



# Scientific and technical challenges of the LHC

*Philippe Lebrun*

CERN, Geneva (Switzerland)



# Contents

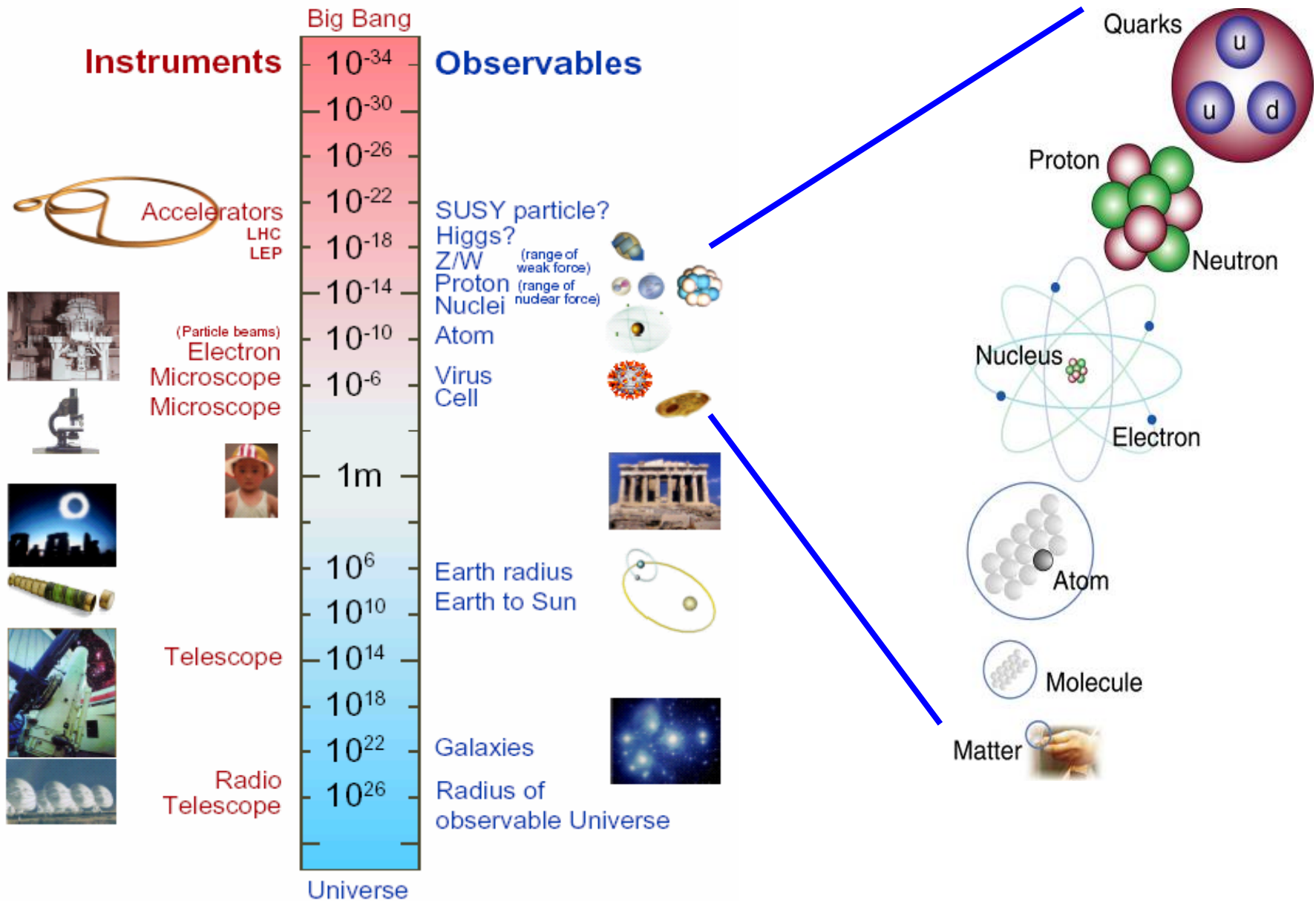
- Particle physics beyond the standard model
- Challenging accelerator physics
- Economy through technology
- Quality and quantity in time from industry
- A global project in a local environment
- Conclusion



# Contents

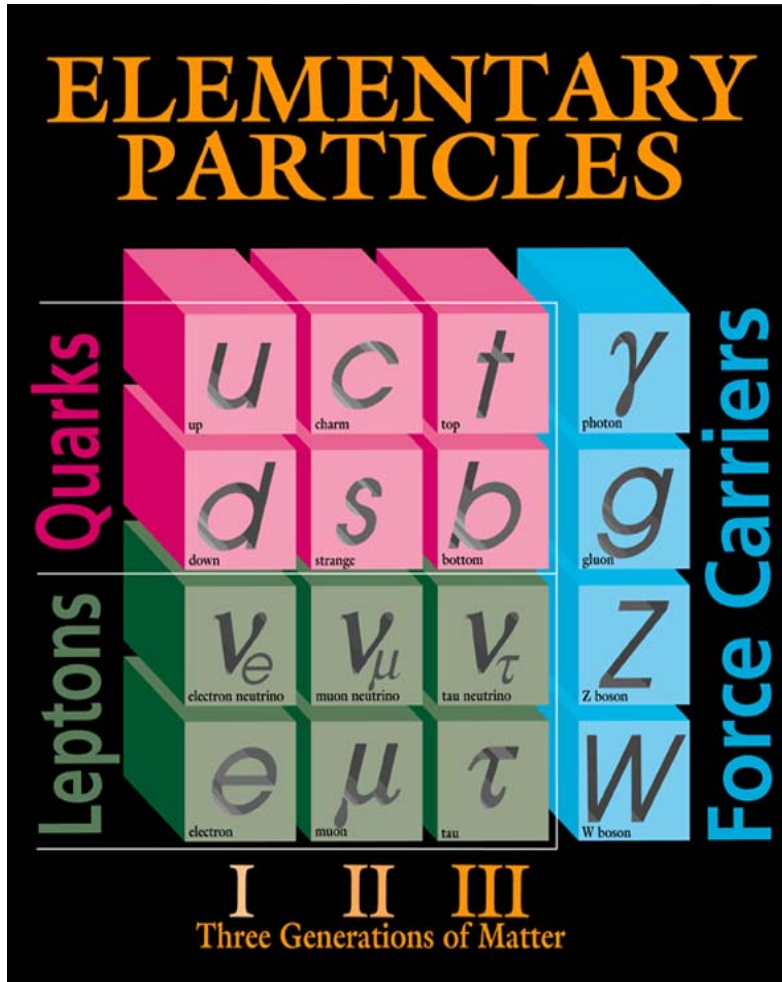
- **Particle physics beyond the standard model**
  - Challenging accelerator physics
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# The size of things





# The Standard Model

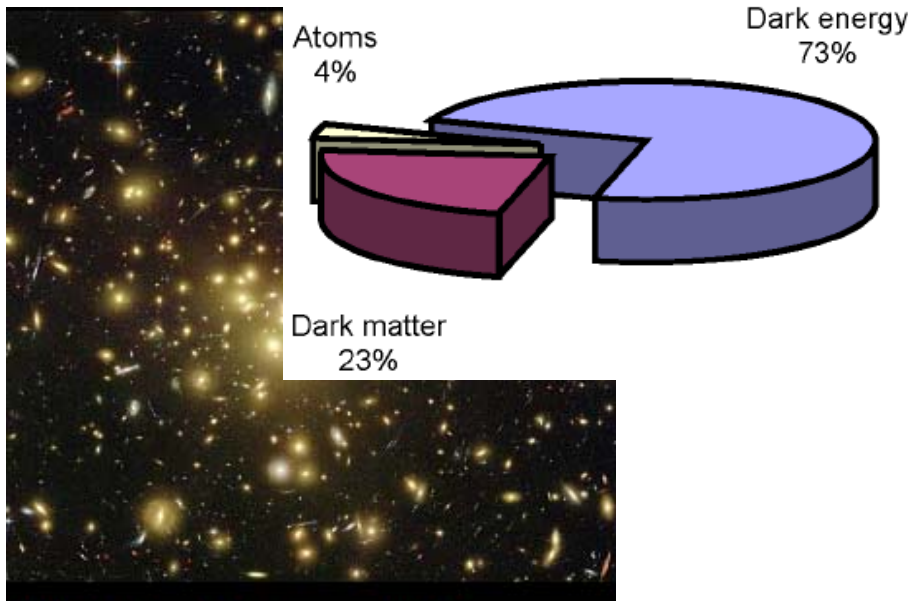
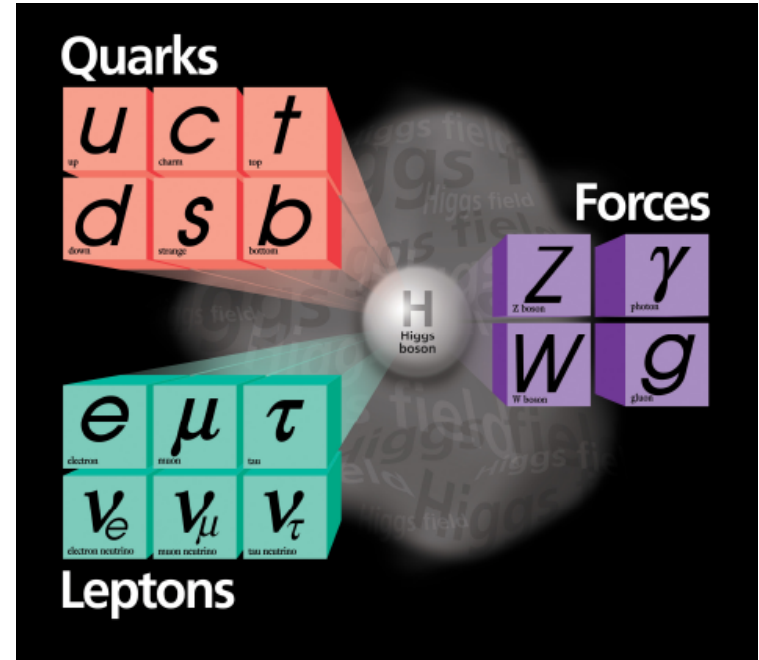


- Matter is composed of fermions (6 quarks and 6 leptons)
- All fermions have their antiparticles
- Three families of fermions of increasing masses, « normal » matter is made of the first family
- Interactions (strong nuclear, electromagnetic, weak) are carried by exchange of bosons (gluons, photons,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



# Limits of the Standard Model

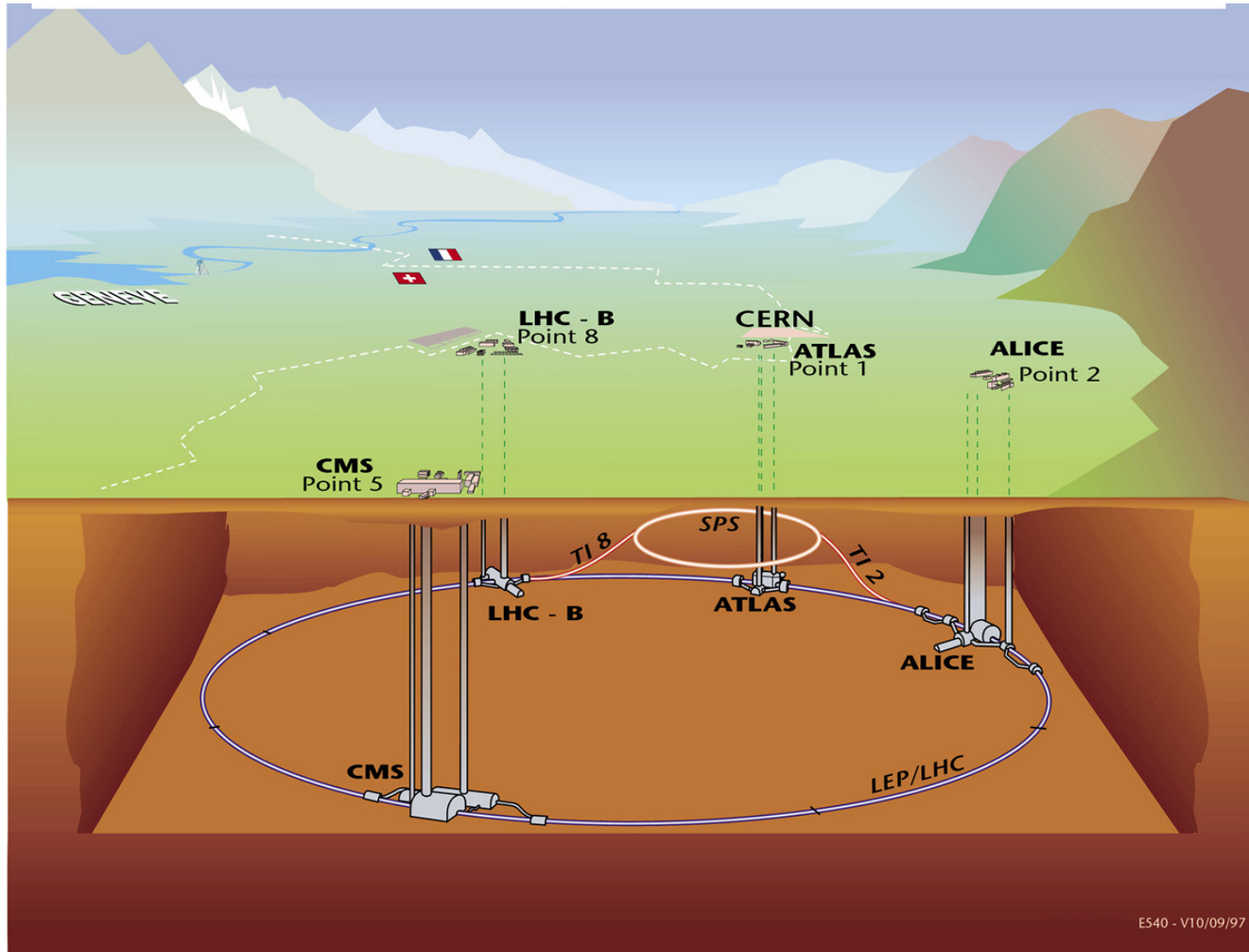
- Origin & hierarchy of particle masses: coupling with Higgs field (boson)?
- Fermion/boson supersymmetry?
- Gravity is not included!
- Unification of forces?



