# Scientific and technical challenges of the LHC

*Philippe Lebrun*
CERN, Geneva (Switzerland)

# Contents

- Particle physics beyond the standard model
- Challenging accelerator physics
- Economy through technology
- Quality and quantity in time from industry
- A global project in a local environment
- Conclusion

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# The size of things

Big Bang

**Instruments** | **Observables**

- $10^{-34}$
- $10^{-30}$
- $10^{-26}$
- $10^{-22}$ — SUSY particle? Higgs? Z/W (range of weak force)
- $10^{-18}$ — Proton Nuclei (range of nuclear force)
- $10^{-14}$ — Atom
- $10^{-10}$ — Virus
- $10^{-6}$ — Cell
- 1m
- $10^{6}$ — Earth radius
- $10^{10}$ — Earth to Sun
- $10^{14}$
- $10^{18}$
- $10^{22}$ — Galaxies
- $10^{26}$ — Radius of observable Universe

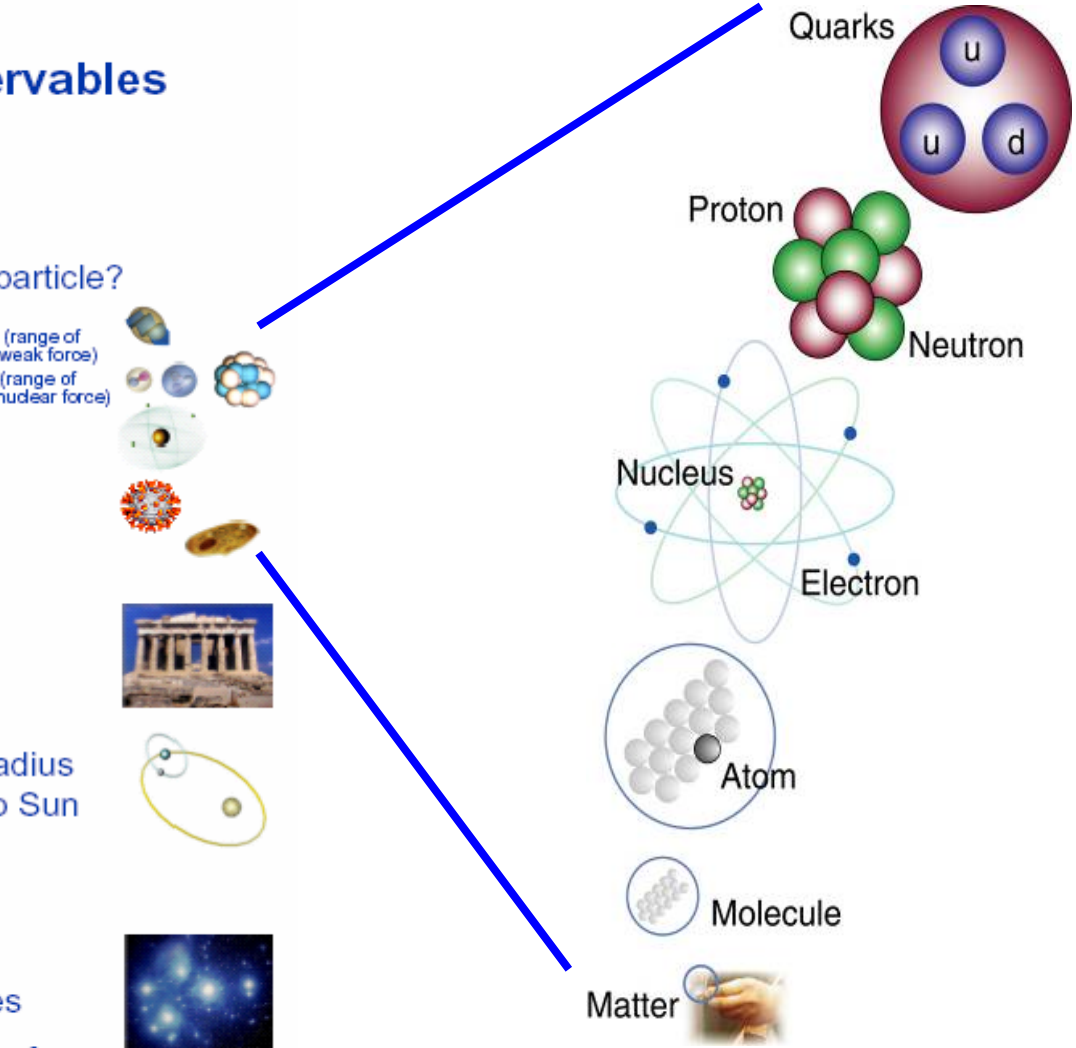
Universe

Accelerators
LHC
LEP

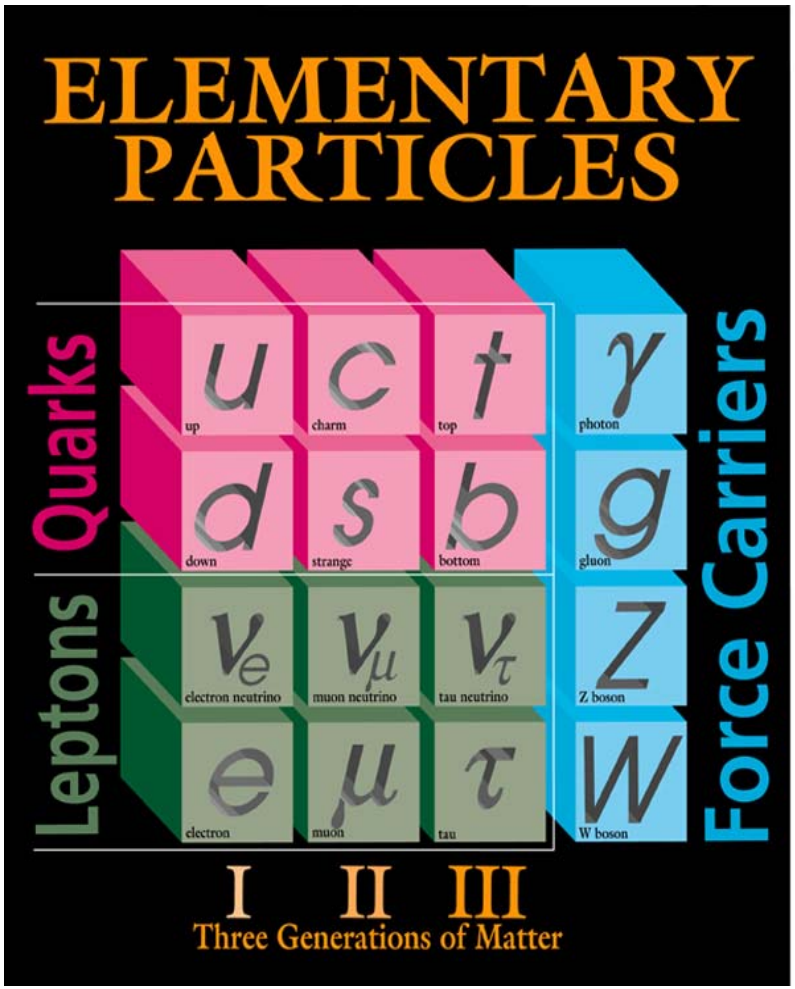
(Particle beams)
Electron Microscope
Microscope

Telescope

Radio Telescope



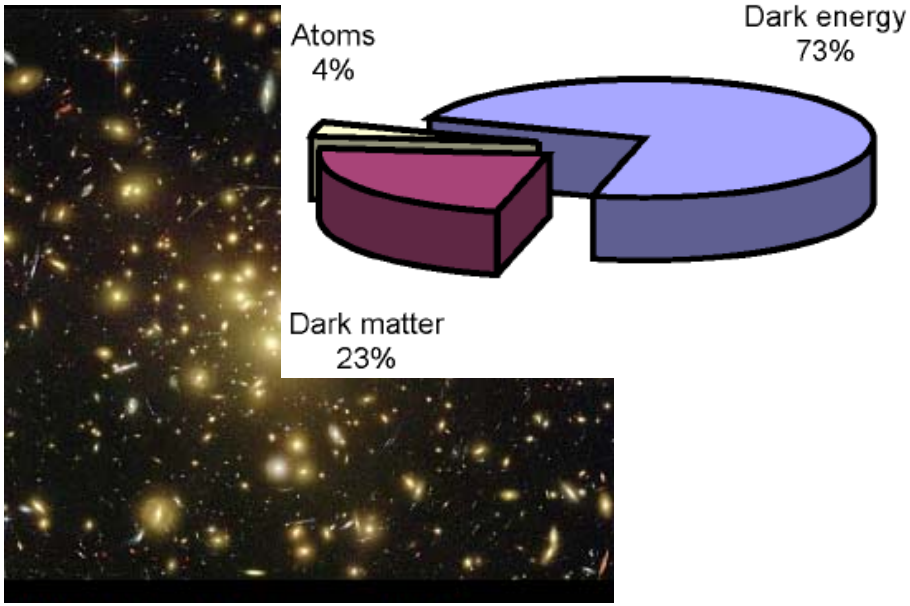
# The Standard Model

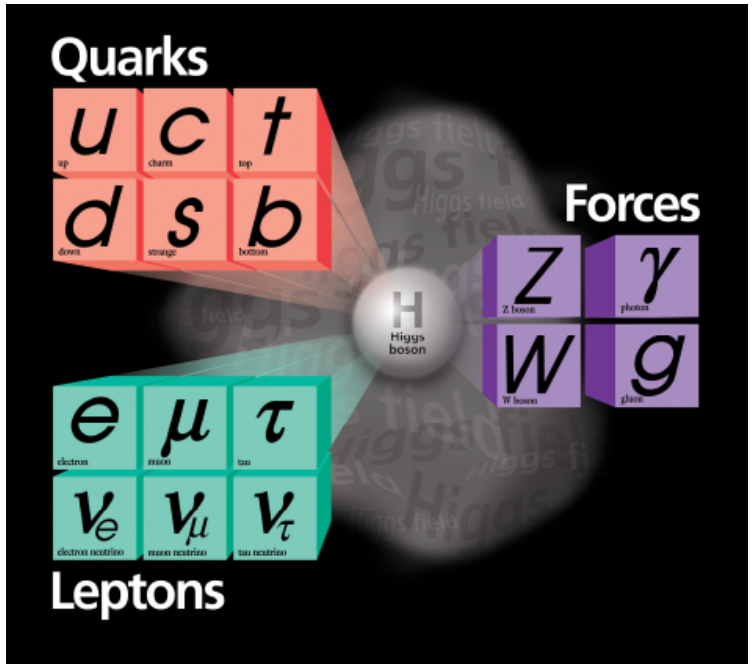



- Matter is composed of fermions (6 quarks and 6 leptons)
- All fermions have their antiparticles
- Three families of fermions of increasing masses, « normal » matter is made of the first family
- Interactions (strong nuclear, electromagnetic, weak) are carried by exchange of bosons (gluons, photons, weak bosons)
- Very successful description of nature, good precision

# Limits of the Standard Model

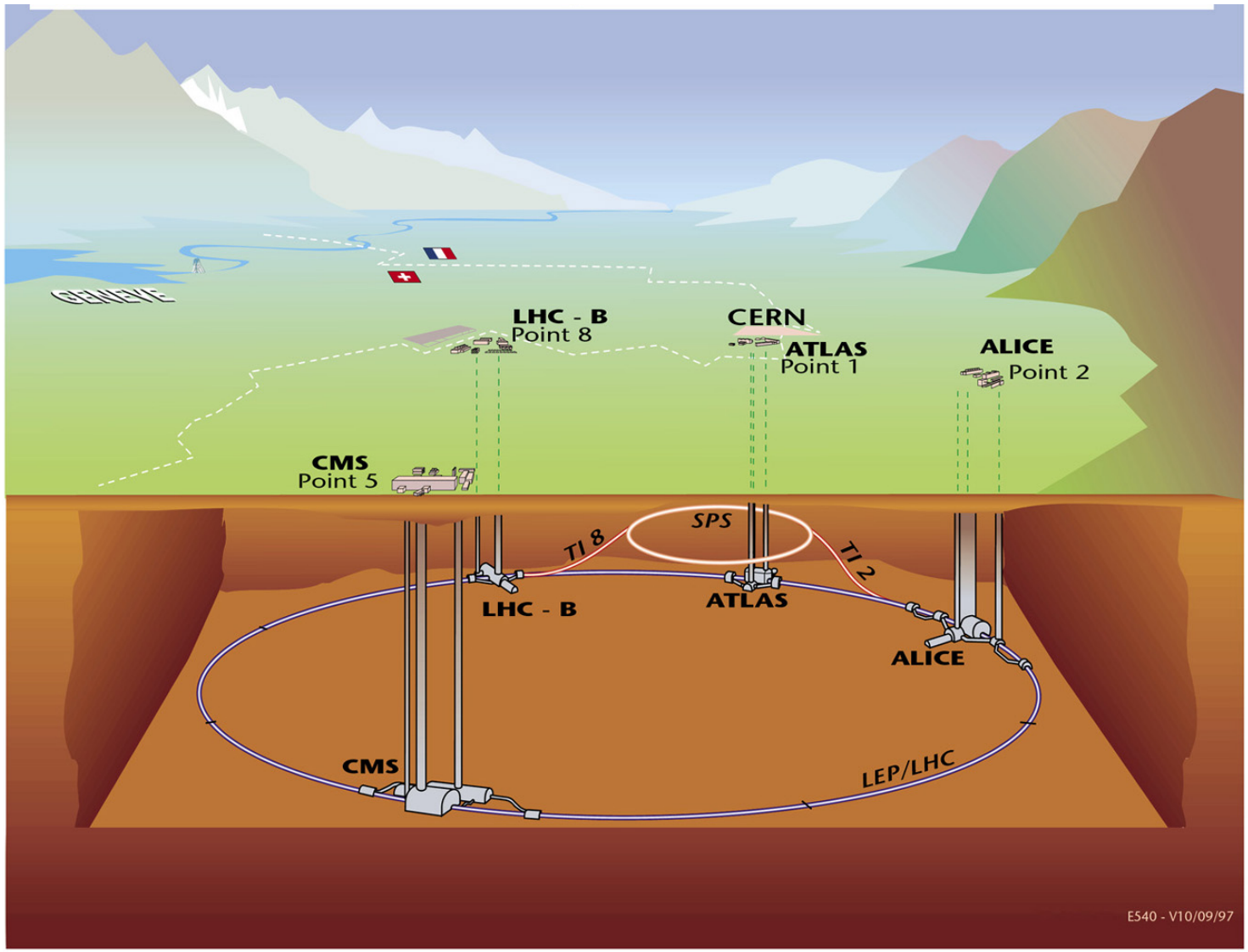
- Origin & hierarchy of particle masses: coupling with Higgs field (boson)?
- Fermion/boson supersymmetry?
- Gravity is not included!
- Unification of forces?



