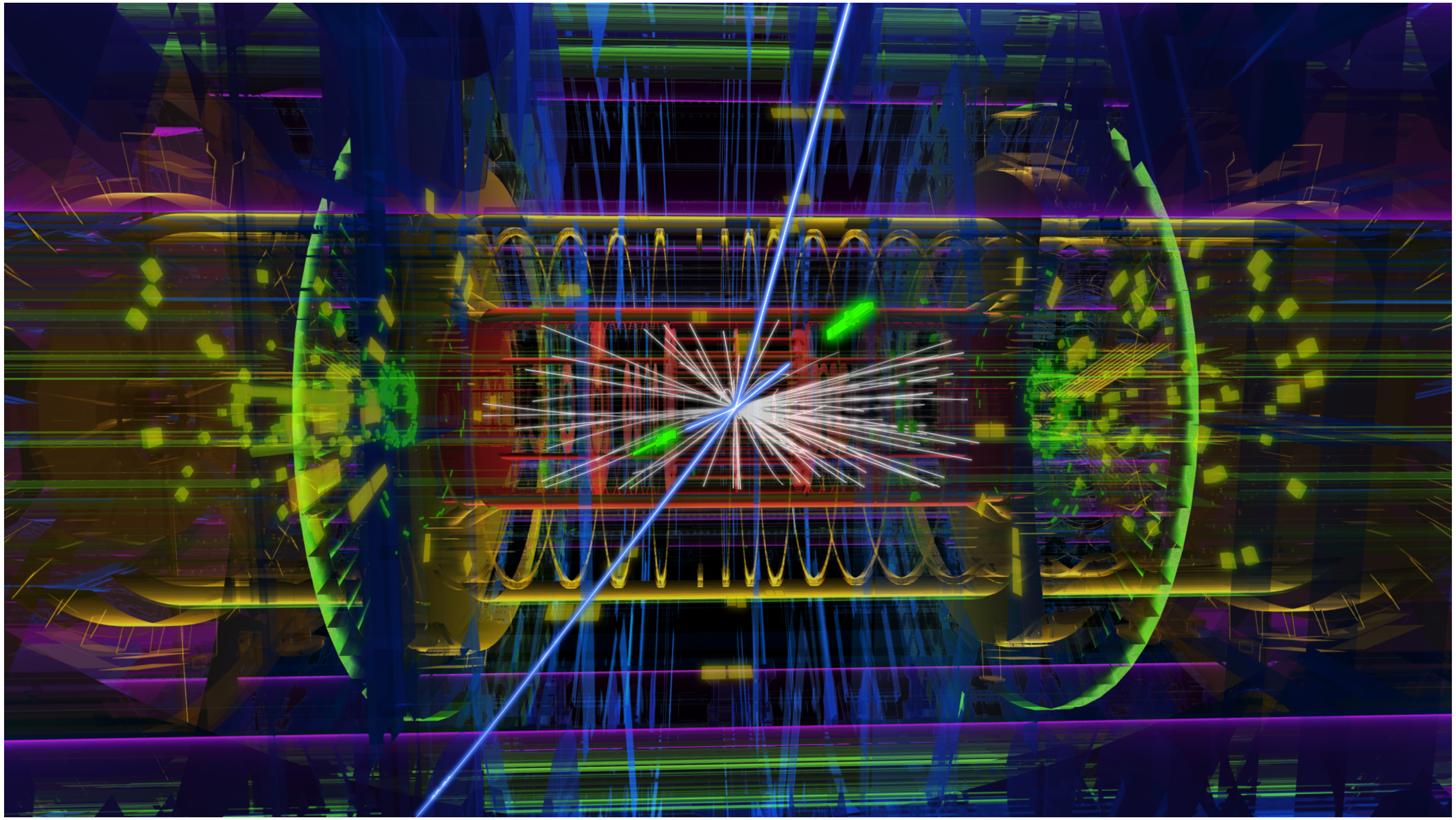


1.) Where are we ?

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

... and why all that ??

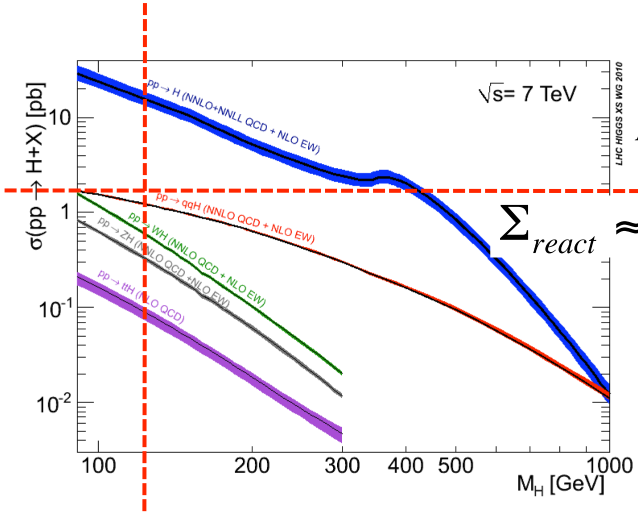
High Light of the HEP-Year 2012 / 13 naturally the HIGGS



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

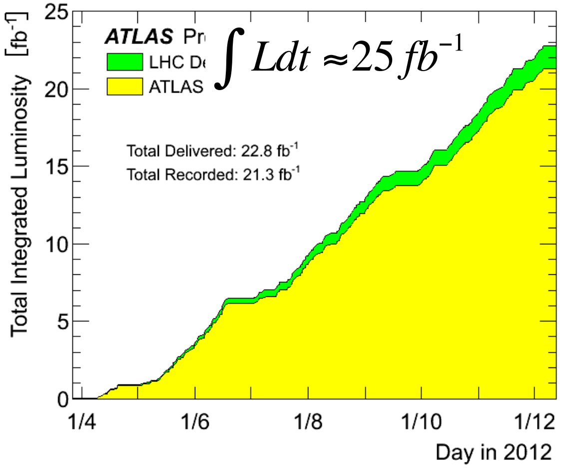
The High light of the year

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



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

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



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

accumulated
collision rate
in LHC run 1

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

The particles are "very small"

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

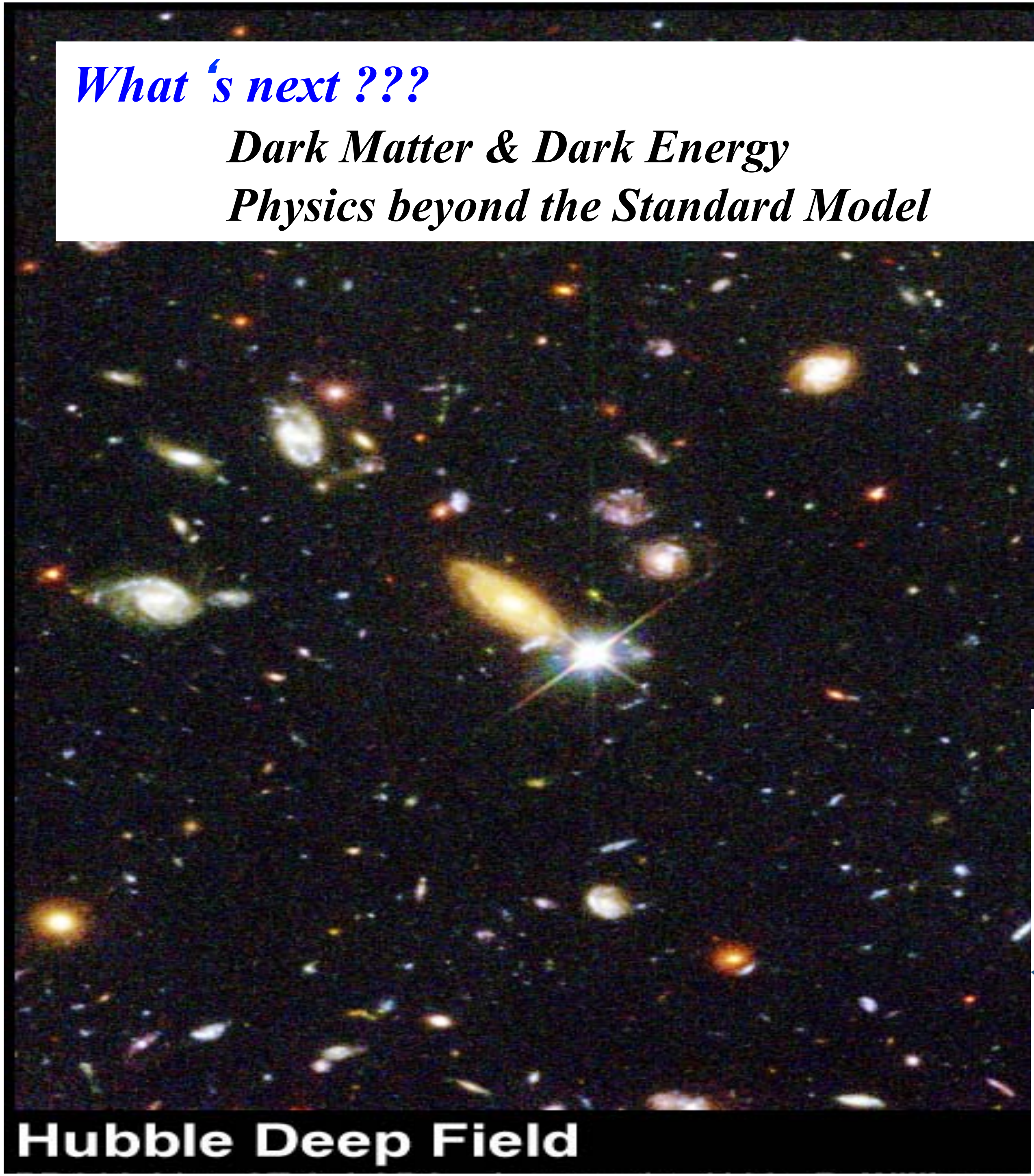
During collider run we had in Run 1 …
1400 bunches circulating,
with 800 Mio proton collisions per second in the experiments
and collected only 450 Higgs particles in three years.

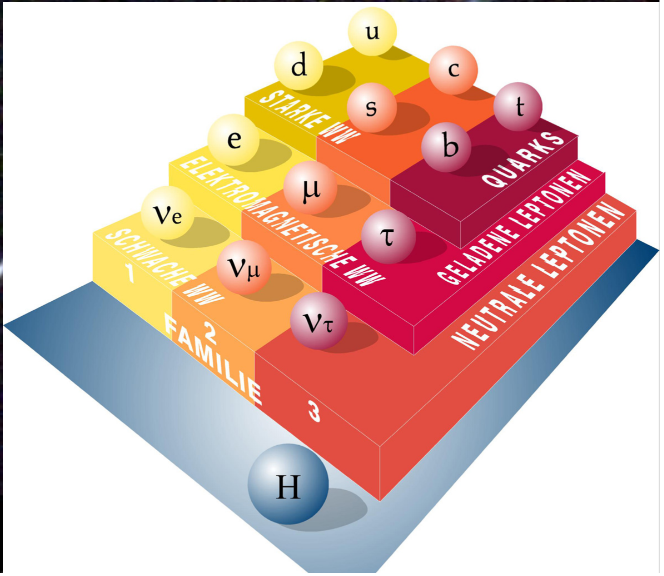
2.) Where do we go ?

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

What ‘s next ???

Dark Matter & Dark Energy
Physics beyond the Standard Model

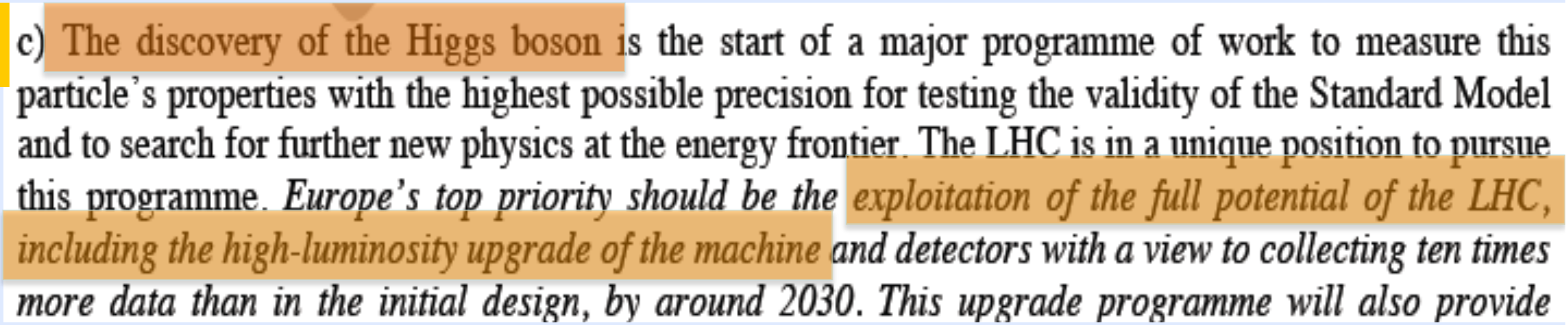




Future Projects

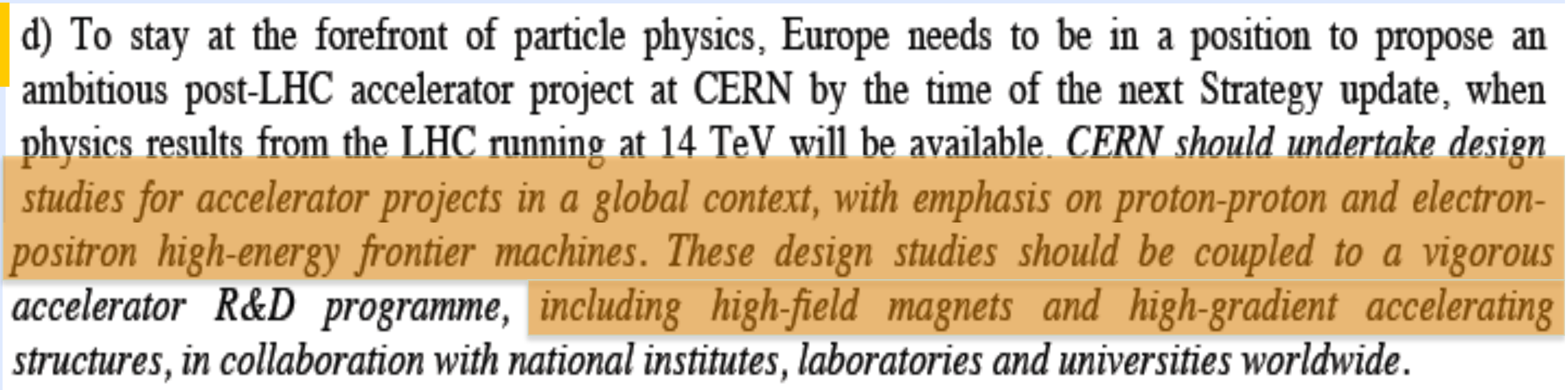
Recommendations from European Strategy Group

#1



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

#2



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

→Proton –Proton Colliders	*=> e+/e- colliders*
LHC / HL-LHC, HE-LHC	***TLEP, CLIC***

3.) The HL-LHC

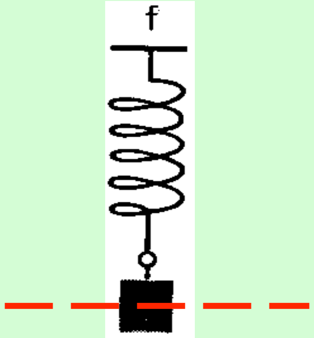
- ***increasing the luminosity of LHC***
- ***higher bunch intensities***
- ***smaller β^****

A Bit of Theory

The big storage rings: „Synchrotrons“

Focusing Properties and Quadrupole Magnets

classical mechanics:
pendulum



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

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

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

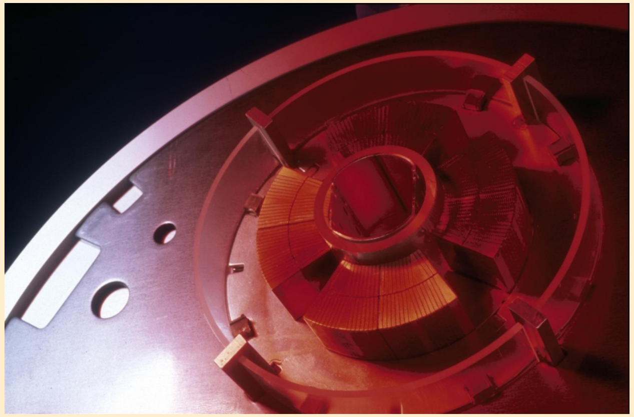
this is how grandma's Kuckuck's clock is working!!!

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

linear increasing magnetic field $\boldsymbol{B_y = g\,x} \qquad \boldsymbol{B_x = g\,y}$

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

LHC main quadrupole magnet $\boldsymbol{g} \approx 25 \ldots 220\ \boldsymbol{T/m}$



Does this mean that the protons in a accelerator behave like the pendulum of Grandma's clock ???

