Collaborating with industry: lessons from the LHC project

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  - State-of-the-art technology for affordable hi-tech
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  - Industrial production in the lab
  - Recovering from industrial difficulties
- Conclusion

A large scientific instrument and a superlative technological project

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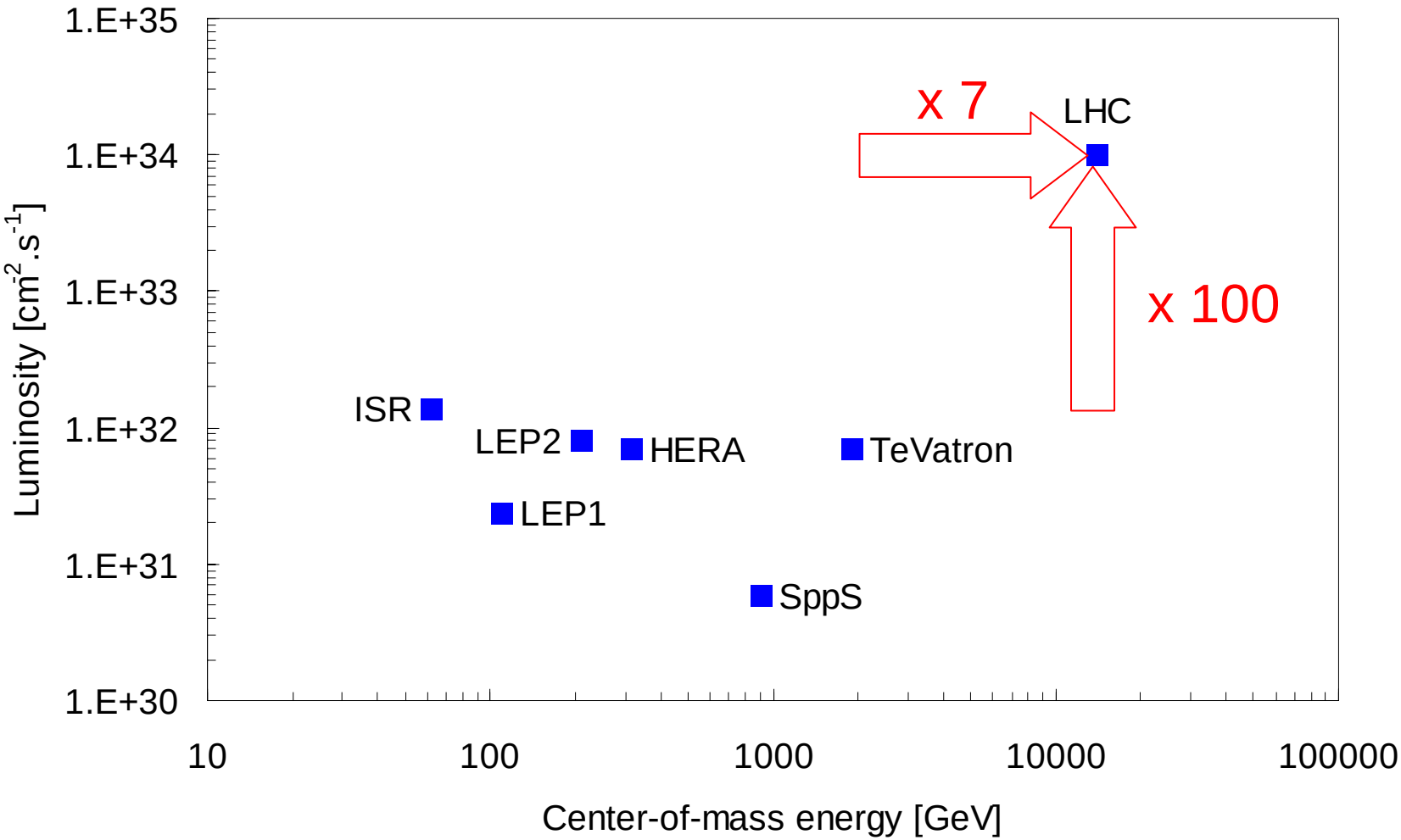
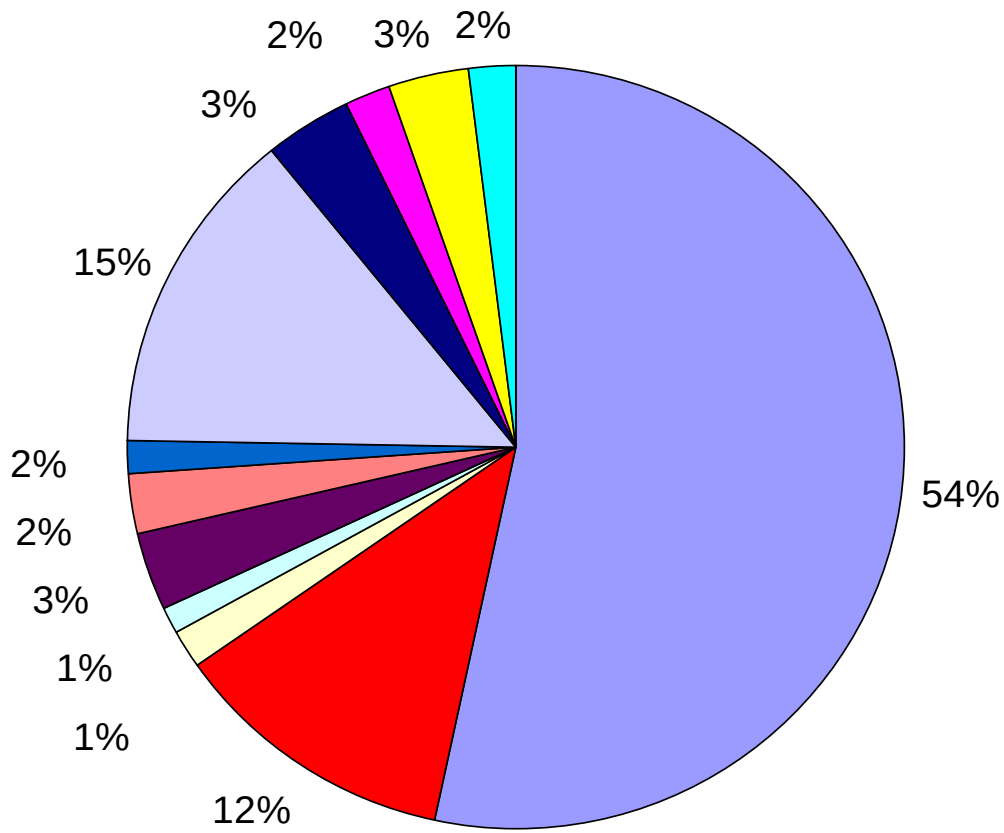
A particle collider well beyond the pre-existing state-of-the-art

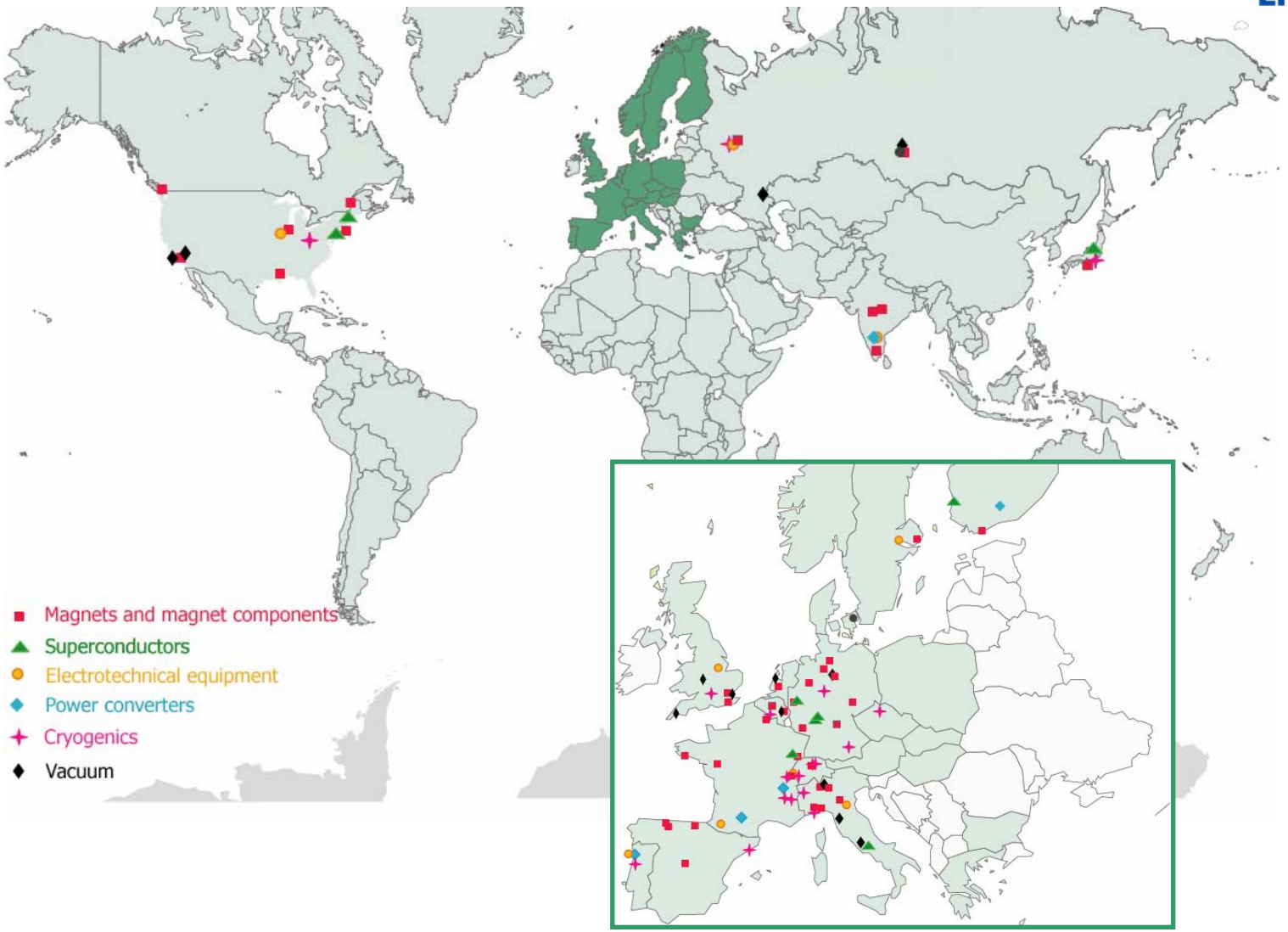


Cost structure of the LHC accelerator



Total ~ 2.2 BEuro

90 hi-tech industrial contracts in the world



A global project spanning space...

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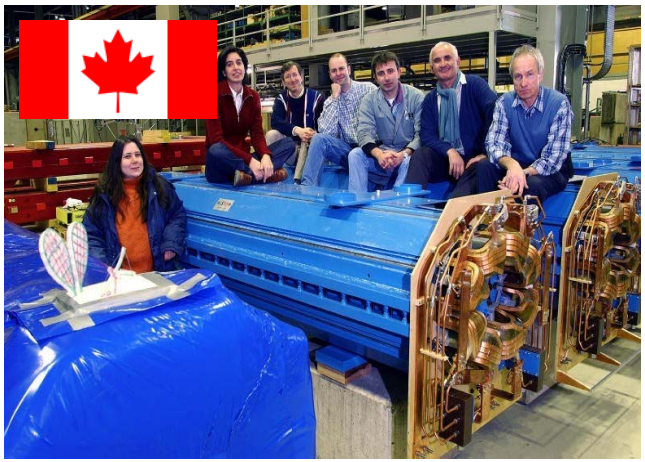

