THE CERN LHC:

the Higgs Boson discovery machine

2013 Nobel prize in physics awarded (on 08/10/13) to F. Englert and P. Higgs for their theoretical work on Higgs boson (1964)

"Higgs-like" particle with a mass of ~ 125 GeV/c^2 (July 4th, 2012)

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- Introduction: CERN, particle accelerators and colliders
- Main figure of merit for a particle collider
- Importance of the particles energy => High-energy physics research
- Brief history of particle colliders
- Brief history (as of today…) of the LHC
- The LHC: how does it work?
- Current status and future

- **CERN: Conseil Européen pour la Recherche Nucléaire**
  - **1954:** Creation of the European Organization for Nuclear Research now called European Laboratory for Particle Physics (on the Franco-Swiss border near Geneva)

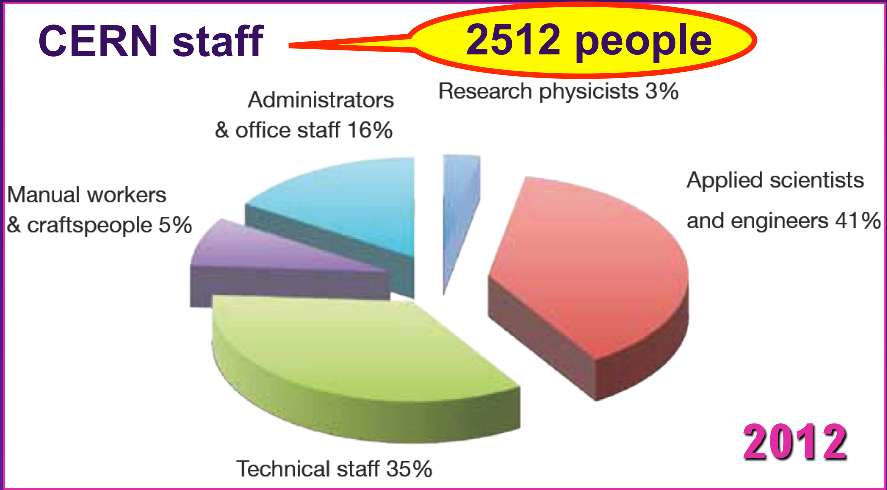
LHC => Largest "particle accelerator & collider" ever built!

LHC is the flagship of CERN's experimental programme, but LHC Physics Program used only 0.018% of the protons produced during 2012!

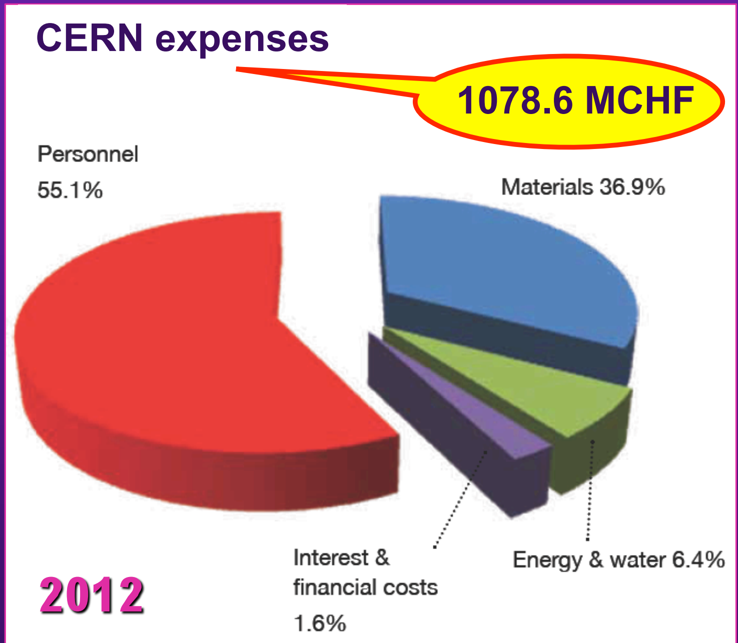
INTRODUCTION (2/11)

- **1957: 1st particle accelerator called Synchrocyclotron**
- **1965: 1st observations of antinuclei (antideuteron) => Also in the US (AGS)**
- **1968: G. Charpak developed the "multi-wire proportional chamber" => 1992 Nobel prize**
- **1971: 1st proton collisions in the ISR**
- **1981: 1st proton-antiproton collisions in the ISR**
- **1983: W and Z particles discovered in the SPS => 1984 Nobel prize for C. Rubbia and S. van der Meer**
- **1990: T. Berners-Lee defined the World Wide Web's basic concepts (URL address, http protocol and html language)**
- **1995: 1st antiatoms produced (antihydrogen) in the LEAR**
- **04/07/2012: Discovery of a "Higgs-like" boson in the LHC**

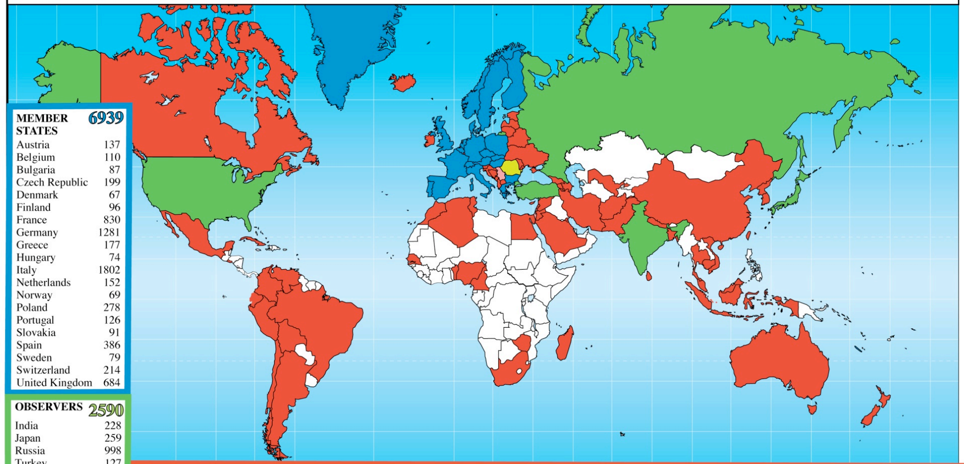
INTRODUCTION (3/11)



20 member states in 2013



Distribution of All CERN Users by Nationality on 14 January 2013



MEMBER STATES	6939
Austria	137
Belgium	110
Bulgaria	87
Czech Republic	199
Denmark	67
Finland	96
France	830
Germany	1281
Greece	177
Hungary	74
Italy	1802
Netherlands	152
Norway	69
Poland	278
Portugal	126
Slovakia	91
Spain	386
Sweden	79
Switzerland	214
United Kingdom	684

OBSERVERS	2590
India	228
Japan	259
Russia	998
Turkey	127
USA	978

CANDIDATE FOR ACCESSION	
Romania	126

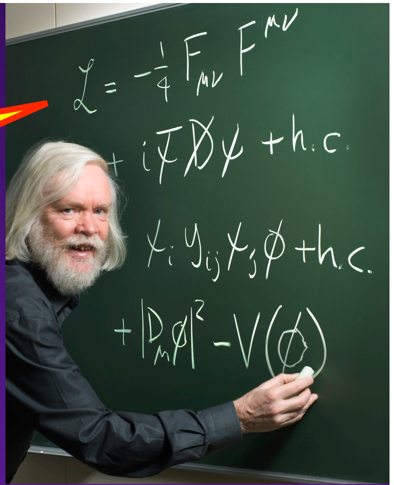
ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP	
Israel	60
Serbia	45

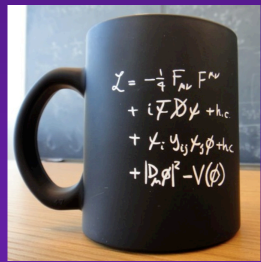
OTHERS													
Afghanistan	1	Bolivia	2	Croatia	31	Iran	31	Malaysia	8	Peru	6	Ukraine	57
Albania	3	Bosnia & Herzegovina	2	Cuba	7	Ireland	22	Malta	2	Saudi Arabia	3	Uzbekistan	2
Algeria	12	Brazil	98	Cyprus	13	Jordan	2	Mexico	62	Senegal	1	Venezuela	11
Argentina	16	Cambodia	1	Ecuador	3	Korea, D.P.R.	2	Moldova	1	Singapore	1	Viet Nam	11
Armenia	23	Cameroon	1	Egypt	12	Korea Rep.	117	Montenegro	3	Slovenia	33	Zimbabwe	2
Australia	23	Canada	140	El Salvador	1	Kuwait	1	Morocco	16	South Africa	14		
Azerbaijan	7	Cape Verde	1	Estonia	15	Latvia	1	Nepal	3	Sri Lanka	7		
Bangladesh	6	Chile	10	Georgia	35	Lebanon	10	New Zealand	8	Syria	2		
Belarus	41	China	266	Gibraltar	1	Lithuania	20	Nigeria	1	Thailand	8	1386	
Bangladesh													
Benin	1	Colombia	35	Indonesia	1	Madagascar	1	Palestine (O.T.).	5	Tunisia	8		

INTRODUCTION (4/11)

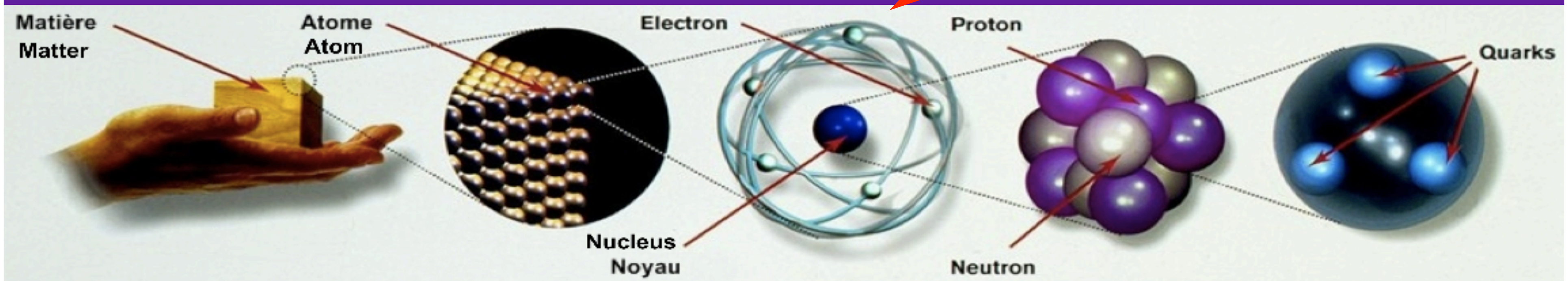
- **What are we doing at CERN?**
  - **Standard model**
    - All matter of our Universe => Atoms
    - Each atom => A nucleus with electrons (e^-) around
    - Each nucleus => Protons (p^+) and neutrons (n)
    - Each p^+ and n => Quarks and gluons

Standard model Lagrangian (John Ellis)





\> 99.99% is empty space…



- After a century of discoveries and measurements, the particle physicists have developed the Standard Model, explaining almost all the components of matter and the forces between them

INTRODUCTION (5/11)

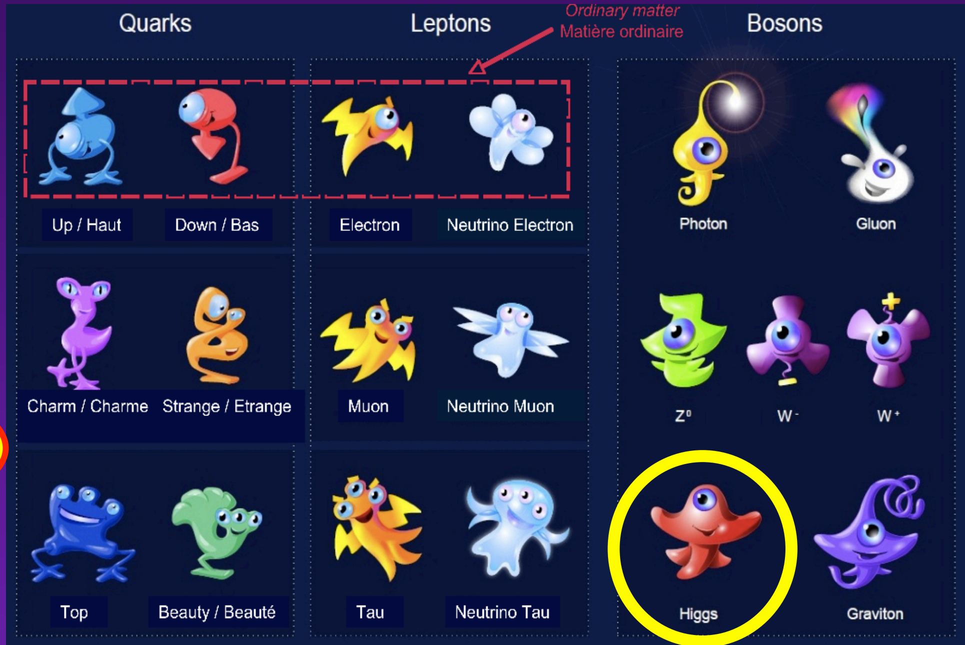
- **Components of matter**
  - **Fermions (1/2 integer spin*)**
    - **12 quarks (6 q + 6 anti-q)**
    - **12 leptons (6 l + 6 anti-l)**

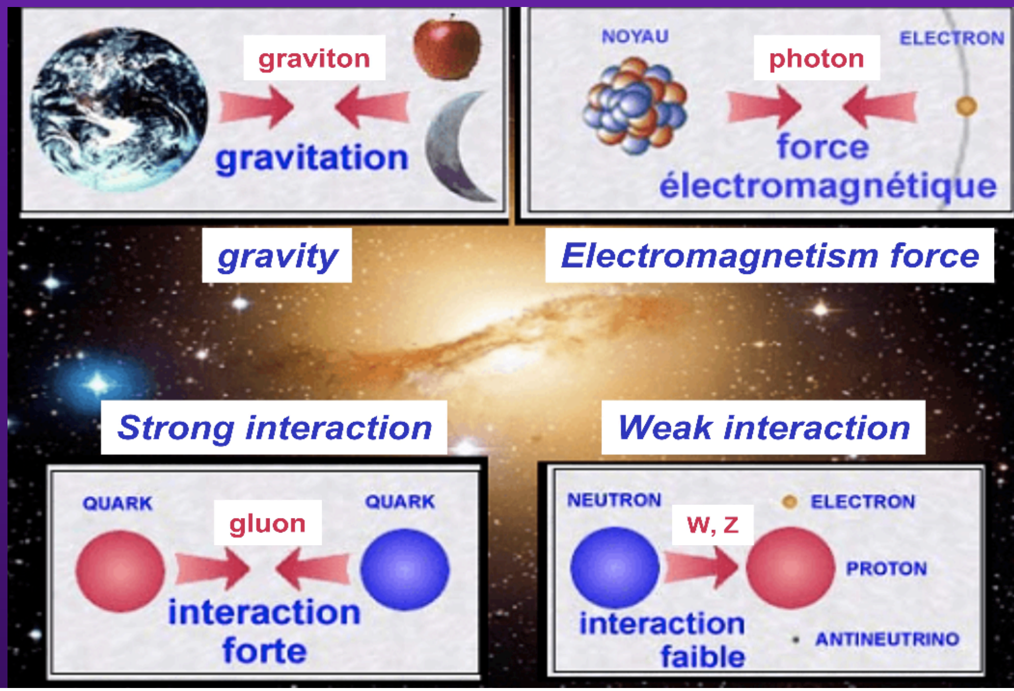
Main distinction between quarks and leptons is that there is NO strong interaction for the leptons

  - **Bosons (integer spin*)**

** The spin of a particle is a quantum characteristic, often represented by a "toupie" rotating around an axis*

Courtesy of M. Goulette





- **Forces of nature**

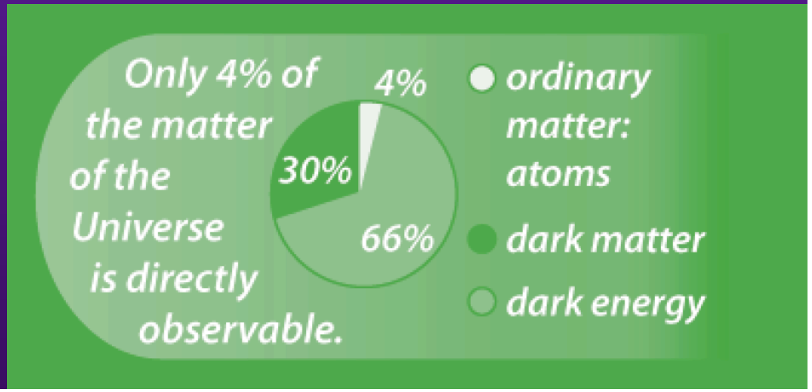
INTRODUCTION (6/11)

- By assembling quarks we create **HADRONS** (= Heavy in Greek) => 2 families
  - **BARYONS** (odd number of quarks => ½ integer spin)
    Ex: p^+, n
  - **MESONS** (even number of quarks => Integer spin)
    Ex: pion

Leptons => Light in Greek

- Unsolved mysteries
  - Why Universe's expansion seems to be accelerating?
  - Where is antimatter (created with matter in the Big Bang)? Or why is there something instead of nothing?
  - What and where is the dark matter (to explain the rotation of galaxies)? Dark energy?
  - Etc.

=> This is what we are looking for at CERN!

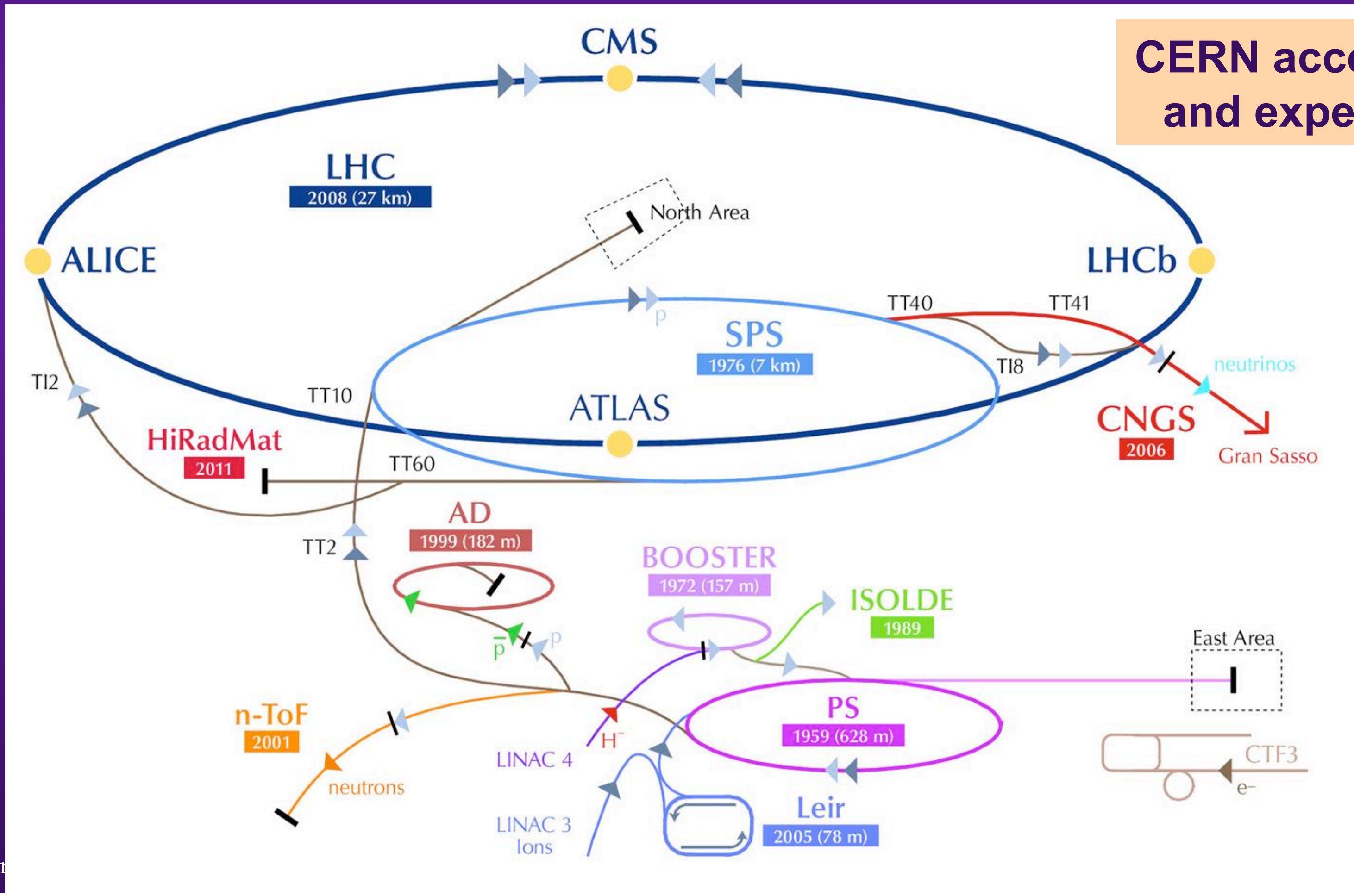


INTRODUCTION (7/11)

- **To perform all these studies, we (create and accelerate and) send a beam of charged particles (e.g. p^+)**
  - **On some targets => FIXED-TARGET mode**
  - **On another beam of charged particles => COLLIDER mode**

Could be CIRCULAR or LINEAR

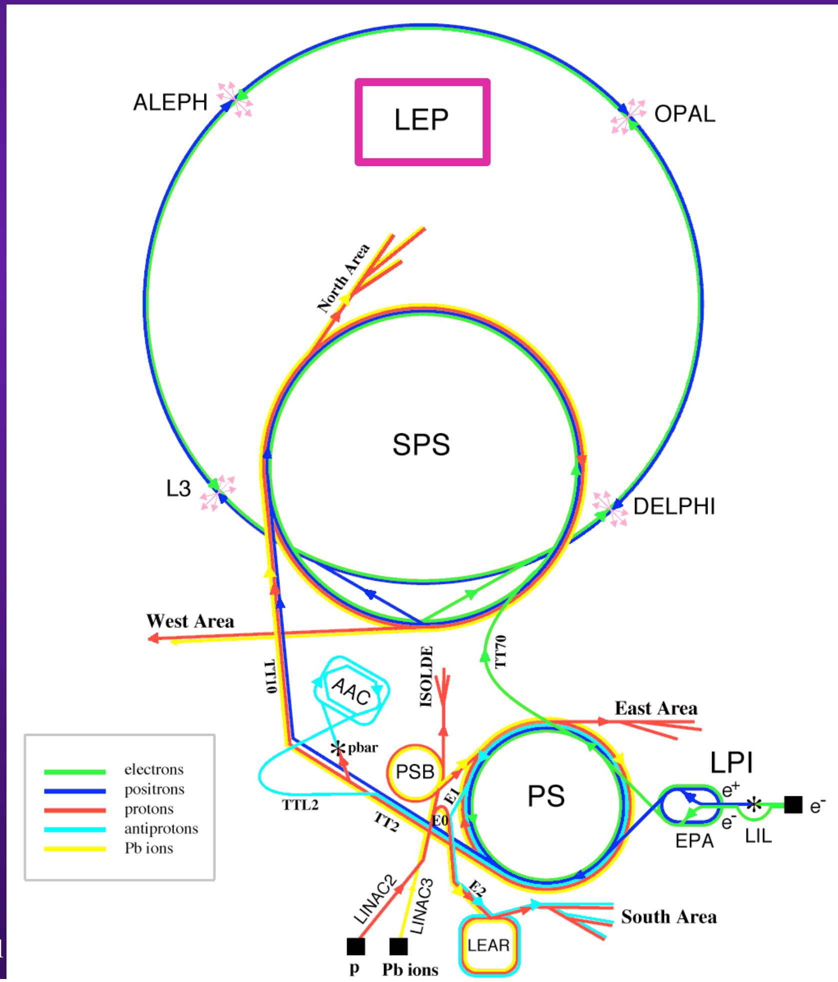
CERN accelerators and experiments



INTRODUCTION (8/11)