... YES !!!

normalise magnet fields to momentum
(remember: ***$B*\rho = p/q$*** *)*

Dipole Magnet

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

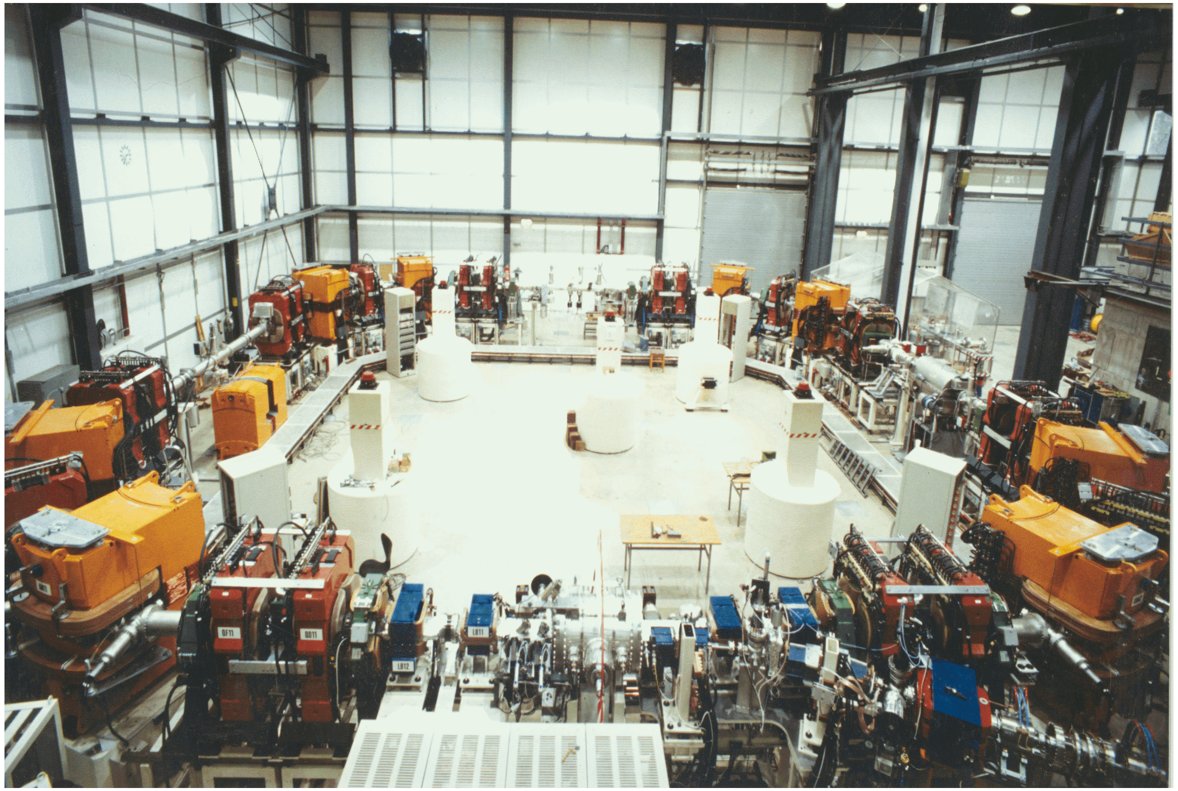
Quadrupole Magnet

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

3.) The Equation of Motion:

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

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



Separate Function Machines:

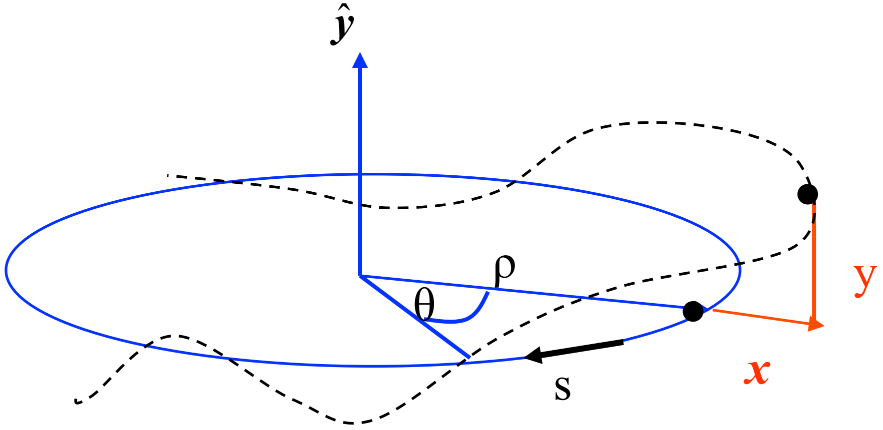
Split the magnets and optimise them according to their job:

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:*

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

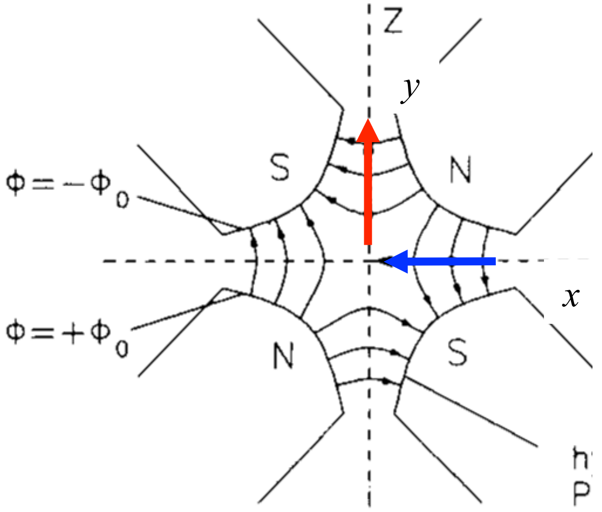
x = particle amplitude
x' = angle of particle trajectory (wrt ideal path line)

- *Equation for the vertical motion:*

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

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

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

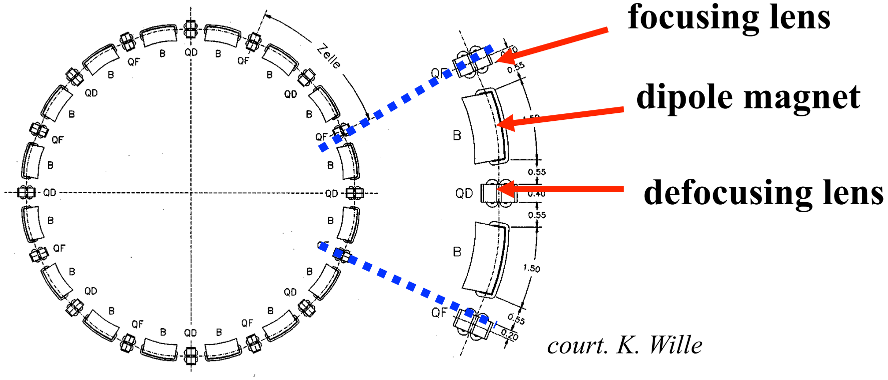


Transformation through a system of lattice elements

combine the single element solutions by multiplication of the matrices

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

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



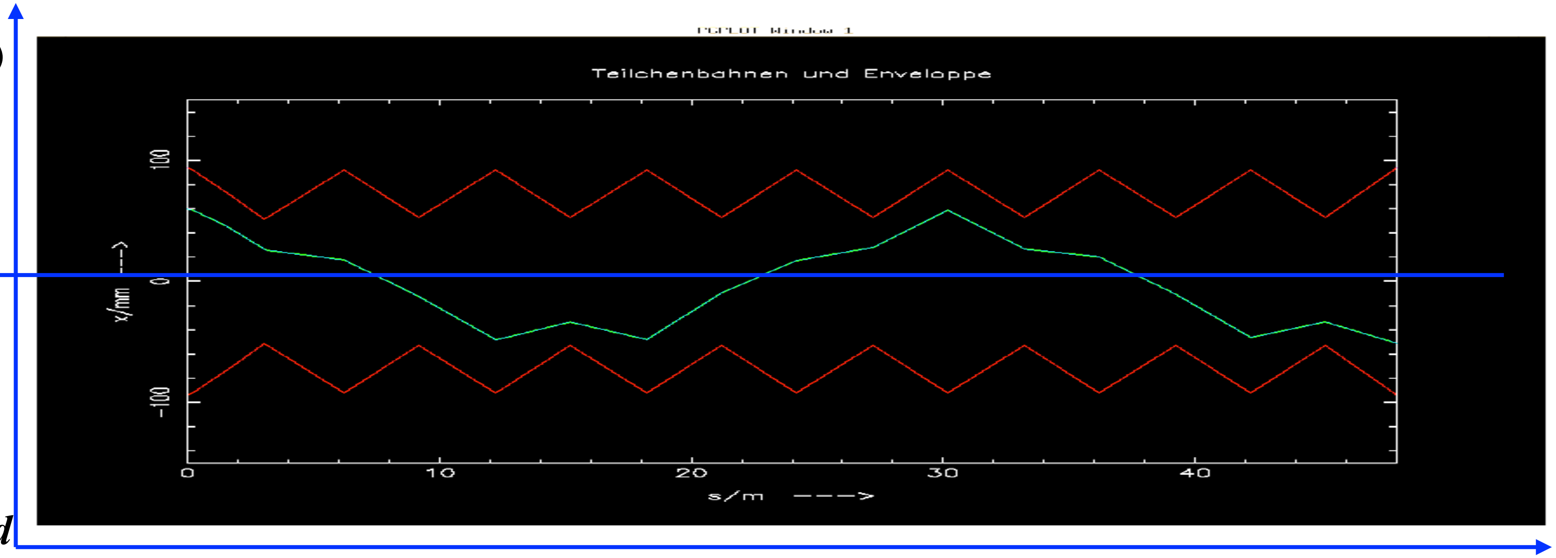
focusing lens

dipole magnet

defocusing lens

court. K. Wille

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

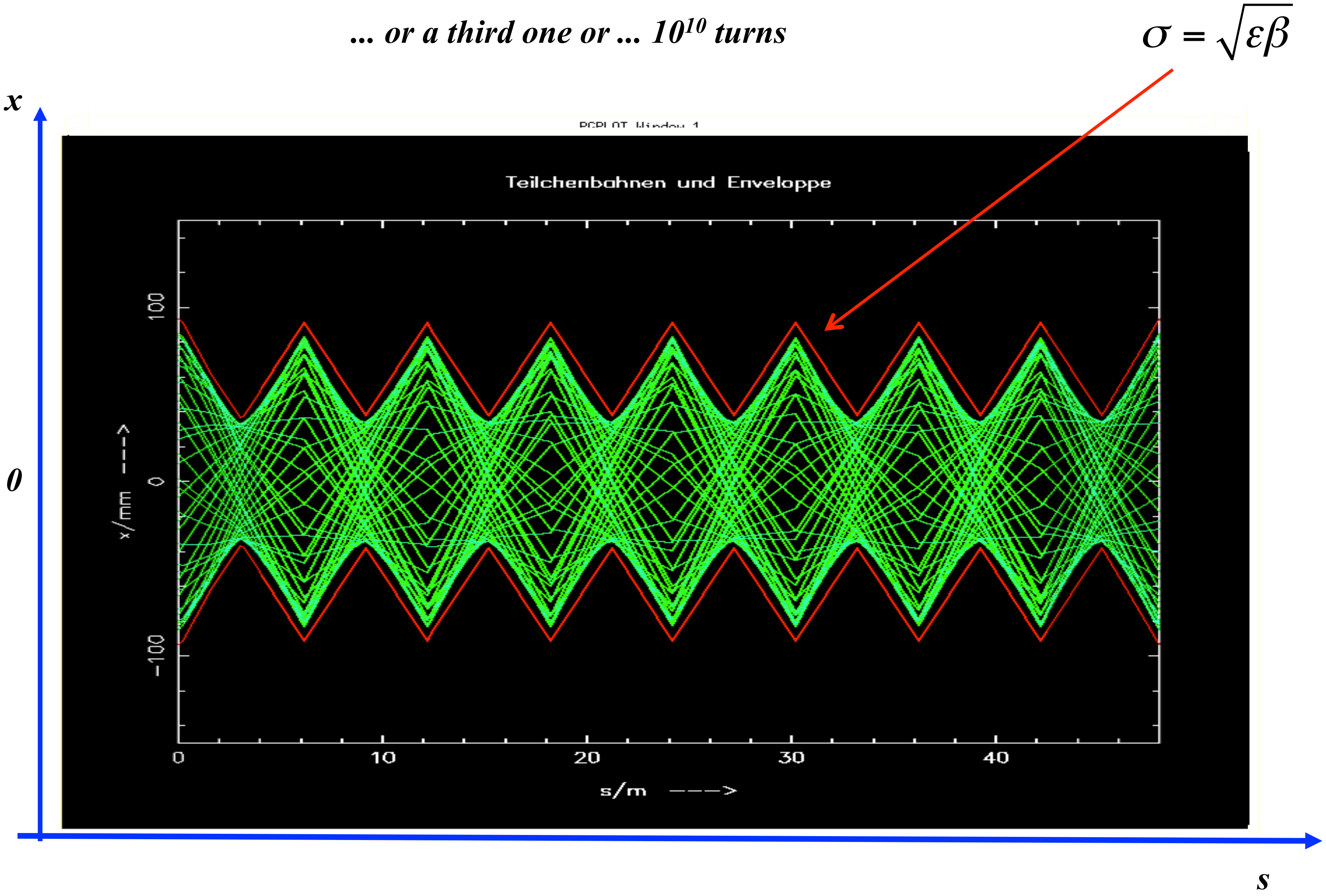


typical values in a strong foc. machine:

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

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

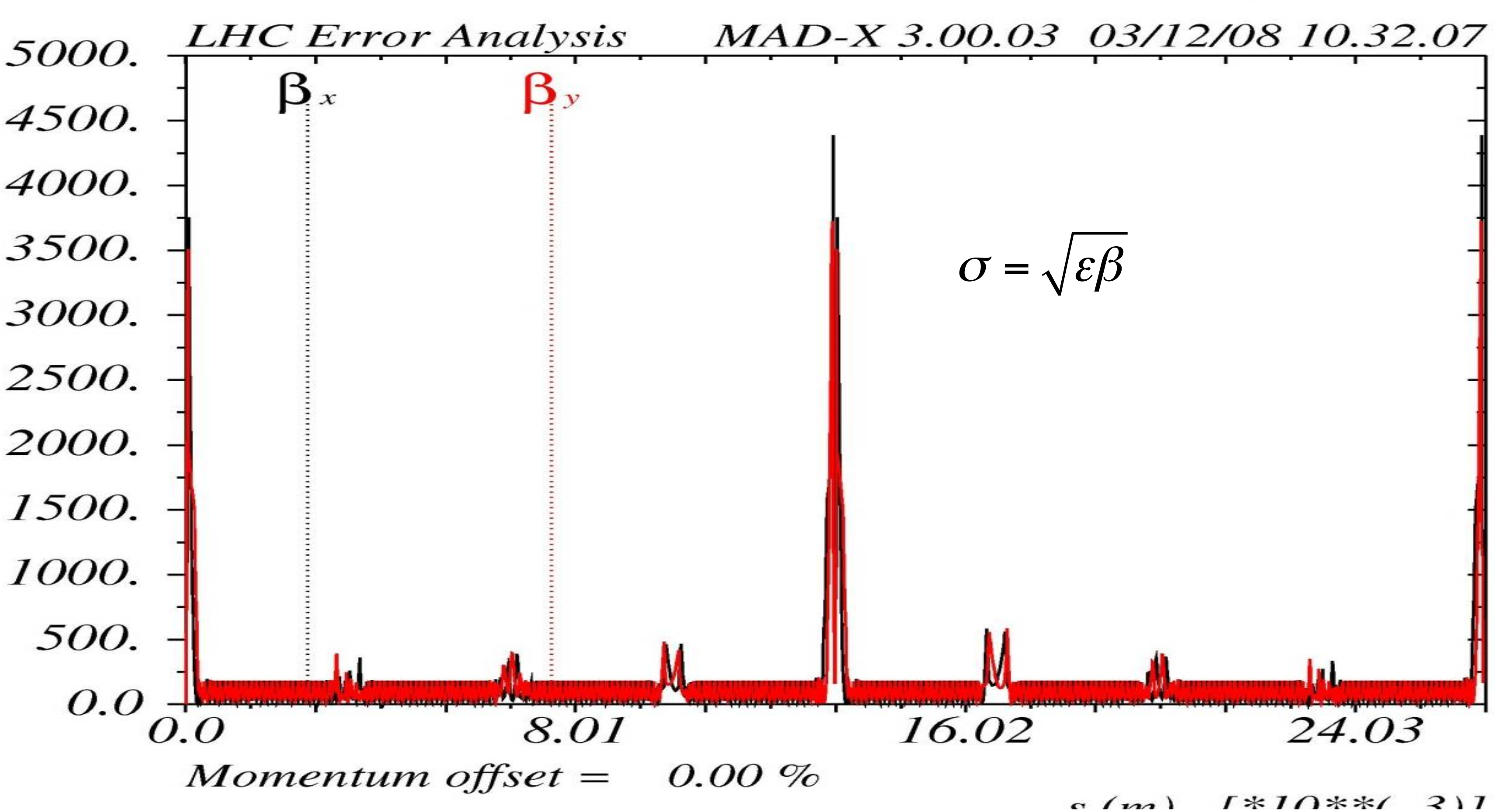
... or a third one or ... 10^{10} turns



The Beta Function:

The beta function determines the maximum amplitude a single particle trajectory can reach at a given position in the ring … And so it determines the size of the complete particle ensemble, which is caled "the beam".

