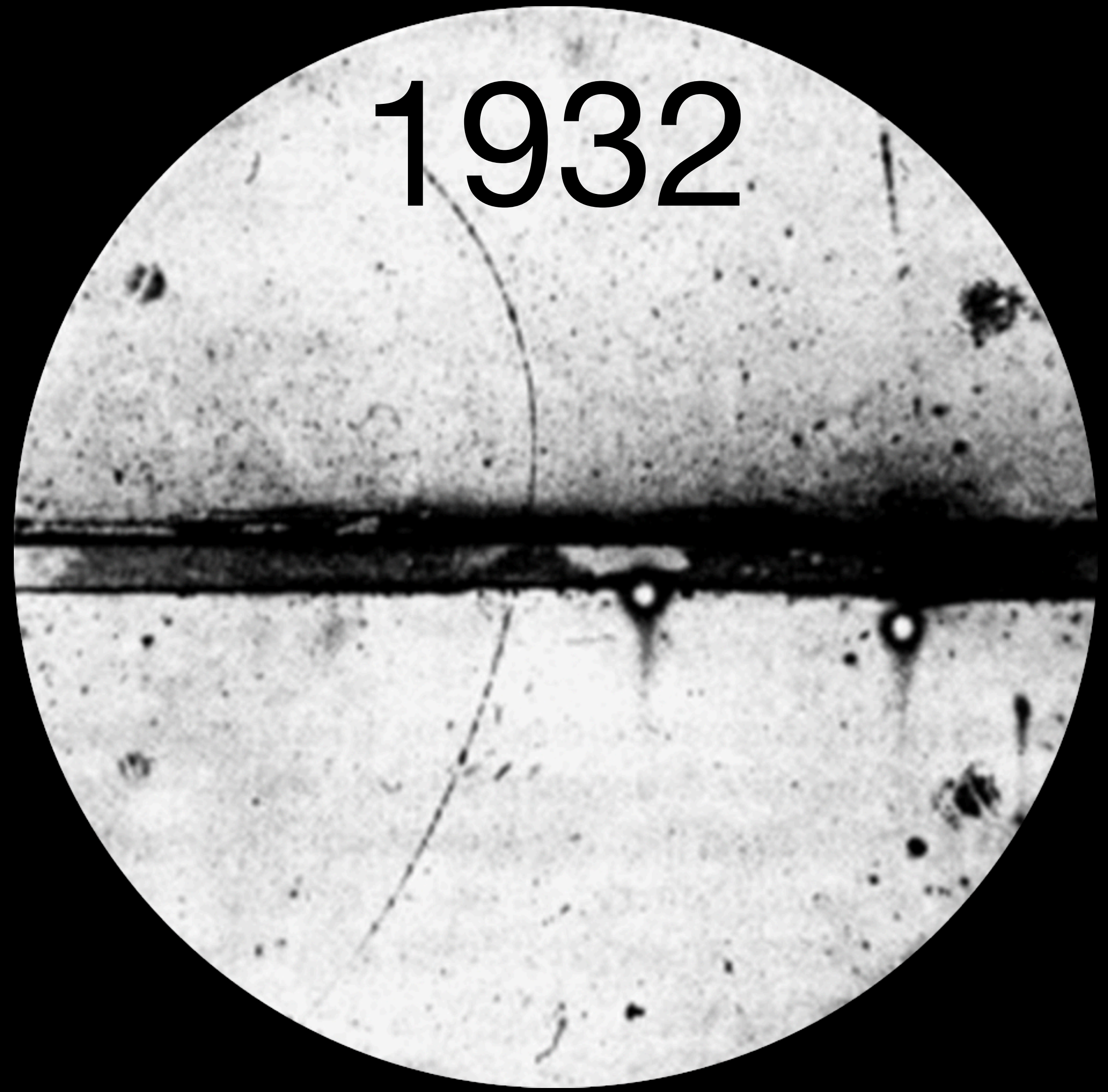
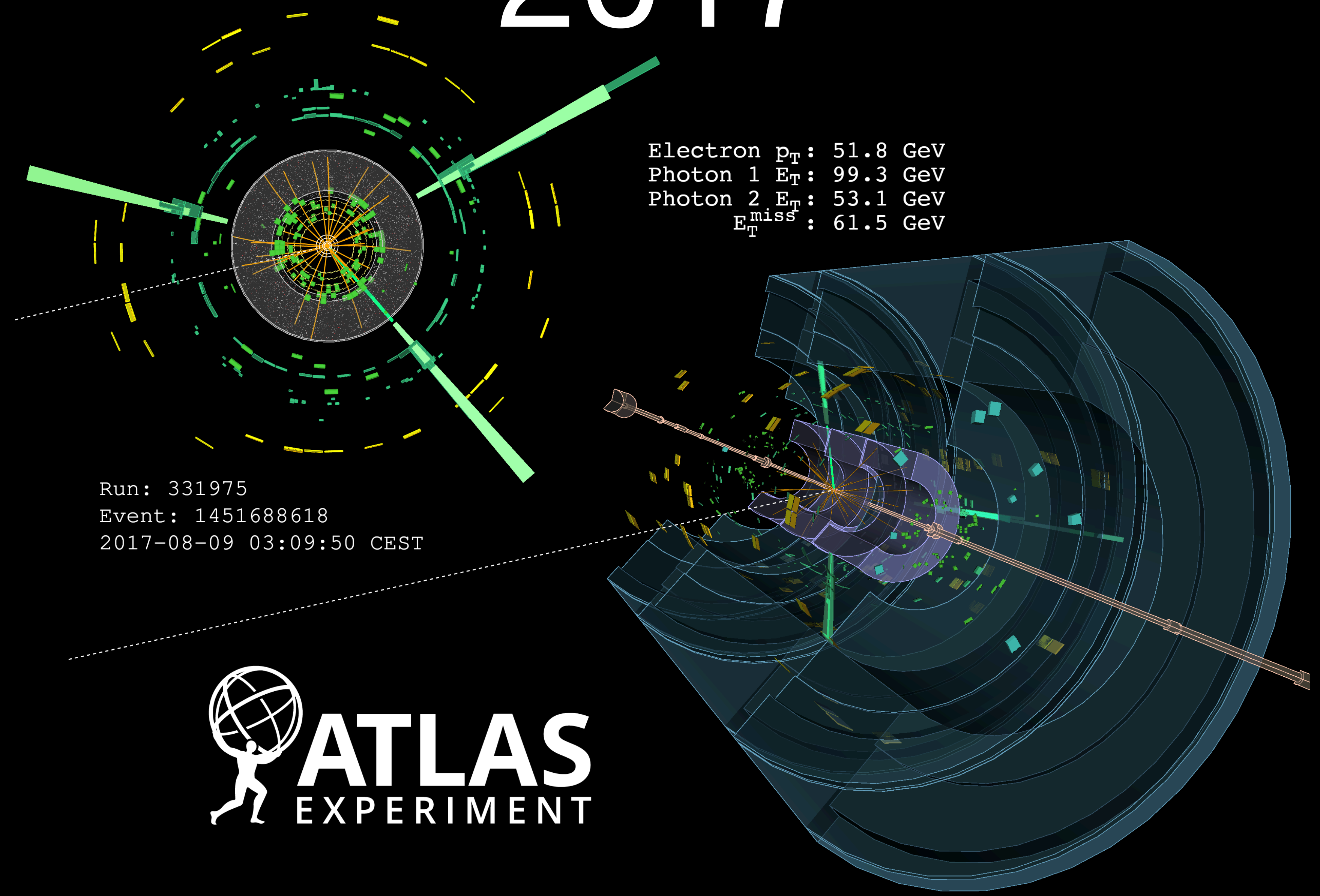
PHYS 7363 - Experimental Particle Detection and Detectors I



