Largest of the Rings
LHC Past, Present and Future

L. Bottura

CERN Centennial Superconductivity Symposium
The Roots of the LHC Technology
December 8th, 2011

Outline

- The LHC pre-history
- The making of the LHC
- Long live the LHC !
- Is there life after the LHC ?

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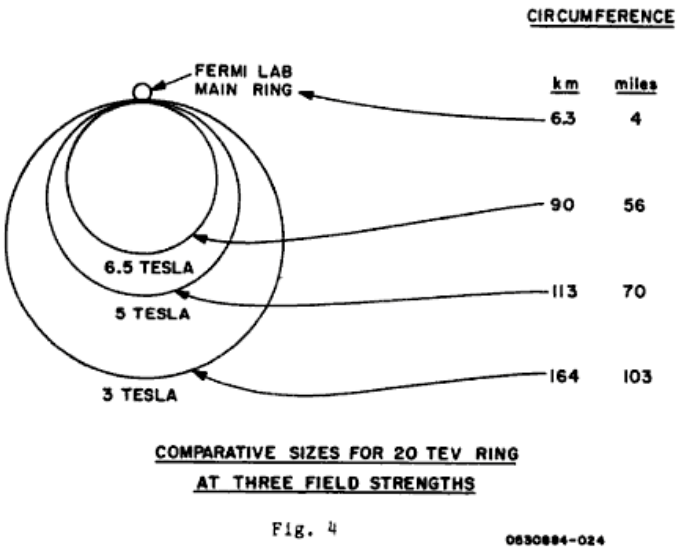
L. Rossi, *Superconductivity and the LHC: the early days*, CERN Courier, **51**(9), November 2011, pp.21-27

1984…

Big Brother is in full control and rules



The National Reference Design Study (RDS) for a 20 TeV proton machine, hosted by LBNL, DOE recommends proceeding with R&D for a **Sine-qua-non Accelerator** (the **SSC**)

Diego Maradona goes to **SSC**

(Societa' Sportiva Calcio) Napoli from FC Barcelona for a ridiculous 13.5 billions Lire

1984 ECFA – Lausanne

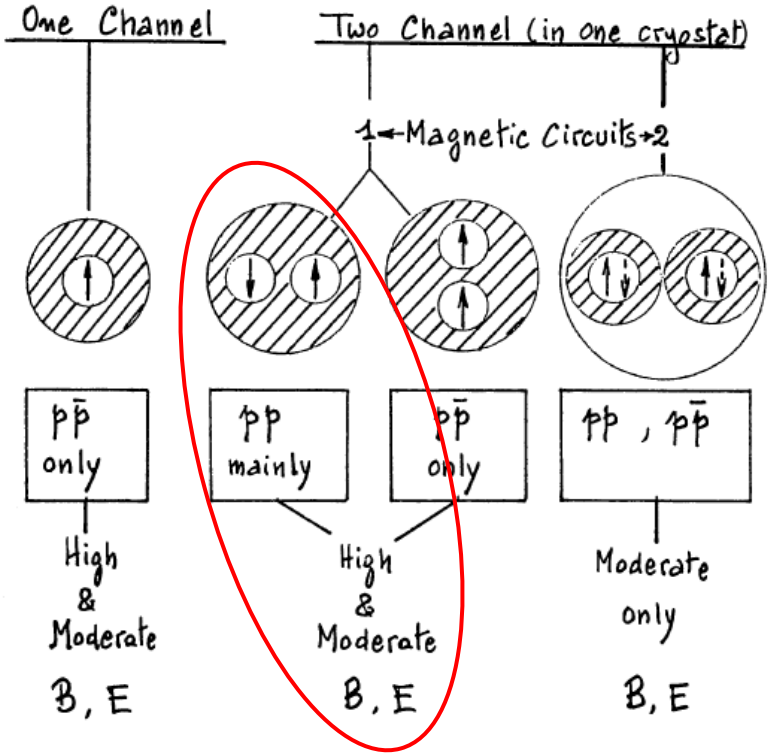
G. Brianti

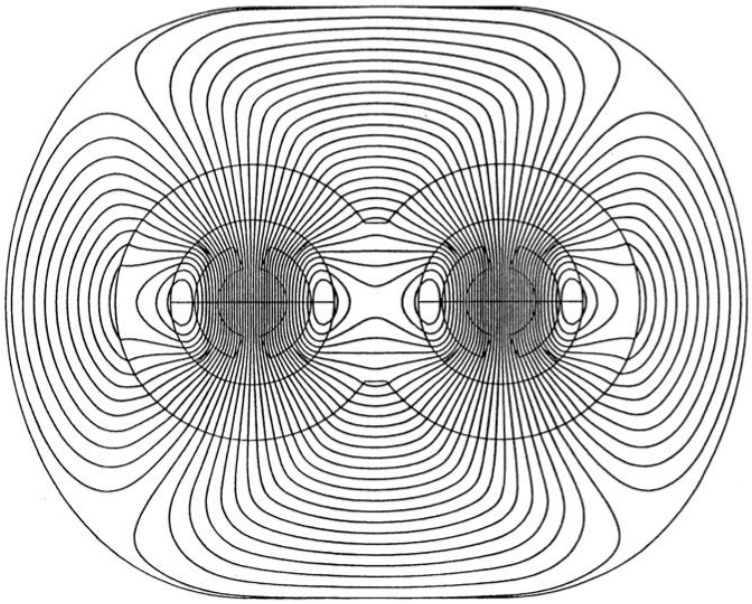
CERN COURIER

Sep 19, 2008

Early days: Lausanne LHC workshop (archive)

In March 1984 a major workshop provided a chance to look to the next step beyond the construction and exploitation of LEP.

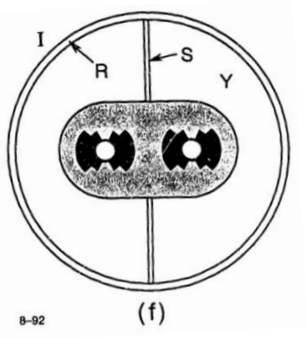




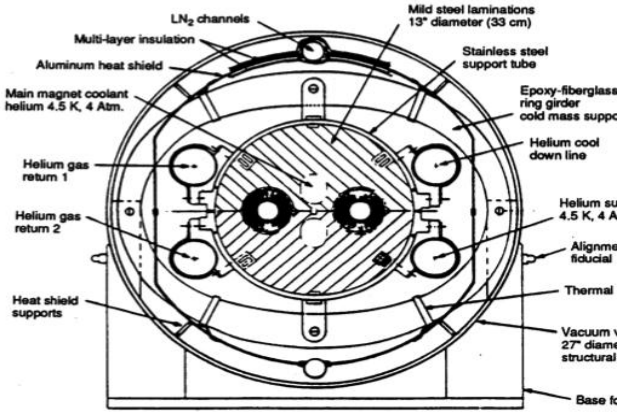
CERN 87-05, G. Brianti and K. Hubner Ed.

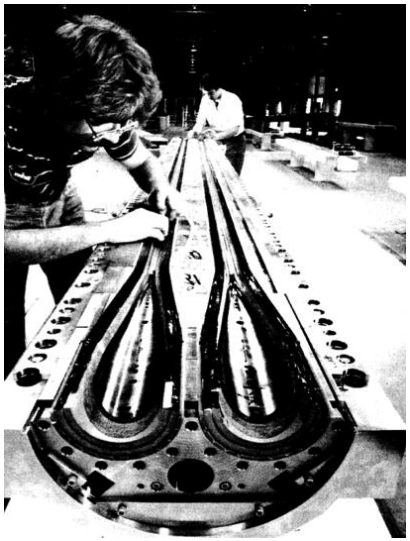
Earlier traces of the *two-in-one* concept

John P. Blewett, 1971

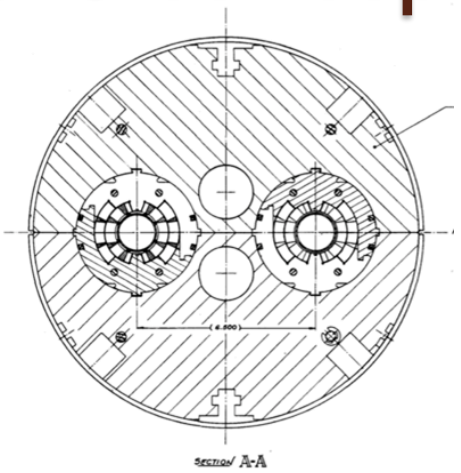


SSC high field option





Assembly work at BNL



Per F. Dahl, The SSC Dipole: Its Conceptual Origin and Early Design History, SSCL-320, 1990

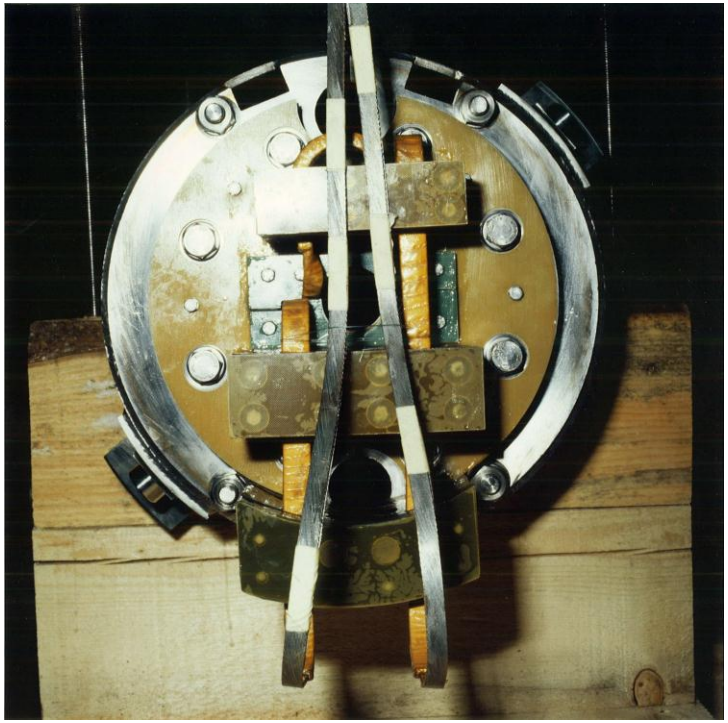
Robert B. Palmer, Superconducting Accelerator Magnets: A Review of their Design and Training, ICHEP 92, SLAC-PUB-5899, 1992

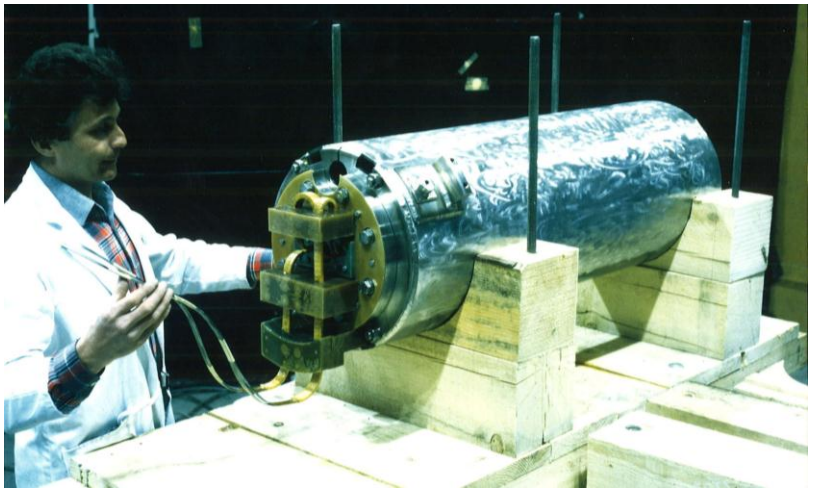
SSC vs. LHC

- G. Brianti had various reasons for *headaches* in the race of the two projects:
  - The existing LEP tunnel imposed a given radius and cross sectional space to the new accelerator – Field !
  - The missing factor in energy (8.5+8.5 TeV for LHC vs. 20+20 TeV for SSC) needed to be compensated by a higher luminosity (design value of 10^{34} 1/cm^2 s for LHC vs. 10^{33} 1/cm^2 s for SSC) – Aperture and quality !
- R&D focus was the key !
  - **High field**: aim at 8 to 10 T bore field
  - **Two-in-one**: to gain space in the crammed tunnel space for the widest possible magnet bore

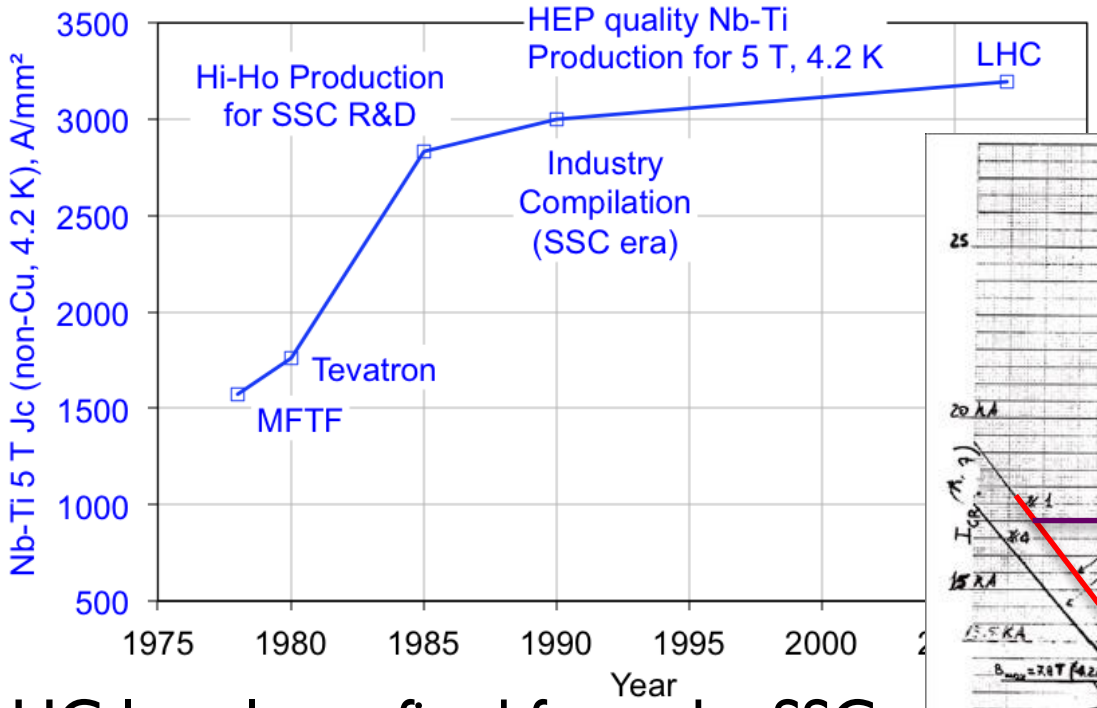
High field – NbTi

- **1987** – R. Perin and D. Leroy built with Ansaldo Componenti a 1-m single aperture model using a 12.6 mm wide Nb-Ti cable
- **1988** – The model magnet reached 8.55 T at the first quench and 9.3 T at 1.6 K in 4 quenches

