Experience from the assembly of the LHC cryostats on site at CERN

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International Workshop on Linear Colliders 2010
(ECFA-CLIC-ILC Joint Meeting)

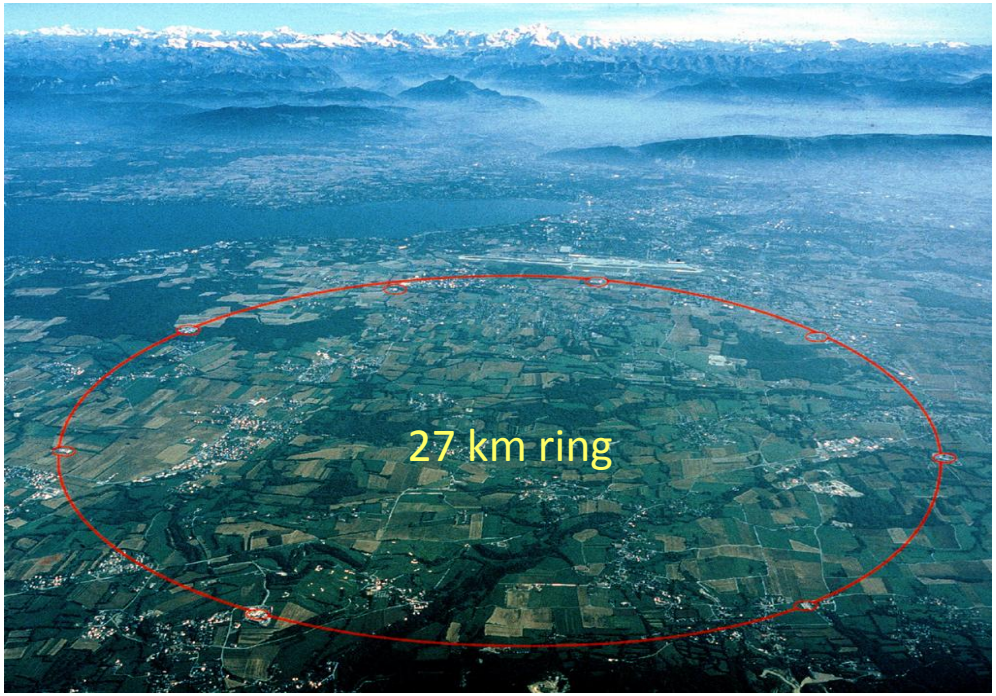
Outline

- Introduction on cryostat types
- The way to mass production
- Cryostat assembly at CERN
  - Dipole cryostats
  - Quadrupole cryostats (SSS)
- Work organization
- Production figures and Non-Conformities
- Summary

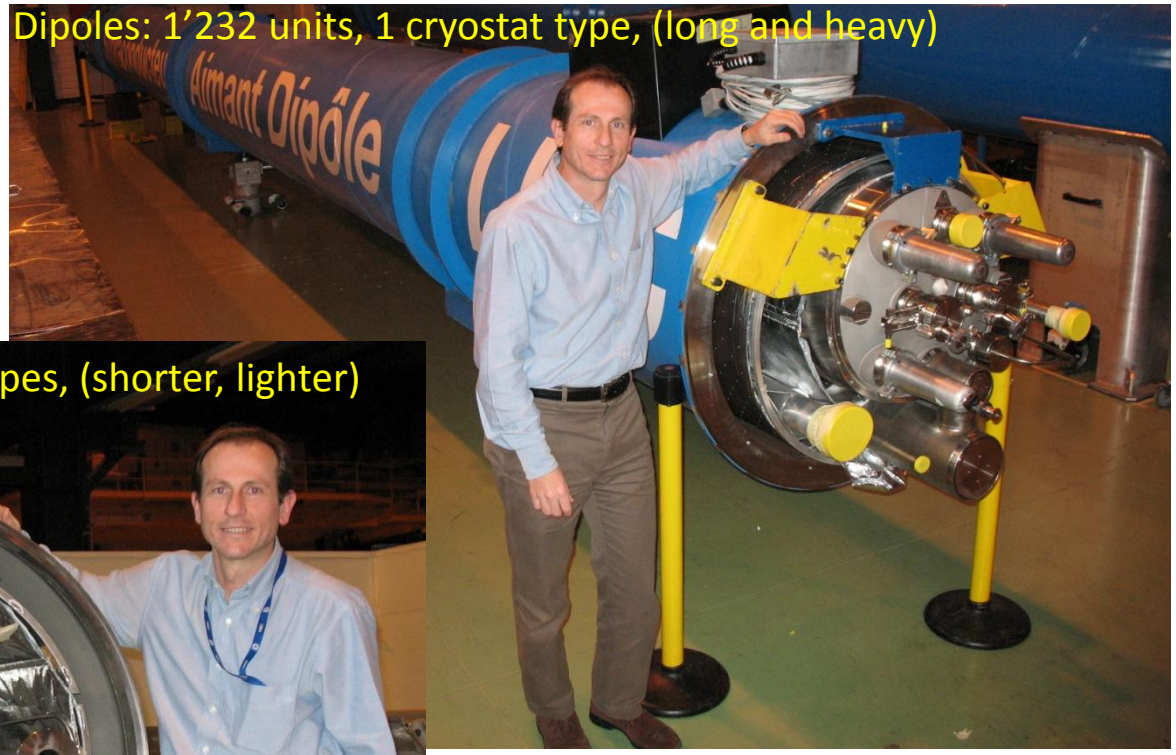
Introduction

LHC cryostats. Key figures:

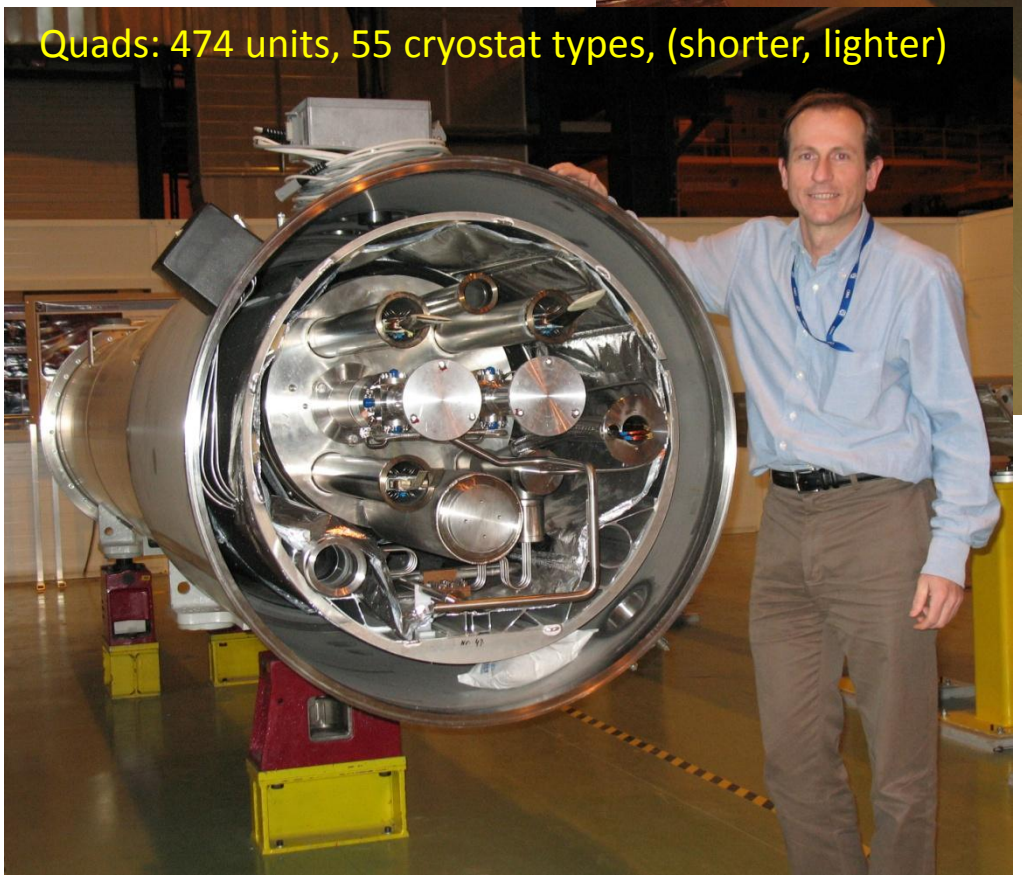
- 8 continuous cryostats ~ 2.7 km each (80% of the ring)
- 1'232 dipoles cryostats
- 474 quads cryostats (Short Straight Sections, SSS):
  - 360 main quad SSS in the arcs
  - 114 insertion quad SSS in the DS and LSS regions



Dipoles vs. Quadrupole cryostats



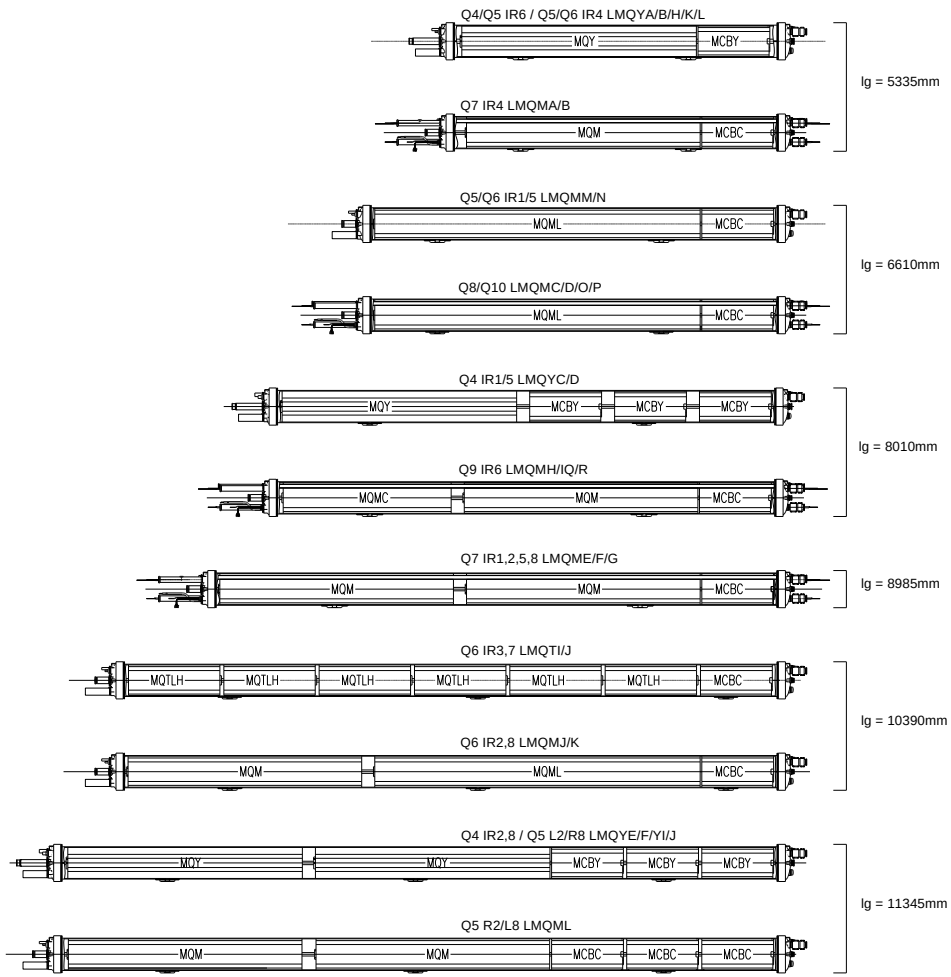
Dipoles: 1’232 units, 1 cryostat type, (long and heavy)

