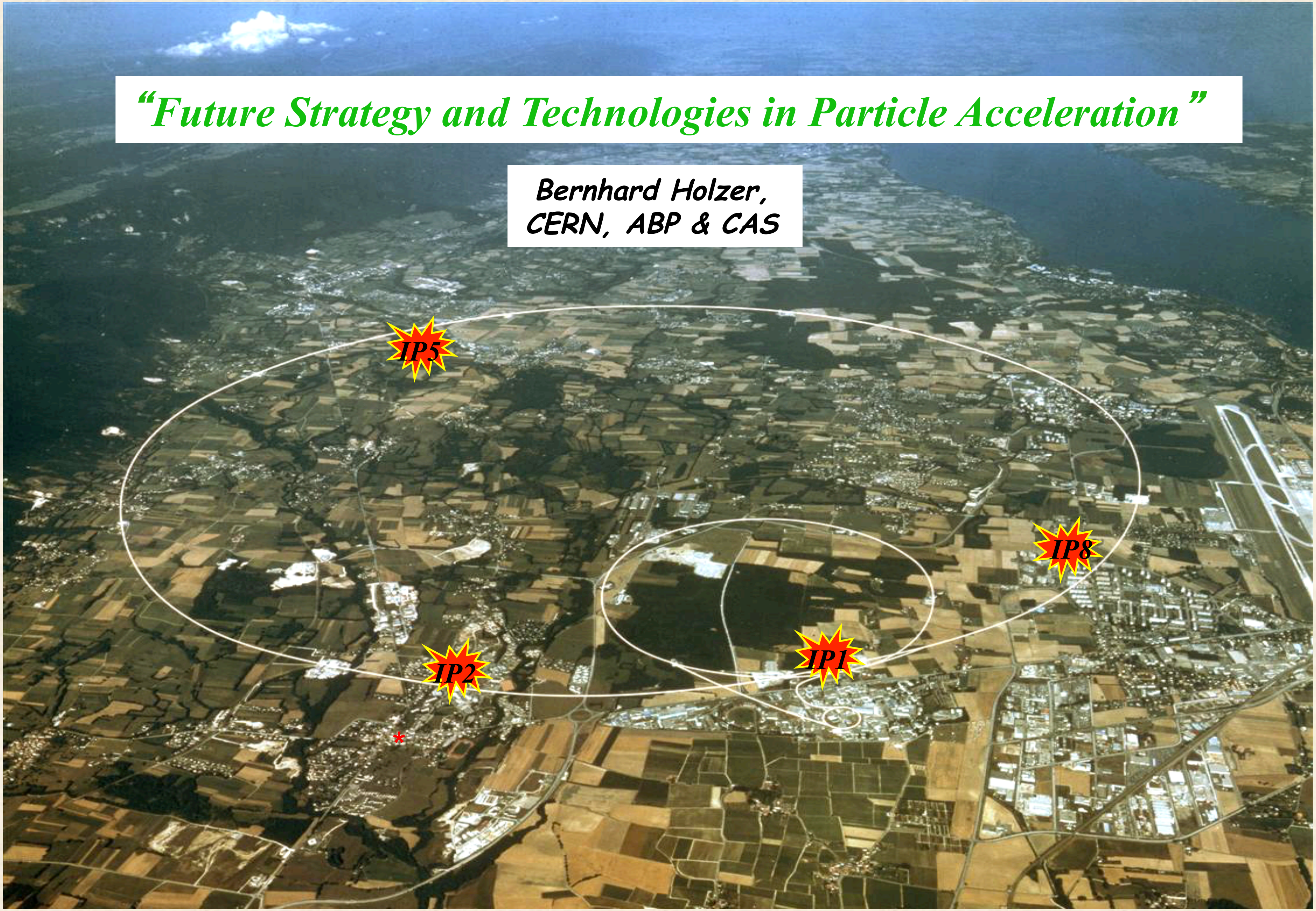
“Future Strategy and Technologies in Particle Acceleration”

Bernhard Holzer,
CERN, ABP & CAS

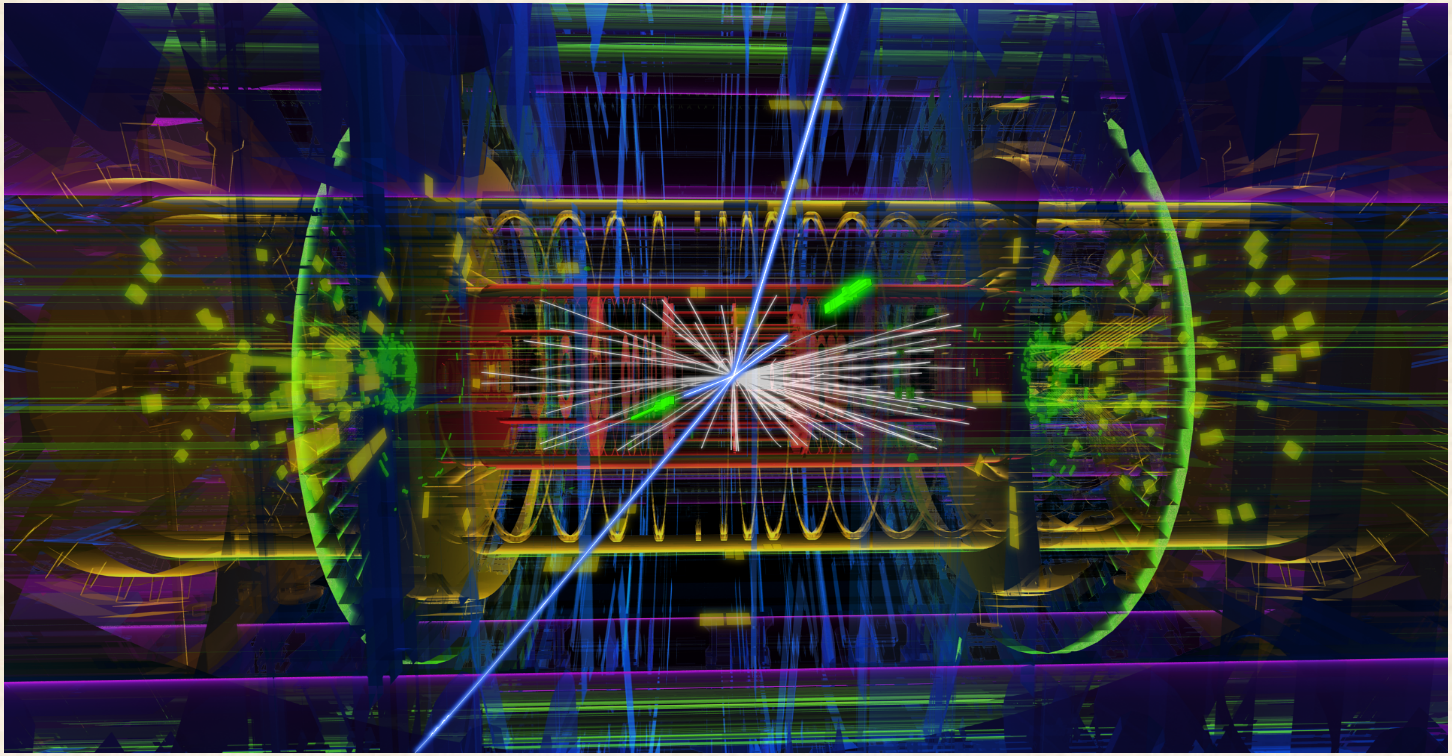


1.) Where are we ?

- ***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

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

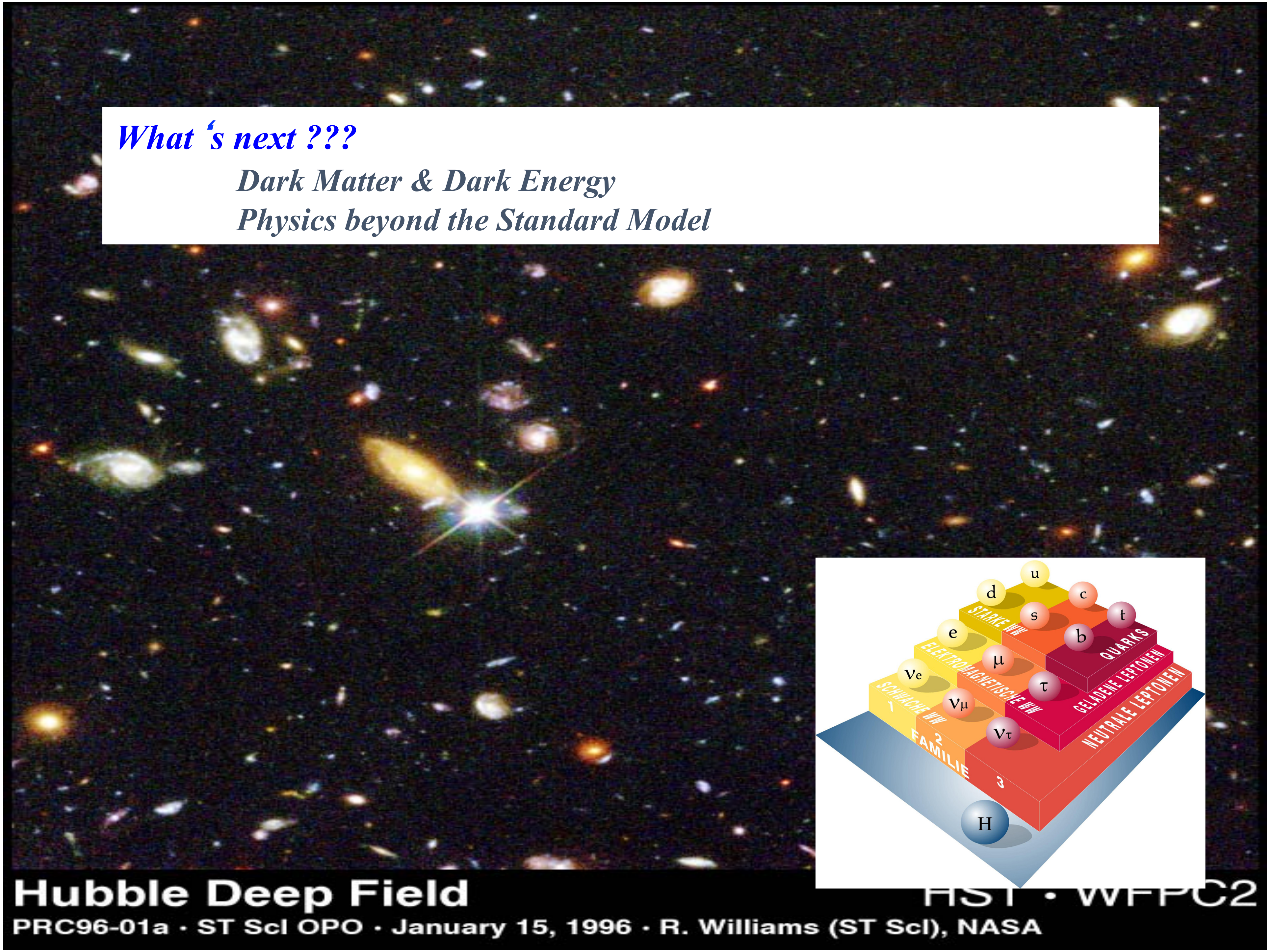
2.) Where do we go ?

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

What ‘s next ???