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




# Overall layout of the LHC and its detectors

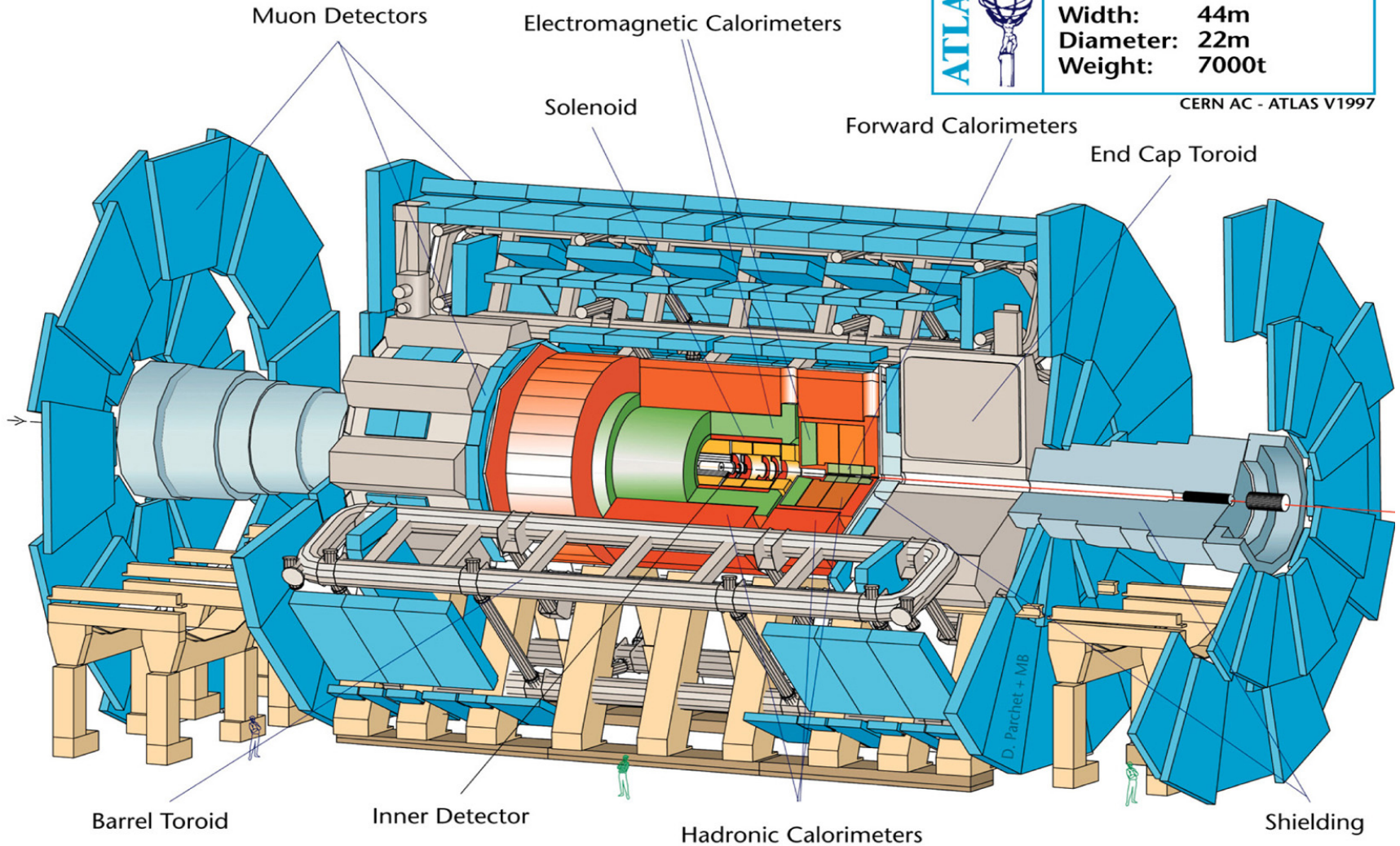




# The ATLAS detector

<b>ATLAS</b> 	<b>Detector characteristics</b>	
	<b>Width:</b>	<b>44m</b>
	<b>Diameter:</b>	<b>22m</b>
	<b>Weight:</b>	<b>7000t</b>

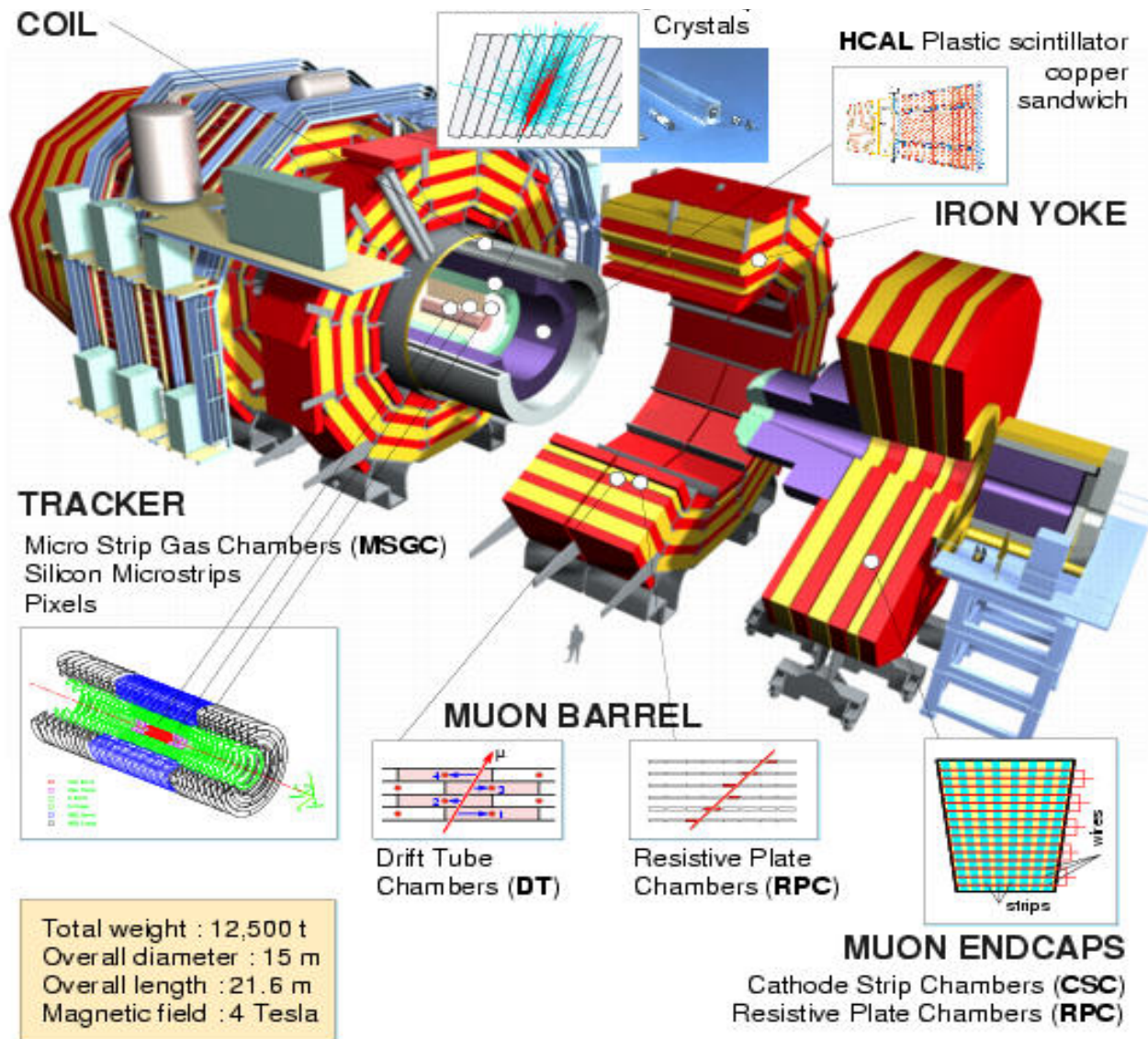
CERN AC - ATLAS V1997







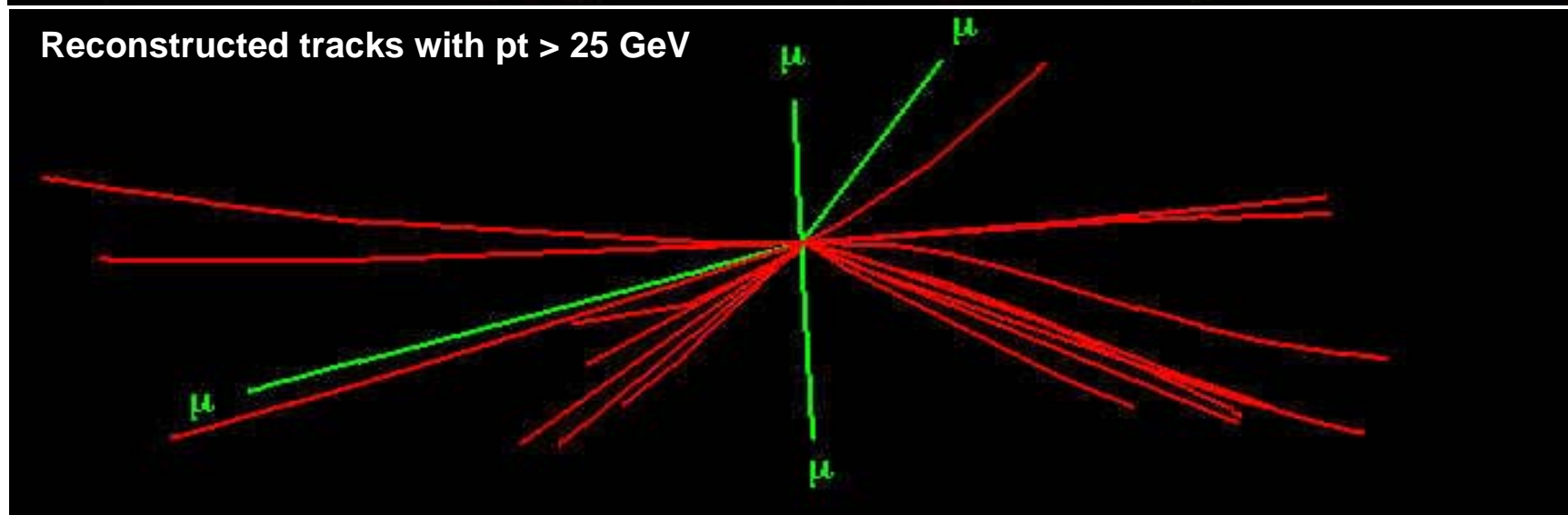
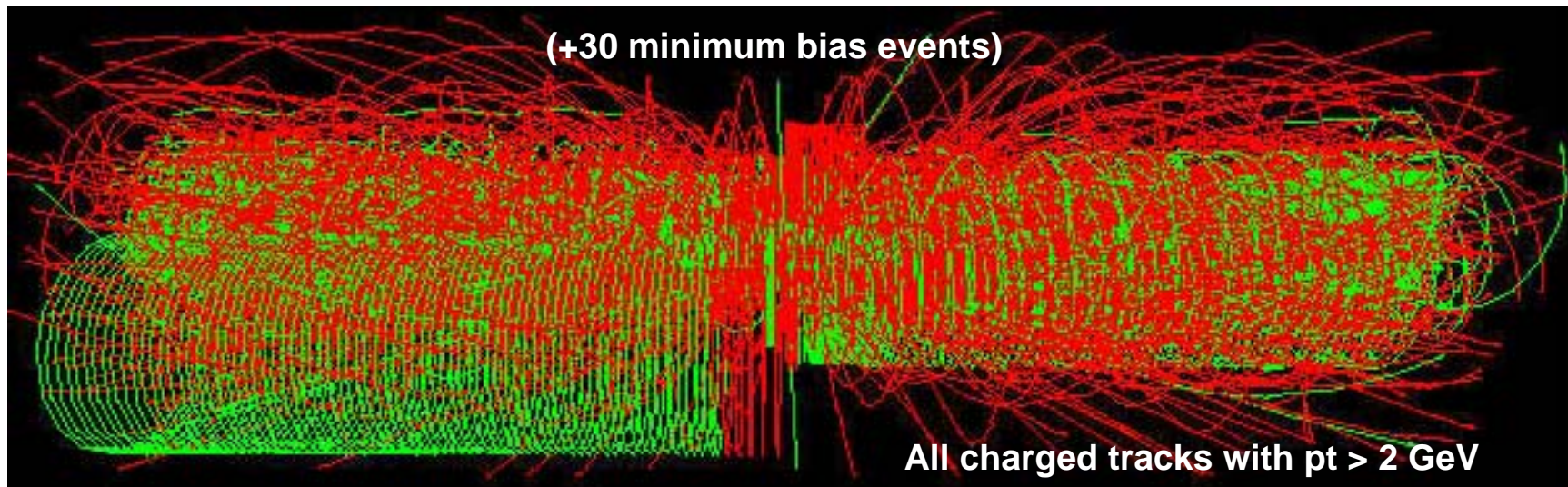
# The CMS detector