- **LHC: What does this mean?**
  - LHC = Large Hadron Collider
  - L = Large => 27 km circumference => Largest accelerator ever built: Tunnel was built for the LEP collider in 1985
  - H = Hadron
  - C = Collider

Large Electron Positron (= e^+ = anti-e^-)



INTRODUCTION (9/11)

- Particle accelerators are devices that handle the motion of particles by means of **electromagnetic fields** => 3 requirements

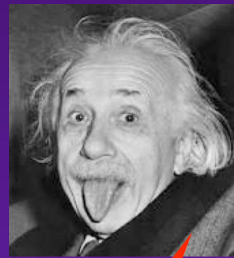
  1) Charged particles
  2) Stable particles during acceleration (i.e. need not to decay) => Limits the number of particles that can practically be accelerated to e^-, p^+ and ions + all their antiparticles
  3) "Vacuum" (where the particles circulate) should be good enough for the particles not to be perturbed

- Driving force => High-energy physics research (small % of activity)

- Several thousand particle accelerators operating in many countries around the world, are now widely used in a variety of applications
  - Applied physics
  - Medicine
  - Industrial processing
  - Possible utilisation in power engineering has been envisaged

INTRODUCTION (10/11)

- **With a collider, we do the opposite as in Nuclear Plants => We create matter (new particles) starting from energy, while in Nuclear Plants we create energy starting from matter (Uranium, etc.)**



$$E = \gamma \, m_0 \, c^2$$

Particle (total) energy

m_0 = particle rest mass

Speed of light
≈ 3 10^8 m/s
(i.e. ~ 30 cm in 1 ns)

Energy and mass are 2 sides of the same coin

Power of ten	Number	Symbol
10^{-12}	0.000000000001	p (pico)
10^{-9}	0.000000001	n (nano)
10^{-6}	0.000001	μ (micro)
10^{-3}	0.001	m (milli)
10^{-2}	0.01	
10^{-1}	0.1	
10^{0}	1	
10^{1}	10	
10^{2}	100	
10^{3}	1000	k (kilo)
10^{6}	1 000 000	M (mega)
10^{9}	1 000 000 000	G (giga)
10^{12}	1 000 000 000 000	T (tera)
10^{15}	1 000 000 000 000 000	P (peta)

$$\beta = \frac{v}{c}$$

Speed of particle

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

INTRODUCTION (11/11)

Control room since March 2006

MAIN FIGURE OF MERIT FOR A PARTICLE COLLIDER (1/2)

- **LUMINOSITY**

$$L = \frac{N_{events/\sec ond}}{\sigma_r}$$

Number of events per second generated in the collisions

Cross-section of the reaction

[cm^{-2} s^{-1}]

$$L \propto \frac{M\, N_b^2\, f_{rev}}{\sigma_x\, \sigma_y}$$

Number of bunches (= group of particles) per beam

Number of particles per bunch

Revolution frequency

Horizontal beam size of the bunches

Vertical beam size of the bunches

MAIN FIGURE OF MERIT FOR A PARTICLE COLLIDER (2/2)

- The LHC experimental challenge is to find rare events at levels of 1 in 10^{13} or more

  => The exploration of rare events in the LHC collisions therefore requires high statistics => High luminosity needed!

- Requested (peak) luminosity for the LHC = 10^{34} cm^{-2} s^{-1}

  => M = 2808 bunches (with a length of ~ 30 cm), N_b = 1.15 10^{11} p/b, f_{rev} = 11.245 kHz, $\sigma_x = \sigma_y \approx 17$ µm (at the Interaction Point)

  Thickness of a human hair ≈ 50 – 100 µm

- The discovery of a new particle requires to reach the

  "5-σ discovery limit"

  Corresponds to a confidence of 99.99994 %

IMPORTANCE OF THE PARTICLES ENERGY (1/4)

- **Energy unit**
  - Many units in physics: Joule (SI unit) or calorie or kilowatt-hour or …
  - In particle physics => electronvolt (eV) or in fact multiple of it

Energy gain by an e^- accelerated by a potential difference of 1 volt = $1.6\ 10^{-19}$ C × 1 V = $1.6\ 10^{-19}$ J

  - Ex.: In the LHC, the total collision energy is 7 + 7 = 14 TeV

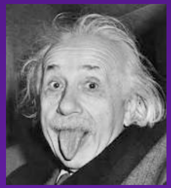
$$14\ \mathrm{TeV} = 14 \times 10^{12} \times 1.6\ 10^{-19}\ \mathrm{J} = 22.4\ 10^{-7}\ \mathrm{J}$$

Very small compared to an object of 1 kg falling down from 1 m => 9.8 × 1 × 1 = 9.8 J = $6.1\ 10^{19}$ eV

IMPORTANCE OF THE PARTICLES ENERGY (2/4)

=> In absolute terms, these energies, if compared to the energies we deal with everyday, are not impressive. In fact, 1 TeV is about the energy of motion of a flying mosquito. What makes the LHC so extraordinary is that it squeezes energy into a space about a million times smaller than a mosquito…

- The 2 roles of energy



1) Producing new particles (see before)

2) Resolving the inner structure of matter

$$E = \frac{h\,c}{\lambda}$$

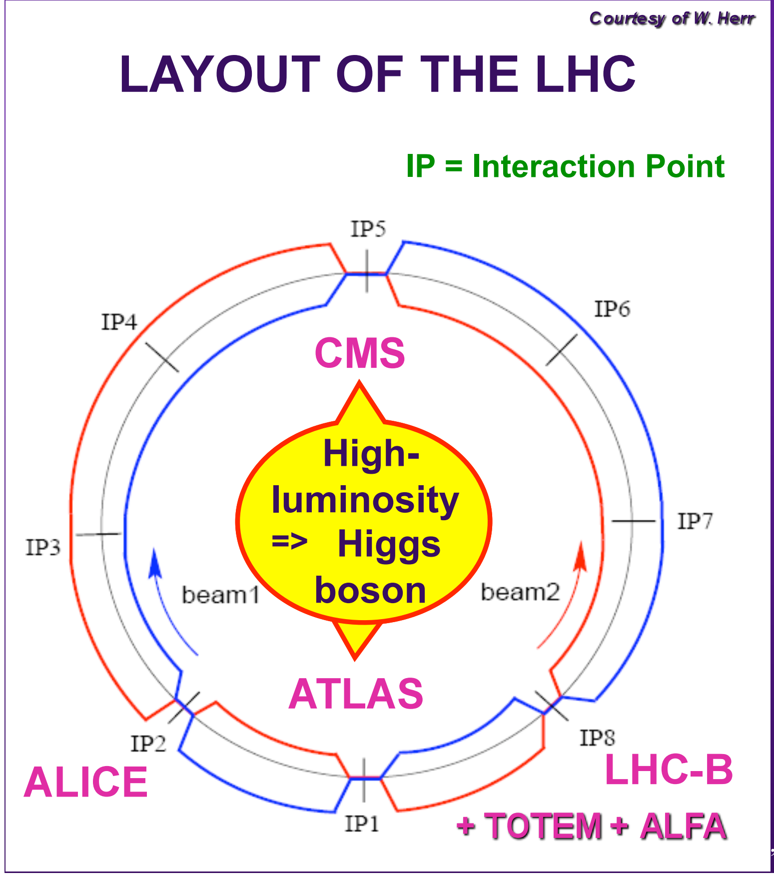
Wavelength => Should be < object to be resolved

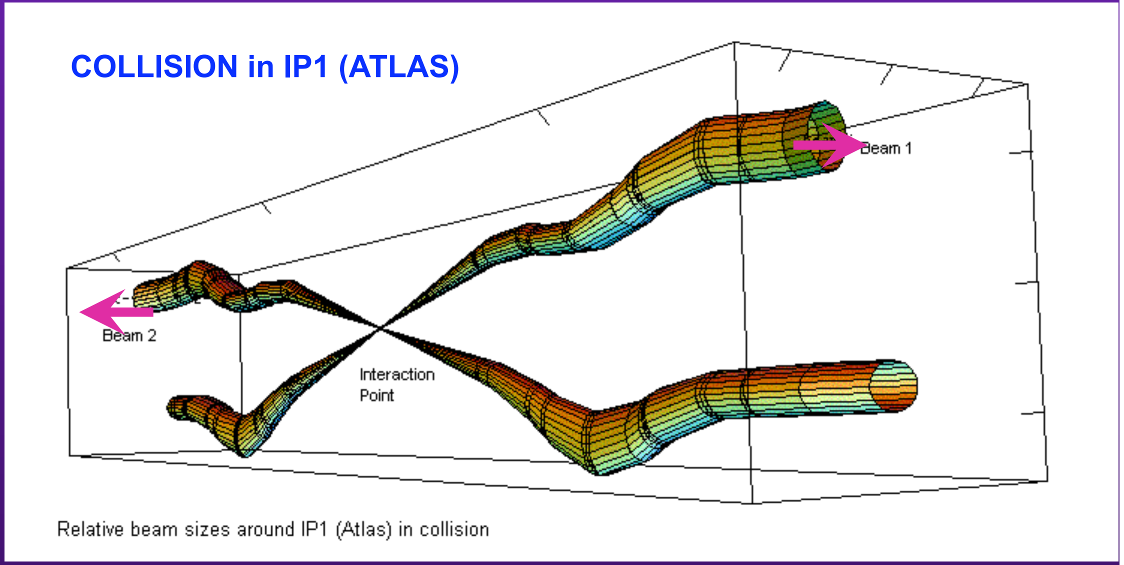
Planck constant ≈ 6.62 10^{-34} Js

Object	Size [m]	Energy needed [GeV]
Atom	10^{-10}	~ 10^{-5}
Nucleus	10^{-14}	~ 0.1
Nucleon	10^{-15}	~ 1
Quark	~ 10^{-19}	~ 10^{4}

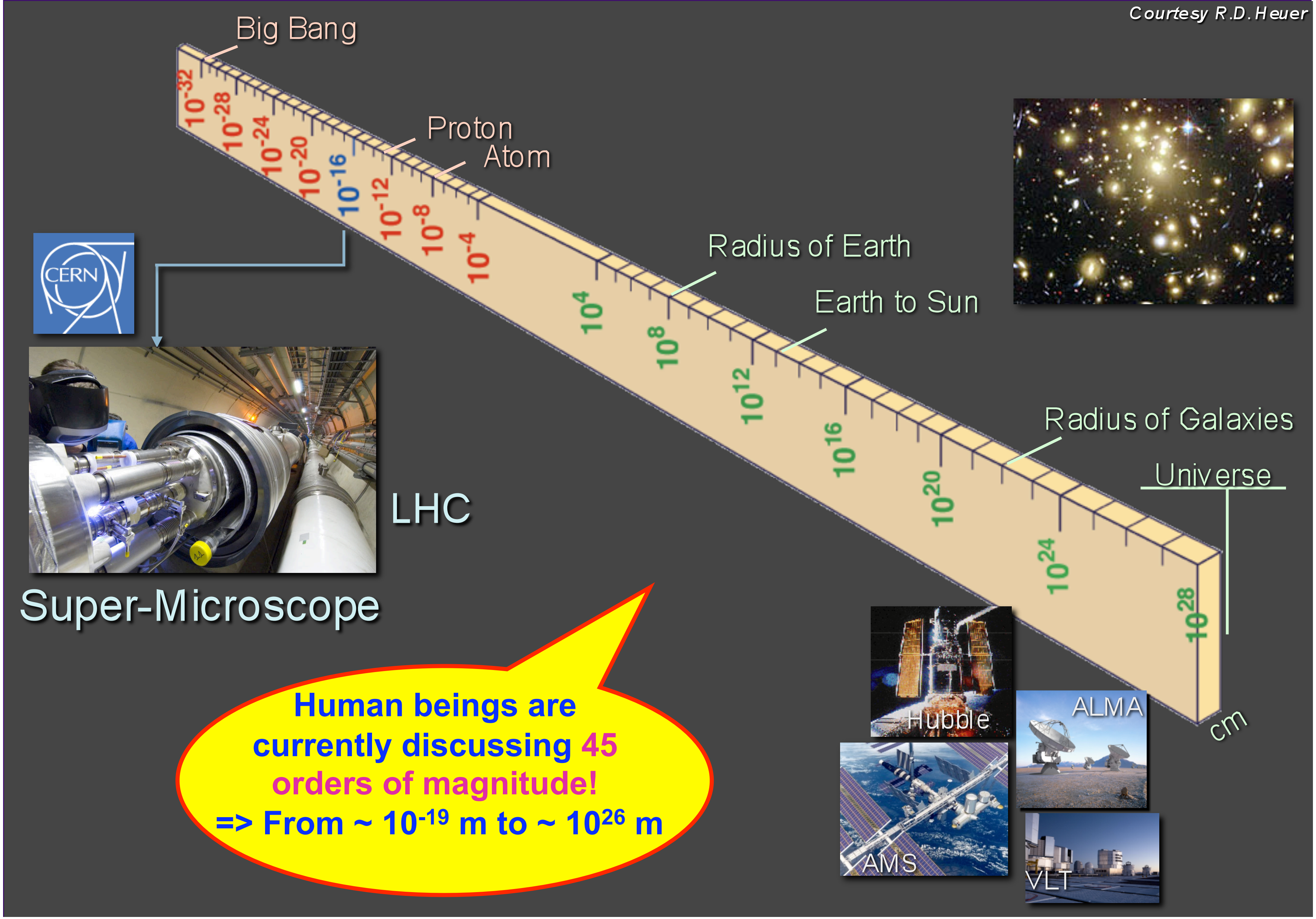
IMPORTANCE OF THE PARTICLES ENERGY (3/4)

- **Why Collider vs. Fixed-Target mode? => Available energy in the centre of mass (to create new particles)**
  - LHC (p^+p^+, 7 TeV / beam)
    - Collider mode => 14 TeV
    - Fixed-target mode => ~ 115 GeV (i.e. ~ 122 times less)





IMPORTANCE OF THE PARTICLES ENERGY (4/4)



BRIEF HISTORY OF PARTICLE COLLIDERS (1/2)

HEP Colliders (1984-2011) (Revision August 30, 2012)

Location	Accelerator	Type	Energy	Operations Period	Impact	Note
SSCL	SSC	p-p	20 x 20 TeV	N/A	Cancellation a blow to the world HEP program, especially in the US	Construction began in 1989 but was canceled by the US Congress in 1993
CERN	LHC	p-p	7 x 7 TeV	2009-present	Highest energy collider, first to use 2-in-1 SC magnet technology, limits on Higgs mass, search for physics beyond SM, Quark-gluon plasma physics	Inauguration in October 2008, re-commissioning in late 2009, currently operating at 4 x 4 TeV
		Pb-Pb	574 x 574 TeV (2.76 x 2.76 TeV per nucleon)			
	LEP	e+e-	104.5 x 104.5 GeV	1989-2000	Precise measurement of Z and W bosons, determination of the number of light neutrino families to be 3, exclusion of Higgs mass below 114 GeV	Highest energy lepton collider
	SPS	p-pbar	315 x 315 GeV	1981-1984	Discovery of W and Z bosons, first to use stochastic cooling technology	Now as both LHC injector (450 GeV) and fixed-target machine (400 GeV)
	ISR	p-p	31.4 x 31.4 GeV	1971-1984	First hadron collider and first p-pbar collider	Also ran in p-d, d-d, p-alpha, alpha-alpha modes
Fermilab	Tevatron	p-pbar	980 x 980 GeV	1983-2011	Discovery of Top quark and Tau neutrino, first large accelerator using SC magnet technology	Ran as both a fixed-target machine and a collider
KEK	KEKB	e+e-	8 (e-) x 3.5 (e+) GeV	1998-2010	CP violation in the decay of B-meson, confirmation of the CKM mattrix	Highest luminosity collider
	TRISTAN	e+e-	32 x 32 GeV	1986-1995	First large accelerator using SC RF technology	

~ 2.1 10^{34} cm^{-2} s^{-1}

Location	Accelerator	Type	Energy	Operations Period	Impact	Note
SLAC	PEP-II	e+e-	9 (e-) x 3.1 (e+) GeV	1999-2008	CP violation in B-Bbar system, confirmation of the CKM mattrix	Record stored beam currents, 3.2 A (e+), 2.1 A (e-)
	SLC	e+e-	46.2 x 46.2 Gev	1988-1998	Precise measurement of Z boson, including most precise indirect constraint on Higgs mass	First (and only) e+e- linear collider, 80% polarized e-
	PEP	e+e-	14 x 14 GeV	1980-1990	Lifetime measurements of Tau lepton and B meson, analysis of gluon jets, QCD studies	Six interaction points
	SPEAR	e+e-	4 x 4 GeV	1972-1988	Discovery of the J/Psi meson and Tau lepton	Early 4π detectors and synchrotron light port
DESY	HERA	e-p	27.5 x 920 GeV	1992-2007	Test of QCD, proton structure function	Polarized e- and e+
	PETRA	e+e-	23.4 x 23.4 GeV	1978-1986	Discovery of Gluon	Ligth source since 2009
	DORIS	e+e-	5.6 x 5.6 GeV	1974-1992	Decays of J/Psi and Ypsilon resonances, B physics	e+/e- collision with hydrogen target in 2012
Cornell	CESR	e+e-	1.8 x 1.8 GeV to 5.5 x 5.5 GeV	1979-2008	Measurement of |Vub|, observation of "penguin" and $b \rightarrow s\gamma$ decays, CKM matrix constraining the unitarity triangle	Currently operating in two modes: light source and damping ring test accelerator
BNL	RHIC	p-p, Au-Au	250 x 250 GeV	2000-present	Quark-gluon plasma discovery, nuclear phase diagram, source of proton spin	
INFN	DAFNE	e+e-	0.51 x 0.51 GeV	1999-present	High precision K physics, crab-waist operation for future Super-B	
IHEP/China	BEPC & BEPC-II	e+e-	1.5 x 1.5 GeV to 2.5 x 2.5 GeV	1988-2005, 2008-present	Charm-τ physics	
BINP	VEPP-200	e+e-	0.2 x 0.2 GeV to 1 X 1 GeV	2010-present	Hadron production measurement; p-pbar and n-npar near threshold	
	VEPP-4M	e+e-	1.5 x 1.5 GeV to 5 x 5 GeV	1984 -present	τ and Psi mass measurement, 2-gamma physics	

BRIEF HISTORY OF THE LHC (1/4)

- 1983 (i.e. several years before LEP started): 1st ideas / estimates
- Dec. 1994: LHC Project approved by CERN Council
- Oct. 1995: LHC Conceptual Design Report, which has served as the basis for the detailed design
- Dec. 1996: Council passed a Resolution approving the construction of the 14 TeV accelerator in a single stage (initially, the budgetary constraints implied that the LHC was to be conceived as a 2-stage project). The LHC is the 1st machine built at CERN with substantial material contribution from non-Member States. Machine hardware constructed in National Laboratories in Canada, India, Japan, Russia and USA
- 2007: LHC was finished
- 2008: LHC commissioning & inauguration
- 30/03/2010: 1st collisions at 7 TeV (3.5 + 3.5)

10/09/2008: LHC startup

BRIEF HISTORY OF THE LHC (2/4)

- **July 4th, 2012: Announcement of the discovery of a new particle ("Higgs-like" boson) => 5-σ limit reached**

A historical day : 4th July 2012

Peter Higgs

Courtesy of R.D. Heuer

BRIEF HISTORY OF THE LHC (3/4)

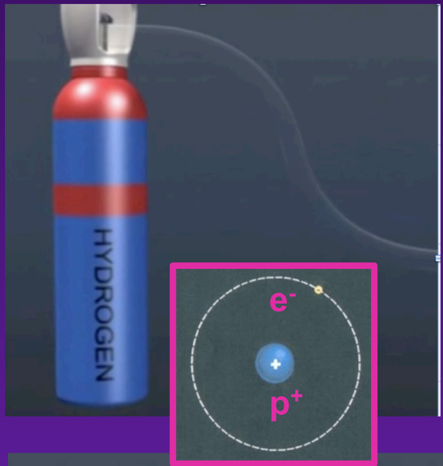
BRIEF HISTORY OF THE LHC (4/4)

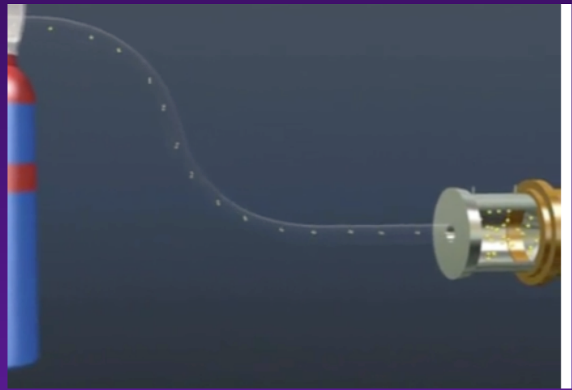
- **Cost: ~ 5 billion CHF for the machine alone. The total project cost breaks down roughly as follows**

