Building large particle accelerators
The LHC, a case in scientific project management

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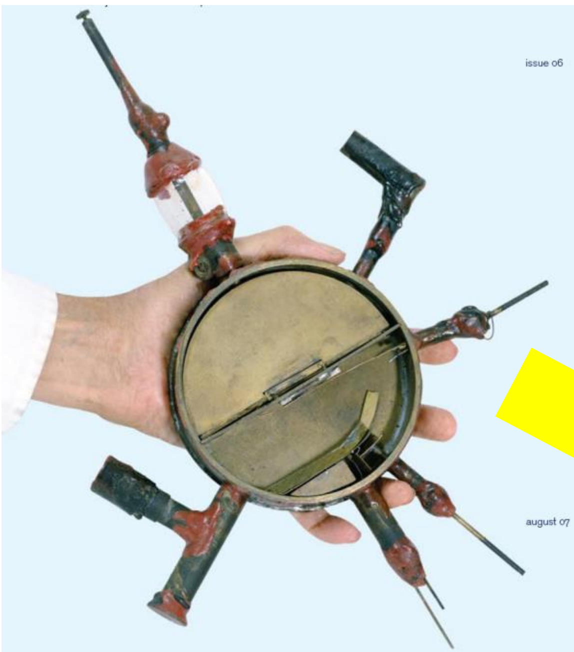
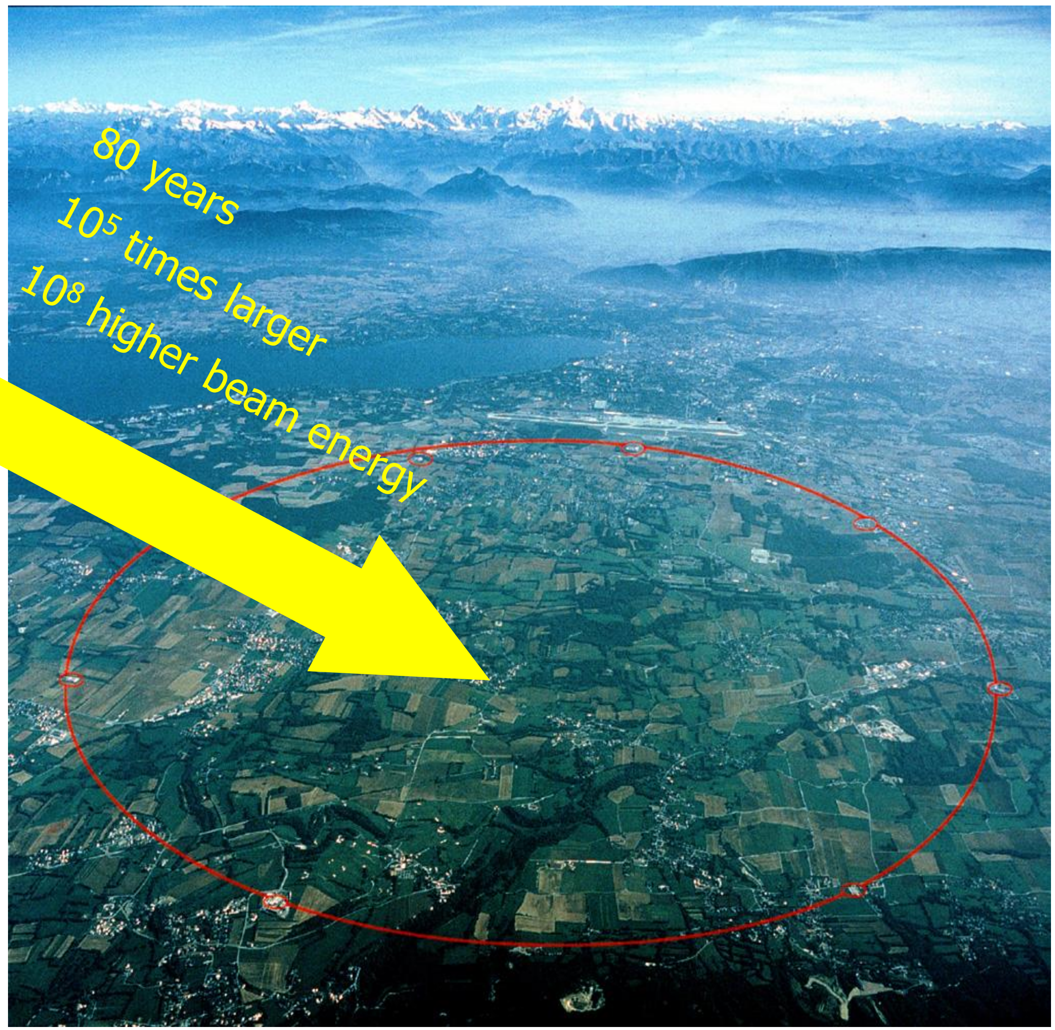
JUAS 2019 Course 2
26 February 2020

Development of circular accelerators
Performance increases faster than diameter!

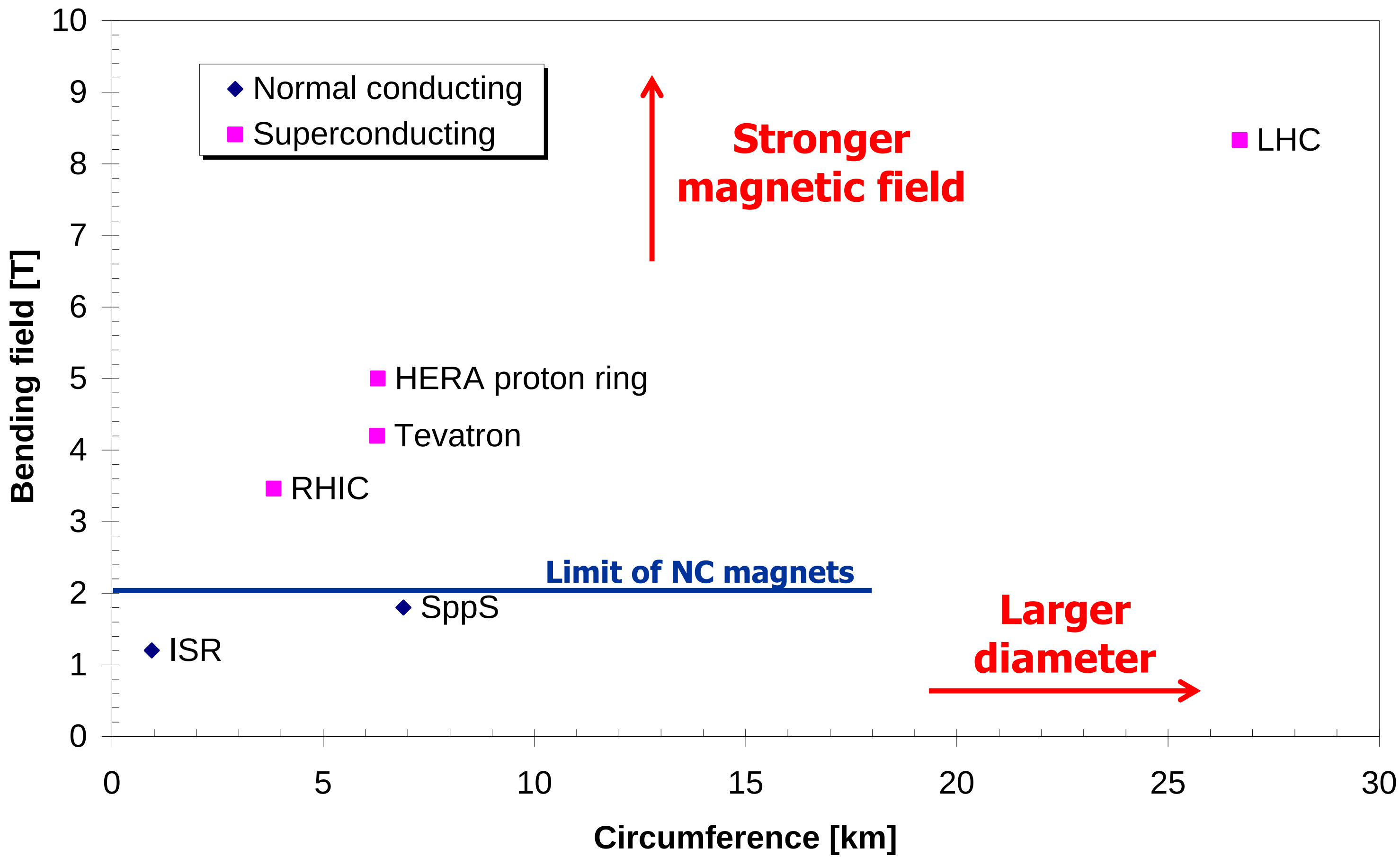


The first cyclotron (1930)

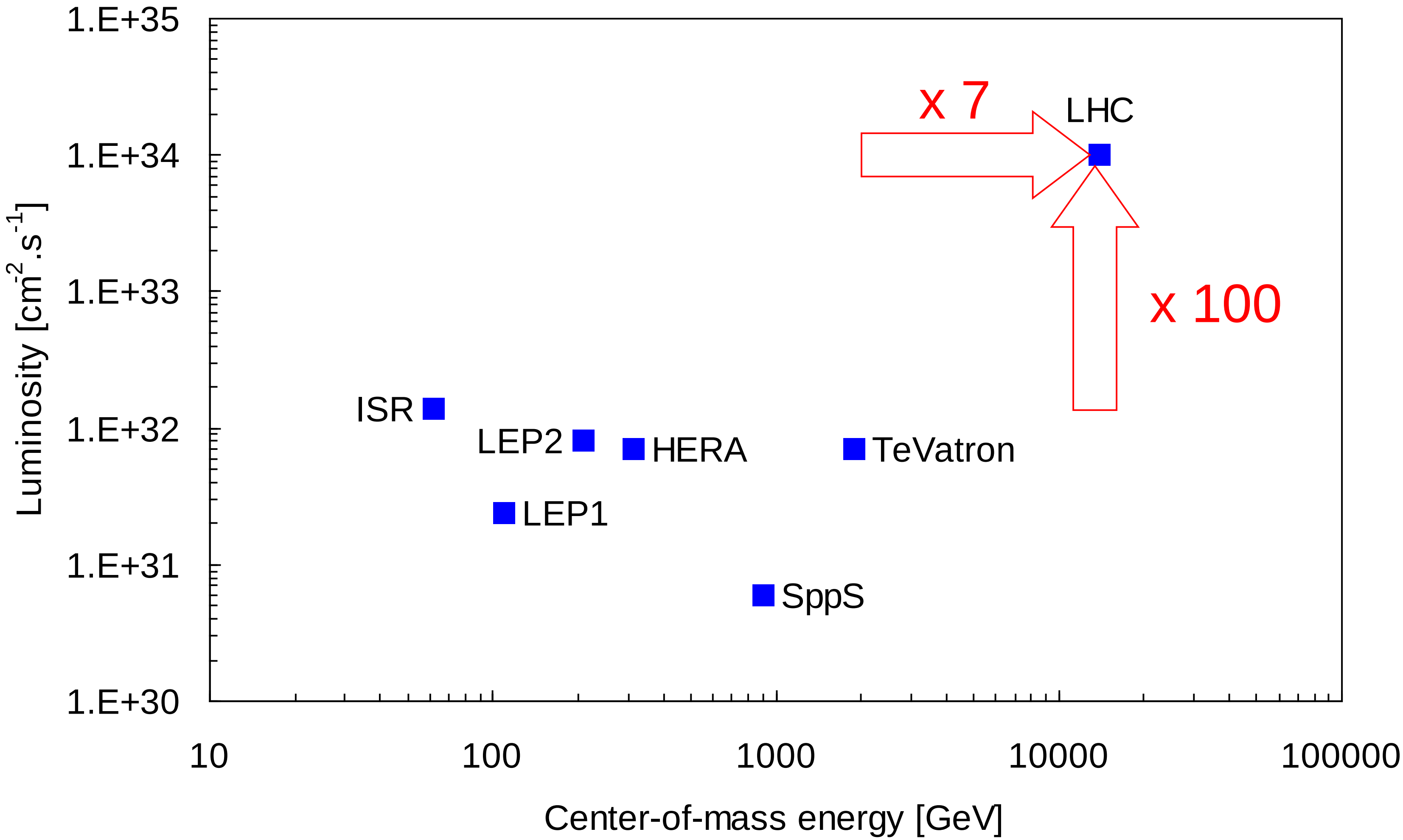


Large Hadron Collider (2009)