Dark Matter & Dark Energy

Physics beyond the Standard Model



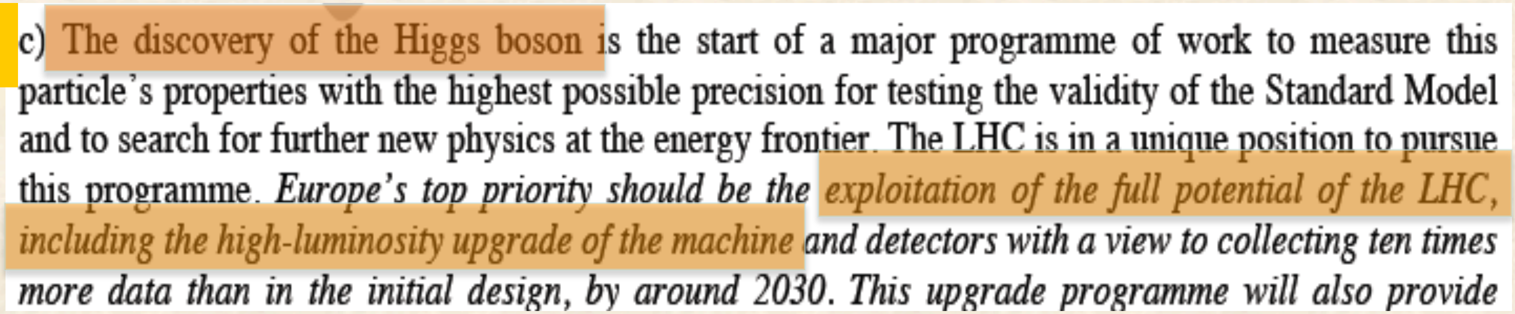
Hubble Deep Field

PRC96-01a · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

Future Projects

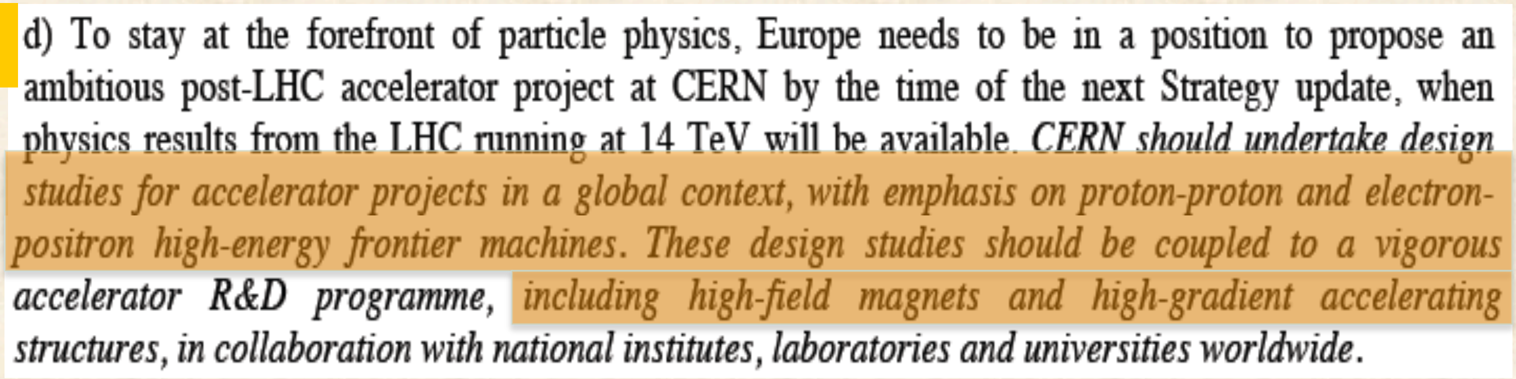
Recommendations from European Strategy Group

#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***

Considered Future High Energy Frontier Colliders

Circular colliders:

FCC (Future Circular Collider … Euro-Circol)

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

Linear colliders

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

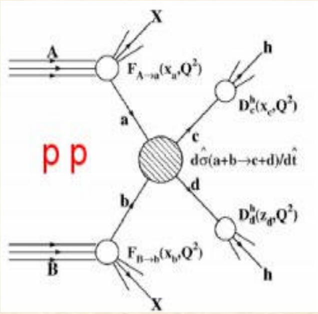
Others

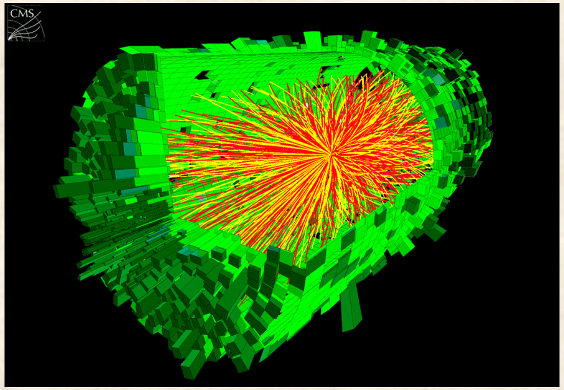
Plasma acceleration

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

Photon-photon collider

Hadron Collisions or Lepton Collisions?





LHC Pb-Pb collision (Atlas)

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

Lepton collisions: Elementary particles / Anti-particles

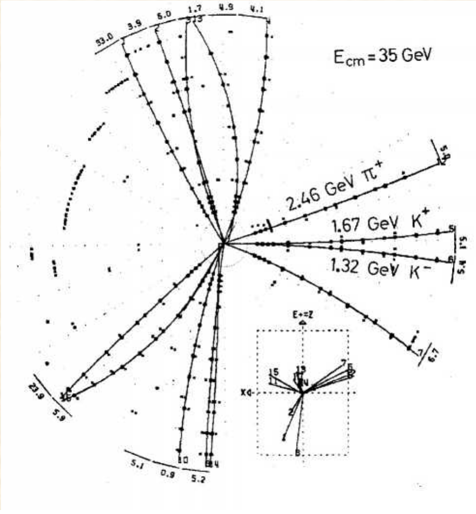
Collision process known

Well defined energy

Other physics background limited

Lepton collisions ⇒ precision measurements

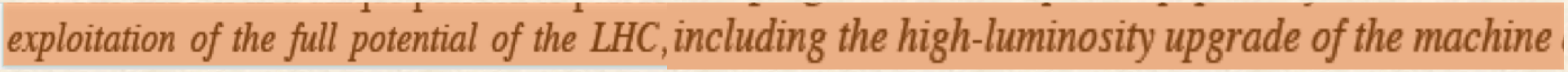
in e+ e- collisions quantum numbers disappear



PETRA: gluon discovery

3.) The HL-LHC

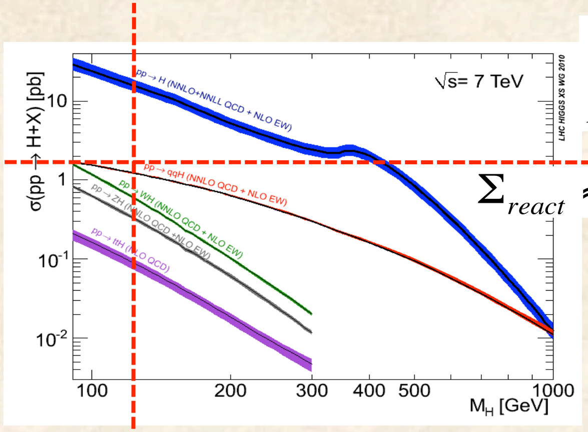
- ***increasing the luminosity of LHC***
- ***higher bunch intensities***
- ***smaller β****



exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine

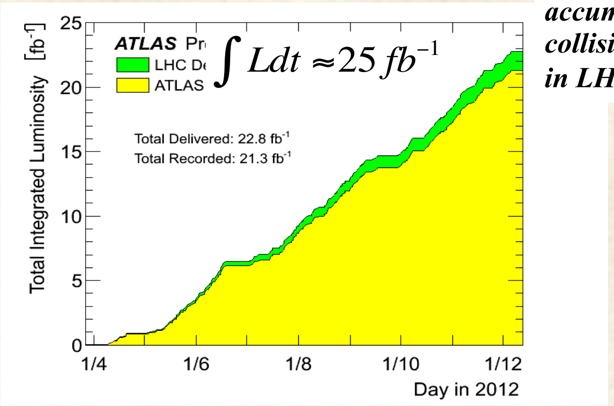
Once more: The Higgs Discovery:

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



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

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



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

accumulated
collision rate
in LHC run 1

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

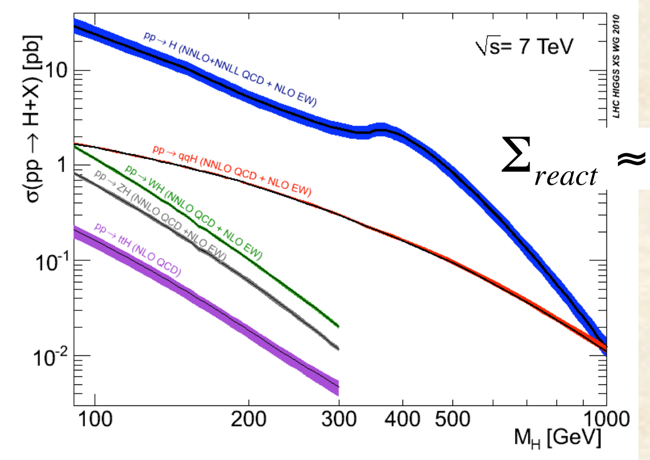
The particles are "very small"

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

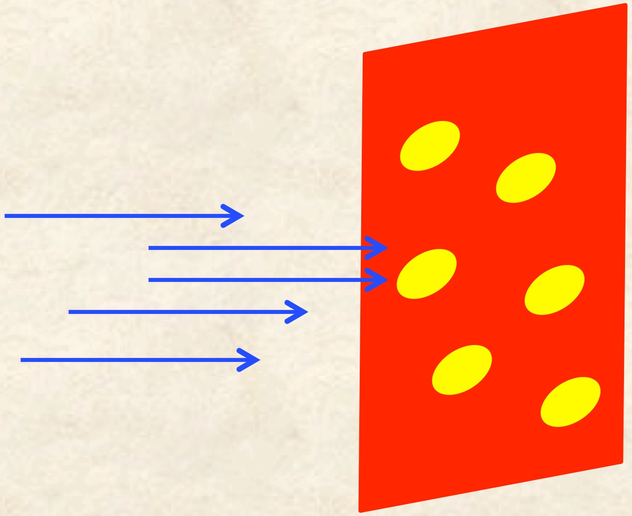
During collider run we had in Run 1 …
1400 bunches circulating,
with 800 Mio proton collisions per second in the experiments
and collected only 450 Higgs particles in three years.

Problem: Our particles are VERY small !!