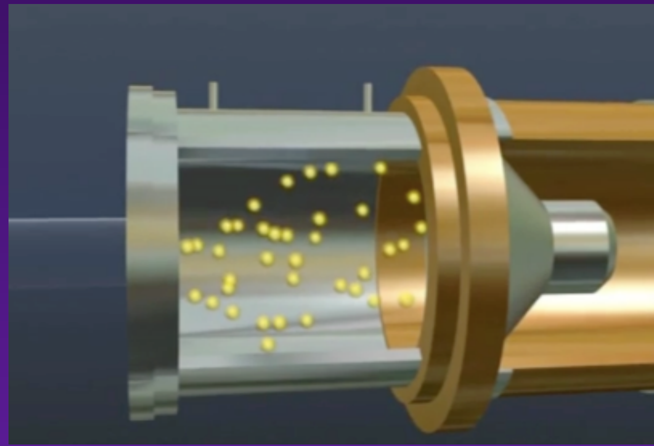
Construction costs (MCHF)	Personnel	Materials	Total
LHC machine and areas*)	1224	3756	4980
CERN share to detectors	869	493	**1362**
LHC computing (CERN share)	85	83	**168**
Total	**2178**	**4332**	**6510**

*) *This includes: Machine R & D and injectors, tests and pre-operation.*

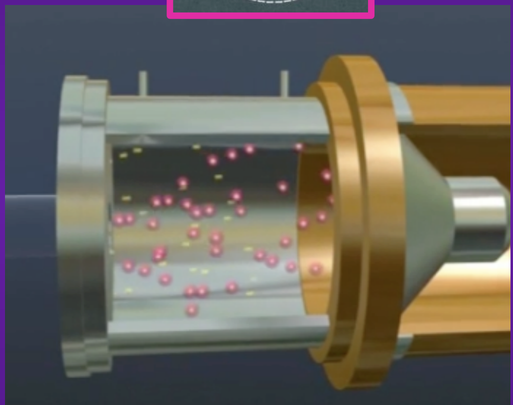
THE LHC: HOW DOES IT WORK? (1/34)



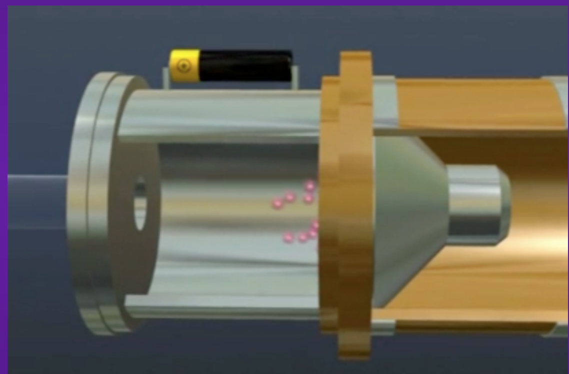




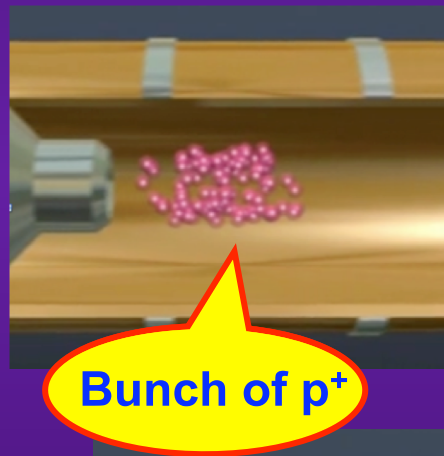
H atoms are taken from a bottle

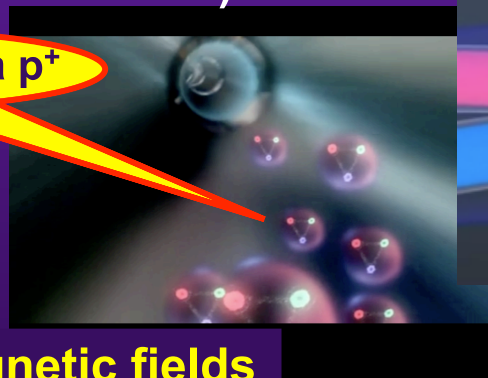


p^+ created by stripping orbiting e^- from H atoms



Acceleration by **electric fields** (voltage differences)



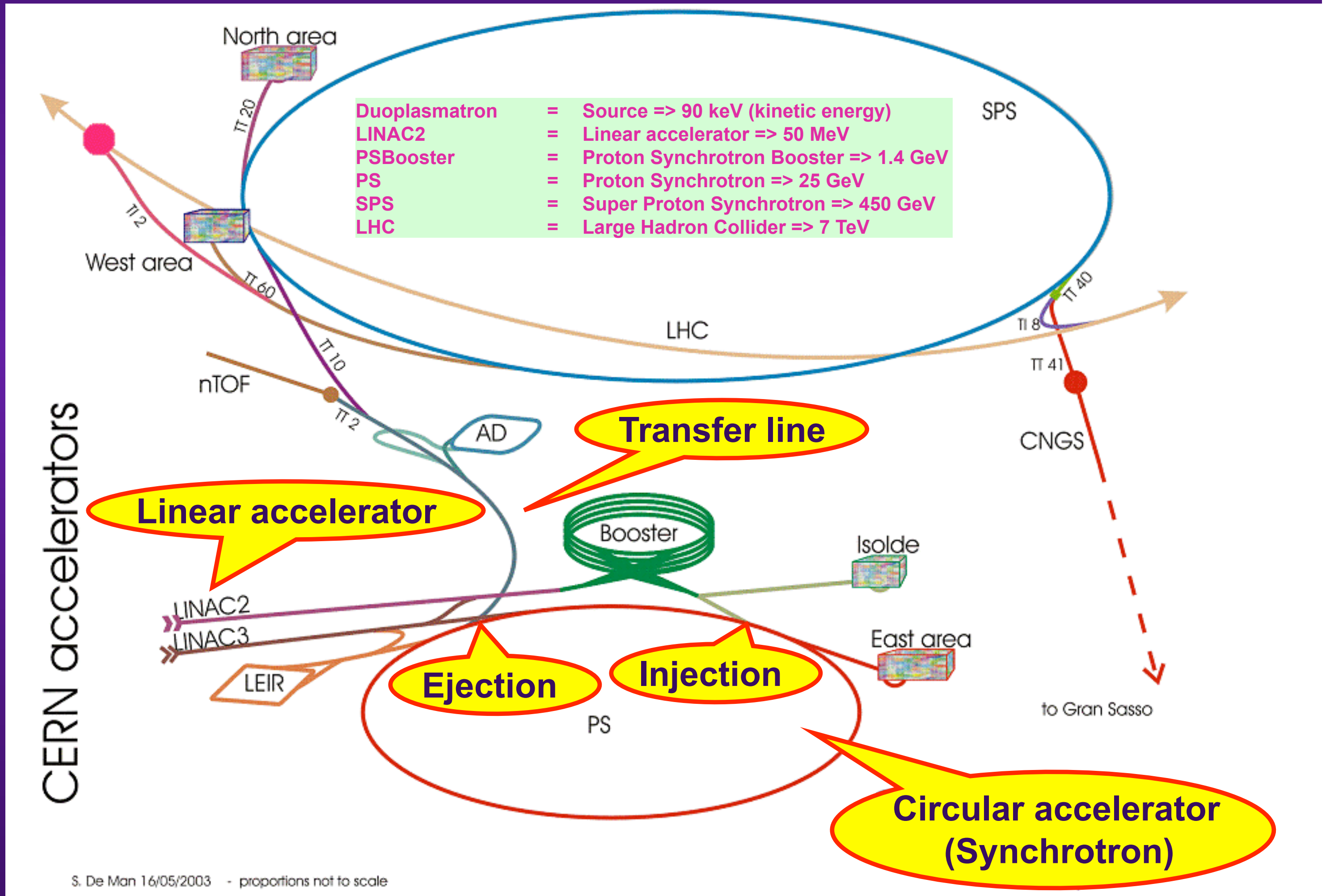


Guidance and focalization by **magnetic fields**

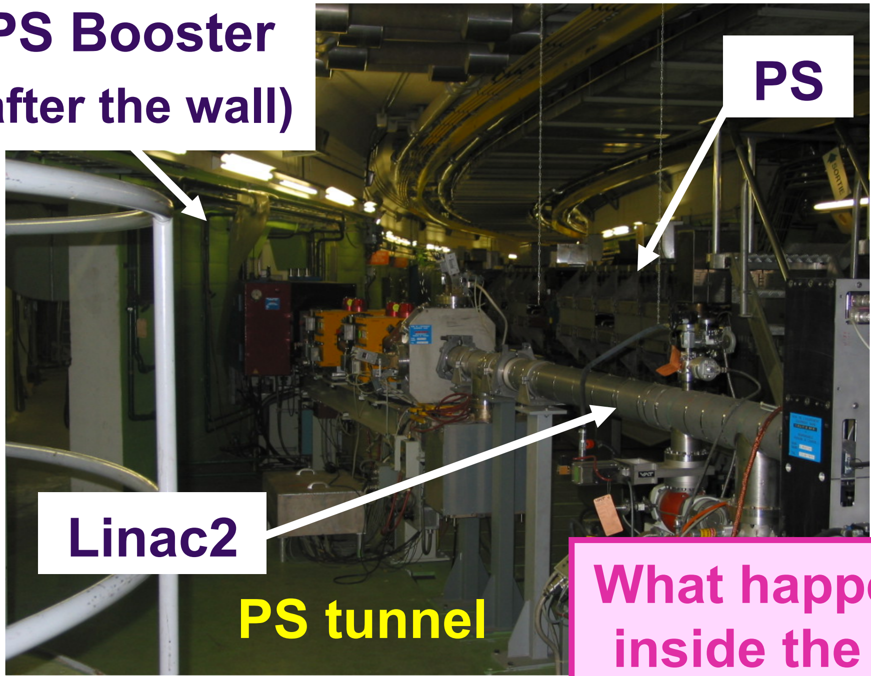
“collision” or “interaction”

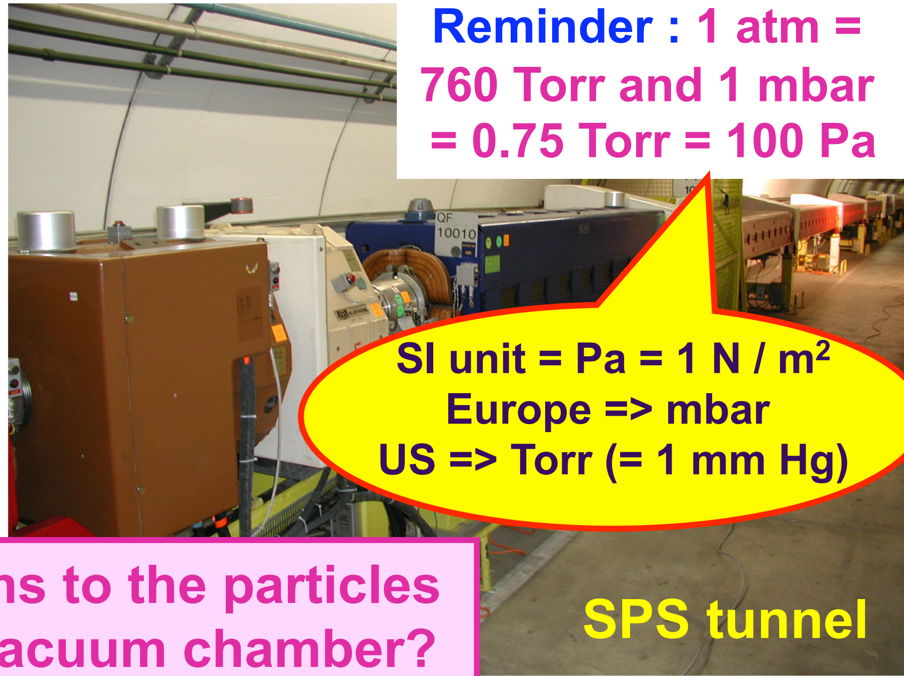
THE LHC: HOW DOES IT WORK? (2/34)

- The LHC is both a particle accelerator and a collider
- It is a SYNCHROTRON as during the acceleration of the particles the machine radius remains the same (≠ from a CYCLOTRON for instance)

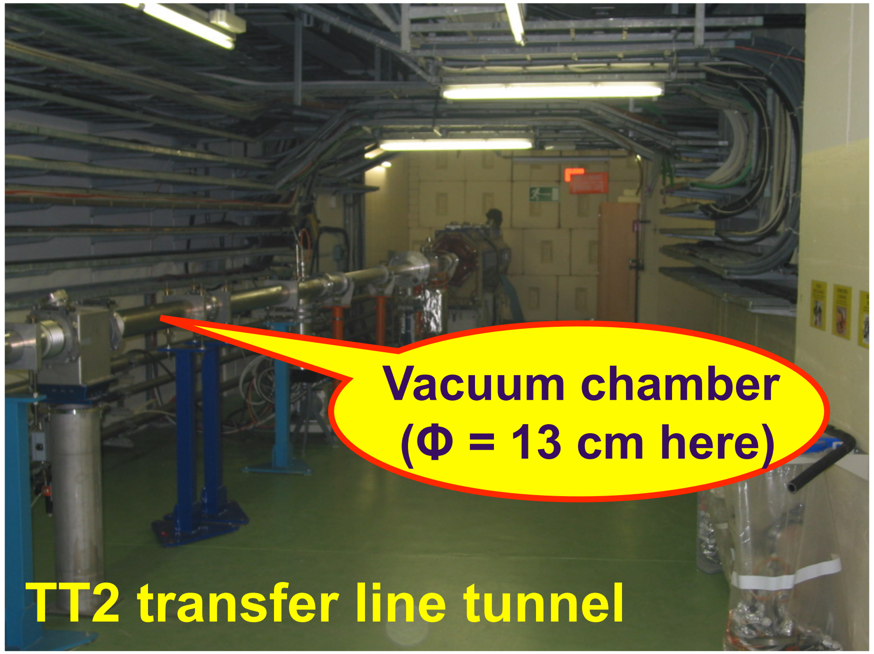


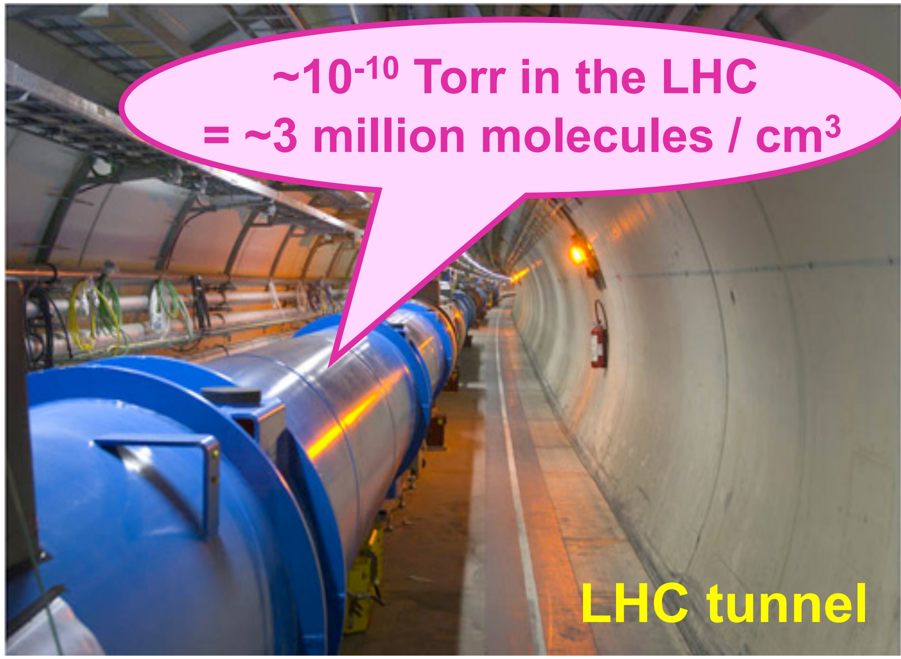
Example of the LHC p beam in the injector chain





What happens to the particles inside the vacuum chamber?



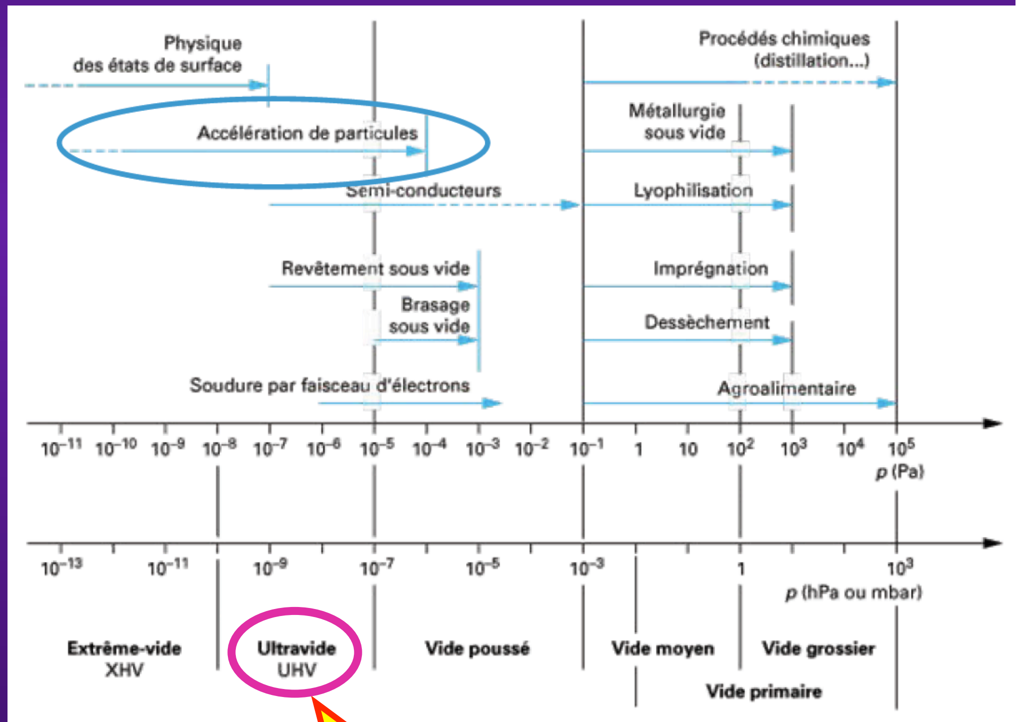


THE LHC: HOW DOES IT WORK? (4/34)

- **Vacuum**

  - **What is vacuum? => Space where P < P_{atm} ⇔ < ~ 3 10^{19} molecules / cm^3**

Altitude	(Km)	P (hPa)
Niveau de la mer	0	1013
Sommet Mont-Blanc	4.8	560
Altitude des jets	15	120
Satellites géostationnaires	35800	2.10^{-5}
Au voisinage du sol lunaire	0	5.10^{-7}
A l'altitude de la lune	384000	5.10^{-9}
Dans notre galaxie	(estim.)	10^{-15} - 10^{-17}
Espace inter-galactique	(estim.)	10^{-22} - 10^{-24}



for the LHC

Courtesy of P. Dolégiéviez

THE LHC: HOW DOES IT WORK? (5/34)

- **LHC has the particularity of having not 1, but 3 vacuum systems**
  - **Beam vacuum**
  - **Insulation vacuum for cryomagnets**
  - **Insulation vacuum for the helium distribution line**

See later

- **The largest volume to be pumped in the LHC is the insulation vacuum for the cryomagnets (~ 9000 m^3 — like pumping down the central nave of a cathedral!)**

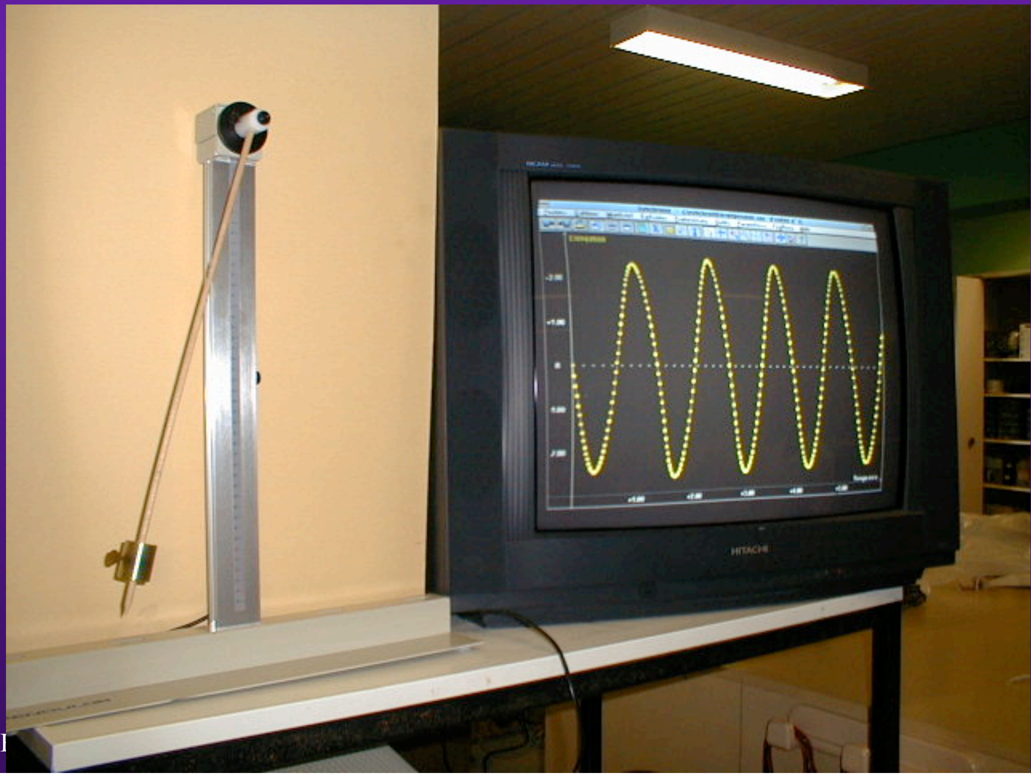
- **The beam particles circulate therefore in a vacuum chamber (where a sufficiently good vacuum has been made)**

=> The shape and material of the vacuum chamber are important for the machine performance