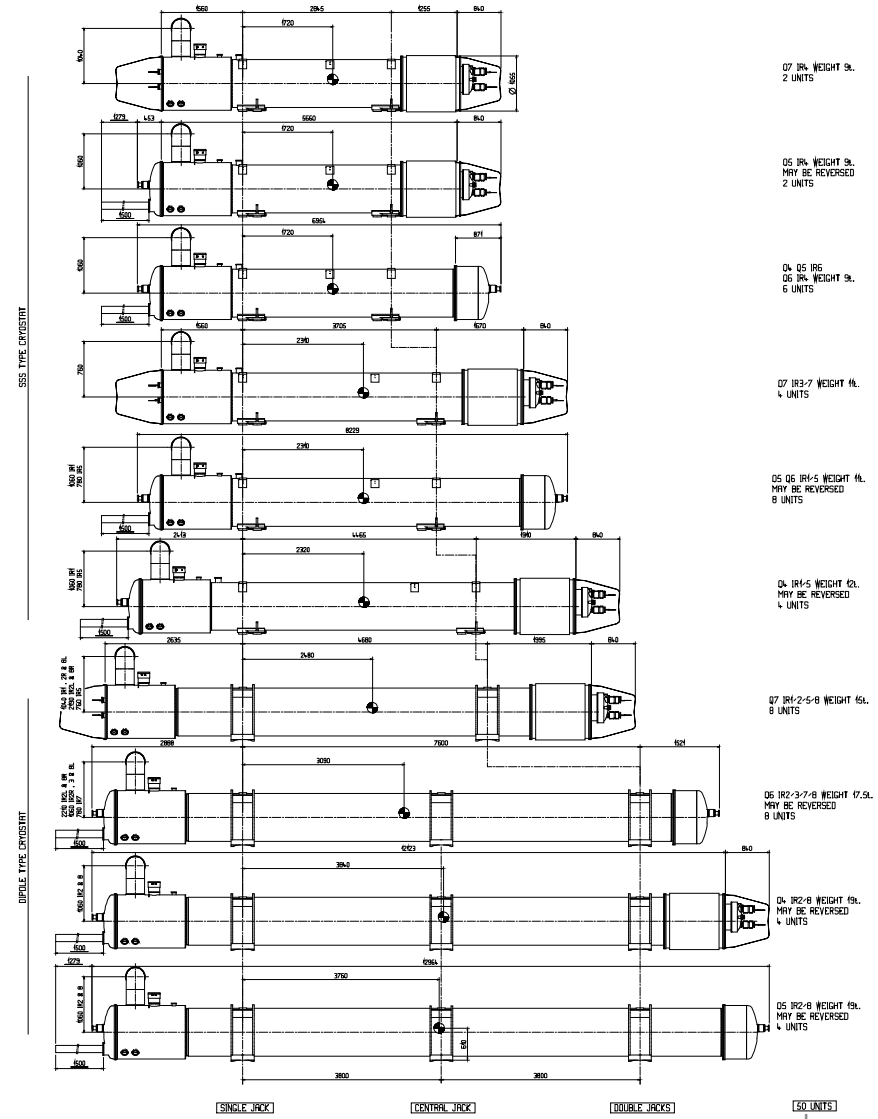


Quads: 474 units, 55 cryostat types, (shorter, lighter)

Quad cryostats (SSS): 474 units

Combining 87 cold mass variants and 55 cryostat types





The Way to Series Production

- **Concepts & technical choices** suited to a large-scale series production
- **Available** and **Affordable** industrial production processes
  - Technically adequate to a large series production
  - Limited development costs
  - Cost effectiveness from economy of scale
- **Confidence gained** from prototyping, extensively tested on full-scale strings of cryo-magnets
  - String 1 (53 m half-cell, 1994-1997). First prototypes
  - String 2 (106 cell, 1998-2000). Validation of final design
- **Cryostat components procurement policy**:
  - **Market survey**: Pre-selection of widest panel of companies with technical competence and production potential
  - **Call for tender**: Competitive tendering on "build-to-print" technical specifications
  - **Splitting** on more than one supplier for security of supply of critical risk components
- **Assembly of dipole cryostats at CERN** based on a **"Result-oriented"** execution contract.

(Assembly of Quadrupole cryostats (SSS) at CERN came as a necessity due to insolvency of the contractor)

Components: managing an integrated supply chain

Benefits

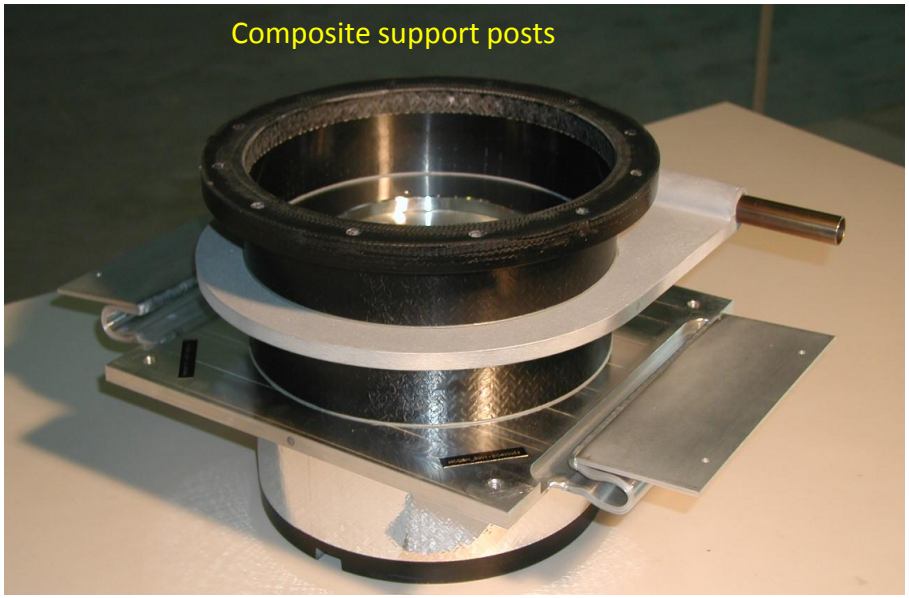
- Technical homogeneity
- Quality assurance
- Economy of scale
- Safety of supply
- Balanced industrial return

Risks & drawbacks

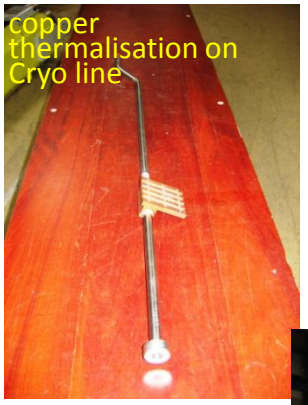
- Responsibility interface
- Additional workload
- JIT breakdown
- Transport, storage, logistics

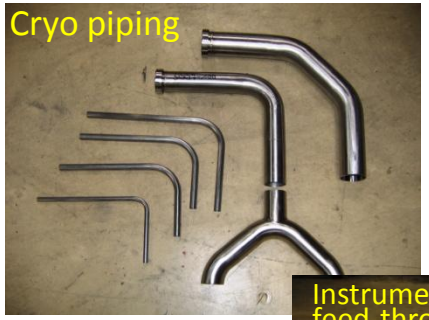
(courtesy Ph.Lebrun)

Dipole cryostat components



SSS cryostat components





Just a few of the 137 main components

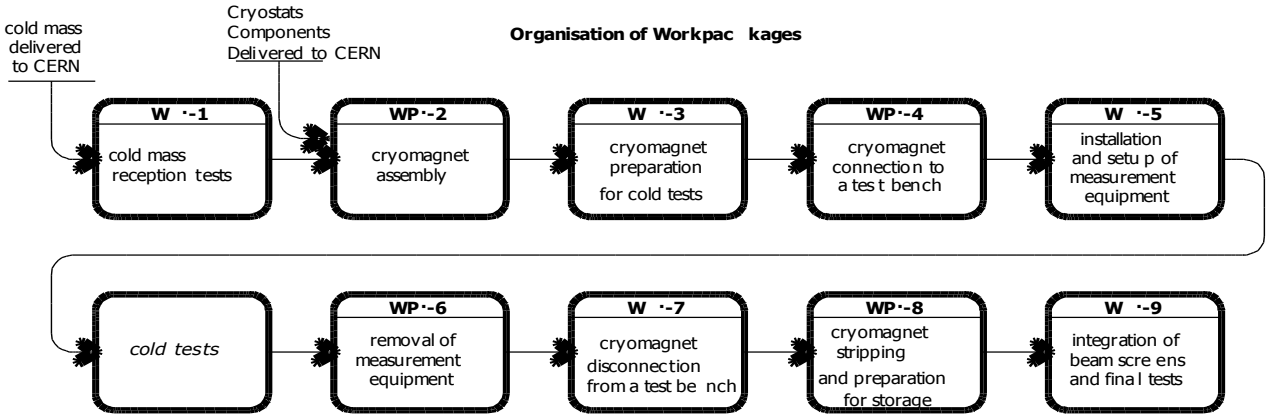
Origin of components in Europe

- Quadrupoles
- Dipoles
- Cryostats
- Cryoline
- Correctors

ISQ

Cryostat Assembly at CERN

- External contractor, "Result-oriented" assembly contract (**87%** contract value):
  - "Work packages" → suited to well defined work
  - Not suited to handle unforeseeable (and certainly occurring!) additional work



- …it included provisions for hourly-rated work (**13%** contract value)
- Performance through shared incentives
- Contractor's profit margins open to CERN
- CERN role:
  - Process definition
  - Making available infrastructure and specific tooling (CERN on site)
  - Make available conforming "ready-for-assembly" components
  - …+ managing what went wrong!
- → Partnership as a key to success