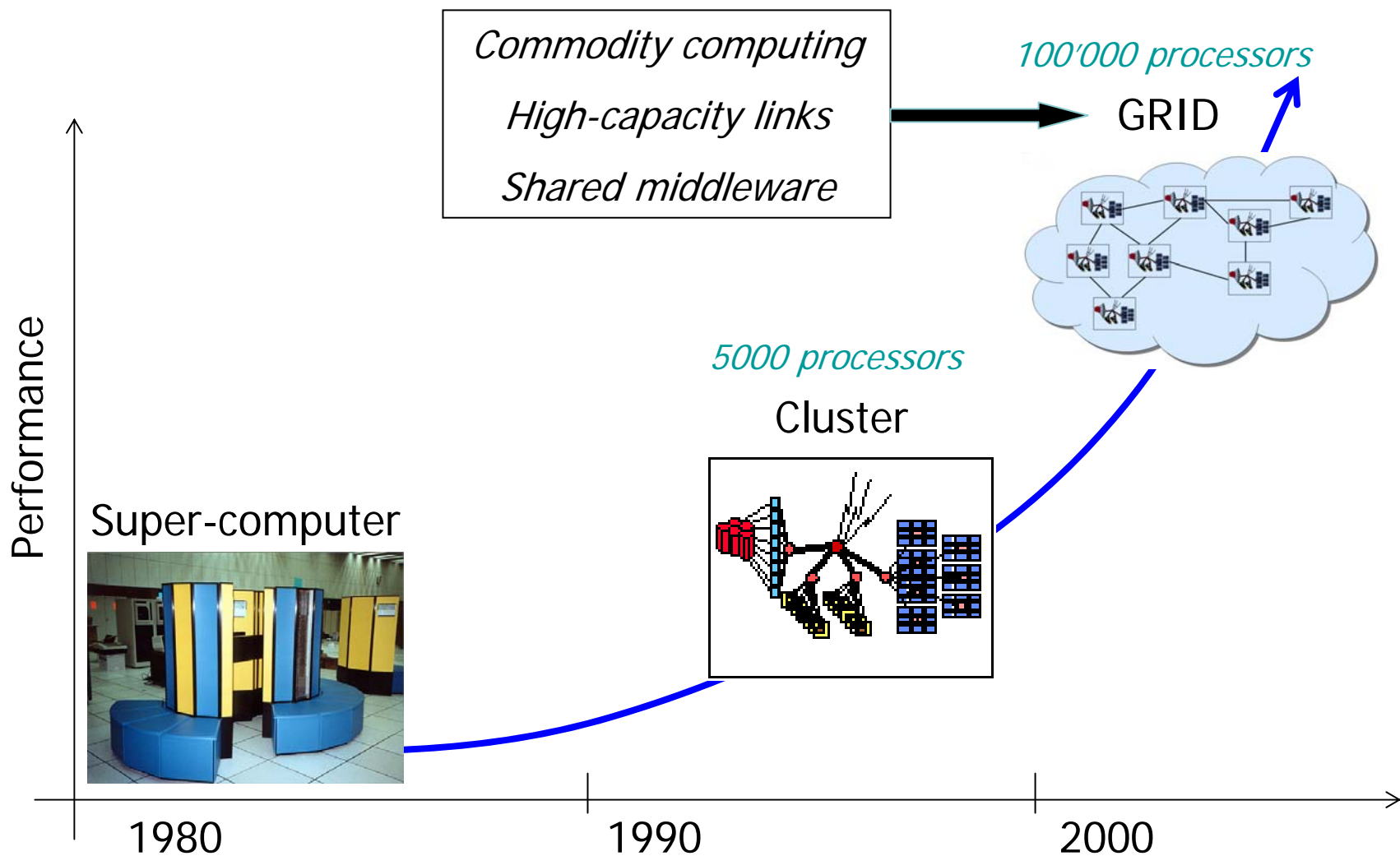
# Searching for the Higgs boson

One needle in 20 million haystacks!





# Towards a world computing « grid »



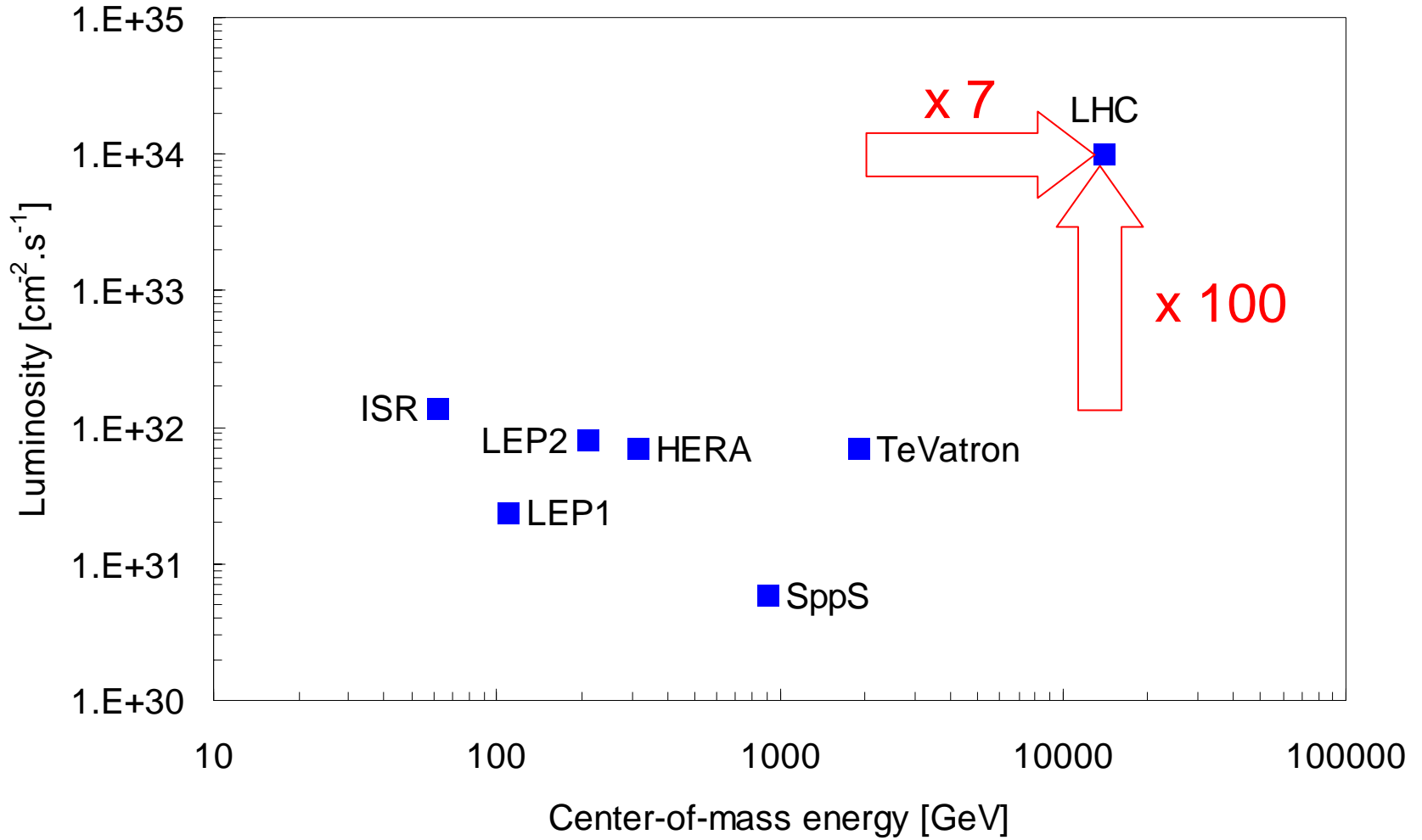


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# Luminosity vs. energy of colliders





# Challenging accelerator physics

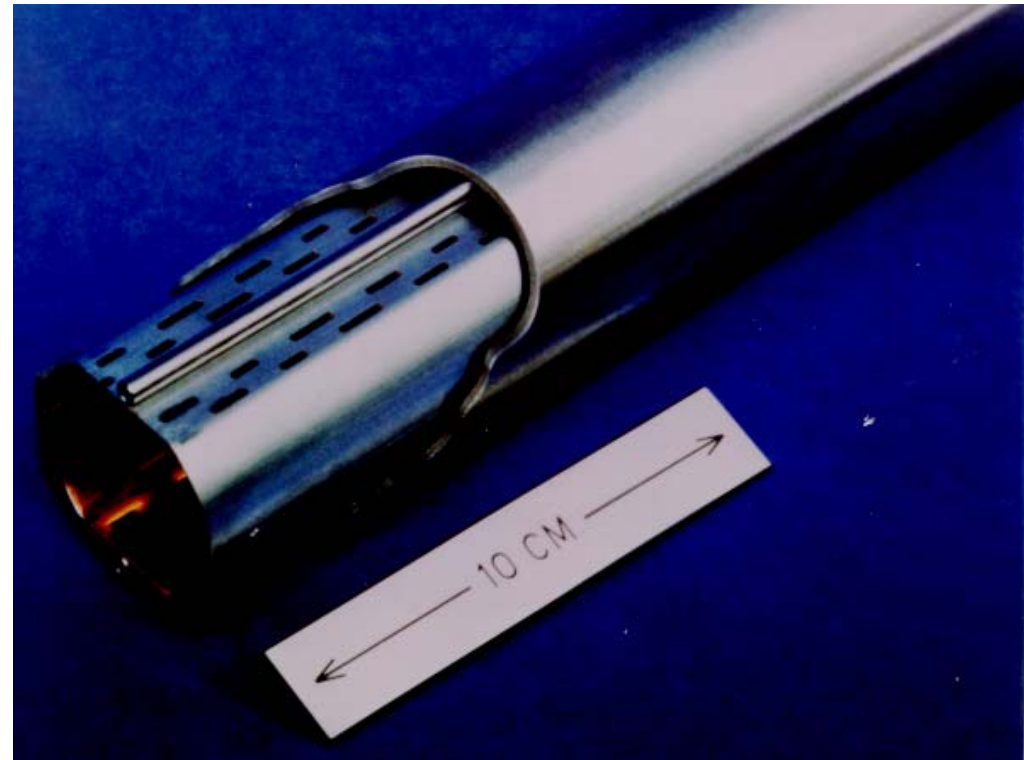
- High luminosity
  - High-intensity beams (2 x 0.584 A)
  - High-brilliance injectors (transverse emittance 3.75  $\mu\text{m}\cdot\text{rad}$ )
  - Large stored energy (2 x 362 MJ)
  - Small tolerance of s-c magnets to beam losses ( $\sim 10 \text{ mJ}/\text{cm}^3$ )
- Beam-beam effect
  - 2808 bunches 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  $\Rightarrow$  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)