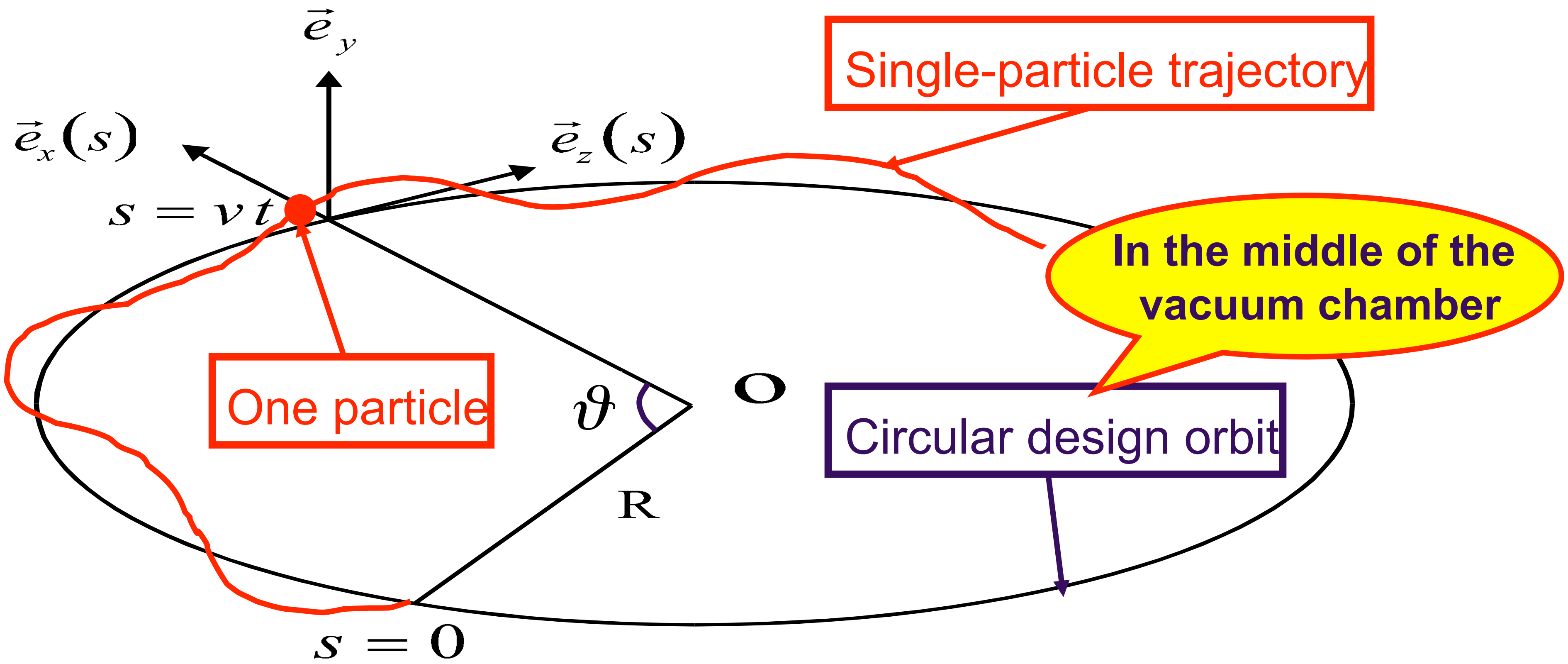
- **Circular or elliptical**
- **Stainless steel or copper**

Usually

- **The TRICK of particle accelerators**
  - **The best way to keep something (here particles) under control (i.e. stable) is to make it oscillate! And this is what we do…**
  - **All the motions are close to the motion of a harmonic oscillator**
    - **The harmonic oscillator and the coupling between different harmonic oscillators are at the basis of everything…**
    - **Example of a pendulum with small-amplitude oscillations**



THE LHC: HOW DOES IT WORK? (7/34)



- The motion of a charged particle (p^+) in a beam transport channel or a circular accelerator is governed by the **LORENTZ FORCE**

$$\vec{F} = e\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Electric field

Magnetic field (induction)

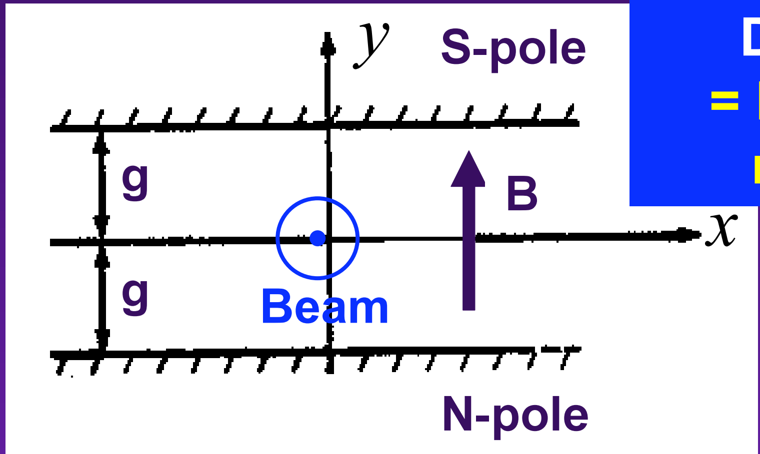
THE LHC: HOW DOES IT WORK? (8/34)

- The Lorentz force is applied in the transverse planes (=> B) as a
  - BENDING FORCE (using DIPOLES) to guide the particles along a predefined ideal path, the DESIGN ORBIT, on which – ideally – all particles should move
  - FOCUSING FORCE (using QUADRUPOLES) to confine the particles in the vicinity of the ideal path, from which most particles will unavoidably deviate

- The Lorentz force is applied in the longitudinal plane (=> E) to
  - GROUP PARTICLES together (in bunches)
  - INCREASE THE PARTICLES ENERGY

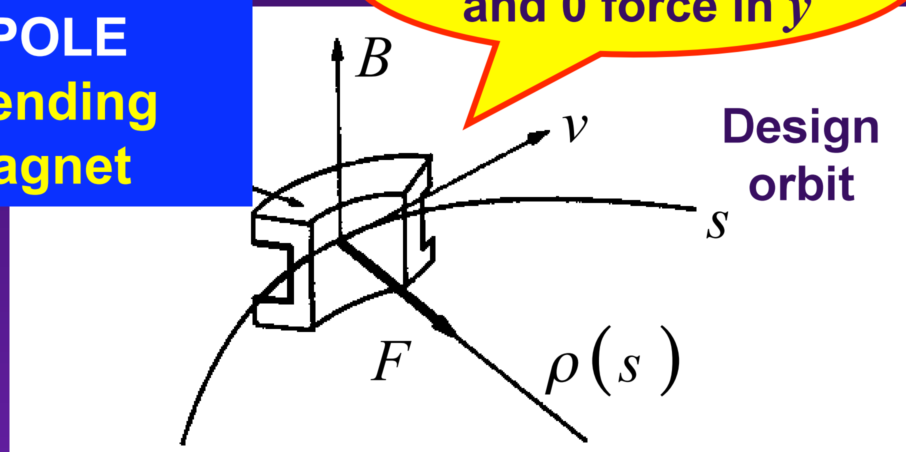
Using RF cavities

THE LHC: HOW DOES IT WORK? (9/34)



DIPOLE
= Bending magnet

Constant force in x and 0 force in y



⇒ **A particle, with a constant energy, describes a circle in equilibrium between the centripetal magnetic force and the centrifugal force**

BEAM RIGIDITY

$$B \rho \left[\mathrm{T\,m} \right] = 3.3356 \, p \left[\mathrm{GeV/c} \right]$$

Magnetic field — Curvature radius of the dipoles — Beam momentum

$$E^2 = E_0^2 + p^2 c^2$$

THE LHC: HOW DOES IT WORK? (10/34)

- LEP vs LHC magnets (in same tunnel) => A change in technology

	LEP	LHC
ρ [m]	3096.175	2803.95
p [GeV/c]	104	7000
B [T]	0.11	8.33

Reminder: magnetic field of the Earth is between ~ 25 and 65 μT => ~ 200000 times bigger

Room-temperature coils

=> Superconducting coils! (needed > ~ 1.5 – 2 T)

- As the machine has to be closed

$$2\,\pi = N_d\;\vartheta_d$$

$$l_d = \rho\,\vartheta_d$$

Total number of dipoles

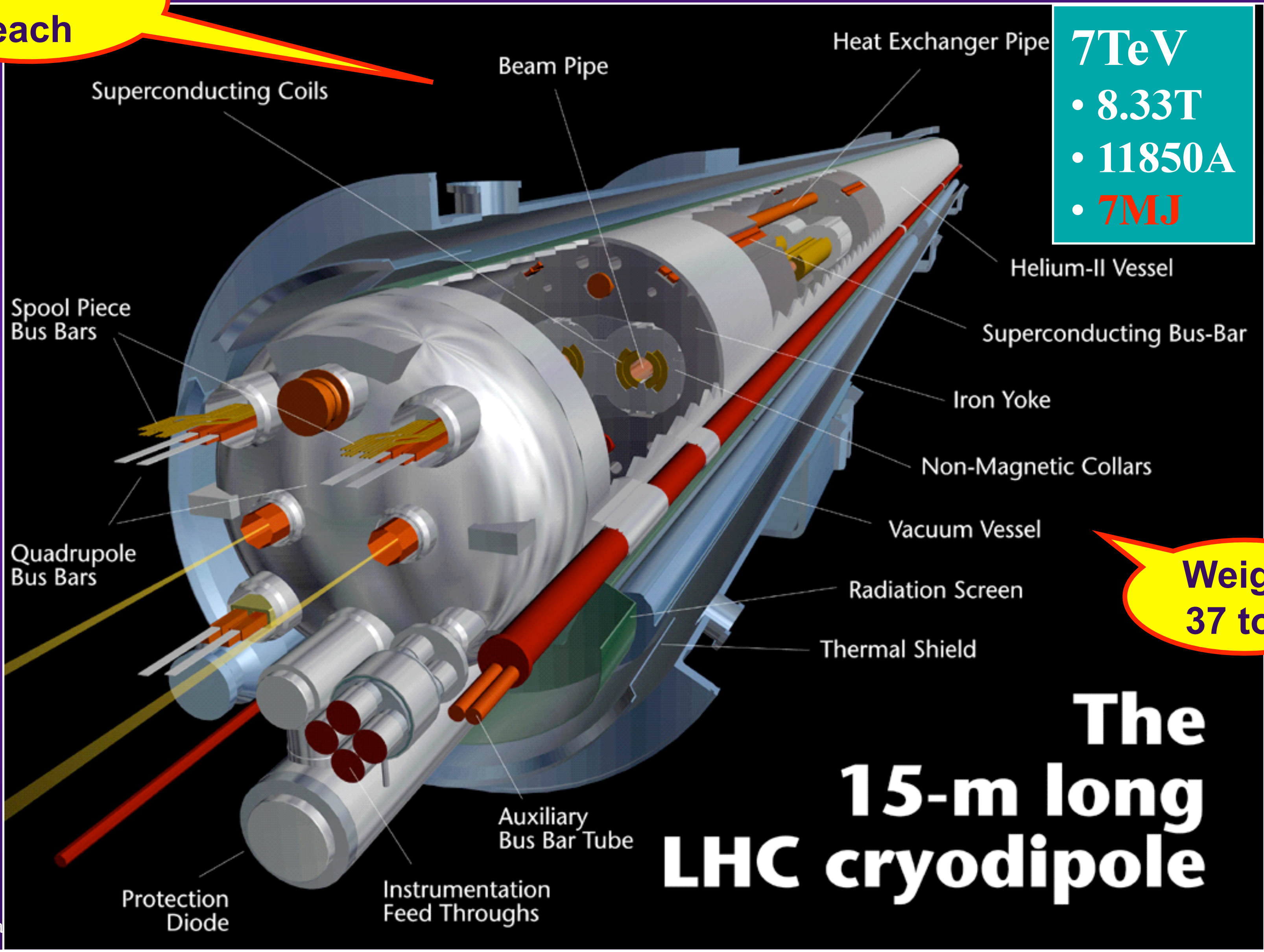
Bending angle of a dipole

Length of a dipole

THE LHC: HOW DOES IT WORK? (11/34)

⇒ 1232 dipoles, occupying therefore ~ 70% of the LHC

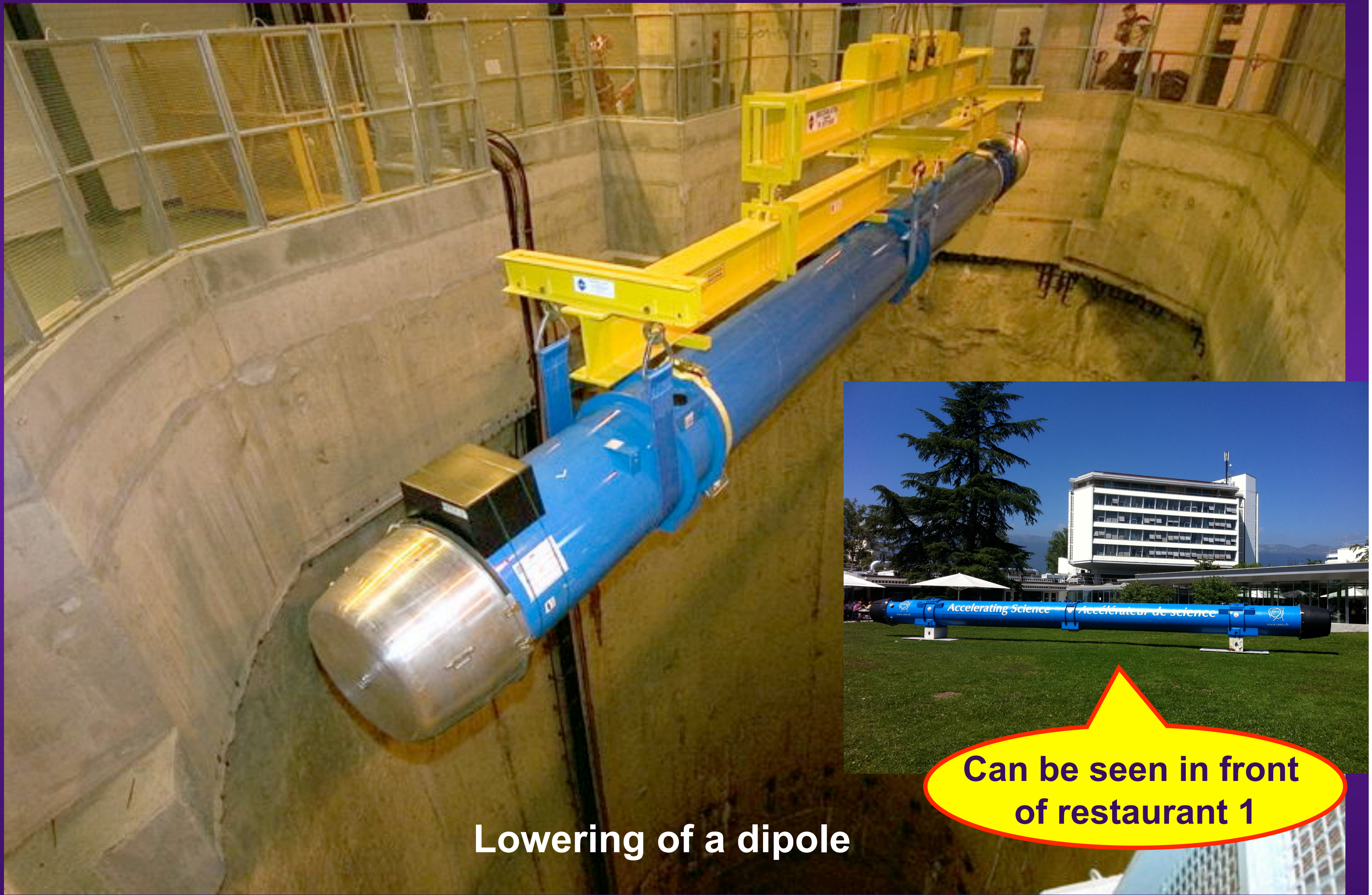
~ 0.5 MCHF each



- 7TeV
- 8.33T
- 11850A
- 7MJ

Weight: 37 tons

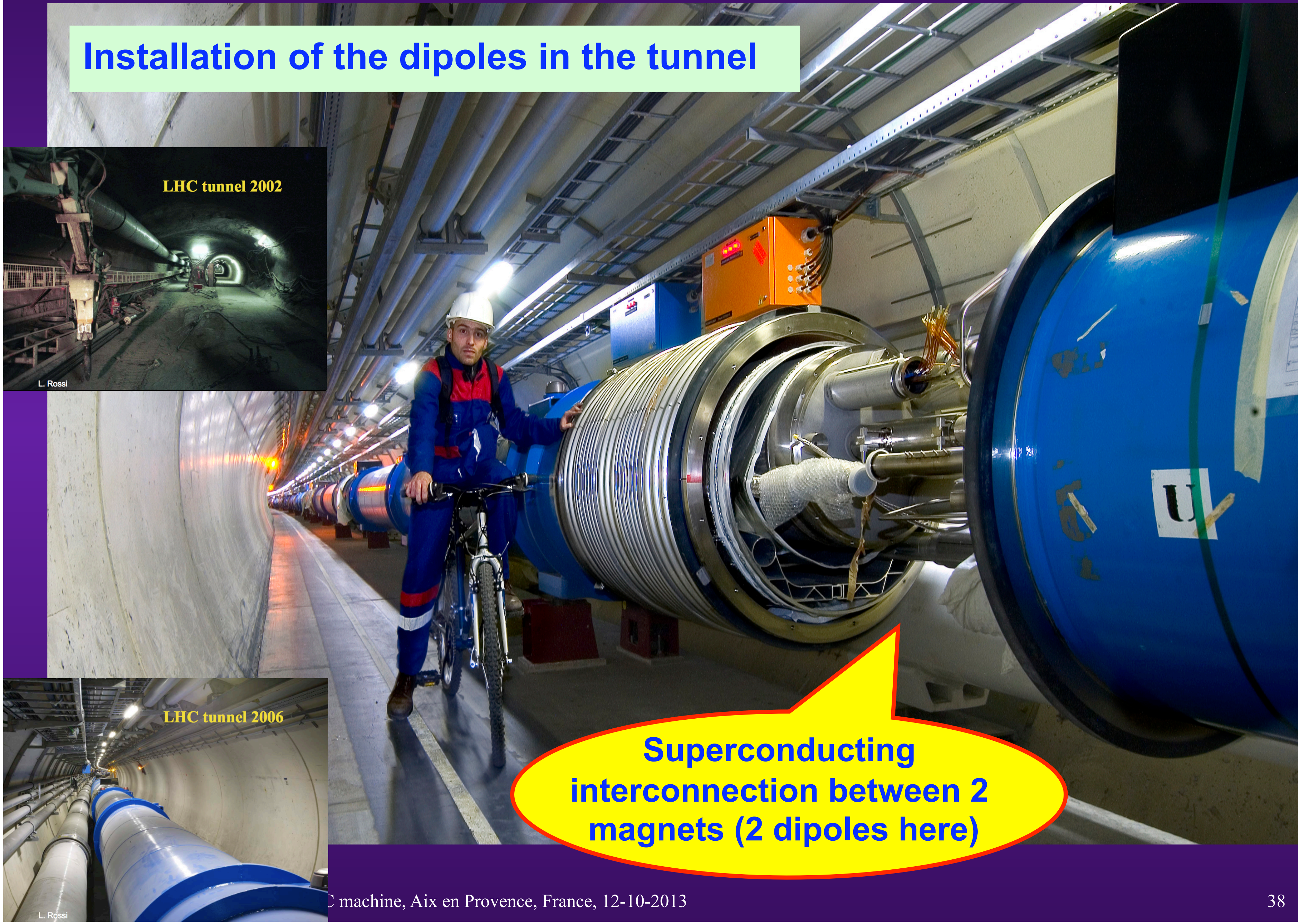
THE LHC: HOW DOES IT WORK? (12/34)



Can be seen in front of restaurant 1

Lowering of a dipole

THE LHC: HOW DOES IT WORK? (13/34)



THE LHC: HOW DOES IT WORK? (14/34)

- **The dipoles represented the most important technological challenge for the LHC design**

  - **The high beam intensities requested excluded the use of anti-p^+ beams and 1 common vacuum and magnet system for both circulating beams (as it was done in the TEVATRON) and implies the use of 2 p^+ beams**

  - **There was not enough room for 2 separate rings of magnets in the LEP tunnel**

=> 1st use of 2-in-1 magnet superconducting technology

THE LHC: HOW DOES IT WORK? (15/34)

- **Superconductivity**

  - The majority of chemical elements become superconducting at sufficiently low temperature

  - Below a certain "critical" temperature, materials undergo transition into the superconducting state, characterized by 2 basic properties

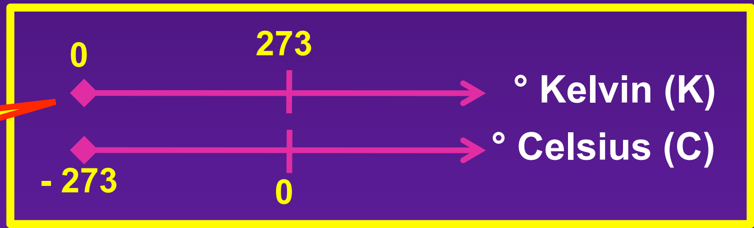
    1) They offer no resistance to the passage of electrical current. When resistance falls to zero, a current can circulate inside the material without any dissipation of energy

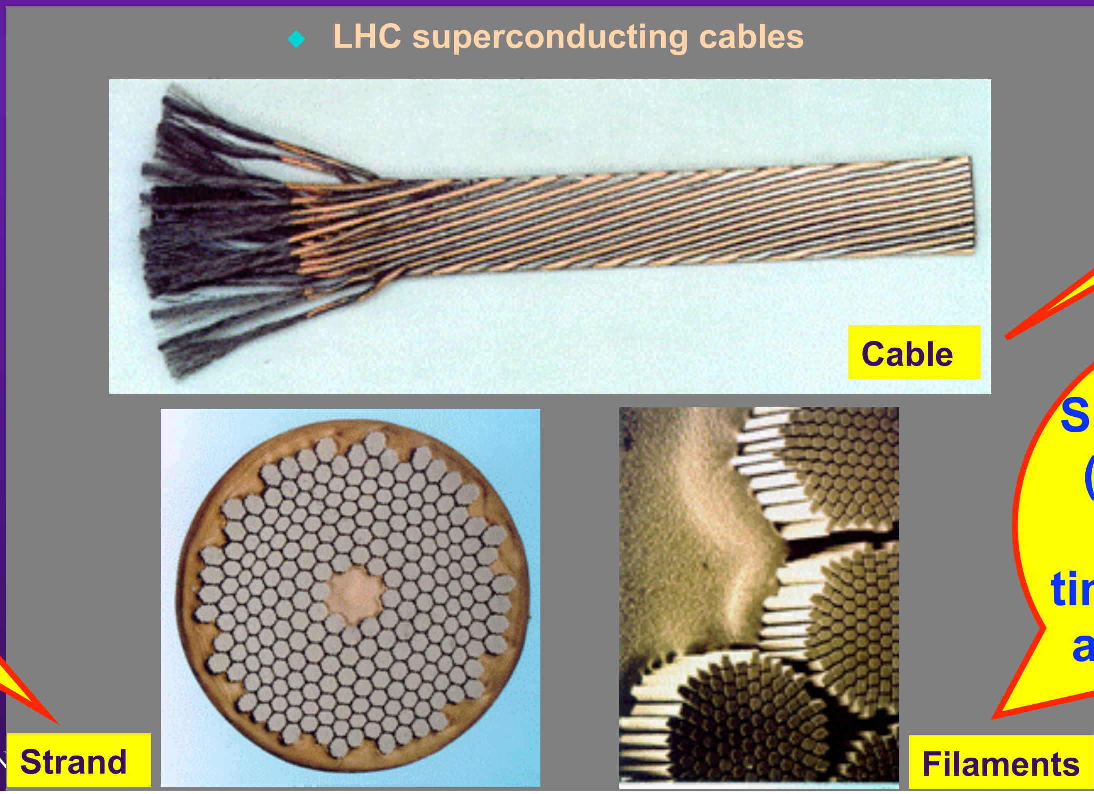
    2) Provided they are sufficiently weak, external magnetic fields will not penetrate the superconductor, but remain at its surface (field expulsion phenomenon known as Meissner effect) => Possible levitation (not used here…)