Contract management

Know-how transfer to the contractor:

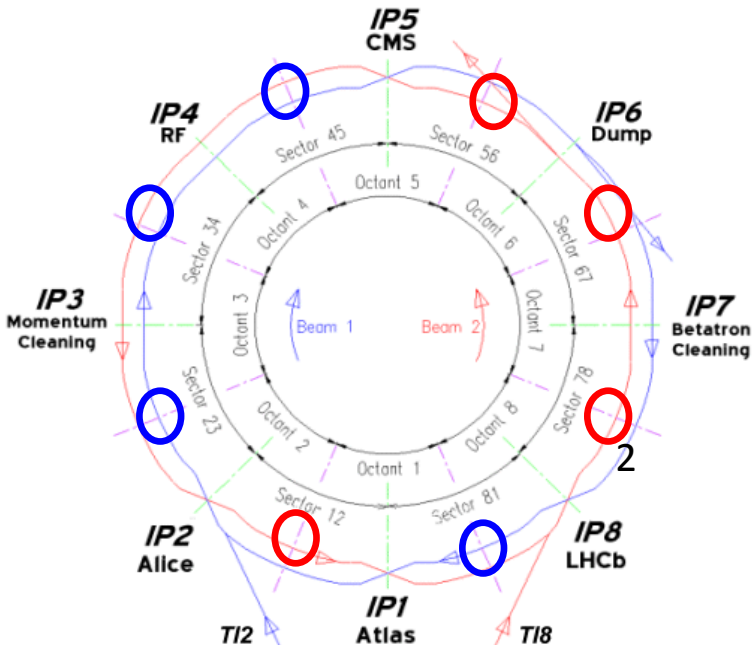
- Execution of first Work-Packages (WP) *hand-in-hand* with CERN specialists, and under CERN's responsibility (paid on hourly-rated work)
- Refining of final WP content, including feedback from contractor
- Adjusting offer for fixed-cost work
- Transfer of responsibility for each WP
- Contractor responsibility:
  - Make qualified (& trained) personnel available
  - Execute WP according to scheduled work volume
  - Fulfill CERN Quality Assurance requirements
- Unexpected work remained (mostly) paid on hourly-rate

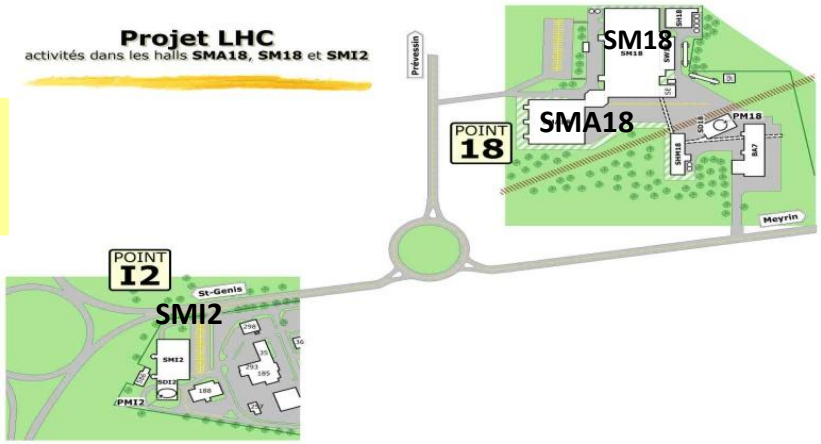
Advantages of the format:

- Flexibility: tuning our needs as discovered
- Addition of extra unexpected work
- Open negotiations (known profit margins)

Dipole activity at CERN

Step 1:	**COLD MASS RECEPTION (ext.contract.)**
Step 2:	**CRYOSTATING (ext.contract.)**
Step 3:	**POWER TESTS (CERN)**
Step 4:	**STRIPPING & FIDUCIALIZATION (ext.contract.)**
	STORAGE
Step 5:	**EXTREMITIES & BEAM SCREEN (ext.contract.)**
	STORAGE
Step 6:	**FINAL CHECK BEFORE TUNNEL TRANSP. (CERN)**





SMA18	**SM18**	**SMI2**

Assembly of dipole cryostats


Cold mass reception


Bottom tray + supports assembly


Al thermal shield rolling machine

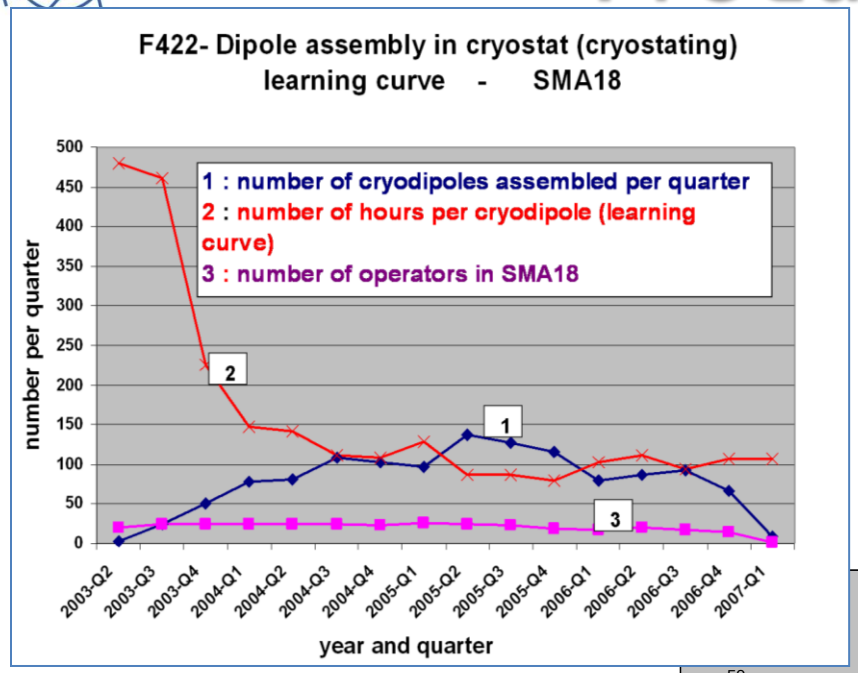
Key Figures:

- 1232 units in 4 yrs
- 30 FTE workers
- 3 hydraulic assembly benches
- Peak rate of 45 units/month (on 2 shifts)


Thermal shield + MLI assembly


Hydraulic assembly bench

Production figures



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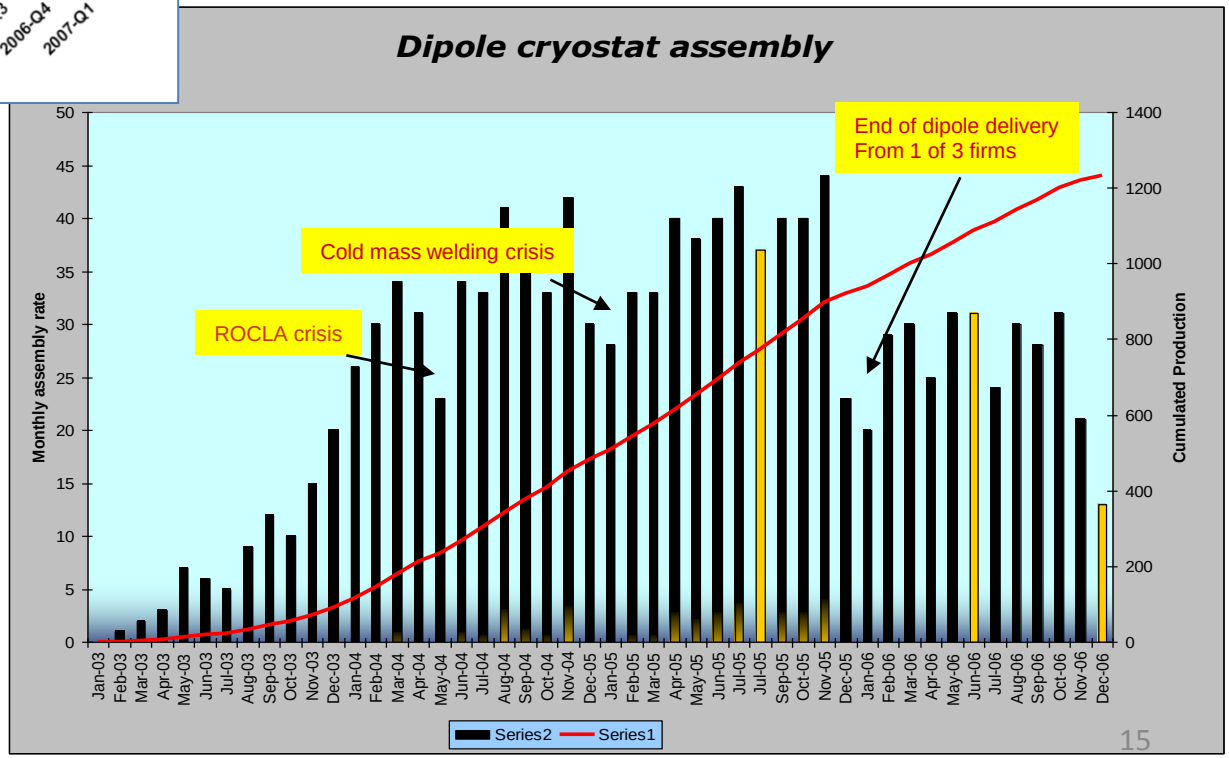
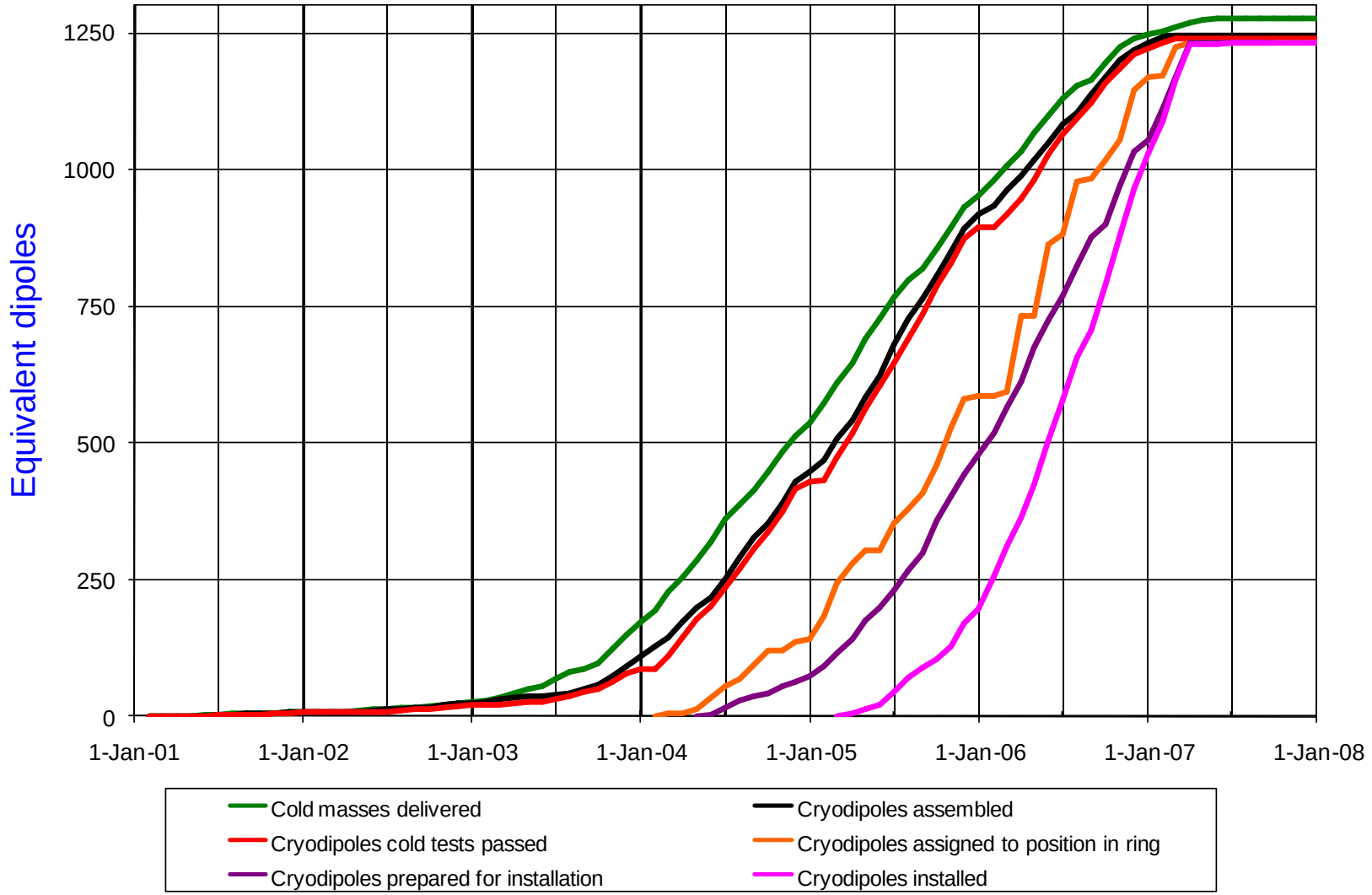