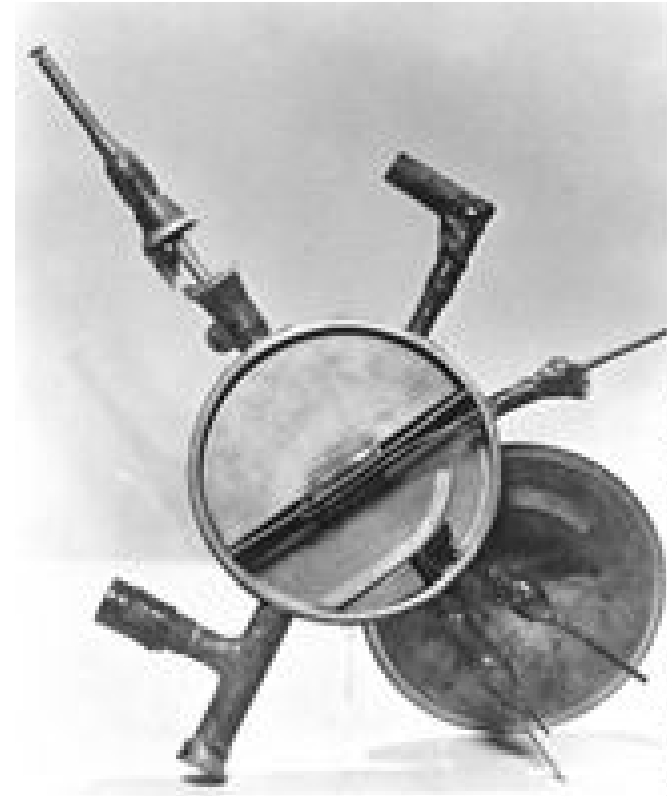
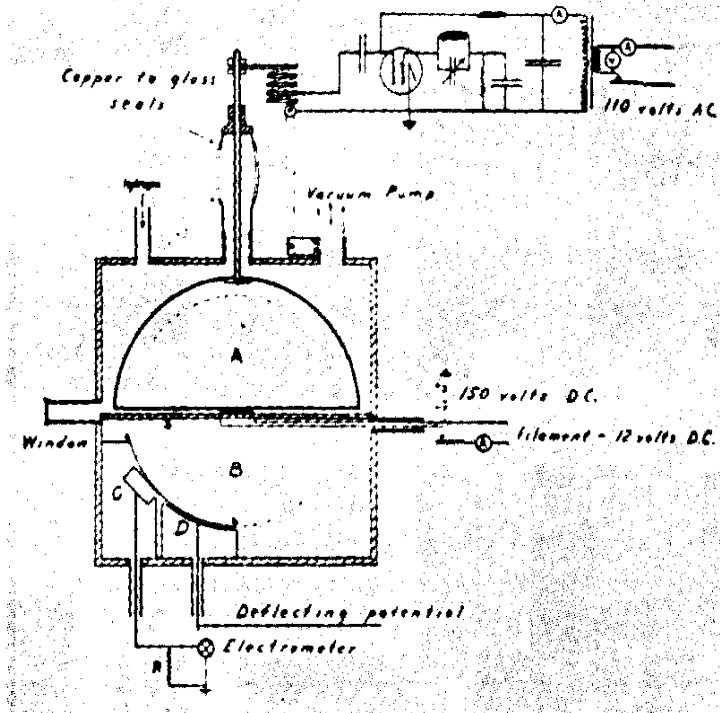
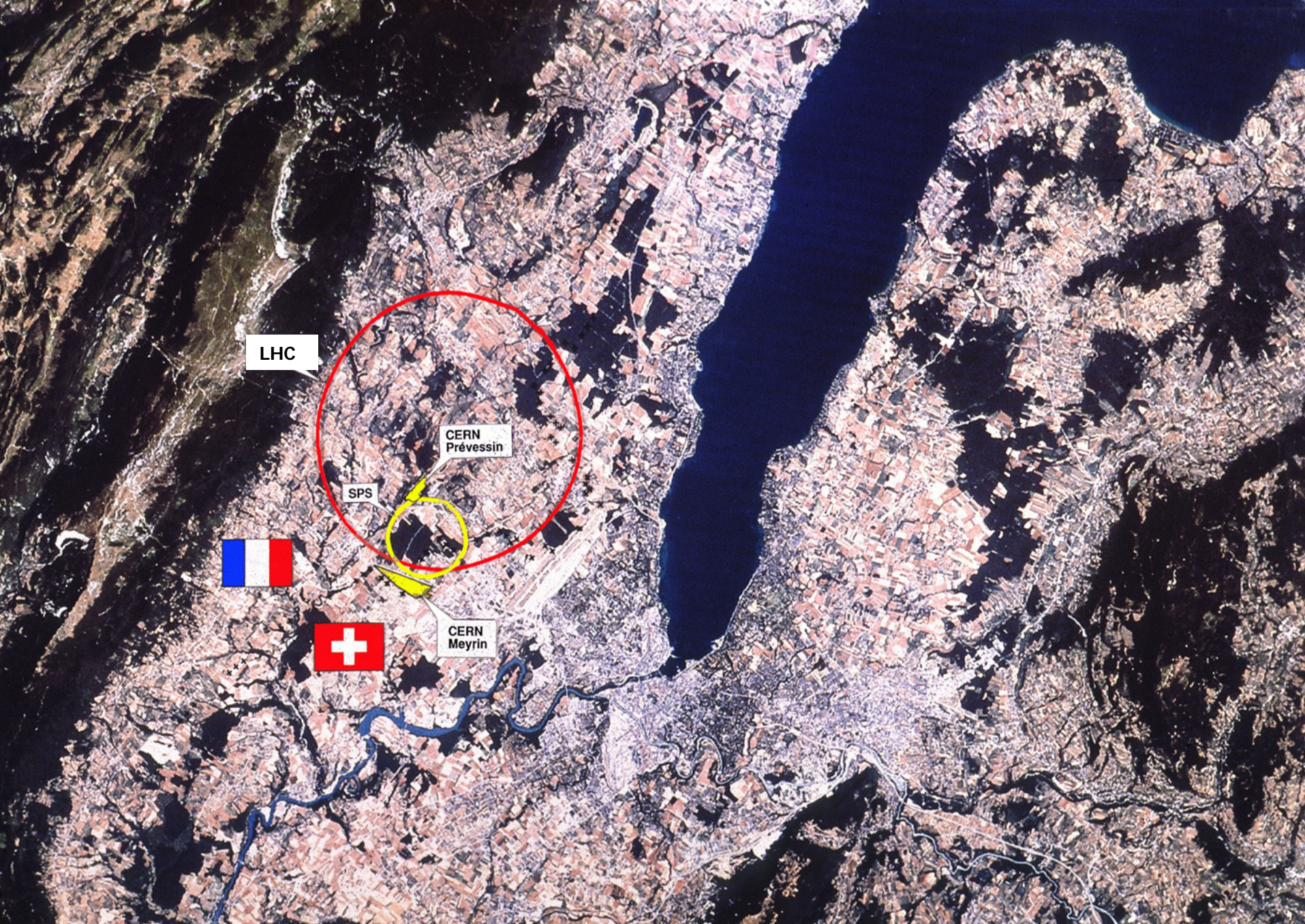


Diagram of the first successful cyclotron constructed by Lawrence and M. S. Livingston. The single dee is five inches in diameter.



LHC

CERN Prévessin

SPS

CERN Meyrin

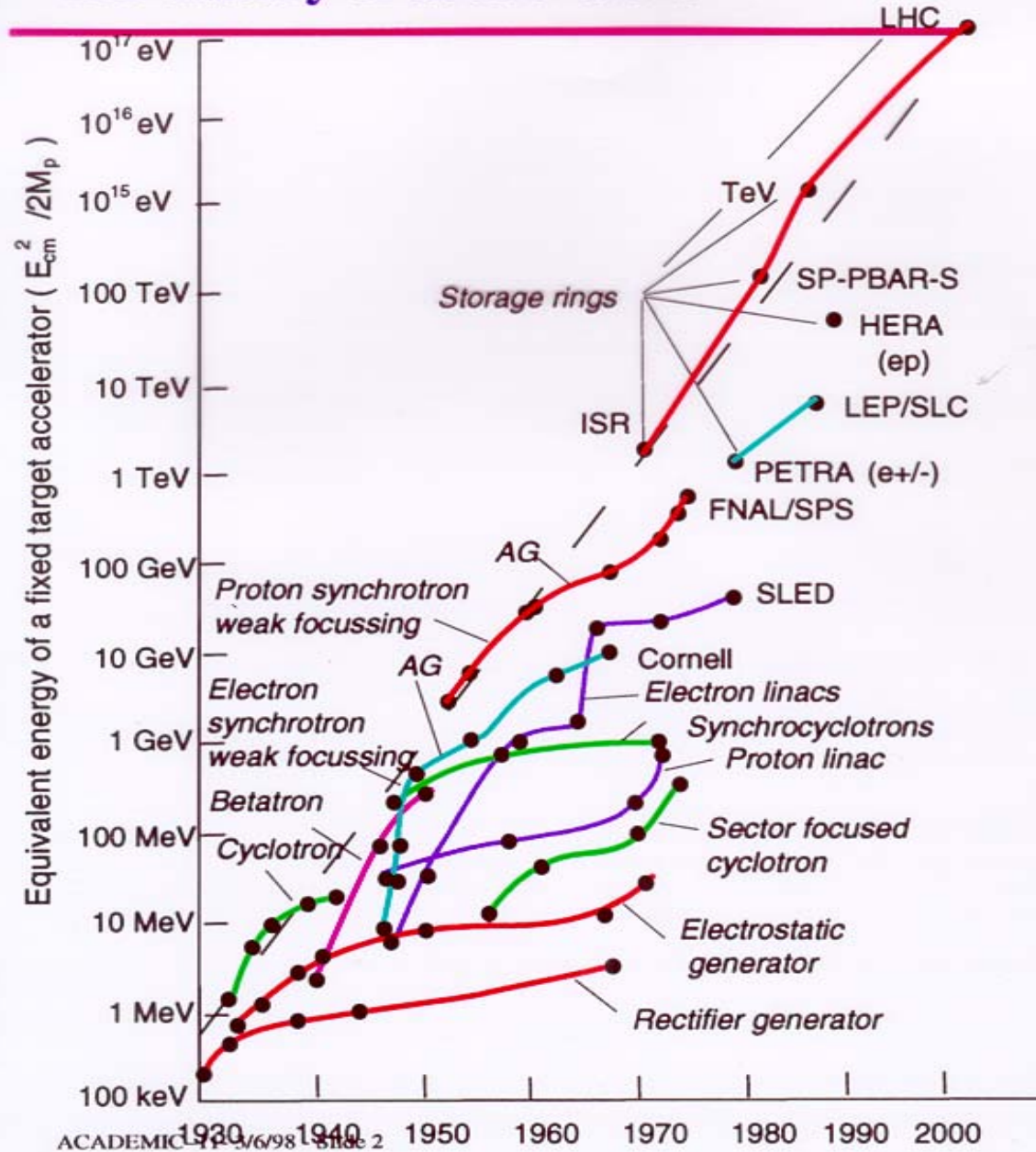




# The history of accelerators

## Livingston's diagram

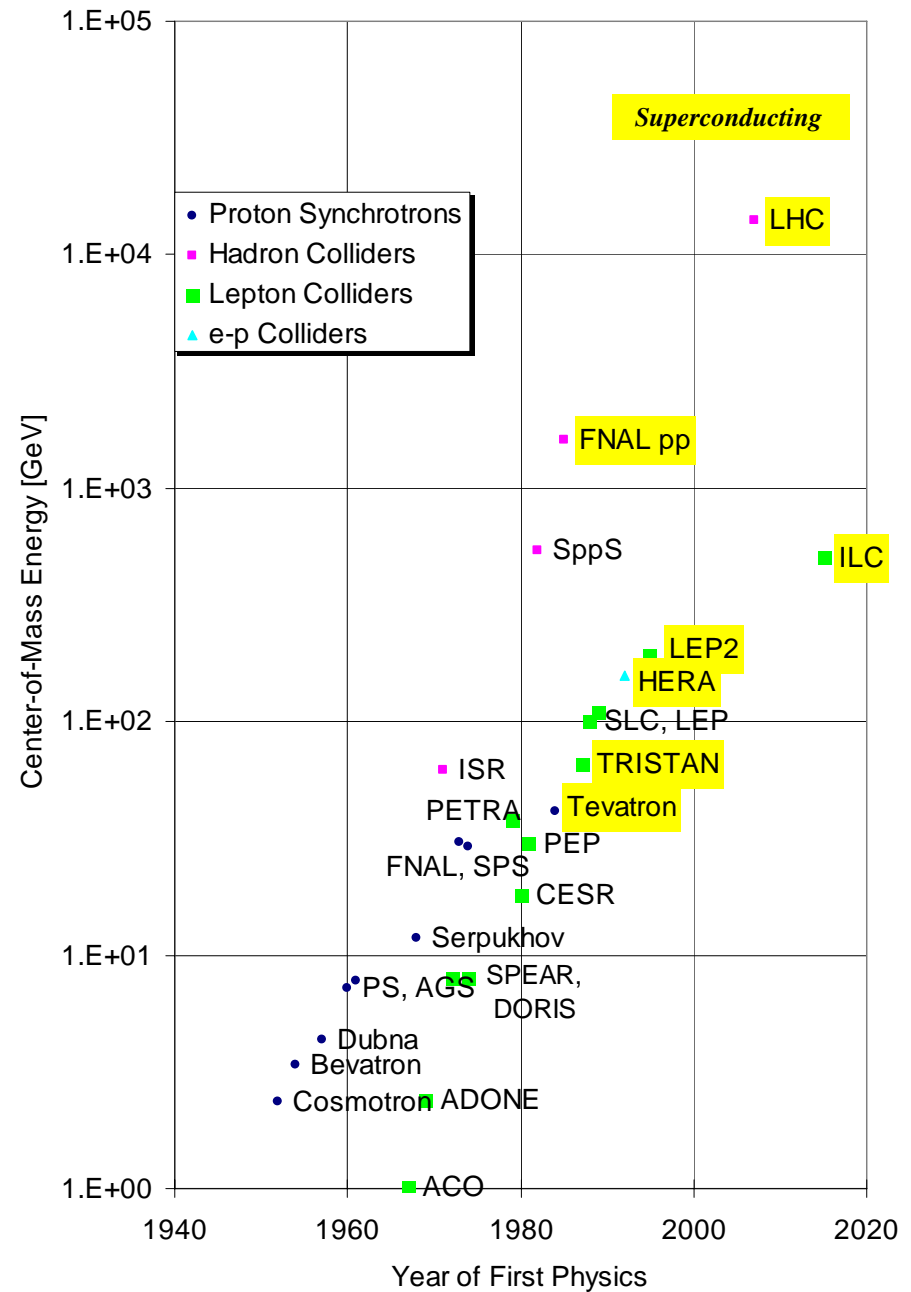
- sustained exponential development over 70 years
- progress achieved through repeated jumps from saturating to emerging technologies



ACADEMIC 11/3/98 Slide 2

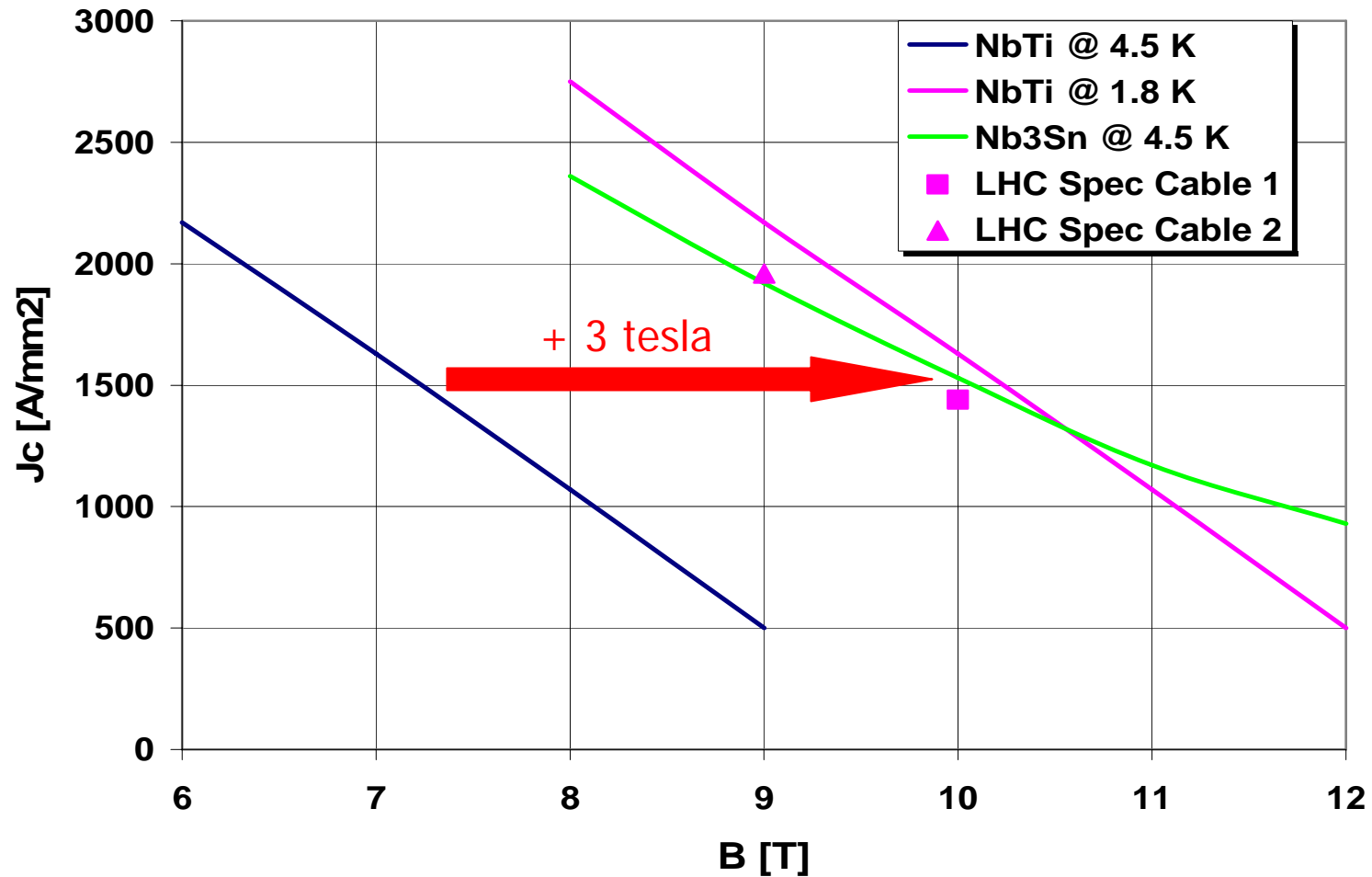


All frontier machines built or projected since the 1980s are based on the use of superconductivity