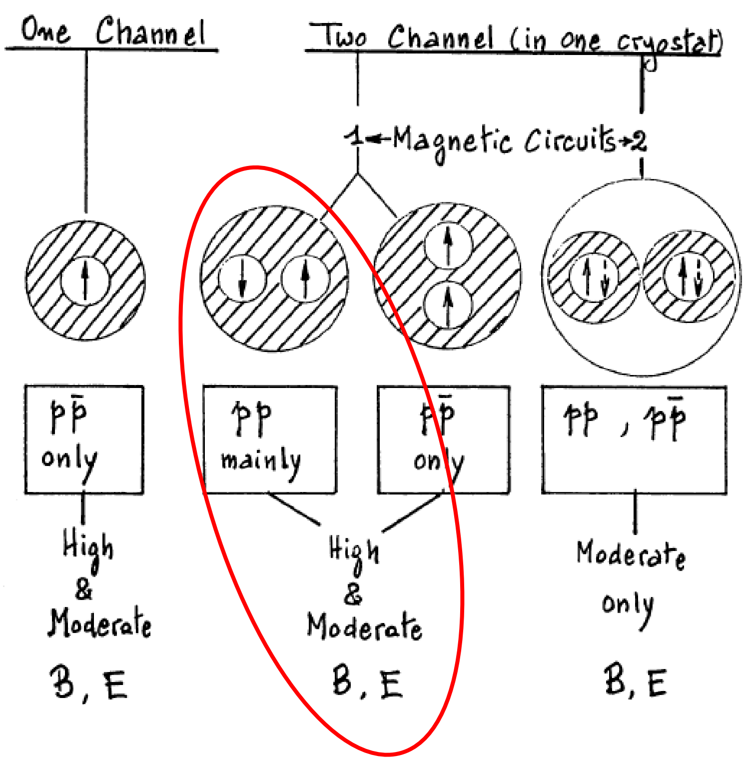
Axes of development of hadron colliders

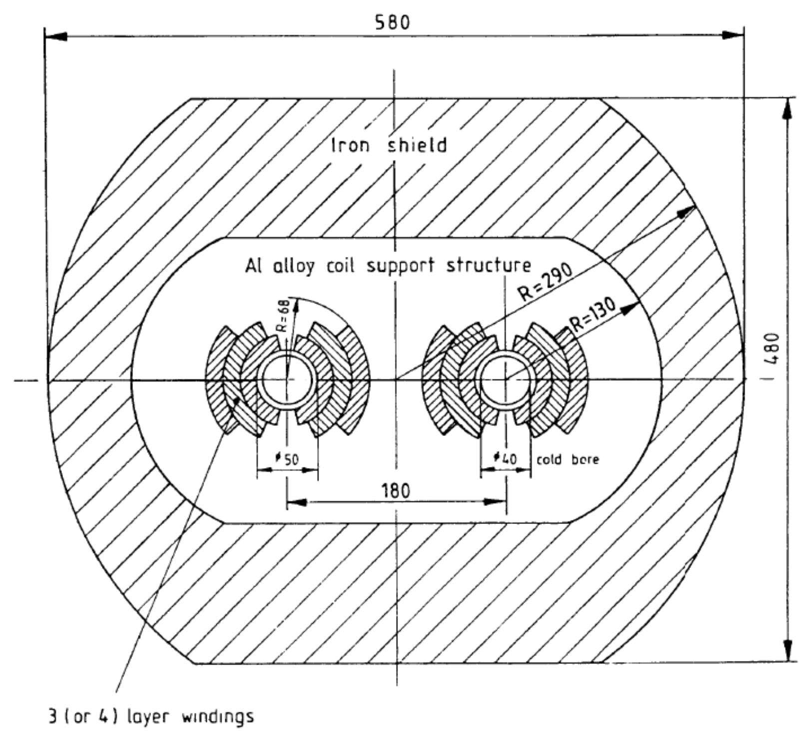


The LHC project
Aiming for a new territory in energy and luminosity

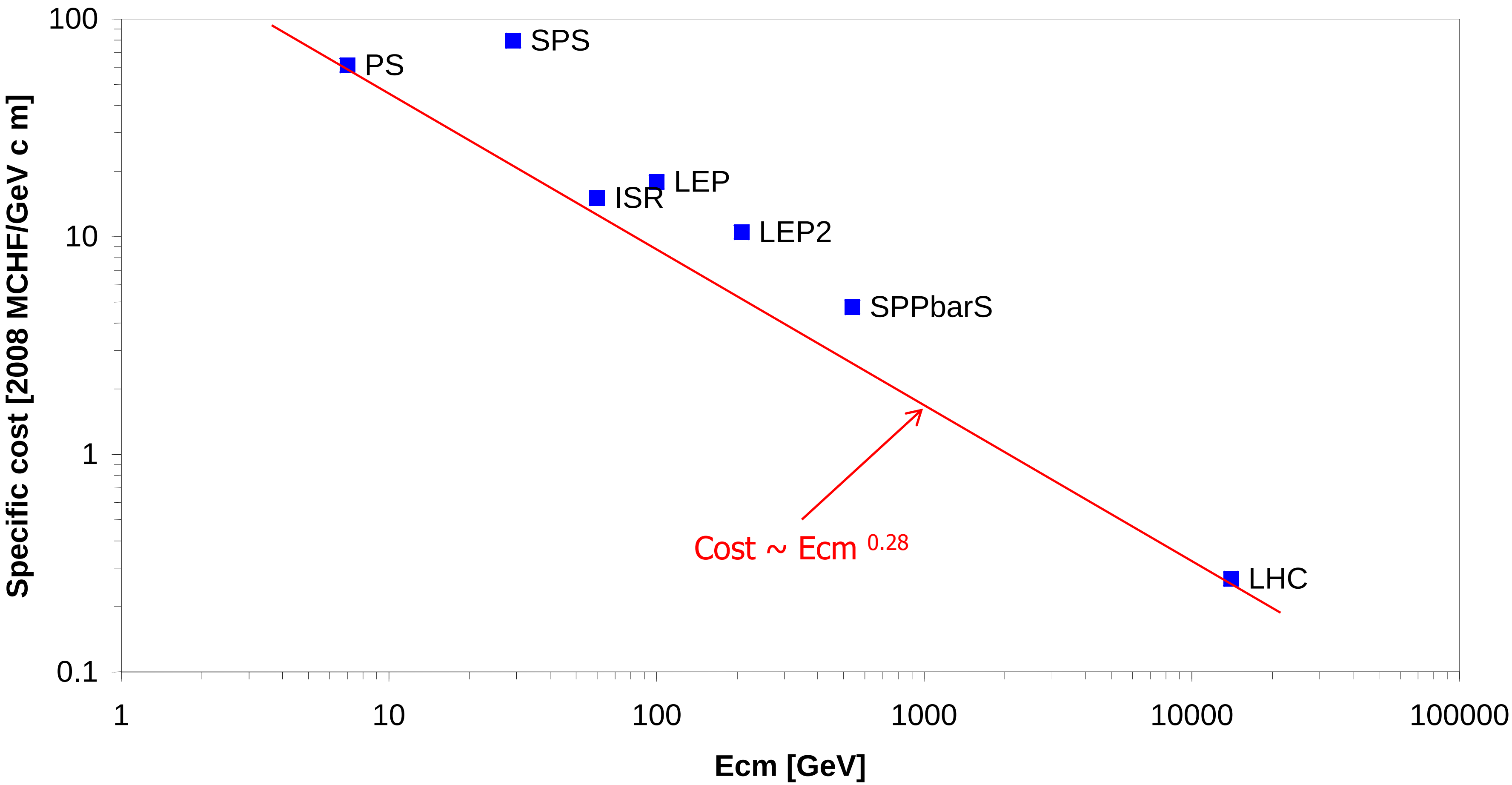


The LHC project: basic decisions
ECFA Workshop Lausanne 1984

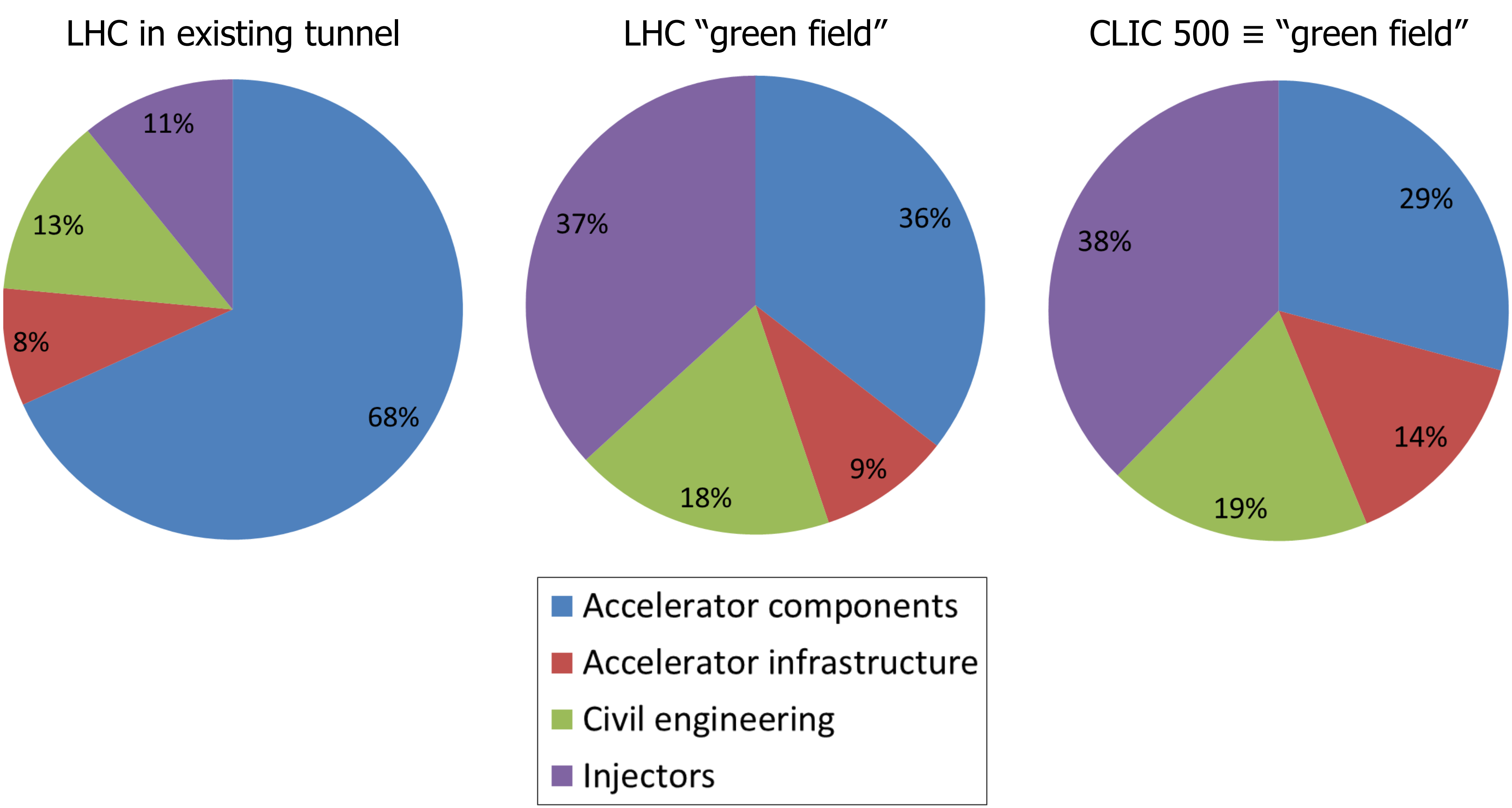




Technical progress + economy of scale = cost efficiency



Cost structure of large accelerator projects



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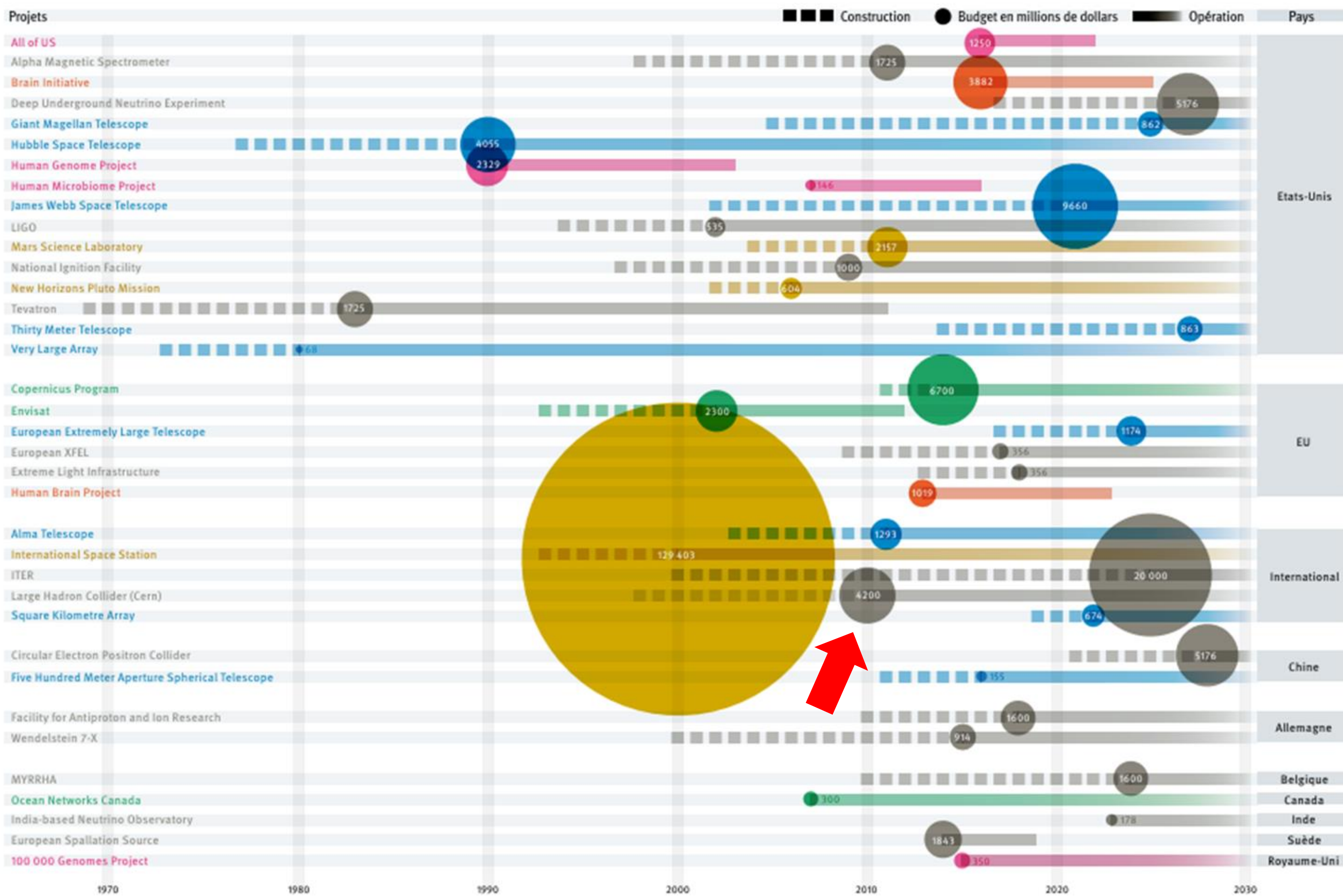
Timeline & cost of big science projects



Technological choices and industrial strategy

- The right level of technology
  - Adaptation & improvement of state-of-the-art for affordability
  - Reasoned & focussed development of emerging technologies
- Doing it in the lab or going to industry?
  - Principle: *go to industry whenever possible*
  - Cases for not going to industry
    - Unability to specify
    - Difficulty to define and manage interfaces
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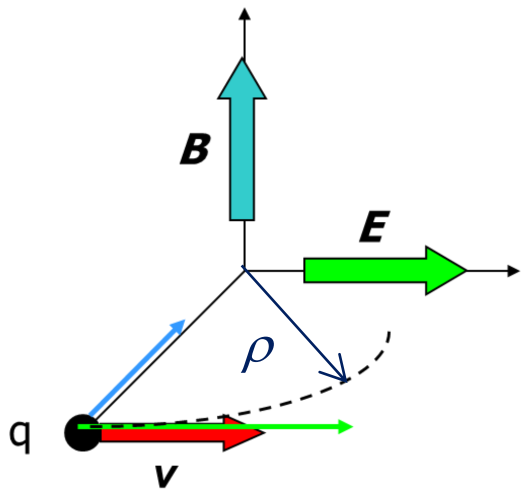
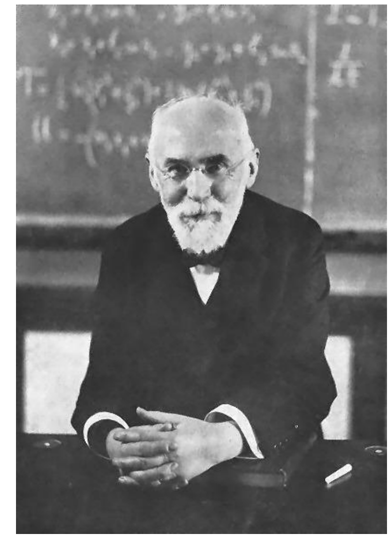
The main technical challenge of LHC: magnetic field



Lorentz force

$$\vec{F} = \frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \times \vec{B})$$



H.A. Lorentz

- In plane normal to $\vec{B}$

$$F = evB = \frac{mv^2}{\rho} = \frac{\gamma m_0 v^2}{\rho}$$

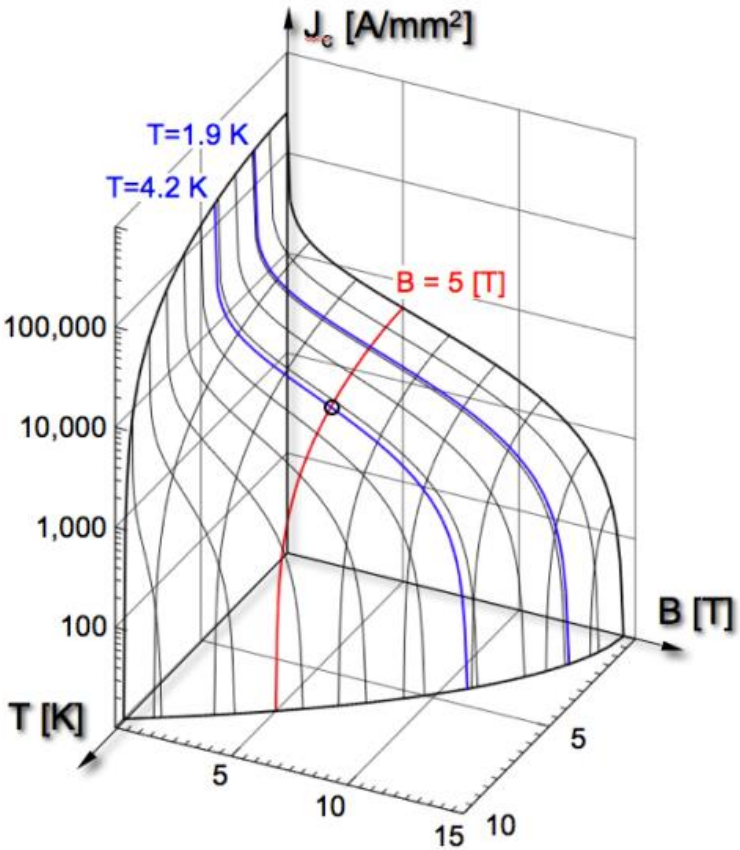
- Hence

$$\frac{p}{e} = B\rho \qquad B\rho[\mathrm{T.m}] \approx \frac{p[\mathrm{GeV/c}]}{0.3}$$

magnetic rigidity

  - Nominal momentum 7000 GeV/c
  - Bending radius 2804 m
  - Nominal field ≈ 7000/ (0.3 x 2804) ≈ 8.3 T ⇒ superconducting magnets

Basics of superconductivity

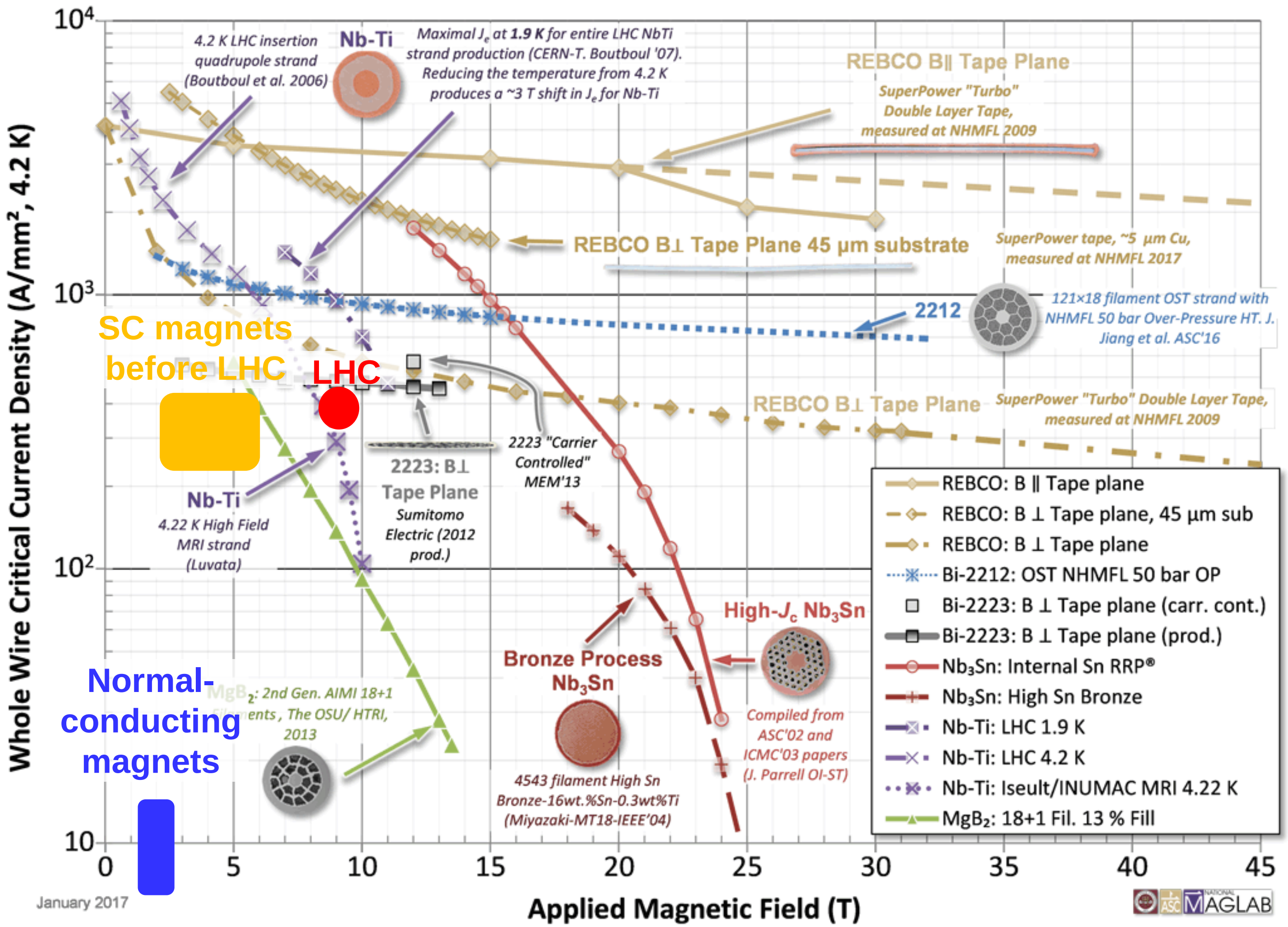


- The superconducting state only occurs in a limited domain of (low) temperature, magnetic field and current density, limited by the «critical surface» of the material
- The working point must remain below the «critical surface» of the superconductor
- Operating at lower temperature increases the working range in the magnet design plane (J_c,B)
- In practice, operate at temperature well below T_c
- Most of superconducting magnets in use today use Nb-Ti with T_c = 9.2 K

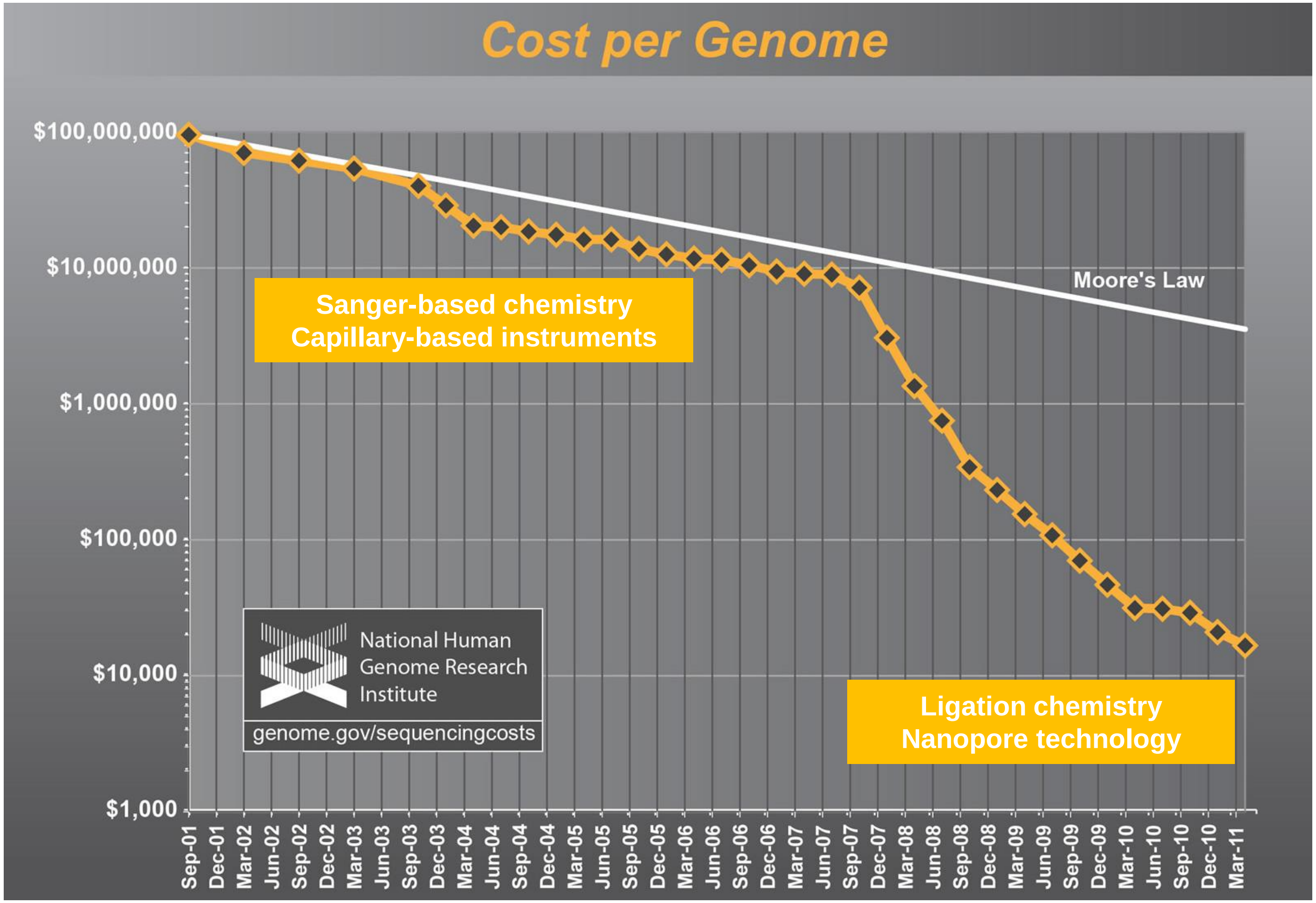
The right level of (superconducting) technology

Why use Nb-Ti at 2 K instead of Nb_3Sn at 4.2 K?