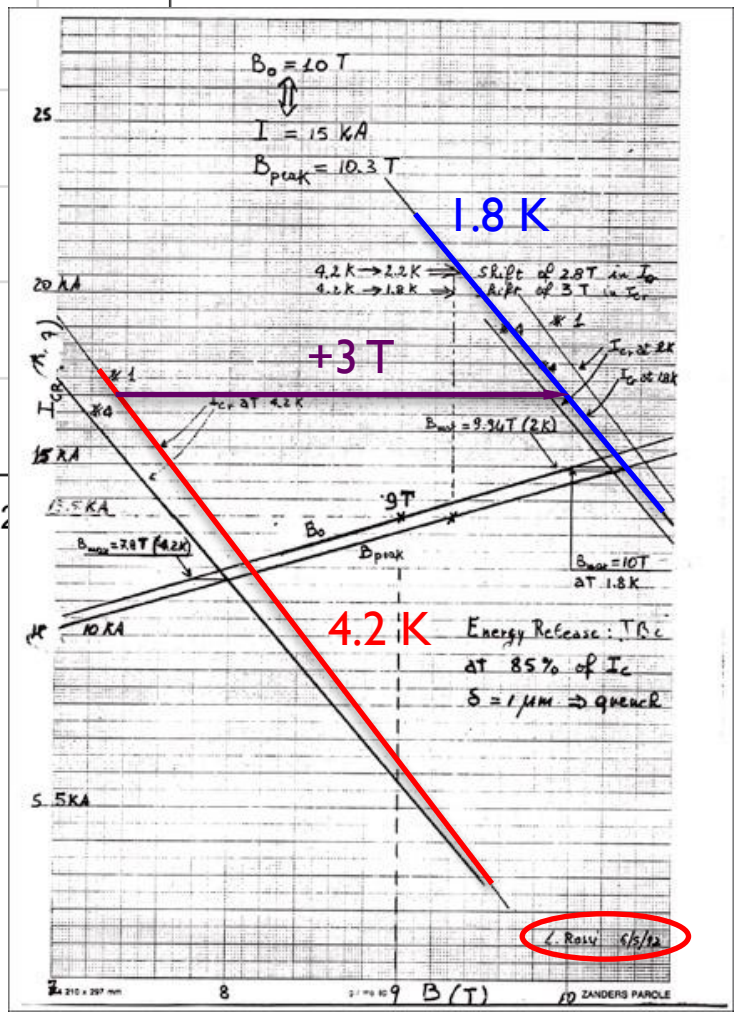




NbTi and superfluid helium



Measurement of Ic of an LHC cable by M. Garber (BNL), 1992



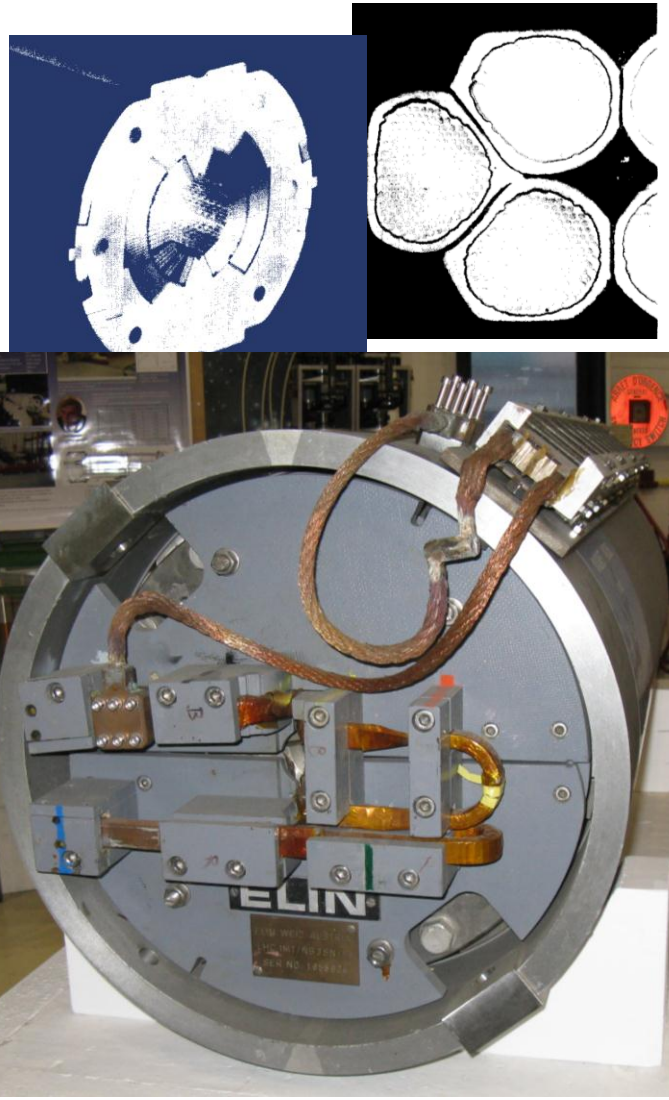
LHC largely profited from the SSC R&D on NbTi for both the critical current (3000 A/mm^2) and the filament diameter (5 to 10 μm)

Still, superfluid He was a must !

High field – Nb_3Sn

- **1989** – A. Asner built with Elin (AT) a 1 m single aperture model using a 17 mm cable and the *wind-and-react* technique
- The magnet reached 9.5 T at 4.3 K, and was re-tested after 8 months, reaching 9.5 T after two quenches
- A single coil in mirror configuration reached 10.1 T, breaking the barrier of 100 kGauss

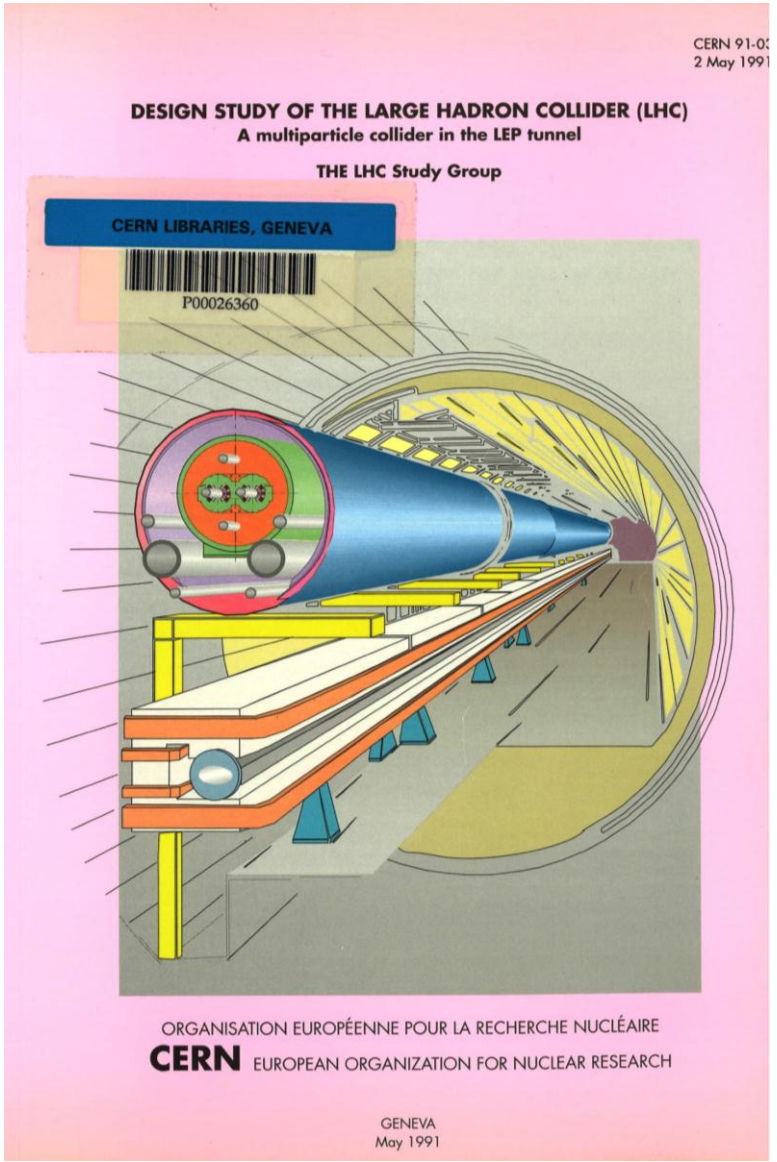
Cable edge
VAC bronze wire



S. Wenger, F. Zerobin, A. Asner,, IEEE Trans. Mag. 25(2), 1989, pp. 1636-1639

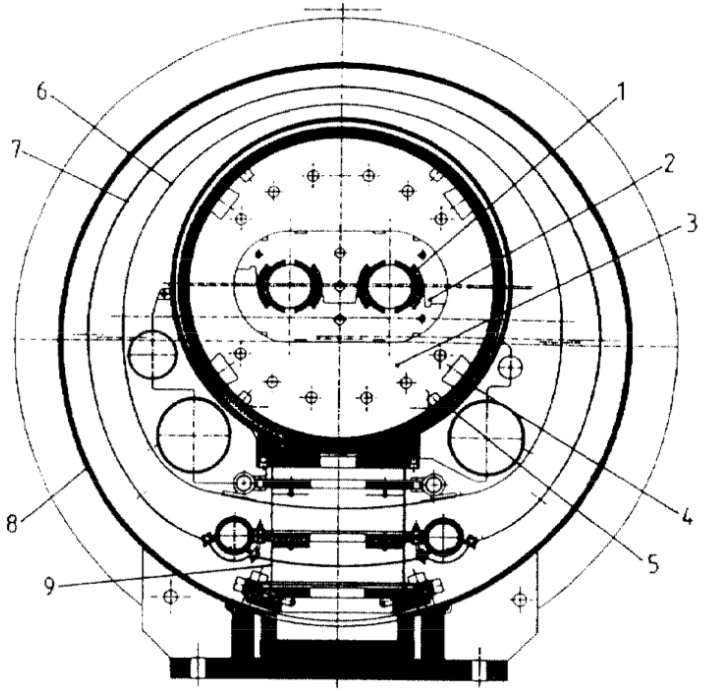
Commit !

- **1991** – LHC Pink Book the decision was taken to use the *more conservative* technology:
  - NbTi twin aperture, fully coupled magnets
  - Cooled over the whole length by superfluid helium at 1.9 K
- 1-m Models Twin Aperture (MTA) program addressing *twin aperture* features
- Twin Aperture (long) Prototype (TAP) program addressing *cooling of long magnets at 1.9 K*

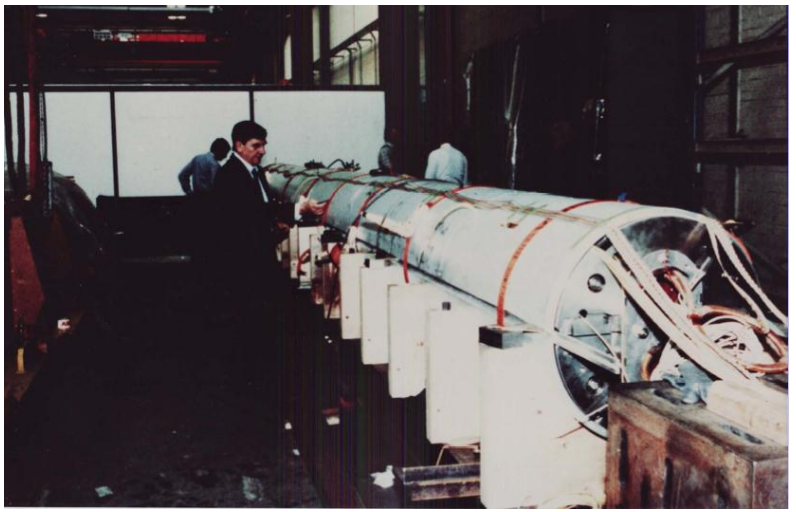


TAP program

- Construction at ABB (cold mass) and FBM-Hudson (cryostat) of a twin aperture magnet using HERA-style coils (ABB cable) under the leadership of J. Vlogaert and Ph. Lebrun
- **1992** – Tests at CEN Saclay, the magnet reaches 5.8 T at 4.3 K and **8.3 T at 1.8 K**



D. Granier, et al., *Performance of the Twin-Aperture Dipole for the CERN LHC*, Proc. EPAC 1992, pp. 1414-1416



MTA program

- **1993** – All models (including KEK models) reached rapidly the expected 8 T range at 4.3 K
- However, at 1.9 K they fell short of the *promised 10 T land*, requiring long training to exceed the 9 T mark
- In perspective, this was still 90 % to 95 % of the *short sample limit*, well above the practical operating point of 80 % of short sample, i.e. a **badly sold success**

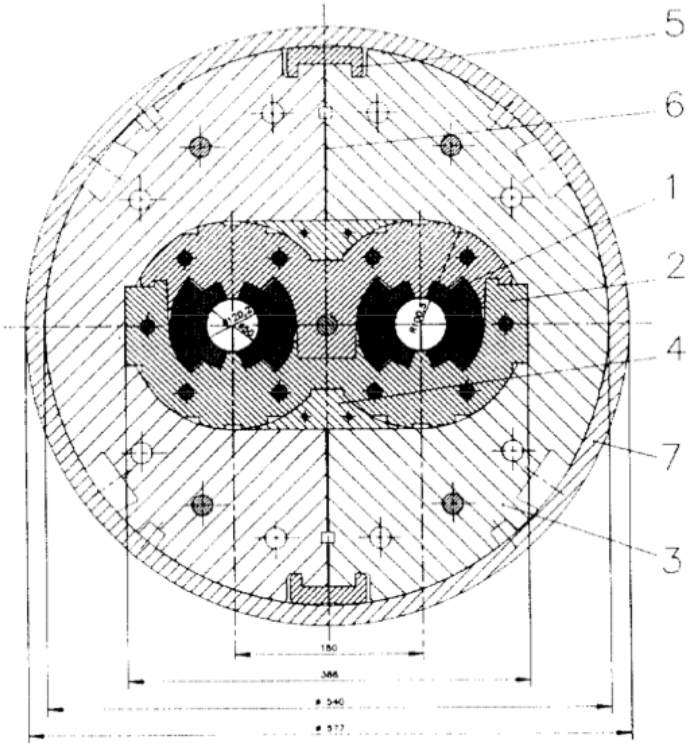
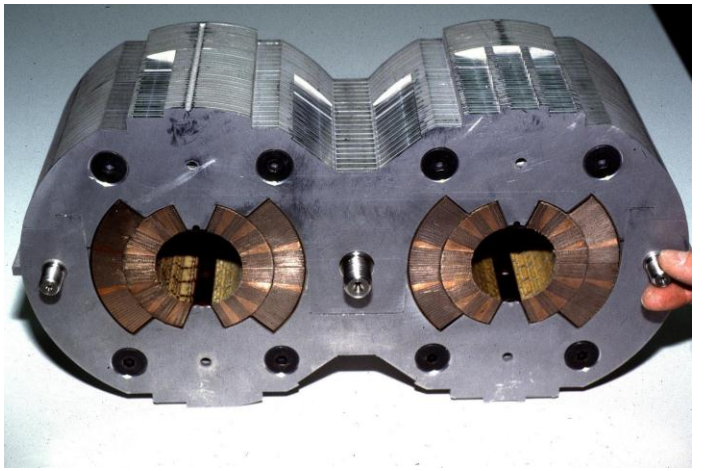


Fig. 1 - Cross-section of the LHC twin-aperture dipole
1. Coils, 2. Al collars, 3. Yoke, 4. Iron insert, 5. Clamp, 6. Gap, 7. Outer shrinking cylinder

D. Leroy and R. Perin, *Development of High-Field Superconducting Magnets for the Large Hadron Collider*, Proc. EPAC 1990, pp. 326-328

LHC prototypes

17 mm Nb-Ti cable in two grades
6 blocks design
Al collars



- **1988** – CERN-INFN Agreement for the development of full-size (10 m), twin aperture prototypes (G. Bellini, E. Acerbi, L. Rossi at INFN, M. Bona at CERN)
- **1989** – Order placed by INFN to Ansaldo Componenti (IT) for the production of two prototypes (MTP1Ax, aka CERN-INFNx), followed by a CERN order for a third prototype (MTP1A3)
- **1990** – Orders placed by CERN at three more EU producers (Noell, Alstom-Jeumont, Elin-Holec)

BABCOCK NOELL

ASG Superconductors

ALSTOM

ELIN AUSTRIA

From SSC to *Desertron* to oblivion

- **1989** – Superconducting Super Collider (SSC) Laboratory established in Texas
- **1991** – Major construction start. Seventeen shafts sunk and 23.5 km (14.6 mi) of tunnel by late 1993
- **1987** – Heated debate on cost. Estimate of 4.4 B$ strongly supported by the Texas representative at Congress
- **1993** – Cost projection reaches 12 B$, similar to the ISS. Strong criticism triggered an audit from DOE
- **October 1993** – Congress cancels the project, after 2 B$ were spent in the program

Construction site

Main shaft

SSC buildings

Sun-Journal, Lewiston, Maine, Friday, October 22, 1993

Congress officially kills super collider project

By MICHELLE MITTELSTADT
Associated Press Writer

WASHINGTON — Congress officially killed the super collider Thursday, halting construction on the giant science machine that was one-fifth complete at a cost of $2 billion.

The $640 million sought by the Clinton administration to continue construction this year will be used

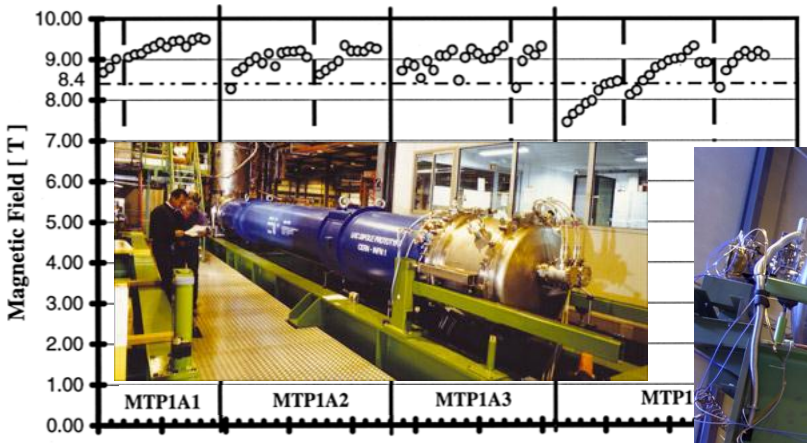
vacuum left by tunneling for the atom smasher.

"Right now, it's a billion-dollar hole in the ground. And they're arguing about whether to fill it back up," said Allan Oakley, a Waxahachie police officer and co-owner of the Kountry Cafe in nearby Maypearl. "People here have a hard time understanding how we could spend so much money and not follow through."

December 1994 – LHC project approved by the CERN Council

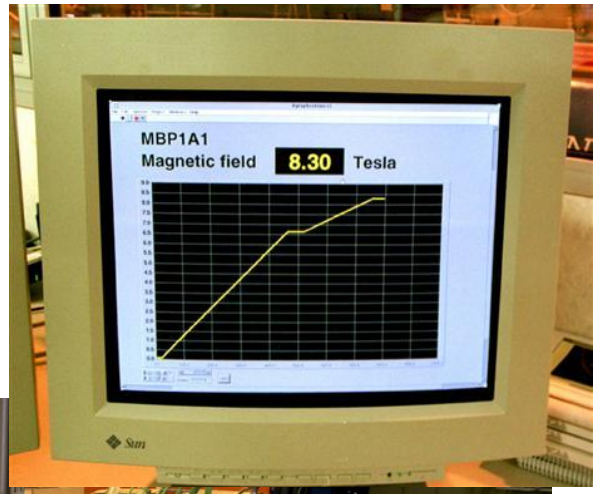
Science, policy and politics

1995 – The CERN-INFN 2 in the background (String-1) of Italian president O. Luigi Scalfaro, between R. Perin (left) and L. Maiani (right)



Training of the first MTP prototypes, from: R. Perin, *Superconducting Magnets*, Proc. PAC 1995, pp. 1282-1287

15 m prototypes



- **1998** – The first 15-m long prototype reaches the LHC nominal operating field

Outline

- The LHC pre-history
- The making of the LHC
- Long live the LHC !
- Is there life after the LHC ?