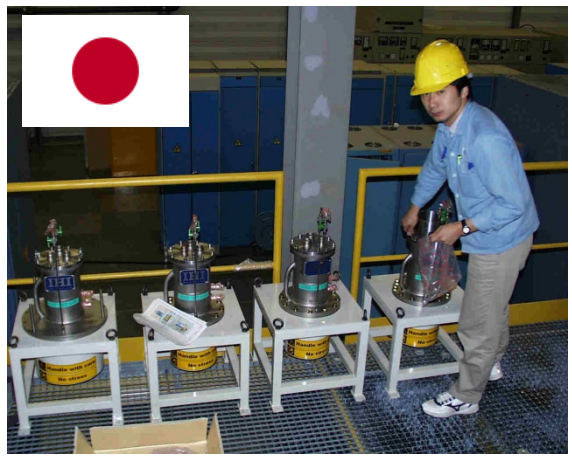

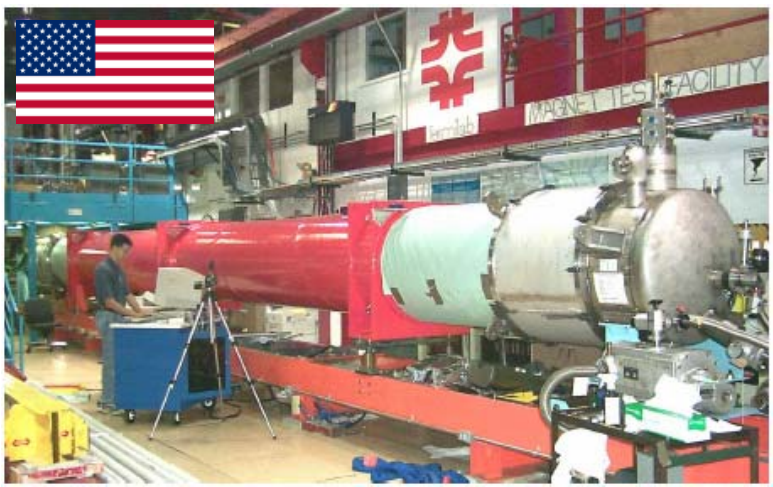

...and time

• 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

Engineering data management system

Single data repository, access to documentation via WWW

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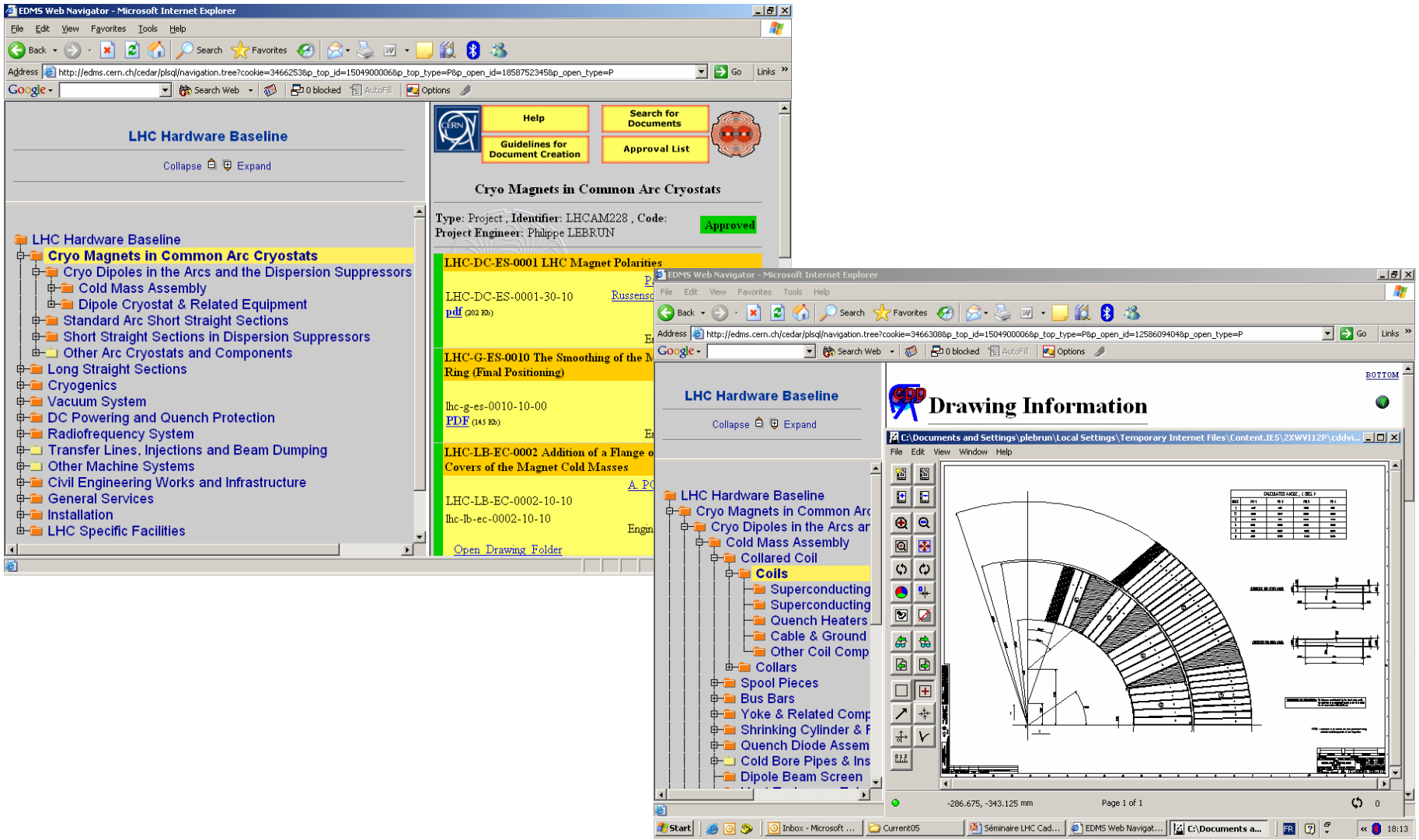

Specification & procurement strategy

- Legal/regulatory framework
  - CERN purchasing rules
  - Seeking « fair return » among CERN Member States
  - Handling special « in-kind» contributions
- Call for tenders
  - Selecting the right companies
  - Building know-how & maintaining interest through prototyping, preseries and series
  - Technical specification: functional & interface vs. build-to-print
- Contract
  - Split: security of supply & balanced return vs. additional follow-up
  - Intermediate supply & logistics
  - MTF and inspection
  - JIT vs. production buffer & sorting
- Cost risk estimate from tender statistics

Managing an integrated supply chain

Benefits

- Technical homogeneity
- Quality assurance
- Economy of scale
- Safety of supply
- Balanced industrial return

Risks & drawbacks

- Responsibility interface
- Additional workload
- JIT breakdown
- Transport, storage, logistics

Procurement logistics

Quality & quantity at the right time in the right place

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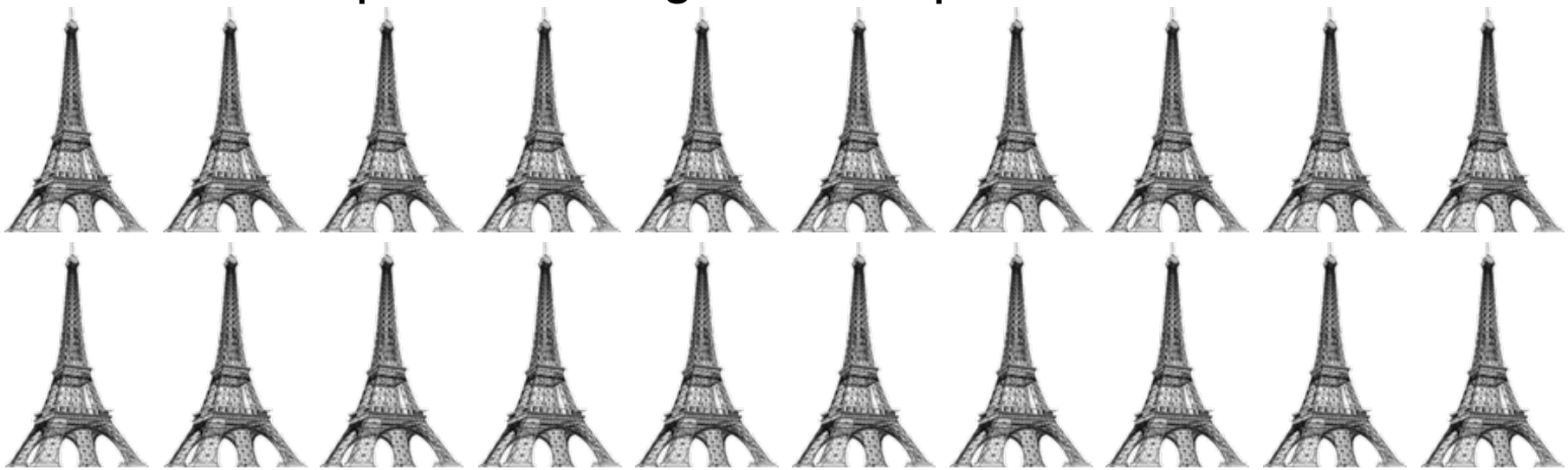
Installed in LHC tunnel: 50 000 t

Transported throughout Europe: ~150 000 t



The Manufacturing & Test Folder (MTF), key to quality assurance in production

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CERN
CH-1211 Geneva 23
Switzerland

the **Large Hadron Collider** project

LHC Project Document No.
LHC-PM-QA-309.00 rev 1.0
CERN Div./Group or Supplier/Contractor Document No.
EDMS Document No.
103562

Date:1999-06-16

Quality Assurance Procedure

MANUFACTURING AND INSPECTION OF EQUIPMENT

Abstract

This document describes the procedures and responsibilities involved in the manufacturing, the assembly and the inspection and test of LHC systems, sub-systems, assemblies, sub-assemblies and parts.

It establishes a policy for the control of all stages of manufacturing and assembly, from raw material procurement until final inspection and test, and it defines responsibilities and procedures to verify that all specified requirements are met.

The policy and guidelines apply to all materials, parts and equipment manufactured and/or assembled by Contractors, collaborating Institutes and CERN Divisions or Groups, that are to be installed in the LHC.

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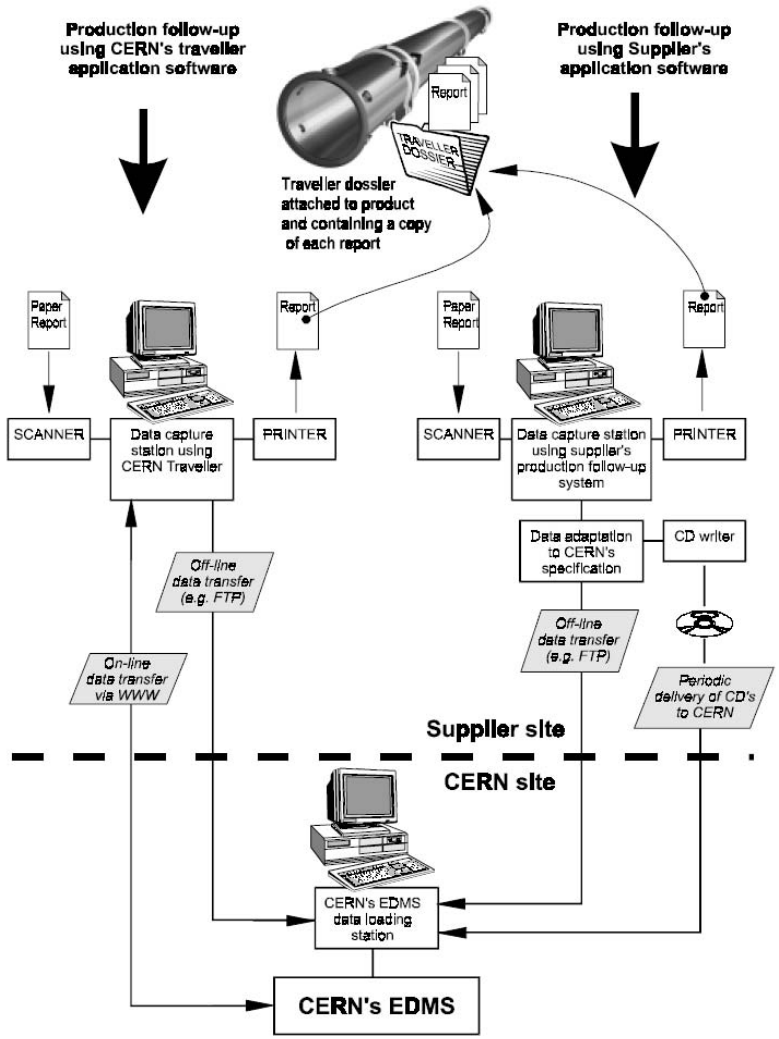

Production buffer enables sorting of magnets for optimized installation in accelerator

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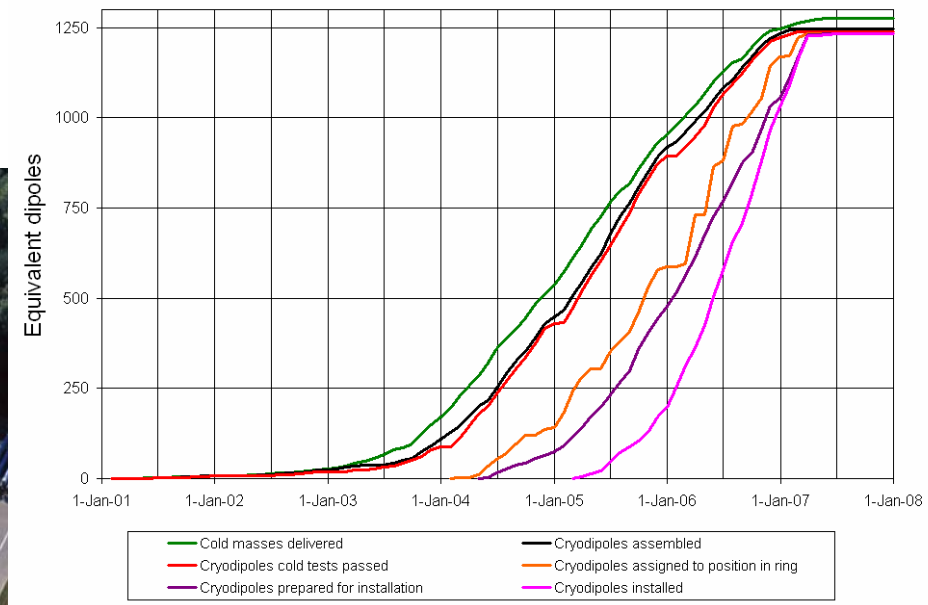
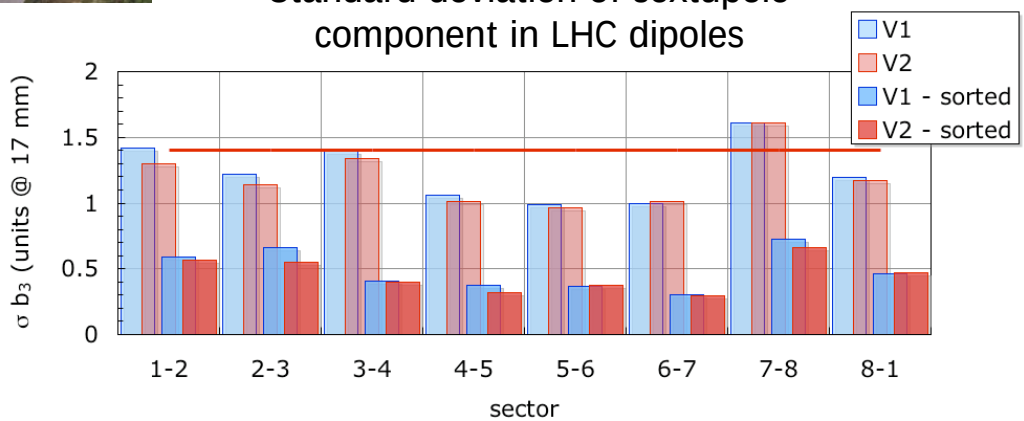
Outdoor storage of cold masses and cryomagnets