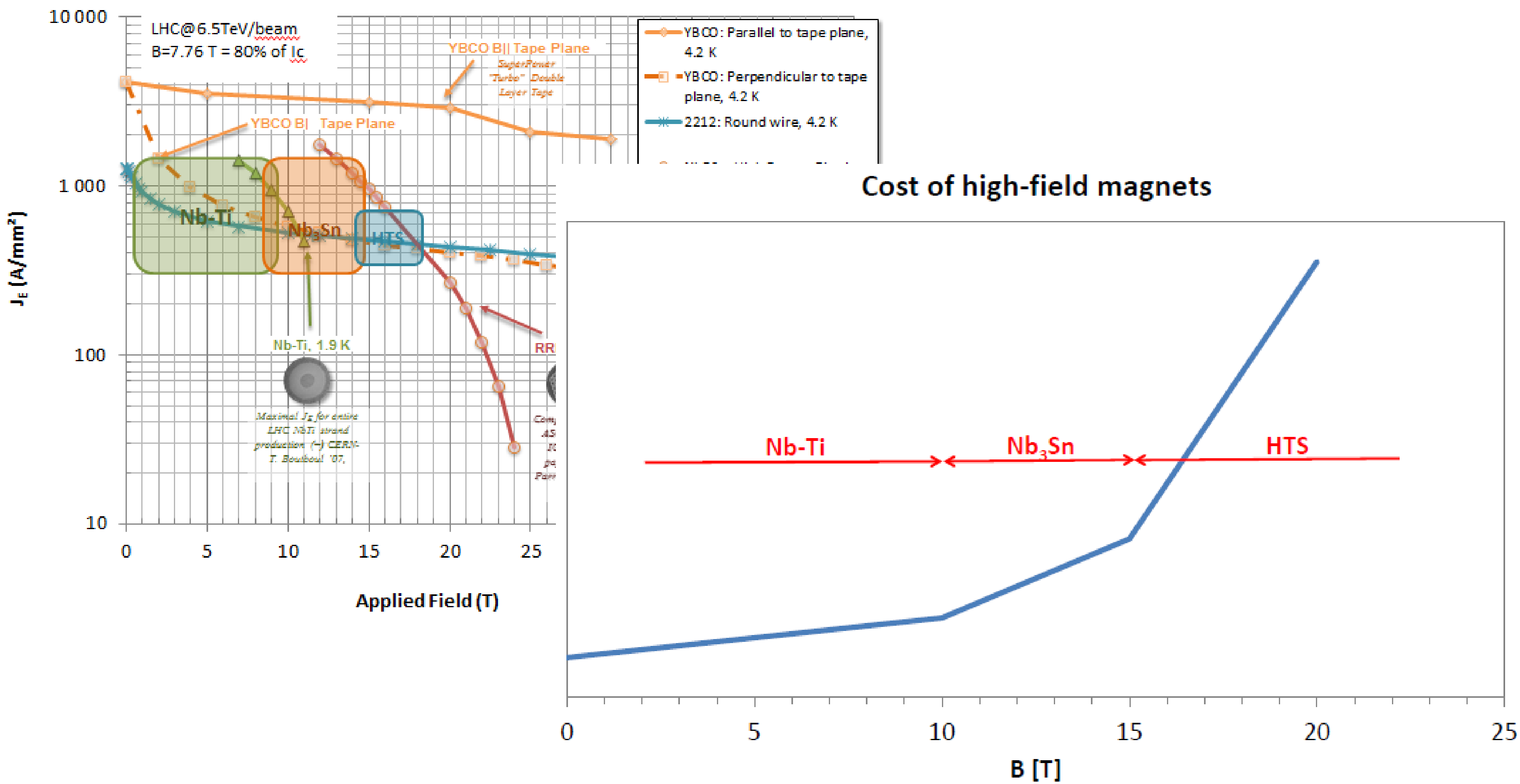
Why not use high-temperature superconductors?



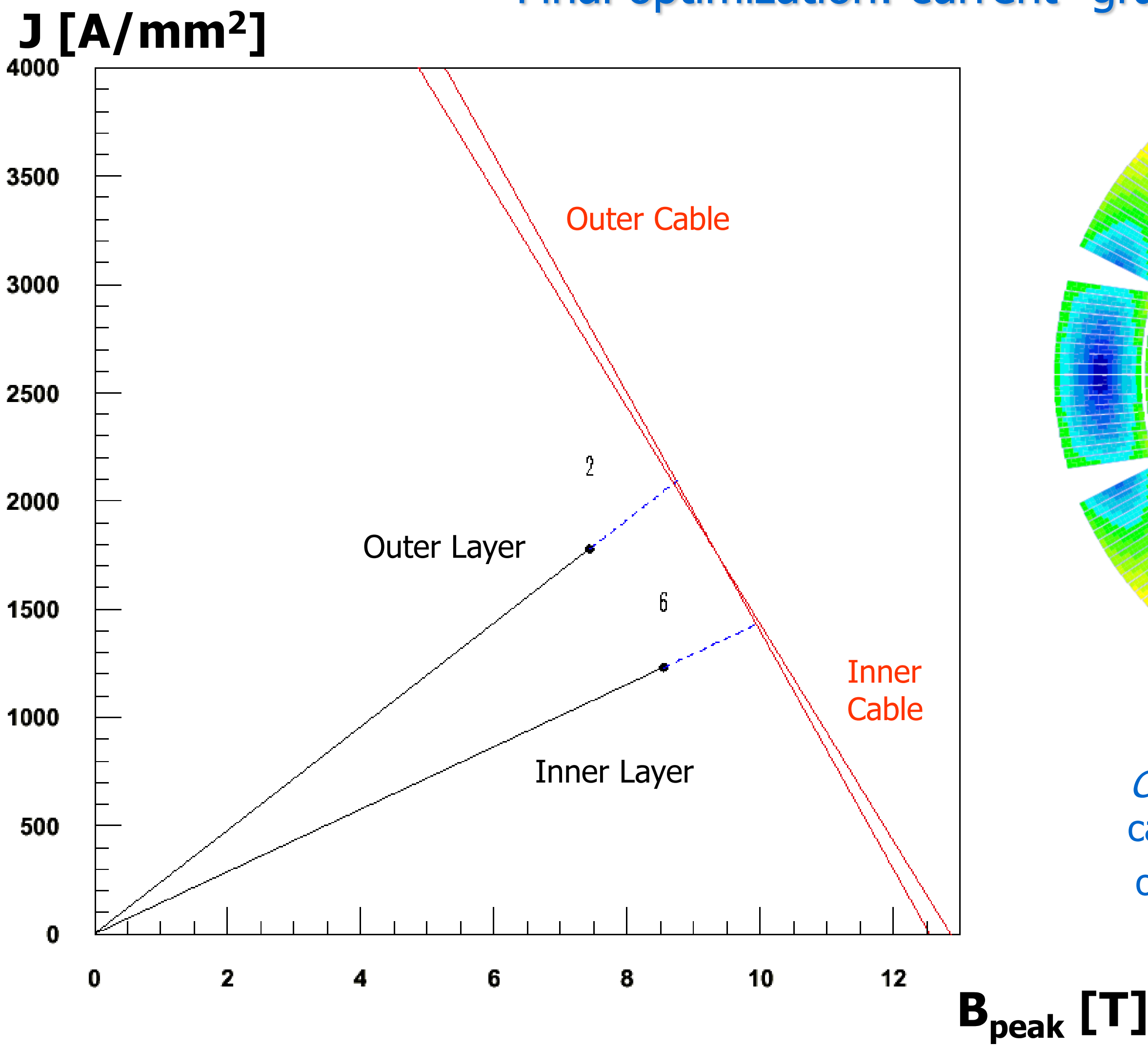
Progress: incremental vs breakthrough
The case of human genome sequencing

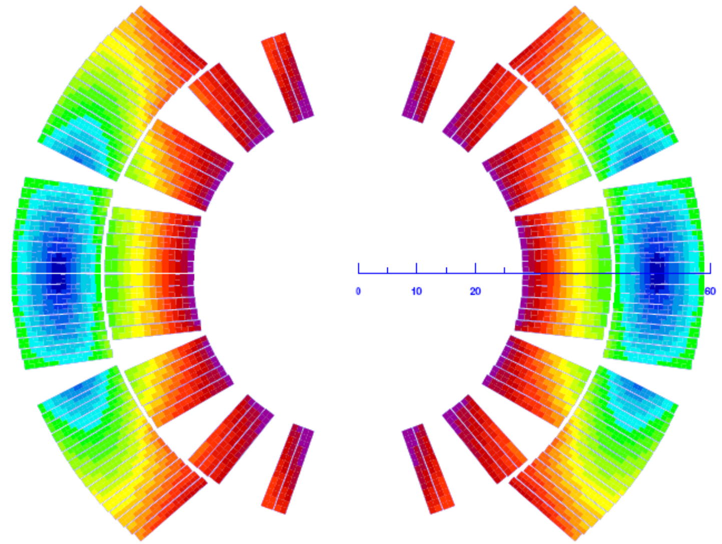


Understanding discontinuities in cost structure
High-field superconducting magnets



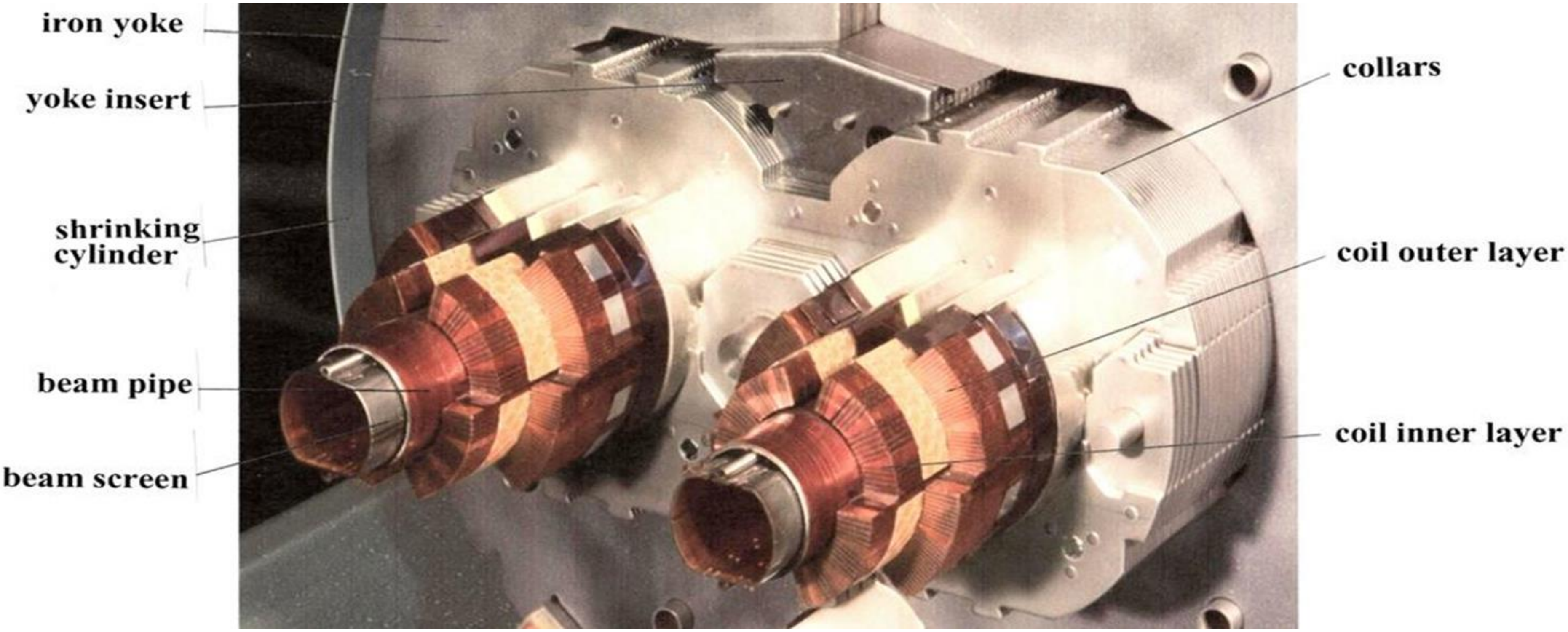
Load lines of LHC main dipole
Final optimization: current "grading"



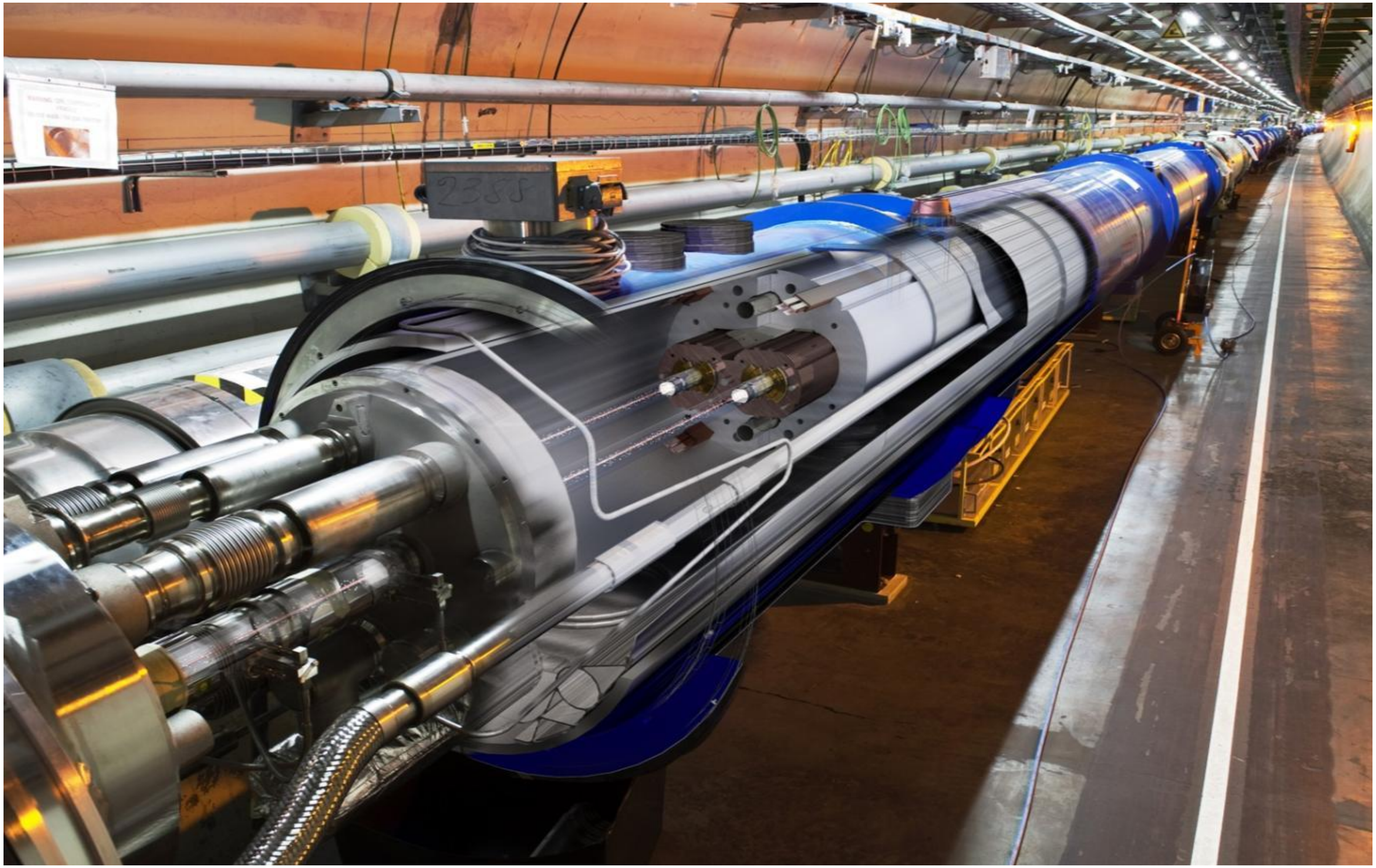


Current grading permits the outer cable, which sees a lower field, to operate at higher current density

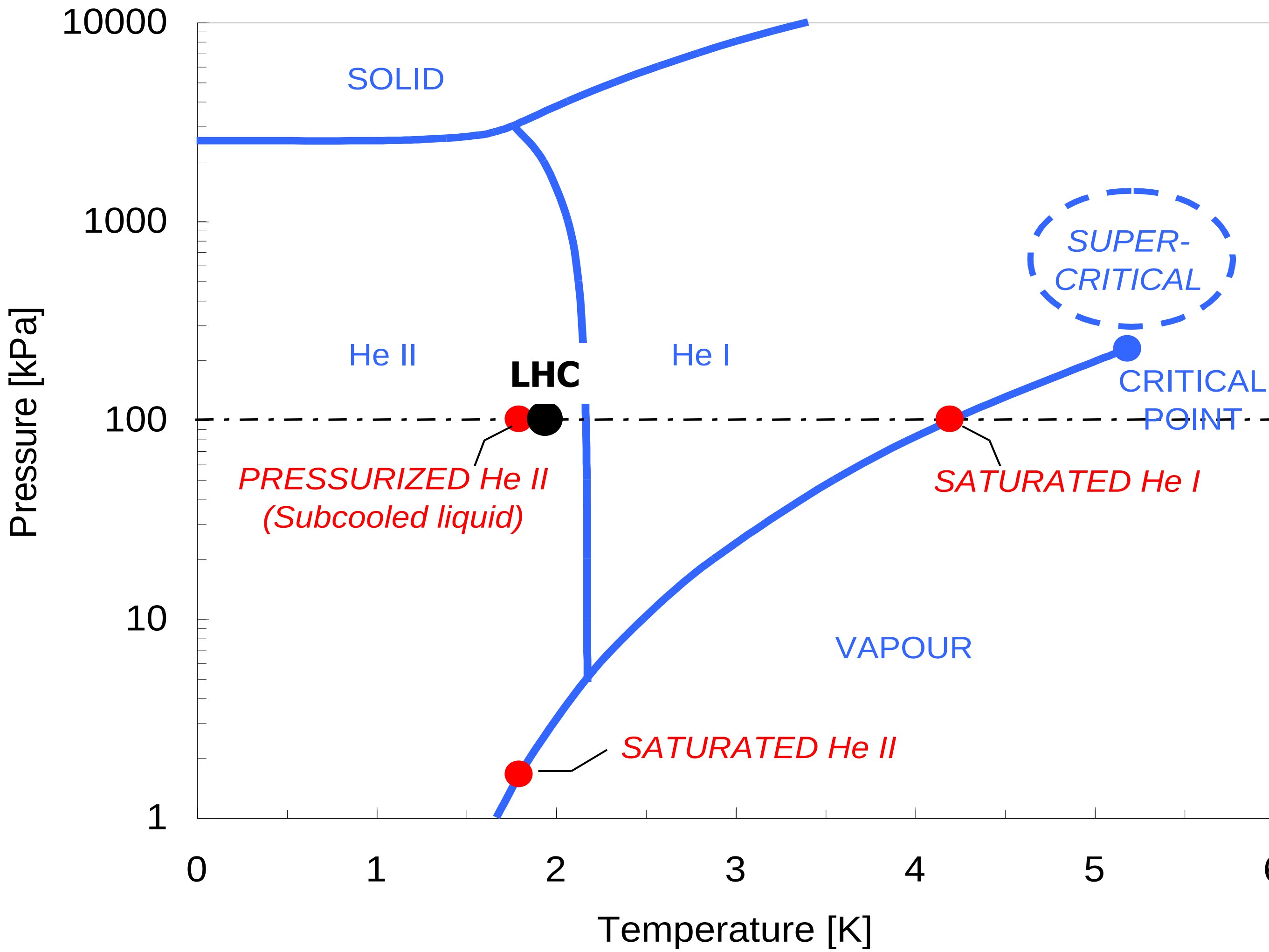
LHC dipole magnet design… & construction
How to produce 20 km of this structure