Overall cross section of the Higgs:



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



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

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

The particles are "very small"

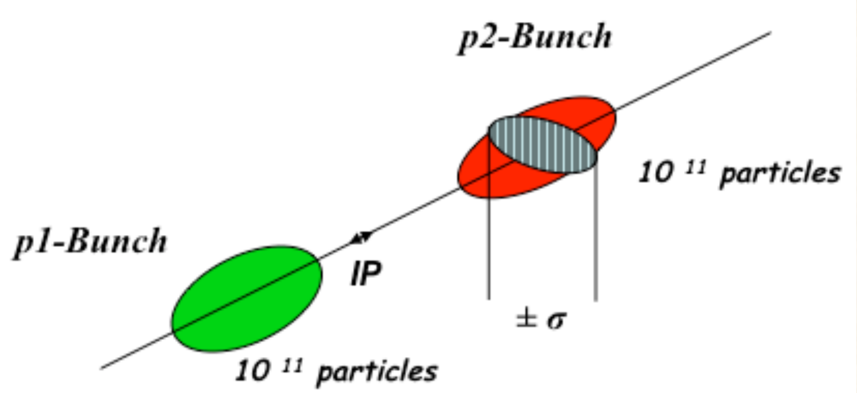
The only chance we have:
compress the transverse beam size … at the IP

LHC typical:

σ = 0.1 mm → 16 µm

Luminosity of a particle collider

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



Example: Luminosity run at LHC

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

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

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

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

$$I_p = 584\, mA$$

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

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

Luminosity Upgrade:

stronger focusing → smaller beam size at the IP

High Gradient/Large Aperture Insertion Quadupole Magnets

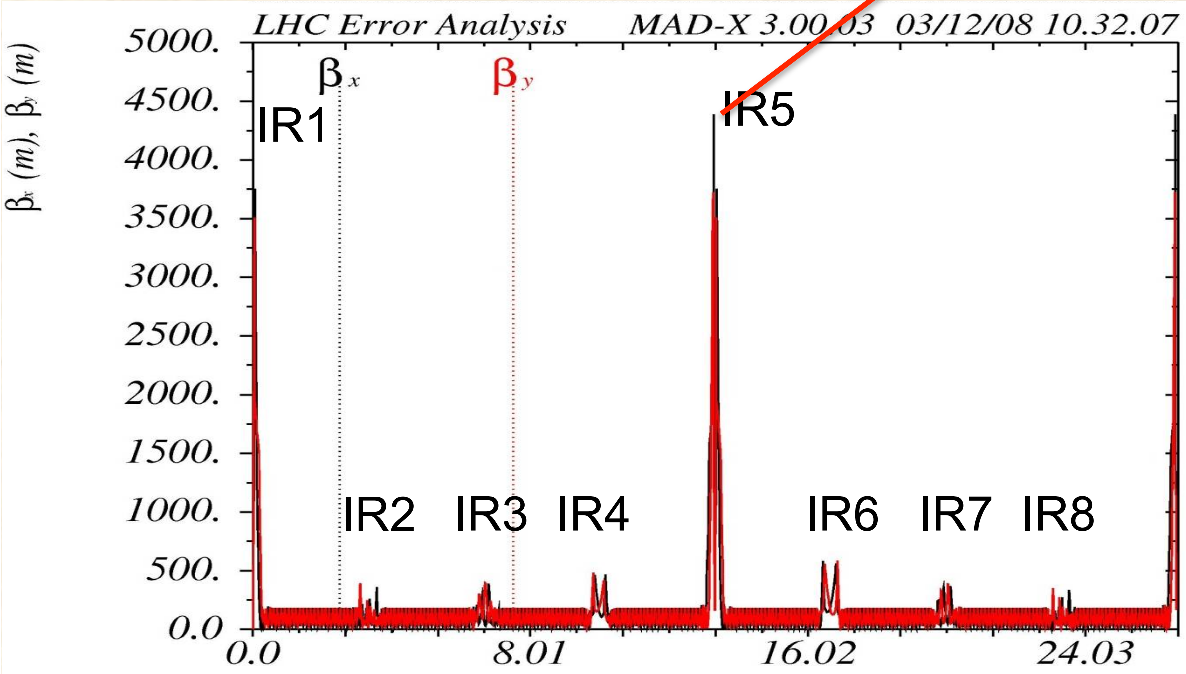
possibly: l = 8 m, G= 175 T/m, A=120 mm,

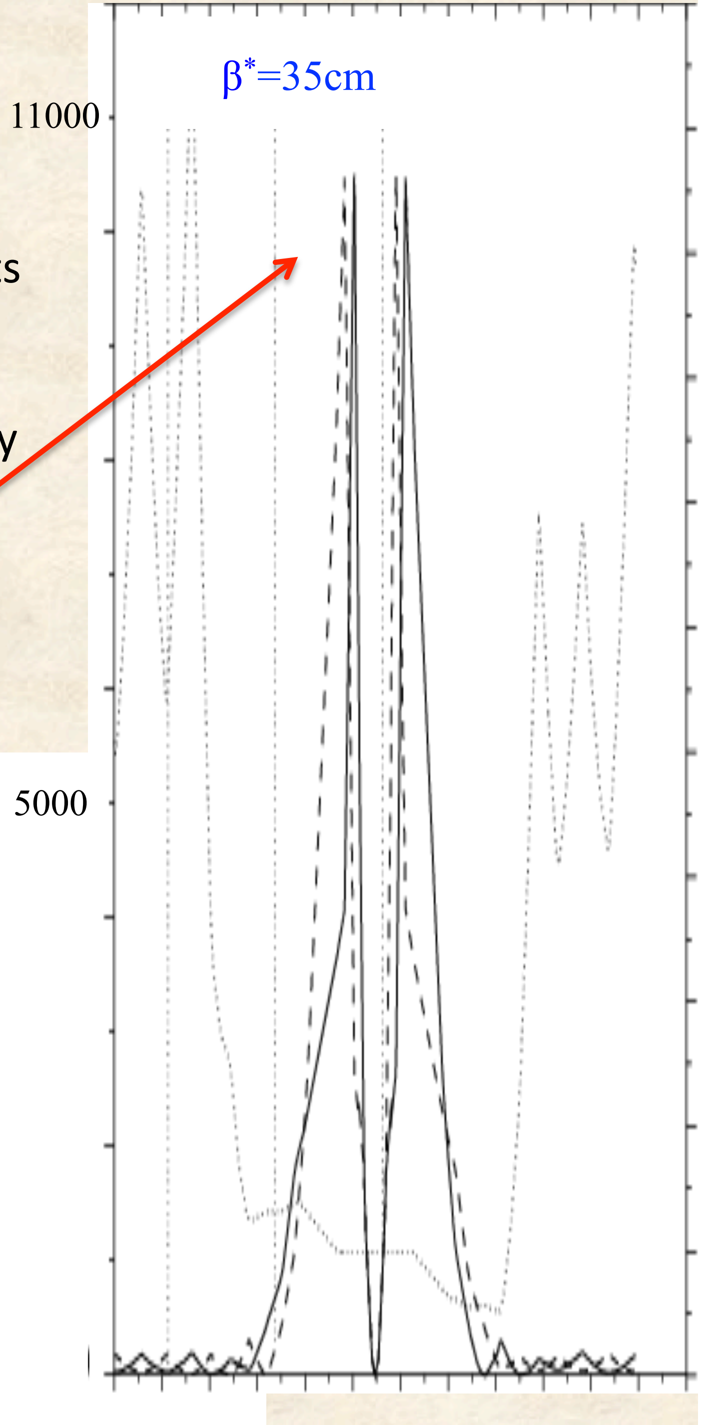
($B_{peak\text{-}ss}$ =13 T)

$\beta^* \leq 22$ cm are possible with a factor ~2.5 in luminosity by itself,

higher gradients & larger aperture

new sc. technology Nb_3Sn





The LHC Upgrade ... what we have to do

Increase the performance by a factor of 10 !!

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

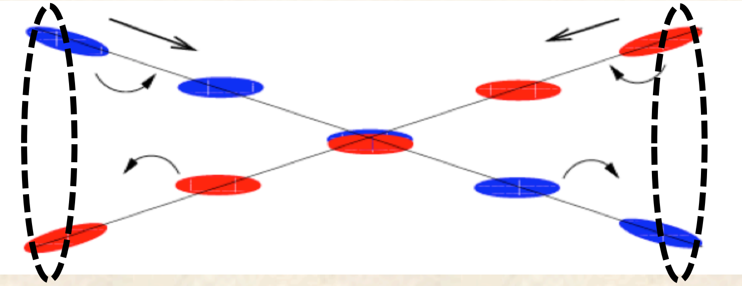
* We need a (much) stronger focusing of the beam, and much larger aperture. New super cond. Quadrupoles in the IR (Nb_3Sn)

* The LHC Lattice & Optics is not strong enough for such a scheme
→ start focusing in the neighboring sectors

