History of the LHC

Lyn Evans

LPCC student lectures, CERN 10th May 2010

The birth of the LHC

It is generally accepted that the kick-off of the LHC Project was the Lausanne Workshop in March 1984 where particle physicists and machine builders under the leadership of Giorgio Brianti got together for the first time.

In reality, the LHC adventure started much earlier…

ISR

Interaction point with crossing angle

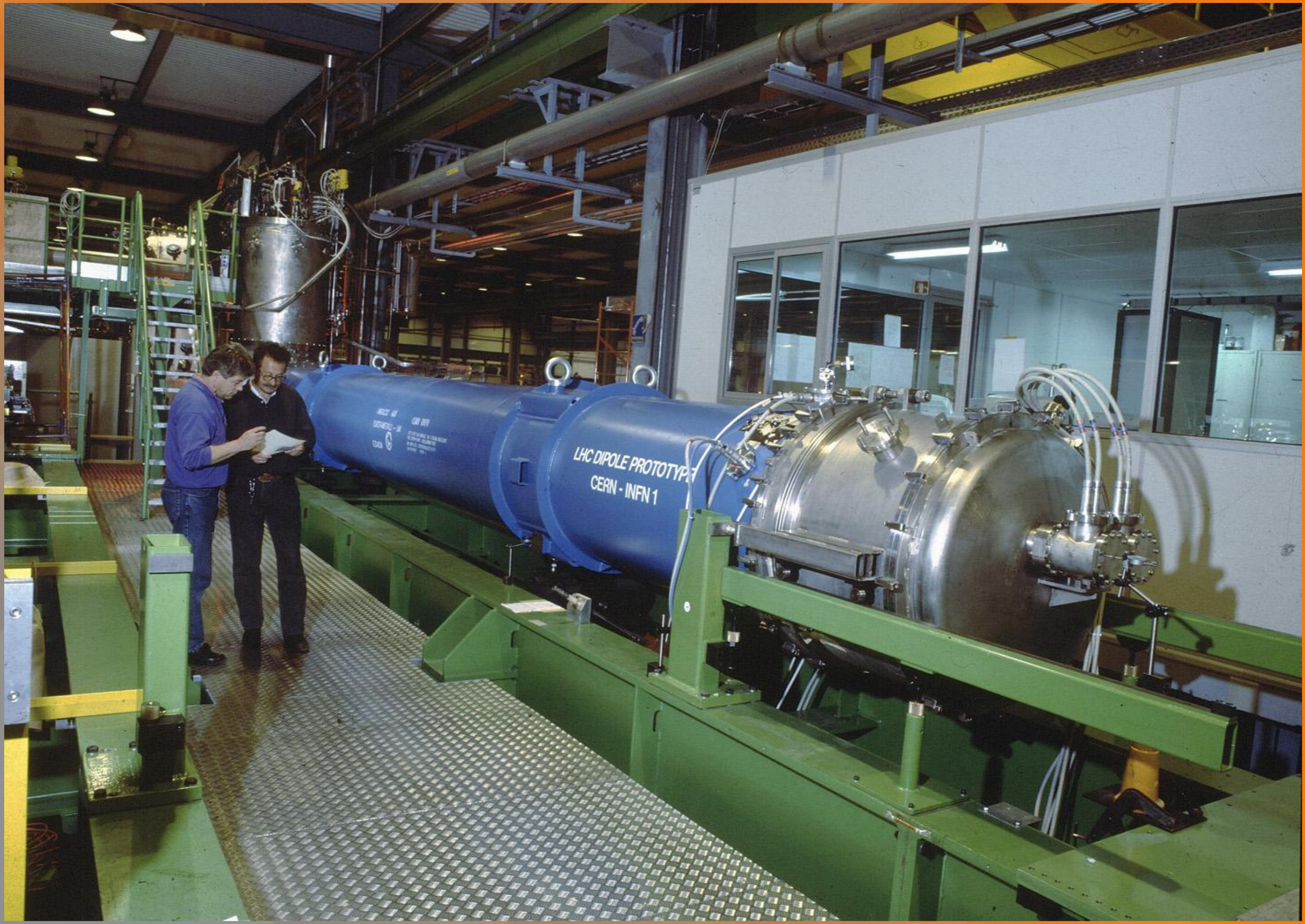
Approval of the LHC

The LHC had a difficult birth. Although the idea of a large proton-proton collider at CERN had been around since at least 1977, the approval of the Superconducting Super Collider (SSC) in the United States in 1987 put the whole project into doubt. The SSC, with a centre-of-mass energy of 40 TeV was almost three times more powerful than what could ever be built at CERN. It was only the resilience and conviction of Carlo Rubbia that kept the project alive.

In December 1993, a plan was presented to the CERN Council to build the machine over a ten-year period by reducing the other experimental program of CERN to the absolute minimum, with the exception of the full exploitation of the LEP collider. An external expert panel chaired by Robert Aymar endorsed the design.

Although the plan was generally well received, it became clear that two of the largest contributors, Germany and the United Kingdom, were very unlikely to agree to the budget increase required. They also managed to get Council voting procedures changed from a simple majority to a double majority, where much more weight was given to the large contributors so that they could keep control.

The 10 metre long prototype bending magnet for LHC, which has reached a field of 8,73 Tesla on 14 April 1994



Finance Committee April 1994

Message de J.P. Gourber et R. Perin

à L. Evans

- on a atteint 8,73 tesla

100 quench

In June 1994, the proposal to build the LHC was made once more to Council. Seventeen member states voted to approve the project. However, because of the newly adopted double voting procedure, approval was blocked by Germany and the UK, who demanded substantial additional contributions from the two host states, France and Switzerland, claiming that they obtained disproportionate returns from the CERN budget. They also requested that financial planning should proceed under the assumption of 2% annual inflation, with a budget compensation of 1%, essentially resulting in a 1% annual reduction in real terms.

In order to deal with this new constraint, we were forced to propose a "missing magnet" machine where only two thirds of the dipoles would be installed in a first stage. The deadlock concerning extra host-state contributions was broken when France and Switzerland agreed to make extra voluntary contributions in the form of a 2% annual inflation adjustment, compared with the 1% adjustment from the other member states. The project was approved for two-stage construction, to be reviewed in 1997 after the size of the contribution offered by non-member states interested in joining the LHC program would be known.

Japan becomes an Observer

June 1995

Japan becomes an Observer of CERN and announces a financial contribution to the LHC.
The Japanese Minister for Education, Sciences and Culture offers a Daruma doll to CERN's Director-General. According to Japanese tradition, an eye is painted on the doll to mark the beginning of the LHC project and the second eye must be drawn at the time of its completion.
Japan makes two other major financial contributions to the LHC project in 1996 and 1998.

1996

March

- India makes a financial contribution to the construction of the LHC.
- And in June, Russia announces a financial contribution to the project.

December

- Canada announces a financial contribution for the LHC, while a protocol of co-operation is defined for participation of the United States.
- In December 1997, the US declares a contribution.

A final sting in the tail came in June 1996 from Germany who unilaterally announced that, in order to ease the burden of reunification, it intended to reduce its CERN subscription by between 8% and 9%. Confining the cut to Germany proved impossible. The UK was the first to demand a similar reduction in its contribution in spite of a letter from the UK Minister of Science during the previous round of negotiations stating that the conditions are "reasonable, fair and sustainable". The only way out was to allow CERN to take out loans, with repayment to continue after the completion of LHC construction.

In December 1996 Council, Germany declared that "a greater degree of risk would inevitably have to accompany the LHC". The project was approved for single-stage construction with the deficit financed by loans. It was also agreed that the final cost of the project was to be reviewed at the half-way stage with a view to adjusting the completion date. With all contingency removed, it was inevitable that a financial crisis would occur at some time, and this was indeed the case when the cost estimate was revised upwards by 18% in 2001.

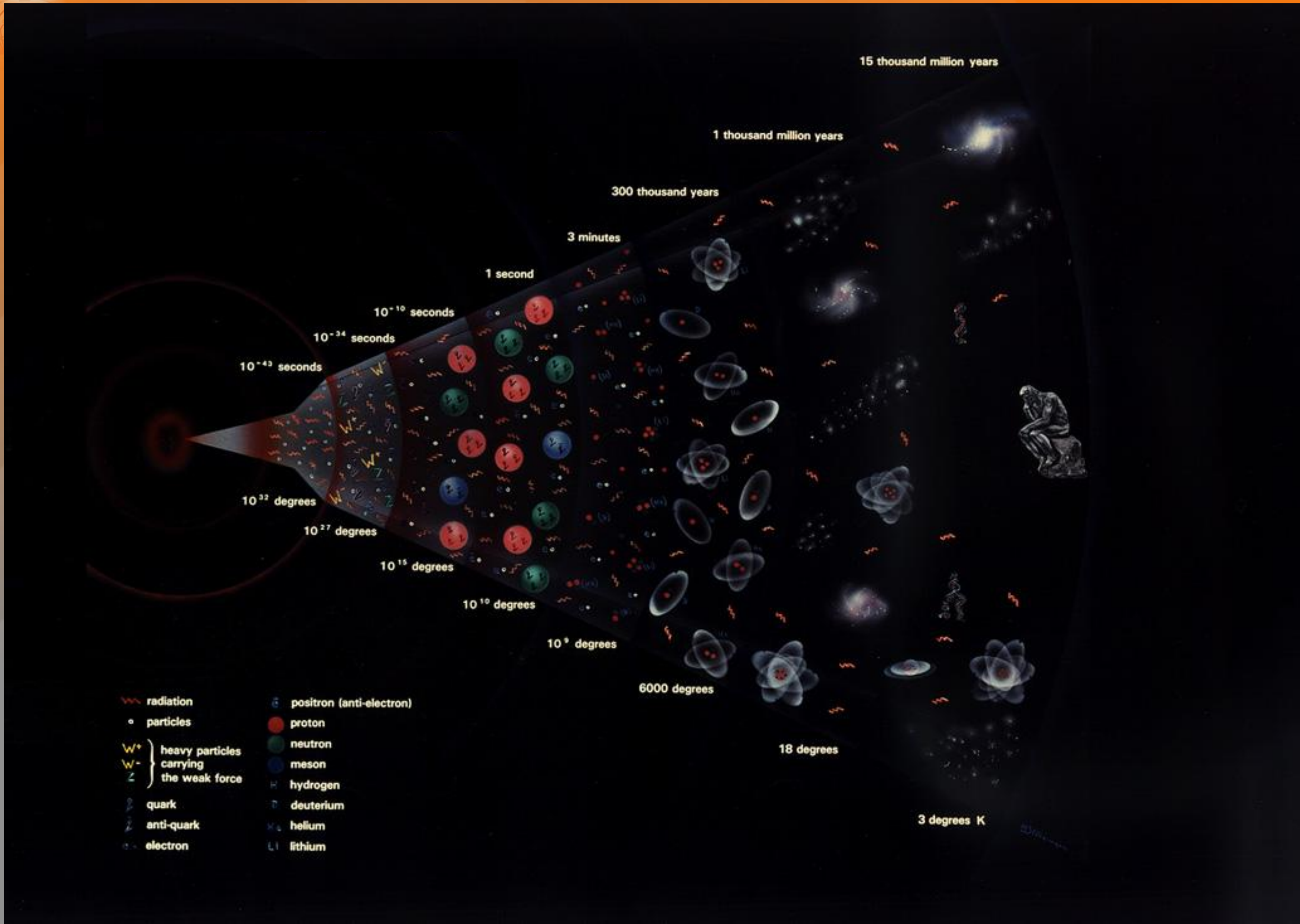
Energy, mass and temperature

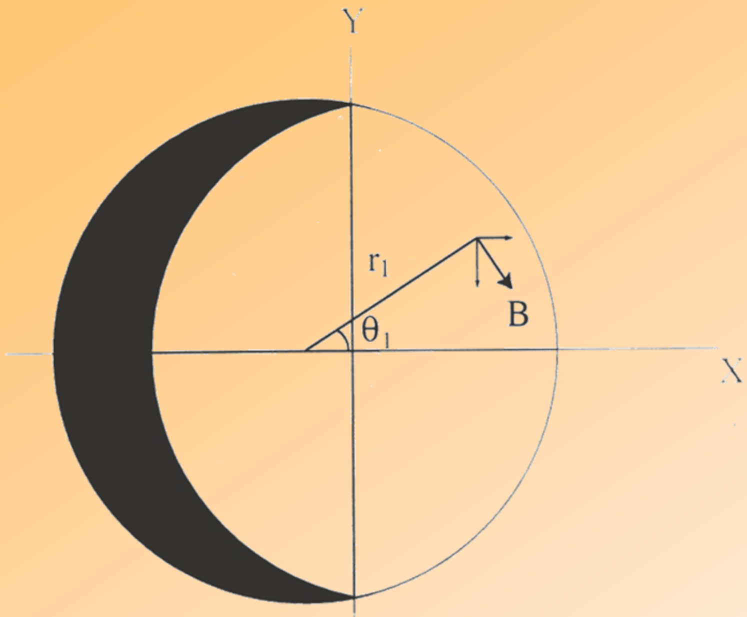
1 electron Volt (eV) $= 1.8 \times 10^{-36}$ kG

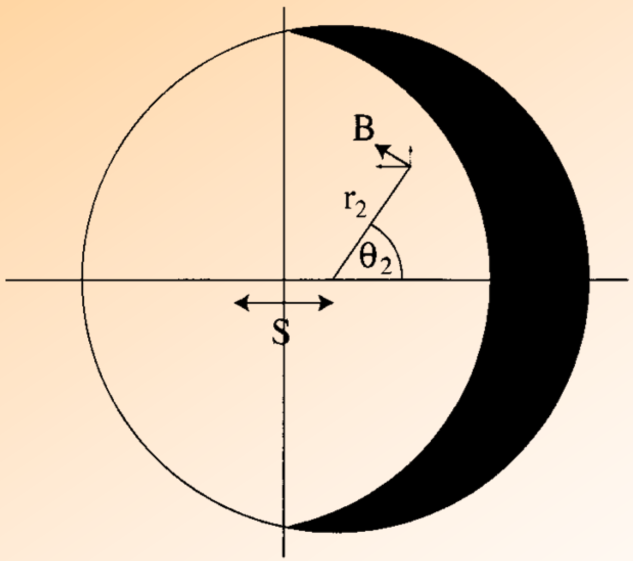
$= 11{,}600\ ^{o}C$

1 Tera electron Volt (TeV) $= 10^{16}\ ^{o}C$

The Big Bang


15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+
W-
Z
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium



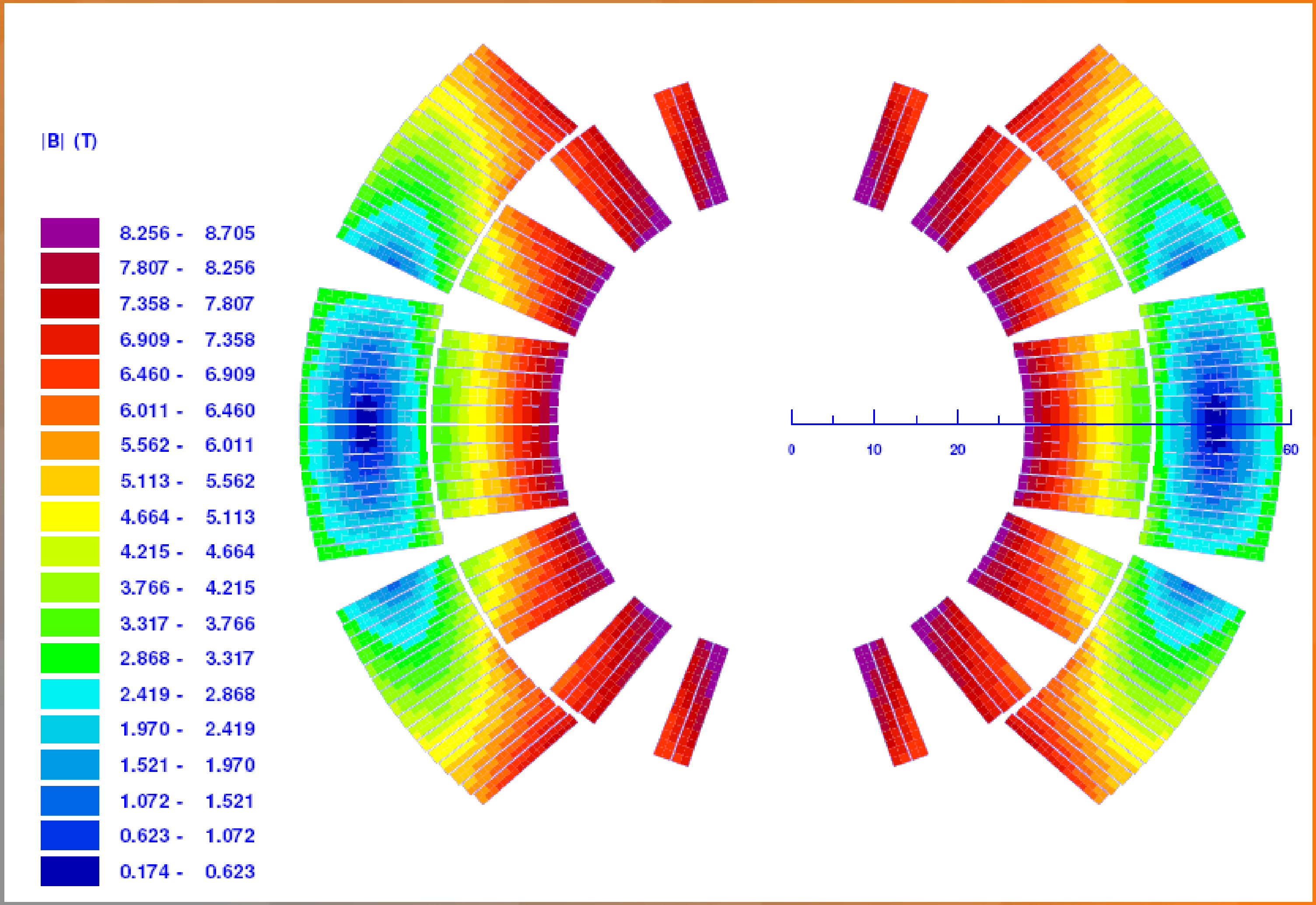


$$B = \frac{\mu_0 \, J \, r}{2}$$

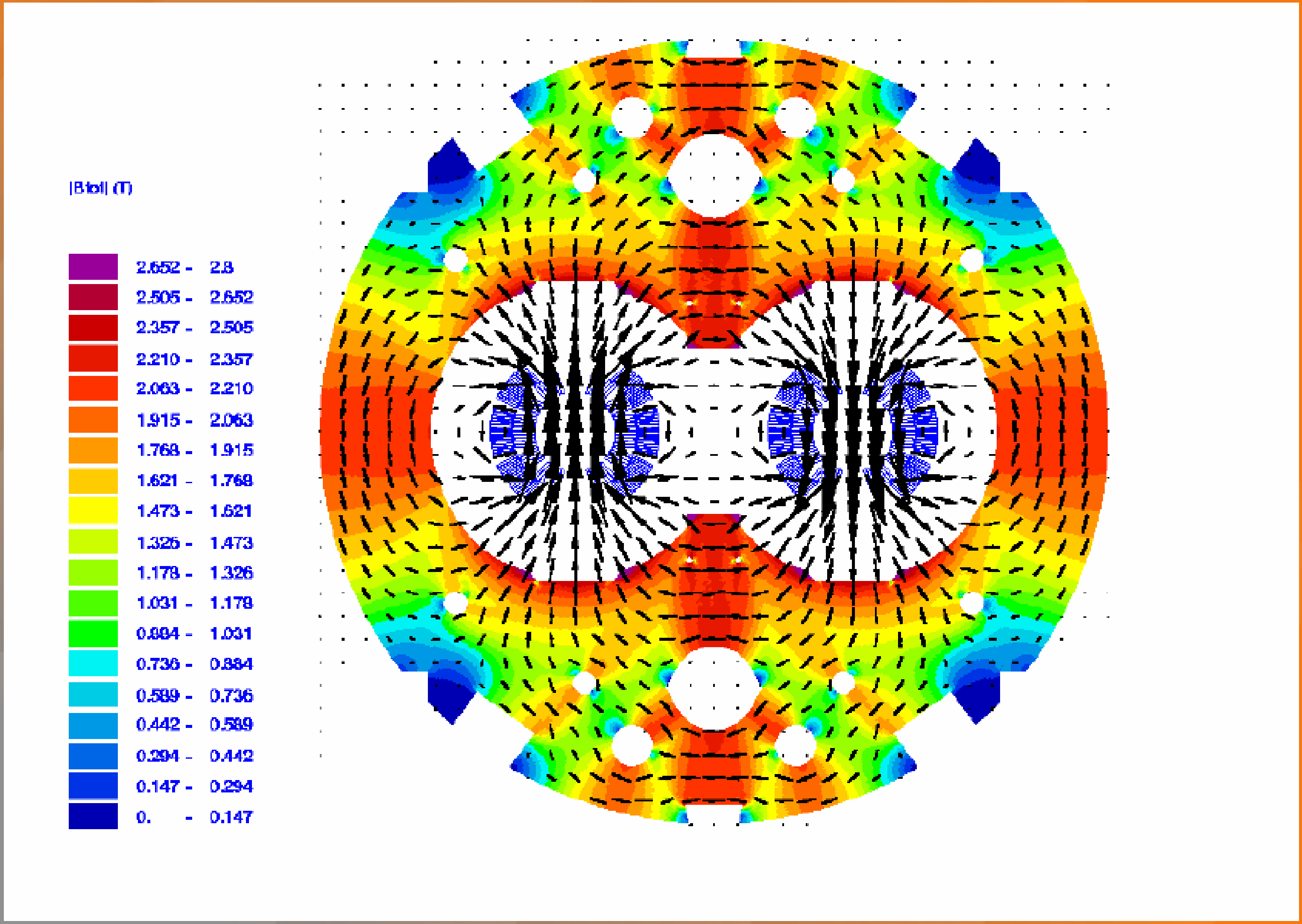
$$B_Y = \frac{\mu_0 \, J}{2} \left\{ - r_1 \cos\theta_1 + r_2 \cos\theta_2 \right\} = -\frac{\mu_0 J \, s}{2}$$

$$B_X = \frac{\mu_0 \, J}{2} \left\{ r_1 \sin\theta_1 - r_2 \sin\theta_2 \right\} = 0$$