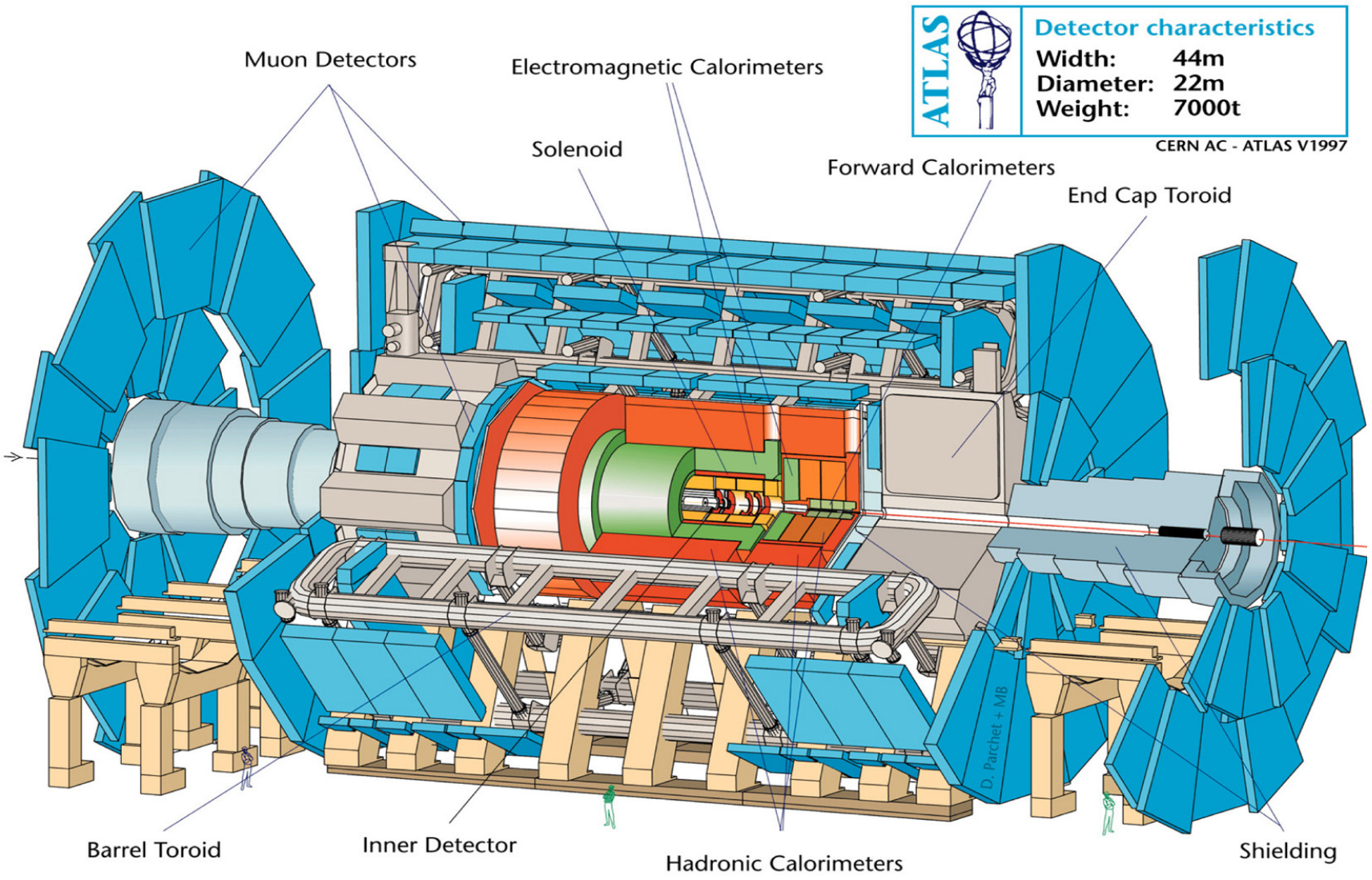




- Origin of matter-antimatter asymmetry in the universe?
- What constitutes dark matter?
- What is dark energy?

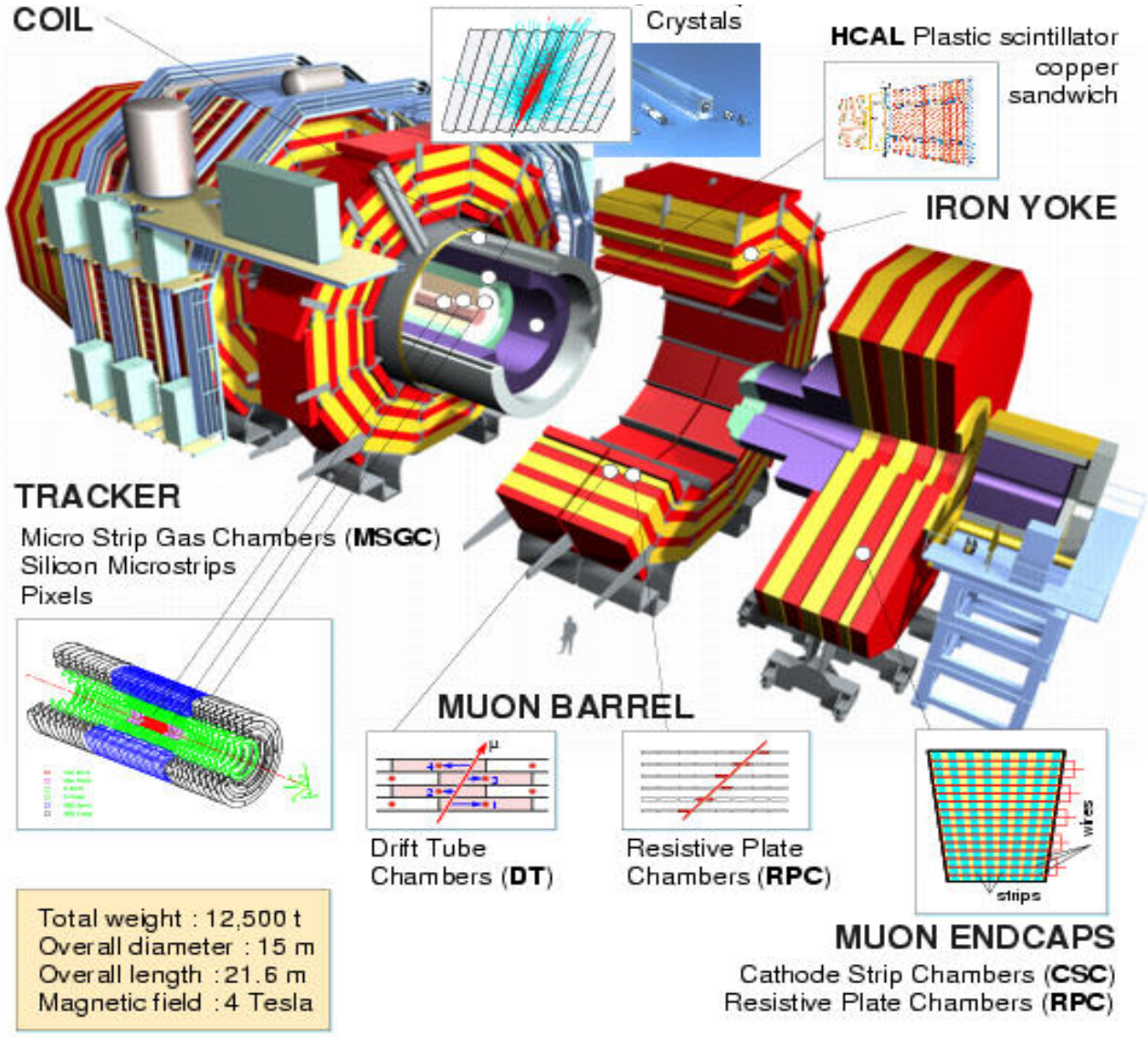
# Overall layout of the LHC and its detectors