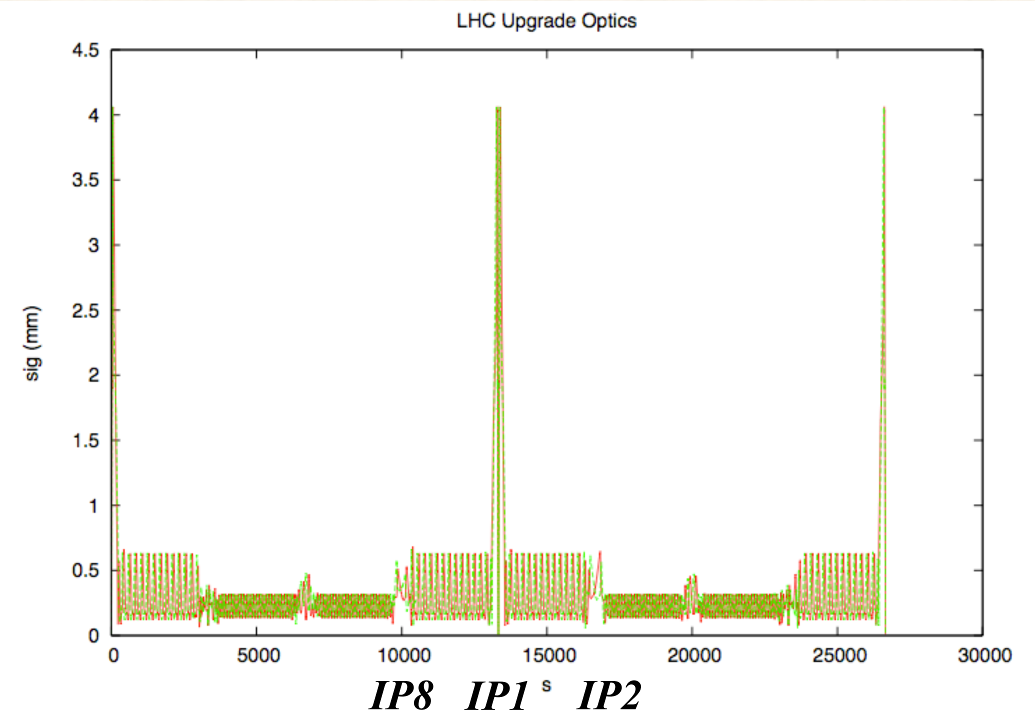
* And there is another little problem…

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

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



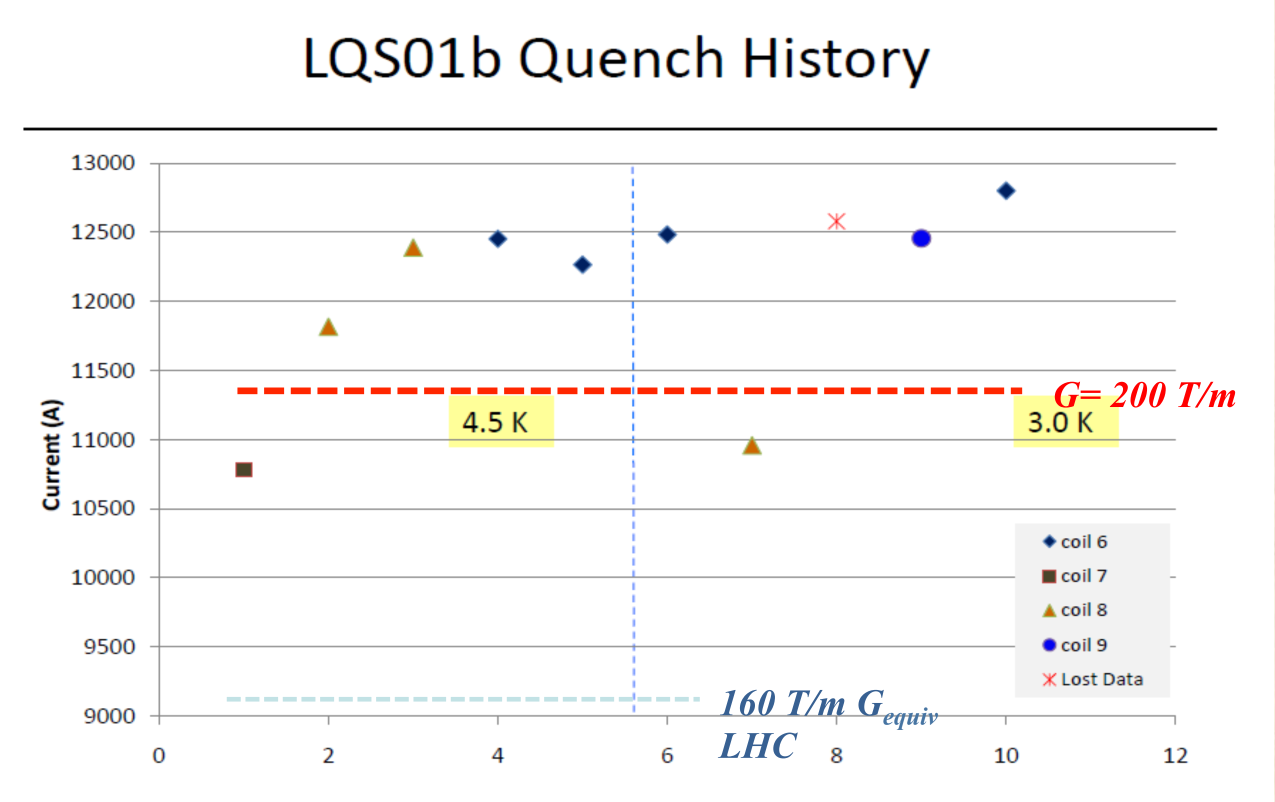
larger aperture need in final focus quadrupoles



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

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

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

... increase number of protons per bunch

$N_{1,}\ N_2 = 1.7*10^{11}$

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

... decrease the beam size at IP

stronger gradients, larger aperture

$\beta_x = \beta_y = 0.15\ m$

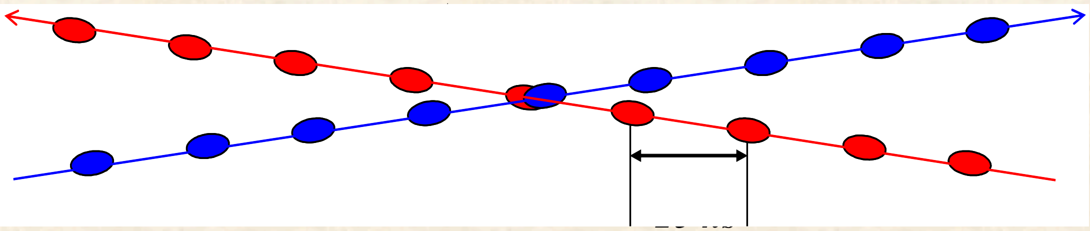
... reduce the geometric loss factor

crab cavities

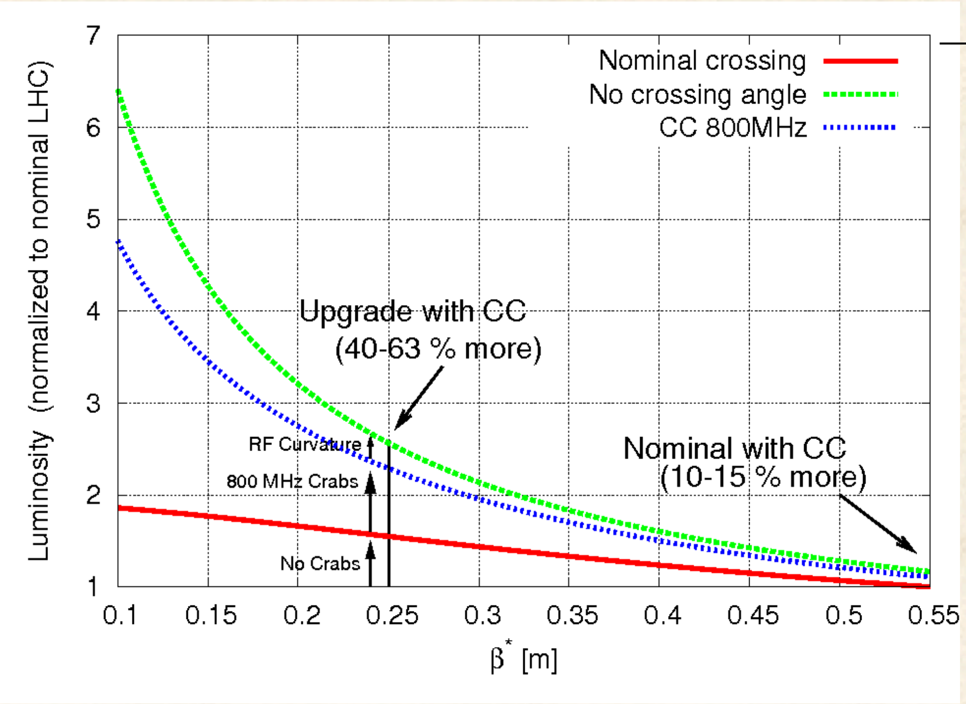
F is a pure crossing angle (Φ) contribution:

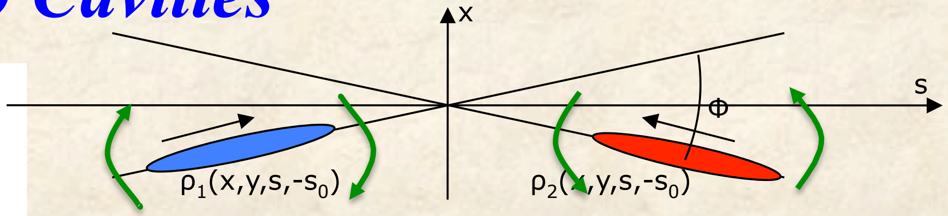
$$F = \frac{1}{\sqrt{1+2\,\frac{\sigma_s^2}{\sigma_{1x}^2+\sigma_{2x}^2}\tan^2\frac{\phi}{2}}}$$

$F_{LHC} = 0.836$, $F_{HL\text{-}LHC} = 0.31$



Challenge: HL-LHC Crab Cavities





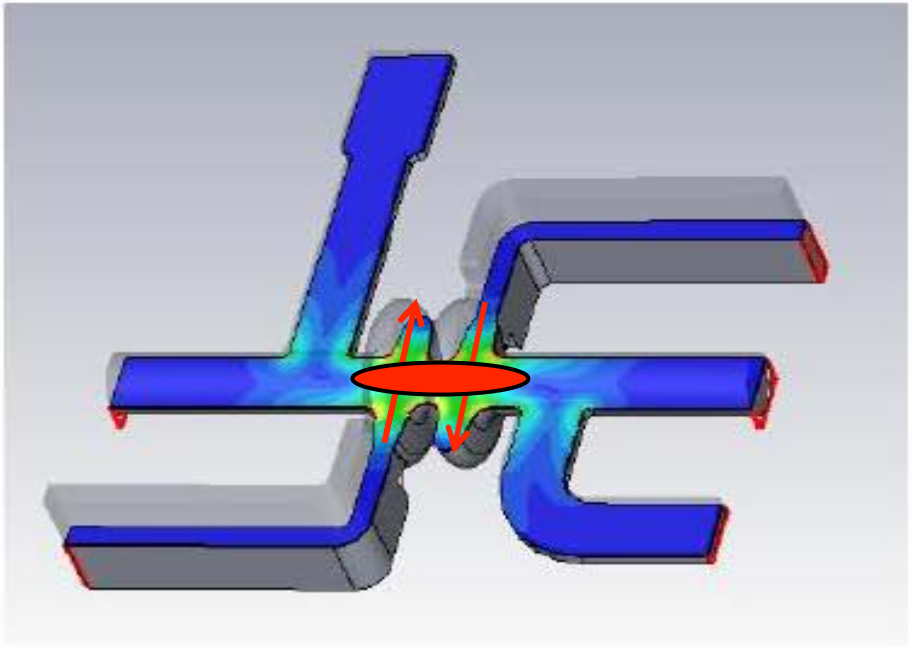
$$L = L_{ideal} * F$$

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

Transverse deflecting cavity at 800 MHz

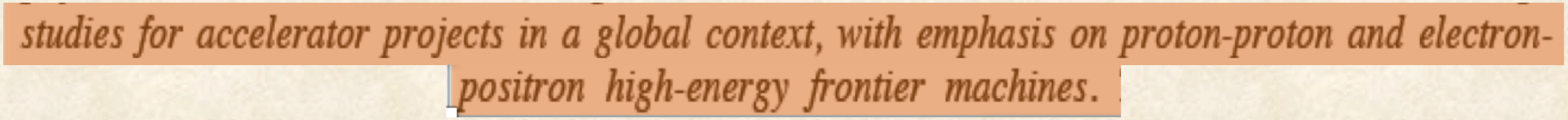
Prototype test in SPS … at the moment technical challenge:

fast, precise, compact,
Fail SAFE !!



4.) Push for higher energy: FCC

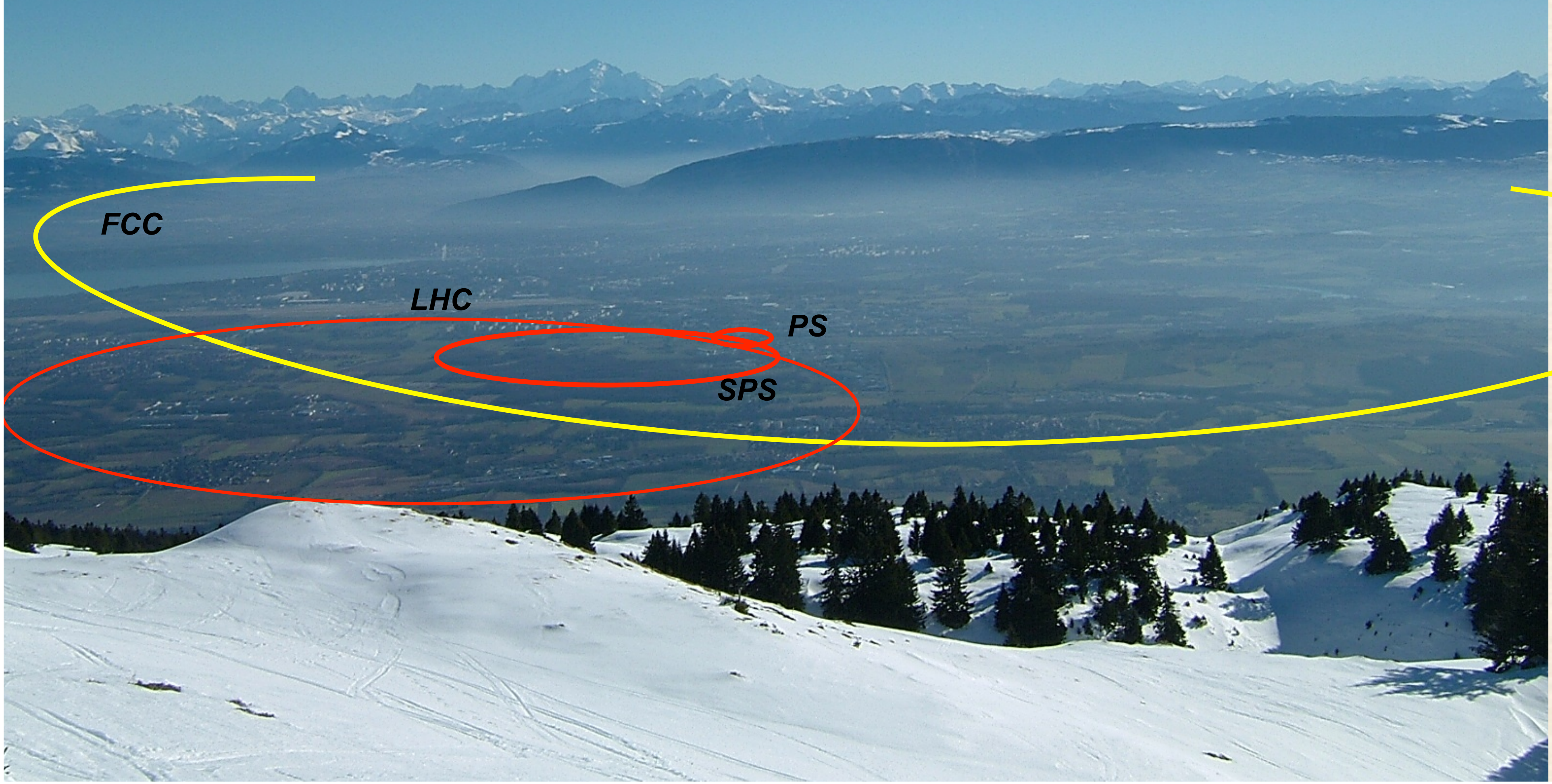
- ***increasing the ring size***
- ***stronger magnets***



studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines.

FCC-pp - Collider

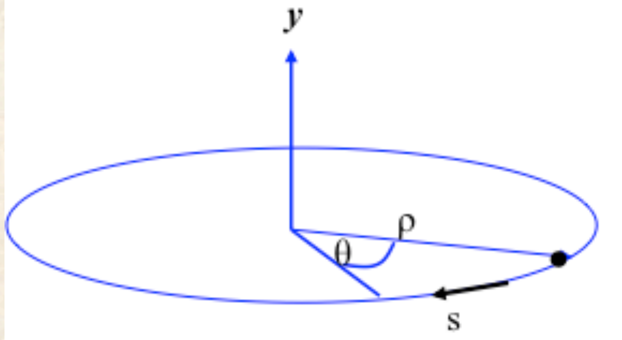
The Next Generation Ring Collider



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

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



circular coordinate system

Condition for an ideal circular orbit:

Lorentz force $$F_L = evB$$

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

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

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

$B\rho$ = "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$_3$Sn

168 *5 Supraleiter im Magnetfeld*

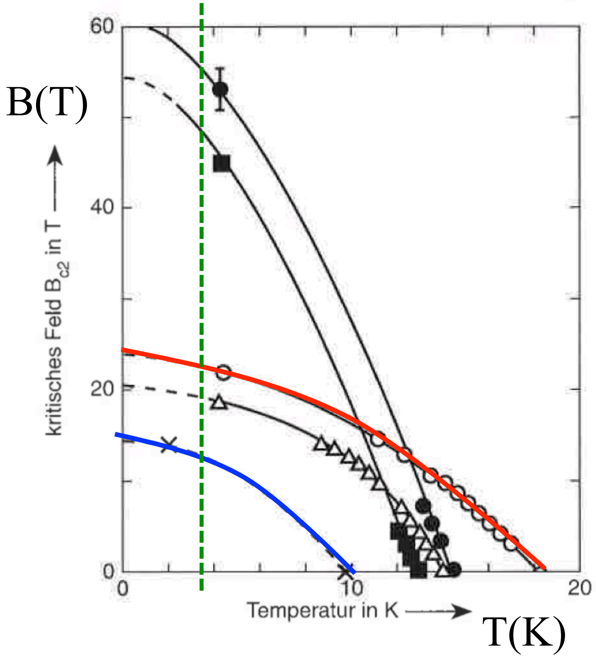
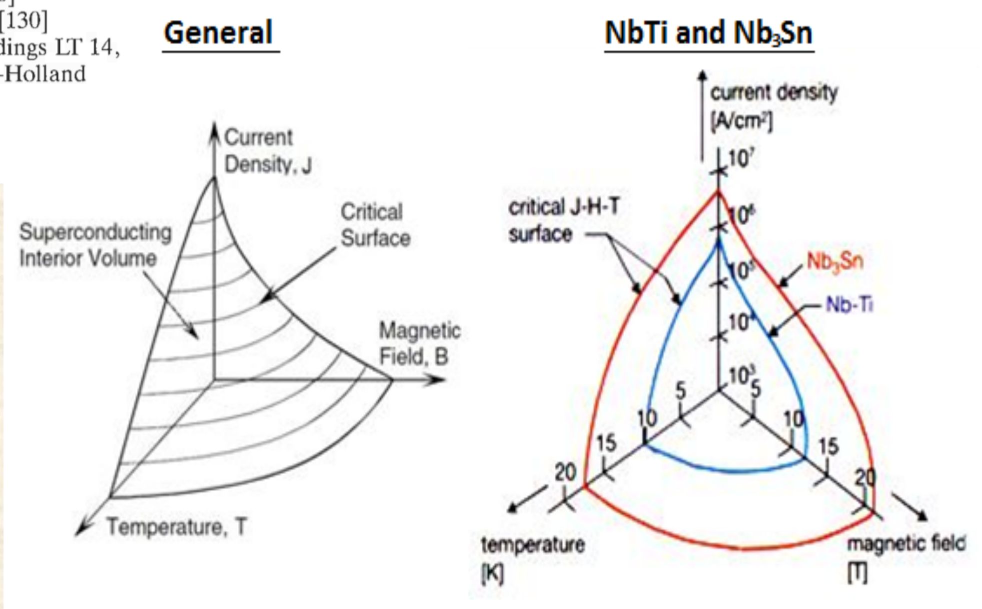


Abb. 77 Oberes kritisches Feld einiger Hochfeldsupraleiter.

−○−○−○− Nb$_3$Sn, Drahtdurchmesser 0,5 mm [127]
−△−△−△− V$_3$Ga, Sinterprobe [127]
−×−×−×− Nb$_{50}$ Ti$_{50}$ [128]
−■−■−■− PbMo$_{6,35}$S$_8$ [130]
−●−●−●− PbGd$_{0,3}$Mo$_6$S$_8$ [130]
(siehe auch Ø. Fischer: Proceedings LT 14, Otaniemi 1975, Band 5. North-Holland Publ. Comp. 1975).

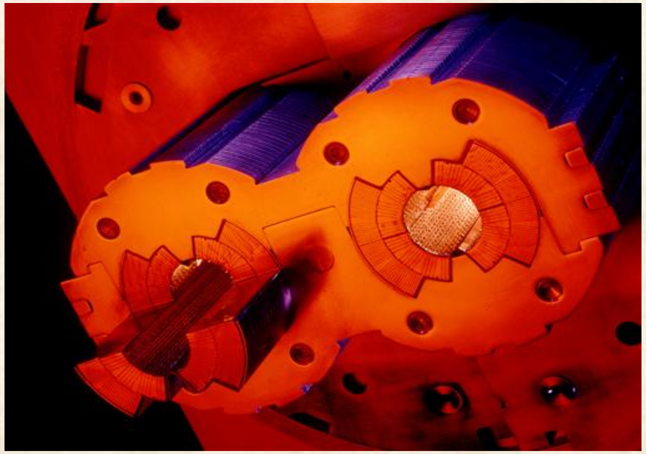
critical field in NbTi and Nb$_3$Sn



… and we do NOT talk about
YBa$_2$Cu$_3$O$_7$ and friends

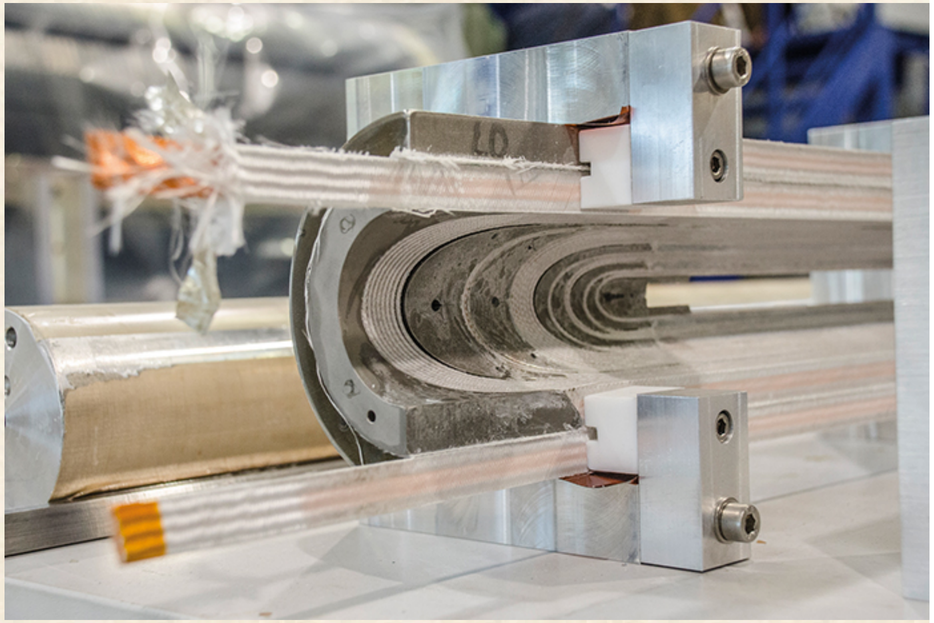
($j_c\perp$ = 100A/mm², $j_c||$ = 800A/mm²)

The Push for Higher Beam Energy



NbTi LHC standard dipoles,
8.3 T

Nb_3Sn FCC type dipole coils,
11 T – 16 T



FCC energy reach:

it is a simple scaling wrt LHC:

circumference 100km /27km
→ Factor 3.7

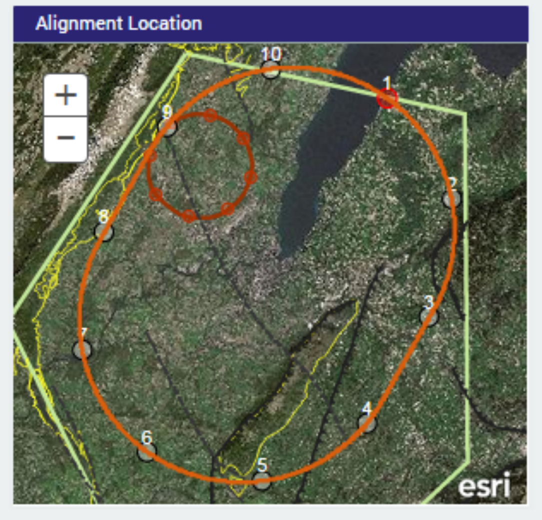
dipole field: 16 T / 8.3 T
→ Factor 1.93