THE LHC: HOW DOES IT WORK? (16/34)

- The LHC dipoles use **Niobium-Titanium (Nb-Ti) cables**, which become superconducting below a temperature of **10°K (- 263°C)**

Absolute 0





36 strands

Φ = 825 μm => 6300 filaments

Superconducting (Nb-Ti) => 6 μm thick, i.e. ~ 10 times thinner than a normal human hair

THE LHC: HOW DOES IT WORK? (17/34)

- **Total superconducting cable required 1200 tons which translates to around 7600 km of cable => Total length of filaments is astronomical: 5 times to the sun and back with enough left over for a few trips to the moon!**

- **Cryogenic system**
  - Choice of the operating temperature for the LHC: 1.9°K
    - Comes from the 'super' properties of helium
    - Note that 1.9°K is even lower than the temperature of outer space (2.7°K)…
  - At atmospheric pressure helium gas liquefies at around 4.2°K, but when it is cooled further it undergoes a 2nd phase change at ~ 2.17°K to its superfluid state => State of matter in which the matter behaves like a fluid with zero viscosity
  - Among many remarkable properties, superfluid helium has a very high thermal conductivity, which makes it the coolant of choice for the refrigeration and stabilization of large superconducting systems

THE LHC: HOW DOES IT WORK? (19/34)

- The LHC is the largest cryogenic system in the world and one of the coldest places on Earth

In total, ~ 120 t of He is needed

- The whole cooling process takes a few weeks => The refrigeration process happens in 3 phases

Done in 2 steps:
1) 80°K thanks to 10 000 t of liquid nitrogen
2) Then 4.5°K thanks to refrigerator turbines

1) Cool down to 4.5°K

2) Filling with liquid helium of the magnet cold masses

3) Final cool down to 1.9°K

- **Expansion and contraction**

  - **Thermodynamics => Heat expands and cold contracts**

  - **But when temperatures swing from ~ 300 K to 1.9 K, it leads to a contraction of more than 80 m across the LHC 27-km-long cryogenic system…**

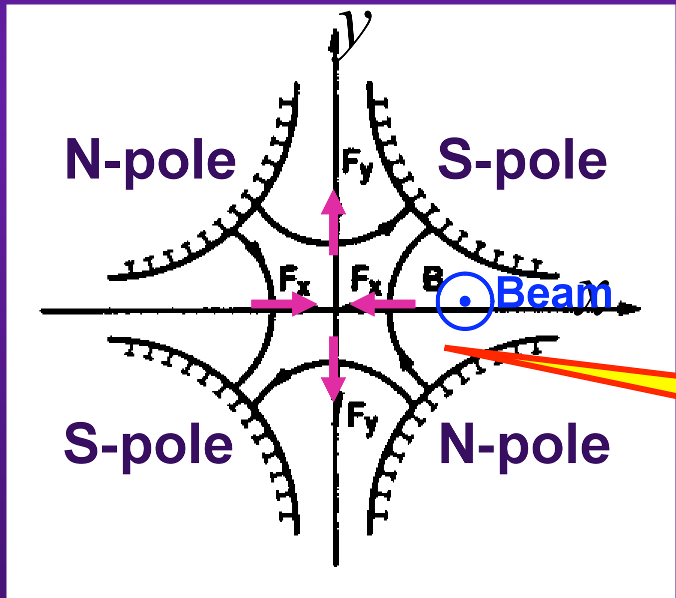
    => Compensators (i.e. bellows) shrink and stretch in response to thermodynamic changes

THE LHC: HOW DOES IT WORK? (21/34)

392 in total in the LHC

QUADRUPOLE = Focusing magnet

In x (and Defocusing in y) ⇒ F-type. Permutating the N- and S- poles gives a D-type

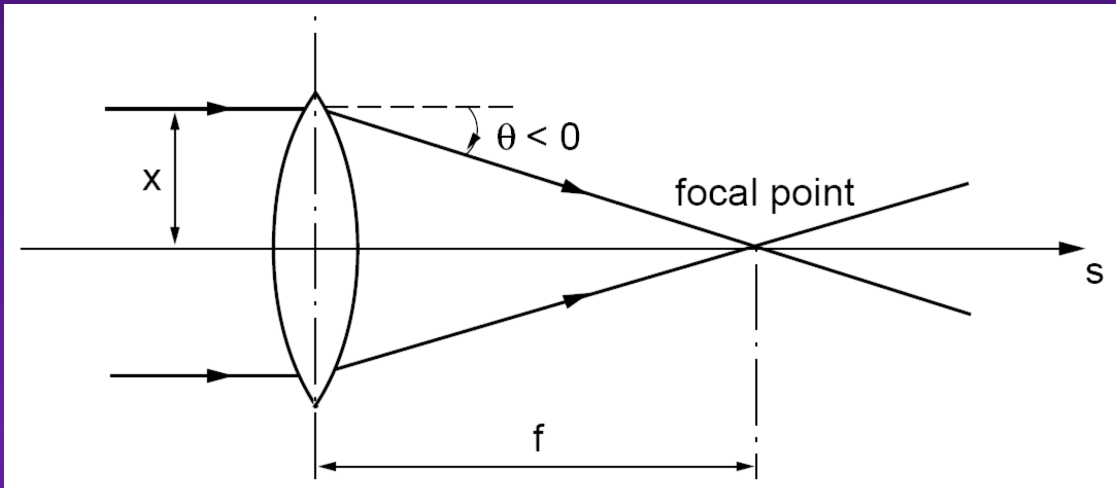


Linear force in x&y

… and SEXTUPOLES (6 poles), OCTUPOLES (8 poles), etc.

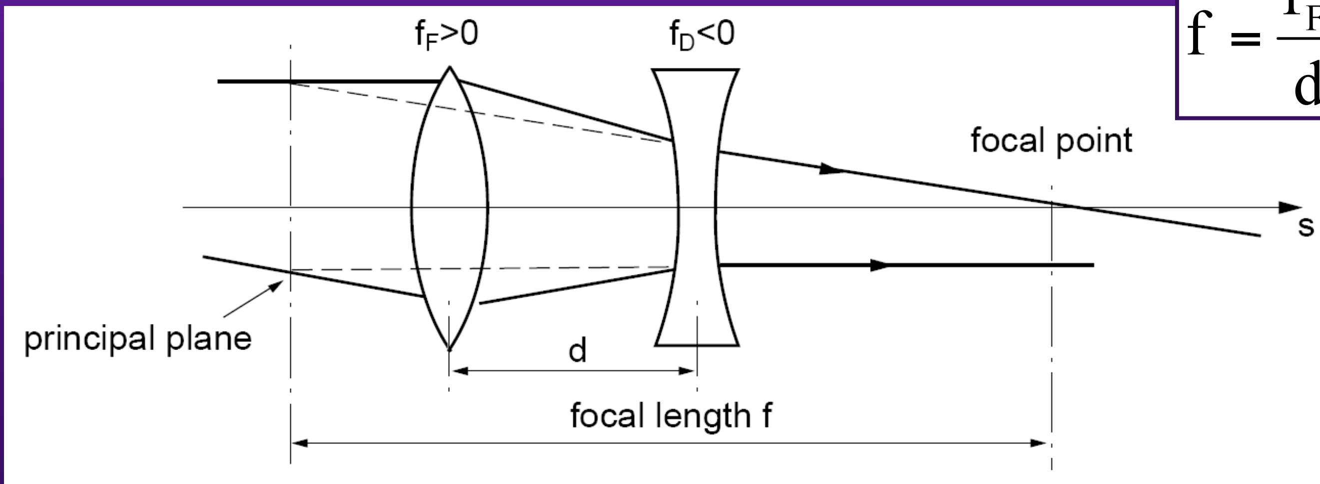
Analogy with light optics

Principle of focusing for light



Principle of STRONG FOCUSING for light

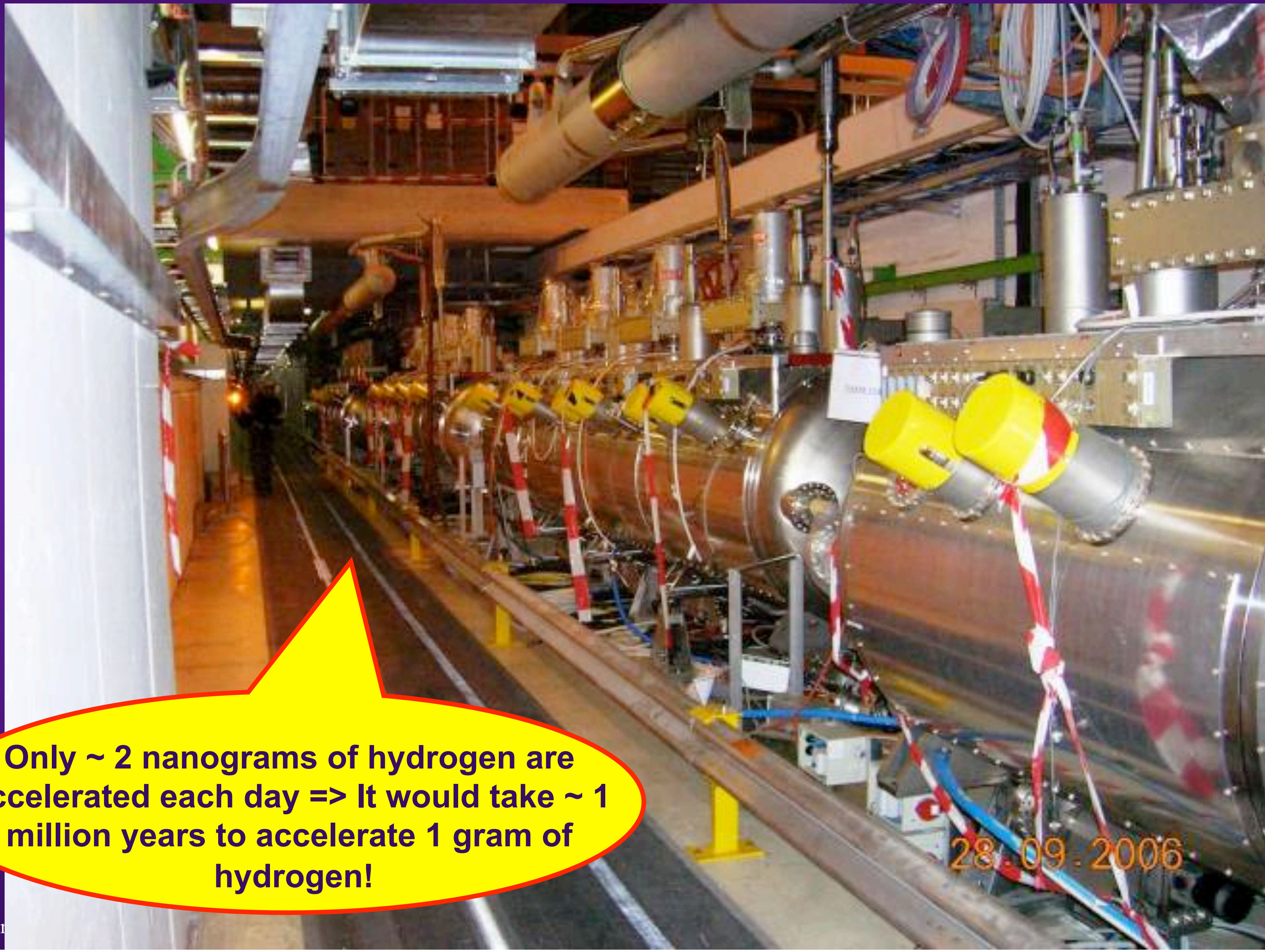
$$f = \frac{f_F^2}{d} > 0 \left(\text{when } f_D = -f_F \right)$$



=> Focusing in both planes

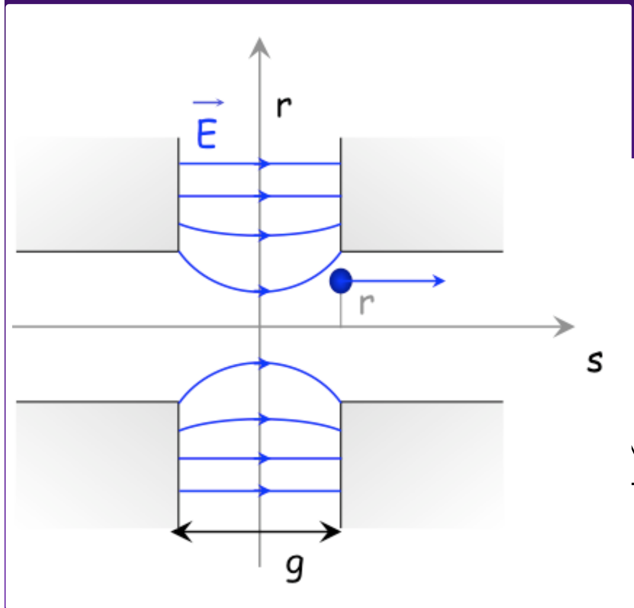
THE LHC: HOW DOES IT WORK? (23/34)

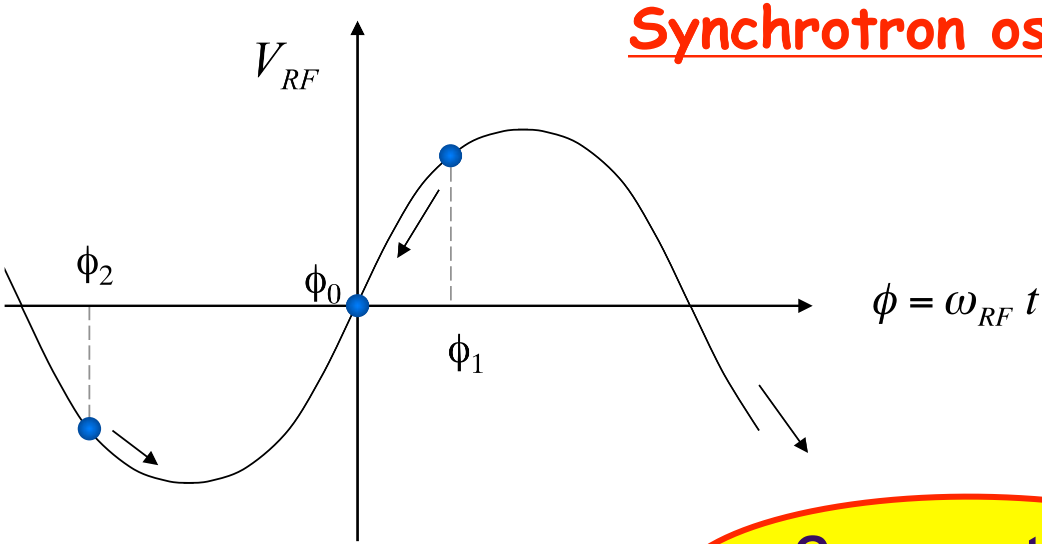
- **RF cavities** (located in IR4) => To “accelerate” the particles



Only ~ 2 nanograms of hydrogen are accelerated each day => It would take ~ 1 million years to accelerate 1 gram of hydrogen!

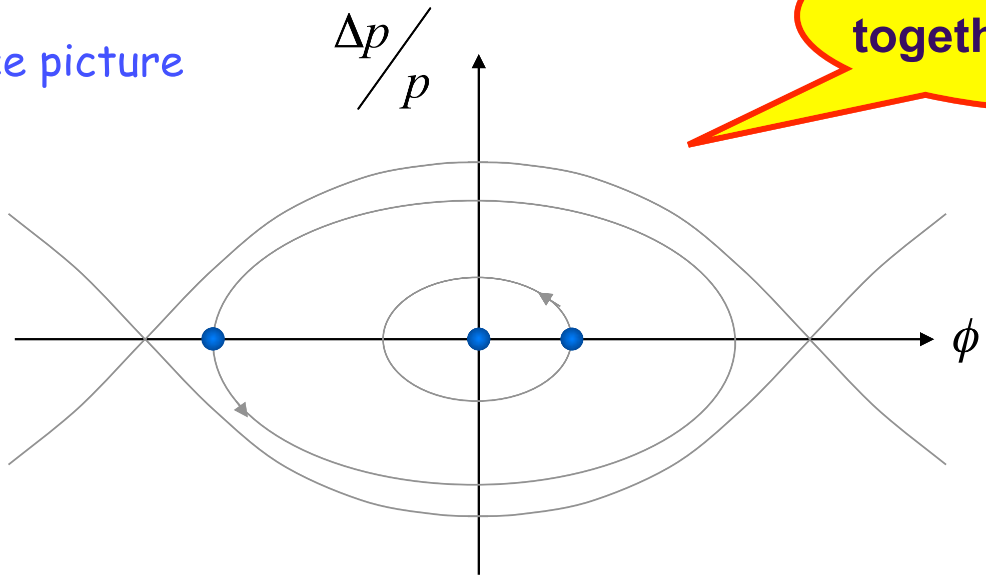
THE LHC: HOW DOES IT WORK? (24/34)





Synchrotron oscillations

Phase space picture



Group particles together in BUNCHES

THE LHC: HOW DOES IT WORK? (25/34)

- **No particle can move with speeds faster than the speed of light in vacuum; however, there is no limit to the energy a particle can attain**

- **And in fact, the LHC should not be called a particle accelerator but a particle MASSIFICATOR as the velocity of the particles is almost not increasing (as it is at the maximum) => Only the mass is increasing**

$$v_{injection} \approx 0.999998\, c$$

$$v_{collision} \approx 0.999999991\, c$$

=>

$$\frac{v_{collision}}{v_{injection}} \approx 1$$

=> The p^+ in the LHC travel at the speed of light

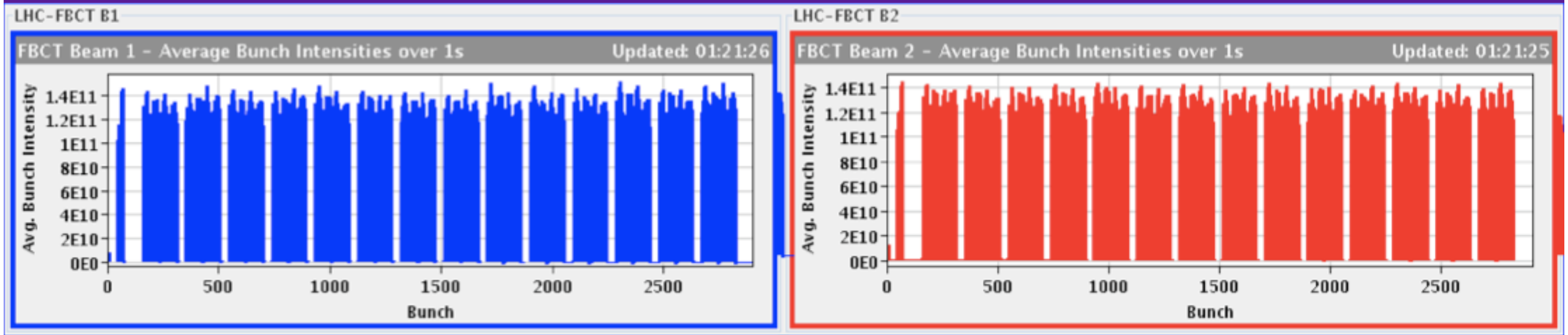
$$m = \gamma\, m_0$$

=>

$$\frac{m_{collision}}{m_{injection}} \approx 15.6$$

THE LHC: HOW DOES IT WORK? (26/34)

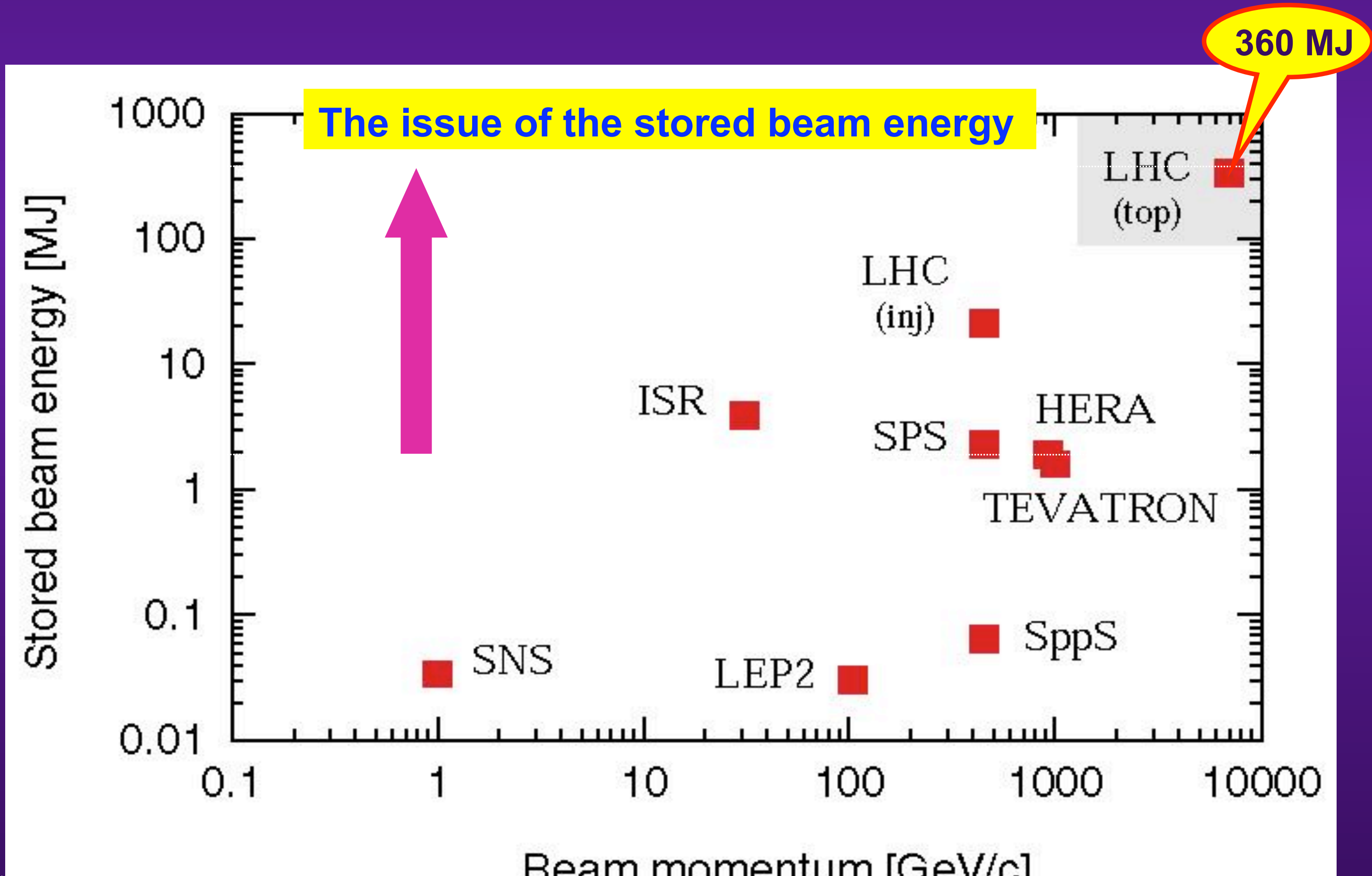
- **Beam diagnostics => The "eyes" of the accelerators**
  - **To measure the**
    - **Number of particles / bunch**