2017



Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection* and *identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we "see" subatomic particles, this course is for you!

Detect Identify Measure

To discuss prerequisites (and any questions on the content of the course), please contact me: saptaparnab@smu.edu

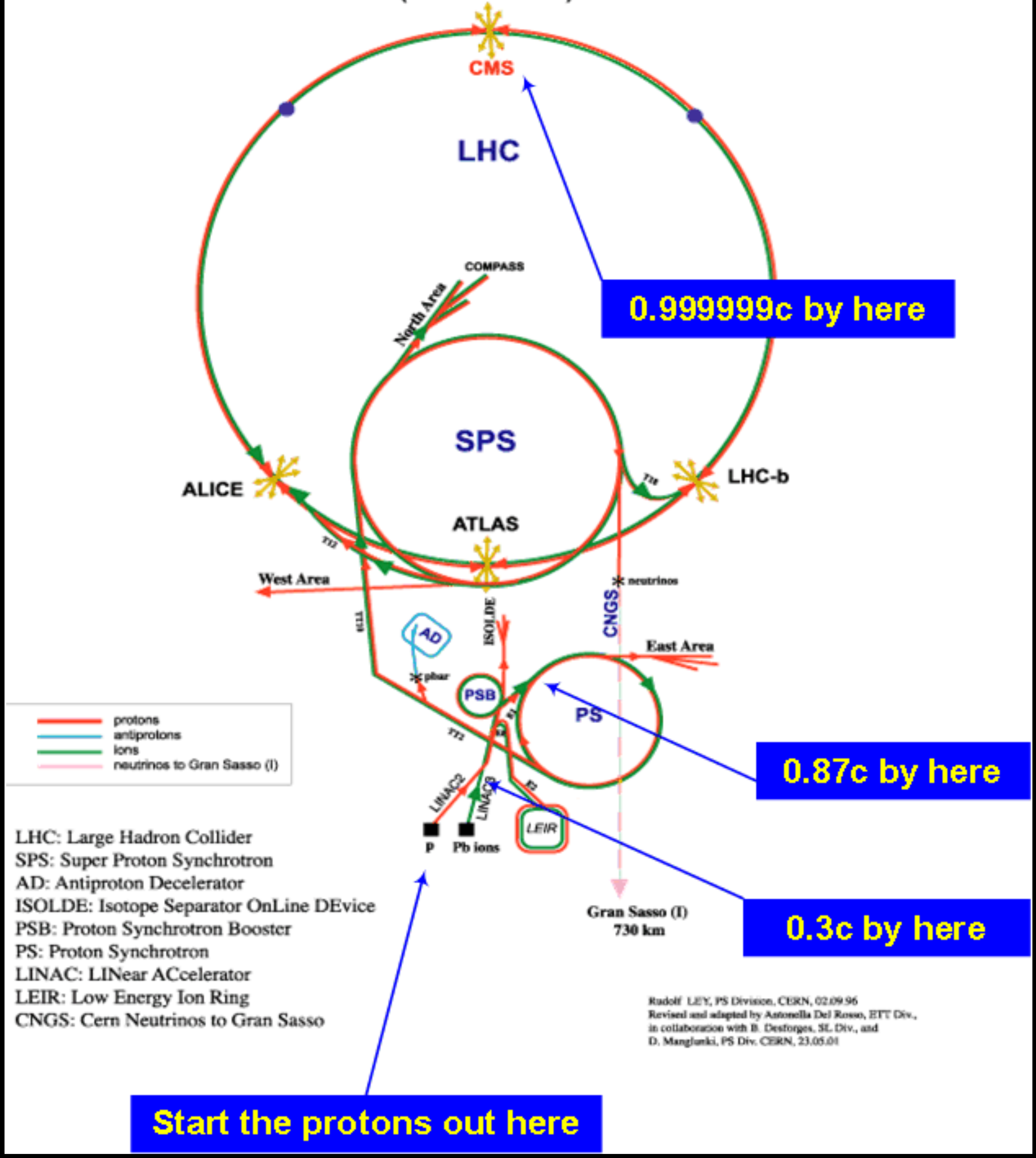
Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
October	6 ✅ 1.5 hours	7	8 ✅ 1.5 hours	9	10	11	12
	13 ✅ 1.5 hours	14	15 ✅ 1.5 hours	16	17 1.5 hours	18	19
	20	21	22	23	24	25	26
	27	28	29	30	31	1	2
November	3	4	5	6	7	8	9
	10	11	12	13	14	15	16
	17	18	19	20	21	22	23
	24	25	26	27	28	29	30
December	1	2	3	4	5	6	7
	8	9	10	11	12	13	14

Relevant parts of the book

- Chapters: 1-3
- Chapter: 8 (Semiconductor detectors)
- Chapter: 9 (Track model)
- Chapter: 15 (Calorimeters)
- What we will cover (at a minimum):
  - Chapter 12-13 (Cherenkov and Scintillation detectors),14 (particle identification), 18 (triggers)
  - Accelerator basics: today

CERN Accelerators
(not to scale)



Large Hadron Collider (LHC) timeline

Key Date	Event
March 1984	Should we build a Large Hadron Collider (LHC) in the preexisting tunnel?
January 1987	President Reagan announces support for the Superconducting Super Collider - a circular accelerator with an 87 km circumference — smash particles at 40 TeV. Still need the LHC?
October 1992	The two multipurpose experiments at the LHC publish letters of intent. Specialized experiment (ALICE) follows suit.
October 1993	Superconducting Super Collider project canceled
April 1994	Magnet prototype built and achieves 8.73 T
December 1994	LHC construction is approved by the CERN Council

Large Hadron Collider (LHC) timeline

Key Date	Event
October 1995	LHC conceptual design report published
January 1997	CMS and ATLAS experiments approved. Other specialized experiments approved.
December 1997	United States admitted as CERN observer state
July 1998	Gallo-Roman ruins discovered at the CMS site — 6 month delay
May 2002-February 2005	ATLAS and CMS caverns excavated, reinforced and inaugurated
April 2007	The last LHC dipole magnet goes underground
September 10 2008	The LHC starts up

How to use magnets to bend beams and collide?