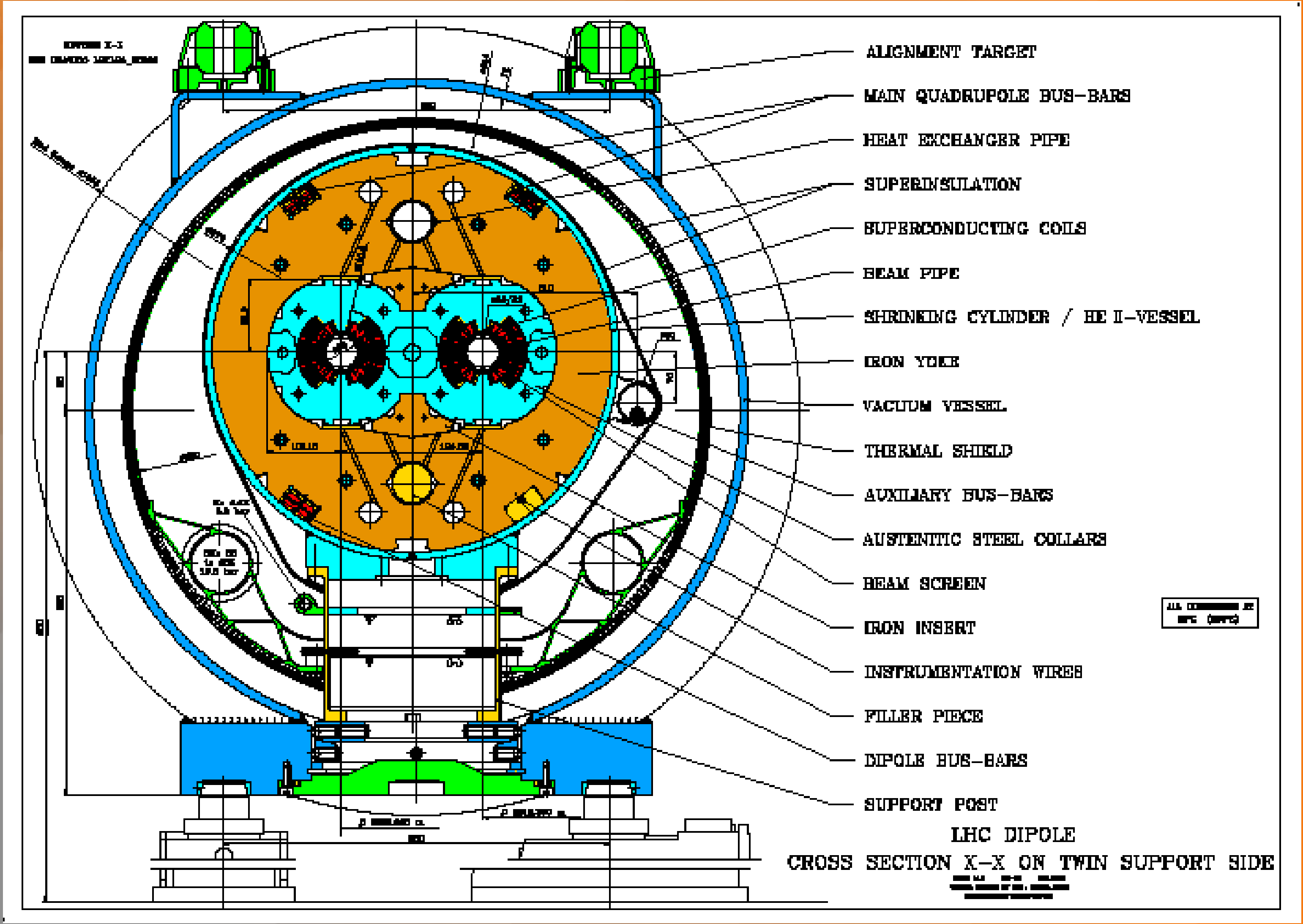
Distribution of conductors in dipole coil

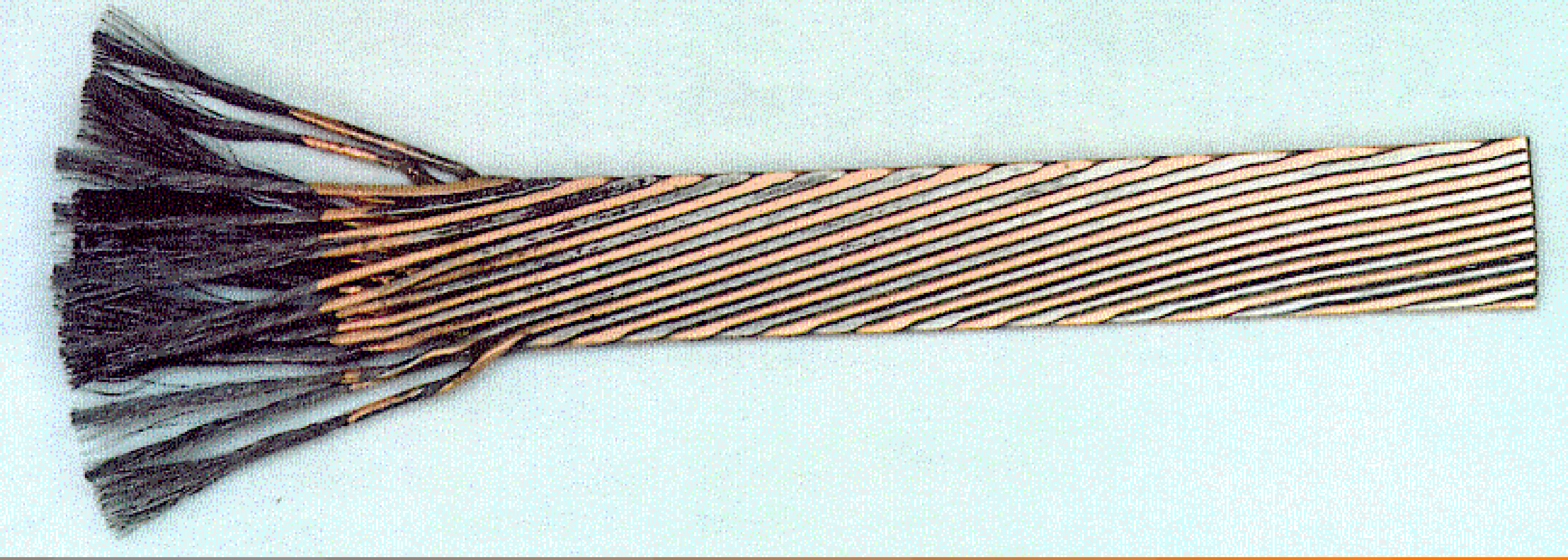


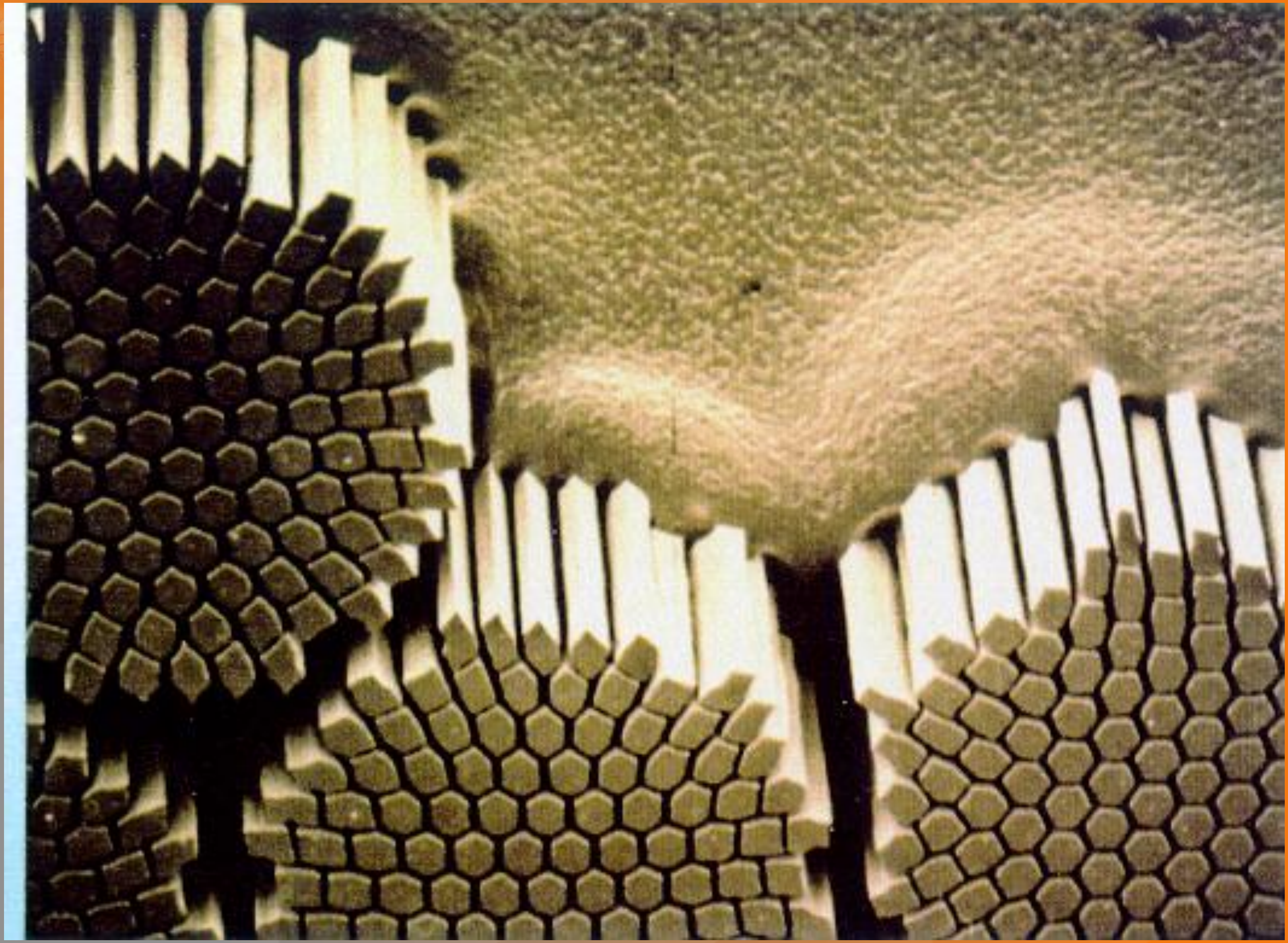
Dipole magnetic flux plot



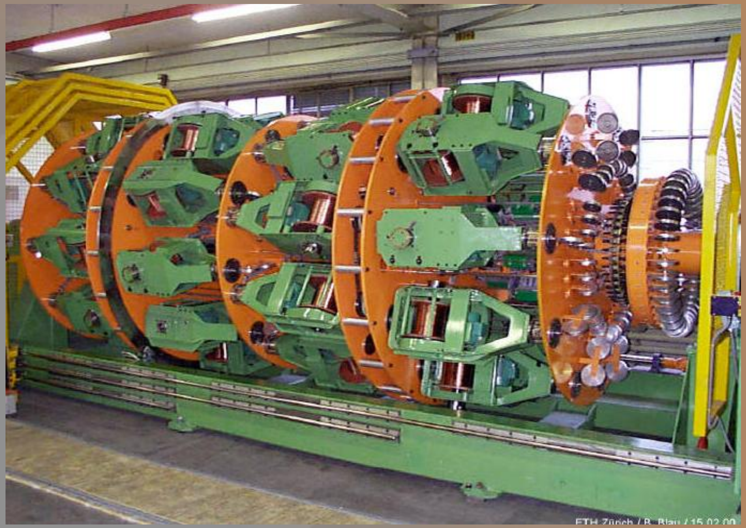
Cross-section of LHC cryodipole







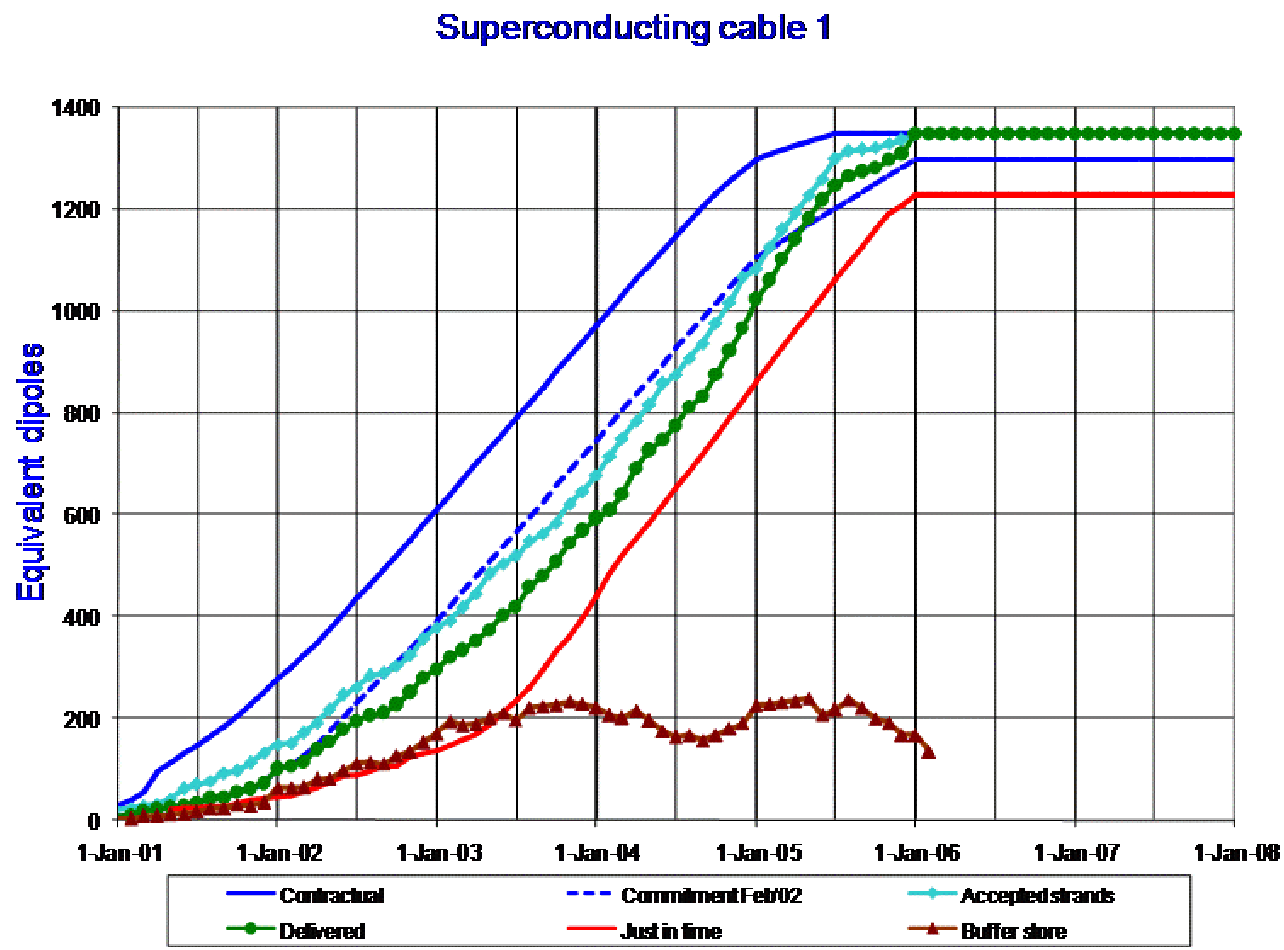
Production of superconducting wires & cables



Superconducting cable 1

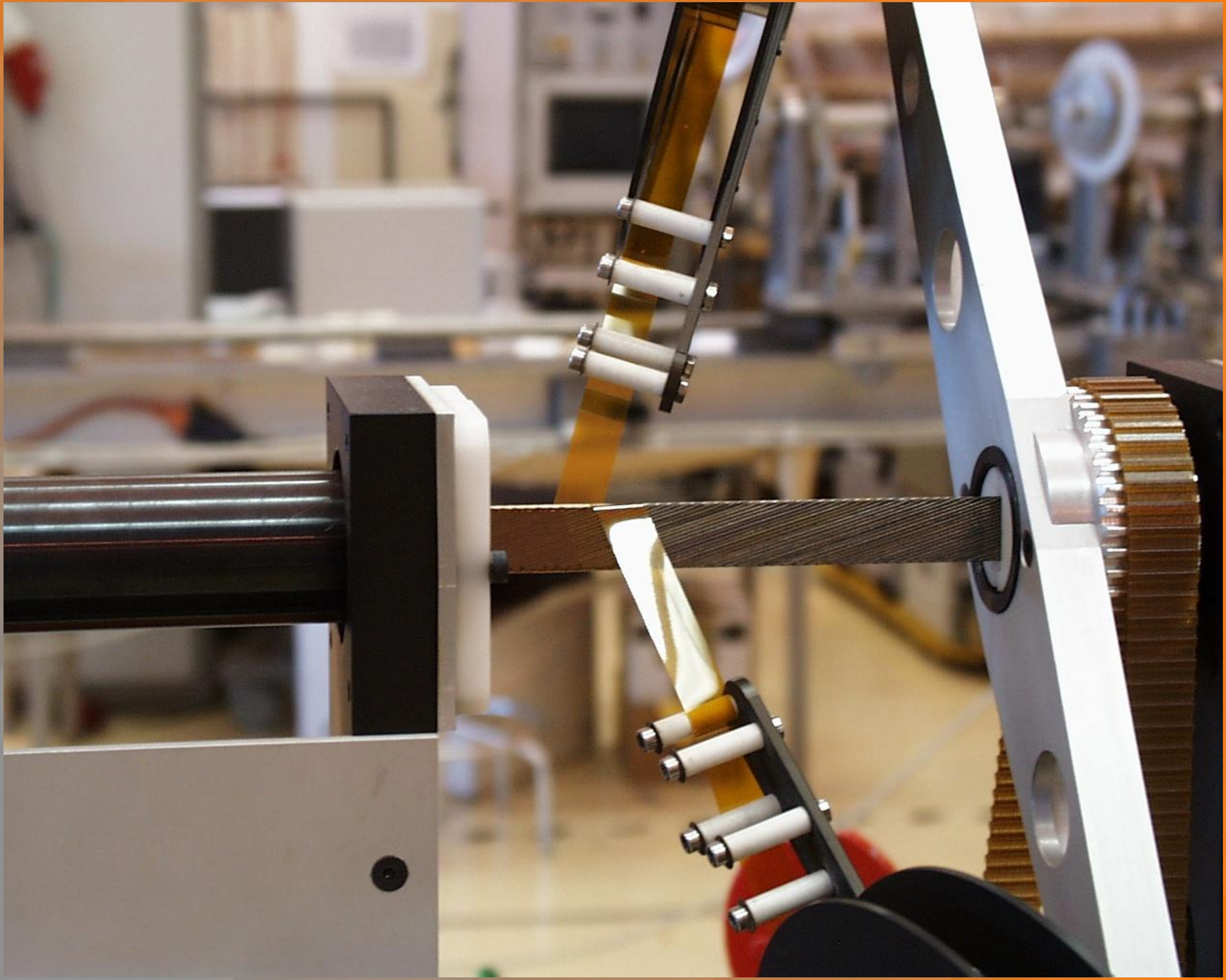
LHC Progress
Dashboard

Accelerator
Technology
Department

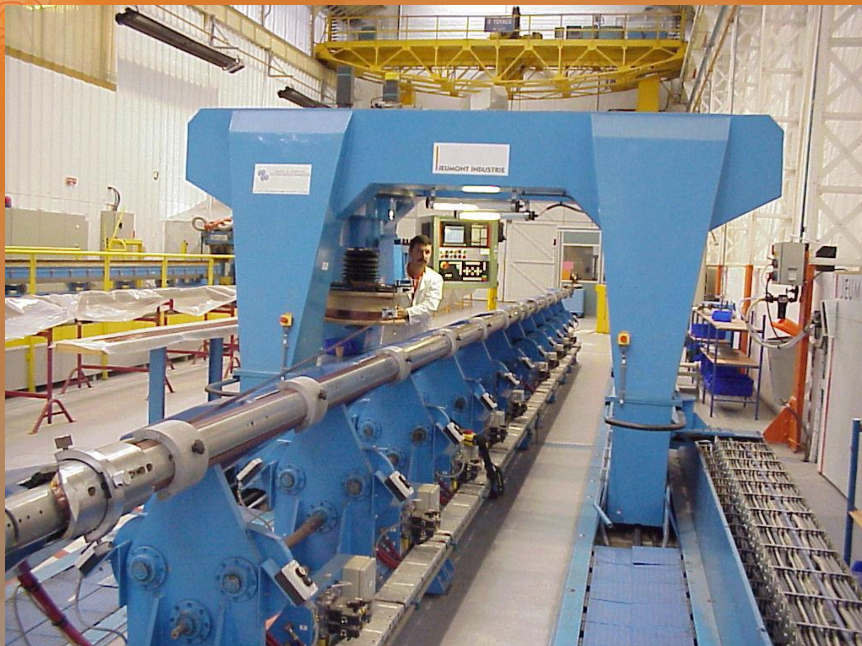


Updated 31 December 2007 Data provided by A. Verweij AT-MCS

Cable insulation by double polyimide wrap



Manufacturing of superconducting coils



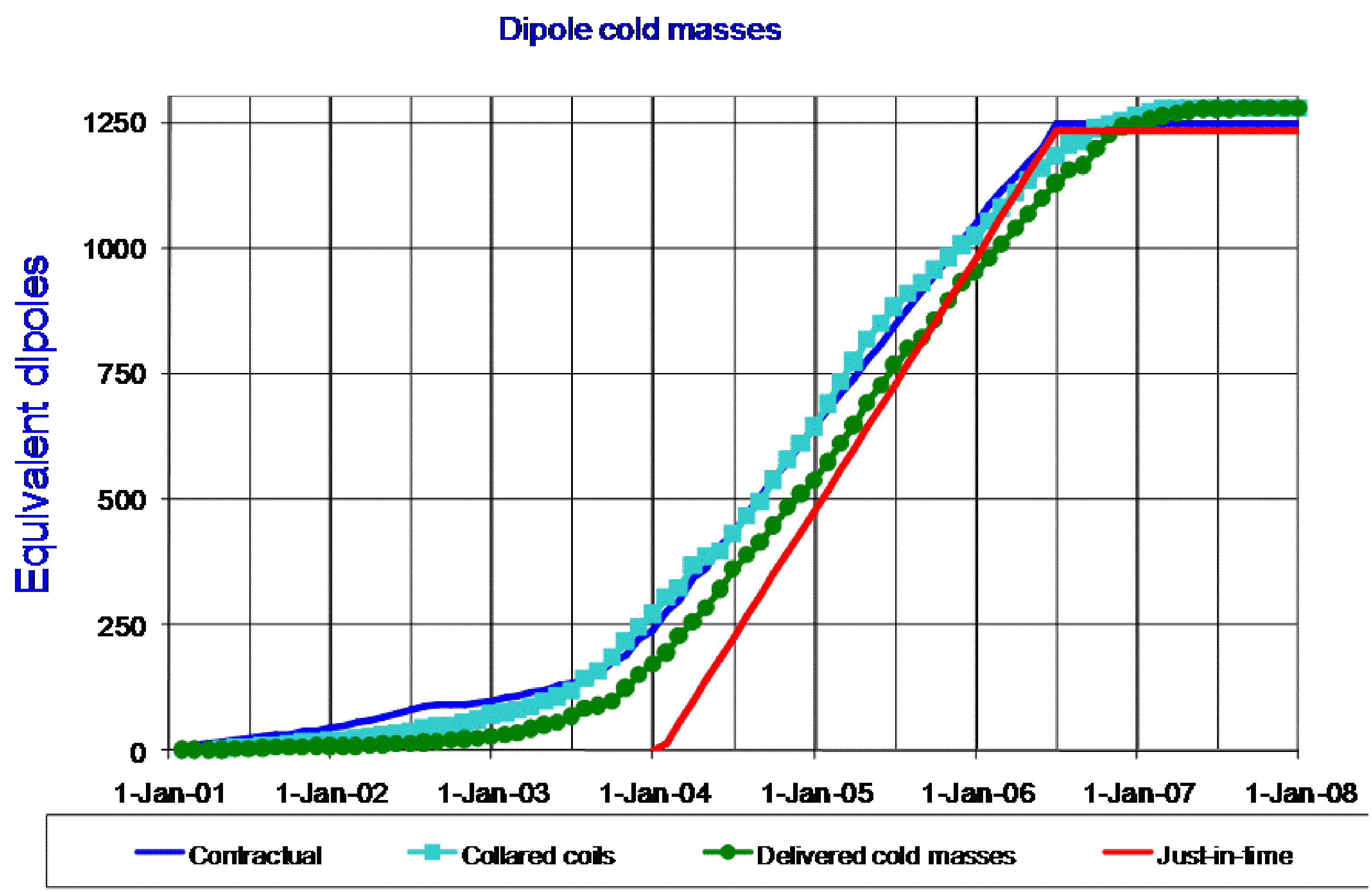
Superconducting coils extracted from mould