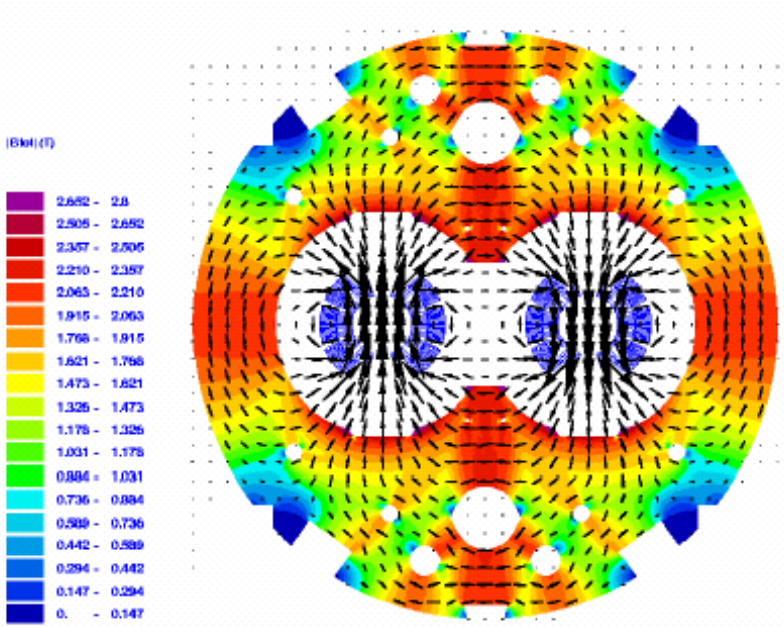
LHC twin-aperture dipole magnets

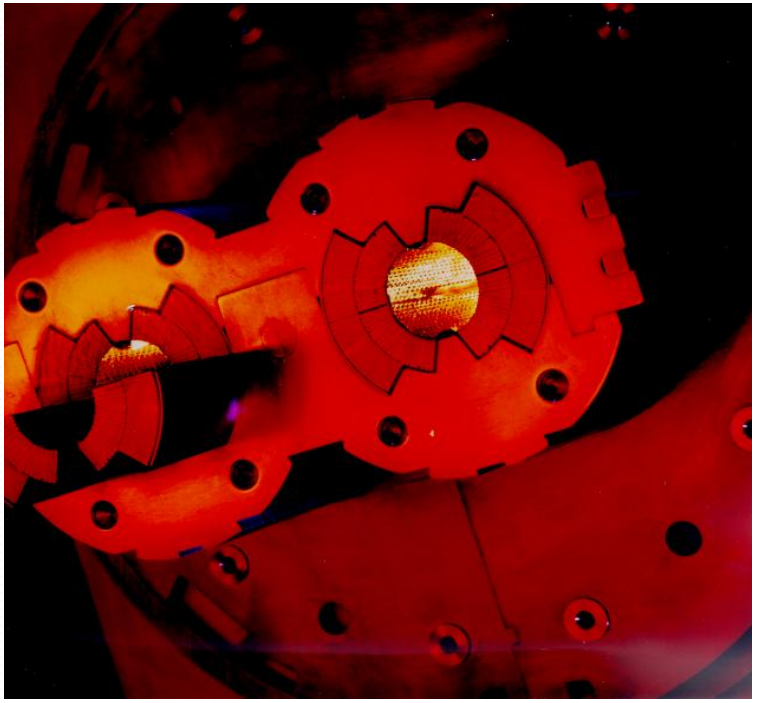
Concept perfected (design), demonstrated (models and prototypes) and realized on a **large industrial scale**

R. Perin

C. Wyss

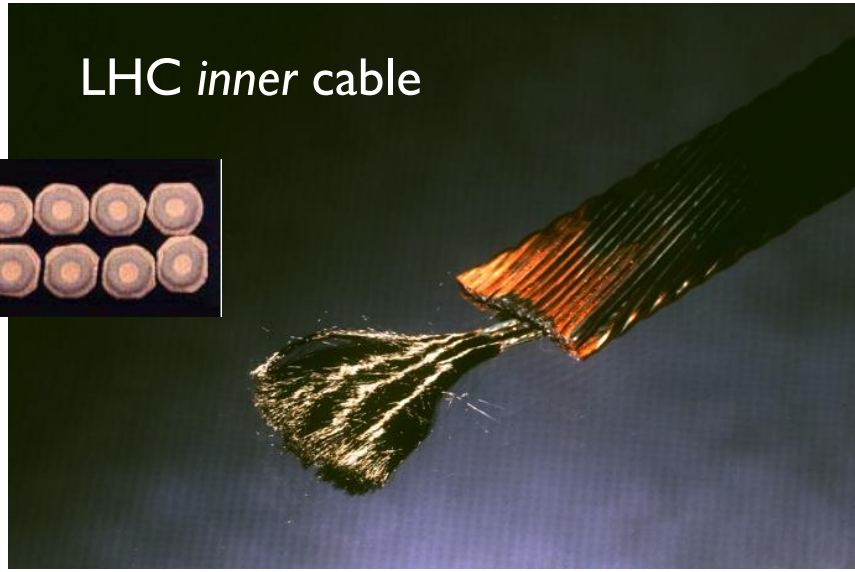
L. Rossi

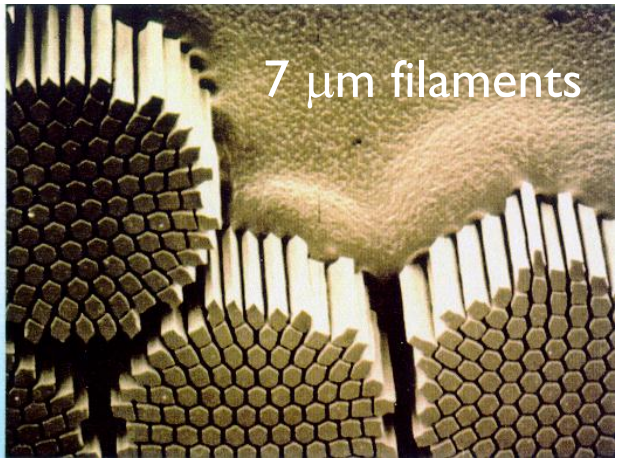




Fine cables

LHC outer cable cross section





Supplier	Number of Cable Maps	Average of ΔM [m T]	σ [m T]	CV [%]
Cable	**01**			
01 B	938	27.06	0.58	2.1
01 E	378	30.81	0.8	2.6
Cable	**02/03**			
02 B	702	21.87	0.42	1.9
02 C	626	22.63	0.48	2.1
02 D	242	20.98	0.21	1.0
02 G	399	21.66	0.33	1.5
02 K	533	21.96	0.27	1.2

6000 billets, 7500 km of superconducting cables with extremely tight property control

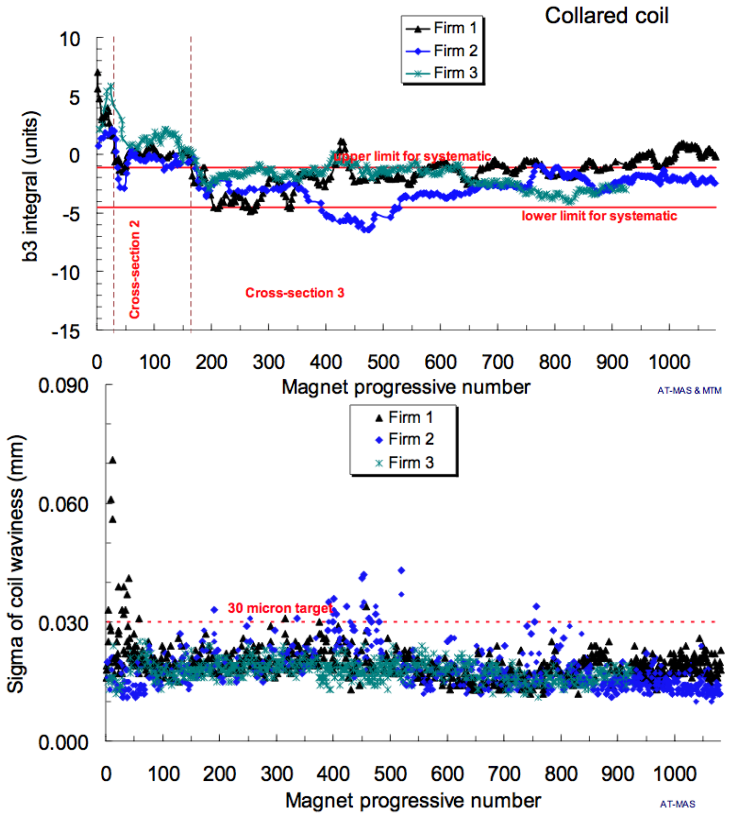
D. Leroy

Supplier	Average Rc [μΩ]	σRc
Cable 01		
01B	43	21
01E	35	16
Cable 02 03		
02B5	122	41
02C0	125	65
02C9	96	41
02D	24	18
02G	40	18
02K	65	23

Stumbling bock for SSC

This is why we can ramp

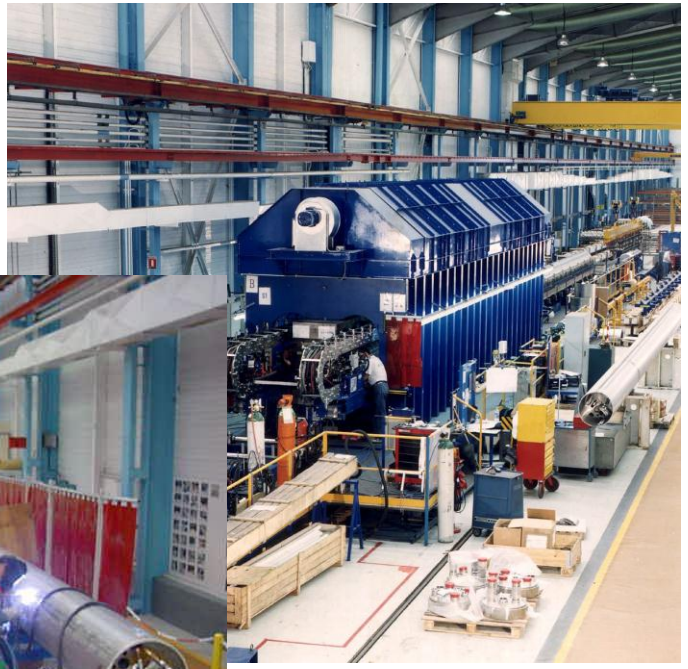
Coil winding



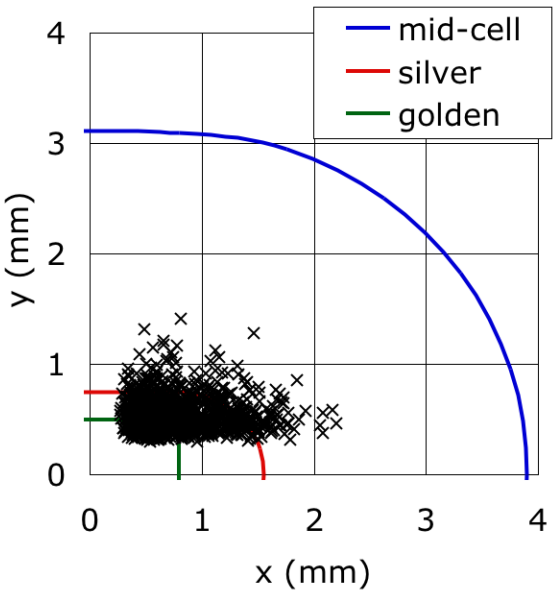
- Tight controls on
  - Winding quality
  - Dimensions (field quality)
- Spectacular precision (typical waviness in the range of 20 μm)

By courtesy of E. Todesco (CERN)

Magnet assembly



Geometry of dipoles



- Industrial process challenges (e.g. welding)
- Tight geometric tolerances
  - Sagitta: 1 mm
  - IC flanges: 0.7 mm
  - Correctors: 0.3 mm

Cryo-magnets and tests

Magnet reception, cryostating, preparation for cold test and "stripping" for installation

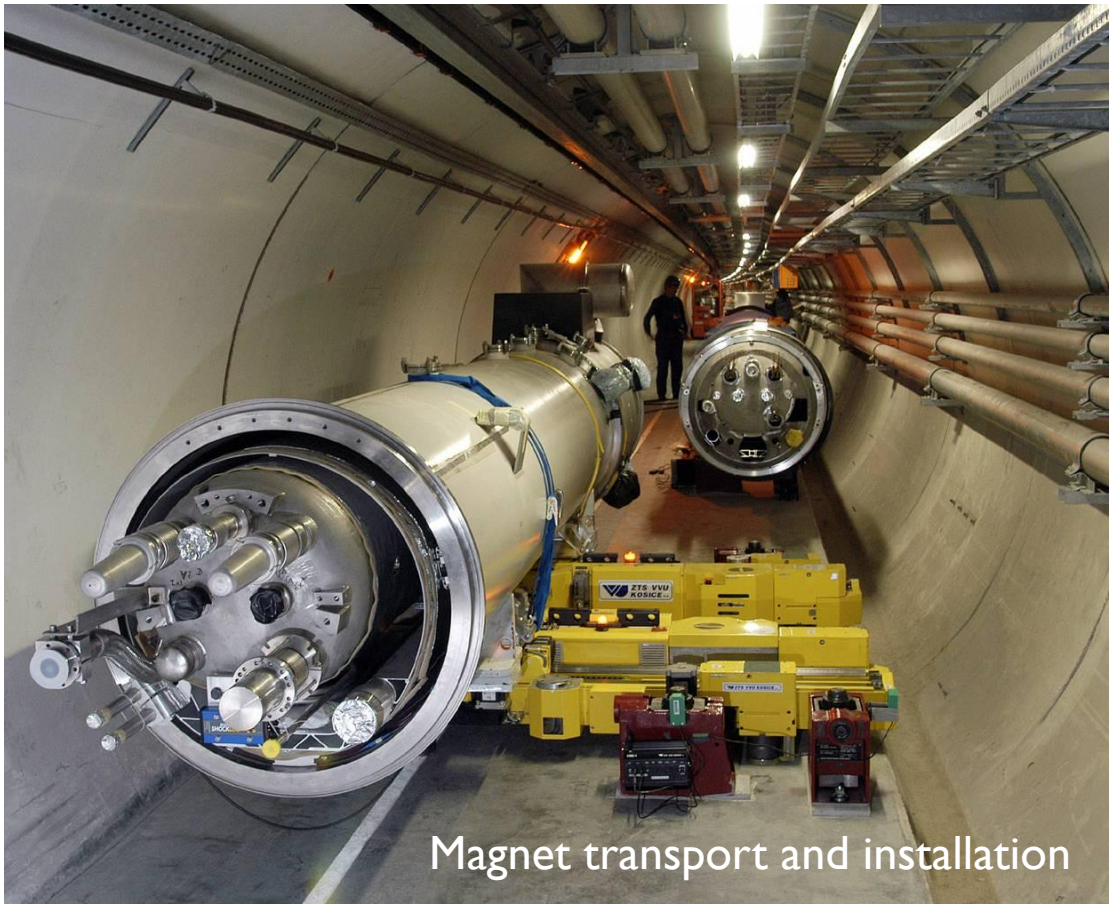
Magnet powering tests and magnetic measurements

