Construction Experience of the LHC Cryostats

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Outline:

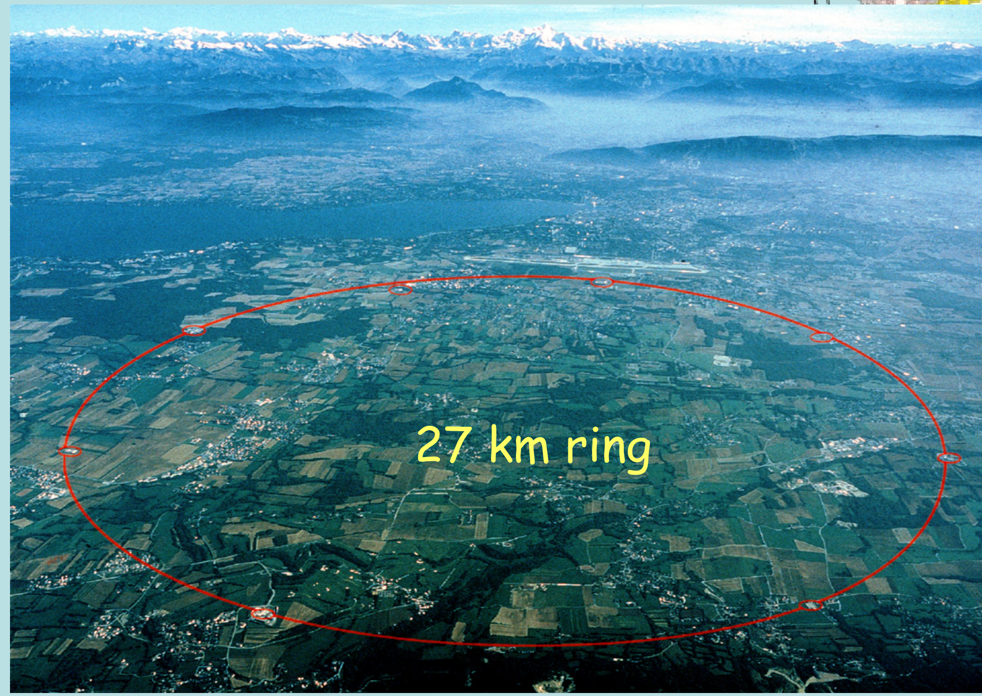
- Design principles
- Main cryostat components
- Cryostat Assembly
- Costs
- Performance
- Summary

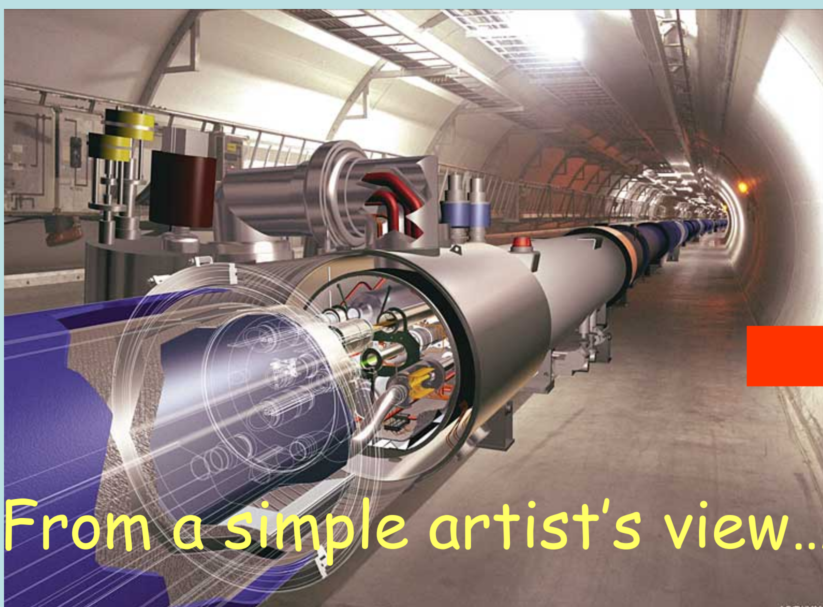
Acknowledgements:
*I wish to acknowledge the work of **all colleagues** who have contributed to the LHC cryostats, in particular the members of CERN's former **AT-CRI group** (now part of AT-MCS) for the work done **between 1996 and 2006**.*

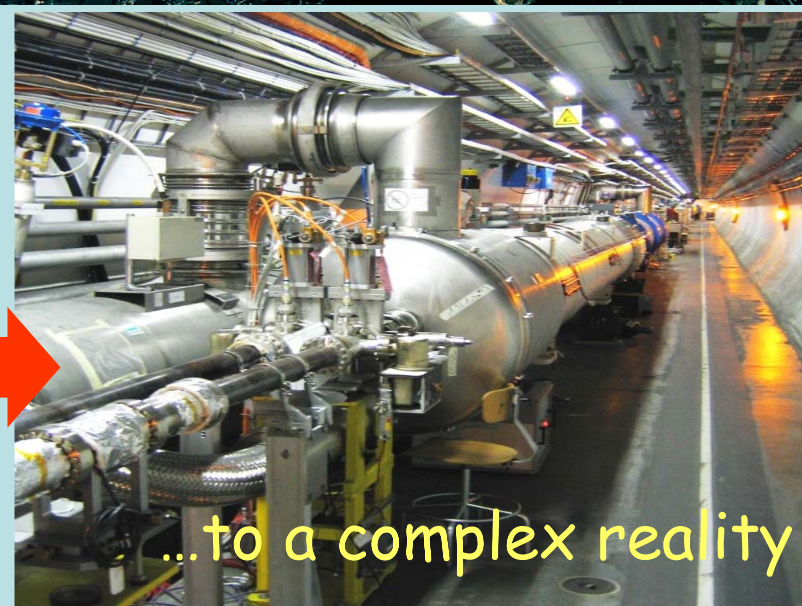
Introduction

LHC cryostats. Key figures:

- 8 continuous cryostats ~ 2.7 km each (80% of the ring)
- 36 individual cryostats (excluding triplets) in the LSS
- 1232 cryo-dipoles
- 474 Short Straight Sections (SSS):
  - 360 main quad SSS in the arcs
  - 114 insertion quad SSS in the DS and LSS regions

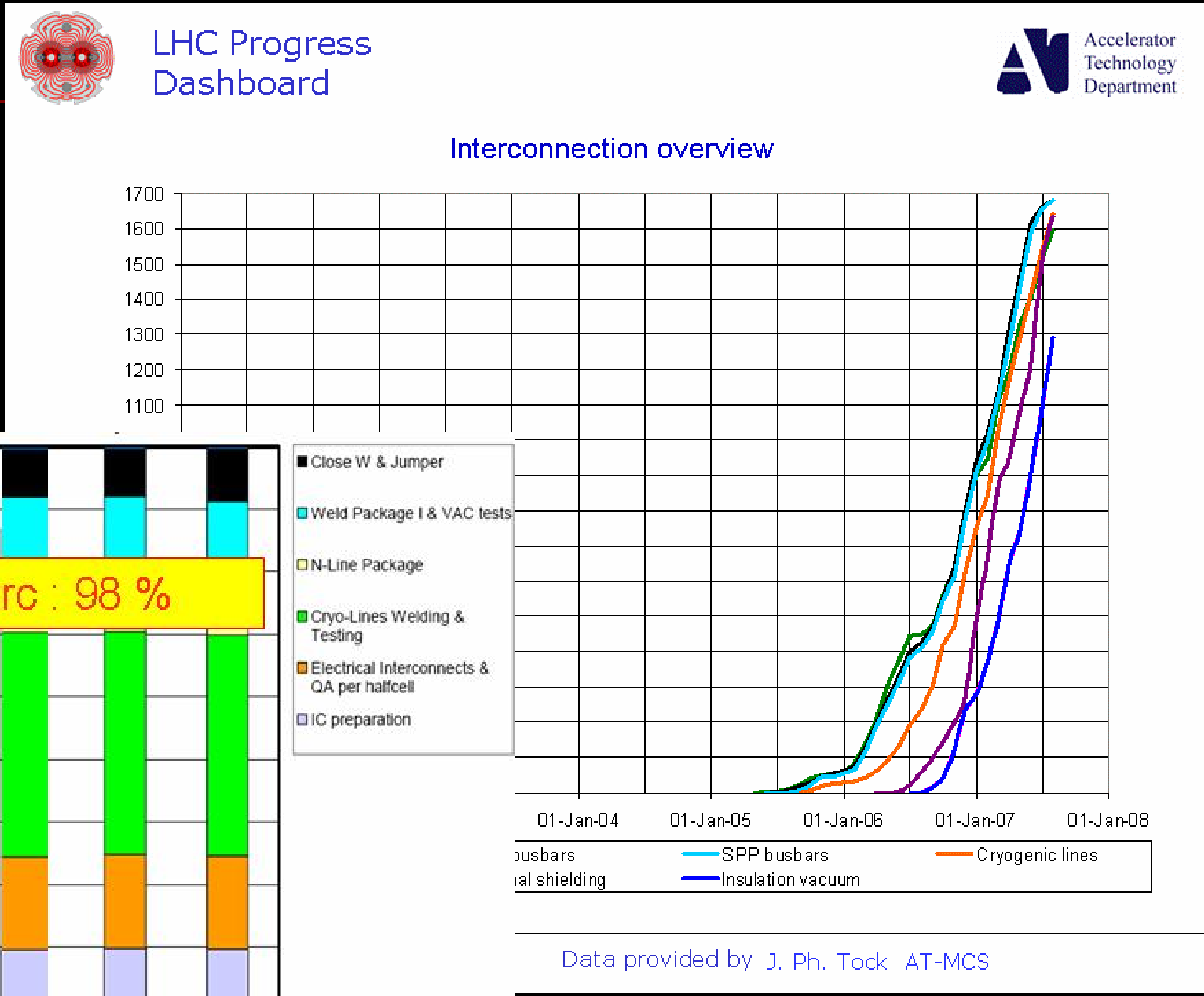


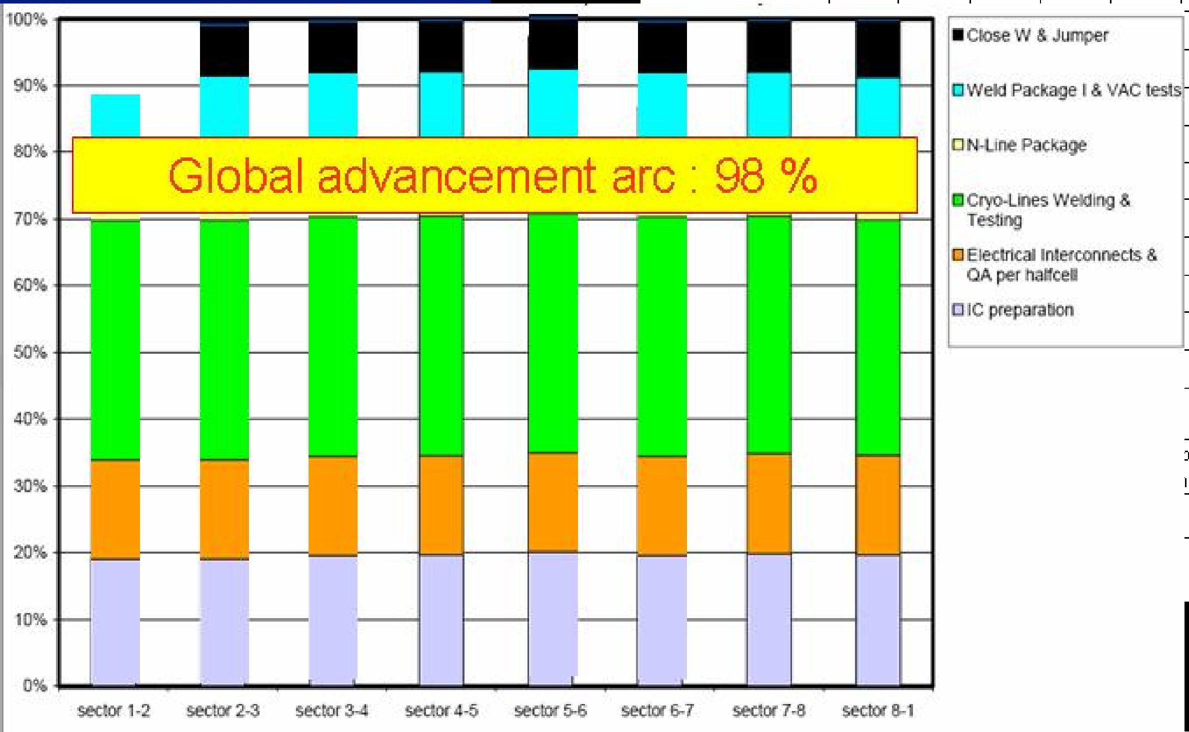




The LHC interconnections

- Overall progress





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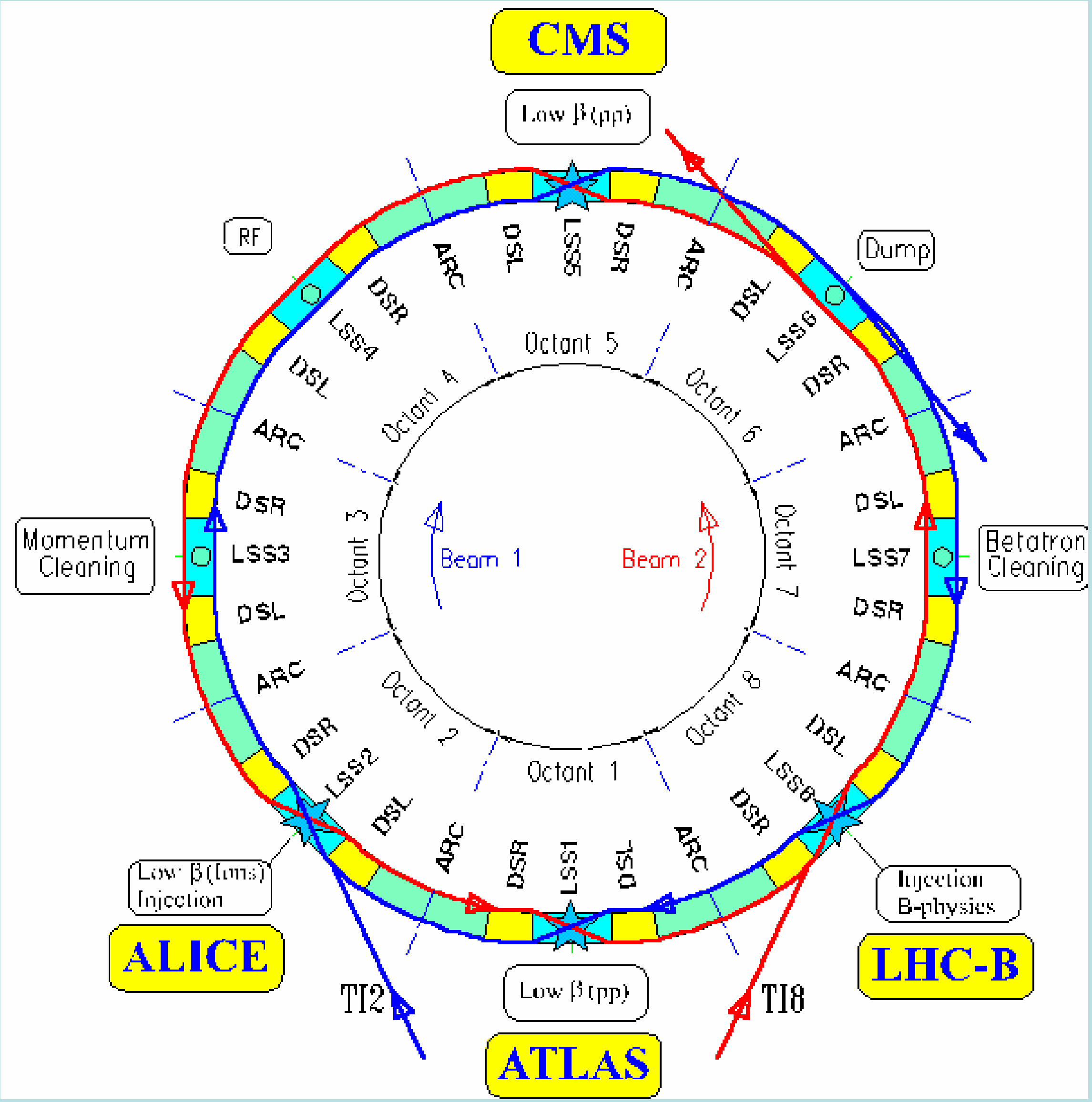
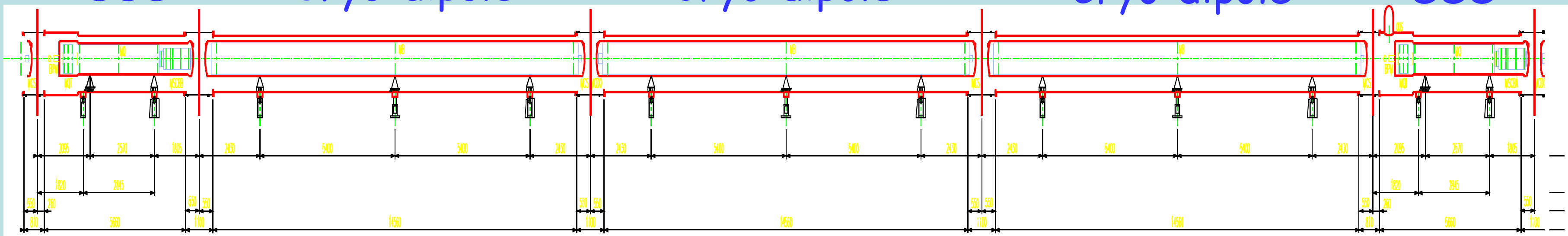
Layout


CMS
Low β(pp)
RF
Dump
Momentum Cleaning
Betatron Cleaning
Octant 1
Octant 2
Octant 3
Octant 4
Octant 5
Octant 6
Octant 7
Octant 8
Beam 1
Beam 2
LSS1
LSS2
LSS3
LSS4
LSS5
LSS6
LSS7
LSS8
ARC
DSR
DSL
Low β(Ions) Injection
ALICE
TI2
Low β(pp)
ATLAS
TI8
Injection B-physics
LHC-B

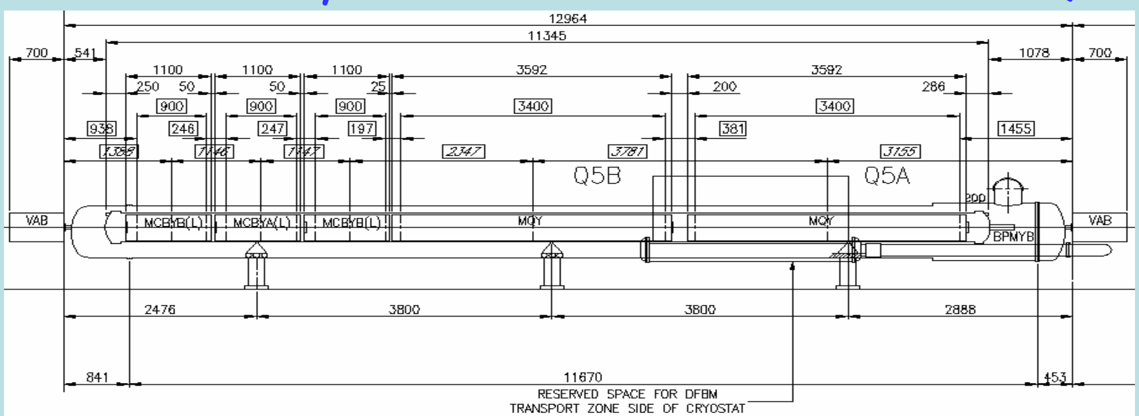
LHC cryostats

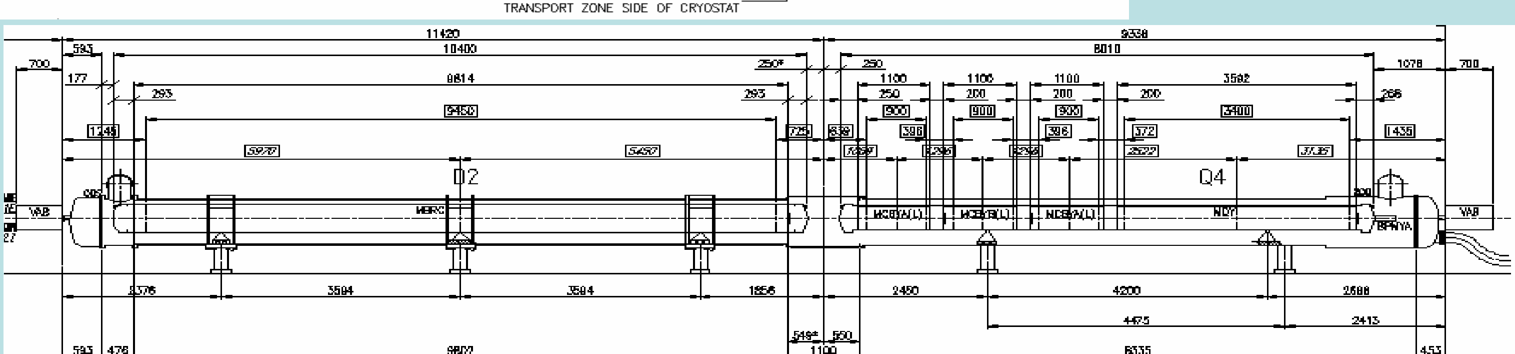
- 8 continuous cryostats in Arcs and DS (21.6 km):

SSS Cryo-dipole Cryo-dipole Cryo-dipole SSS



- Individual cryostat assemblies in the LSS (36 units, ~300 m):





LHC cryostat functions

Recalling Basic Functions:

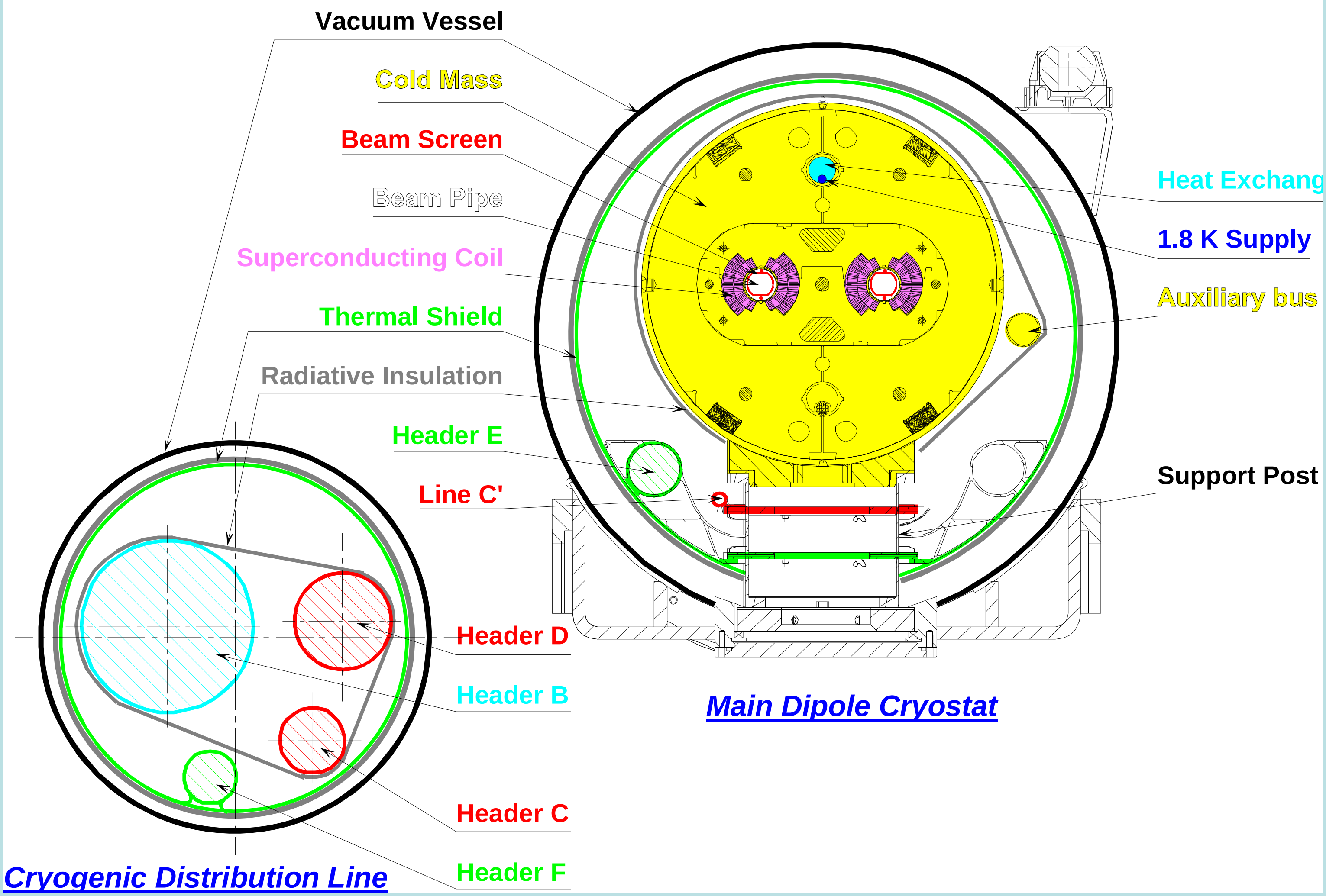
- **Mechanical housing of cold masses:**
  - Supporting of heavy superconducting magnets in their cold masses
  - Accurate & stable positioning of cold mass in vacuum vessels
  - Allow precise magnet alignment capabilities (via external jacks)
- **Thermal insulation:**
  - **1.9 K** cold masses housing the magnets
  - Cryogenic piping and components

Other functions:

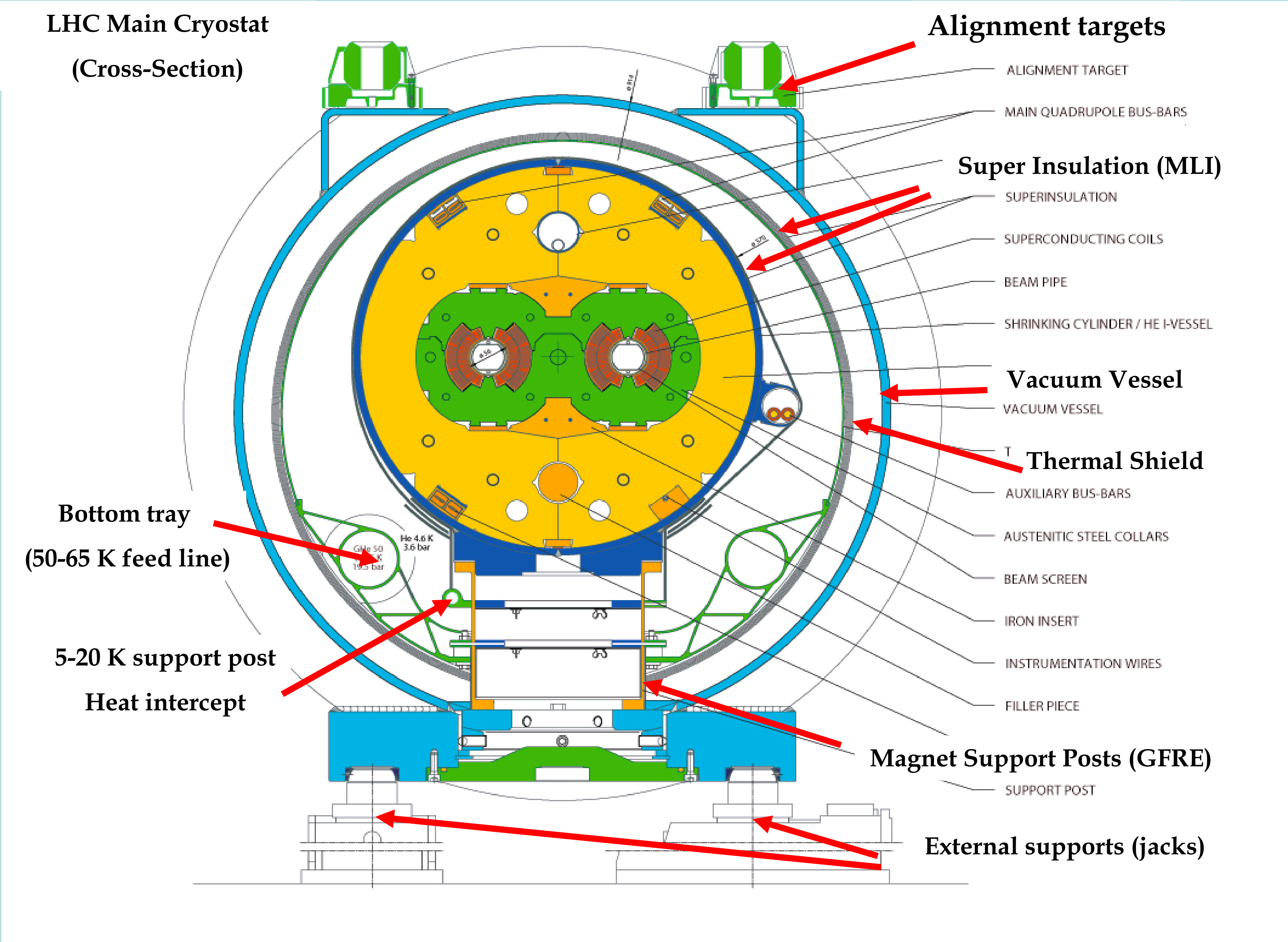
- Magnetic shielding
- Integrate various equipment: BPMs, cryogenic and vacuum H/W, magnets and cryogenic diagnostics instrumentation…
- Allow (limited) maintenance: ex. exchange of diodes
- Allow interconnecting magnets
- Permit handling and transport of cryo-magnets throughout CERN activity sites

Separate Cryogenic Distribution Line (QRL)

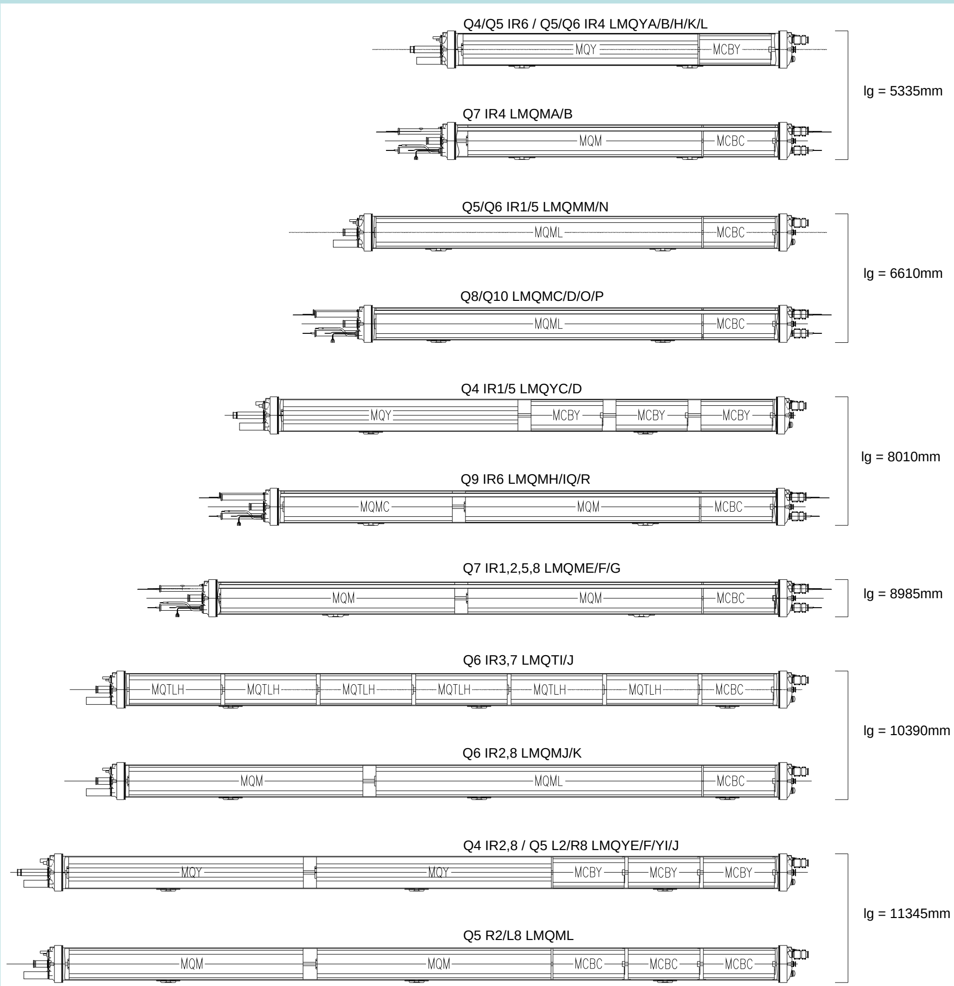
Typical LHC Cross-section

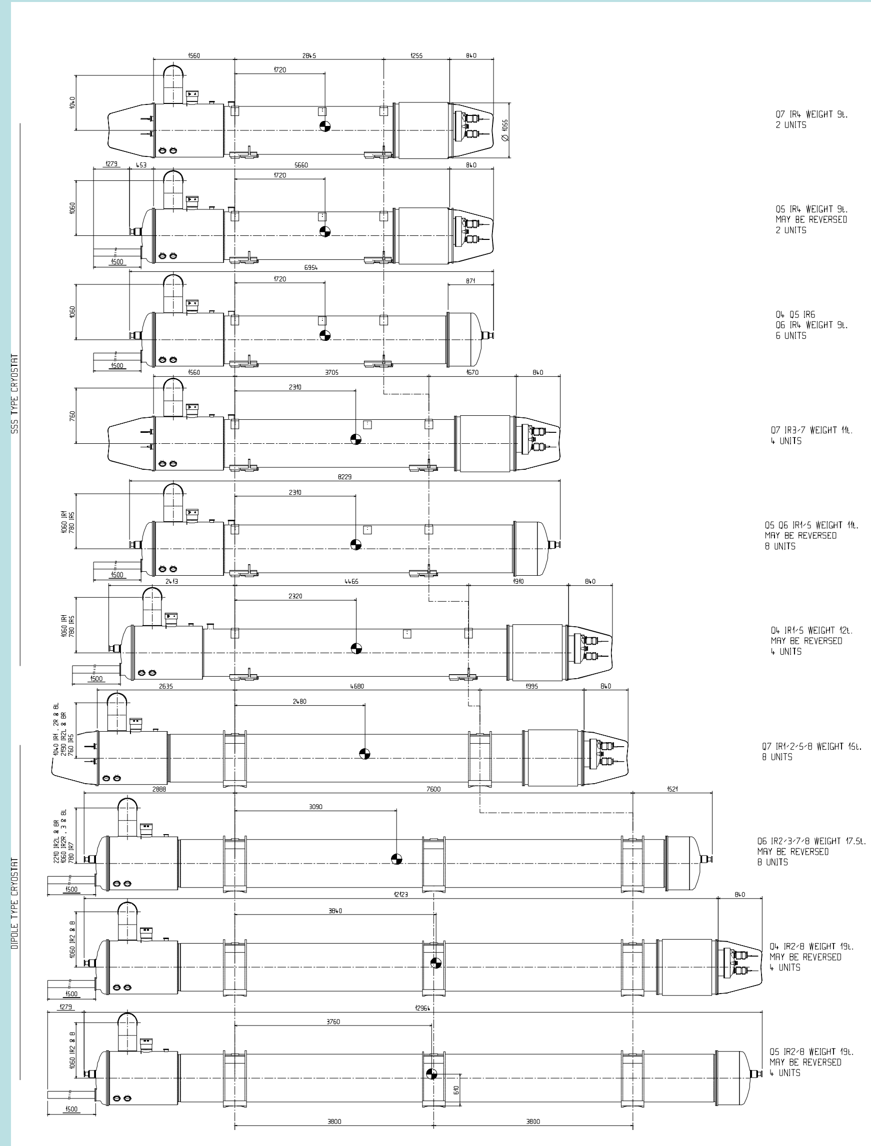


Cryostats: main features

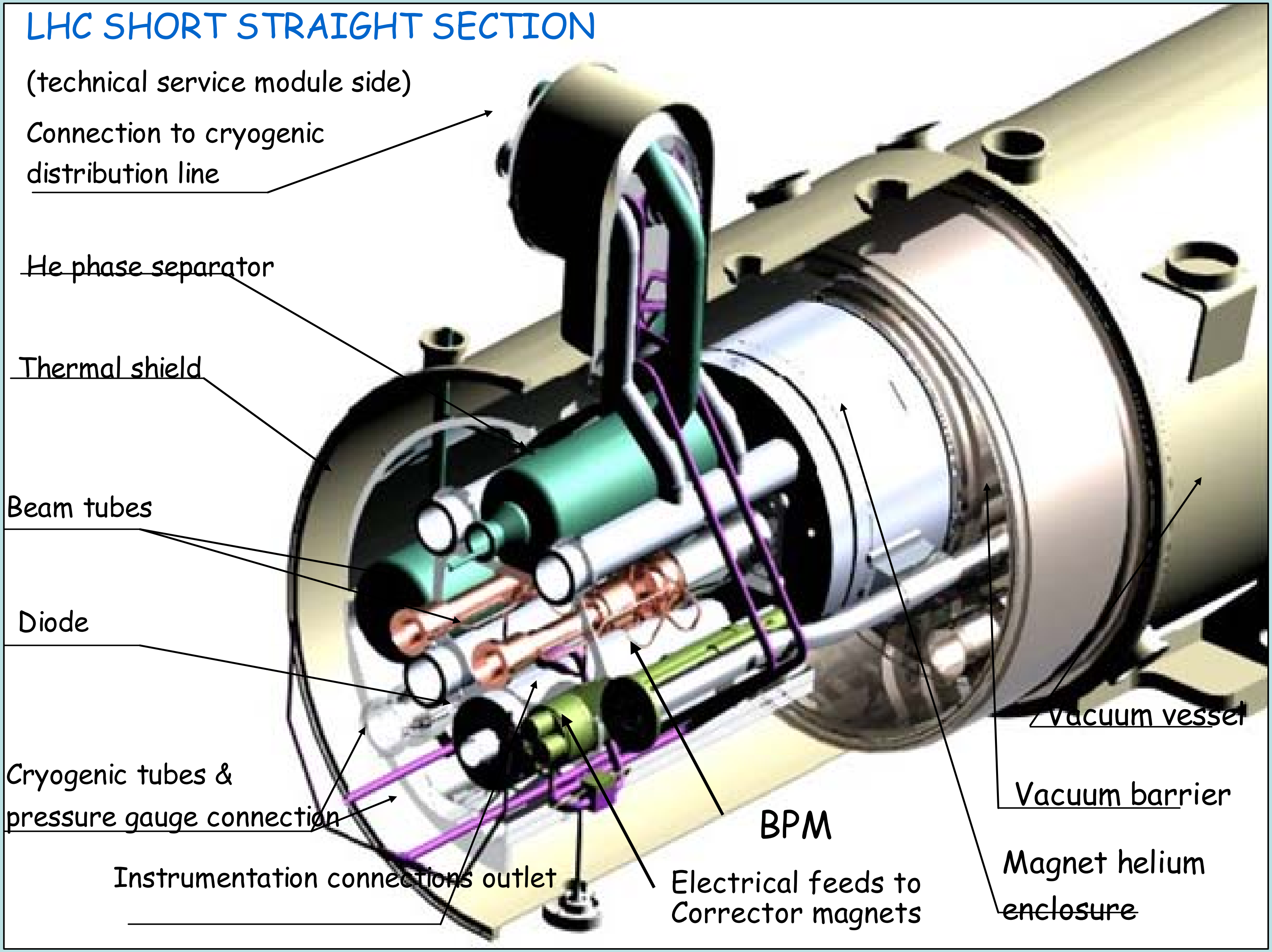


Cryostats: SSS variety





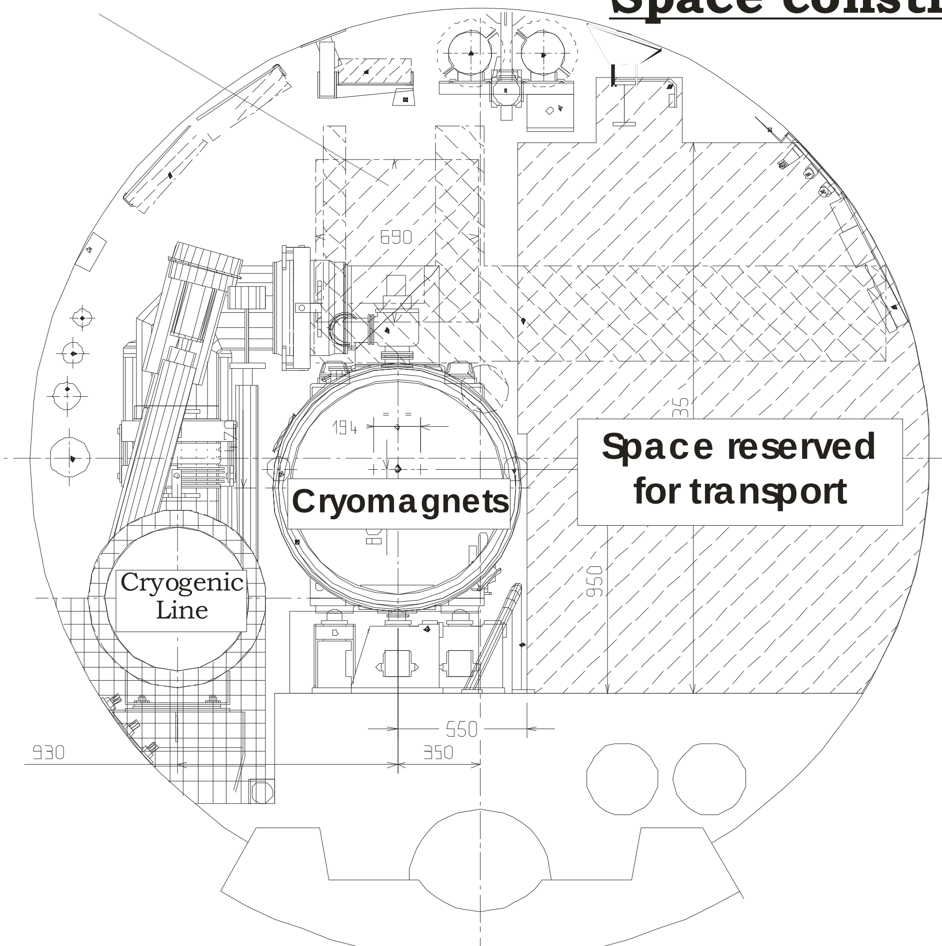
The SSS


LHC SHORT STRAIGHT SECTION
(technical service module side)
Connection to cryogenic distribution line
He phase separator
Thermal shield
Beam tubes
Diode
Cryogenic tubes & pressure gauge connection
Instrumentation connections outlet
BPM
Electrical feeds to Corrector magnets
Magnet helium enclosure
Vacuum barrier
Vacuum vessel

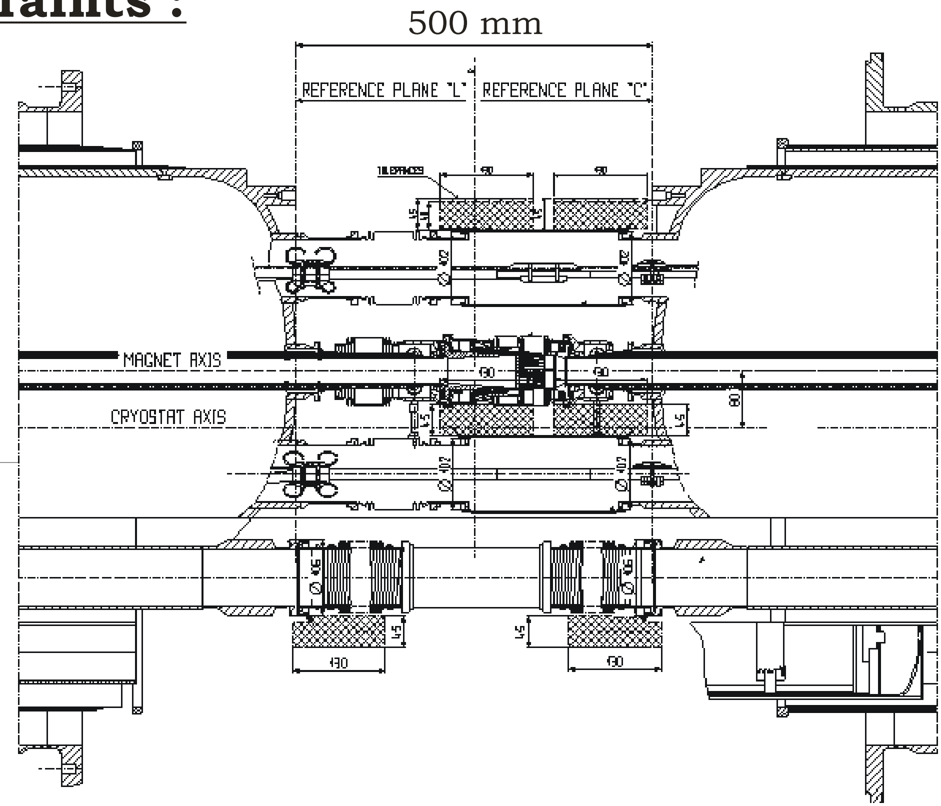
The LHC interconnections

- Space constraints

Space constraints :