Assembly of dipole cold masses

Dipole cold masses

LHC Progress Dashboard

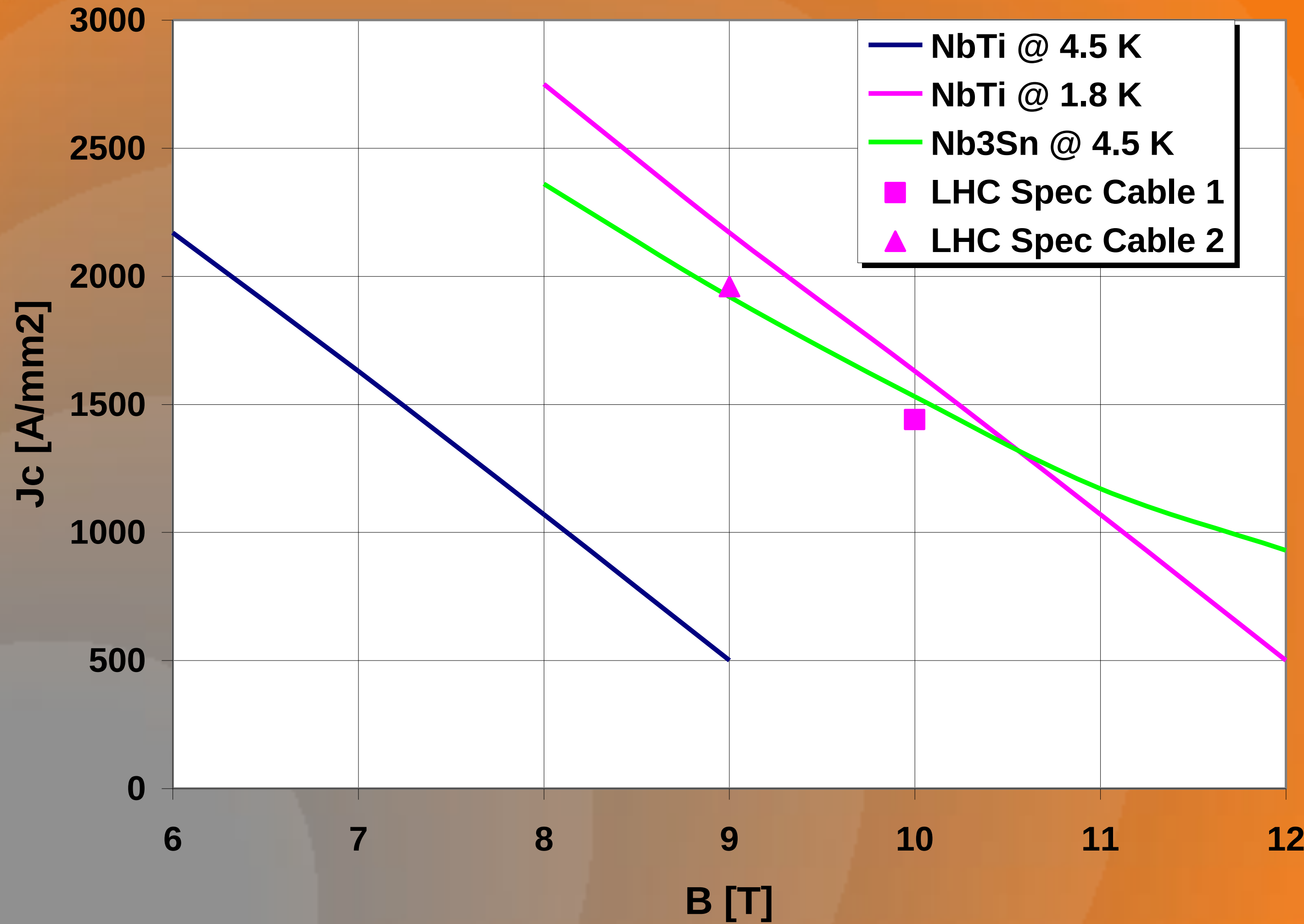
Accelerator Technology Department



Updated 31 December 2007 Data provided by G. de Rijk AT-MCS

Final assembly of cryomagnets at CERN

Critical current density of technical superconductors

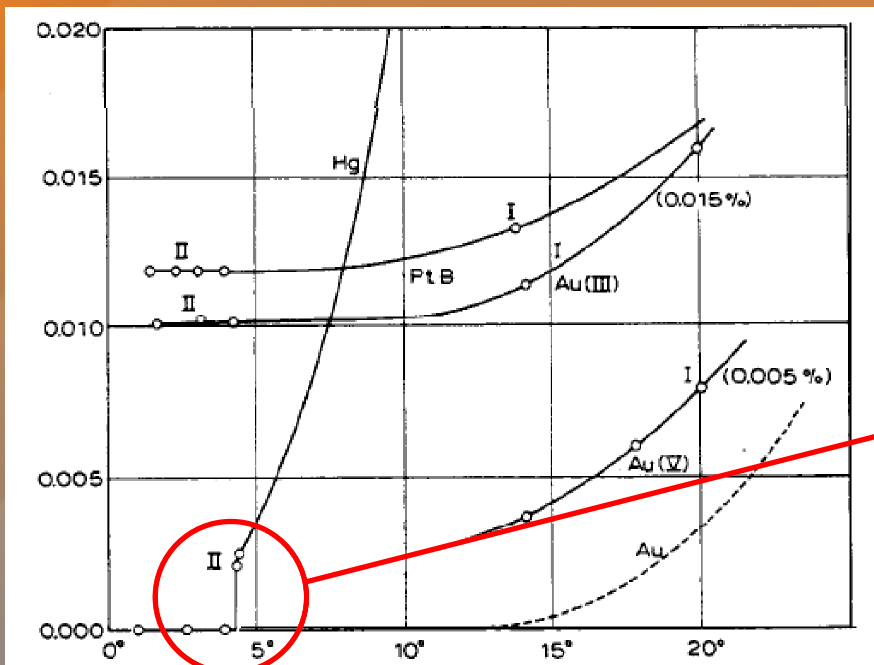


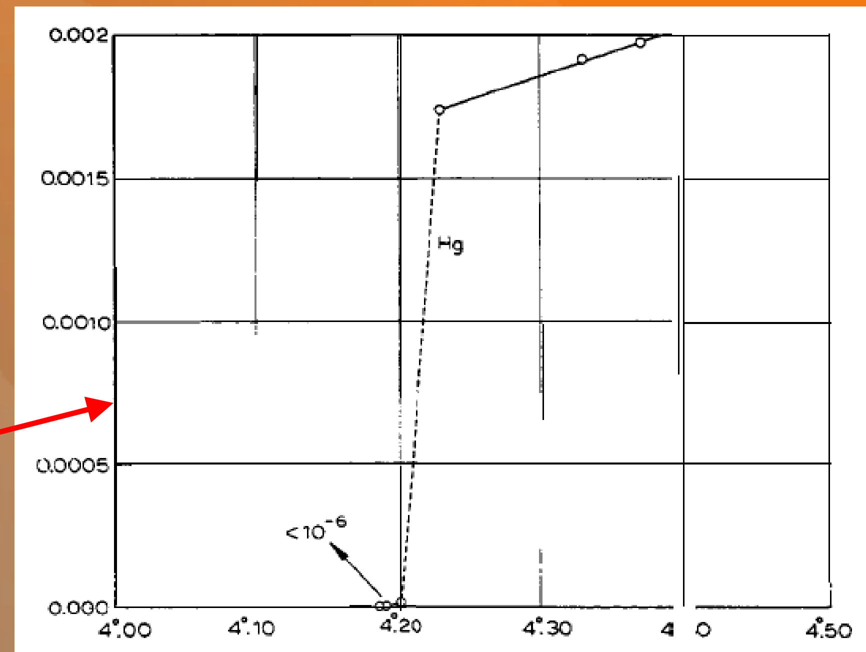
...at the physics laboratory of Leyden, helium was first liquified

Heike Kamerlingh Onnes

"Door meten tot weten"
To knowledge through measurement

Discovery of superconductivity (1911)





Thus the mercury at 4.2°K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity.

Unsuccessful attempt to solidify helium

Naturally the question arose as to whether helium can also be converted into the solid state. An experiment aimed at lowering the temperature of helium sufficiently by evaporating it without supply of heat was not successful, and only served to reach the lowest temperature recorded up to that time.

The evaporation of even a very small quantity, when the pressure of the vapour is small, demands the continuous carrying away of colossal volumes of vapour. With vacuum pumps of very large capacity we succeeded in lowering the pressure to 0.2 millimetre. The temperature then reached was 1.15°K according to the law of vapour pressure found. (Of course we can only make an estimate here. The working out of the thermometry of these low temperatures with, amongst other things, the aid of the Knudsen hot wire manometer is still in its initial stages.) Since it would have needed new equipment, I deferred the question as to whether helium can be made to freeze in favour of other, more urgent problems, which could be tackled with the equipment available.

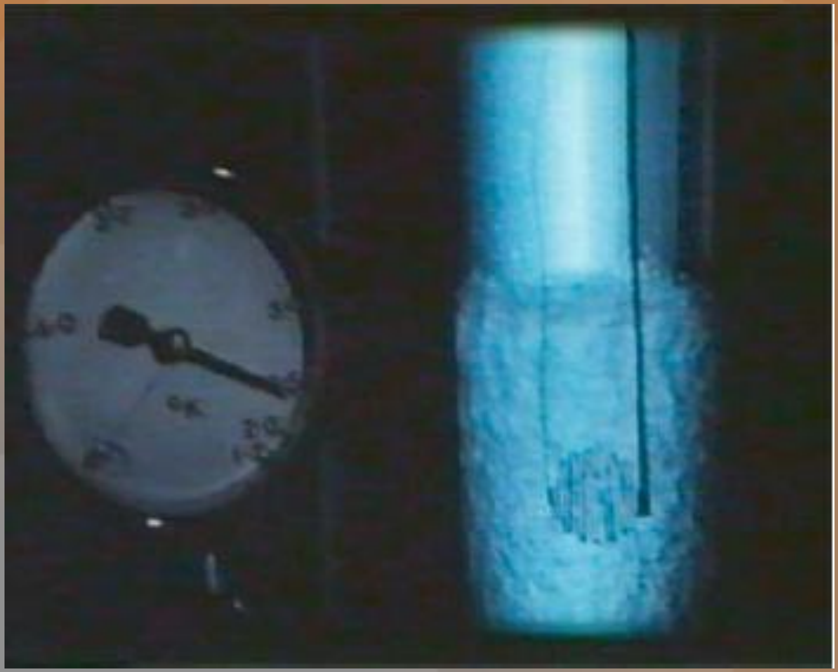
Hint of a quantum effect...?

It is very noticeable that the experiments indicate that the density of the helium, which at first quickly drops with the temperature, reaches a maximum at 2.2°K approximately, and if one goes down further even drops again. Such an extreme could possibly be connected with the quantum theory.

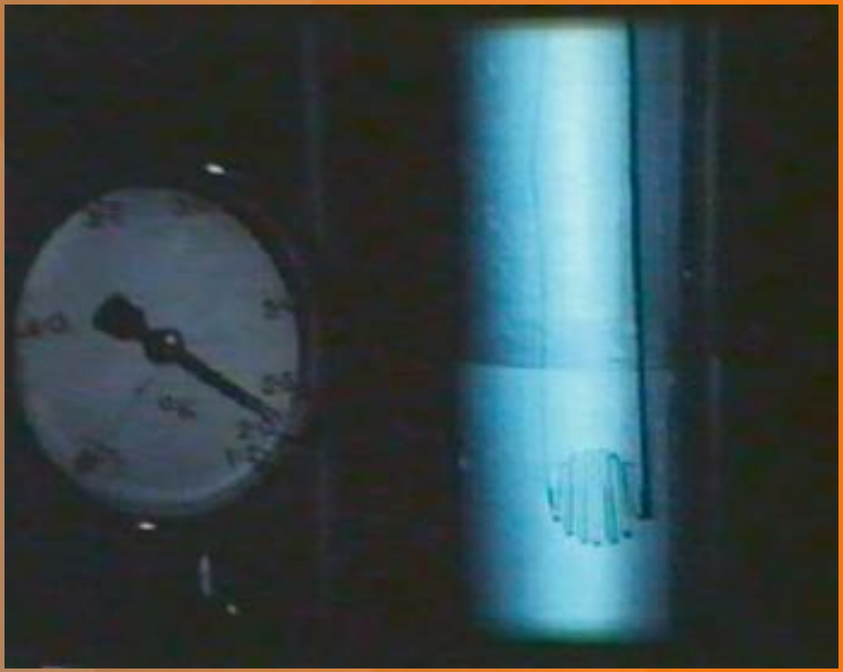
Discovery of superfluidity in He II (1938)

J.F. Allen & A.D. Misener (Cambridge)
P.L. Kapitsa (Moscow)

Vaporization of liquid helium



He I (T=2.4 K)



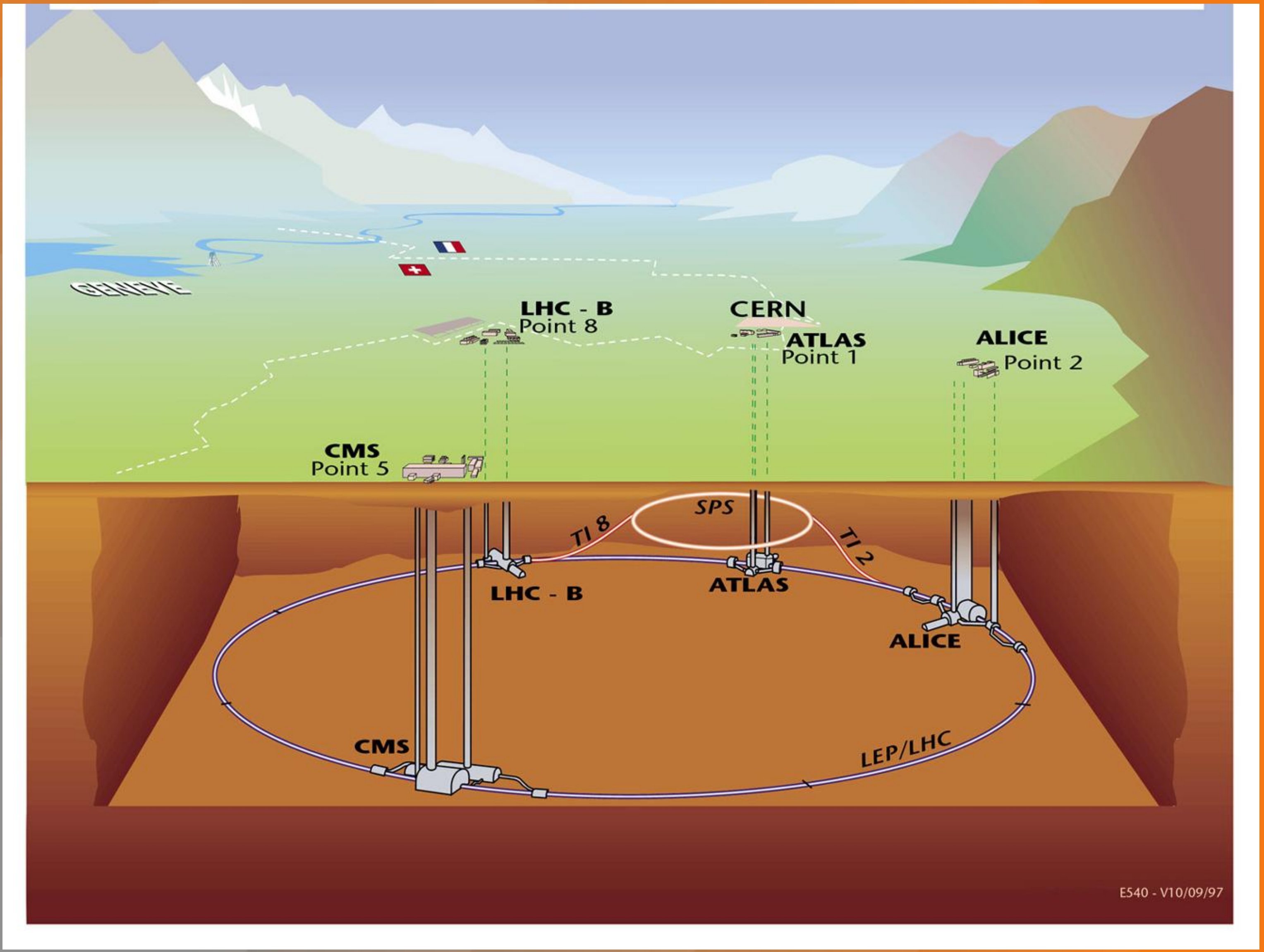
He II (T=2.1 K)

J. F. Allen

« In my PhD work in Toronto on superconductivity, I had often seen the sudden cessation of boiling at the lambda temperature T_λ but had paid it no particular attention. It never occured to me that it was of fundamental significance. »

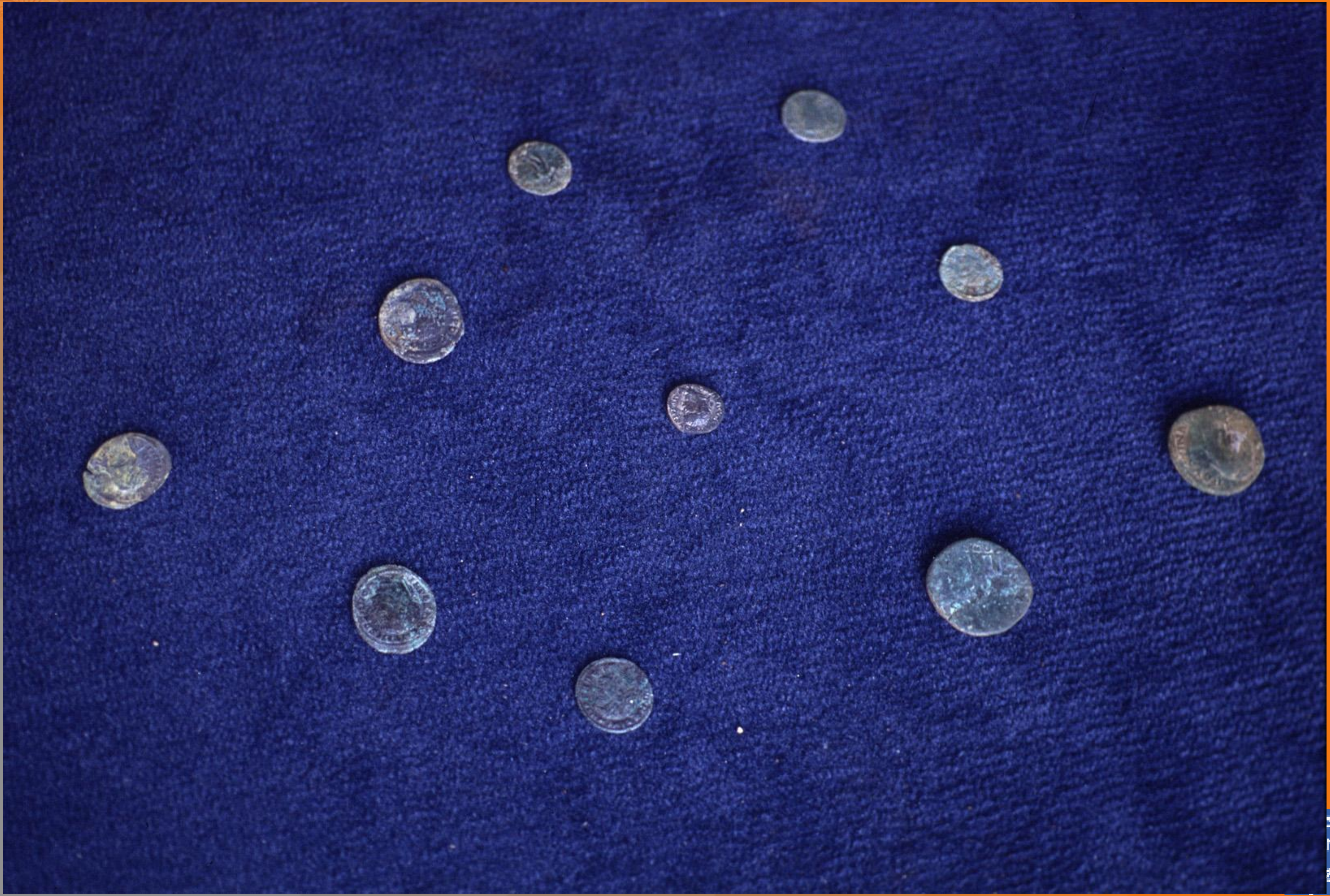
J. Allen, Physics World, November 1988, p 29.

The LHC and its detectors



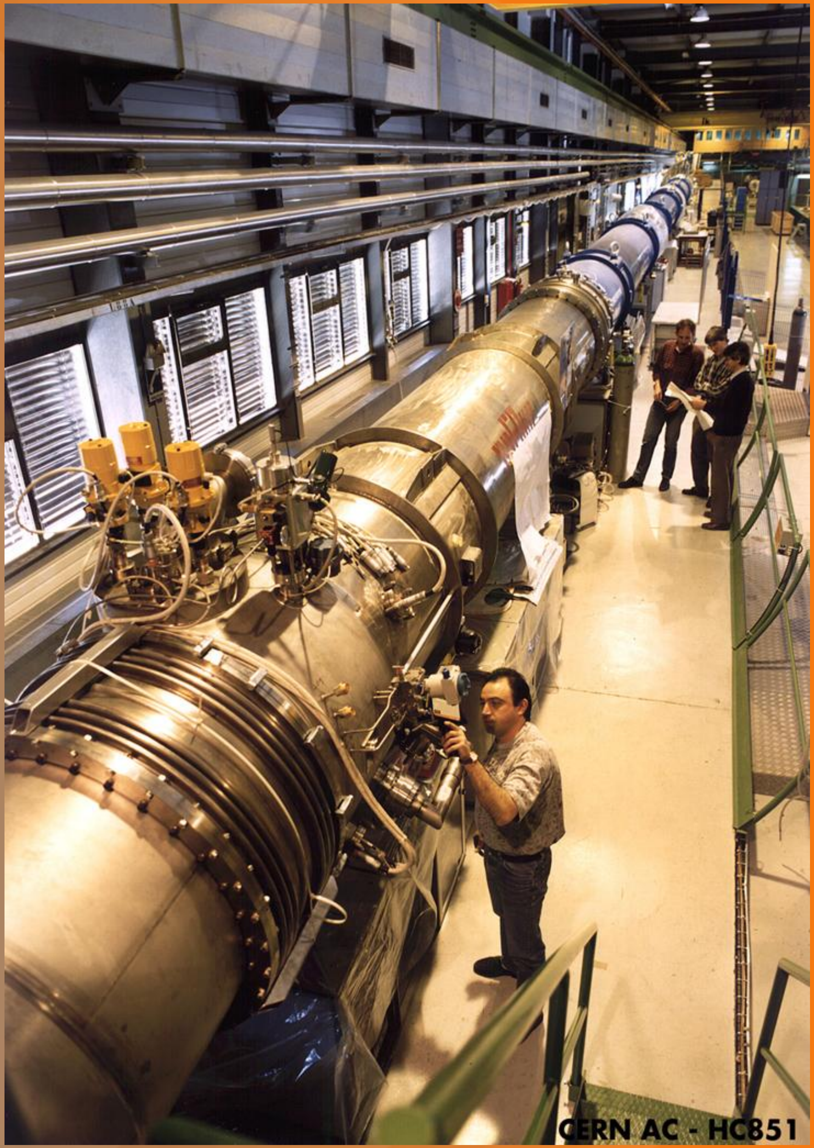
Aerial view of Point 5
Gallo-roman vestiges 1998

Roman coins found during archeological excavations at Point 5



December 1998

Four years after its start-up, the first test string of the LHC comes to the end of its operation. Composed of prototypes, it made it possible to test and validate the various components and systems of the LHC.