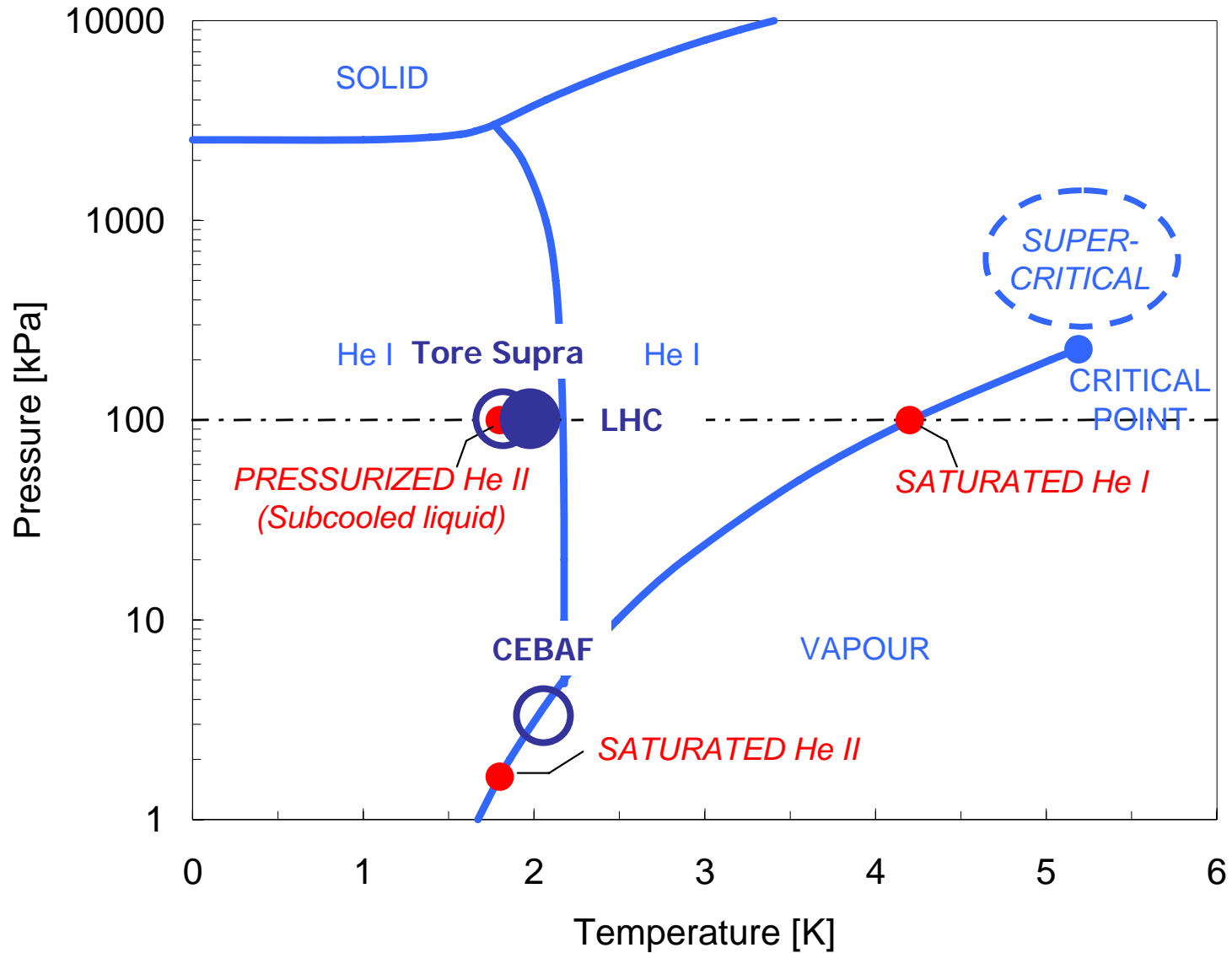


# Doping Nb-Ti performance at 1.9 K





# Superfluid helium cooling



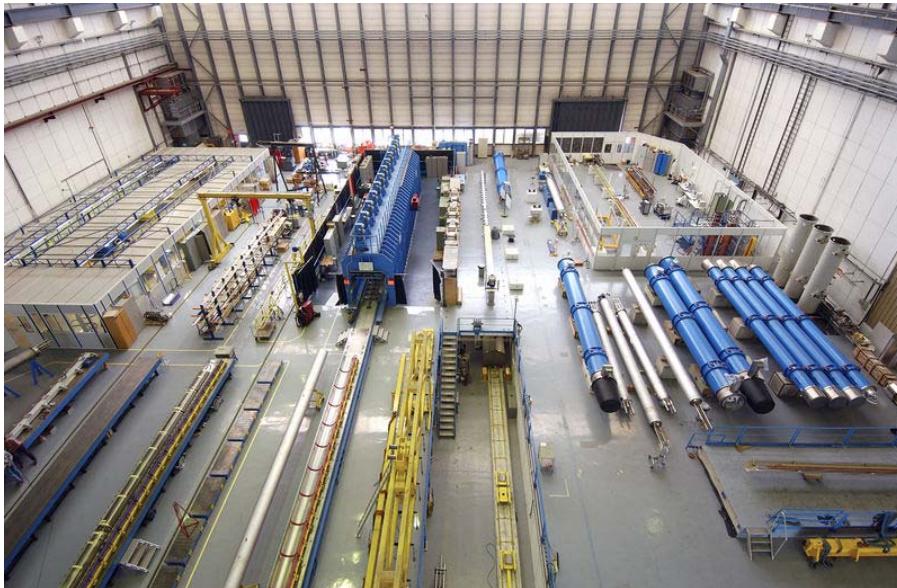


# High-field superconducting magnets

1232 twin-aperture dipoles (8.3 T)

474 twin-aperture quadrupoles

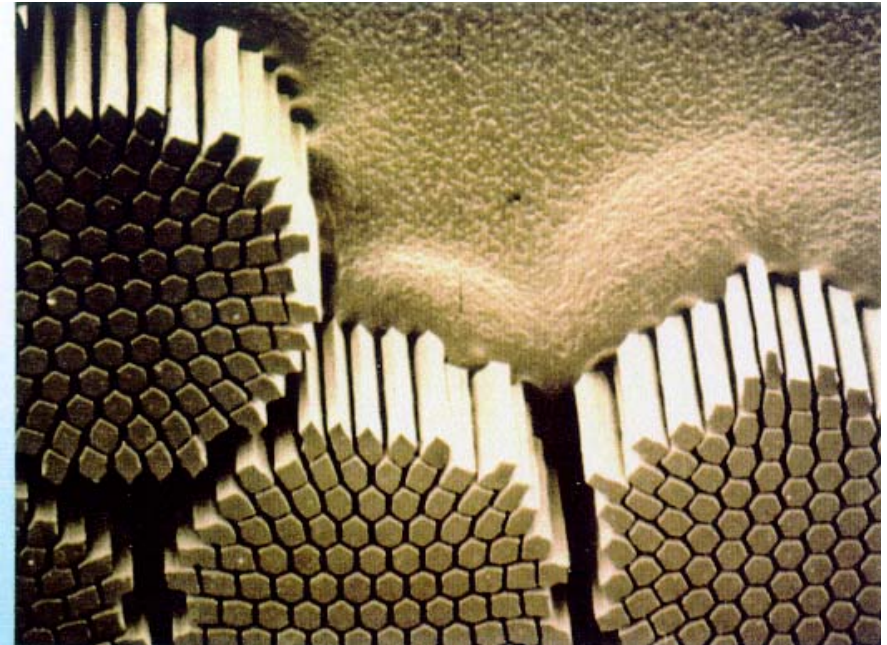
7612 corrector magnets integrated  
in main magnet cryostats





# 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 $\mu\text{m}$	6 $\mu\text{m}$
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 $^\circ$	0.90 $^\circ$
Transposition length	115 mm	100 mm
Ratio Cu/Sc	$\geq 1.6$	$\geq 1.9$







# Magnet powering with high-T superconductors

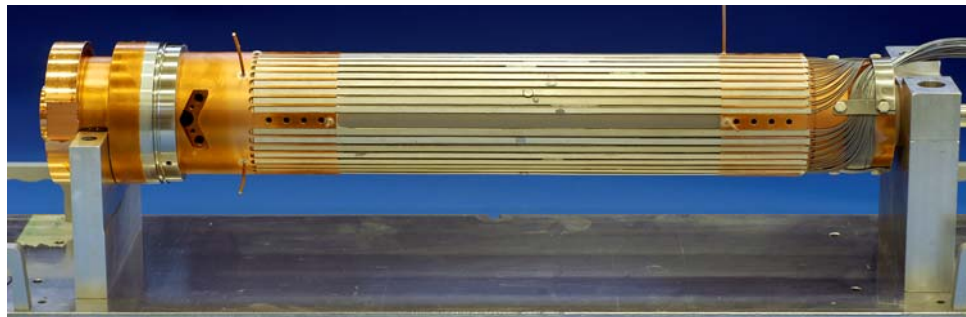
1720 electrical circuits, total current 1.7 MA

3286 current leads using Bi-2223 multi-filamentary tape



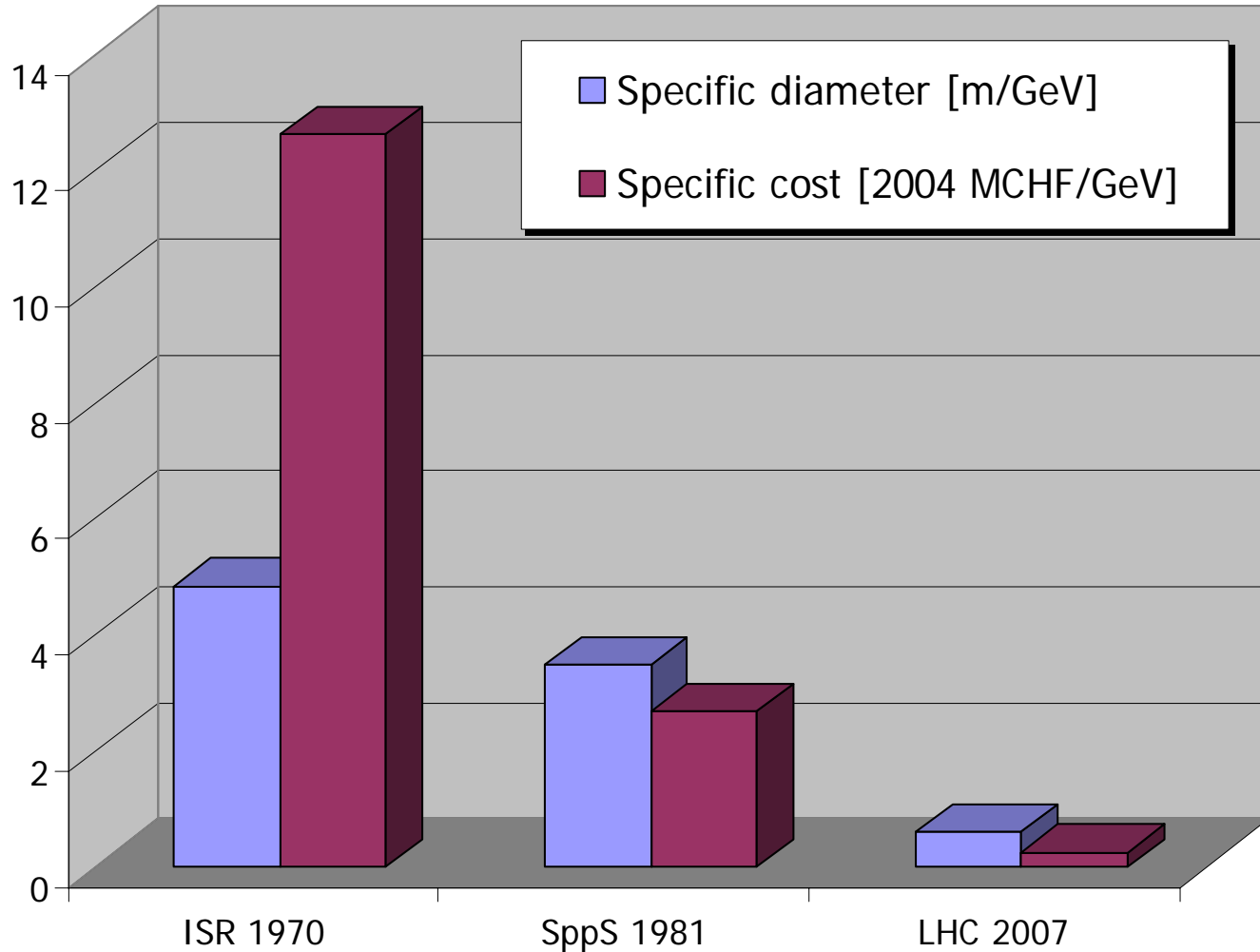
Number	Current rating (A)
64	13000
298	6000
820	600
2104	60-120