- An industrial approach to the laboratory work

Magnet installation

- Logistic and planning

Descent in the tunnel



Magnet transport and installation

Interconnection

65’000 electrical joints

Induction-heated soldering

Ultrasonic welding

Very low resistance

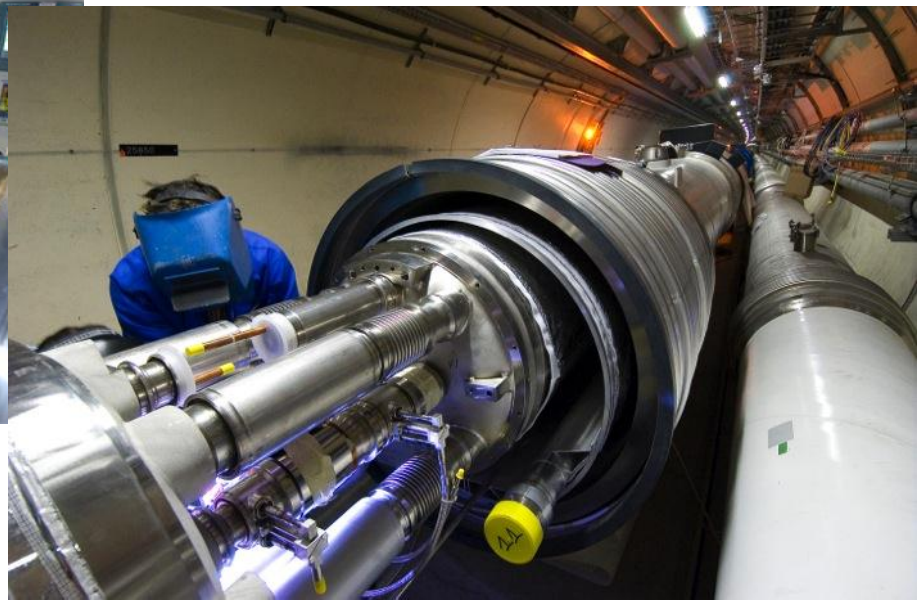
HV electrical insulation

40’000 cryogenic junctions

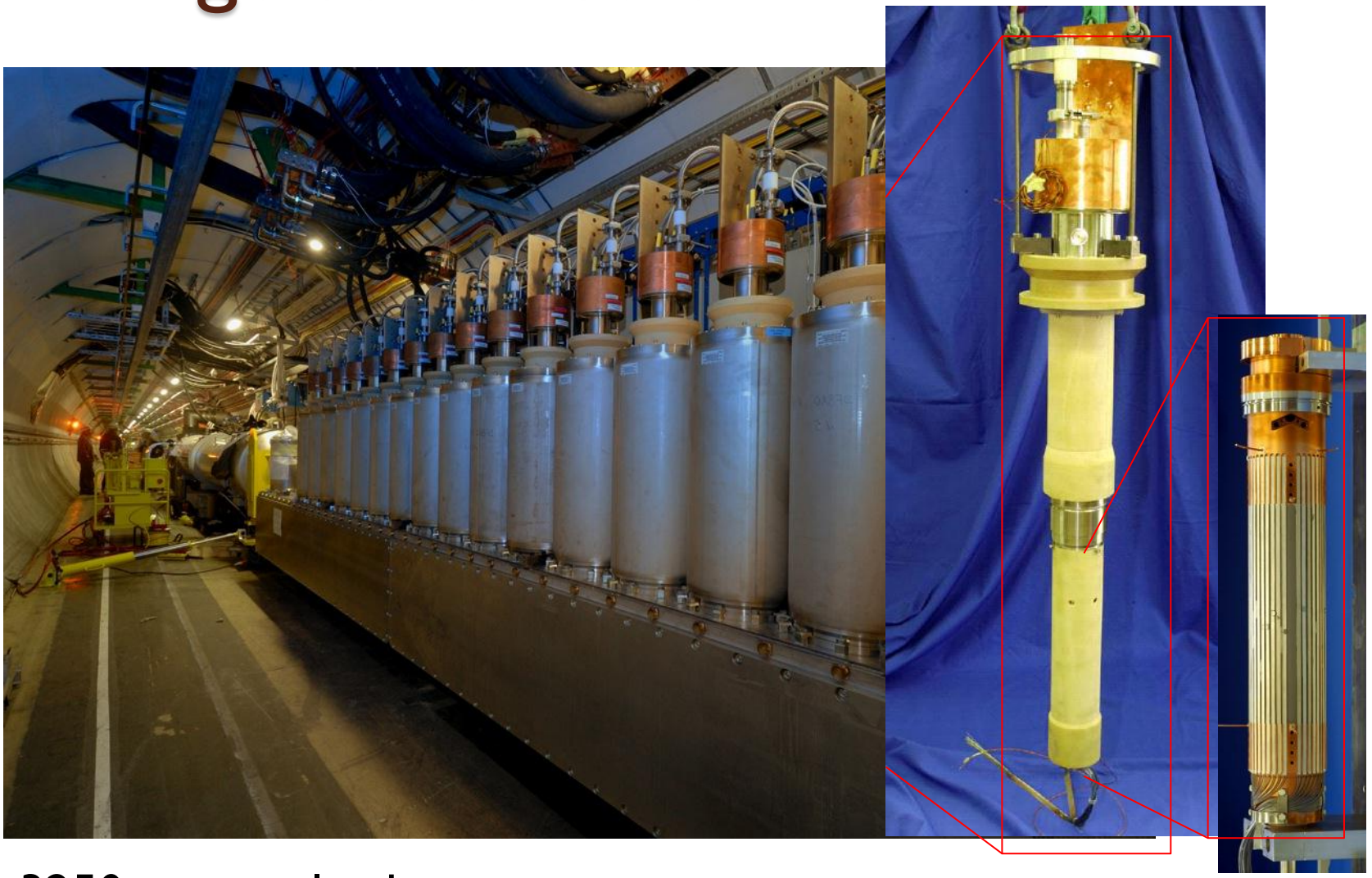
Orbital TIG welding

Weld quality

Helium leaktightness

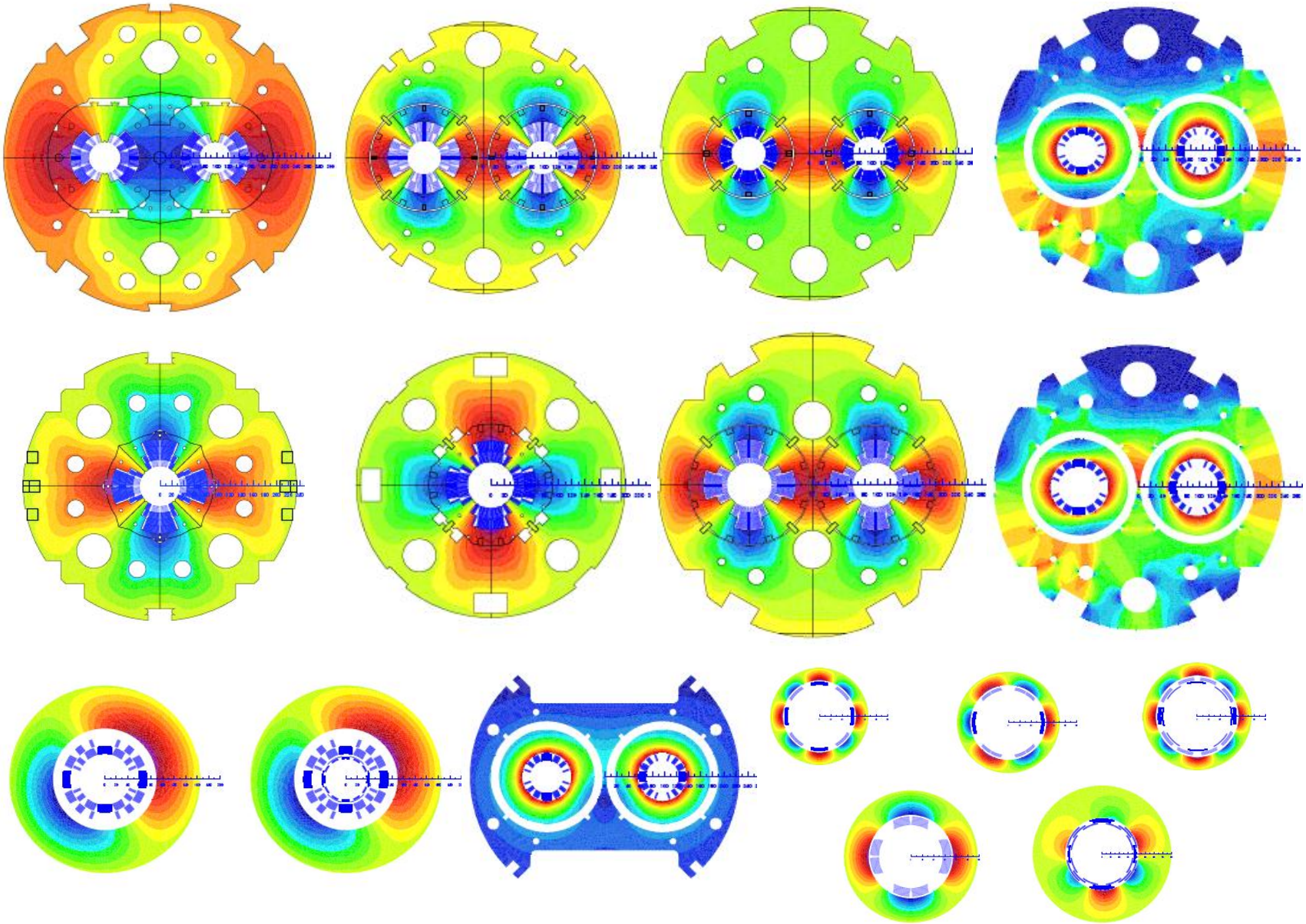


Large scale use of HTS



3250 current leads
31 km of BSCCO-2223 tape

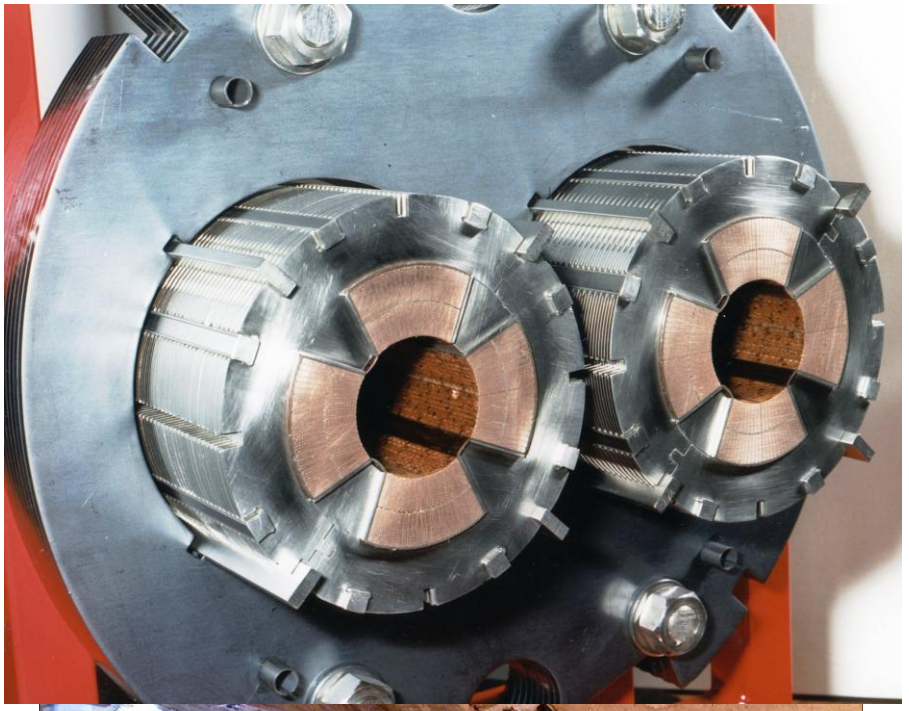
The LHC superconducting magnet *zoo*



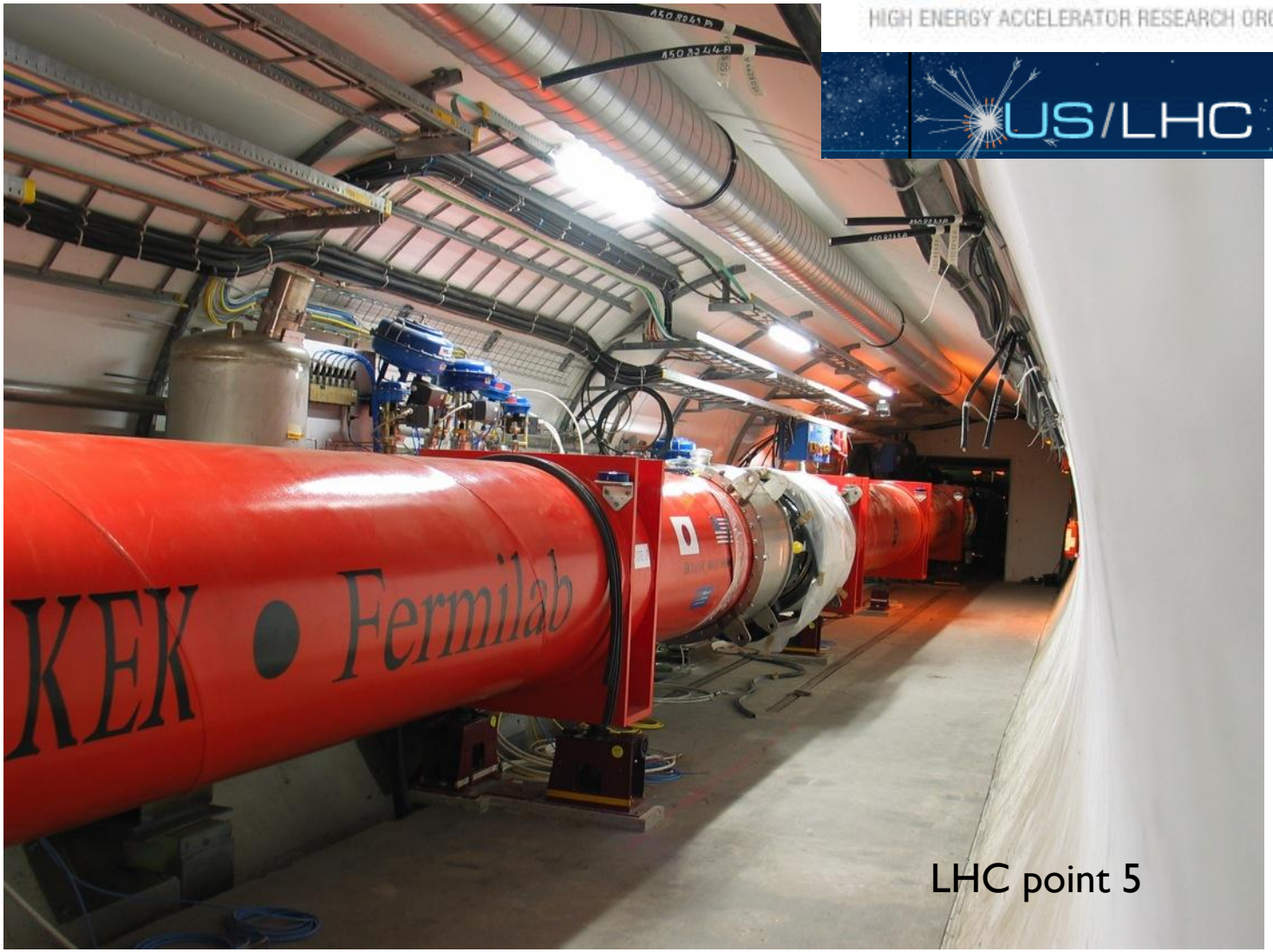
By courtesy of S. Russenschuck (CERN)

Short Straight Sections

- **1994** – CEA short straight sections (SSS) prototypes reach CERN and are assembled in String-I
- **14 February 1996** – CNRS-CEA-CERN collaboration protocol signed for the procurement of 392 main quadrupoles and assembly in the LHC-SSS
- **2006** – production completed



