LHC project

The LHC Industrialization Experience of Main Dipoles

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THE PUSH FOR ENERGY: GIANT SIZE

$B_{dip} \cong 8.3$ T
$R_{dip} \cong 3$ km
$L_{dip} \cong 15$ m $\times$ 1232
1700 large magnets
$L_{tunnel} = 27$ km

1500 tonnes of top quality SC cables

15000 MJ of magnetic energy (inc. detector)

1800 Power Converter from 60 A to 24 kA

1800 HTS Leads
11 kW@1.9 K

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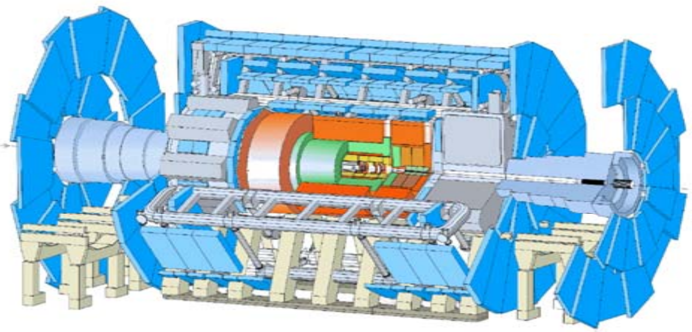
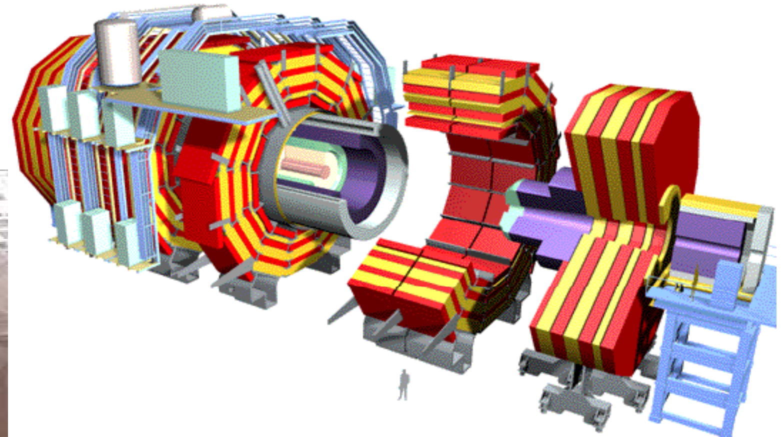
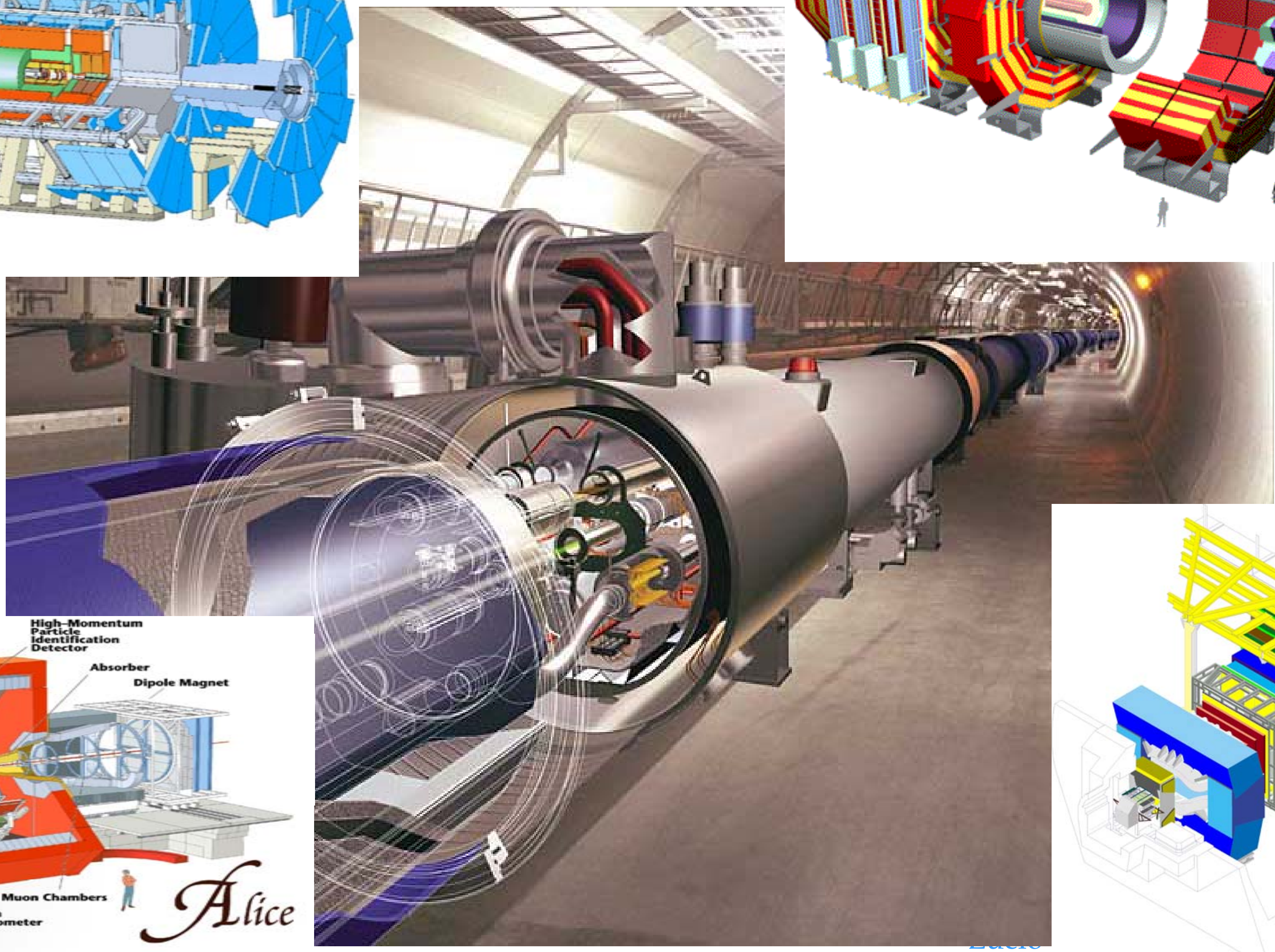
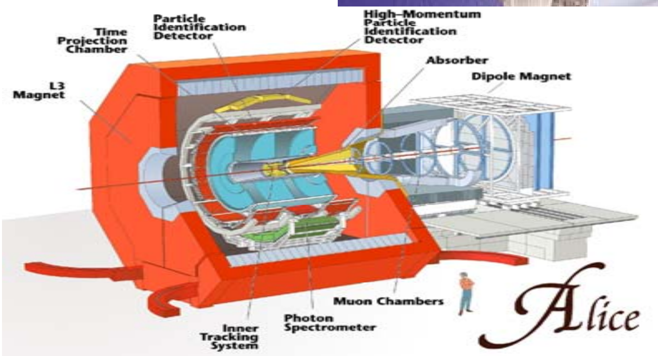
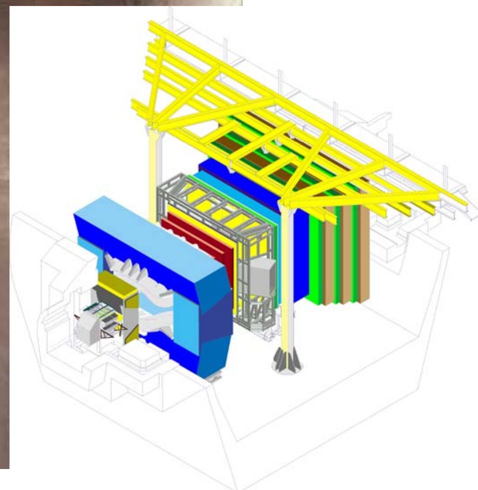
The LHC: For 20 years it has been a **picture**











COST STRUCTURE OF THE LHC

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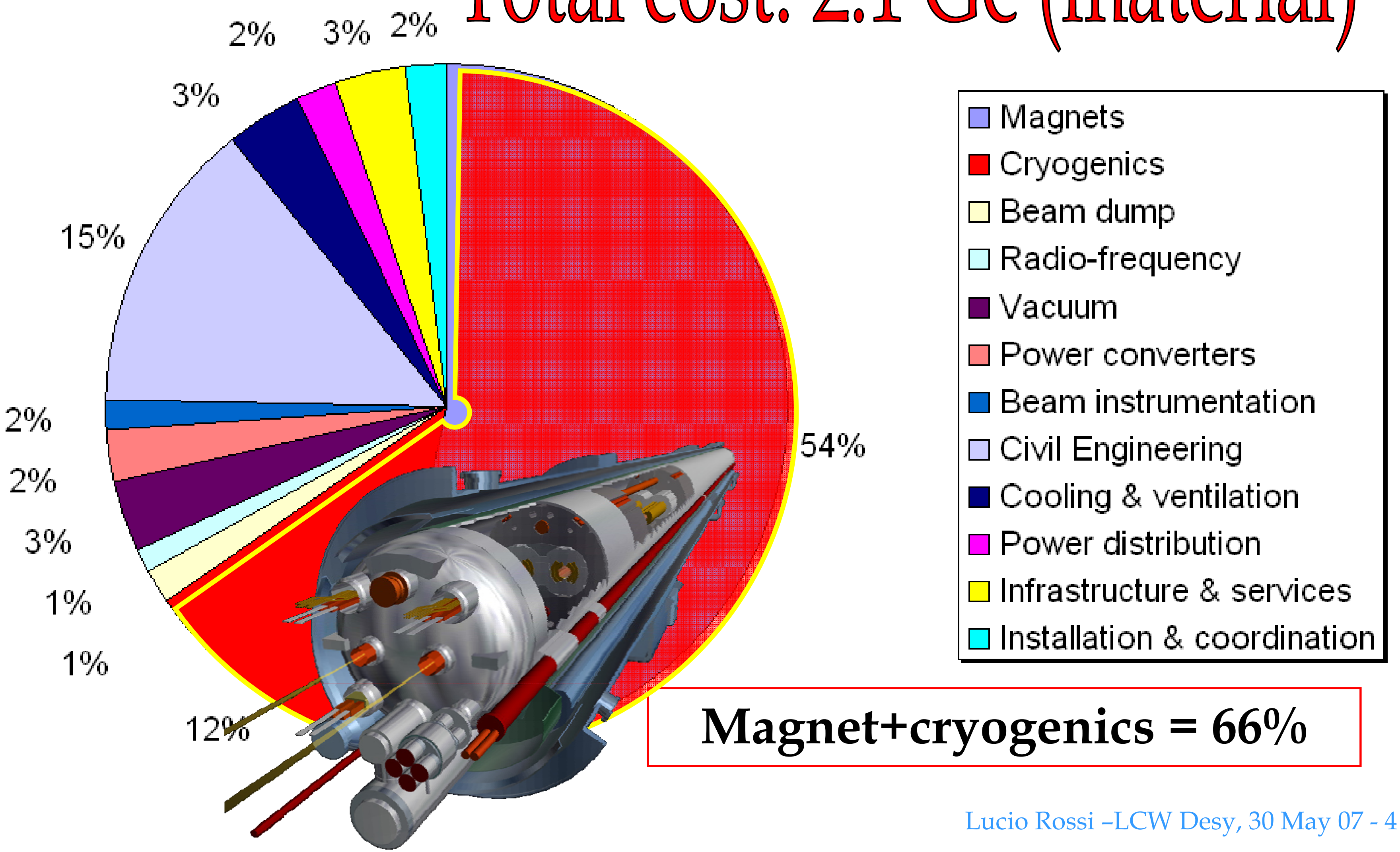
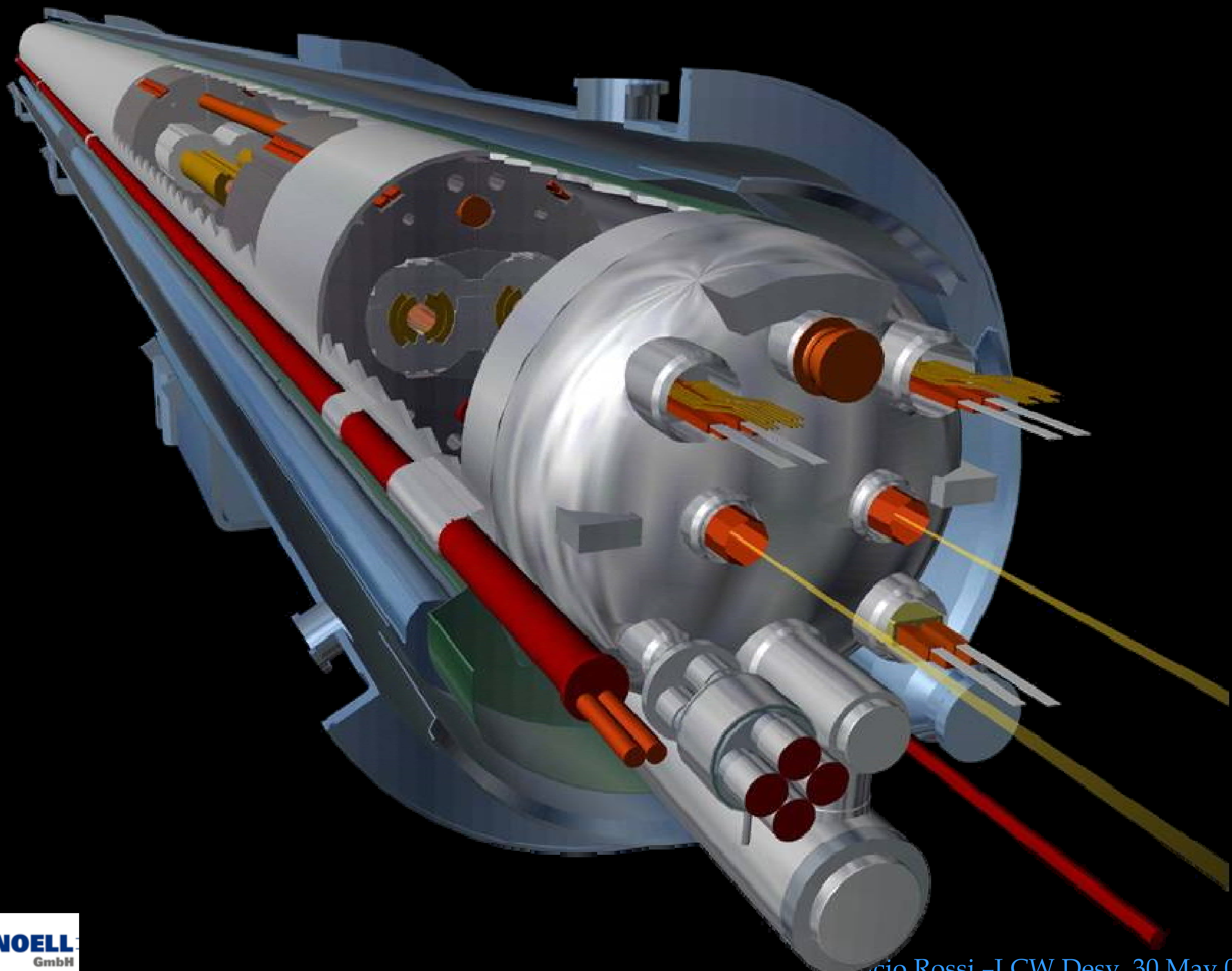
Total cost: 2.1 G€ (material)