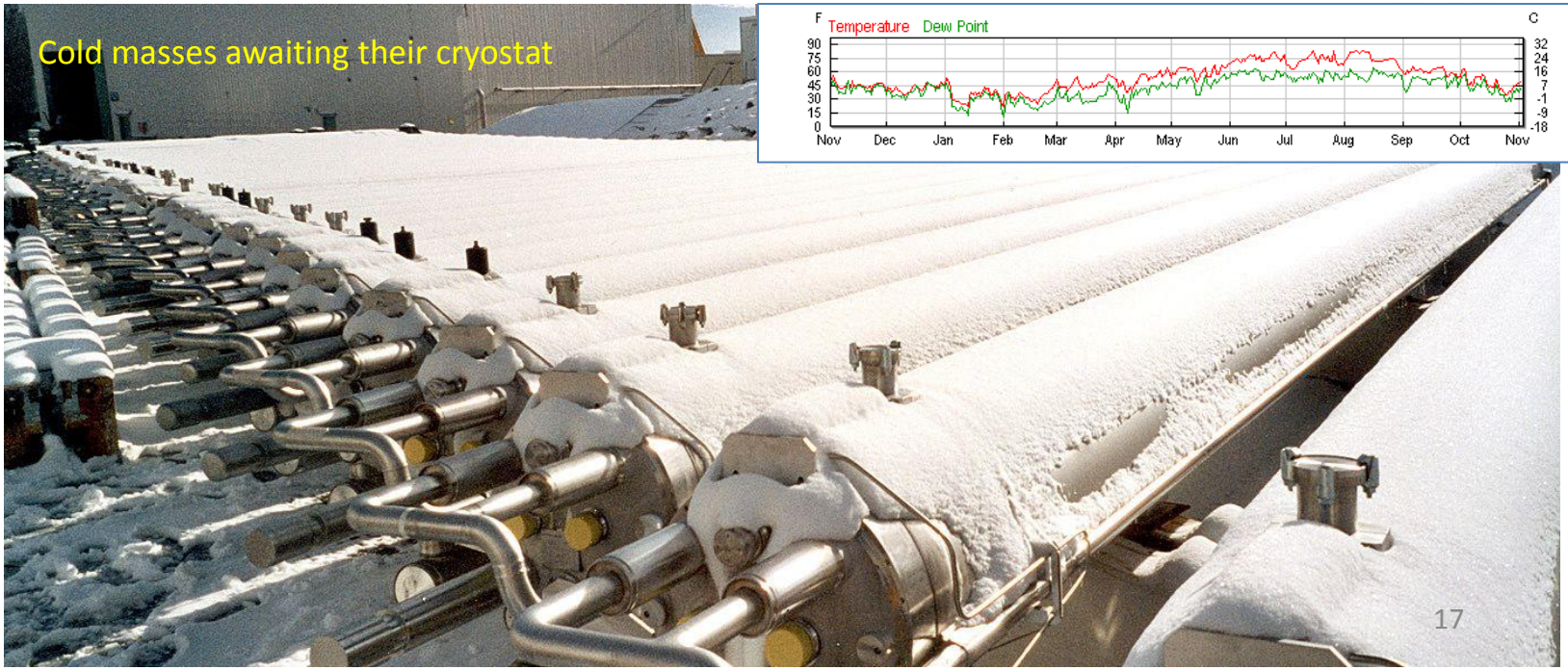
Cryodipole overview



Storage, an unavoidable reality…

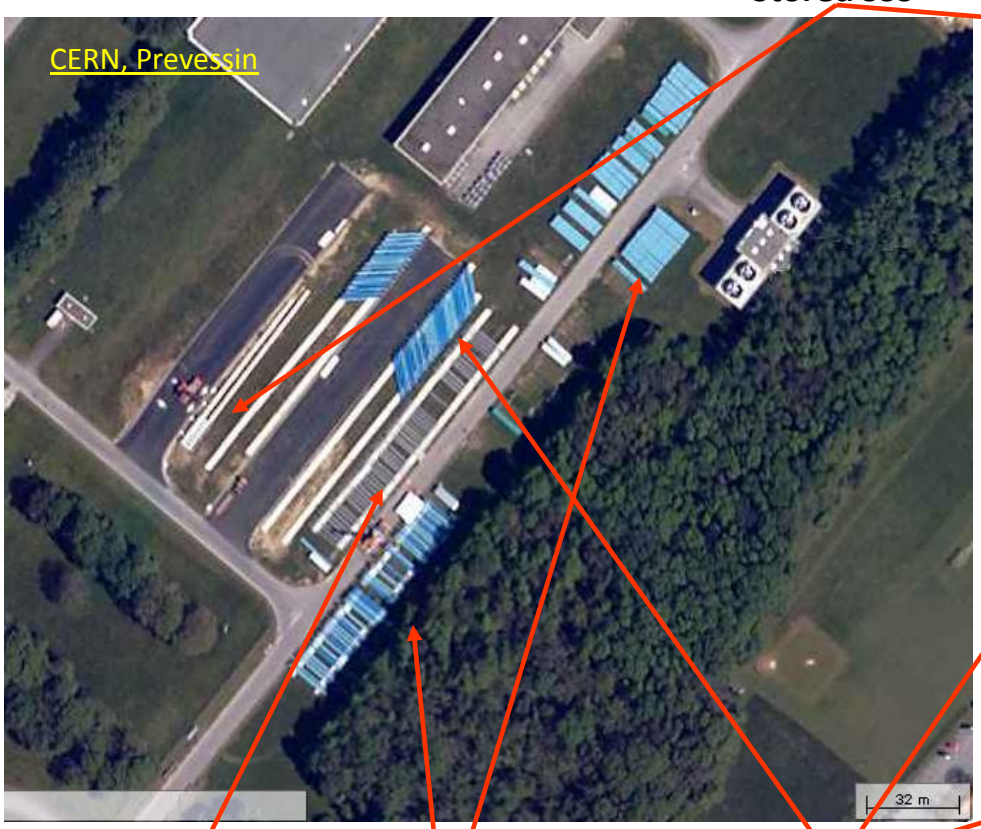

Magnets waiting for cold tests or tunnel installation


Out-doors storage of vessels at CERN


Cold masses awaiting their cryostat

…a logistics endeavor…

From "Google Earth",
Aerial view of CERN sites (~2005)