} HTS



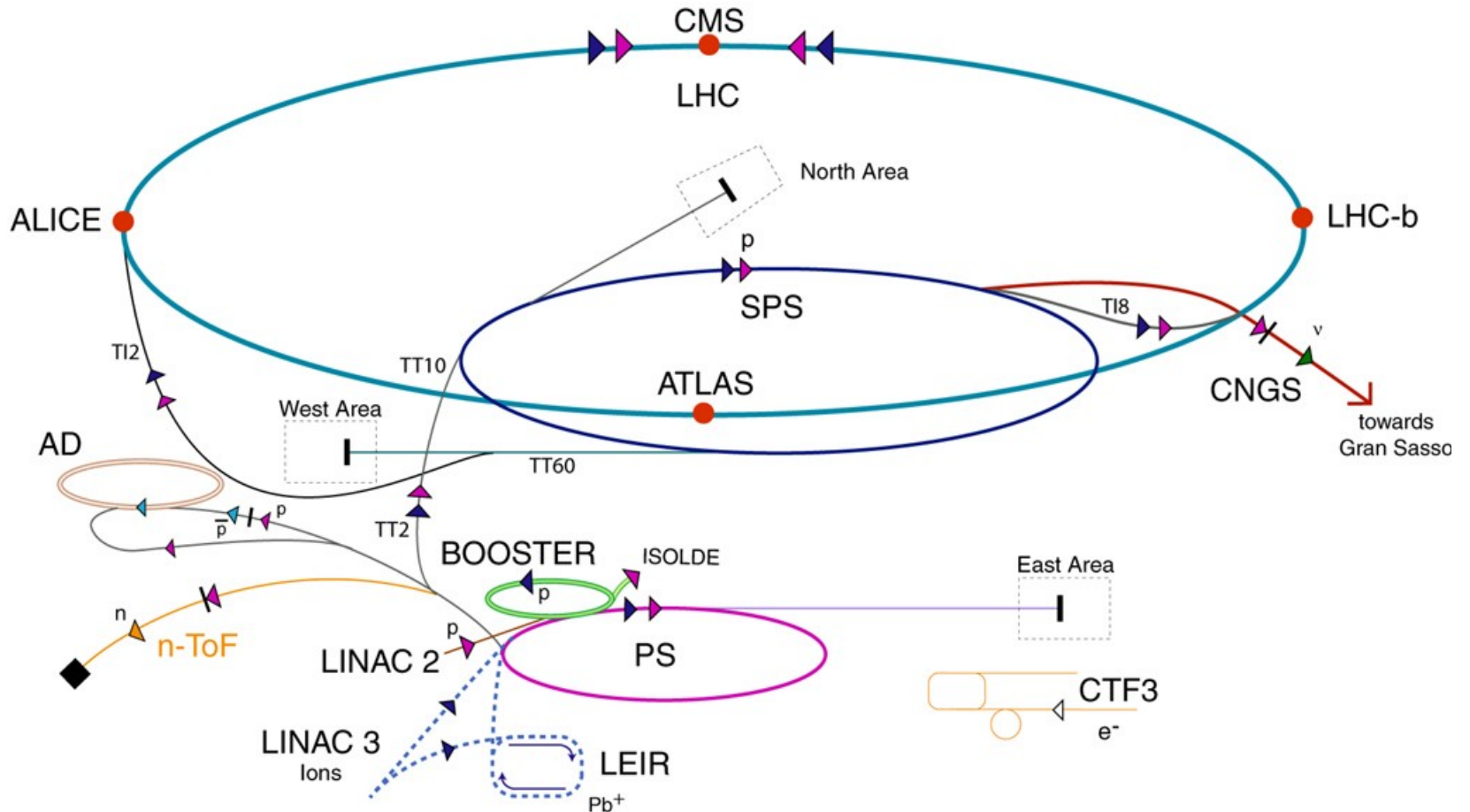


# Size & cost of CERN hadron colliders





# Reusing the CERN accelerator network



- ▶ protons
- ▶ ions
- ▶ neutrons

- ▶ antiprotons
- ▶ electrons
- ▶ neutrinos

- AD Antiproton Decelerator
- PS Proton Synchrotron
- SPS Super Proton Synchrotron

- LHC Large Hadron Collider
- n-ToF Neutron Time of Flight
- CNGS CERN Neutrinos Gran Sasso

CTF3 CLIC Test Facility 3



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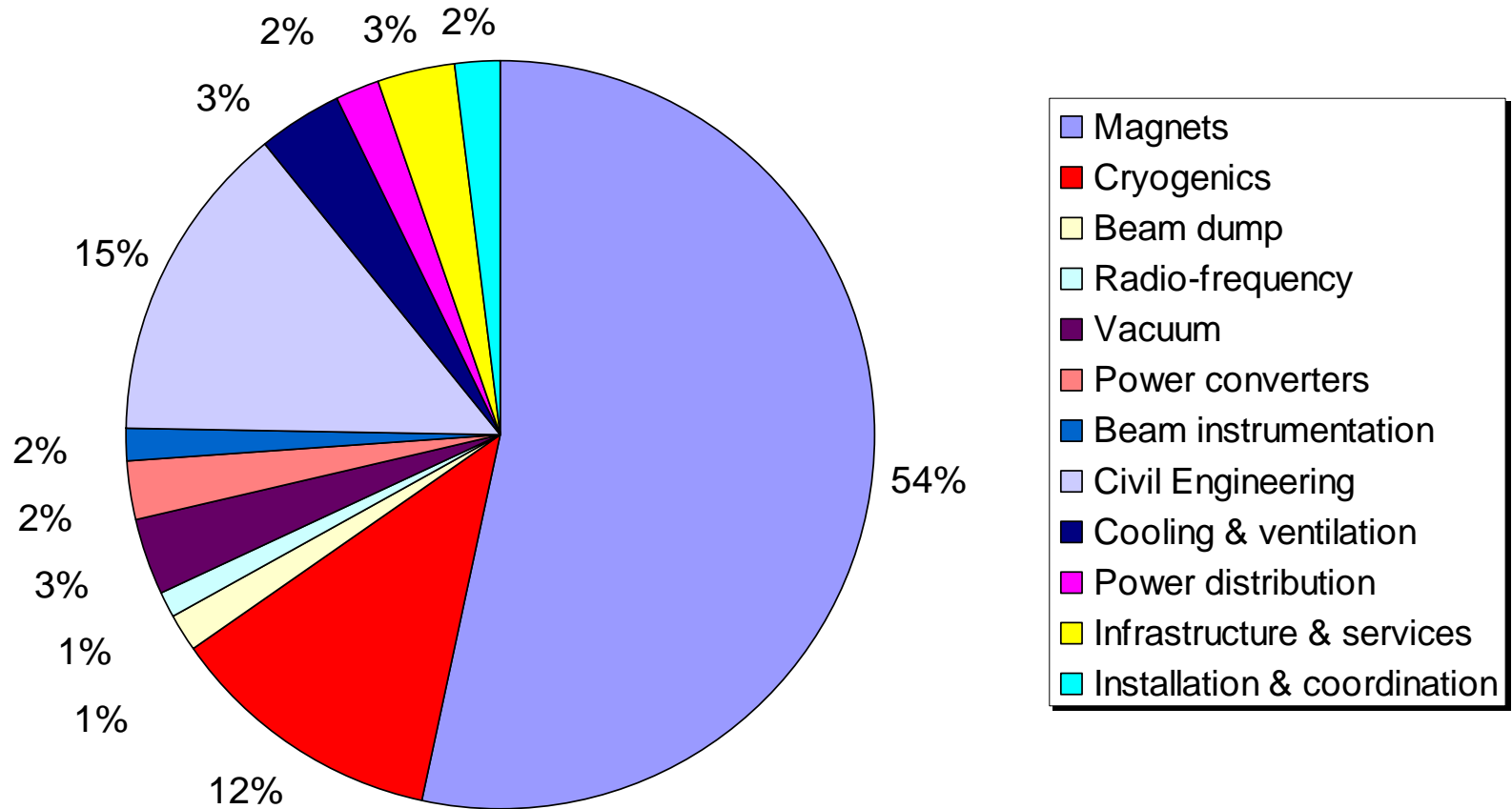


# Historical milestones of the LHC

- 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?