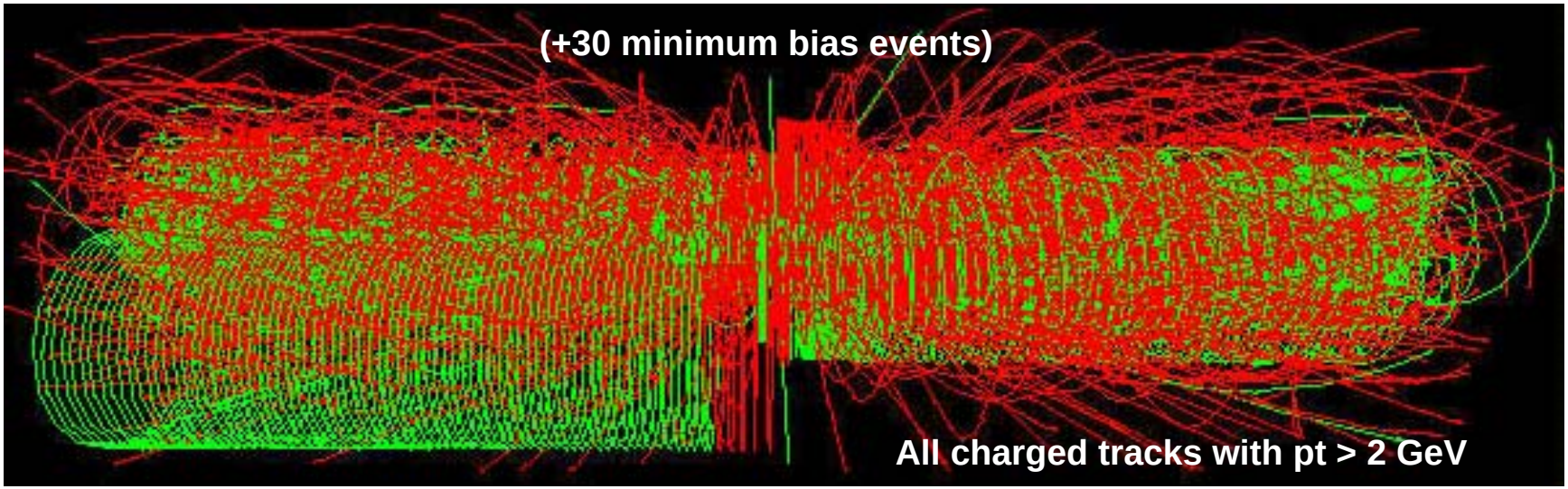
# The ATLAS detector

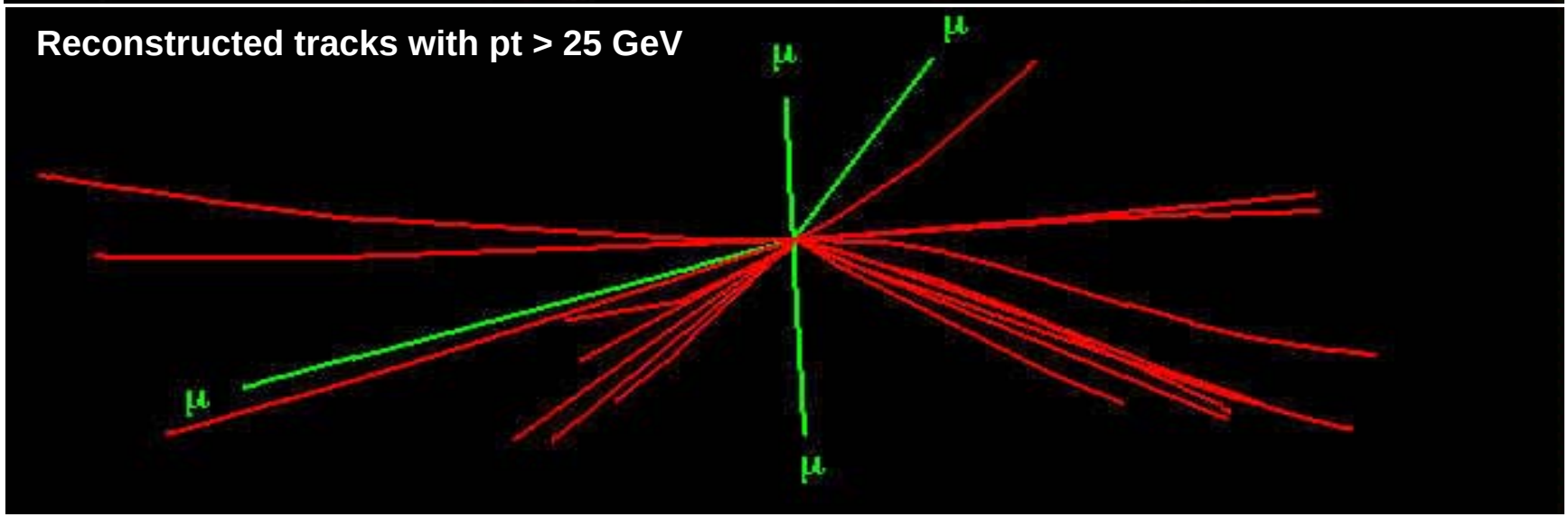


# The CMS detector



# Searching for the Higgs boson
## One needle in 20 million haystacks!



# Towards a world computing « grid »

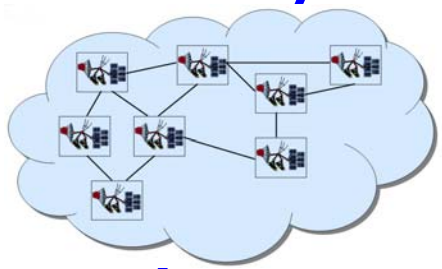
*Commodity computing*

*High-capacity links*

*Shared middleware*

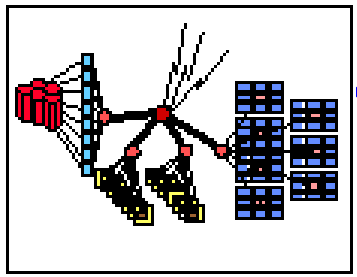
*100'000 processors*

GRID



*5000 processors*

Cluster



Super-computer

Performance

1980

1990

2000

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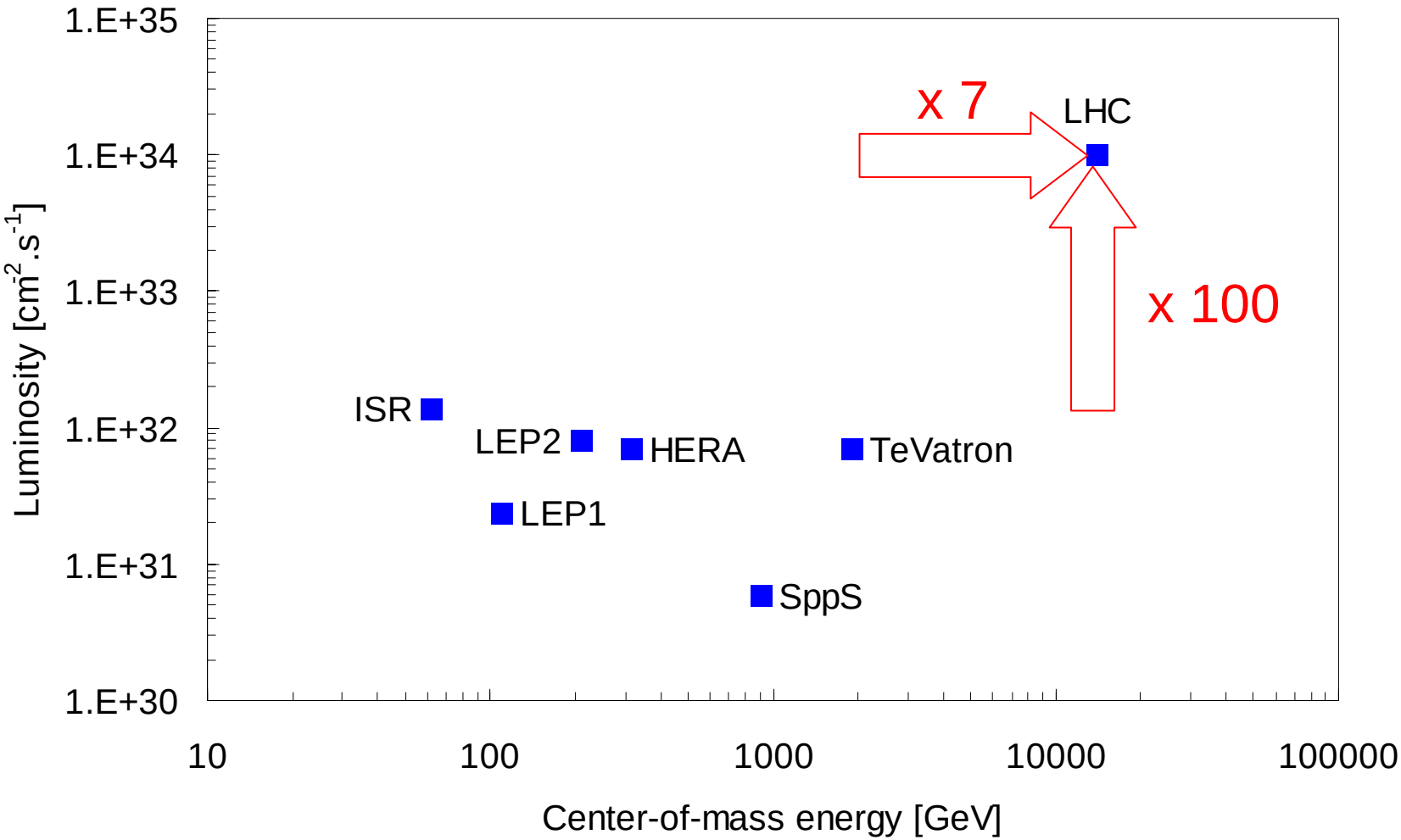
# Luminosity vs. energy of colliders



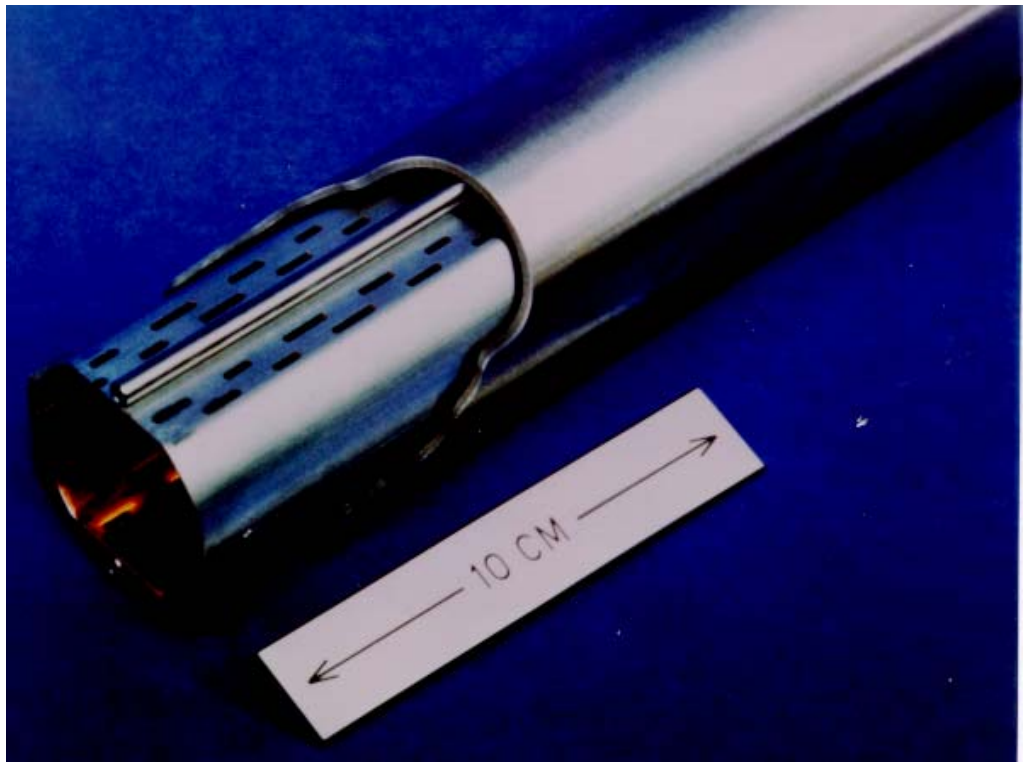
# Challenging accelerator physics

- High luminosity
  - High-intensity beams (2 x 0.584 A)
  - High-brilliance injectors (transverse emittance 3.75 μm.rad)
  - Large stored energy (2 x 362 MJ)
  - Small tolerance of s-c magnets to beam losses (~ 10 mJ/cm$^3$)
- Beam-beam effect
  - 2808 bunches with 25 ns spacing
  - Minimum crossing angle
- Long-term stability ("dynamic aperture")
  - Particles will circulate for 400 million turns (11 billion km)
  - Sets tight constraints on field quality in magnets
- Control of collective instabilities
  - Vacuum chamber impedance (copper liner)
  - Non-linear lenses and RF feedback system
- Synchrotron radiation
  - Beam-induced desorption ⇒ dynamic vacuum
  - Photo-emission & resonant acceleration of electrons ("electron cloud")

# The beam screen

## A multi-function object required by beam physics

- Interception of beam-induced heat loads at 5-20 K (supercritical helium)
- Shielding of the 1.9 K cryopumping surface from synchrotron radiation
- High-conductivity copper lining for low beam impedance
- Low-reflectivity sawtooth surface at equator to reduce photoemission and electron cloud



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# The first circular accelerator

## Lawrence and Livingston's 80 keV cyclotron (1930)

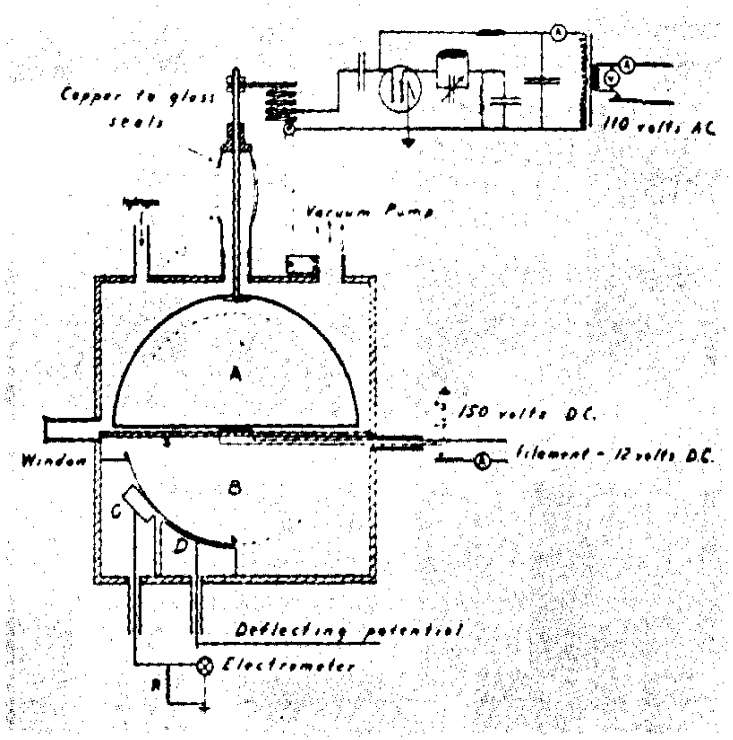
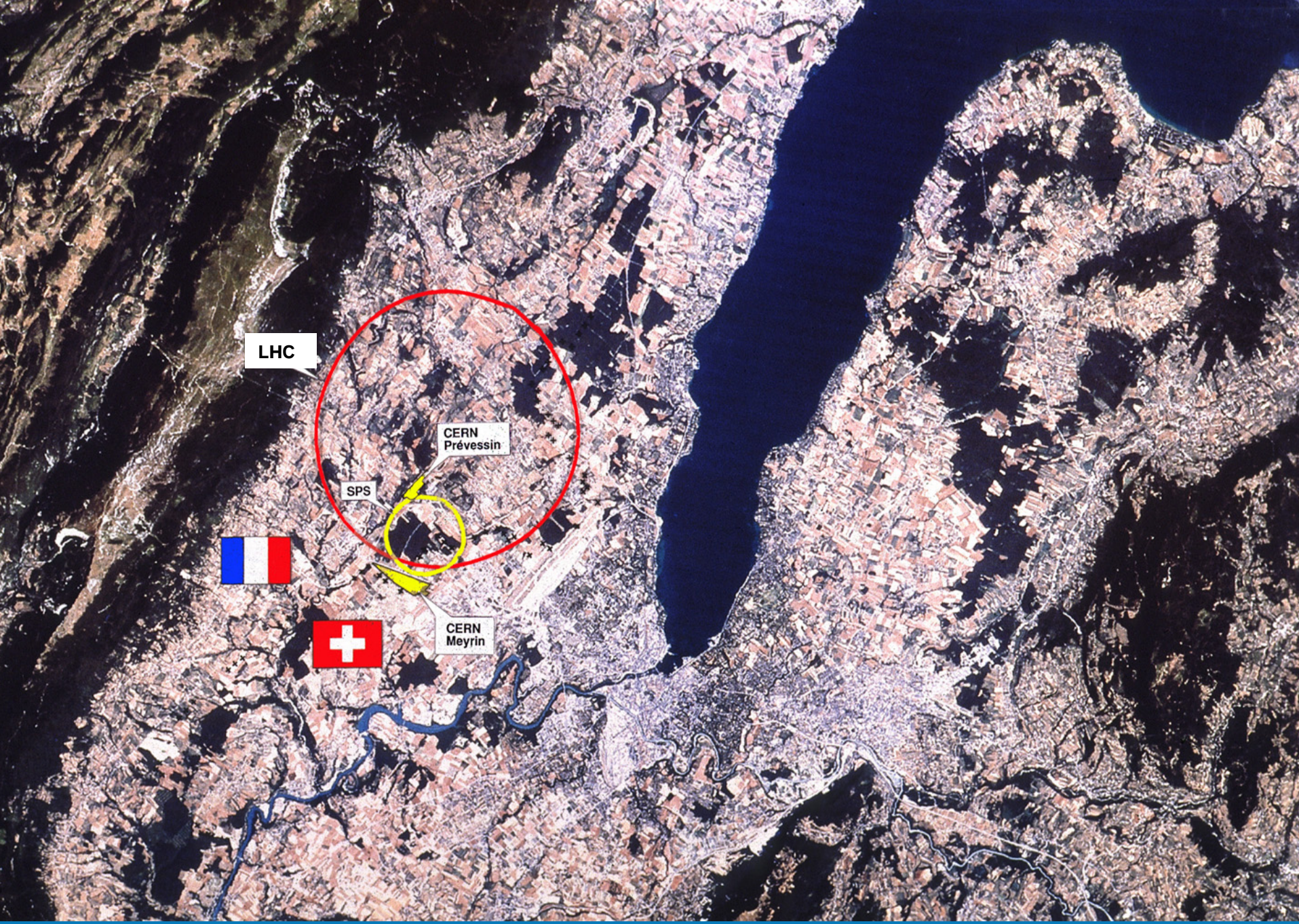
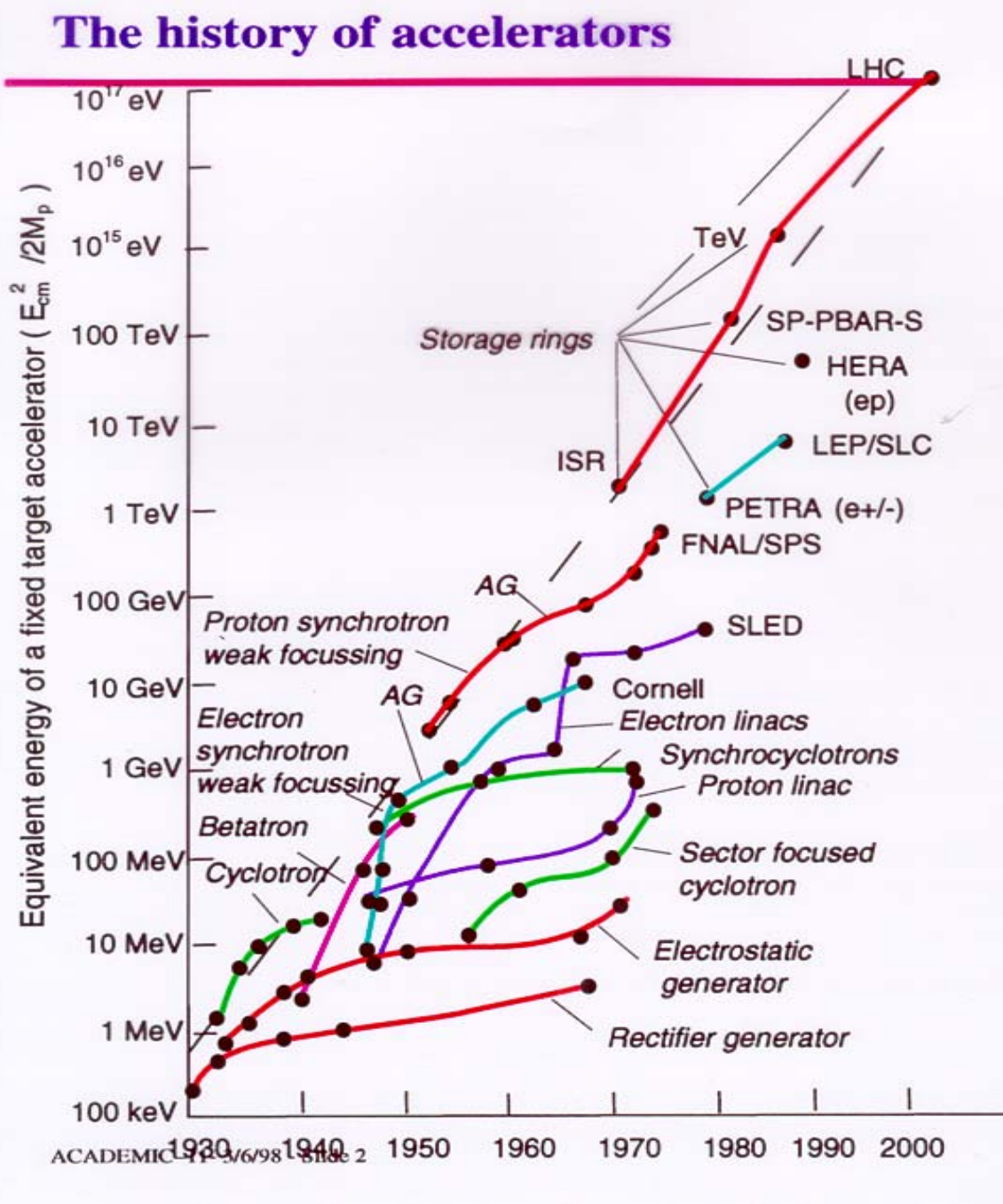



Diagram of the first successful cyclotron constructed by Lawrence and M. S. Livingston. The single dee is five inches in diameter.