    - **Length and longitudinal profile of the bunches of particles**
    - **Transverse beam sizes**
    - **Beam losses => Important also for the machine protection**
    - **Etc.**

- **Collimation**

  - **Energy stored in the LHC beams is unprecedented, threatening to damage accelerator equipment in case of uncontrolled beam loss, so everything is done to ensure that this never happens**



Courtesy of R. Assmann

THE LHC: HOW DOES IT WORK? (28/34)

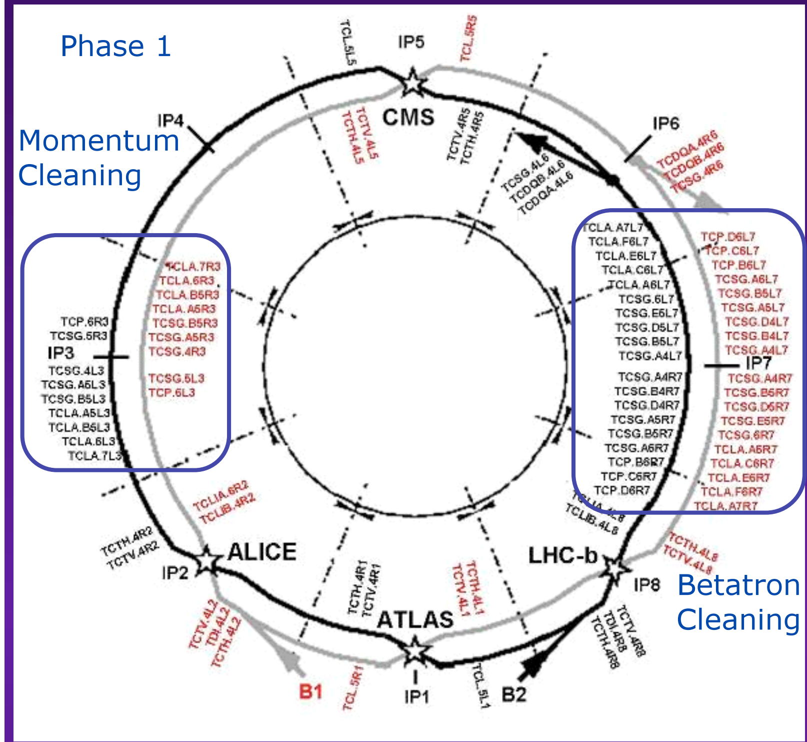
- Total energy in each beam at maximum energy is ~ 360 MJ, which is about as energetic as a 400 t train, like the French TGV, traveling at 150 km/h. The total energy stored in the LHC magnets is some 30 times higher (11 GJ)

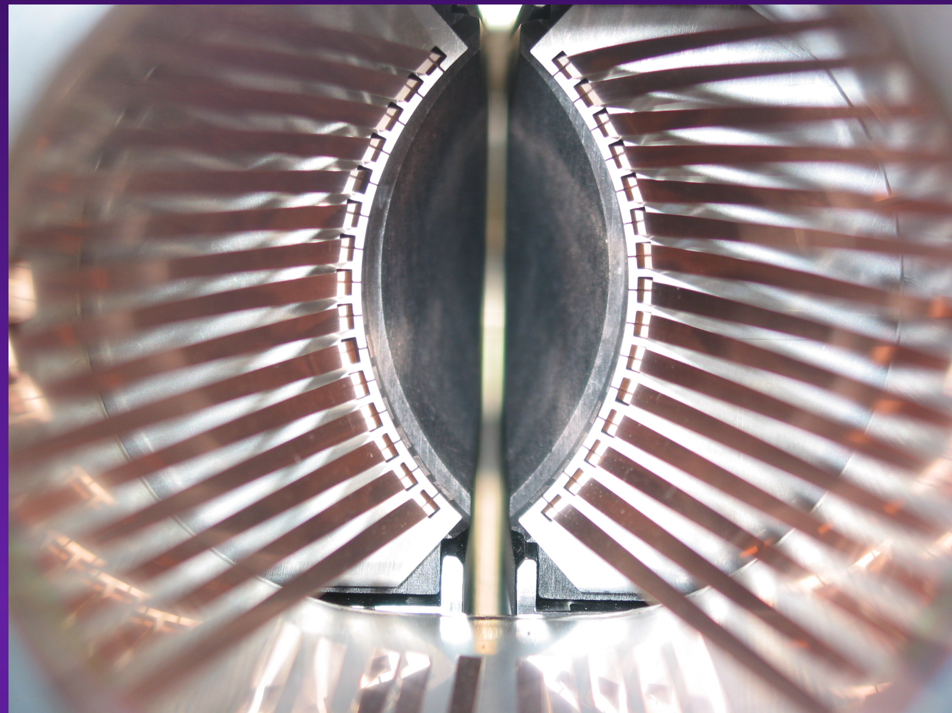
i.e. lose its superconducting state

- Tiny fractions of the stored beam suffice to "quench" a super-conducting LHC magnet or even to destroy parts of the accelerators

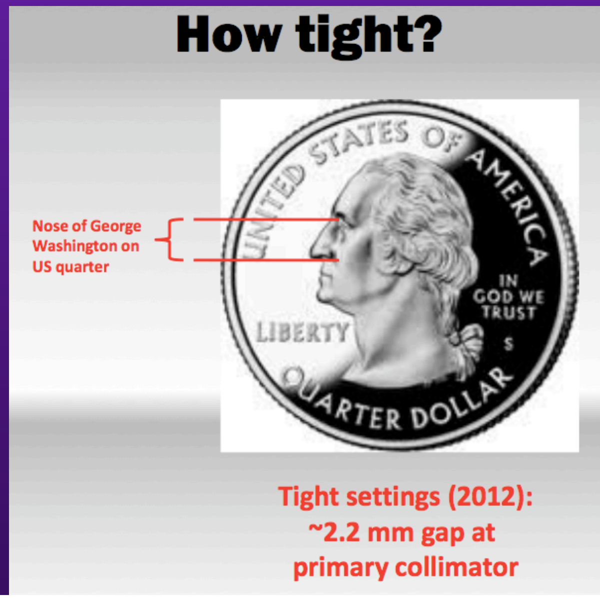
- Note that a 10^{-5} fraction of the nominal LHC beam will damage Copper. The energy in the two LHC beams is sufficient to melt almost 1 ton of copper!

THE LHC: HOW DOES IT WORK? (29/34)





Many collimators have been installed to protect the machine



THE LHC: HOW DOES IT WORK? (30/34)

- **Why LHC has been built underground?**
  - LHC re-uses the LEP tunnel

    When tunnel was excavated, the 2 ends met to within 1 cm

  - Underground tunnel was the best solution because
    - Cheaper to excavate a tunnel rather than acquire the land to build at the surface and reduced impact on landscape
    - Earth's crust provides good shielding for radiation
  - Mean depth of 100 m, due to geological considerations (translating into cost) and slight gradient of 1.4% => Depth varies between 175 m (under the Jura) and 50 m (towards the Lake)
  - Was essential to have a depth of at least 5 m below the top of the 'molasse' (green sandstone) stratum

What about radiation?

- Activation risks with e^- was minimal but with p^+ it is more delicate => Radioactivity evolved at CERN

- **Radioactivity** is a consequence due to the unbalance between the number of p^+ and n => 3 possibilities
  - Too many n => β^- decay
  - Too many p^+ => β^+ decay
  - Too many of both n and p^+ => α decay

- In a particle accelerator, beam losses induce nuclear transmutations and the machine elements (vacuum chamber, magnets, etc.) become radioactive => β and γ are thus emitted even when the accelerator is stopped

γ (and X) are energetic photons with $E\gamma$ >> EX

THE LHC: HOW DOES IT WORK? (32/34)

- **LHC power consumption**

  - ~ 120 MW (230 MW for all CERN), which corresponds to the power consumption for households in the Canton of Geneva

  - CERN is supplied mainly by the French company EDF => 400 kV (Swiss companies EOS and SIG are used only in case of shortage from France)

  - A large fraction of the LHC electrical consumption is to keep the superconducting magnet system at the operating temperatures

  - Thanks to the superconducting technology, the nominal consumption of the LHC is not much higher than that of the SPS, even though the LHC is much larger and higher in energy

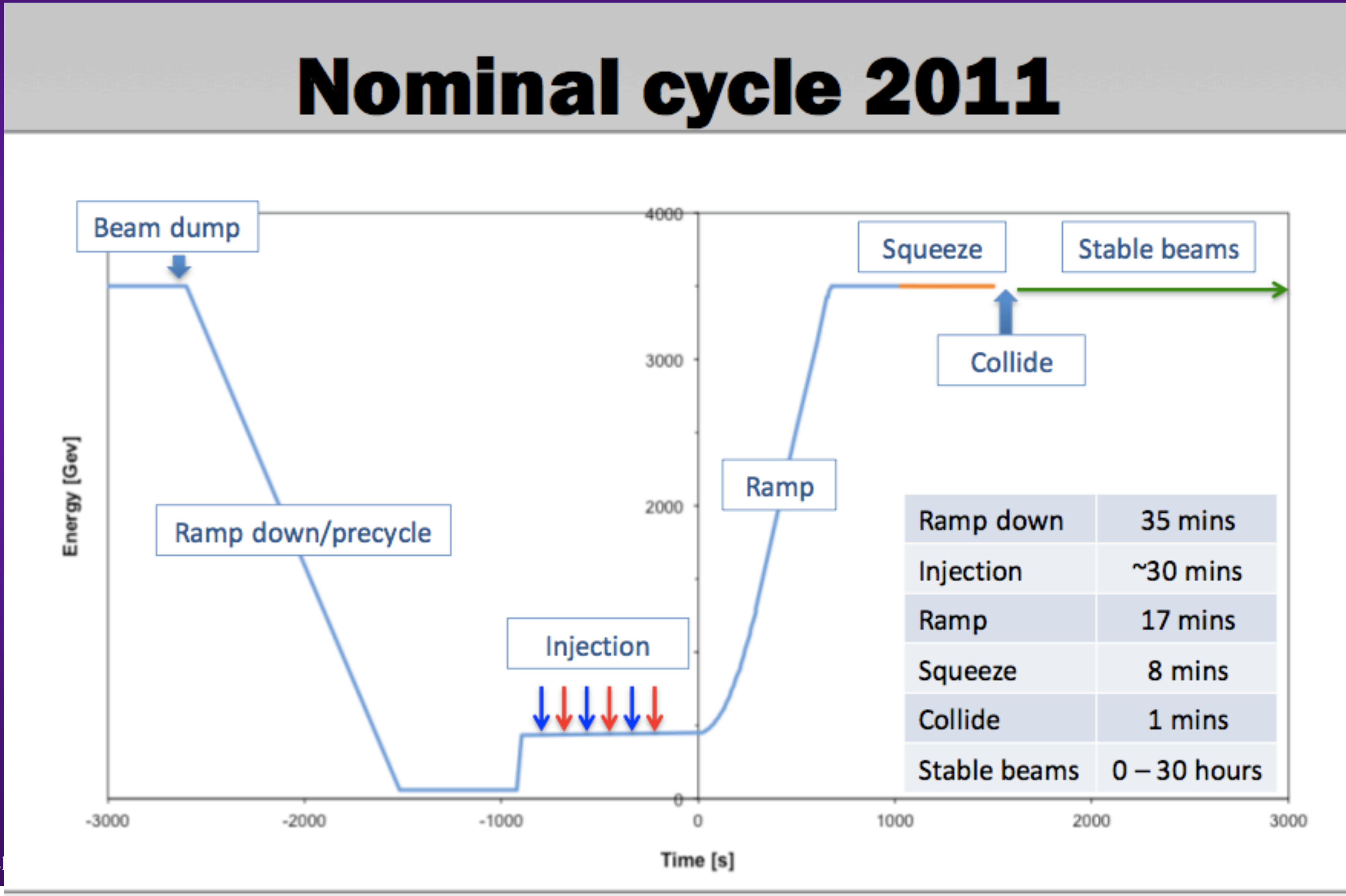
THE LHC: HOW DOES IT WORK? (33/34)

- **The LHC machine performance is limited by several effects**
  - **Maximum dipole field and magnet quench limits**
  - **Energy stored in the circulating beams and in the magnetic fields**
  - **Mechanical aperture**
  - **Field quality**
  - **Collective effects => Interaction between**
    - **p^+ themselves**
    - **p^+ and their environment**
    - **2 counter-rotating p^+ beams**
    - **p^+ beams and e^- clouds which can be created in the vacuum chamber**

What we are studying in our team => Working on the "beam dynamics"

THE LHC: HOW DOES IT WORK? (34/34)

- **Typical cycle in the LHC**



CURRENT STATUS AND FUTURE (1/4)

- We found already a new particle: "Higgs-like" boson => Great!
- We reached ~ 77% of the design luminosity => Not yet there…
- In fact, just after the start of the LHC, we had a major incident…

Fault in a dipole-quadrupole interconnect ("splice")

9 days after the LHC start-up…

- Long Shutdown 1 (2013-2014) => Priorities
  - Implement the necessary safety mitigation measures
  - Perform the necessary consolidation and upgrade activities
  - Perform the full maintenance of equipment
  - Other Activities

=> Ensure operation of the LHC > 13 (6.5 + 6.5) TeV and reliable operation of the accelerator complex

CURRENT STATUS AND FUTURE (2/4)

The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

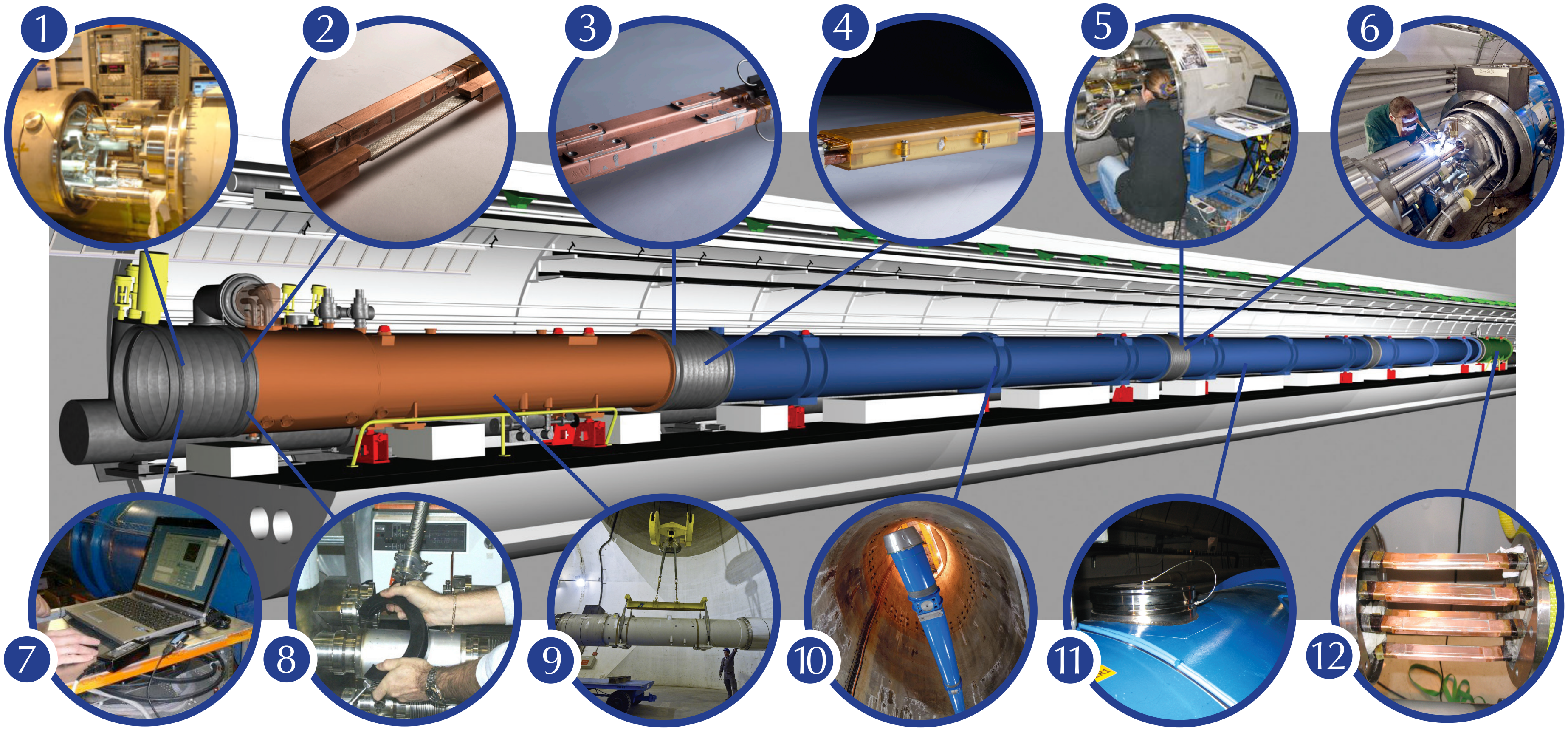
Complete reconstruction of 1500 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

4 quadrupole magnets to be replaced

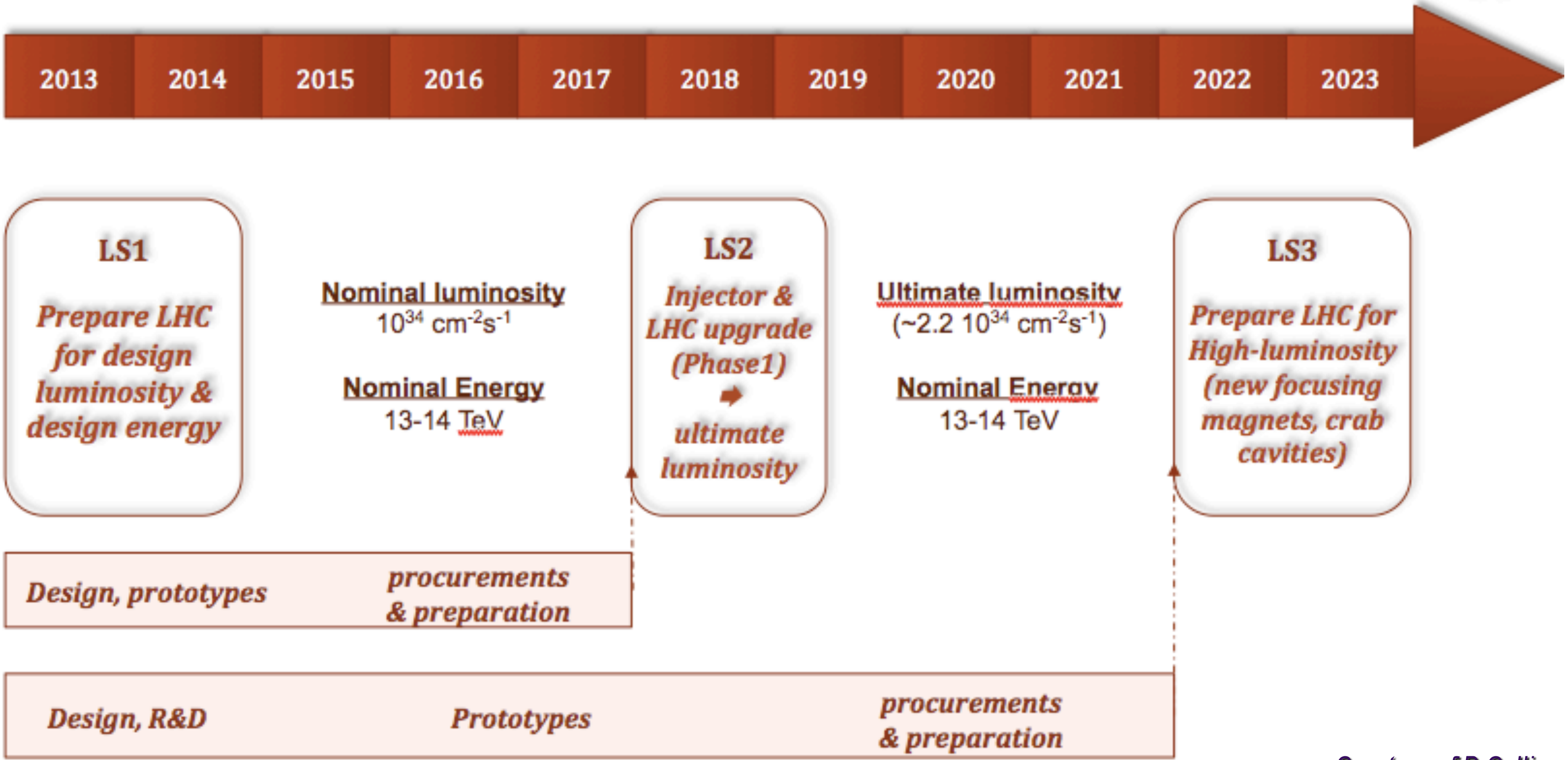
15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

CURRENT STATUS AND FUTURE (3/4)

