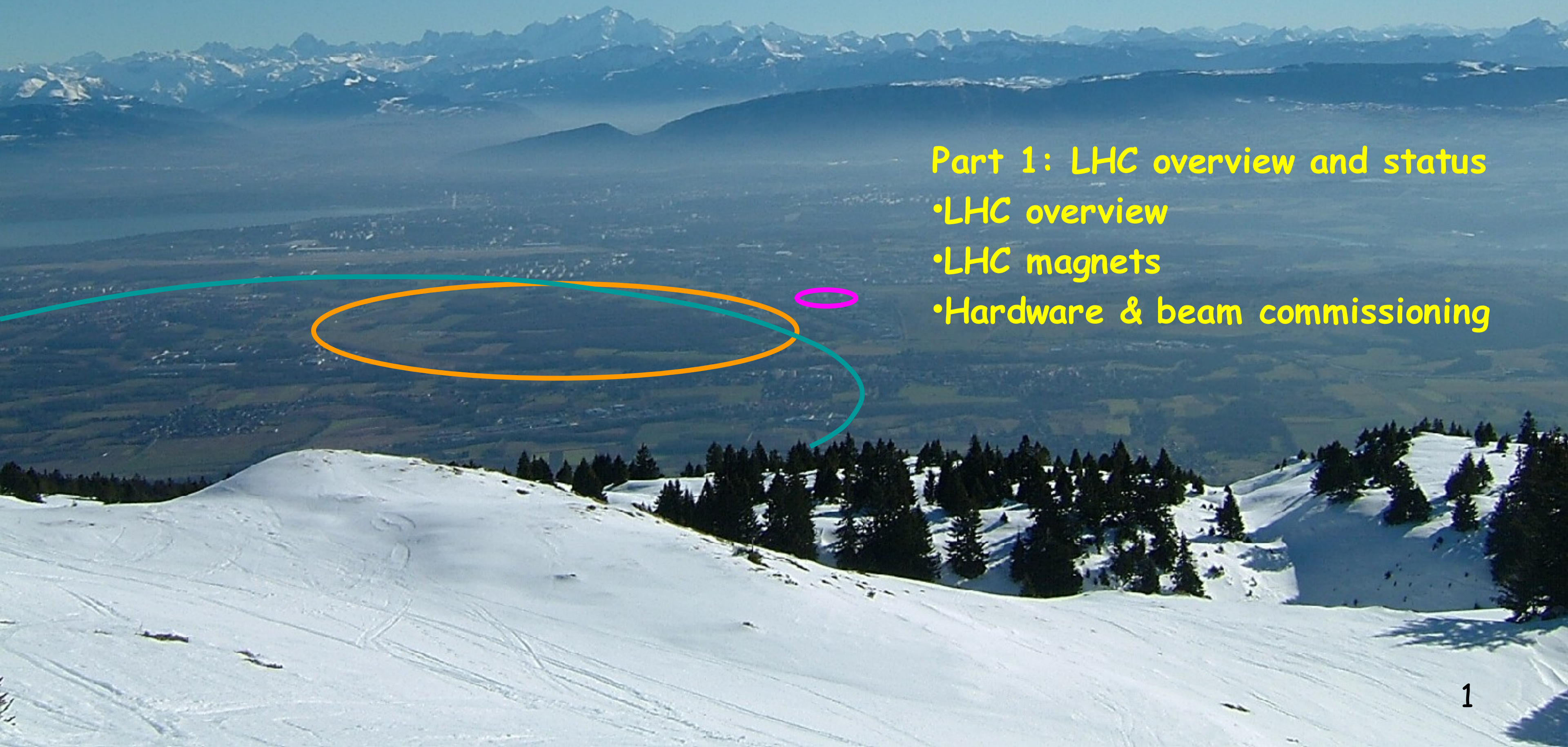
Operational challenges of the LHC

Jörg Wenninger
CERN Accelerators and Beams Department
Operations group

November 2007



Part 1: LHC overview and status

- LHC overview
- LHC magnets
- Hardware & beam commissioning

Outline

- LHC overview
- LHC magnet system
- LHC commissioning

Part 1

- Luminosity
- LHC injector chain
- Machine protection
- Collimation

Part 2

LHC History

1982 : First studies for the LHC project

1983 : Z0/W discovered at SPS proton antiproton collider (SppbarS)

1989 : Start of LEP operation (Z boson-factory)

1994 : Approval of the LHC by the CERN Council

1996 : Final decision to start the LHC construction

1996 : LEP operation > 80 GeV (W boson -factory)

2000 : Last year of LEP operation above 100 GeV

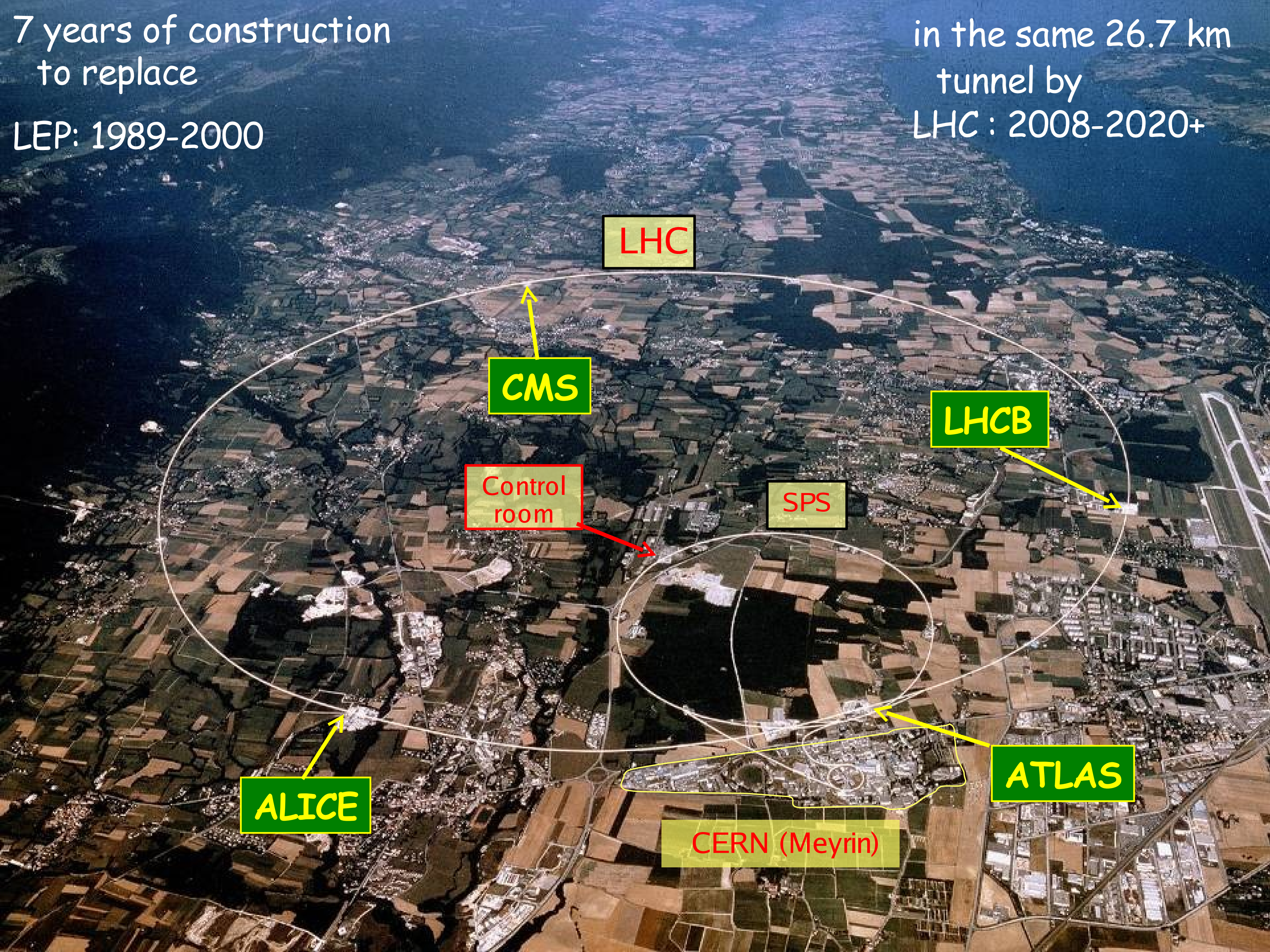
2002 : LEP equipment removed

2003 : Start of the LHC installation

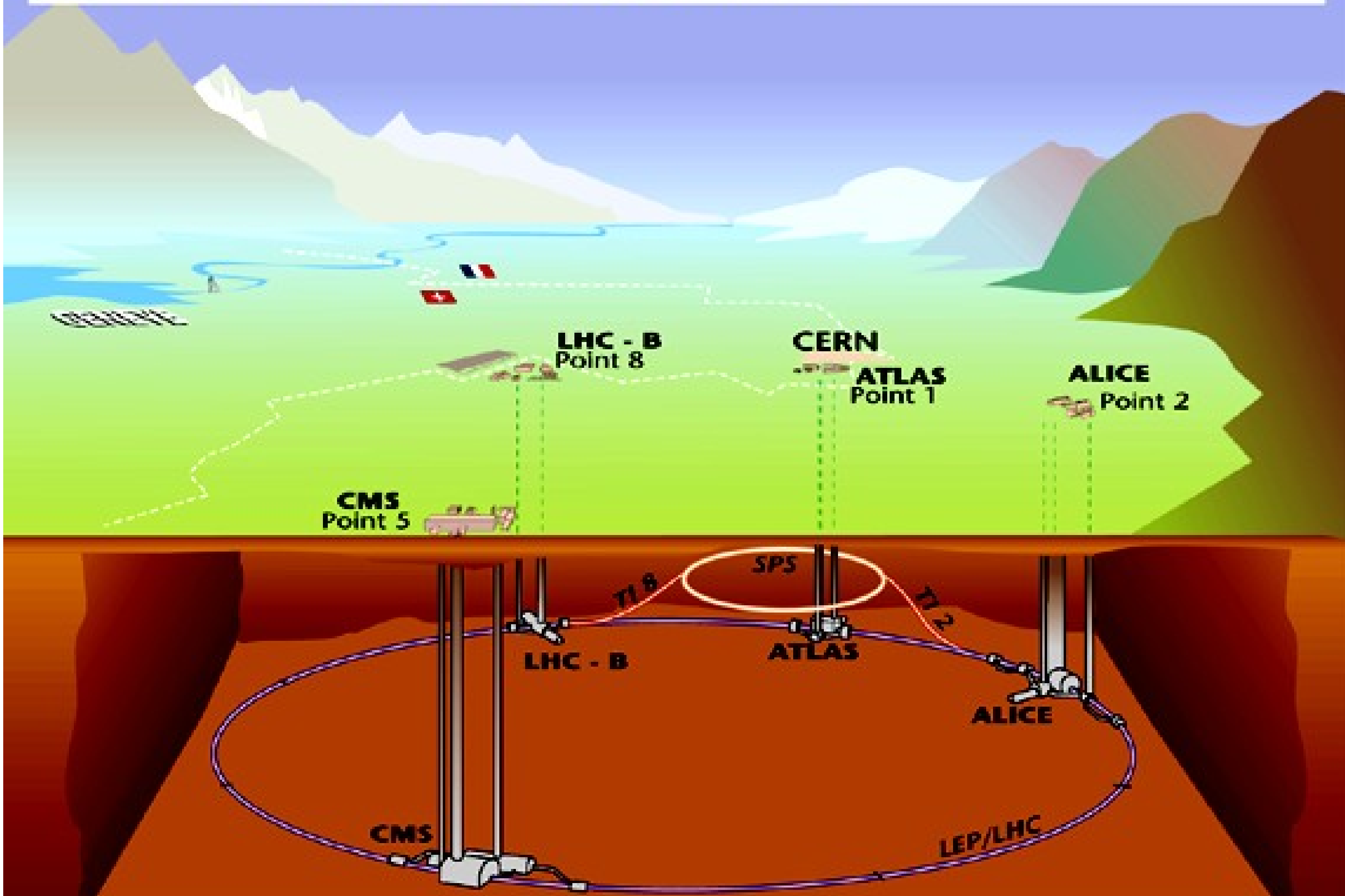
2005 : Start of LHC hardware commissioning

2007 : First sector at 1.9K, all magnets at 1 TeV.

2008+ : Expected LHC commissioning with beam


7 years of construction
to replace
LEP: 1989-2000
in the same 26.7 km
tunnel by
LHC : 2008-2020+
LHC
CMS
LHCB
Control
room
SPS
ALICE
ATLAS
CERN (Meyrin)

Overall view of the LHC experiments.

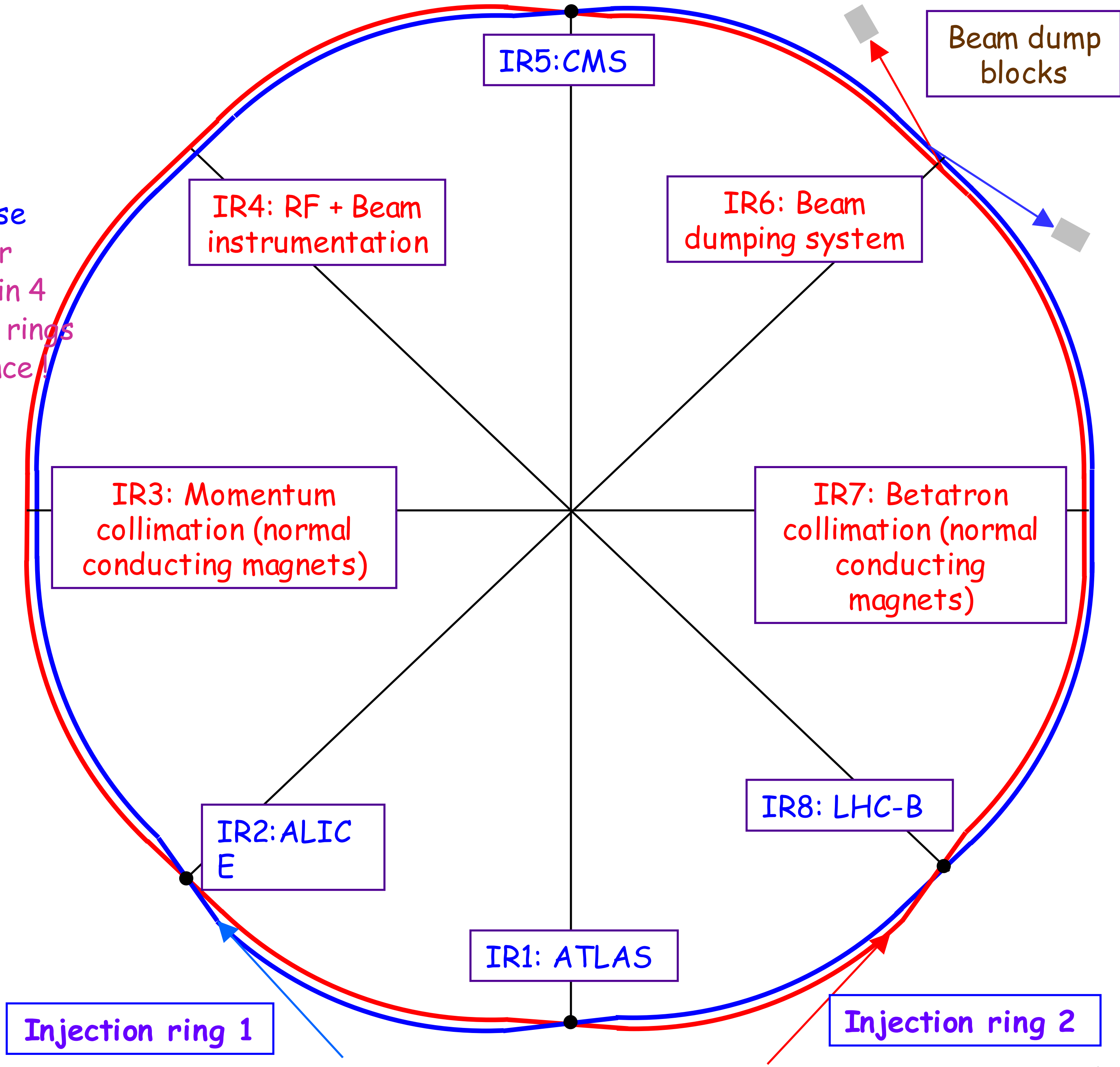


Tunnel circumference 26.7 km, tunnel diameter 3.8 m
Depth : ~ 70-140 m – tunnel is inclined by ~ 1.4%