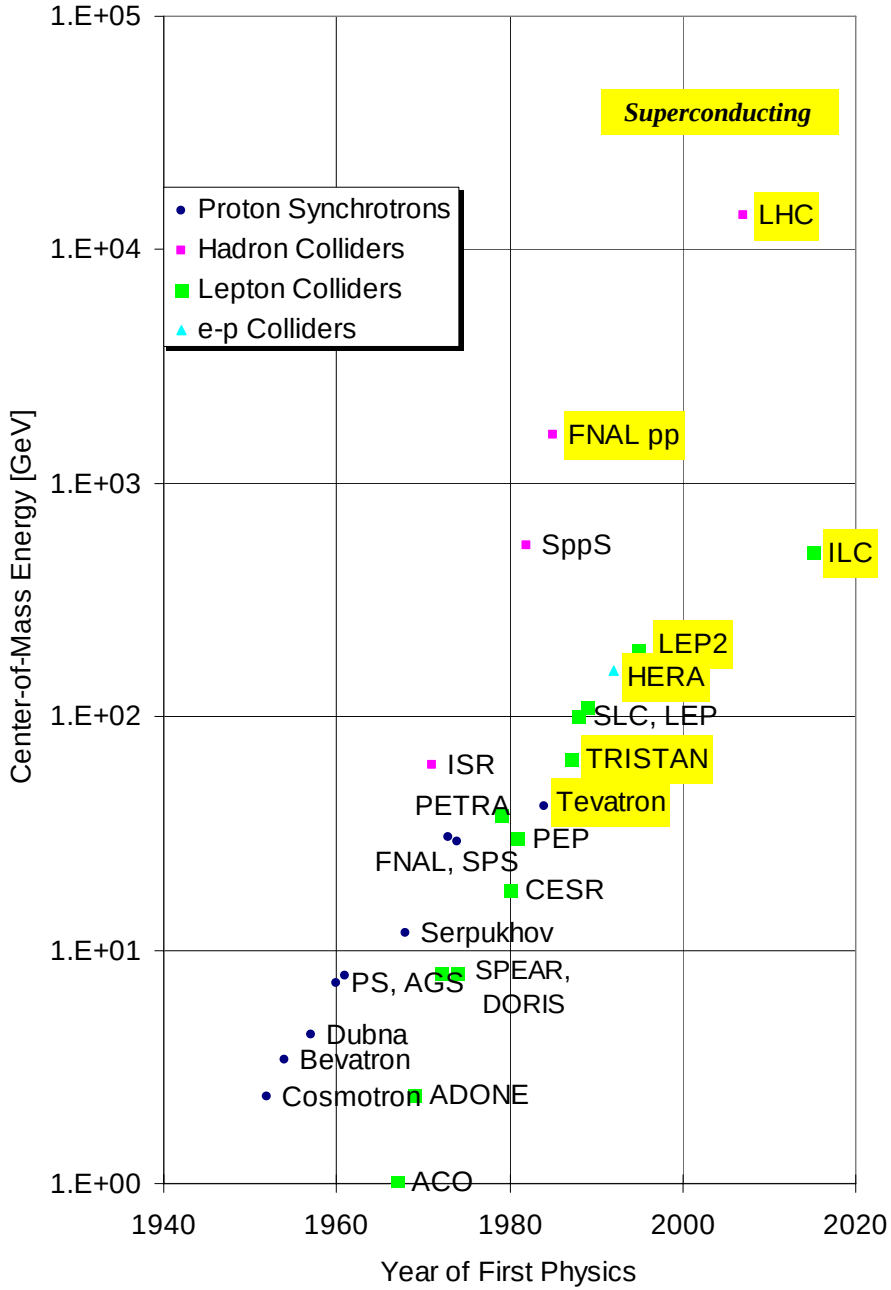

LHC
CERN
Prévessin
SPS
CERN
Meyrin

Livingston's diagram

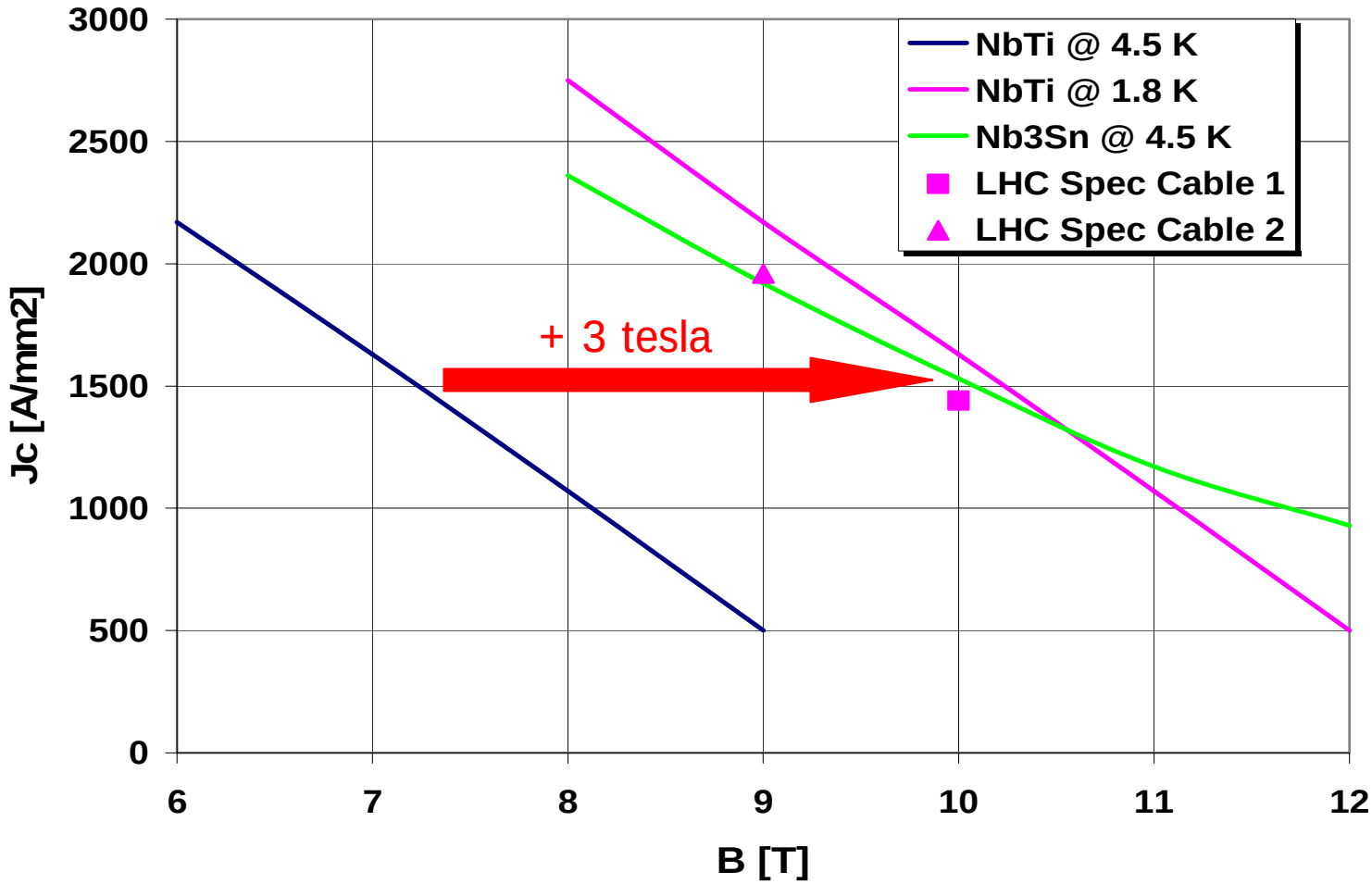
- sustained exponential development over 70 years
- progress achieved through repeated jumps from saturating to emerging technologies



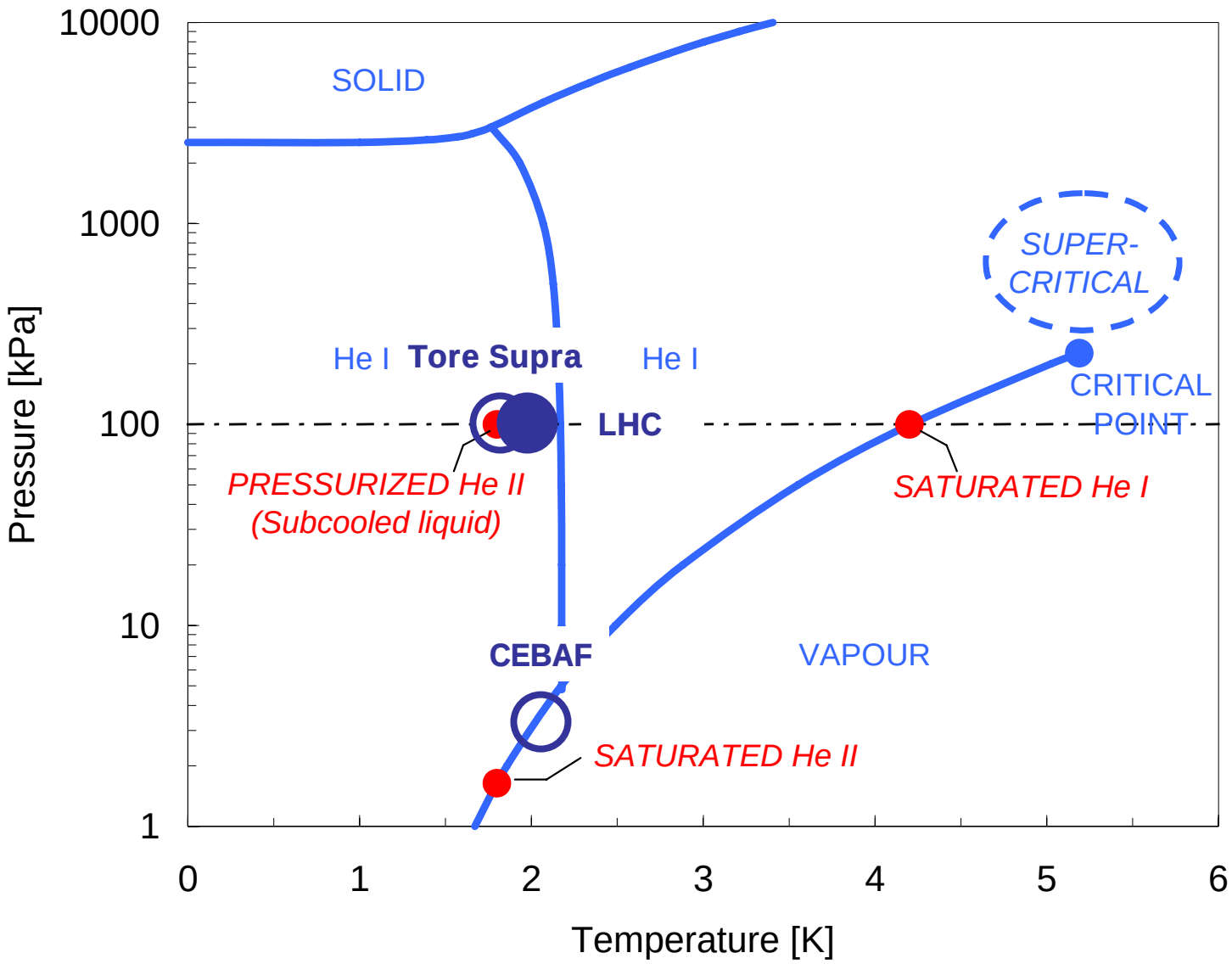
All frontier machines built or projected since the 1980s are based on the use of superconductivity



# Doping Nb-Ti performance at 1.9 K



# Superfluid helium cooling

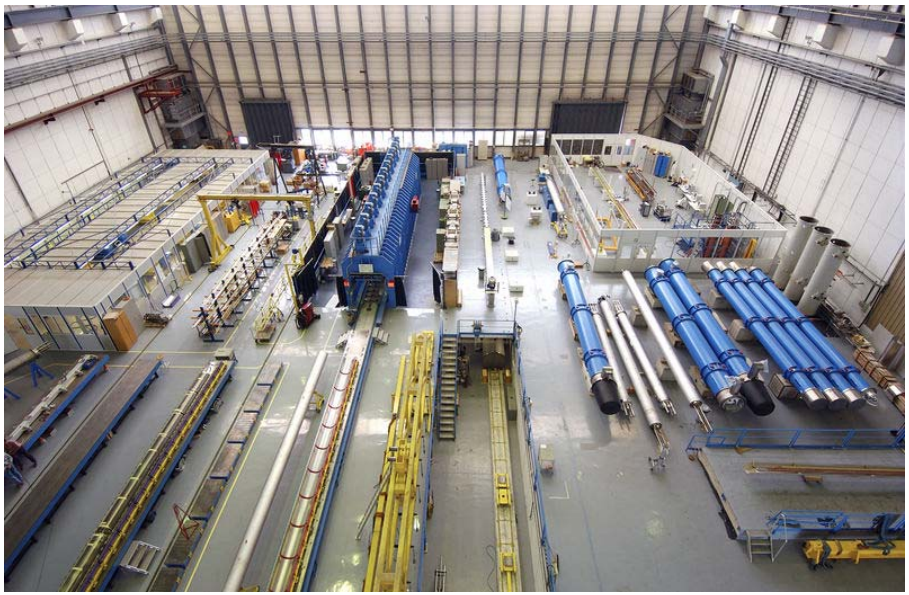


# High-field superconducting magnets

1232 twin-aperture dipoles (8.3 T)