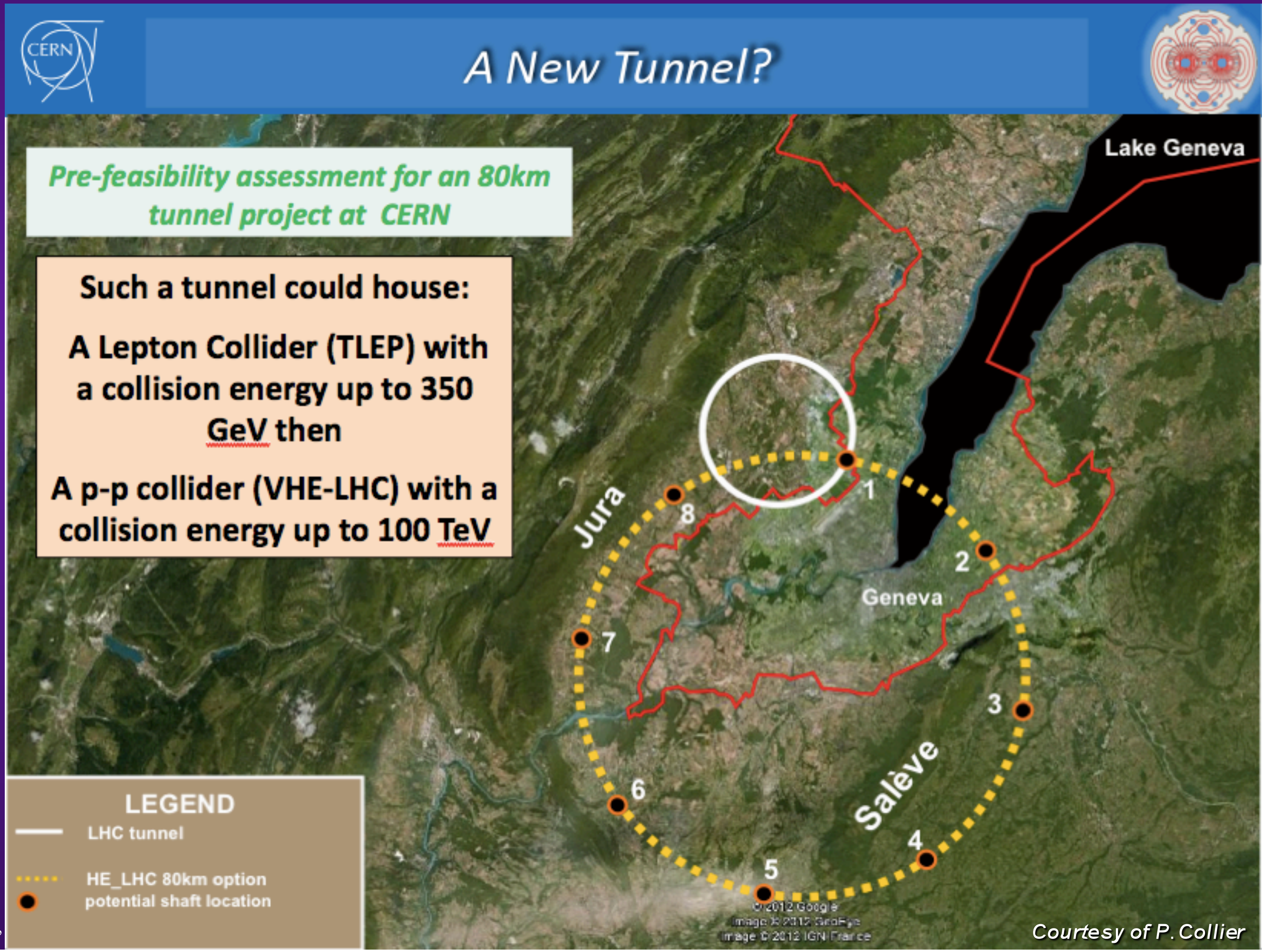
- **There is a program at the energy frontier with the LHC for at least 20 years**



Courtesy of P. Collier

CURRENT STATUS AND FUTURE (4/4)

- **Many discussions ongoing for the long-term future…**



APPENDIX (1/25)

Units of physical quantities

Quantity	unit	SI unit	SI derived unit
Capacitance	F (farad)	$m^{-2}\ kg^{-1} s^4 A^2$	C/V
Electric charge	C (coulomb)	As	
Electric potential	V (volt)	$m^2\ kg\ s^{-3} A^{-1}$	W/A
Energy	J (joule)	$m^2\ kg\ s^{-2}$	Nm
Force	N (newton)	$m\ kg\ s^{-2}$	N
Frequency	Hz (hertz)	s^{-1}	
Inductance	H (henry)	$m^2\ kg\ s^{-2} A^{-2}$	Wb/A
Magnetic flux	Wb (weber)	$m^2\ kg\ s^{-2} A^{-1}$	Vs
Magnetic flux density	T (tesla)	$kg\ s^{-2} A^{-1}$	Wb/m^2
Power	W (watt)	$m^2\ kg\ s^{-3}$	J/s
Pressure	Pa (pascal)	$m^{-1}\ kg\ s^{-2}$	N/m^2
Resistance	Ω (ohm)	$m^2\ kg\ s^{-3} A^{-2}$	V/A

APPENDIX (2/25)
Fundamental physical constants

Physical constant	symbol	value	unit
Avogadro's number	N_A	6.0221367×10^{23}	/mol
atomic mass unit ($\frac{1}{12}m(C^{12})$)	m_u or u	$1.6605402 \times 10^{-27}$	kg
Boltzmann's constant	k	1.380658×10^{-23}	J/K
Bohr magneton	$\mu_B = e\hbar/2m_e$	$9.2740154 \times 10^{-24}$	J/T
Bohr radius	$a_0 = 4\pi\epsilon_0\hbar^2/m_e c^2$	$0.529177249 \times 10^{-10}$	m
classical radius of electron	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	$2.81794092 \times 10^{-15}$	m
classical radius of proton	$r_p = e^2/4\pi\epsilon_0 m_p c^2$	$1.5346986 \times 10^{-18}$	m
elementary charge	e	$1.60217733 \times 10^{-19}$	C
fine structure constant	$\alpha = e^2/2\epsilon_0 hc$	1/137.0359895	
$m_u c^2$		931.49432	MeV
mass of electron	m_e	$9.1093897 \times 10^{-31}$	kg
$m_e c^2$		0.51099906	MeV
mass of proton	m_p	$1.6726231 \times 10^{-27}$	kg
$m_p c^2$		938.27231	MeV
mass of neutron	m_n	$1.6749286 \times 10^{-27}$	kg
$m_p c^2$		939.56563	MeV
molar gas constant	$R = N_A k$	8.314510	J/mol K
neutron magnetic moment	μ_n	$-0.96623707 \times 10^{-26}$	J/T
nuclear magneton	$\mu_p = e\hbar/2m_u$	$5.0507866 \times 10^{-27}$	J/T
Planck's constant	h	6.626075×10^{-34}	J s
permeability of vacuum	μ_0	$4\pi \times 10^{-7}$	N/A^2
permittivity of vacuum	ϵ_0	$8.854187817 \times 10^{-12}$	F/m
proton magnetic moment	μ_p	$1.41060761 \times 10^{-26}$	J/T
proton g factor	$g_p = \mu_p/\mu_N$	2.792847386	
speed of light (exact)	c	299792458	m/s
vacuum impedance	$Z_0 = 1/\epsilon_0 c = \mu_0 c$	376.7303	Ω

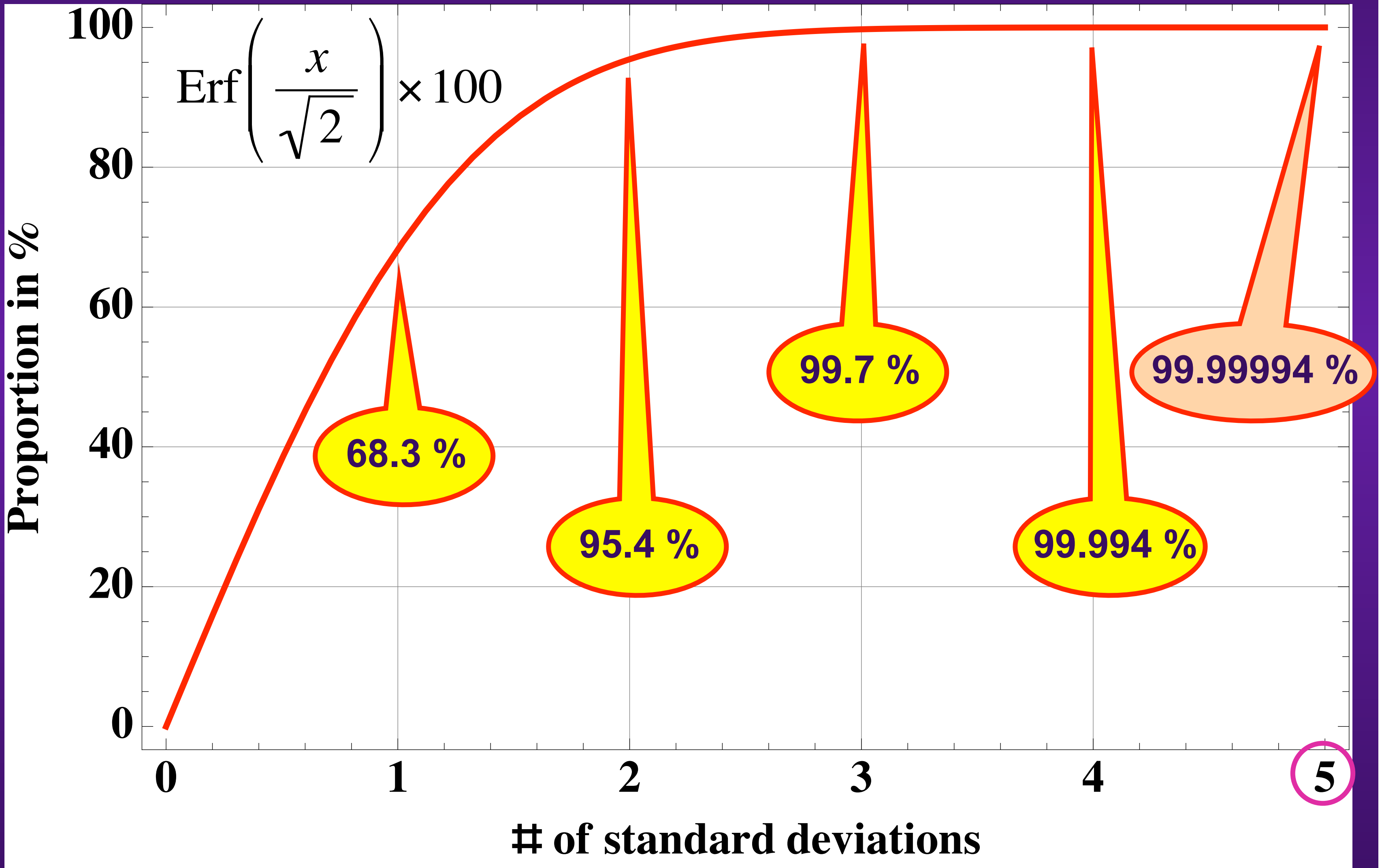
APPENDIX (3/25)

- Métaux
- Semi-conducteur
- Non-métaux
- Gaz nobles
- Lanthanides et actinides

	I	II											III	IV	V	VI	VII	VIII
1	H 1																	He 2
2	Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
3	Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
4	K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
5	Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
6	Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
7	Fr 87	Ra 88	Ac 89	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Uum 110	Uuu 111	Uub 112	Uut 113	Uuq 114	Uup 115	Uuh 116	Uus 117	Uuo 118

Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

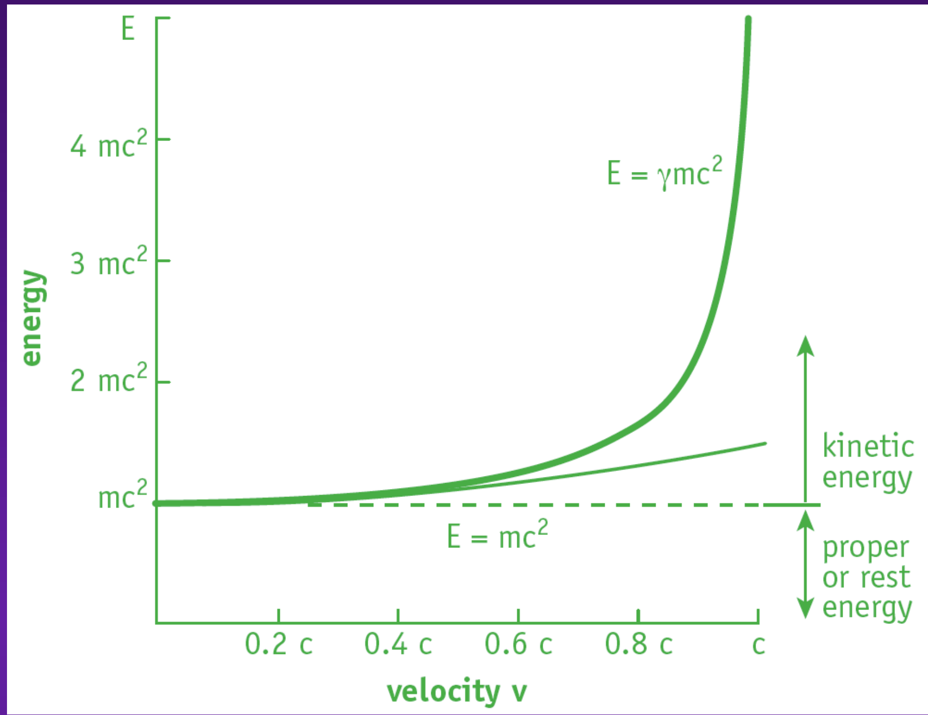
- **If a data distribution is approximately normal then the proportion of data values within *n* standard deviations (σ) of the mean is defined by**



APPENDIX (5/25)

- **RF cavities**
  - The main role of the cavities is to keep the 2808 proton bunches tightly bunched to ensure high luminosity at the collision points and hence, maximize the number of collisions
  - They also deliver radiofrequency (RF) power to the beam during acceleration to the top energy
  - Superconducting cavities with small energy losses and large stored energy are the best solution
  - The LHC uses 8 cavities per beam, each delivering 2 MV (an accelerating field of 5 MV/m) at 400 MHz
  - The cavities operate at 4.5 K (- 268.7ºC)
  - They are grouped in 4 in cryomodules, with 2 cryomodules per beam, and installed in a long straight section of the machine where the transverse interbeam distance will be increased from the normal 195 mm to 420 mm

APPENDIX (6/25)

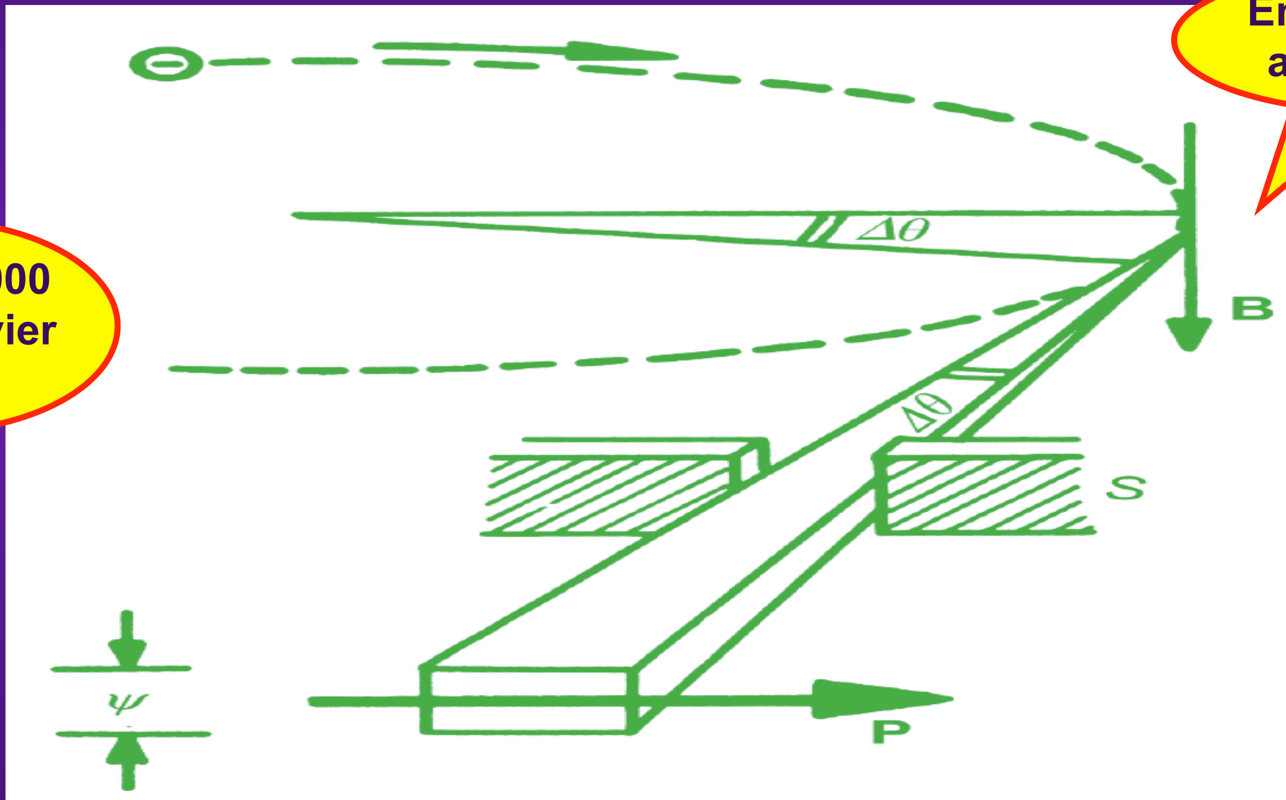


Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c^2

- The issue of synchrotron radiation (the lighter the particles the worse)

p^+ are ~ 2000 times heavier than e^-



Energy loss in a curve path

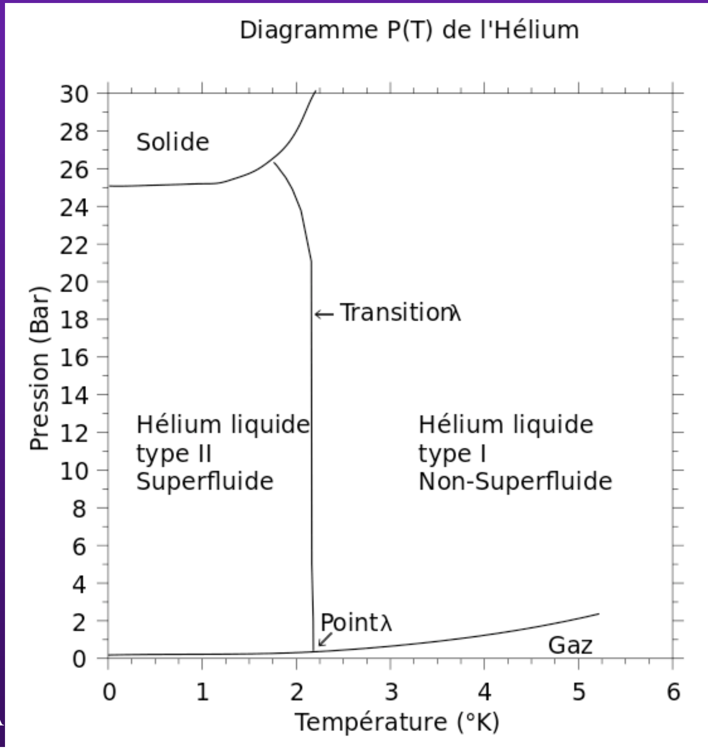
APPENDIX (8/25)

- **Superconductivity (1911)**

  - In 1911, while studying the properties of matter at very low temperature, the Dutch physicist Heike Kamerlingh Onnes and his team discovered that the electrical resistance of mercury goes to zero below 4.2 K (-269°C). This was the very first observation of the phenomenon of superconductivity

APPENDIX (9/25)

- **Superfluidity (1937)**
  - State of matter in which the matter behaves like a fluid with zero viscosity (1937)
  - Viscosity is due to the friction between neighboring parcels of the fluid that are moving at different velocities => For example, honey has a higher viscosity than water
  - Zero viscosity is observed only at very low temperatures, in superfluids. Otherwise all fluids have positive viscosity



APPENDIX (10/25)

- **Radiation**
  - Radiation is unavoidable at particle accelerators like the LHC. The particle collisions that allow us to study the origin of matter also generate radiation. CERN uses active and passive protection means, radiation monitors and various procedures to ensure that radiation exposure to the staff and the surrounding population is as low as possible and well below the international regulatory limits
  - For comparison, note that natural radioactivity — due to cosmic rays and natural environmental radioactivity — is about 2400 µSv / year in Switzerland. A round trip Europe–Los Angeles flight accounts for ~ 100 µSv. The LHC tunnel is housed 100 m underground, so deep that both stray radiation generated during operation and residual radioactivity will not be detected at the surface. Air will be pumped out of the tunnel and filtered. Studies have shown that radioactivity released in the air will contribute to a dose to members of the public of no more than 10 µSv / year

APPENDIX (11/25)

- Radiation dose (in Gray) => 1 Gy = 1 J / kg (absorbed dose)
- Biological effects (in Sievert) => 1 Sv = 1 Gy with some weighting factors according to the type of radiation
  - For X, β and γ: 1 Sv = 1 Gy
  - For α: 1 Sv = 20 Gy
  - For n: 1 Sv = 5-20 Gy
- Short-term effects
  - 4000 mSv: Semi-lethal dose (50% of people die without care)
  - 6000-8000 mSv: Lethal dose (100% people die without care)
- Long-term effects
  - ~ 5% risk for 1 Sv to develop a cancer (risk from other reasons is ~ 30%)
- Limits at CERN
  - Category A: 20 mSv / year (law) and 15 mSv / year at CERN
  - Category B: 6 mSv / year (medical service every 2 years)
  - Public: 1 mSv / year
  - Natural sources in Switzerland: 2-4 mSv / year

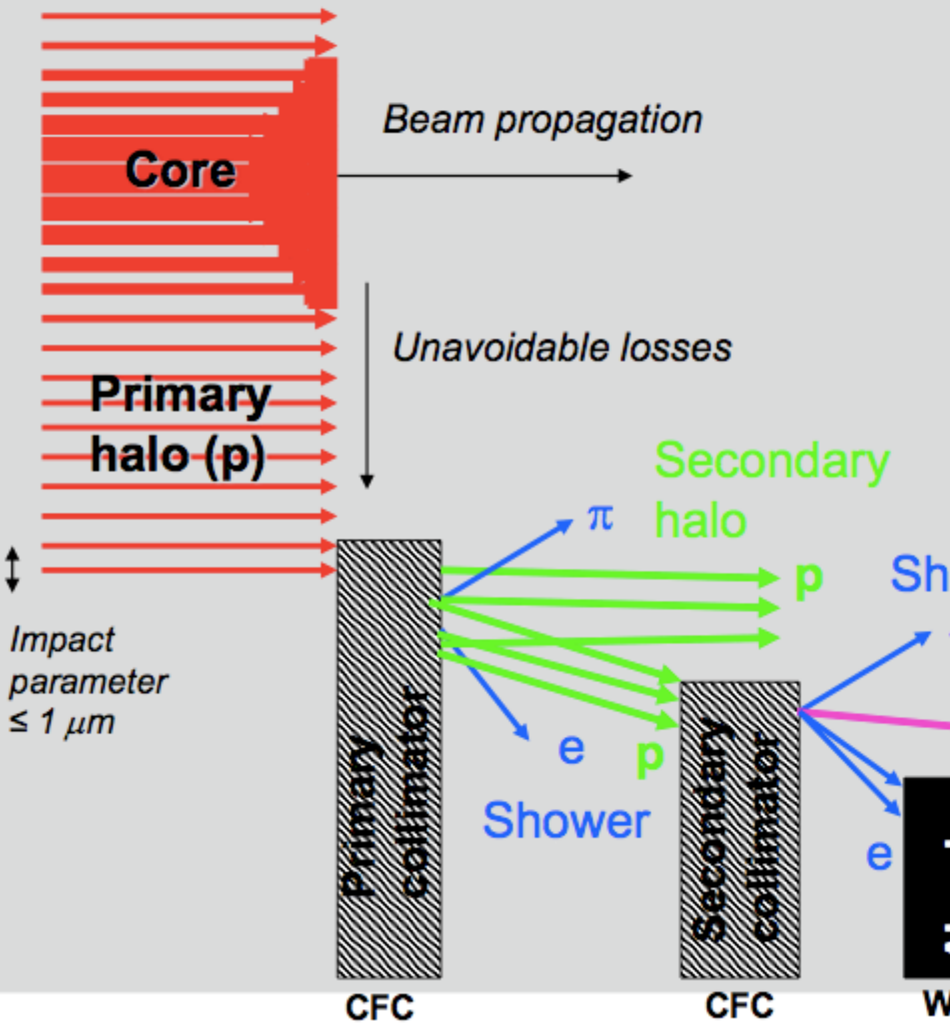
APPENDIX (12/25)

- **Important parameters for the LHC**

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1 x 10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

(*) Energy per nucleon

LHC – multistage cleaning



Without beam cleaning (collimators):

Quasi immediate **quench of super-conducting magnets** (for higher intensities) and stop of physics.