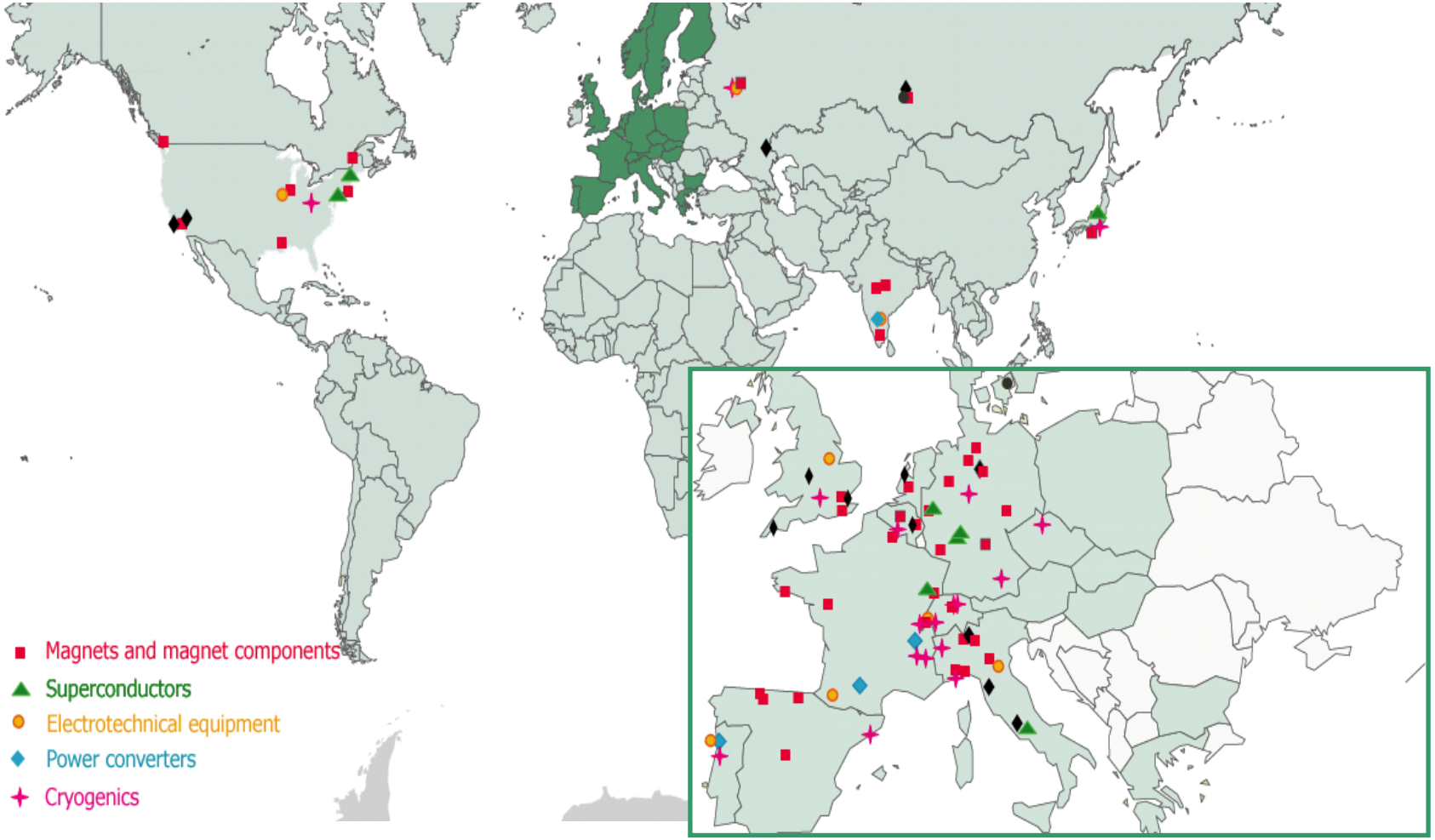
High luminosity insertion



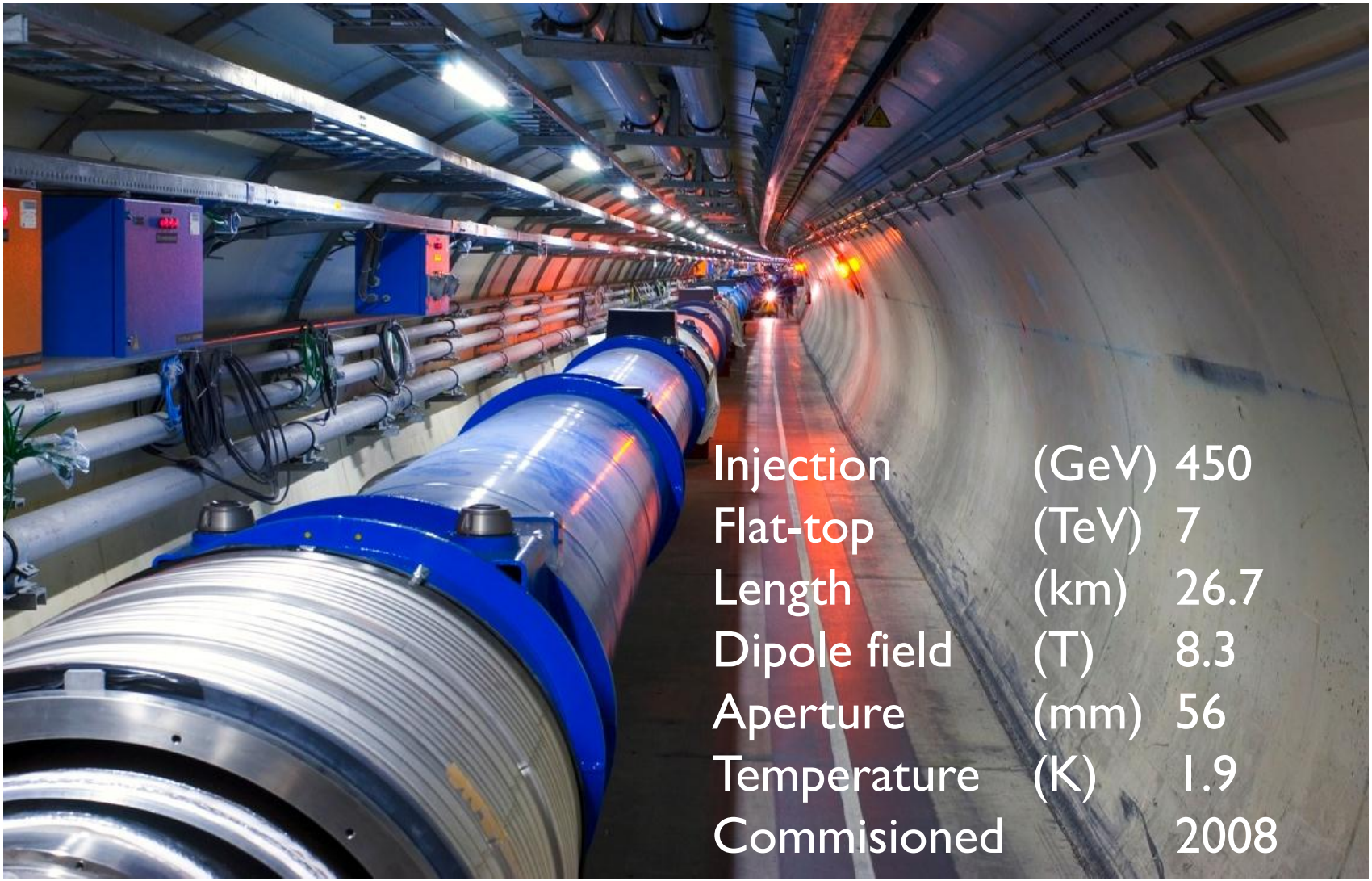
LHC point 5

World-Wide Works

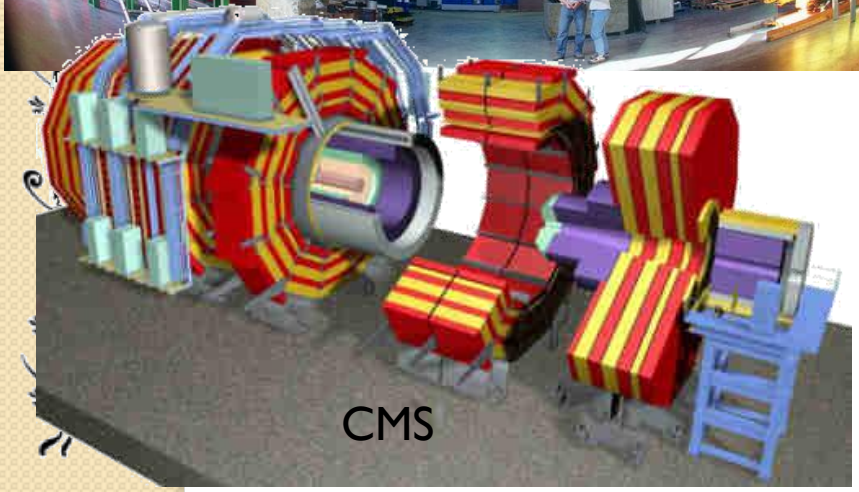
Approximately 100 contracts and international contributions



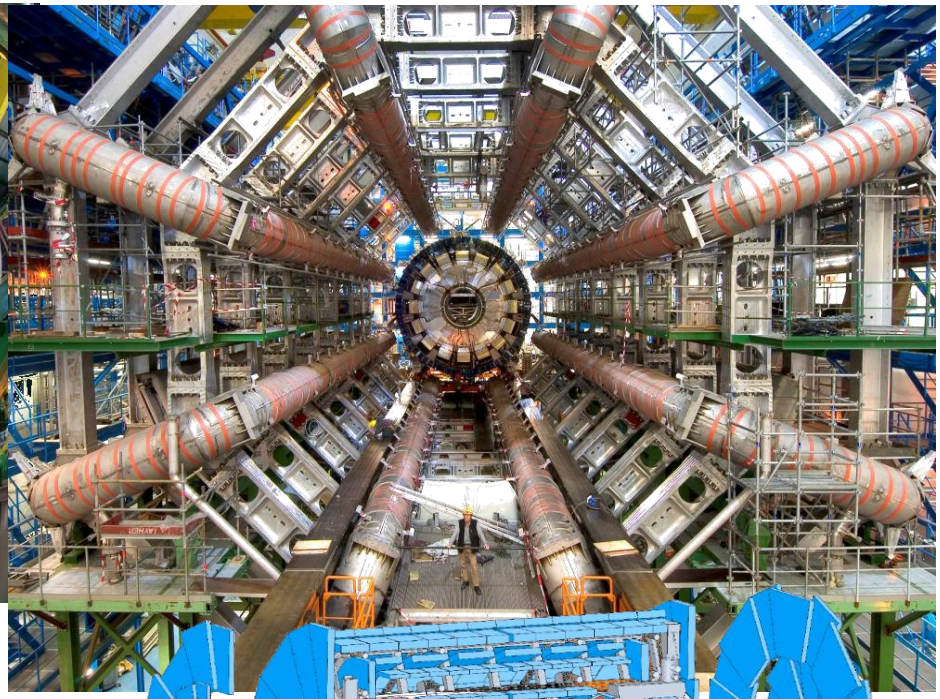
LHC !

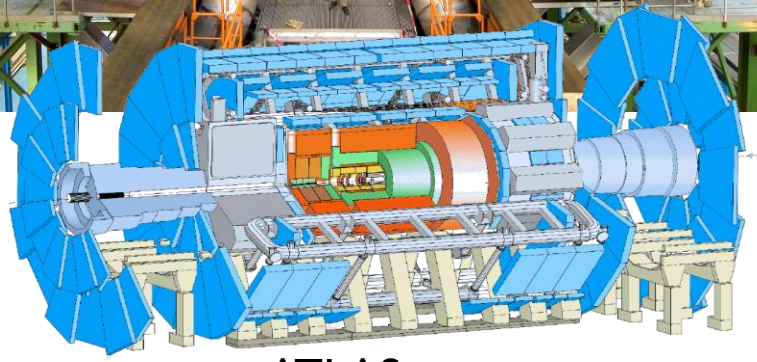

Injection (GeV) 450
Flat-top (TeV) 7
Length (km) 26.7
Dipole field (T) 8.3
Aperture (mm) 56
Temperature (K) 1.9
Commisioned 2008