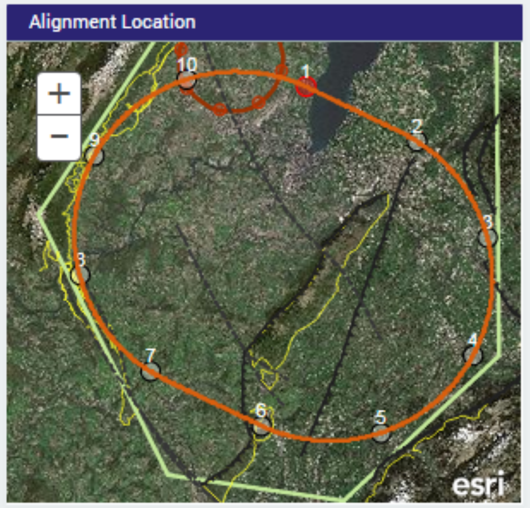
LHC: $E_{cm} = 2 * 7$ ***TeV =14 TeV***

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

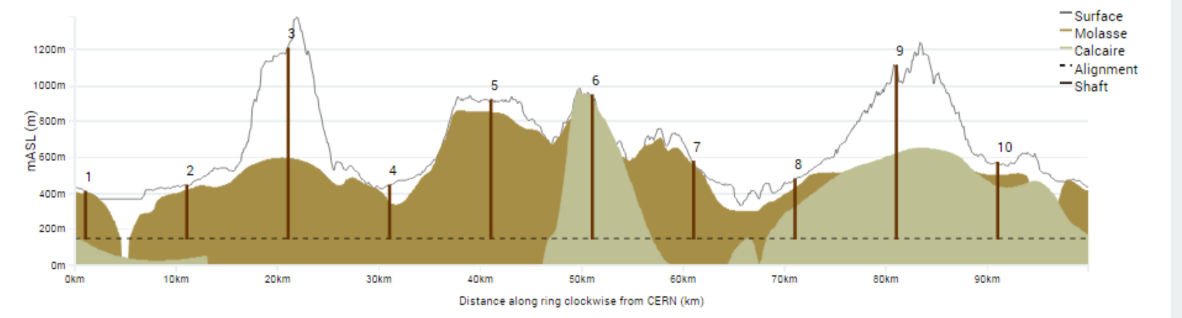
Latest News: Geographical / Geological Considerations

J. Osborne and Family





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



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

5.) High Energy Lepton Colliders

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

FCC-ee Collider

The next Generation e+/e- Ring Collider

Synchrotron Radiation

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

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

radiation power

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

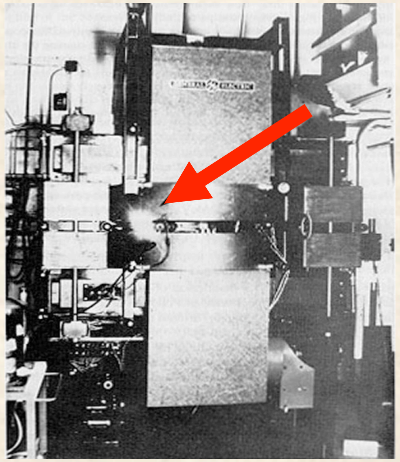
energy loss

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

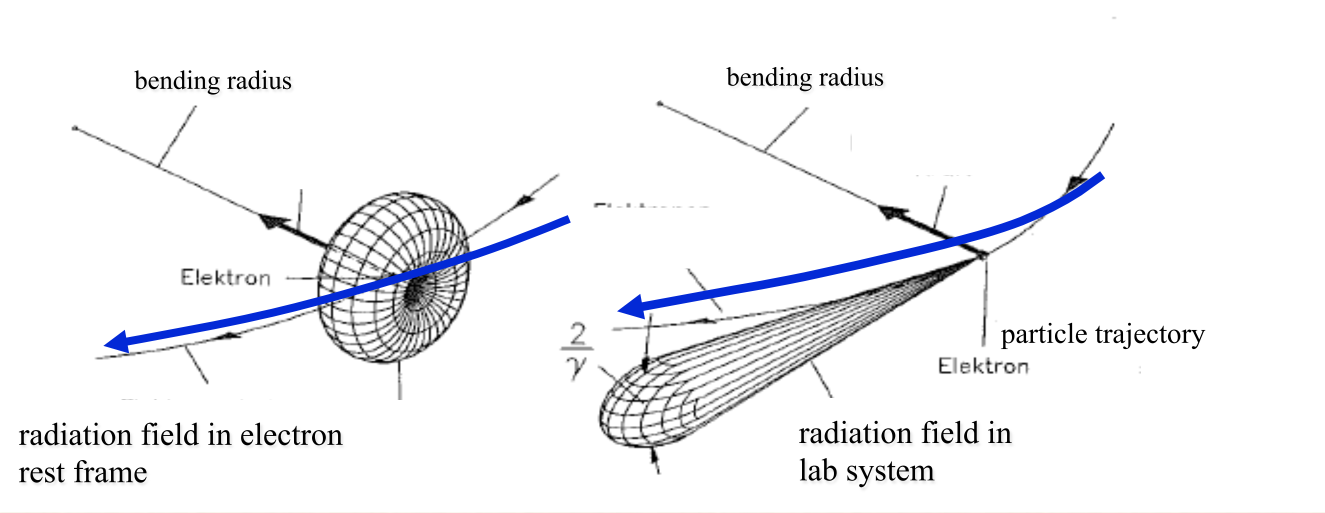
critical frequency

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

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



1946 observed for the first time in the General Electric Synchrotron



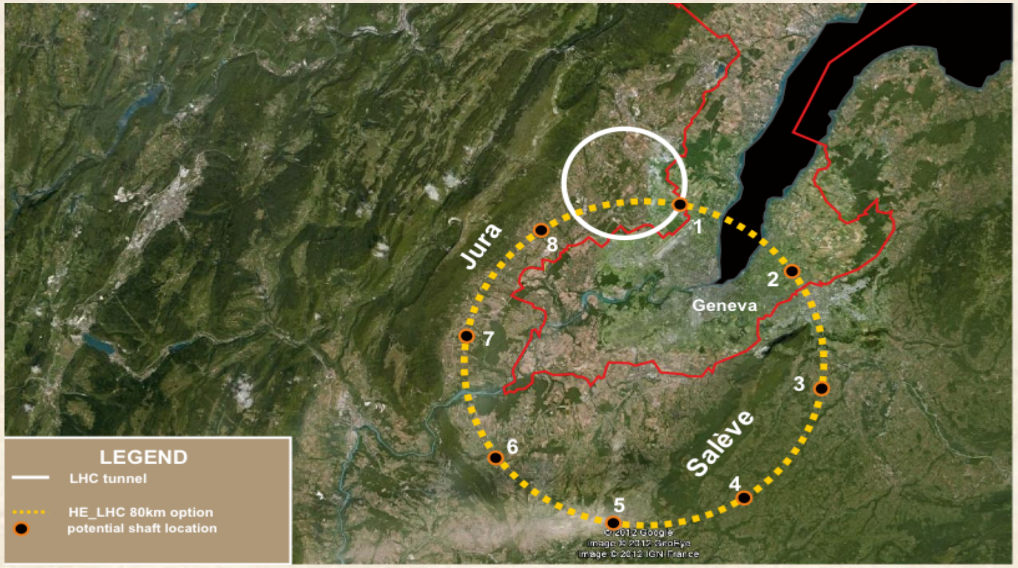
court. K. Wille

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***

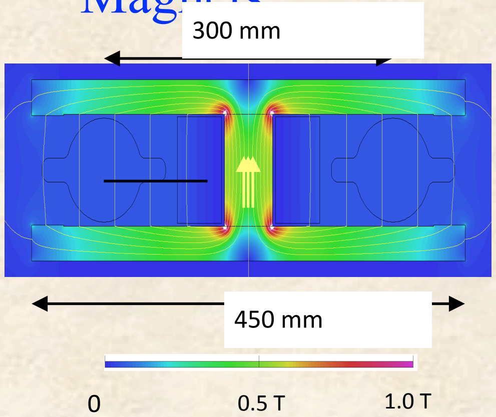
Circular e+ / e- colliders are severely limited by synchrotron radiation losses and have to be replaced for higher energies by linear accelerators

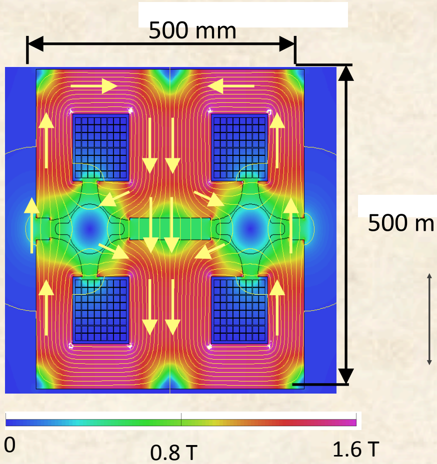
FCC-ee

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.

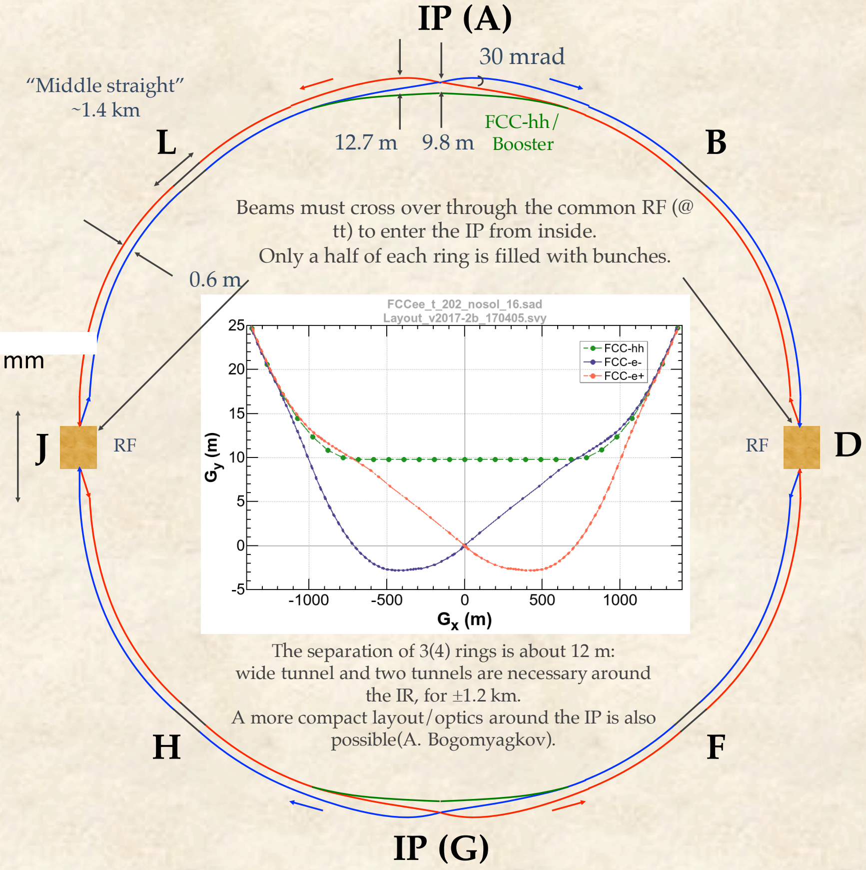
Twin Aperture Magnets





220 A × 64 turns
2.2 A/mm^2 on Cu

9.9 T/m



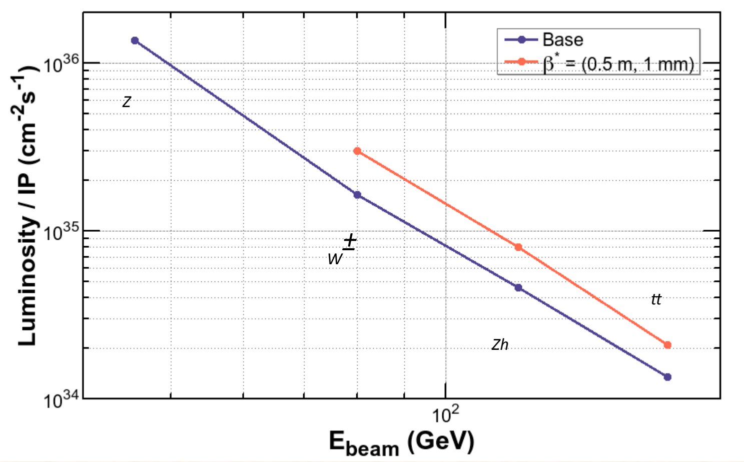
Beams must cross over through the common RF (@ tt) to enter the IP from inside.
Only a half of each ring is filled with bunches.