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Point 1 - UX15 cavern - Concreting of vault panel n°2 - April 10, 2001 - CERN ST-CE

LHC Point 1 - UX 15 Cavern - Concrete walls 6th lift - 20-02-2003 - CERN ST-CE

Point 5 -Excavation commencement of PM54 shaft - July 09, 1999 - CERN ST-CE

Point 5 - UXC55 cavern excavation - LEP demolition - January 23, 2002 - CERN ST-CE

TI2 Area - Start of excavation of PMI 2 shaft - February 17, 1999 - CERN ST-CE

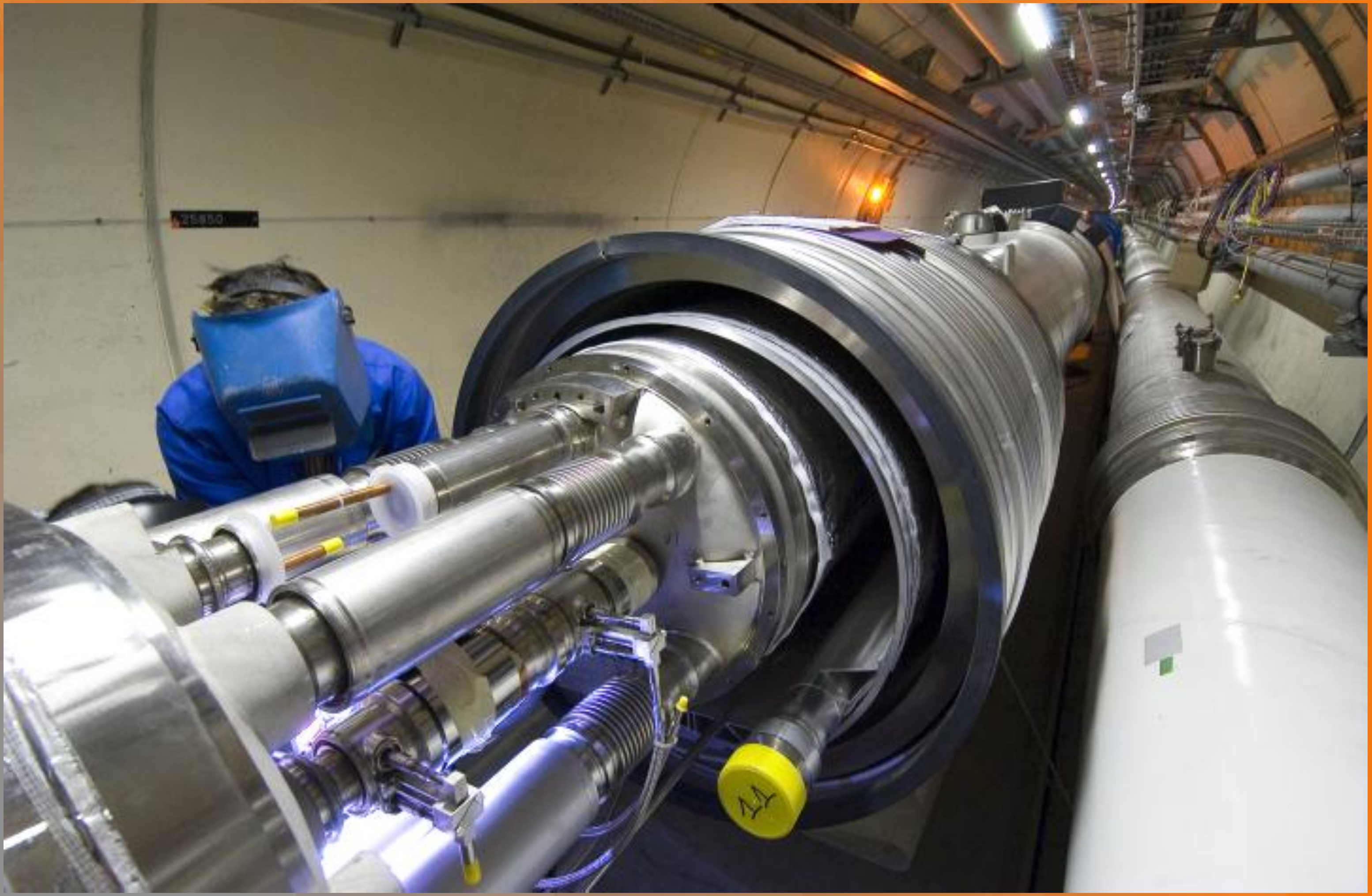
QRL crisis June 2004

Magnet rows

Magnet rows

Dipole-dipole interconnect: electrical splices

Dipole-dipole interconnect



Inner triplet crisis Feb 2005

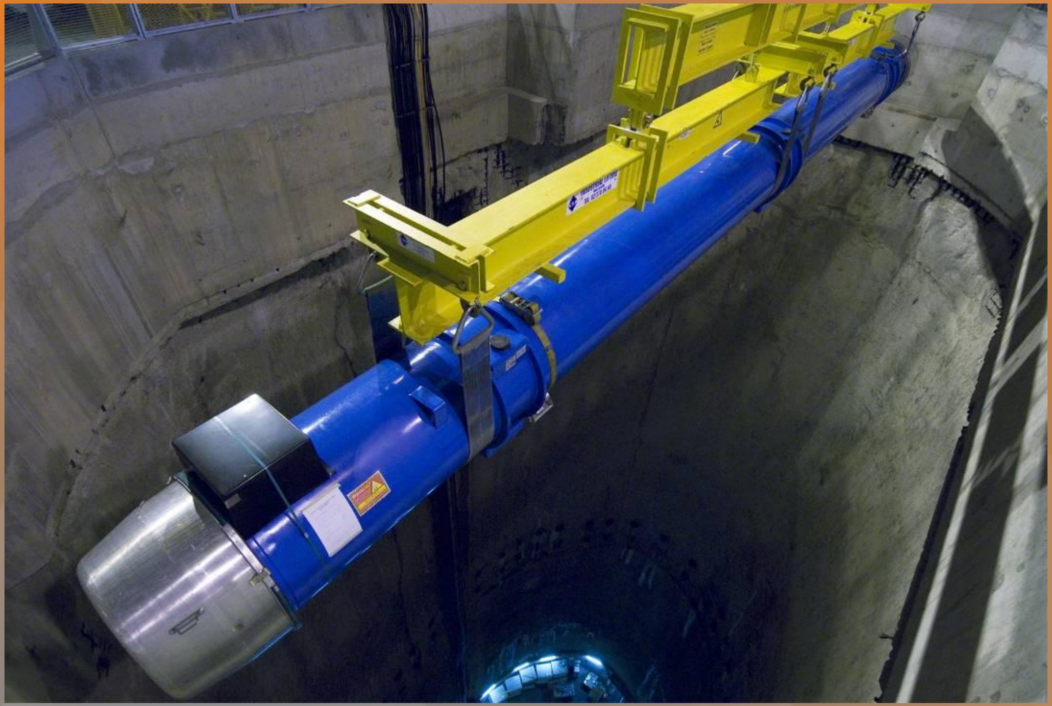
Quarks and Photons: The Strangest Little Things in Nature

FOX NEWS.COM, THURSDAY, NOVEMBER 09, 2006

AP

The CERN Large Hadron Collider in Geneva, Switzerland, which will be the world's largest particle accelerator when it enters full operation in 2008.

Descent of the last magnet, 26 April 2007



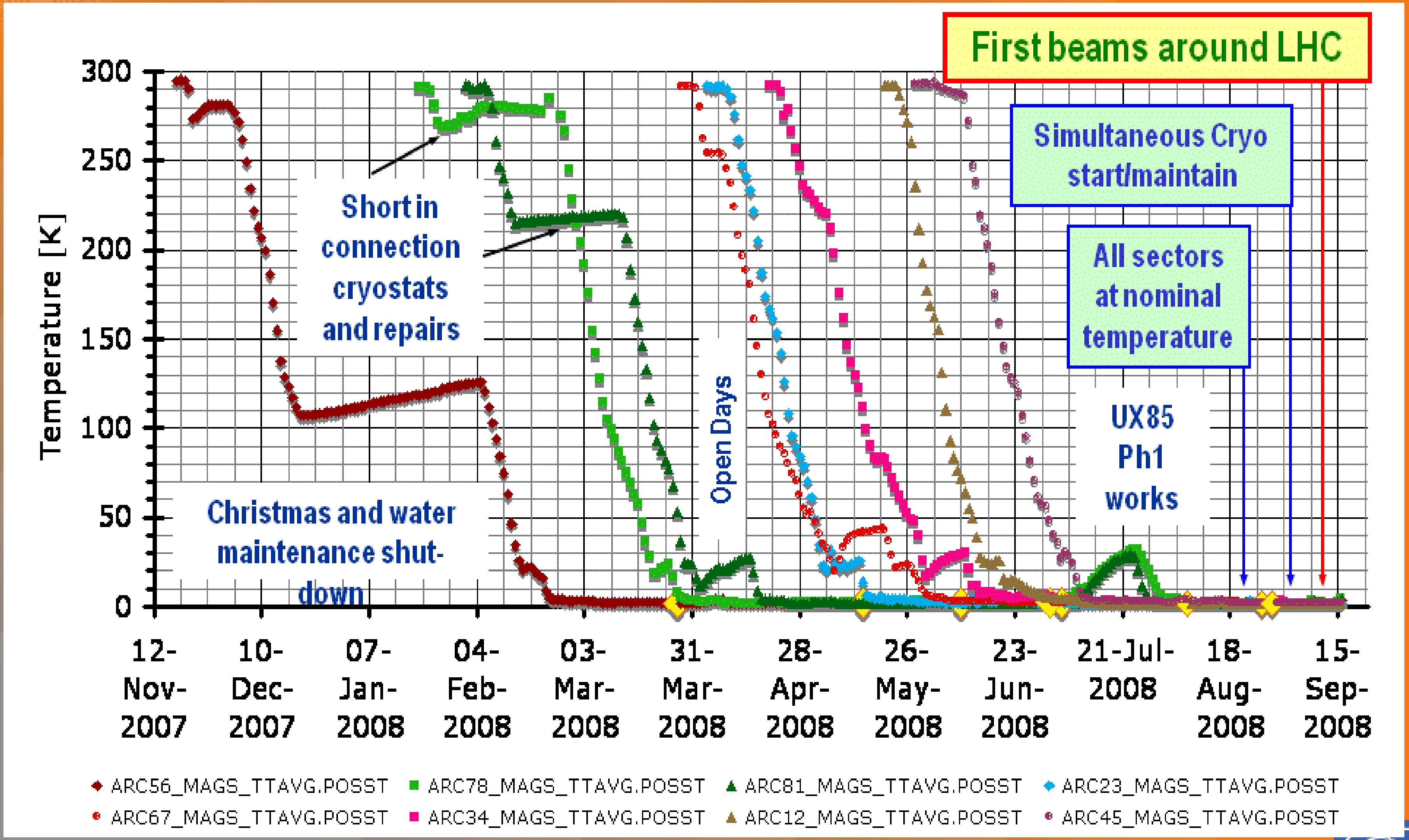
30’000 km underground at 2 km/h!

Cooldown of LHC sector (4625 t over 3.3 km)

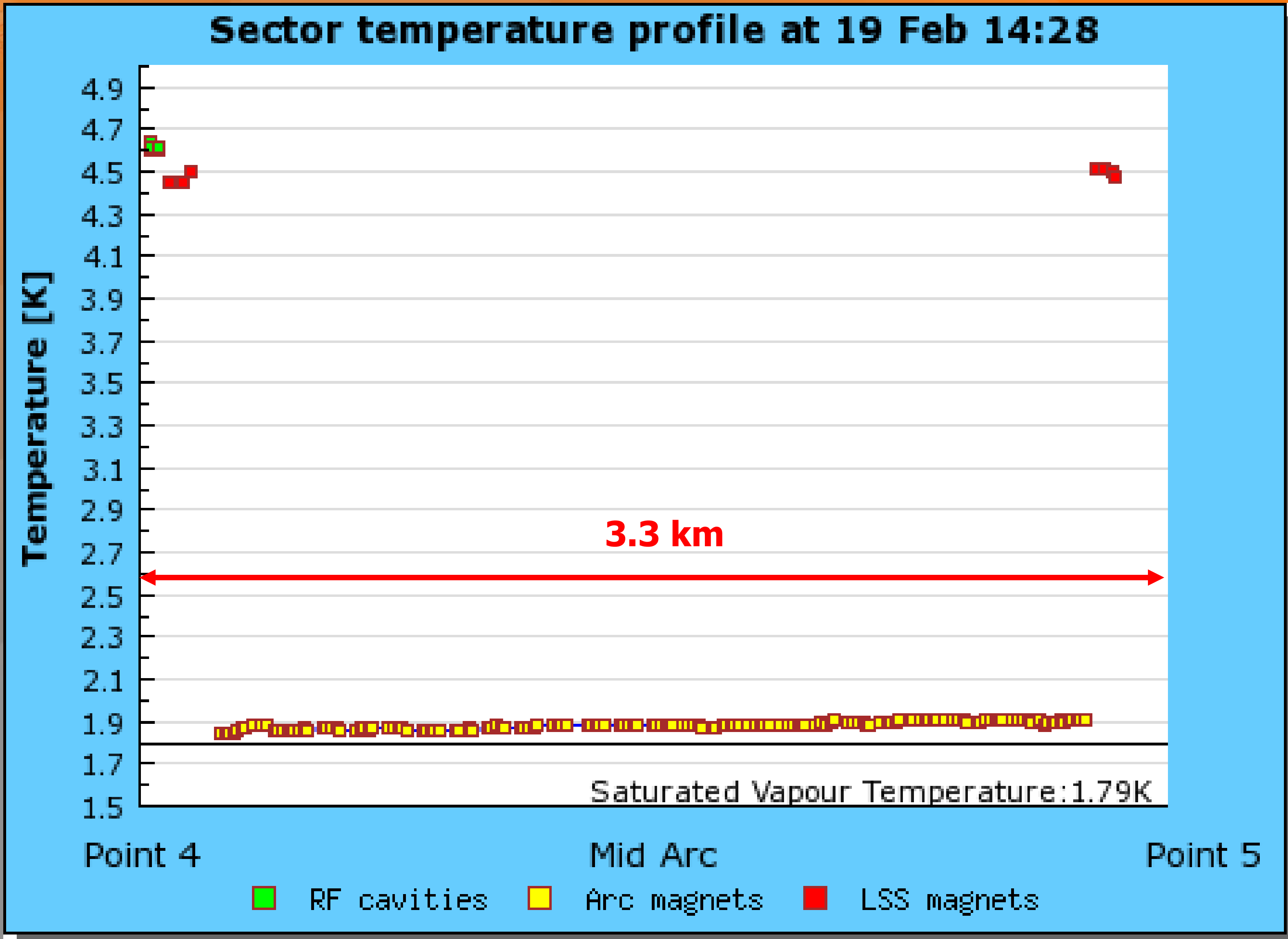
Unloading of LHe & LN2

600 kW precooling to 80 K with LN2 (up to ~5 tons/h)