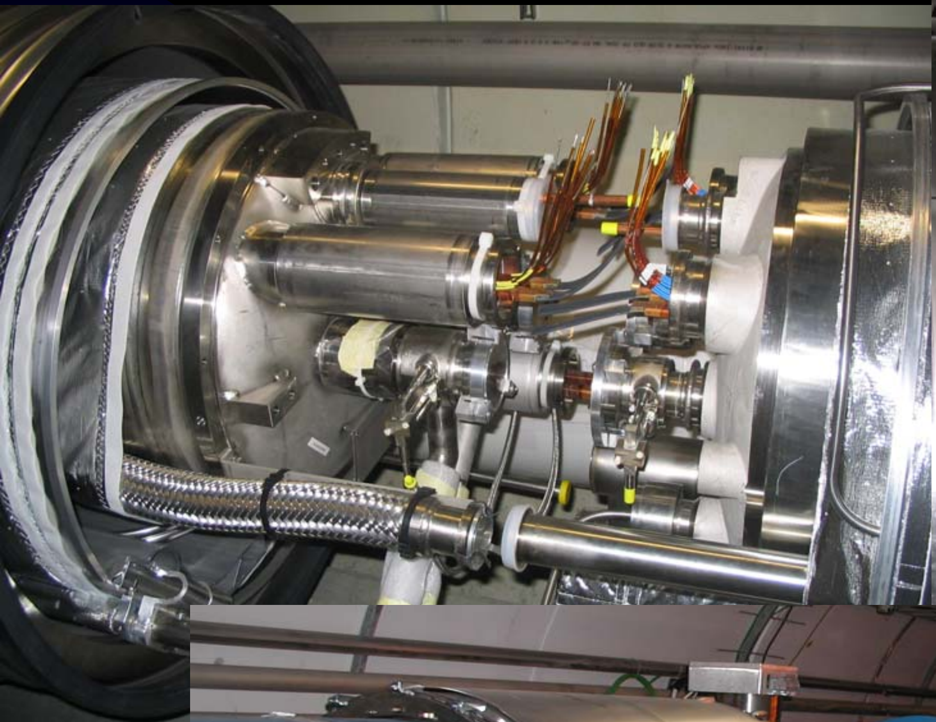
Typical cross-section of the LHC tunnel

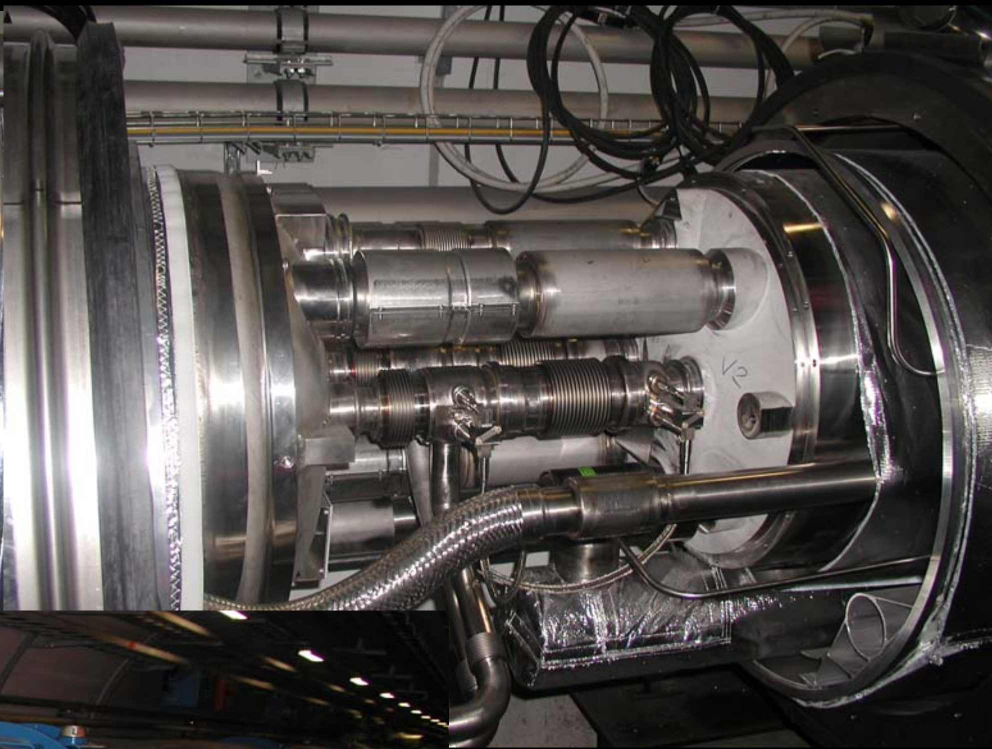


Typical longitudinal section of a LHC interconnection

The LHC interconnections

- Optimised interconnexion ; before, during and after





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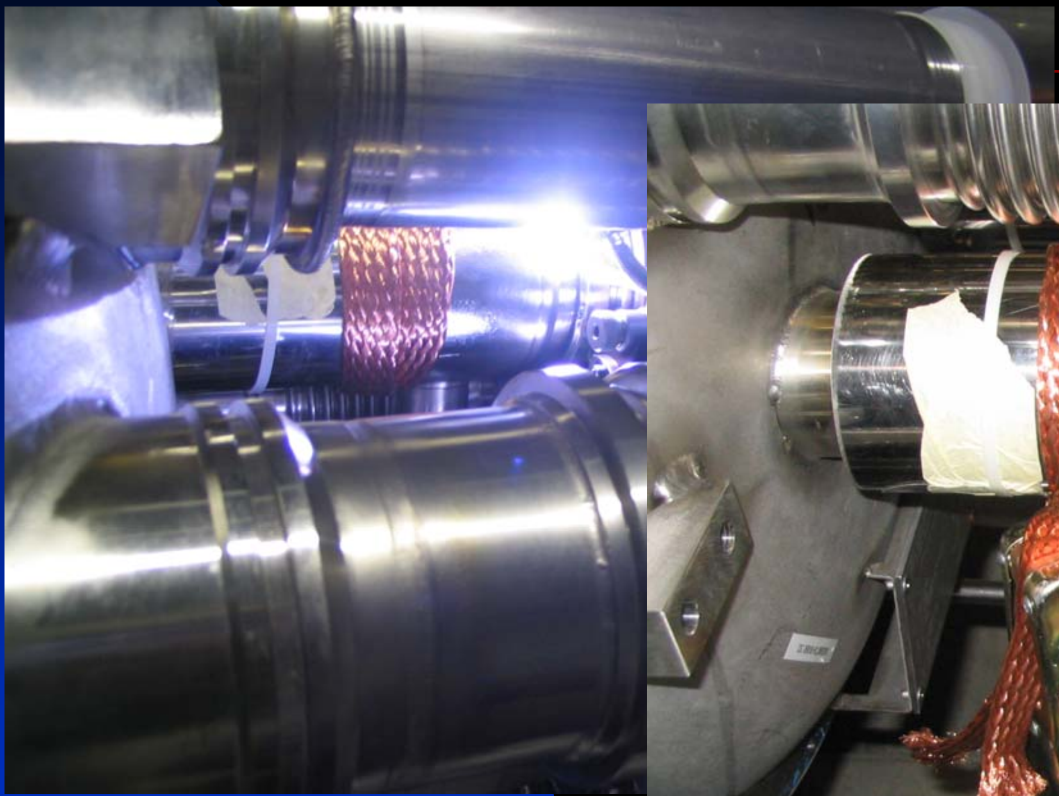
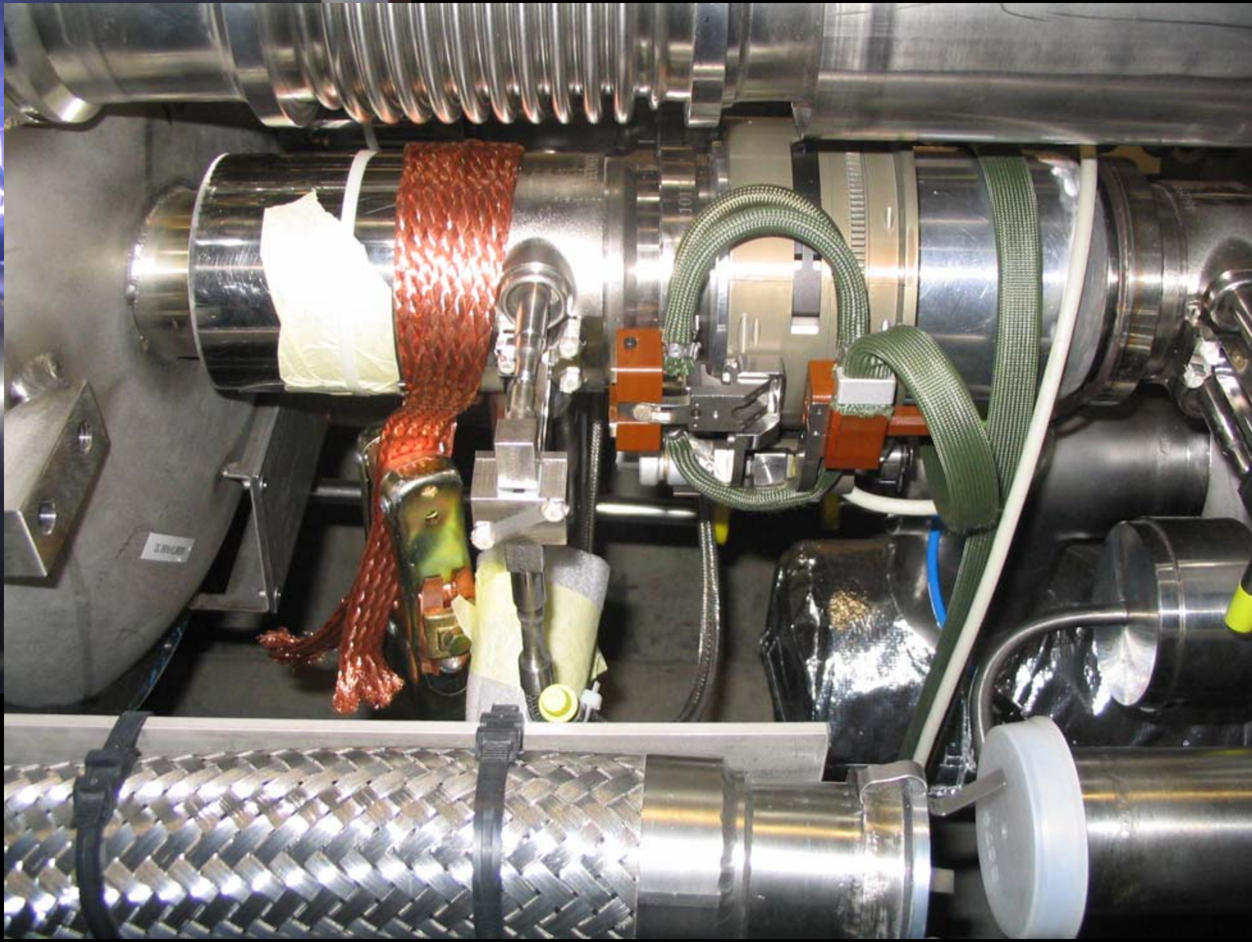
The LHC interconnections

- 40 000 leak tight TIG welds in crowded places





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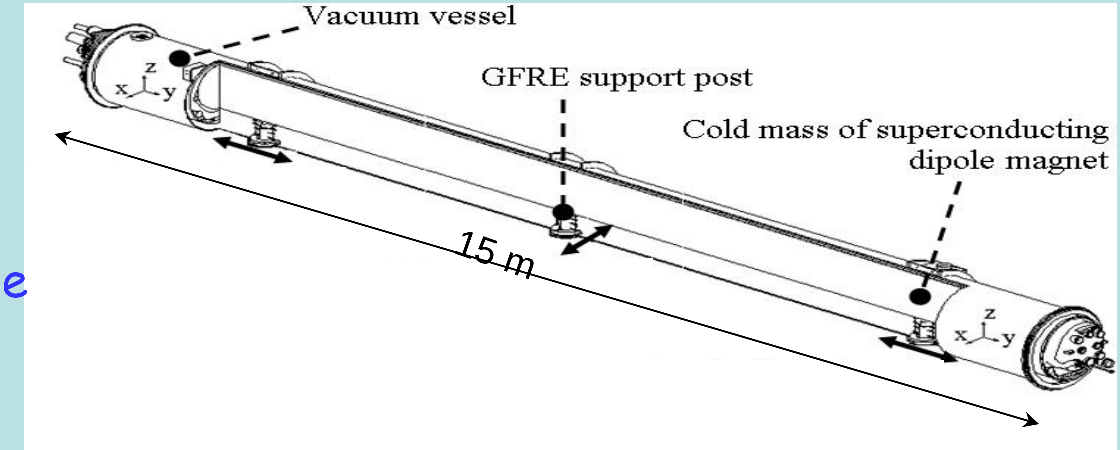
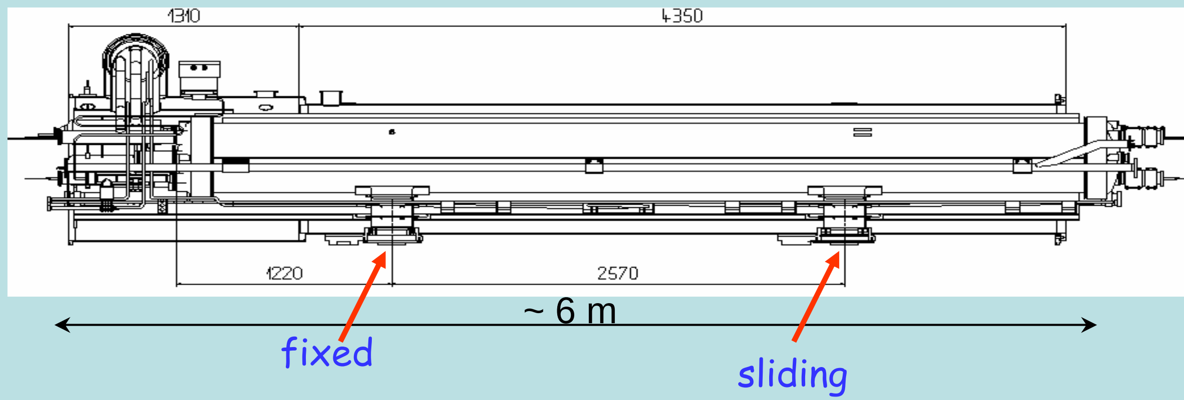
Magnet Supporting Systems

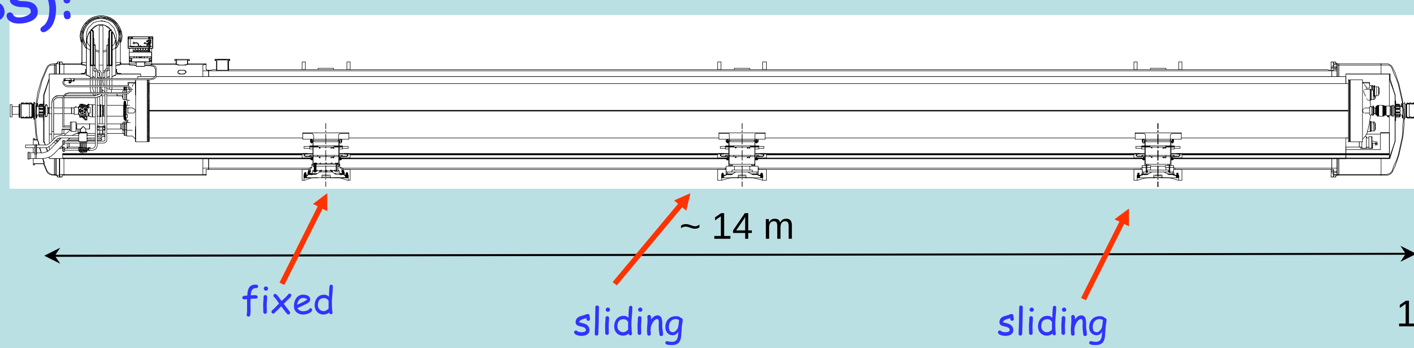
Cryo-dipole:
- 3 supports
- central support fixed
- extremity supports slide



Arc SSS:
- 2 supports
- left support fixed
- right support slides



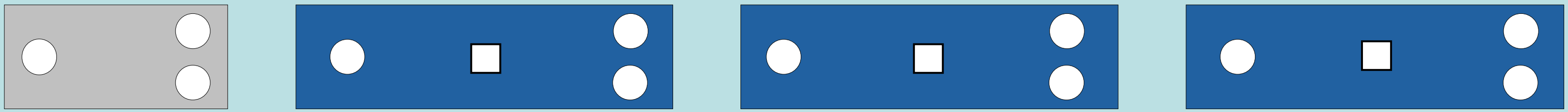
Longest SSS (in LSS):
- 3 supports
- left support fixed
- other 2 slide



External Supporting System

LHC arc half-cell (top view)

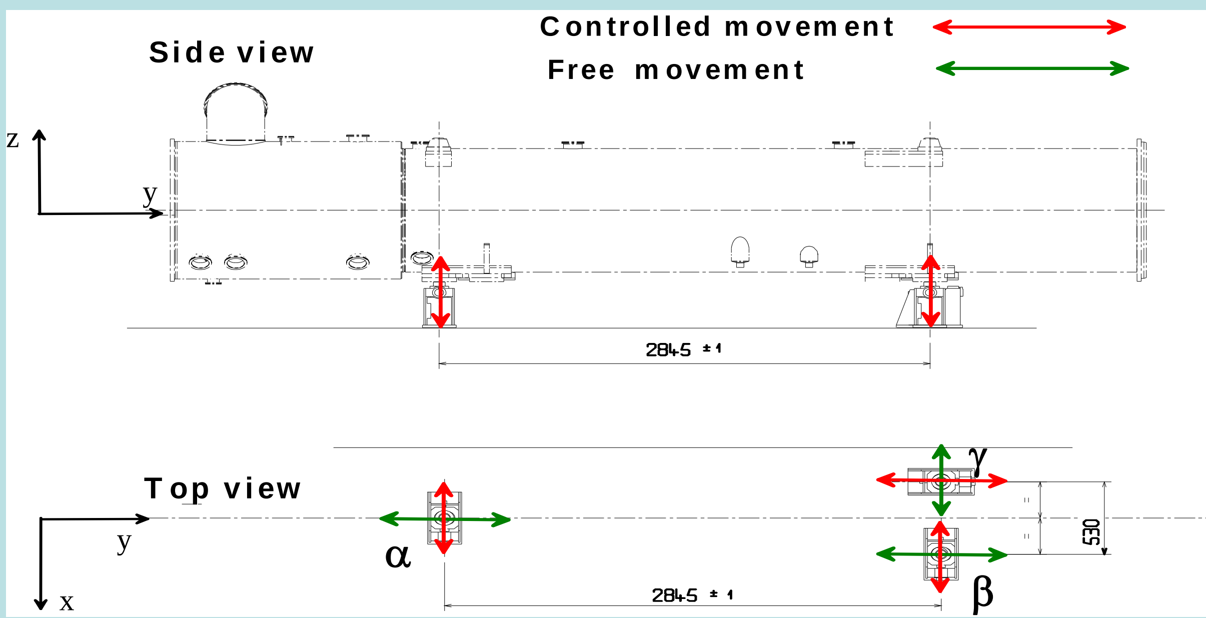
SSS Cryo-dipole Cryo-dipole Cryo-dipole



○ Jack

□ Central jack ("crutch" for vertical sag adjustment only)

SSS



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-magnet
  - String 1 (53 m half-cell, 1994-1997). first prototypes; 10-m dipoles
  - String 2 (106 cell, 1998-2000); validation of *quasi*-final cryostat 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 1 supplier for critical risk components
- **Assembly of cryostats at CERN** based on a **"Result-oriented"** execution contract.