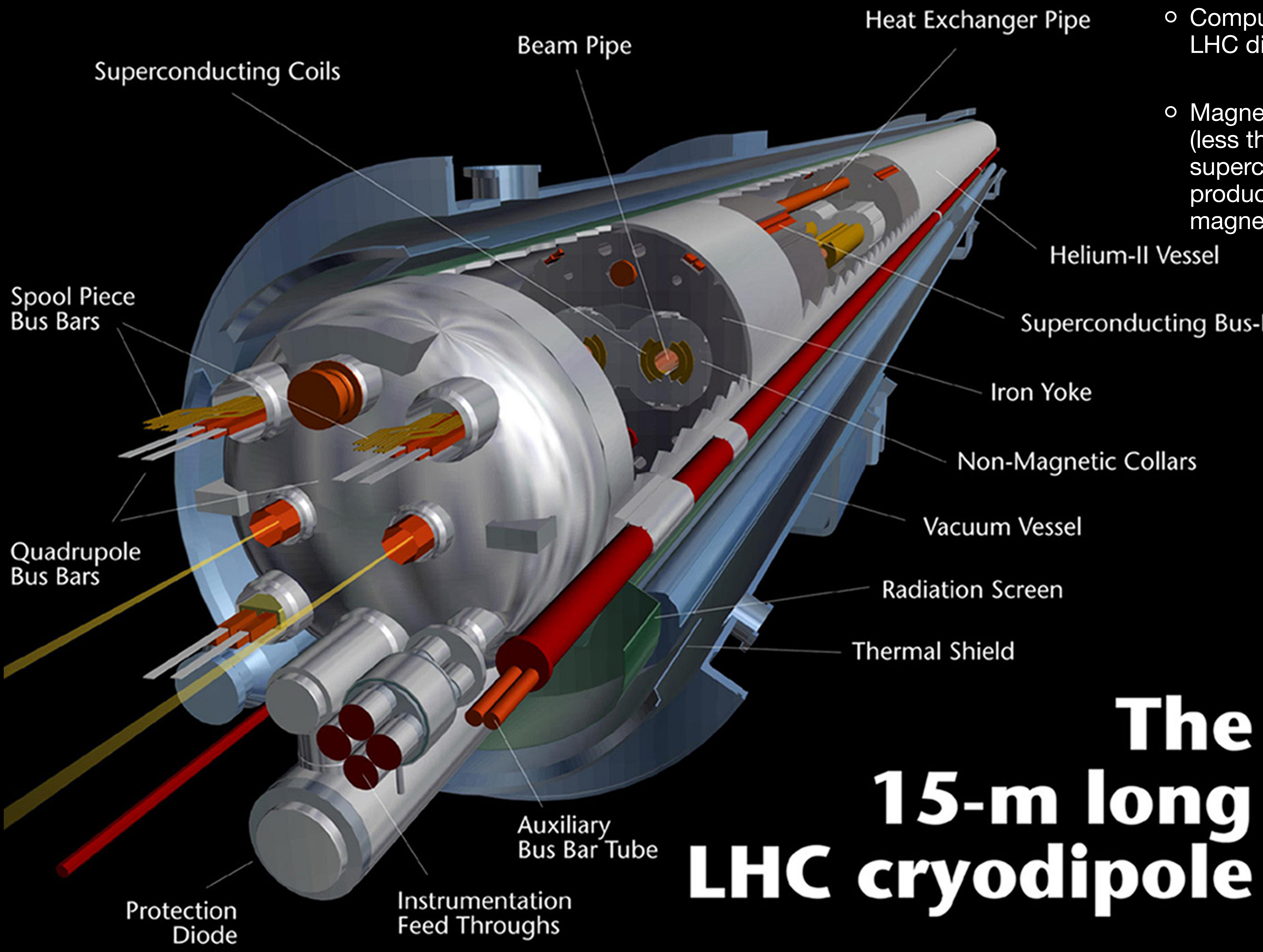
- Dipole magnets are used to bend the paths of the protons around the 27 km ring
- Squeezed for collision into a space narrower than human hair
- Require huge forces to control them