Required **very good cleaning efficiency**

R. Assmann

APPENDIX (14/25)

- On 19 September 2008, during powering tests on the LHC, a fault occurred in a superconducting interconnection between 2 magnets – a dipole and a quadrupole – resulting in mechanical damage and release of helium from the magnet cold mass into the tunnel. Proper safety procedures were in force, the safety systems performed as expected, and no-one was put at risk. But the fault did delay work on the LHC
- After the incident, CERN engineers decided that such interconnections should be upgraded to avoid similar electrical faults in future. As a precaution, beams in the LHC were accelerated below the LHC's design limit for the first 3 years of running. Upgrading the interconnections is one of the main activities at the LHC during its two-year shutdown, allowing the LHC to run at 7 TeV per beam when it starts up again
- There are 10000 "splices" (= superconducting connections between magnets) on the LHC. Each splice carries 13 000 A

APPENDIX (15/25)

- During the Long Shutdown 1, technicians add an additional piece – a "shunt" – to each splice. The shunt is a low-resistance connection that forms an alternative path for a portion of the current in the event that the splice loses its superconducting state. A total of 27 000 shunts will be installed in the 27-kilometre accelerator

APPENDIX (16/25)

THE LHC: HOW DOES IT WORK?

- From of bottle of hydrogen till collision
- Vacuum
- Trick of particle accelerators => Make the particles oscillate (through electric and magnetic fields)
  - Dipoles => Superconductivity => Cryogenics
  - Quadrupoles, etc.
  - RF cavities
- Diagnostics
- Collimation
- Why LHC has been built underground?
- What about radiation?
- LHC power consumption
- The LHC machine performance is limited by several effects

APPENDIX (17/25)

$$E = k_B\, T$$

Boltzmann constant

≈ 8.63 10^{-5} eV / K

- **What about radiation?**

  - Chemical representation of an element

A = Mass number
= Number of nucleons
(n + p^+)

$${}^{A}_{Z}X$$

Element symbol

Z = Atomic number
= number of protons
(p^+)

Also used in the LHC

- Ex: ${}^{1}_{1}H$ ${}^{12}_{6}C$ ${}^{208}_{82}Pb$ ${}^{238}_{92}U$

APPENDIX (19/25)

- **Radioactivity** is a consequence due to the unbalance between the number of p^+ and n => 3 possibilities

  - Too many n => β^- decay (n → $p^+ + e^-$)

Radioactive

$$ {}^{14}_{6}C^* \rightarrow {}^{14}_{7}N + \beta^- + \text{emw} $$

Particle β^- ejected from the nucleus (+ also emw => Ex: γ)

  - Too many p^+ => β^+ decay (p^+ → n + e^+)

$$ {}^{14}_{8}O^* \rightarrow {}^{14}_{7}O + \beta^+ + \text{emw} $$

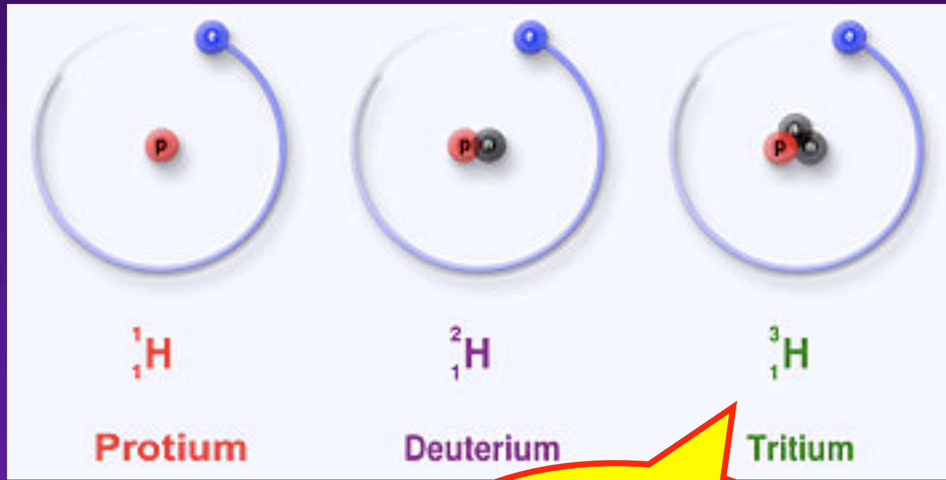
Particle β^+ ejected from the nucleus (+ also emw => Ex: X)

  - Too many of both n and p^+ (for Z > 82 or A > 208, i.e. Lead) => α decay

Particle α = ${}^{4}_{2}He$

$$ {}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He $$

- Isotopes of H



Unstable or radio-isotope

- Activity of a source = number of desintegrations / unit of time => In Becquerel (Bq)
  - 1 Bq = 1 desintegration / second
  - Other unit => 1 Curie = 37 billions of Bq

$$A(t) = A_0 \, 2^{-\frac{t}{T}}$$

Radioactive period (Ex: 4.5 billion years for Uranium)

APPENDIX (21/25)

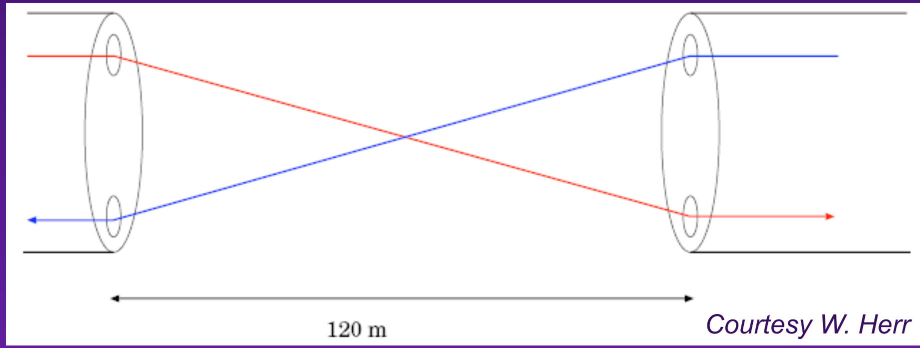
- **Mean path**
  - α => ~ 5 cm in air and few μm in matter (stopped by a sheet of paper)
  - β => ~ 1 m in air, 5 mm in human body and few mm in plexiglas (usually used to stop them)
  - γ and X (i.e. energetic photons with E_γ >> E_X) => Few 100s m in air, go through the human body, generally stopped with Lead
  - n => Few 100s m in air, go through always everything, even Lead. Generally stopped with concrete (could be also marble, and the best is water => Therefore very bad for us!)

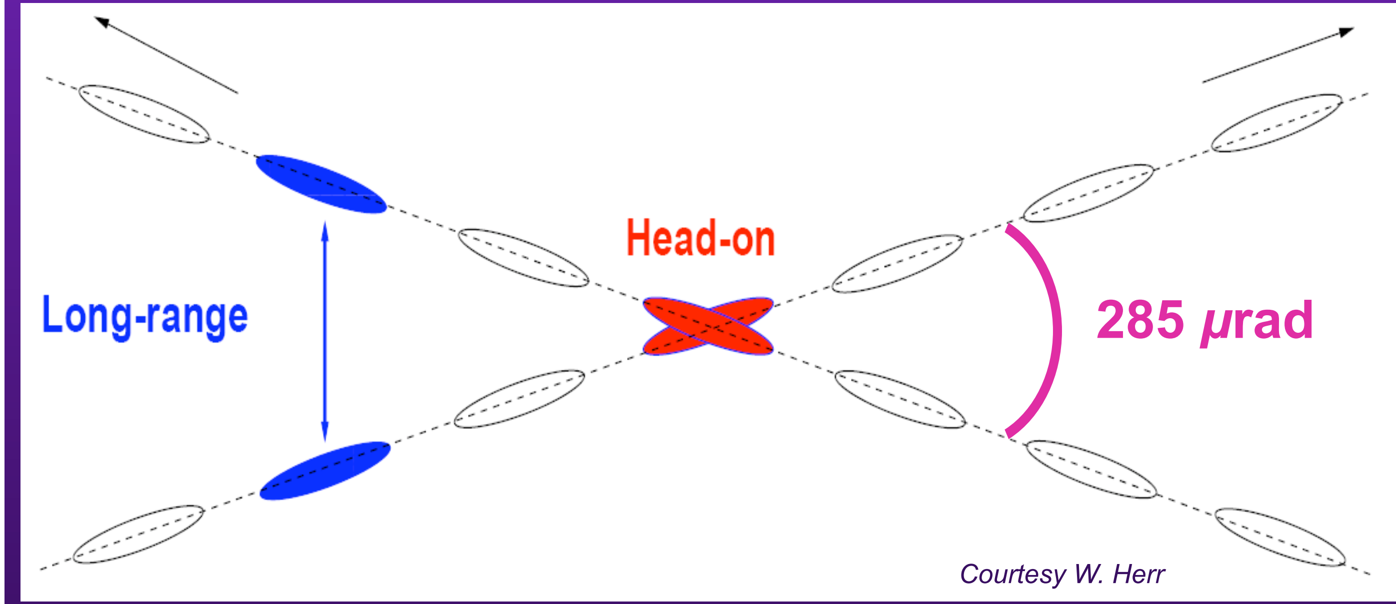
- **In a particle accelerator, beam losses induce nuclear transmutations and the machine elements (vacuum chamber, magnets, etc.) become radioactive => β and γ are thus emitted even when the accelerator is stopped**

APPENDIX (22/25)

BEAM-BEAM

CROSSING ANGLE ⇒ To avoid unwanted collisions, a crossing angle is needed to separate the 2 beams in the part of the machine where they share a vacuum chamber



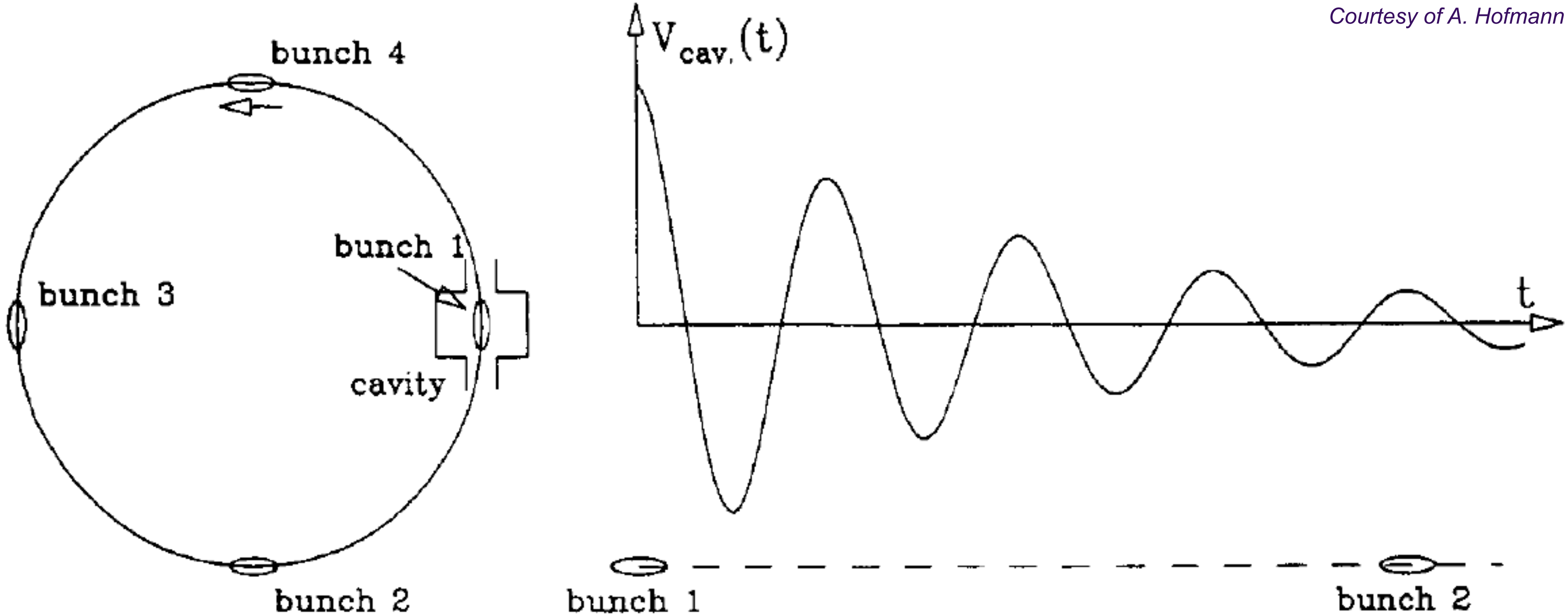


- **30 long-range interactions around each IP ⇒ 120 in total**
- **Separation: 9 σ**

APPENDIX (23/25)

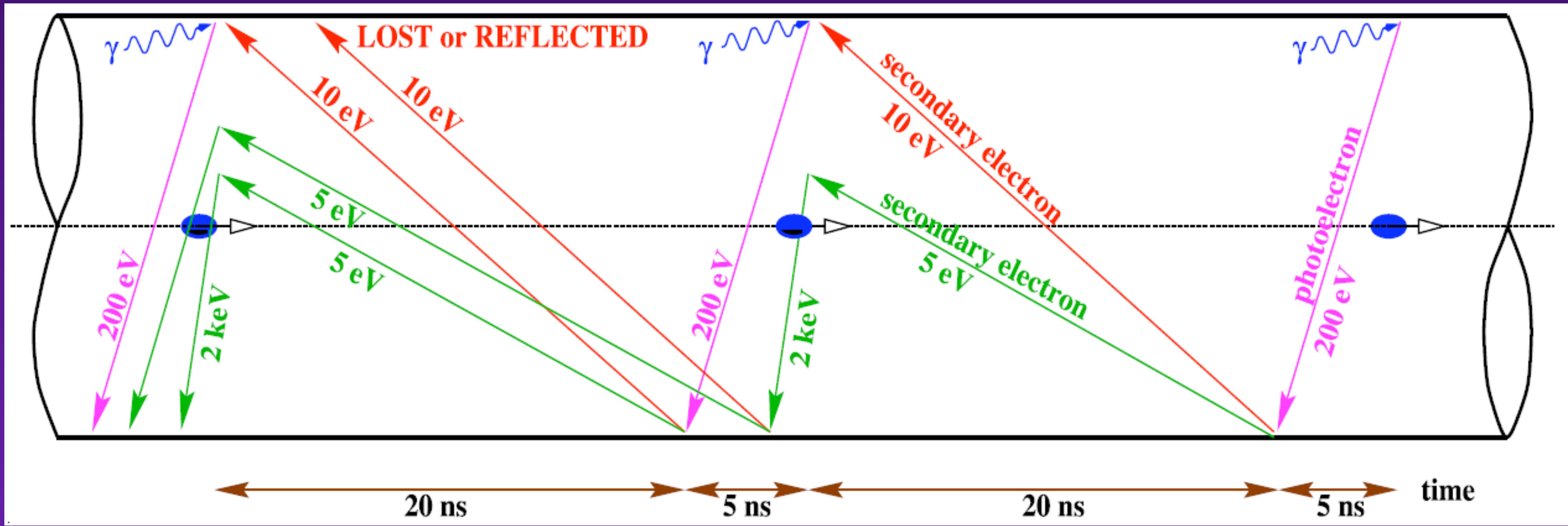
IMPEDANCE

Courtesy of A. Hofmann

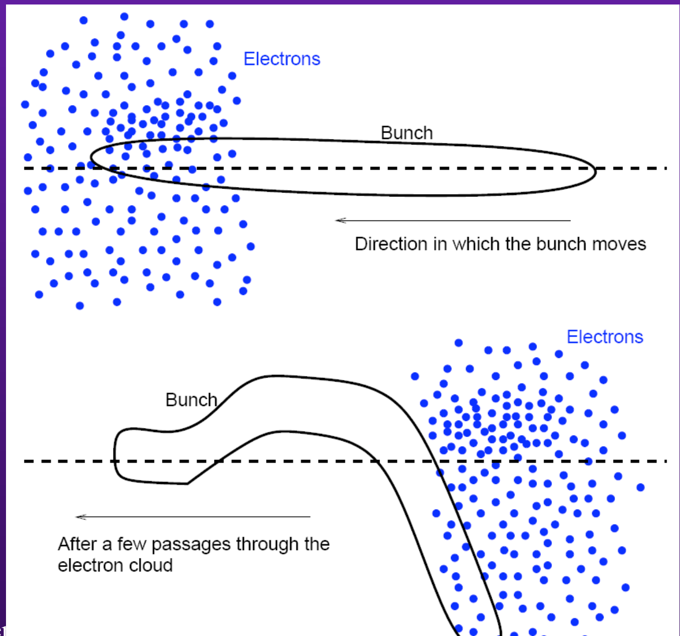


APPENDIX (24/25)

ELECTRON CLOUD



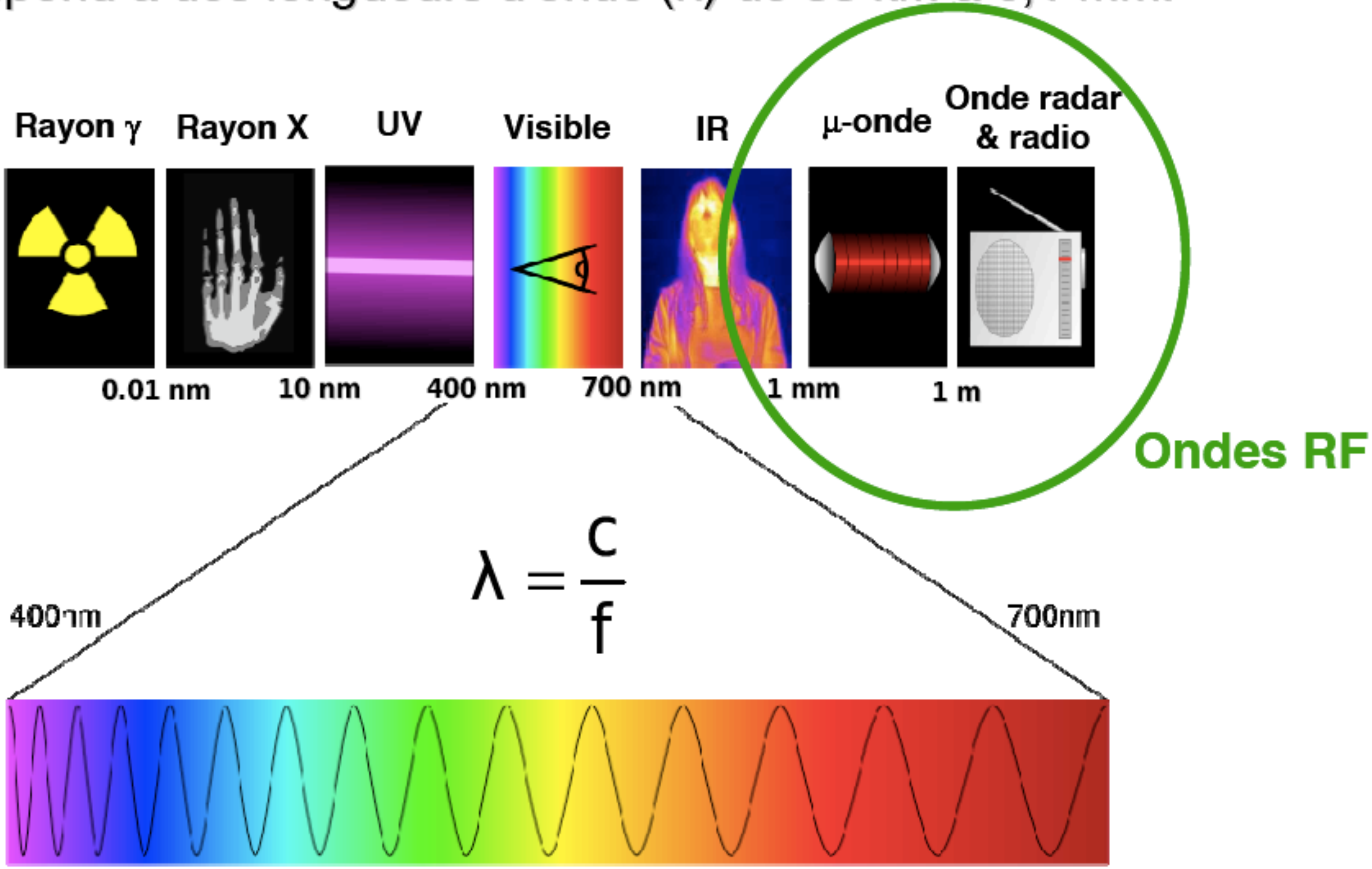
Courtesy F. Ruggiero



Courtesy G. Rumolo

APPENDIX (25/25)

Une onde radio-fréquence (RF) est une onde électromagnétique dont la fréquence d'onde (f) est par convention comprise **entre 9 kHz et 3000 GHz**, ce qui correspond à des longueurs d'onde (λ) de 33 km à 0,1 mm.



$$\lambda = \frac{c}{f}$$

Courtesy J.L. Biarrotte