Vacuum Vessels


Stress relieving


Forged cradle

Main features:

- 36-inch OD, 12-mm thick, low carbon steel (DIN GS-21 Mn5) tubes
- Resilience: 28 J/cm2 at -70°C
- Forged cradles, welded rings reinforcements
- St. steel extremity flanges
- Stress relieving by vibration for dimensional stability
- Final machining to achieve tolerances at interface

Production (including spares):

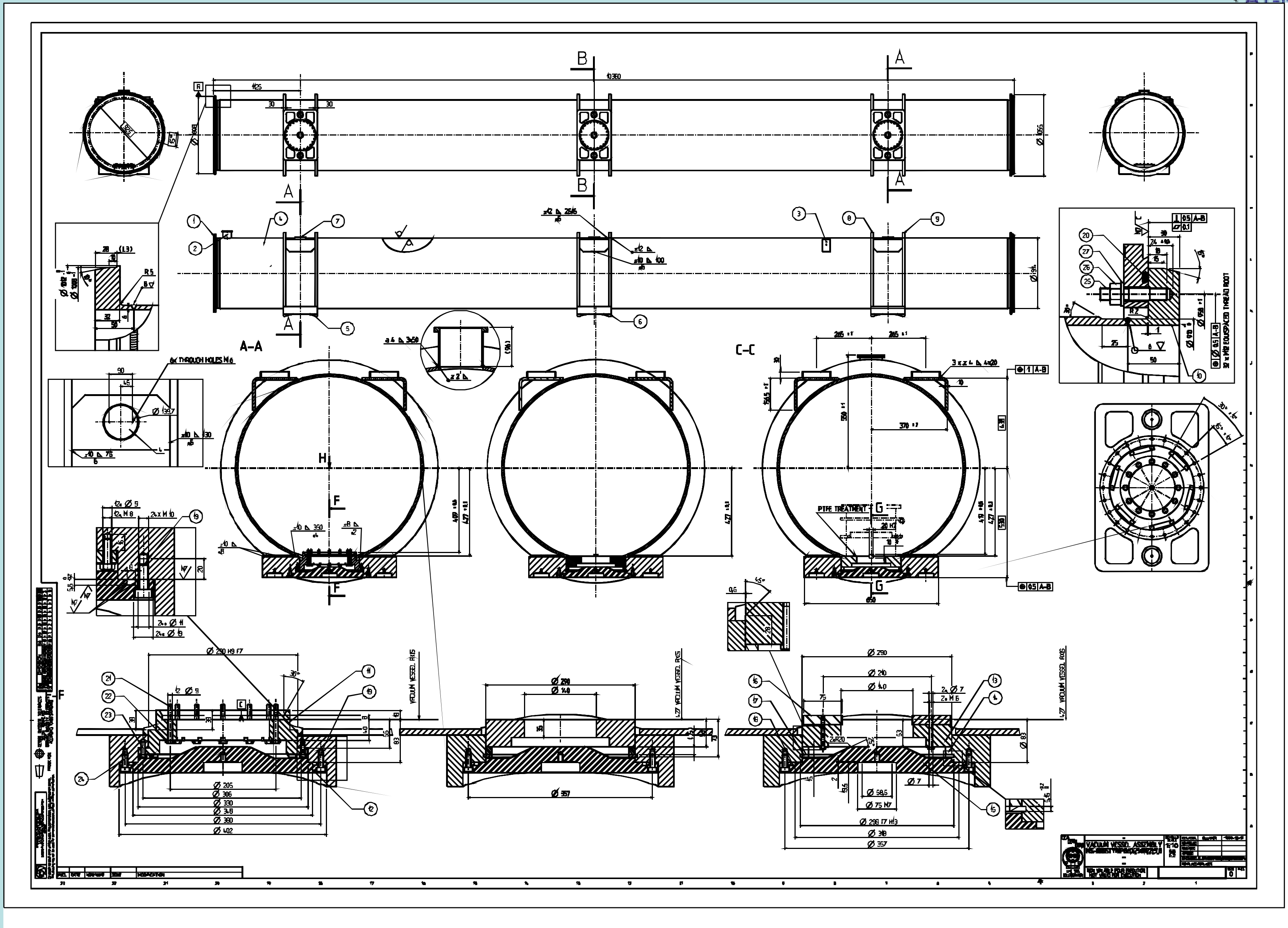
- 1250 units for dipoles
- 500 units for SSS
- 2 firms for dipoles
- 1 firm for SSS
- 4 yrs of production
- Tooling cost: 20% of contracts value


Out-doors storage at CERN

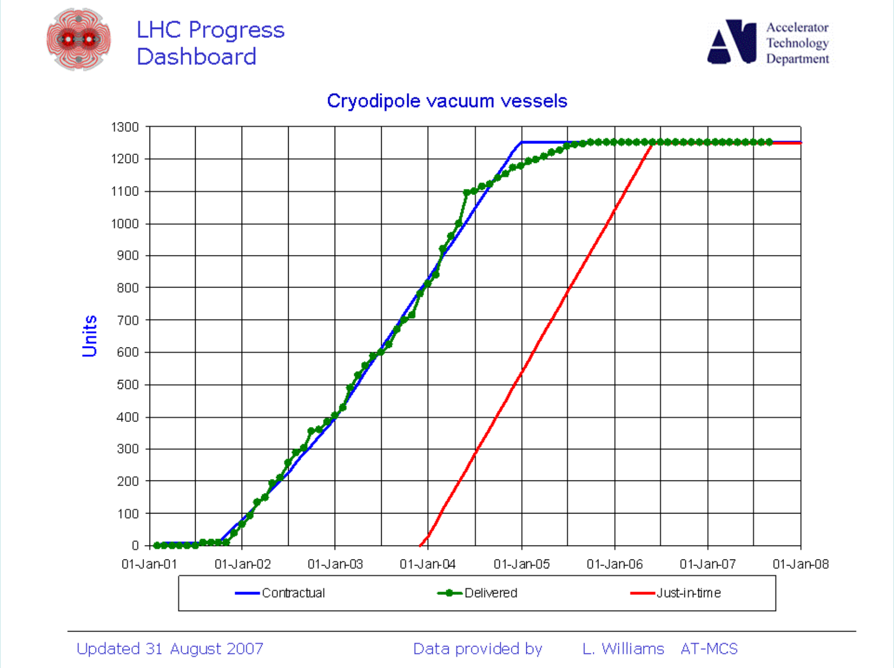

Final lathe machining


3-D dimensional control in Industry

Dipole vacuum vessel



Vacuum vessels (cont.d)



Main lessons learned:

- Started on 1 supplier….
- ….then splitting on 2 suppliers for dipoles, (+1 supplier for SSS) to ensure production
- Suppliers (small/medium size sheet-metalwork companies) had to learn the "cryostats culture":
  - Leak-tight welding
  - Leak detection (<10-9 mbar.l/s) using helium mass spectrometry
  - Cleanliness
- Technical issues:
  - Dimensional and shape tolerances at flanges
  - Other but minor issues

Aluminum Thermal Shields

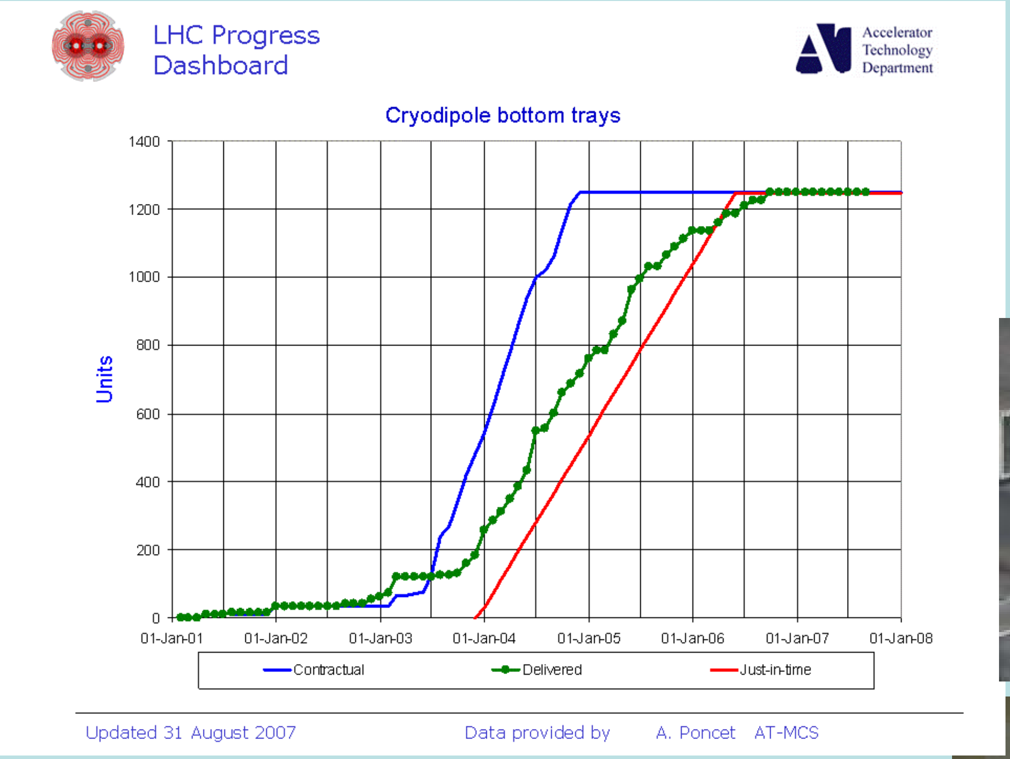
Main features:

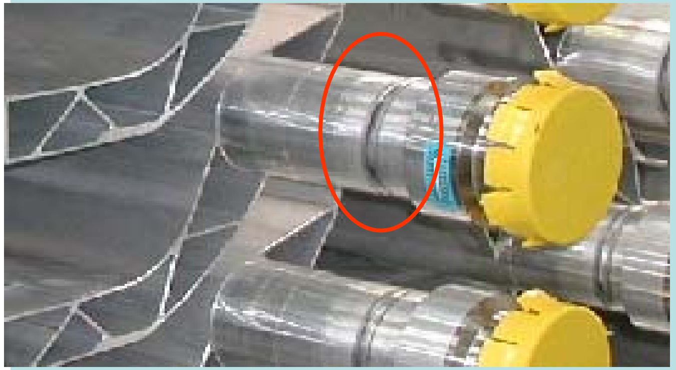
- Al 6060 double-walled extruded tray with cryogenic cooling channel
- Al-st.steel transitions at cryogenic channel's ends
- Al rolled sheets with longitudinal welds to tray

Production (including spares):

- 1250 units for dipoles
- 500 units for SSS
- 2 suppliers
- 4 yrs of production
- Tooling cost: 15% of contracts value

Aluminum Thermal Shields

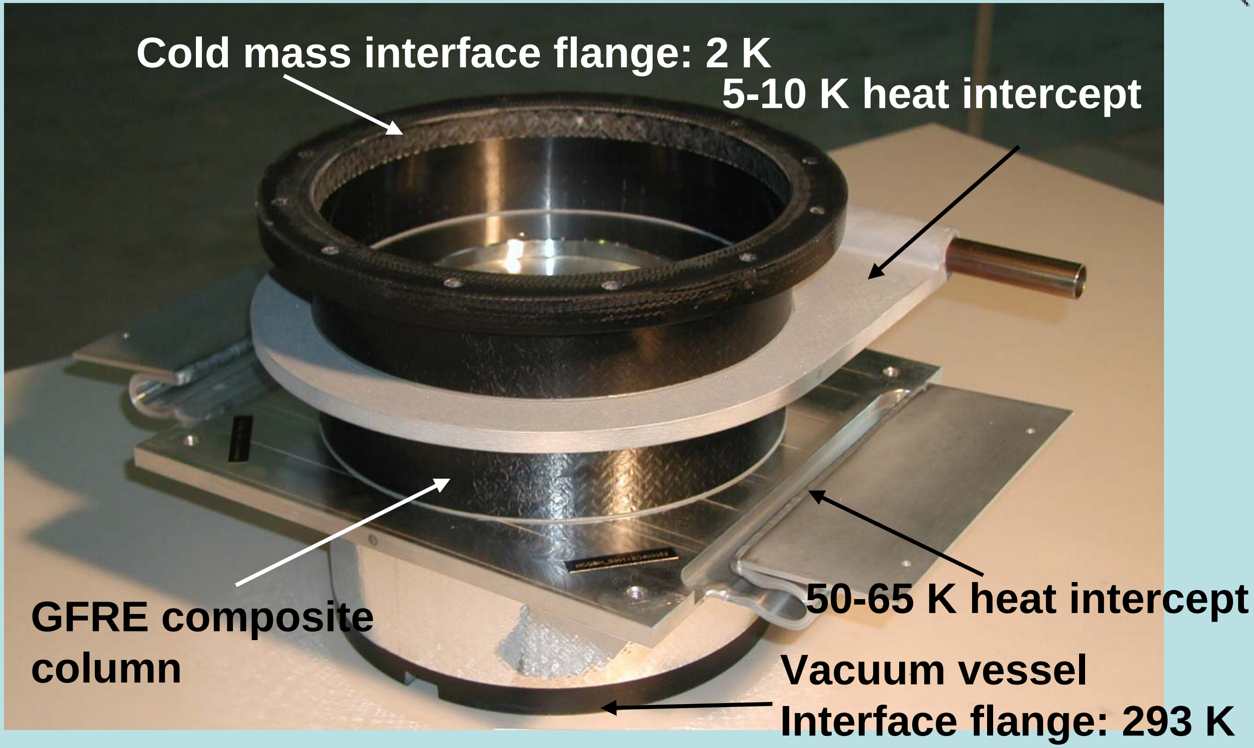




Main lessons learned:

- Started on 1 supplier which became insolvent
- New Call for Tender and splitting on 2 suppliers
- Technical issue:
  - Al-Al weld quality of Al-st.steel transitions
  - CERN in sourcing of activity…
  - …then outsourced competence to firms

GFRE Support Posts

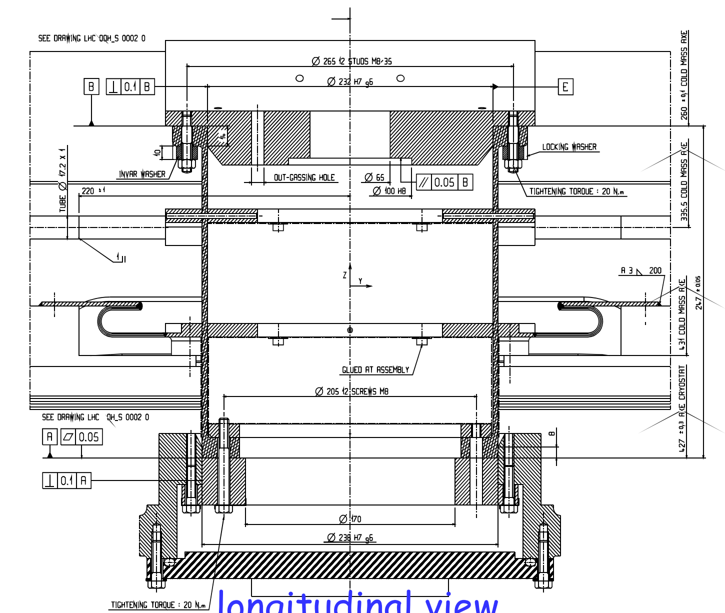


Features:

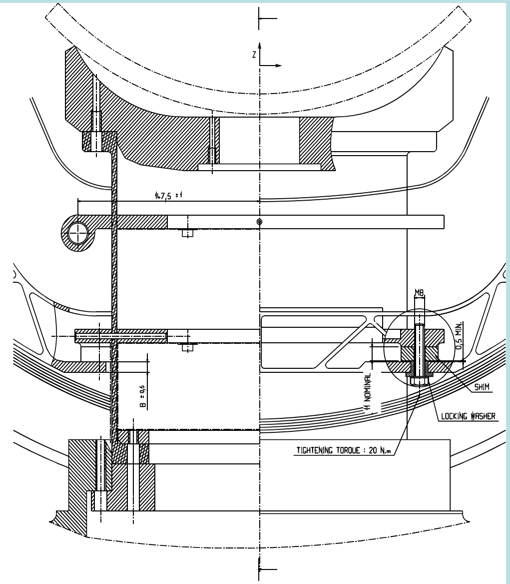
- **4-mm thickness**, single-part composite column (integrating interface flanges)
- Manufactured by **Resin Transfer Moulding (RTM):**
  - Suited to a large-scale industrial production
  - High reproducibility in quality
- <u>Limited</u> **machining** at interface, for tight dimensional tolerances (H7/g6 at assembly) without undermining mechanical integrity
- 2 aluminum **heat intercepts** at 5-10 K and 50-75 K to enhance thermal performance

Assembly interface (SSS)

Fixed support

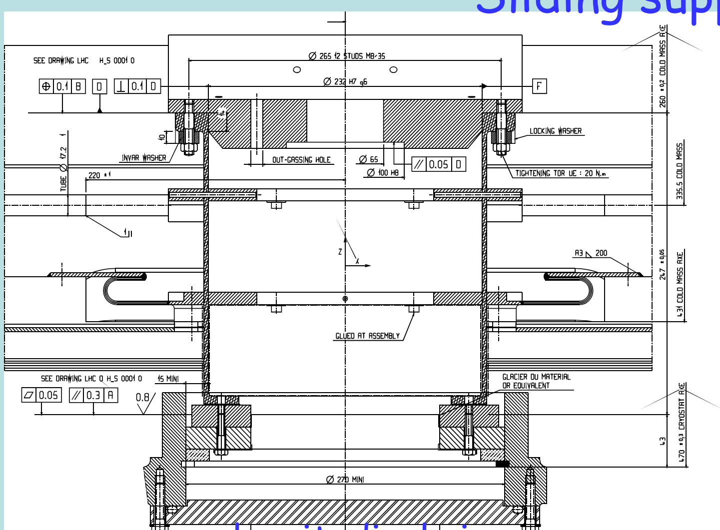


longitudinal view

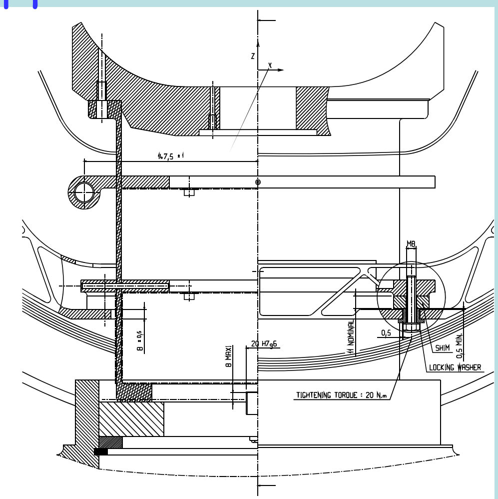


transversal view

Sliding support



longitudinal view



transversal view

RTM processing

Cutting the fabrics to length

Lay-up stacking

Sealed closing of mould

RTM processing
(complete manufacture cycle: 4 hrs)

Columns as de-moulded

Composite material

Constituents:

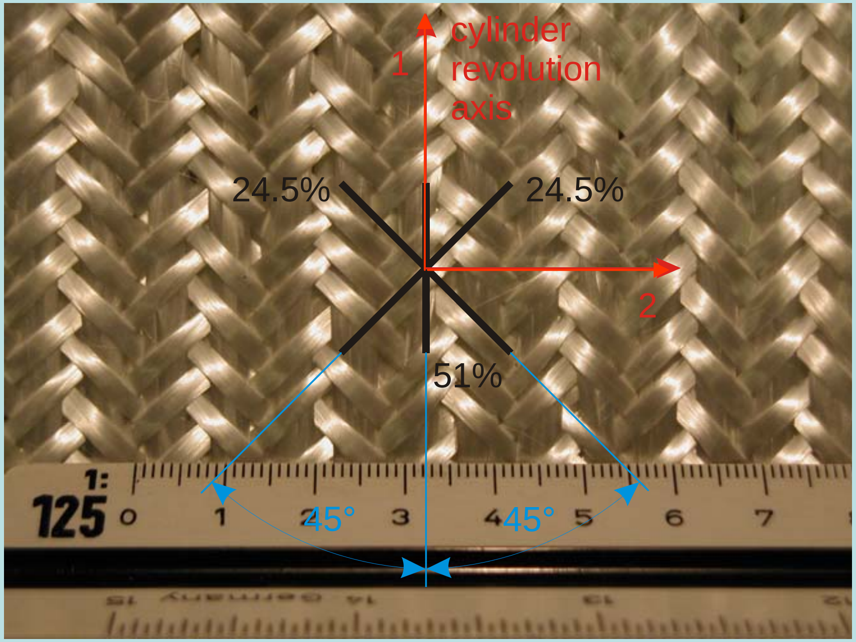
- Epoxy resin system (DGEBA type) :
  - 823 RTM by *Cytec-Fiberite*
  - Curing: 1 h dwell at 125°C
- E-glass dry fabric braids by *A&P Technology*
  - 232-mm diam. tubular tri-axial braid for column wall:
    - 51% fibre volume at 0°
    - 49% fibre volume at ±45 °
    - Mass/area: 1199 g/m2
  - 19-mm diam. tubular bi-axial braid for flanges:
    - fiber orientation ±45 °
    - Mass/area: 1041 g/m2

Composite material:

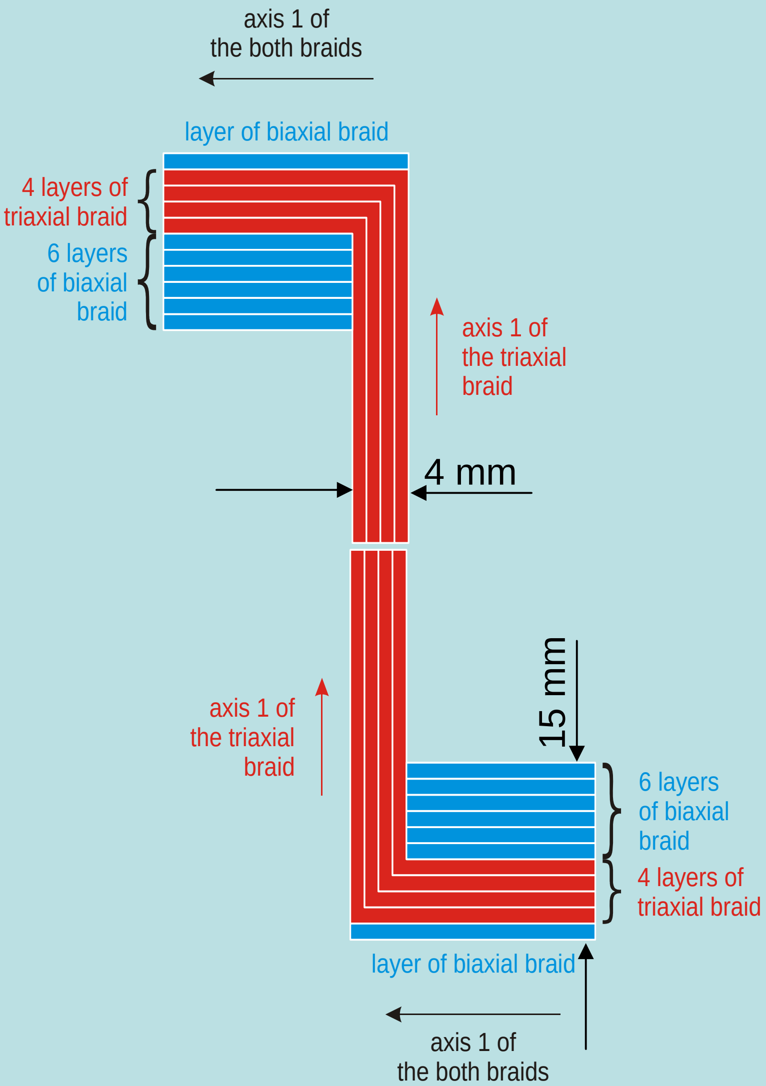
Property	Value	Comment
Glass-fibre volume fraction (Vf)	46.3%	Standard ISO 11667
Maximum void content	0.8%	1% specified