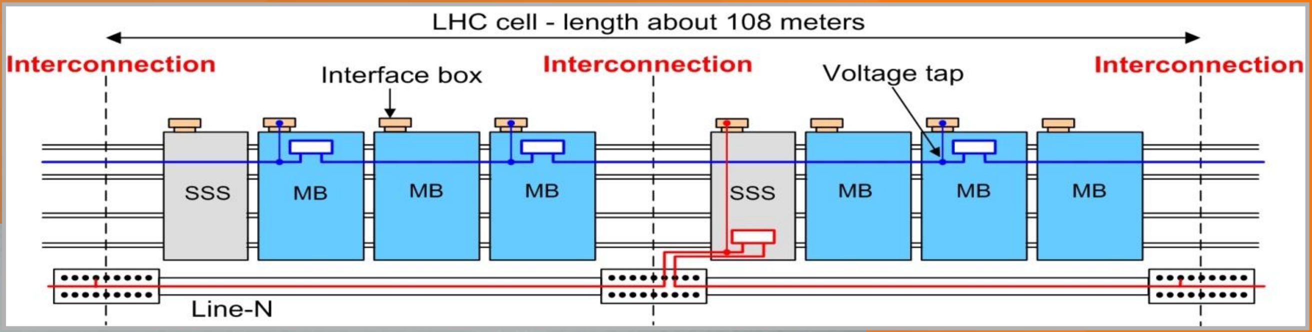
First cool-down of LHC sectors

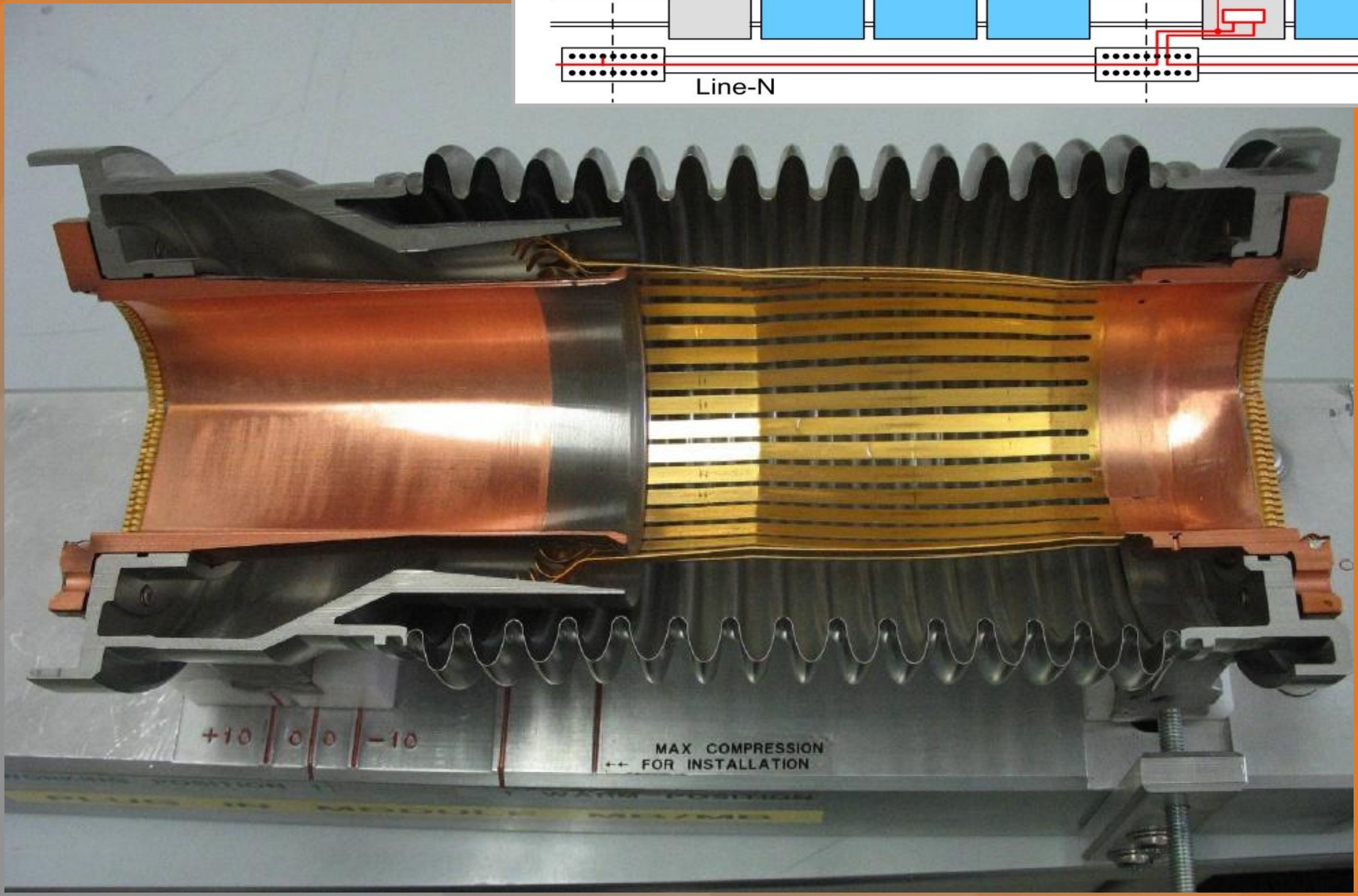


Cryogenic operation of LHC sector

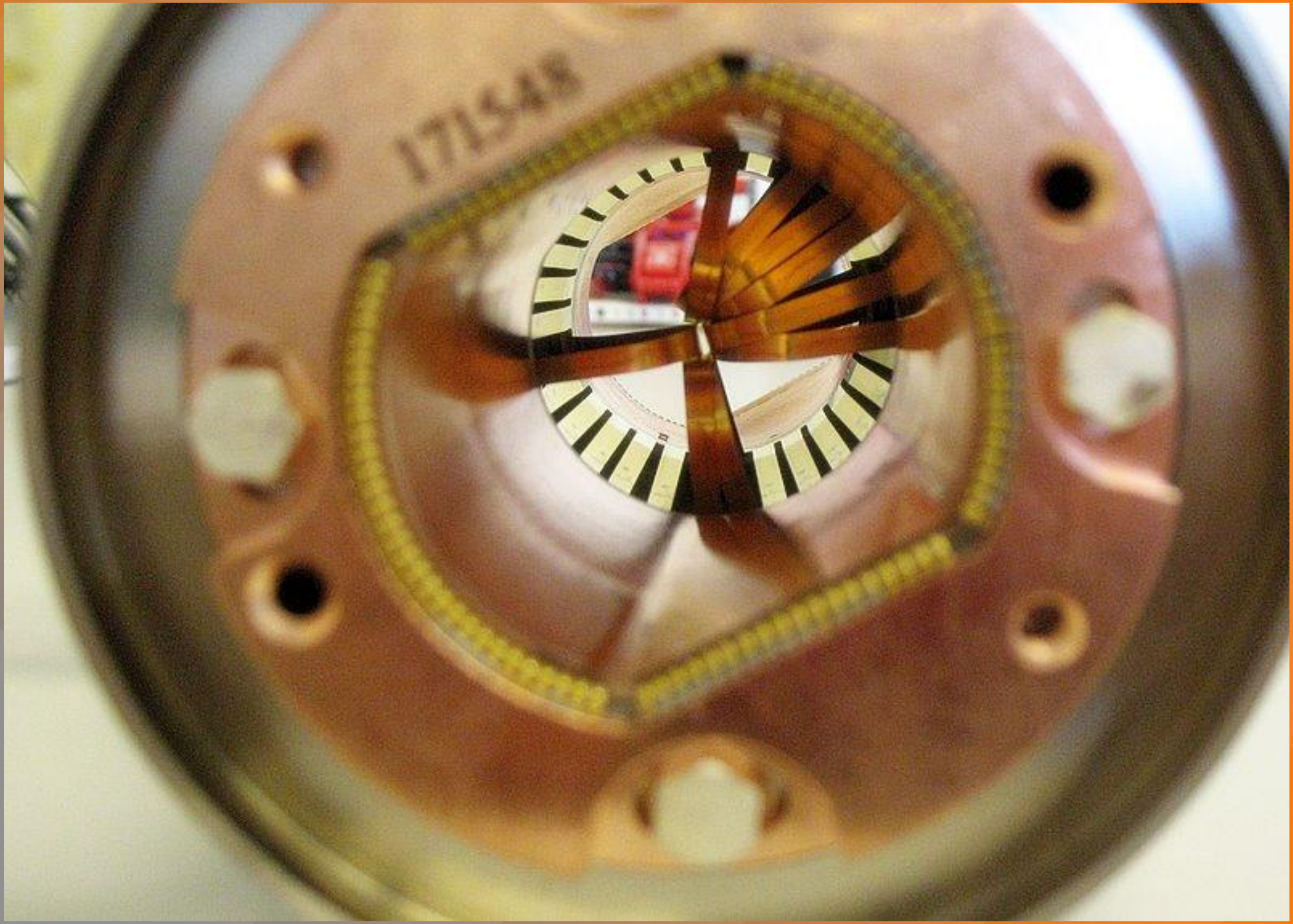


The crisis of the PIM's

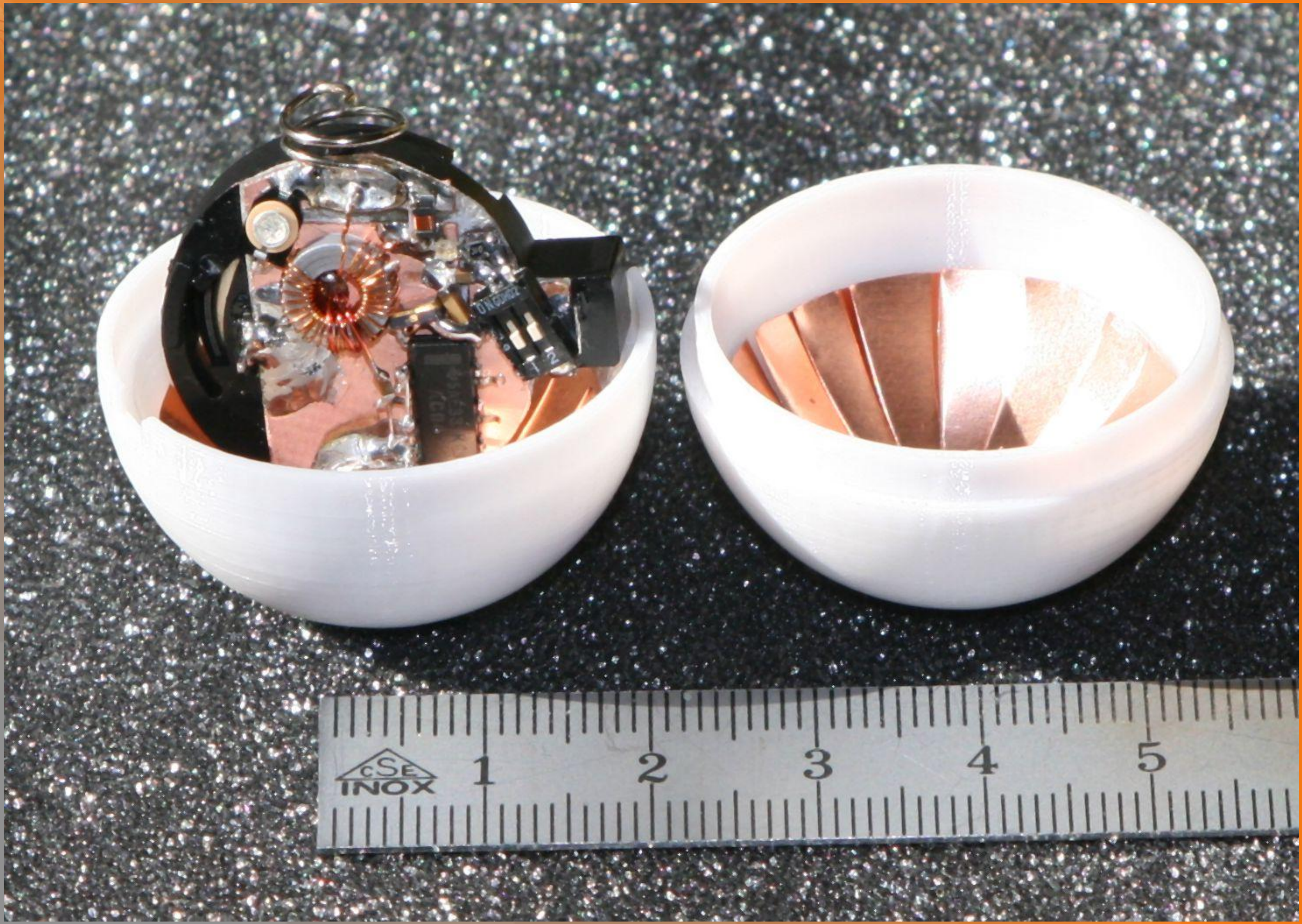




Arc plug-in module with damaged fingers

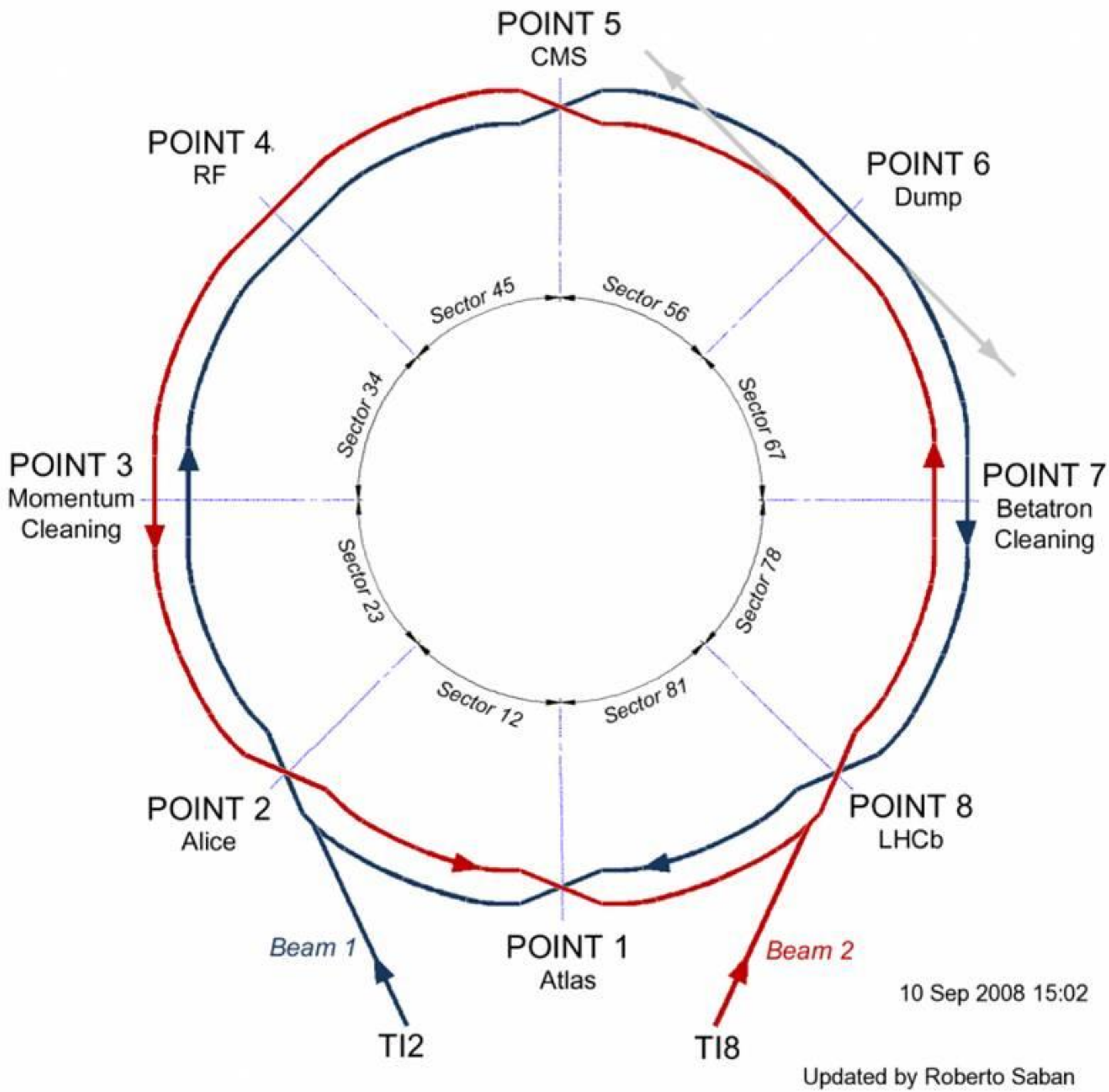


Transmitter ball



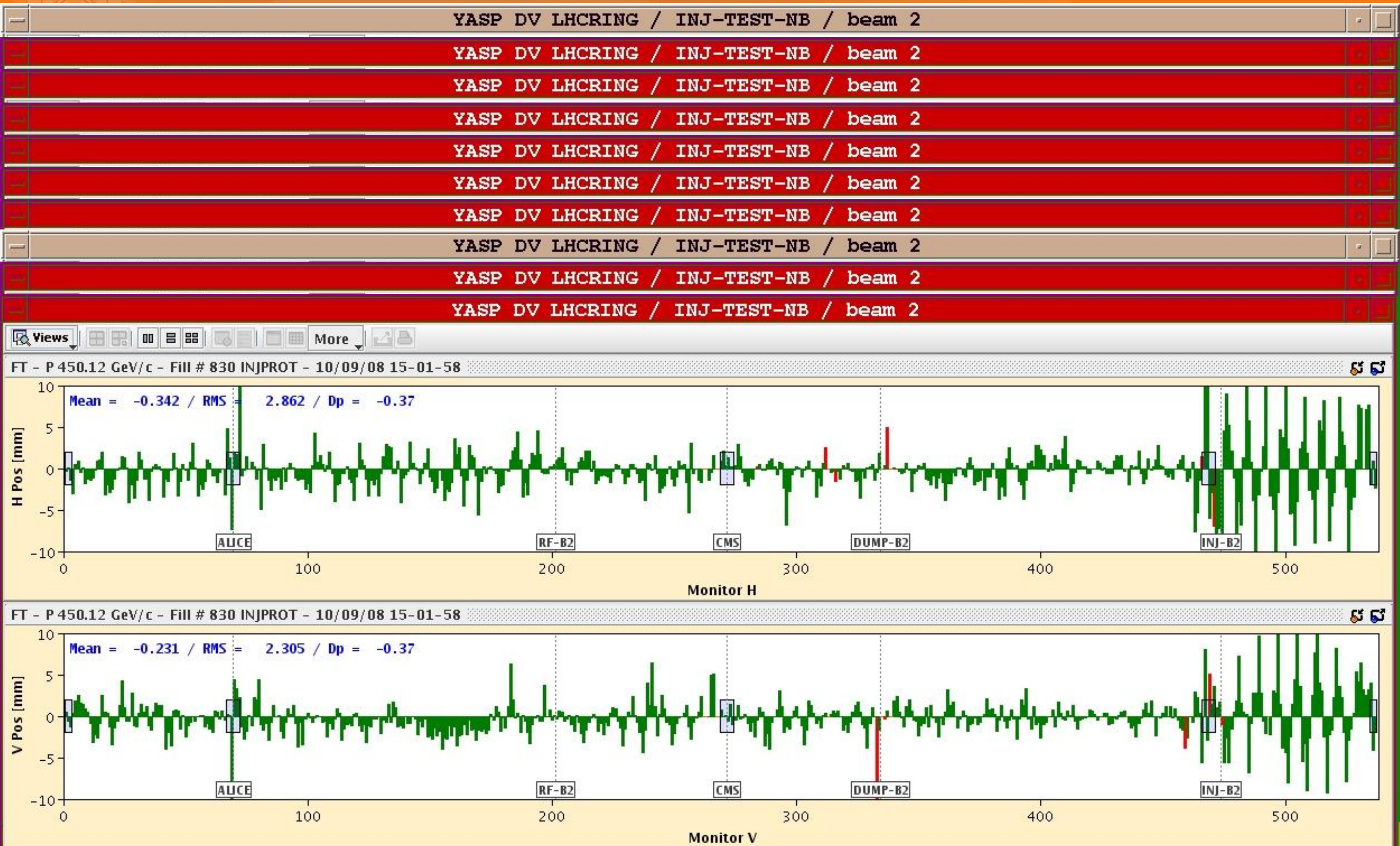
Situation on 10th September

- 7 out of 8 sectors fully commissioned for 5 TeV operation and 1 sector (3-4) commissioned up to 4 TeV.

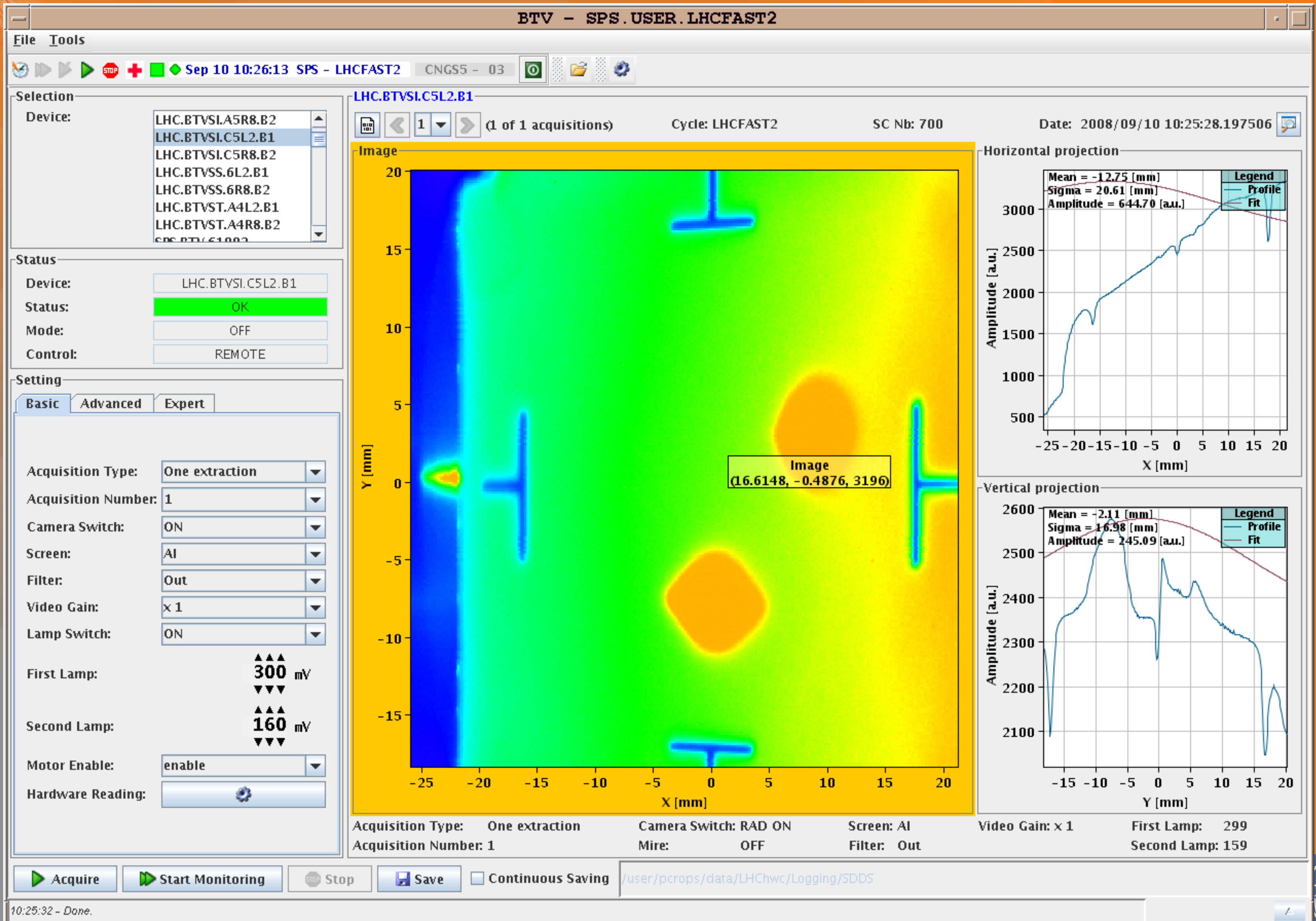


POINT 5
CMS
POINT 4
RF
POINT 6
Dump
Sector 45
Sector 56
Sector 34
Sector 67
POINT 3
Momentum
Cleaning
POINT 7
Betatron
Cleaning
Sector 23
Sector 78
Sector 12
Sector 81
POINT 2
Alice
POINT 8
LHCb
Beam 1
POINT 1
Atlas
Beam 2
10 Sep 2008 15:02
TI2
TI8
Updated by Roberto Saban