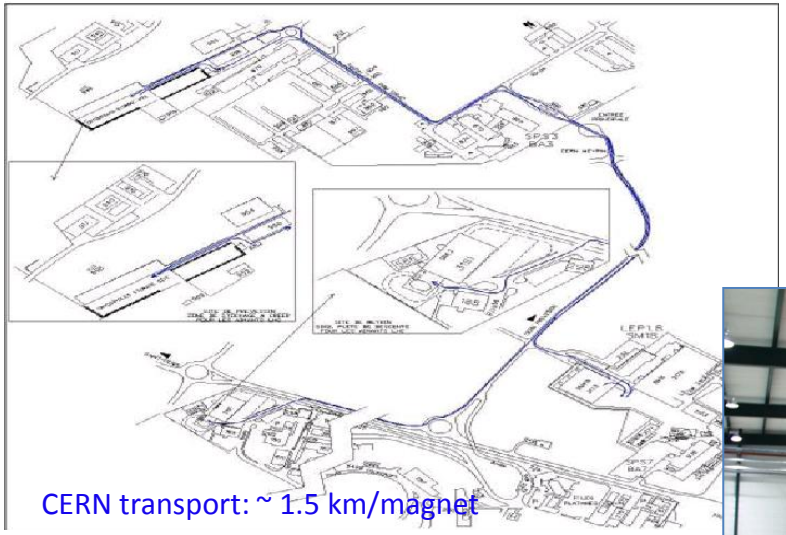
Stored SSS

Stored Cold masses

Stored vessels

Stored Cryo-dipoles

…handling and transport



CERN transport: ~ 1.5 km/magnet

Special handling

Speed limit 20 km/h

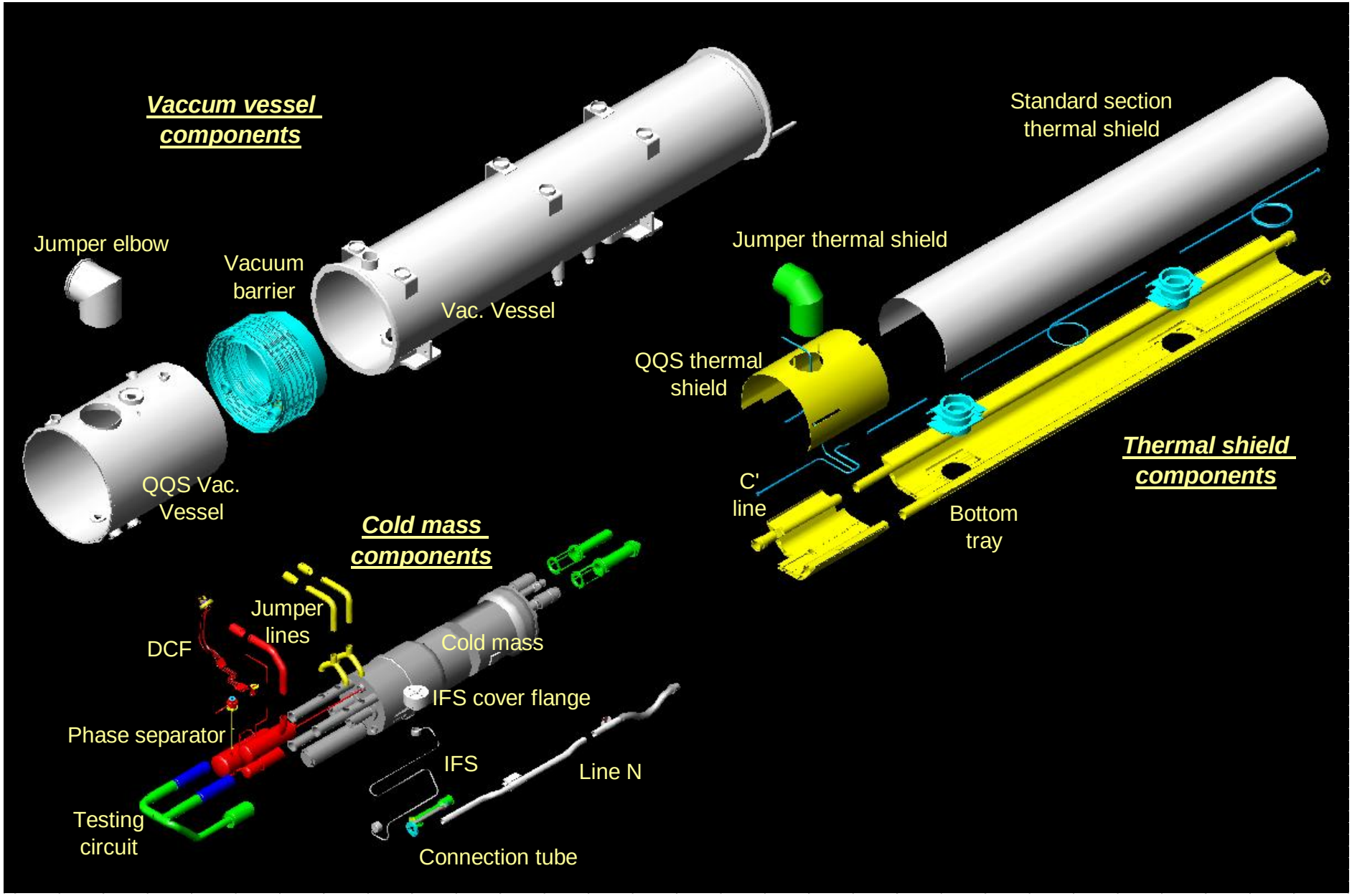
End restraints and shock-logs

The assembly of the Quadrupole cryostats (SSS) at CERN

Internalization after insolvency of contractor

- Setting-up of a 2'000 m^2 hall equipped with specialized tooling developed by CERN
- Recovery of component supply contracts from subcontractors (~10 major contracts)
- Staffing by industrial support contract (same as dipole cryostat)
- Setting up a CERN team for configuration management, Quality Control and Inspection

Complexity of a Short Straight Sections (SSS)



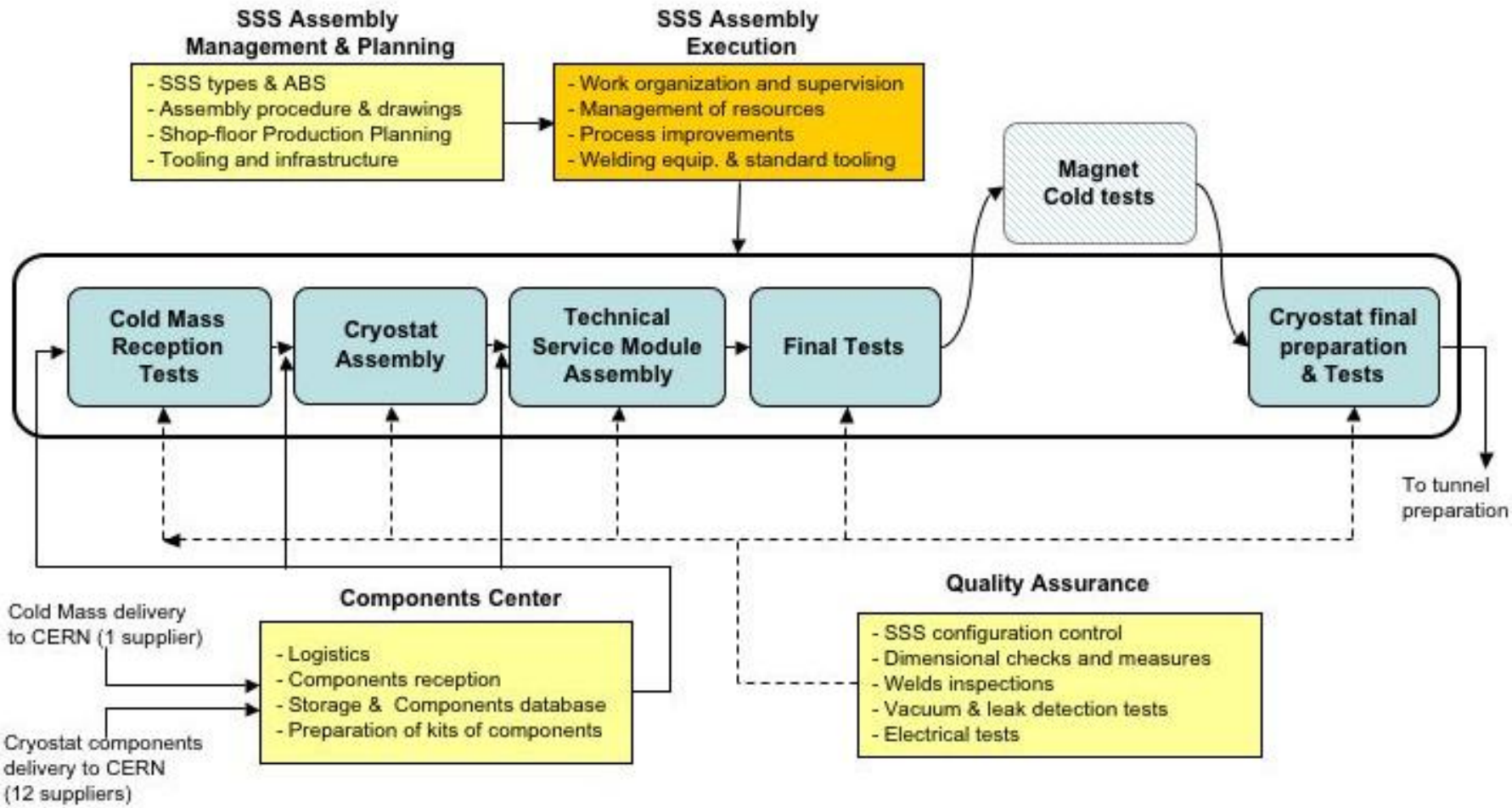
Assembly of the Short Straight Sections (SSS)

Key figures:

- 474 units and 136 variants
- 370 component types
- 60 FTE workers at peak production
- > 6 km of leak-tight welds
- 3300 leak detection tests
- 3.5 yrs of production

SSS assembly: Organization

Teamwork of 3 contractors + CERN



Resources and Qualifications

Assembly Activity	No. FTE	Quality assurance	No.FTE	Components center	No.FTE
Supervision	3	SSS configuration control	2	Logistics	3
Mechanical workers	6	Vacuum technicians	5	Storage	2
Welders	6	Welding inspectors	1	Components inspections	1
Electro-mechanical workers	10	Electrical checks	2		
Electricians	7				
Sheet metal workers	3				
Handling operators	3				
Totals	**38**		**10**		**6**

Most critical professionals to find on the market:

- Vacuum technicians, leak detection specialists (virtually none)
- Qualified (manual) welders
- Electricians & brazing technicians