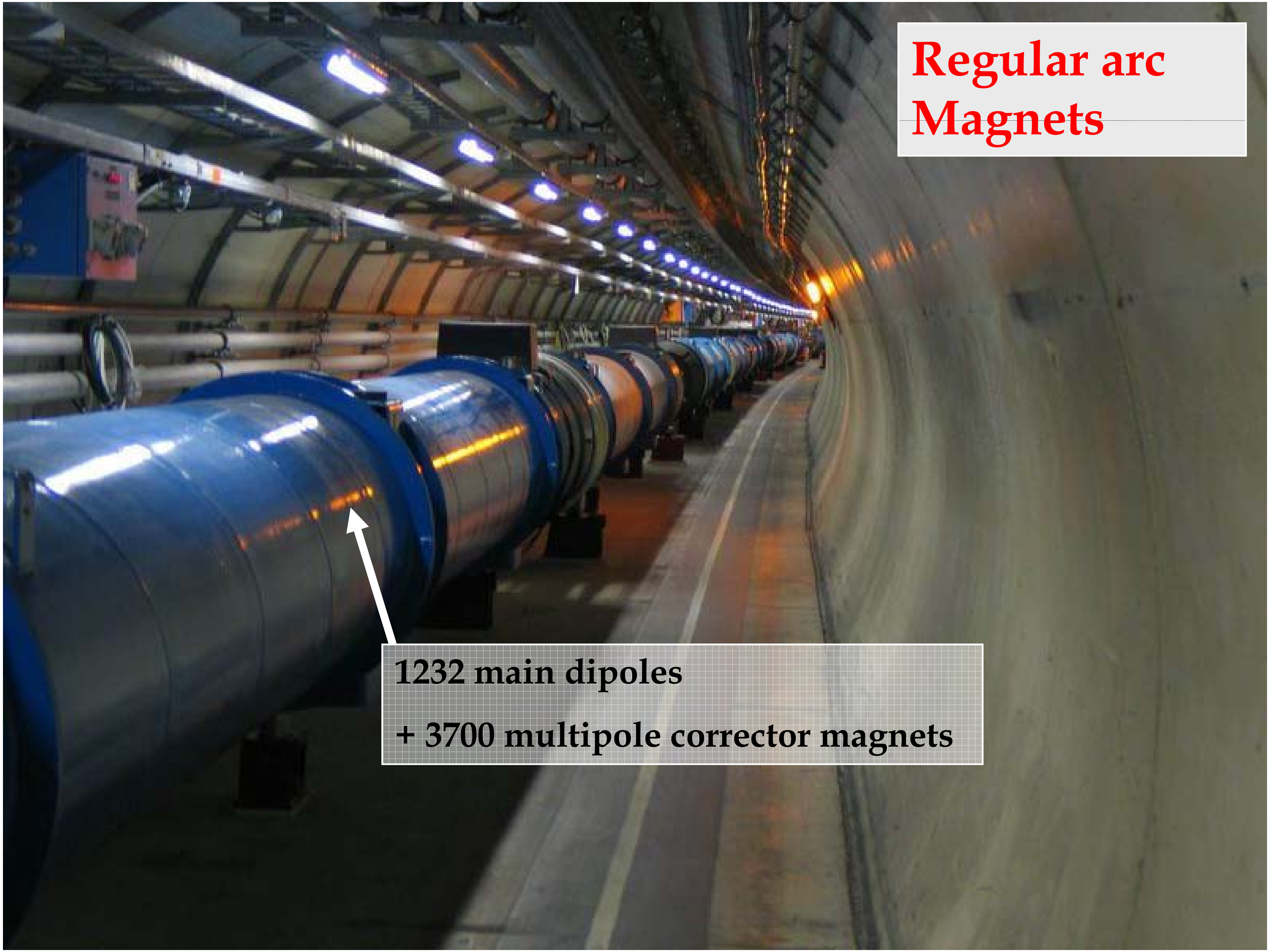


Magnet+cryogenics = 66%

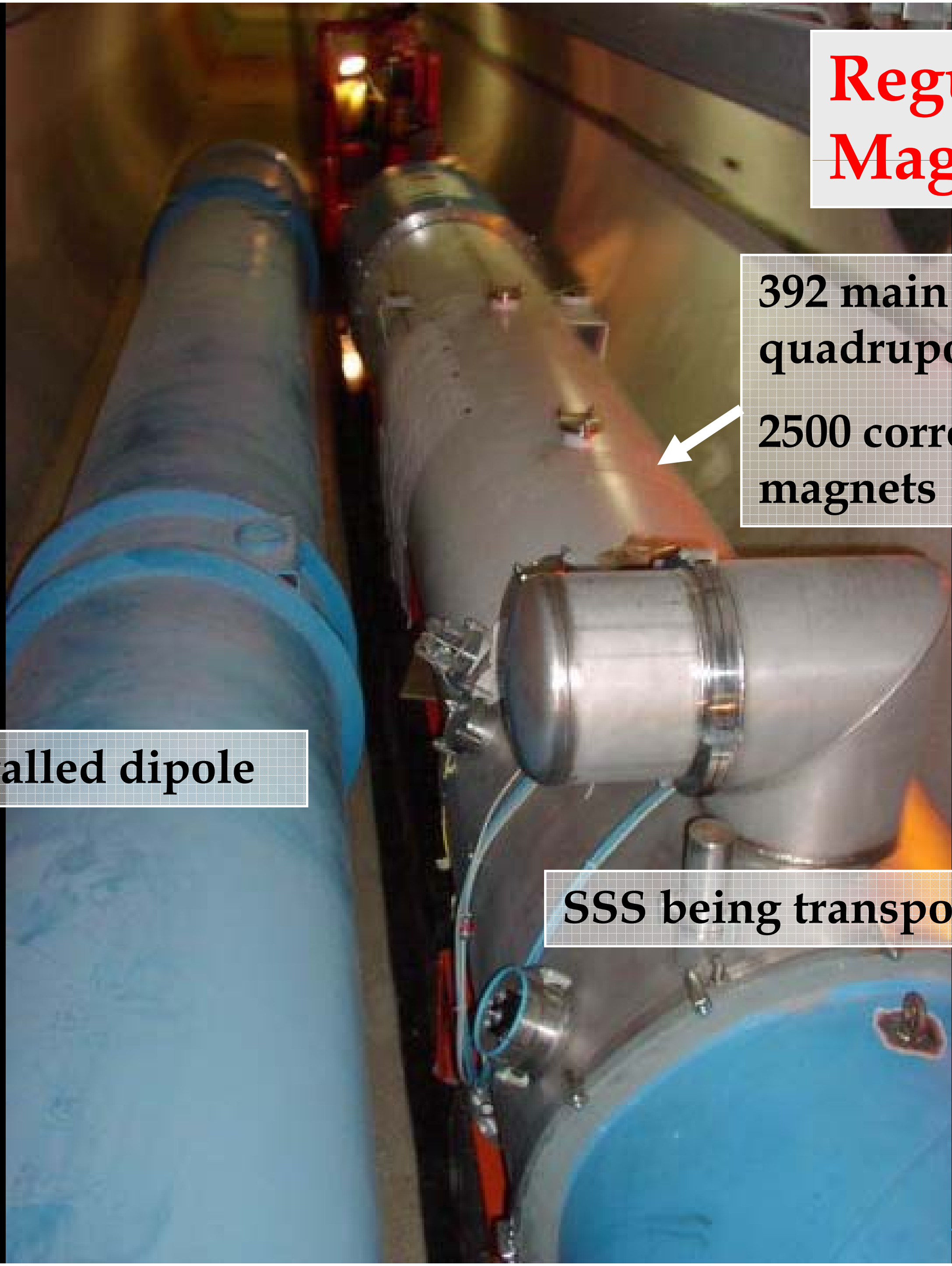


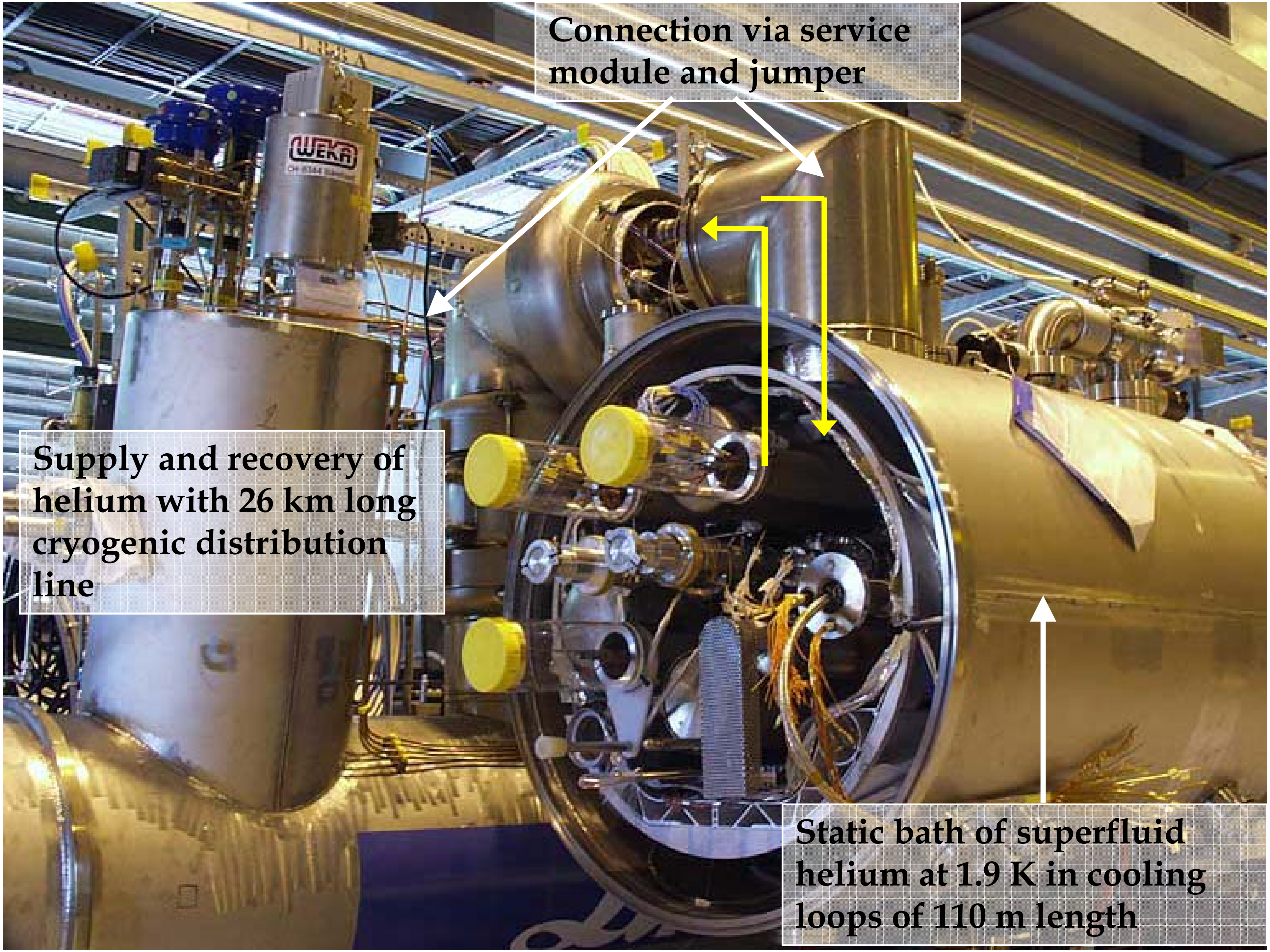

LHC tunnel 2002


LHC tunnel 2006

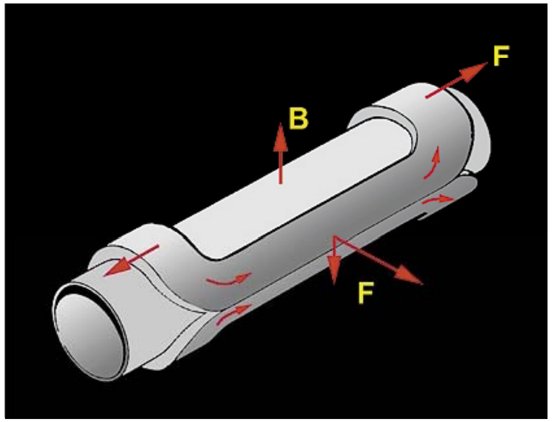

Regular arc
Magnets
1232 main dipoles
+ 3700 multipole corrector magnets

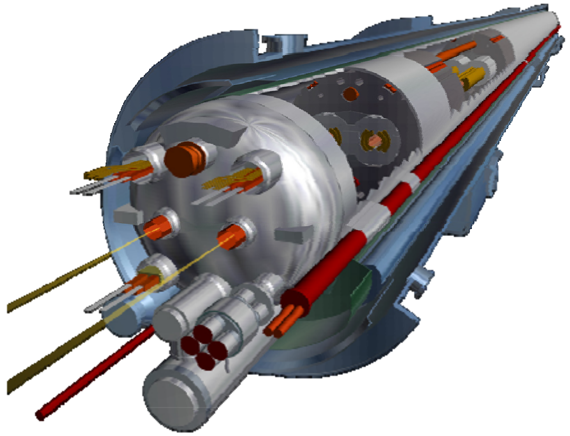
Regular arc Magnets




Connection via service module and jumper
Supply and recovery of helium with 26 km long cryogenic distribution line
Static bath of superfluid helium at 1.9 K in cooling loops of 110 m length
WEKA

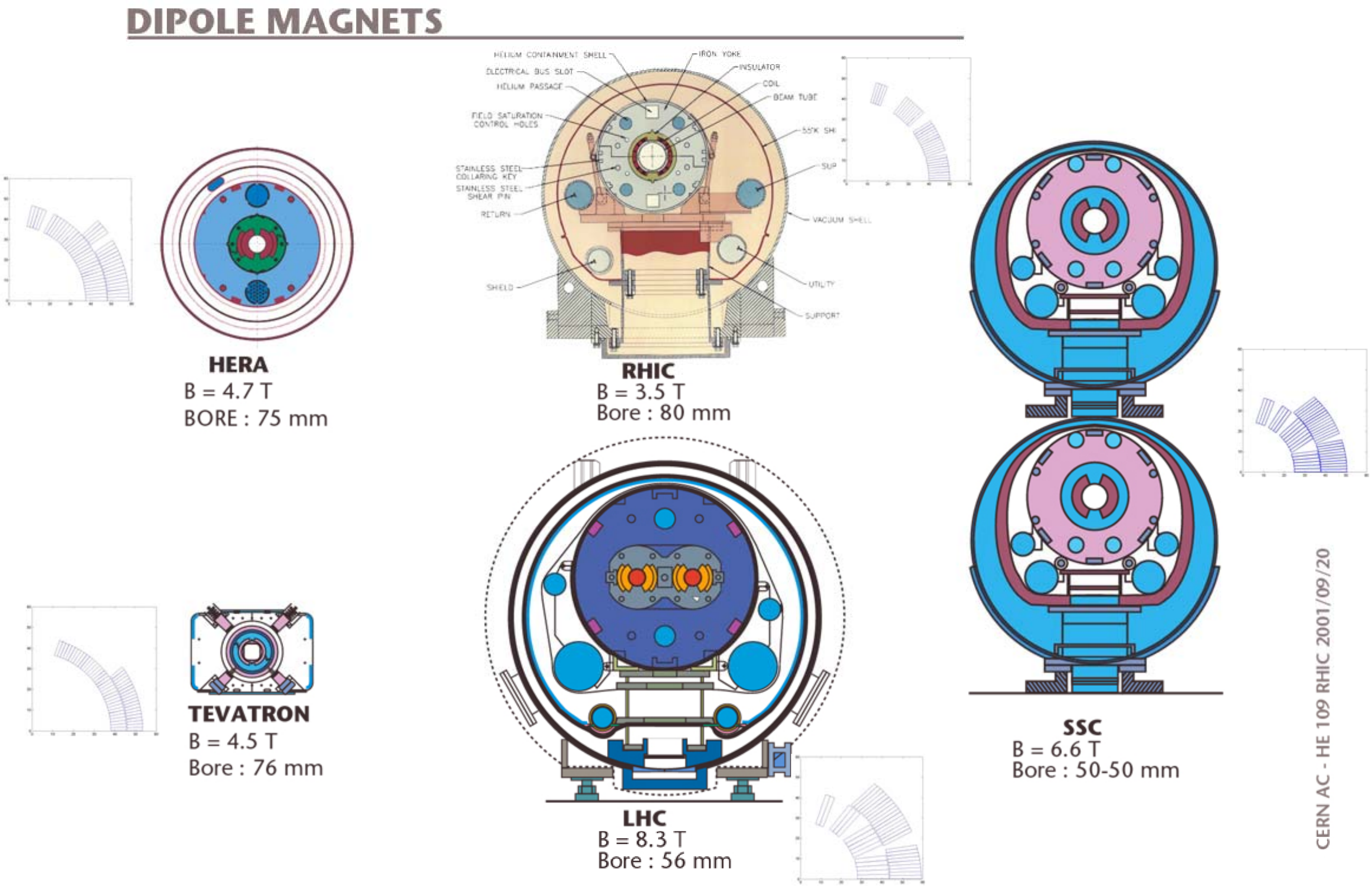
Accelerator magnets issues





- Beam will circulate 500 Millions times in the LHC ! Field accuracy: 10-100 ppm
- Necessity to have all dipoles equal in bending strength BL within ~ 0.1%
- Operated in series each octant:154/circuit
- Extremely high current density: operation 85% of Ic (on load line), little stabilizer to increase J $\Rightarrow$ Training quench. BUT we cannot train them at long (it costs too much) and **they should not re-training.**
- After the cool down the **worst magnet will determine the energy of the accelerator.**

THE HYSTORICAL OUTLOOK



LHC THE STARTING

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- 1987 a 1 m long 1 bore magnet passed 9 T
- 1988 a series of 4 1 m-long magnets Twin were ordered to industry. D… 8-10 T.
- Bare magne… tested in the…
- **Tested in 19… range 8.5-9.…**
- Bore passed… and field do… later 8.65 T
- In 1991 CER… manufactur… in its works…

All this happened well before the results of 1 m model that triggered considerable change. However it created a good dynamics and support for LHC

- CERN lauched in 1989 the long prototype, designed for 10 T max, 10 m, 50 mm twin aperture
- INFN took care of the first 2 magnets ordered in 1989, including cables
- CERN ordered cables and assembly for further 4 magnets in 1990
- Big tooling was designed and built by industry.
- The experience of HERA was a good base, however LHC proved to be more difficult to digest.