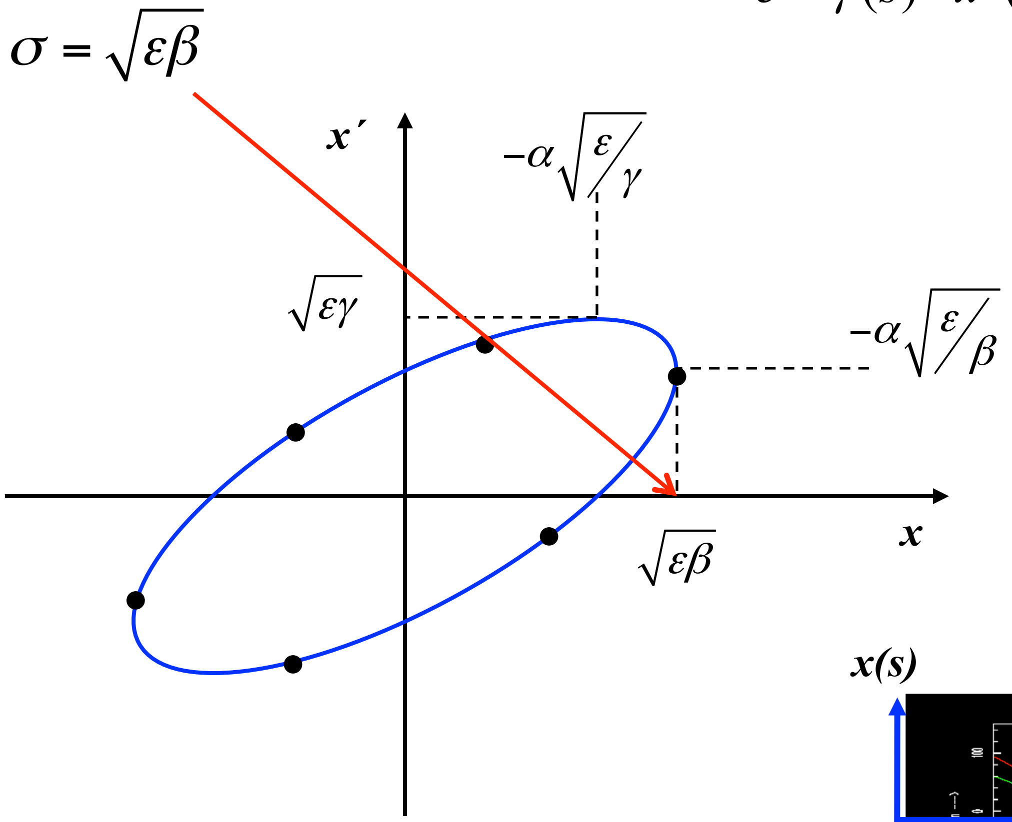
It is determined by the focusing properties of the lattice and follows the periodicity of the machine.



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

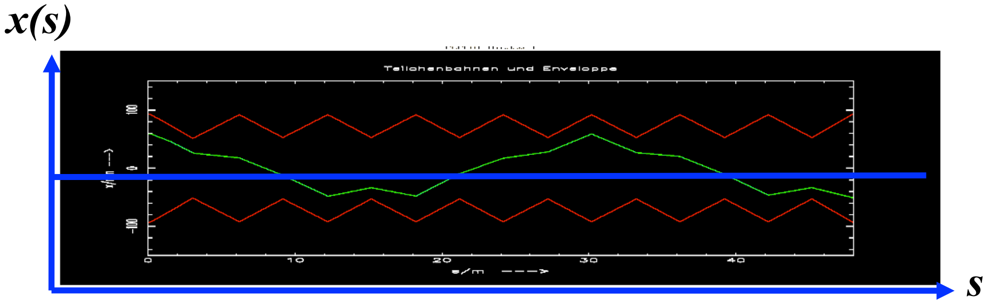
Beam Emittance and Phase Space Ellipse

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



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

$A = \pi * \varepsilon = const$

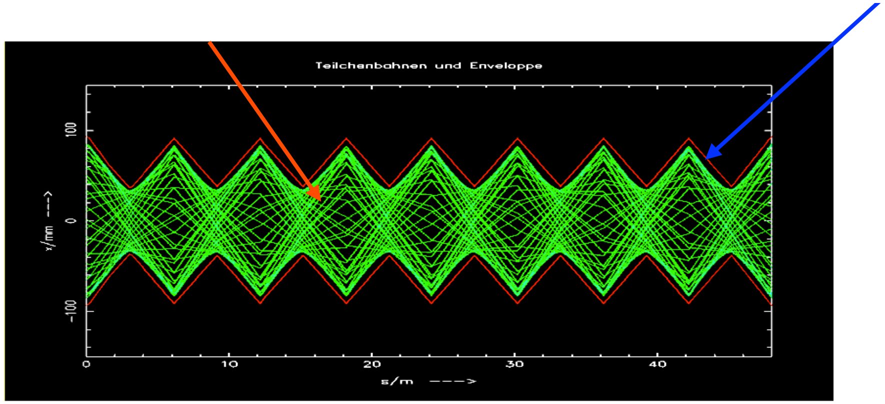


ε beam emittance = woozilycity of the particle ensemble, intrinsic beam parameter,
cannot be changed by the foc. properties.

Scientifiquely spoken: area covered in transverse x, x´ phase space … and it is constant !!!

Emittance of the Particle Ensemble:

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



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

Gauß Particle Distribution:

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

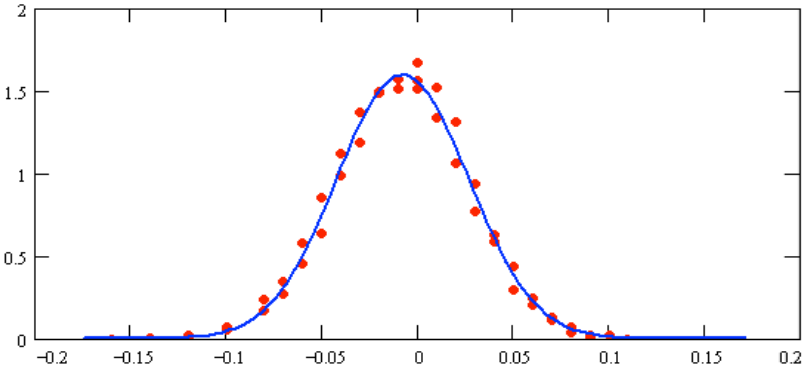
particle at distance 1 σ from centre
↔ 68.3 % of all beam particles

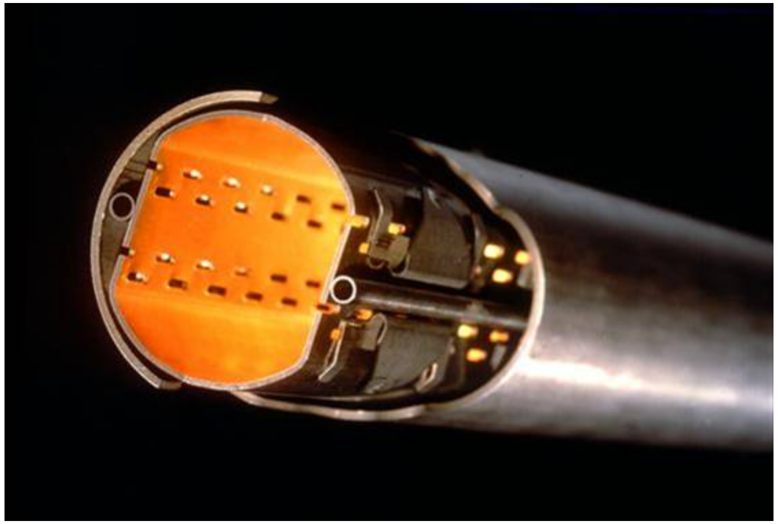
LHC:

$$\beta = 180\,m$$

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

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

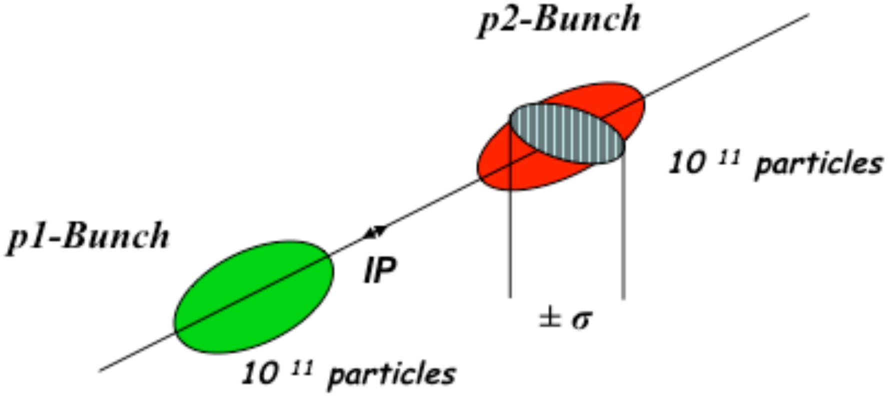




aperture requirements: $r_0 = 17 * \sigma$

Luminosity of a particle collider

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



Example: Luminosity run at LHC

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

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

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

$f_0 = 11.245\ kHz$

$n_b = 2808$

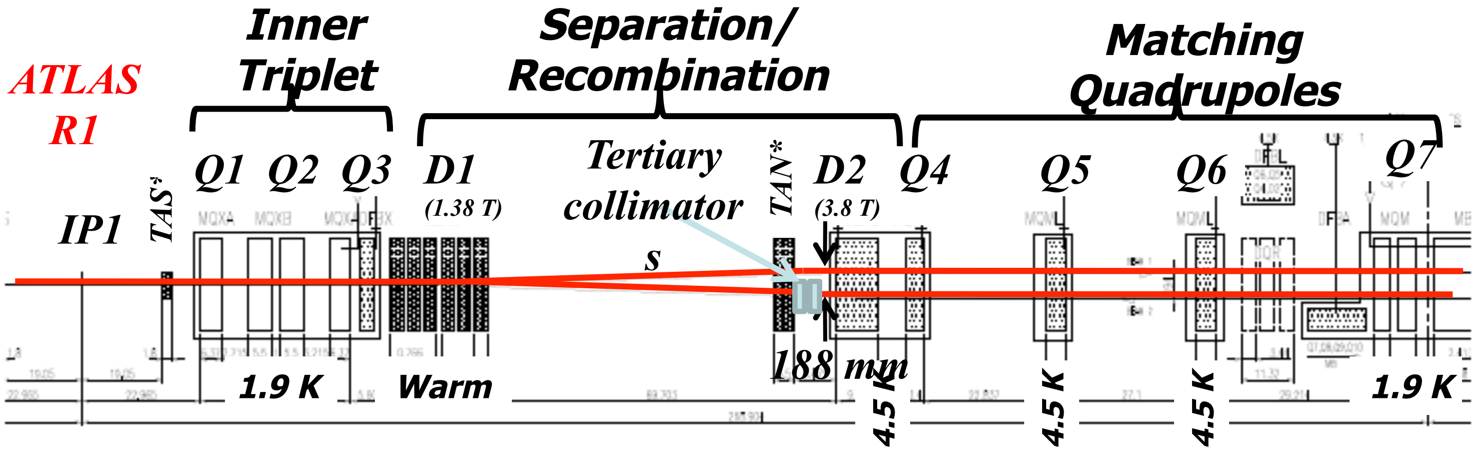
$I_p = 584\ mA$

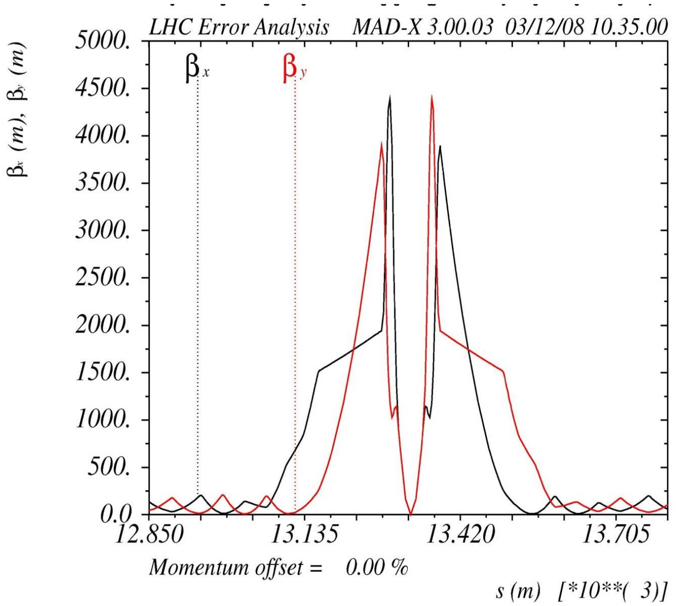
$$L = \frac{1}{4\pi e^2 f_0 n_b} * \frac{I_{p1} I_{p2}}{\sigma_x \sigma_y}$$

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

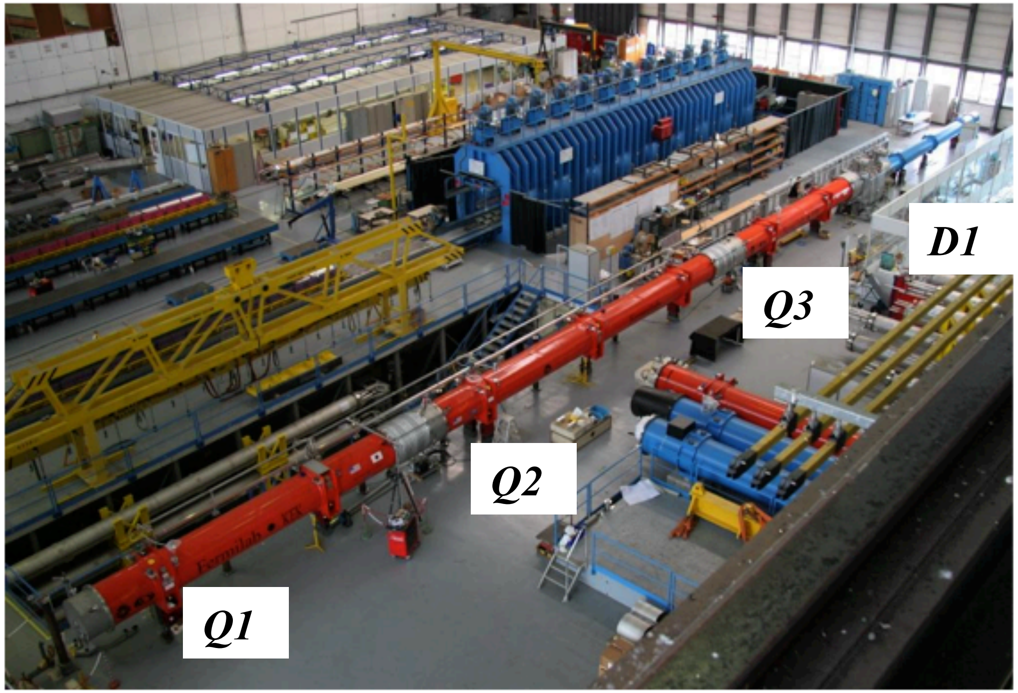
Make the beam size at the IP as small as possible → mini beta insertions

The LHC Mini-Beta-Insertions





mini β optics



Mini-Beta-Insertions in phase space

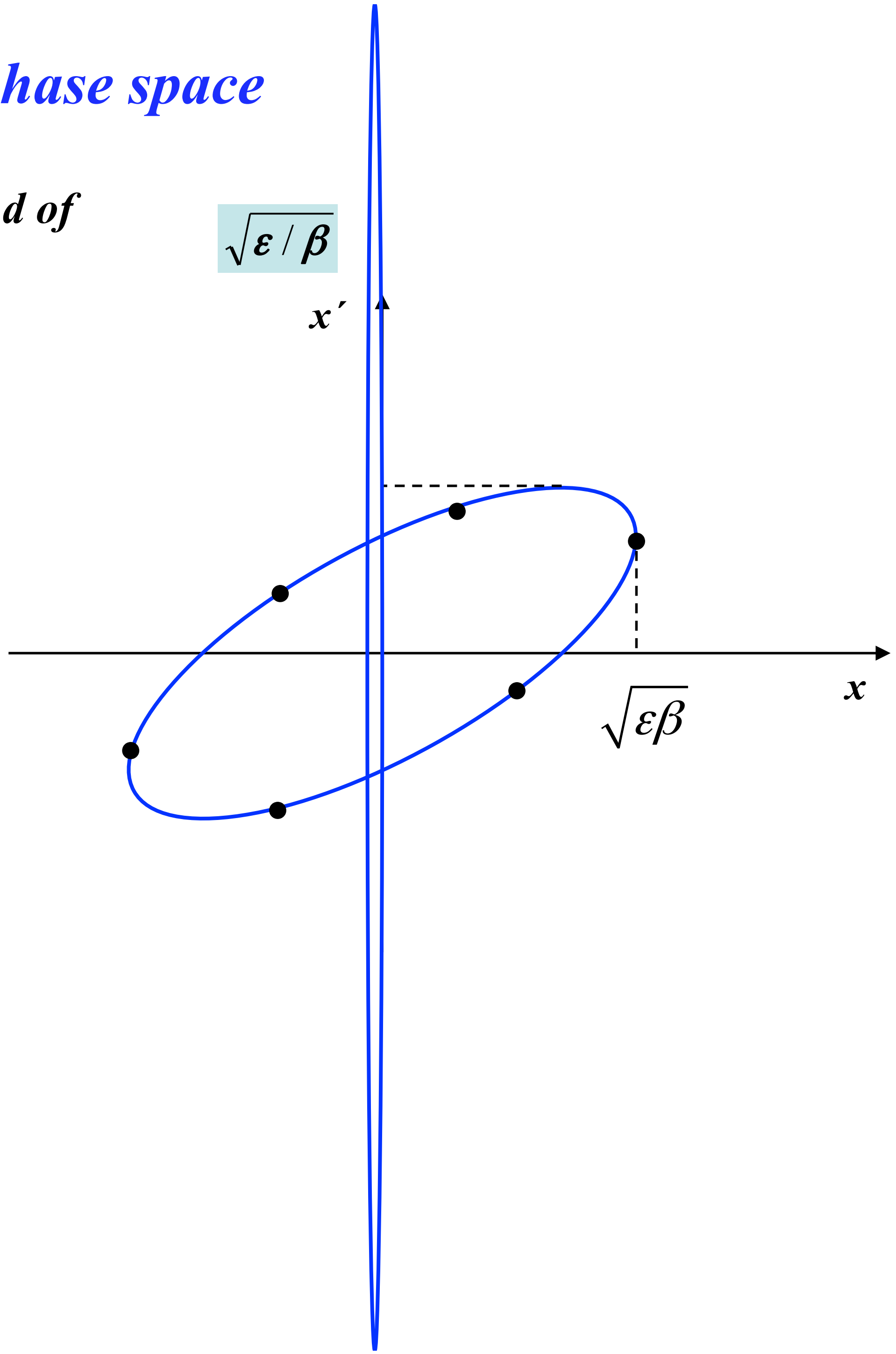
A mini-β insertion is always a kind of

special symmetric drift space.