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

FCC-ee Parameters 2017

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

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



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

$$\Delta U(keV)=89 * E{\uparrow}4 \,/(mc{\uparrow}2\,)1$$

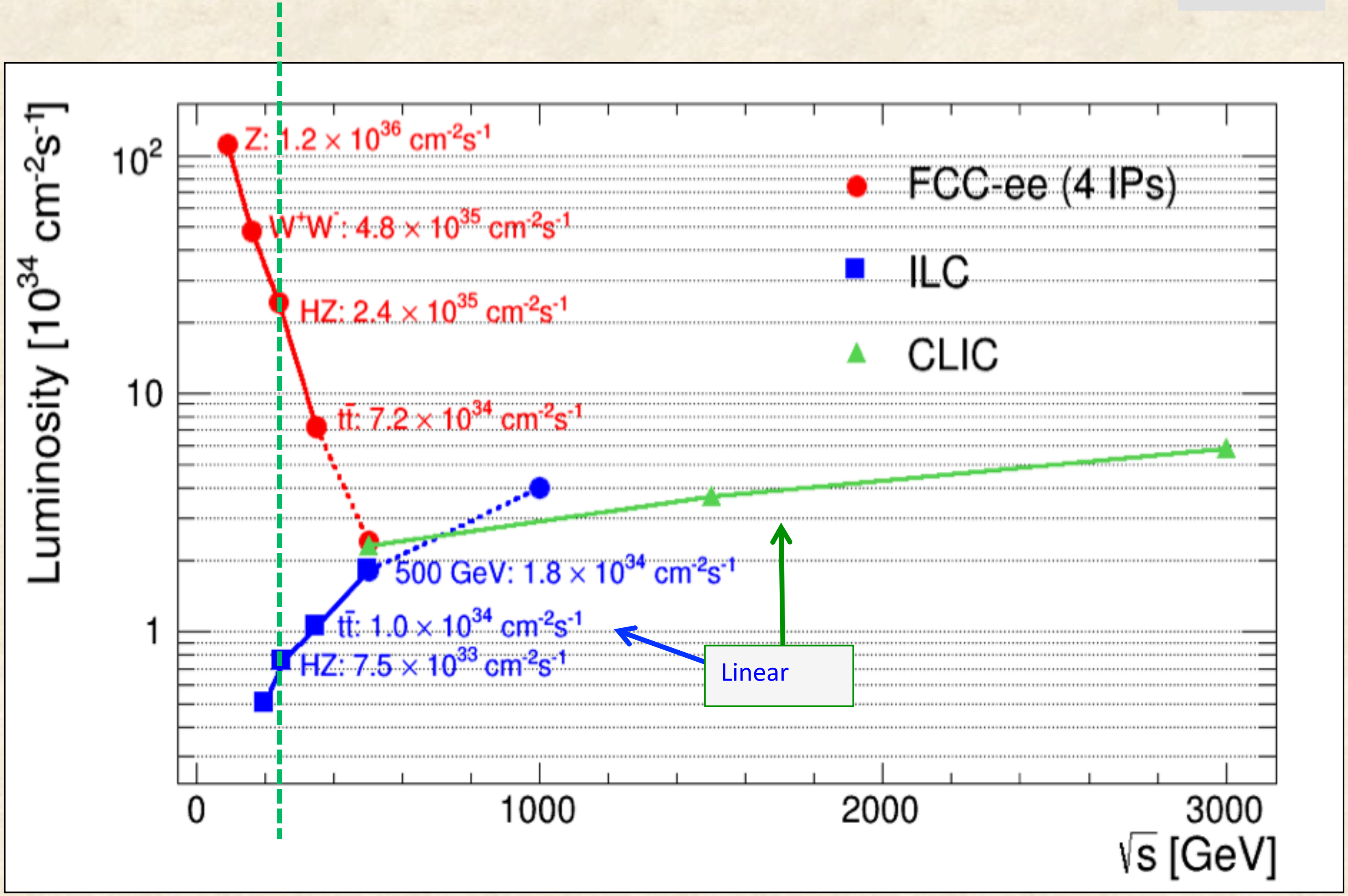
6.) Push for higher lepton energy

- *go linear*
- *higher acceleration gradients*

Circular vs. Linear Colliders

… the light problem

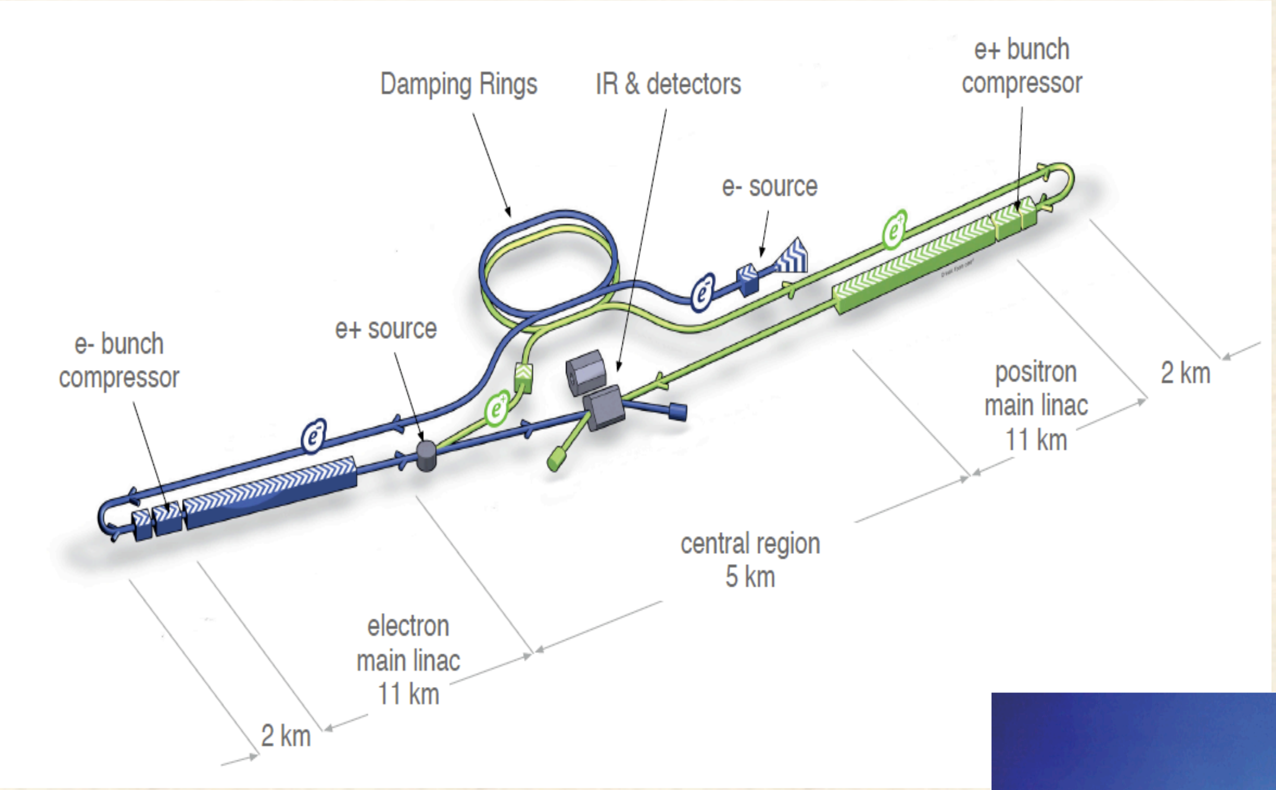
F. Gianotti



Linear

ILC Layout

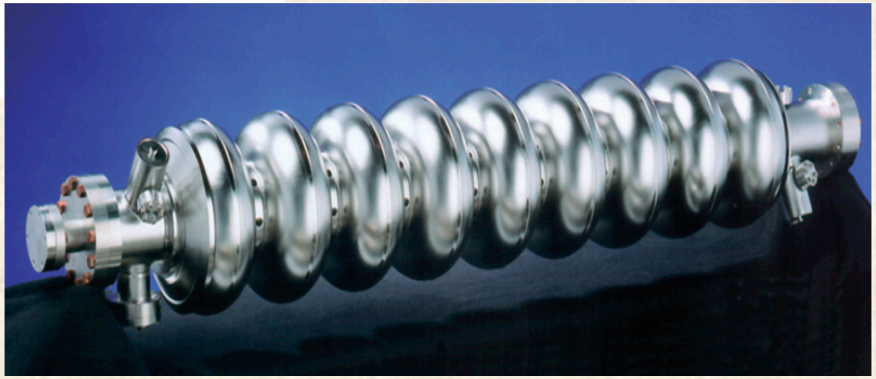
Avoid bending magnets => no synchrotron radiation losses
=> energy gain has to be obtained in ONE GO