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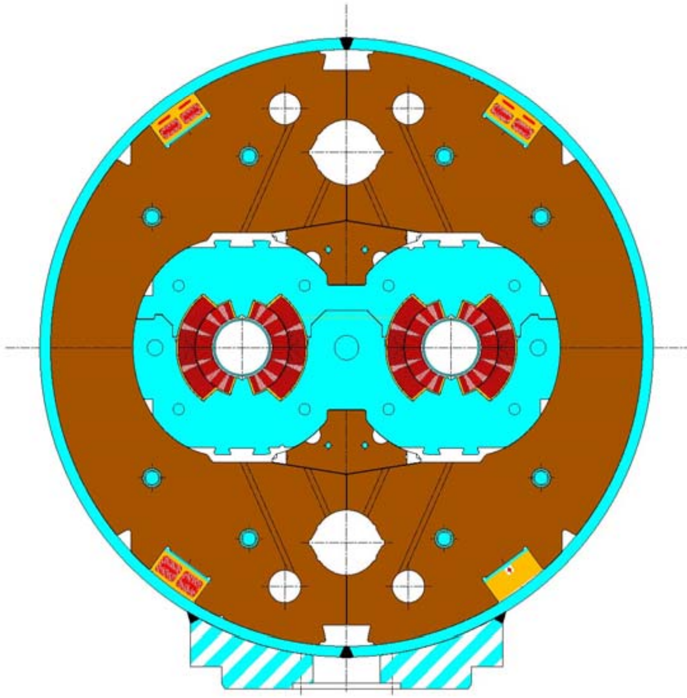
June 1994 : Test of first LHC prototype

- The first 10 m prototype reached 8.65 T at first quench and 9 T in three quench (today would be a bonus magnet)
- But the design was already changed based on 1 m long magnets
- The success was the base for the (first) approval of LHC in Dec '94.

THE TECHNICAL CHANGE

- Aperture 50 to 56 mm
- Increased distance among apertures
- Coil configuration (arrangement of conductor)
- Collar shape
- Length (from 10 to 13 and finally 15 m) and curved!



CHANGE IN GENERAL APPROACH

- From functional specification to “built-to-print”, “built-to-process”, also in the components
- Chopping the work as much as possible, ordering main components directly. Components are strictly related to design, the design was changing, main components had to be under direct control of CERN

- In addition to the 1 m model facility, a cold mass facility for 15 m assembly was set up at CERN (but not the part concerning the collaring coils) to finalize the procedures and technologies not yet defined.

THE LONG ROUTE OF INDUSTRIALIZING AND MAKING COST EFFECTIVE

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- Further changes
  - Change of coils configuration (almost back to previous one!). This had a large impact on the plan.
  - The quench test in between 1995 and 1998 were far being glorious, the field was almost lowering: good results, the nominal field was eventually fixed to 8.3 T. We suffer in interconnection but I think it was sane.
  - Changes of material for collars (from Al to 316LN)
- Continuous order of superconducting cables
- Continuous orders of long magnets to the 4 (then 3) companies selected: keeping them in the business was fundamental for the tendering and production.
- Ideally you would want re-optimize after every change, but it is impossible. Many items are far from being optimal, but: **THE BEST IS THE ENEMY OF THE GOOD**

THE LHC SUPERCONDUCTOR 7000 KM OF CU/NB-TI CABLE

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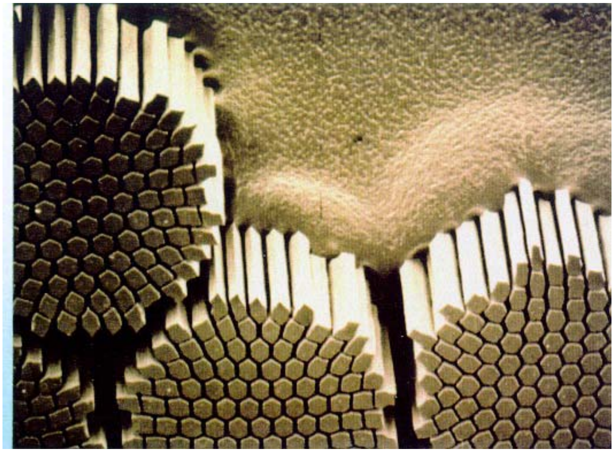
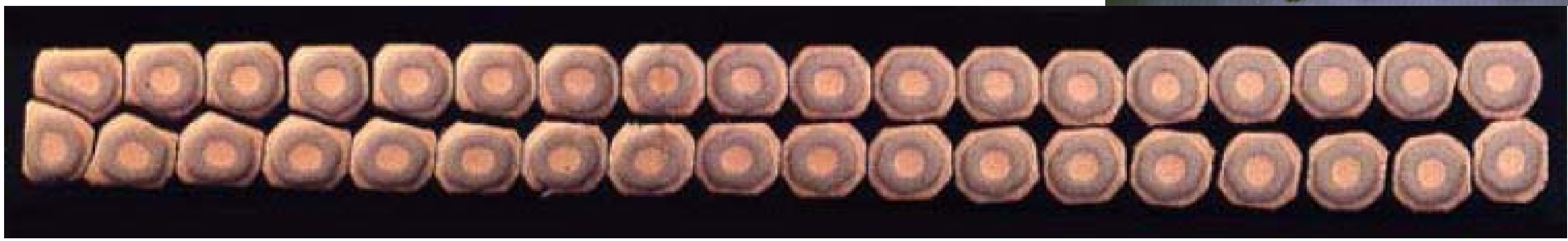
STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (μm)	7	6
Number of filaments	8800	6425
Jc (A/mm^2) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ_0M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5
CABLE	**Type 01**	**Type 02**
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm)	1.900 ±0.006	1.480 ±0.006
Keystone angle (degrees)	1.25 ±0.05	0.90 ±0.05
Cable Ic (A) @ 1.9 K	13750 @ 10T	12960 @ 7T
Interstrand resistance (μΩ)	10-50	20-80





Critical Current of LHC Inner Cable

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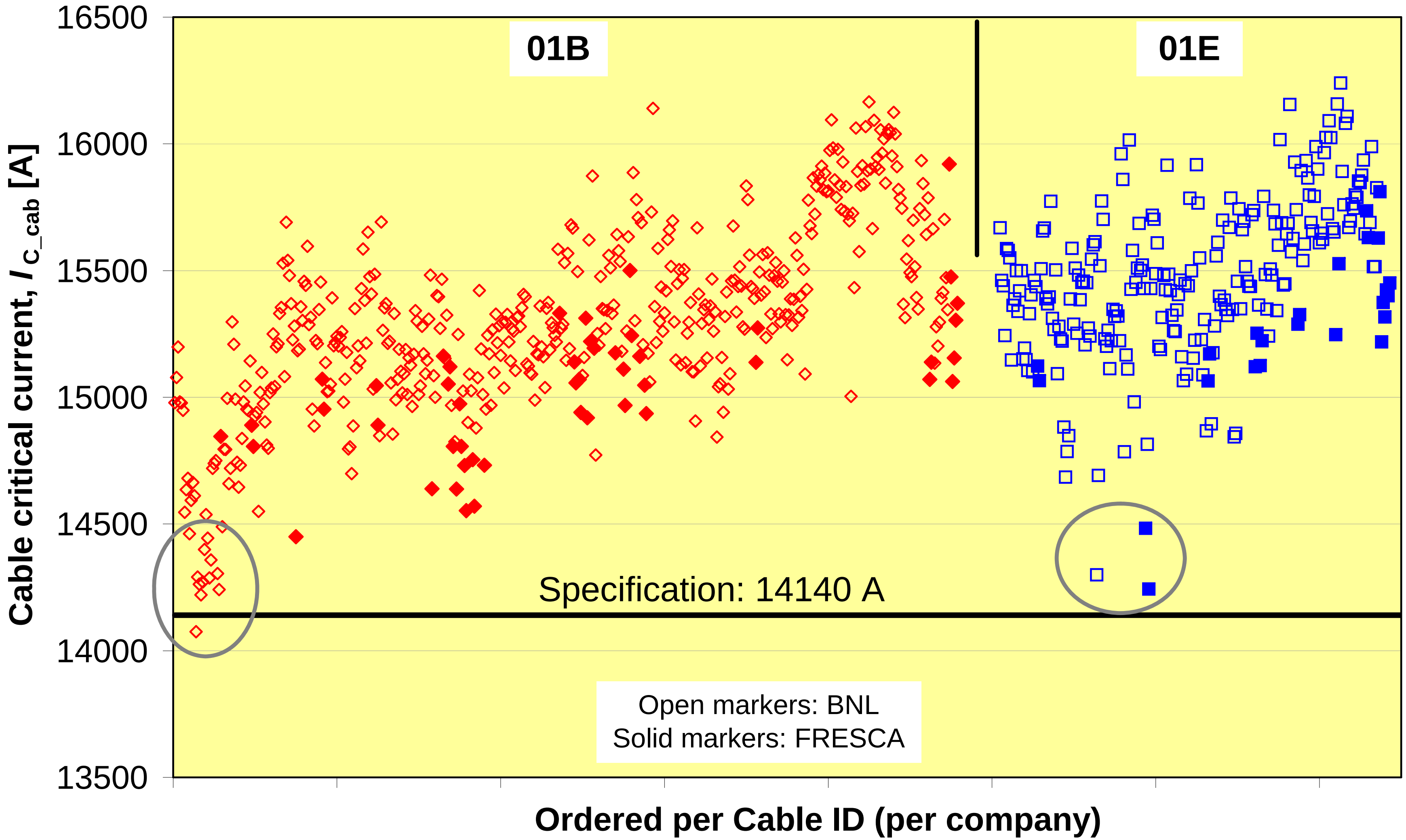

Controlling the contact resistance

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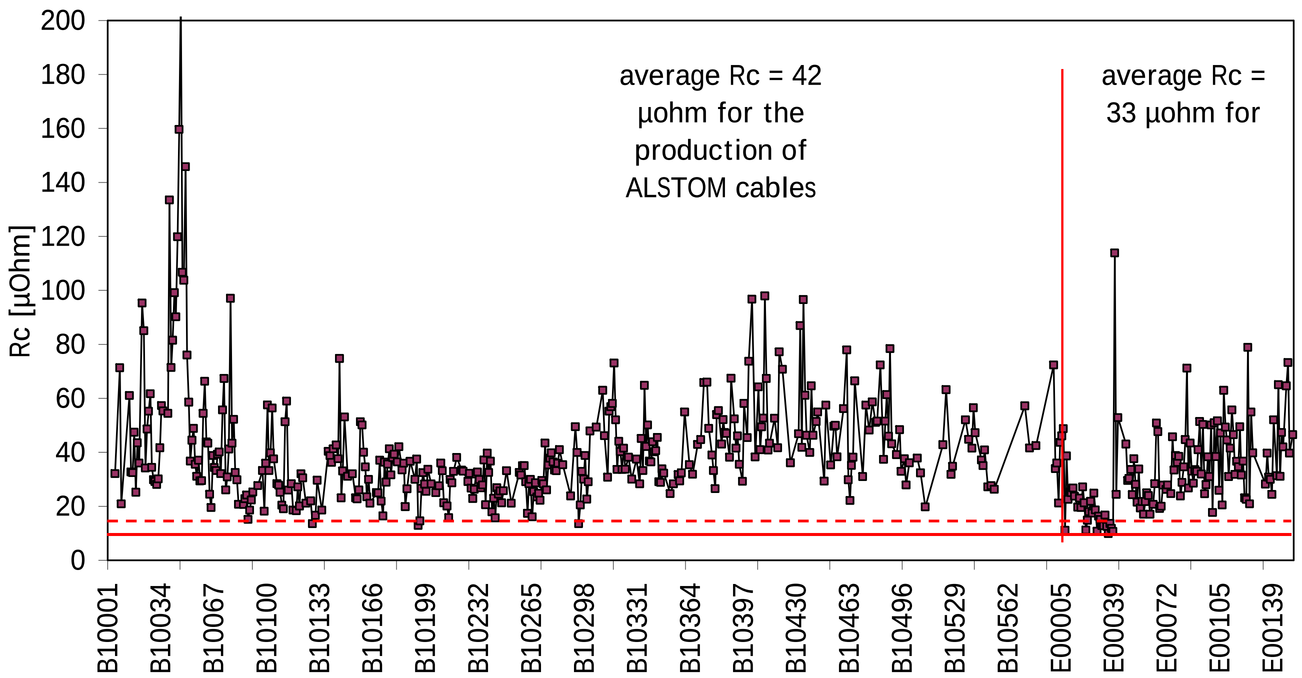
Rc measured by CERN on the cables for the inner dipole layer



CERN has developed the controlled oxidation method

Value too low gives field errors

Too high may give instability

Procedure came just-in time!