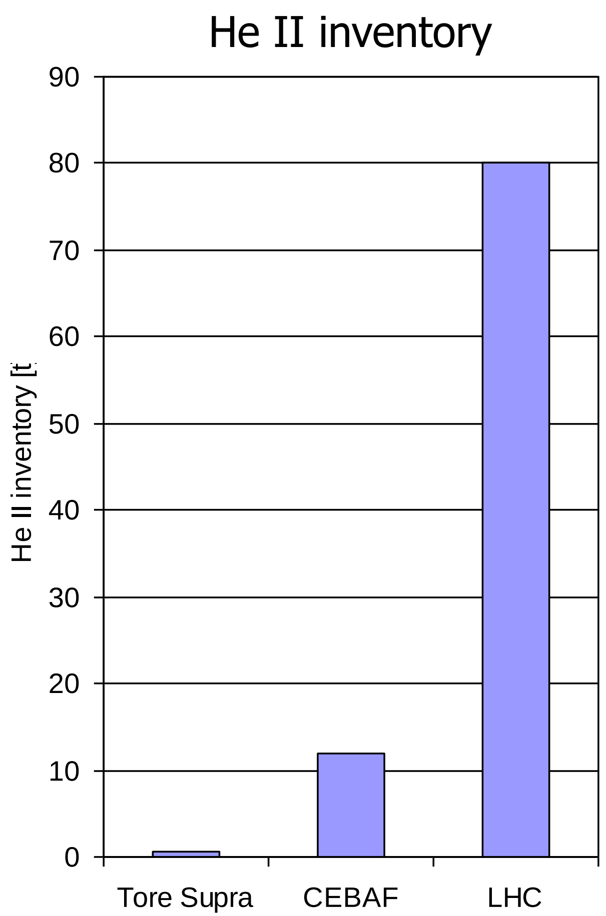
1232 twin-aperture superconducting dipoles
23 km of superfluid helium cryostats

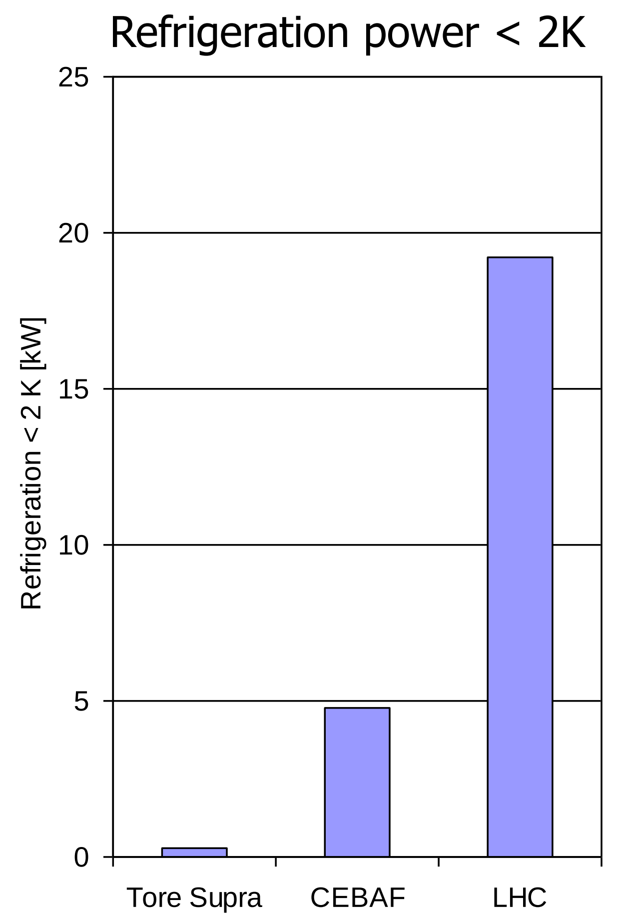


Cooling LHC magnets with superfluid helium

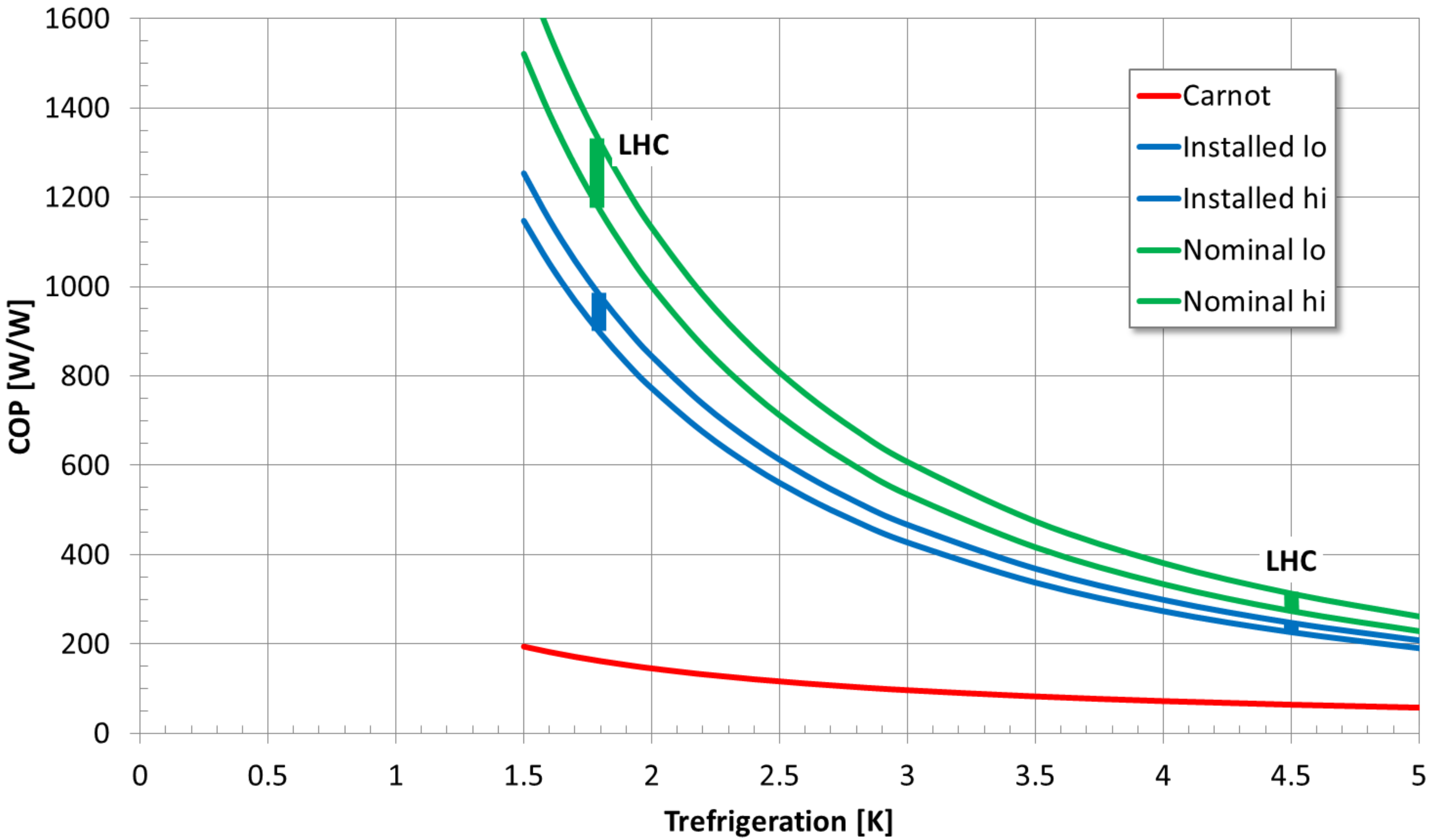


Well beyond the previous state-of-the-art
Superfluid helium on an unprecedented scale

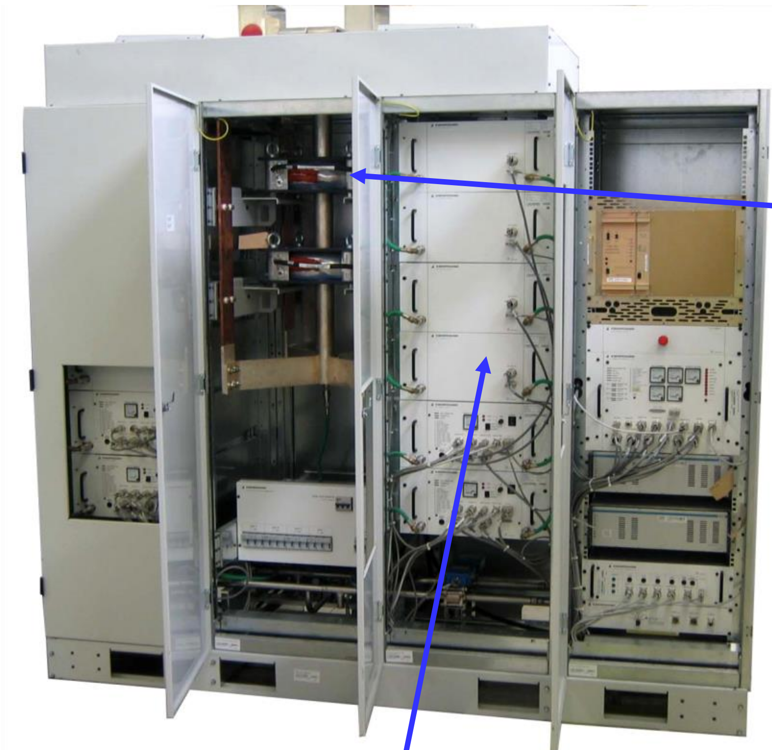




Thermodynamic cost of low-temperature refrigeration
C.O.P. of cryogenic plants



State-of-the-art technology for affordable hi-tech
Modular switched-mode power converters

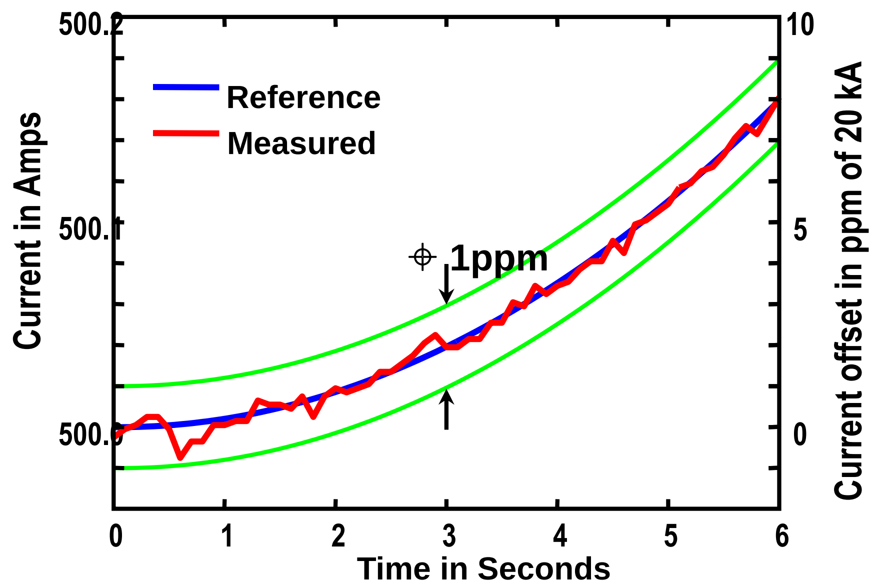


[2kA,8V] converters

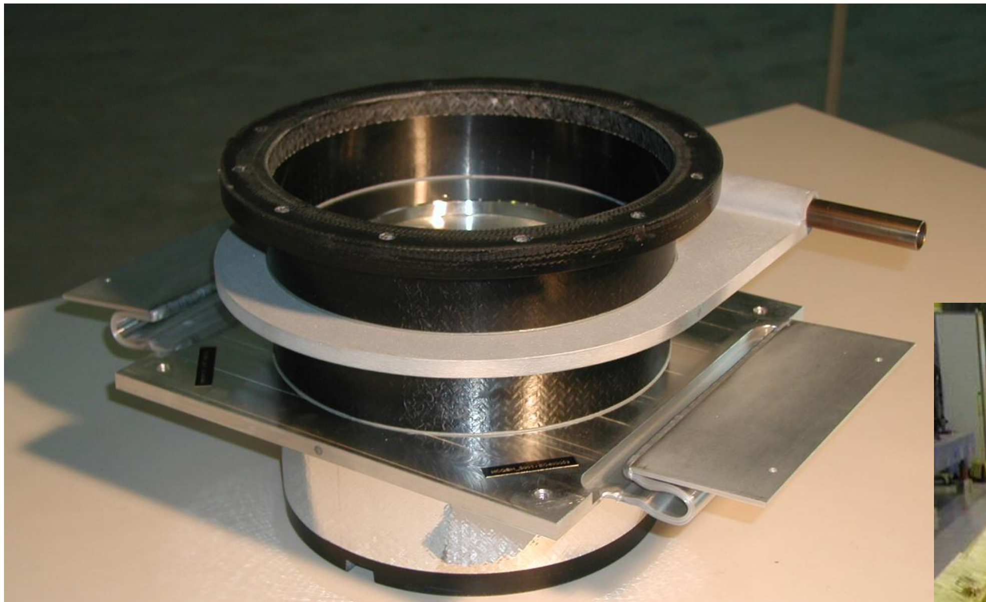
KEMPOWER, TRANSTECHNIK

High-precision DCCT

HITEC



State-of-the-art technology for affordable hi-tech
Industrial solutions for magnet cryostats



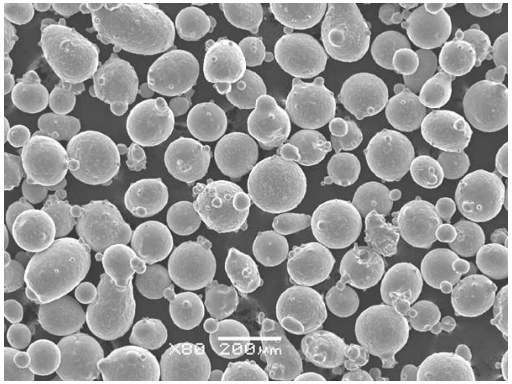
Low heat inleak
GFRE support post

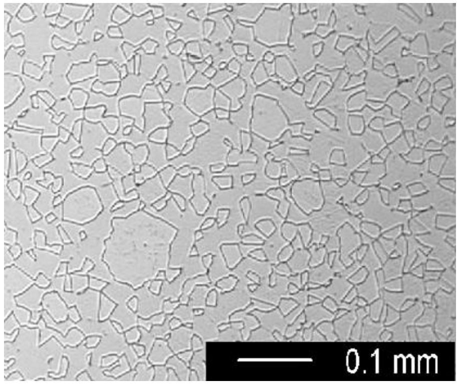
EWK

CASA ESPACIO

Aluminium extrusion
for thermal shield

Developing emerging technologies
HIP powder metallurgy for He-tight stainless steel covers



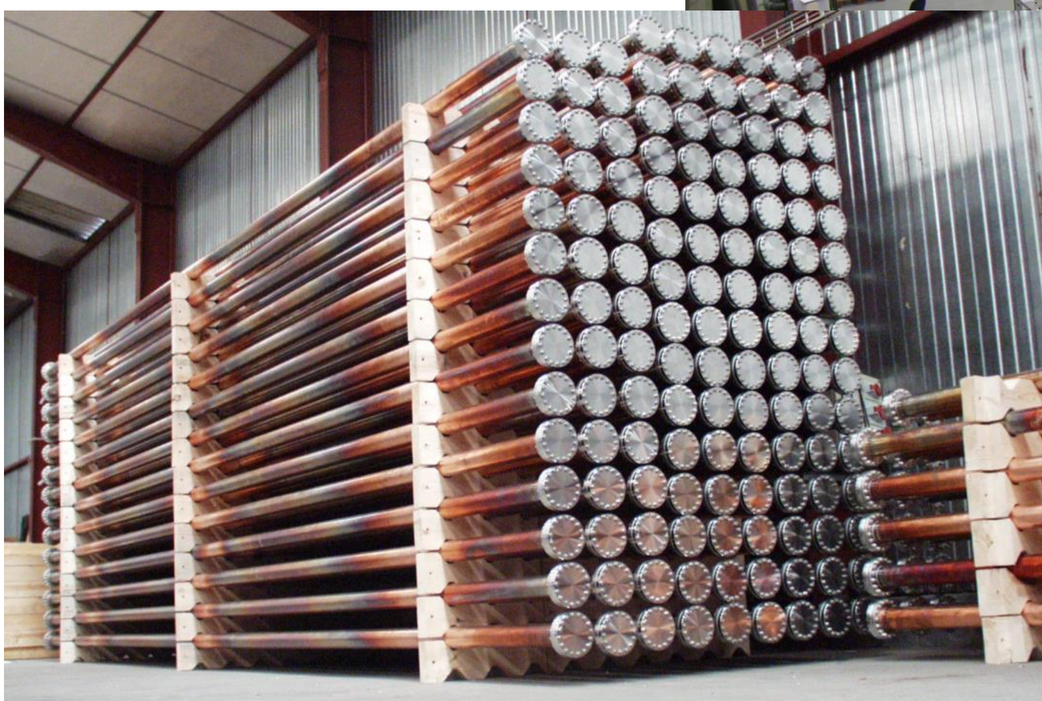


Better, cheaper than conventional forgings

METSO

Developing emerging technologies
NEG-coating of vacuum chambers by magnetron sputtering

Non-evaporable getters sputtered on the inner surface of vacuum chambers provide distributed pumping, reduce secondary electron emission yield

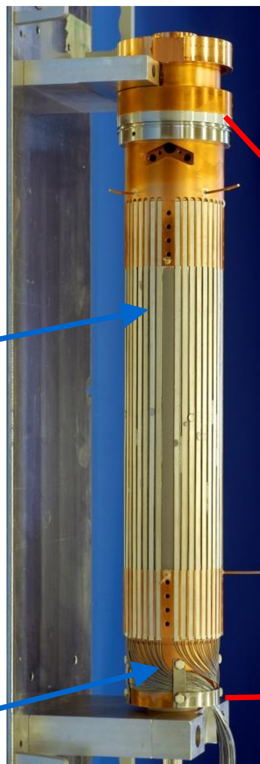


Developing emerging technologies
1200 current feedthroughs (0.6 to 12 kA) based on HT superconductors

13 kA HTS current lead

BSCCO 2223 tapes

Nb-Ti wires



Economy ~ 3400 W @ 4.5 K ~ 5000 l/h liquid He

⇒ capital: save extra cryoplant

⇒ operation: save ~ 3.2 MW

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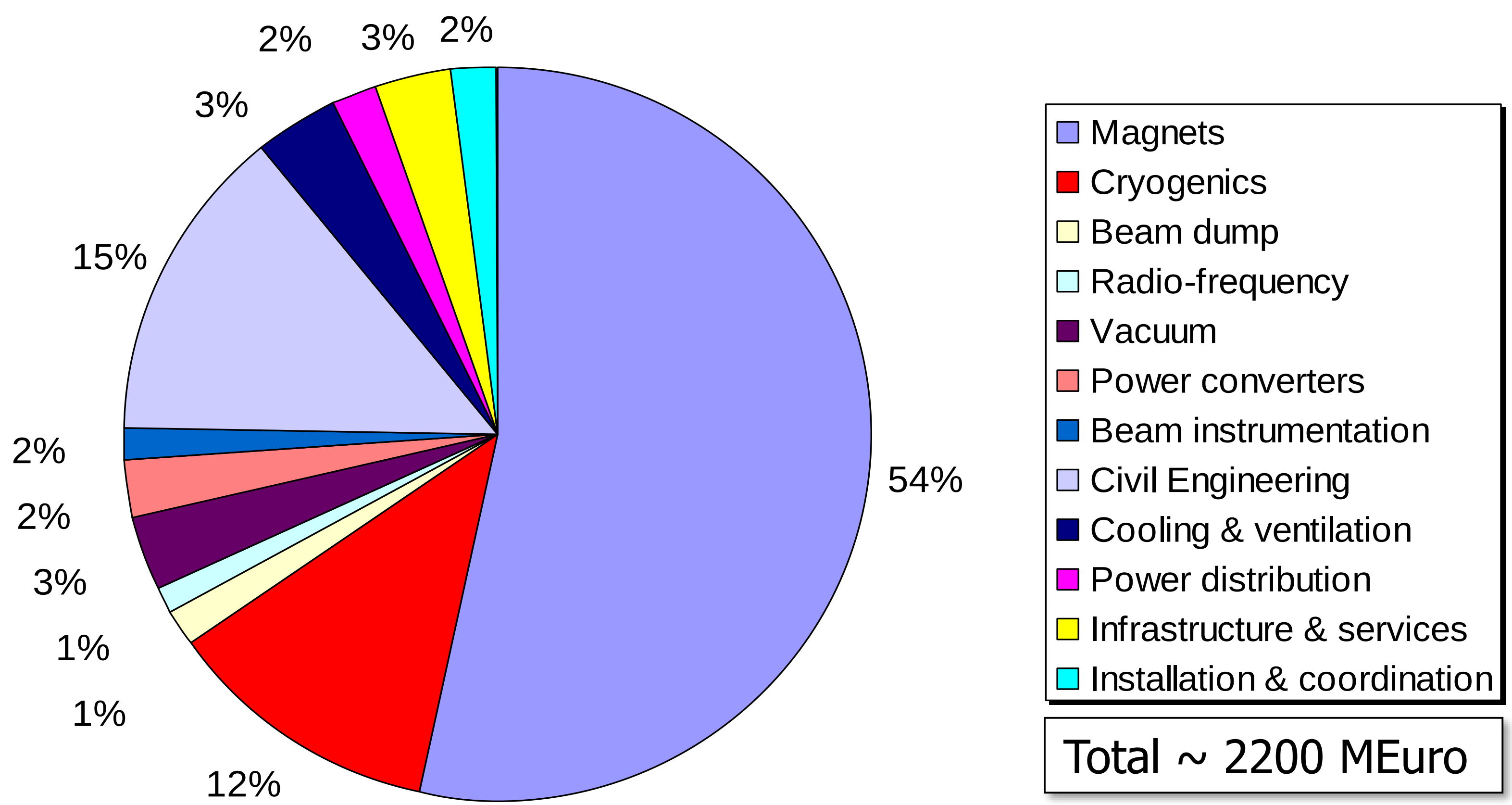
Cost structure of the LHC accelerator (main ring)