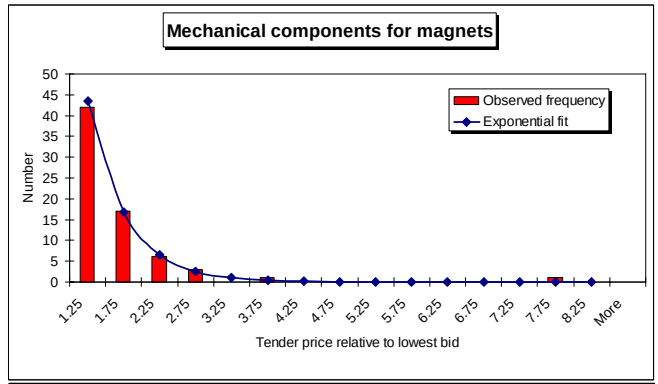


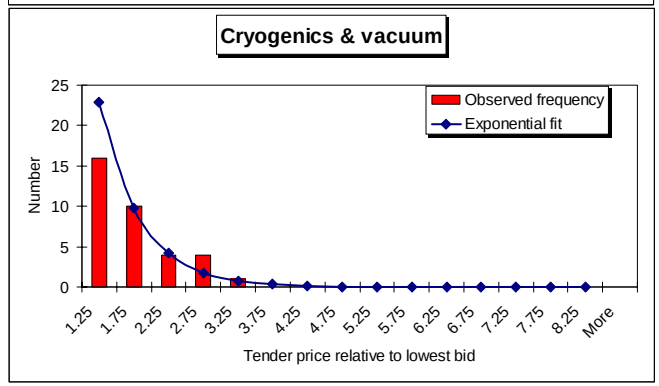
Standard deviation of sextupole component in LHC dipoles

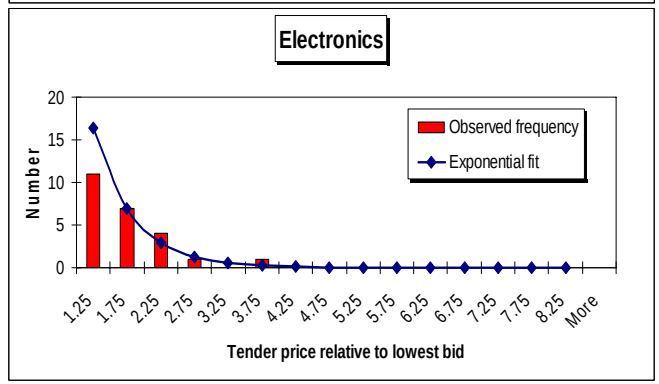


Probabilistic cost assessment from analysis of quoted tender prices

- Number of LHC industrial contracts allows statistical analysis of tender prices, grouped by type of technology
- Distribution of quoted prices is taken as measure of the industrial cost variability of work packages in the project
- Observed distributions are clearly skew, and better fitted by exponential than normal probability density function
- Probabilistic assessment of future project costs should be based on skew, e.g. exponential rather than normal probability density functions for individual work packages



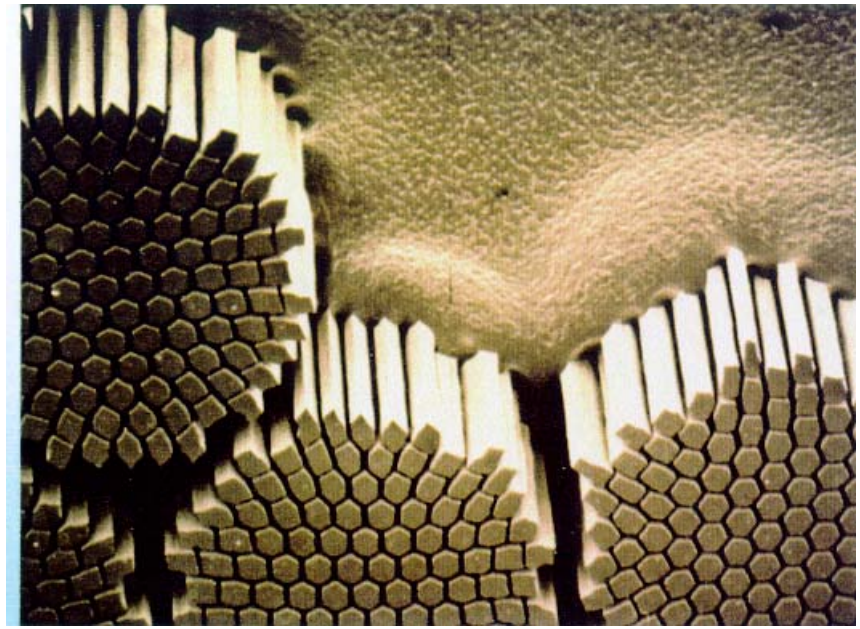




Qualitative jumps in technology

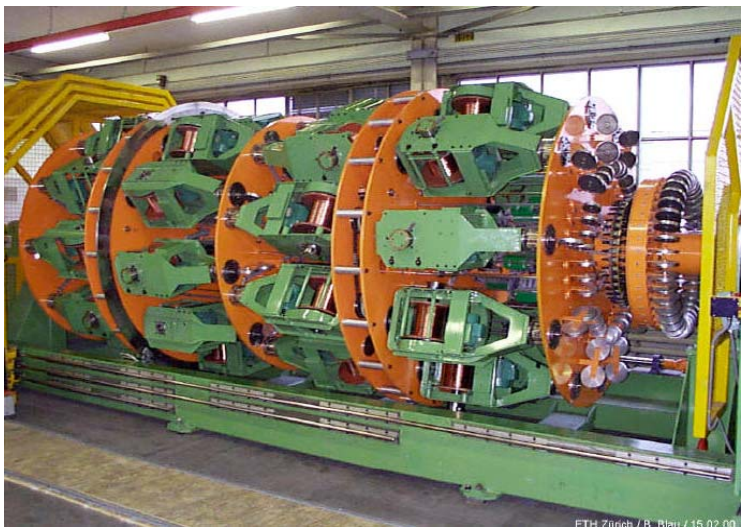
7000 km superconducting cable with controlled properties

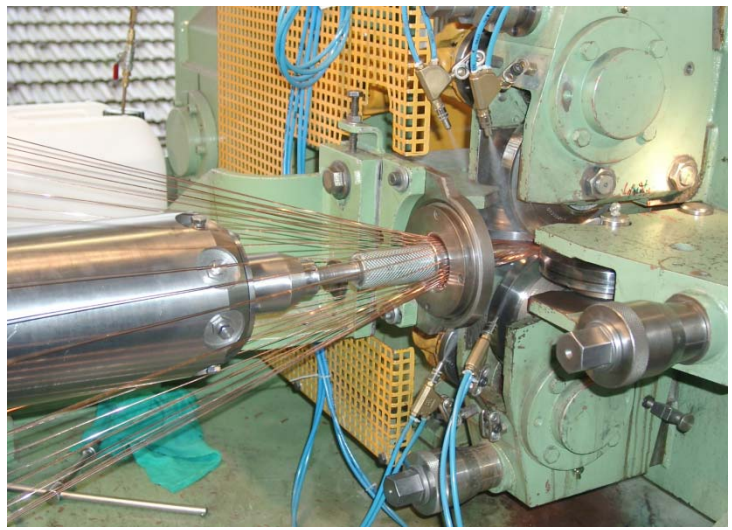
	Inner Cable	Outer Cable
Number of strands	28	36
Strand diameter	1.065 mm	0.825 mm
Filament diameter	7 µm	6 µm
Number of filaments	~ 8900	~ 6520
Cable width	15.1 mm	15.1 mm
Mid-thickness	1.900 mm	1.480 mm
Keystone angle	1.25 °	0.90 °
Transposition length	115 mm	100 mm
Ratio Cu/Sc	≥ 1.6	≥ 1.9



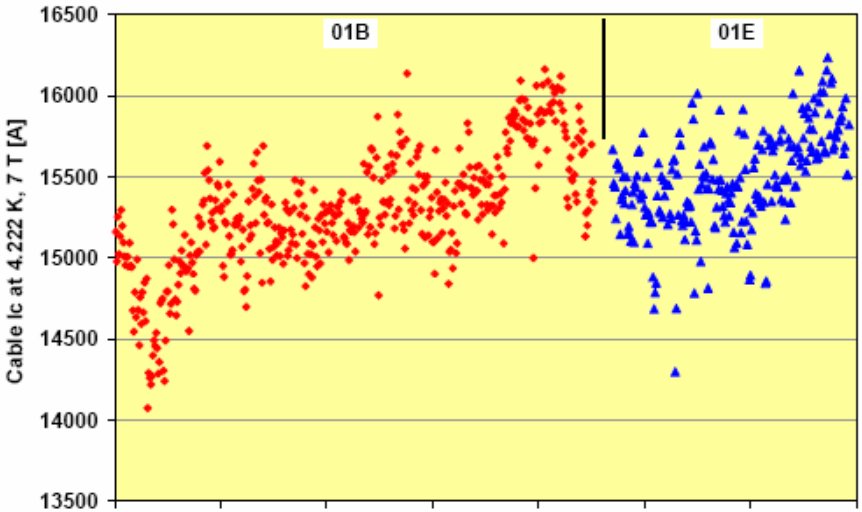
Superconducting wire & cable production

ALSTOM, EAS, FURUKAWA, LUVATA (LMI, OUTOKUMPU, IGC)