The lay-up

Braid of glass fiber



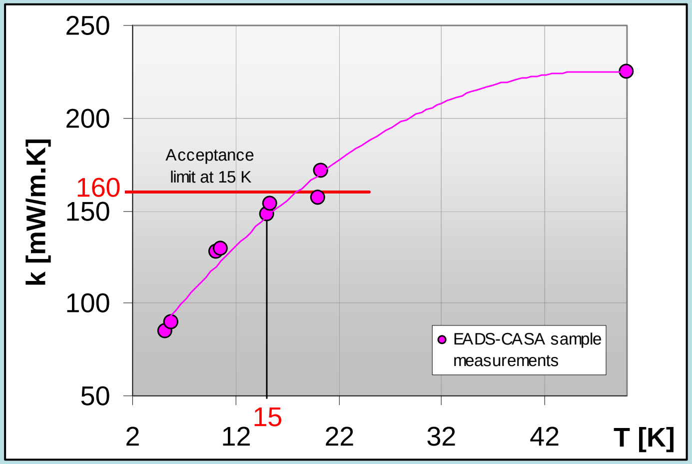
Fiber fractions

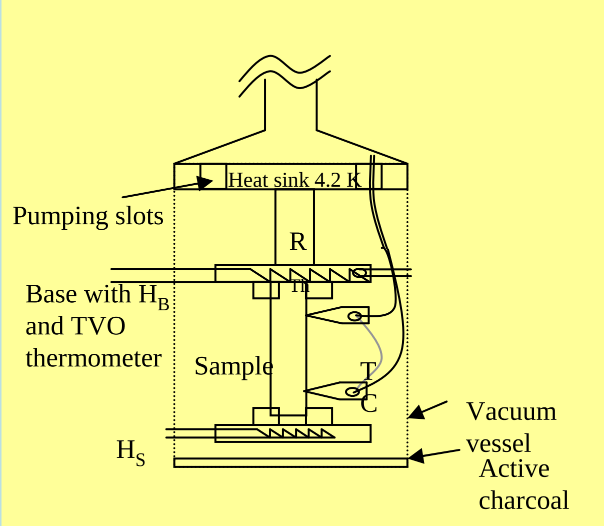


Braid layer stacking sequence

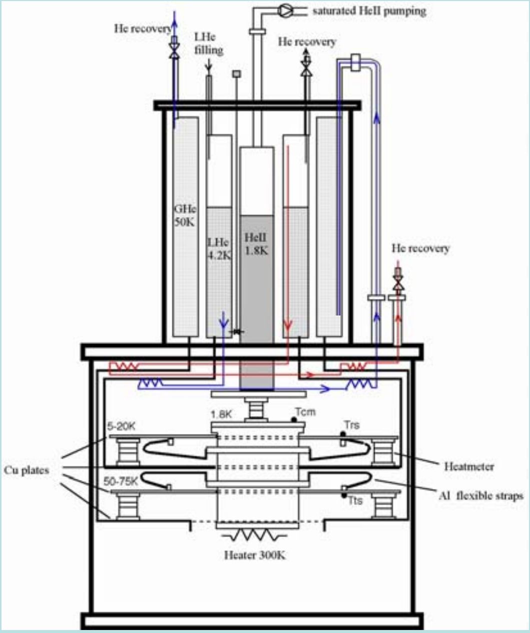
Thermal performance

- Material sample measurements
(longitudinal direction, ASTM C-518-98)





Heat flow-meter measurements



- Support posts measurements
  - 49 ± 10% mW @ 1.9K
  - 450 ± 10% mW @ 4.5-10K
  - 7.1 ± 5% W @ 50-65K

Courtesy: CERN cryo-lab

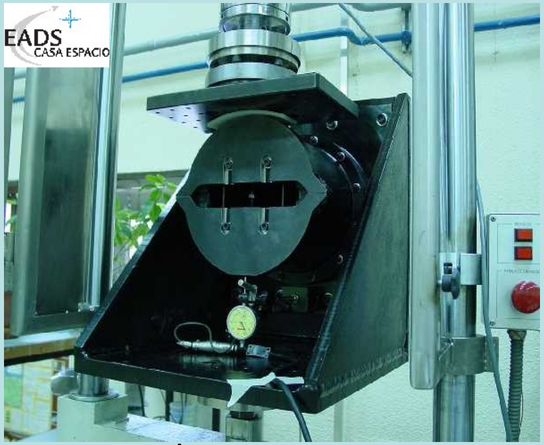
Dimensional control on 100% production

Dimensional control of columns with *go/no-go gauges*

Dimensional control of complete support with *go/no-go gauges*

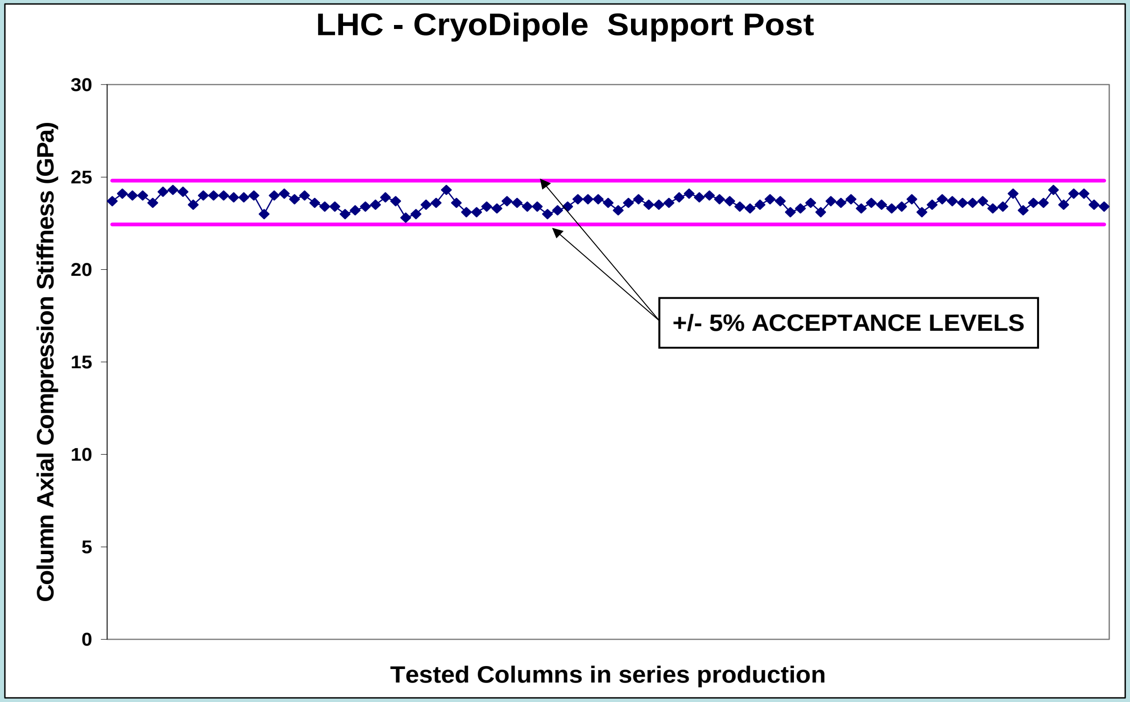
Mechanical testing

- 5% of produced columns tested
- About 2 columns over 40 produced per week, chosen randomly
- Average stiffness: **23.5 GPa**, dispersion within acceptance
- Failure to pass test (occurred on 4 supports only):
  - Segregation of resin batch production
  - 100% testing of production concerned

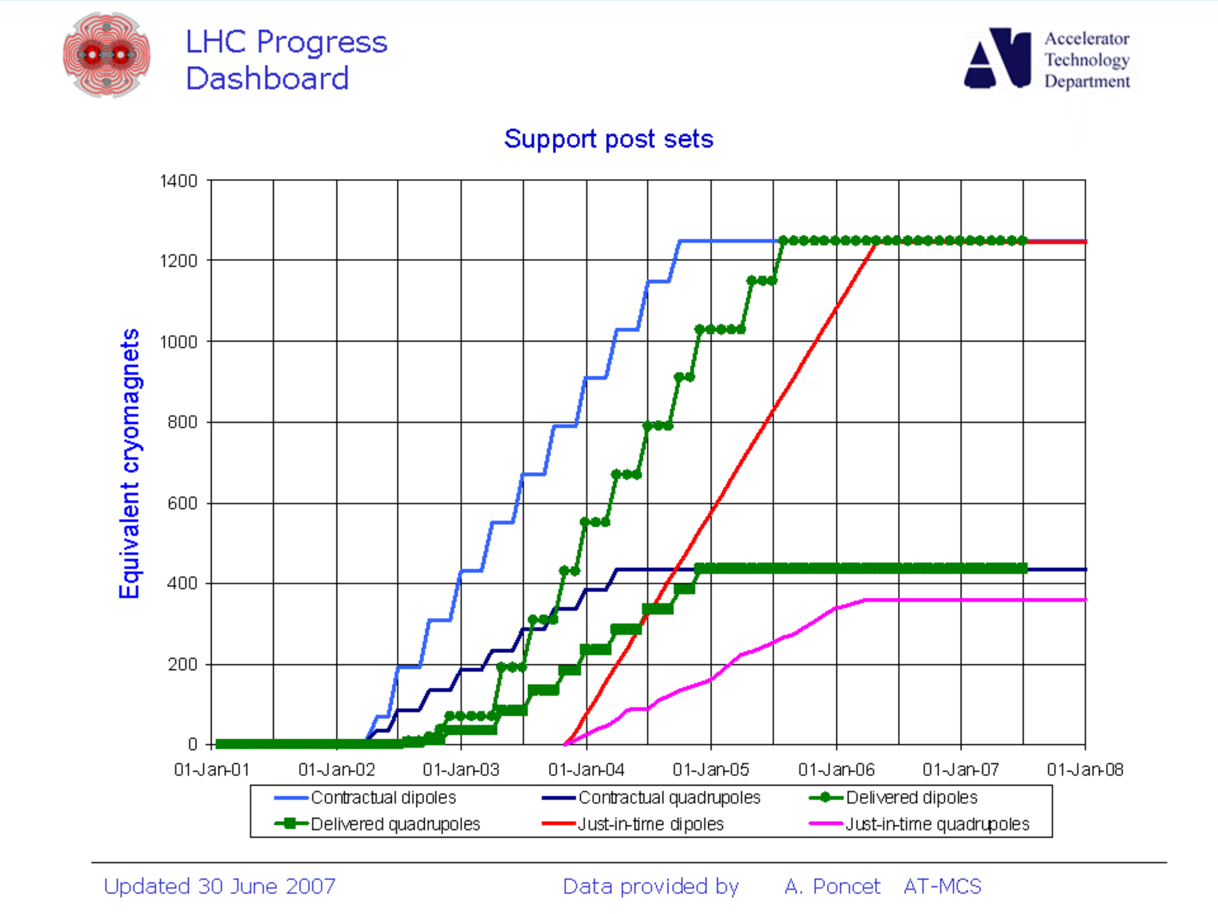


Shear test

Compression test



Production figures



- 4700 support posts manufactured
- 1 year for development and pre-series of 80 units
- ~3 yrs of manufacture
- 10 RTM sets (including spares for repair and maintenance)
- 7 FTE RTM operators, single shift 5 days/week
- No contractual nor technical issues

Multi Layer Insulation (MLI)


Interleaved reflectors and spacers


Velcro™ fasteners


Blanket manufacturing

Features:

- 1 blanket (10 reflective layers) on cold masses (1.9 K)
- 2 blankets (15 reflective layers each) on Thermal Shields (50-65 K)
- Reflective layer: double aluminized polyester film
- Spacer: polyester net
- Stitched Velcro™ fasteners for rapid mounting and quality closing


1 blanket on CM, 2 on thermal shield

Production:

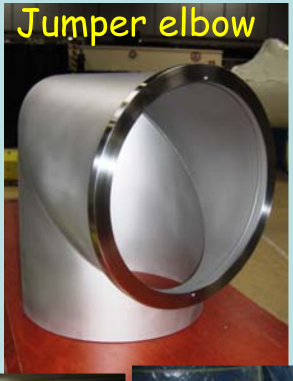
- ~2 km² of reflecting film
- *Ready-to-use* packaging: specific kits for cryostat type:
  - 10 blankets per dipole
  - 10 to 20 blankets per SSS
- 1 supplier for cryostats
- 1 supplier for interconnects (collaboration with IHEP-Protvino)
- 4 Yrs of production.

Mock-ups for complex geometries


Diode box


Vacuum Barrier

Photo gallery of some SSS-specific components

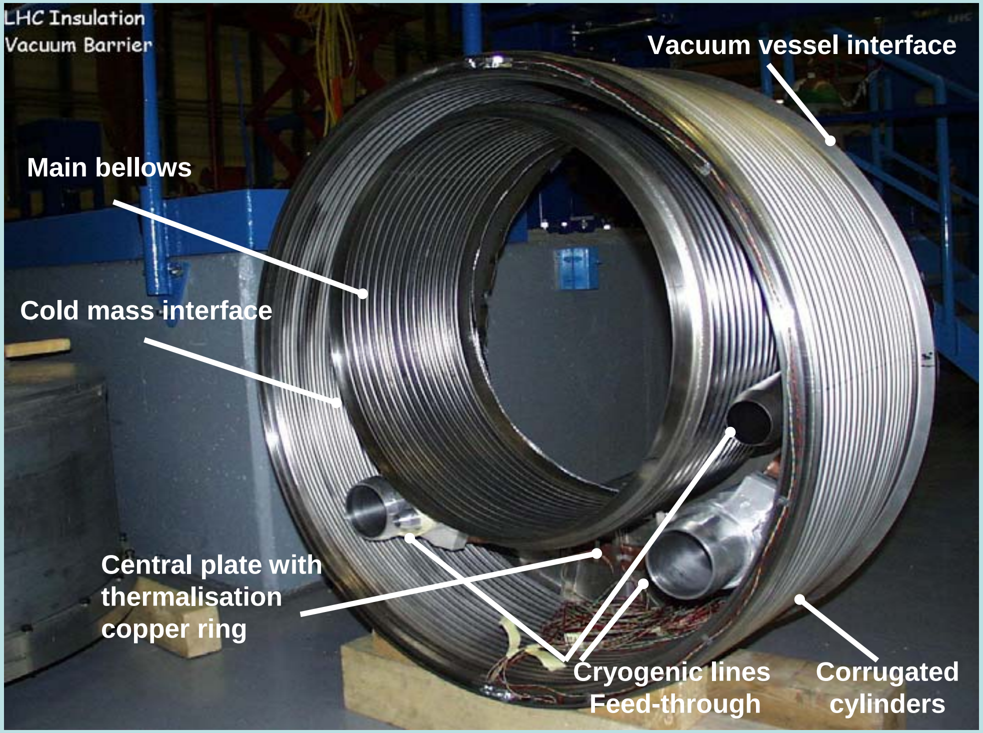


Insulation Vacuum Barriers

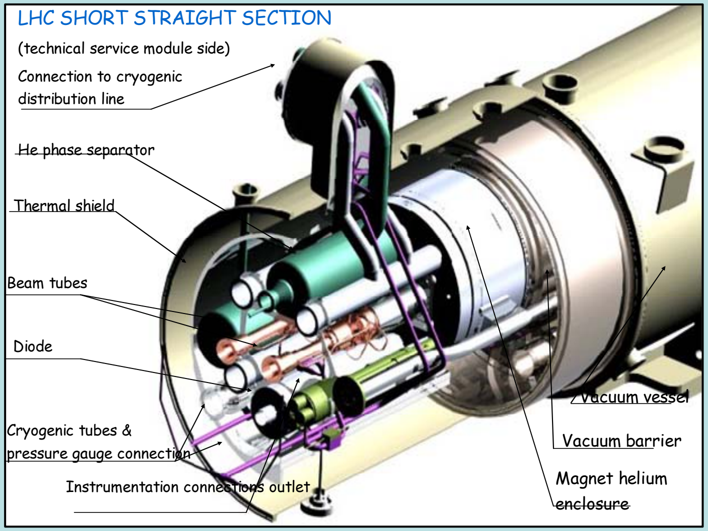
Functions:

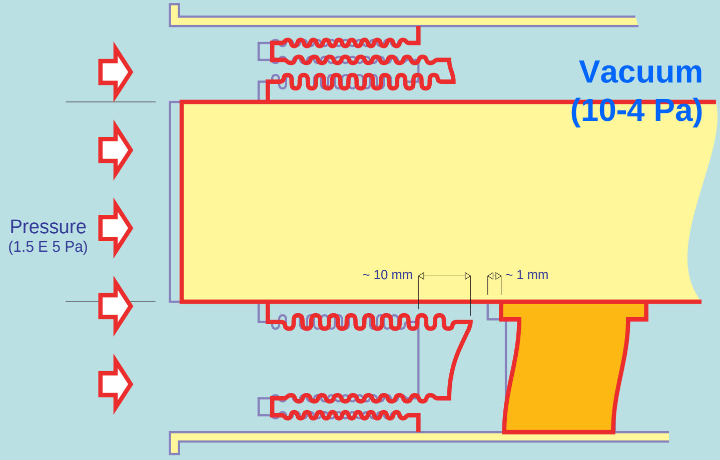
- Segmentation of insulation vacuum compartments (200m long)
- Piece-wise installation/commissioning of LHC vacuum systems
- Ease localisation of leaks
- Containment of accidental vacuum degradation
- Allow local intervention for machine maintenance

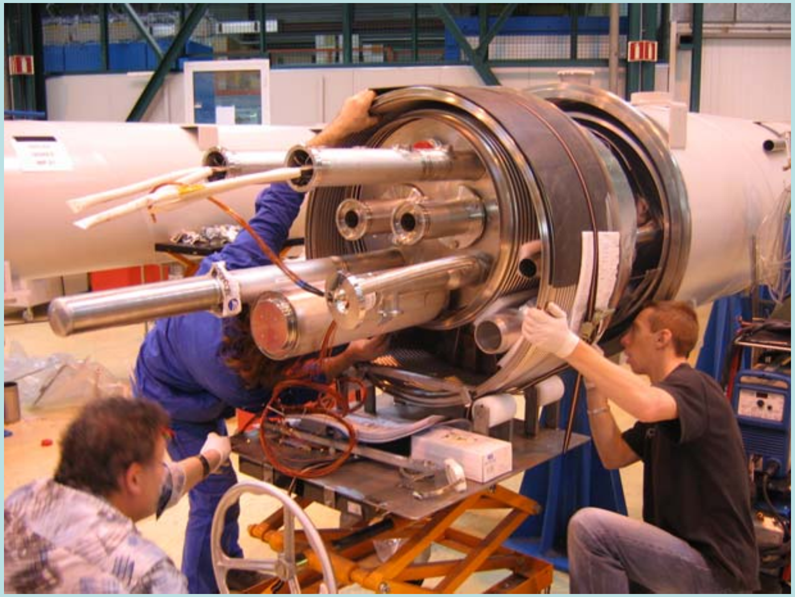
→ ~ 100 Vacuum Barriers required



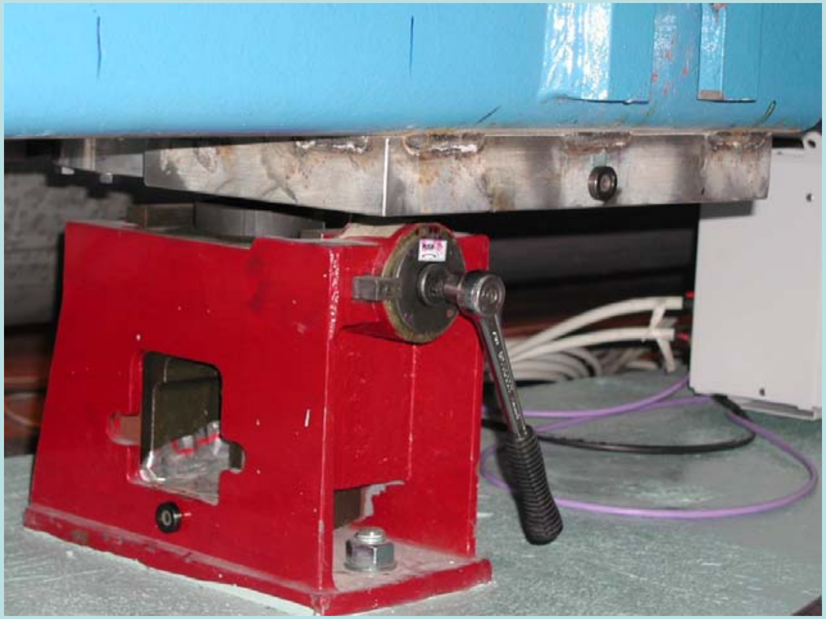
Vacuum Barrier (cont.d)

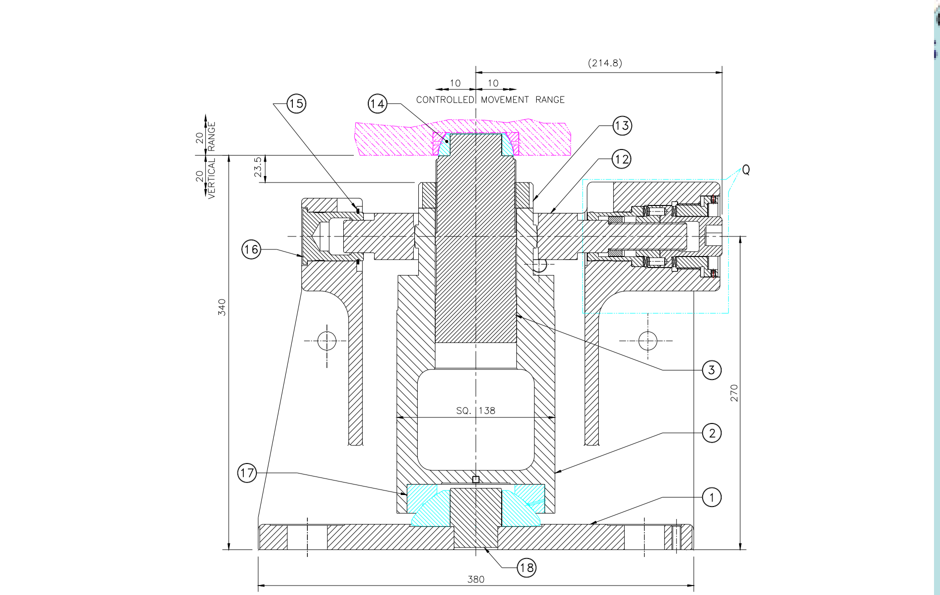






The LHC Jacks

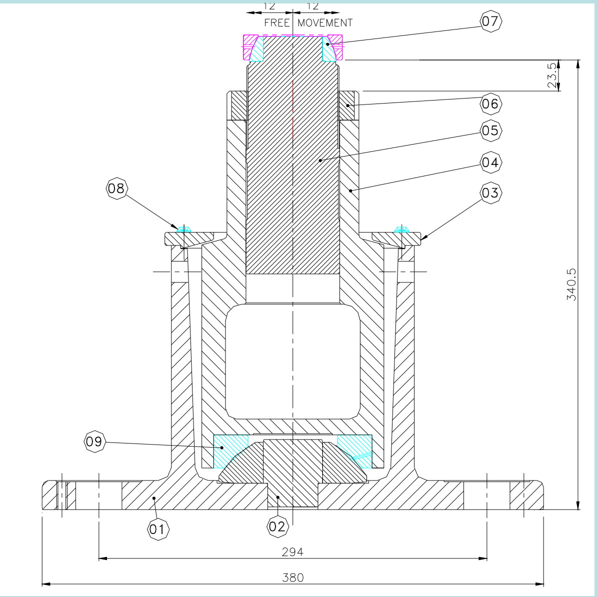




Main Jack

Main Requirements (main jack)