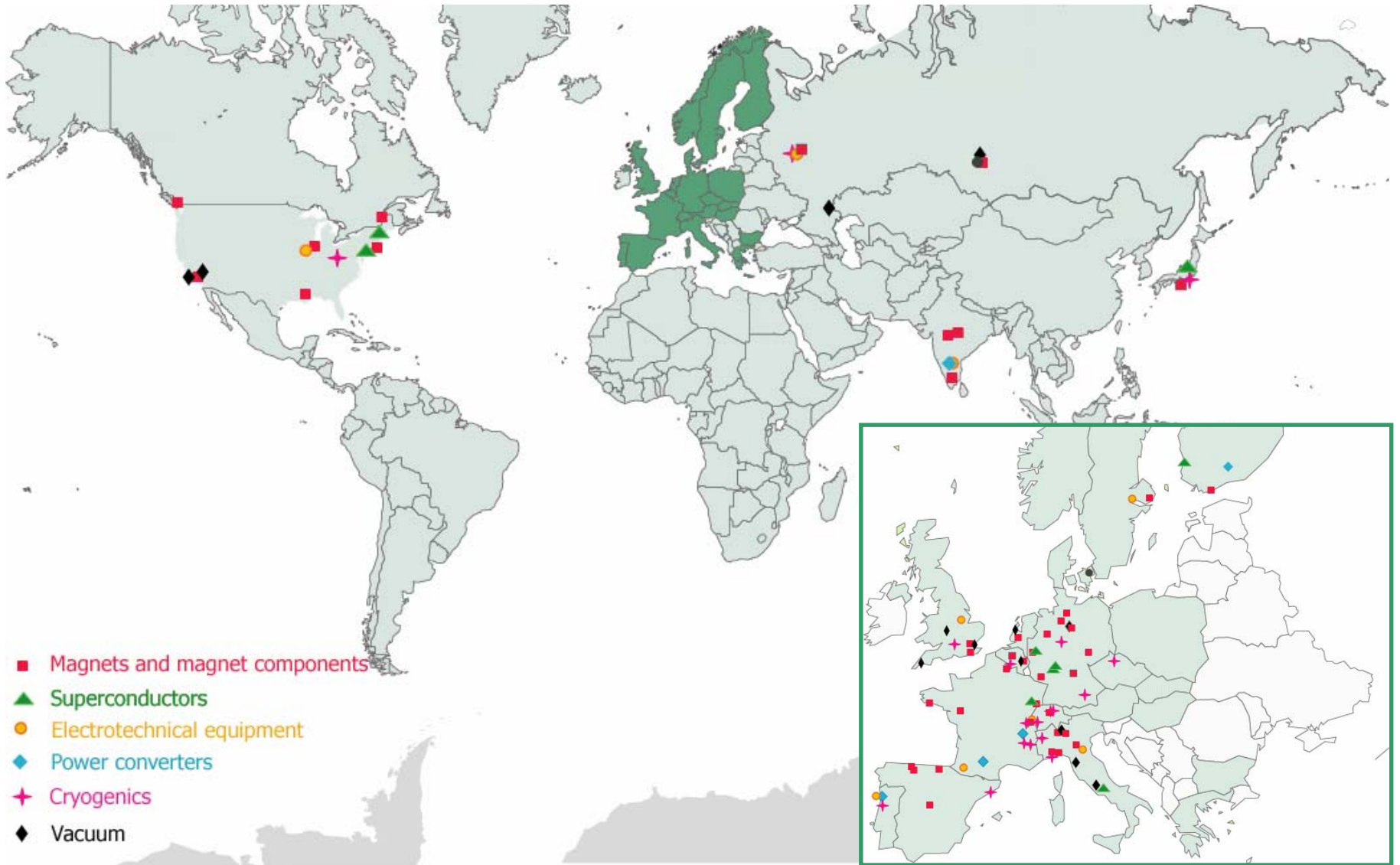
# Cost structure of the LHC accelerator



Total ~ 2.2 BEuro



# 90 main industrial contracts in the world





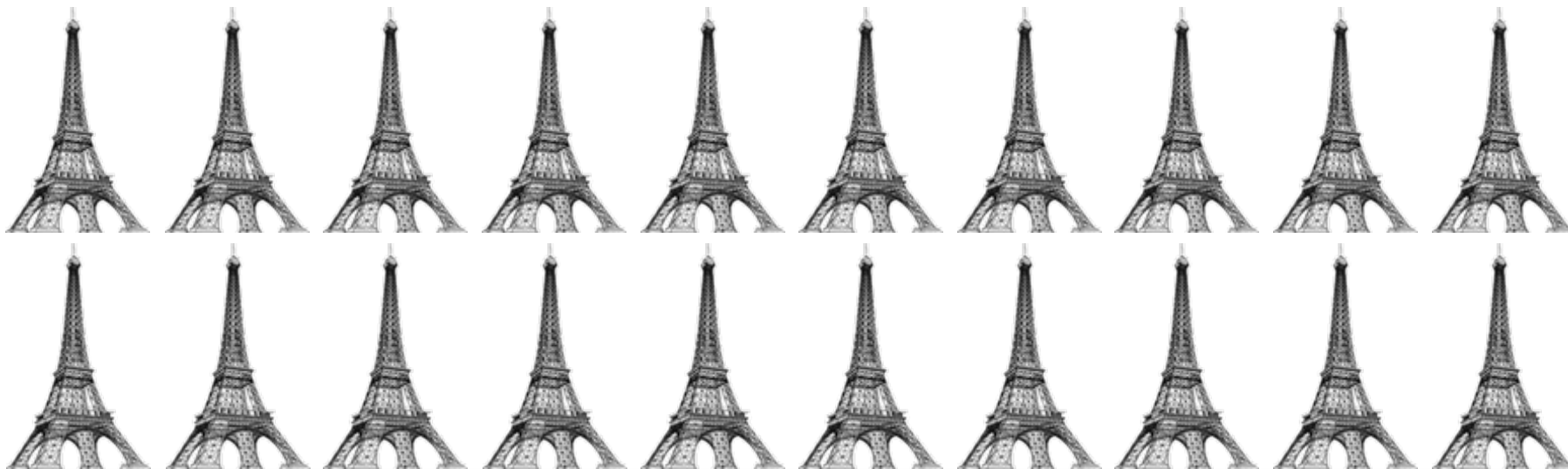
# Procurement logistics

## 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



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

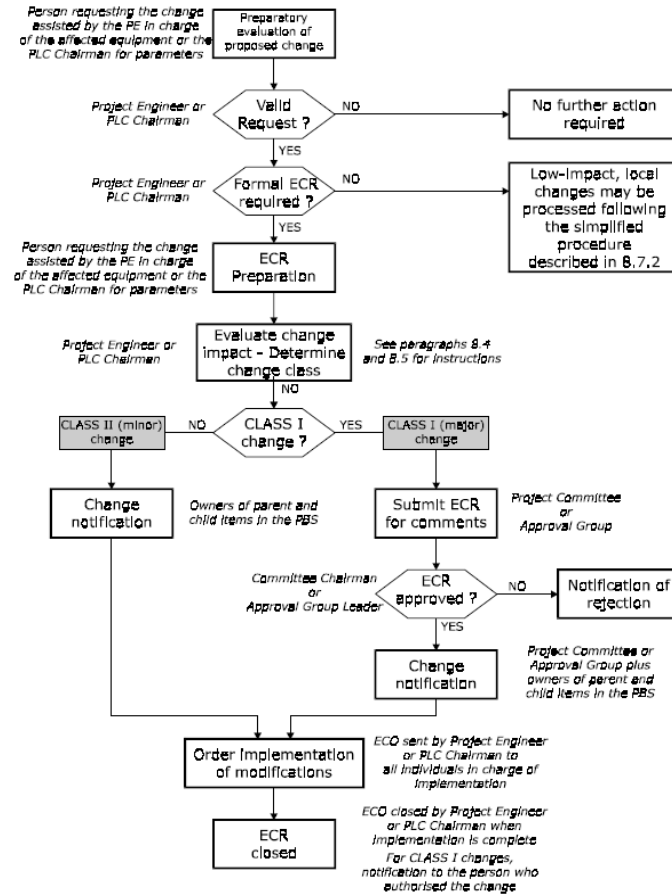
## Quality Assurance Procedure

### 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.

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

LHC\_Homepage - Microsoft Internet Explorer


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Address http://lhc.web.cern.ch/lhc/ Go Links



## LHC - THE LARGE HADRON COLLIDER



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[SEARCH](#)




[LHC dashboard](#)



[Magnet test facility](#)



[LHC NEWS](#)



[Design report](#)



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schedule and status](#)

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[Hardware Commissioning](#)

[Sector Test](#)

[Beam Commissioning](#)



**New CERN Control Centre (CCC)**

https://edms.cern.ch/cedar/plsql/navigation.tree?cookie=1123634&top=1504900006&style=DEFAULT\_STYLE

Local intranet

Start Current05 The LHC, a global scienc... LHC\_Homepage - Mic... FR 15:53



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

EDMS Web Navigator - Microsoft Internet Explorer

Address: [http://edms.cern.ch/cedar/plsql/navigation.tree?cookie=34662538p\\_top\\_id=1504900006&p\\_top\\_type=P&p\\_open\\_id=1858752345&p\\_open\\_type=P](http://edms.cern.ch/cedar/plsql/navigation.tree?cookie=34662538p_top_id=1504900006&p_top_type=P&p_open_id=1858752345&p_open_type=P)

**LHC Hardware Baseline**

Collapse Expand

- LHC Hardware Baseline
  - Cryo Magnets in Common Arc Cryostats**
    - Cryo Dipoles in the Arcs and the Dispersion Suppressors
      - Cold Mass Assembly
      - Dipole Cryostat & Related Equipment
    - Standard Arc Short Straight Sections
    - Short Straight Sections in Dispersion Suppressors
    - Other Arc Cryostats and Components
  - Long Straight Sections
  - Cryogenics
  - Vacuum System
  - DC Powering and Quench Protection
  - Radiofrequency System
  - Transfer Lines, Injections and Beam Dumping
  - Other Machine Systems
  - Civil Engineering Works and Infrastructure
  - General Services
  - Installation
  - LHC Specific Facilities

**Help** **Search for Documents** **Guidelines for Document Creation** **Approval List**

**Cryo Magnets in Common Arc Cryostats**

Type: Project , Identifier: LHCAM228 , Code: **Approved**  
 Project Engineer: Philippe LEBRUN

<b>LHC-DC-ES-0001 LHC Magnet Polarities</b>	
LHC-DC-ES-0001-30-10	<a href="#">Paul Proudlock, Stephan Russenschuck, Markus Zerlauth</a>
<a href="#">pdf</a> (202 Kb)	Date:2004-12-15
	Released
	Engineering Specification
<b>LHC-G-ES-0010 The Smoothing of the Magnets of the LHC Ring (Final Positioning)</b>	
lhc-g-es-0010-10-00	<a href="#">Christophe PODEVIN</a>
<a href="#">PDF</a> (145 Kb)	Date:2002-01-22
	Released
	Engineering Specification
<b>LHC-LB-EC-0002 Addition of a Flange on Domed End Covers of the Magnet Cold Masses</b>	
LHC-LB-EC-0002-10-10	<a href="#">A. PONCET, P. BONNAL</a>
lhc-lb-ec-0002-10-10	Date:2001-01-16
	Accepted
	Engineering Change Request

[Open Drawing Folder](#)

Local intranet



# ...and to updated technical documents

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Address [http://edms.cern.ch/cedar/plsql/navigation.tree?cookie=3466308&p\\_top\\_id=1504900006&p\\_top\\_type=P&p\\_open\\_id=1258609404&p\\_open\\_type=P](http://edms.cern.ch/cedar/plsql/navigation.tree?cookie=3466308&p_top_id=1504900006&p_top_type=P&p_open_id=1258609404&p_open_type=P) Go Links

Google Search Web 0 blocked AutoFill Options

### LHC Hardware Baseline

Collapse Expand

- LHC Hardware Baseline
  - Cryo Magnets in Common Arc
  - Cryo Dipoles in the Arcs ar
  - Cold Mass Assembly
    - Collared Coil
    - Coils**
      - Superconducting
      - Superconducting
      - Quench Heaters
      - Cable & Ground
      - Other Coil Comp
    - Collars
    - Spool Pieces
    - Bus Bars
    - Yoke & Related Comp
    - Shrinking Cylinder & F
    - Quench Diode Assem
    - Cold Bore Pipes & Ins
    - Dipole Beam Screen

## Drawing Information

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File Edit View Window Help

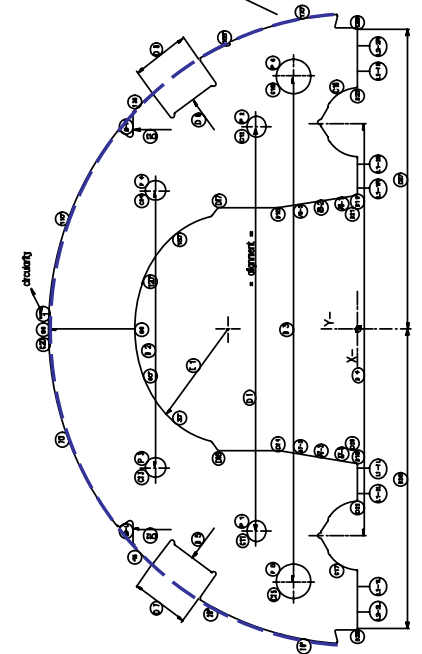
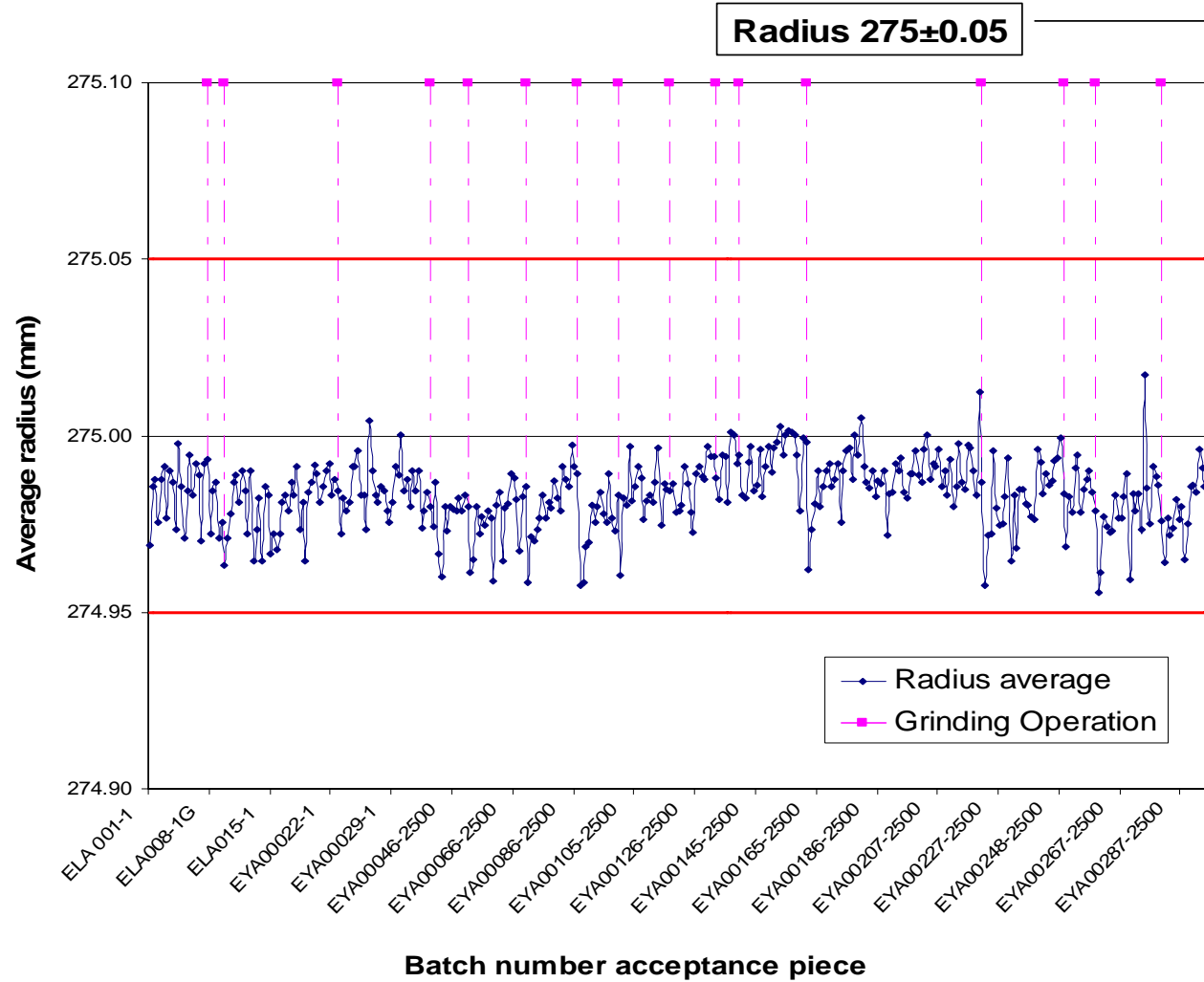
CALCULATED ANGLE ( DEG )				
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1	180	180	180	180
2	180	180	180	180
3	180	180	180	180
4	180	180	180	180
5	180	180	180	180

-286.675, -343.125 mm Page 1 of 1

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# Statistical production control & traceability