Number of tests in 2003 at CERN

Number of billets approved in 2003 : 1578

Number of UL received in 2003 : 2818

Wire		Cable	
◆ Ic	462 /month	◆ Ic (BNL)	54 /month
◆ RRR	482 /month	◆ Rc	120 /month
◆ Magnetisation	137 / month		
		◆ Bend test	88 /month
◆ Bend test	311 /month	◆ Residuel Twist	83 /month
◆ Spring back	235 /month		
		◆ CMM	88 /month
◆Diameter	251 /month	◆ 10-stack	111 /month
◆ Cu/Sc	850 /month	◆ Sharp edges	93 /month
◆ Coating	454 /month		
◆ Twist pitch	175 /month		

QA: LABORATORY EQUIPMENT (300 K TESTS)

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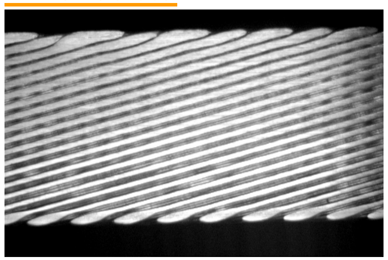
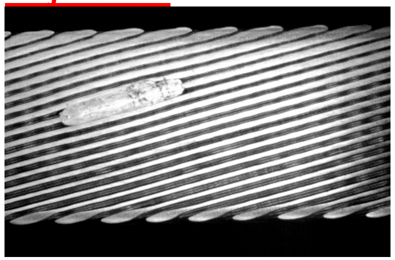
QA: LABORATORY EQUIPMENT

Examples of defects detected **C. I. S.**

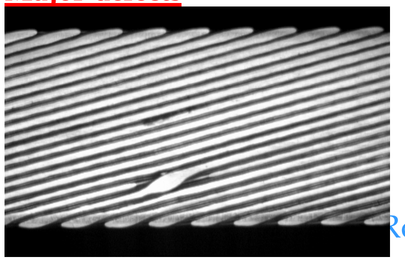
Minor defect



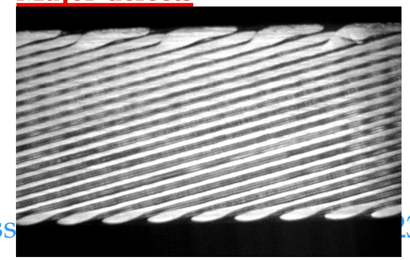
Major defect



Major defects



Major defects



Cable for main dipoles : delivery

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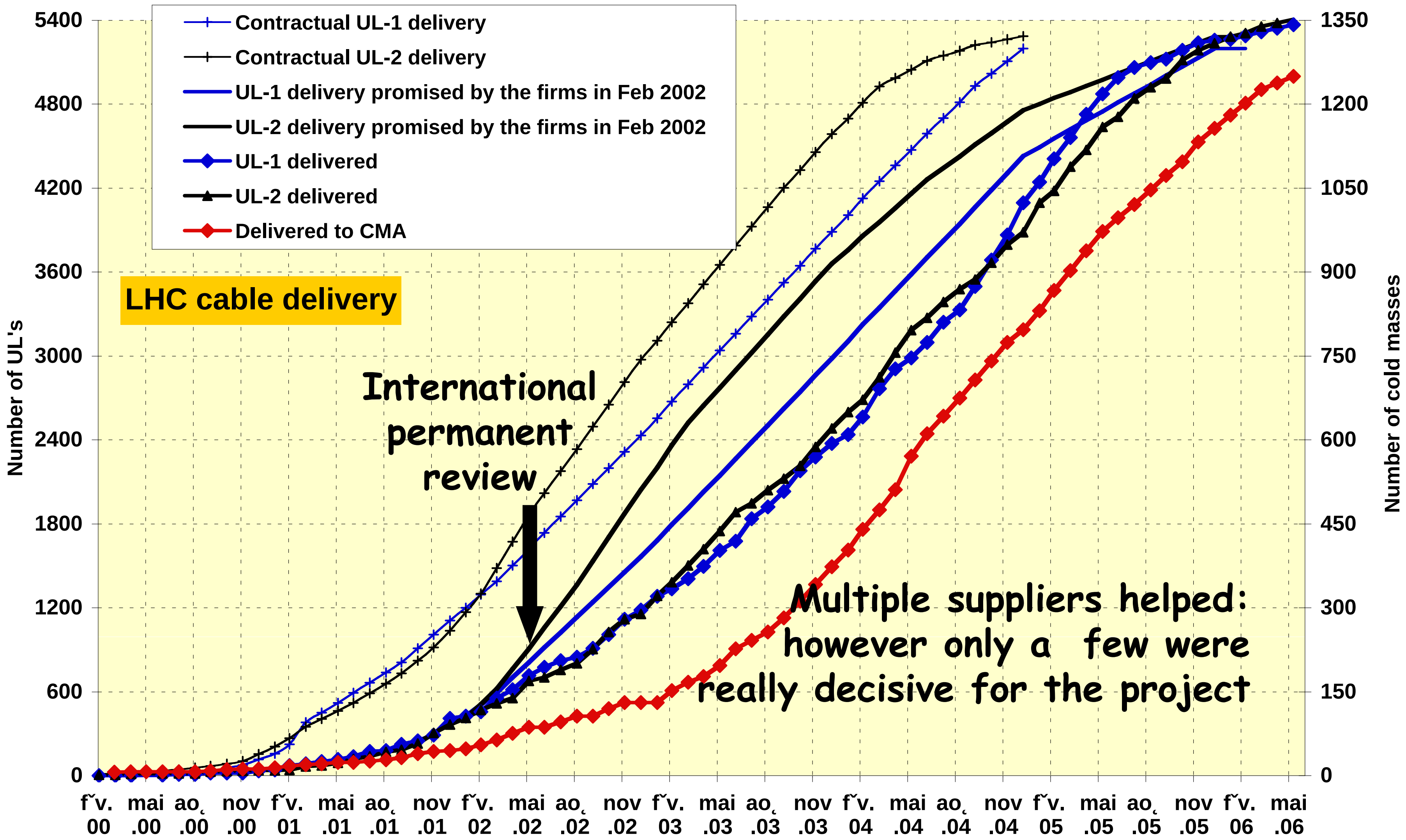

A. Verweij, AT/MAS/SC, 1/6/2006

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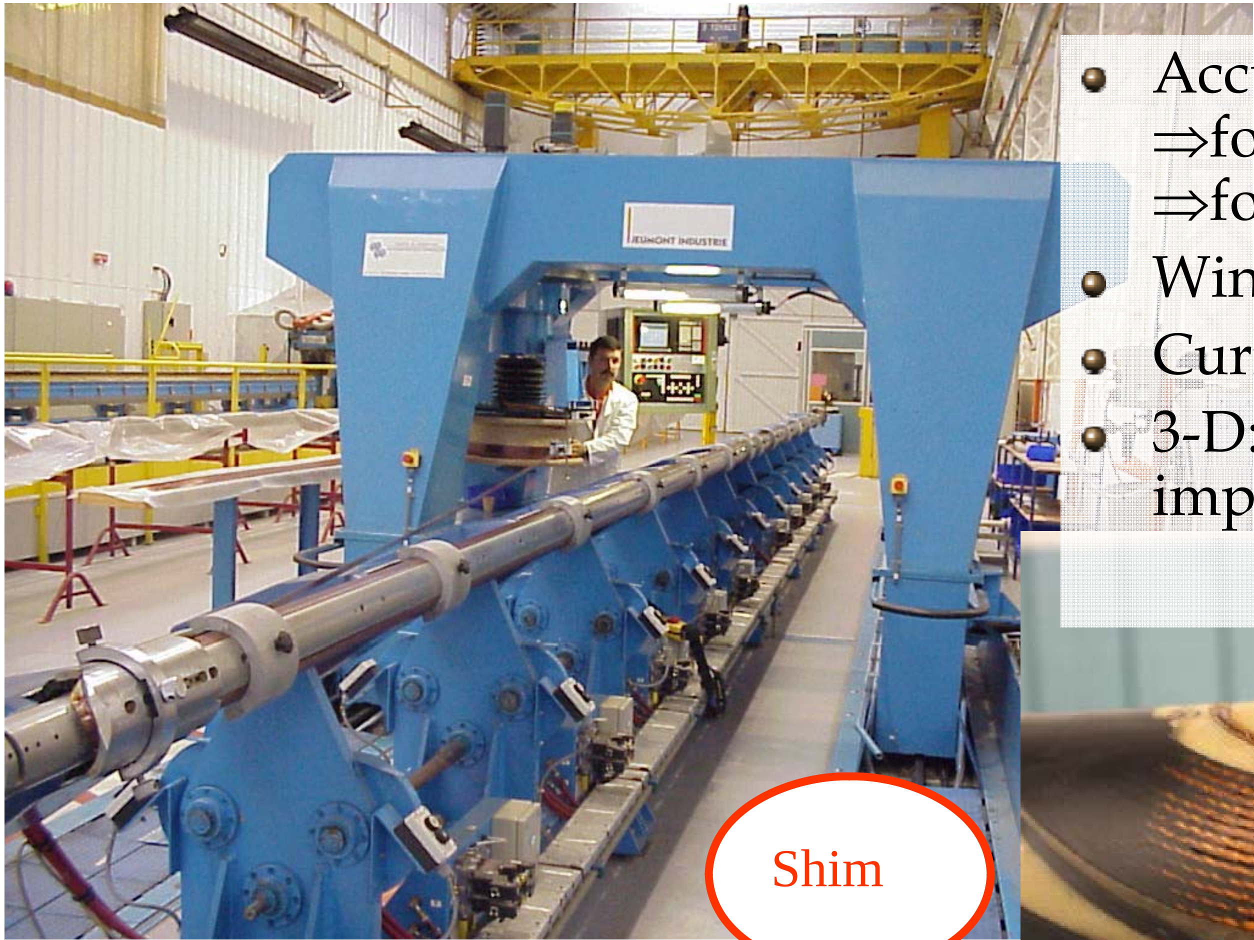
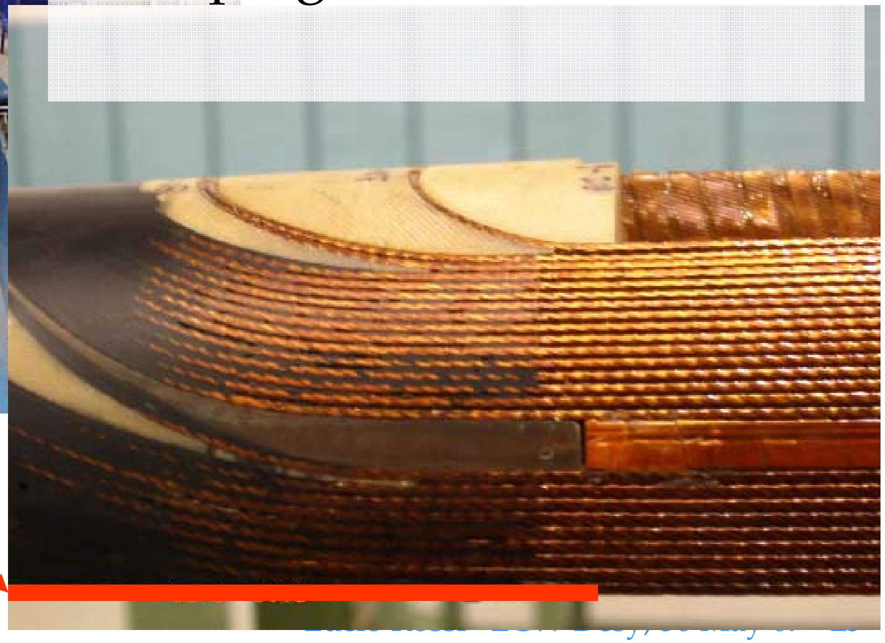
COILS - WINDING



- Accurate positioning
  ⇒for quench
  ⇒for field accuracy
- Winding
- Curing at 185 °C
- 3-D: ends. Quasi-impregnation



QA: MAGNETIC MEASUREMENTS

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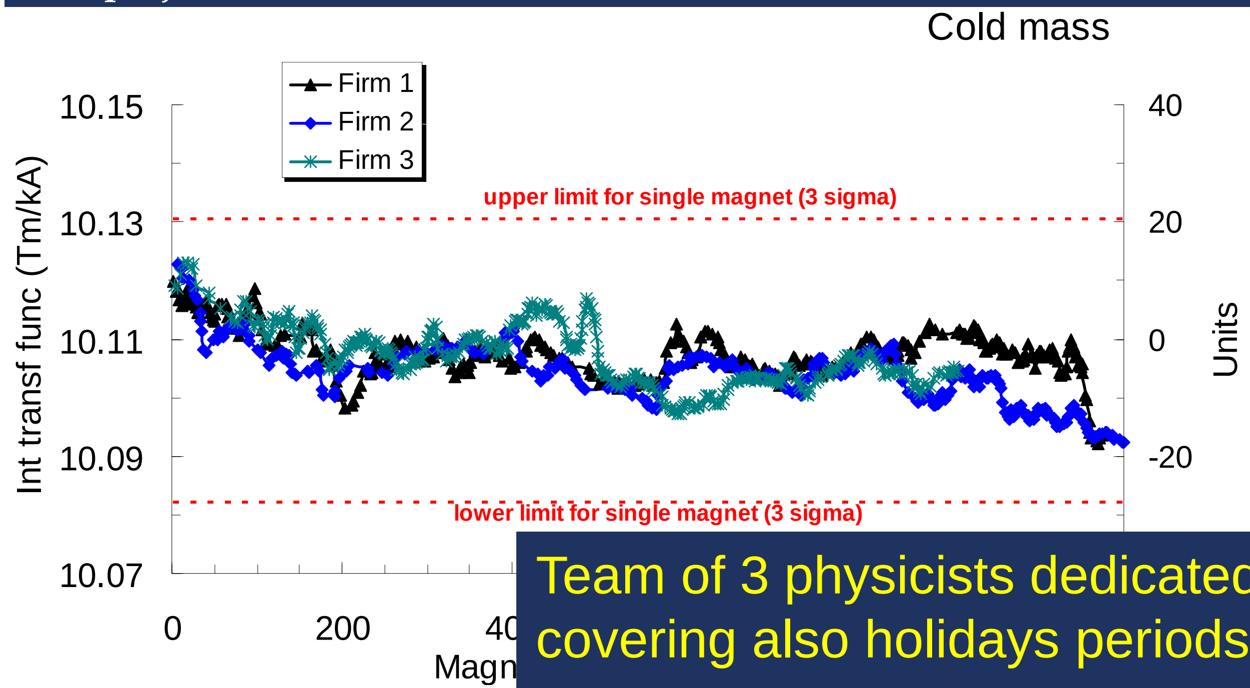


Introduced first to steer the FQ toward beam dynamics targets.

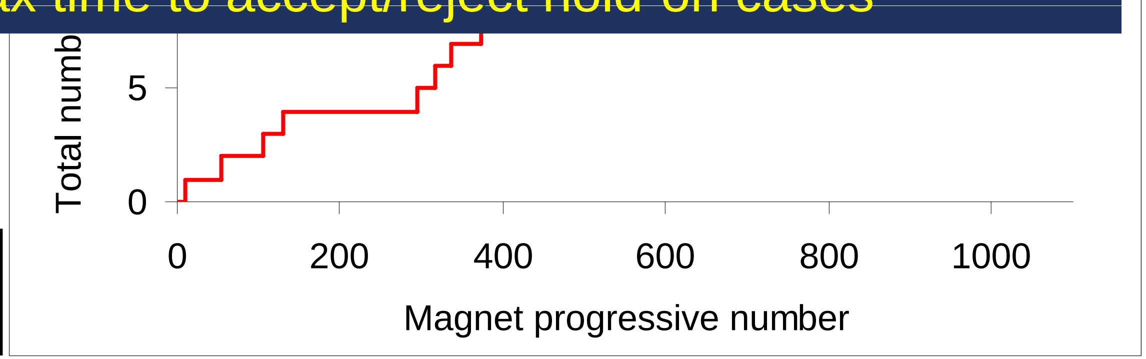
Team of 3 physicists dedicated to on-time analysis covering also holidays periods.

4 hours to react yes-no-hold;

2 days max time to accept/reject hold-on cases

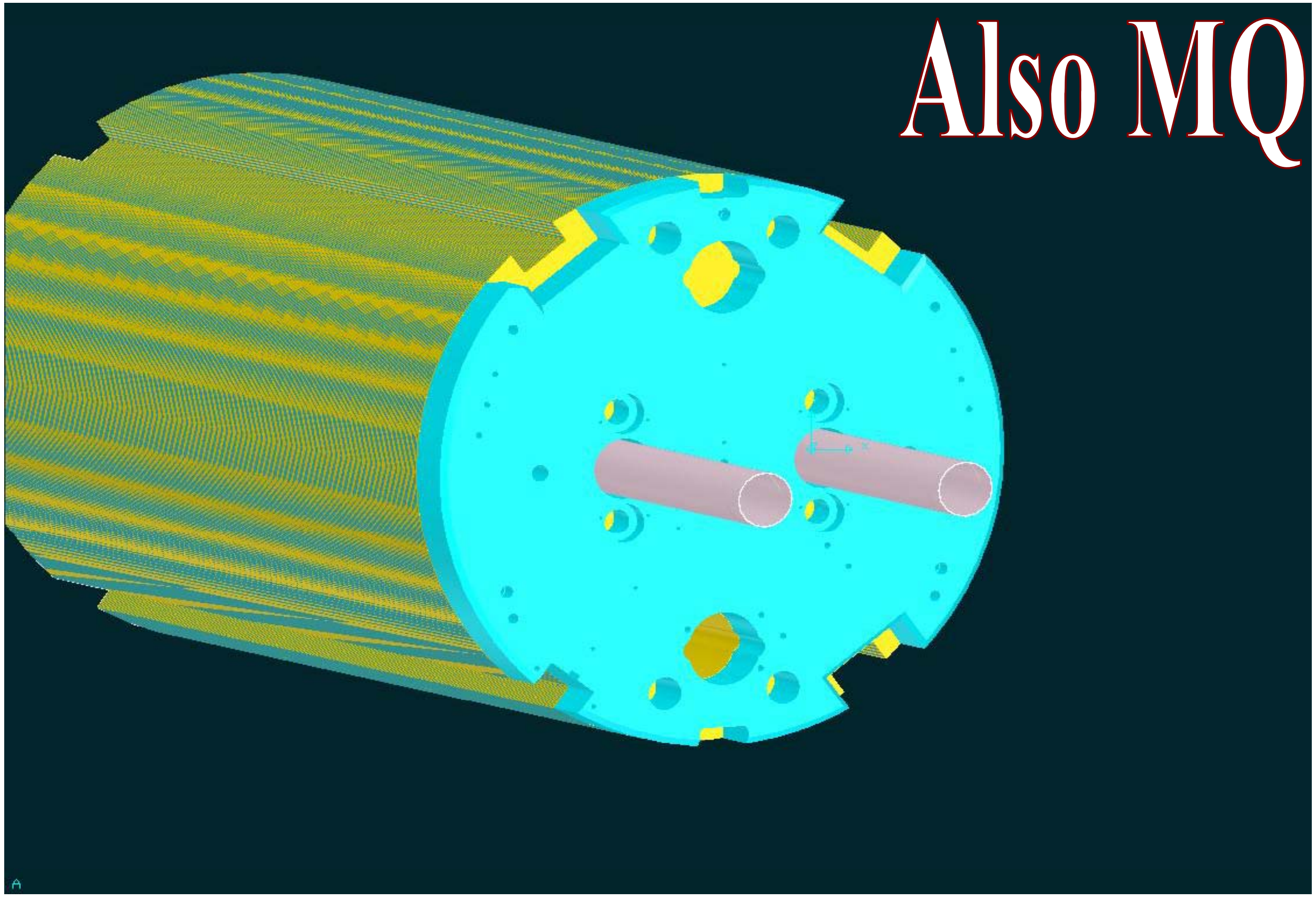
It has also helped to detect a number of defects.