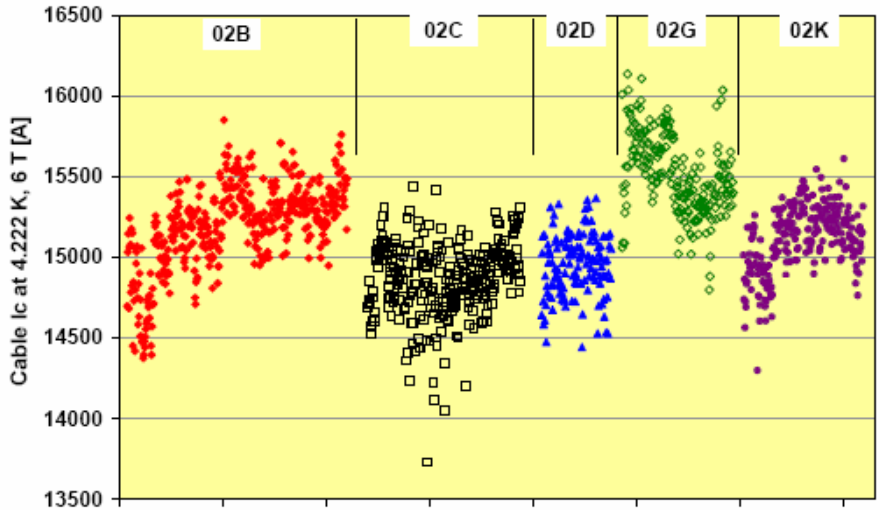




Superconducting cable production statistics



Specified 14140 A at 4.2 K, 7 T



Specified 13236 A at 4.2 K, 6 T

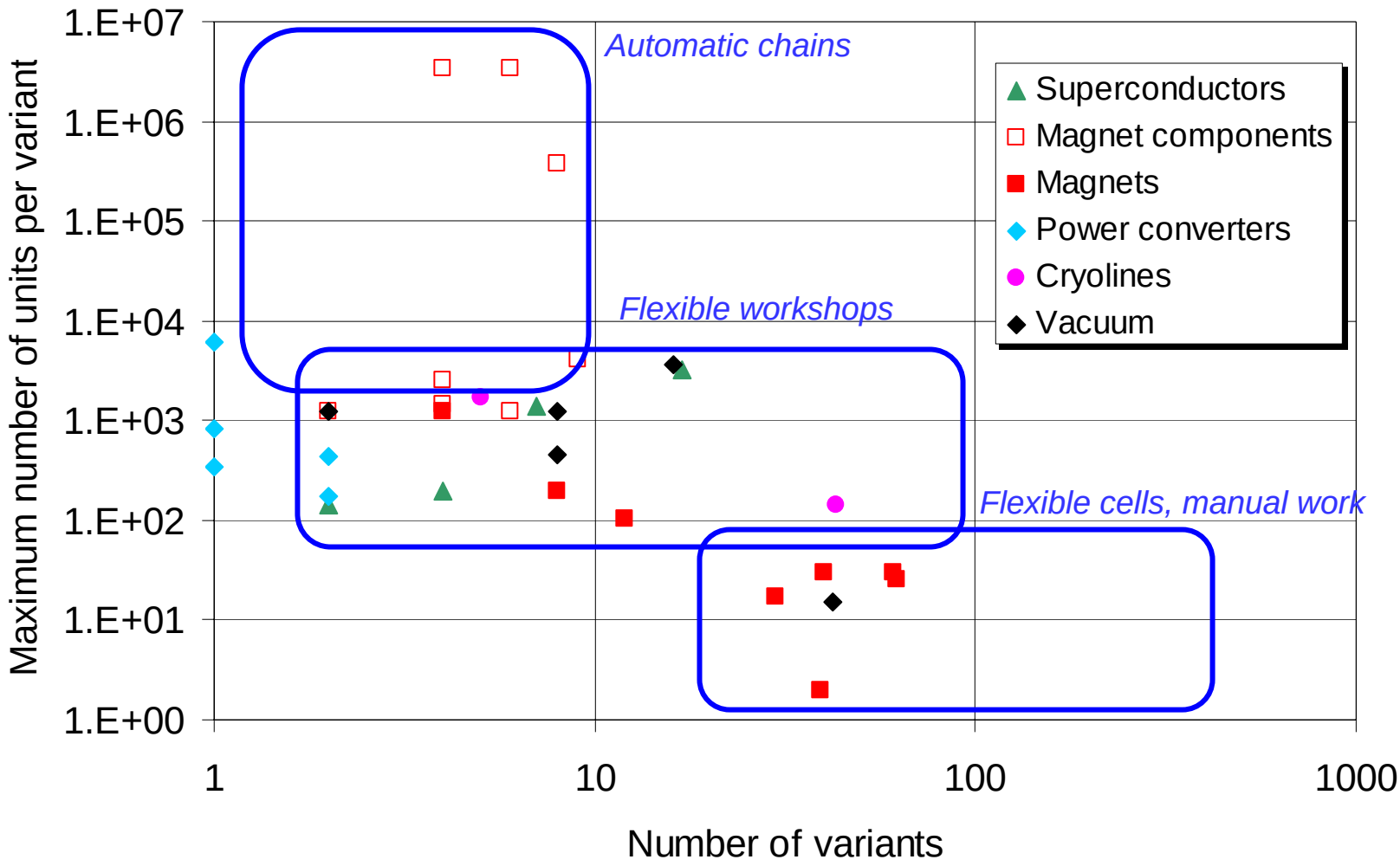
- Critical current ~10% above specified value
- Magnetization and inter-strand resistance under control
- Cables within tight dimensional tolerances
- Rejection/declassification rate < 1%