Magnets are key

- LHC uses the tunnel built for a previous generation of experiment
- Often referred to as a “poisoned gift” as obvious way to increase energy = construct a bigger tunnel
- Build stronger magnets!
- Not so easy! Increasing magnetic field by factors of two is highly non-trivial
- Need magnetic fields stronger six times stronger than an MRI machine

Magnets are key

- In 1986, when R&D on the LHC started, three key issues needed to be addressed:
  - High field
  - Superfluid He
  - Two-in-one design (two separate magnetic coils share the same cryogenic and magnetic infrastructure)
- Revolutionary two-in-one design used → perfect for usage in small tunnels
- Two magnetic channels are hosted in the iron yoke → can be housed with a small cryogenic module
- Originally developed at Brookhaven National Lab but deemed unnecessary at the time → we will build a big tunnel for the Superconducting Super Collider
- Huge win for the LHC when a field of 9 T at 1.8 K was reached in 1987 → most critical milestone



- Computer-generated image of an LHC dipole magnet
- Magnets must be cooled to 1.9 K (less than –270.3°C) → superconducting coils can produce the required 8 T magnetic field strength

CERN's incredible supply chain

CERN Courier

The incredible supply chain

All the components of a main LHC superconducting dipole magnet shown in figure 1, and indeed a few more, have been priced by CERN; they constitute more than half of the value of the entire magnet. Additional components were procured for the pre-series production, that is, the first 90 magnets.

For a few critical components – namely the superconducting cable that generates the magnetic field, the austenitic (non-magnetic) steel collars that preserve the geometry of the coils against the magnetic forces of 400 tonnes per metre, and the magnetic steel laminations of the flux-return yoke – CERN procured the raw material, supplied it to the companies producing the finished components, and eventually supplied the components to the magnet manufacturers. This was a supply chain in which logistics, QA, traceability in real time and weekly evaluation of the near- and long-term needs, with consequences also for storage, were far from simple. In total, CERN moved about 120 000 tonnes of material all around Europe, equivalent to three times the total mass that will be cooled down to 1.9 K in the LHC. On average 10 heavy trucks a day were cruising Europe for the dipole project during the three years at the full production rate.

Storage and logistics:

"we moved 120,000 tonnes of material around Europe, with five international road transport operations a day for more than four years"

CERN's incredible supply chain

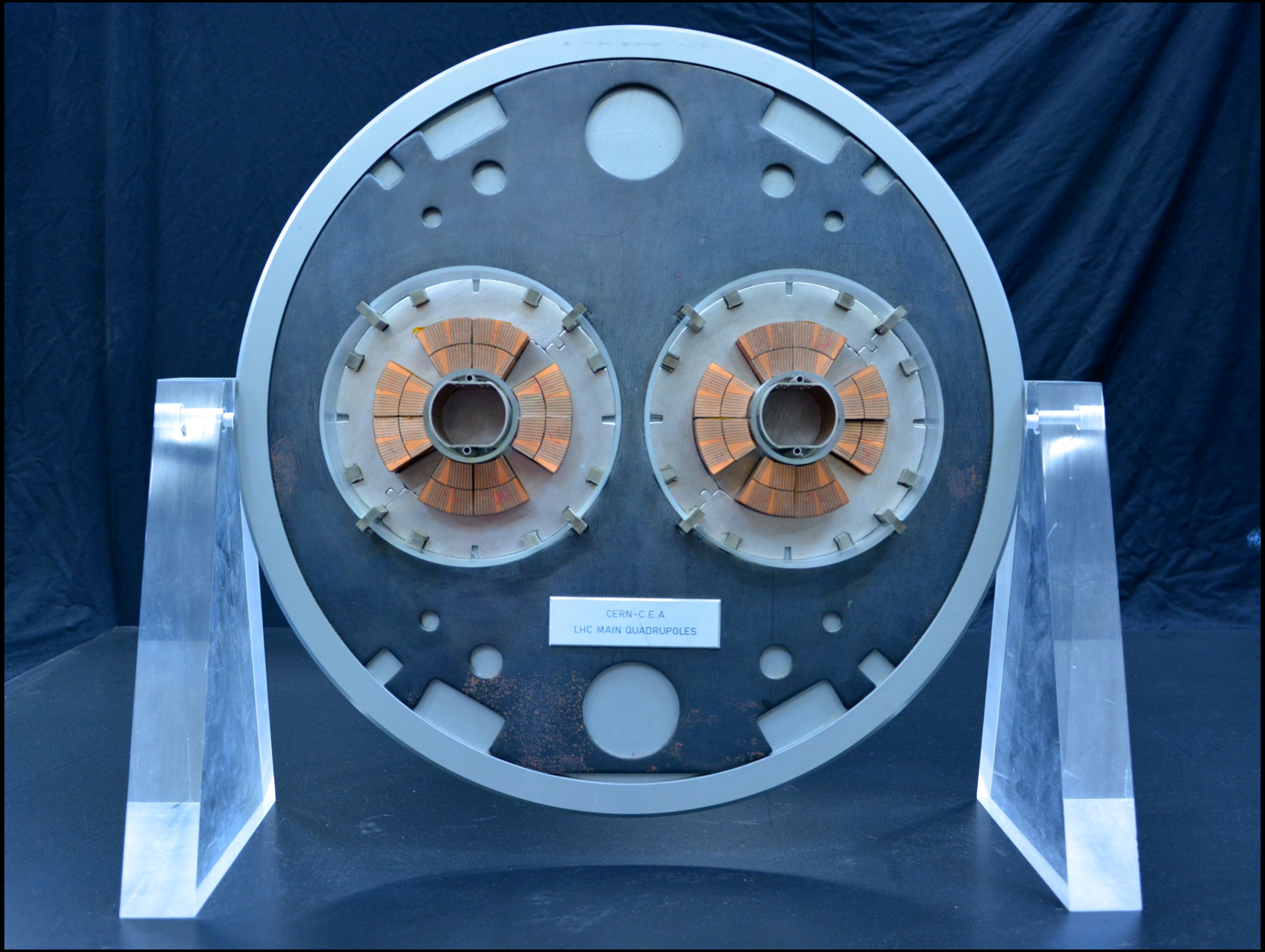
First Fermilab LHC magnet leaves Illinois, bound for CERN