It has also been used to detect subtle electrical shorts

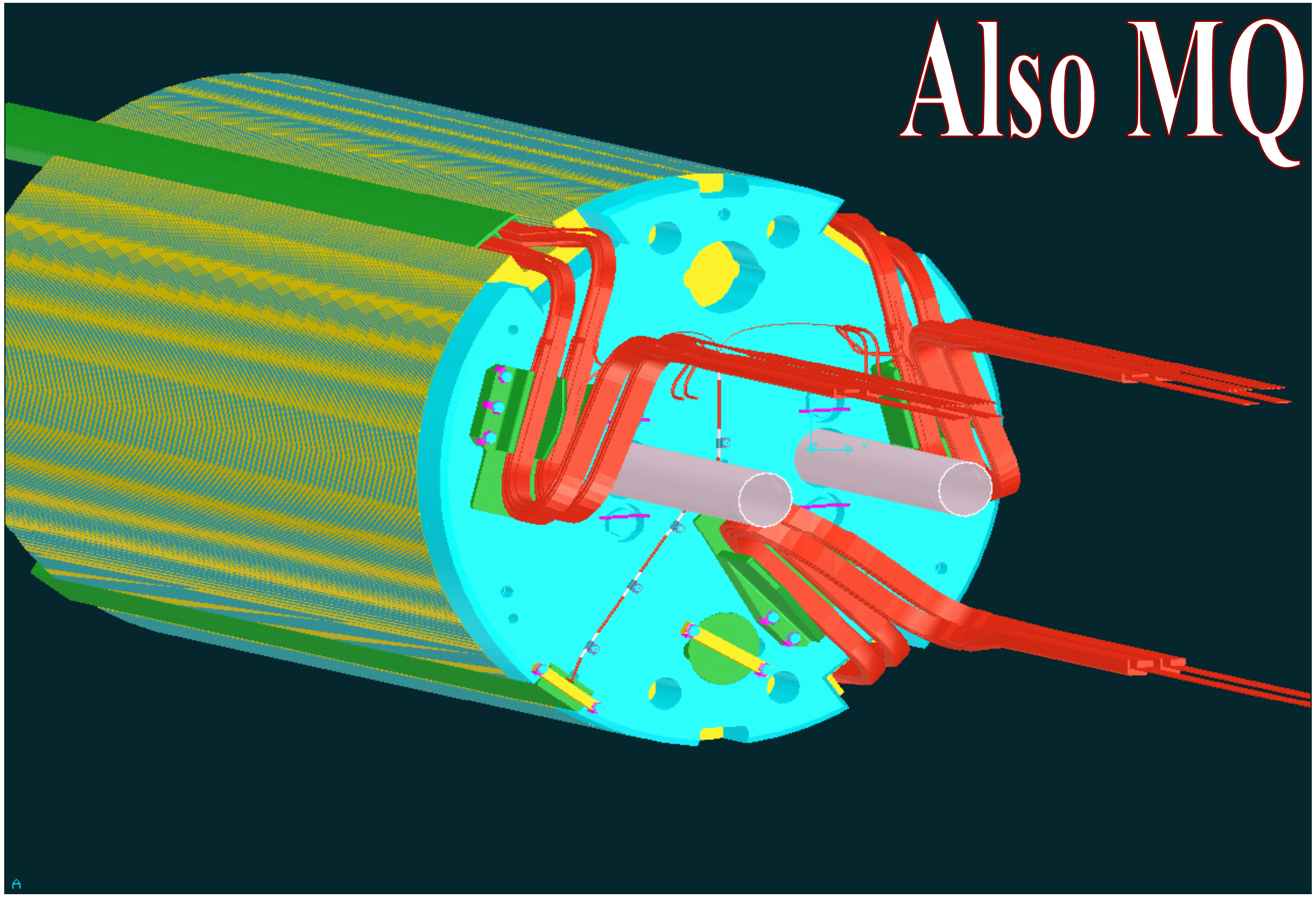


Courtesy of E. Todesco and C. Vollinger

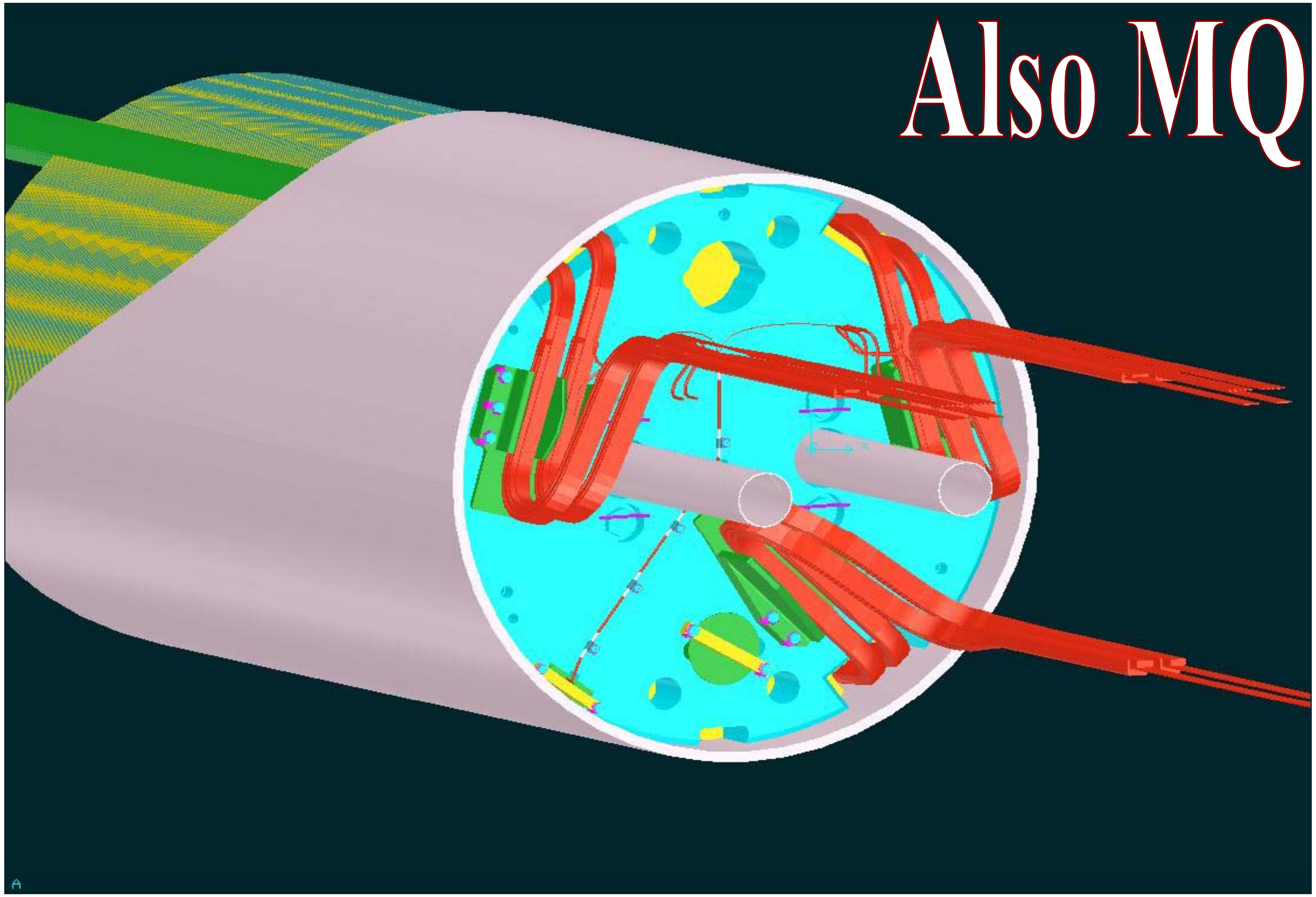
Dipole -End Part
End Plate



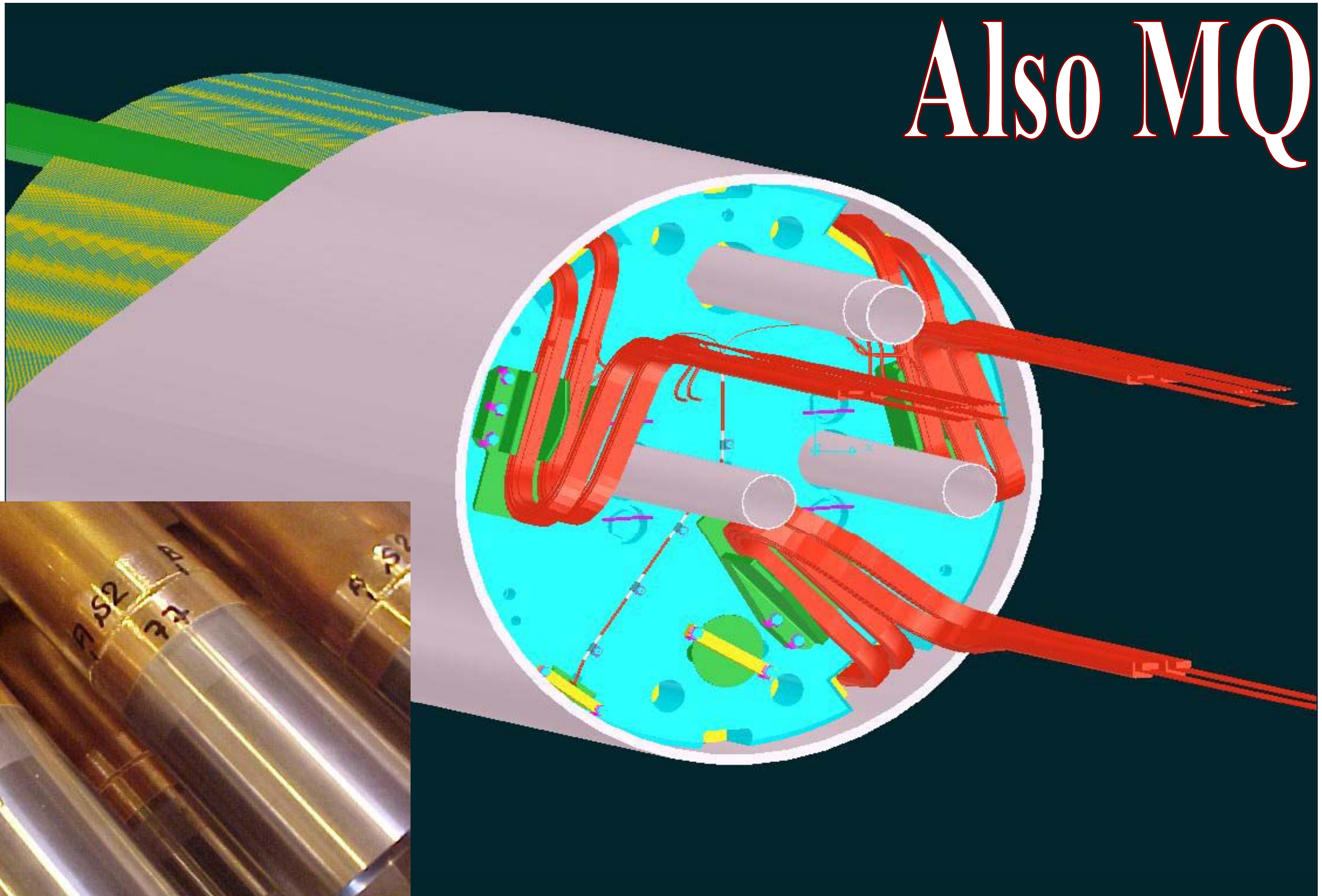
Dipole-end part
bus bars



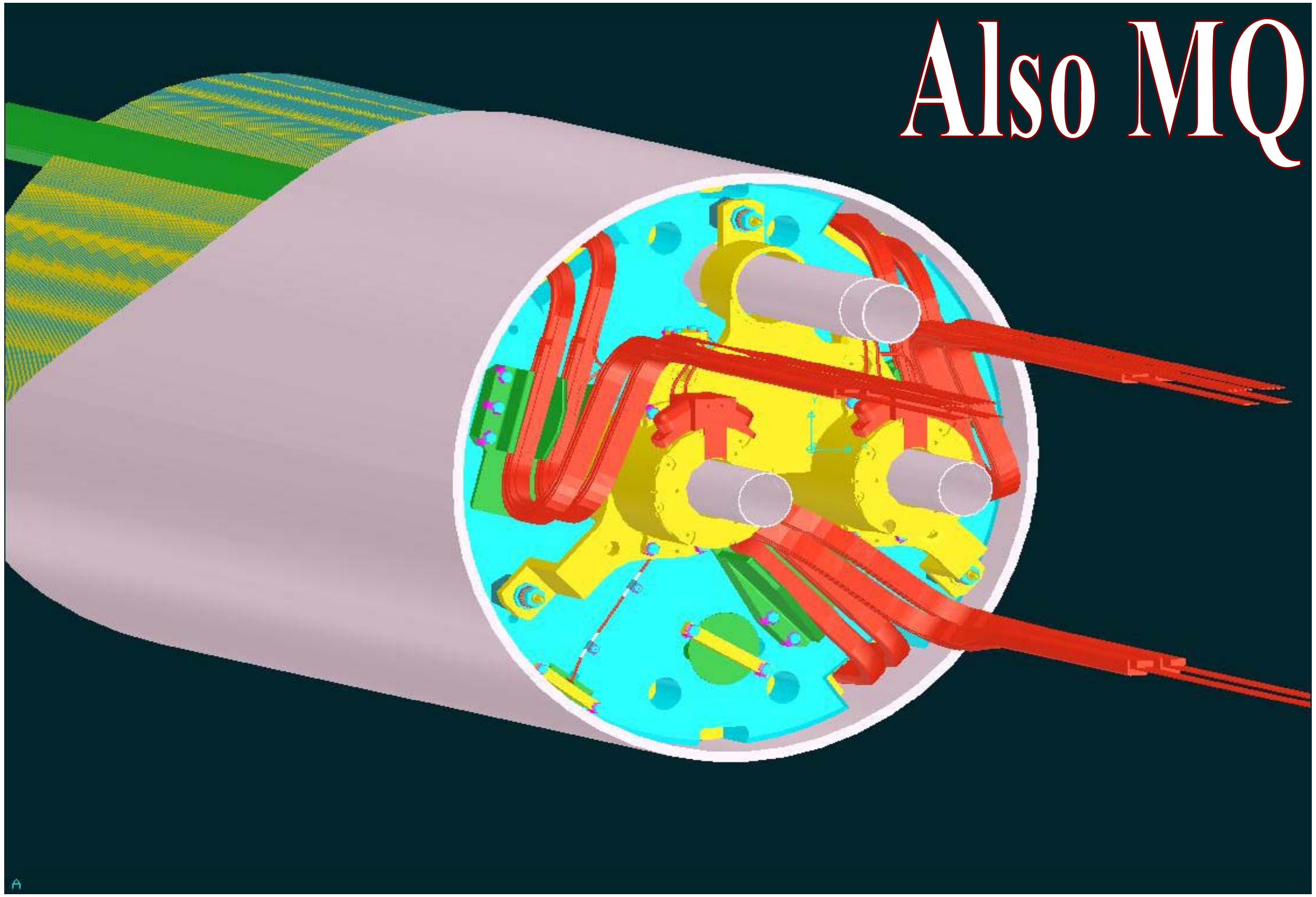
Dipole -End Part
Shrinking Cyilinder



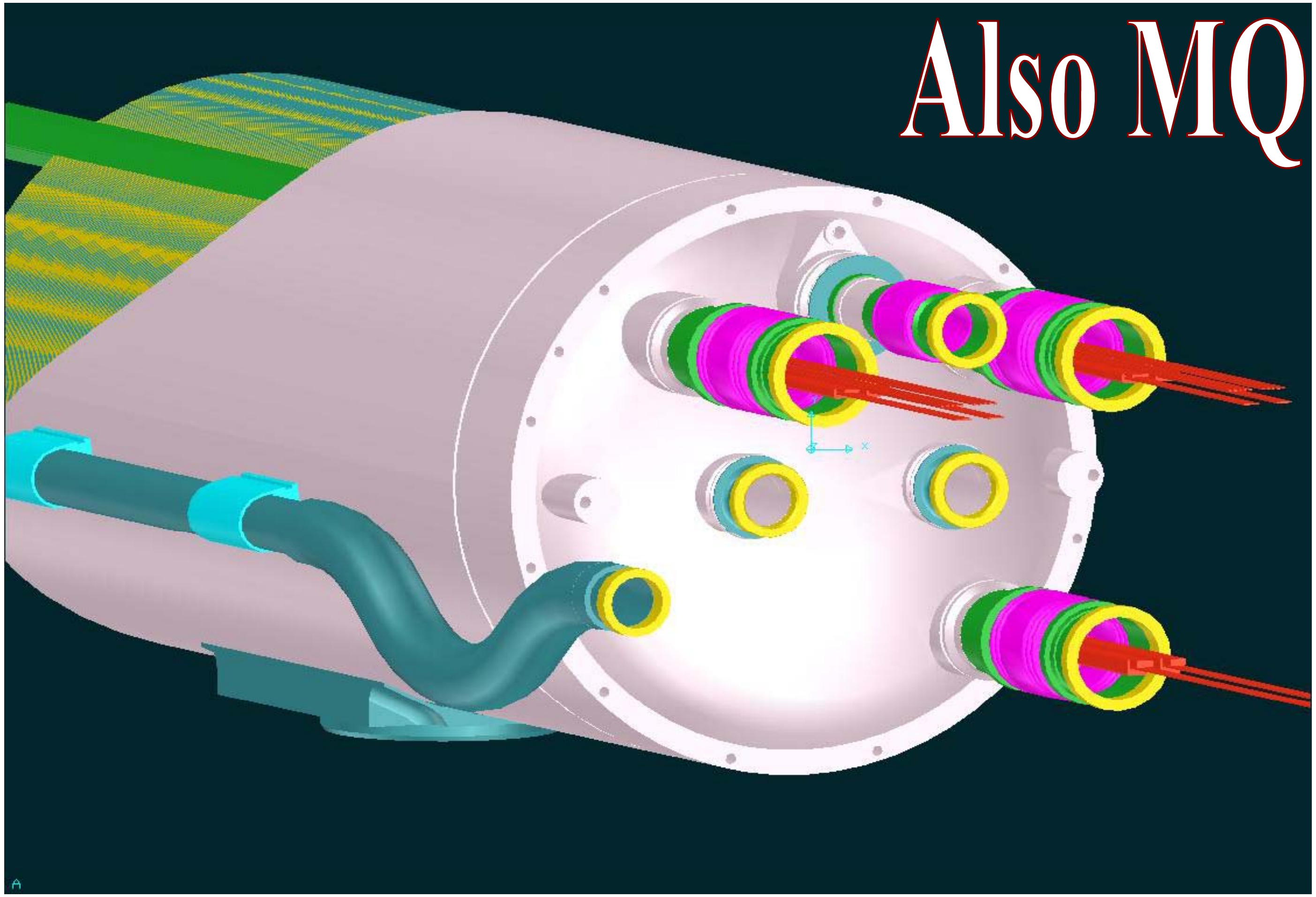
DIPOLE -END PART
CU HXT



Dipole -End Part Corrector Magnets



Dipole -End Part
Cold foot, bellows and N-line



Snapshot at industry: superconducting poles

Snapshot at industry: Coil aperture assembly

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SNAPSHOT AT INDUSTRY: COLLARING PROCESS

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SNAPSHOT AT INDUSTRY: COLD MASS

Laser Tracking measurements

Snapshot at industry: cold mass waiting test or delivery

Snapshot at industry: Delivery to CERN

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SUPERCONDUCTING LHC DIPOLES: THE CONTRACT STRATEGY

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1988-98 short models and six prototypes for each of the three generation design were built by industry/CERN