Internat. Linear Collider (based on "TESLA") Super-cond. Technology

Studied in Europe (DESY)
Favorised by the Japan HEP community

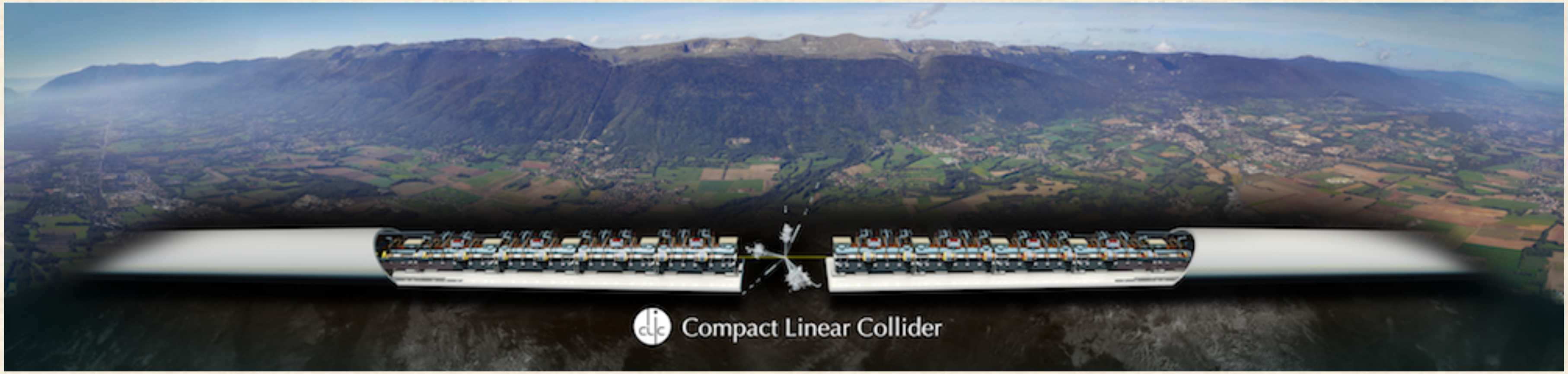
Energy range E_{cm} = 500 GeV



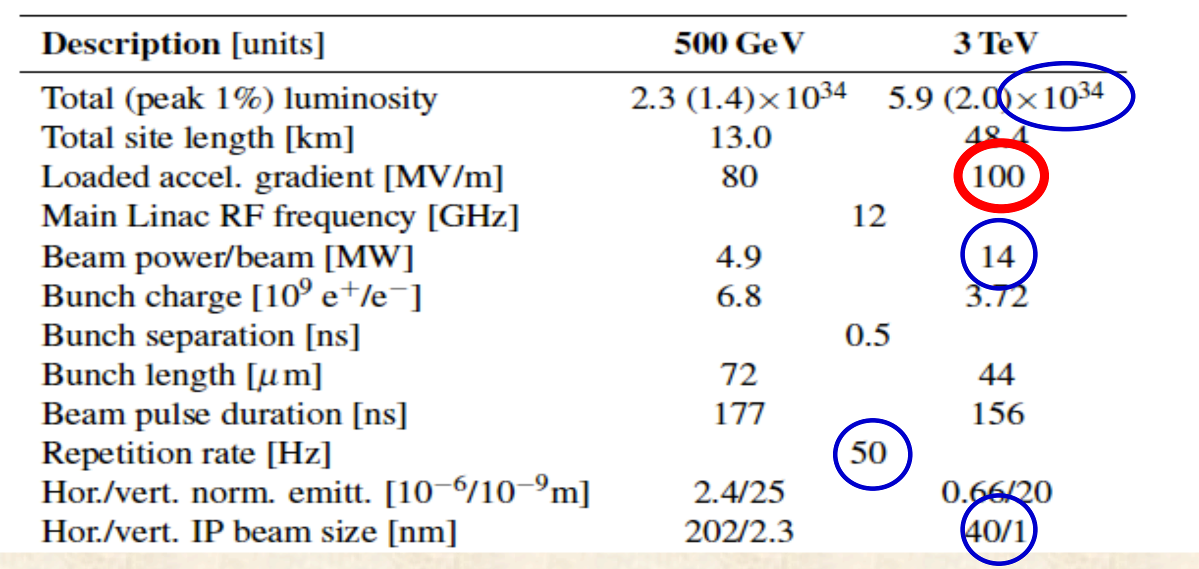
Accelerating Gradient: 35 MV/m
Determined by quench limit of the cavities

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

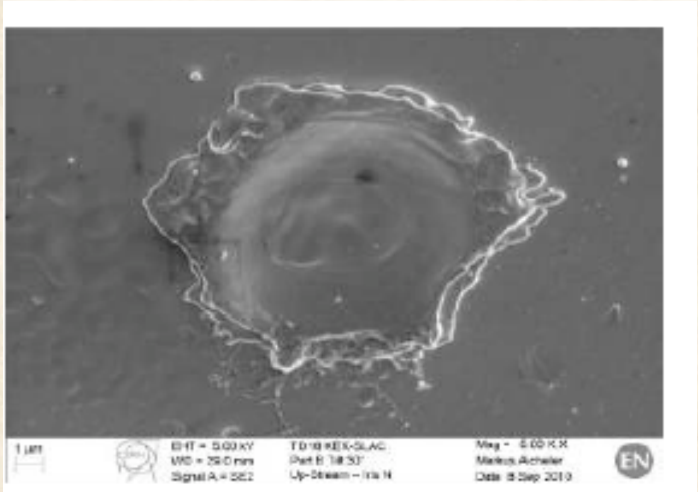
challenge: running at the break down limit

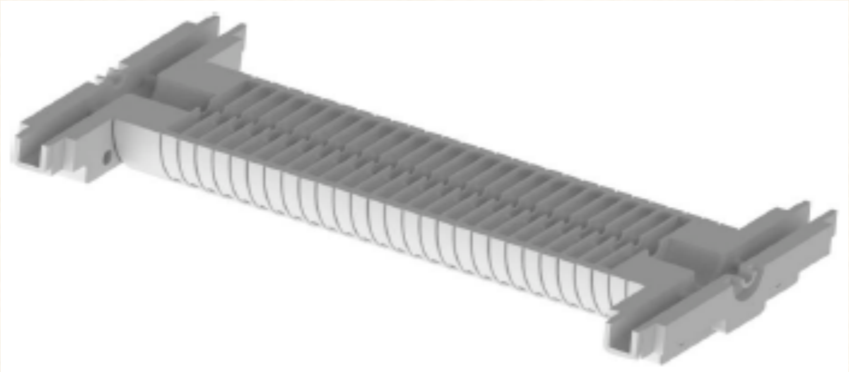
Accereration Gradient 100MV/m studied & optimised since years

“ 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***



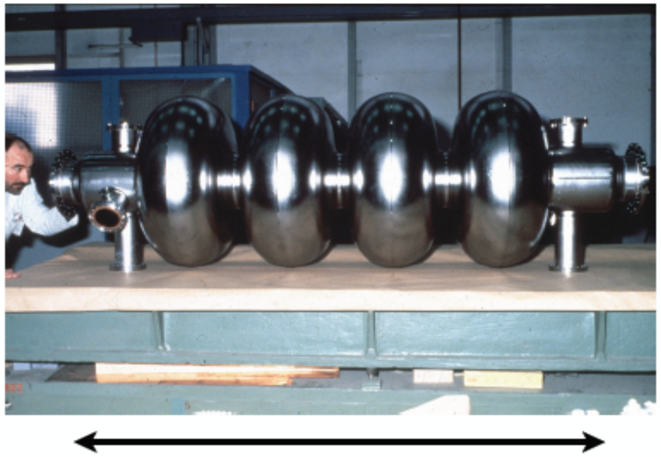


7.) Push for higher energy

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

Plasma Wake Acceleration

RF Cavity



1 m => 50 MeV Gain

Electric field < 100 MV/m

Electric field > 100 GV/m

z.B. AWAKE:

Proton driven Wake Acceleration Experiment at CERN

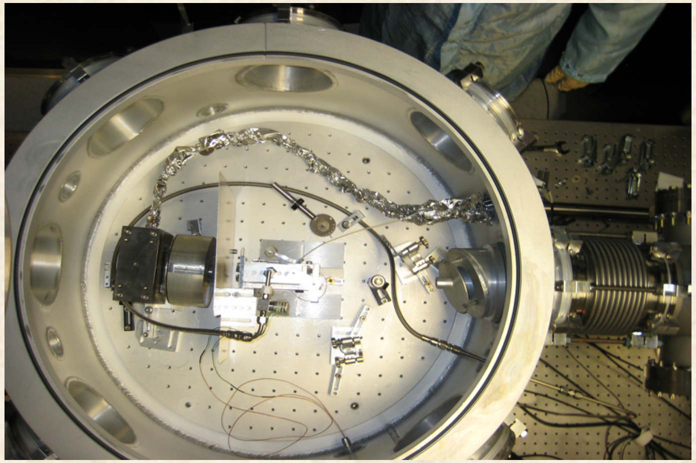
Study of High Gradient Acceleration Techniques

Plasma Wake Acceleration
particle beam driven / LASER driven

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

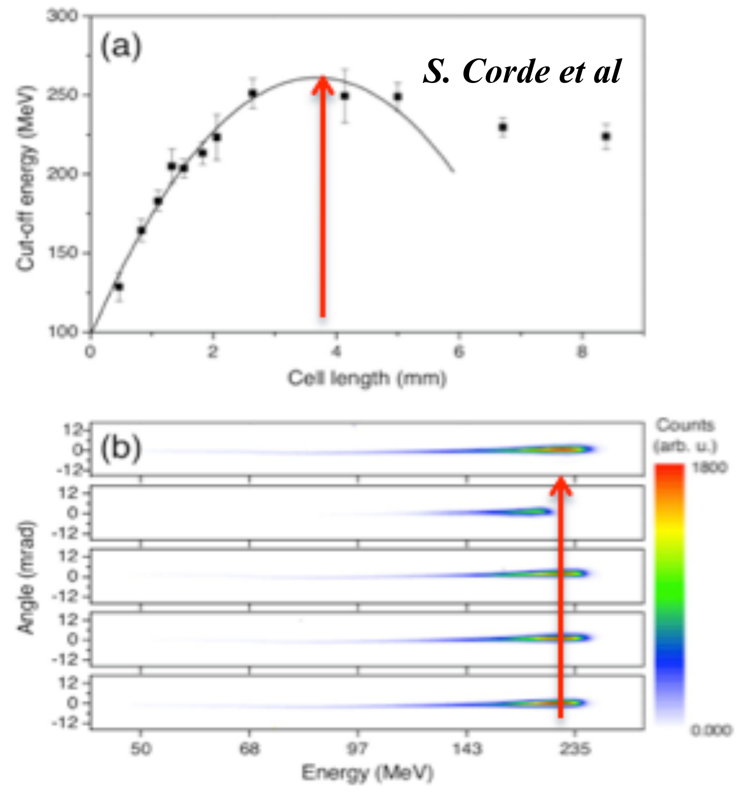
Plasma wake field gradient accelerates electrons that 'surf' on the plasma wave

Field Gradients up to 100 GeV /m observed



Plasma cell Univ. Texas, Austin
E_e =2 GeV

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



S. Corde et al

"The European PWA-Landscape"

UK

Oxford	*Andrei Seryi, Simon Hooker*
Strathclyde	*S. Cipiccia, D. Jaroszynski, R. Bingham*
Manchester	*Andy Wolski*
Lancaster	*G. Burt, Alec Thomas*
Liverpool	*C. Welsch*
Astec	
Cockcroft	*G. Burt*
STFC	*Susie Sheehy*
JAI	*Andrei Seryi, Laura Corner, P. Burrows*
Uni Coll. London	*P. Sherwood*
Imperial Coll London	*Z. Najmudin, S. Mangles*
Queens Uni Belfast	Gianluca Sarri
RAL	*R. Trines*

Port

Lisboa	*Luis Silva, R. Fonseca, J. Vieira*

F

Luli	P Audebert, JR Marquès
Soleil	ME Couprie
LPGP	B Cros
LOA	*Victor Malka, J. Faure*
CEA Lydil	P. Martin, S Dobosz,
Lab lePrince Ringuet	A Specka
LAL	N Delerue
Ecole Poly	*Gerard Mourou*

It

INFN (Sparc)	*Massimo Ferrario*
Pisa Uni	A. Giulietti
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ELI	*Gerad Mourou, Kazuo Tanaka*
Wigner Inst.	*Daniel Barna*

S

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D

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MPI Phys.	*Alan Caldwell, P. Muggli*
MPI Plasma Phys, Greifswald	*Buttenschoen*
Erlangen	*Peter Hommelhoff*

CH

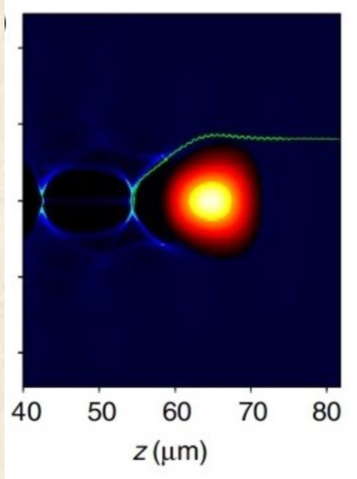
CERN, AWAKE	*Edda, Freddy, Eckardt*
Plasma Center Lausanne	*Plyushchev*

N

Oslo	*Erik Adli*

PWA

A “new” field which
is extremly promising



PWA key-players in Europe

CERN Accelerator School
on plasma wake acceleration

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 ?