→ greetings from Liouville

the smaller the beam size

the larger the bam divergence



Goal for the LHC Upgrade ... and what we have to do

The HL-LHC Lattice & Optic has to establish β* at IP1 & 5 to reach a luminosity of

$$L = 2.2 * 10^{35} \frac{1}{cm^2 s}$$

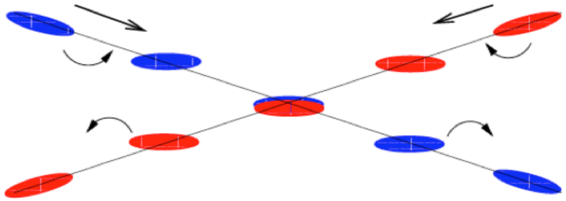
and for the given bunch intensit

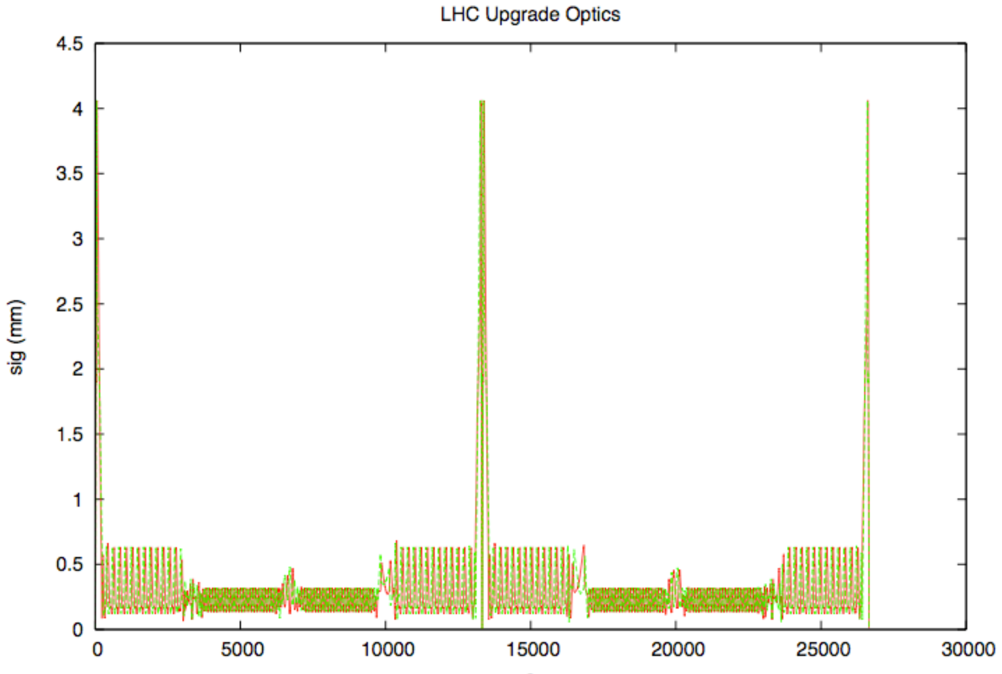
$$\beta_x^* = \beta_y^* \approx 55cm \rightarrow 15cm$$

but there is a little problem ….

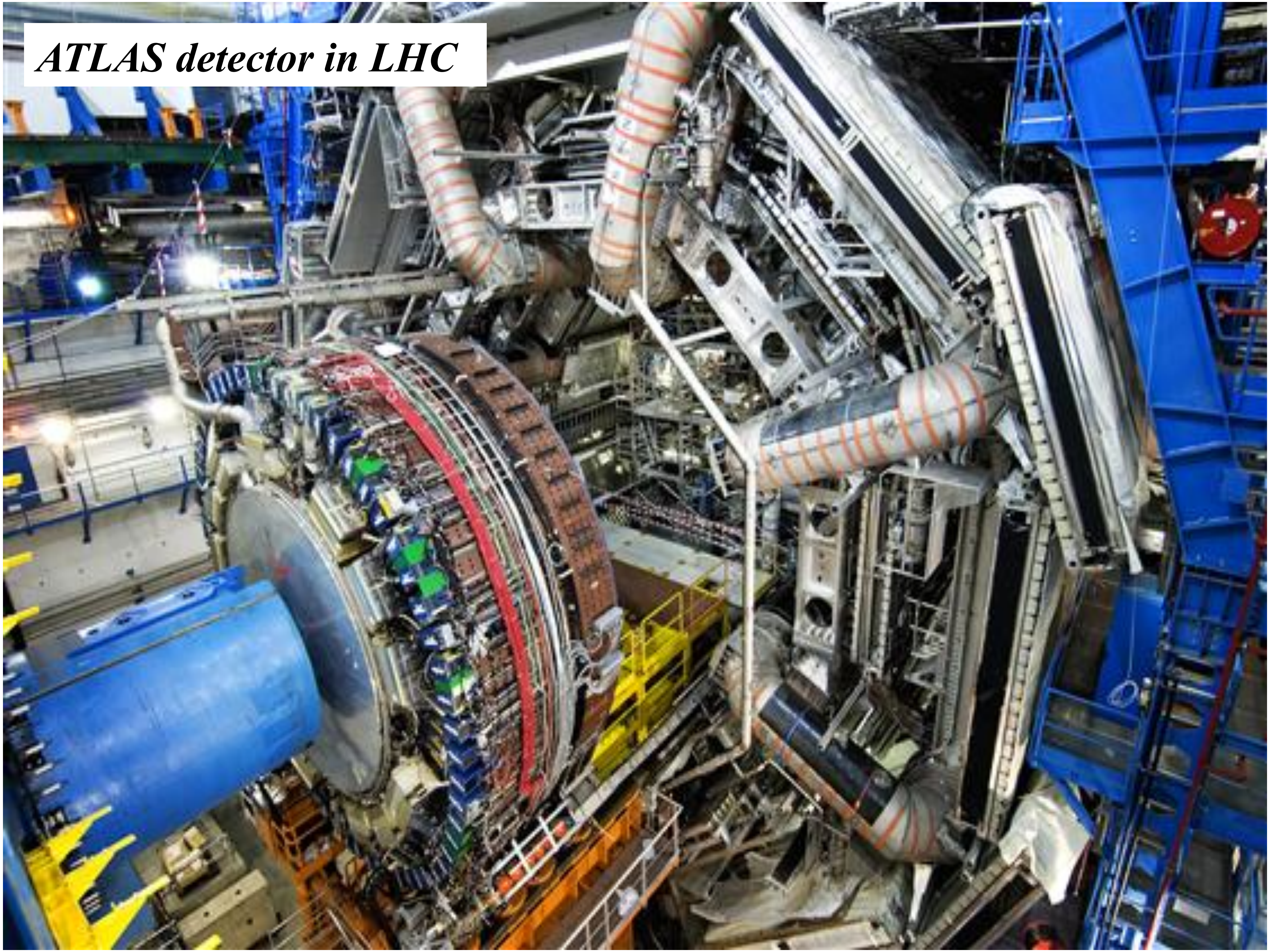
$$L = L_{ideal} * F$$

where F is the geometrical loss factor in case we do not collide head on.





ATLAS detector in LHC



Luminosity Upgrade:

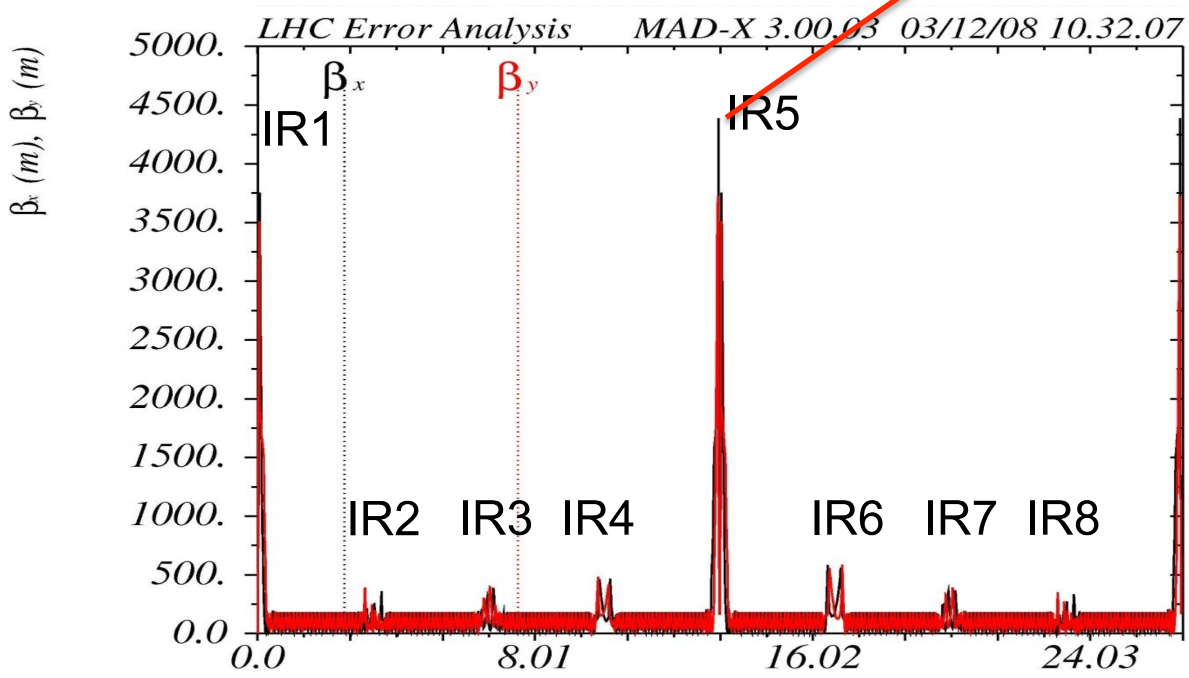
stronger focusing → smaller beam size at the IP

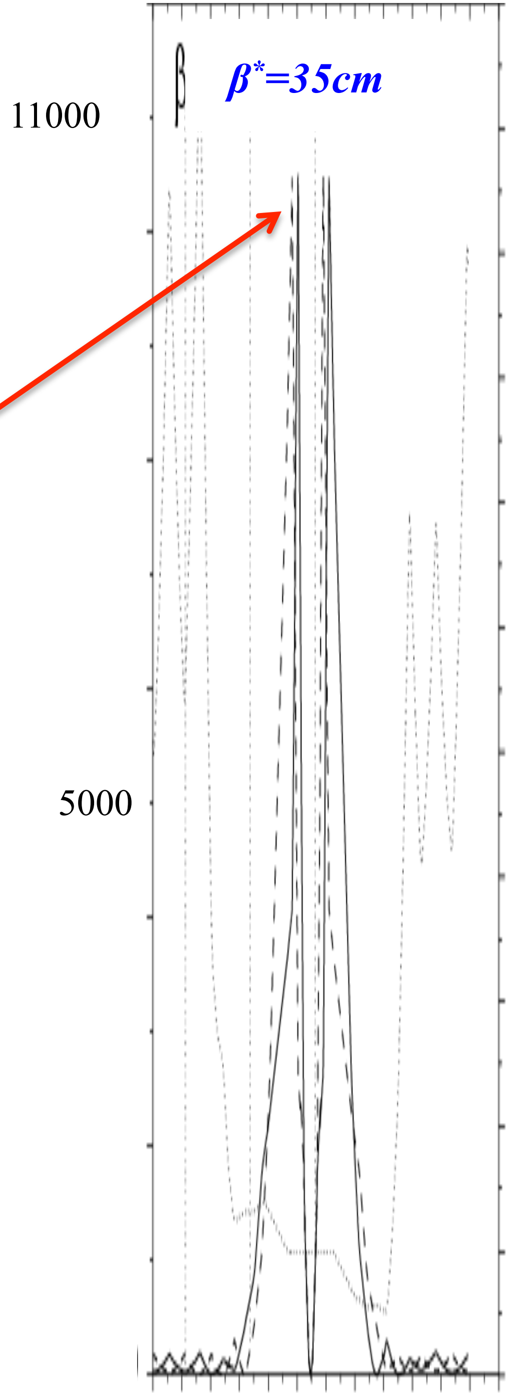
Beam divergence in a long symmetric drift:

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

higher gradients & larger aperture

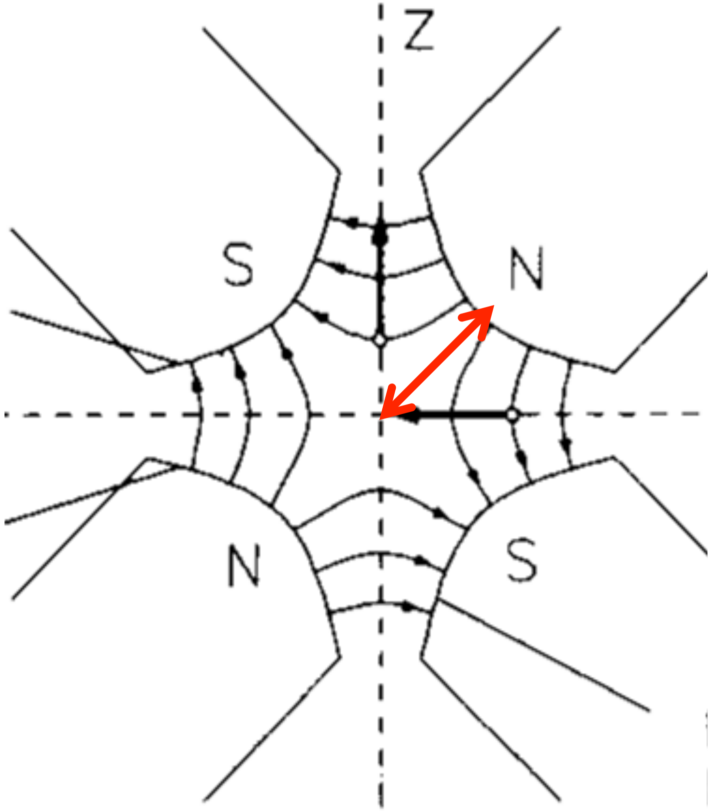
new sc. technology Nb_3Sn





HL-LHC: the challenges

smaller β → larger β at the quadrupoles*
→ larger aperture need, same gradient (!) $B_y = g\,x$ $B_x = g\,y$



for the same gradient
a larger B-field is needed at the coil

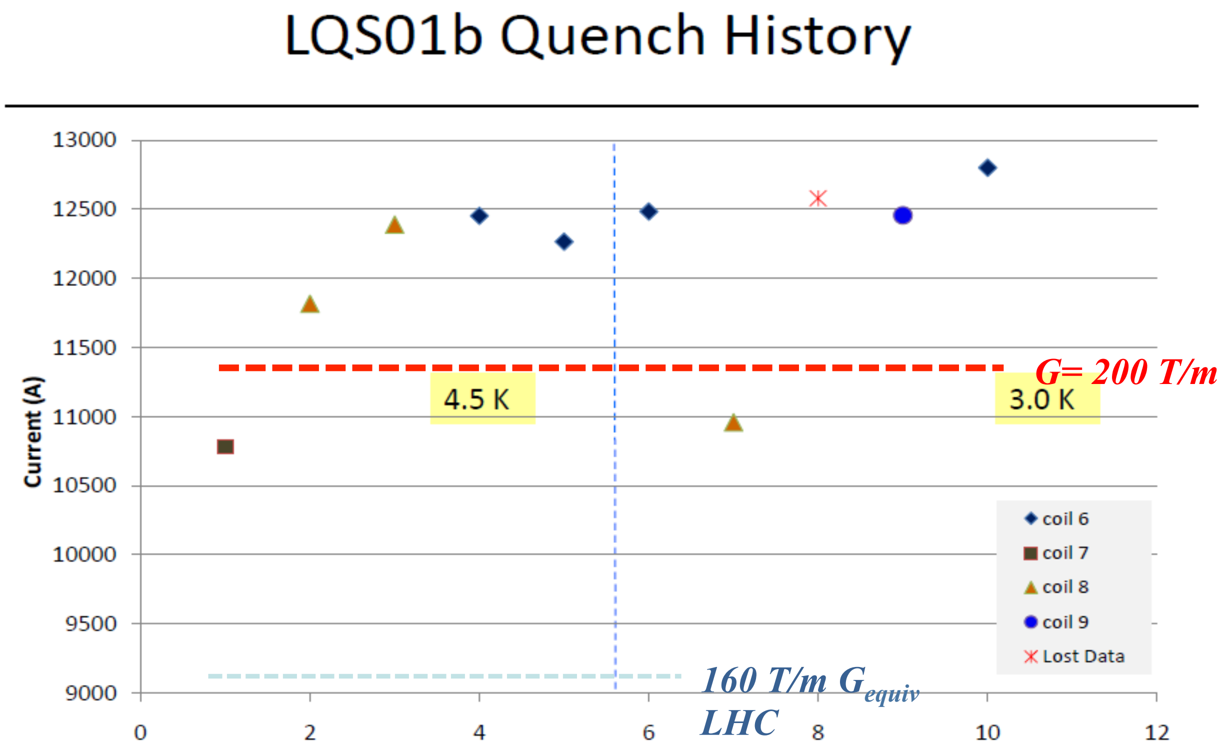
and we need a material that can
withstand this higher field
in its super conducting phase !!!

Nb_3Sn

LHC: *NbTi,* *g = 220T/m,* *r = 31mm*
HL-LHC: Nb_3Sn*,* *g =200T/m,* *r = 60mm*

High Field Nb_3Sn Quad

- Nb_3Sn is becoming a reality (first LQ long -3.6 m – quad 90 mm)
- This year we expect a second LQ **and a 1 m long - 120 mm** aperture model
- In 3 years: 4-6 m long magnets, 120 mm ap., G=180-200 T/m



court. L. Rossi

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

HL-LHC Geometric Loss Factor

... increase number of protons per bunch

$N_1, N_2 = 1.7 * 10^{11}$

... decrease the beam size at IP

stronger gradients, larger aperture

$\beta_x = \beta_y = 0.15$ m

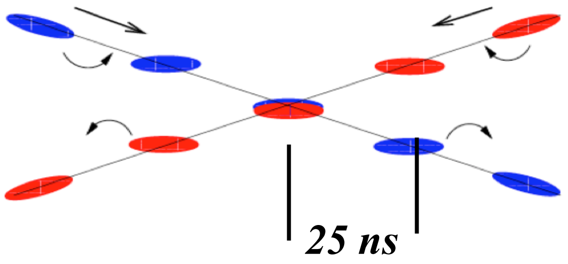
... reduce the geometric loss factor
with crab cavities

	LHC nominal	HL-LHC
N_p [10^{11}]	1.15	2.2
n_b	2808	2808
β* [m]	0.55	0.15
ε_n[μm]	3.75	2.5
bunch distance	25ns	25ns
x-angle [μrad]	300	590
L_{peak}	$1*10^{34}$	$2.2*10^{35}$

$$L = \frac{N_1 N_2 f_{rev} n_b}{2\pi\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}} F$$

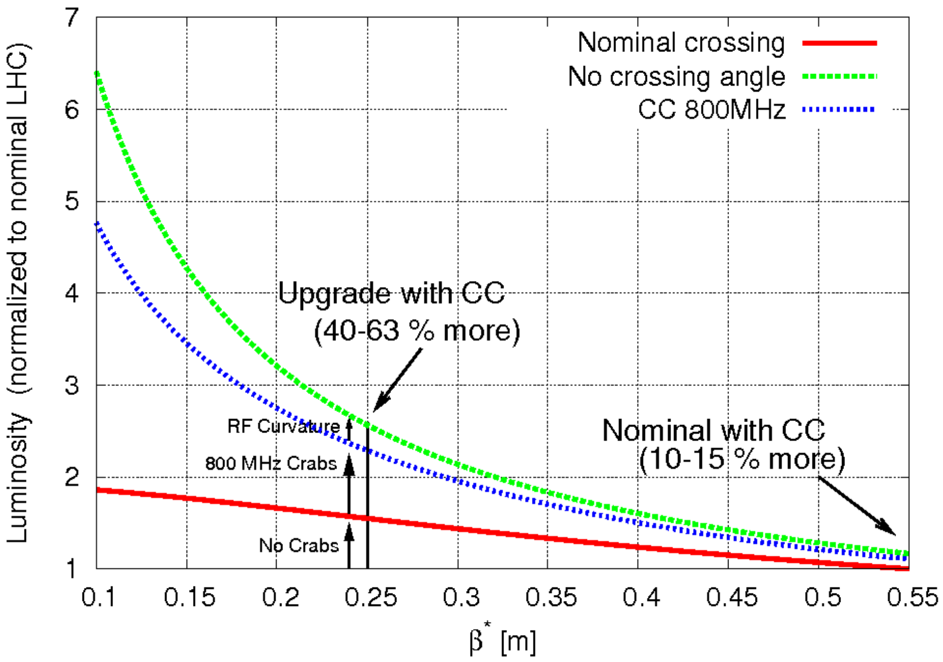
$$F = \frac{1}{\sqrt{1 + 2\frac{\sigma_s^2}{\sigma_{1x}^2 + \sigma_{2x}^2}\tan^2\frac{\phi}{2}}}$$

$F_{LHC} = 0.836$
$F_{HL\_LHC} = 0.31$.



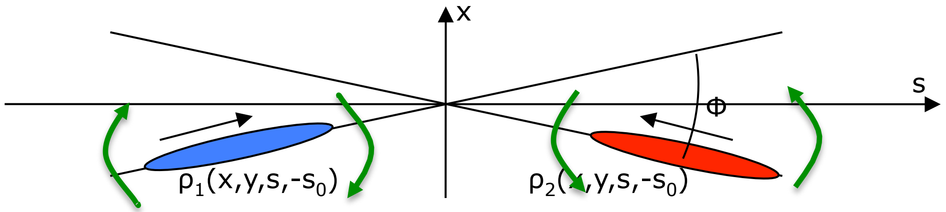
F is a pure crossing angle (*Φ*) contribution:

HL-LHC Crab Cavities



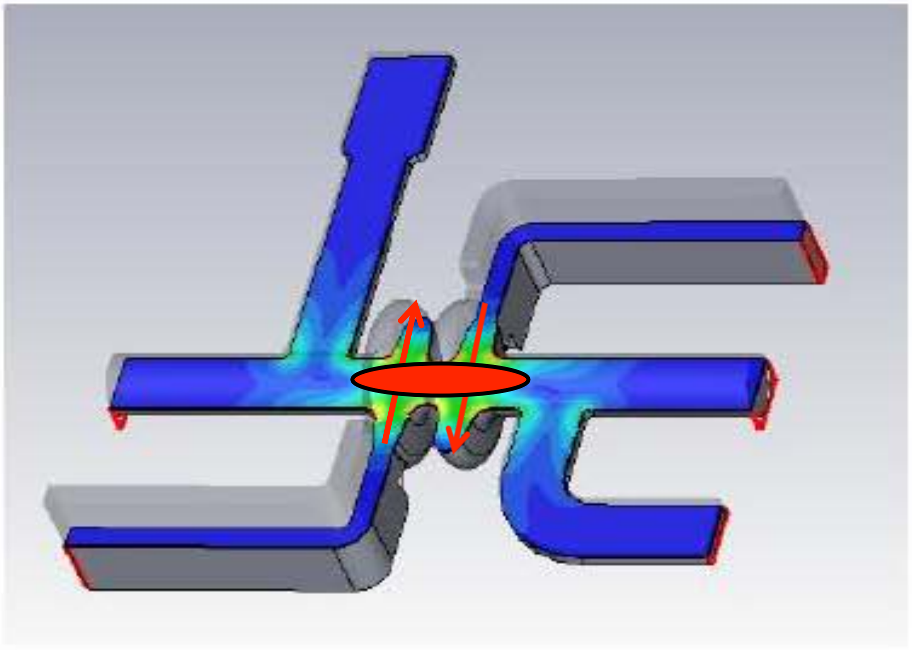
Elliptical 800 MHz not far from being designed
technical challenge:

fast, precise, compact,
Fail SAFE !!



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

$$L = \frac{f_{rev}\, n_b}{4\pi} * \frac{N_1\, N_2}{\sigma_x\, \sigma_y} * F$$



4.) Push for higher energy: FCC

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

FCC-pp - Collider

The Next Generation Ring Collider

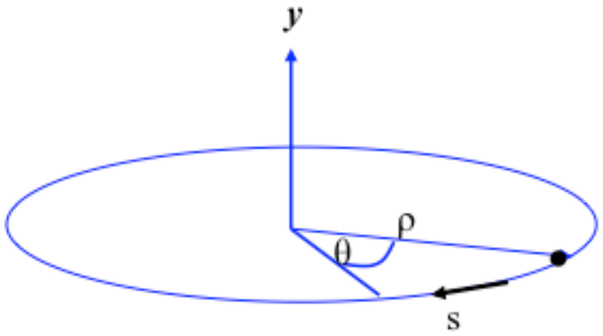
Maximum Beam Energy in a Storage Ring:

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

... and so the energy

$$\cancel{E = mc^2}$$

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



circular coordinate system

Condition for an ideal circular orbit:

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

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

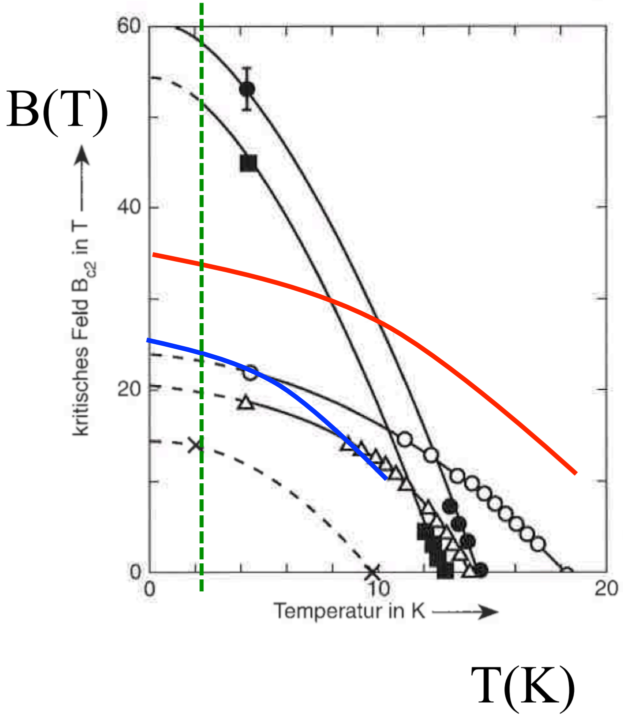
$$\frac{\gamma\, m_0\, \cancel{v^2}}{\rho} = e\,\cancel{v}\,B$$

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

B ρ = "beam rigidity"

Two key players in sc magnet technology: NbTi and Nb_3Sn

168 *5 Supraleiter im Magnetfeld*

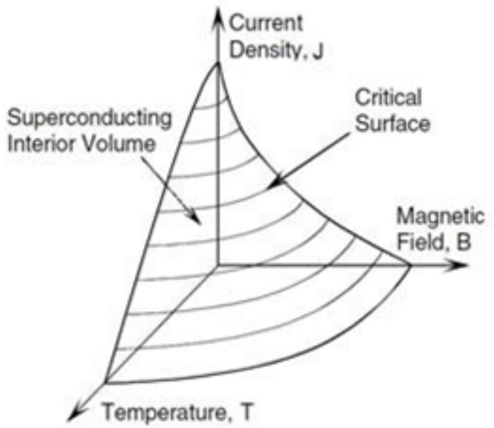


critical field in NbTi and Nb_3Sn

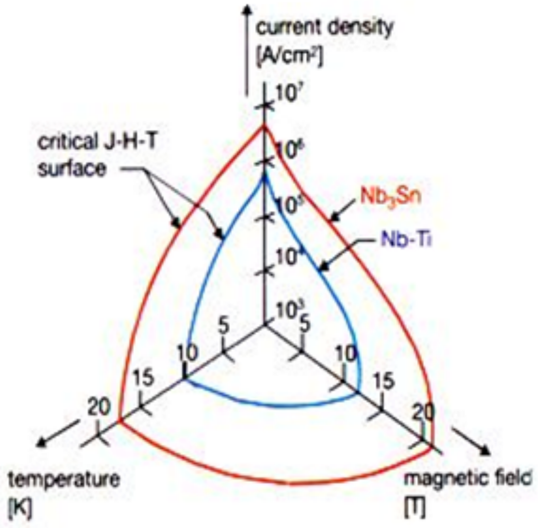
Abb. 77 Oberes kritisches Feld einiger Hochfeldsupraleiter.

–○–○–○– 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. Fische
Otaniemi 1975, Band
Publ. Comp. 1975).

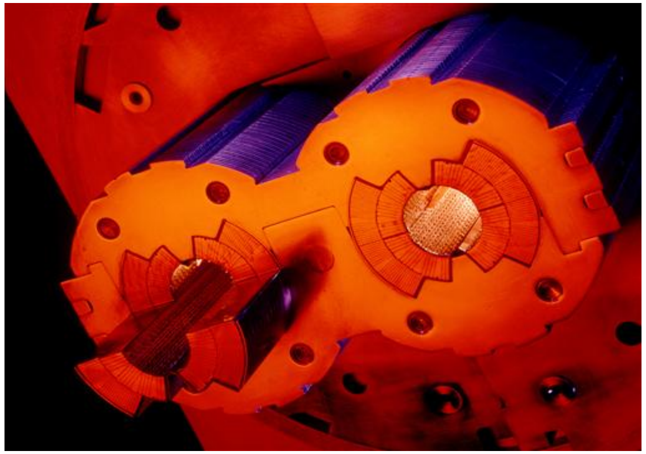
General



NbTi and Nb_3Sn

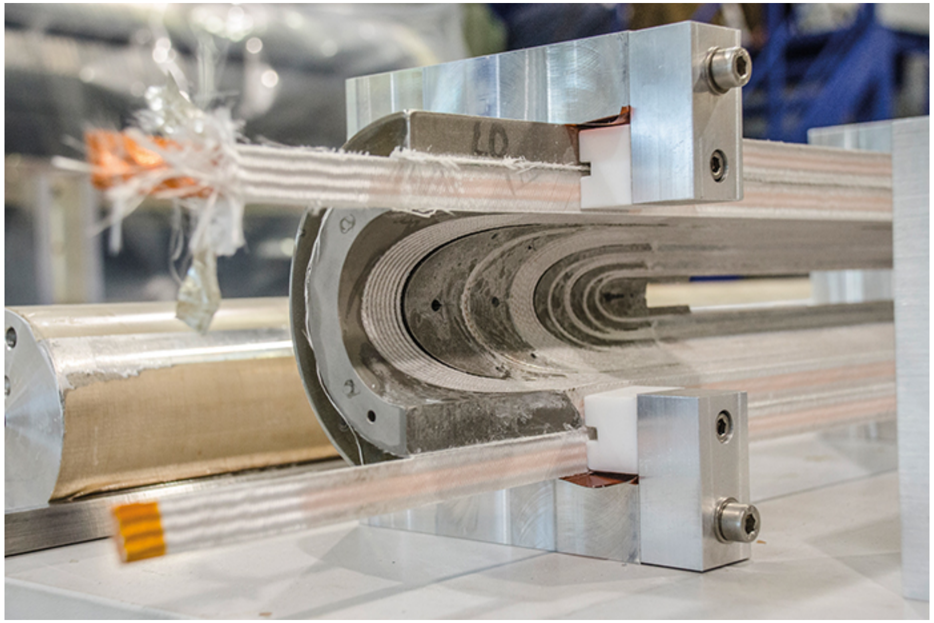


The Push for Higher Beam Energy



NbTi LHC standard dipoles,
8.3 T

Nb_3Sn FCC type dipole coils,
11 T – 16 T



it is a simple scaling wrt LHC:

circumference 100km /27km
→ Factor 3.7

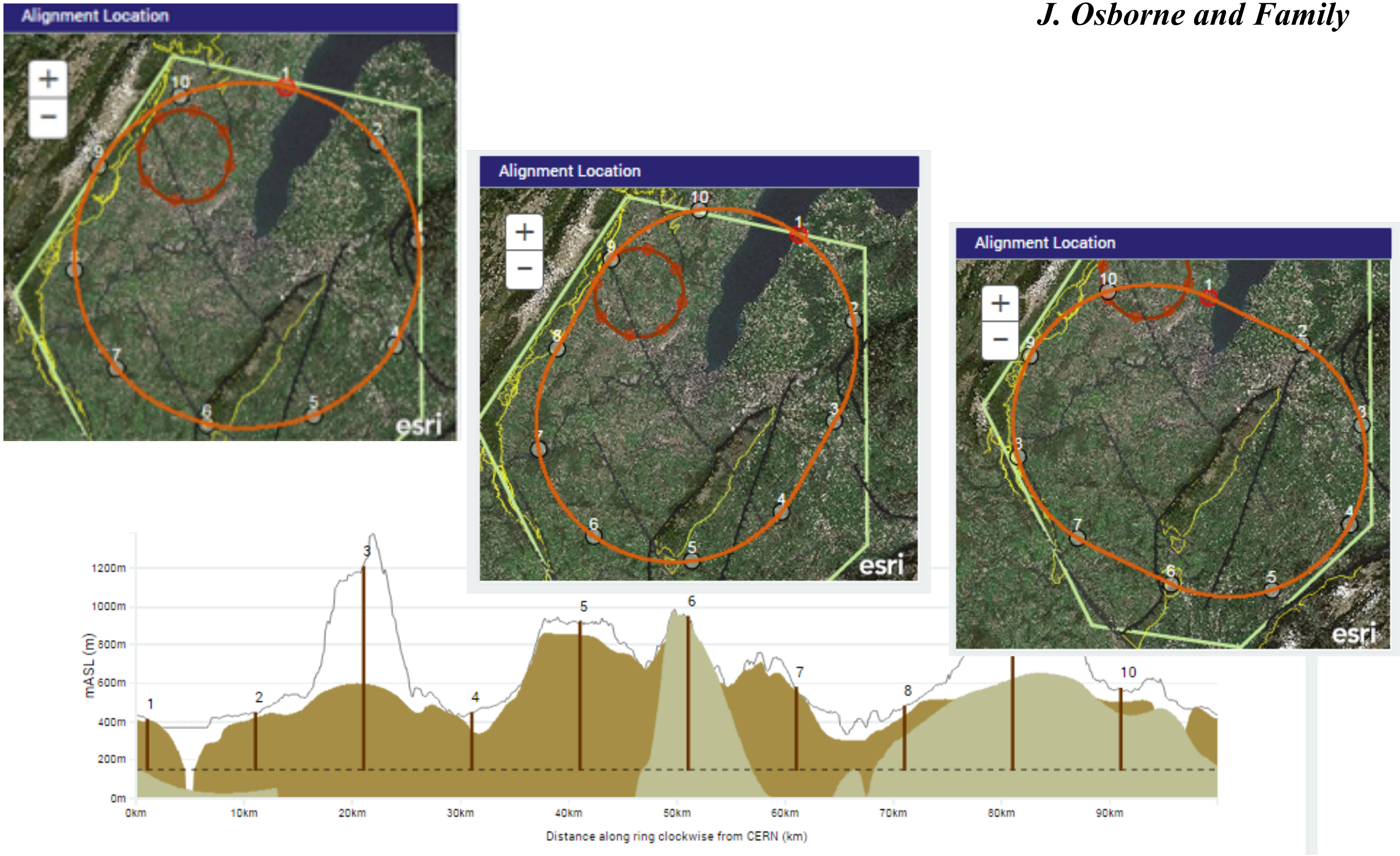
dipole field: 16 T / 8.3 T
→ Factor 1.93

LHC energy E_{cm} = 2* 7 TeV * 7.1

FCC energy E_{cm} = 100 TeV centre of mass

Latest News: Geographical / Geological Considerations

J. Osborne and Family



Build the Lattice Design on a modular basis using building blocks that are matched / or "matchable" to each other to follow a large variety of geometries

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

Pushing the limit (Dipole Fill Factor):

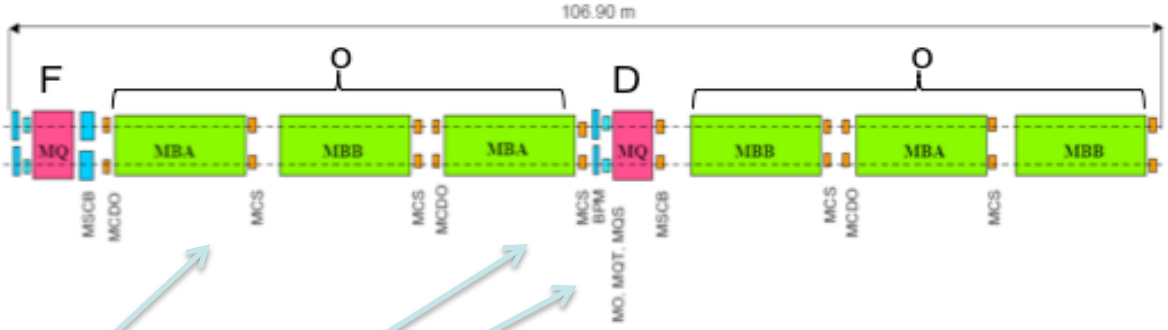
12 dipoles per cell, l_{dipole}=14.2m
34 cells per arc
12 arcs
dipole field = 15T <--> 50TeV
or 16T <--
> 53.33TeV

5016 dipoles
drifts a la LHC: dipole-quad=3.6m
dipole-dipole=1.3m

$$\zeta = \frac{L(\Sigma_{dipoles})}{L_{cell}} = 82\%$$

Arc-Cell: 200m FoDo
12 dipoles a 15m length

scaled from LHC design



Variables:
dipole length
dipole number
cell length

Constants (??):
drift (dipole-dipole) =1.3m
drift (dipole-quadrupole) =3.6m
quadrupole length =3.1m

to be discussed !!!

5.) High Energy Lepton Colliders

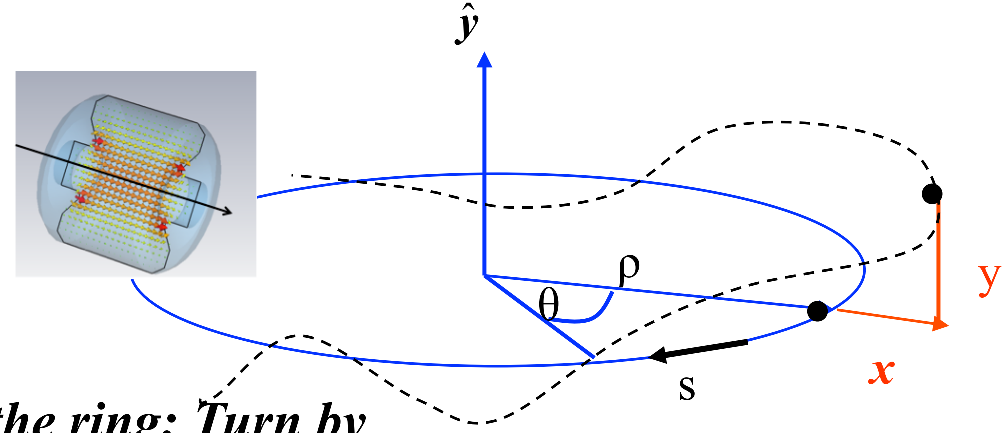
**** Limited by Synchrotron Radiation***

**** and RF Power***

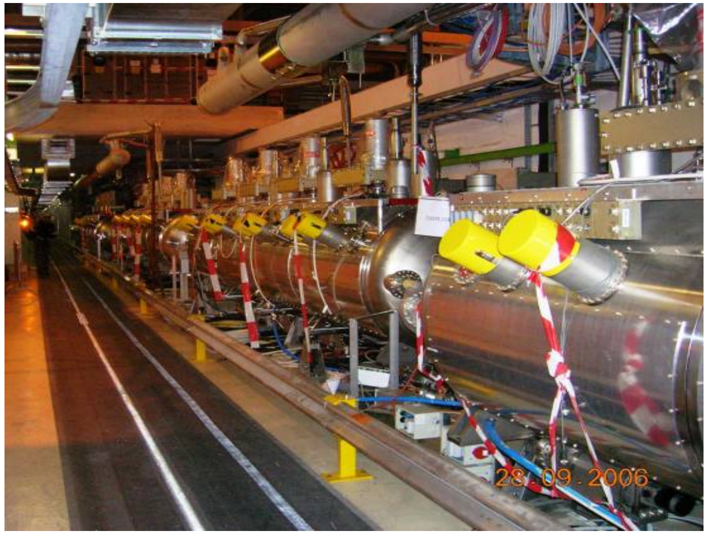
FCC-ee Collider

The next Generation e+/e- Ring Collider

Beam Acceleration in LHC



Install an RF accelerating structure in the ring: Turn by turn the particles will receive a kick and "speed up"



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

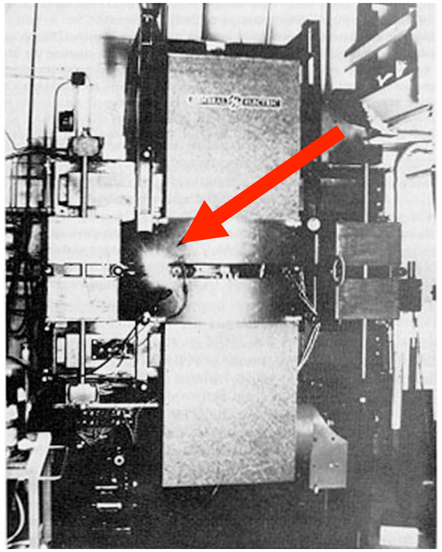
Bunch length (4σ)	ns	1.06
Energy spread (2σ)	10^{-3}	0.22
Synchr. rad. loss/turn	keV	7
RF frequency	MHz	400
RF voltage/beam	MV	16
Energy gain/turn	keV	485

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 lose energy via emission of intense light.



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

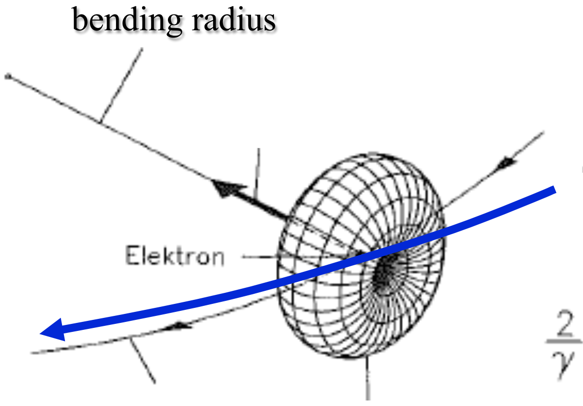
$$\Delta E = \frac{4}{3}\pi\alpha\hbar c \boxed{\frac{\gamma^4}{\rho}}$$ ***energy loss***