Requirement	Value
No.of Units	7000
Vertical Load	17000 kg
Transverse Load	8000 kg
Setting Resolution	0.05 mm
Adjustable range	≥ ±10 mm
Max. operating torque/force	60 Nm/25 kg
Long term stability	< 0.1 mm/year



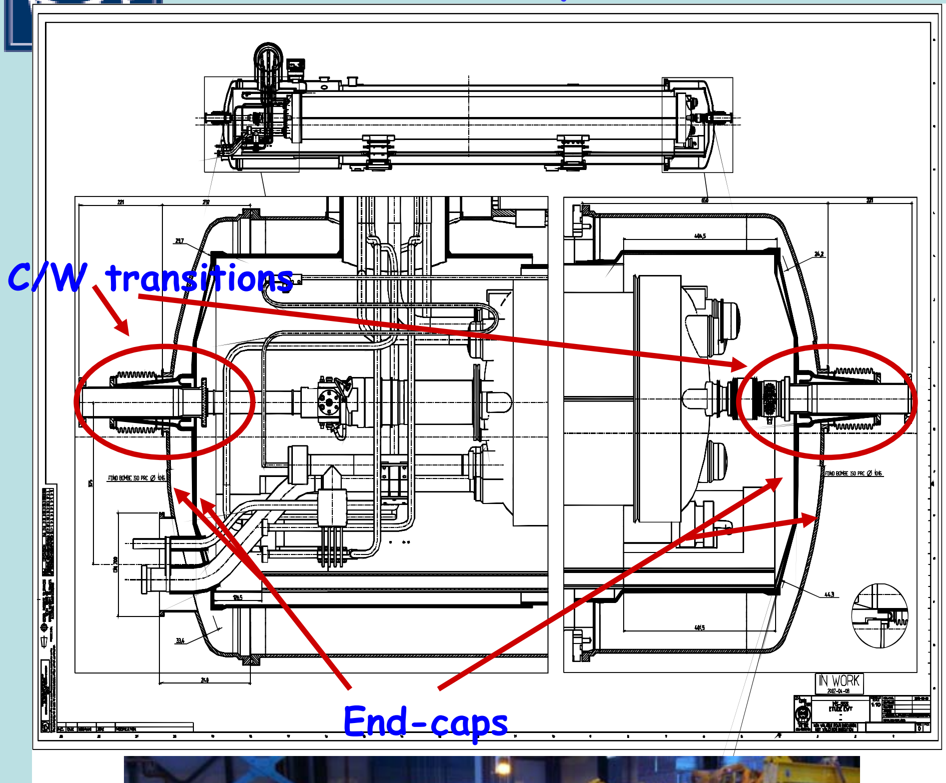
Central Jack ("crutch")

The LHC jacks (cont.d)

- Developed/Supplied in the frame of a collaboration between CERN and India's Dept of Atomic Energy (DAE)
- Design/follow-up by the Center of Advanced Technologies (CAT-Indore)
- 2 series of prototypes made first. Only minor technical difficulties in the development phase (e.g. plating and casting quality)
- Manufactured in India by 2 suppliers
- Industrial follow-up and QA by CAT
  - "Smooth" seen from our side
  - Some logistics and customs difficulties
- Full technical satisfaction so far
- The same jacks were motorised for remote alignment of the Low β triplet

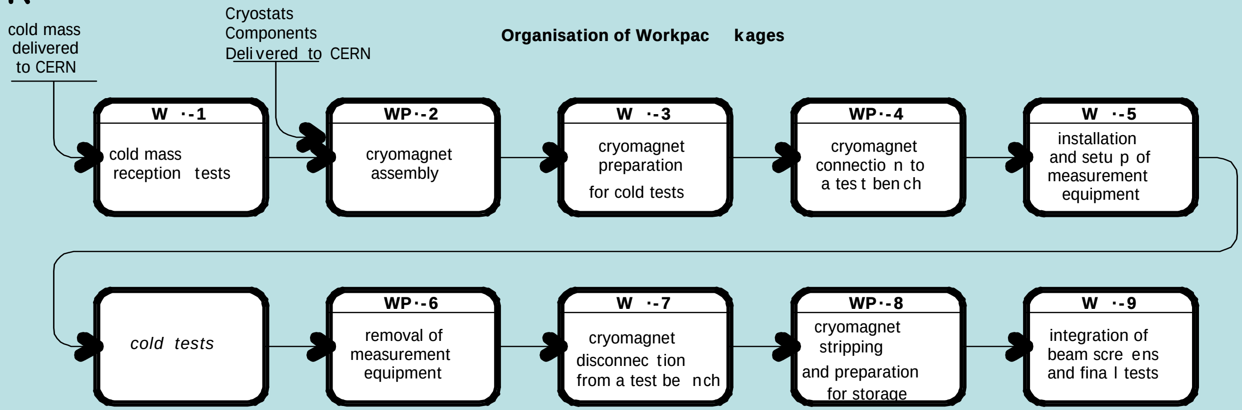
QA and packing

SSS Cryostat with Cold-to-Warm transitions



Cryostat Assembly at CERN

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



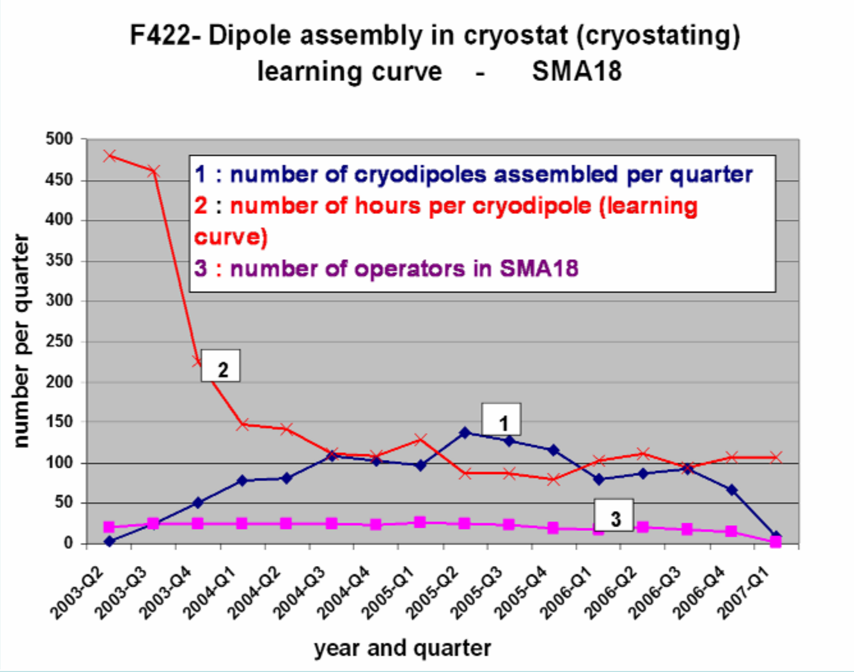
- …it included provisions for hourly-rated work (13% contract value)
- Performance through shared incentives

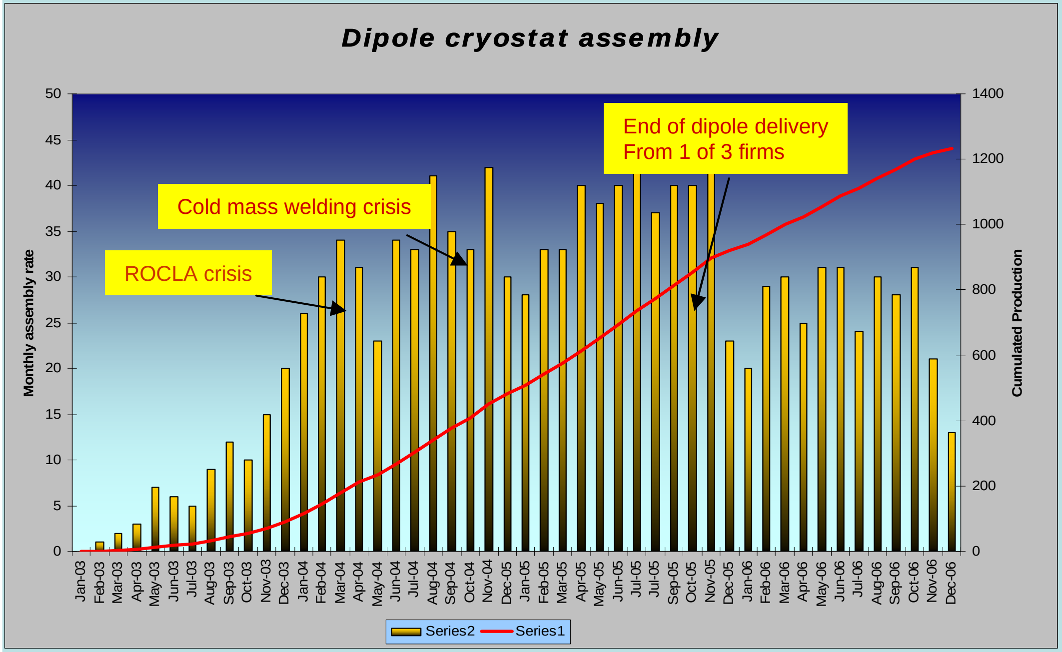
→ Partnership is a key to success.

Assembly of dipole cryostats

Key Figures:

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





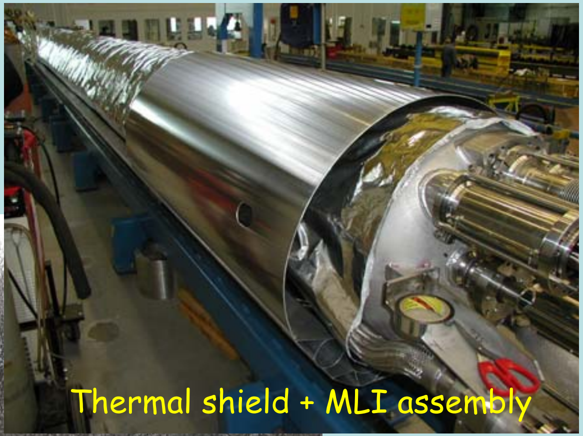
Cryo-dipole assembly tooling

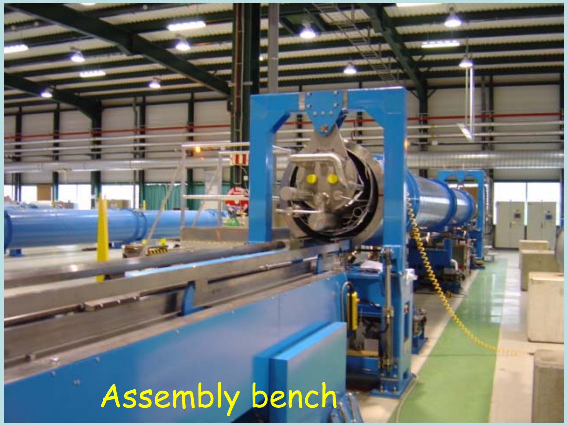
Highlights from the cryo-dipole assembly


Cold mass reception


Bottom tray + supports assembly

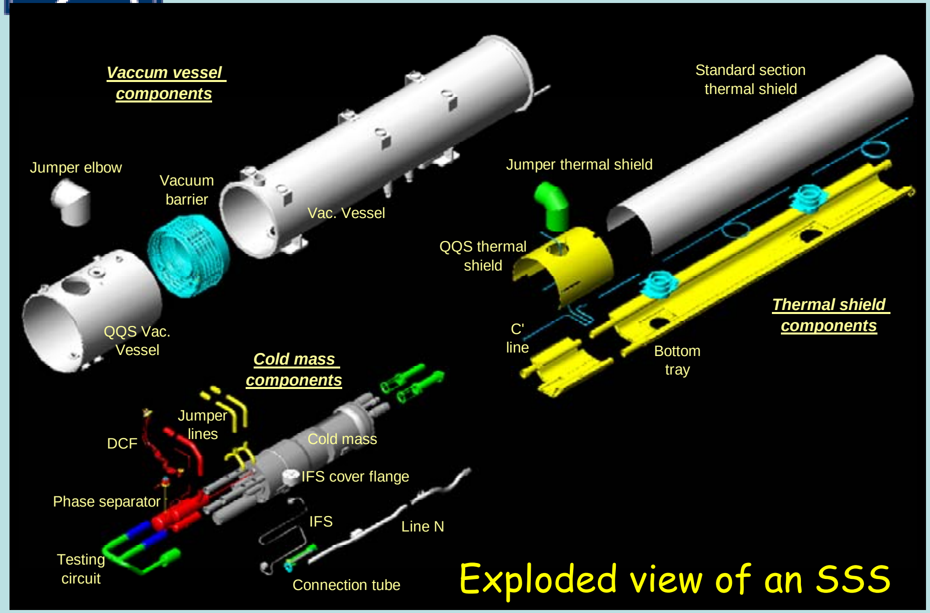

Al thermal shield rolling machine


Thermal shield + MLI assembly


Assembly bench

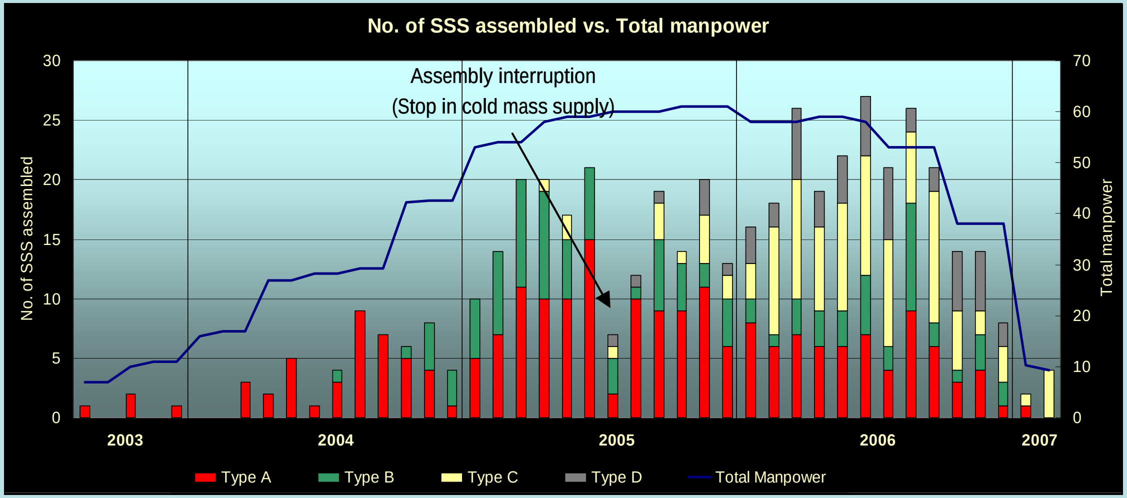

Outdoors storage

Assembly of the Short Straight Sections (SSS)



Exploded view of an SSS

SSS assembly hall at CERN

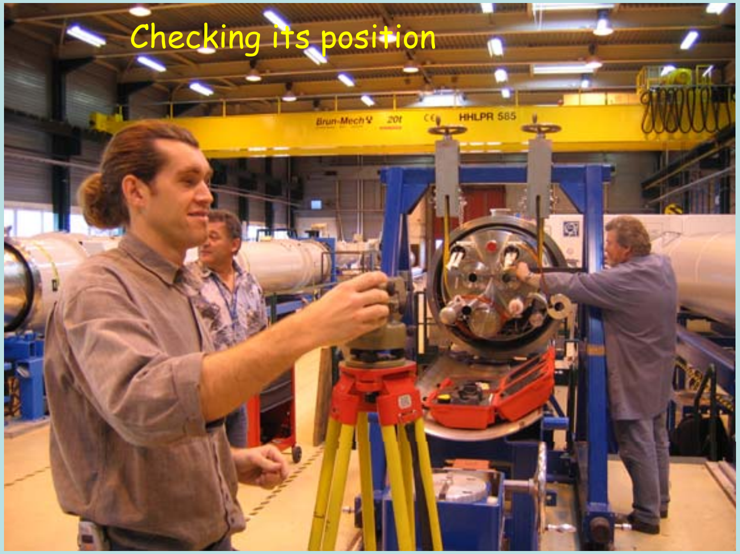


Key figures:

- 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 tooling

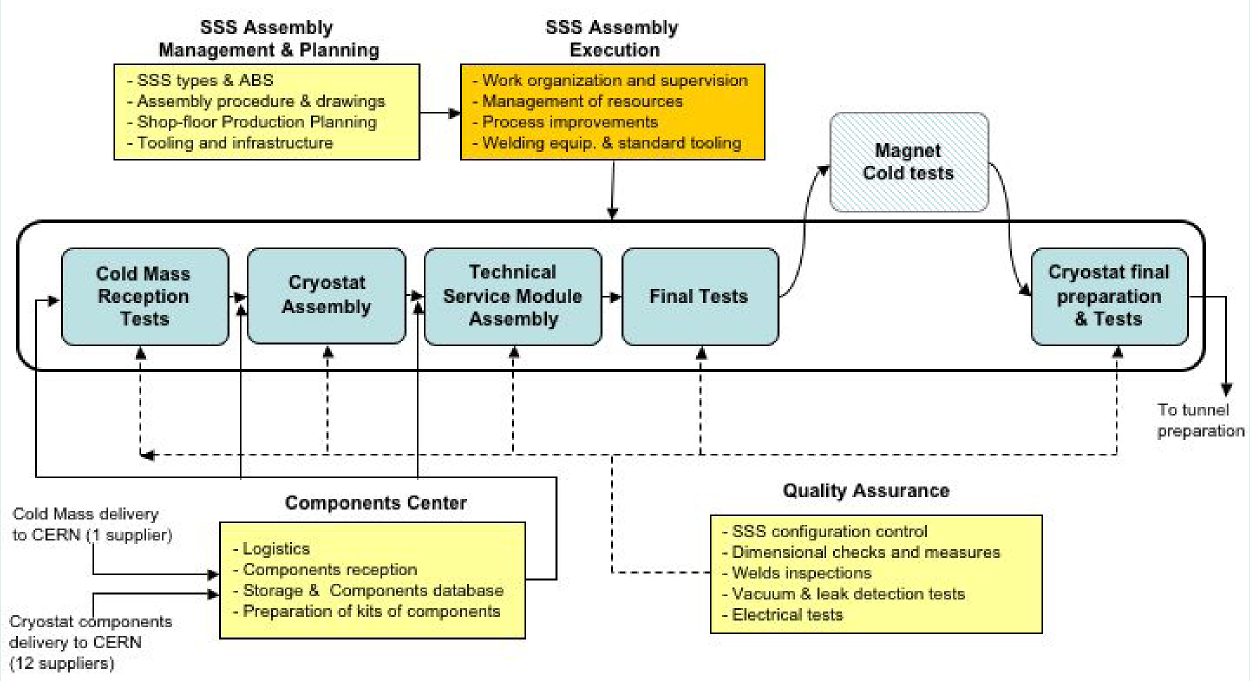

Pushing a cold mass in its vessel



Checking its position


Technical service mounting benches

SSS assembly: Organization



Co-activity of 3 contractors + CERN

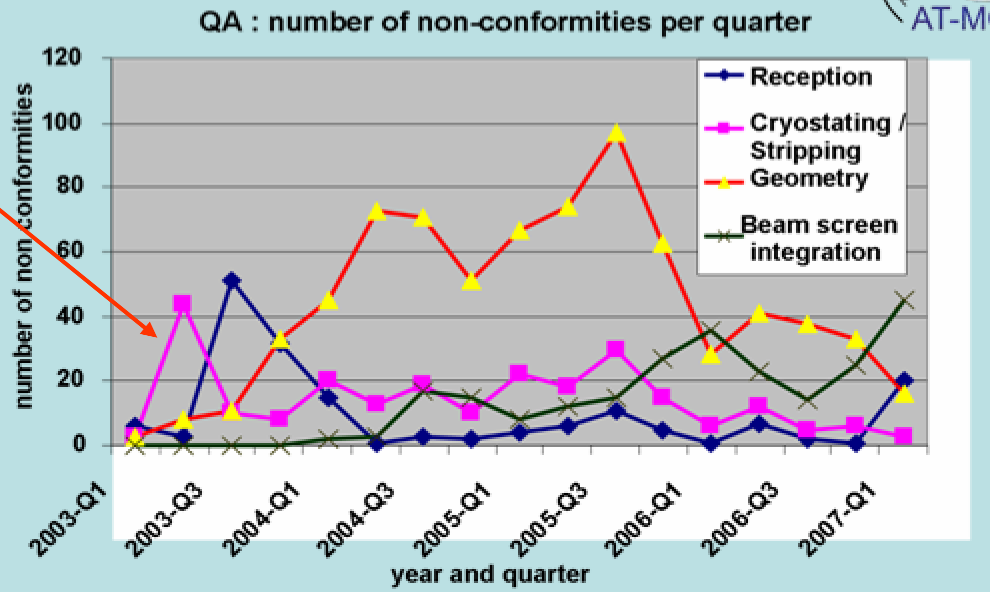
Assembly Activity	No. FTE	Quality assurance	No.FTE	Components center	No.FTE
Supervision	3	SSS configuration control	2	Logistics	3
Mechanical workers	6	Vacuum technicians	5	Storage	2
Welders	6	Welding inspectors	1	Components inspections	1
Electro-mechanical workers	10	Electrical checks	2		
Electricians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

Photo Gallery of SSS

Quality Assurance: Non-Conformities (NC)