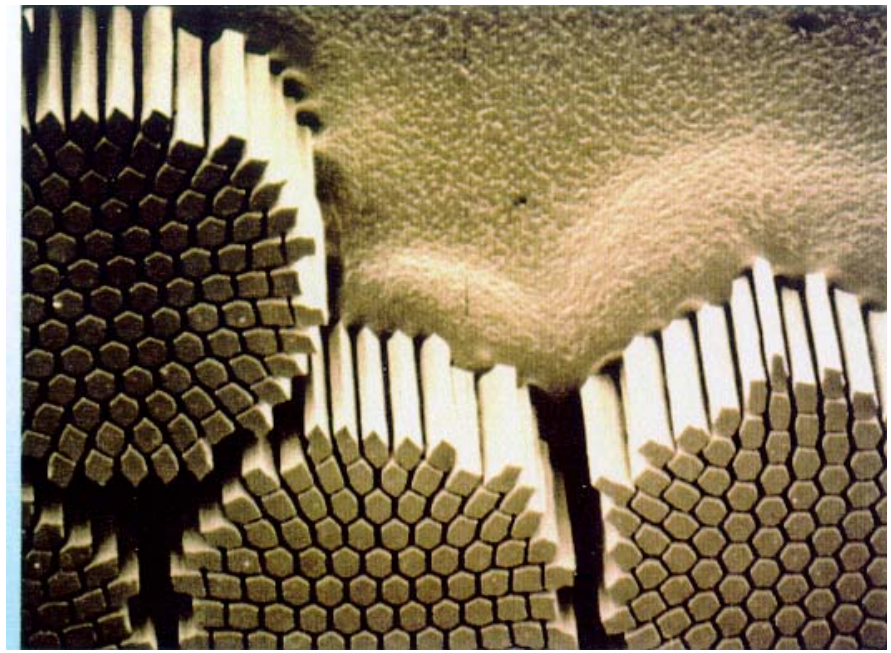
474 twin-aperture quadrupoles

7612 corrector magnets integrated in main magnet cryostats



# 7000 km Nb-Ti superconducting cables

| | Inner Cable | Outer Cable |
|---|---|---|
| **Number of strands** | 28 | 36 |
| **Strand diameter** | 1.065 mm | 0.825 mm |
| **Filament diameter** | 7 µm | 6 µm |
| **Number of filaments** | ~ 8900 | ~ 6520 |
| **Cable width** | 15.1 mm | 15.1 mm |
| **Mid-thickness** | 1.900 mm | 1.480 mm |
| **Keystone angle** | 1.25 ° | 0.90 ° |
| **Transposition length** | 115 mm | 100 mm |
| **Ratio Cu/Sc** | ≥ 1.6 | ≥ 1.9 |



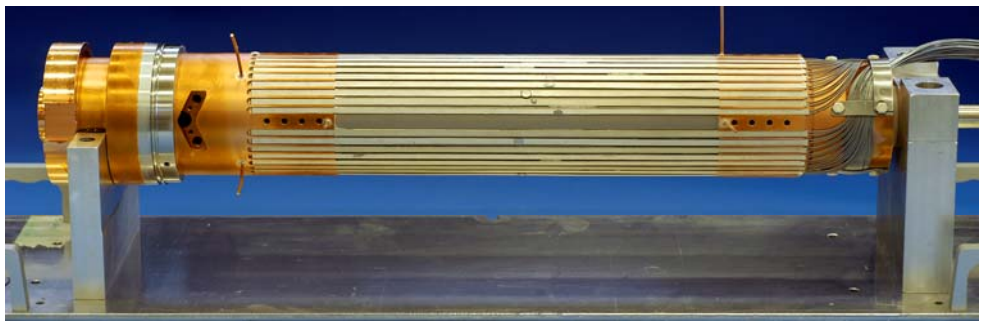
# Magnet powering with high-T superconductors

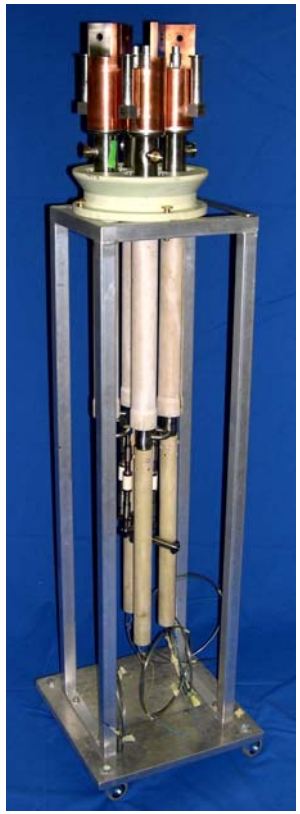
1720 electrical circuits, total current 1.7 MA

3286 current leads using Bi-2223 multi-filamentary tape

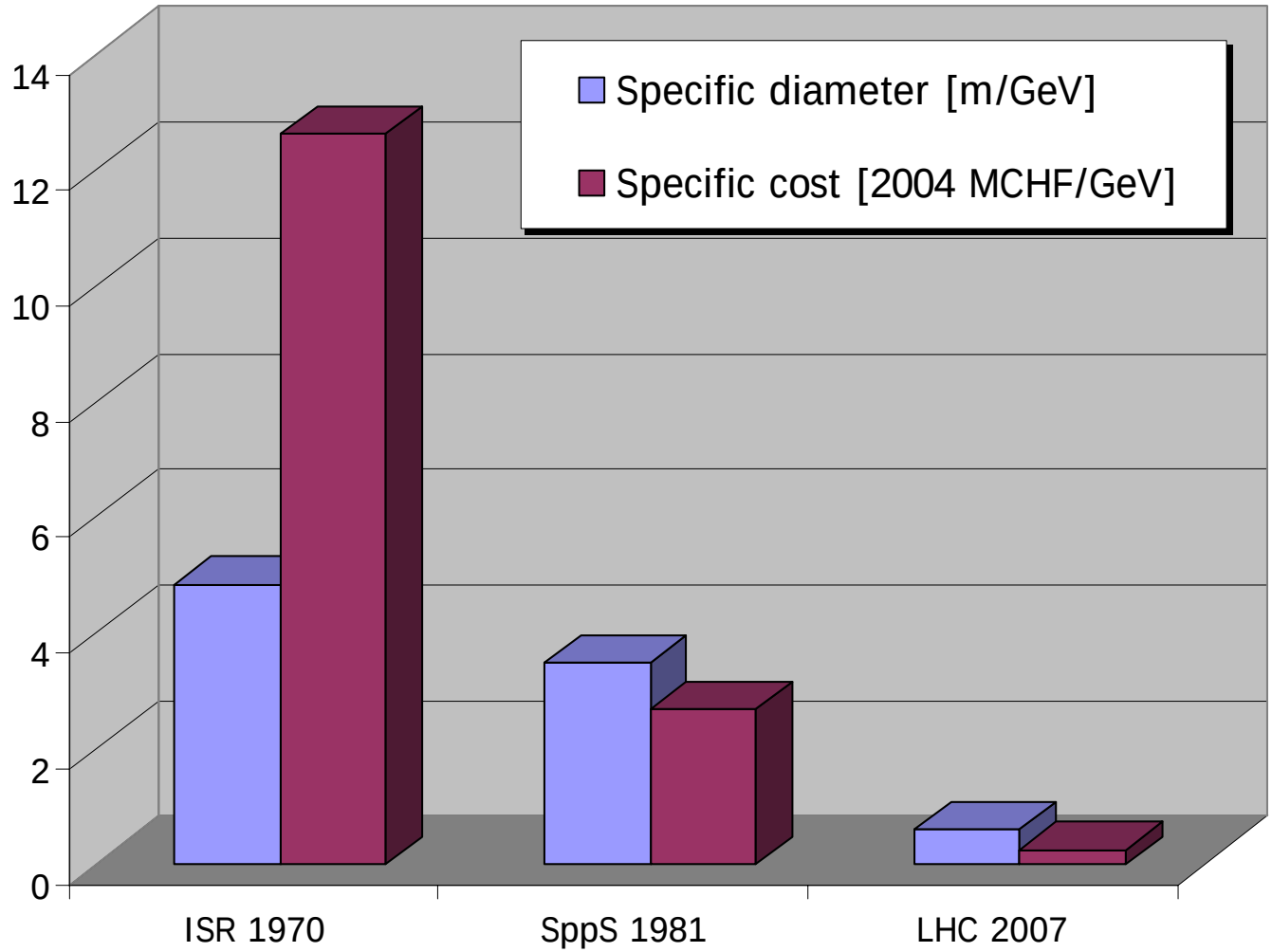
| Number | Current rating (A) |
|---|---|
| 64 | 13000 |
| 298 | 6000 |
| 820 | 600 |
| 2104 | 60-120 |

HTS

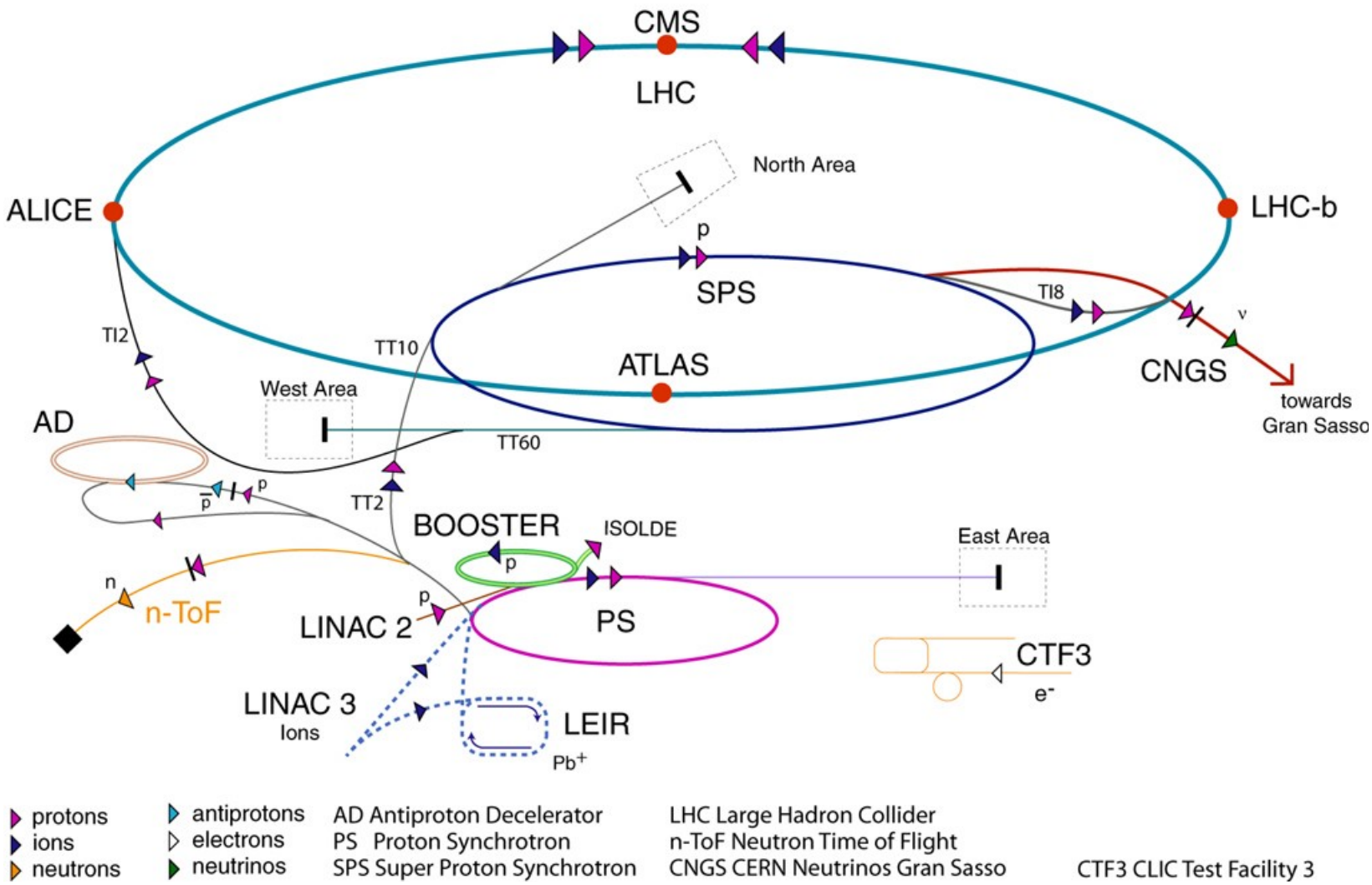




# Size & cost of CERN hadron colliders



# Reusing the CERN accelerator network



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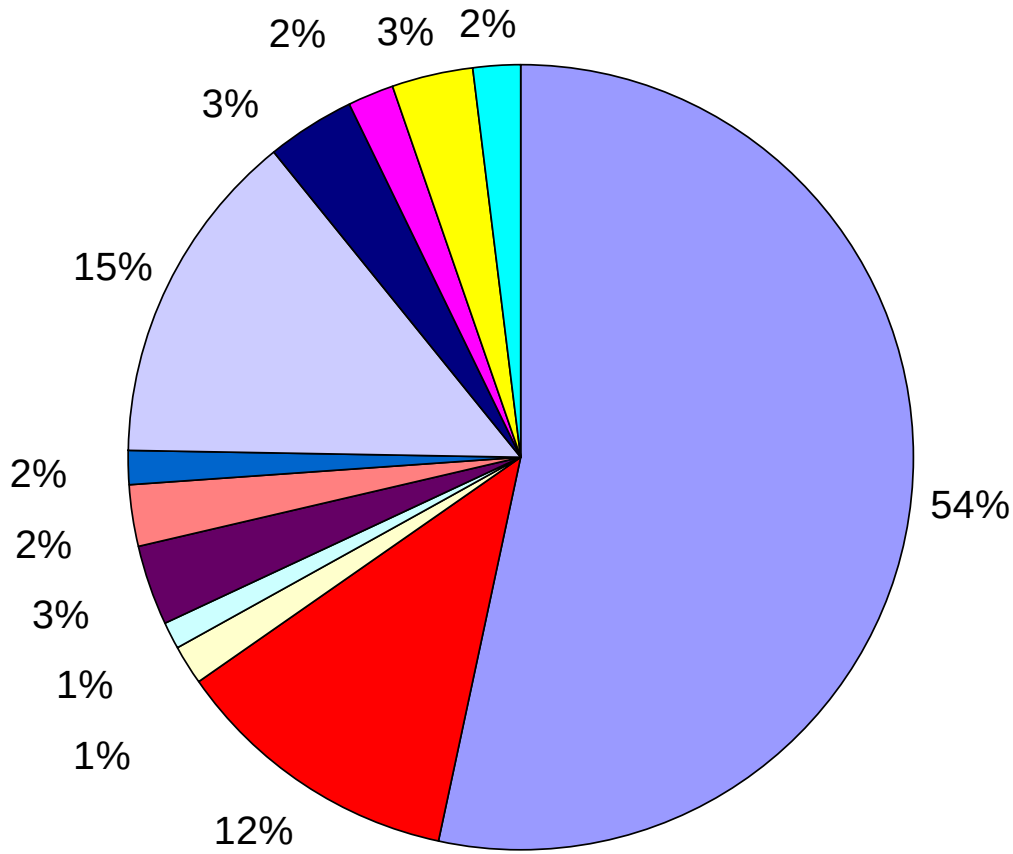
# Historical milestones of the LHC