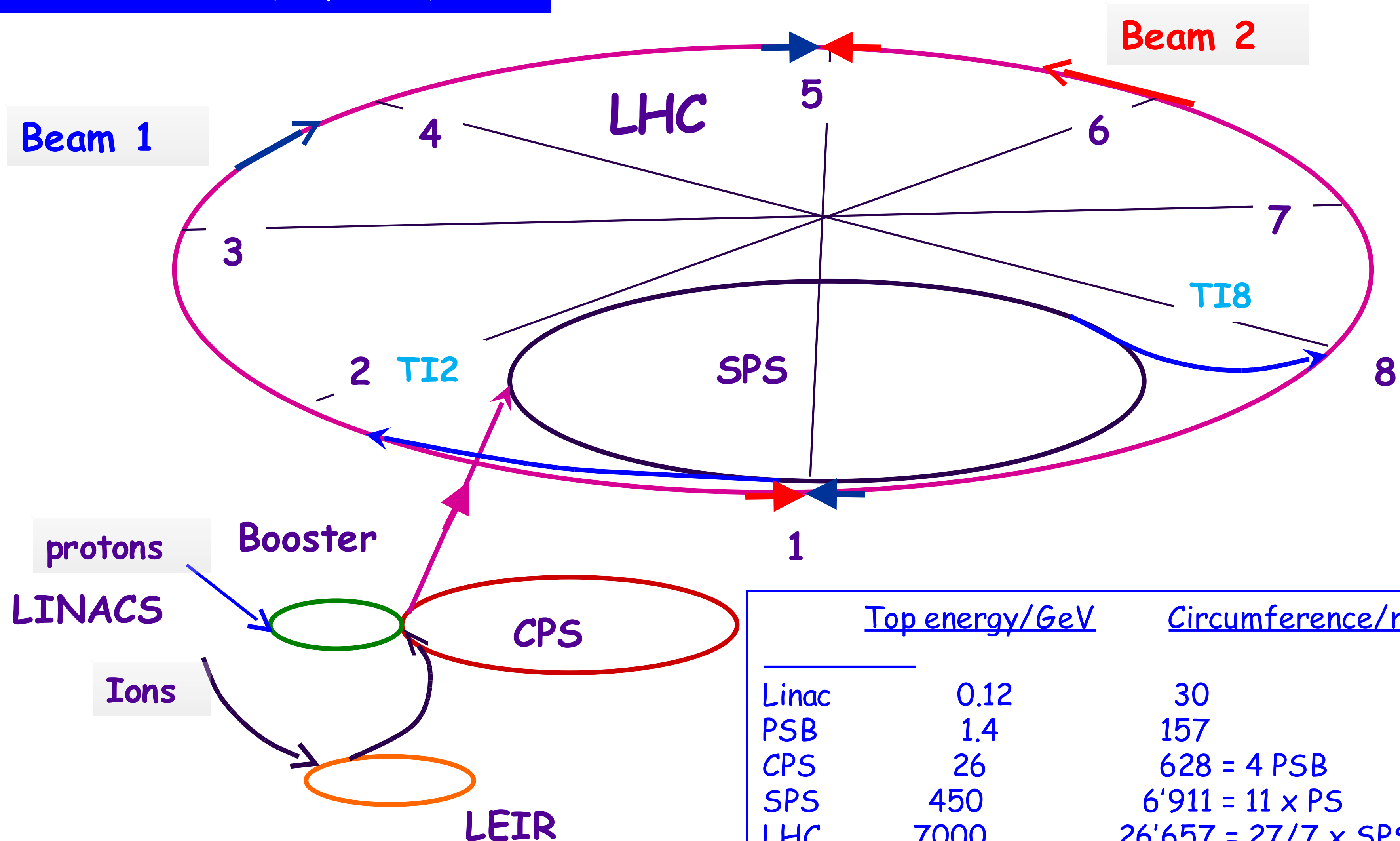
LHC Layout

- 8 arcs.
- 8 long straight sections (insertions), ~ 700 m long.
- beam 1 : clockwise
- beam 2 : counter-clockwise
- The beams exchange their positions (inside/outside) in 4 points to ensure that both rings have the same circumference !

The main dipole magnets define the geometry of the circle !



In total > 50 km of beam lines



	Top energy/GeV	Circumference/m
Linac	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS

Note the energy gain/machine of 10 to 20 – and not more !
The gain is typical for the useful range of magnets !!!

LHC – yet another collider?

The LHC surpasses existing accelerators/colliders in 2 aspects :

- The energy of the beam of 7 TeV that is achieved within the size constraints of the existing 26.7 km LEP tunnel.

LHC dipole field	8.3 T
HERA/Tevatron	~ 4 T

A factor 2 in field

A factor 4 in size

- The luminosity of the collider that will reach unprecedented values for a **hadron** machine:

LHC	pp	~ 10^{34} cm^{-2} s^{-1}
Tevatron	$p\bar{p}$	2×10^{32} cm^{-2} s^{-1}
SppbarS	$p\bar{p}$	6×10^{30} cm^{-2} s^{-1}

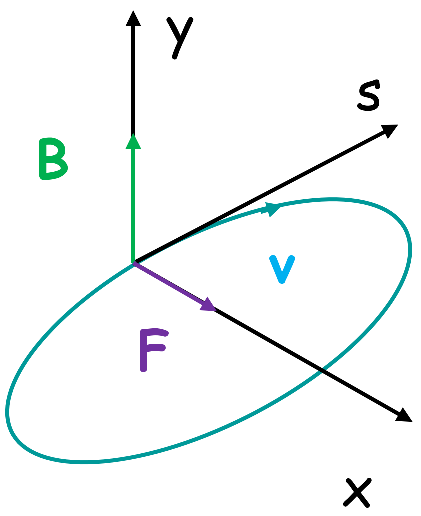
A factor 100 in luminosity

The combination of very high field magnets and very high beam intensities required to reach the luminosity targets makes operation of the LHC a great challenge !

Field challenges

The force on a charged particle is given by the Lorentz force which is proportional to the charge, and to the vector product of velocity and magnetic field:

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$



To reach a momentum of 7 TeV/c given the LHC (LEP) bending radius of 2805 m:

- Bending field B = 8.33 Tesla
- Superconducting magnets

$$B = \frac{p}{e_0 \cdot R}$$

To collide two counter-rotating proton beams, the beams must be in separate vaccum chambers (in the bending sections) with opposite B field direction.

→ There are actually **2** LHCs and the magnets have a 2-magnets-in-one design!

Luminosity challenges

The event rate N for a physics process with cross-section σ is proprotional to the collider Luminosity L:

$$N = L\sigma$$

$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}$$

k = *number of bunches* = *2808*
N = *no. protons per bunch* = 1.15×10^{11}
f = *revolution frequency* = *11.25 kHz*
σ^*_x, σ^*_y = *beam sizes at collision point (hor./vert.)* = *16 μm*

To maximize L:

- **Many bunches (k)**
- **Many protons per bunch (N)**
- **A small beam size $\sigma^*_u = (\beta^*\varepsilon)^{1/2}$**

β^* : characterizes the beam envelope (optics), varies along the ring, mim. at the collision points.

ε : is the phase space volume occupied by the beam (constant along the ring).

High beam "brillance" N/ε (particles per phase space volume)

→ **Injector chain performance !**

Small envelope

→ **Strong focusing !**

The price of high fields & high luminosity…

When the LHC is operated at 7 TeV with its design luminosity & intensity,

- the LHC magnets store a huge amount of energy in their magnetic fields:
  - per dipole magnet E_{stored} = 7 MJ
  - all magnets E_{stored} = 10.4 GJ
- the 2808 LHC bunches store a large amount of kinetic energy:
  - $E_{bunch} = N \times E = 1.15 \times 10^{11} \times 7$ TeV = 129 kJ
  - $E_{beam} = k \times E_{bunch} = 2808 \times E_{bunch}$ = 362 MJ

→ **> 1000 x above damage limit for accelerator components !**

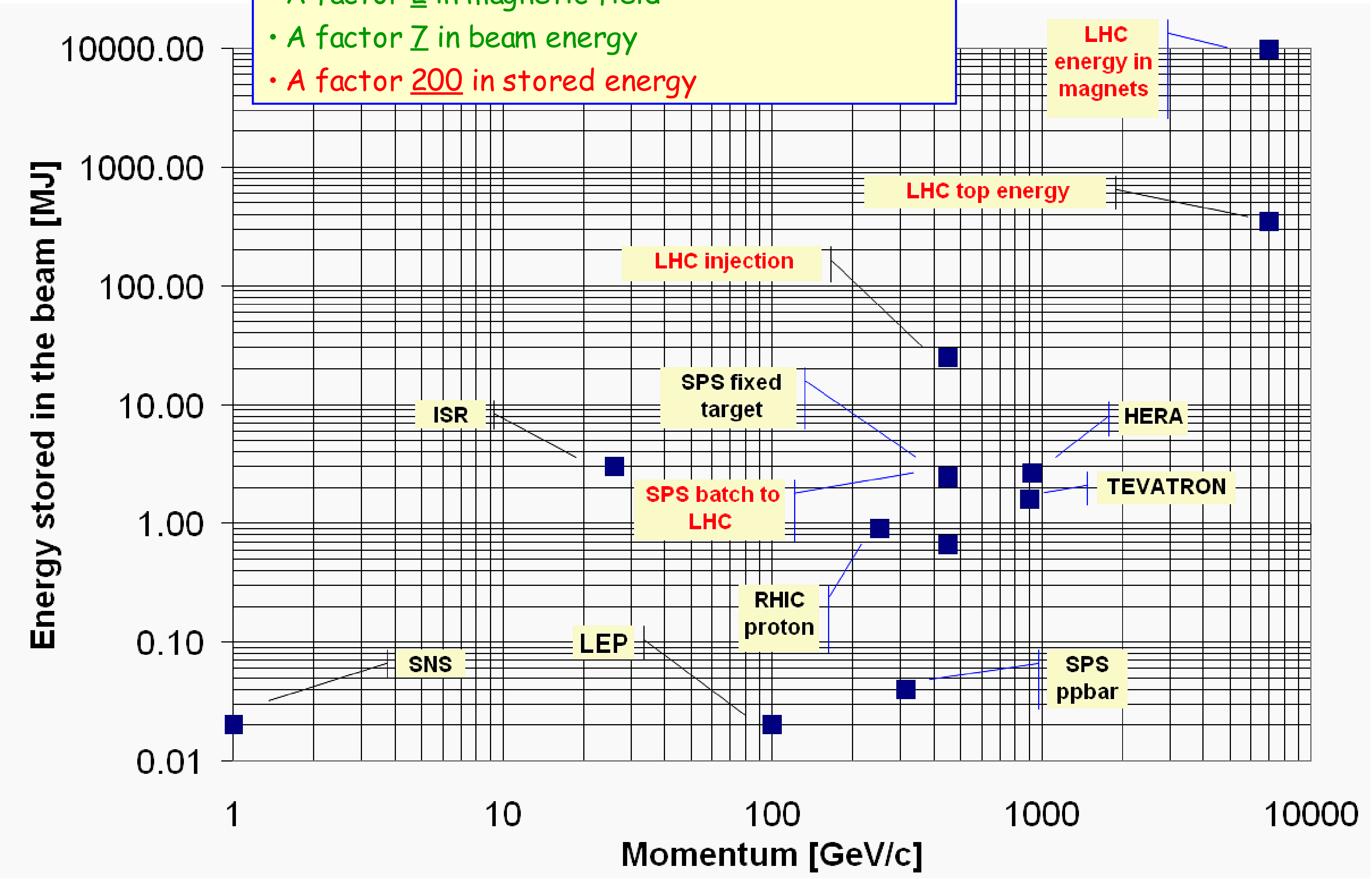
To ensure safe operation will be a major challenge for the LHC operation crews !

Protection of the machine components from the beam is becoming a major issues for all new high power machines (LHC, SNS, …).

Stored Energy

Increase with respect to existing accelerators :

- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored energy



Comparison…

The energy of an A380 at 700 km/hour corresponds to the energy stored in the LHC magnet system :

Sufficient to heat up and melt 12 tons of Copper!!

The energy stored in one LHC beam corresponds approximately to…

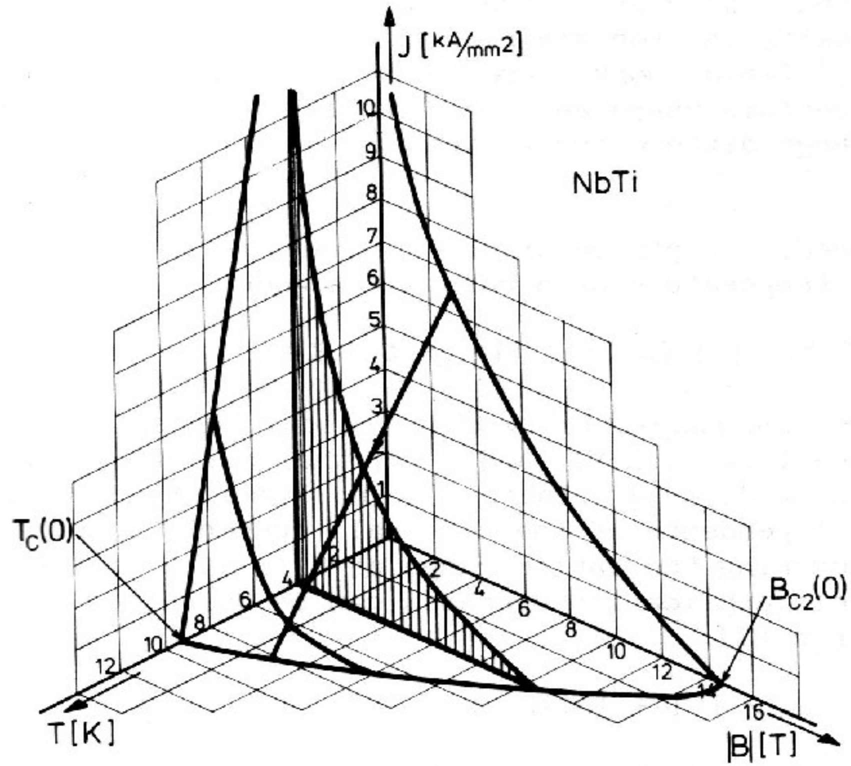
- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate

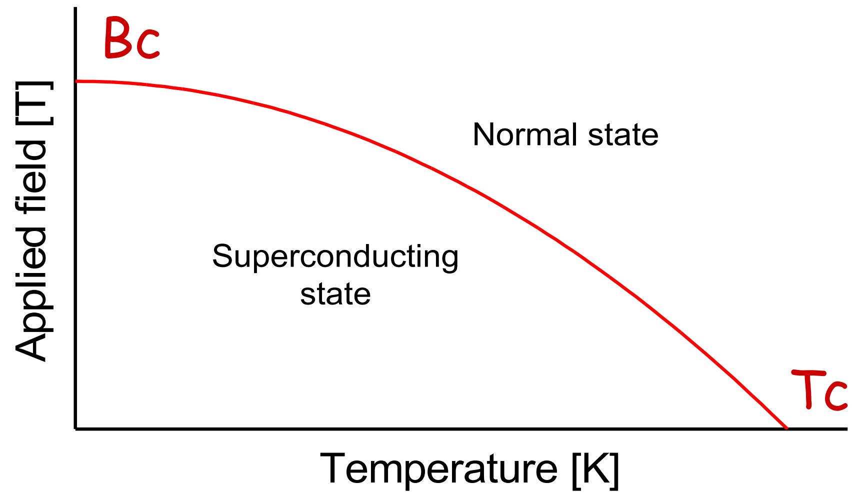
It's how ease the energy is released that matters most !!