Beam 2 first beam – D-Day

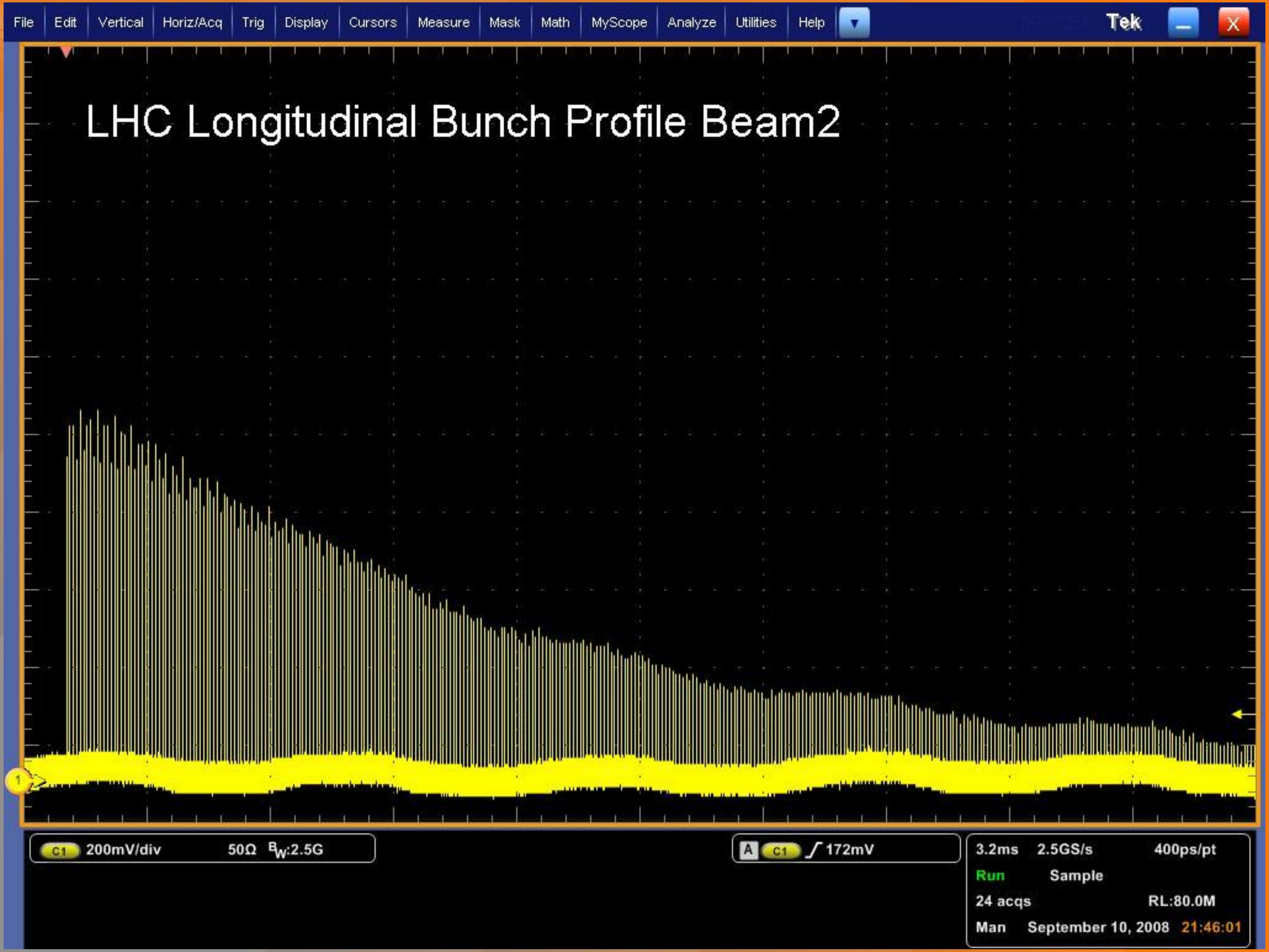


Beam on turns 1 and 2



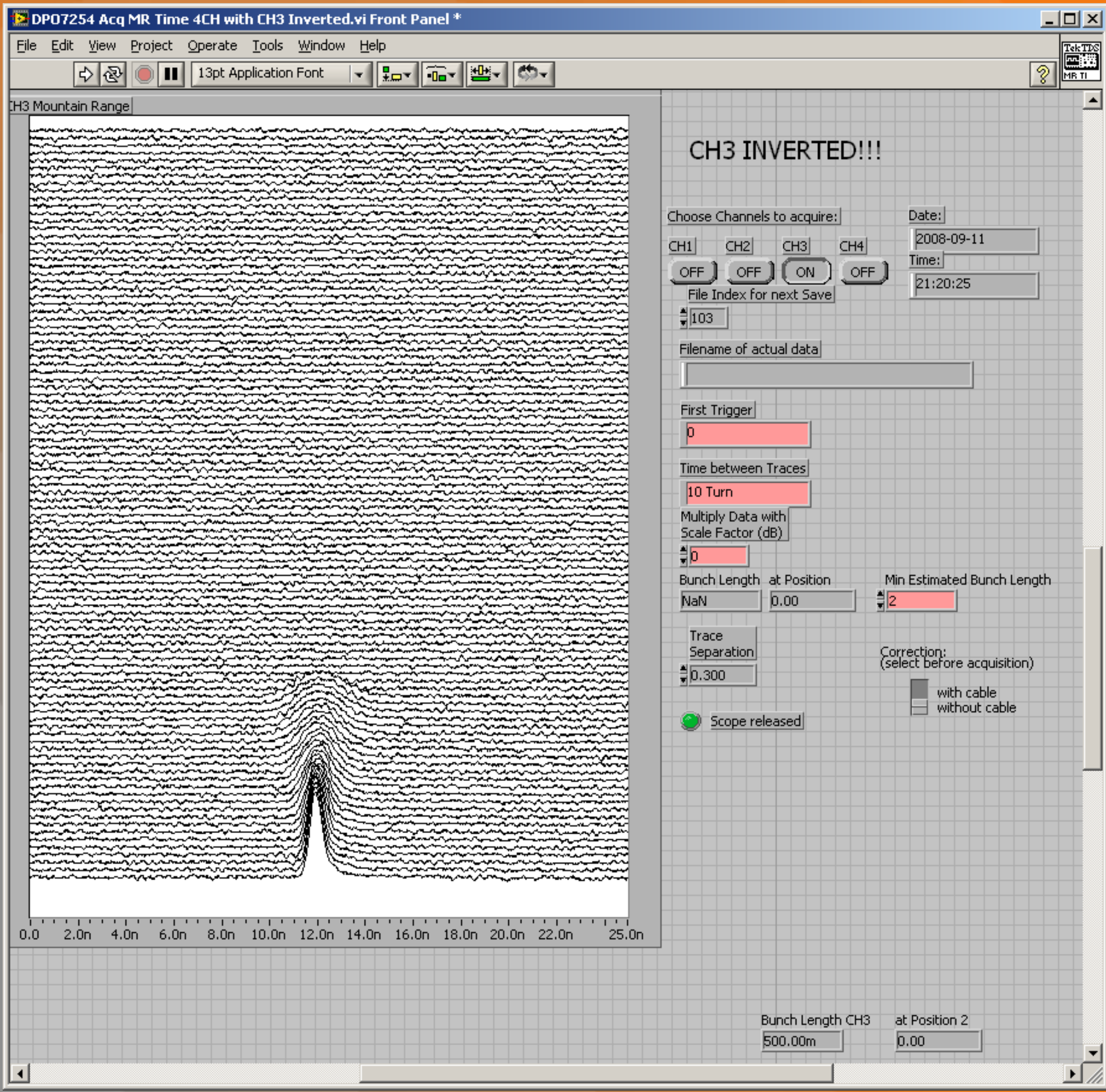
Courtesy R. Bailey

Few 100 turns



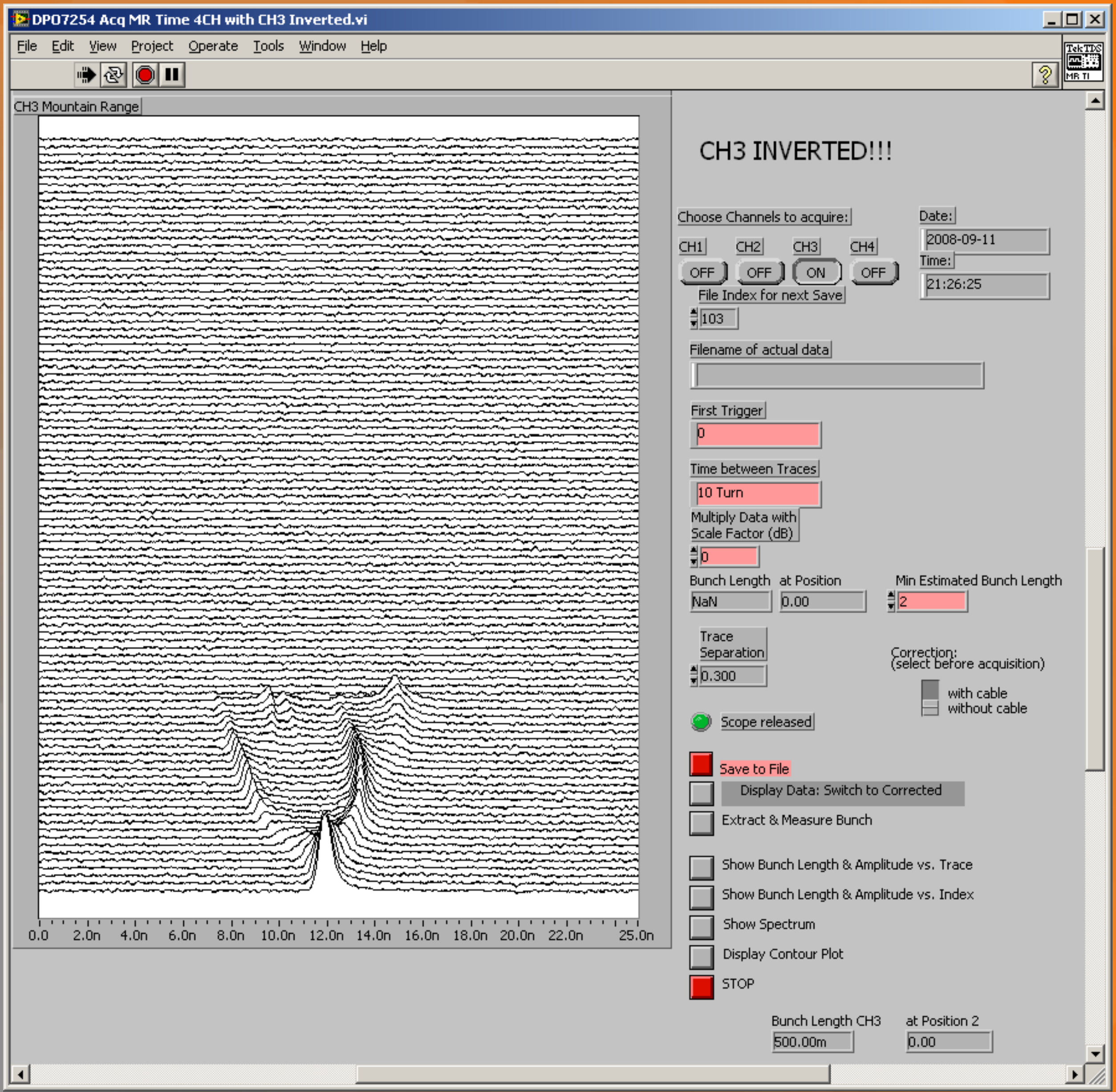
Courtesy R. Bailey

No RF, debunching in ~ 25*10 turns, i.e. roughly 25 mS



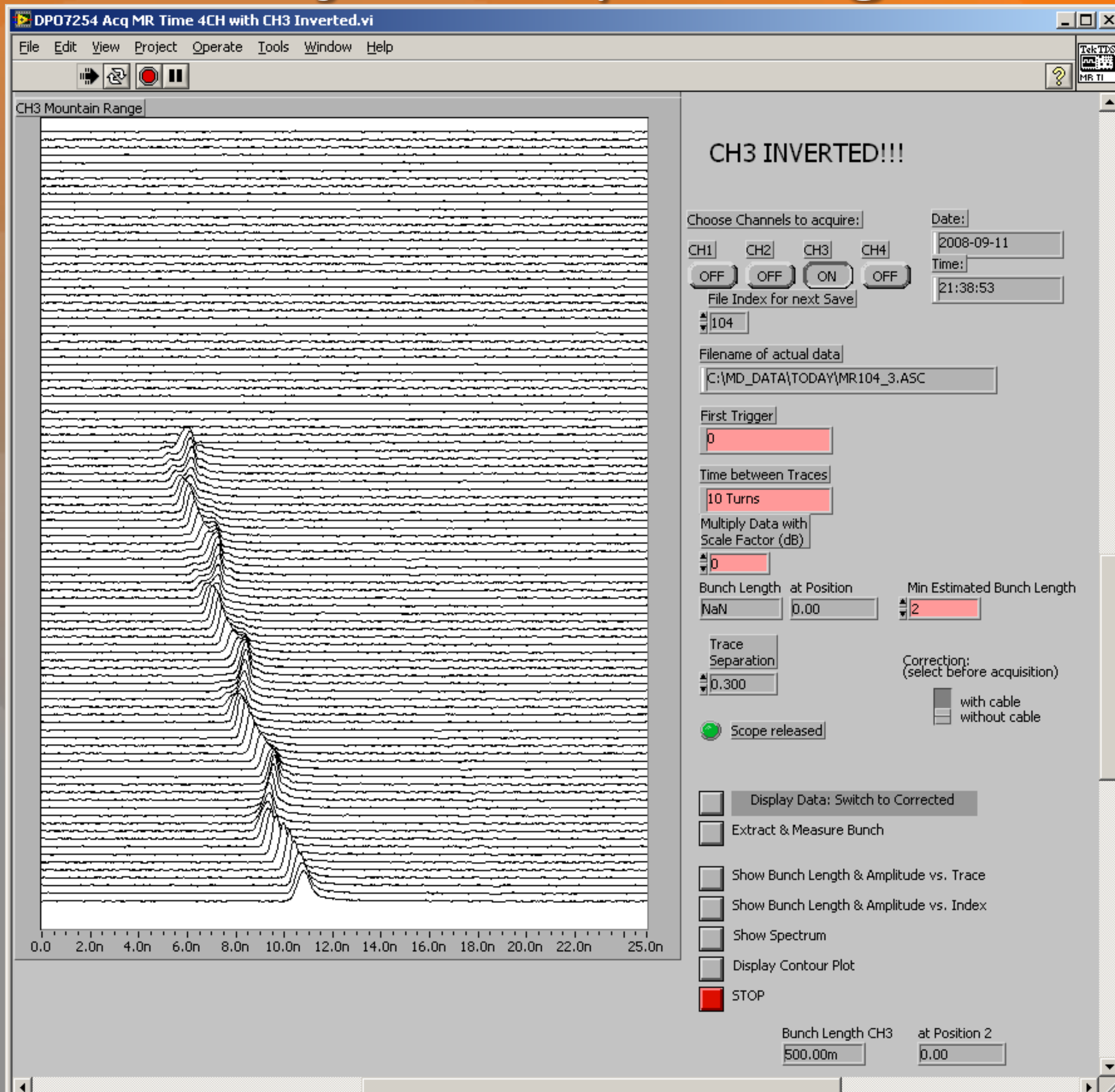
 Courtesy E. Ciapala

First attempt at capture, at exactly the wrong injection phase…



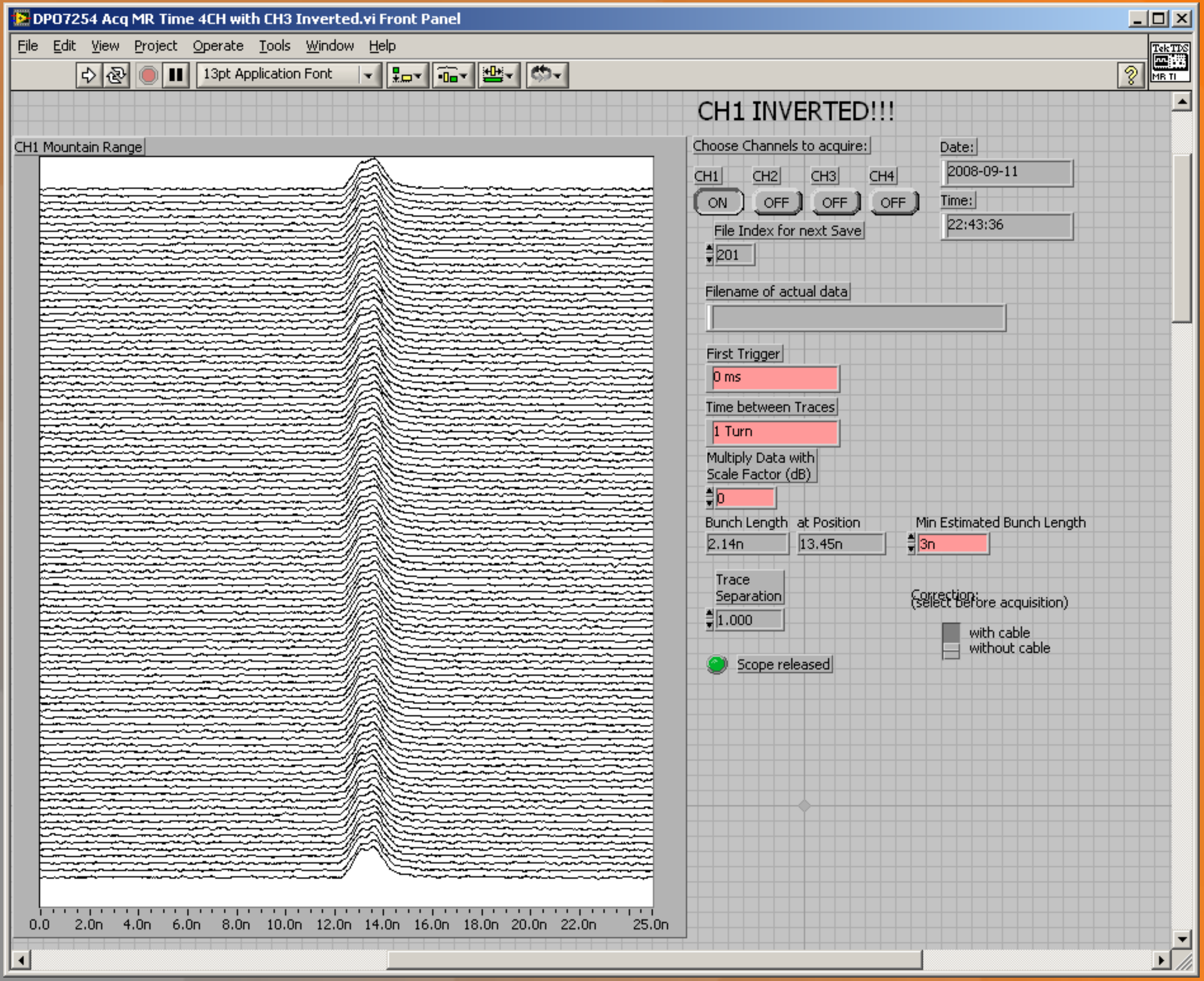
Courtesy E. Ciapala

Capture with corrected injection phasing



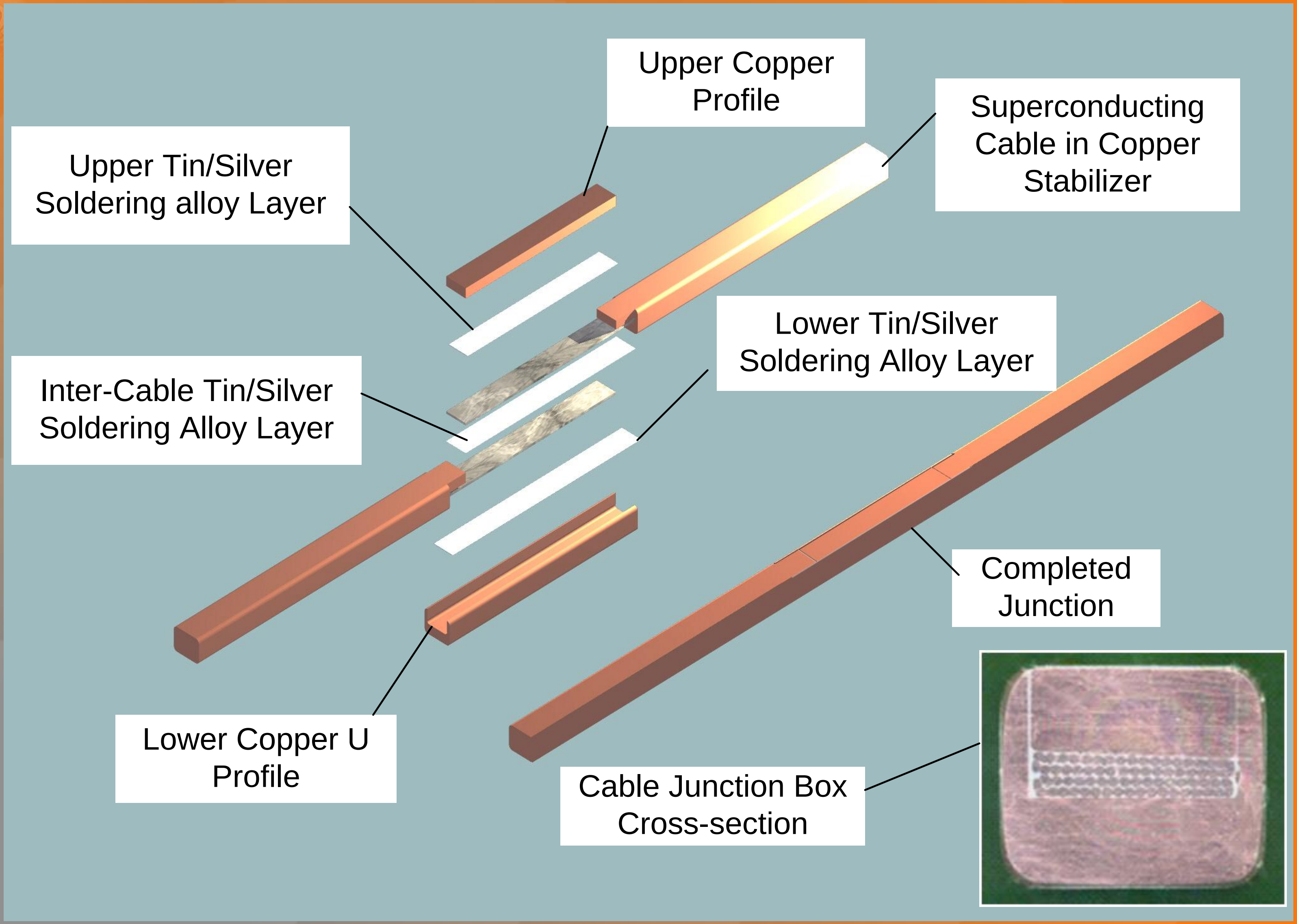
Courtesy E. Ciapala

Capture with optimum injection phasing, correct reference

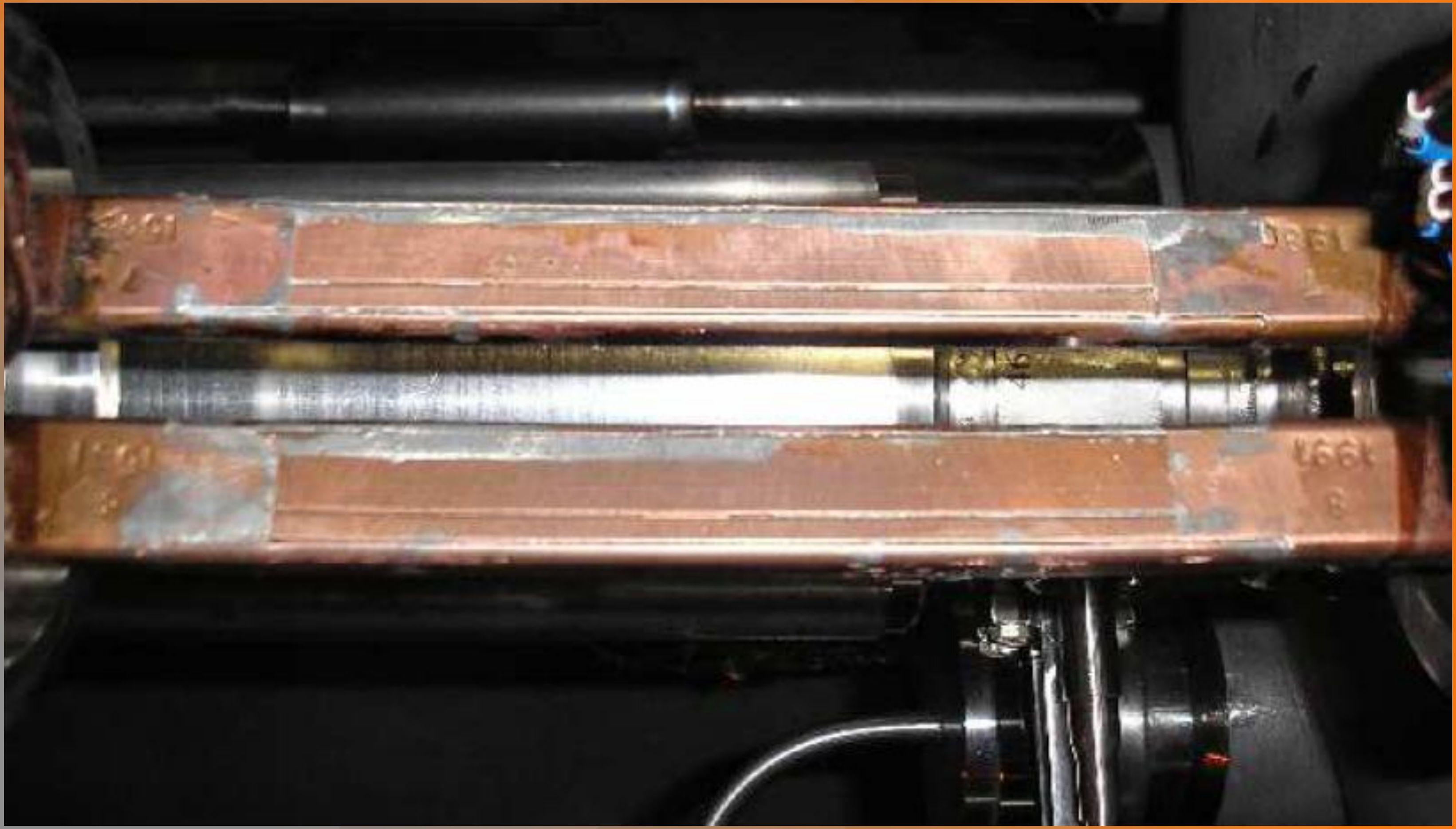


Courtesy E. Ciapala

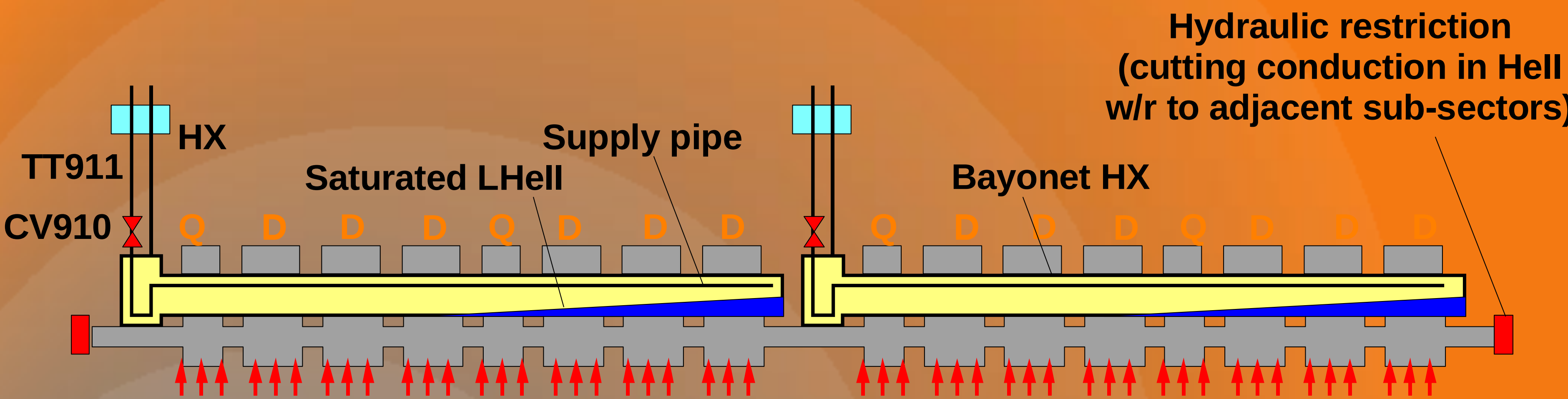
Busbar splice



Busbar splice



Sub-sector magnet cooling scheme

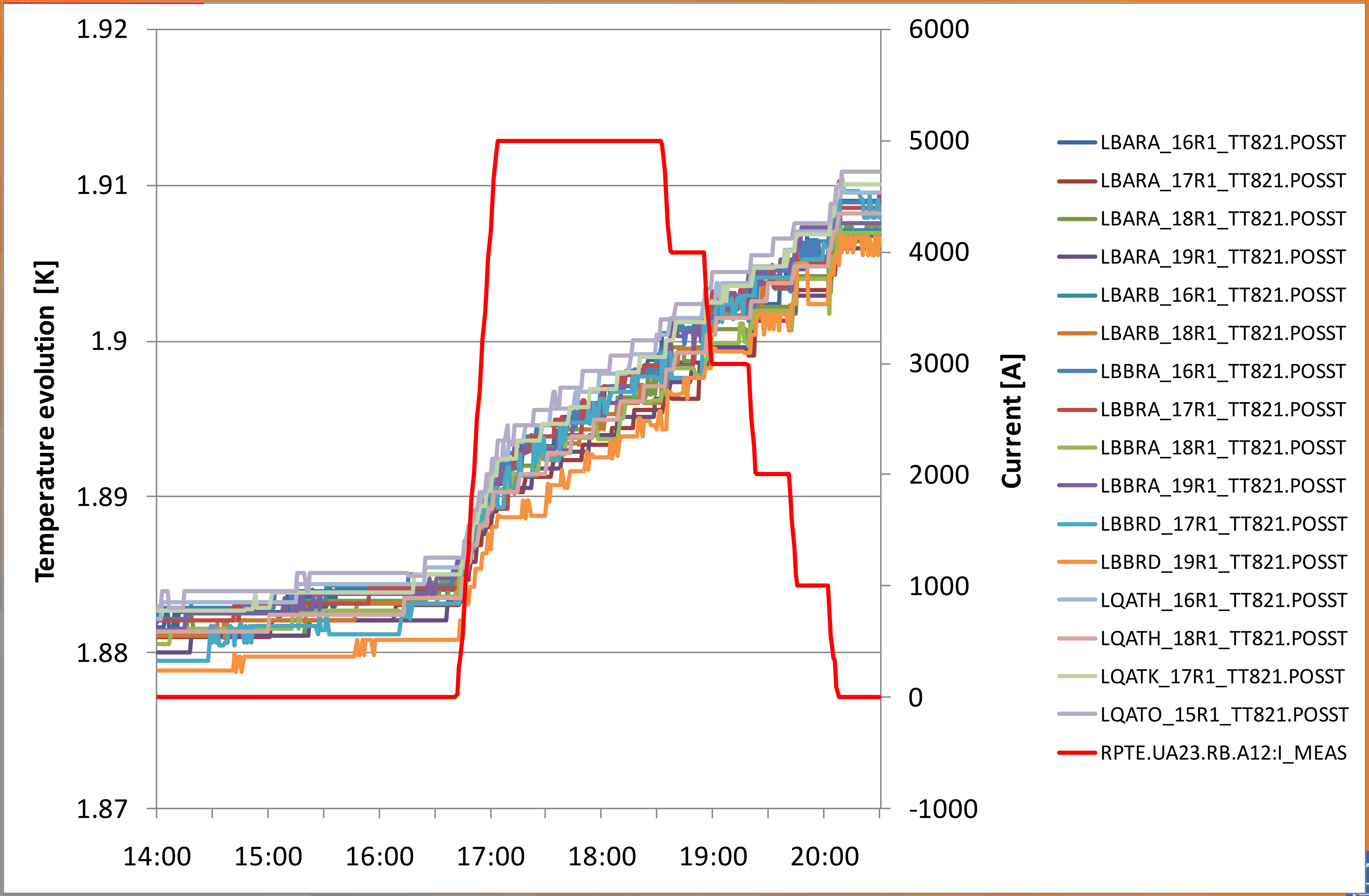


Principle:

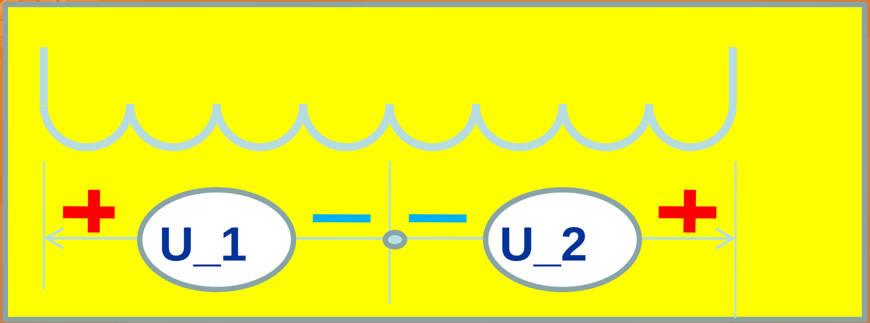
→ **Blocking of the JT valve (CV910) at a value to extract the static heat inleaks before the powering**

→ **Then, the temperature drift is mainly due to electrical resistive heating dissipated during the powering**

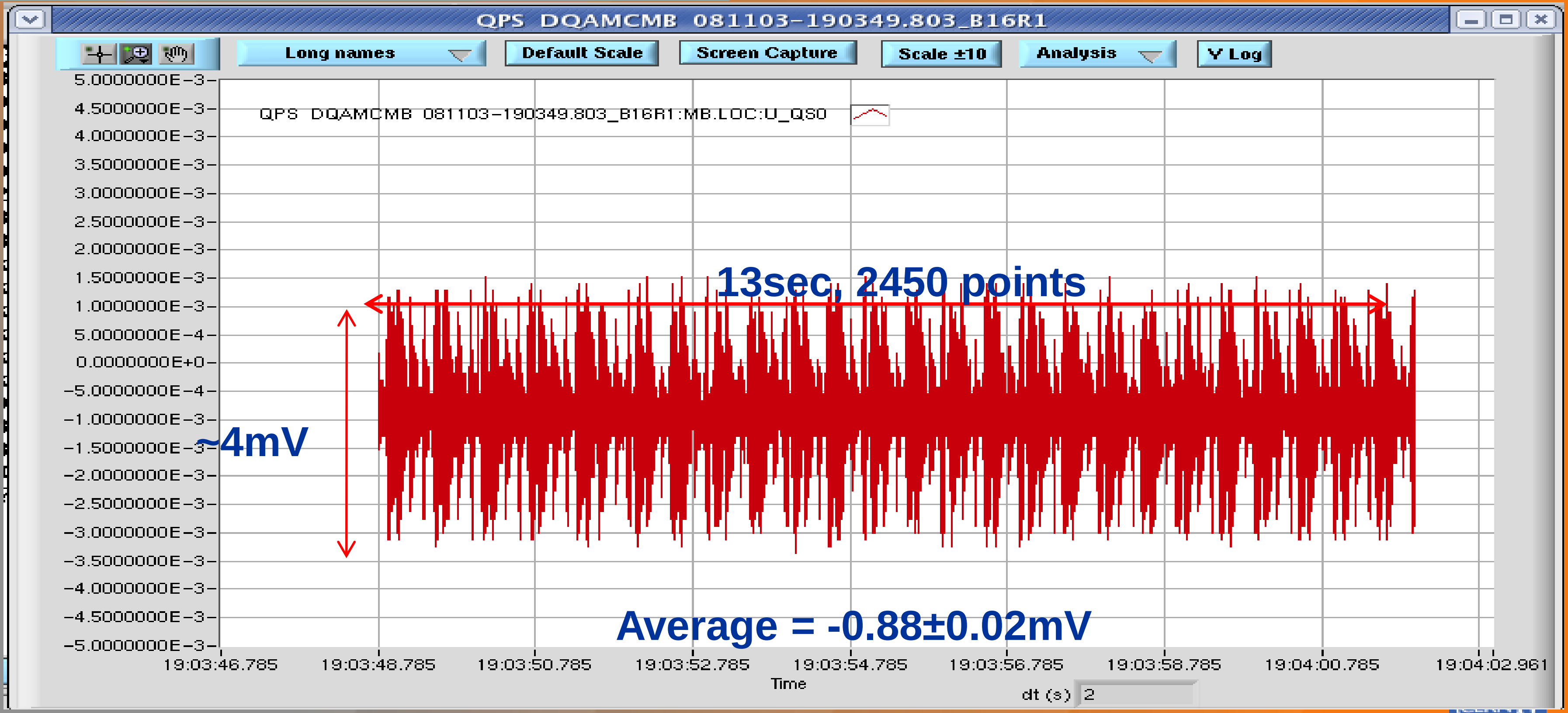
Powering example:
15R1 powering @ 5000A



Sector A12: A15R1 – C19R1: "splice" measurements on 03.11.08



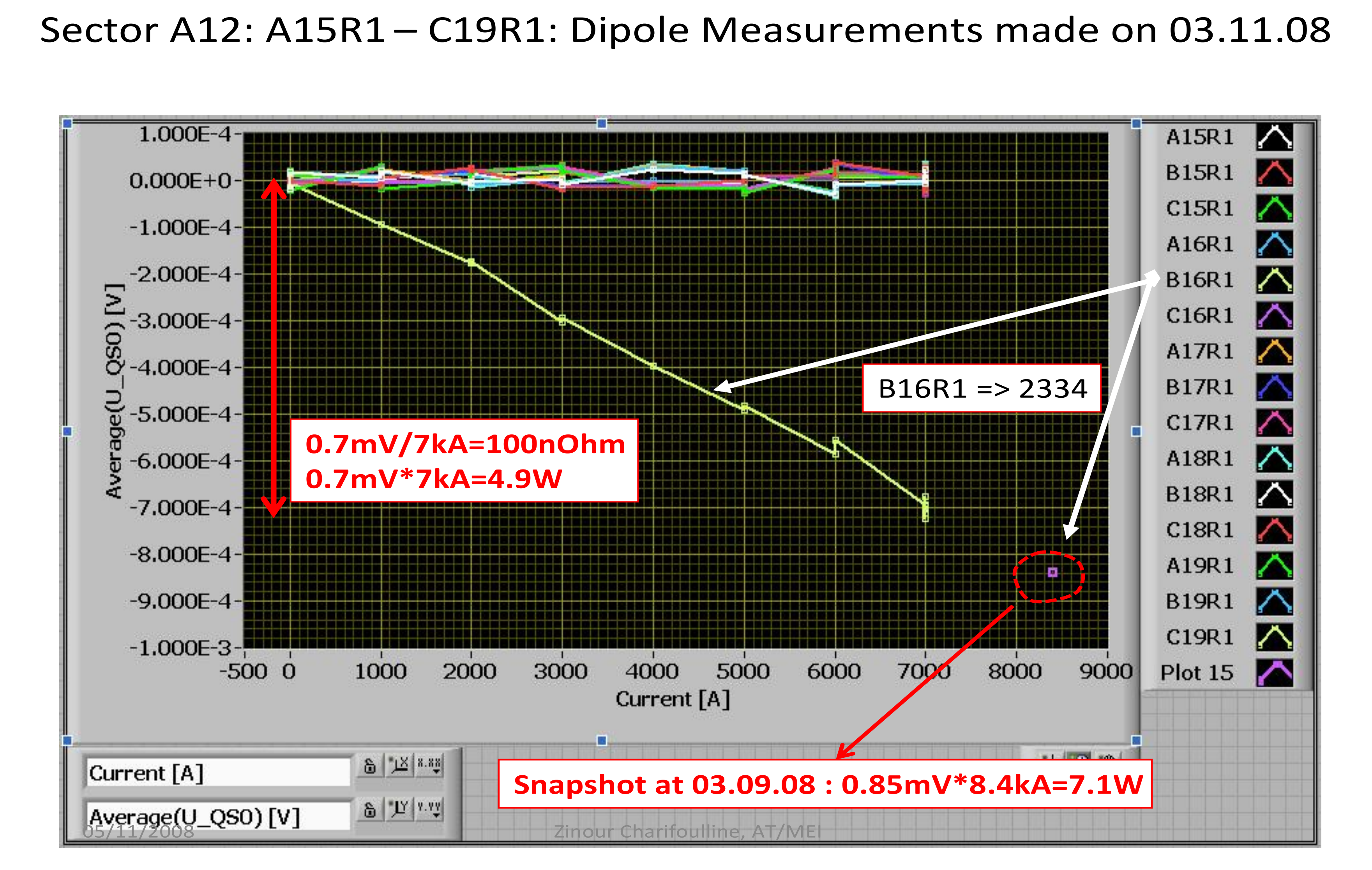
U_QS0 => -(U_1+U_2)
Sampling Rate = 5ms
Resolution = 0.125mV
Quench Threshold = 100mV@10ms



Sector A12: A15R1 – C19R1: measurements on 03.11.08

Courtesy Z. Charifoulline

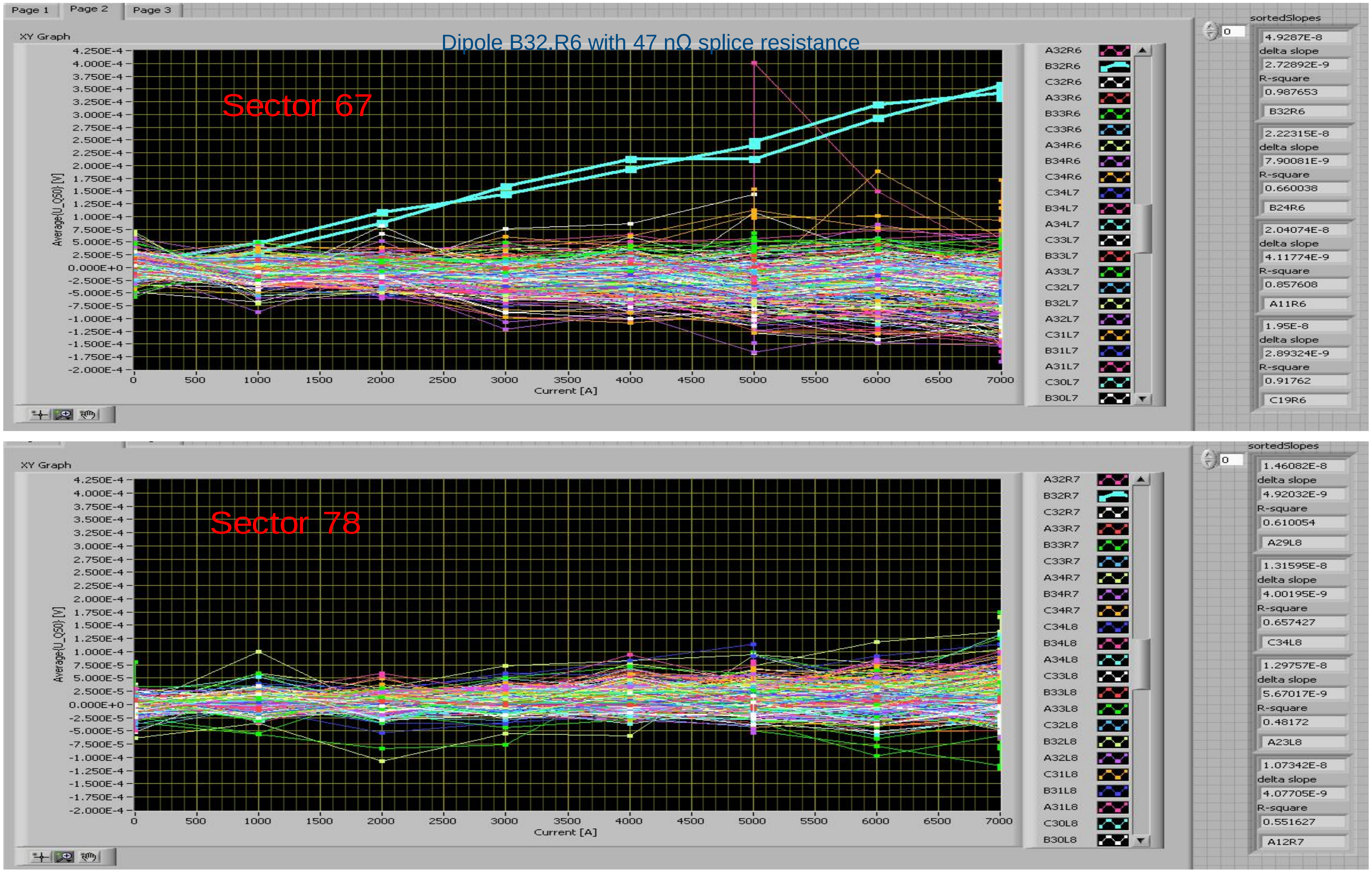
Proof of the missing source of heating, representing 100 nΩ, located in dipole B16.R1 (in the joint between the two apertures).



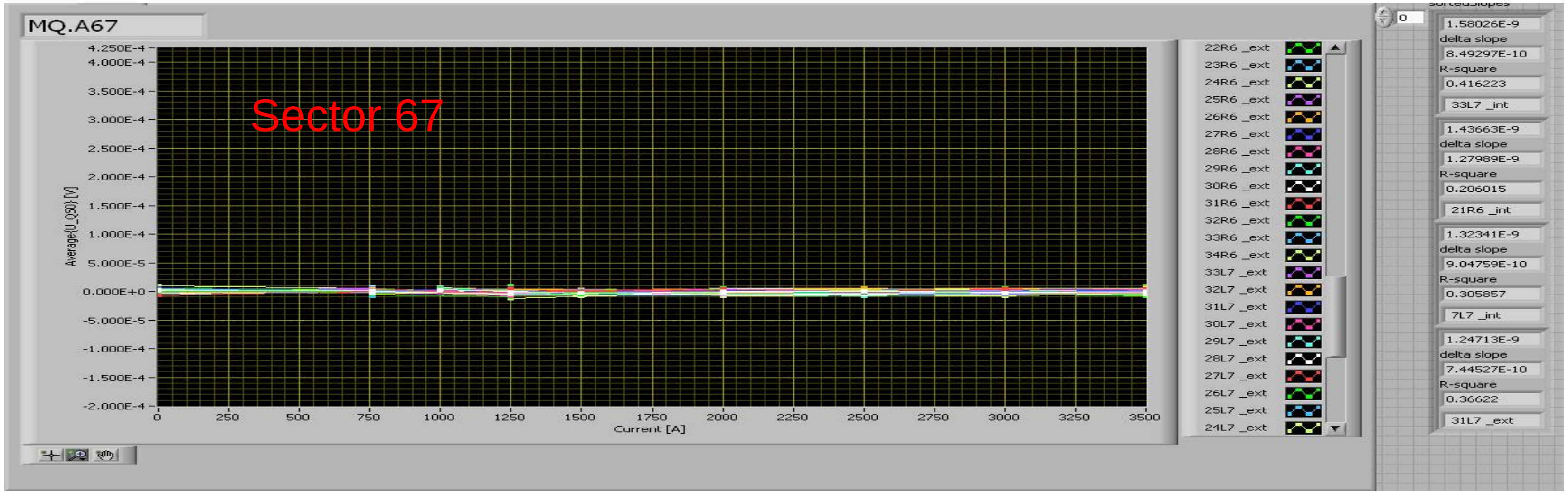
Compatible with SM18 data (resolution ±20 nΩ)

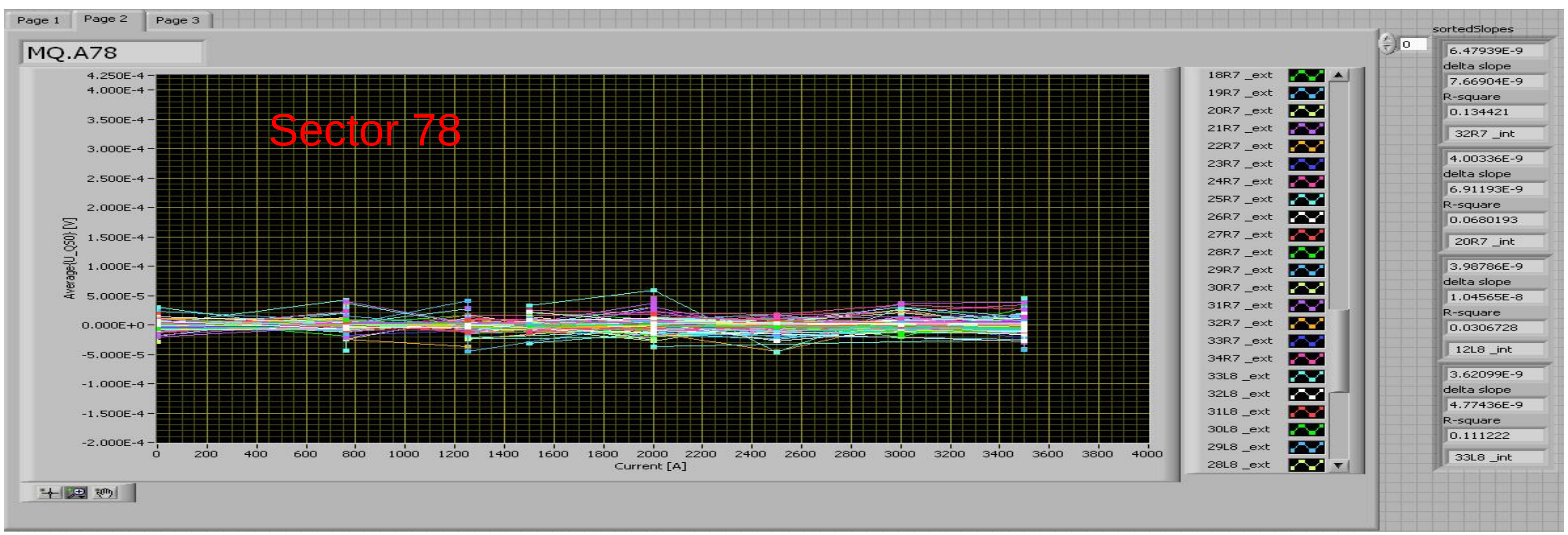
Snapshots in S67 and S78 on all 154 dipoles - B32.R6 with a high (47 nΩ) joint resistance between the poles of one aperture