Quantitative jumps in technology

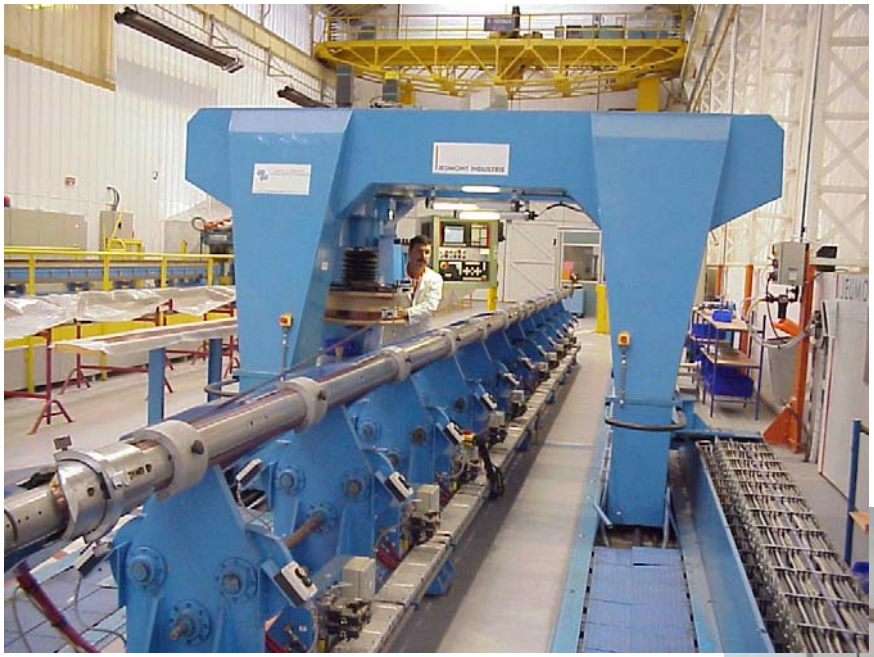
23 km of superconducting magnets

1232 dipoles, 474 quadrupoles, 7612 correctors

Series production of LHC components



Manufacturing of superconducting coils



JEUMONT, NOELL, ANSALDO

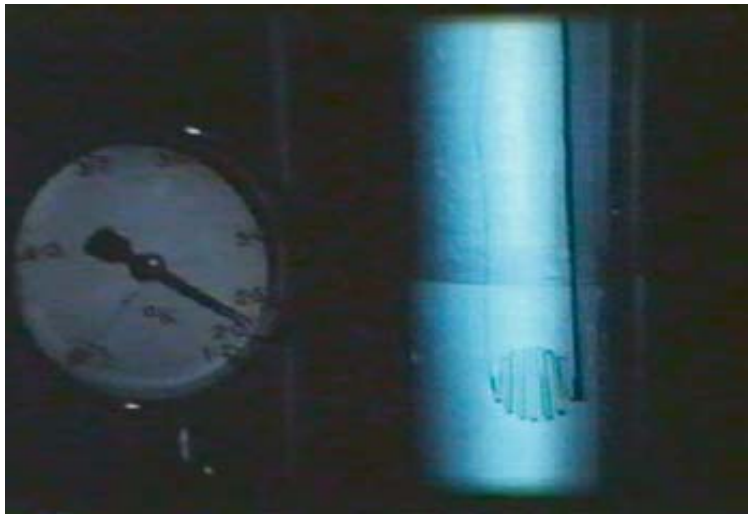
Assembly of superconducting magnets

ALSTOM, NOELL, ANSALDO

Quantitative jumps in technology

Superfluid helium as technical coolant

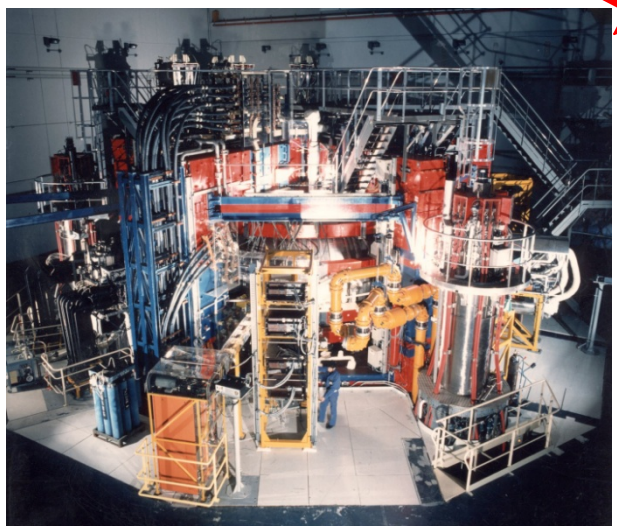
1 liter in the laboratory



CEBAF

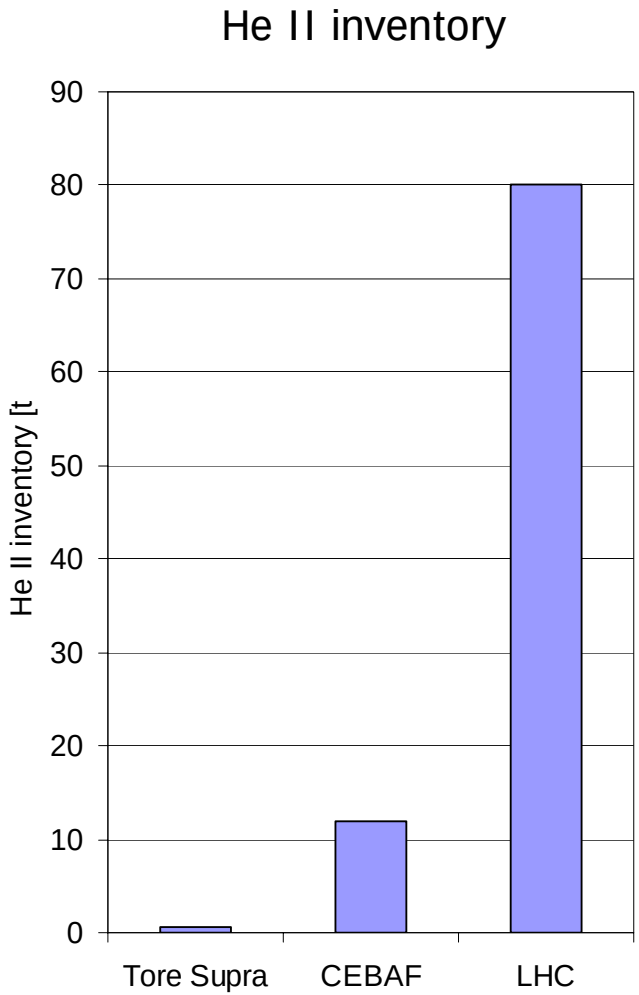
500'000 liter in the LHC

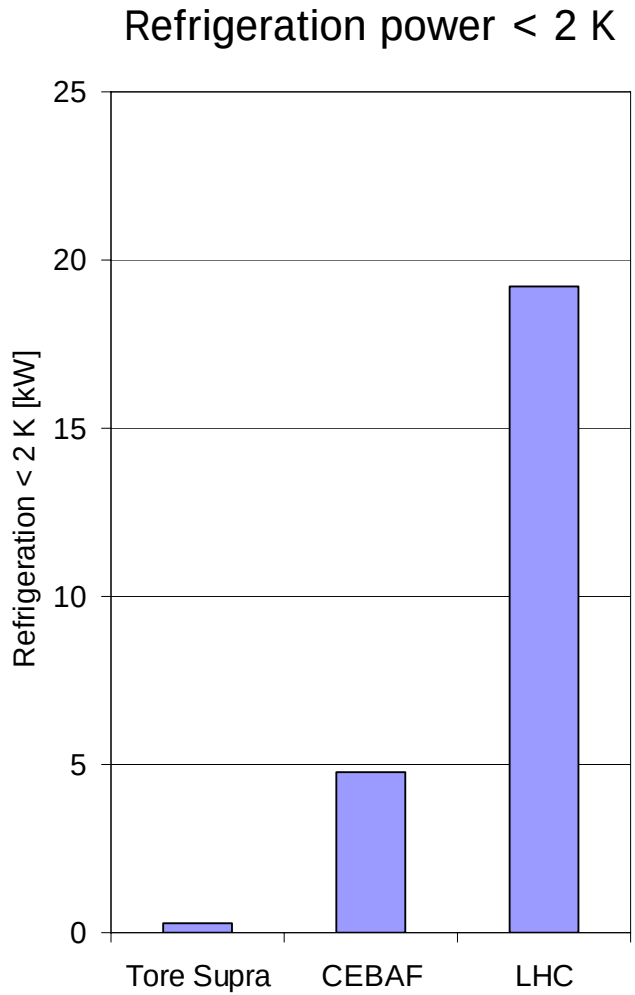
Tore Supra



Quantitative jumps in technology

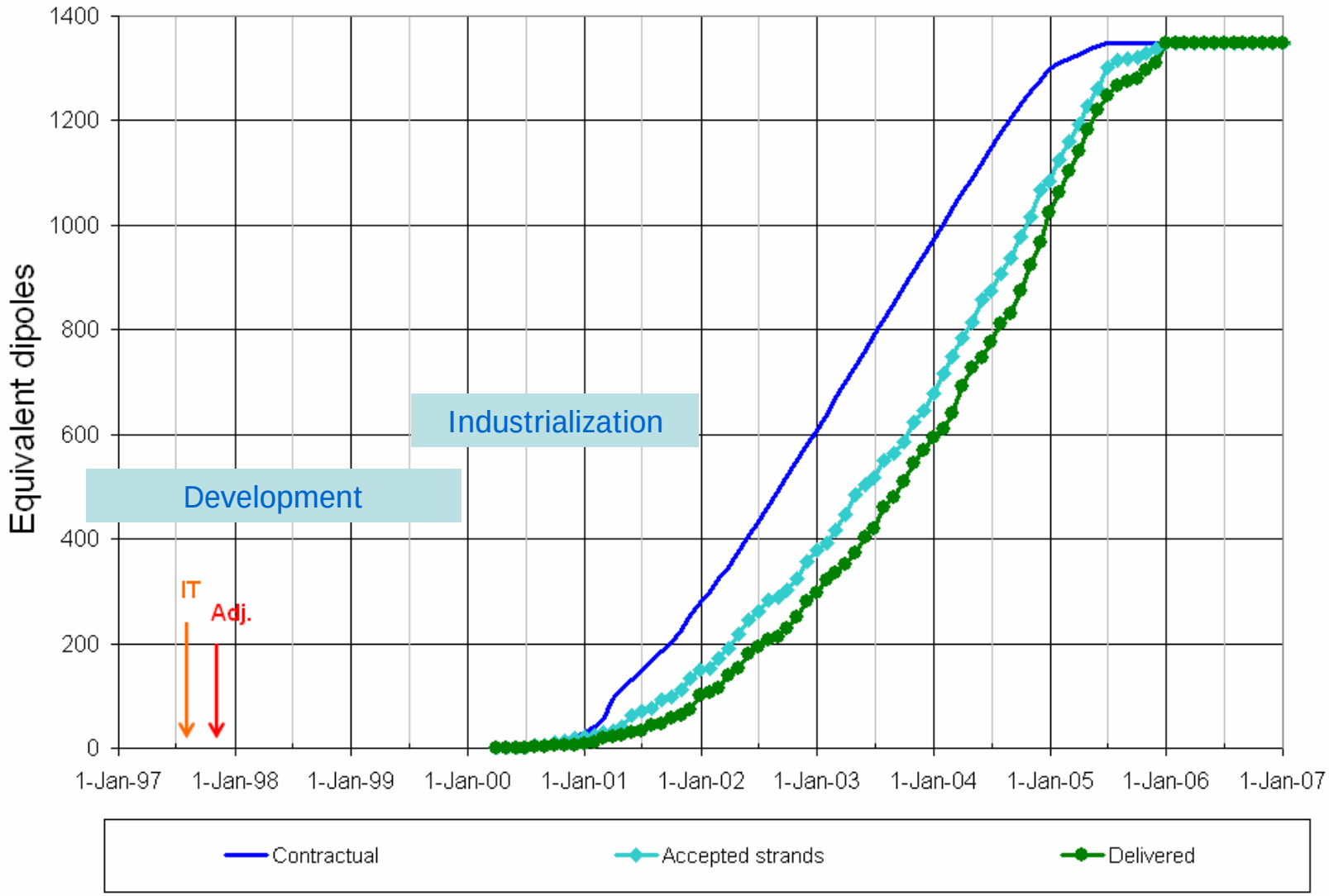
Large-scale superfluid helium systems





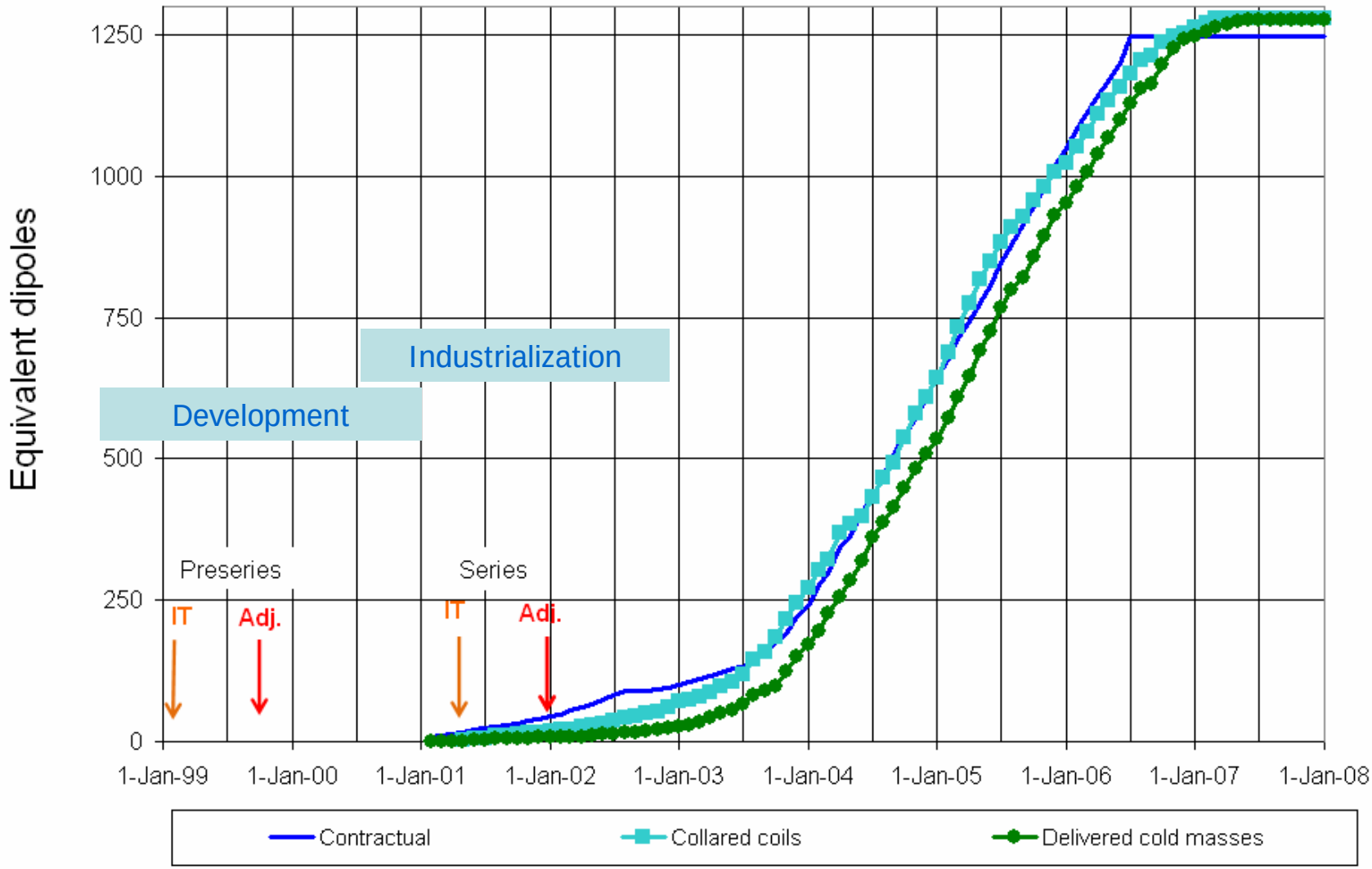
Industrialization & production ramp-up

Superconducting cable



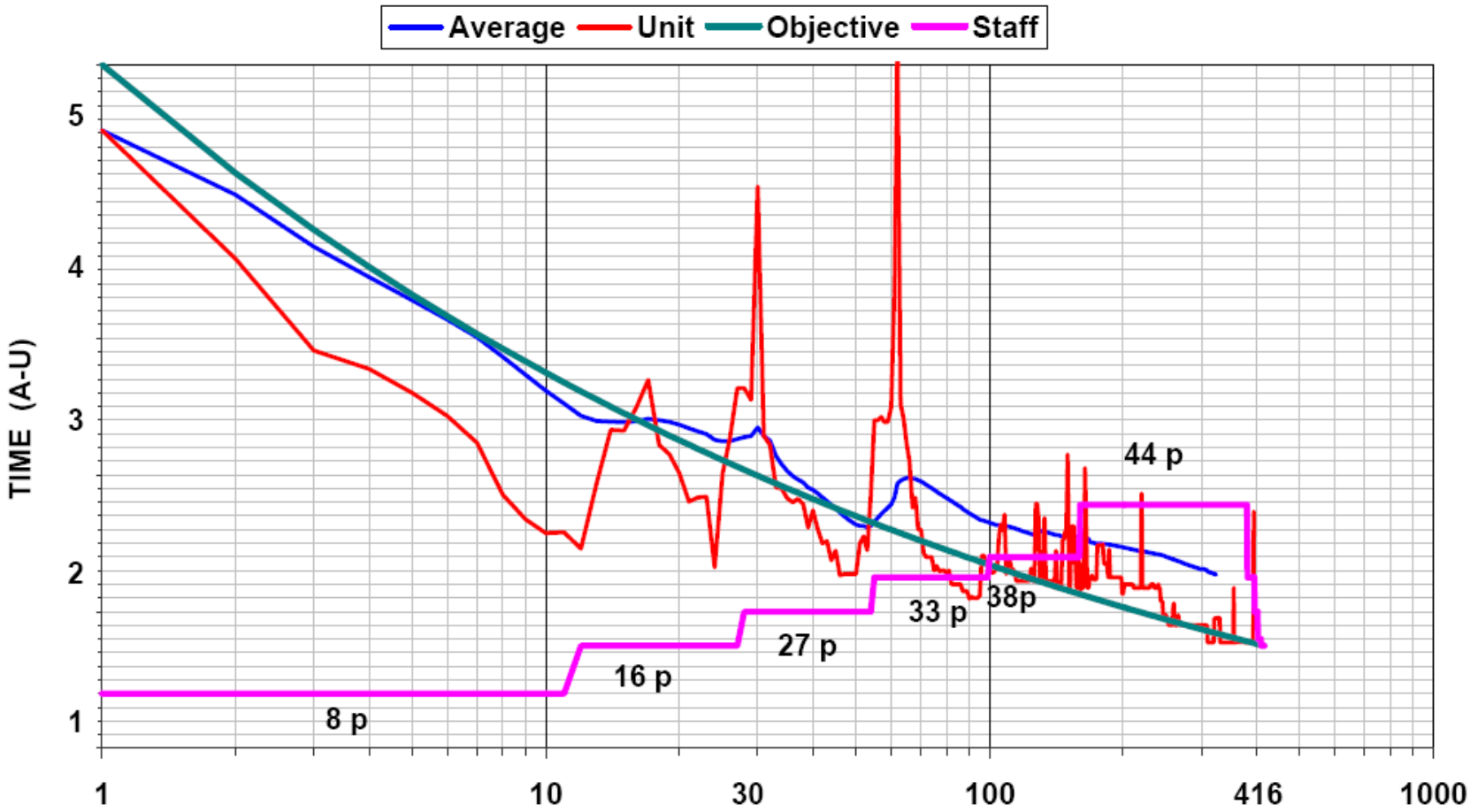
Industrialization & production ramp-up

Superconducting dipoles



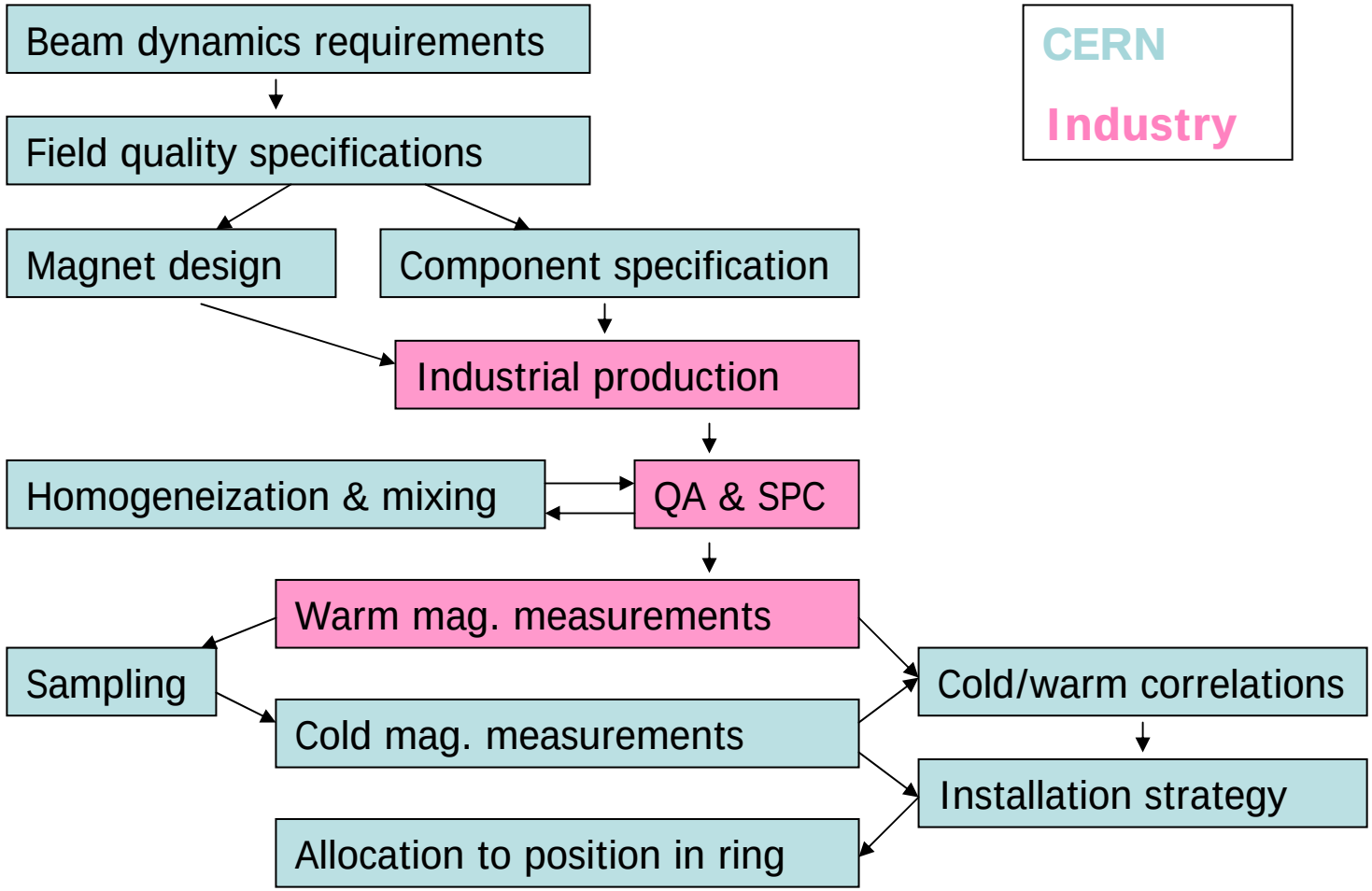
Industrialization & production ramp-up

Learning curve for superconducting dipoles

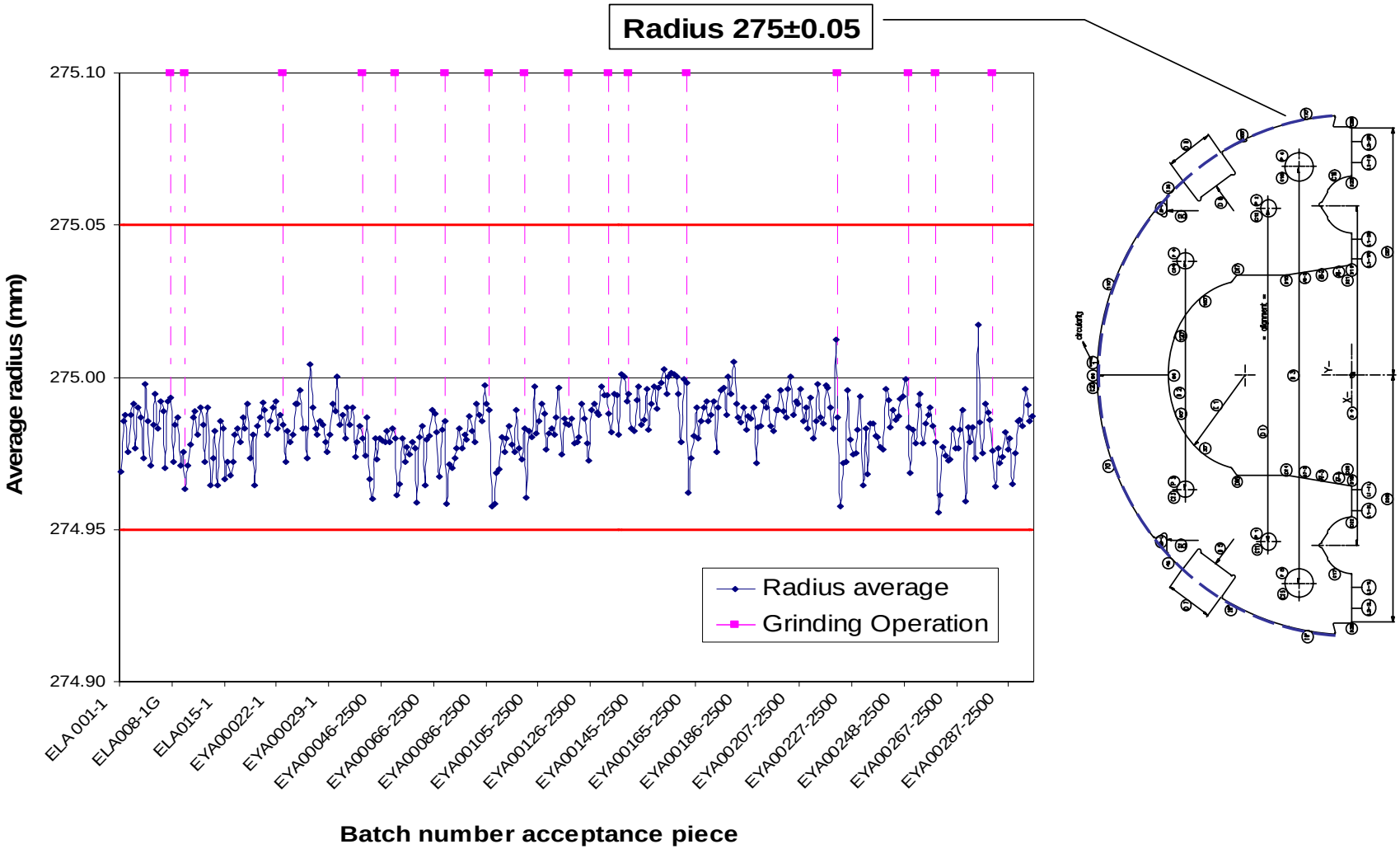