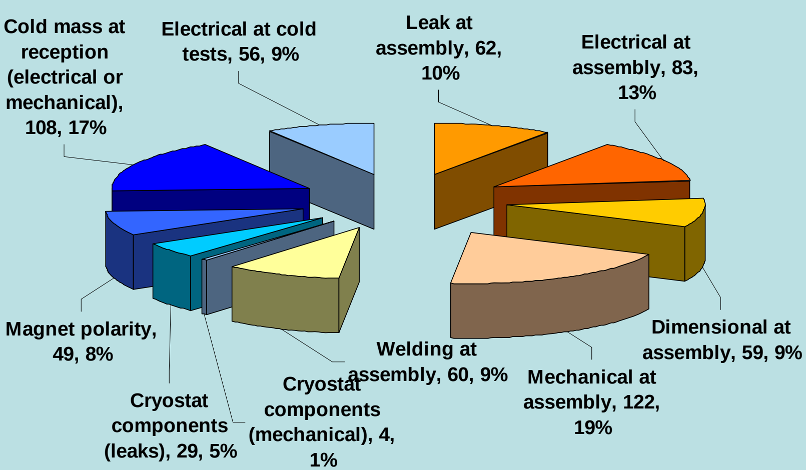
- **Dipole cryostat assembly:**

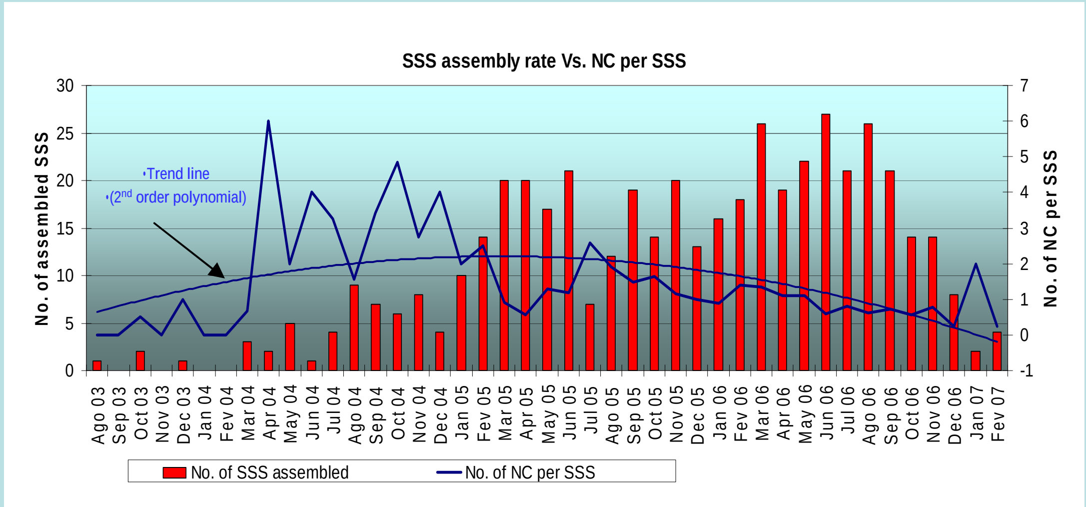
250 NC on 1232 units:
  - Mechanical: 95%
  - Electrical: 3%
  - Welds: 1%
  - Leaks : 1%



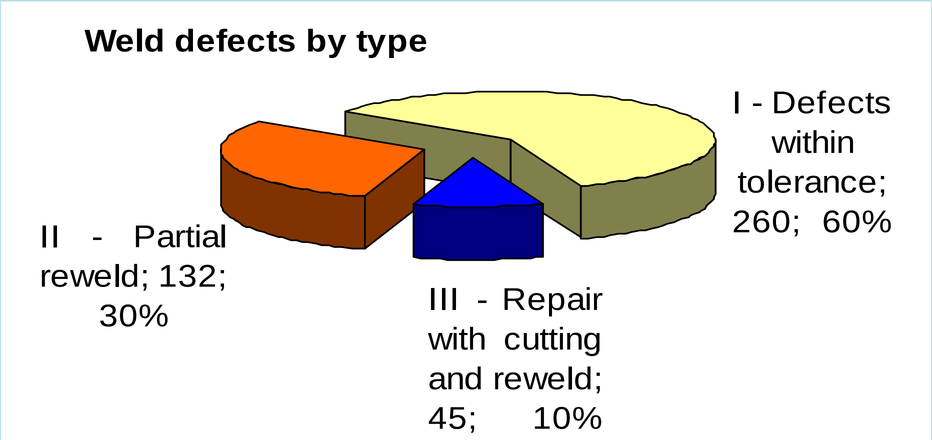
- **SSS assembly:**

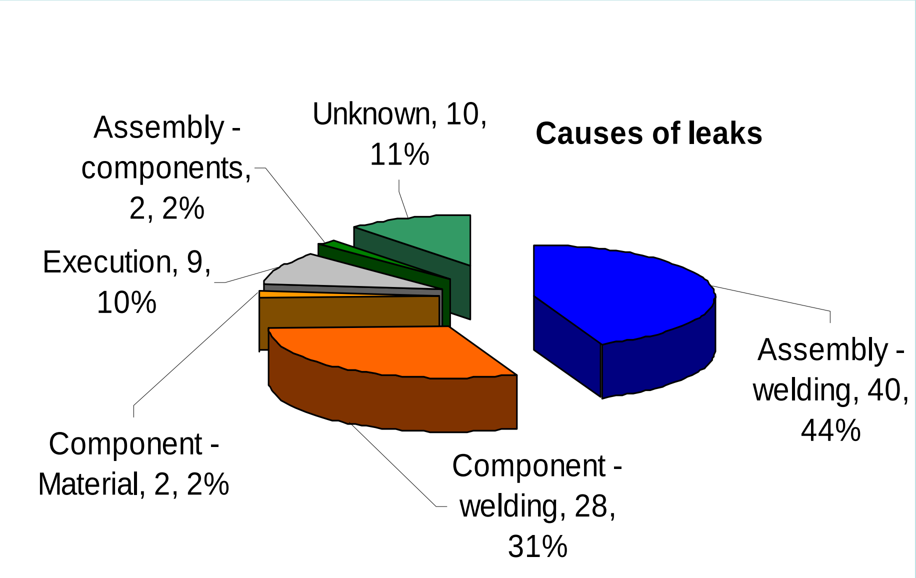
600 NC on 474 units





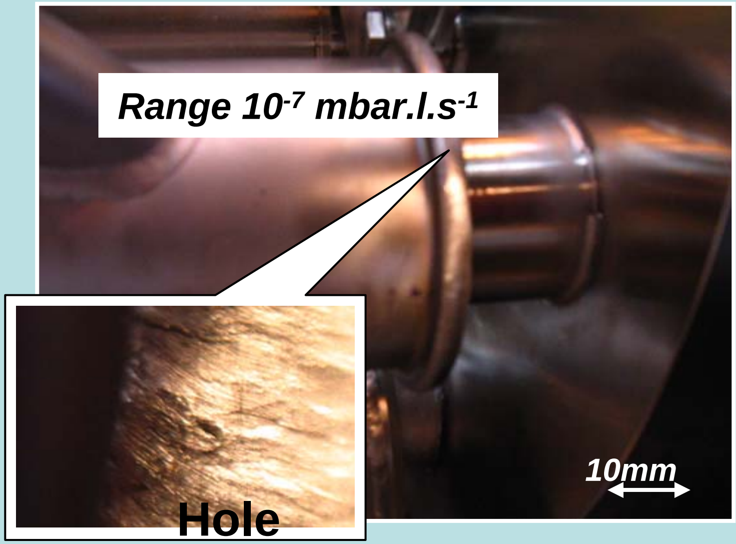
Leak-tight welding

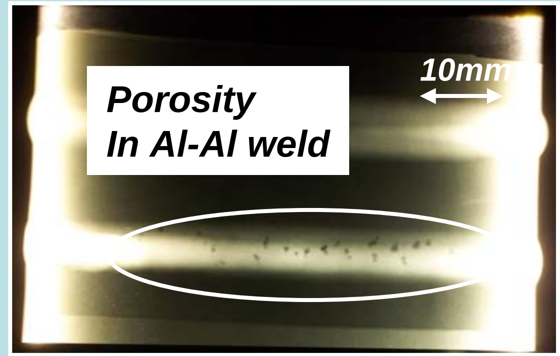


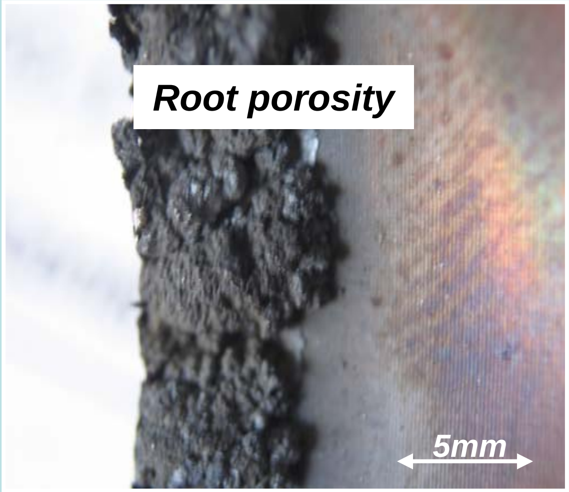


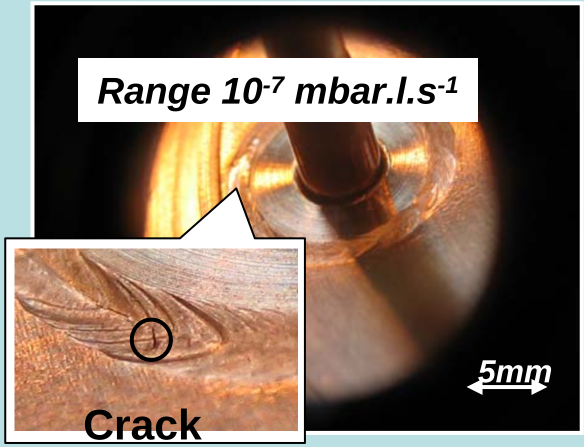
- 20'000 welds, (mostly manual)
- 2% of defective weld rate
- 3300 leak detection tests (40% more than initial plans)
- ~ 100 leaks (0.5% of welds)
- No "cold leaks" (but a few leaks broke open at cold)
- Some very difficult leaks to localise → several months stop for some SSS !
- Some leaks "appeared" in the tunnel → very difficult to localise

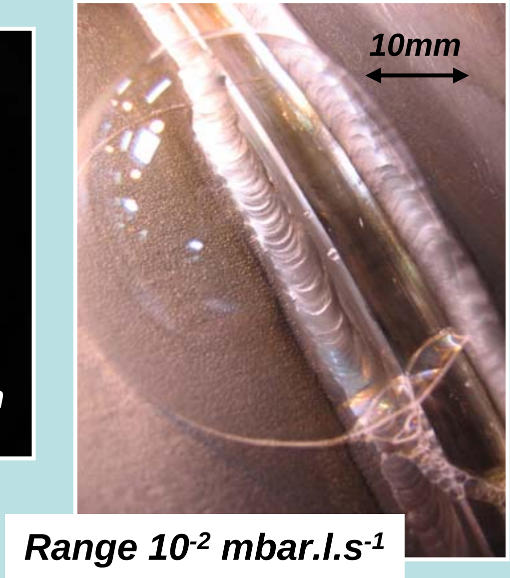
Photo Gallery

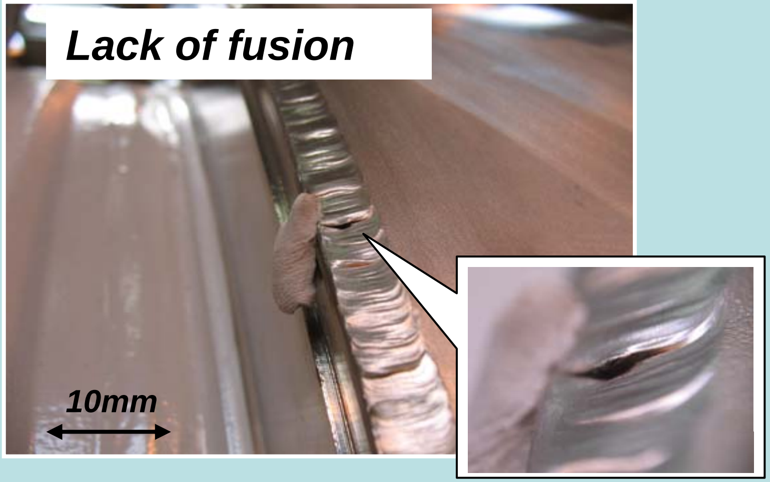












Material Quality

• 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!)

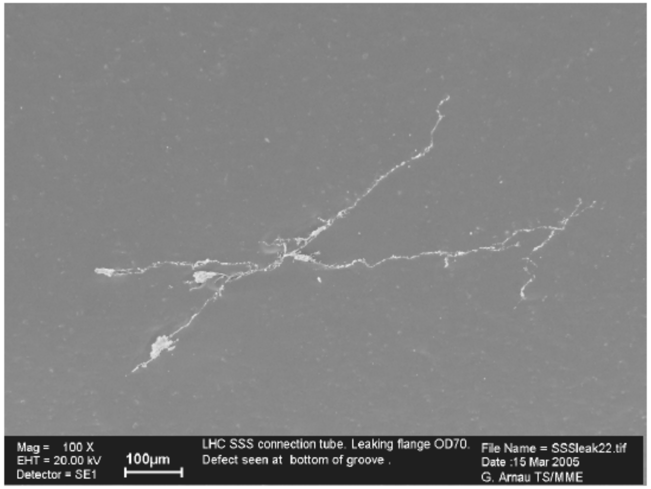
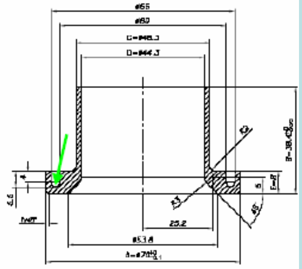
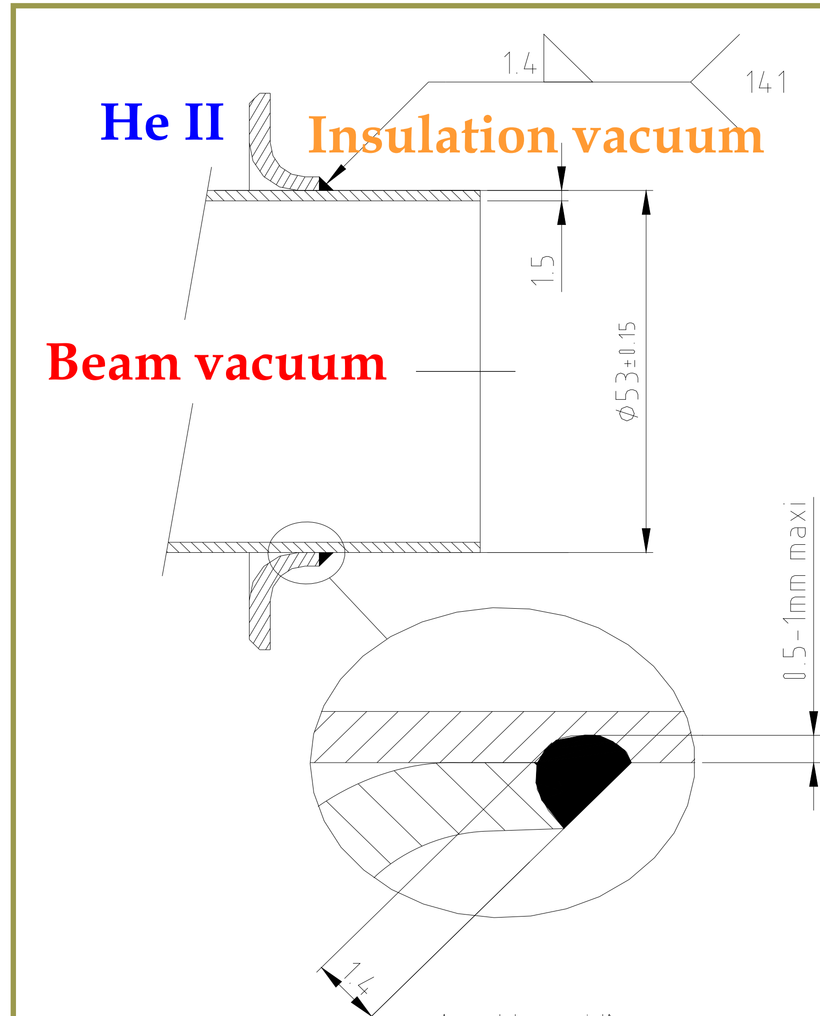


Fig. 6.1.
Mag.: × 100
Electro-polished sample.
Defect seen at the bottom of the groove at position pointed by He leak detection.

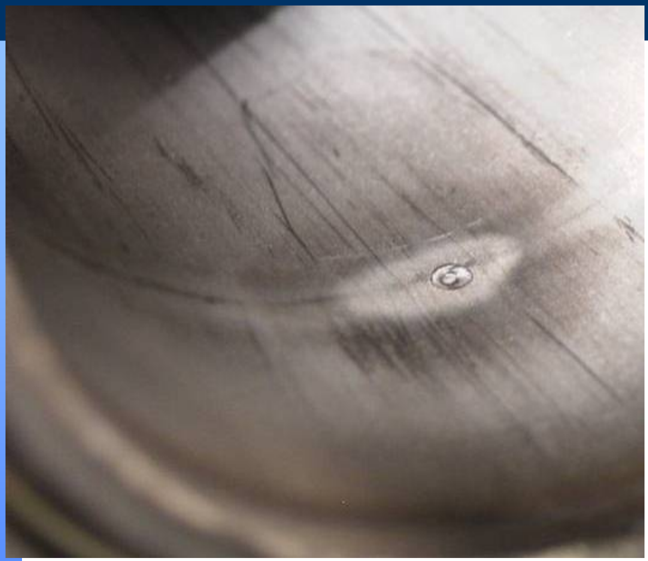


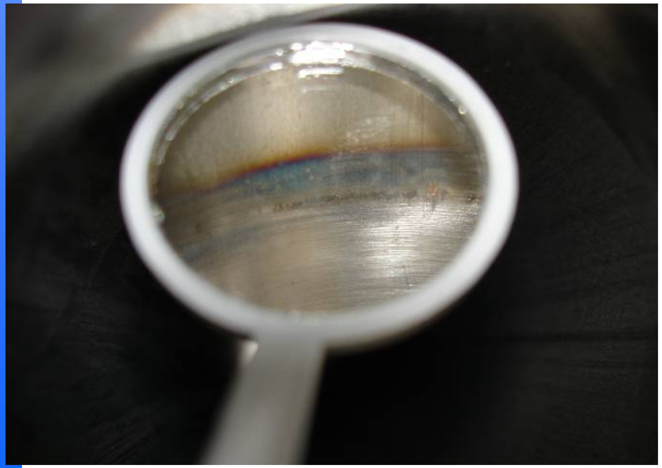
The cold bore tube to welding flare fillet weld
The requirements



Courtesy of F.Savary, AT-MCS

Visual defects observed in the Main Dipoles





Types of defect:

- corrosion at root
- root concavity
- root porosity
- full penetration+ corrosion

→Risk of leaks in Beam vacuum

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 is a must:

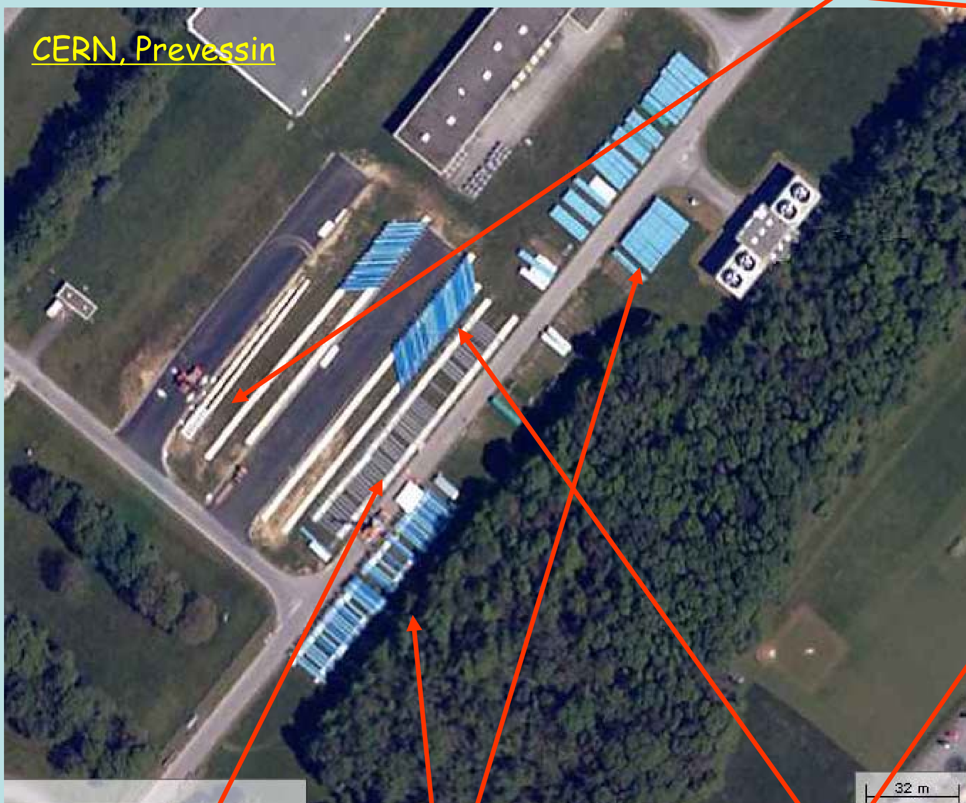
Space, resources, and methodology

A Logistics Endeavour

From "Google Earth",

Aerial view of CERN sites (~2005)

Stored SSS

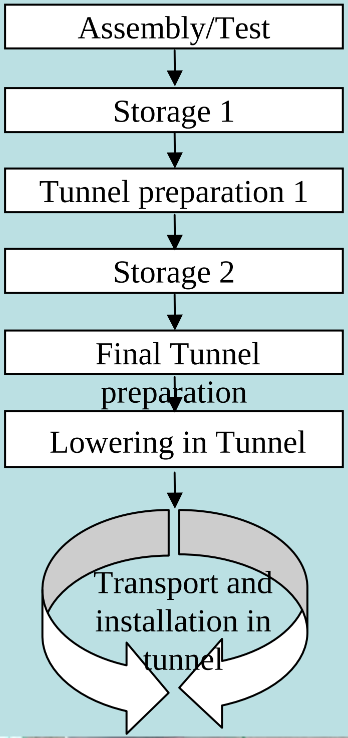


Stored Cold masses

Stored vessels

Stored Cryo-dipoles

Cryo-magnet Transport at CERN

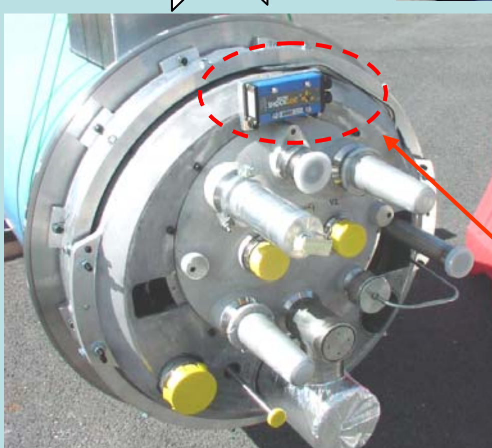


Surface transports:

- Between 100 and 150 cryo-magnets transported per week
- 12000 truck journeys, **40000 km driven**
- 4 road trucks, 3 mobile cranes, 7 over head traveling cranes, 3 "ROCLA"
- 15 operators
- At one point up to **800 cryo-magnets stored** on surface

Underground:

- 47000 t of cryo-magnets installed in LHC tunnel
- 21000 km driven
- 50 operators 24h/24h, 7 days/week



Each transport equipped with transport restraints and Shocklog device

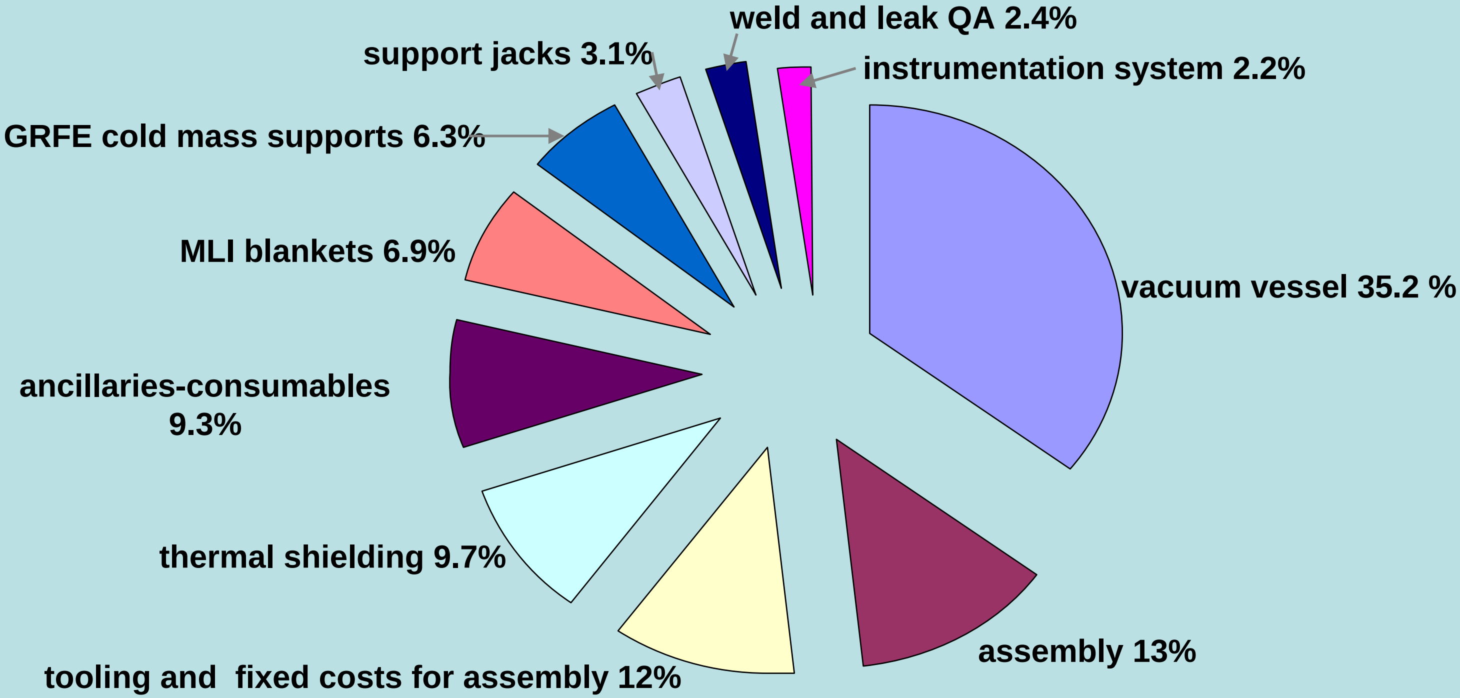
Courtesy of CERN TS-IC

Costs of Assembled Dipole Cryostat

- **100 kCHF (~81.4 kUSD)** per cryo-dipole assembled cryostat (2007 value)
- **Cost/m: 6.85 kCHF/m (5.6 kUSD/m)**
- Overall cost (1232 units): 122.3 MCHF (100.3 MUSD)
- Compared to 1996 costs estimates:
  - 25% cost saving on Vacuum vessels
  - 60% cost saving on MLI

(1 CHF = ~0.82 USD)

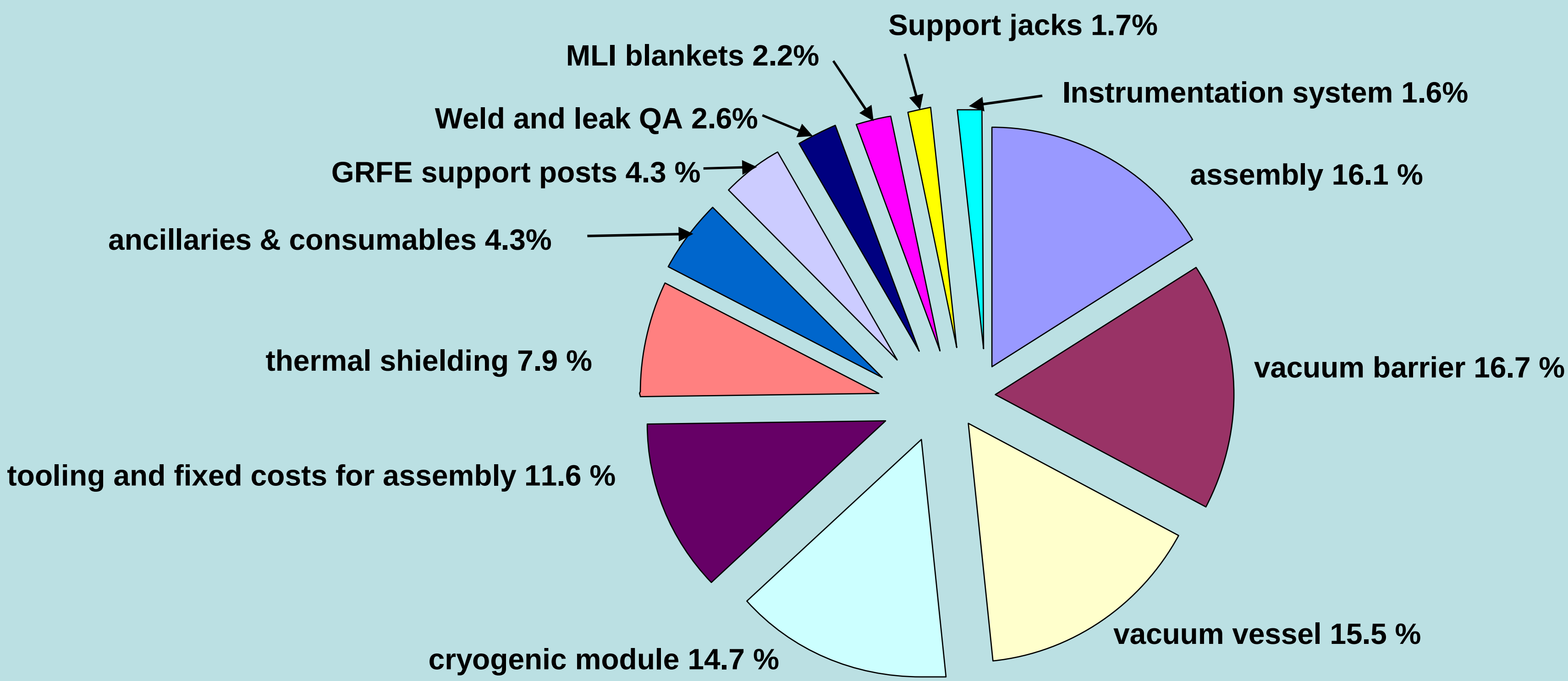
Cost break-down



Costs of Assembled SSS

- Unit cost: **114-136 kCHF (93.5-111.5 kUSD)** depending on SSS complexity (2007 value)
- **Average cost/m: 16.3 kCHF/m (13.4 kUSD/m)**
- Overall cost (474 units): 56.6 MCHF (46.4 MUSD)

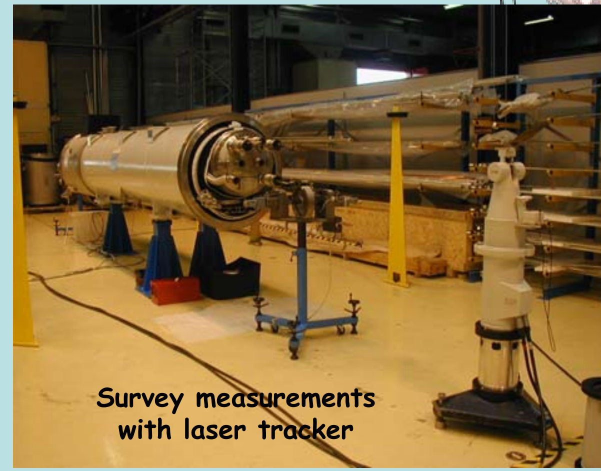
Cost break-down



Geometrical Stability: survey measurements

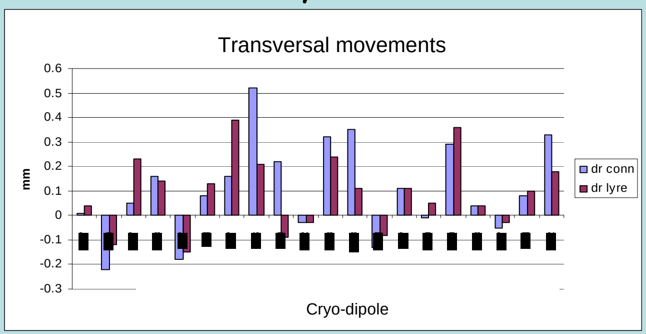
- SSS positional stability and reproducibility at cold

Arc SSS (392 units)	Horizontal		Vertical	
	Mean [mm]	St.Dev. [mm]	Mean [mm]	St.Dev. [mm]
Positional reproducibility after 1 cool-down/warm-up cycle	-0.08	0.42	0.04	0.43
Cool-down movements	-0.17	0.22	-1.3	0.36

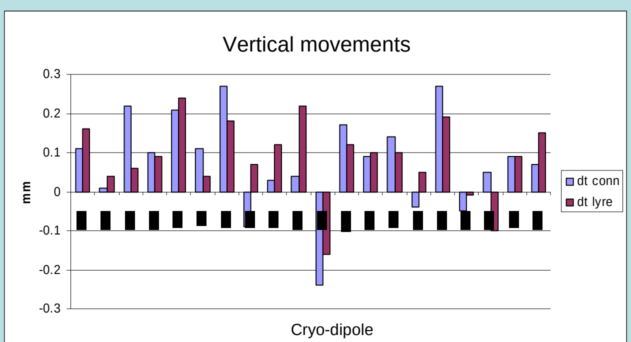


- Cryo-dipole positional stability after transport to tunnel

Cold mass stability w.r.t. fiducials measurements on 20 cryo-dipoles



- Mean: +0.1mm; St.dev.: 0.17mm



- Mean: +0.08mm; St.dev.: 0.11mm

Courtesy of CERN Survey (TS-SU)

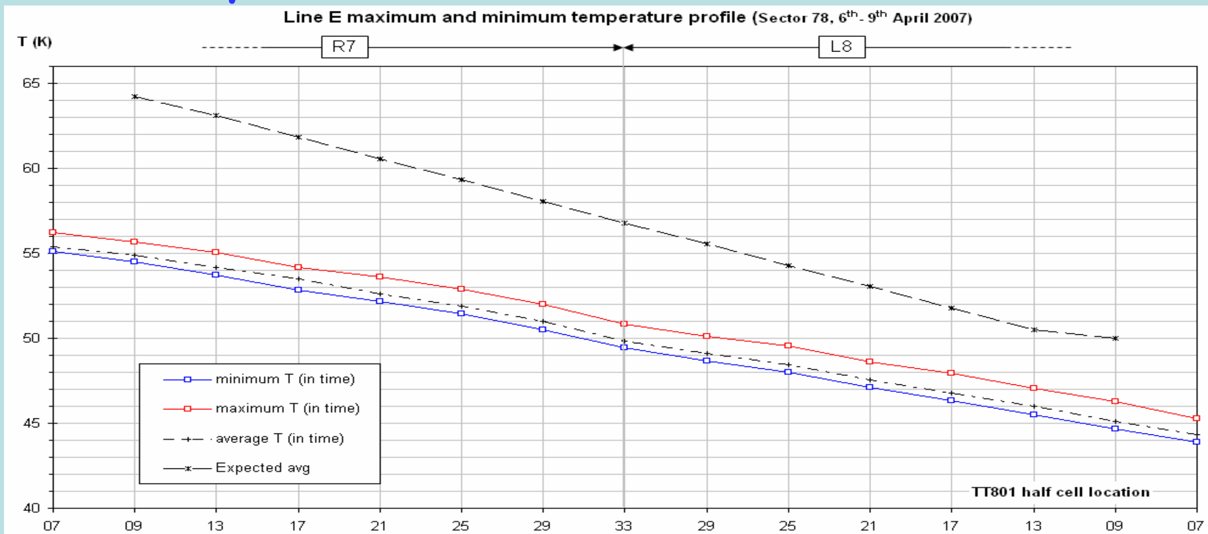
Arc Thermal Performance: preliminary results from sector 7-8

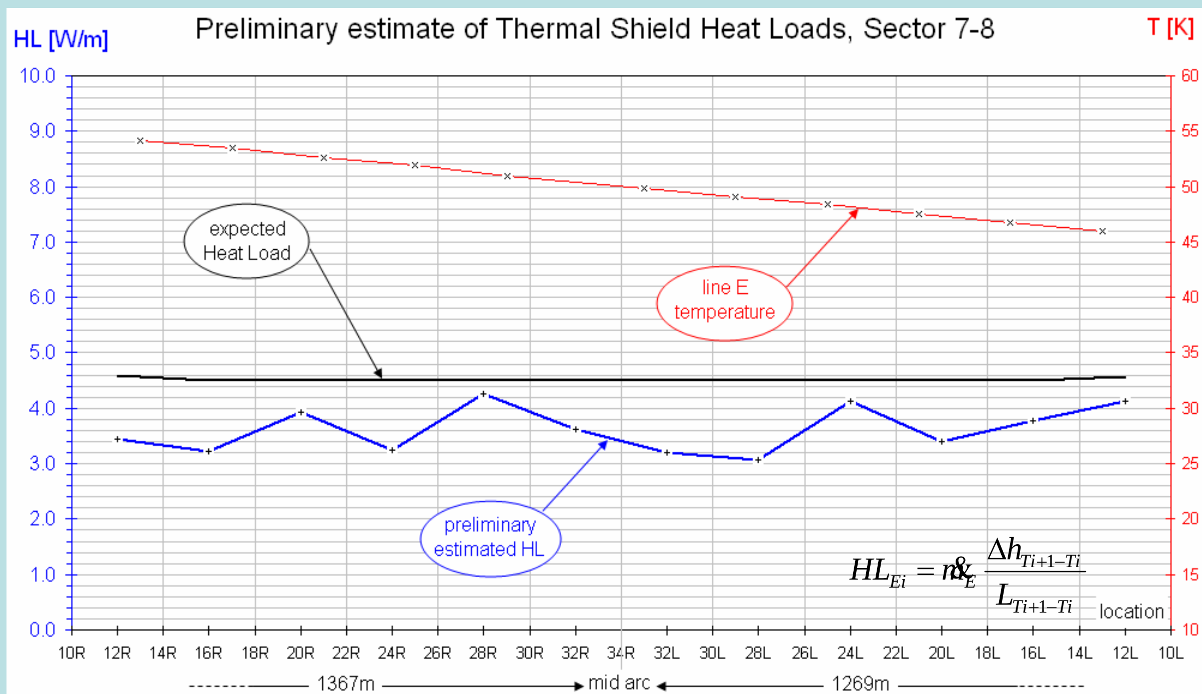
Static Heat In-leaks: Budget Break-down

Cryostat component	Q.ty	Overall length (m)	Overall budgeted static heat loads		
			50-75 K [W]	4.6-20 K [W]	1.9 K LHe [W]
LHC continuous arc cryostat (sum of 8 sectors):		22,564			
Dipole vacuum vessel (14.6 m unit length)	1232	17,938			
SSS vacuum vessel (6 m average)	438	2,617			
Interconnection sleeve (1.185 m average)	1695	2,009			
Service Module QQS	438			4	53
Longitudinal Vacuum Barrier VB	104		5,081	13	186
Magnet support post	4620		32,890	2,053	225
Thermal shield sub-assembly	3365		62,278		
Radiative insulation sub-assembly	3365			178	2,329
Instrumentation feedthrough system (IFS)	1670				888
Other components (not described in this paper):					
Beam Screen	3340				334
Beam vacuum feedthrough	432		526		92
Dipole corrector feedthrough (DCF)	324		2,786	526	117
Beam position monitor (BPM)	680			203	132
TOTAL [W]			103,052	2,976	4,355

- 0.2 W/m @ 1.9 K
- 0.13 W/m @ 1.9 K
- 4.5 W/m @ 50-75 K (thermal shield)

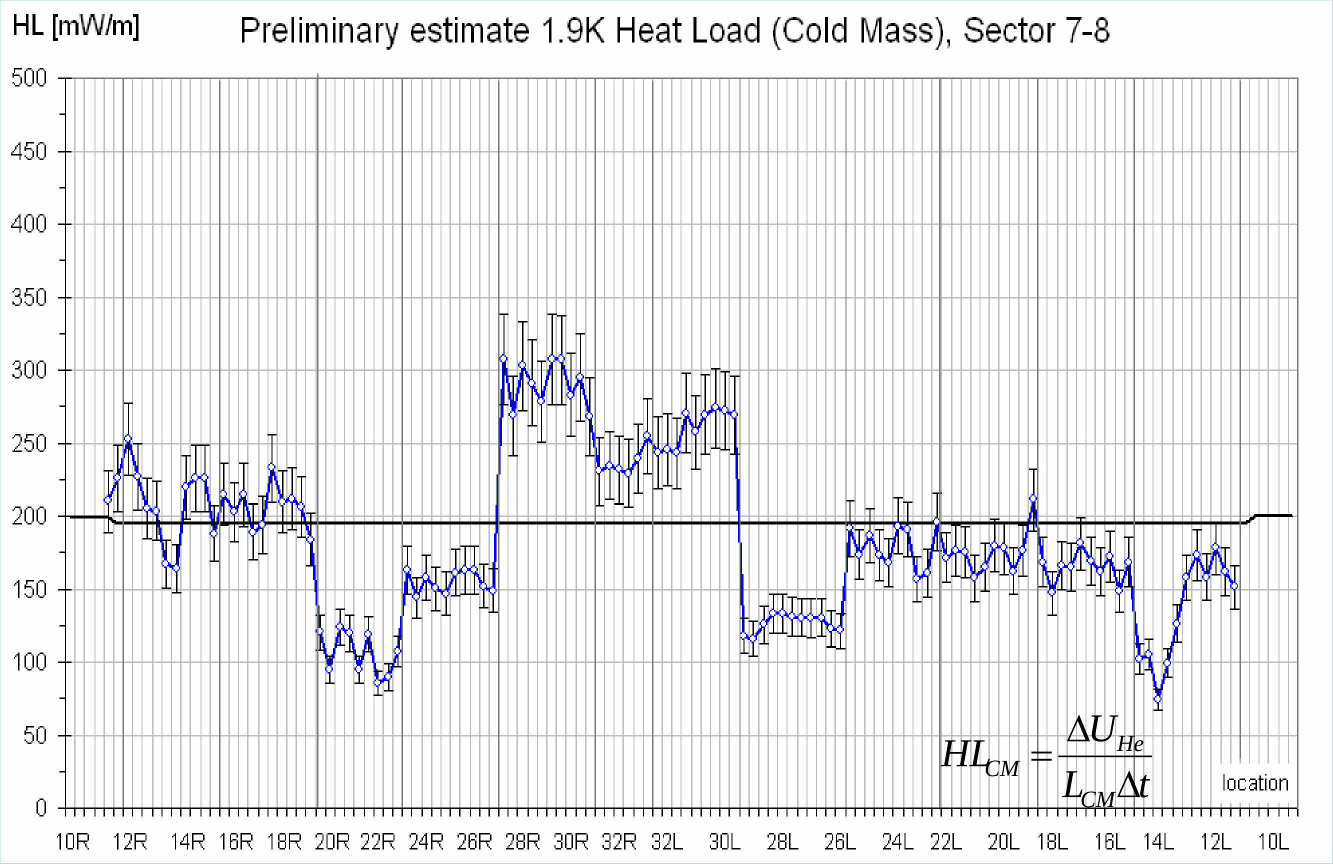
Arc Thermal Performance: preliminary results from sector 7-8 (cont.d)





- HL to Thermal Shield lower than estimated

Arc Thermal Performance: preliminary results from sector 7-8 (cont.d)



- HL to 1.9 K:
  - in average lower than estimated…
  - but some peaks still to be understood (due to leaks?)

Summary

- The **basic functions** of the LHC cryostats were recalled
- **Conceptual and technical choices** were made for an **affordable** cryostat, taking advantage from economy of scales and selecting firms on a competitive basis and on "build-to-print" specifications
- The series **production** of the **cryostat components** lasted between 3 and 4 years
- The **assembly of cryostats** was made at CERN in the frame of a "result-oriented" contract
- **Industrial-type learning curves** allowed the assembly of the about 1700 cryostats in less than 4 years
- An analytical **cost break-down** of components and assembly was presented and discussed
- Linear cost of assembled cryostats: 8 kCHF/m (**6.5 kUSD/m**)
- A larger than expected economy of scale achieved on the vacuum vessels
- Survey measurements confirm the **mechanical stability** of the cryostats
- Preliminary heat load assessments on the first LHC commissioned sector, indicate a **good thermal performance** of the cryostats

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

Thank you for
your attention!