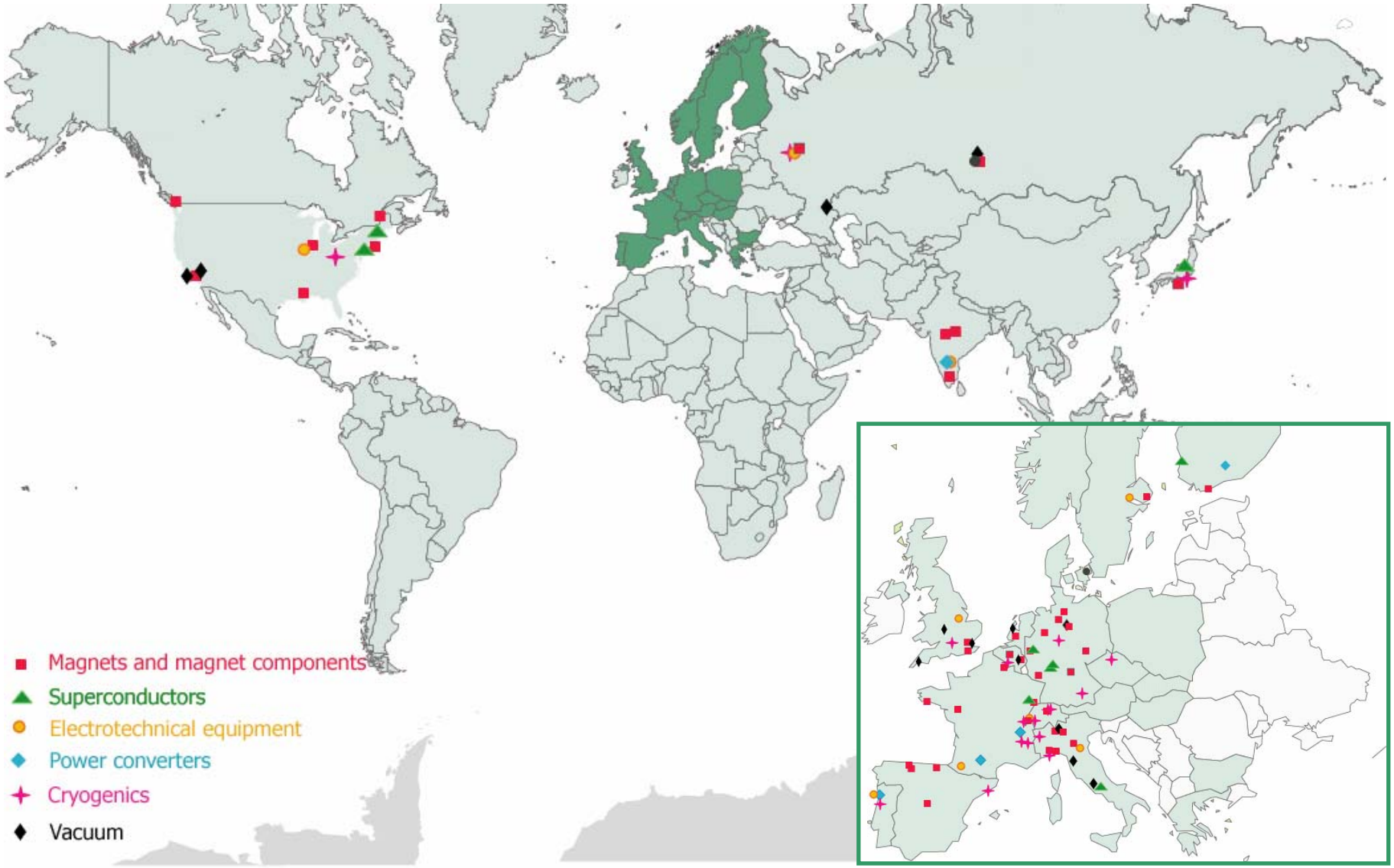
| | |
|---|---|
| • Preliminary conceptual studies | 1984 |
| • First magnet models | 1988 |
| • Start structured R&D program | 1990 |
| • Approval by CERN Council | 1994 |
| • Industrialization of series production | 1996-1999 |
| • DUP & start civil works | 1998 |
| • Adjudication of main procurement contracts | 1998-2001 |
| • Start installation in tunnel | 2003 |
| • Cryomagnet installation in tunnel | 2005-2007 |
| • Functional test of first sector | 2007 |
| • Operation for physics | 2008-2030? |

# Cost structure of the LHC accelerator




Total ~ 2.2 BEuro

# 90 main industrial contracts in the world

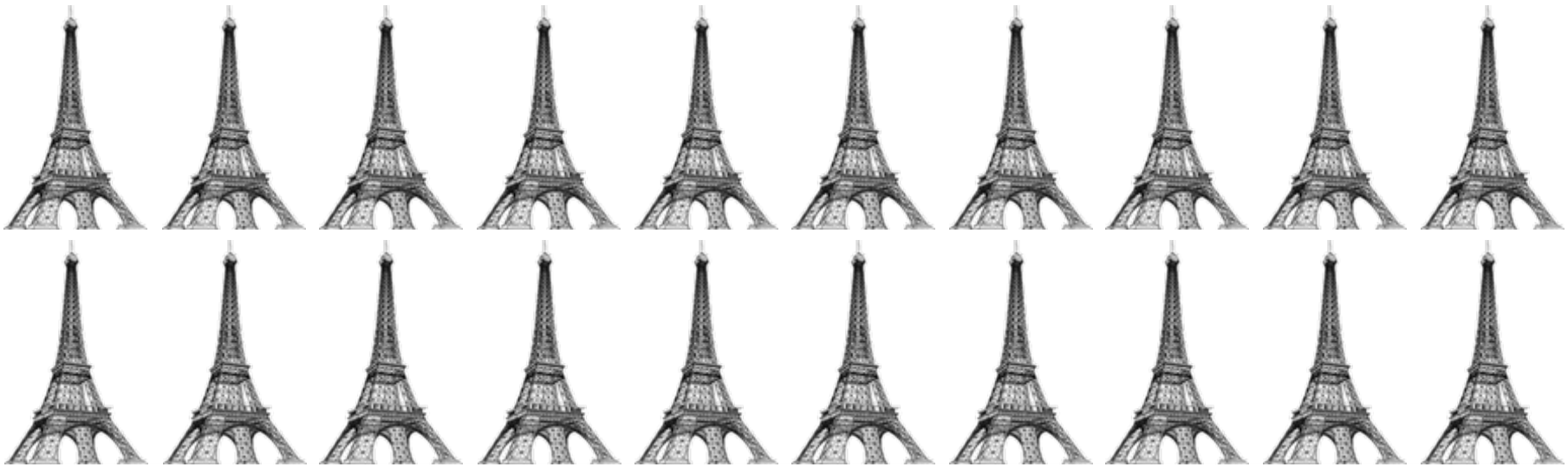


# Procurement logistics

## Quantity & quality in time at the right place

Installed underground: 50 000 t

Transported throughout Europe: ~150 000 t



# Strict configuration management

**CERN**
CH-1211 Geneva 23
Switzerland

the **Large Hadron Collider** project

LHC Project Document No.
**LHC-PM-QA-304.00 rev 1.1**

CERN Div./Group or Supplier/Contractor Document No.

EDMS Document No.
**103557**

Date:1999-11-16

**Quality Assurance Procedure**

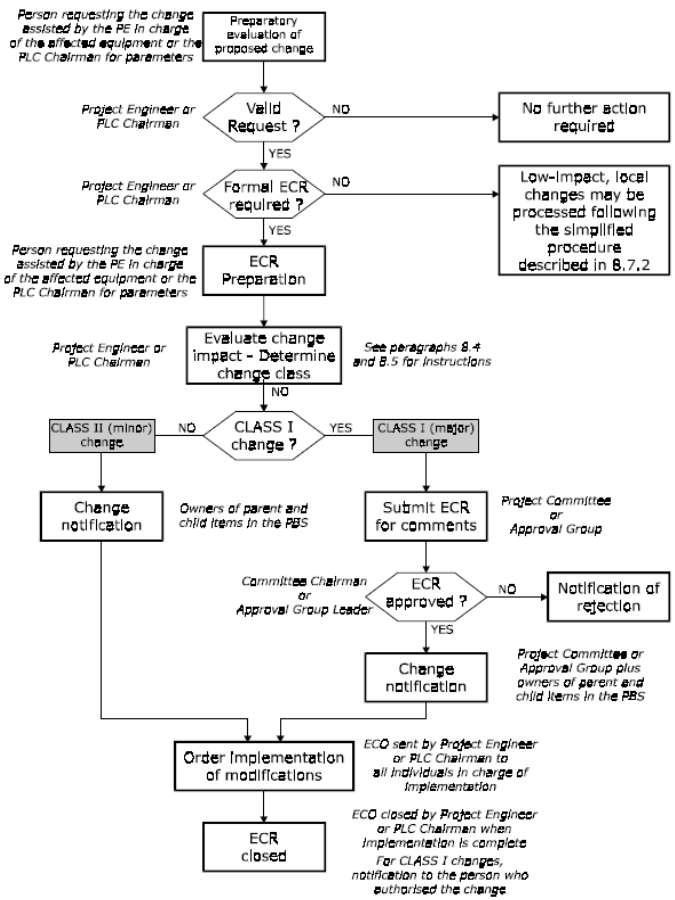
## CONFIGURATION MANAGEMENT - CHANGE PROCESS AND CONTROL


***Abstract***

This document describes the procedures and responsibilities for the systematic and uniform review of all engineering changes to the LHC configuration baseline, to ensure that the impact of changes on performance, cost and schedule are identified and thoroughly evaluated before the decision to incorporate them is taken.



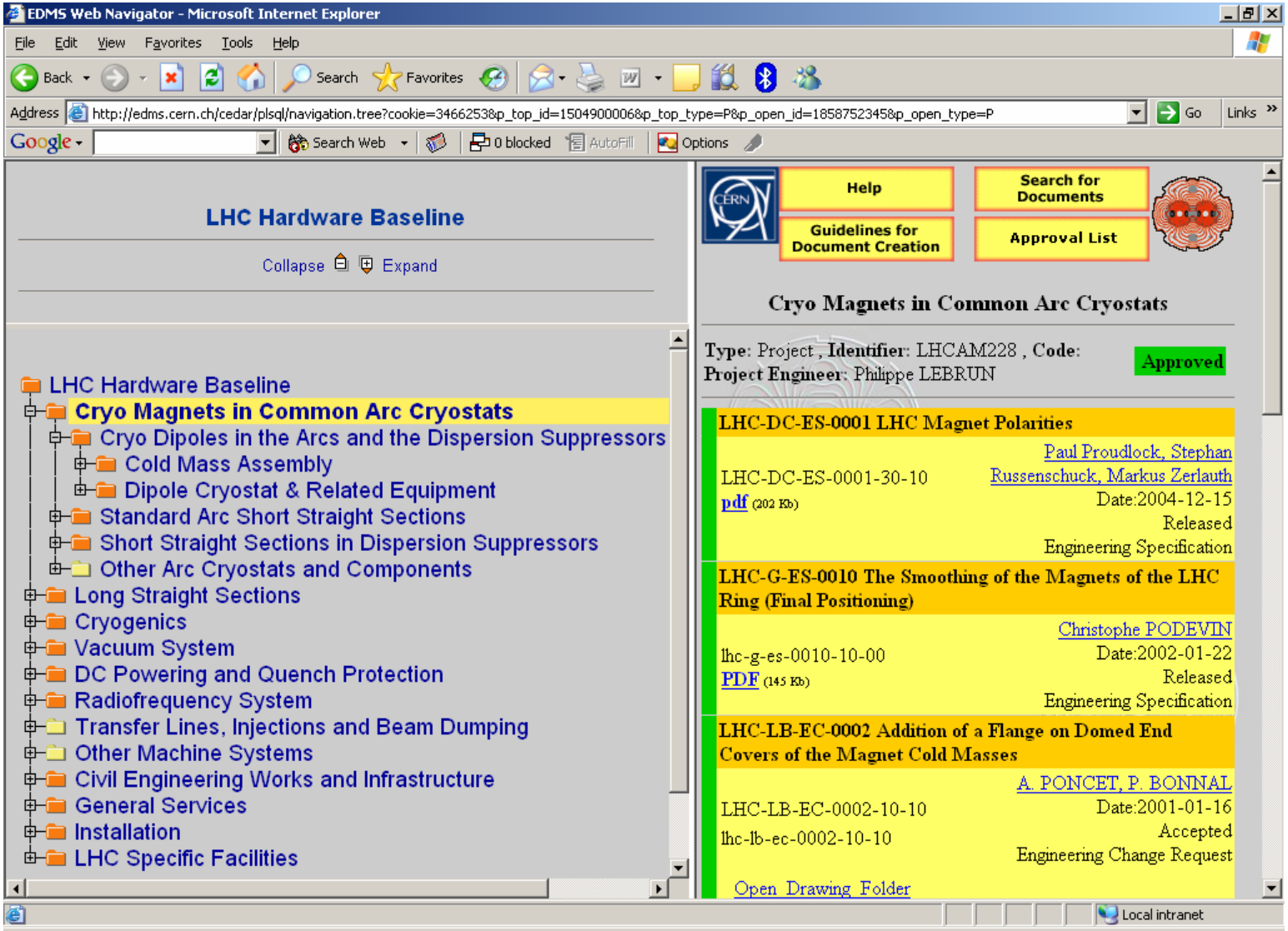
| *Prepared by :* | *Checked by :* | *Approved by :* |
|---|---|---|
| **M Mottier**<br>EST/ISS<br>Marcel.Mottier@cern.ch | **LHC Quality Assurance Working Group** | **Paul Faugeras**<br>Deputy to LHC Project Leader for Quality Assurance |