LHC Magnets

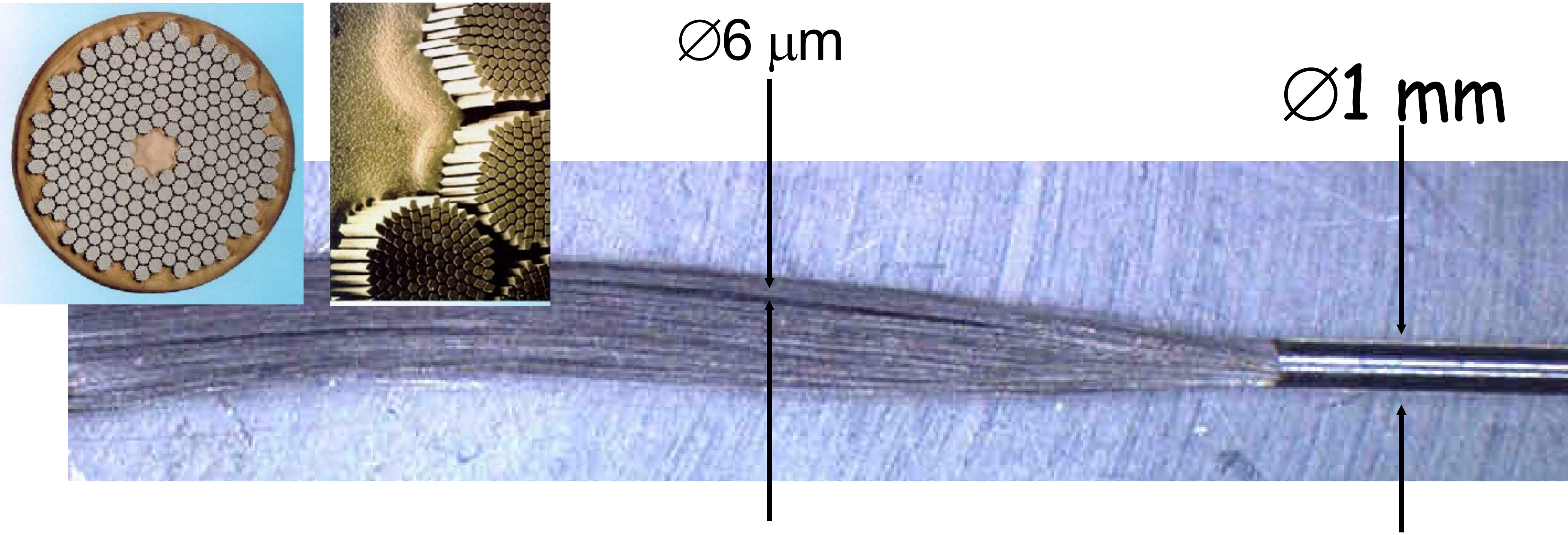
Superconductivity

- The very high DIPOLE field of 8.3 Tesla required to achieve 7 TeV/c can only be obtained with superconducting magnets !
- The material determines:
  - **Tc** critical temperature
  - **Bc** critical field
- The cable production determines:
  - **Jc** critical current density
- Lower temperature ⇒ increased current density ⇒ higher fields.
- Typical for NbTi @ 4.2 K
  - 2000 A/mm2 @ 6T
- To reach 8-10 T, the temperature must be lowered to 1.9 K – superfluid Helium !

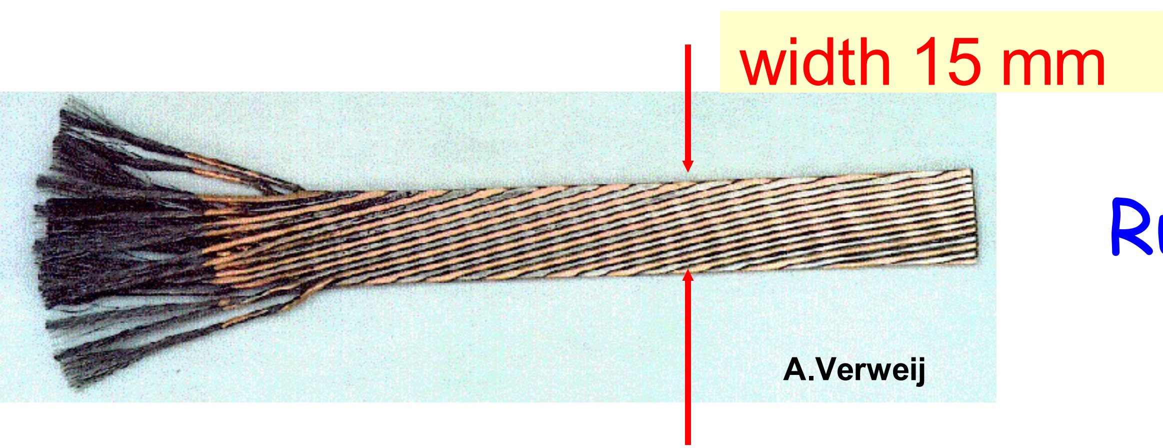




The superconducting cable

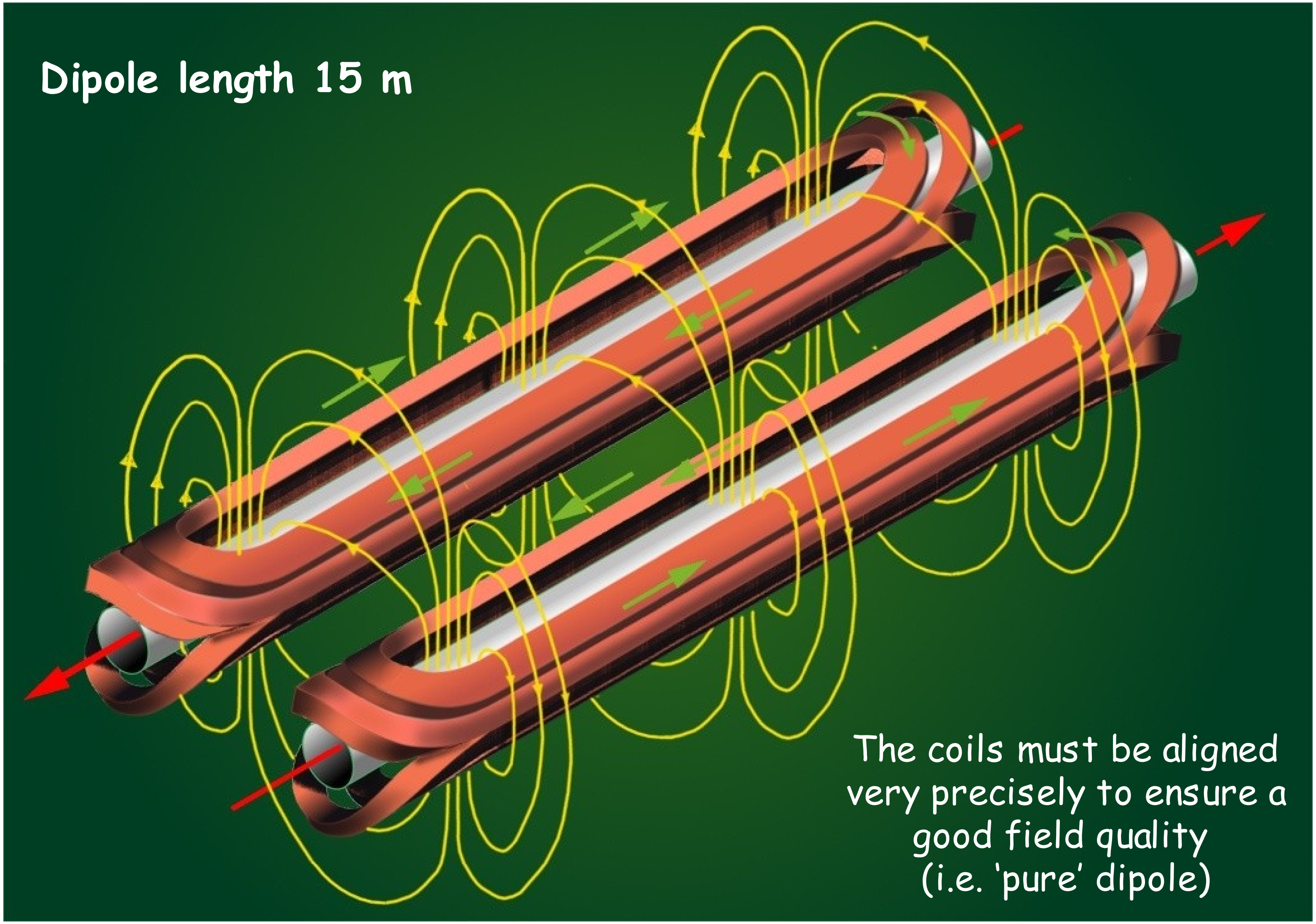


Typical value for operation at 8T and 1.9 K: 800 A

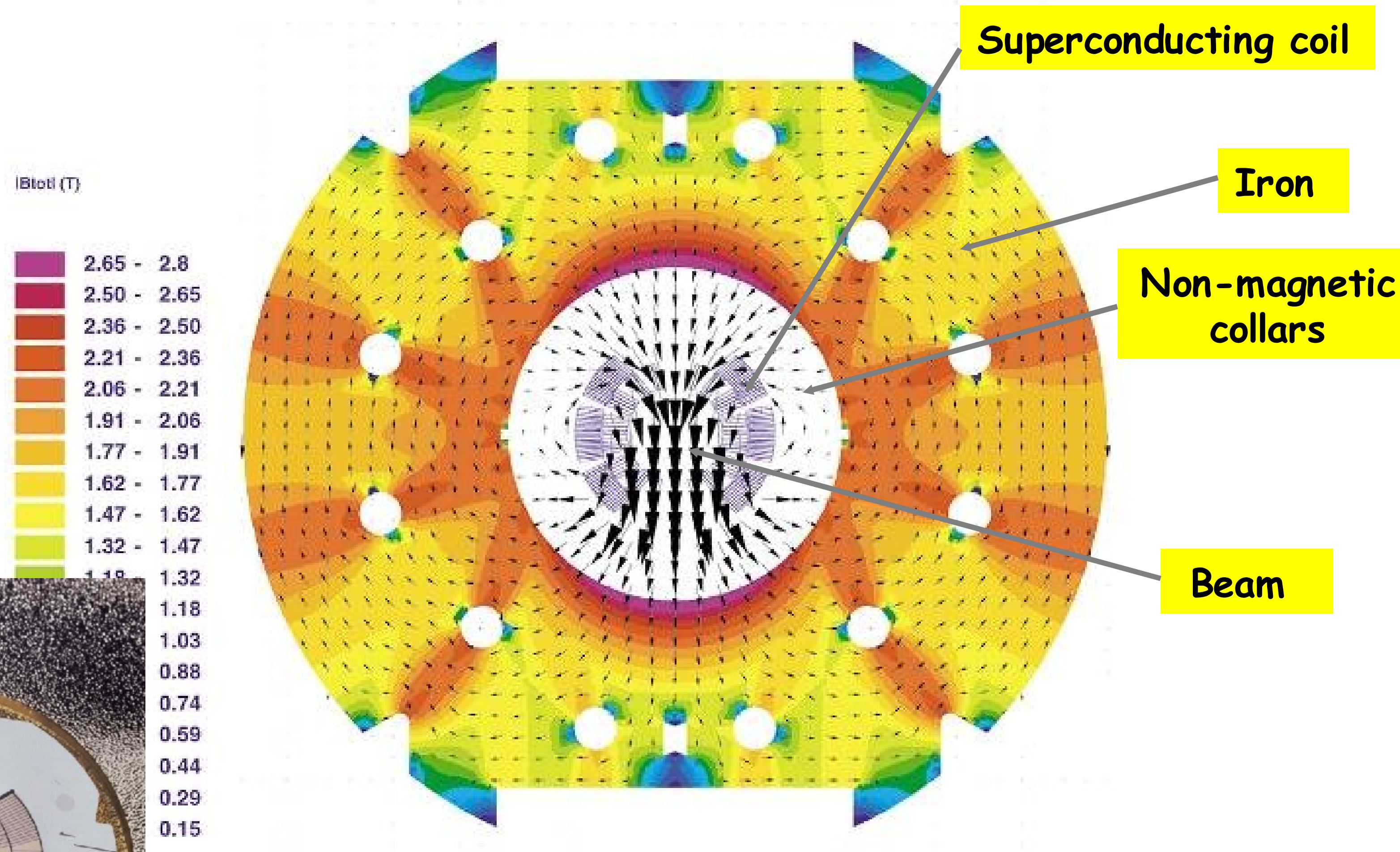


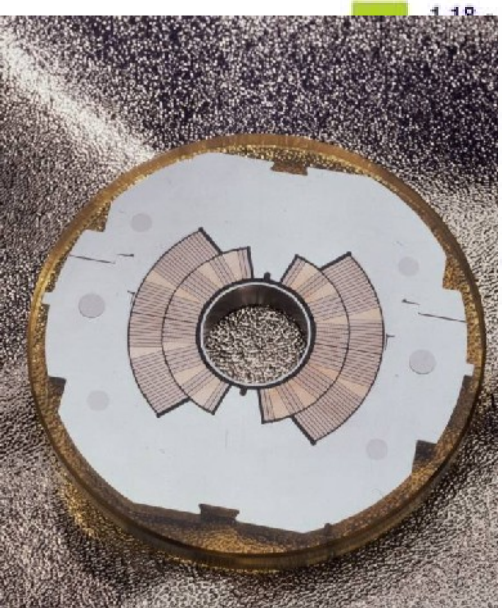
Rutherford cable

Coils for dipoles

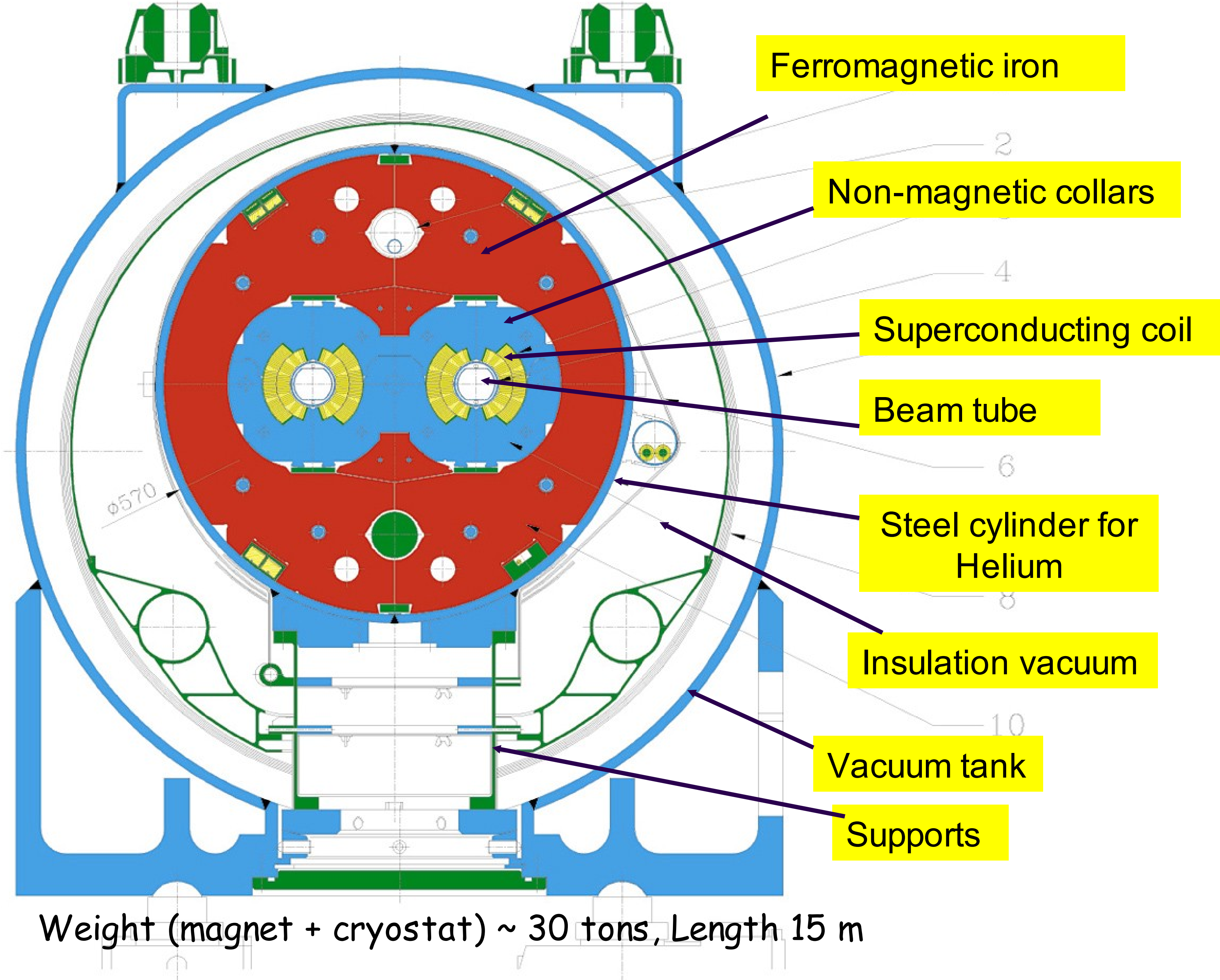


Dipole field map - cross-section





B = 8.33 Tesla   I = 11800 A   L = 0.1 H



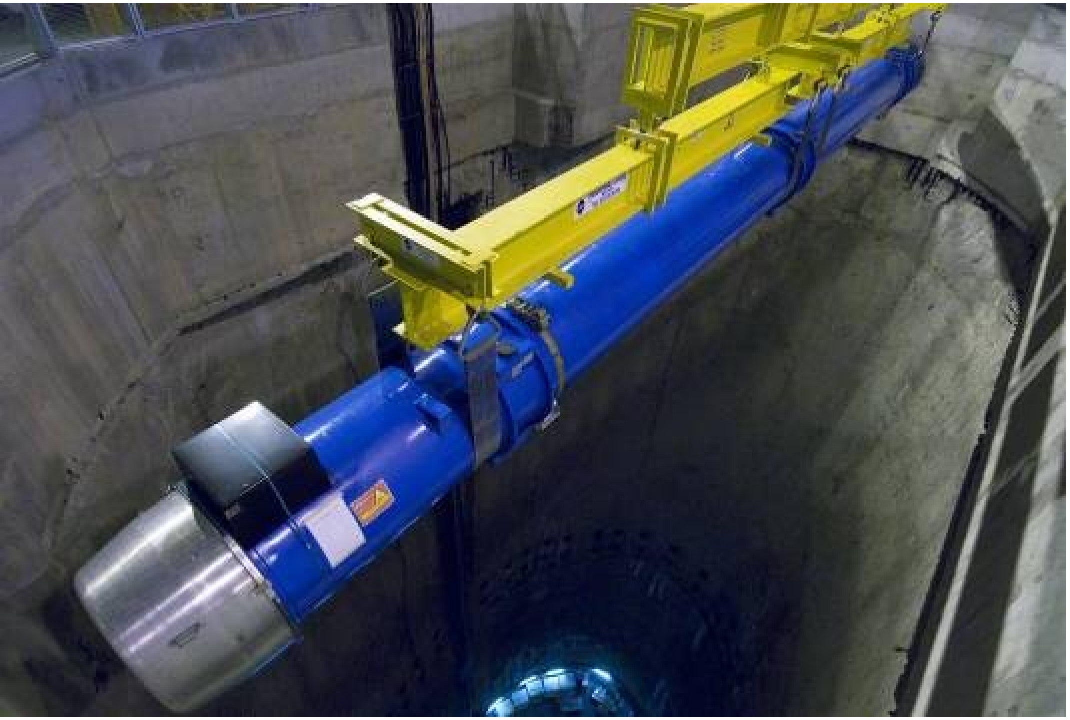
Weight (magnet + cryostat) ~ 30 tons, Length 15 m

Dipole magnet production challenges

- The field quality must be excellent:
  - Relative field errors due to multipoles much less than 0.1 %.
  - The coils/collars must be positioned to some 10 μm.
- The geometry must be respected – and the magnet must be correctly bent ('banana' shape) to follow the curvature of the trajectory.
- All magnets had to be produced in time, delivered to CERN, installed in the cryostats, cold tested, and finally installed into the LHC tunnel.