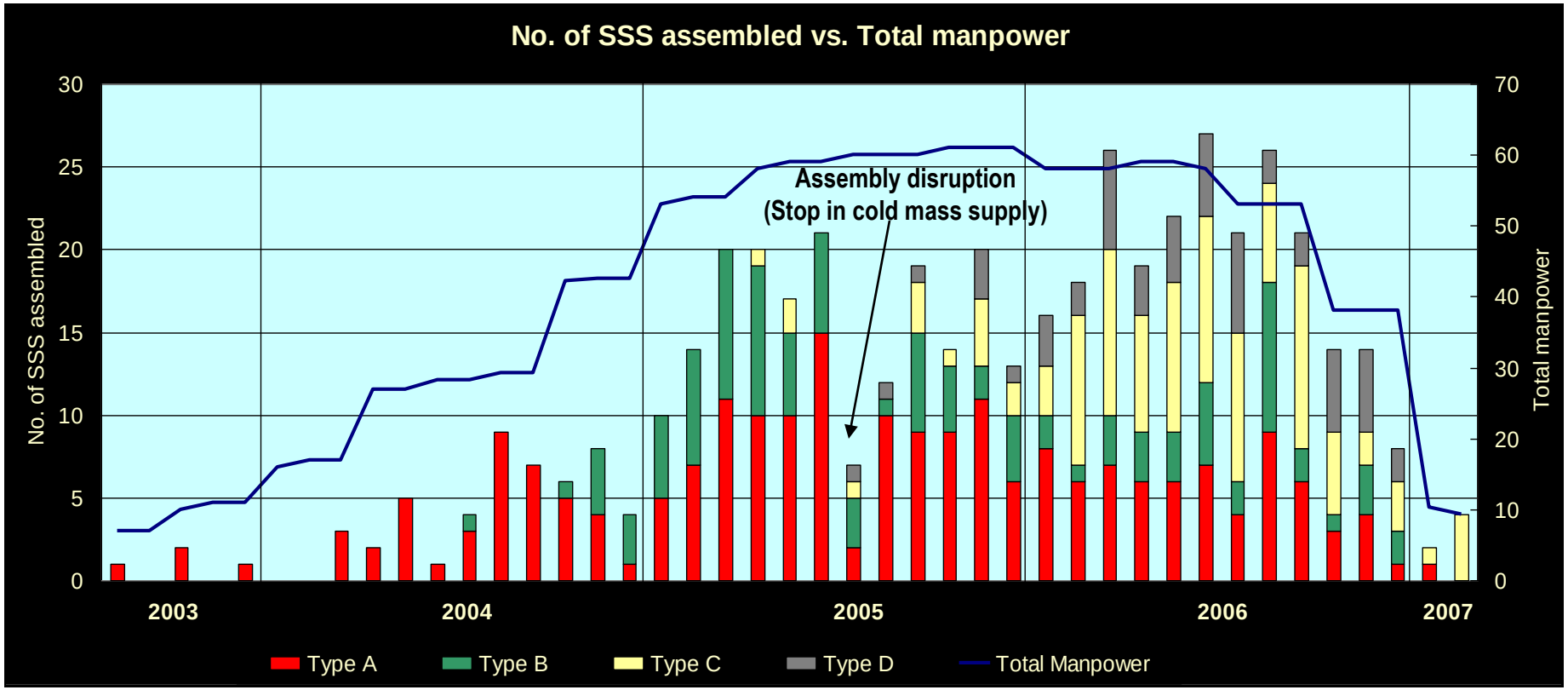
Storage of cryostat components

- ~ 370 different components
- …size: from several meters to a few cm!!
- Storage space set-up lately in the project (we hoped in "just-in-time" supply, just an illusion!!)
- Logistics platform (also lately set-up):
  - Prepare "kits" of components ahead of need
  - Follow-up of used parts, scraps, remaining stock and need for spares

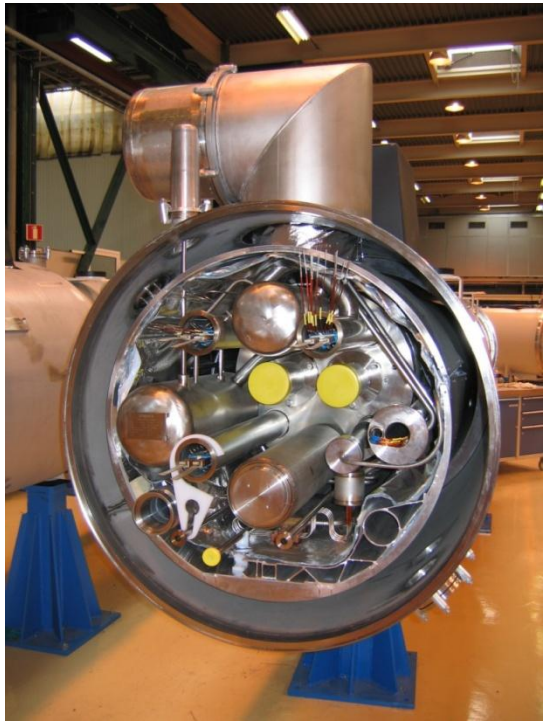
→Setting-up a storage/logistics platform was a must: Space, resources, and methodology

Certainly an underestimated issue!!

Production figures



Highlights

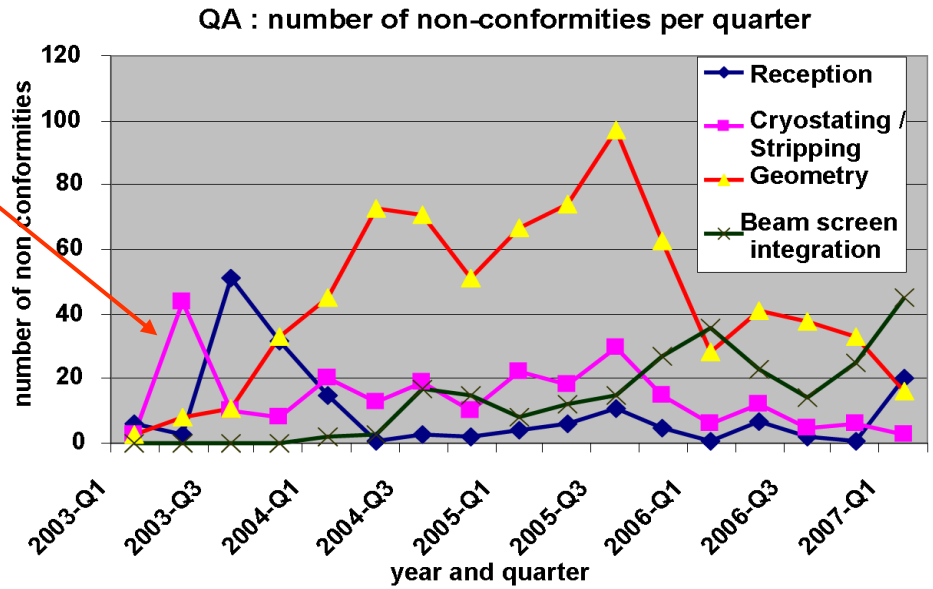


Quality Assurance: Non-Conformities (NC)

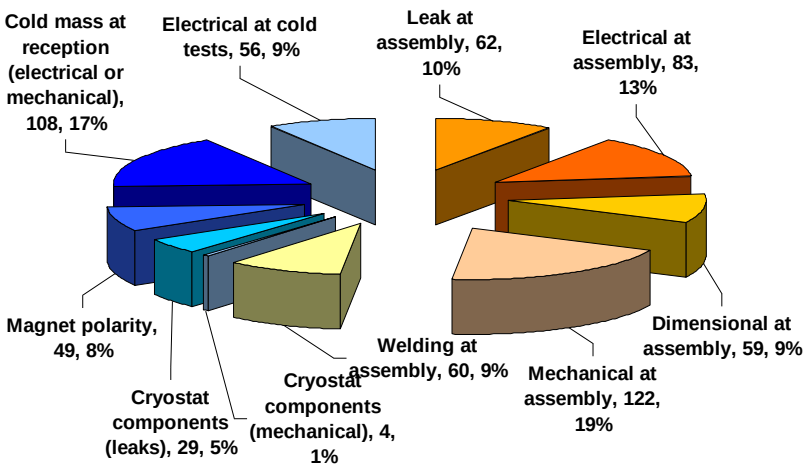
- **Dipole cryostat assembly:**

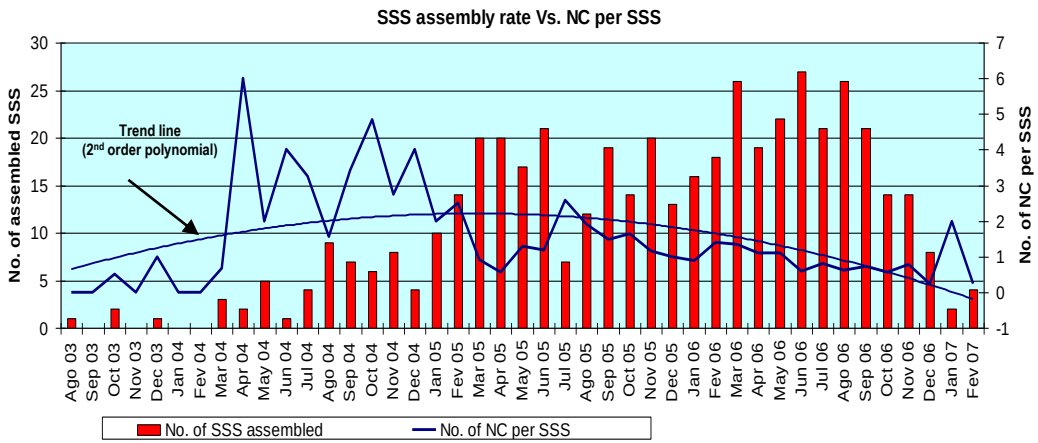
250 NC on 1232 units:

- Mechanical: 95%
- Electrical: 3%
- Welds: 1%
- Leaks : 1%

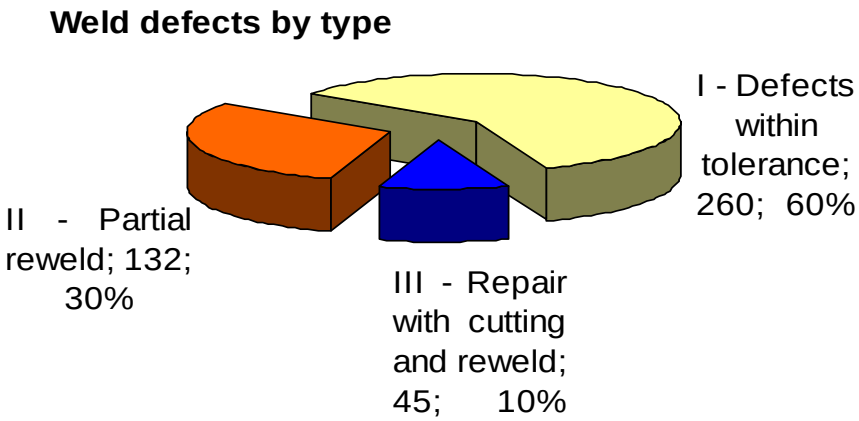


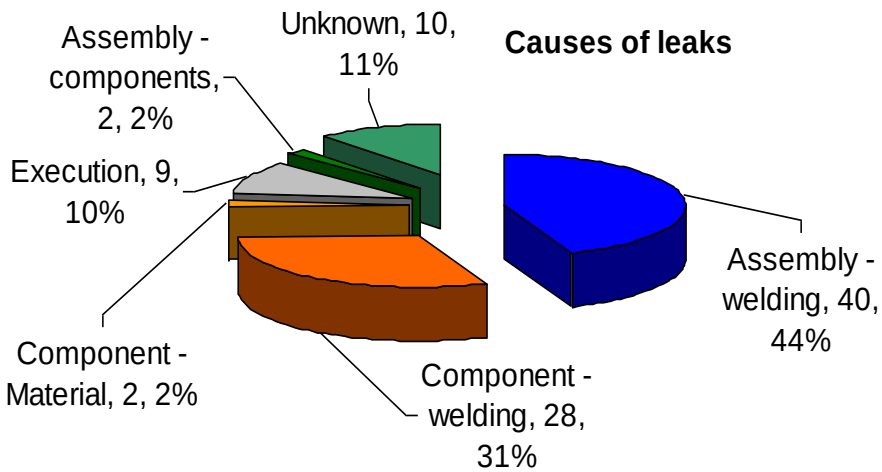
SSS assembly:
600 NC on 474 units





Leak-tight welding





Key figures and findings:

- 20˙000 welds, (mostly manual)
- 2% of defective weld rate
- 3'300 leak detection tests (40% more than initial plans)
- ~ 100 leaks (0.5% of welds)
- No "cold leaks" (but a few leaks broke open at cold)
- Some very difficult leaks to localize → several months stop for some SSS !
- Some leaks "appeared" in the tunnel → very difficult to localize

Summary

- A thorough *product development* and *industrialization*, validated by prototyping and pre-series, is an absolute pre-requisite before production
- The series production of the cryostat components lasted between 3 and 4 years
- Insolvencies of firms or unexpected technical difficulties were tackled by reactive recovery plans made possible by resources and technical competence in the home laboratory
- Splitting of contracts to secure critical supplies was an unavoidable necessity in a few cases
- A major recovery plan for the insolvency of the SSS assembly firm lead to the successful in sourcing of an industrial-type activity.
- The assembly of cryostats was made at CERN in the frame of a *result-oriented* contract, but with very useful provisions for hourly-rated work
- Industrial-type learning curves allowed the assembly of the about 1'700 cryostats in less than 4 years

Thank you for your attention!