1999: 3x30 pre-series magnets were ordered from three firms. A first attempt to go for larger production (160 dipoles) failed against high price

Three contracts for the fabrication of 1146 (+30 spares) magnets have been signed March 2002 (price 1/3 of the pre-series). Releasing company responsibilities from has been fundamental to get there.

INTEGRATED SUPPLY CHAIN MANAGEMENT

CERN took care of most components
The same can be said for the main tooling

Benefits

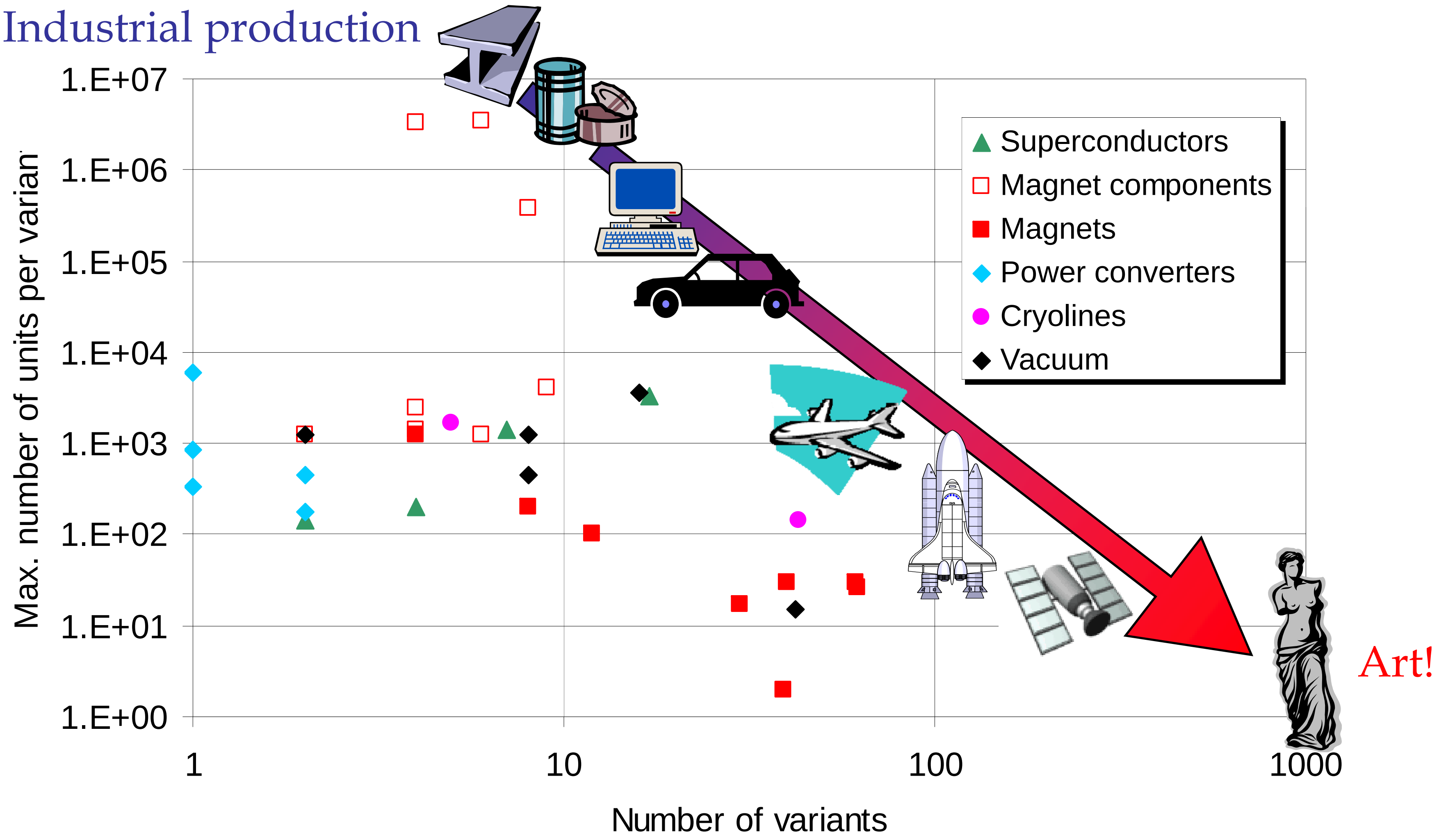
- Technical homogeneity
- Quality assurance
- Economy of scale
- We could advance the purchasing
- Security of supply
- Balanced industrial return

Risks & drawbacks

- Responsibility interface
- Additional workload
- Liability for delays (just in time!)
- Transport, storage & logistics: we have moved 120,000 tonnes around Europe (5 TIRs a day for 5 years)

LHC Components & Industrial Products

Industrial production



Courtesy of Ph. Lebrun

SERIES PRODUCTION OF LHC COMPONENTS

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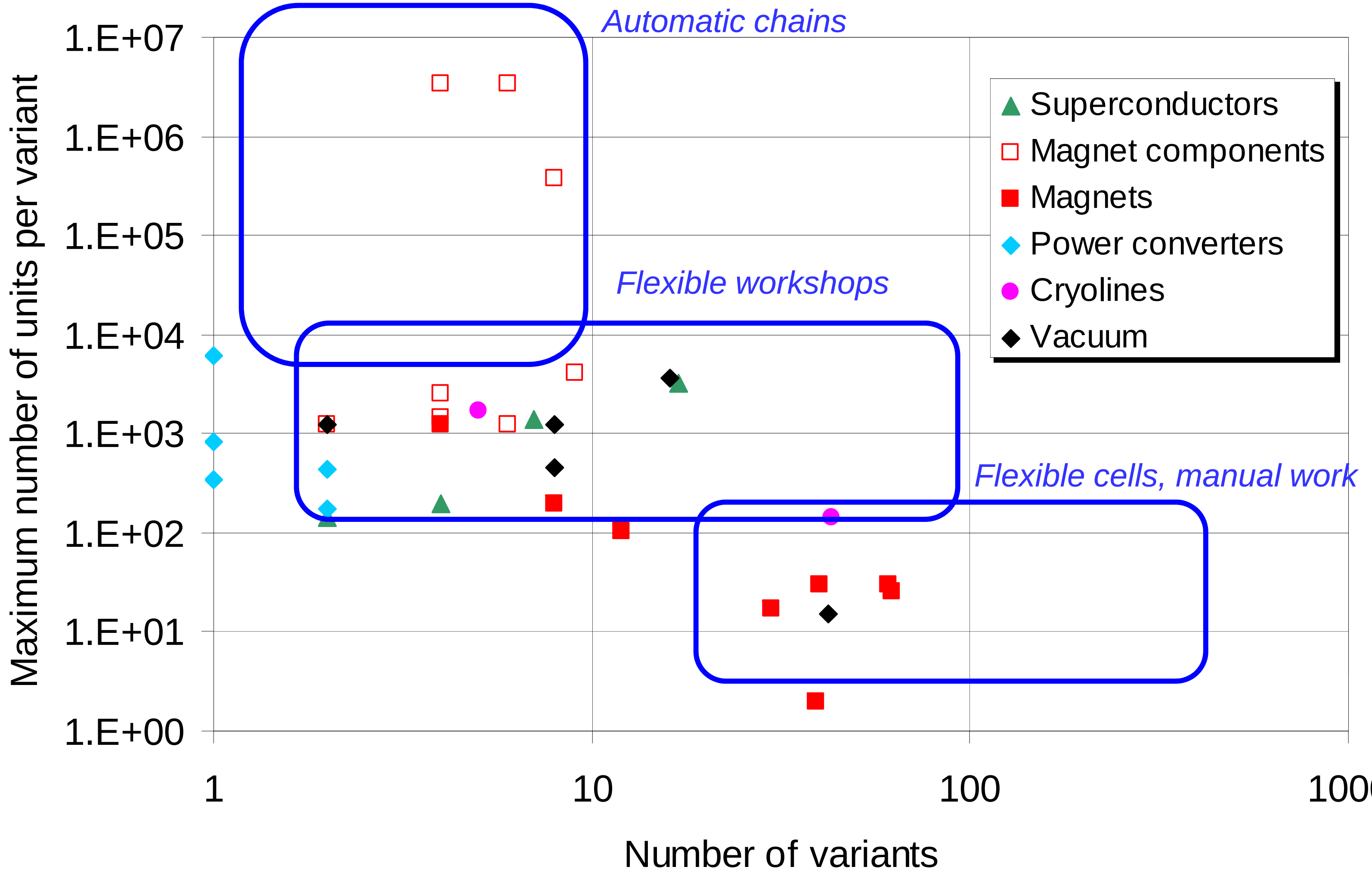
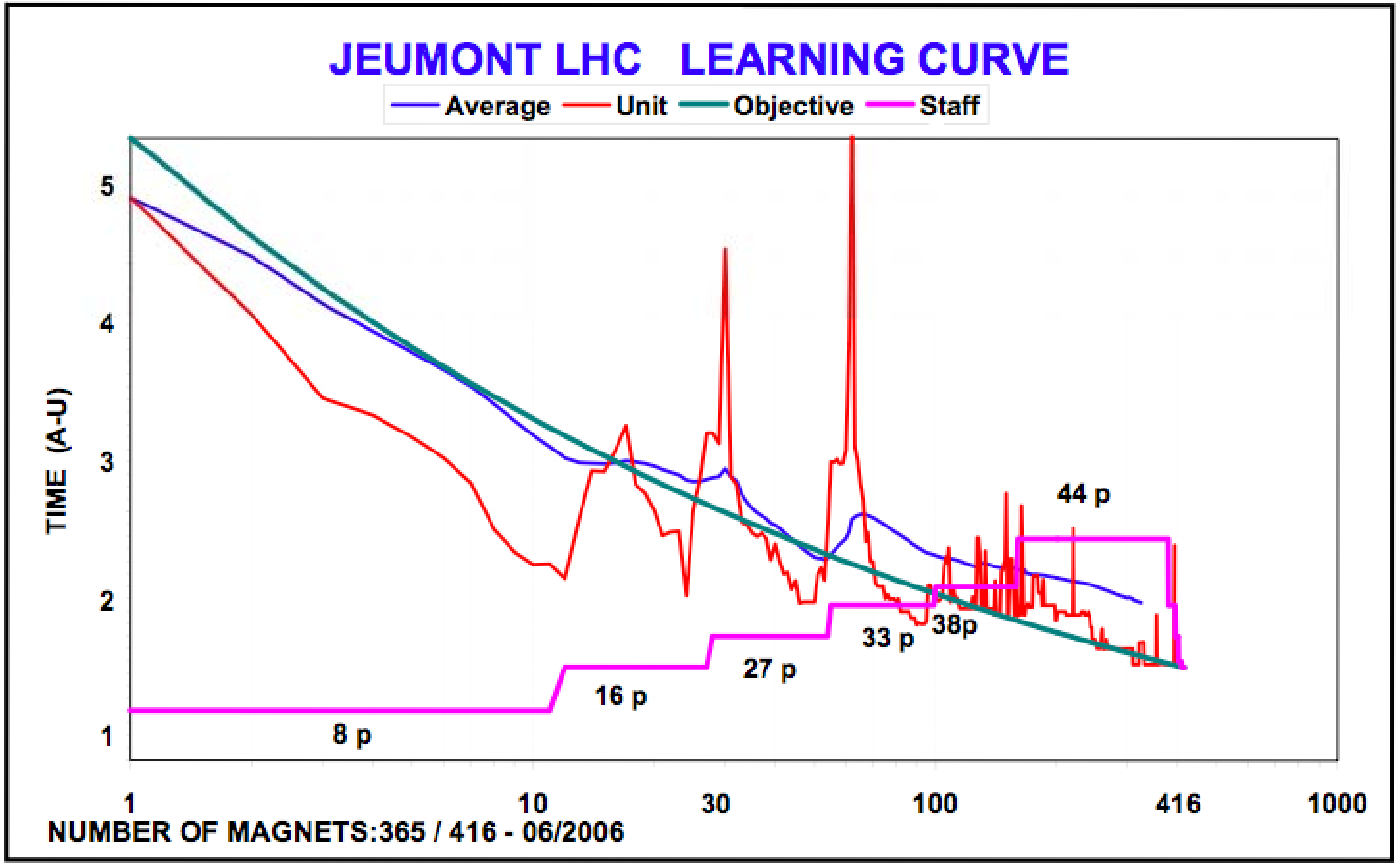