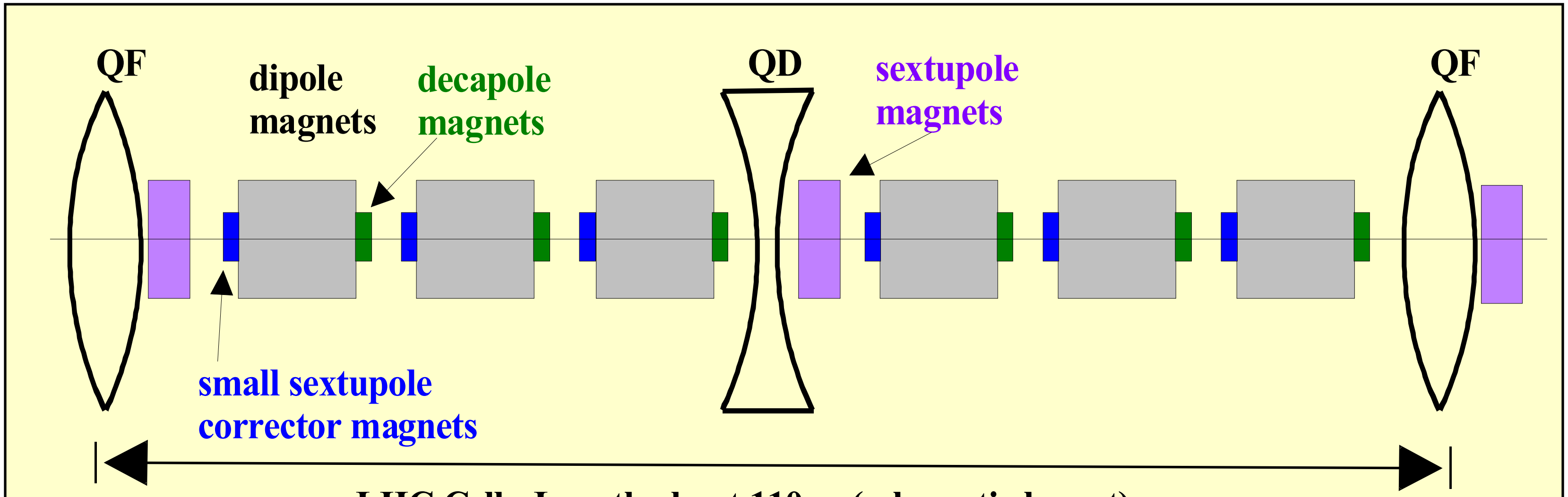
- The magnets must reach a field of at least 8.3 Tesla, and possibly 9 Tesla.

First dipole lowered on 7 March 2005



Only one access point for 15 m long dipoles, 35 tons each

LHC arc lattice : not just dipoles

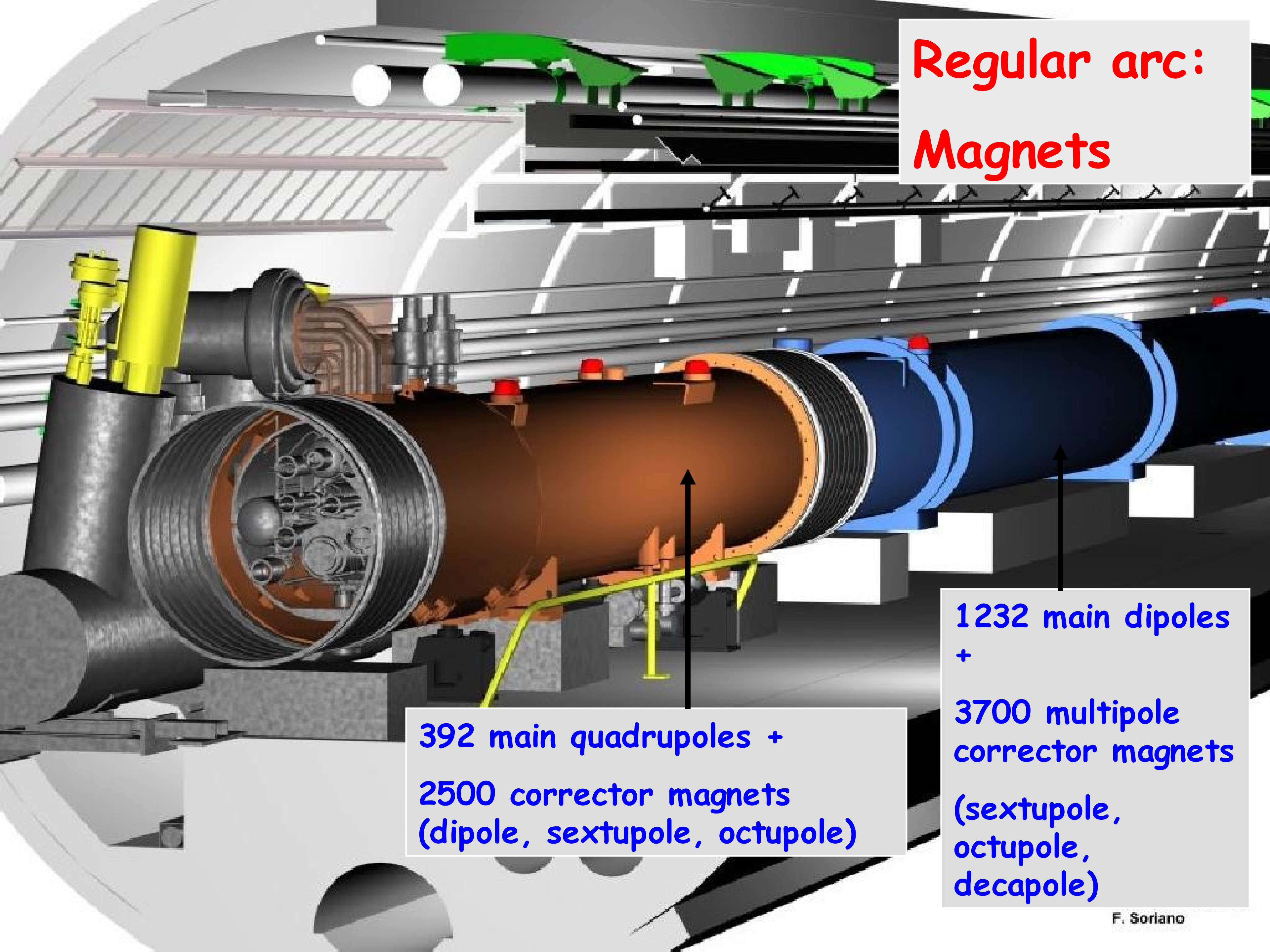


LHC Cell - Length about 110 m (schematic layout)

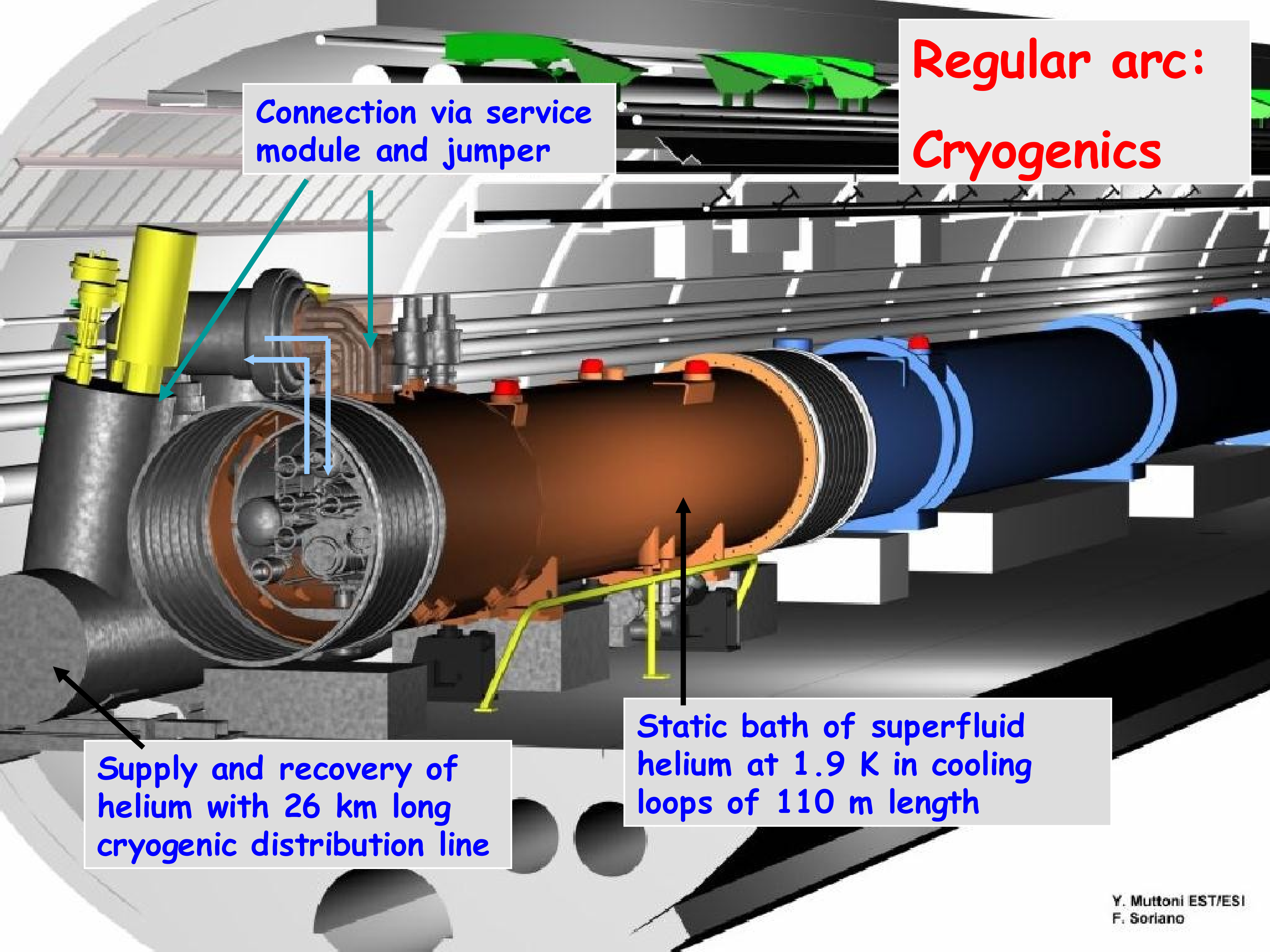
- Dipole- und Quadrupol magnets
  - Provide a stable trajectory for particles with nominal momentum.
- Sextupole magnets
  - Correct the trajectories for off momentum particles (‚chromatic' errors).
- Multipole-corrector magnets
  - Sextupole - and decapole corrector magnets at end of dipoles
  - Used to compensate field imperfections if the dipole magnets. To stabilize trajectories for particles at larger amplitudes – beam lifetime !

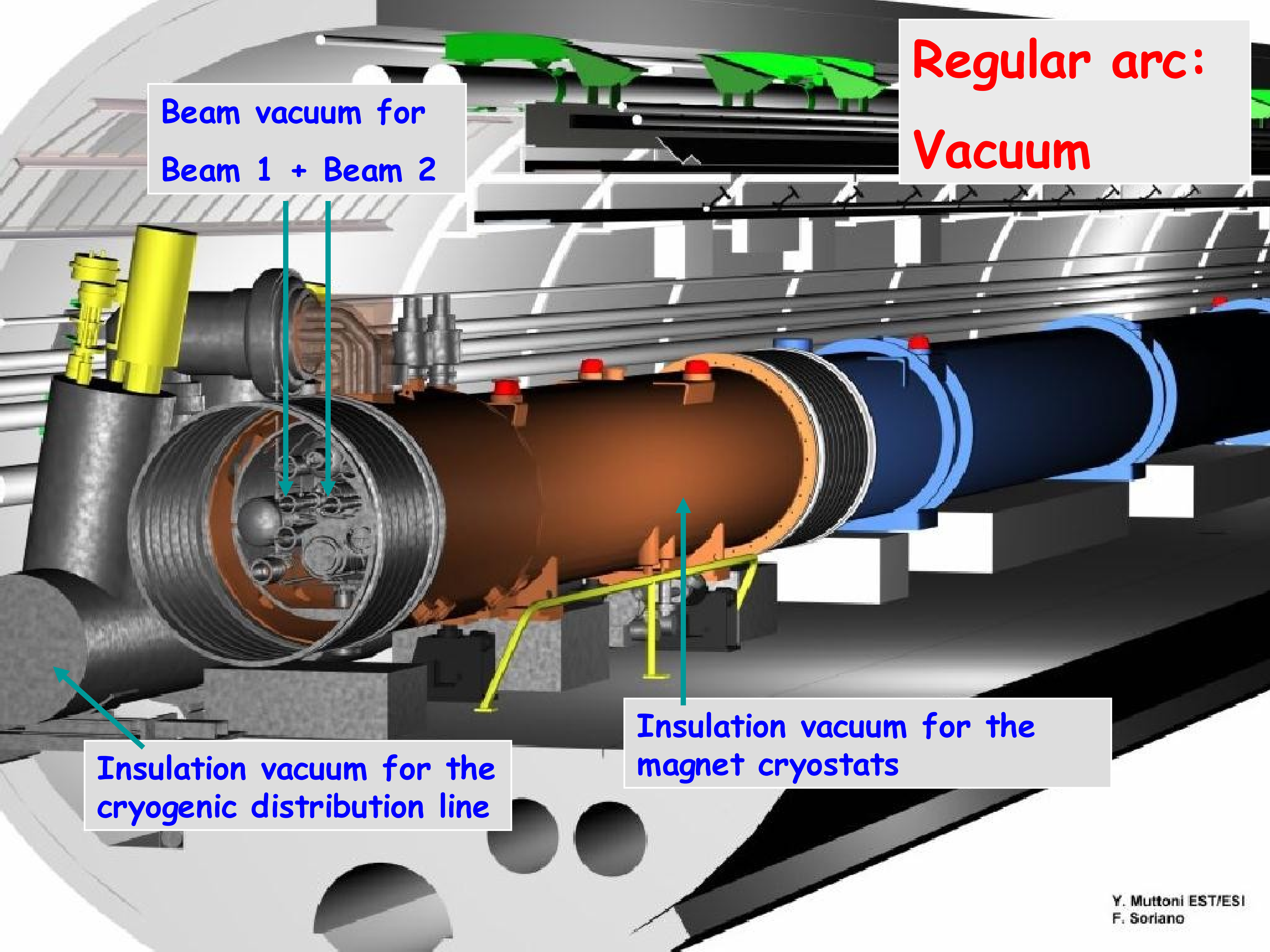
~ 8000 superconducting magnets ae installed in the LHC