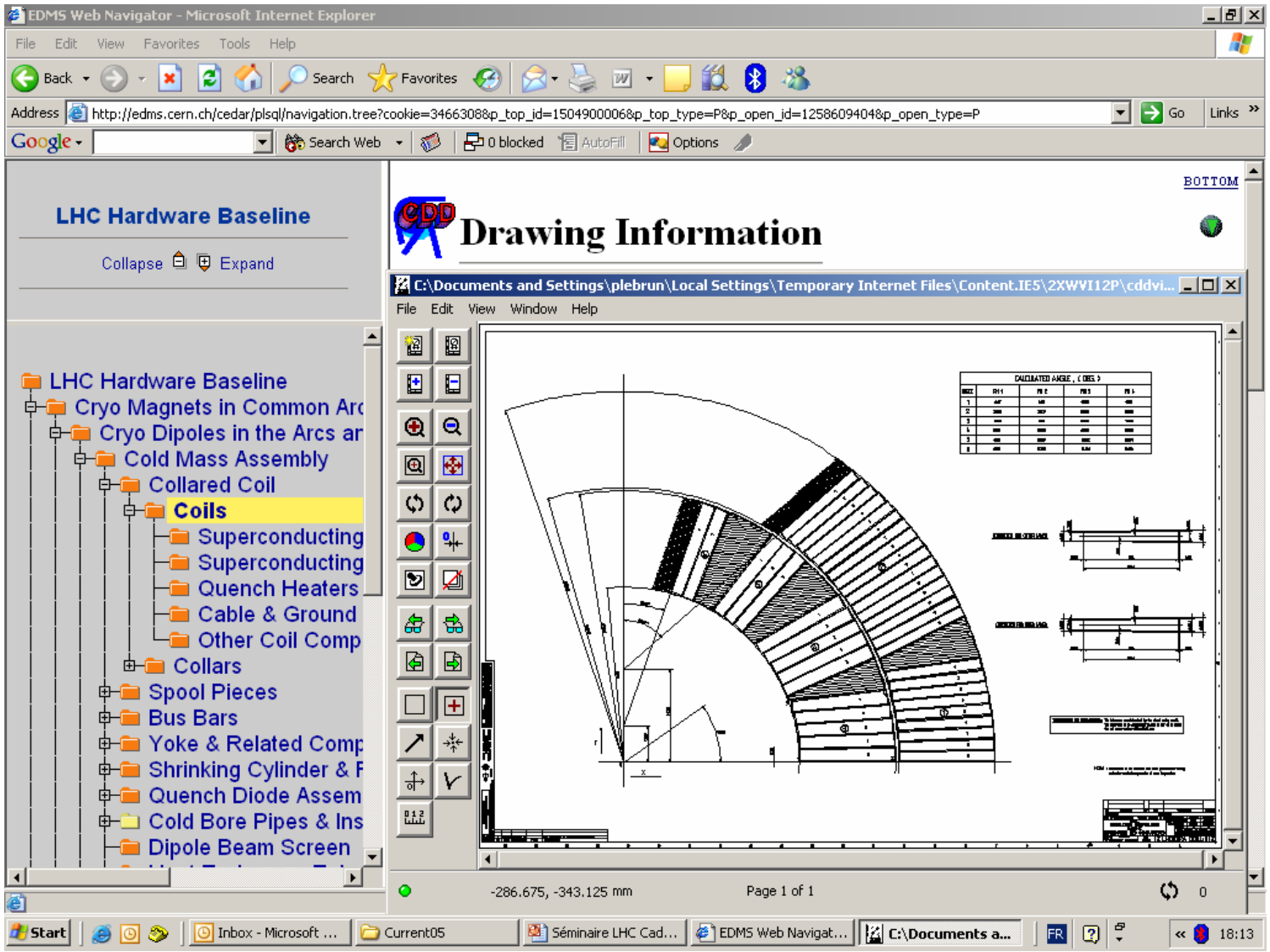

| | *Local change* | *Extended change* |
|---|---|---|
| ***Low impact change*** | CLASS II | CLASS I |
| ***High impact change*** | CLASS I | CLASS I |

# A web-based engineering data management system...

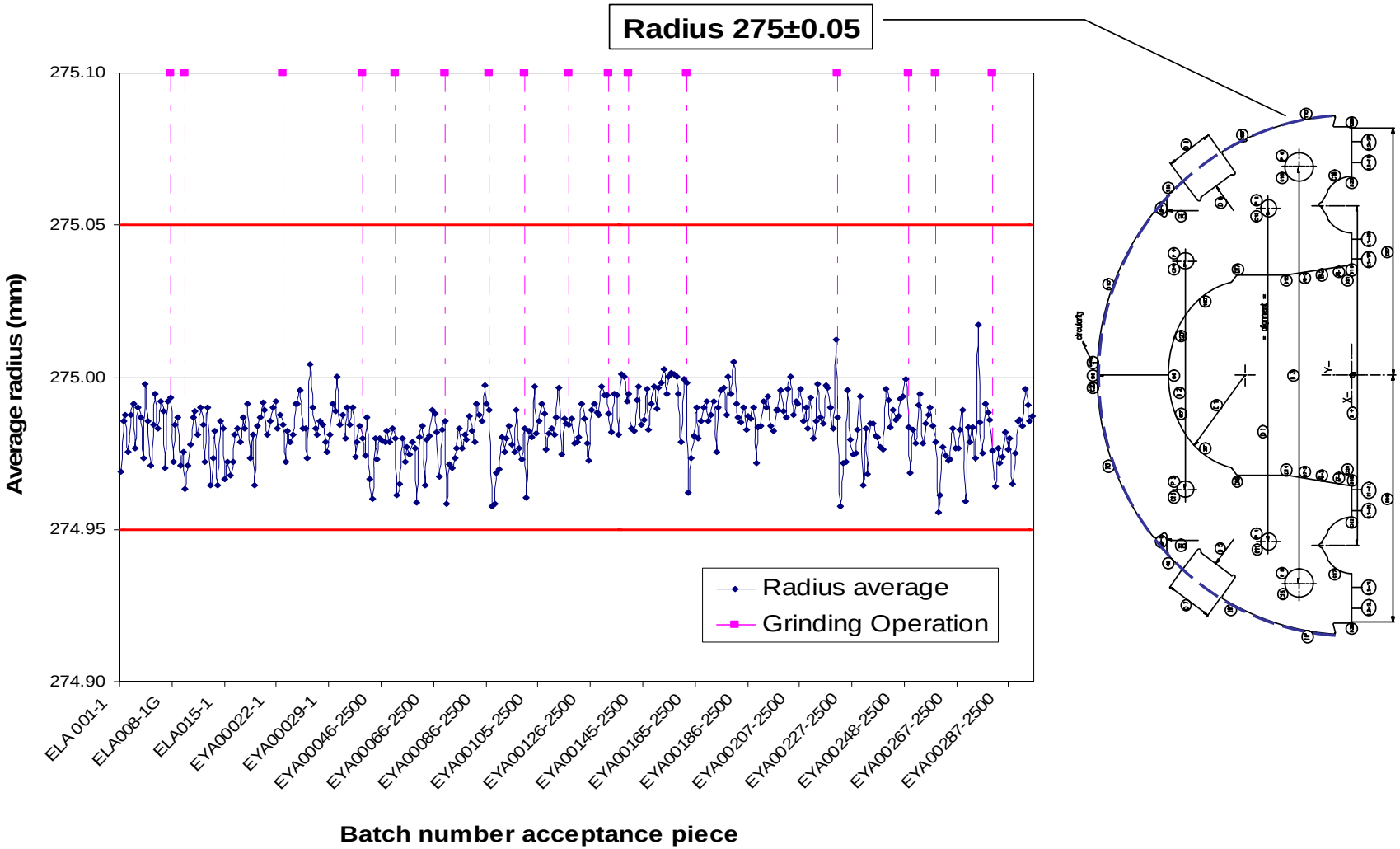
# ...giving access to the WBS...



# ...and to updated technical documents

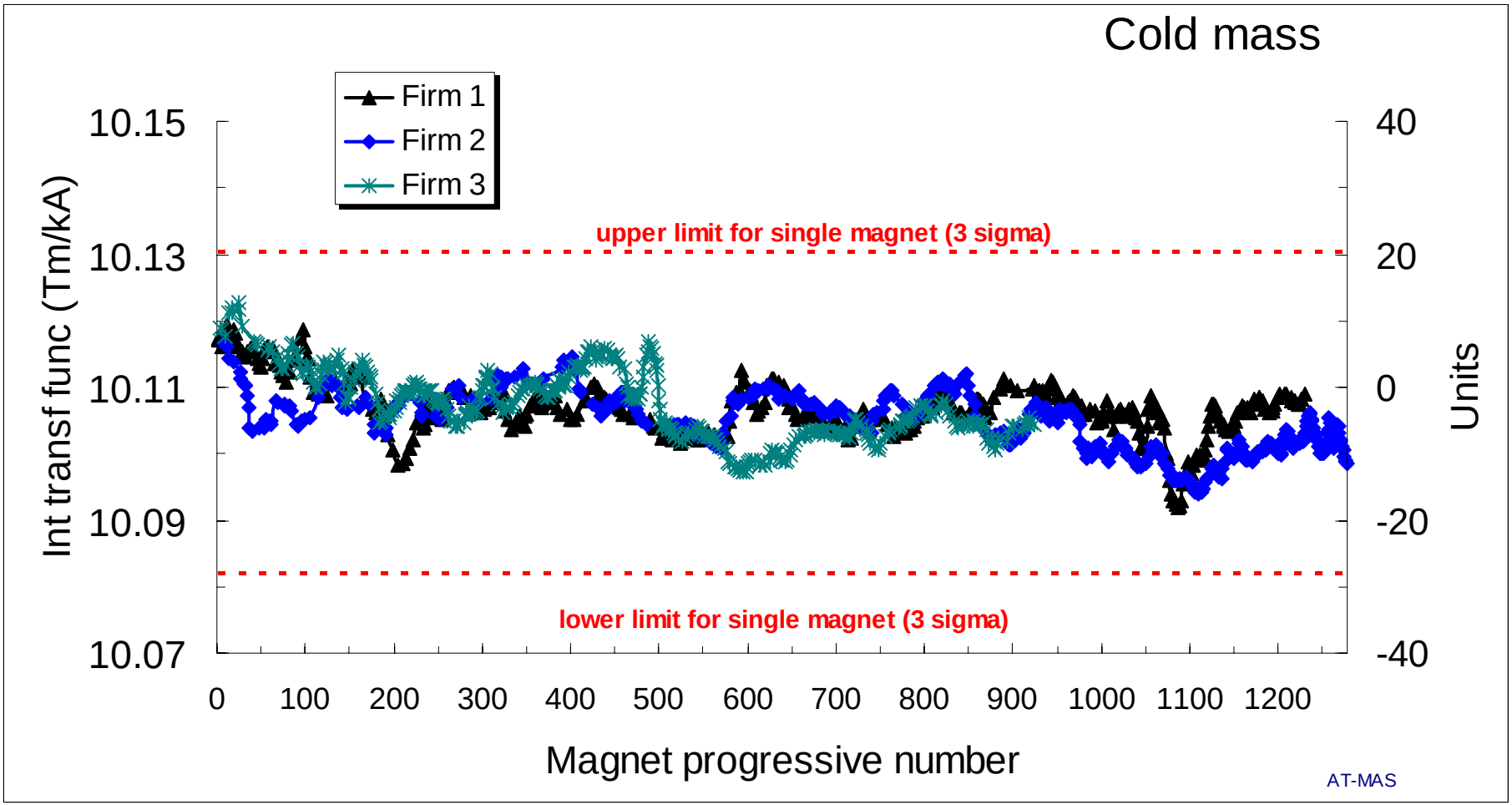


# Statistical production control & traceability



# Cold reception tests of 2000 superconducting magnets

# Homogeneity of magnet population



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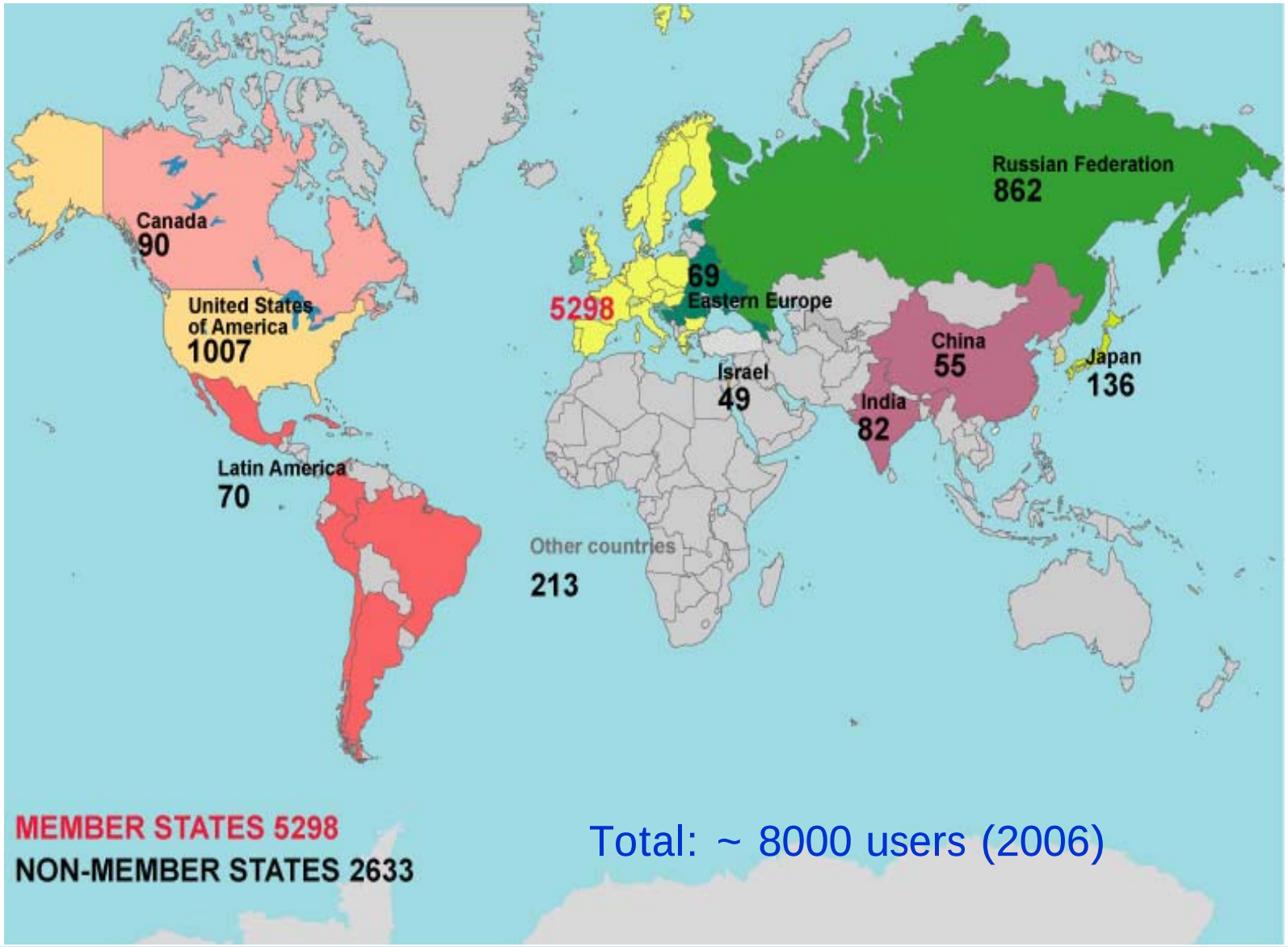
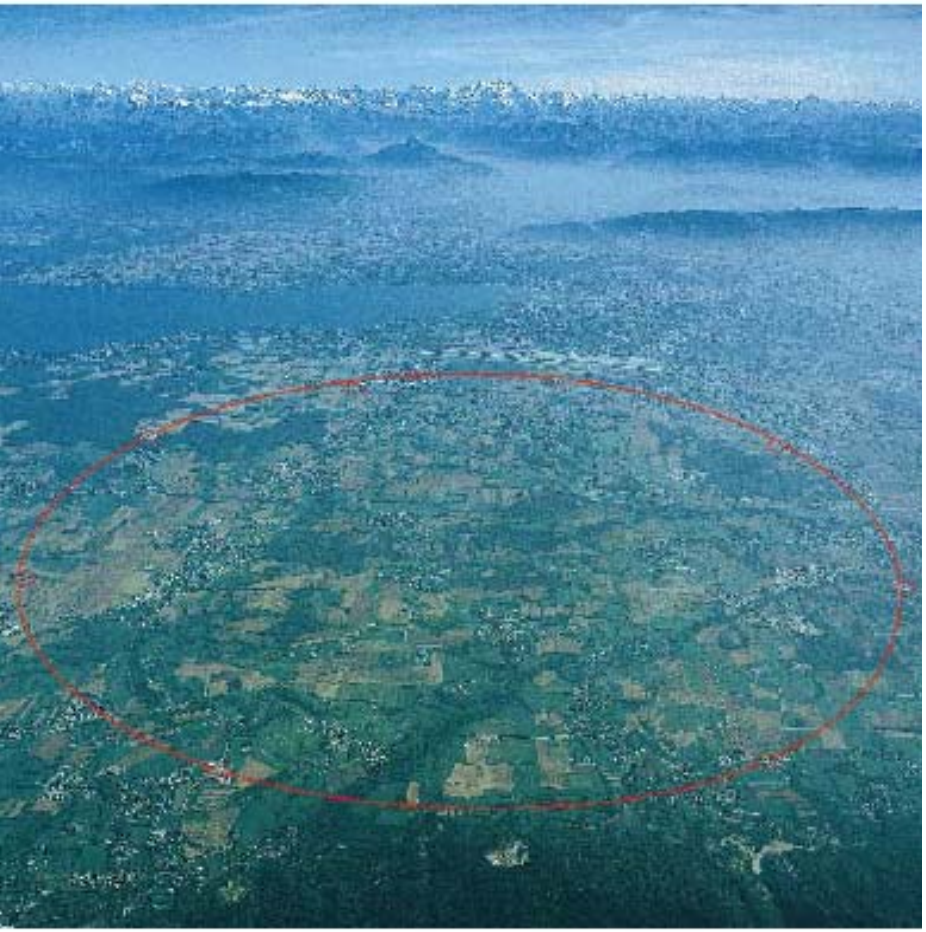
# CERN has 20 Member States in Europe...