11 MAY, 2004

Photo Fermilab 2004

- The shipment of an advanced superconducting magnet from Fermilab to CERN sent on May 2004
- "This first magnet from Fermilab is a tangible symbol of the important collaboration between our two leading accelerator laboratories," CERN's Director General, Dr. Robert Aymar
- Culmination of decade-long effort at Fermilab to design, develop and manufacture and test these magnets

LHC magnets



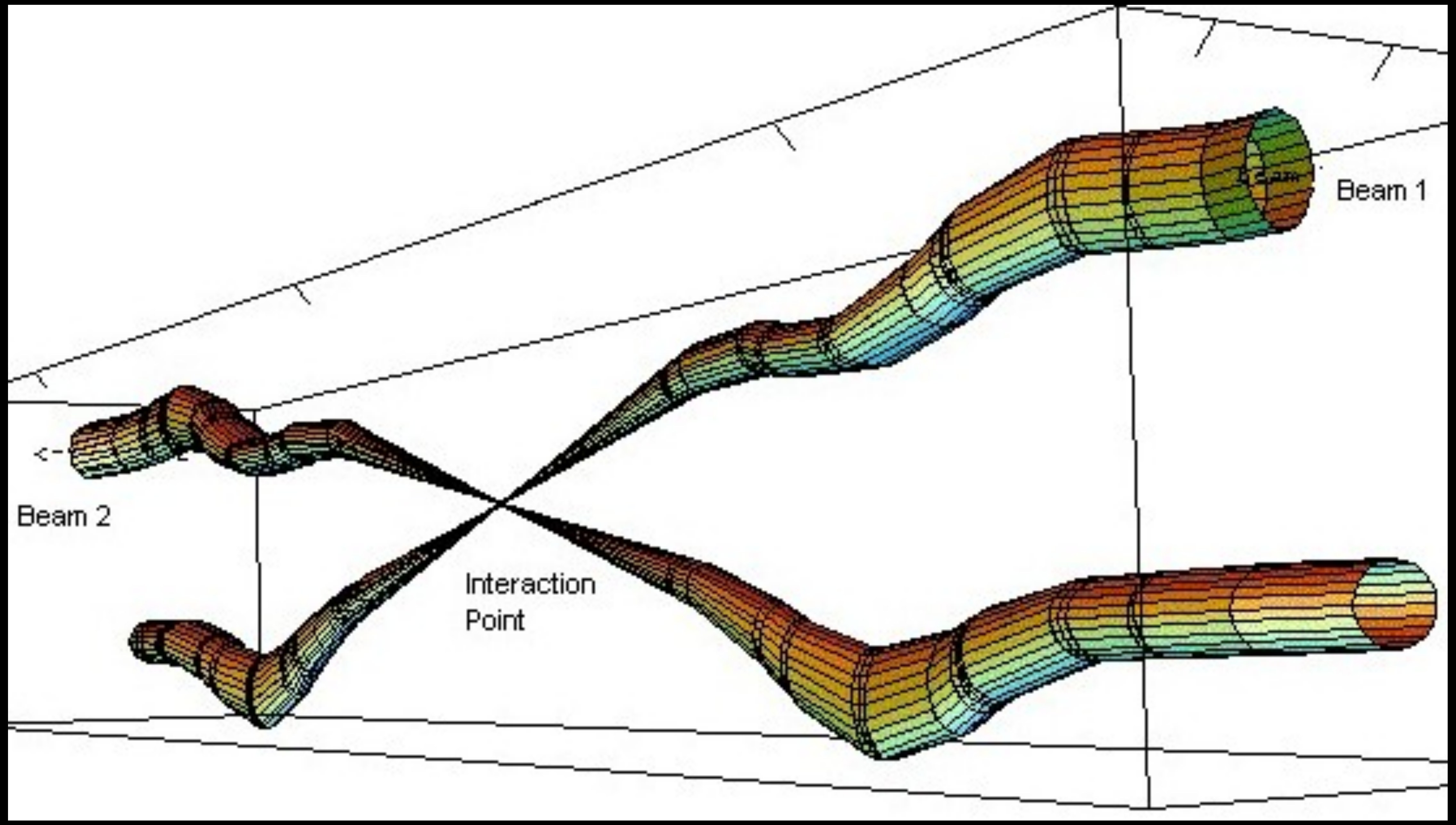
A quadrupole focusing magnet

- Use a quadrupole magnet to focus beams
- Quadrupole magnets focus the proton beams
  - Squeeze them so that more particles collide when the beams cross paths