Regular arc: Magnets



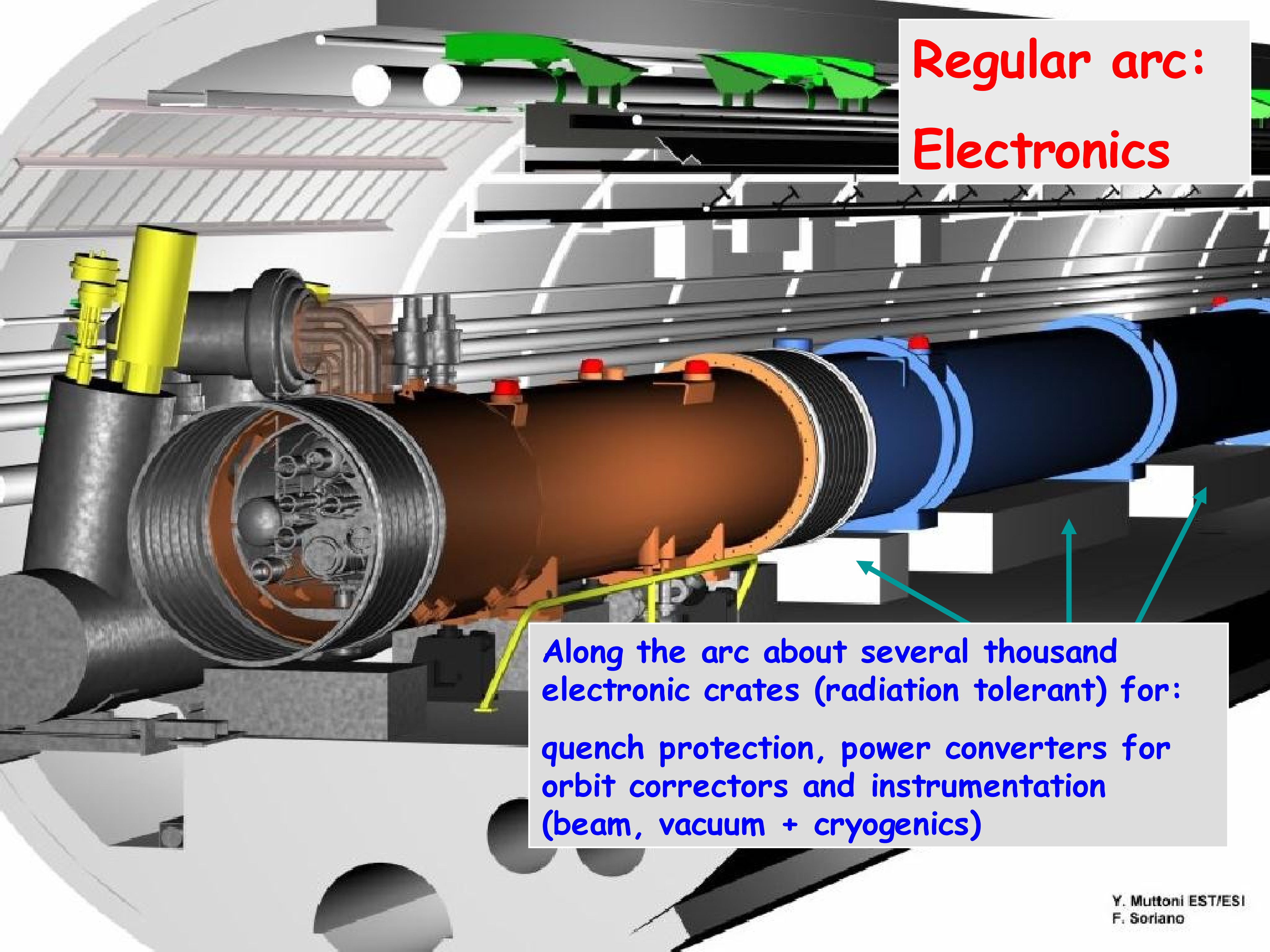
Regular arc: Cryogenics





Regular arc: Vacuum
Beam vacuum for Beam 1 + Beam 2
Insulation vacuum for the magnet cryostats
Insulation vacuum for the cryogenic distribution line
Y. Muttoni EST/ESI
F. Soriano

Regular arc: Electronics



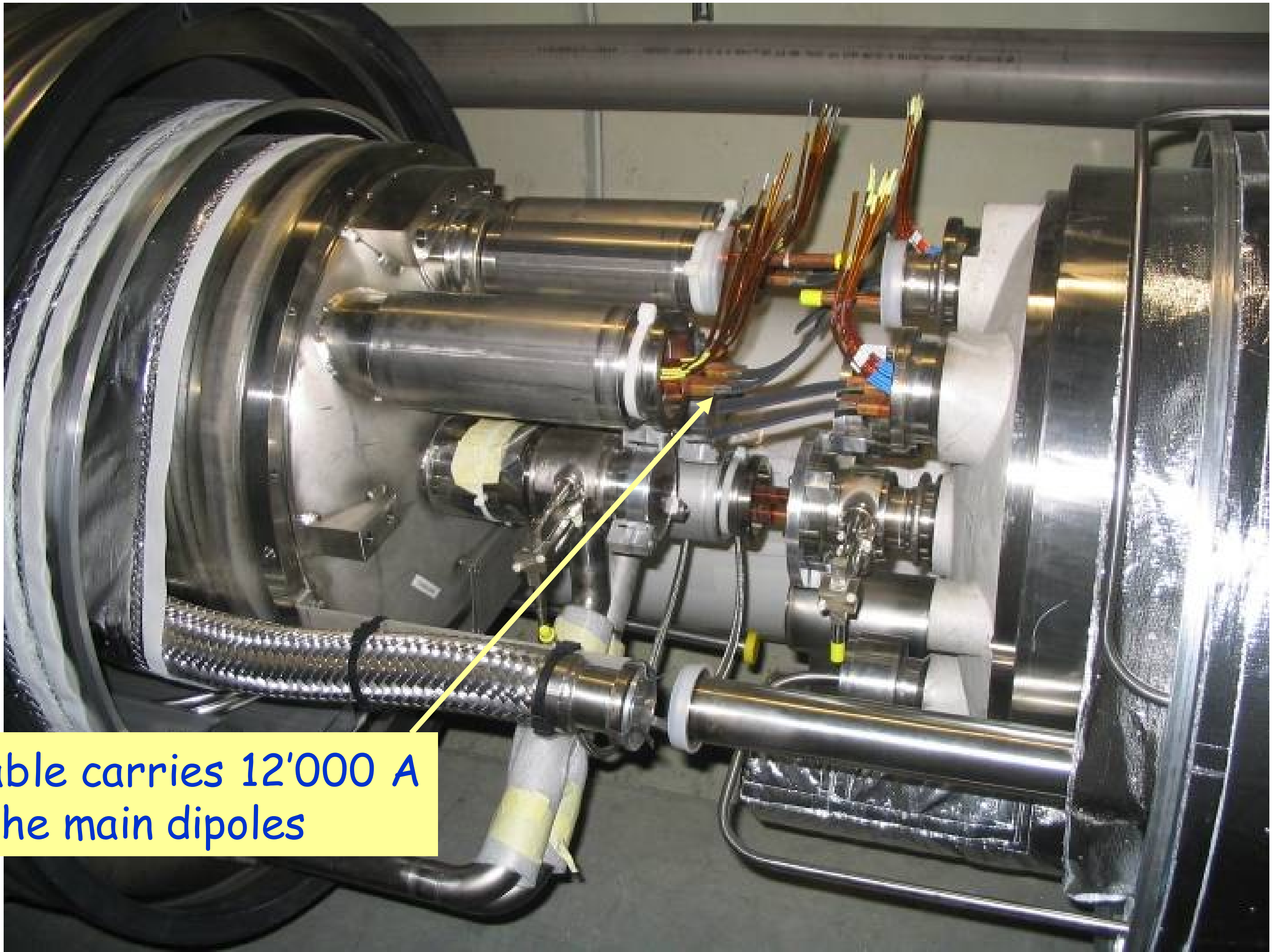
Along the arc about several thousand electronic crates (radiation tolerant) for:

quench protection, power converters for orbit correctors and instrumentation (beam, vacuum + cryogenics)

Tunnel view

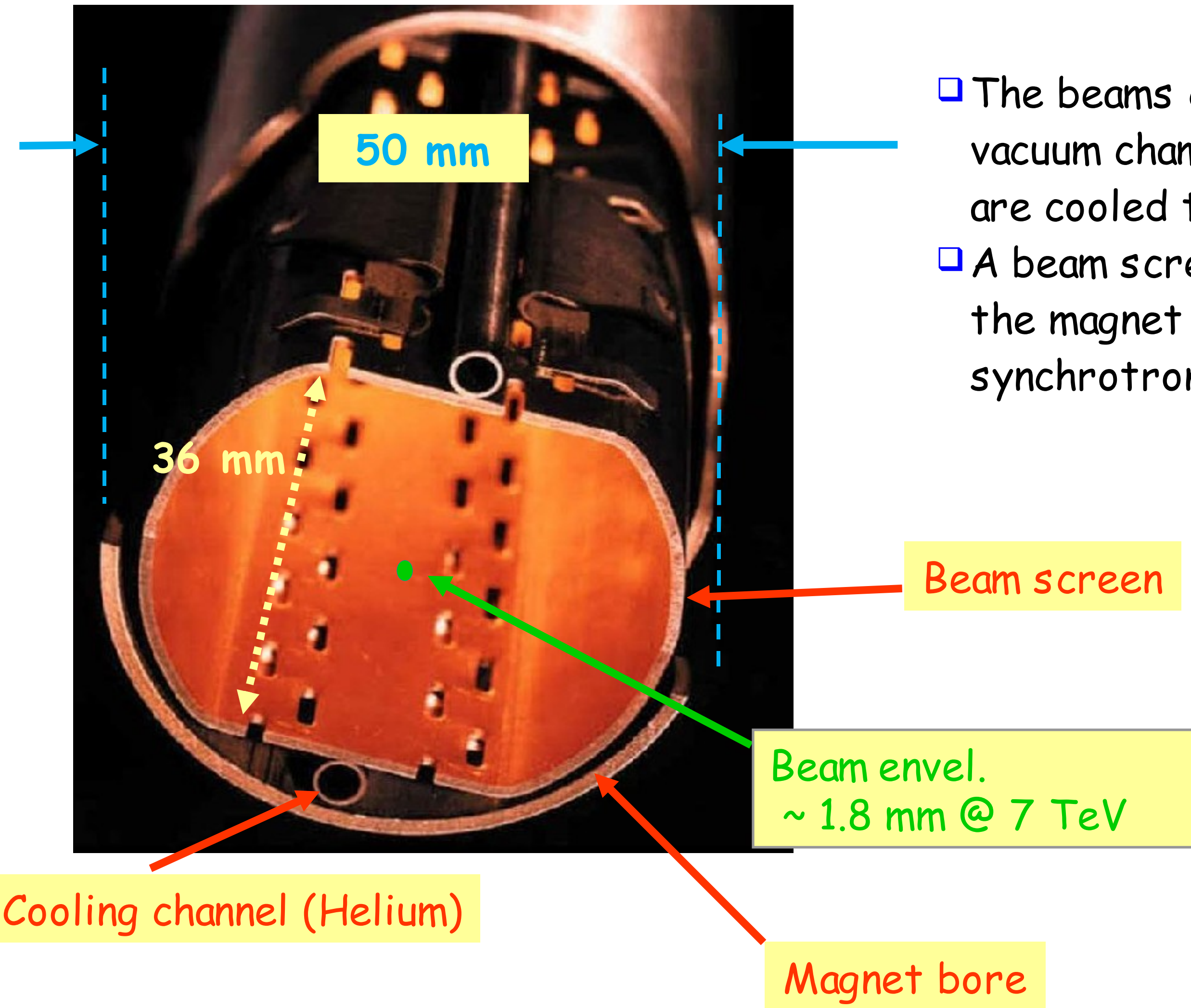
Complex interconnects

Many complex connections of super-conducting cable that will be buried in a cryostat once the work is finished.



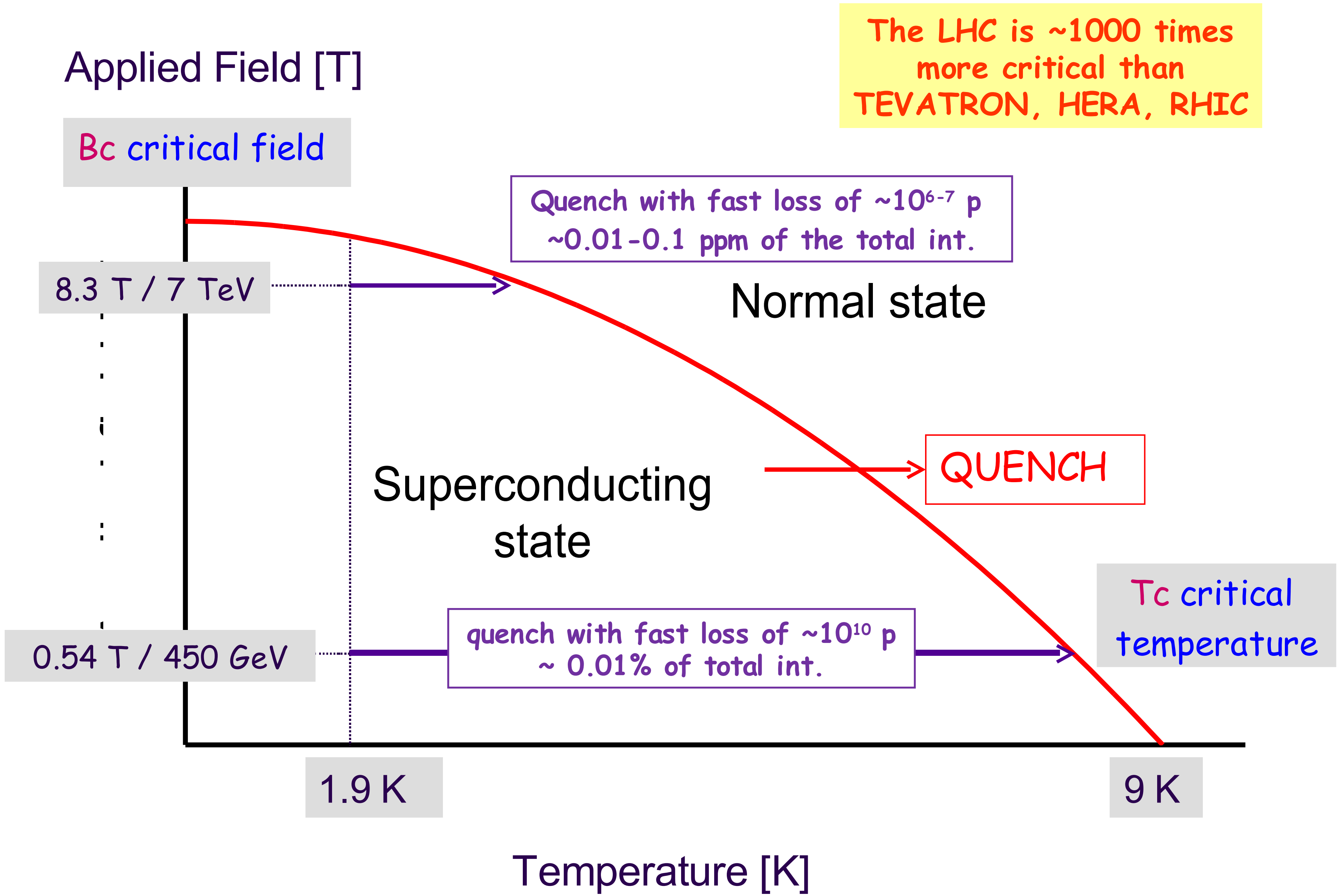
This SC cable carries 12'000 A for the main dipoles

Vacuum chamber



- The beams circulate in two ultra-high vacuum chambers made of Copper that are cooled to T = 4-20 K.
- A beam screen protects the bore of the magnet from image currents, synchrotron light etc from the beam.

Operational margin of SC magnet



'Cohabitation'

- Even to reach a luminosity of 10^{33} cm^{-2} s^{-1}, i.e. 10% of the design, requires unprecedented amounts of stored beam energy.

- The stored energy will be circulating a few cms from extremely sensitive super-conducting magnets, which can quench following a fast loss of less than 1 part per million of the beam:

  >>> requires a very large collimation system (> 100 collimators).

- LHC commissioning has to be much more rigorous than what was done for previous machines – no shortcuts and dirty 'tricks' can be used to go ahead as soon as the intensities exceed a few % of the design.

>>> Predictions on the commissioning duration are particularly tricky!