Total ~ 2200 MEuro

Procurement from industry
CERN legal & regulatory framework

- CERN purchasing rules
  - Preference given to suppliers from CERN Member States
  - Simple (simplistic?) rule: adjudication to lowest bidder meeting the technical specification
  - Possibility to use « best value for money » for service contracts
  - Basically no price negotiation after opening of the bids
- Seeking « fair return » among CERN Member States
  - A *de facto* requirement for a multinational organization
  - Difficult to achieve with lowest-bidder rule
  - Amendment to the rules: bidders from « poorly balanced » Member States may align their price on lowest bidder and be awarded contract, within limits
- Handling special « in-kind » contributions
  - Must be defined in terms of deliverables
  - Valued at « European market » prices
  - Should not allow to bypass lowest-bidder rule: value must be competitive in order not to prejudice Member State industries

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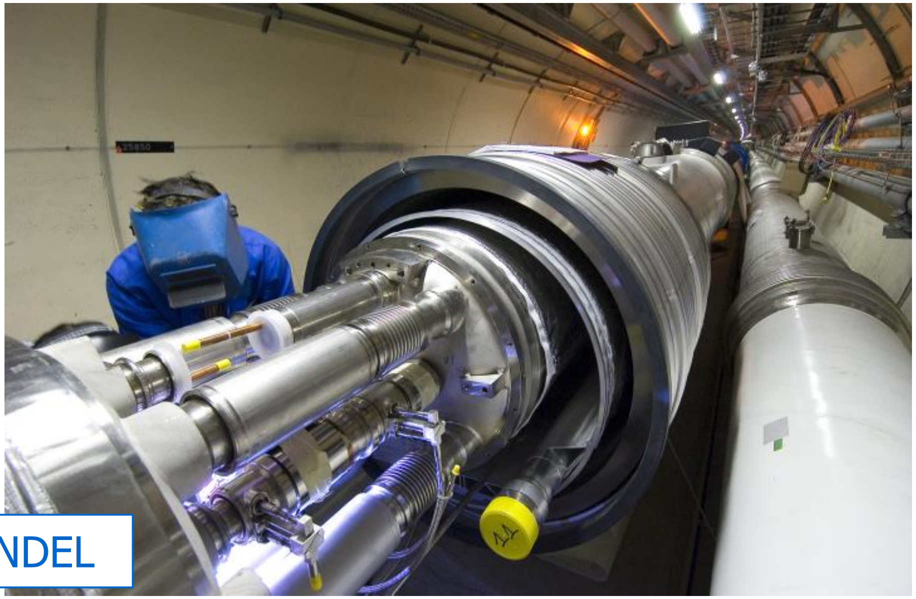
Bringing industry to the laboratory
Cryostat assembly by industry on CERN site

ICS Consortium

Cryostating 425 FTE.years

Bringing industry to the laboratory
Interconnections in the LHC tunnel

65’000 electrical joints	40’000 cryogenic junctions
Induction-heated soldering	Orbital TIG welding
Ultrasonic welding	
Very low residual resistance	*Weld quality*
HV electrical insulation	*Helium leaktightness*



INEO-ENDEL

Producing in-house with industrial methods
Cryogenic magnet test station at CERN

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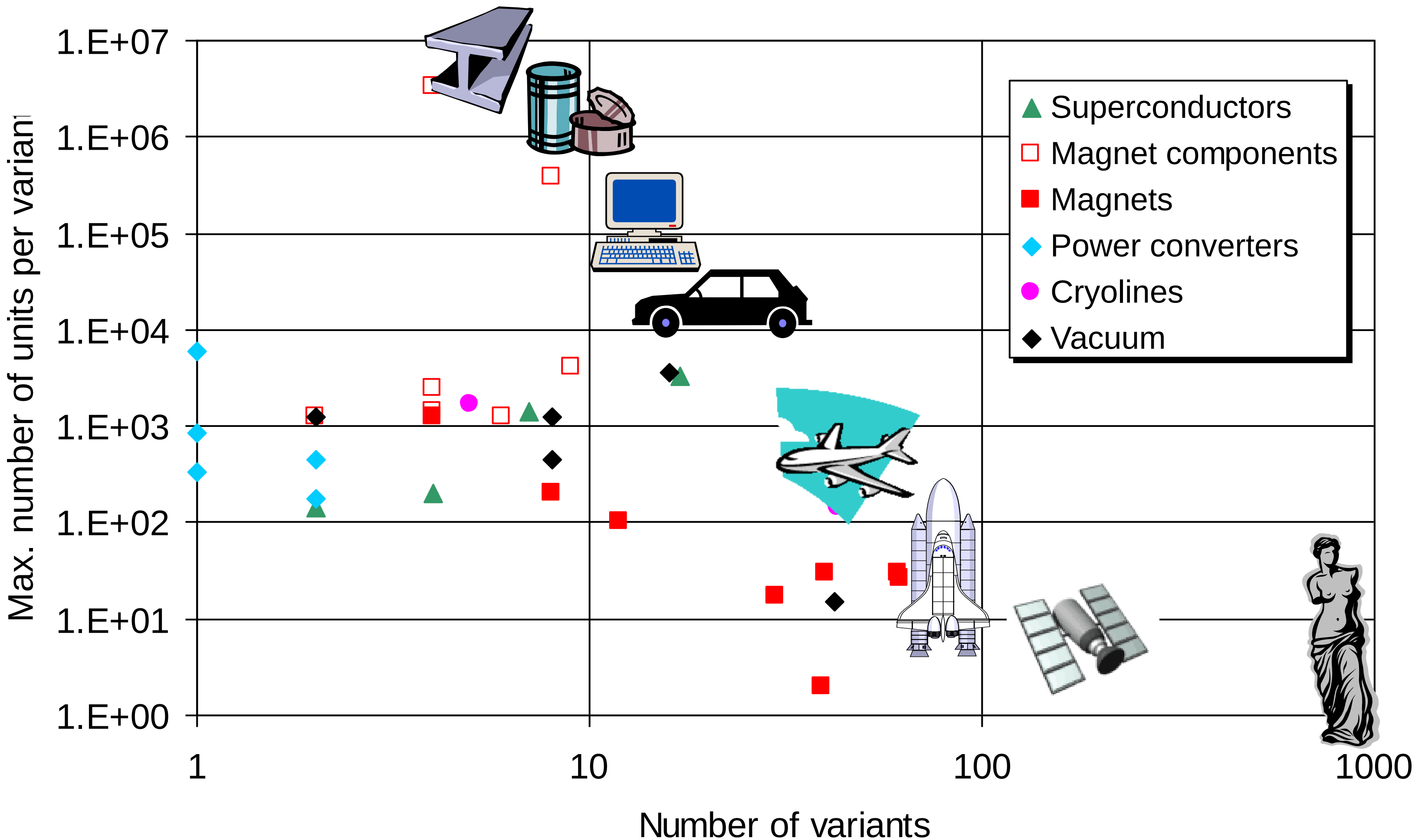
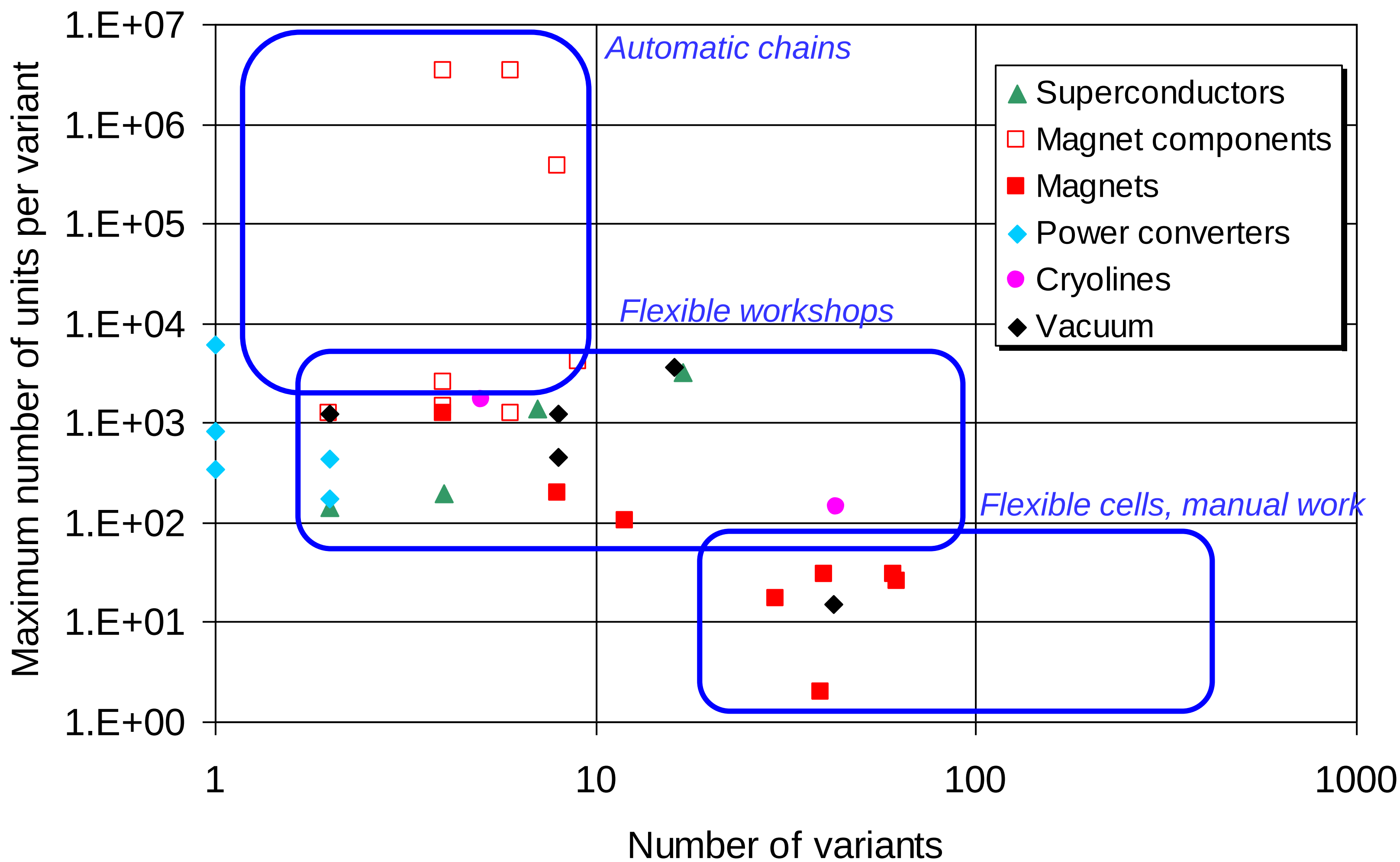
LHC components & industrial products



Series production of LHC components



Experimental learning curves
LHC superconducting dipole magnets

- <u>Unit cost c(n) of nth unit produced</u>

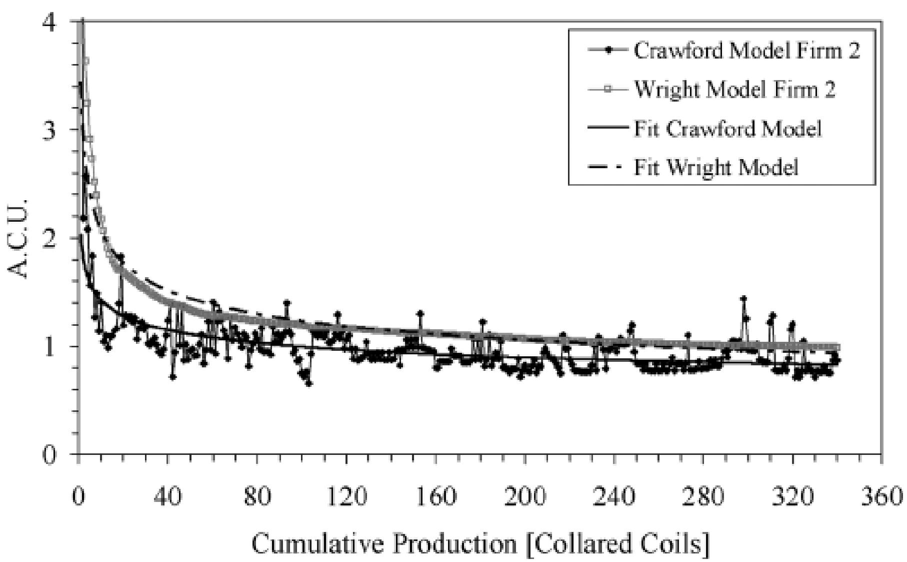
$$c(n) = c(1)\, n^{\log_2 a}$$

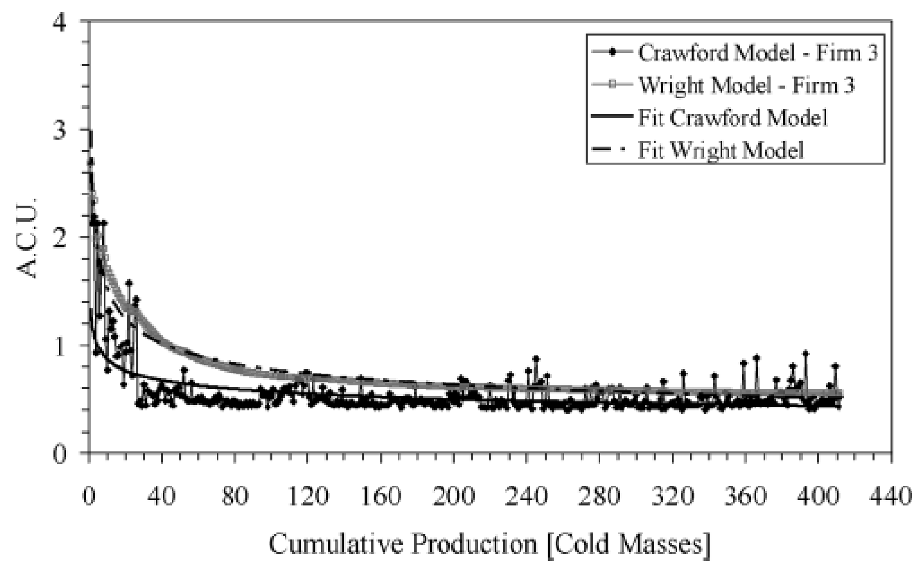
with a = « learning percentage », i.e. remaining cost fraction when production is doubled

- <u>Cumulative cost of first nth units</u>

$$C(n) = c(1)\, n^{1+\log_2 a} / (1+\log_2 a)$$

with C(n)/n = average unit cost of first nth units produced





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Learning coefficients

TABLE IV
LEARNING PERCENTAGE OF SELECTED REFERENCE INDUSTRIES

Industry	ρ
Complex machine tools for new models	75%-85%
Repetitive electrical operations	75%-85%
LHC magnets	80%-85%
Shipbuilding	80%-85%
Aerospace	85%
Purchased Parts	85%-88%
Repetitive welding operations	90%
Repetitive electronics manufacturing	90%-95%
Repetitive machining or punch-press operations	90%-95%
Raw materials	93%-96%

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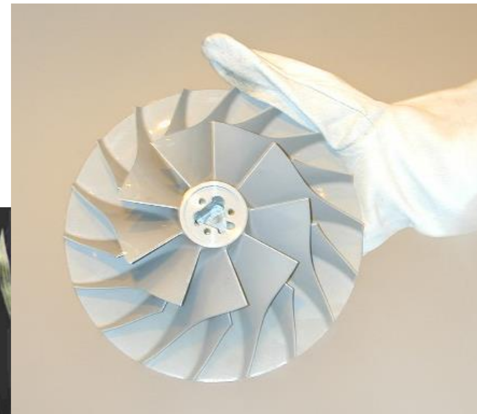
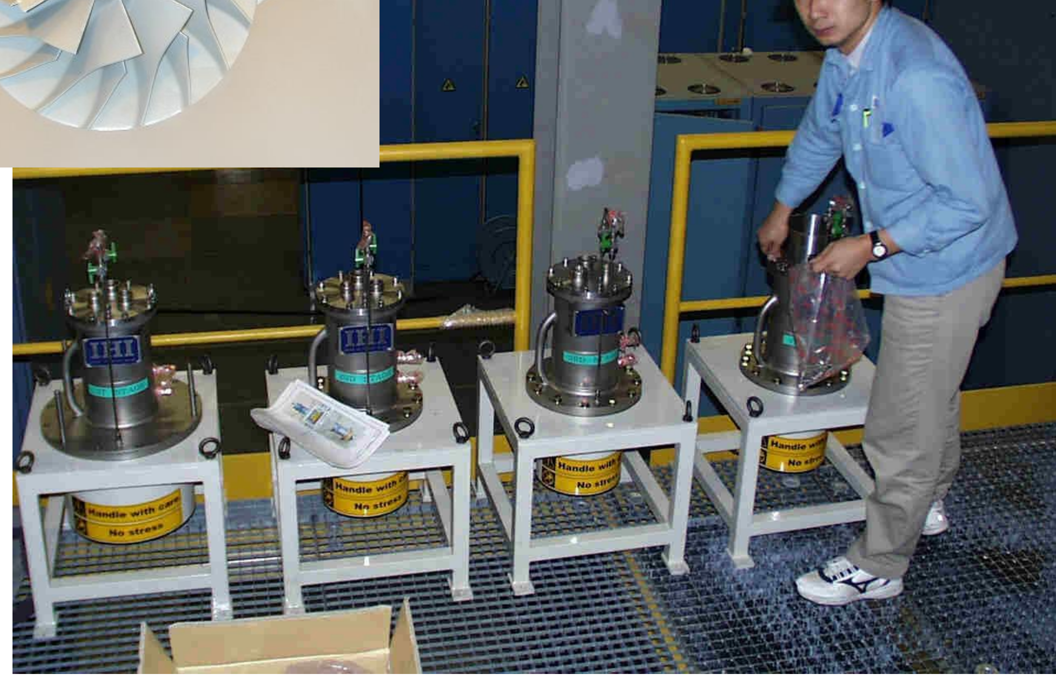
From emulation in R&D to competition in market
Cold compressors for refrigeration at 1.8 K