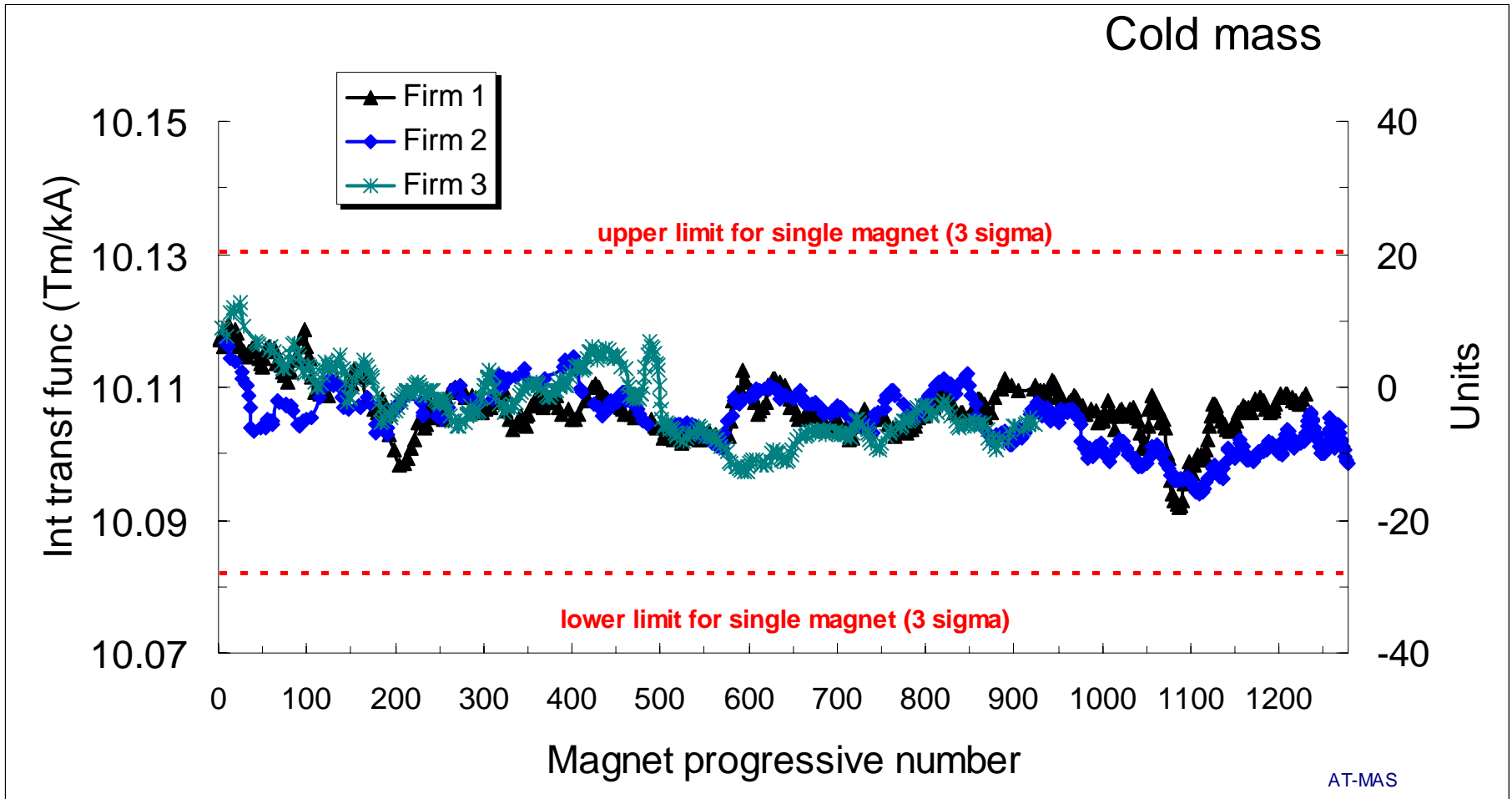


# Cold reception tests of 2000 superconducting magnets





# Homogeneity of magnet population





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# CERN has 20 Member States in Europe...



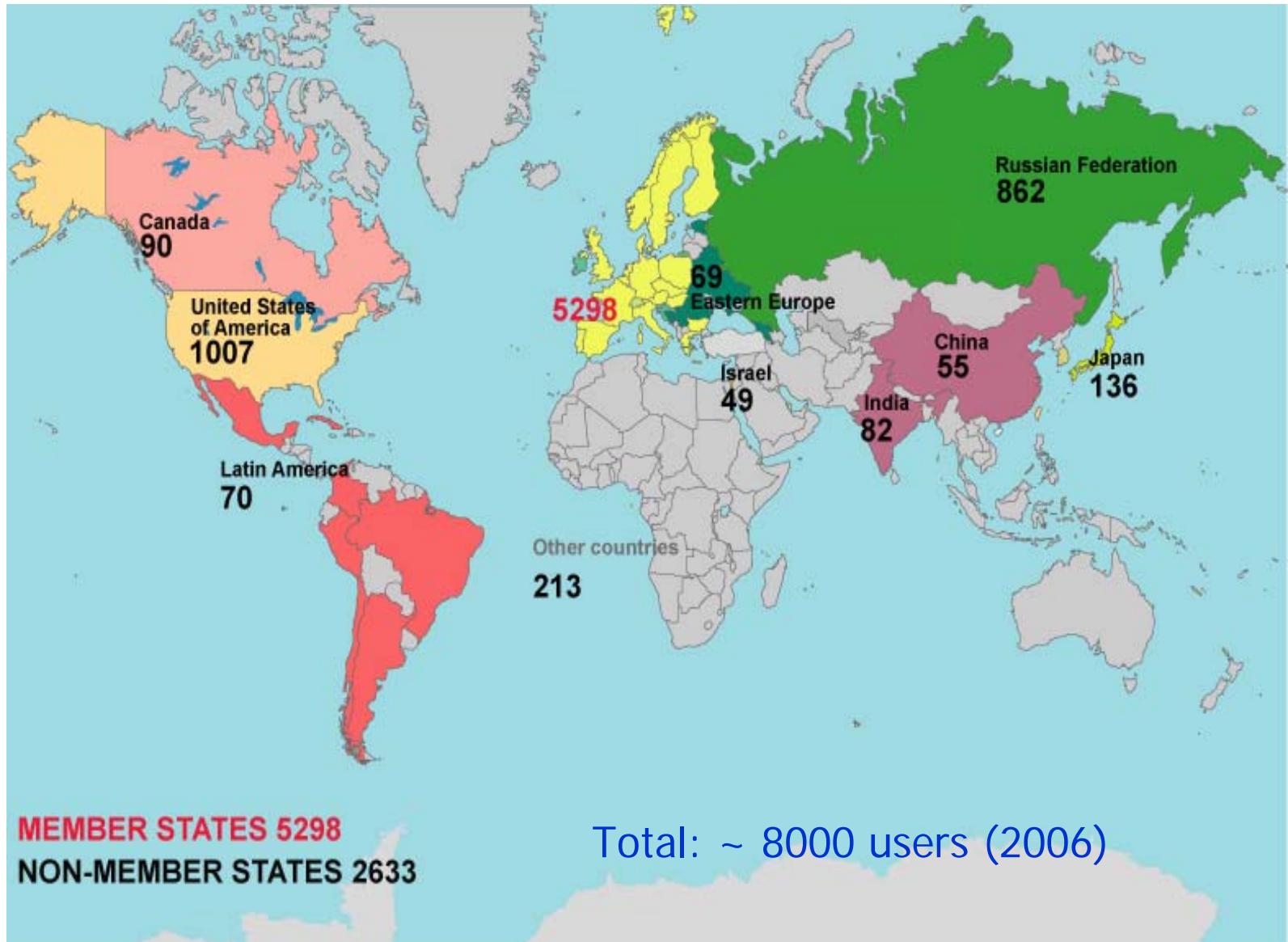
## Member States (Dates of Accession)

 AUSTRIA (1959)	 DENMARK (1953)	 GREECE (1953)	 NORWAY (1953)	 SPAIN (1/1961-12/1968-1/1983)
 BELGIUM (1953)	 FINLAND (1991)	 HUNGARY (1992)	 POLAND (1991)	 SWEDEN (1953)
 BULGARIA (1999)	 FRANCE (1953)	 ITALY (1953)	 PORTUGAL (1986)	 SWITZERLAND (1953)
 CZECH FR (1993)	 GERMANY (1953)	 NETHERLANDS (1953)	 SLOVAK FR (1993)	 UNITED KINGDOM (1953)

CERN-AS-01-114 FEBRUARY 1999 16/16/99



...but serves the world's physics community





# LHC



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

*étude d'impact  
sur l'environnement*



# Environment in its initial state



Gentiane jaune sur le Jura

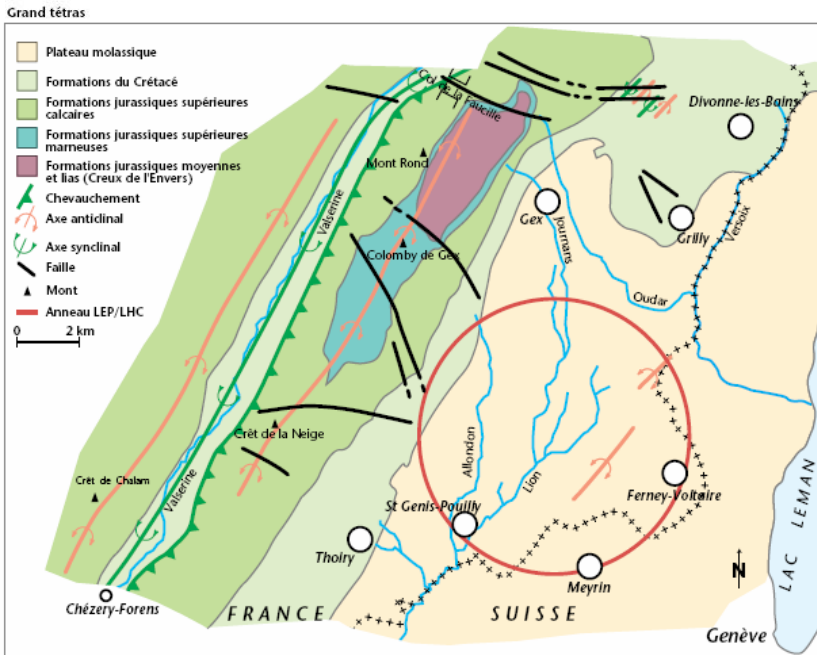
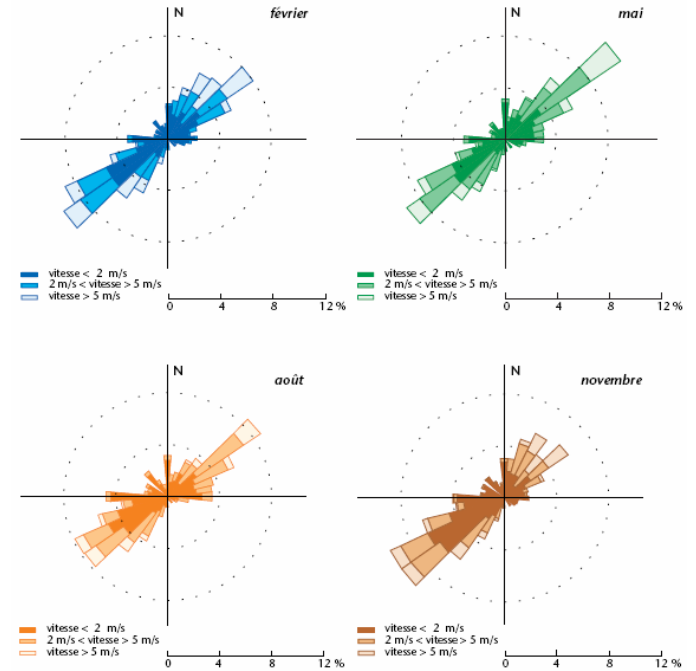


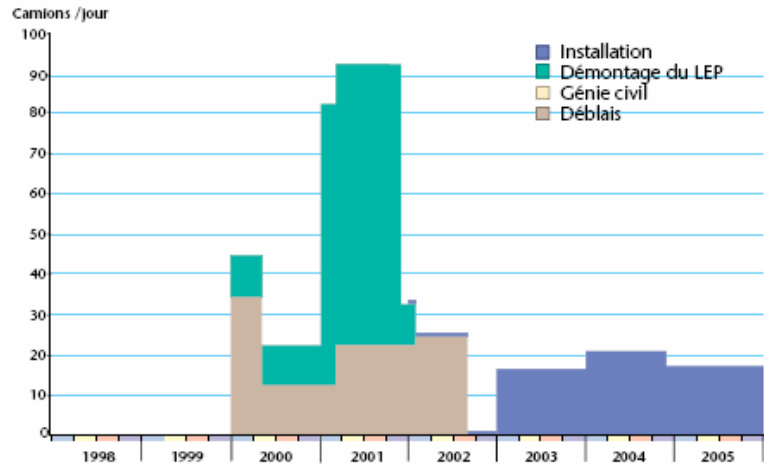
Figure 6.6 Schéma structural et géologie simplifiée



4 Vents enregistrés à Genève-Colintrin de 1982 à 1995



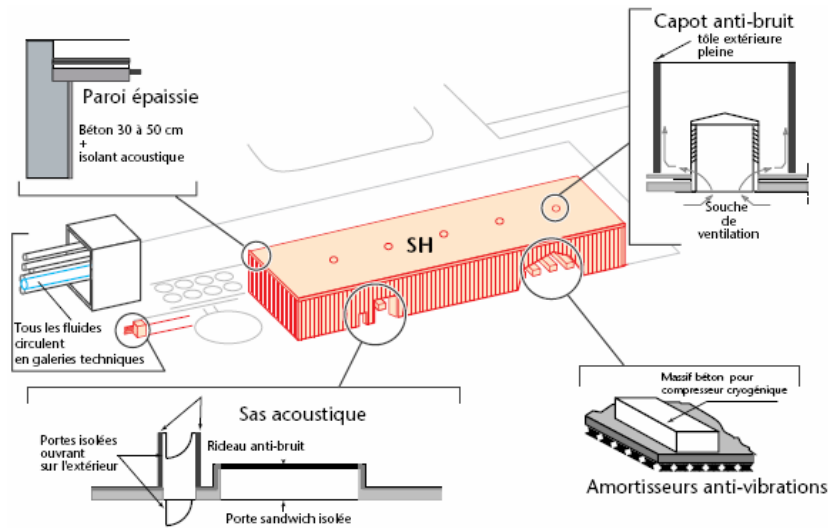
# Minimizing impacts



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

## Installation Nucléaire de Base

### 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. 1<sup>er</sup>.** - 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-

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RPS section I.1

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DOCUMENT D'EXPLOITATION

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

#### SECTION I.1 INTRODUCTION

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# 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*