# ...but serves the world's physics community



# LHC



## étude d'impact sur l'environnement

Le Conseil du CERN a décidé à l'unanimité, le 16 décembre 1994, de construire le grand collisionneur de hadrons (LHC), qui donne aux physiciens des particules européens et du monde un instrument exceptionnel pour la poursuite de leurs travaux.

Cet instrument sera réalisé sur le domaine que la Suisse et la France, Etats-hôtes de l'Organisation, ont mis à la disposition de celle-ci.

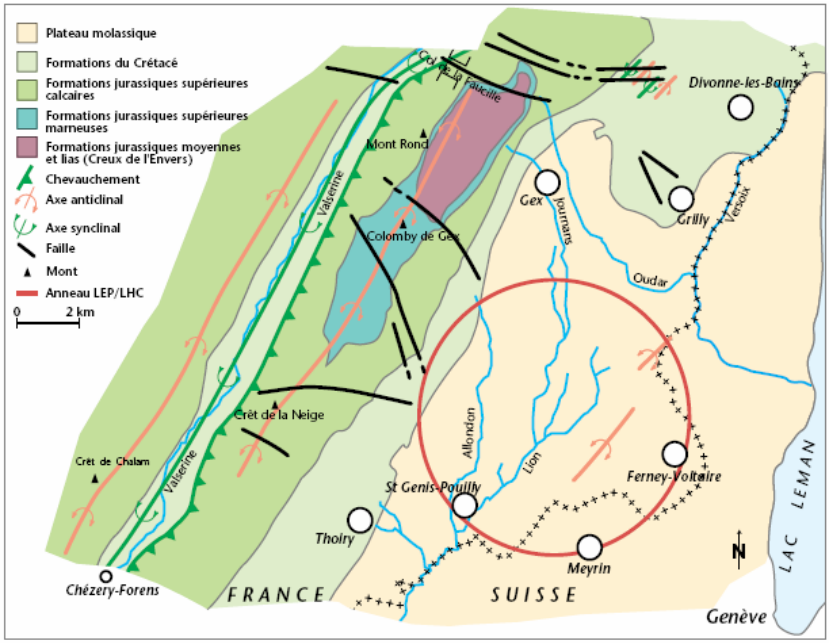
Comme il l'a fait pour ses grands accélérateurs antérieurs, en particulier le SPS et le LEP, le CERN réalisera le LHC en concertation avec les autorités nationales et les élus locaux.

**Hubert Curien**
Président du Conseil du CERN
lors de l'approbation du projet LHC
Ancien Ministre de la Recherche
du Gouvernement français

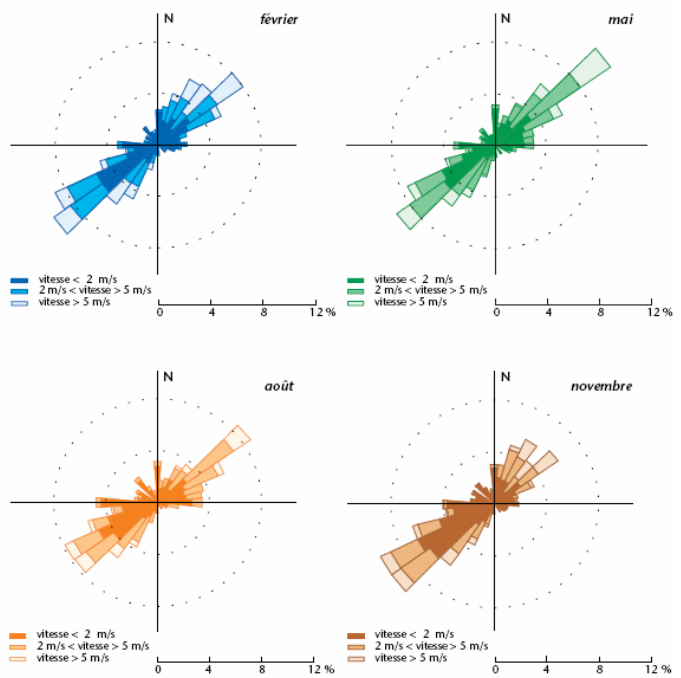
# Environment in its initial state

Grand tétras

Gentiane jaune sur le Jura

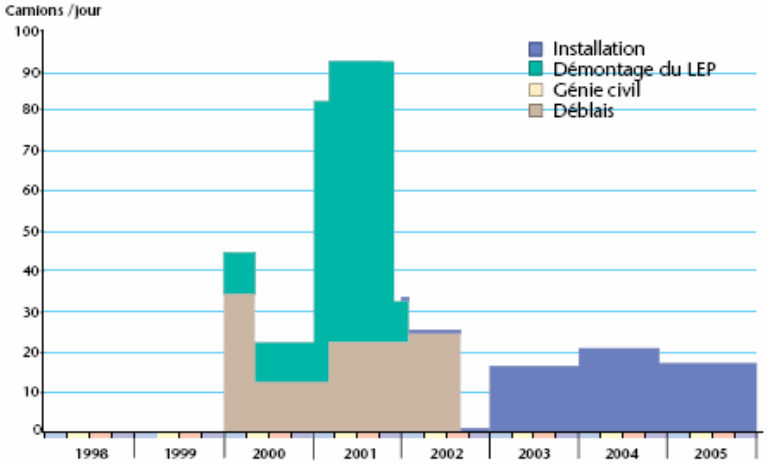



igure 6.6 Schéma structural et géologie simplifiée



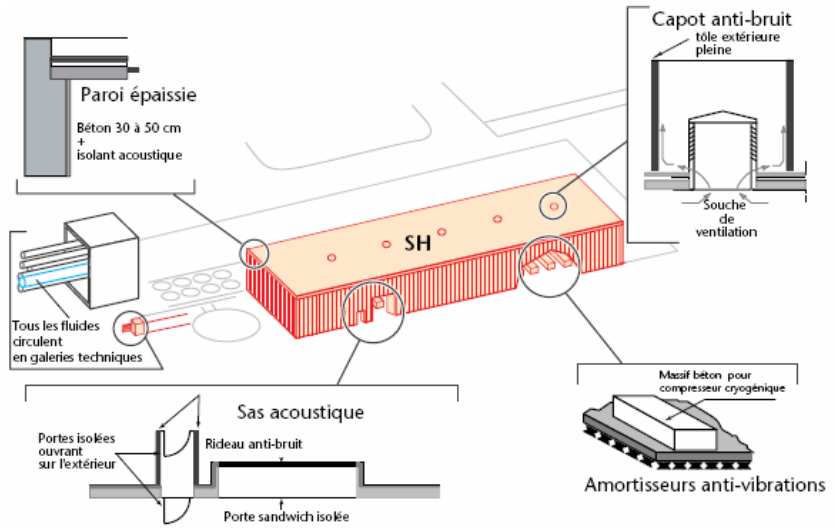

4 Vents enregistrés à Genève-Cointrin de 1982 à 1995

# Minimizing impacts




Trafic LHC sur la RD 984 entre le rond-point et la route VC 5 de Prévessin

Vue du Point 5 côté village : de la phase 1 ...




e 8.7 Isolation phonique des bâtiments de type SH

Vue du Point 5 côté village : ... à la phase 2

# Abiding by the laws & regulations of the host states

## Déclaration d'Utilité Publique

6 août 1998 JOURNAL OFFICIEL DE LA RÉPUBLIQUE FRANÇAISE 12039

**MINISTÈRE DES AFFAIRES ÉTRANGÈRES**

**Décret du 30 juillet 1998 déclarant d'utilité publique et urgente l'acquisition d'immeubles non bâtis sis sur le territoire des communes de Cessy, Crozet, Echenevex, Ferney-Voltaire, Ornex, Prévessin-Moëns, Sergy, Saint-Genis-Pouilly et Versonnex (Ain) en vue de la réalisation d'un grand collisionneur de hadrons, dit LHC, par l'Organisation européenne pour la recherche nucléaire (CERN) et emportant mise en compatibilité des plans d'occupation des sols des communes de Cessy, Echenevex, Ferney-Voltaire, Prévessin-Moëns et Versonnex (Ain)**

NOR : *MAEA9820244D*

Le Premier ministre,

Sur le rapport du ministre de l'éducation nationale, de la recherche et de la technologie et du ministre des affaires étrangères,

Vu le code de l'expropriation, et notamment ses articles L. 11-1 à L. 15-5, R. 11-14-1 à R. 11-14-15 et R. 15-1 à R. 15-8 ;

Vu le code de l'urbanisme, et notamment ses articles L. 123-8, R.* 123-35-3 et R. 123-36 ;

Décrète :

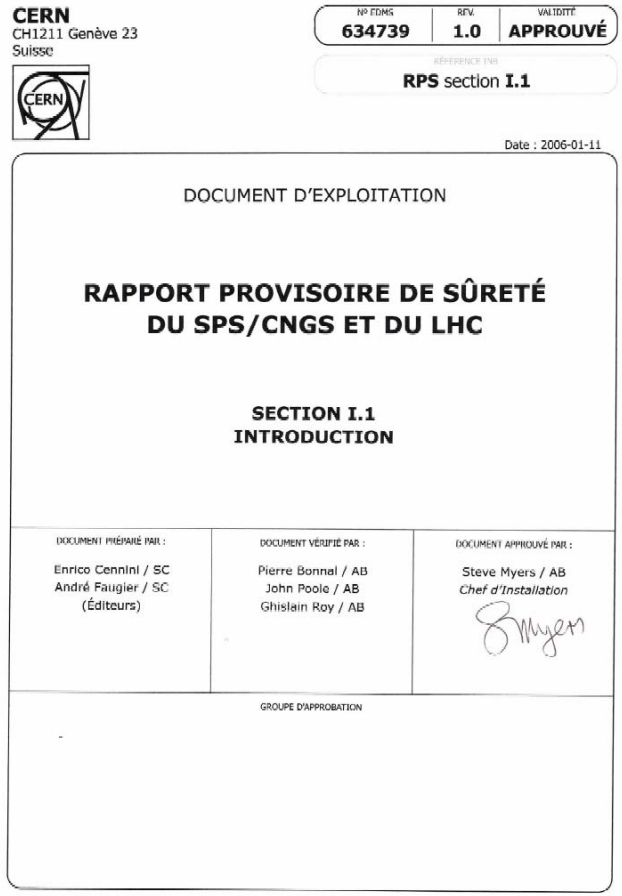
**Art. 1er.** – Est déclarée d'utilité publique et urgente en vue de la réalisation d'un grand collisionneur de hadrons, dit LHC, par l'Organisation européenne pour la recherche nucléaire (CERN) l'acquisition par l'Etat des immeubles non bâtis sis dans le département de l'Ain, arrondissement de Gex, sur le territoire des communes de Cessy, Crozet, Echenevex, Ferney-Voltaire, Ornex, Prévessin-Moëns, Sergy, Saint-Genis-Pouilly et Versonnex, d'une contenance totale de 18,4 hectares en surface et 5,3 hectares en tréfonds, tels qu'ils sont délimités sur le plan au 1/1 000 annexé au présent décret, tant en ce qui concerne l'emprise des ouvrages souterrains que l'emprise des ouvrages de surface.

**Art. 2.** – Les expropriations éventuellement nécessaires devront être réalisées dans un délai de cinq ans à compter de la publication du présent décret.

**Art. 3.** – Le maître d'ouvrage est tenu de remédier aux dommages causés aux exploitations agricoles en application des dispositions de l'article 10 de la loi du 8 août 1962 susvisée.

**Art. 4.** – Le présent décret emporte mise en compatibilité des plans d'occupation des sols des communes de Cessy, Prévessin-Moëns et Versonnex au 1/5 000 et Echenevex et Ferney-

## Installation Nucléaire de Base



CERN
CH1211 Genève 23
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|---|---|---|
| 634739 | 1.0 | APPROUVÉ |

RÉFÉRENCE INB
**RPS section I.1**

Date : 2006-01-11

DOCUMENT D'EXPLOITATION

**RAPPORT PROVISOIRE DE SÛRETÉ DU SPS/CNGS ET DU LHC**

**SECTION I.1**
**INTRODUCTION**

| DOCUMENT PRÉPARÉ PAR : | DOCUMENT VÉRIFIÉ PAR : | DOCUMENT APPROUVÉ PAR : |
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| Enrico Cennini / SC<br>André Faugier / SC<br>(Éditeurs) | Pierre Bonnal / AB<br>John Poole / AB<br>Ghislain Roy / AB | Steve Myers / AB<br>*Chef d'Installation* |

GROUPE D'APPROBATION

# Conclusion

It is a long way from a pioneering vision...

- Building competent teams
- Conducting focused R&D
- Setting up international collaboration
- Establishing a solid industrial basis
- Enforcing strict configuration control and QA
- Sustaining production effort
- Recovering from technical, organizational and financial difficulties

... to a large instrument breaking new ground and serving the world's physics community

« There is no favourable wind for he who does not know his destination »

Seneca, *Letters to Lucilius*