Partnership in commercial contracts

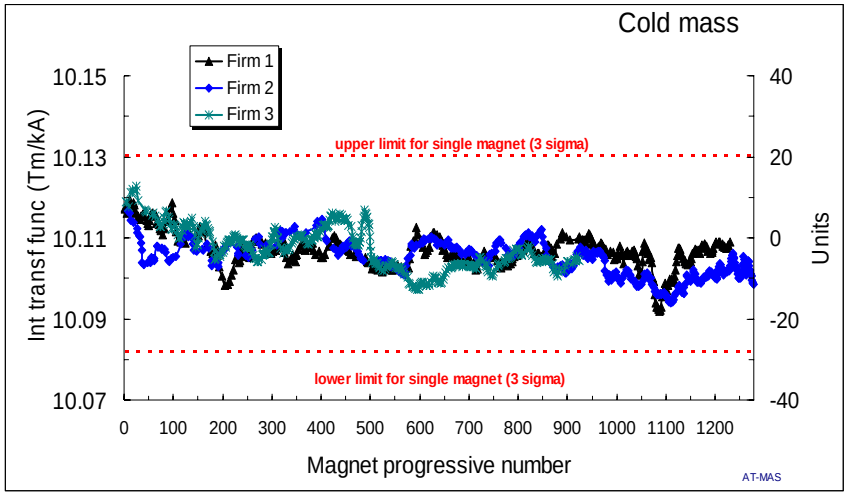
Steering magnet production for quality and homogeneity

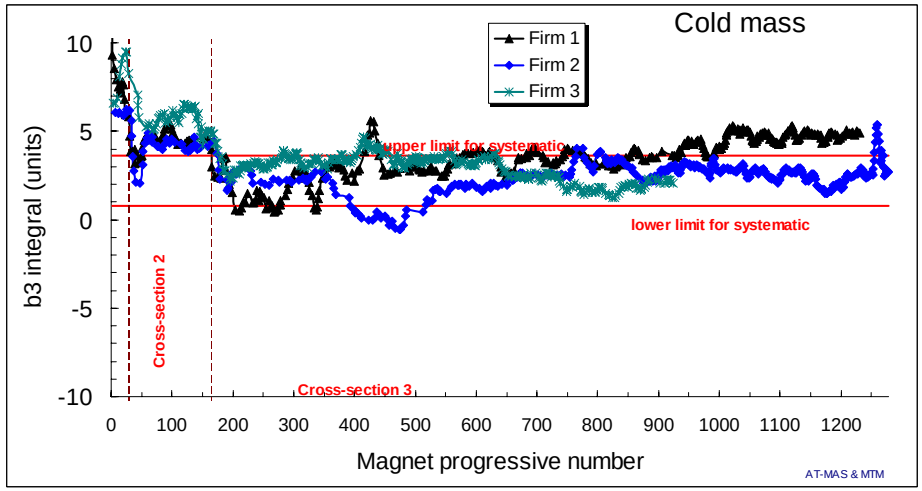


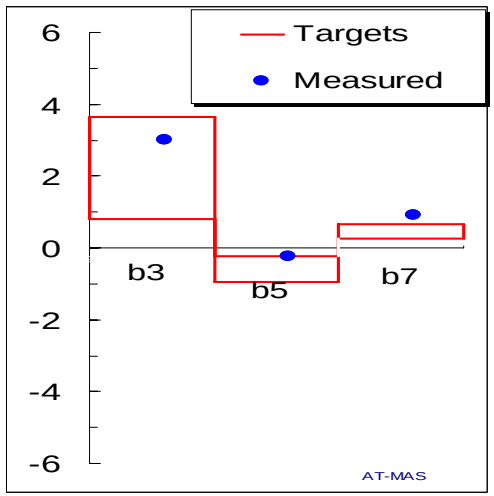
Statistical production control of components

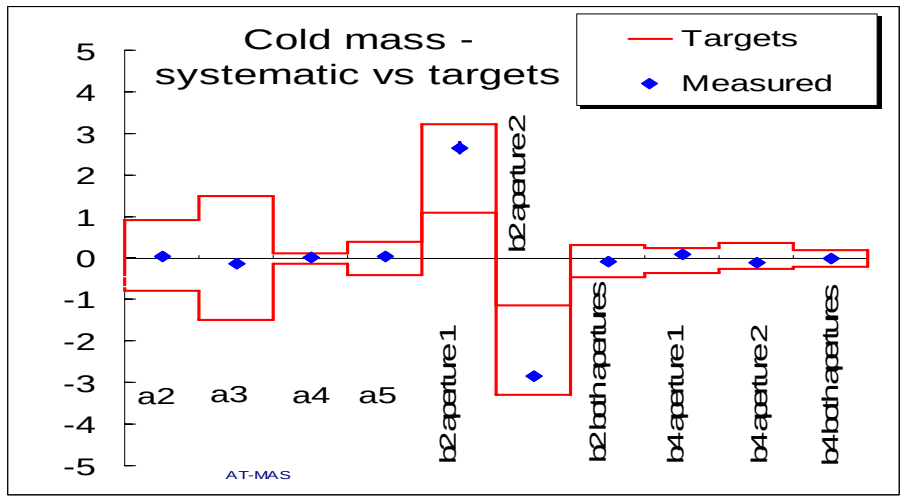


Field quality achieved in series magnets









Performance through shared incentives

Efficiency of cryogenic plants

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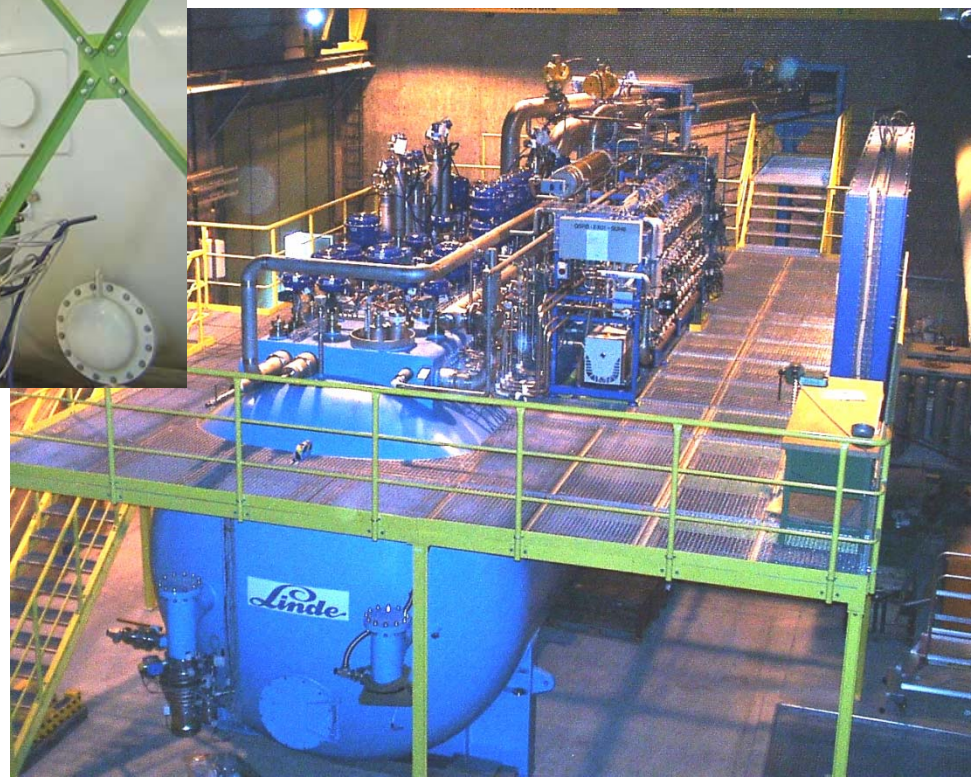
33 kW @ 50 K to 75 K
23 kW @ 4.6 K to 20 K
41 g/s liquefaction

AIR LIQUIDE



Eight 18 kW @ 4.5 K
helium refrigerators

LINDE

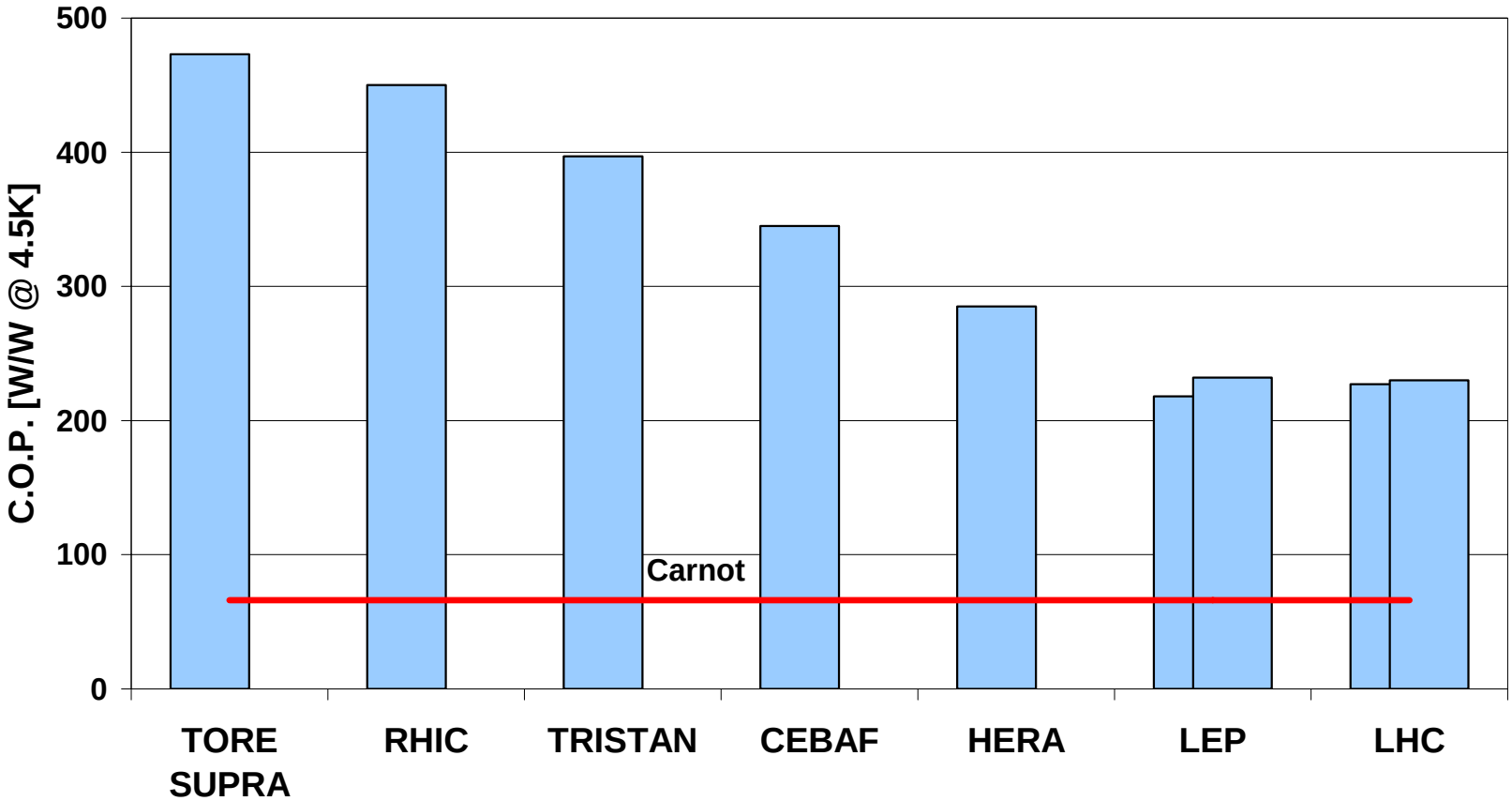
Performance through shared incentives

Specifying cryogenic plants for efficiency

- Include capital & operating costs over amortization period *(10 years)* in adjudication formula
- Operating costs dominated by *electricity*
- Include *externalities* in electricity costs
  - distribution & transformation on CERN site
  - heat rejection in aerorefrigerants
- Shared incentive in the form of *bonus/malus* on measured vs. quoted electrical consumption