Oh, of course, some of the most impressive detectors ever built



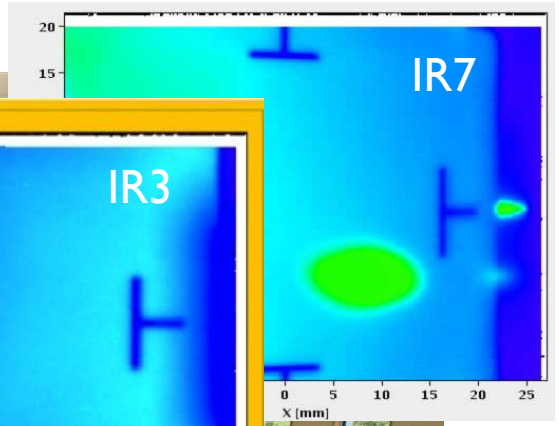
CMS

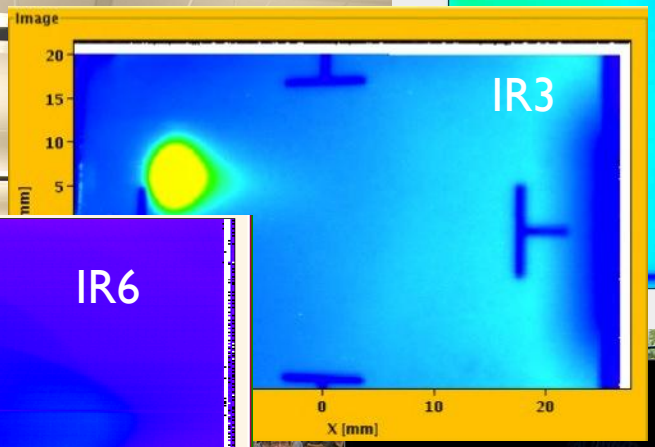


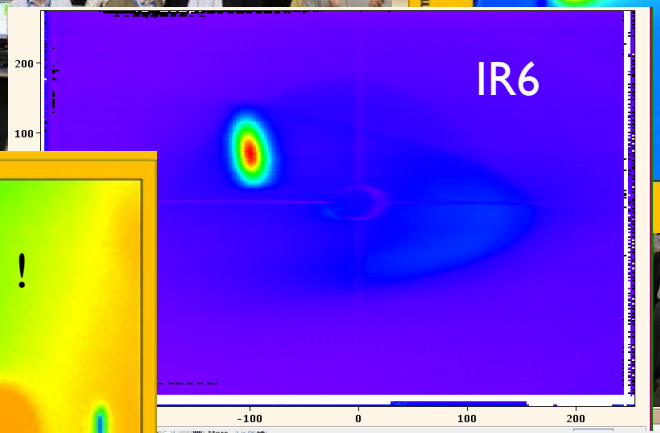


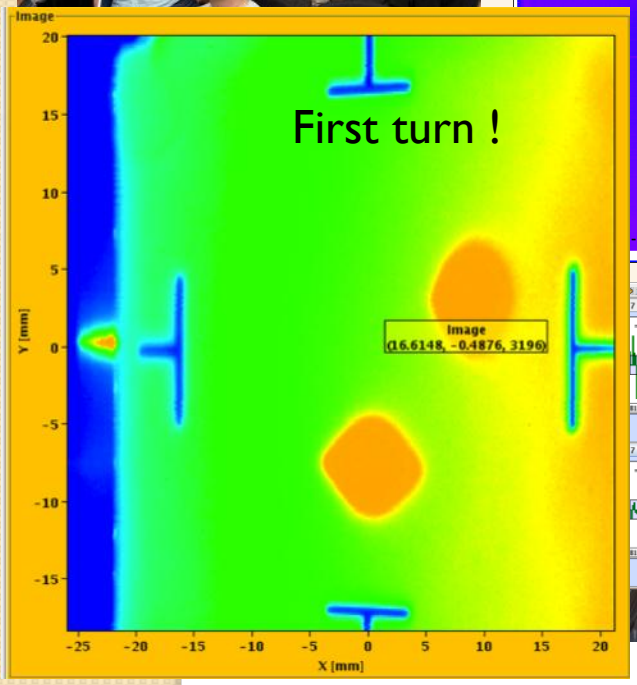
ATLAS

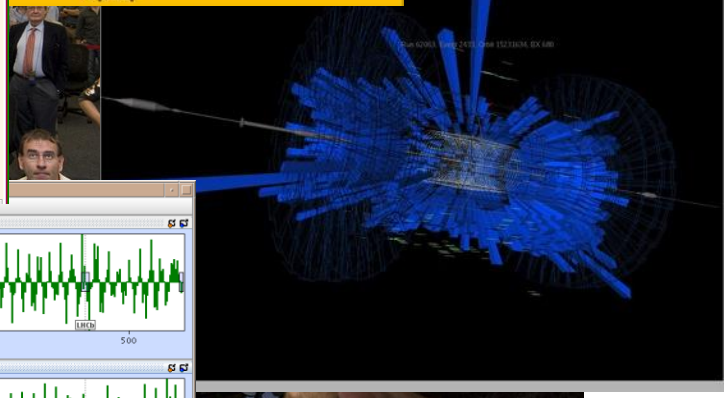
September 10th, 2008…

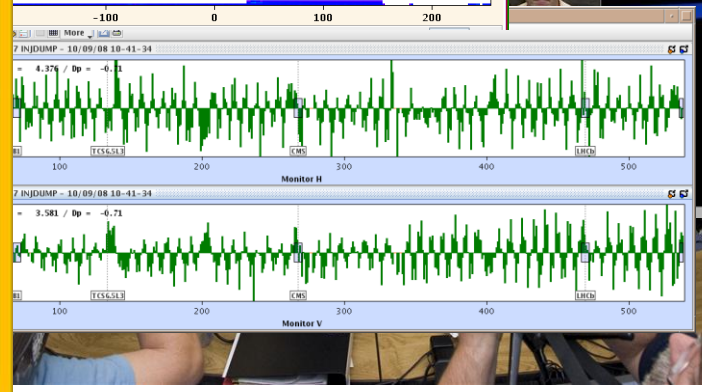


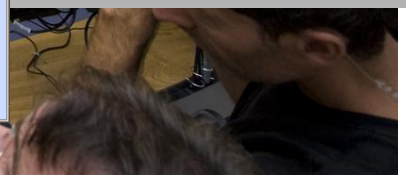








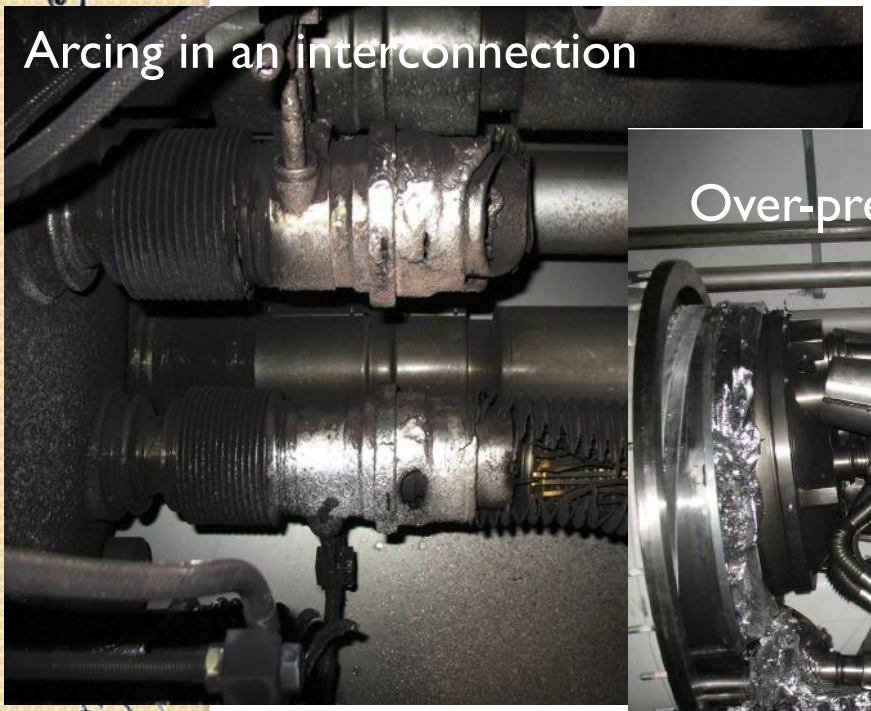




…September 19th, 2008…

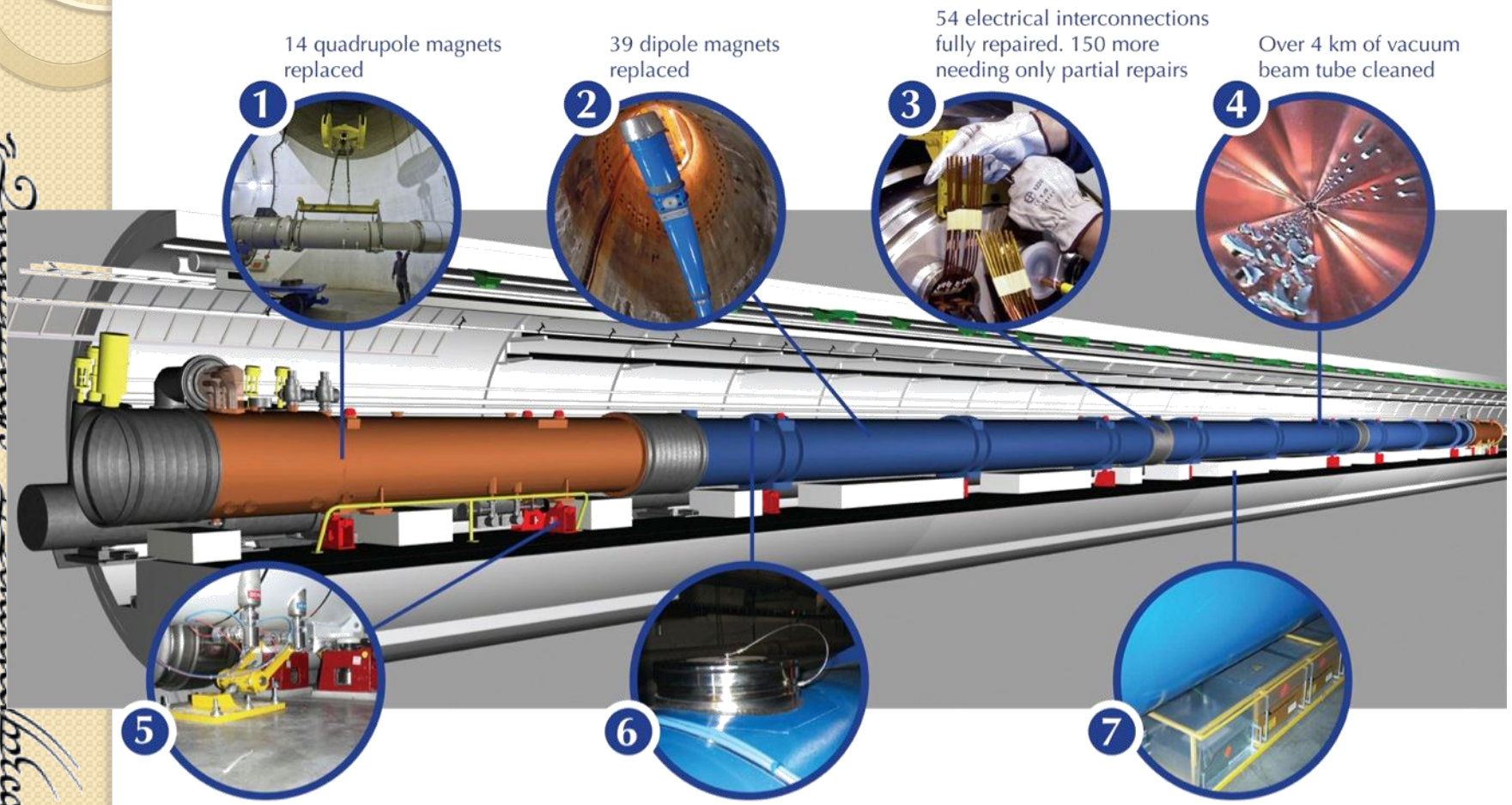
Initiated by an **unprotected quench** of defective joint

NOTE: this is an intentional defect built for testing purposes



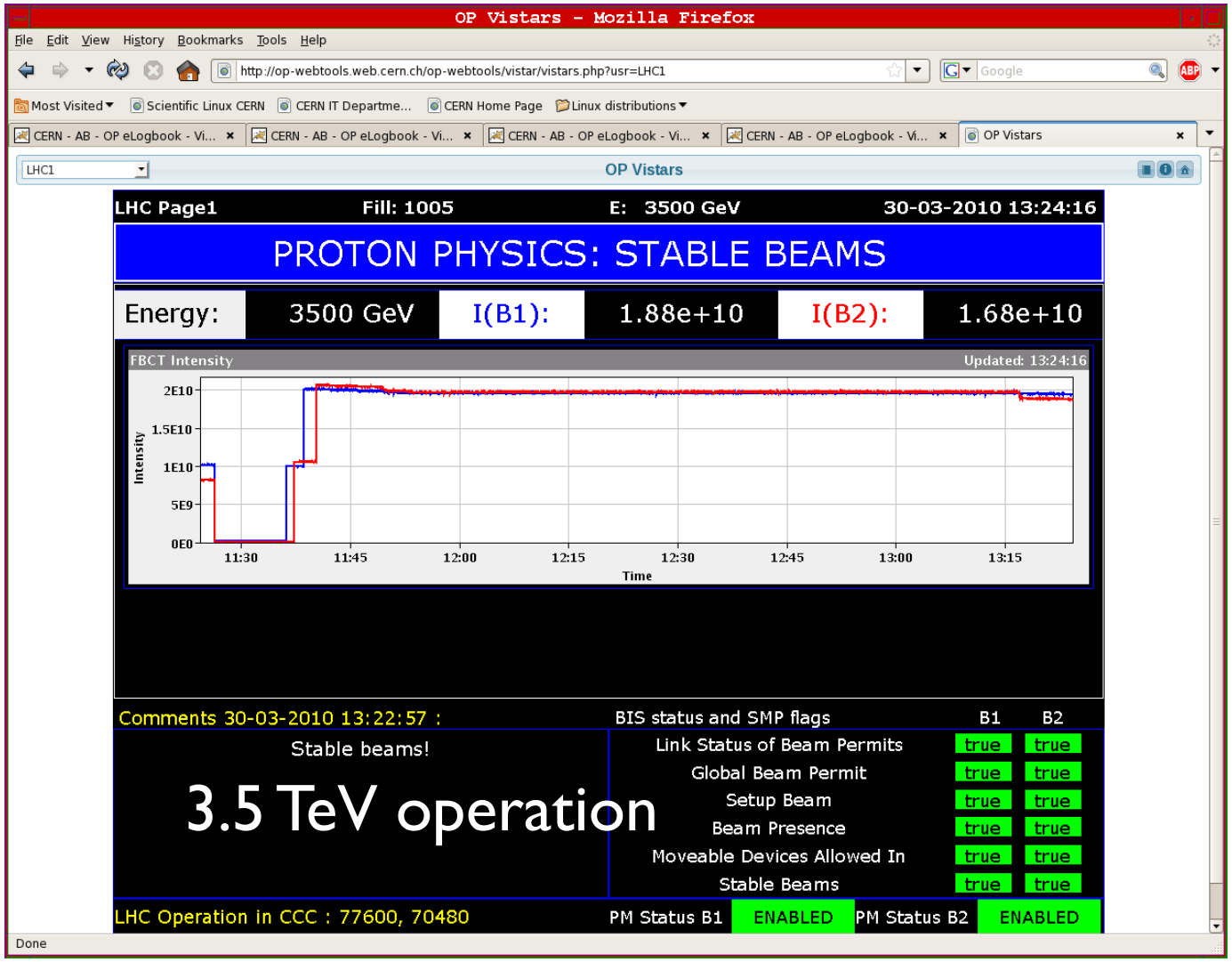
Magnet displacement

…back to work in 2009…



…November 30th, 2009…

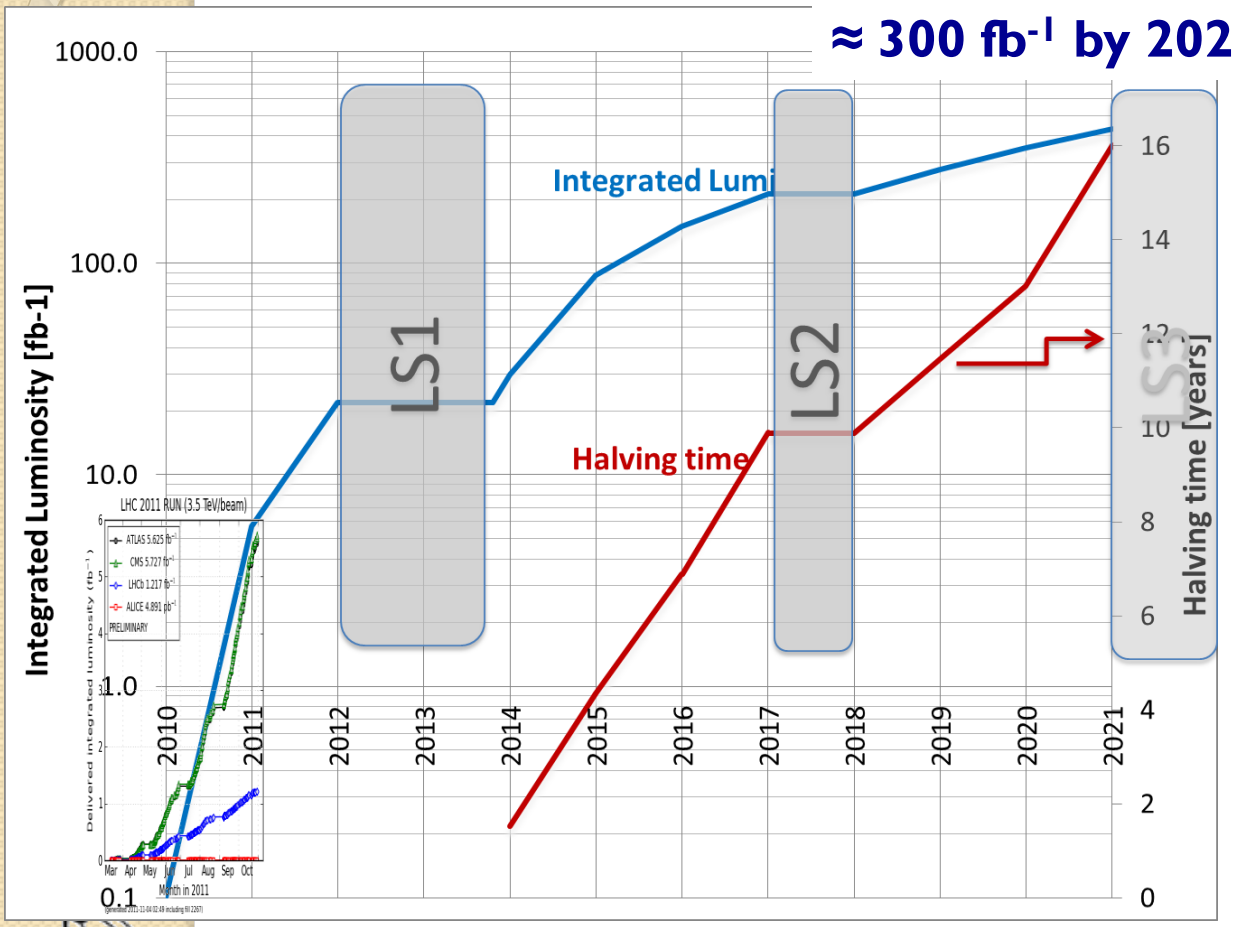
… March 30th, 2010



Outline

- The LHC pre-history
- The making of the LHC
- Long live the LHC !
- Is there life after the LHC ?

LHC luminosity in the future



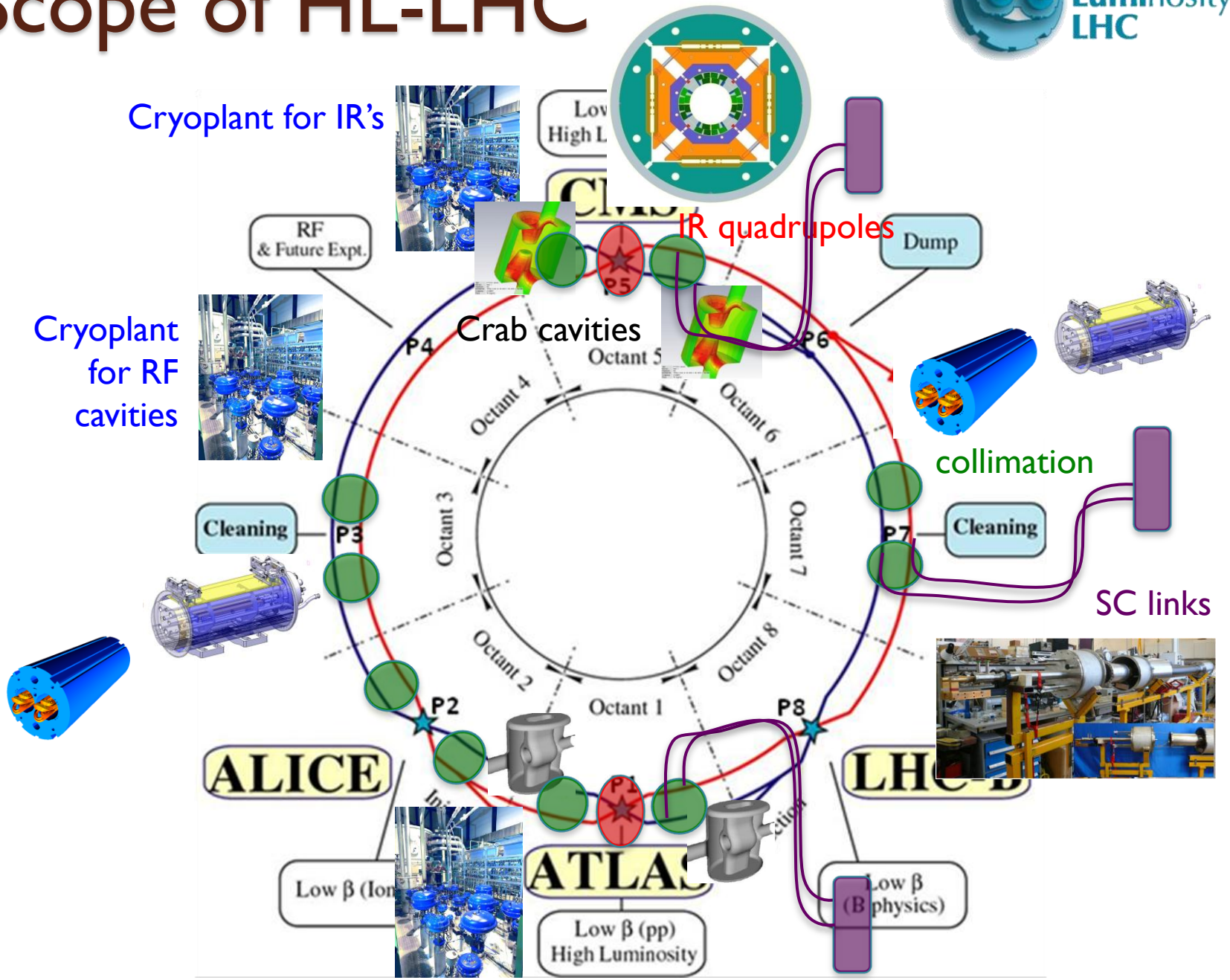
- The target for the projected LHC lifetime is **3000 fb^{-1}**
- We will need an upgrade by ≈2021:

HL-LHC

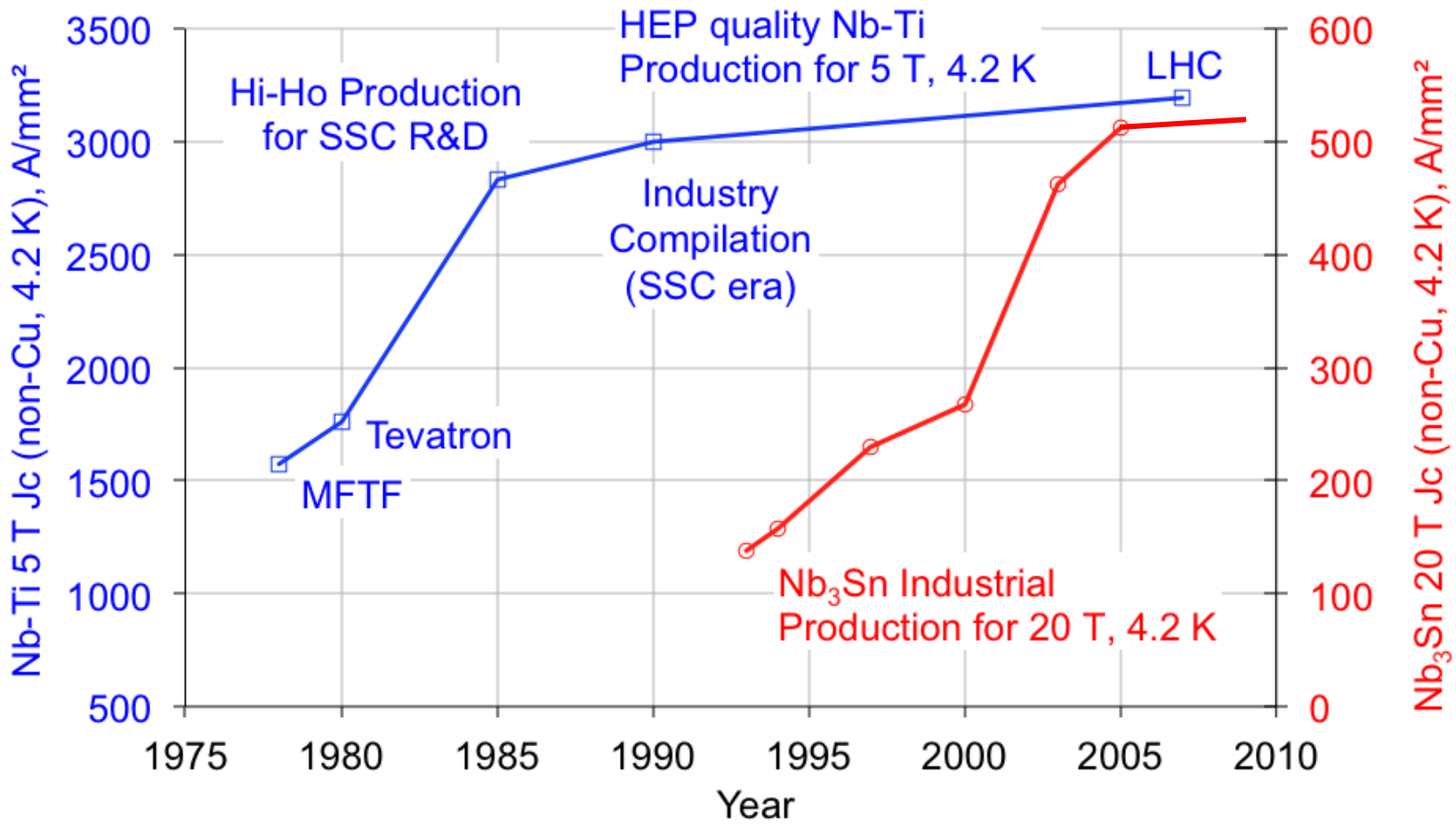
M. Lamont (CERN), Private communication

Any reference to existing accelerators and physical quantities is purely accidental

Scope of HL-LHC

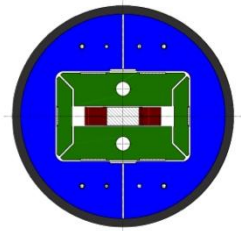


Nb_3Sn knocks at the door



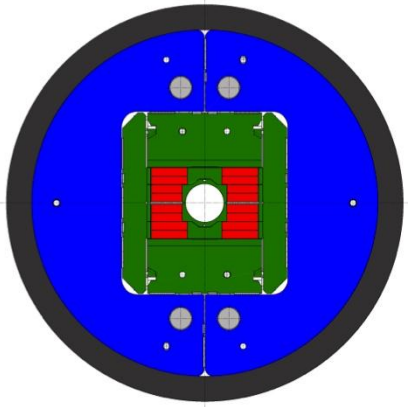
New magnets for HL-LHC

Nb_3Sn NbTi

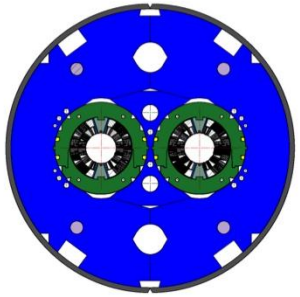


Short Model Coil

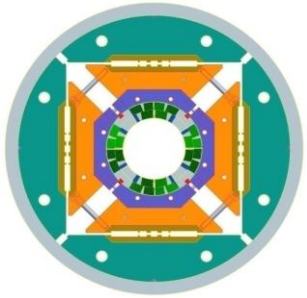
US-LARP program



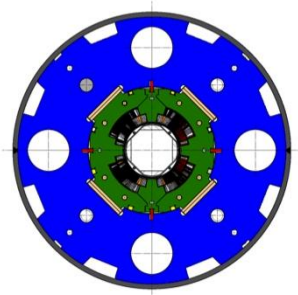
FReSCa2
Nb_3Sn Dipole



11 T DS
Nb_3Sn Dipole

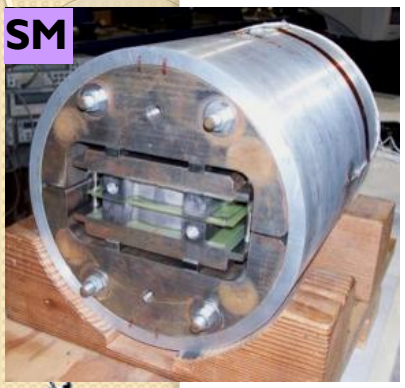


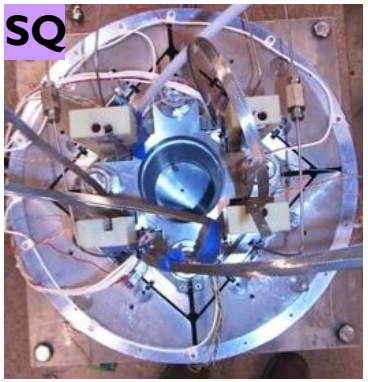
HQ/LHQ
Nb_3Sn Quadrupole

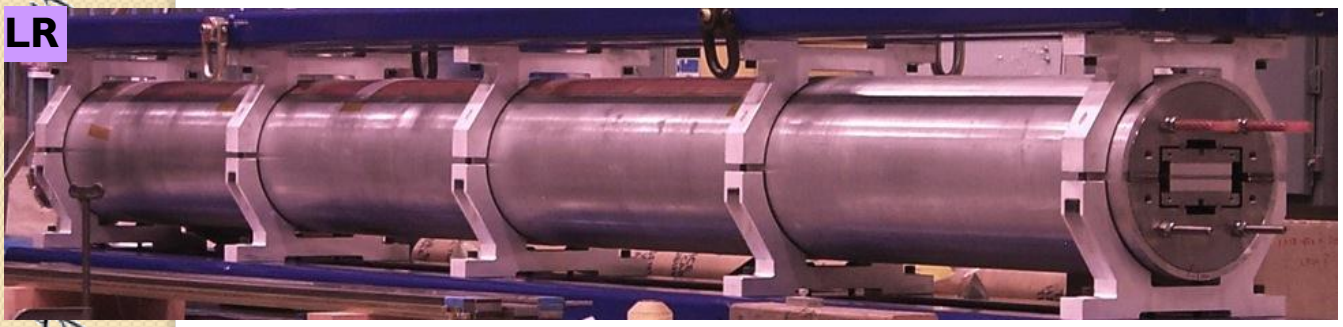


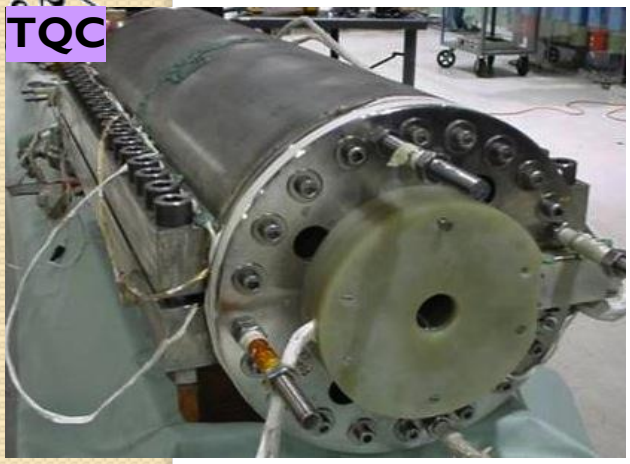
MQXC
NbTi Quadrupole

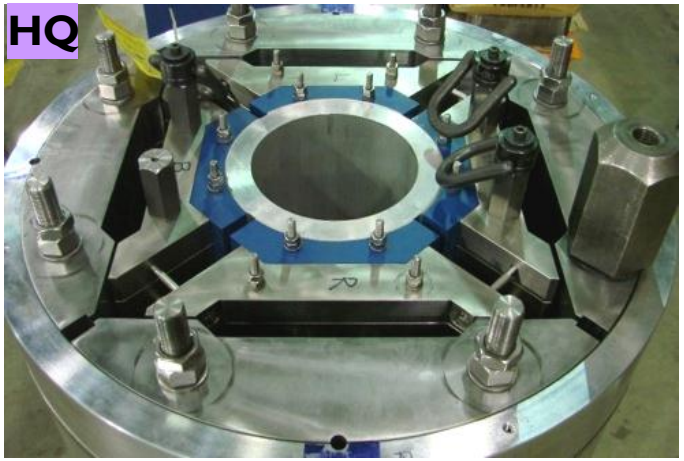
US-LARP magnets



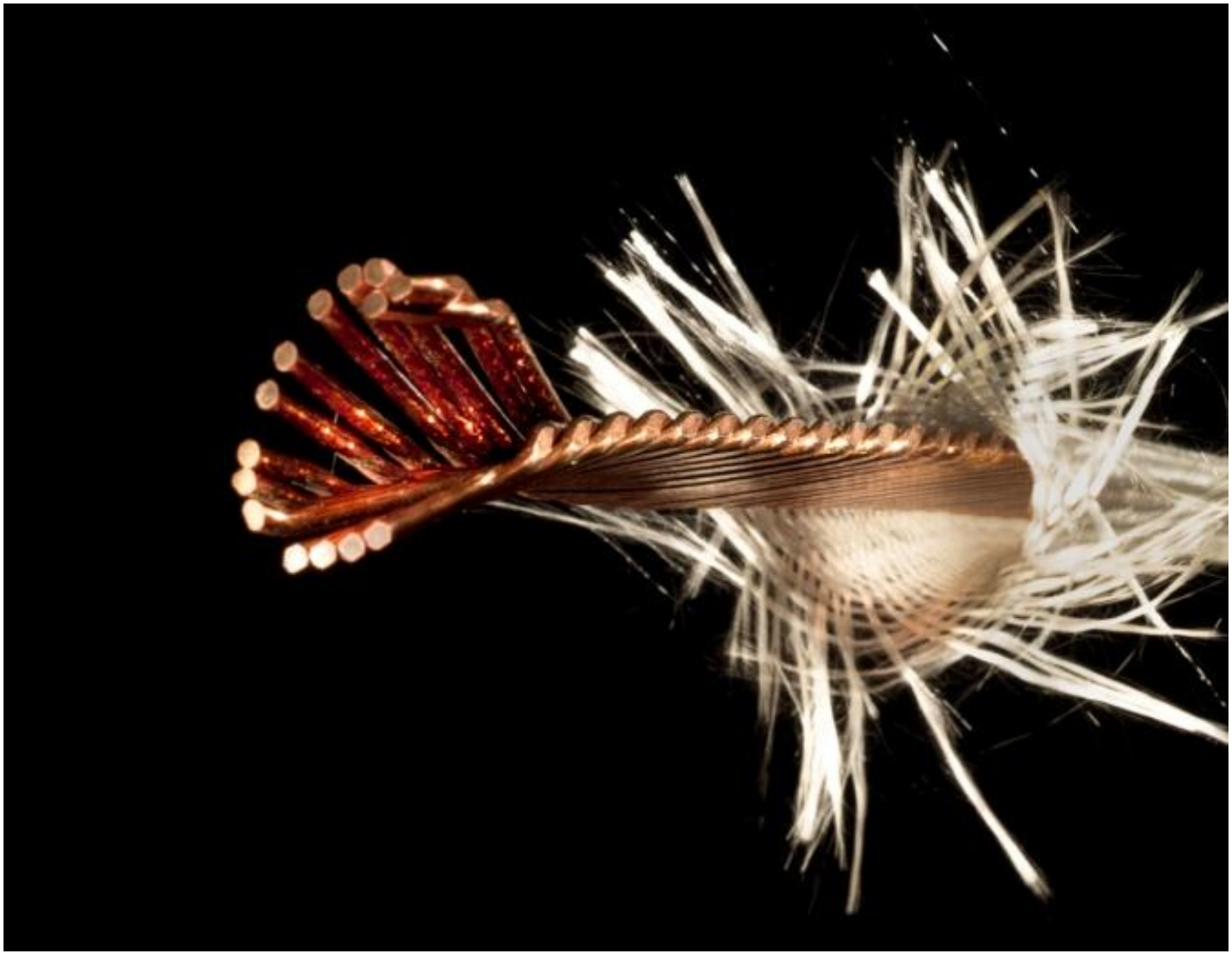






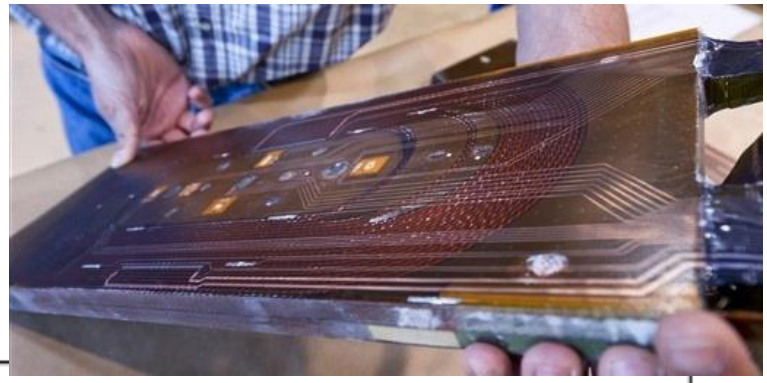


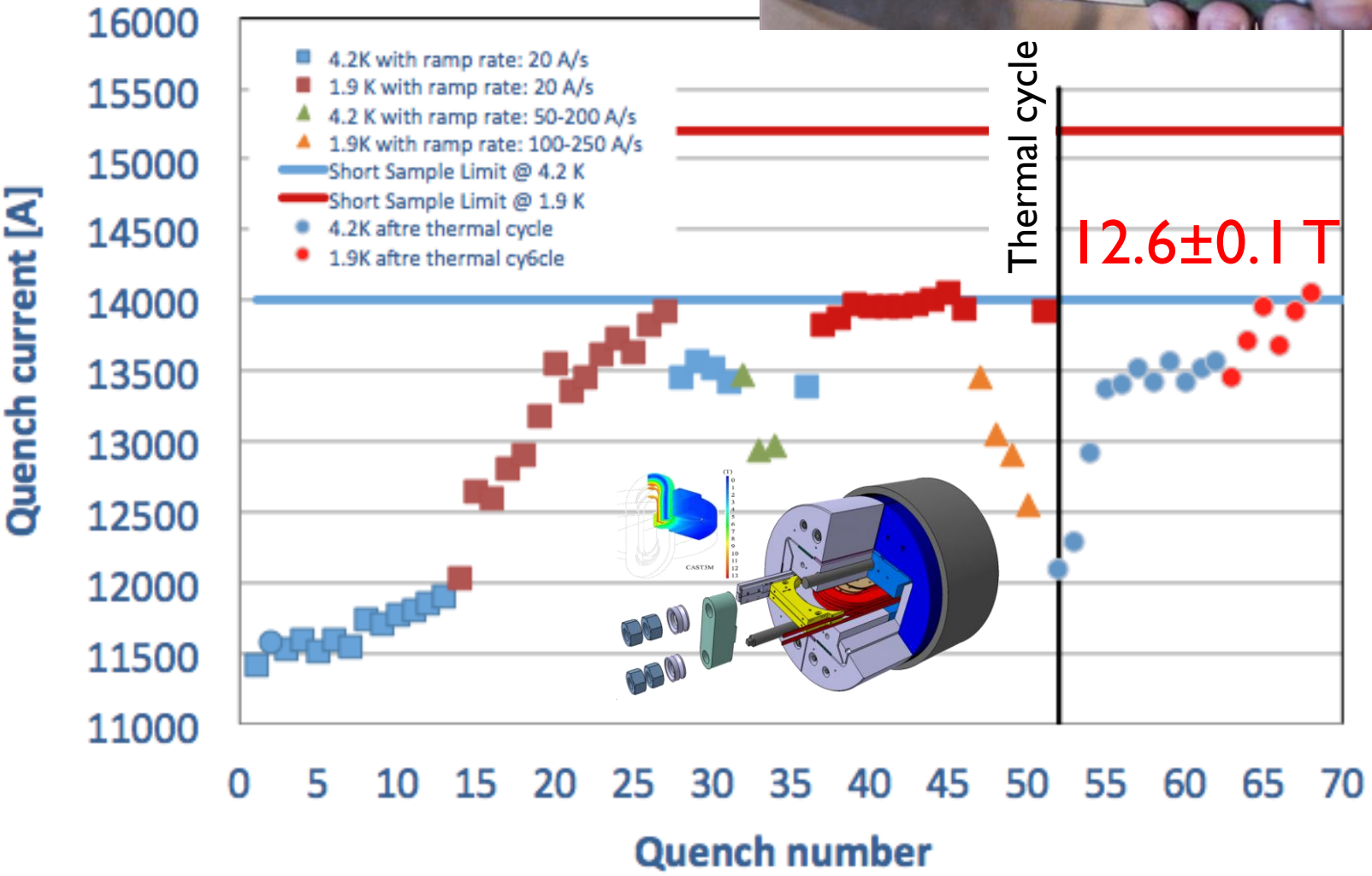
Nb_3Sn cables poised to break limits



SMC cable, 1.25 PIT Nb_3Sn wire

SMC-3 at CERN




16000
15500
15000
14500
14000
13500
13000
12500
12000
11500
11000
Quench current [A]
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Quench number
4.2K with ramp rate: 20 A/s
1.9 K with ramp rate: 20 A/s
4.2 K with ramp rate: 50-200 A/s
1.9K with ramp rate: 100-250 A/s
Short Sample Limit @ 4.2 K
Short Sample Limit @ 1.9 K
4.2K aftre thermal cycle
1.9K aftre thermal cy6cle
Thermal cycle
12.6±0.1 T