LHC Harware Commissioning

LHC Commissioning

Commissioning of the LHC equipment ('Hardware commissioning') has started in 2005 and is now in full progress. This phase includes:

- Testing of ~10000 magnets (most of them superconducting).
- 27 km of cryogenic distribution line (QRL).
- 4 vacuum systems, each 27 km long.
- > 1600 magnet circuits with their power converters (60 A to 13000 kA).
- Protection systems for magnets and power converters.
- Checkout of beam monitoring devices.
- Etc...

Hardware commissioning sequence

The present LHC commissioning phase is designated as 'Hardware Commissioning'. The main job is the commissioning of the magnets and their powering systems.

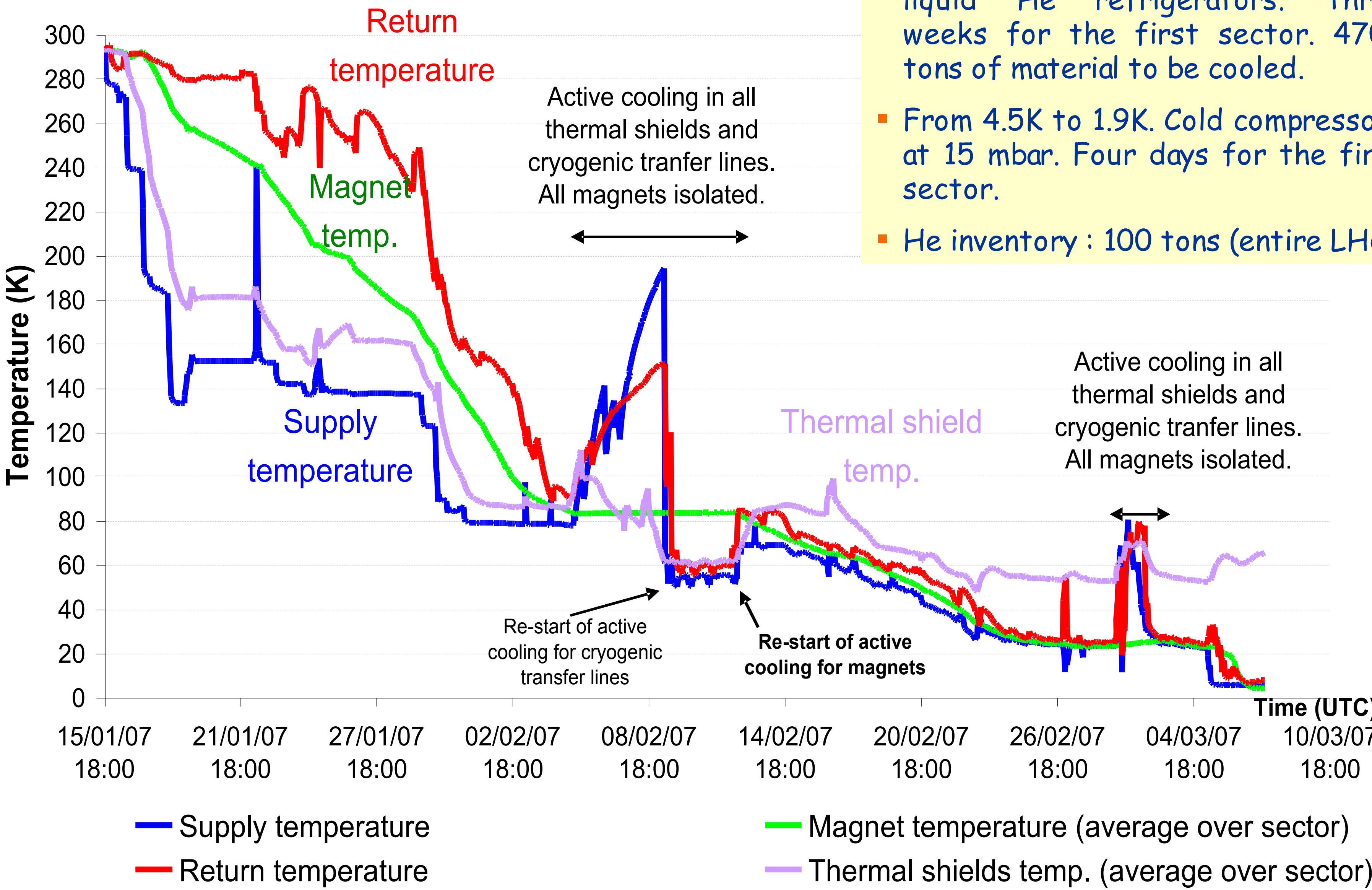
When all magnets of one of the eight LHC sectors installed and interconnected:

- Pumping vacuum system to nominal pressure.
- Cooling down to 1.9 (4.5) Kelvin.
- Connection of the power converter to the magnets.
- Commissioning of the power converter + interlock system + magnet protection system (low current).
- Commissioning of magnet powering + magnet protection system (high current).
- Powering of all magnets in a sector to nominal current.

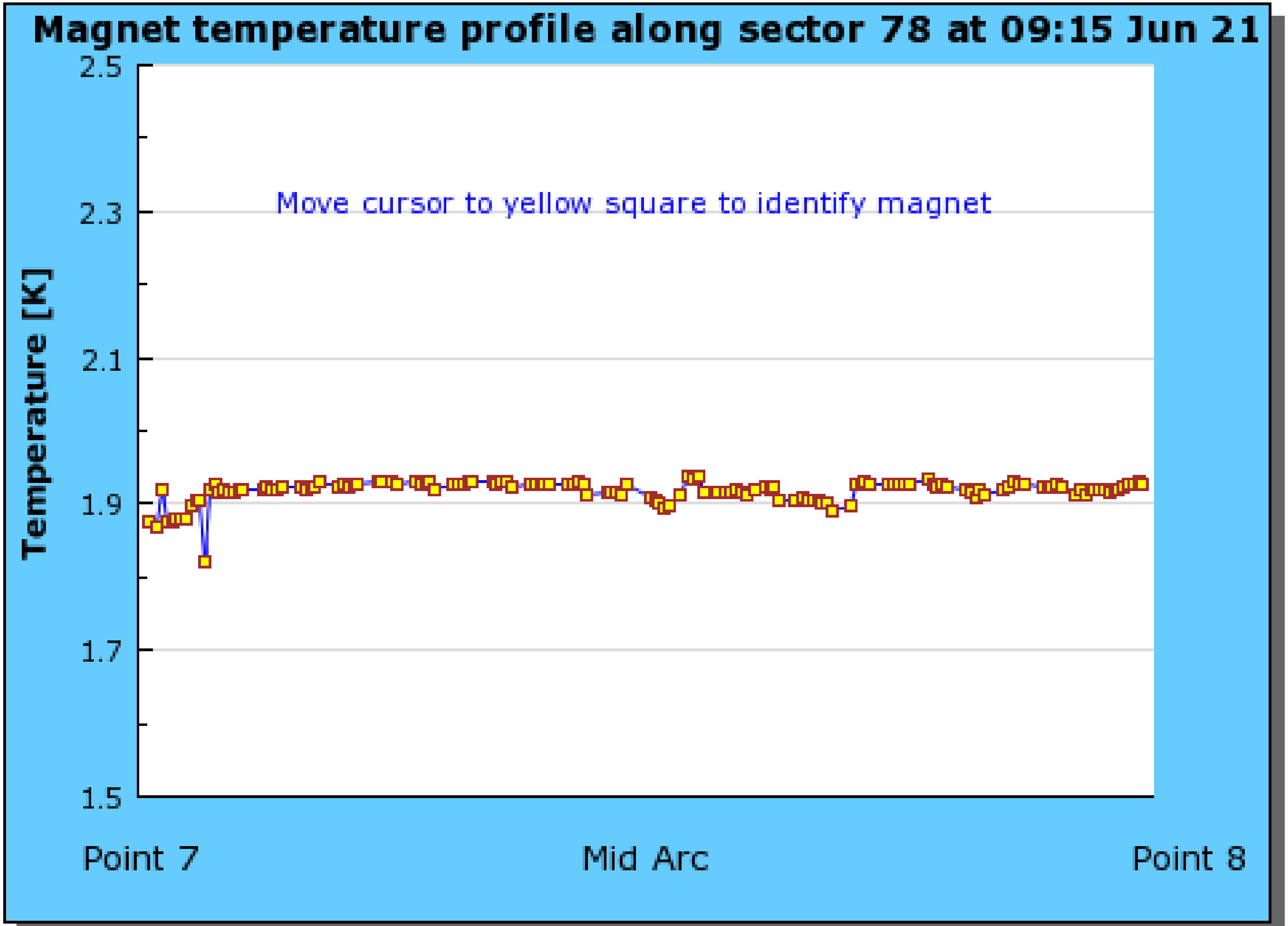
This commissioning sequence is run individually on each of the 8 LHC sectors (arcs).

LHC Sector 78 – First cooldown

- From 300K to 80K pre-cooling with 1200 tons of liquid N2 (60 trucks !). Three weeks for first sector.
- From 80K to 4.5K. Cool-down with liquid He refrigerators. Three weeks for the first sector. 4700 tons of material to be cooled.
- From 4.5K to 1.9K. Cold compressors at 15 mbar. Four days for the first sector.
- He inventory : 100 tons (entire LHC).



Finally - June 2007



Commissioning status

- Magnet production is completed.
- Installation and interconnections finished for magnets. Some components still missing (collimators…).
- Cryogenic system :
  - One sector (IR8→IR7) was cooled down to 1.9 K in June/July 2007.
  - Cool-down of 4 (1/2 LHC) sectors starting/in progress (until Christmas).
- Powering system:
  - Power converter commissioning finished.
  - Cool-down and commissioning of the first complete sector (7-8) was performed in June/July 2007:
    - » All circuits with individual magnets have been commissioned (except triplets).
    - » The main magnets were commissioned to 1 TeV: limited by electrical non-conformities that have been repaired during a warm up of the sector September-October.
  - **Main commissioning campaign starts in December 2007.**
- Other systems (RF, beam injection and extraction, beam instrumentation, collimation, interlocks, etc) are essentially on schedule for first beam in 2008.

Commissioning problems…

Given that:

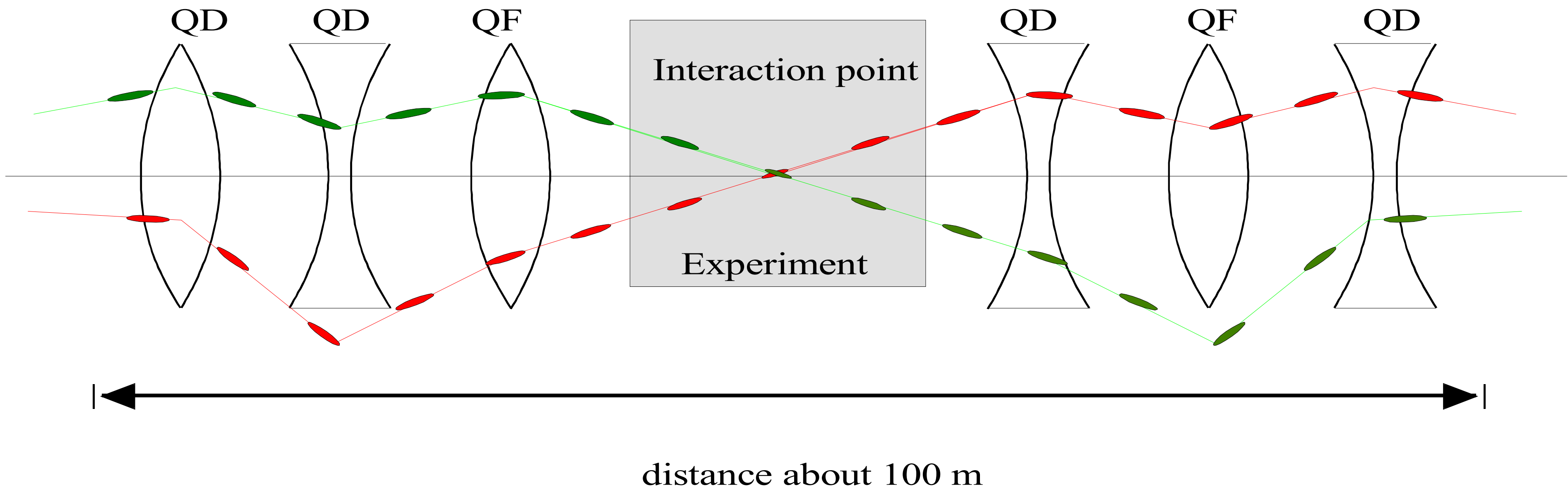
- The LHC is of unprecedented complexity,
- The LHC performance/technology is pushed to the limits,

it is not really surprising that the history of the LHC is filled with more or less severe problems that were related to dipole magnets, cryogenics distribution line, collimators…

Two recent problems that concern the machine commissioning:

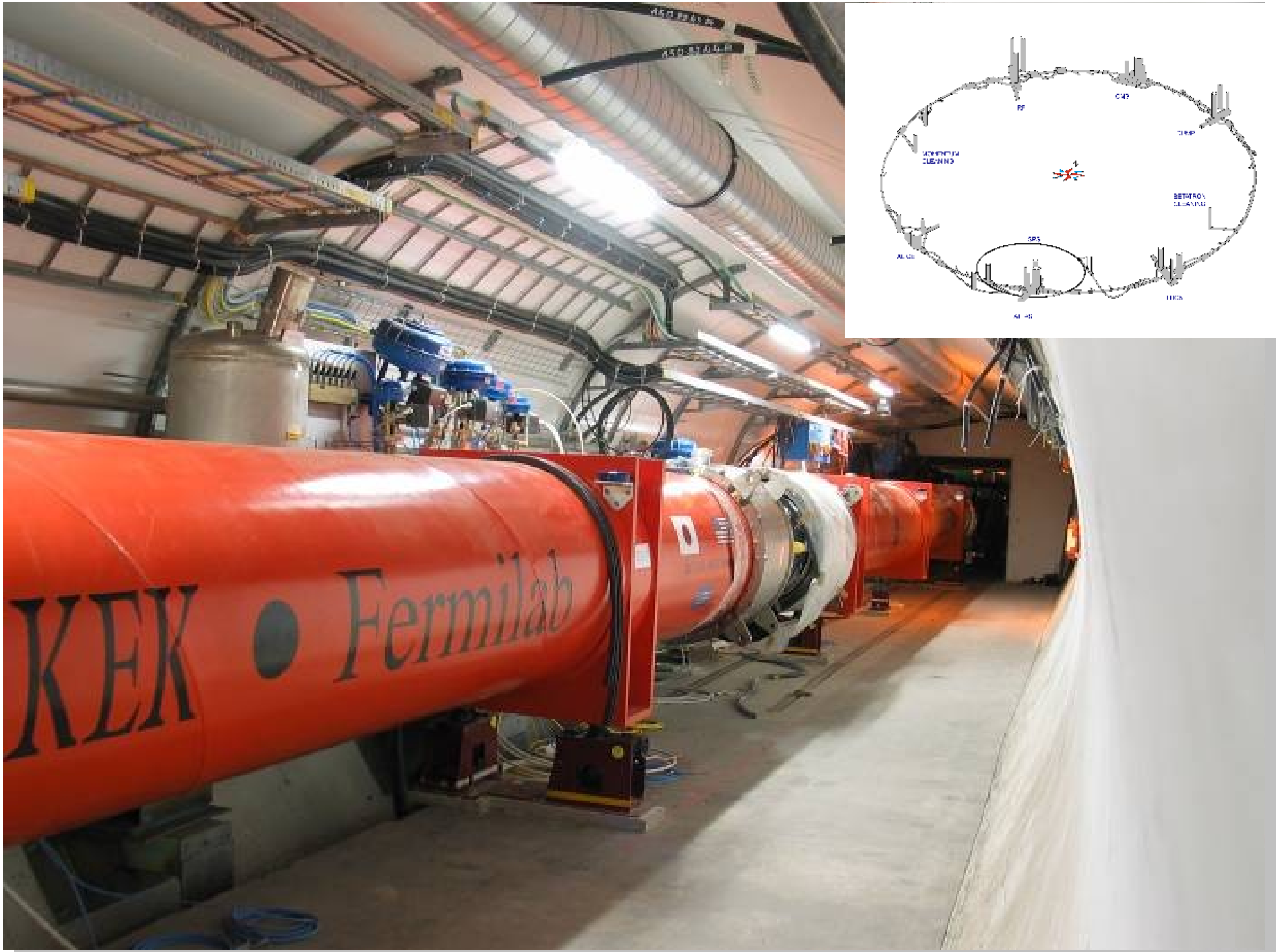
- 'Inner triplets'
- RF fingers

The (inner) 'Triplets'



- The large aperture quadrupoles called 'inner triplets' are high gradient and large aperture magnets that provide the focussing for the collision point in both planes. They are provided as part of the US & JAPAN contributions to CERN :
  - Large beam size ~ 100 x size at IP
  - Large beam separation from crossing angle ~ 12 mm
- Beam sizes :
  - at IP (ATLAS, CMS) 16 μm
  - in the triplets ~1.6 mm
  - in the arcs ~0.2 mm