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

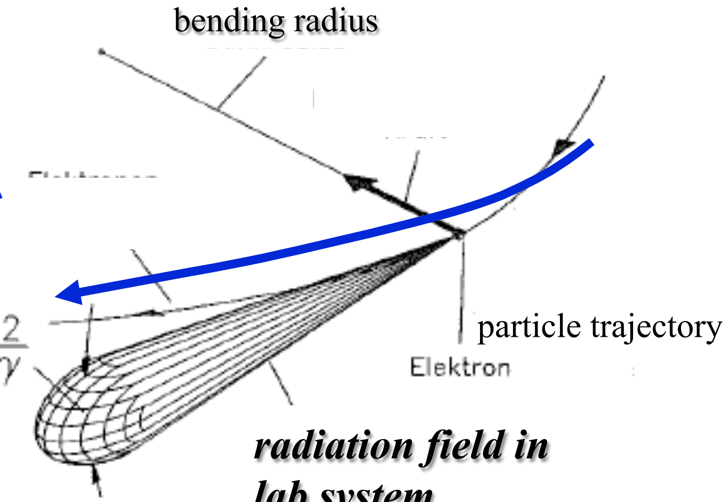
$$\alpha \approx \frac{1}{137}$$

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

1946 observed for the first time in the General Electric Synchrotron



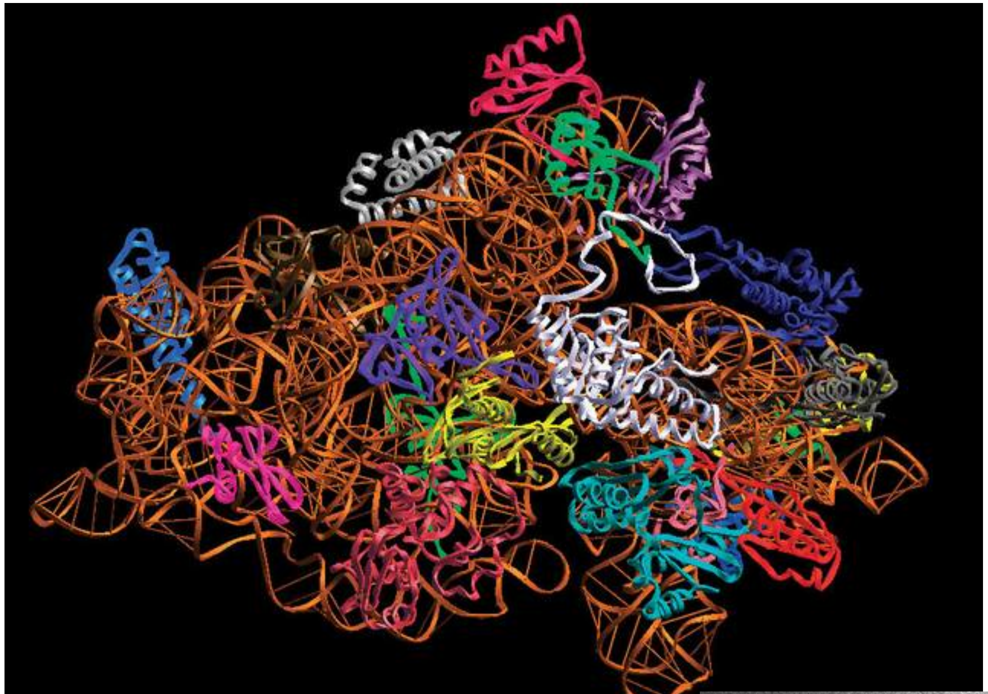
radiation field in electron rest frame



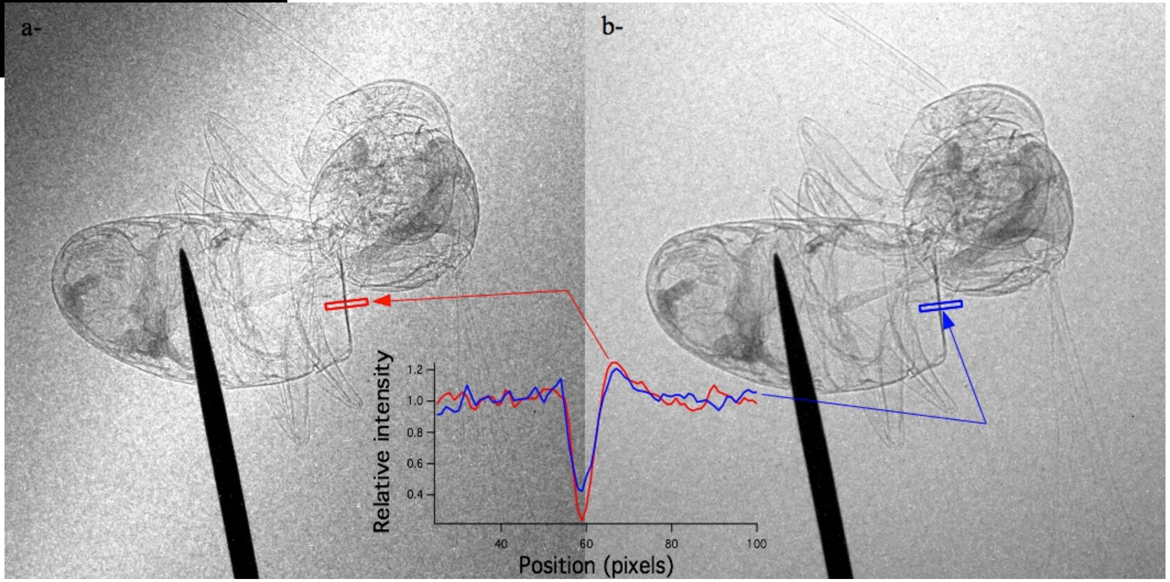
radiation field in lab system

court. K. Wille

Synchrotron Radiation as useful tool



structure analysis with
highest resolution
Ribosome molecule

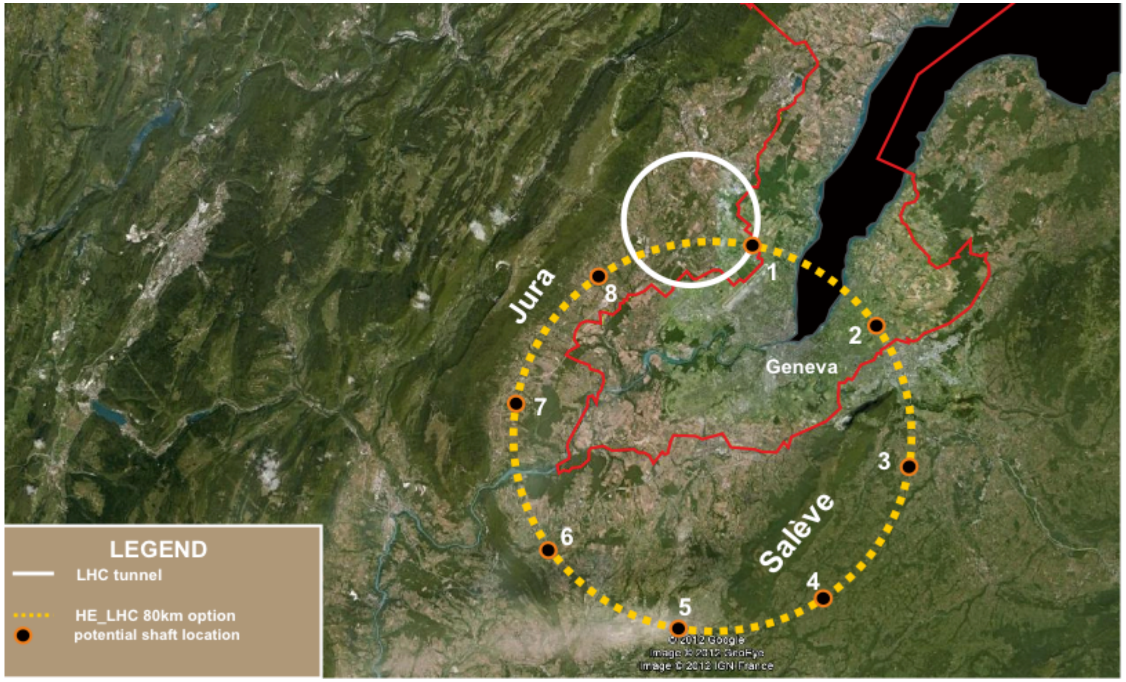


Absorption Line Radiographie

Planning the next generation e+ / e- Ring Colliders

Design Parameters FCC-ee

$E = 175\ GeV / beam$
$L = 100\ km$



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

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

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

$$\Delta P_{sy} \approx 47\ MW$$

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

6.) Push for higher energy

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

Lepton Colliders: Linear / Storage Rings

Avoid bending forces → go linear

Storage Ring:

dipole magnets

synchrotron radiation

energy loss per turn

$$P_\gamma = \frac{c\,C_\gamma}{2\pi}\frac{E^4}{\rho^2}\;,\quad C_\gamma = 8.9*10^{-5}\,m/GeV^3$$

high RF power to compensate losses

very efficient,

turn by turn acceleration

Linear Collider:

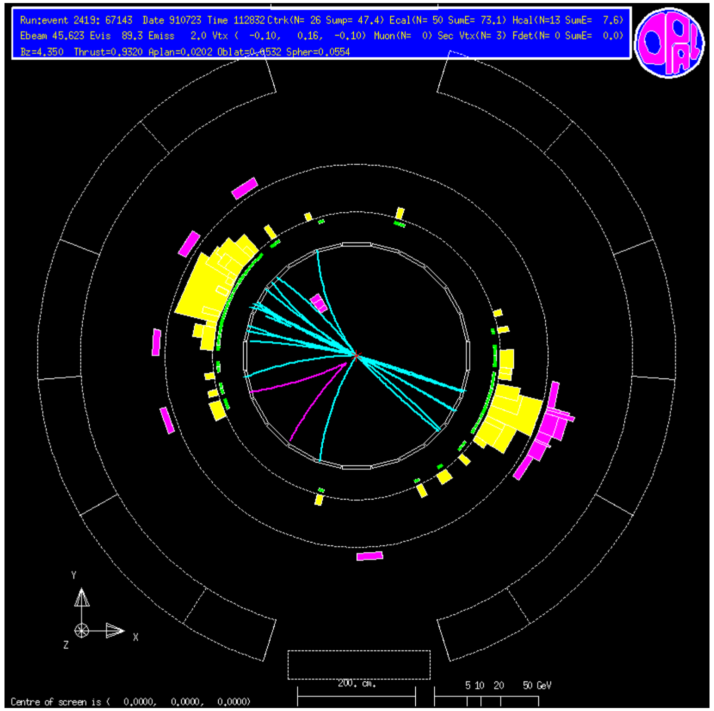
no synchr. Radiation

limited efficiency:

N^{10}-1 particles are lost after the collision

need highest acceleration gradient

"one turn" machines"



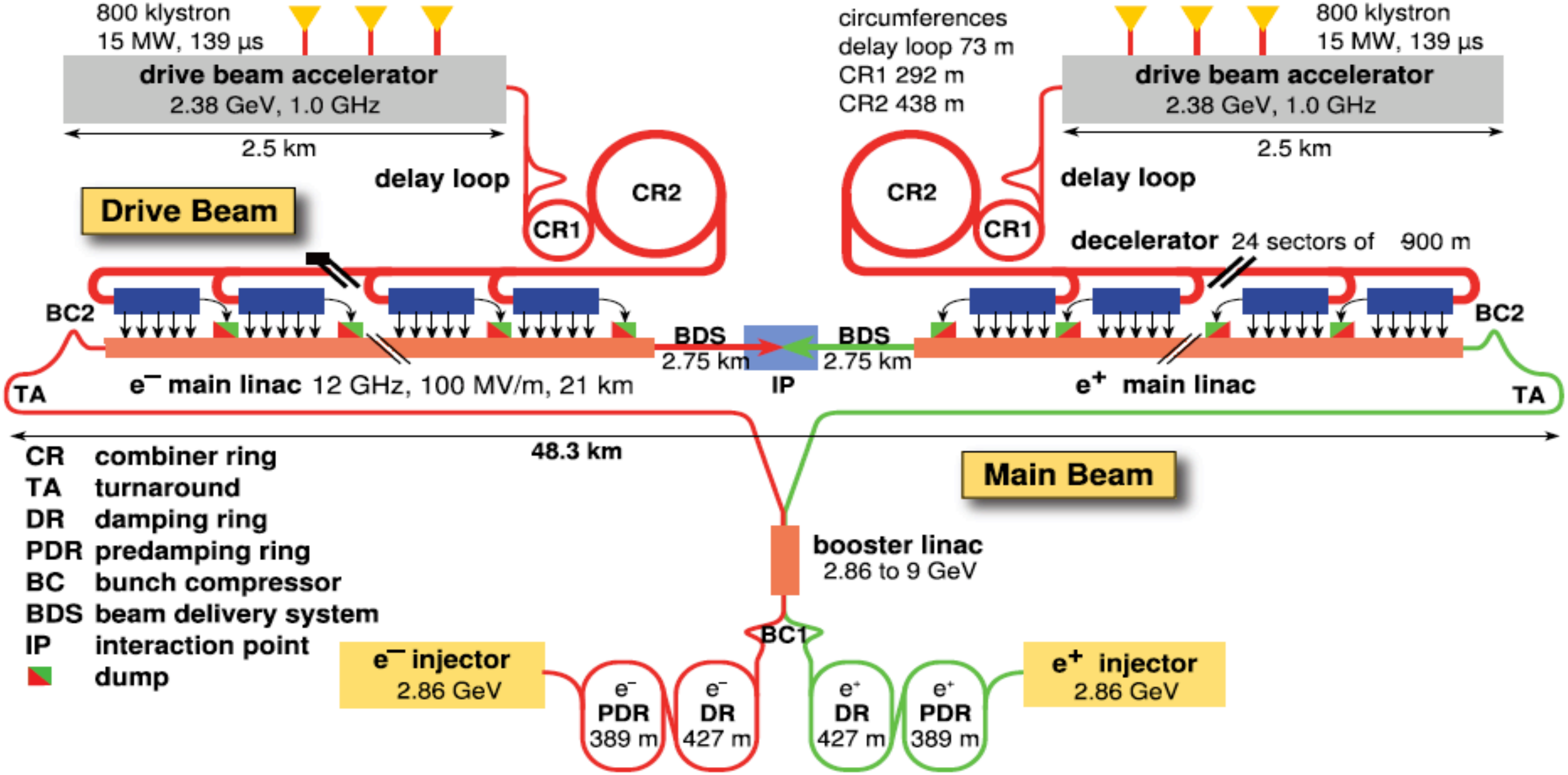
```
Run:event 2419: 67143  Date 910723 Time 112832 Ctrk(N= 26 Sump= 47.4) Ecal(N= 50 SumE= 73.1) Hcal(N=13 SumE=  7.6)
Ebeam 45.623 Evis  89.3 Emiss   2.0 Vtx (  -0.10,   0.16,  -0.10) Muon(N=  0) Sec Vtx(N= 3) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9320 Aplan=0.0202 Oblat=0.0532 Spher=0.0554
Centre of screen is (   0.0000,   0.0000,   0.0000)
```

lepton colisions are "*clean*"

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

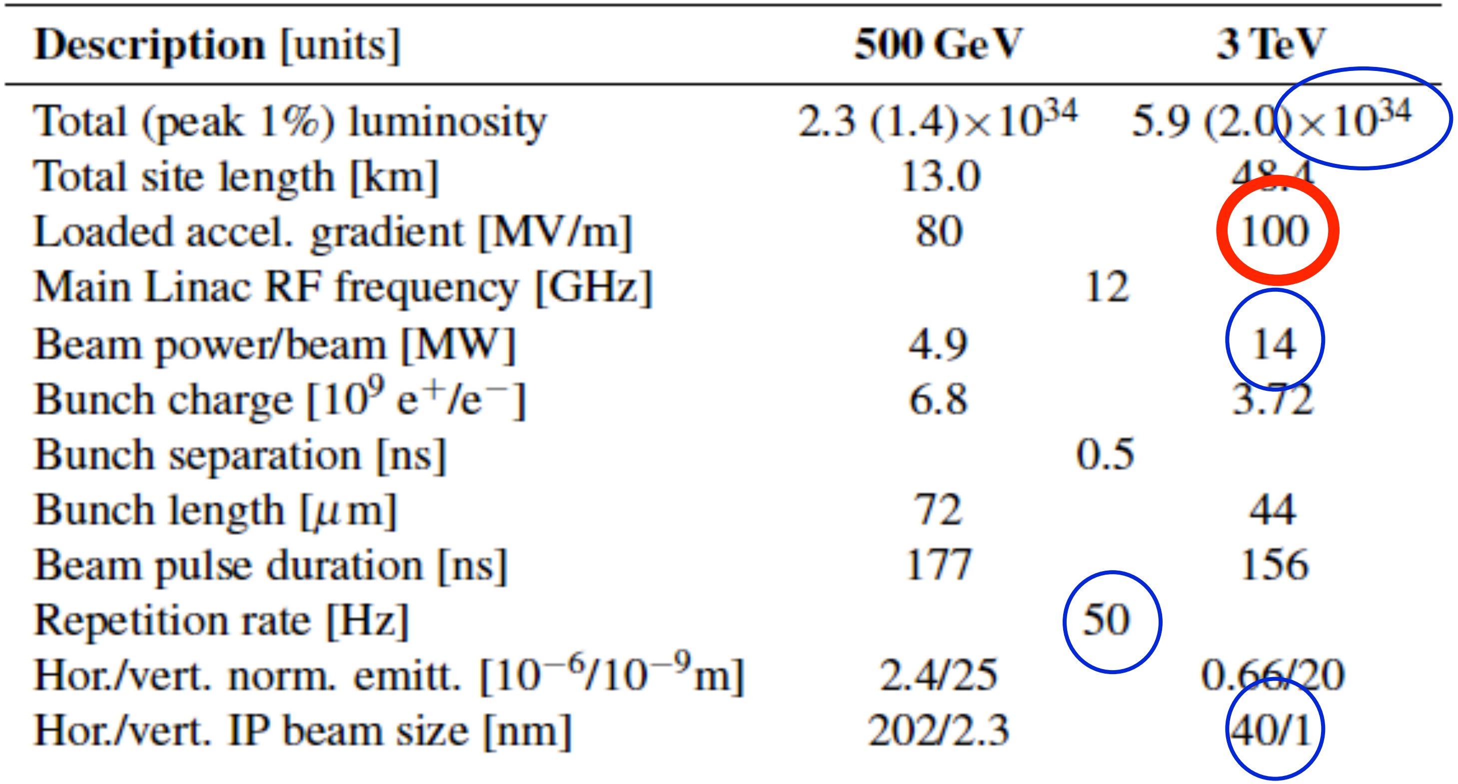
Avoid bending magnets => no synchrotron radiation losses

=> energy gain has to be obtained in ONE GO



CR	**combiner ring**
TA	**turnaround**
DR	**damping ring**
PDR	**predamping ring**
BC	**bunch compressor**
BDS	**beam delivery system**
IP	**interaction point**
🟥	**dump**

CLIC Parameter List

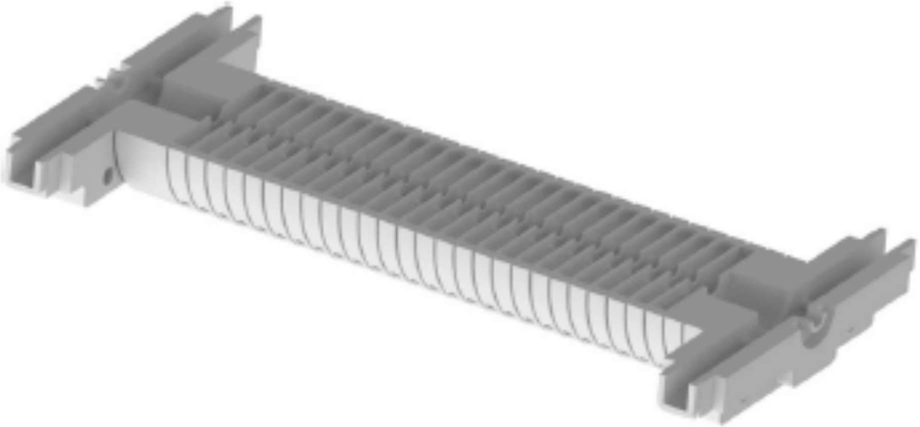


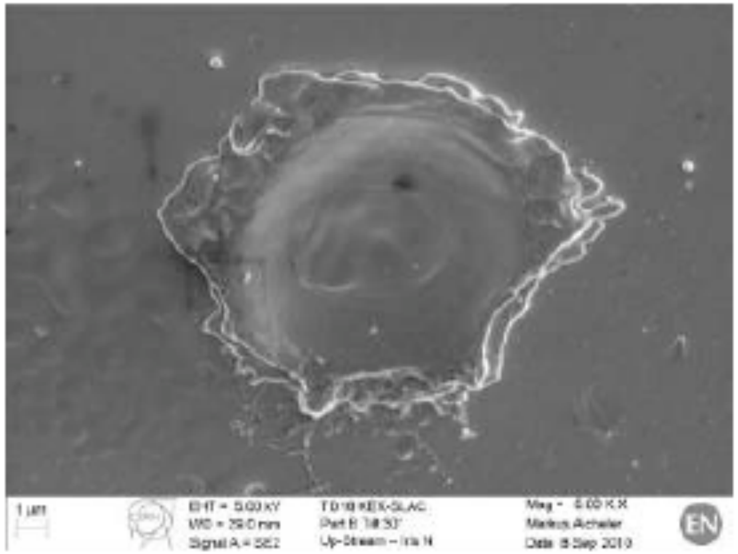
Description [units]	**500 GeV**	**3 TeV**
Total (peak 1%) luminosity	2.3 (1.4)×10^{34}	5.9 (2.0)×10^{34}
Total site length [km]	13.0	48.4
Loaded accel. gradient [MV/m]	80	100
Main Linac RF frequency [GHz]	12	
Beam power/beam [MW]	4.9	14
Bunch charge [10^9 e^+/e^-]	6.8	3.72
Bunch separation [ns]	0.5	
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