Air Liquide & IHI-Linde



Axial-centrifugal impeller

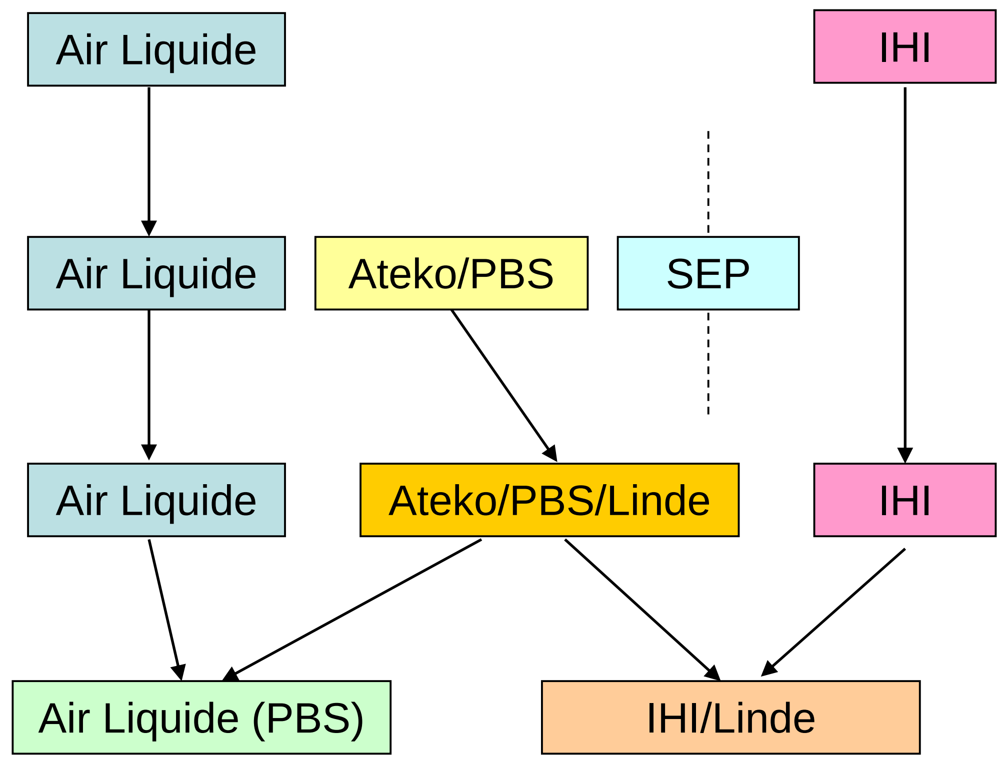
Cartridge 1st stage



4 cold compressor stages

From emulation in R&D to competition in market
Development of LHC cold compressors

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



Contracting and manufacturing

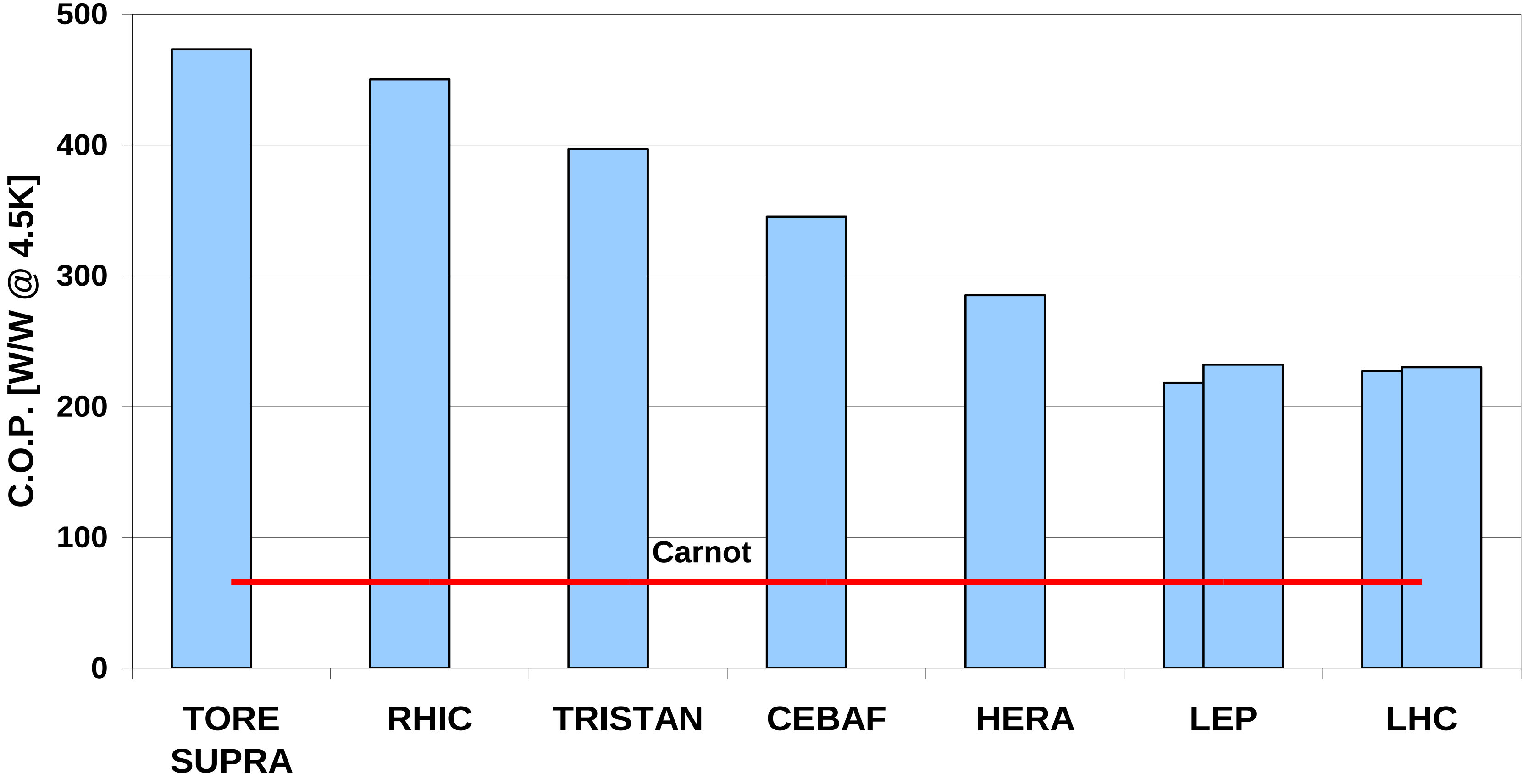
- Technical specification
  - Principle: *do not push to industry risks which they are not in a position to assess*
  - Functional & interface vs build-to-print specification
  - Definition & ownership of specialized tooling
  - Use of performance incentives
- Single or multiple-sourcing
  - Leverage on security of supply and balanced returns in Member States
  - Need for additional production and QA follow-up
  - Intermediate supplies
- Engineering data management
  - Making sure everyone works on the same project
  - Maintaining technical memory in time
- Enforcing QA
  - Documents and procedures
  - Inspections and audits
  - Tests
- Managing the production ramp-up
  - Lead times and conditions for ramp-up
  - Just-in-time vs. production buffers
- Recovering from industrial difficulties

Functional-&-interface specification with 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 and heat rejection)
- Shared incentive in the form of *bonus/malus* on measured vs quoted 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)*

The outcome of this process
C.O.P. of cryogenic helium refrigerators



Build-to-print specification
Manufacturing of superconducting magnets

ACCEL, ALSTOM, JEUMONT, NOELL, ANSALDO

Contracting and manufacturing

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  - Functional & interface vs build-to-print specification
  - Definition & ownership of specialized tooling
  - Use of performance incentives
- Single or multiple-sourcing
  - Leverage on security of supply and balanced returns in Member States
  - Need for additional production follow-up
  - Intermediate supplies require heavy logistics
- Engineering data management
  - Making sure everyone works on the same project
  - Maintaining technical memory in time
- Enforcing QA
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CERN SUPPLIED COMPONENTS—MAIN DIPOLES

Component	Nb Units	Quantity
Superconducting cables (for inner & outer layers)	9856	~ 6000 km
Polyimide tapes for cable and copper wedges insulation (two types)	-	55 t
Copper wedges (4 types)	~ 158000	330 t
Polyimide (in rolls) for the coil ground insulation	-	18 t
Head Spacers, Chips and Wedge-Tips*	90 sets	-
Coil Interlayer*	90 sets	-
Layer Jump Box and Filling Pieces*	90 sets	-
Cable Stabiliser*	90 sets	-
Quench Heaters*	720	-
Austenitic steel for collars	-	11200 t
Austenitic steel for nested laminations	-	1400 t
Collars (6 types)	~ 11.4 M	-
Low-carbon steel for half-yoke and insert laminations	-	~ 43000 t
Half yoke standard laminations & inserts	~ 11.6 M	~ 21600 t
End yoke laminations, austenitic/magnetic	770000/406560	-
Insulated cold bore tubes	2464	~ 38.6 km
Bus bars assemblies equipped with the spool cables	1232	~ 115 km
Shells for shrinking cylinders	2464	~ 2700 t
Spool pieces (sextupole and decapole/octupole corrector magnets)	3964	-
End covers	2464	240 t
Helium heat exchanger tubes	1232	~ 18.5 km
Interconnection bellows	6160	-
Instrumentation and wiring for the cold mass	1232 sets	~ 300 km
Protection diode stacks	1232	-
Line N tubes	1232	~ 18.5 km

* These items were supplied for the 90 pre-series cold masses

For the 90 preseries only

CERN-supplied components for the LHC dipoles

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Managing an integrated supply chain
Benefits & risks

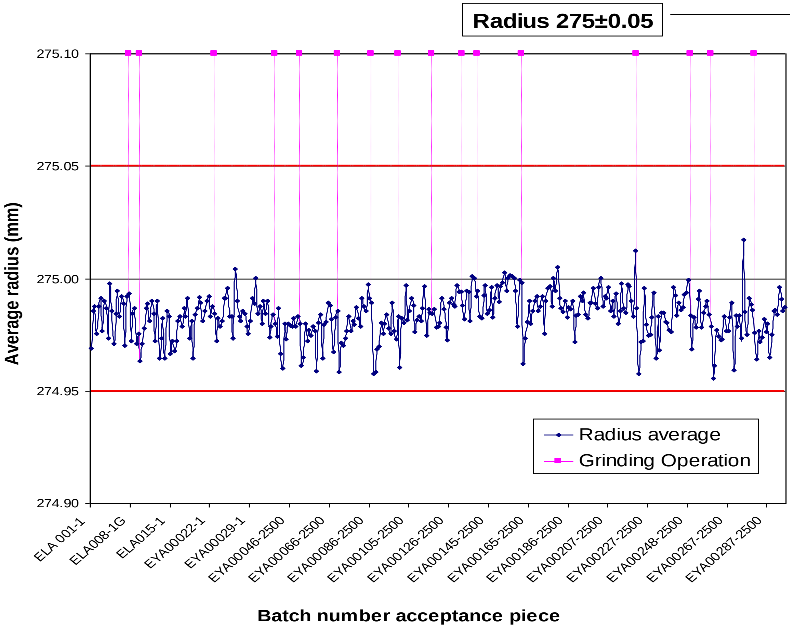
Benefits

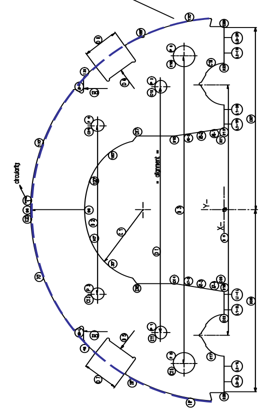
- Technical homogeneity
- Quality assurance
- Economy of scale
- Safety of supply
- Balanced industrial return

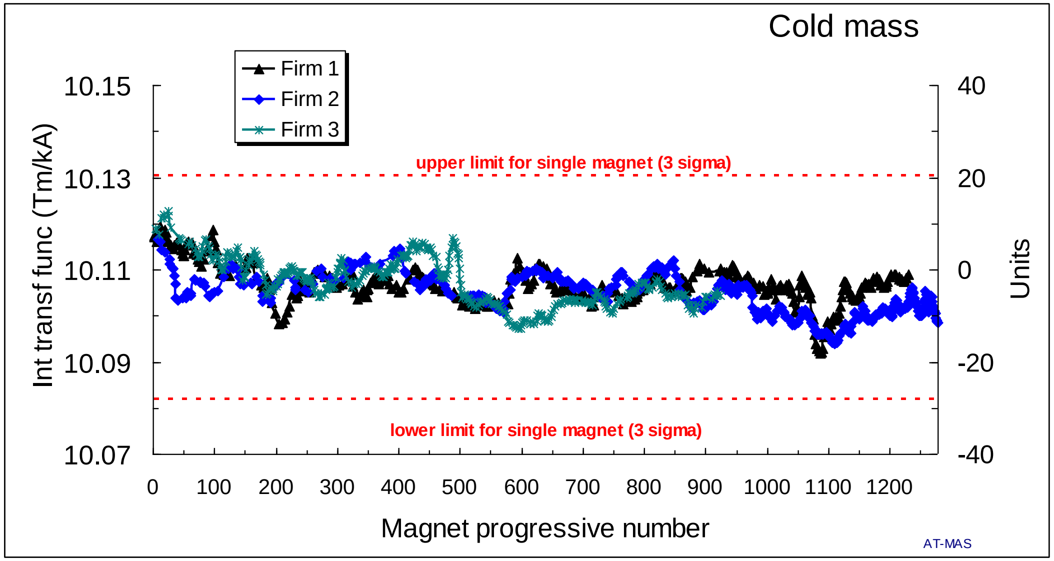
Risks & drawbacks

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

Production control of components drives quality of the finished magnets

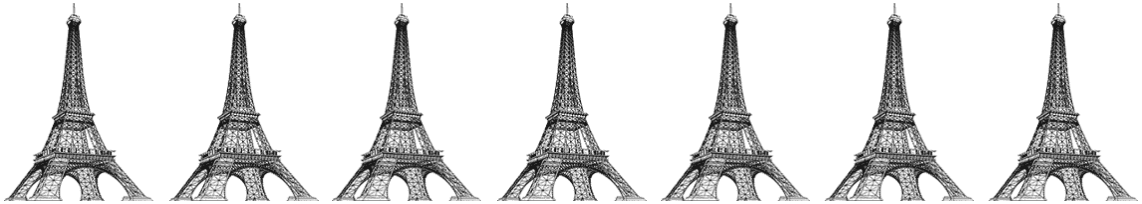




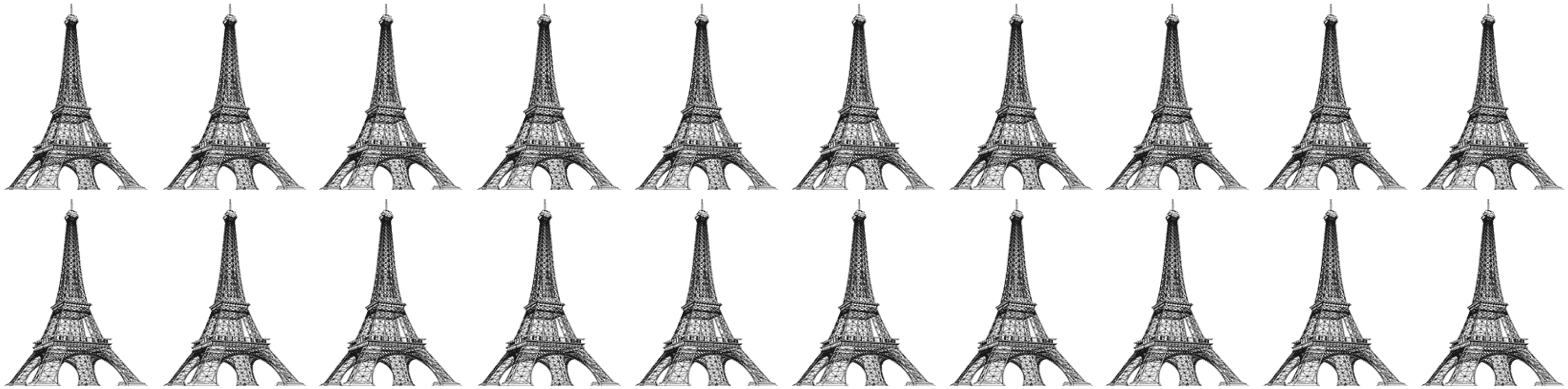


Heavy logistics and transport

Installed in tunnel: 50 000 t



Transported across Europe: ~150 000 t



Contracting and manufacturing

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  - Functional & interface vs build-to-print specification
  - Definition & ownership of specialized tooling
  - Use of performance incentives
- Single or multiple-sourcing
  - Leverage on security of supply and balanced returns in Member States
  - Need for additional production and QA follow-up
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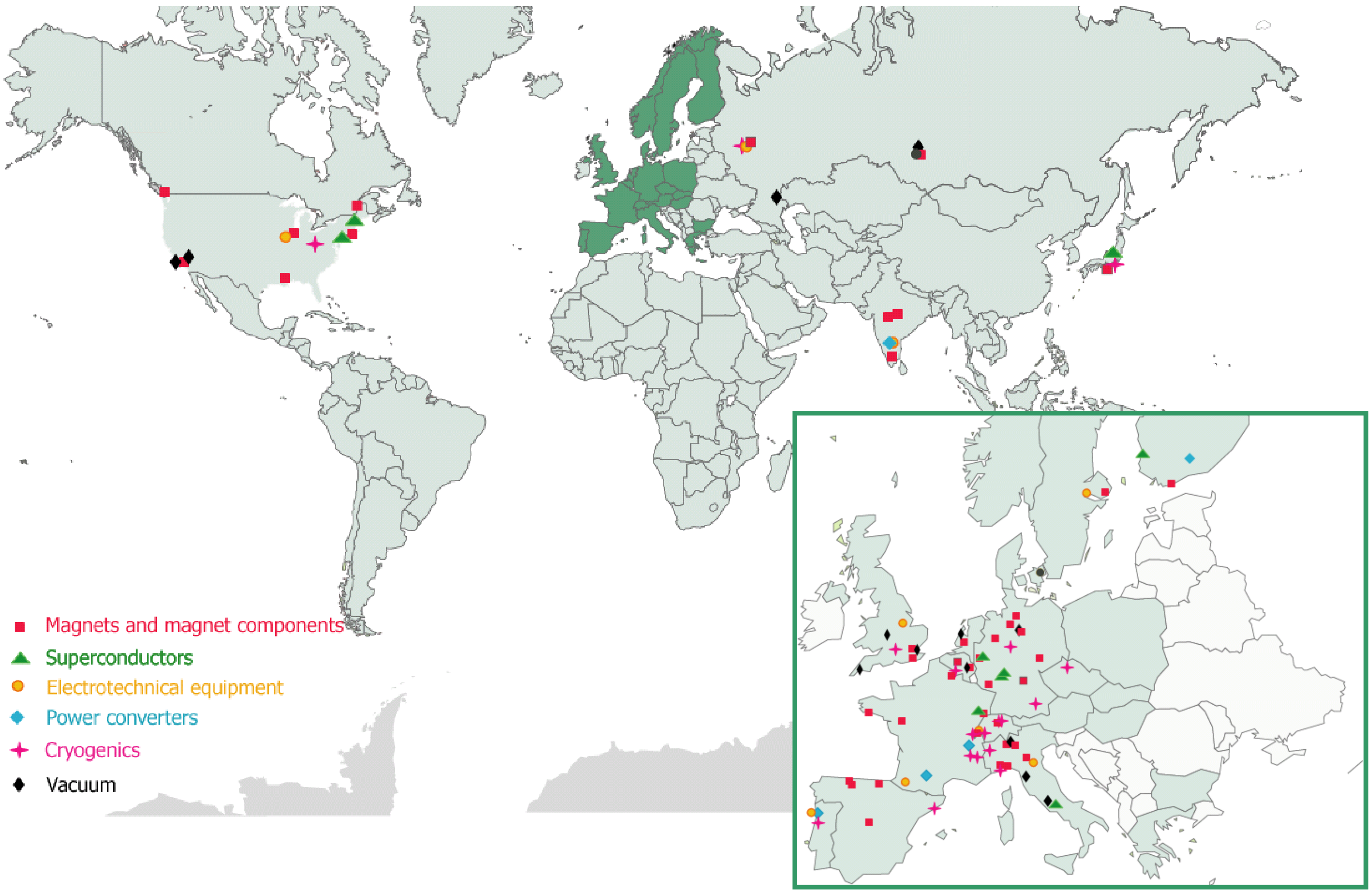
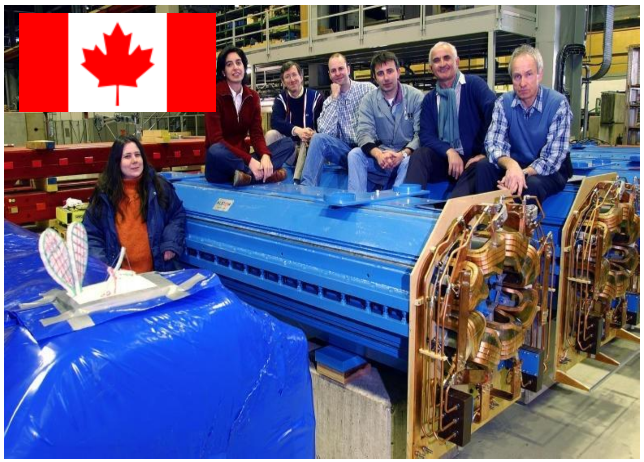
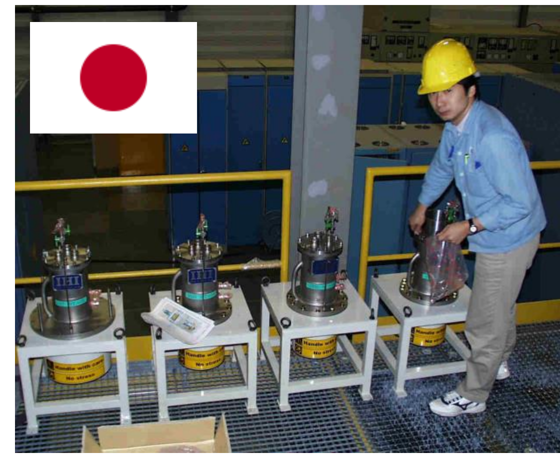
90 main hi-tech industrial contracts
Multiple production sites