⇒ *breach of "high efficiency = high investment" legend:*
for given (specified) output, a more efficient plant is not only cheaper to operate, but also smaller, resulting in lower investment (direct & indirect)

C.O.P. of cryogenic helium refrigerators



From emulation in R&D to competition in market

Cold compressors for refrigeration at 1.8 K

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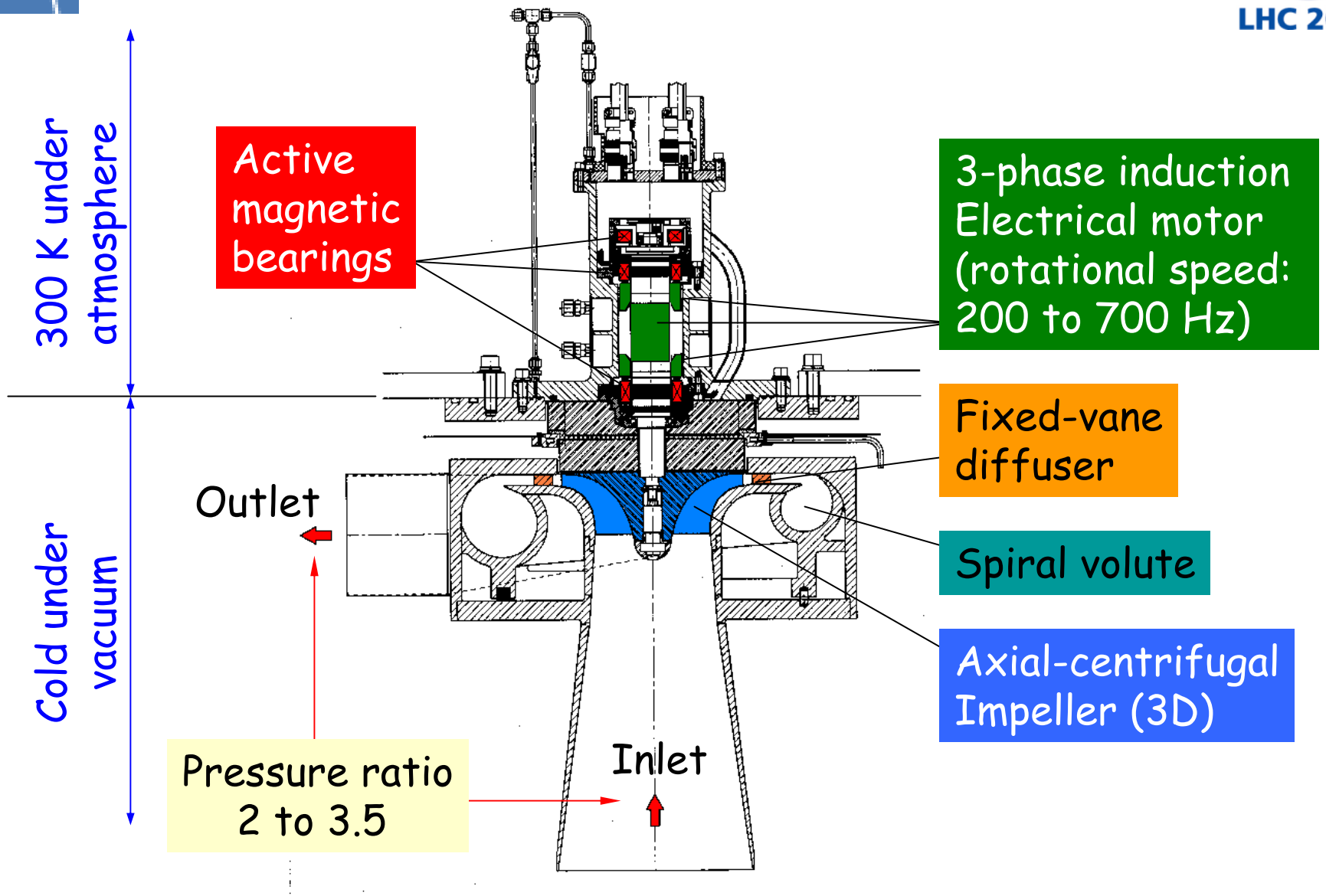
Air Liquide &
IHI-Linde

Axial-centrifugal impeller

Cartridge 1st stage

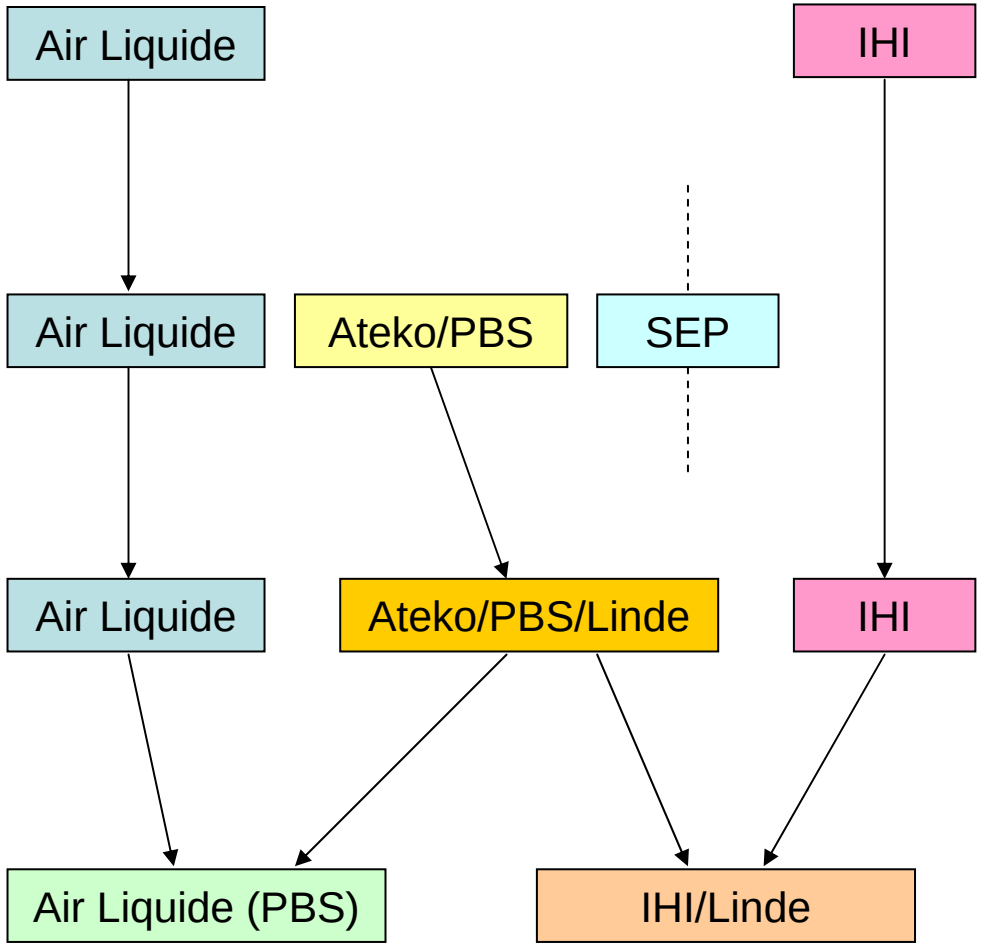
4 cold compressor stages

Specific features of LHC cold compressors



Development of LHC cold compressors

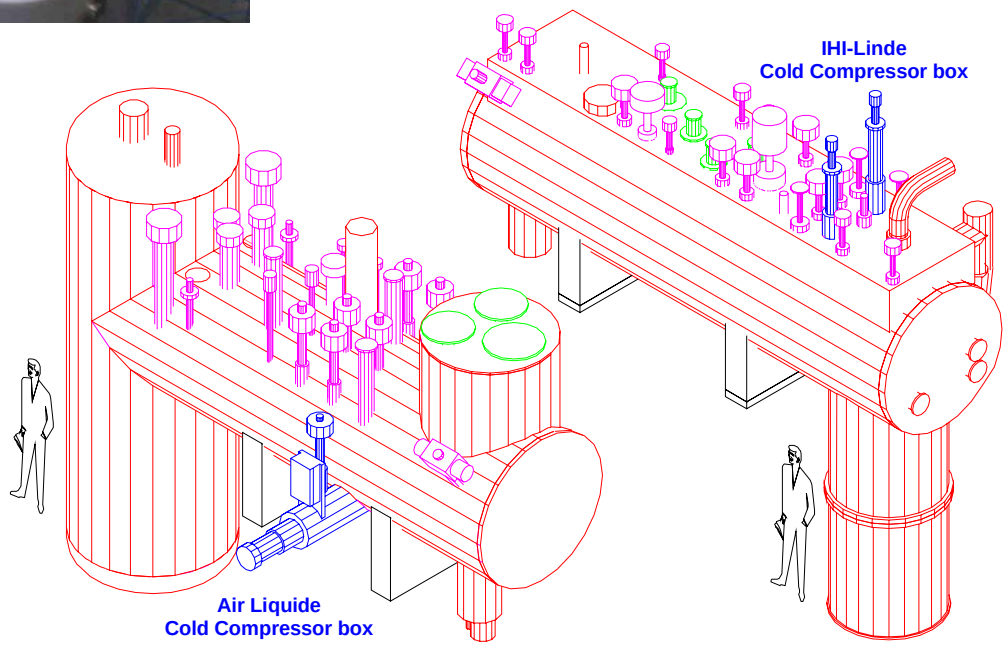
- Preexisting state-of-the-art
- Preliminary studies
- Prototypes
- Preseries/series