Published papers on the industrialisation of the LHC cryostats :

• **CEC/ICMC 2007**, “Series-produced helium II cryostats for the LHC magnets: technical choices, industrialization, costs”.
• **CEC/ICMC 2007,** “The assembly of the LHC Short Straight Sections cryostats at CERN: work organization, Quality Assurance and lessons learned.”
• **CEC/ICMC 2007,** “Leak-tight welding experience from the Industrial assembly of the LHC cryostats at CERN.”
• **PAC 2007,** “Industrial aspects of the Assembly and Quality Control of the LHC cryomagnets at CERN. Lessons learned”.
• **PAC 2005**, “The assembly of the LHC Short Straight Sections (SSS) at CERN: project status and lessons learned”.
• **PAC 2005**, “The Short Straight Sections in the LHC Matching Sections (MS SSS): an extension of the arc cryostat to fulfill specific machine functionalities”.

Spare slides

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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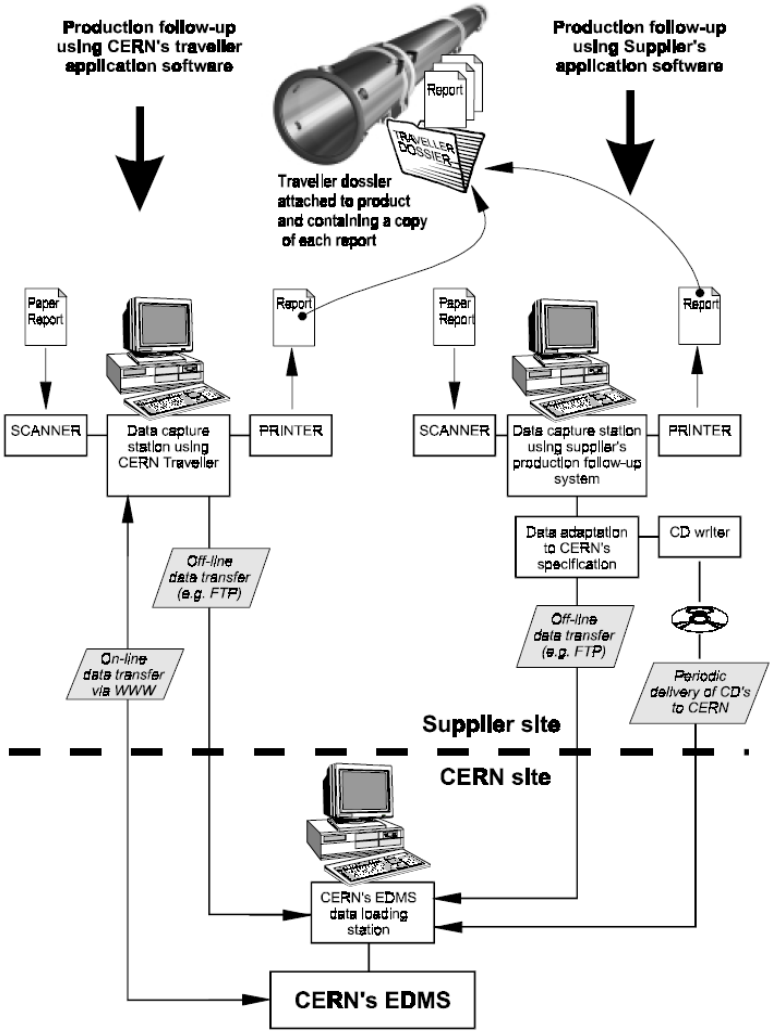

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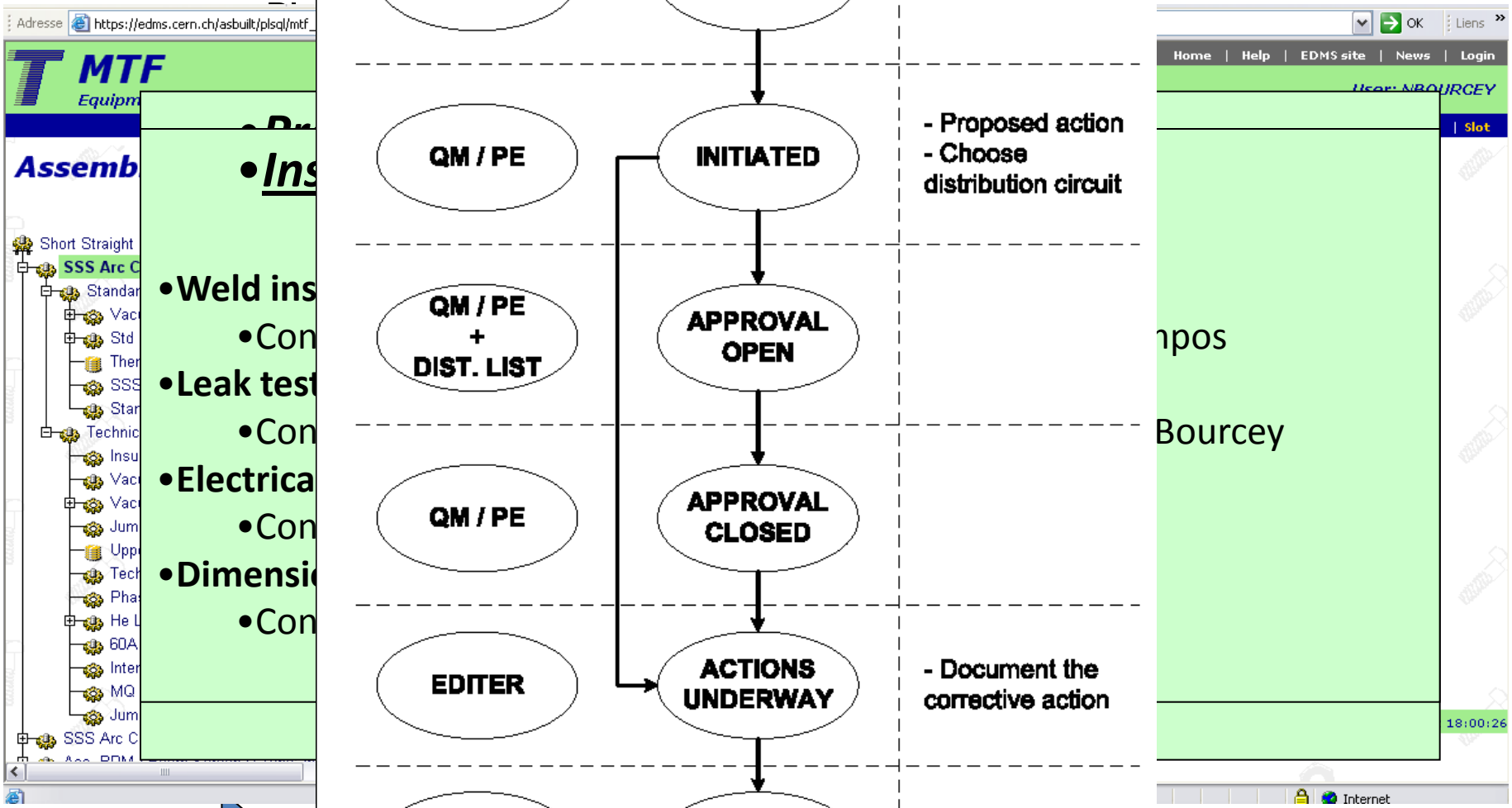


Material Quality

Material defects (AISI316LN with inclusions) in a batch of material supplied by CERN to industry
Helium leaks in flanges

Could have been avoided by:
→More severe quality control
→or 3-D forged flanges (costly!)

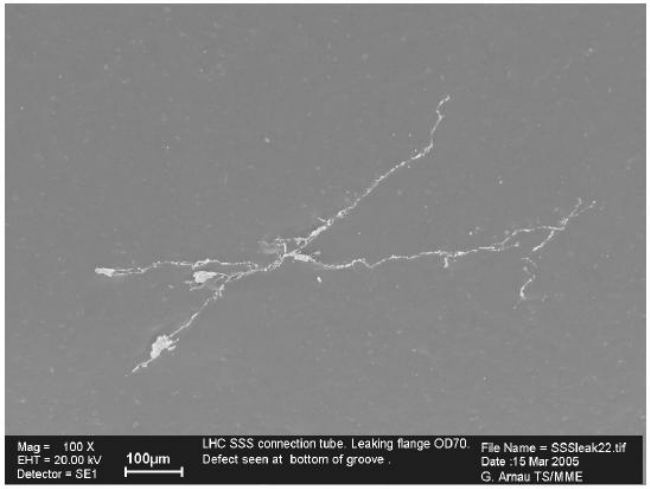
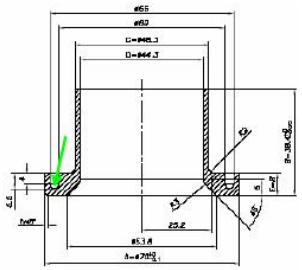
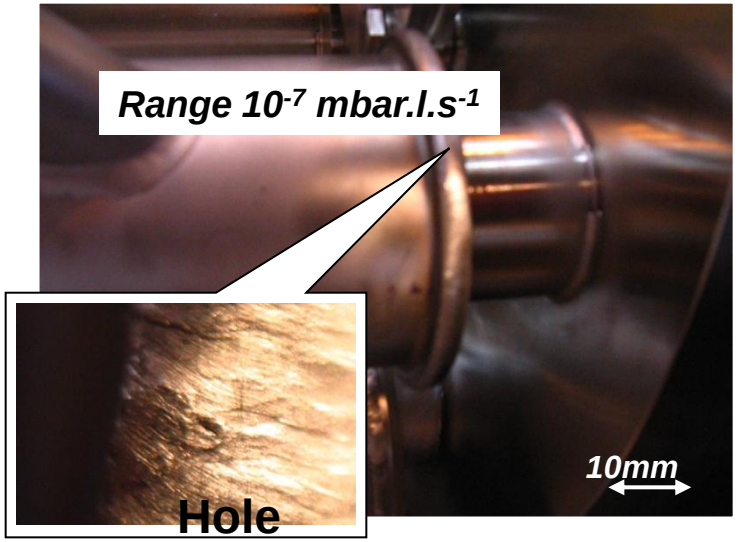
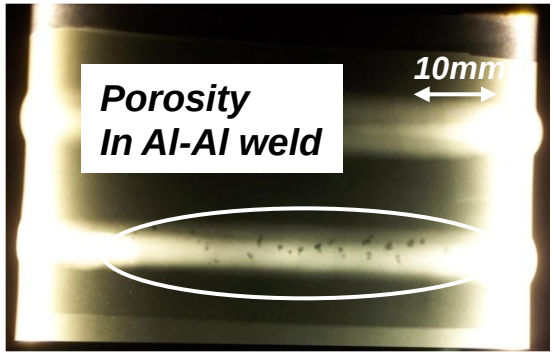