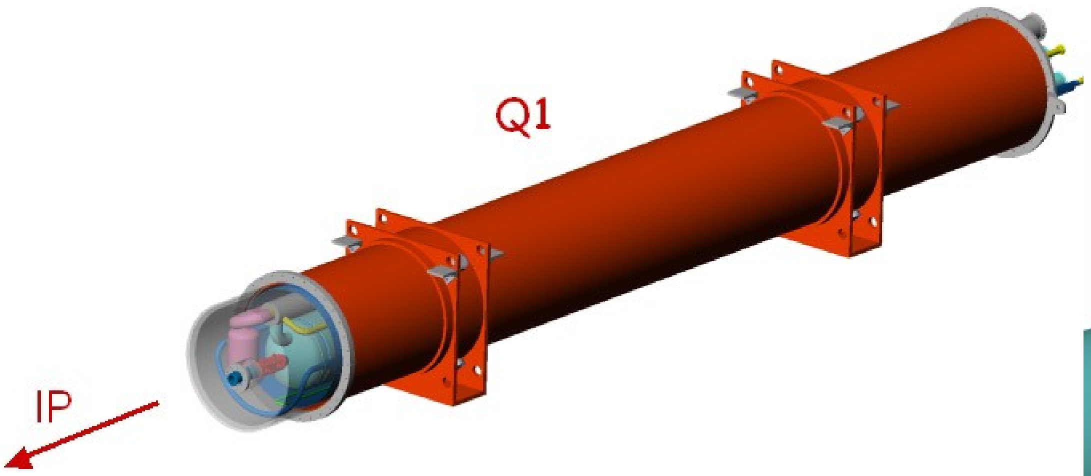
Triplets viewed from LHC tunnel



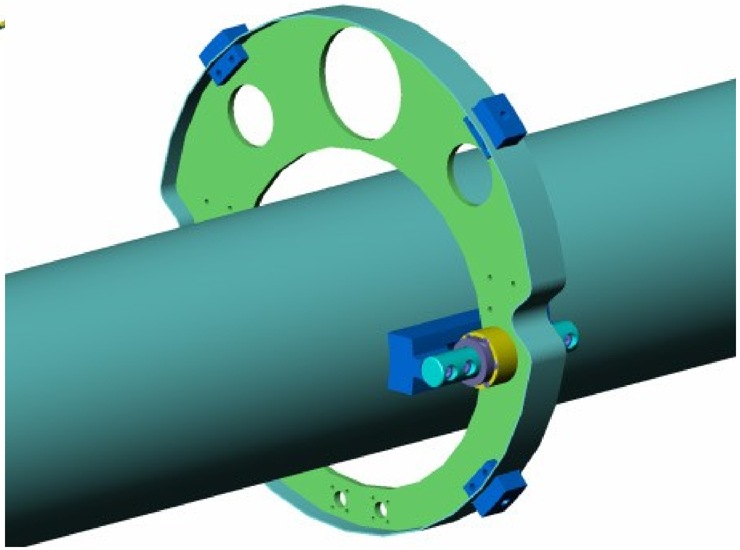
Triplet viewed from the CMS cavern

Triplet problems

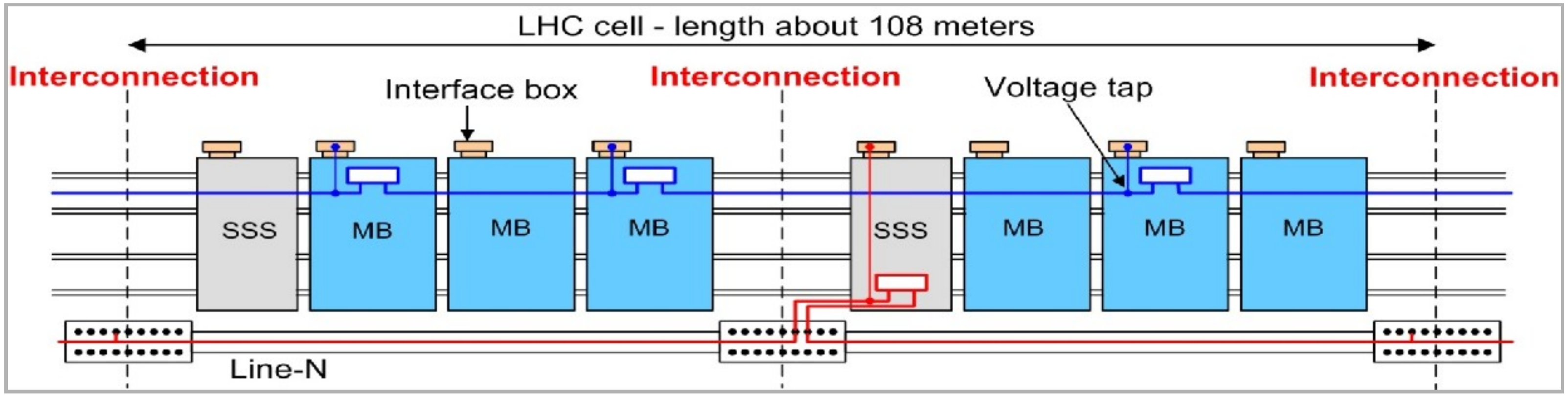
- In February 2007 a triplet magnet in point 5 was damaged during a (routine) pressure test. The support that holds the magnet in the cryostat could not sustain the longitudinal force during the pressure test.
- A crash programme was initiated in collaboration with FNAL to repair the magnets, partly in situ.
- All magnets are now repaired.

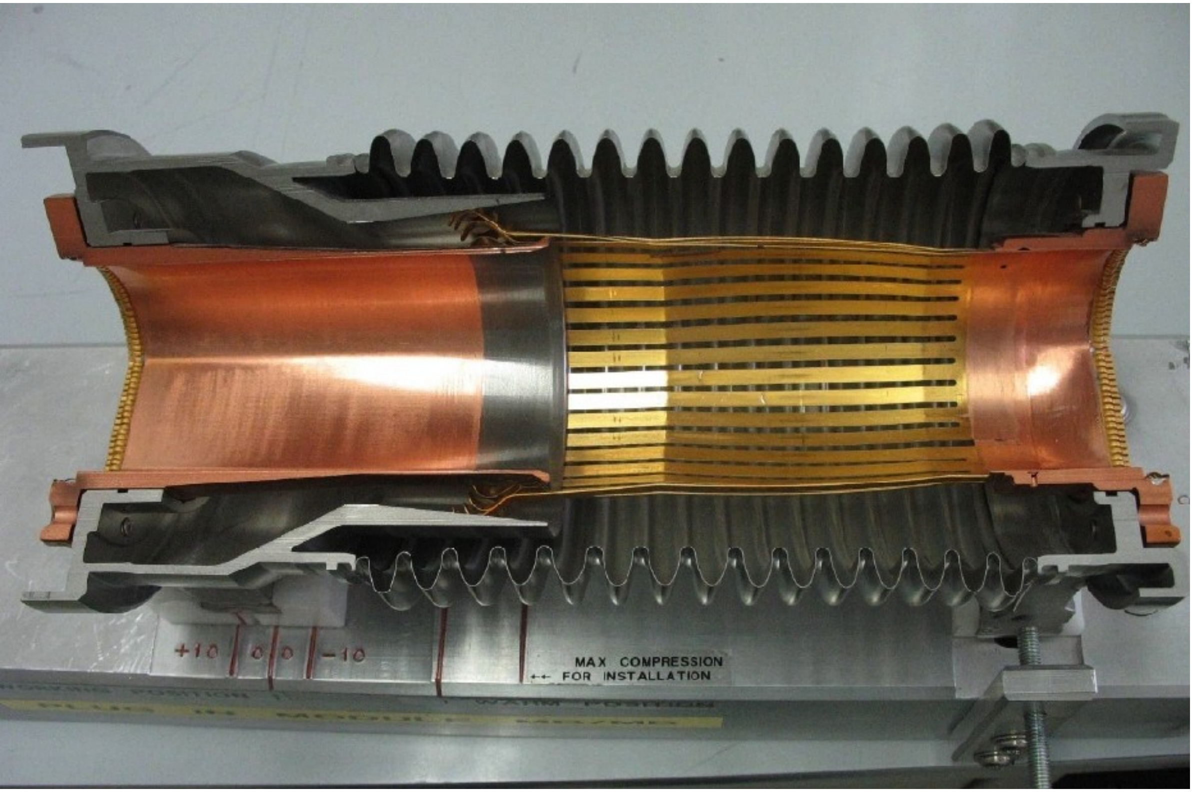


The faulty support



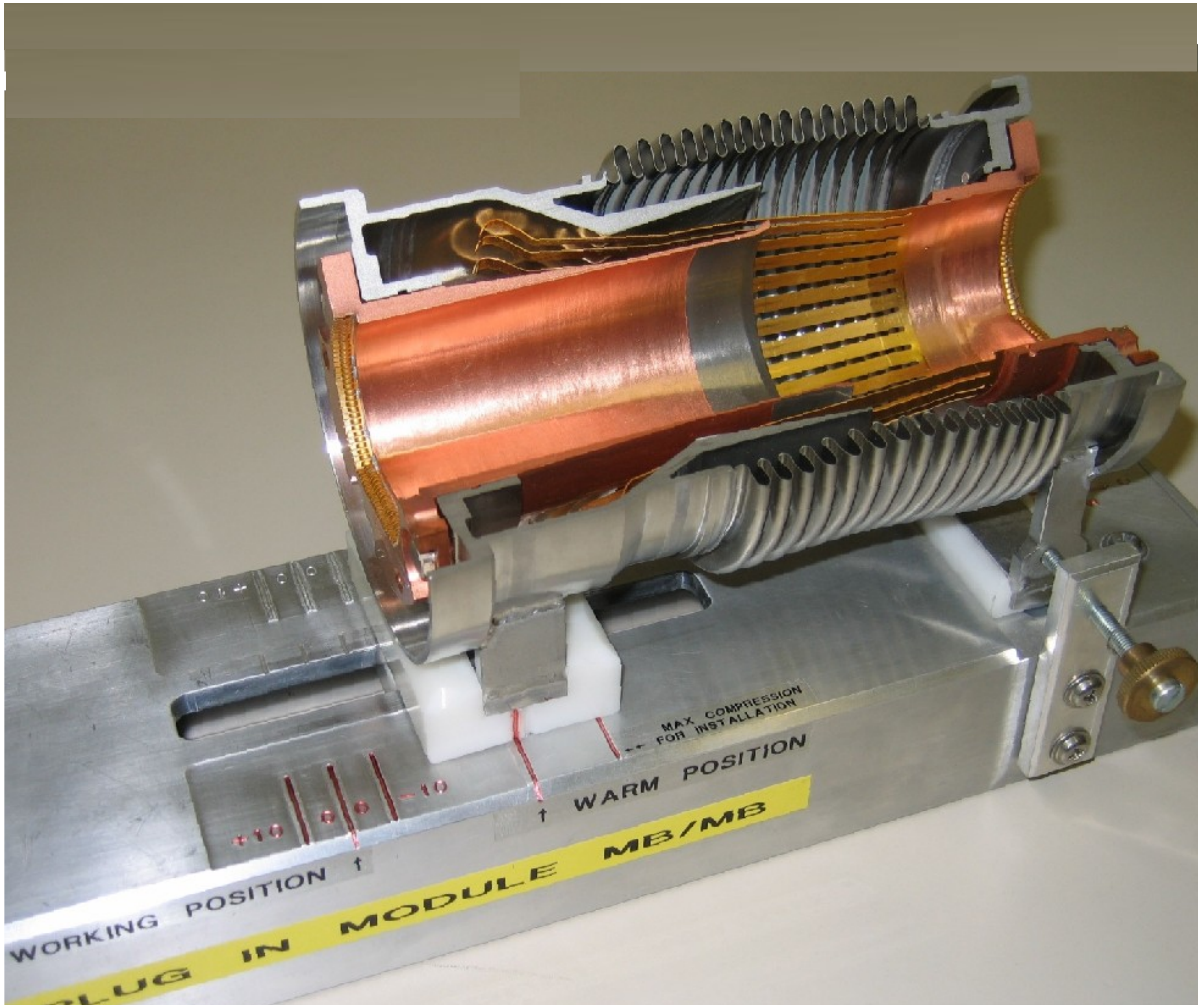
'RF fingers' problems



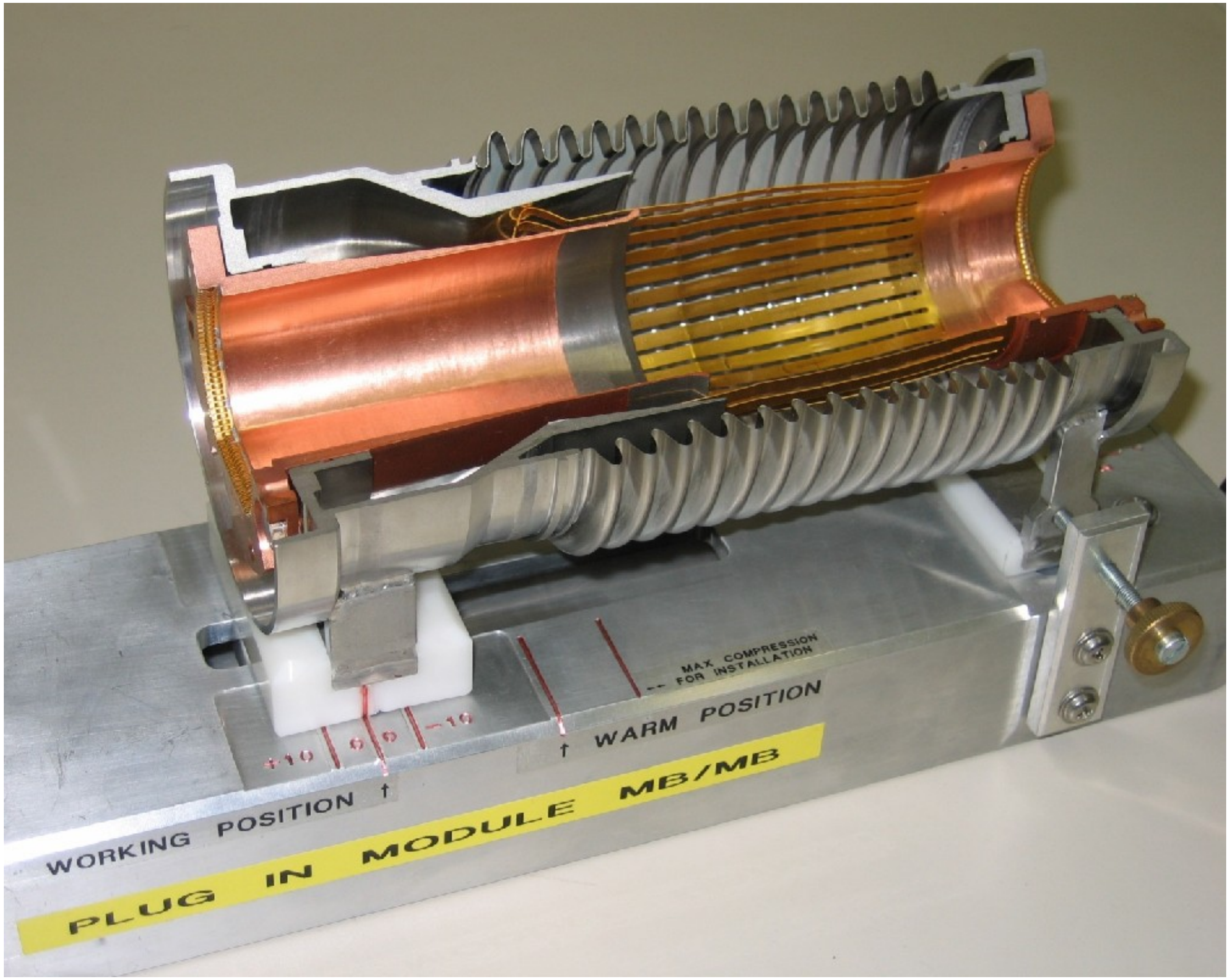


- RF bellows are used to maintain electrical contact between adjacent pieces of vacuum chamber (essential for beam stability).
- The bellows must cope with the thermal expansion of ~ 4 cm between 1.9 K and room temperature (when the magnets are cooled down/warmed up).
- Bellows are installed at every interconnection (1700 in total).