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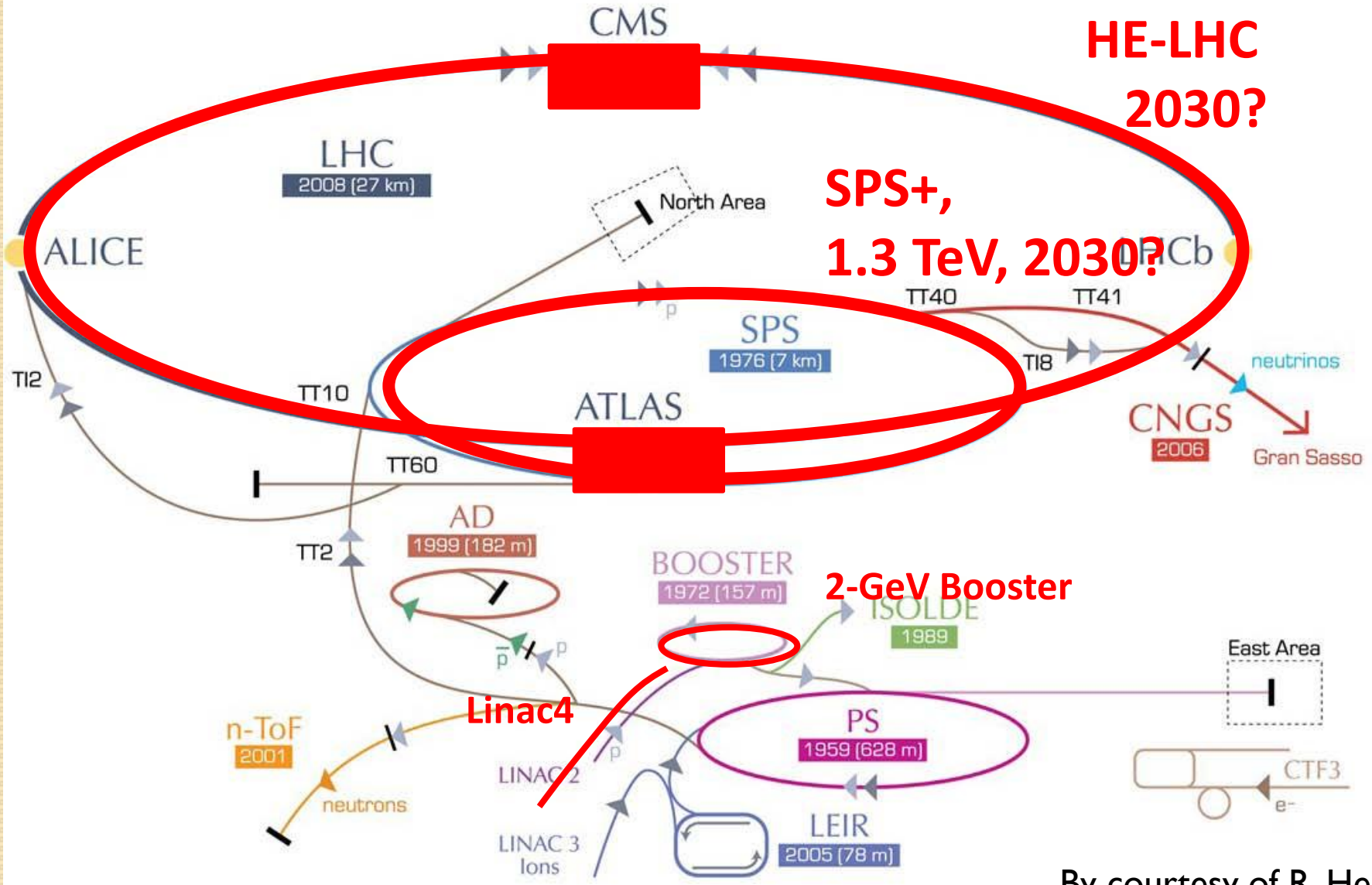
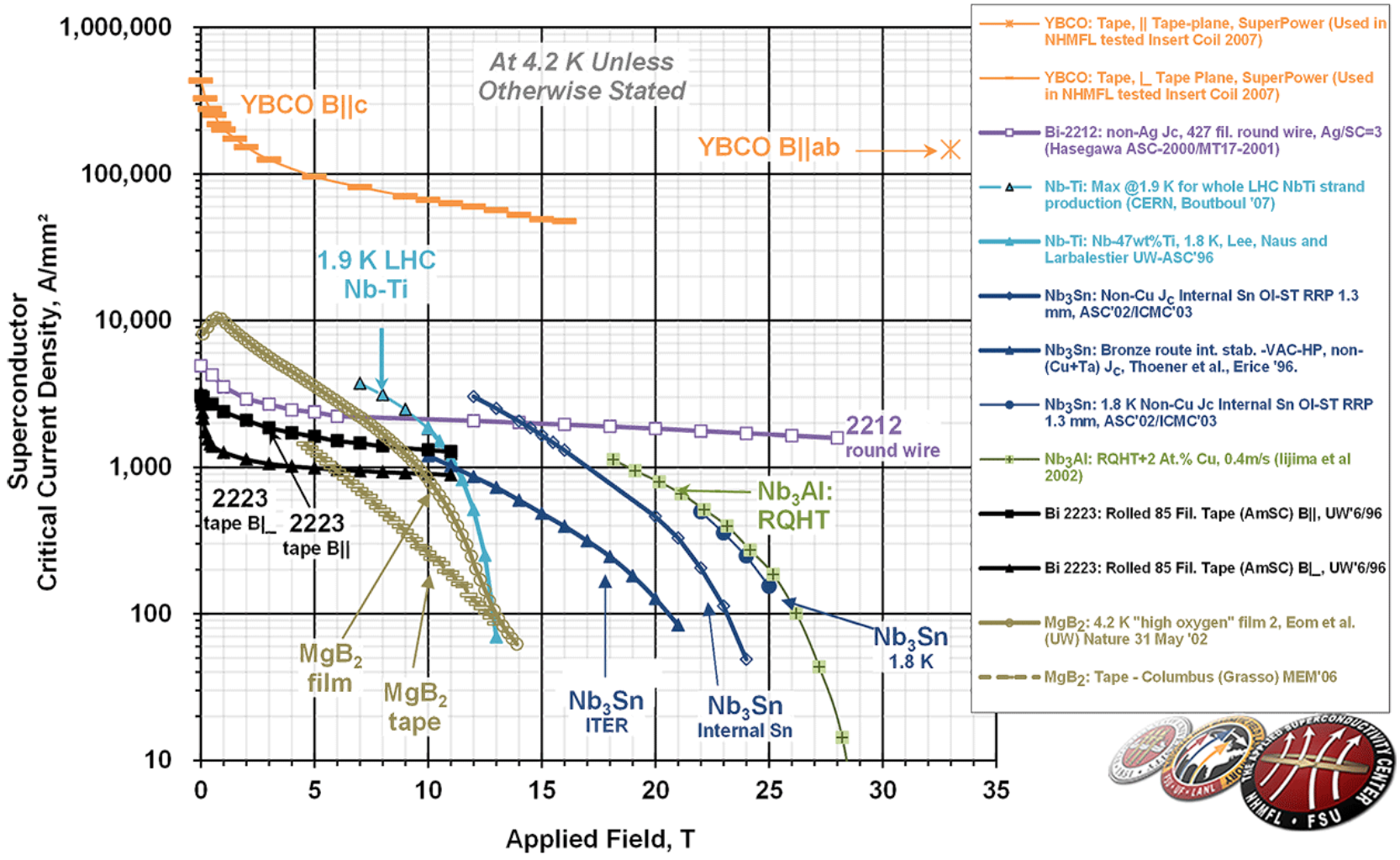
HE-LHC – (33 TeV cms)



By courtesy of R. Heuer

The path to 20 T

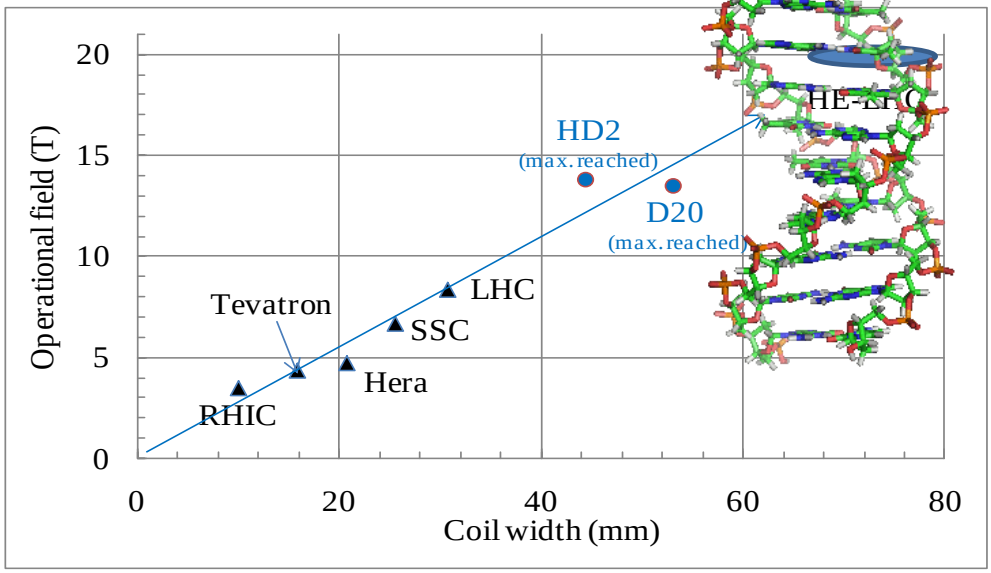


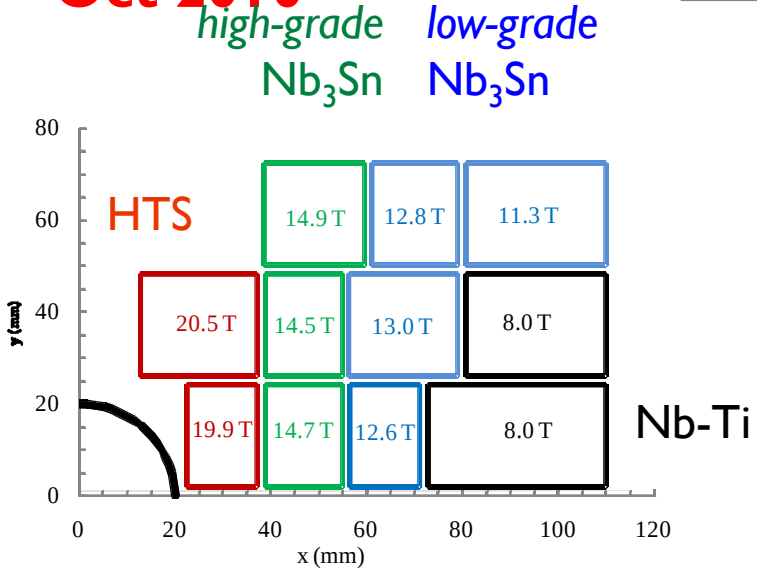
By courtesy of P. Lee, Applied Superconductivity Center, NHMFL

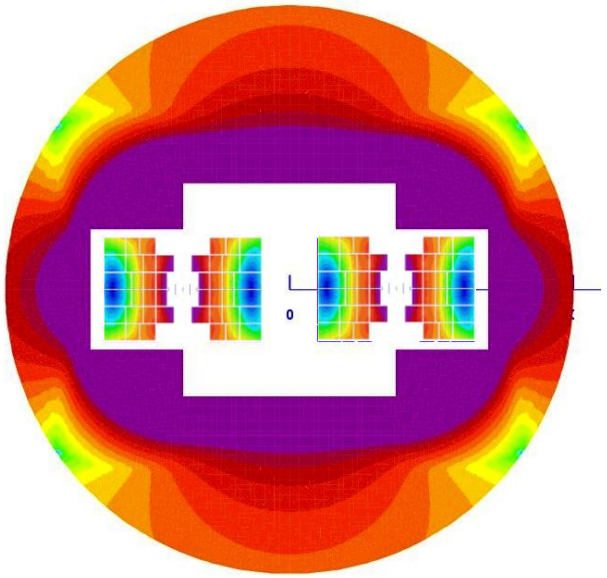
Time for a genetic mutation ?!?

Magnets for HE-LHC

- For a 17 + 17 TeV collider in the LHC tunnel: 20 T dipoles
- Present idea: HTS/Nb_3Sn/Nb-Ti nested coil magnet
- **Scenario set during the Malta workshop in Oct 2010**



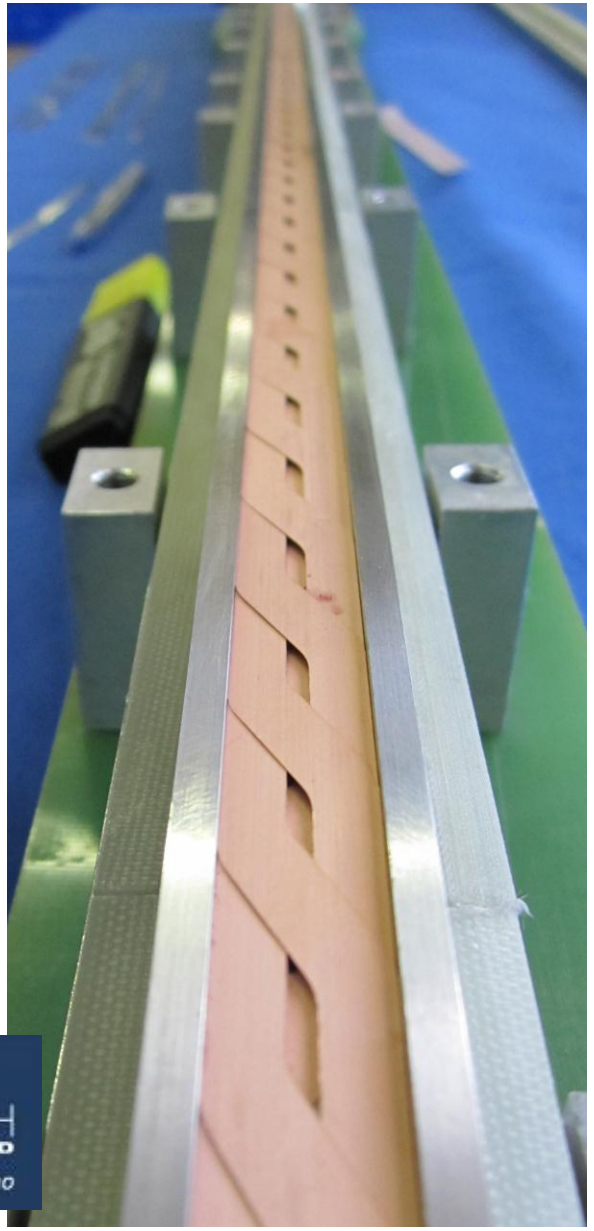




By courtesy of E. Todesco, CERN

A (maybe) 20 T cable

- Roebel cables of punched HTS tapes after an idea of W. Goldacker (KIT)
- Manufacturing by IRL Ltd.
- First test at liquid helium (4.3 K) and in high field (10 T) show a current carrying capacity of **4 to 10 kA**



IRL INDUSTRIAL RESEARCH LIMITED
Te Tauihu Pūtaiao

By courtesy of J. Fleiter, Ph. Denis, G. Peiro, A. Ballarino (CERN)

Conclusions – 1/2

- The history of LHC is a history of applied superconductivity.
- A history that started 100 years ago…

March 19th –
International Wo

May 25th: Panc
raging in Me

December 14th: Roald Amundsen reaches the South Pole

April 8th – K. Onnes discovers *supraconductivity*

August 22nd: Mona Lisa stolen

Conclusions – 2/2

- The history of LHC is also, and foremost, a history of people…
- … our supporting sponsors, the DG's in the period 1984-2010 that defined, defended and did the job
  - Herwig Schopper
  - Carlo Rubbia
  - Christopher Llevellyn Smith
  - Luciano Maiani
  - Robert Aymar
  - Rolf-Dieter Heuer
- … two strong project leader of remarkable fiber that navigated very rough seas
  - Giorgio Brianti
  - Lyn Evans

… and those who made it !