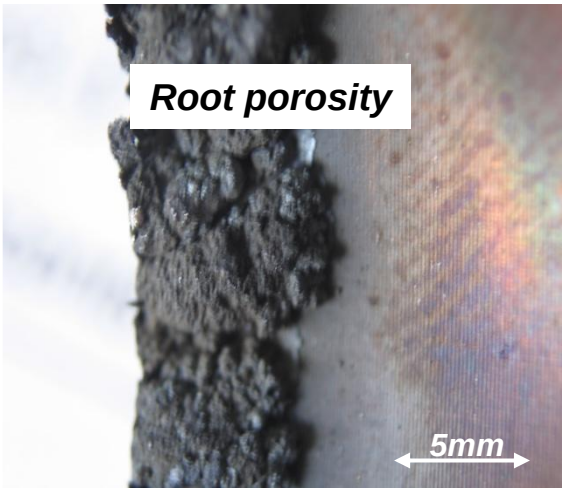
Fig. 6.1.
Mag.: × 100
Electro-polished sample.
Defect seen at the bottom of the groove at position pointed by He leak detection.

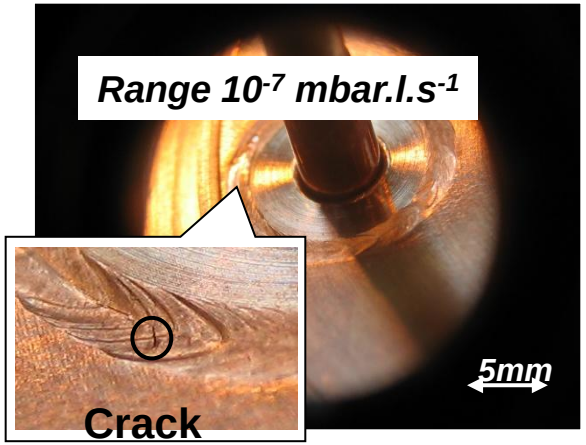


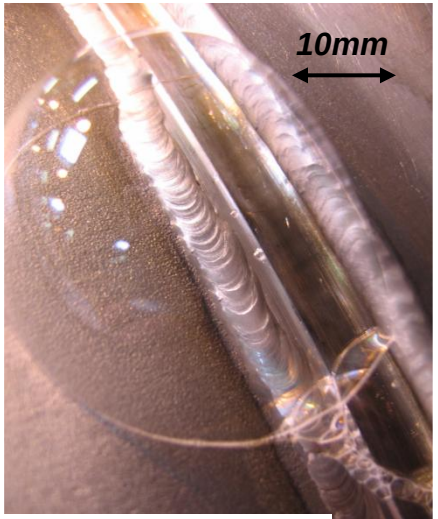
Leaks: Photo Gallery











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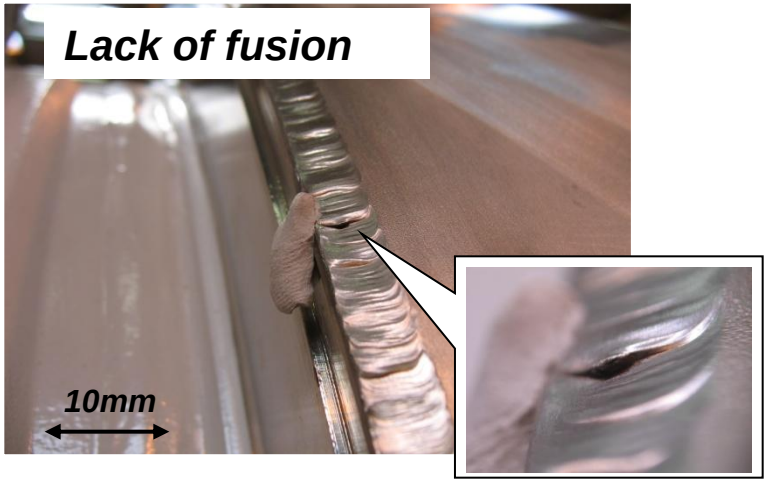


What did we get wrong (or could have done better) ?

…among the tens of stories and lessons learned we have in mind:

Contract management: surviving in the "business jungle"

- Insolvency of firms: can we avoid it? No but…
  - Risk management → reaction plans
  - Needs high reactivity
- Choose splitting contracts for risk-critical supplies: costs more but pays back at the end

Cryostat design:

- Avoid Al-Al welding if possible
- Improve design of welds for easy execution and checks

Technologies:

- Leaks in components from industry → QA
- Leaks in materials → Manufacture, QA
- Leak detection: a key competence in cryostats
  - Lack of competent personnel (in particular for localisation of leaks)
  - Industrial leak check methods is a must: "clam-shells" for example
- Welding:
  - Weld execution:
    - Proper backing (specific tooling)
    - Qualified welders
- Brazing of copper to st.steel
  - Use of acid cleaning agents → slow corrosion leading to leaks
  - A CERN qualified brazing flux esists

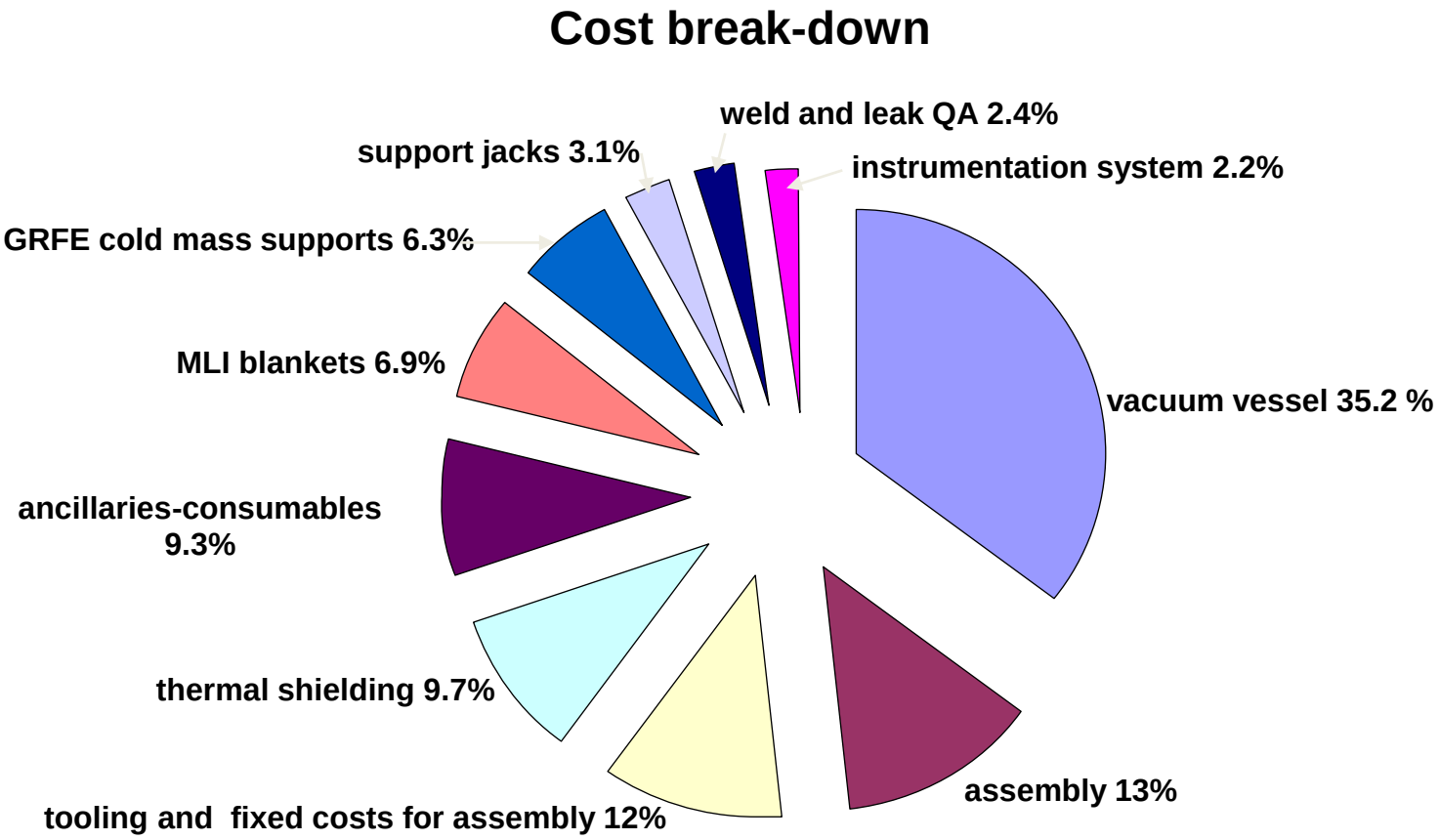
Production follow-up:

- QA inspections in industry:
  - Never believe blindly in paper work (certificates of conformity): repeat tests, it costs but it pays back!
  - Requires qualified and well trained inspectors
- Logistics & storage

Costs of Assembled Dipole Cryostat

100 kCHF (~81.4 kUSD) per cryo-dipole assembled cryostat (2007 value)

(1 CHF = ~0.82 USD)



Costs of Assembled SSS

Unit cost: **114-136 kCHF** (**93.5-111.5 kUSD**) depending on SSS complexity (2007 value)