At room temperature

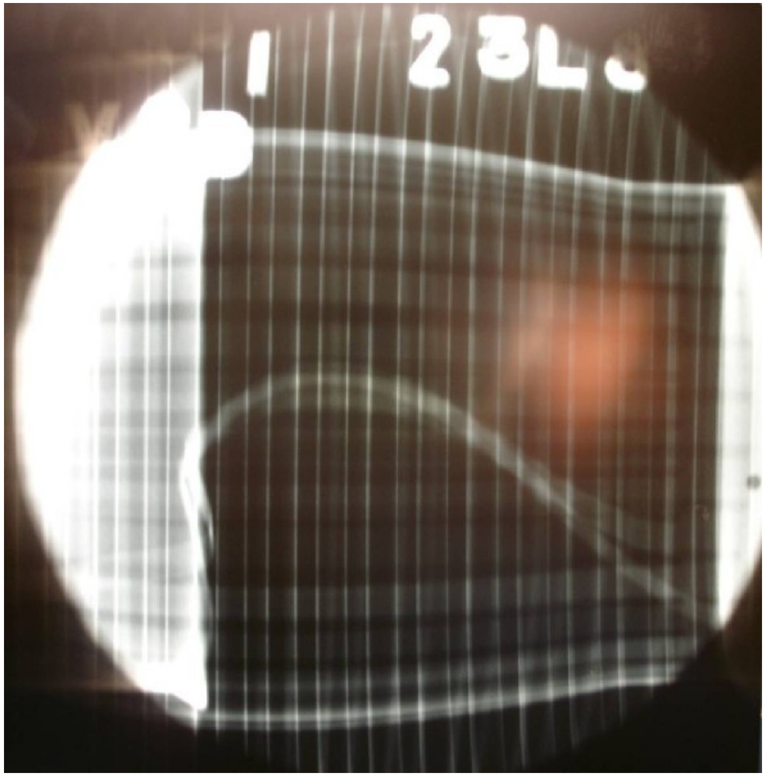


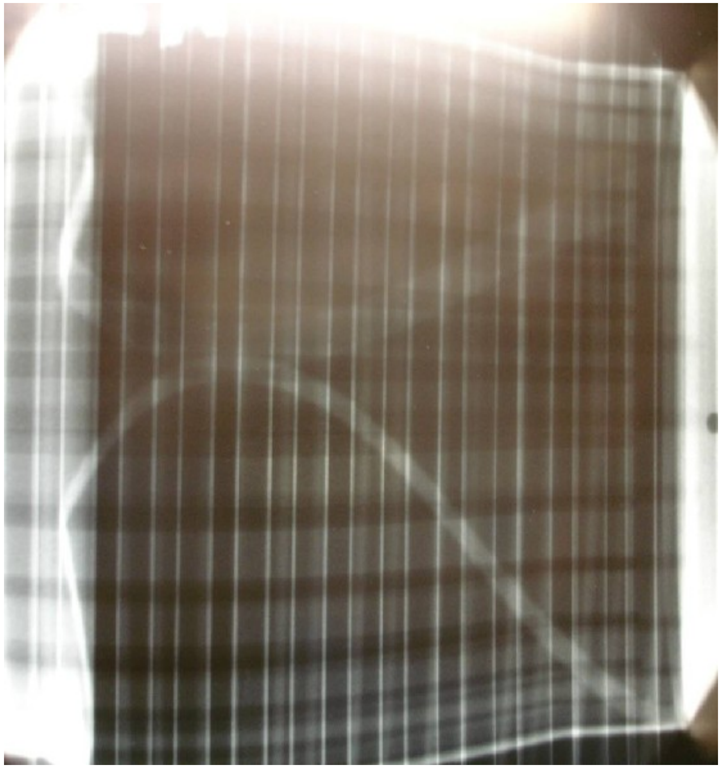
At operating temperature



Damaged bellows

- RF fingers that bend into the beam are a classic problem for accelerators. RHIC suffered a lot from it…
- So no excuses for not being careful in design and manufacturing !
- And yet it happened ! X-ray imaging of some bellows revealed bend fingers in the sector that was tested in July and warmed up since then for repair.

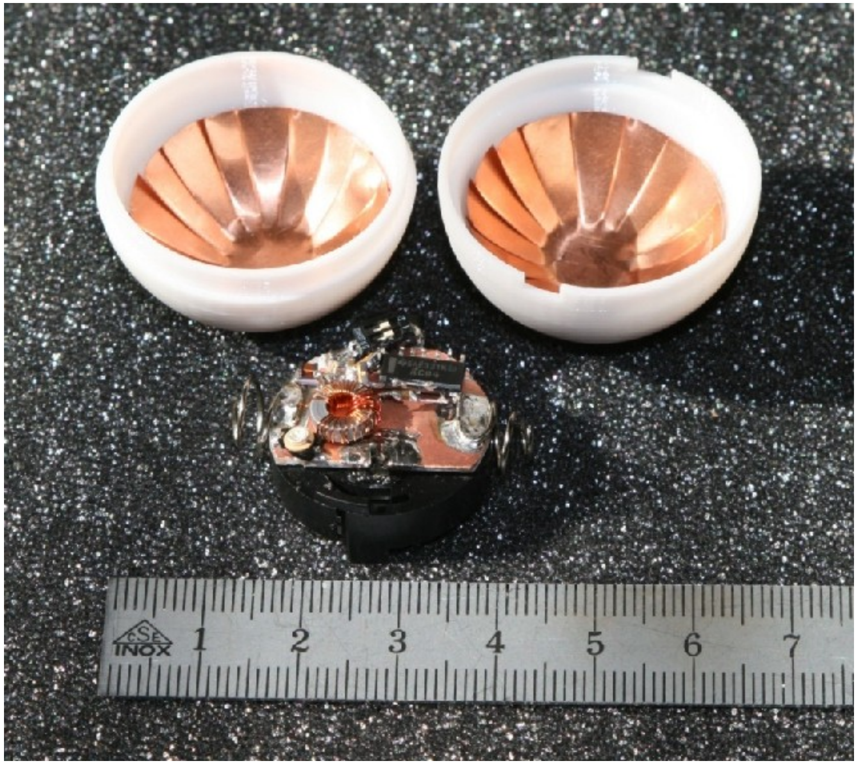




Cause & solution for RF fingers

- The fingers bend due to a combination of a wrong 'finger angle' PLUS a gap between the magnet apertures larger than nominal (still inside specification).
- Only few interconnects are affected.
- Complete survey of one sector was performed using X-ray techniques.
- Repair is not difficult…once the bad fingers are found.

>> This problem will stay around until every sector is warmed up again in 200X…



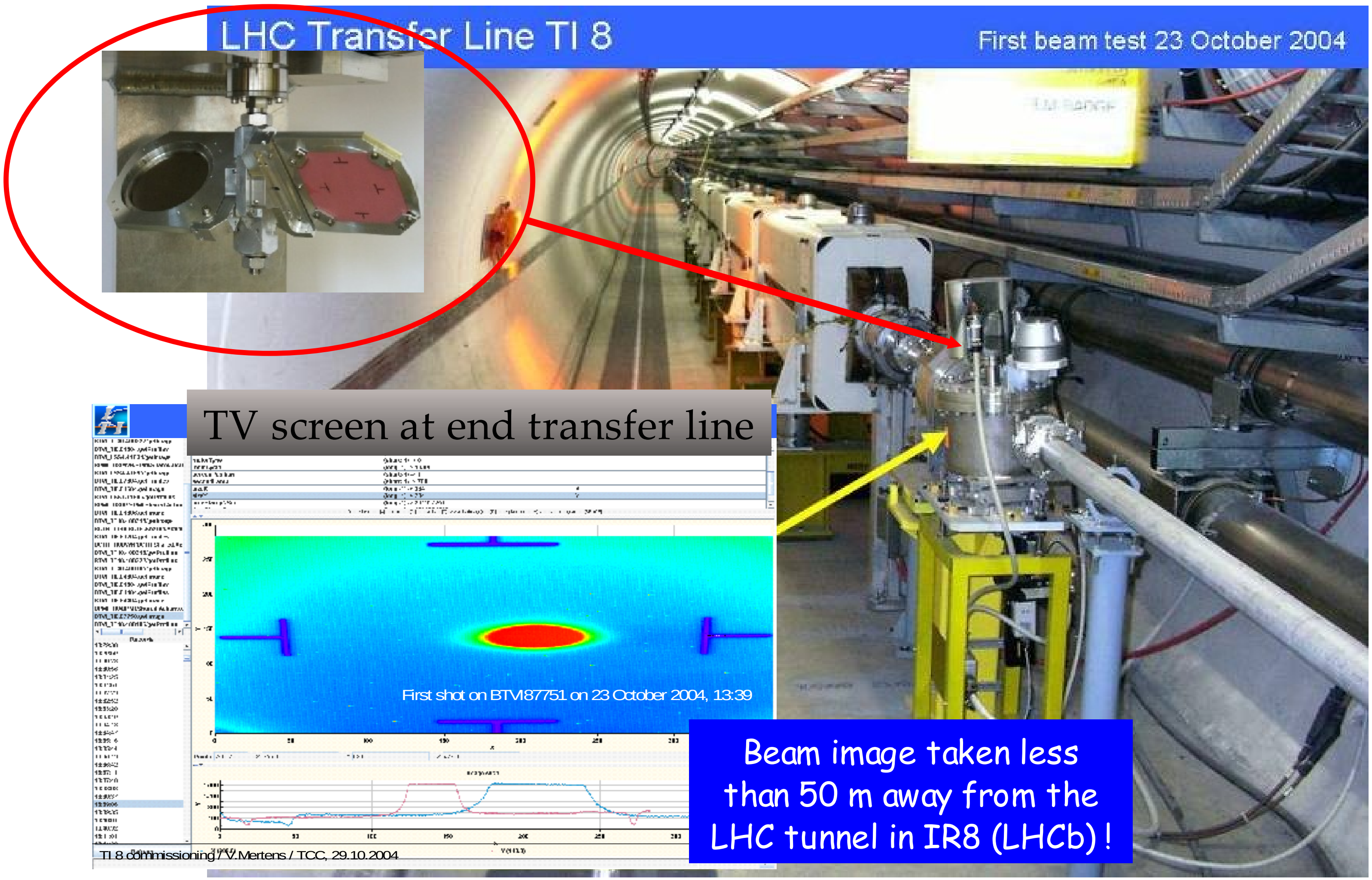
'Solution':

- ✓ A small (ping-pong size) ball equipped with a 40MHz transmitter is blown through the beam vacuum pipe with compressed air.
- ✓ Beam position monitors are used to follow the ball as it rolls inside the vacuum chamber until it stops or exits on the other end..

Towards First Beam

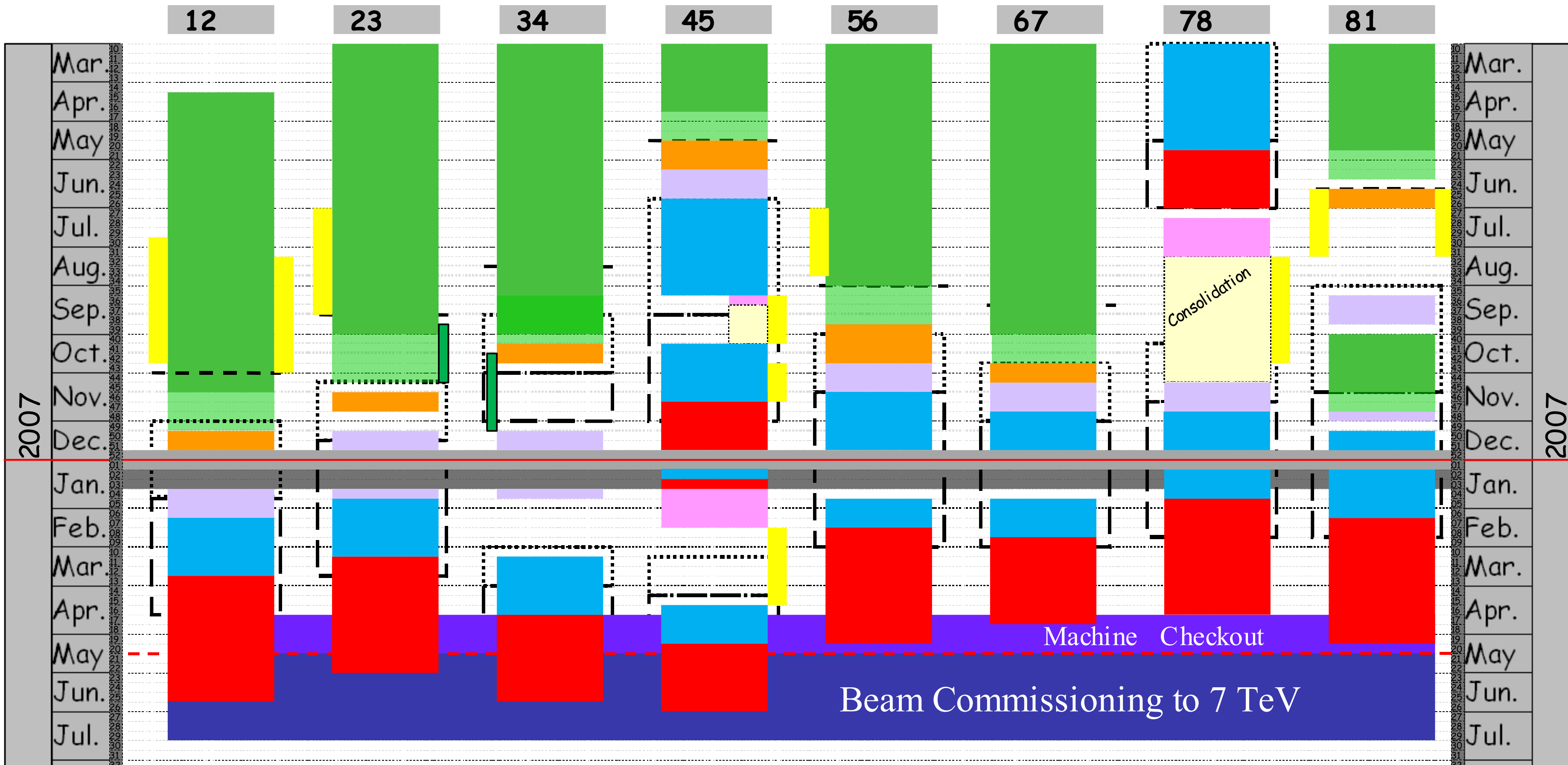
Injector status : beam at the gate to the LHC

- The LHC injectors are ready after a long battle to achieve the nominal beam brightness: instabilities, e-clouds etc.
- The nominal LHC beam can be produced at 450 GeV in the SPS.



Latest 'schedule'

Pushed to the limit – no contingency ! Expect changes ... !!!!!!



General schedule Baseline rev. 4.0

- Global pressure test &Consolidation
- Cool-down
- Powering Tests
- Interconnection of the continuous cryostat
- Leak tests of the last sub-sectors
- Inner Triplets repairs & interconnections
- Global pressure test &Consolidation
- Flushing
- Cool-down
- Warm up
- Powering Tests

Towards beam…

- The latest schedule is VERY aggressive:

  Assumes parallel commissioning of almost the entire machine, while the initial schedules assumed parallel commissioning of only 1/4 LHC in parallel.

- There is no contingency for problems.

  It is likely that at least one of the 7 sectors that have never been cooled down will reveal some problem(s) that require a warm up before they can be fully commissioned to 7 TeV.

Some scenarios for 2008 that are under discussion assume:

- Push hardware commissioning as far as possible without repairs.
- If one (or more) sectors cannot be run at 7 TeV and require a warm up for repair, start with beam commissioning at 450 GeV to gain experience before performing the repair.

Beam commissioning

Beam commissioning will proceed in phases with increased complexity:

- Number of bunches and bunch intensity.
- Crossing angle (start without crossing angle !).
- Less focusing at the collision point (larger 'β^*').

It will most likely take YEARS to reach design luminosity !!!

Parameter	Phase A	Phase B	Phase C	Nominal
k / no. bunches	43-156	936	2808	2808
Bunch spacing (ns)	2021-566	75	25	25
N (10^{11} protons)	0.4-0.9	0.4-0.9	0.5	1.15
Crossing angle (μrad)	0	250	280	280
$\sqrt{(\beta^*/\beta^*_{nom})}$	2	$\sqrt{2}$	1	1
σ^* (μm, IR1&5)	32	22	16	16
L ($cm^{-2}s^{-1}$)	6×10^{30}-10^{32}	10^{32}-10^{33}	$(1-2)\times10^{33}$	10^{34}

Summary

We are getting there at last !!!!

- After many years of delay the LHC is now really taking shape in the tunnel.
- A first 1/8th of the LHC was tested to 1 TeV last summer, expected to reach 7 TeV during the winter.
- The other 7/8th will be commissioned during the coming winter/spring.

Beam is knocking at the door :

- The injectors are ready.
- It is now very likely that beam will be injected into the LHC in 2008.
- But the road to 7 TeV collisions is long, and it is difficult to predict when the experiments will see first collisions at 7 TeV, or high luminosity !!