- Precision needed analogous to colliding two knitting needles launched from either side of the Atlantic Ocean

To recapitulate…

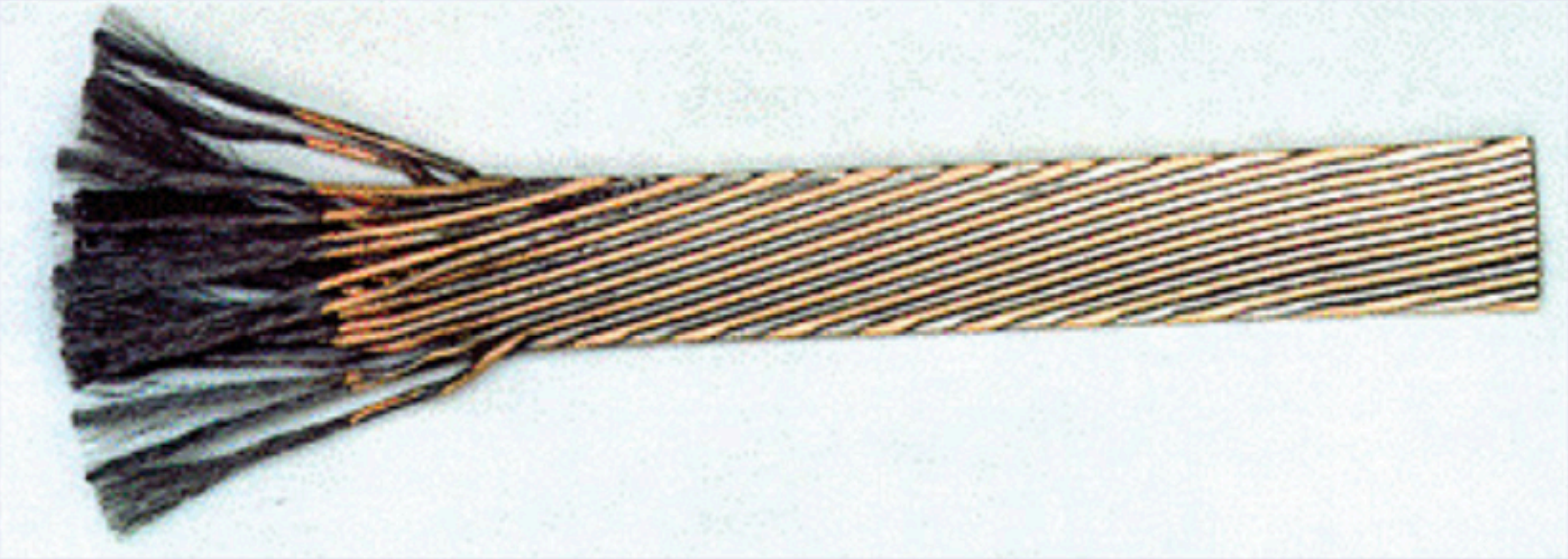
- Two kinds of magnets needed

1. Dipole magnets to bend the beams of protons
2. Quadrupole magnets to focus the proton beams at the detectors



The super conducting cables

- Super conducting filament made with niobium-titanium alloy (Nb-Ti)
  - Workhorse of superconductivity
  - Other alloys were being tested simultaneously (niobium-tin Nb_3Sn)
  - Practical choice won but simultaneous tests of other materials crucial for future projects