Courtesy of Ph. Lebrun

9 0 main supply contracts WORLDWIDE

PERSONNEL TRAINING IN COIL PRODUCTION

Courtesy of Jeumont, France



LHC: Learning Curve Collared Coil Production

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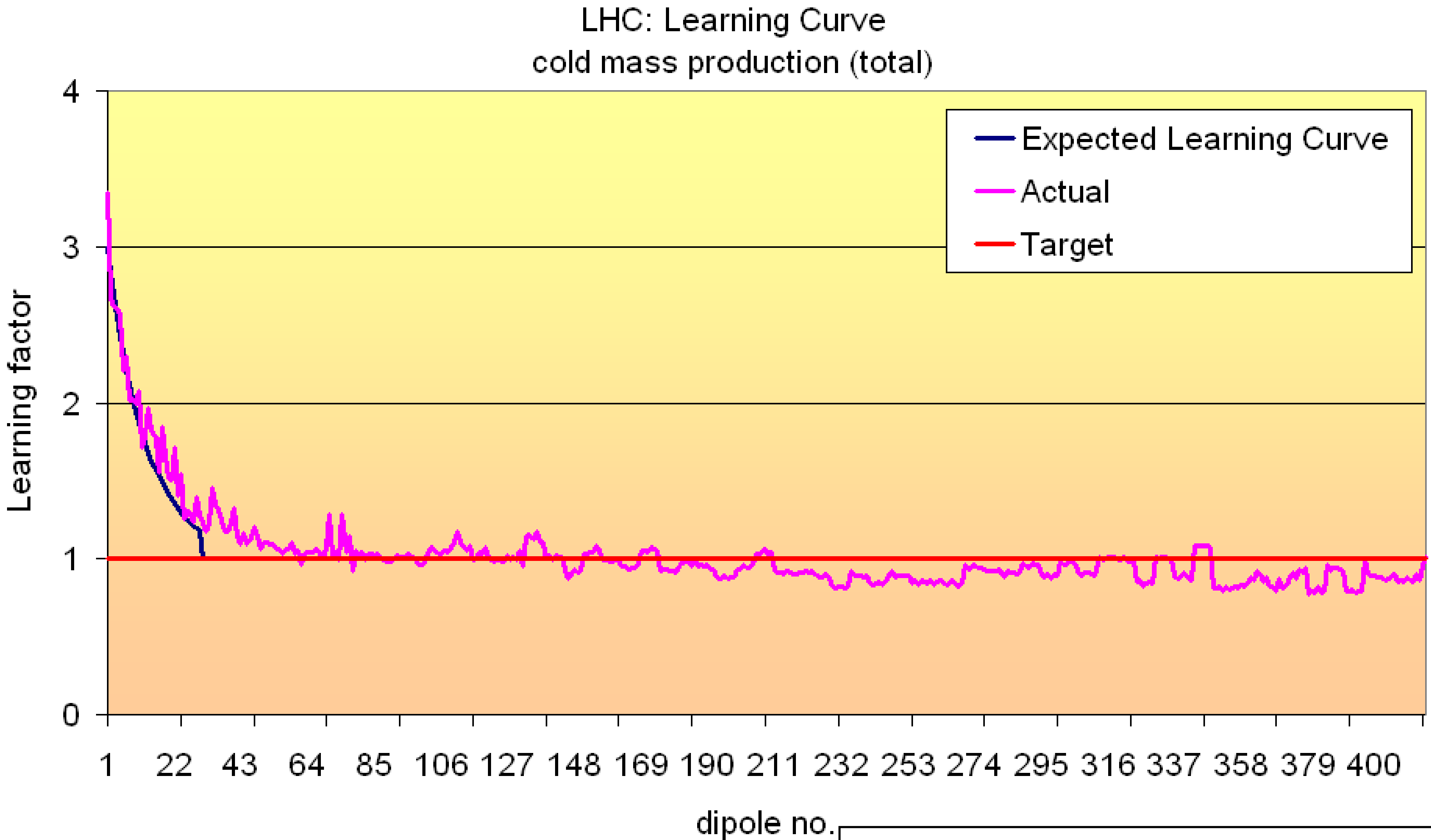

Courtesy of Babcock Noell, Germany

LOG LINEAR MODEL LEARNING CURVES: FIRM 3 (ANALYSIS BY CERN)

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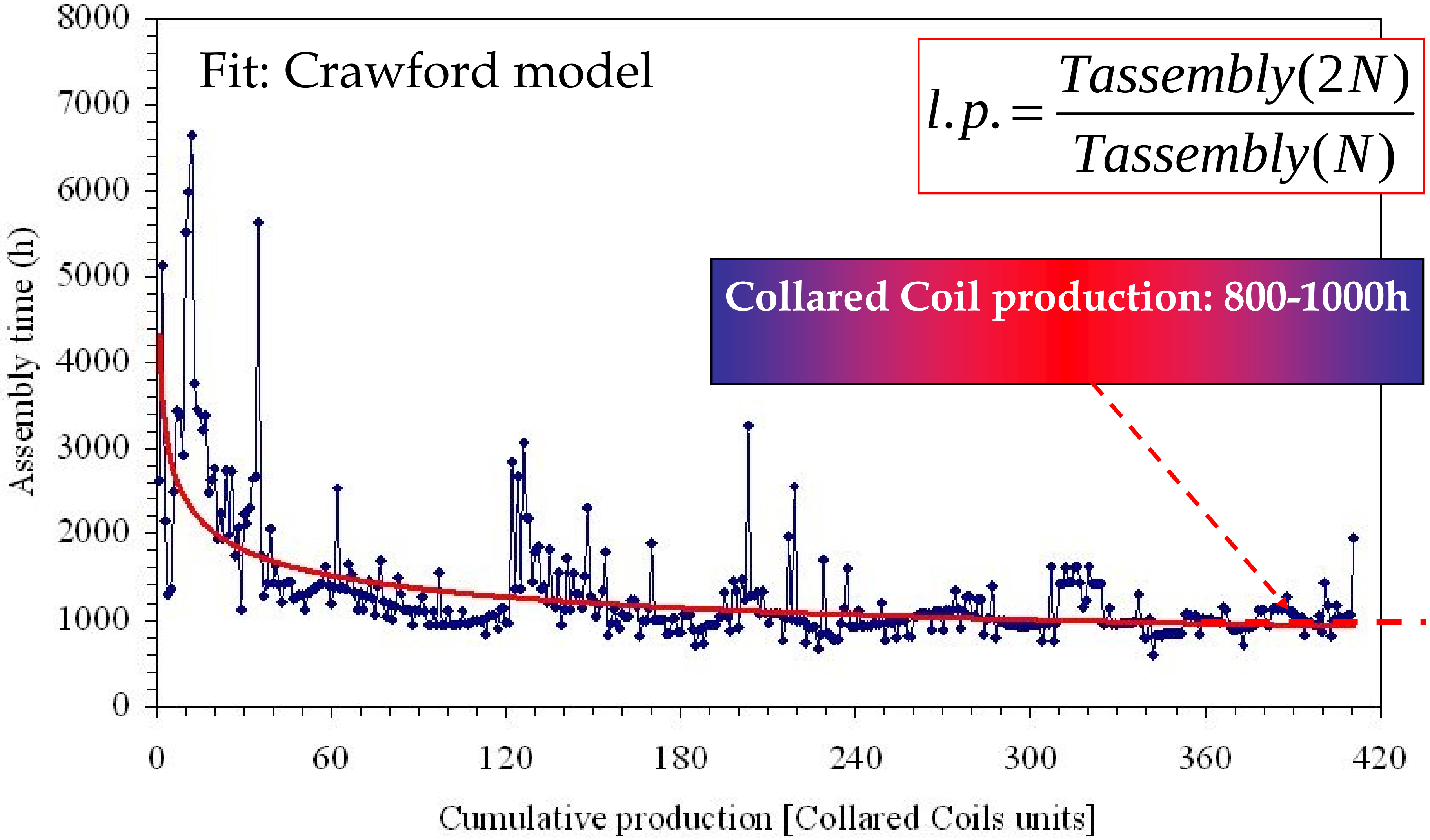

$$l.p. = \frac{Tassembly(2N)}{Tassembly(N)}$$

Work done with P. Fessia

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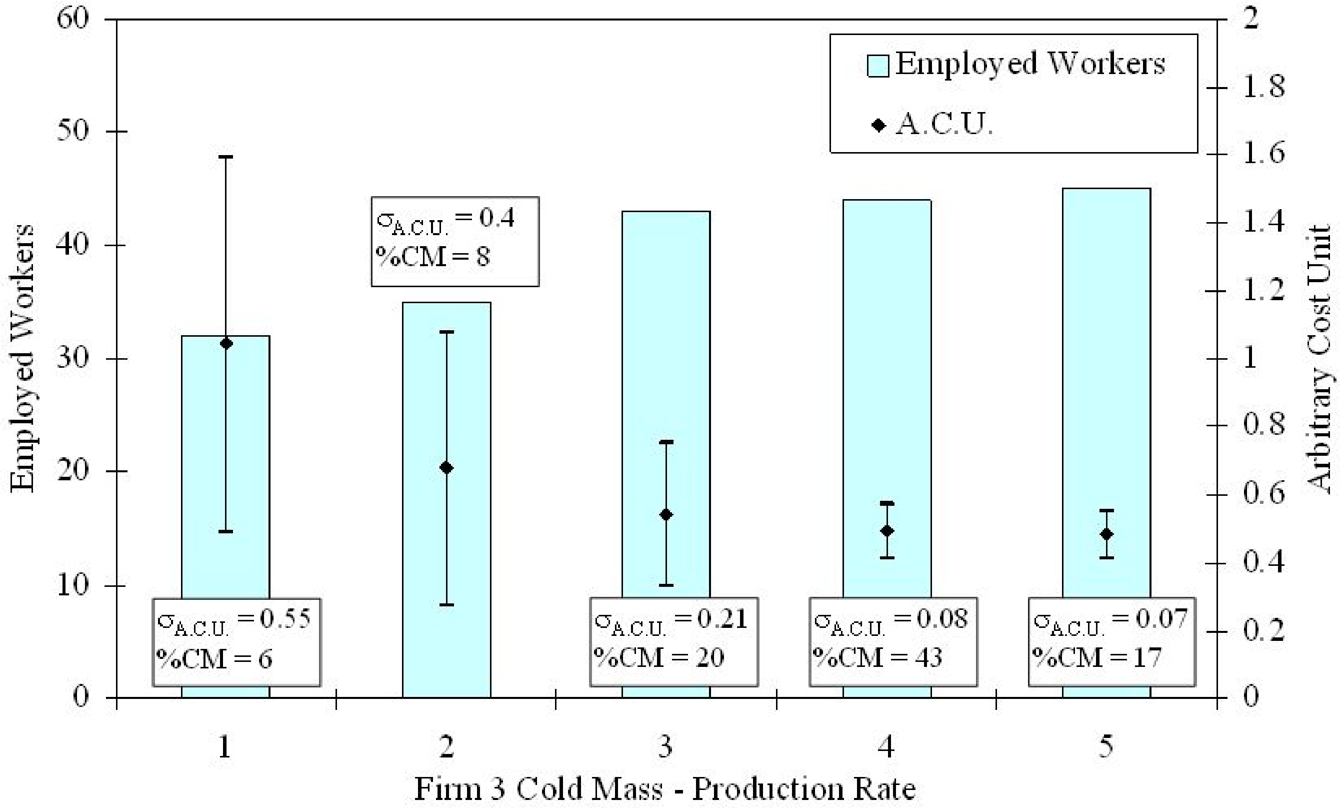
Comparison
WITH OTHER INDUSTRIES

Industry	ρ
Complex machine tools for new models	75%-85%
Repetitive electrical operations	75%-85%
Shipbuilding	80%-85%
LHC magnets	80%-85%
RHIC	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%

LHC Main Dipoles

Number of tooling
NUMBER OF FIRM

- The number of tooling has been correct (the goal was 3-4/week per company
- Less companies (for example 2 instead of three) would not have lessened significantly the unit price and would have led to high risk



Dipole Performance

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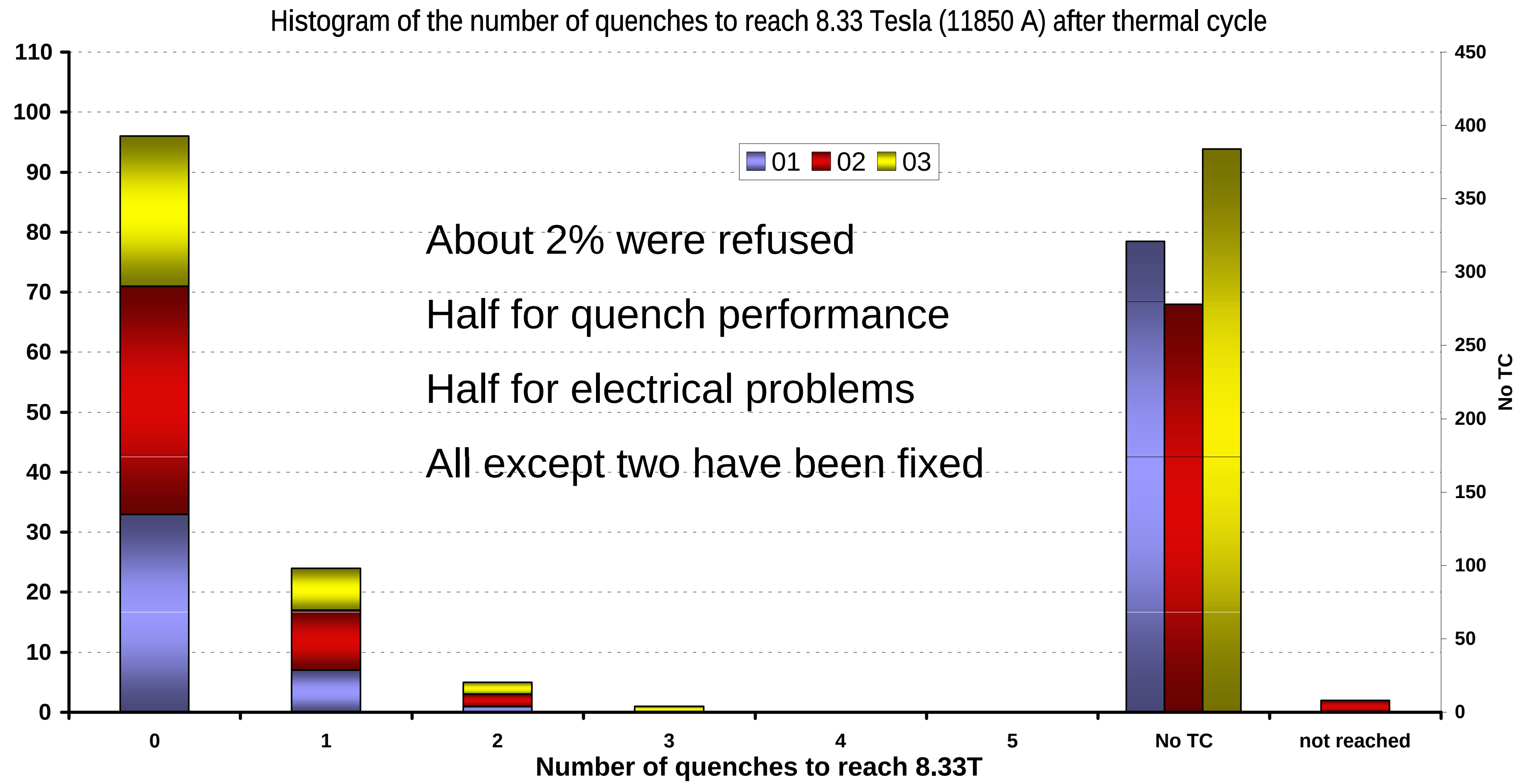