RF break downs have to be studied and understood in detail

as they have impact on

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





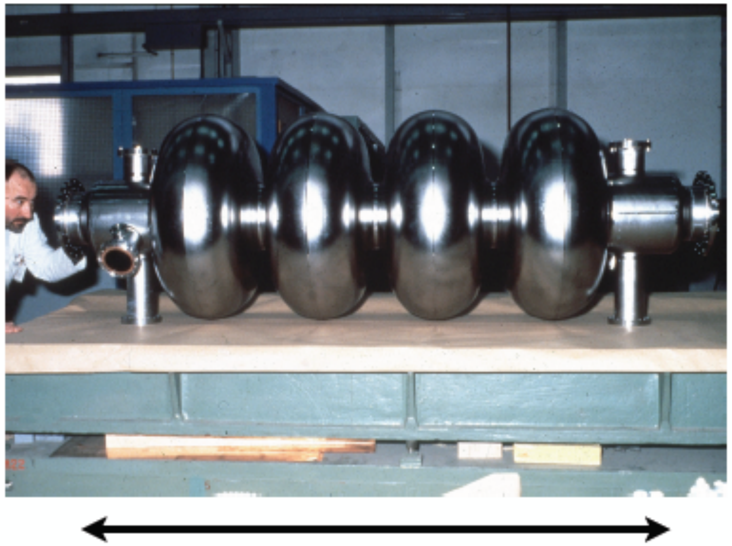
“ how far can we go and how much can we optimise such a future accelerator before we reach technical limits and how can we push these limits ? ”

7.) Push for higher energy

- ***higher acceleration gradients***
- ***new acceleration techniques***

Plasma Wake Acceleration

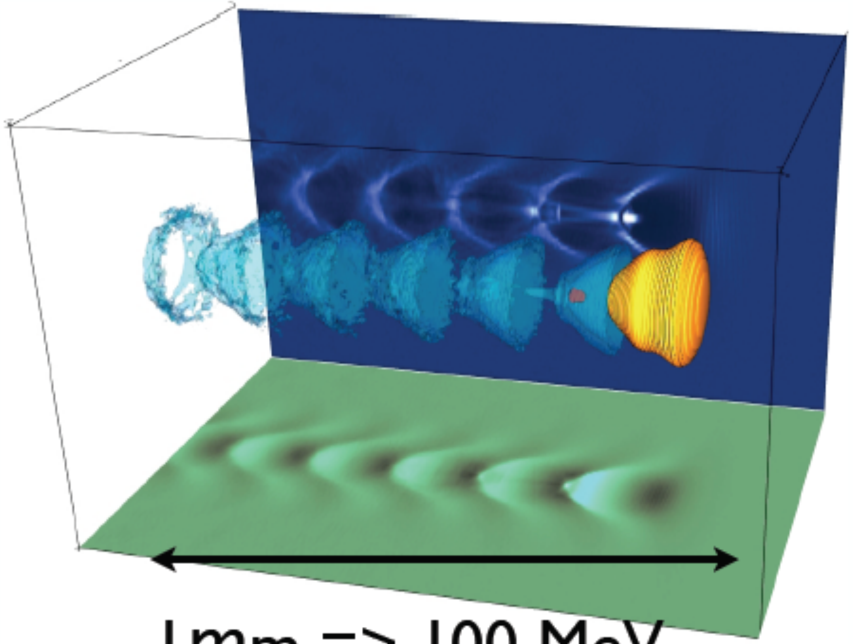
RF Cavity



1 m => 50 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



1mm => 100 MeV

Electric field > 100 GV/m

Study of High Gradient Acceleration Techniques

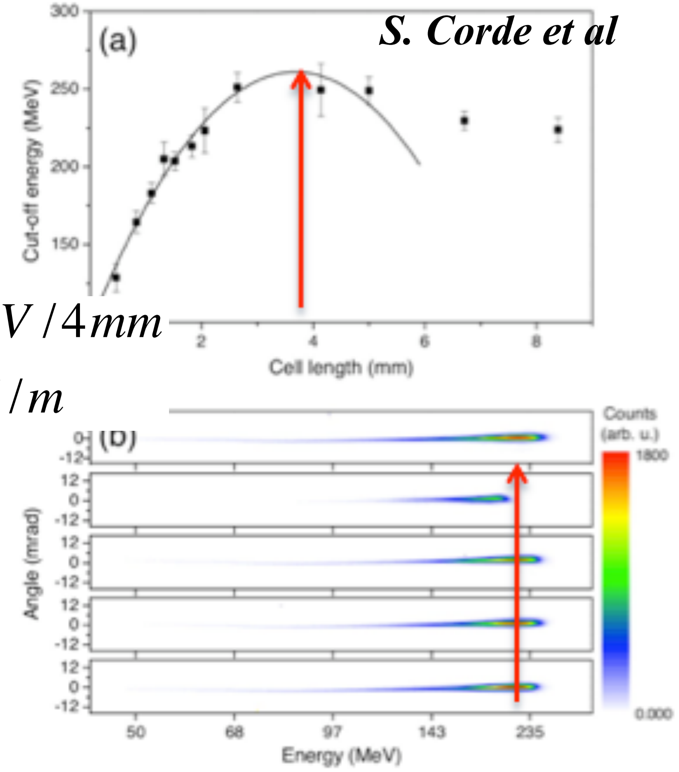
Plasma Wake Acceleration

particle beam driven / LASER driven

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

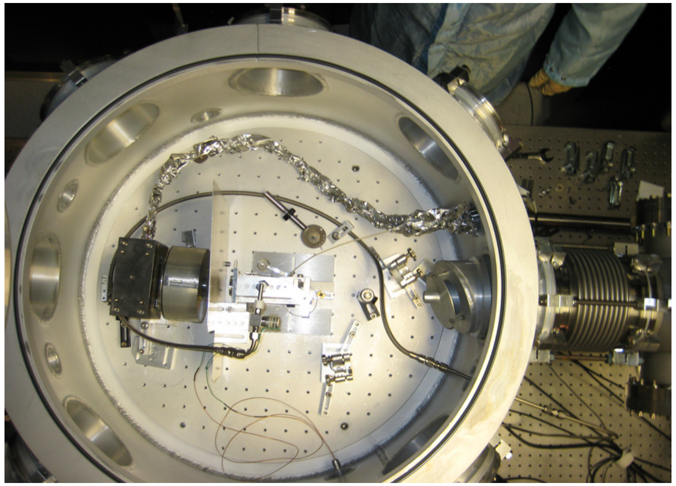
Plasma wake field gradient accelerates electrons that 'surf' on the plasma wave

Field Gradients up to 100 GeV /m observed



S. Corde et al

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



Plasma cell Univ. Texas, Austin
E_e =2 GeV

Problem: High Power LASERS are not really compact

Lasers for acceleration - state of the art: BELLA (LBL)
$28M project for 10GeV accelerator study

Laser system: Titanium-doped sapphire, commercial system, by Thales

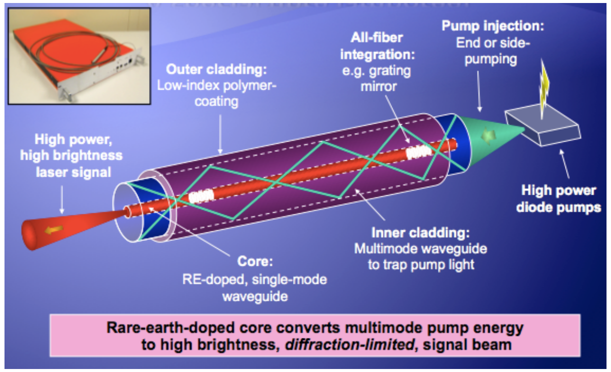
- *Pulse energy: 42 J, pulse length: 40 fs: Petawatt peak power*

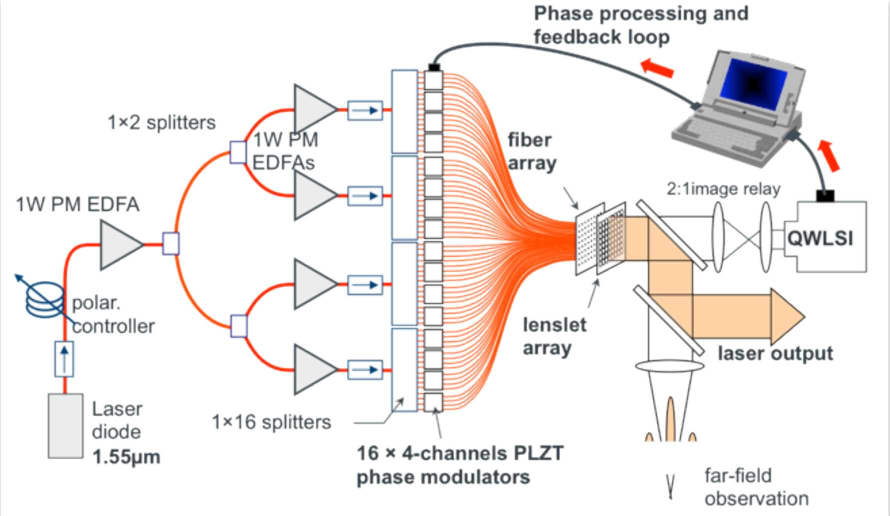
Repetition rate: 1 Hz
Efficiency:
40W out for 130kW in:
0.03%

ICAN: Spatial pulse division

Replace one high power LASER by MANY low power fibre lasers

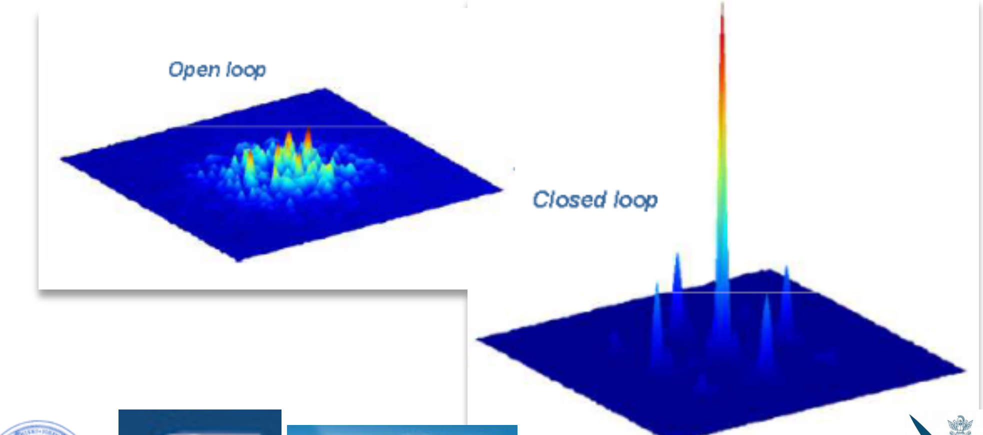
- Splitting into thousands of channels straightforward
- Final amplifiers are few mJ, 10 kHz – 30-50W average each
- Example – coherent combination of 61 Er^{3+} fibre amplifiers:



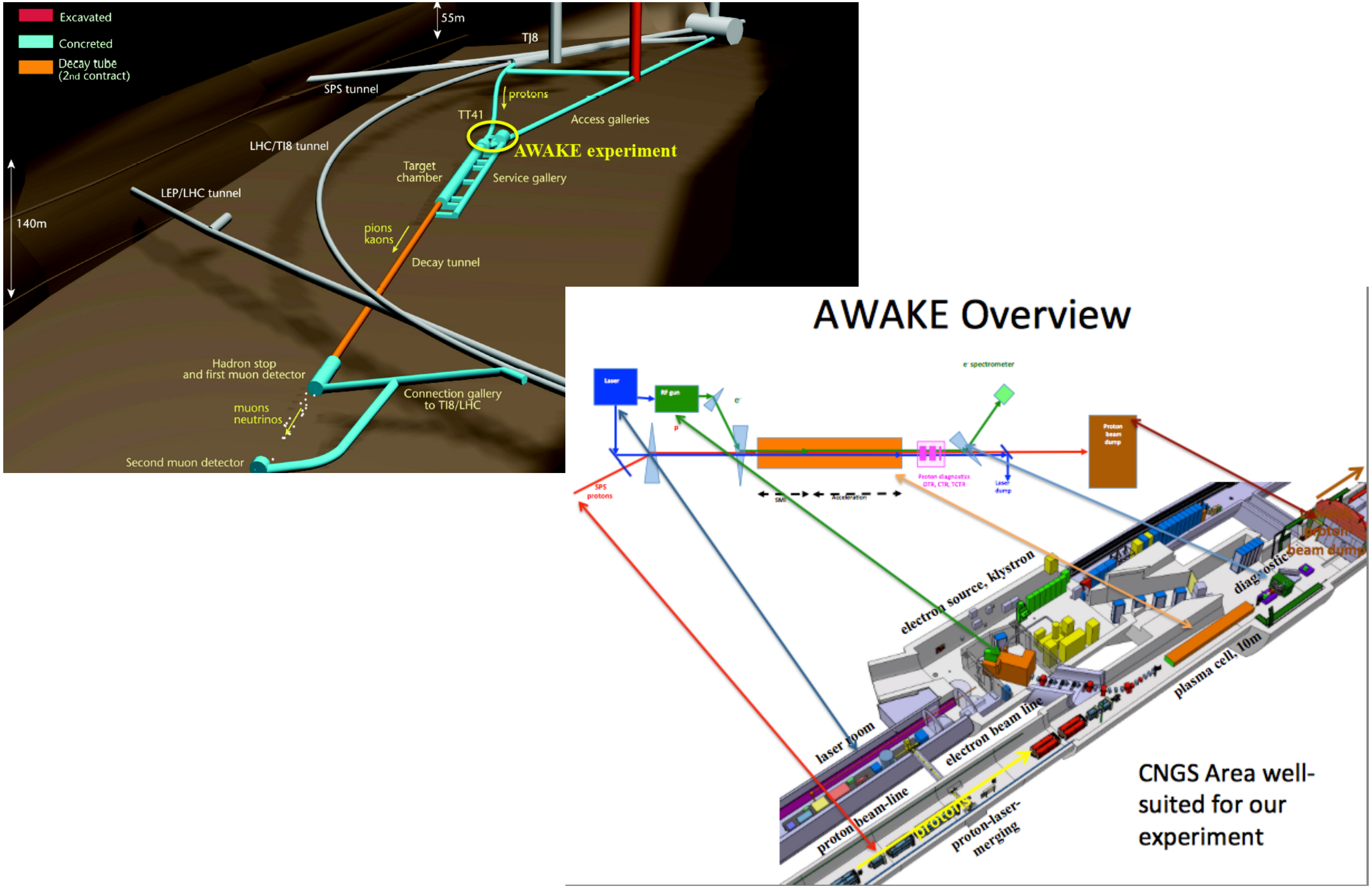


Estimated Overall Efficiency:

30 % !!



AWAKE: Proton Driven Wake Acceleration Experiment at CERN



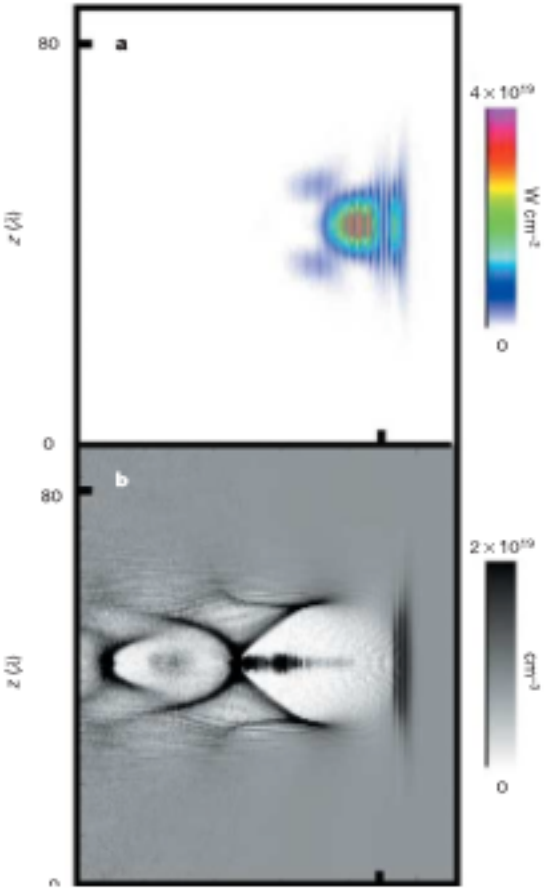
AWAKE Overview

CNGS Area well-suited for our experiment

Plasma Wakefield Acceleration

Original Proposal: T. Tajima and J. W. Dawson, *Phys. Rev. Lett.* **43** (1979) 267.

Figure from
J. Faure et al.,
Nature **43**



Plasma frequency depends only on density:

$$\omega_p^2 = \frac{4\pi n_p e^2}{m}$$

$$k_p = \frac{\omega_p}{c}$$

$$\lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1 \cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

Produce an accelerator with mm (or less) scale ‘cavities’

100 GeV/m acceleration demonstrated with lasers, 50 GeV/m with electrons.

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

Resumé :

“Future Strategy and Technologies in Particle Acceleration”

In a Worldwide Effort we are preparing the next step in particle energy for physics beyond the standard model

- ***exploit fully the LHC potential**: E_{cm}=13-14 TeV*
- ***increase the luminosity of the present LHC: HL-LHC, β^*=15cm***
- ***study the design of a 100 km, 100 TeV pp collider***
  100 km, 175 GeV ee collider
- ***finalise the design of a linear ee-collider up to E_{cm}= 3 TeV***
- ***study worldwide new plasma wake acceleration techniques***
  laser driven / electron beam driven / or
  proton beam driven: AWAKE at CERN