Results from provoked massive Post-Mortem of all dipoles in sectors 67 & 78

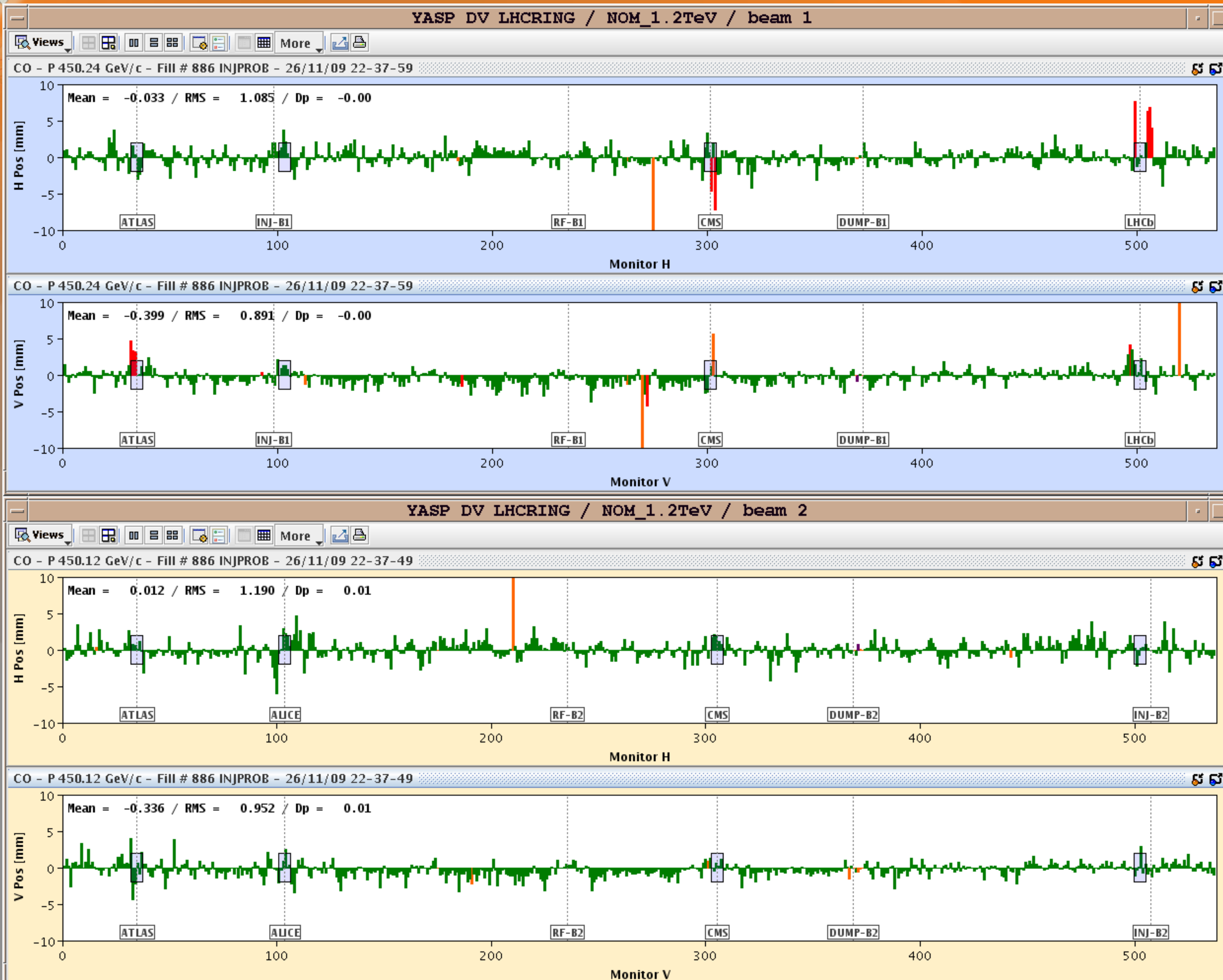


Main quadrupoles in S67 and S78
Results of global snapshots

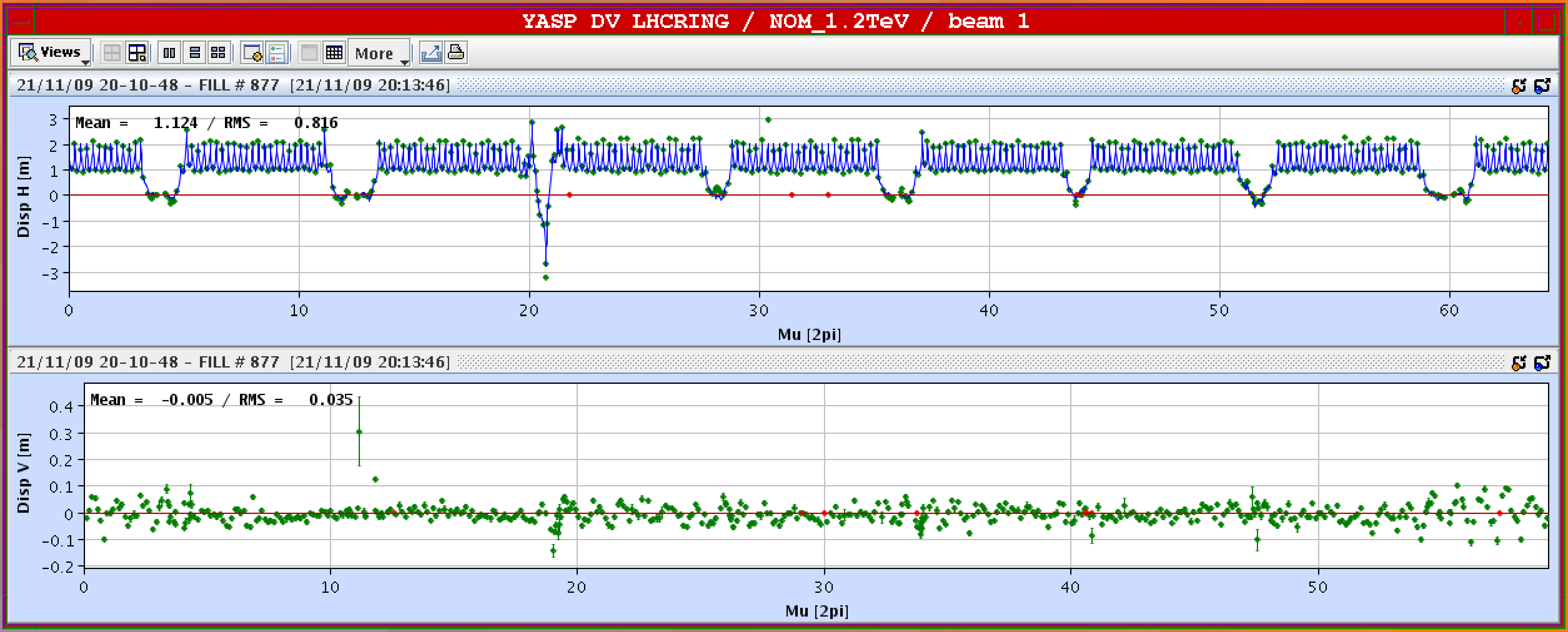




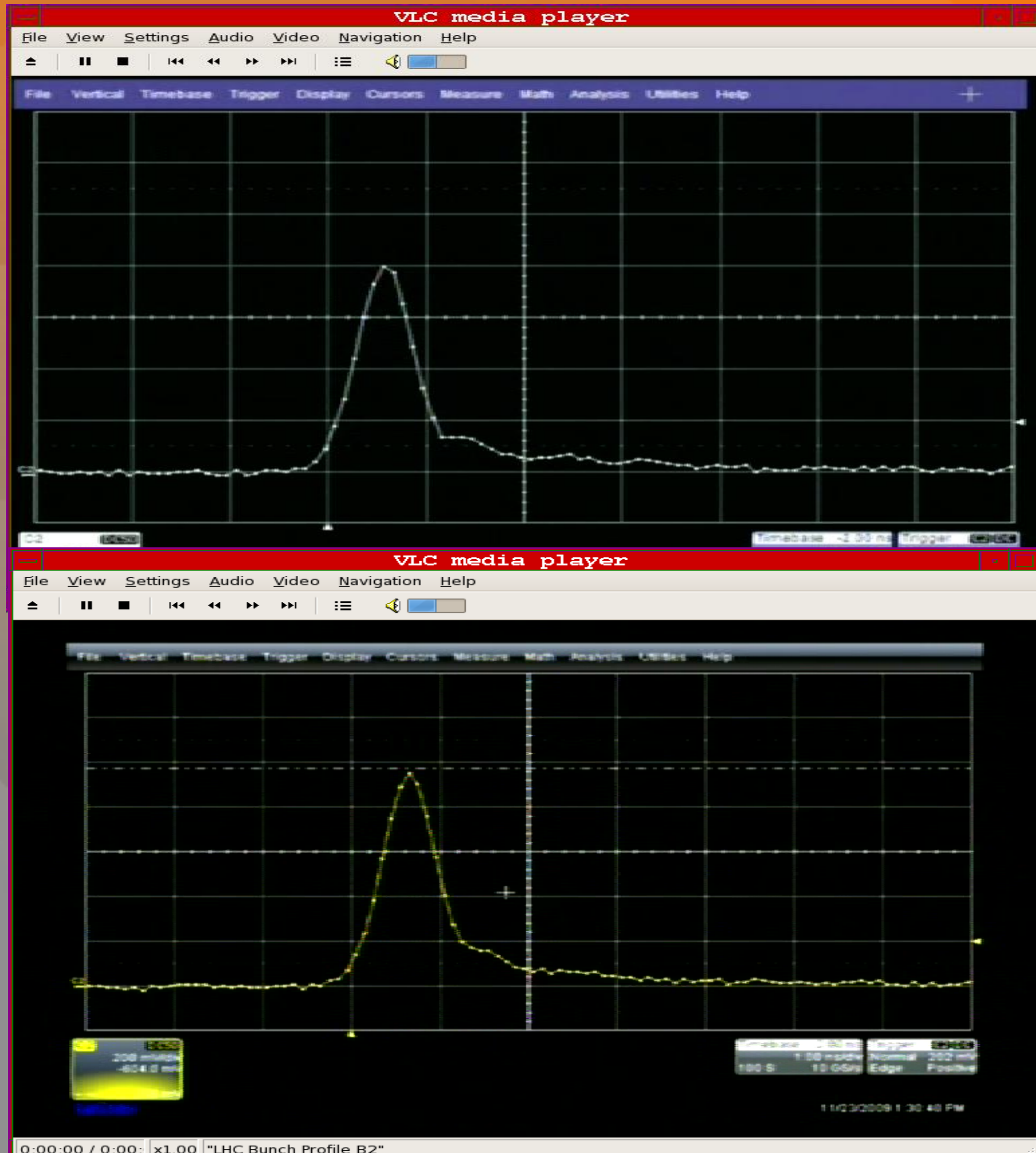
Orbits


YASP DV LHCRING / NOM_1.2TeV / beam 1
Views
More
CO - P 450.24 GeV/c - Fill # 886 INJPROB - 26/11/09 22-37-59
Mean = -0.033 / RMS = 1.085 / Dp = -0.00
H Pos [mm]
ATLAS
INJ-B1
RF-B1
CMS
DUMP-B1
LHCb
Monitor H
CO - P 450.24 GeV/c - Fill # 886 INJPROB - 26/11/09 22-37-59
Mean = -0.399 / RMS = 0.891 / Dp = -0.00
V Pos [mm]
Monitor V
YASP DV LHCRING / NOM_1.2TeV / beam 2
CO - P 450.12 GeV/c - Fill # 886 INJPROB - 26/11/09 22-37-49
Mean = 0.012 / RMS = 1.190 / Dp = 0.01
H Pos [mm]
ATLAS
ALICE
RF-B2
CMS
DUMP-B2
INJ-B2
Monitor H
CO - P 450.12 GeV/c - Fill # 886 INJPROB - 26/11/09 22-37-49
Mean = -0.336 / RMS = 0.952 / Dp = 0.01
V Pos [mm]
Monitor V

Dispersion B1

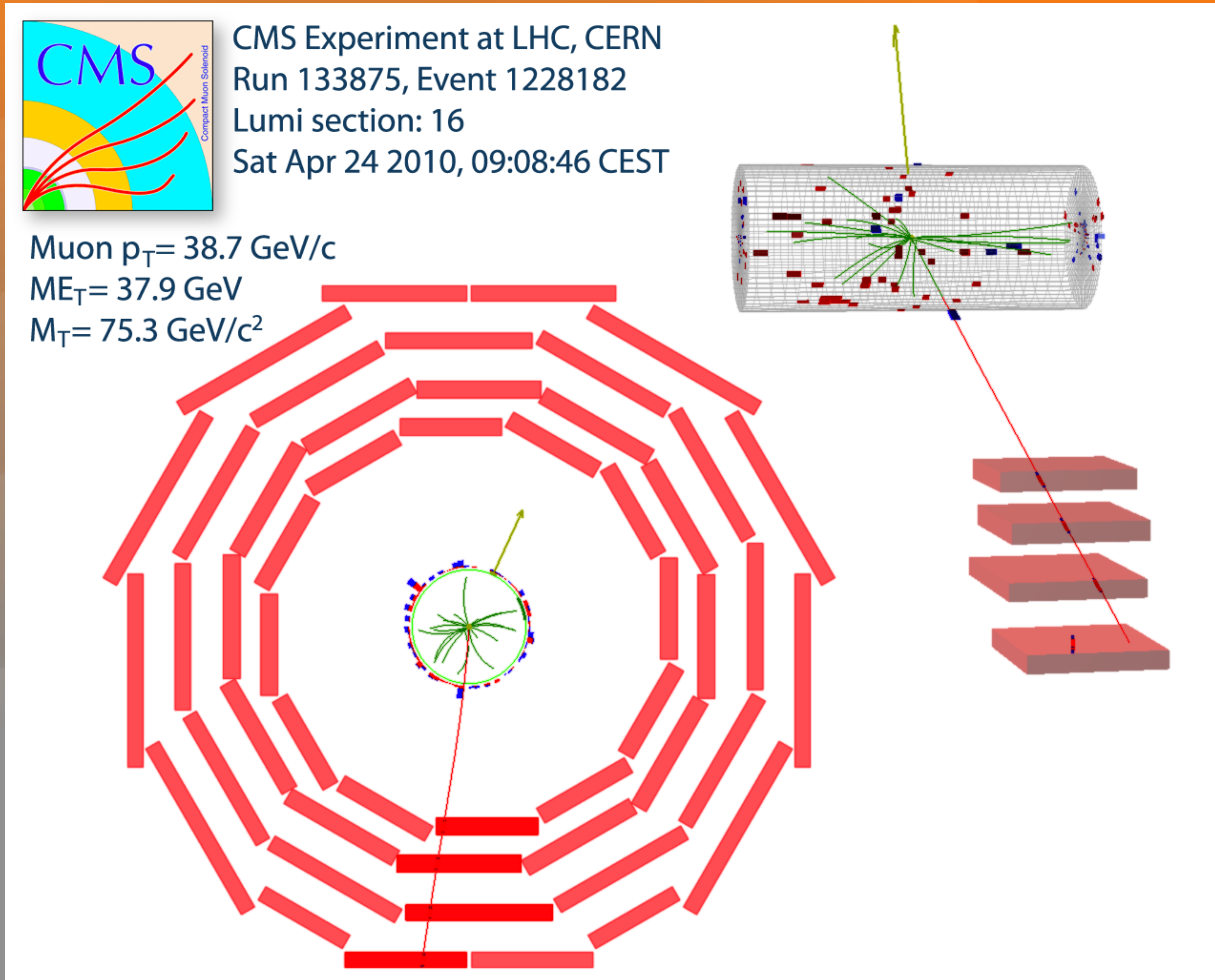


2 beams in the machine



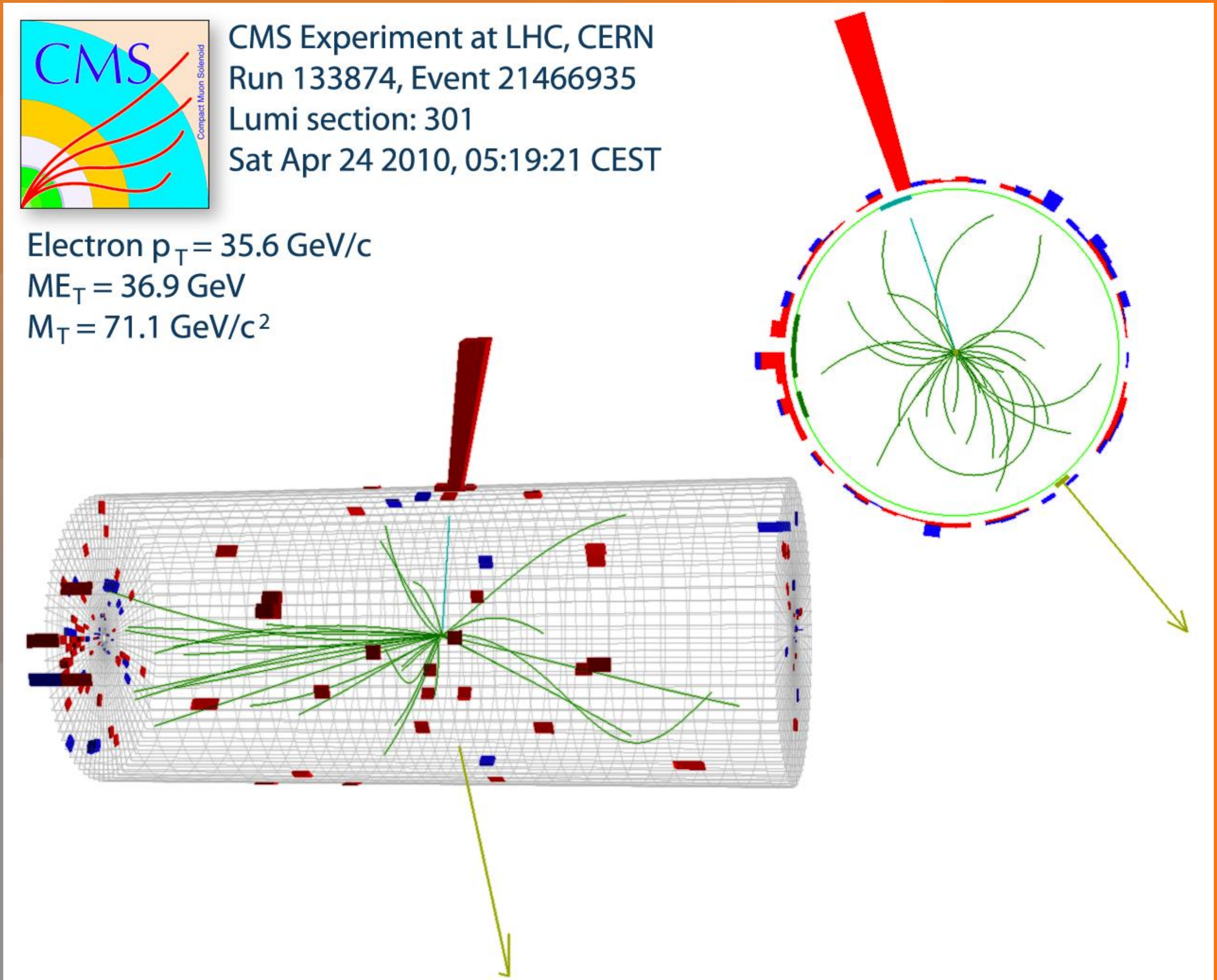
30 November 2009
twin beams at 1.18 TeV

Candidate for W $\rightarrow \mu\nu$



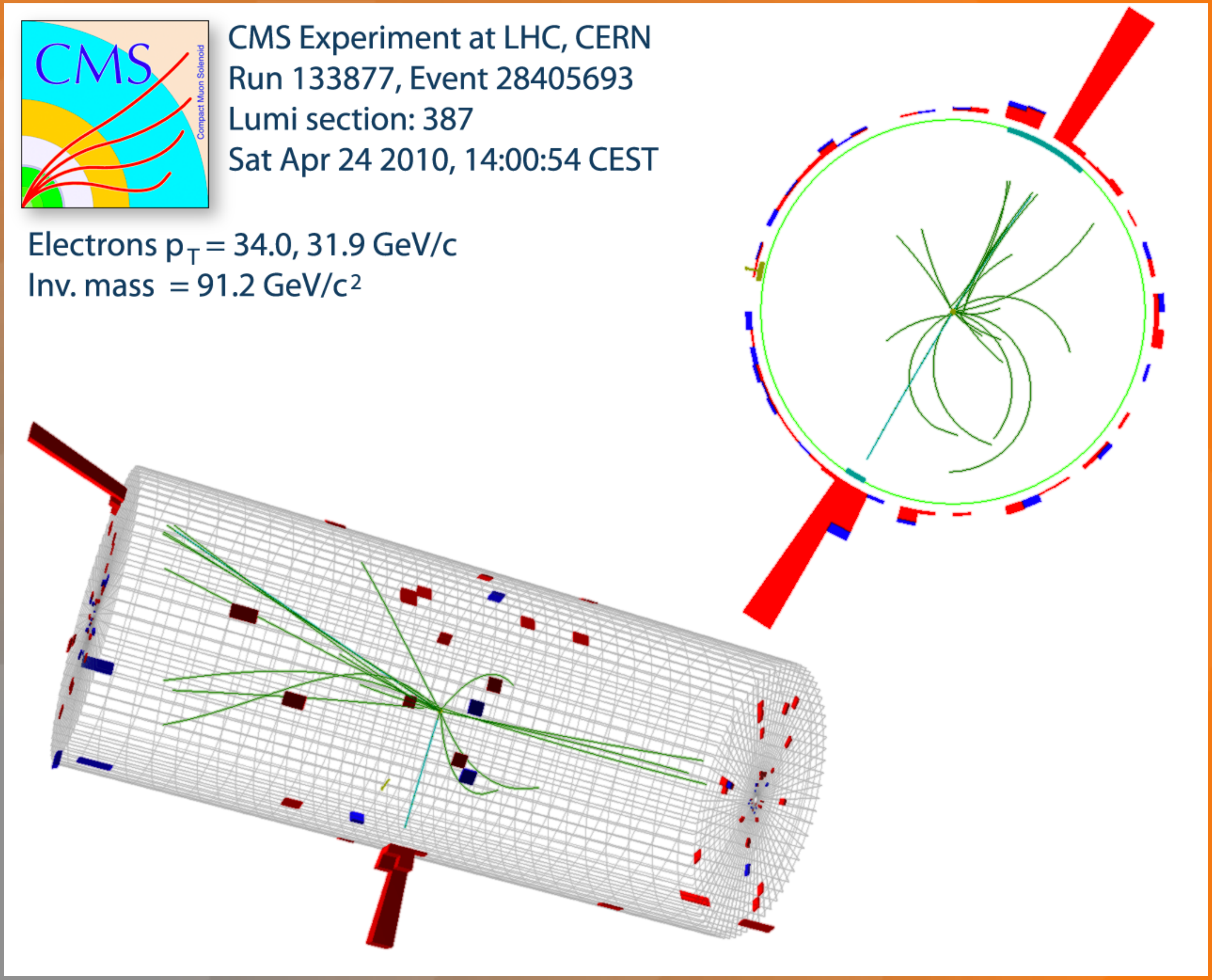
Courtesy J. Virdee

Candidate for W $\rightarrow e\nu$



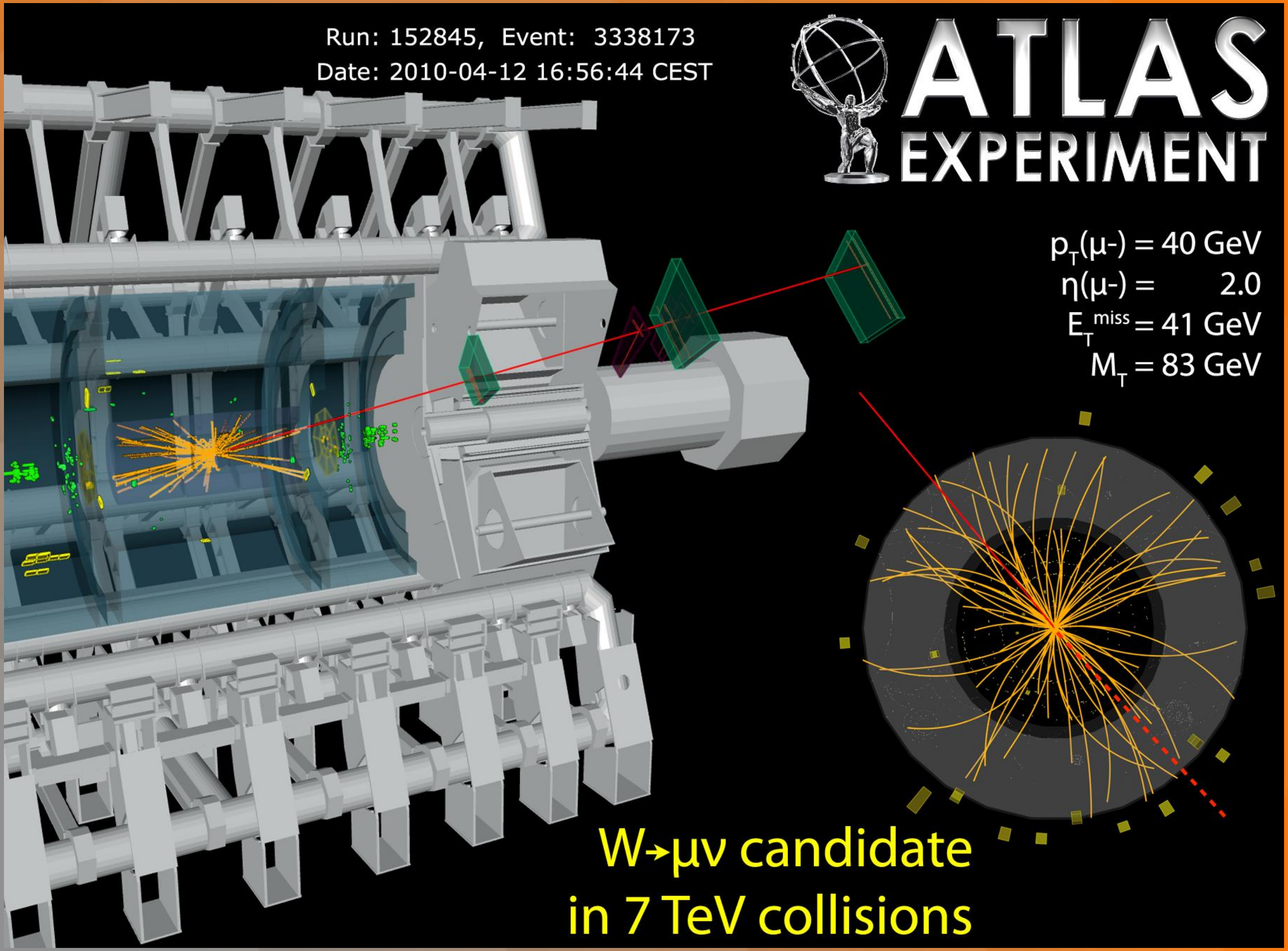
Courtesy J. Virdee

Candidate for Z → **e** e



Courtesy J. Virdee

Candidate for W $\rightarrow \mu\nu$



 Courtesy F. Gianotti

Conclusions

The adventure of LHC construction is finished. Now let the adventure of discovery begin.