The great success: the dipole delivery

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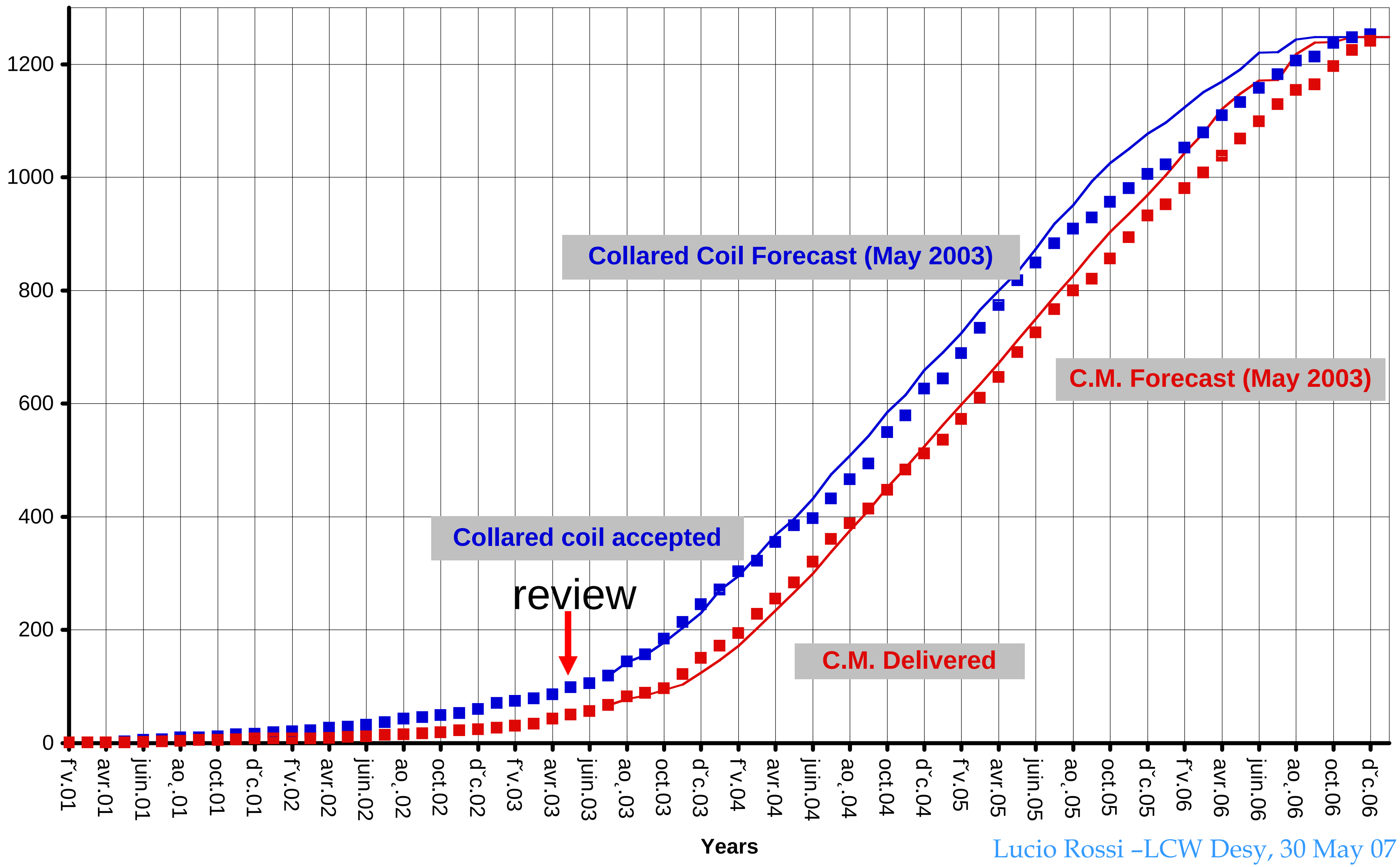
Total CC and C.M. Delivery Schedule (December 1st 2006)



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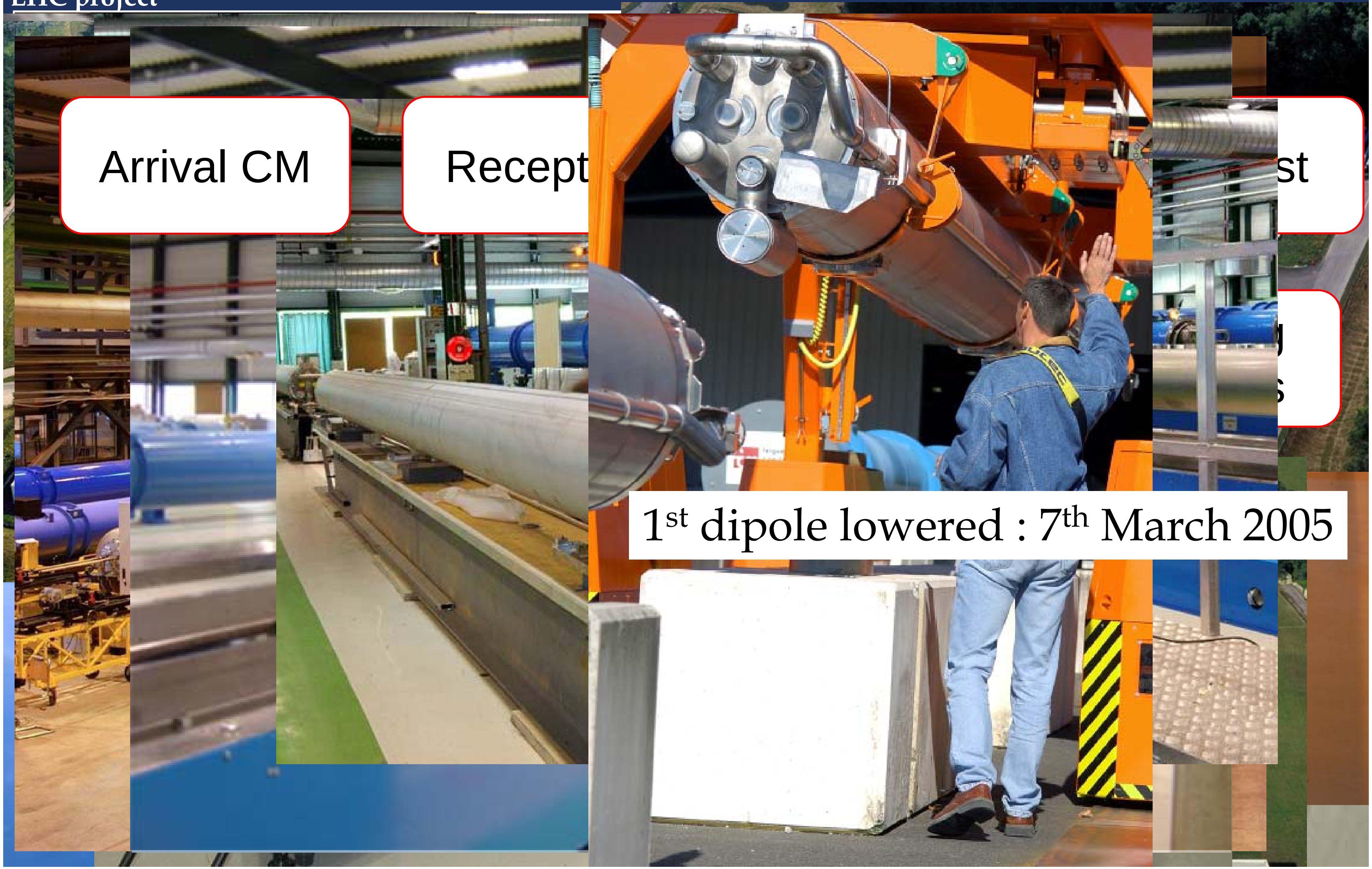
Magnet work flow at CERN before beam test



1st dipole lowered : 7th March 2005

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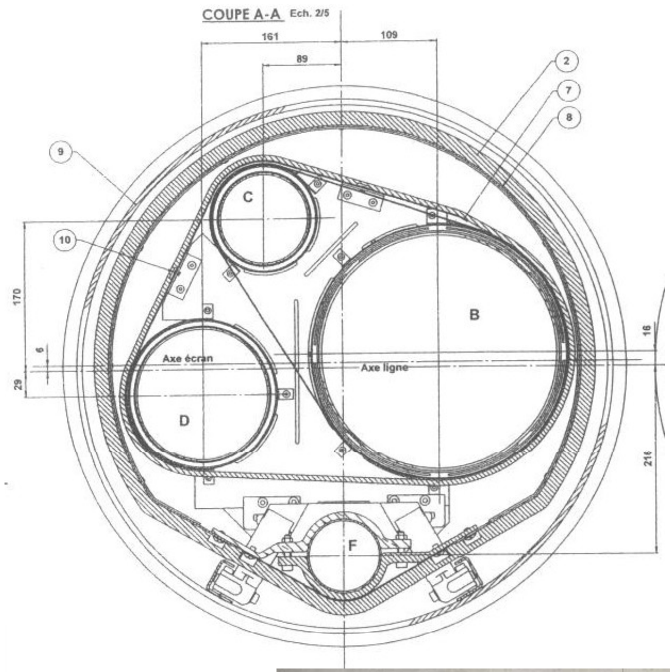
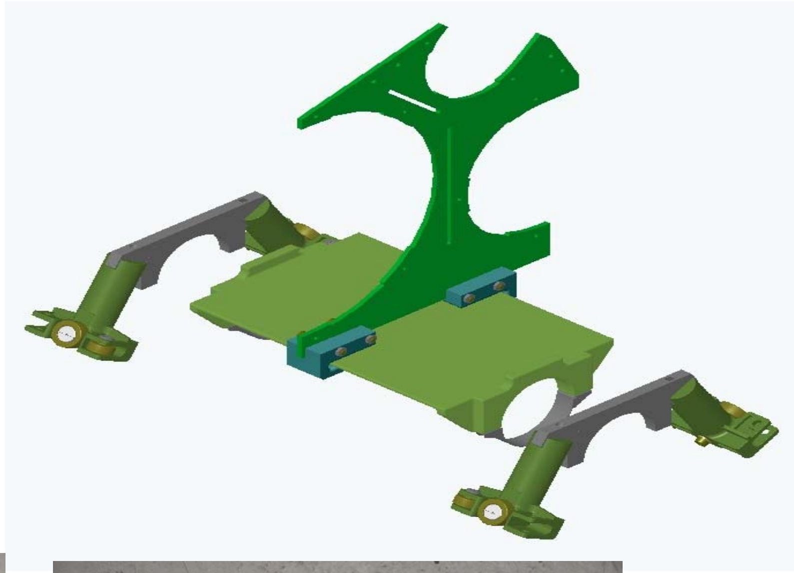
Turn-key contracts and setbacks: QRL also here industrialization path,?

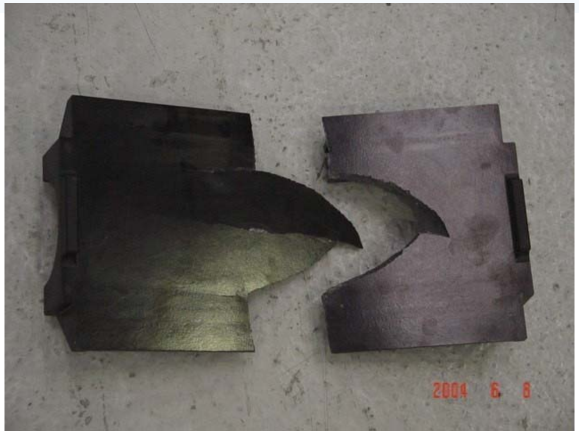
- In Dec 2001 the contract to single supplier awarded to Air Liquide
- Installation started 21 July 2003
- Suspended after a few months: conflicts between AL and subcontractors
- Re-started in spring 2004 and then suspended in May for leaks, when a good part of 7-8 was already installed. The delays were already consistent
- Endoscopic examination in June 2004 revealed broken support. Work were stopped

QRL

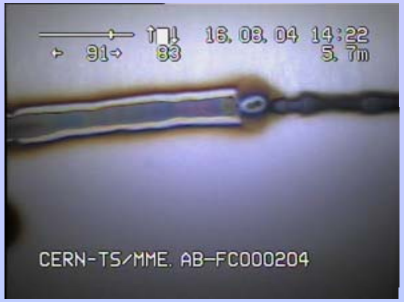
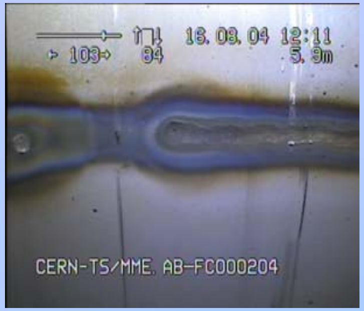
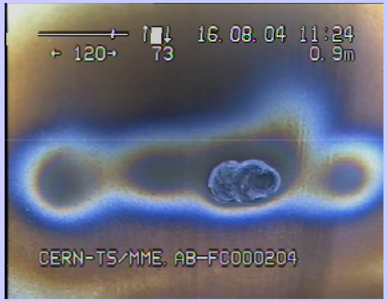
Sliding table







Welding defects – inspection of 18 service modules in August 2004

	Temper colour 100 %		Scaled surface 100 %
	End crater pipe 100 %		Root concavity 30 %
	Root porosity 50 %		Incomplete root penetration 45 %

Inspections of other elements at CERN and at factory will continue

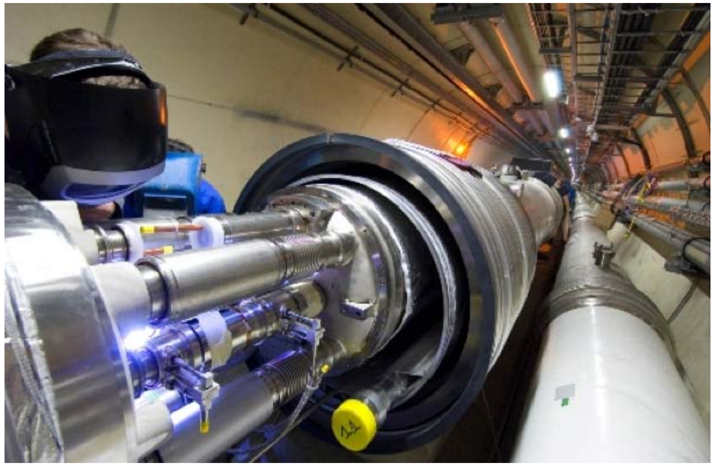
QRL handled

- The company, near to drop the contract, has re-committed itself to the project.
- CERN took over the dismounting, repair and re-installation for all 7-8
- CERN has supported follow in subcontracting and coped (also financially) in a high rate plan to catch up the delays.
- AL and CERN has reviewed all design (tables, weldings, alignment, bellow instability, etc.)
- **The first octant completed 1.8 months delay**
- **The last "only" less than 1 year in delay**
- However the consequence are still there (for example the ICs team was widely "diverted" to QRL repair and then IC did not start with the wanted quality. The rate requested for installation and IC has been double than foreseen

For magnets work is not finished: we are still "learning" on IC

LHC project

- Late start, accelerated rate
- 200 people in the tunnel
  - 100 contractor
  - 100 CERN+associated for managing, QA, repair, in-sourcing of special WPs
- Also in the IC we are observing a learning curve similar to MB construction
  - 1.5 year the first octant
  - Less than 6 months for the last one.



BUT… THE BEST IS BEHIND US

LHC project