Eight 2400 W@1.8 K refrigeration units integrating 28 cold compressors

AIR LIQUIDE

IHI-LINDE



State-of-the-art technology for affordable hi-tech

Cryostat assembly by industry on CERN site

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ICS Consortium

State-of-the-art technology for affordable hi-tech

Industrial solutions for magnet cryostats

Low heat inleak
GFRE support post

EWK

CASA ESPACIO

Aluminium extrusion
for thermal shield

State-of-the-art technology for affordable hi-tech

Interconnections in the LHC tunnel

LHC 2008

65’000 electrical joints

Induction-heated soldering

Ultrasonic welding

Very low residual resistance

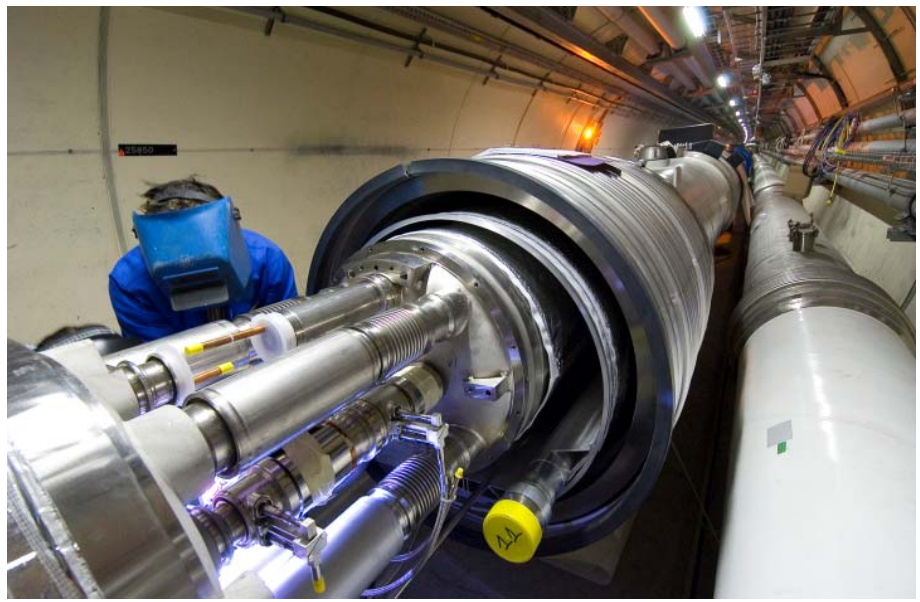
HV electrical insulation

40’000 cryogenic junctions

Orbital TIG welding

Weld quality

Helium leaktightness



INEO-ENDEL

Developing emerging technologies

Modular switched-mode power converters

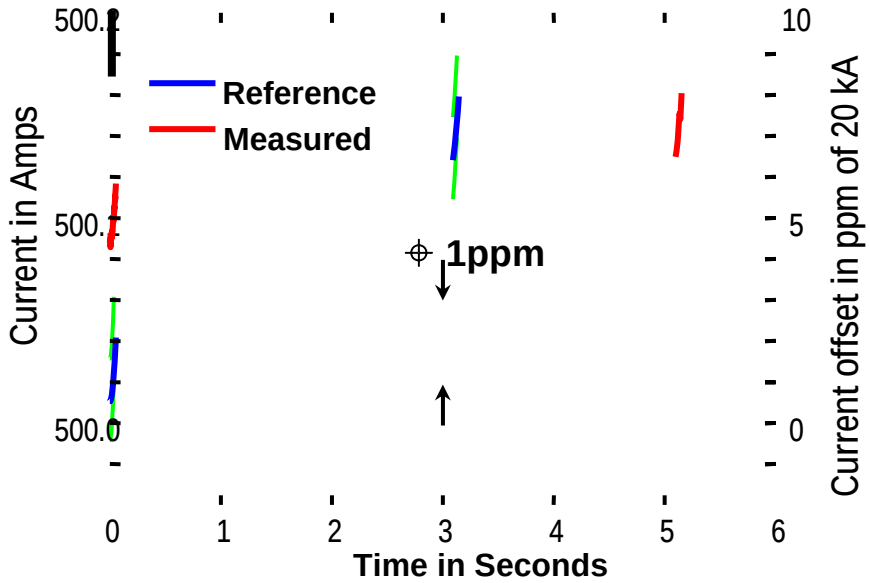
LHC 2008

[2kA,8V] converters

KEMPOWER, TRANSTECHNIK

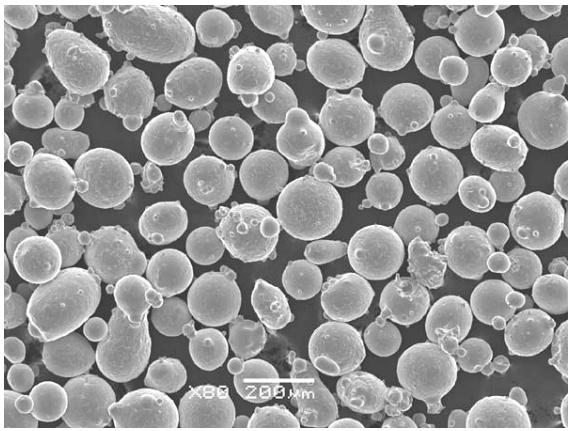
High-precision DCCT

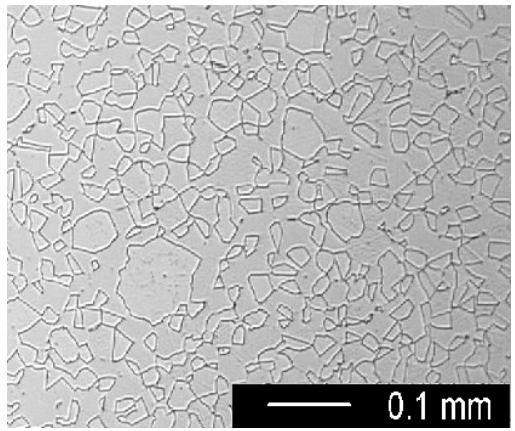
HITEC



Developing emerging technologies

HIP powder metallurgy for He-tight stainless steel covers

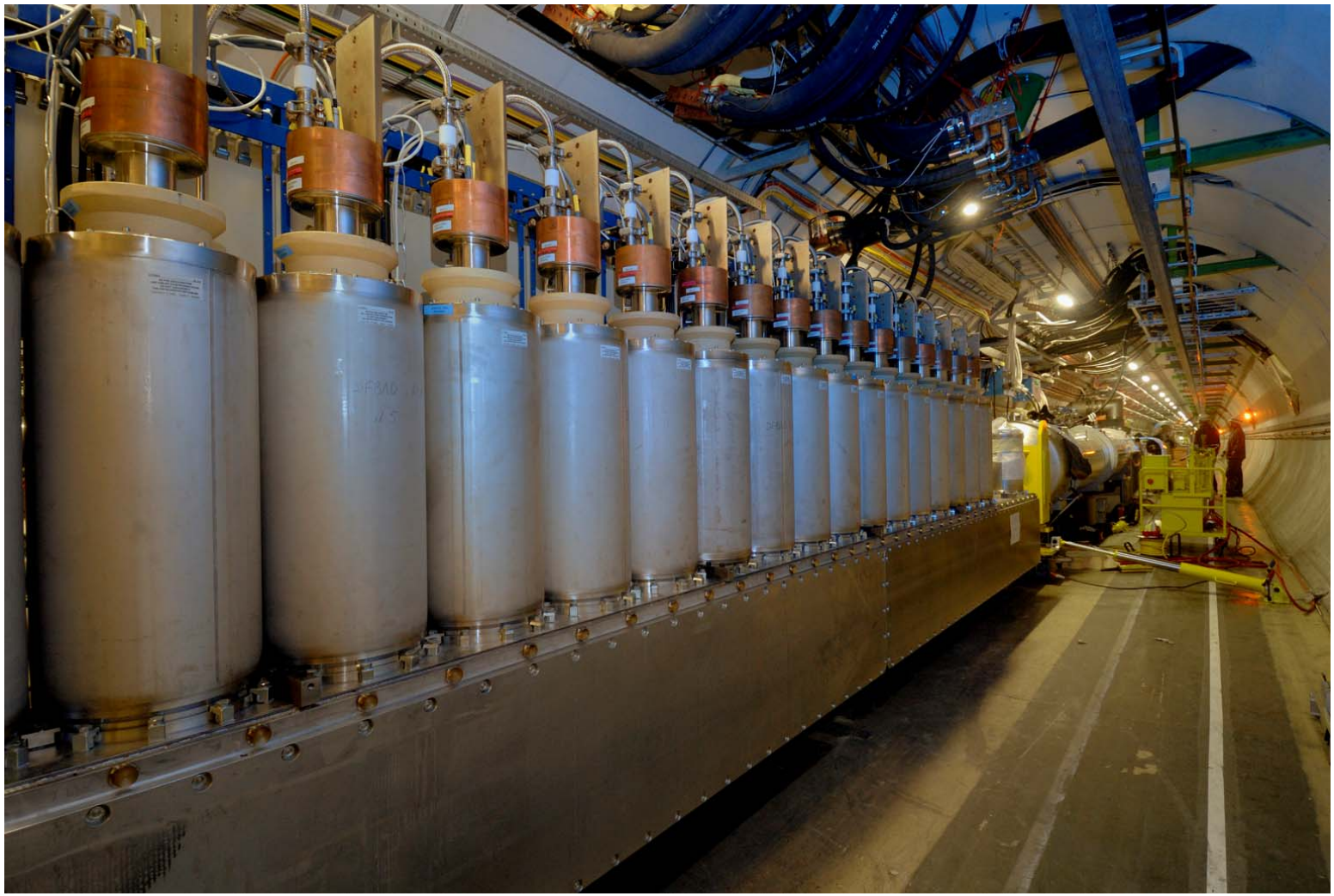




METSO POWDERMET

Developing emerging technologies

1200 current feedthroughs (0.6 to 12 kA) based on high-Tc superconductors



EAS, ASC

Industrial production in the lab

Cryogenic magnet test station at CERN

Cryostating	425 FTE.years
Cold tests	640 FTE.years

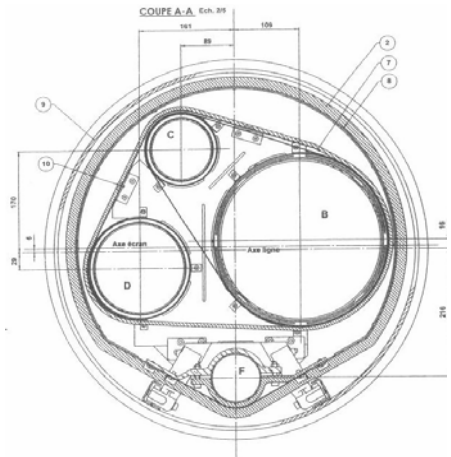
Recovering from industrial difficulties

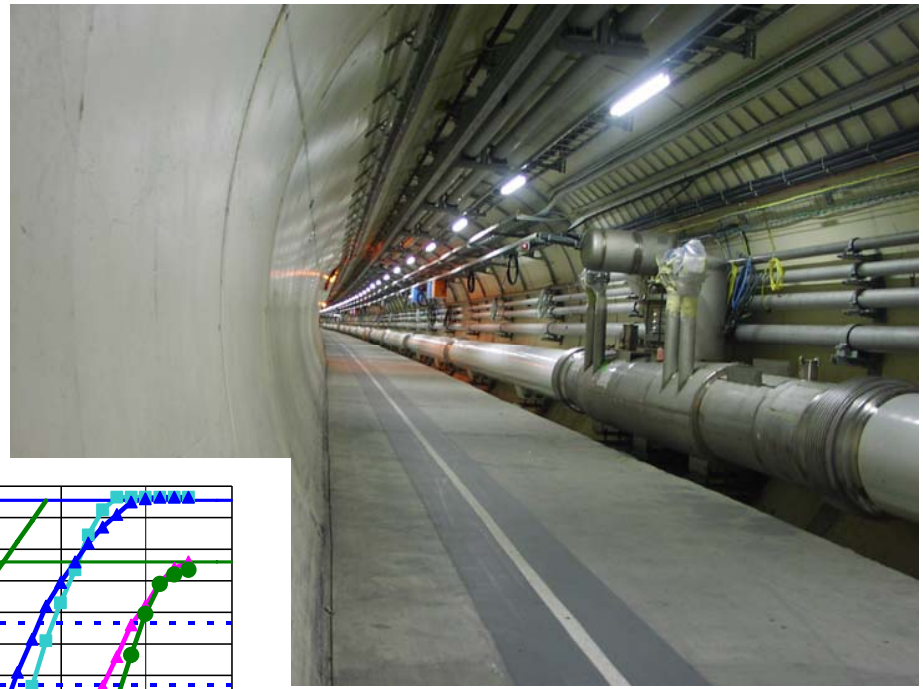
Internalization of SSS assembly after insolvency of contractor

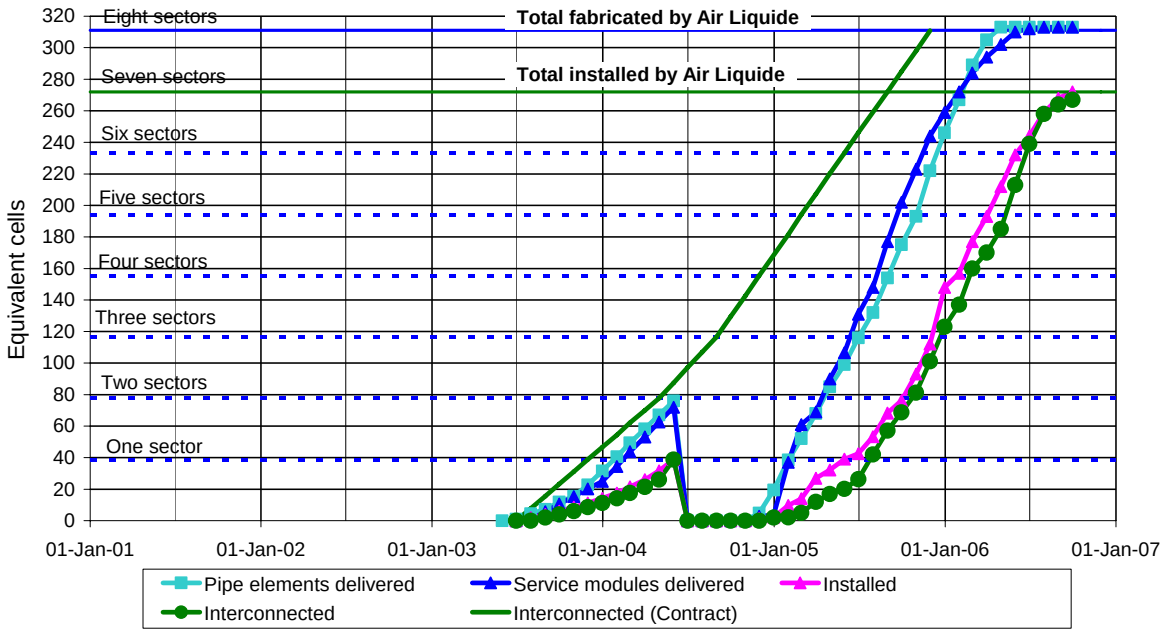
Recovering from industrial difficulties

Repair & reinstallation by CERN of cryogenic ring line sectors following technical/managerial production errors

LHC 2008







Conclusions

The sole end of science is the honor of the human mind...

Carl Gustav Jacobi

...however, large scientific instruments such as the LHC require massive investment of human and material resources and unprecedented level of organization, making them *industrial-size global projects in advanced technology*

- *Cooperation with industry* is essential from early stages of the project in order to achieve success within business constraints
  - Develop and maintain interest in a one-off, technically risky supply
  - Series production of innovative items at market prices
  - Competition with other products/markets
- Industrial competencies and production capacities developed for the LHC constitute a *comparative advantage*: they can now be applied to other projects sharing similar technologies

Projects sharing LHC technology

LHC 2008