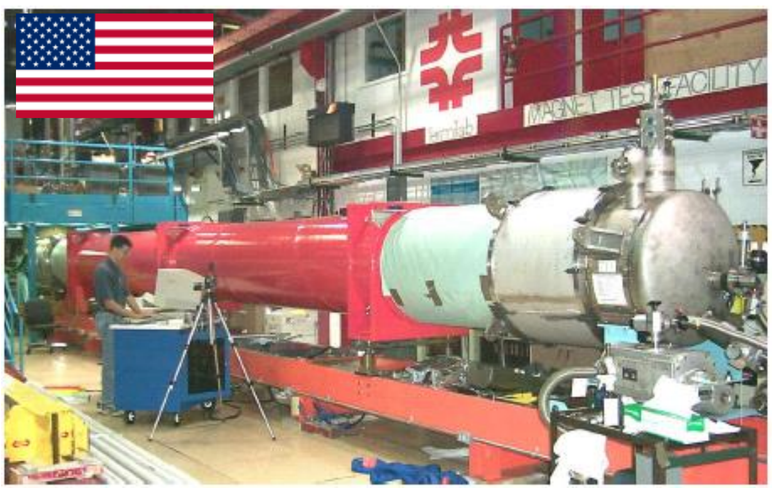


Special contributions from Non-member States

Mostly in-kind, ~15% of the project value



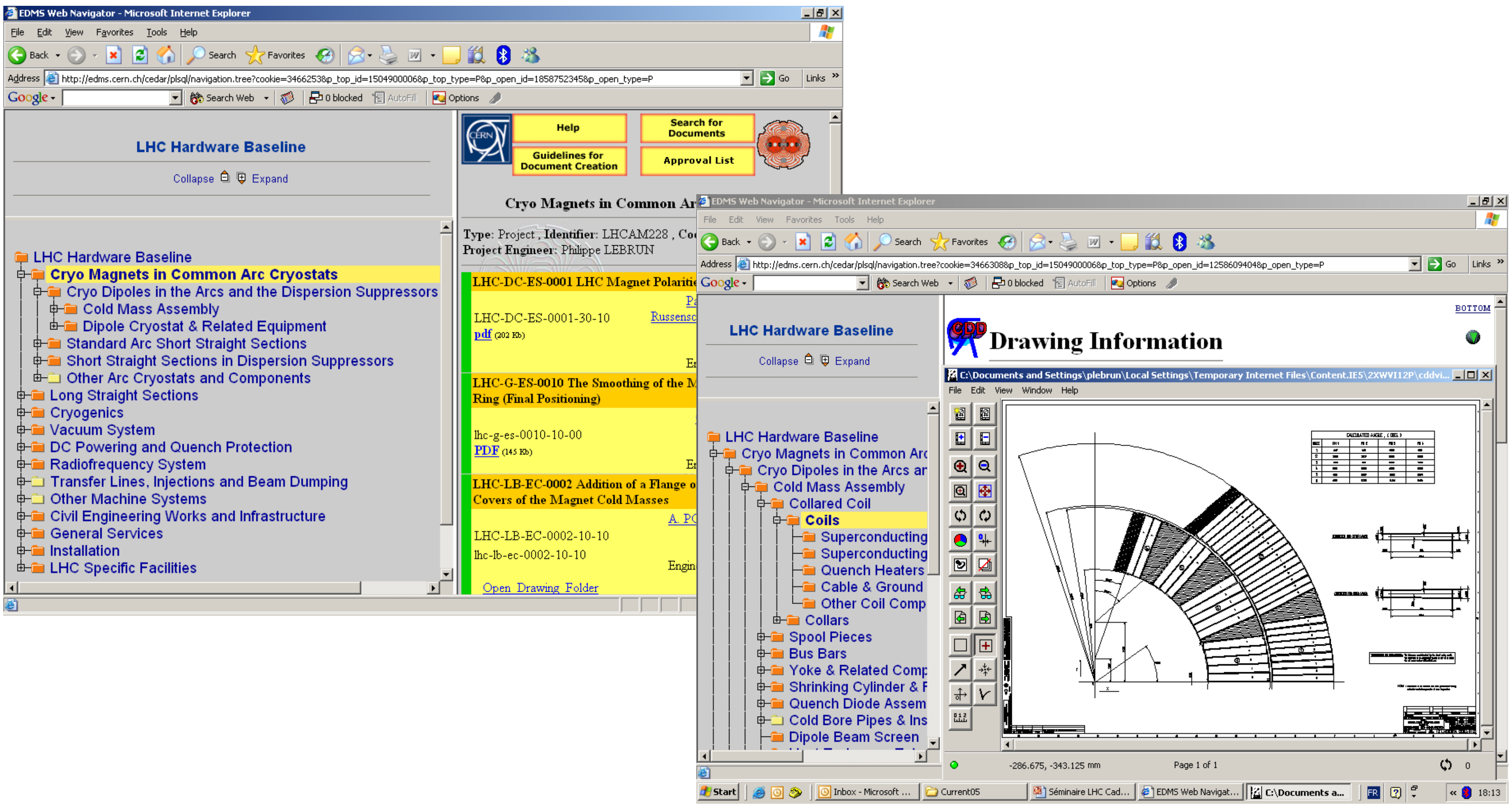




Lifecycle longer than a professional career

• 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
• First commissioning with beam	2008
• Final commissioning	2009
• Operation for physics	2010-2040?

Engineering data management system
Single data repository, access to documentation via WWW



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

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.

Prepared by :	*Checked by :*	*Approved by :*
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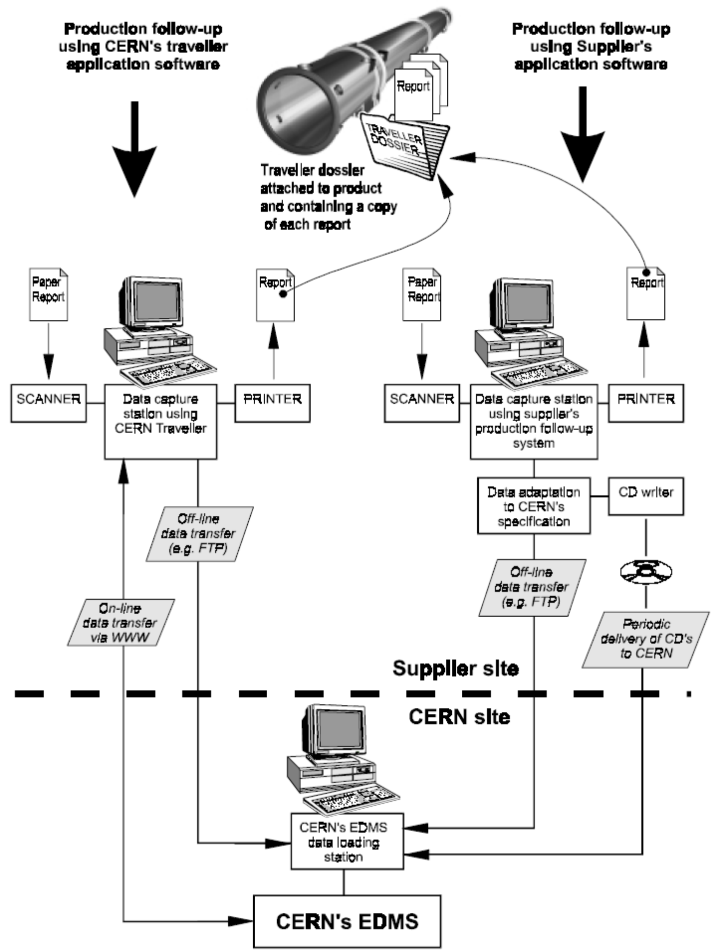


Enforcing QA procedures
Inspection

- Contract with inspection company (ISQ)
  - 20 resident inspectors
  - 6 itinerant inspectors
  - Initial training and periodic de-briefing at CERN
- Mandate of inspectors
  - Follow manufacturing at suppliers and on-site installation
  - Incoming reception of materials at manufacturer's
  - Attend tests according to Inspection & Test Plan and at random
  - Report and follow-up of non conformities
  - Facilitate CERN-Supplier interface
  - Prepare and/or supervise the preparation of Manufacturing & Test Folders at manufacturer's
  - Report to CERN contract engineers

LHC components inspected in Europe

- Quadrupoles
- Dipoles
- Cryostats
- Cryoline
- Correctors

ISQ

Joint Universities Accelerator School

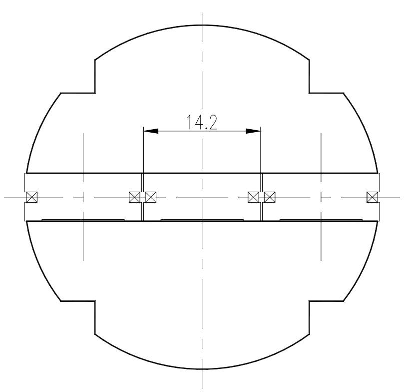
Electrical tests on main dipoles

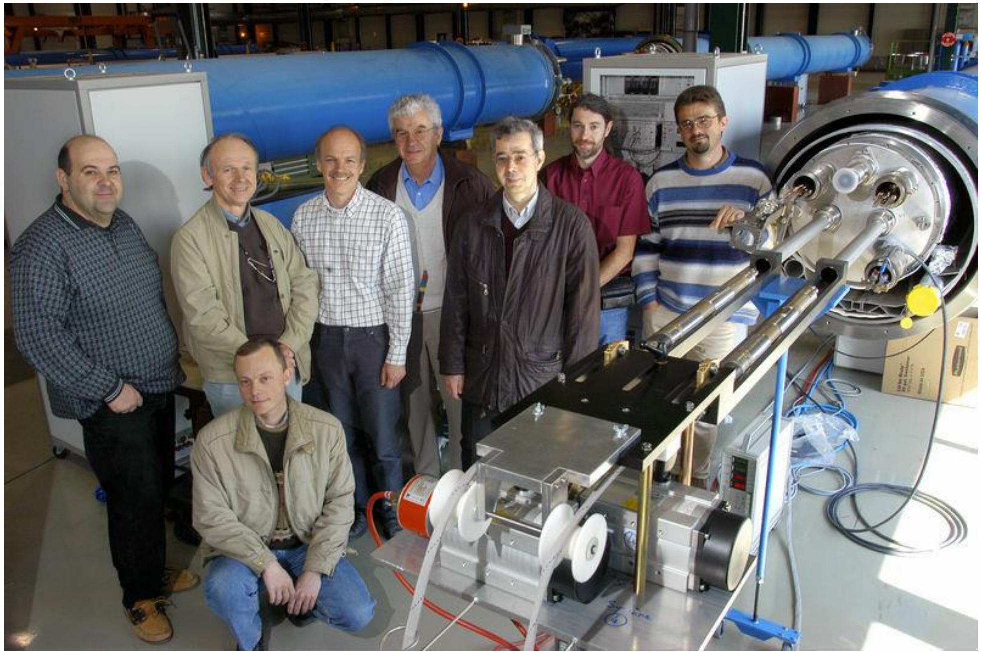
- Basic principles
  - Intercept potential faults as early as possible in production chain
  - Decreasing harshness of tests along production chain
  - Ensure sufficient safety factor w.r. to operating conditions

Test	Layers and Poles	Collared Coil	Cold Mass
DC resistance at 1 A	x	x	x
Inductance at 10 Hz, 100 Hz and 1 kHz	x	x	x
DC resistance of the 8 quench heater circuits	-	x	x
Continuity of voltage taps circuits	-	-	x
Capacitance of the qh vs. dipoles and dipoles vs. ground	-	x	x
Oscillation period during a discharge test	120 V/turn on layers and 100 V/turn on the poles	100 V/turn on poles, dip. and magnet	25 V/turn
Insulation resistance of the copper wedges in the layers at 500 V	x	-	-
Insulation resistance @ 1 kV (@ 1.5 kV on the cold mass)	Between inner and outer layer / each pole	Poles to P. Poles, dip. vs. qh and dip. vs. ground	All to ground, qh to magnet Bus bars to ground
Resistance of the splice	Inner to outer layers @ 1 A	-	Pole to pole and dip. to dip. @ 20 A
Leakage current poles to ground	-	@ 6 kV	@ 5 kV
Leakage current	-	Poles to qh and upper to lower pole in dip. @ 3 kV	All to ground @ 5 kV Qh to magnet @ 3 kV
Discharge test @ 850 V, 2.5 kJ, on the quench heater circuits	-	x	-

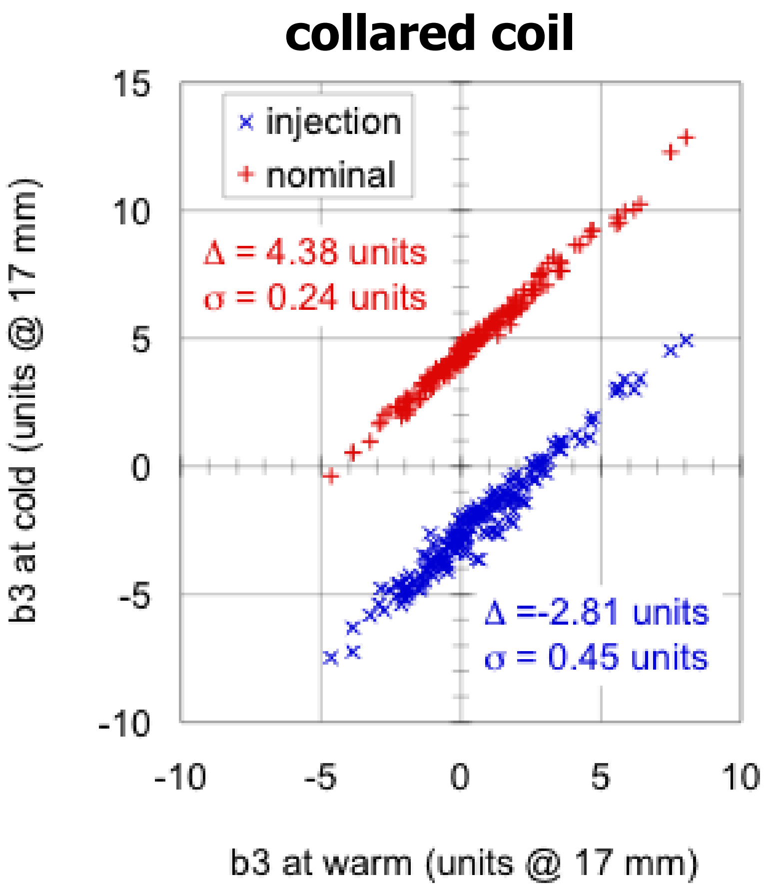
Early detection of manufacturing errors through magnetic measurements at room temperature

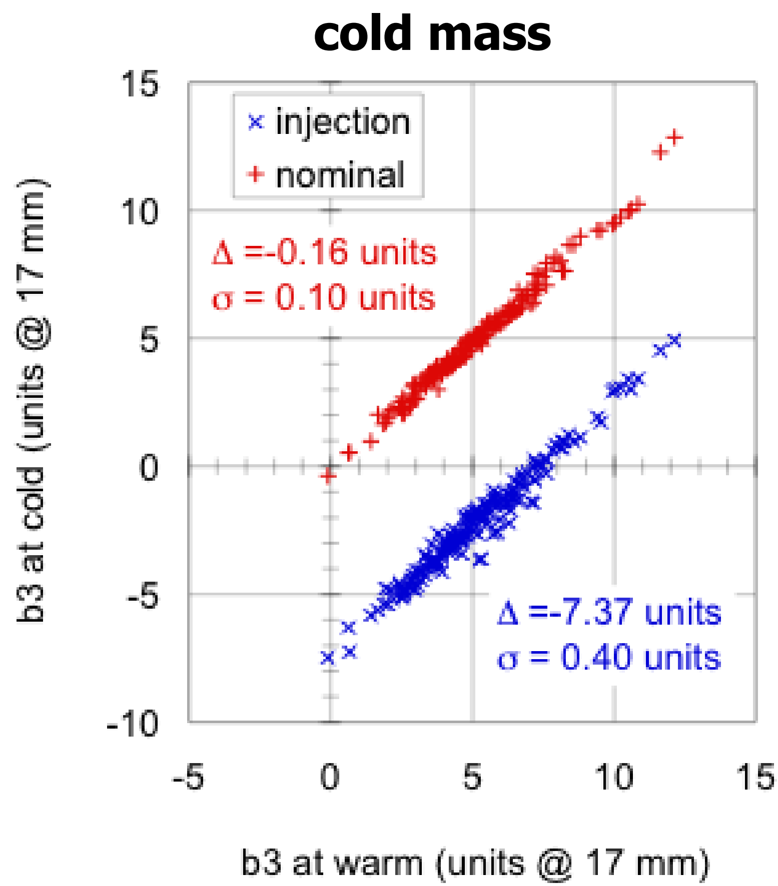
- 24 "moles", each carrying 3 radial rotating coils
- Fully automated measurement ~ 2 h per magnet
- Data transfer from industry to CERN for analysis and clearance





Cold/warm correlations for field errors





Some defects found by room-temperature magnetic measurements

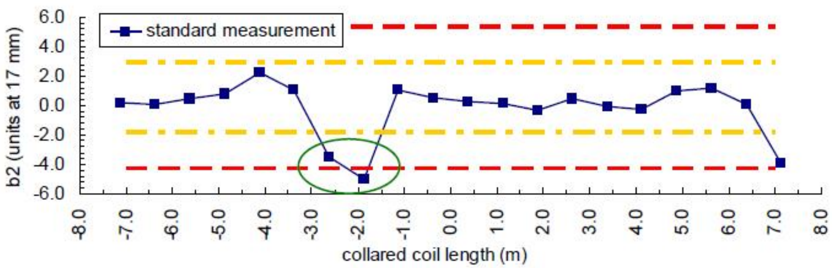


Fig. 2. Measurement of multipole b2 along the magnet axis with alarm limits at 4σ and 8σ (dashed lines) for a collared coil with missing pole shim.

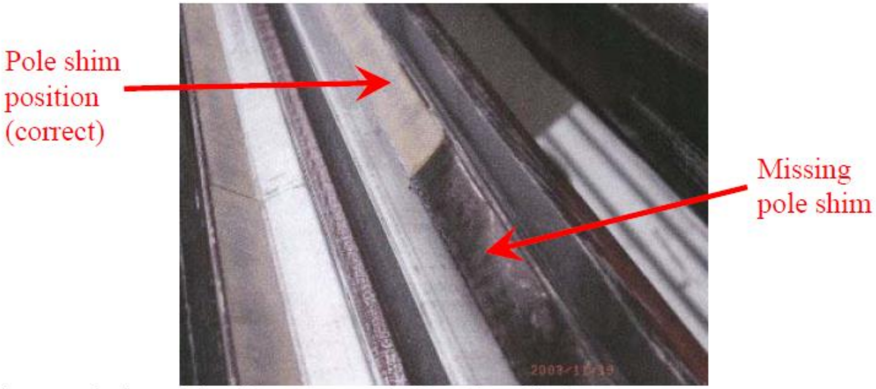


Fig. 3. Missing pole shim observed after de-collaring.

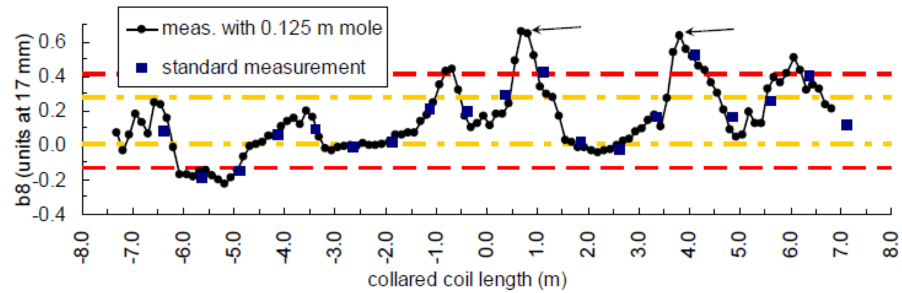


Fig. 8. Measurement of multipole b8 along the magnet axis with alarm limits at 4σ and 8σ (dashed lines) for a collared coil with curing problem.

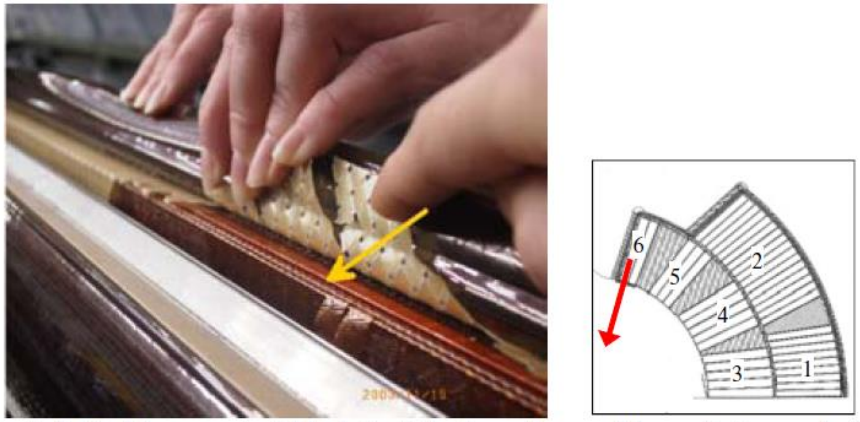


Fig. 9. Left: Movement of block 6 of the inner layer of the coil observed after de-collaring. Right: Illustration of the predicted defect and block numbering.

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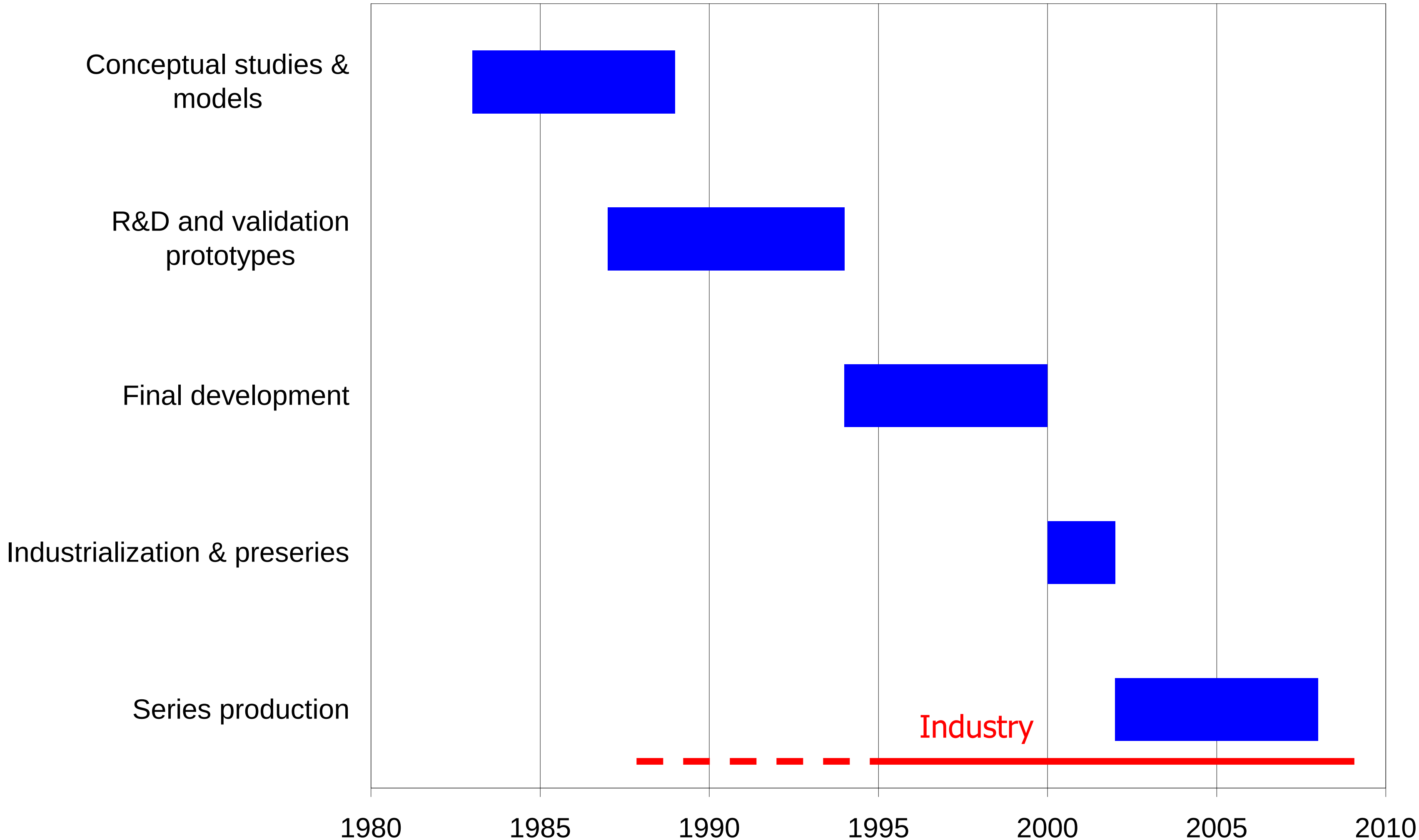
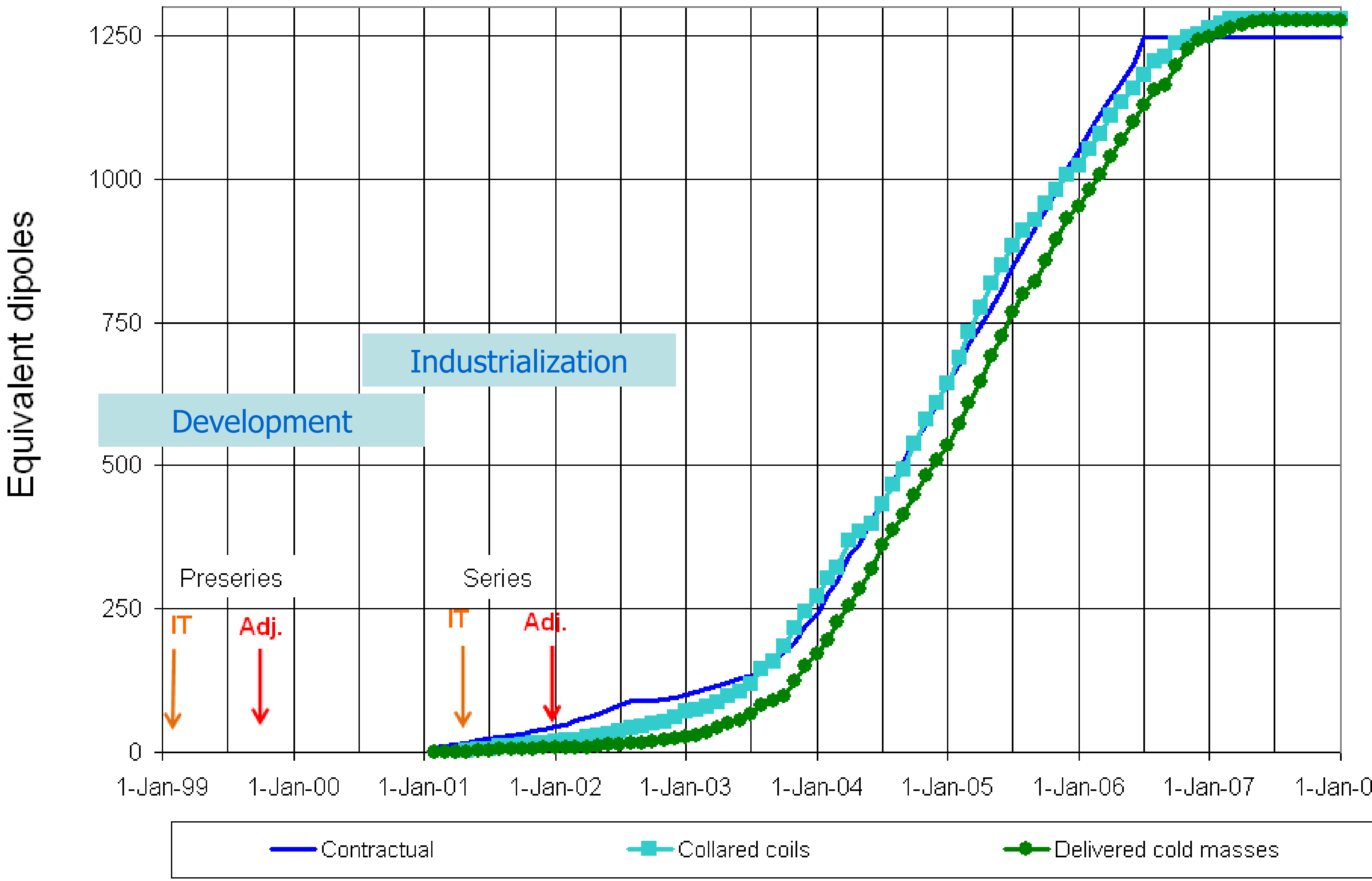
Timeline of LHC superconducting dipole magnets
Early involvement of industry, well before series production

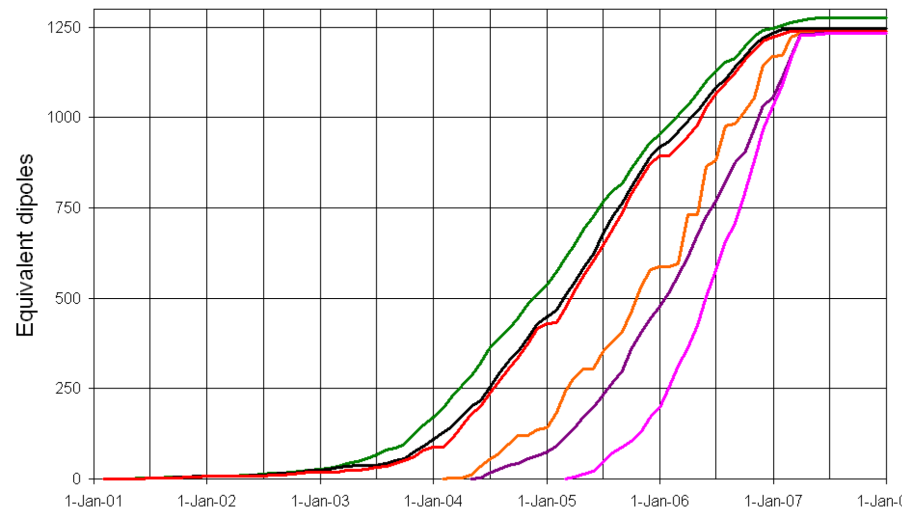


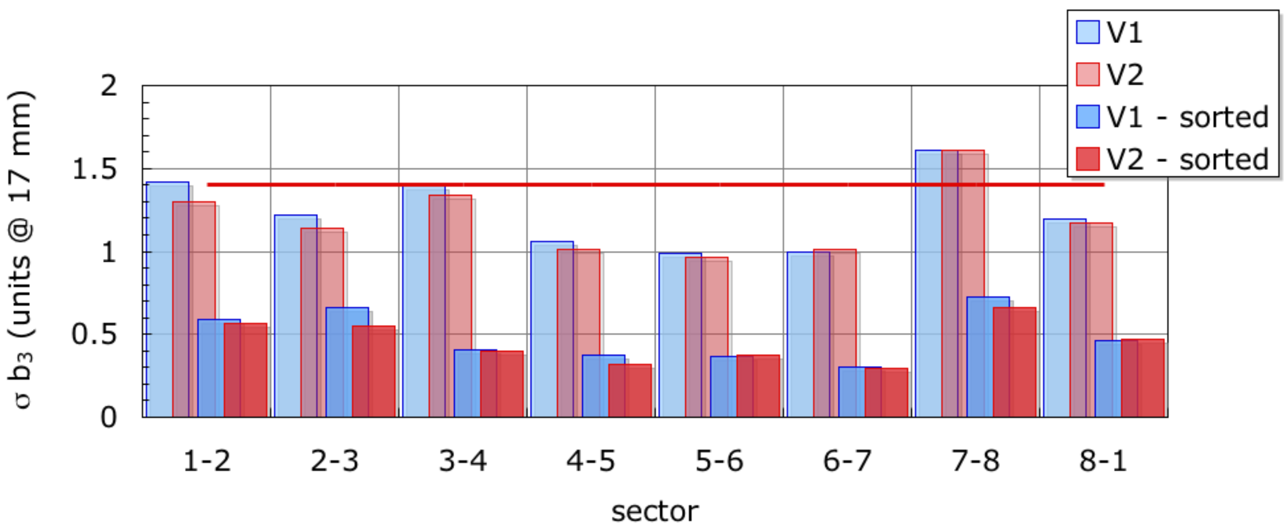
Industrialization & production ramp-up
LHC superconducting dipole magnets



Buffer storage vs just-in-time delivery

Restores production flexibility, allows sorting, reduces dispersion





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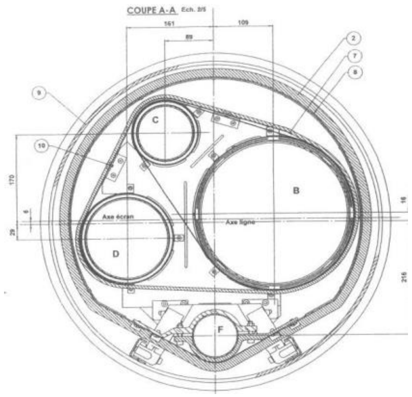
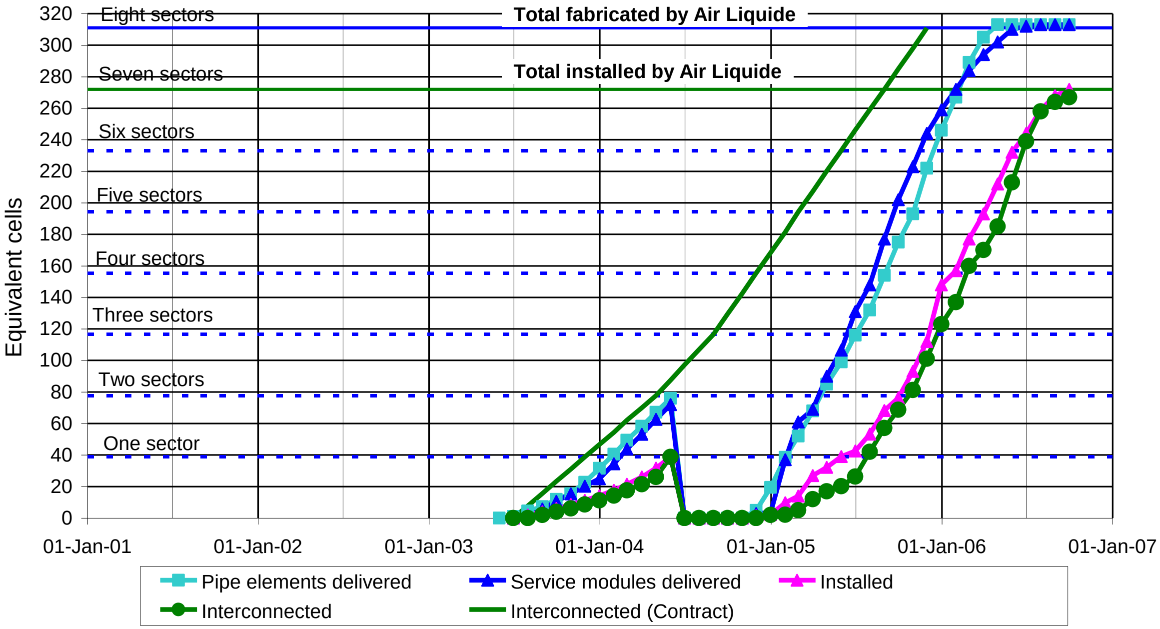
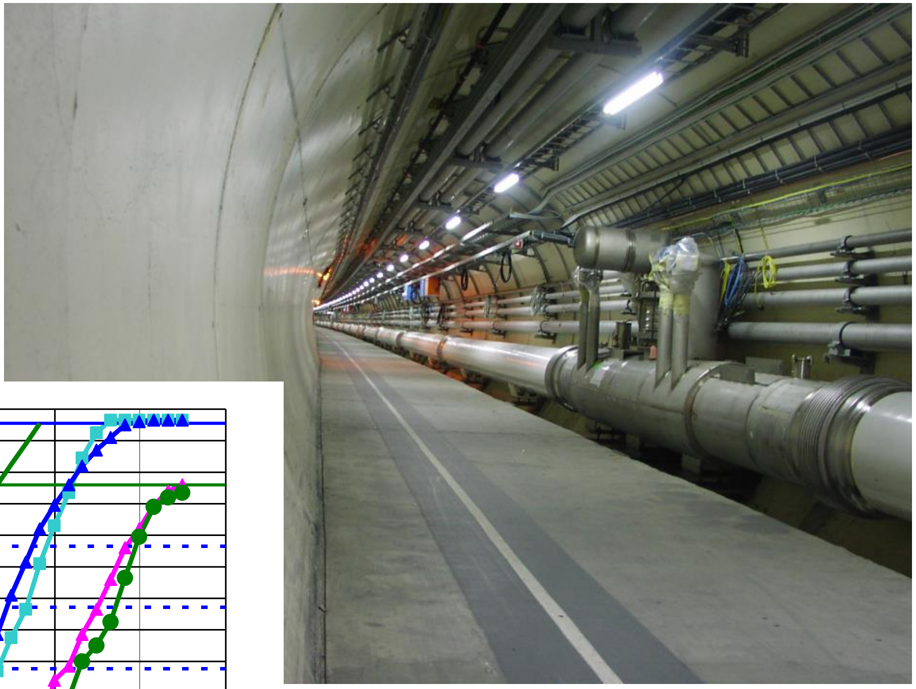
Recovering from industrial difficulties
Internalization of SSS assembly after insolvency of contractor

- Recovery of specialized tooling from insolvent contractor
- Recovery of component supply contracts from subcontractors
- Installation of new assembly workshop at CERN
- Staffing by industrial support contract

Recovering from industrial difficulties
Repair & reinstallation by CERN of cryogenic ring line sectors







Conclusions

- Large scientific instruments such as particle accelerators demand massive investment of human and material resources and unprecedented level of organization, making them *industrial-size global projects in advanced technology*
- Managing *technological risk* requires striking a delicate balance between adoption of state-of-the-art solutions and introduction of emerging alternatives
- *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-of, technically risky supply
  - Series production of innovative items at market prices
  - Competition with other products/markets
  - Quality and performance through shared incentives
- Completion of *product development and industrialization* is an absolute prerequisite for production ramp-up in industry
- Achieving *quality throughout the project* requires the establishment and enforcement of a comprehensive QAP
  - Configuration management, engineering data management
  - Manufacturing and test plan
  - Inspection
- Maintaining *sufficient resources in the home laboratory* is necessary to cope with
  - tasks outside the interest and capabilities of industry
  - unexpected technical or commercial difficulties
- Conversely, industrial competencies and production capacities developed for the LHC constitute a *comparative advantage* for the suppliers, who can later apply them to other large-scale technological projects

Two useful references