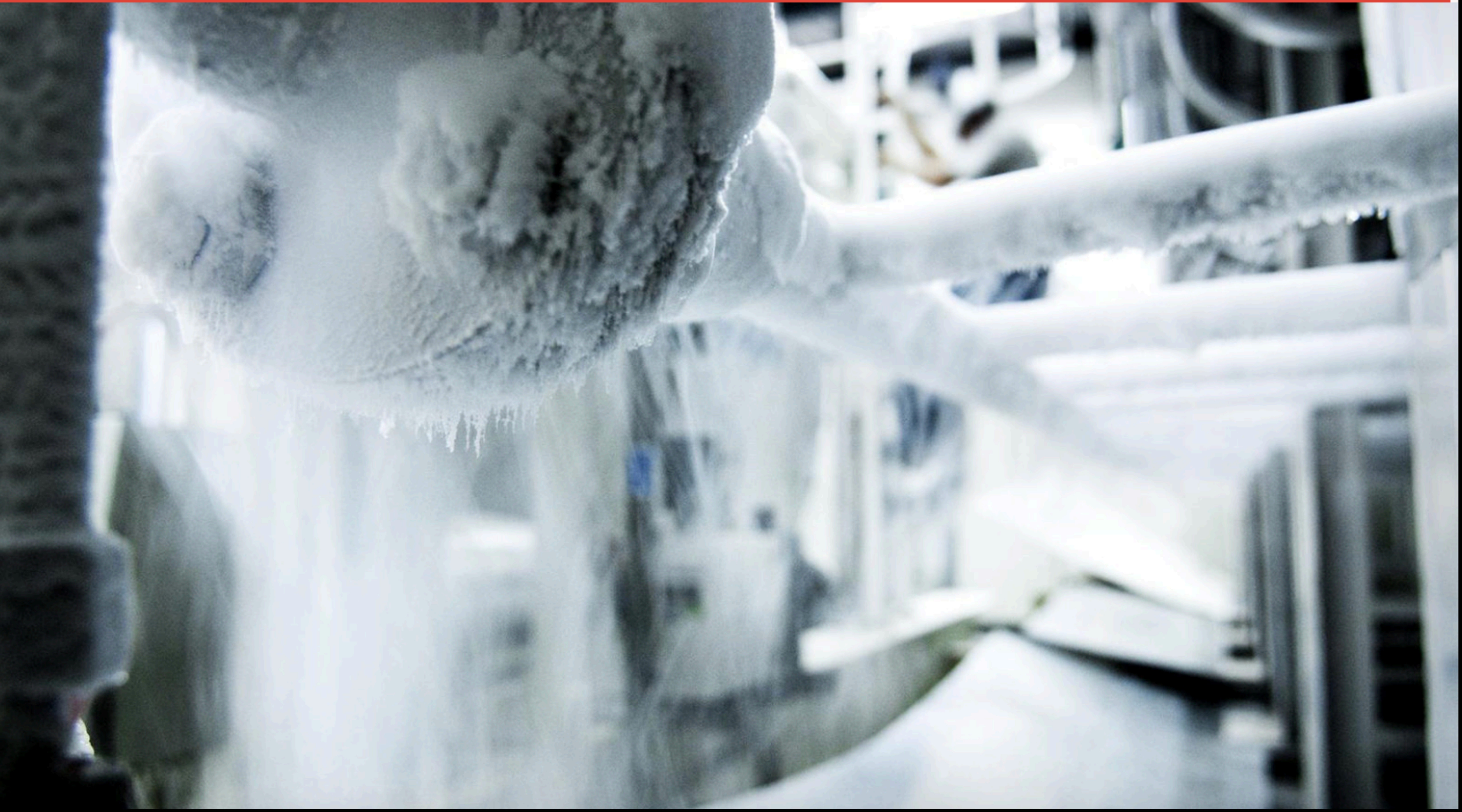


View of the flat side, with one end etched to show the Nb-Ti filaments

LHC filled with liquid helium

12/17/14 | By Sarah Charley

The Large Hadron Collider is now cooled to nearly its operational temperature.



"The Large Hadron Collider isn't just a cool particle accelerator. It's the coldest."

Cooling with liquid Helium

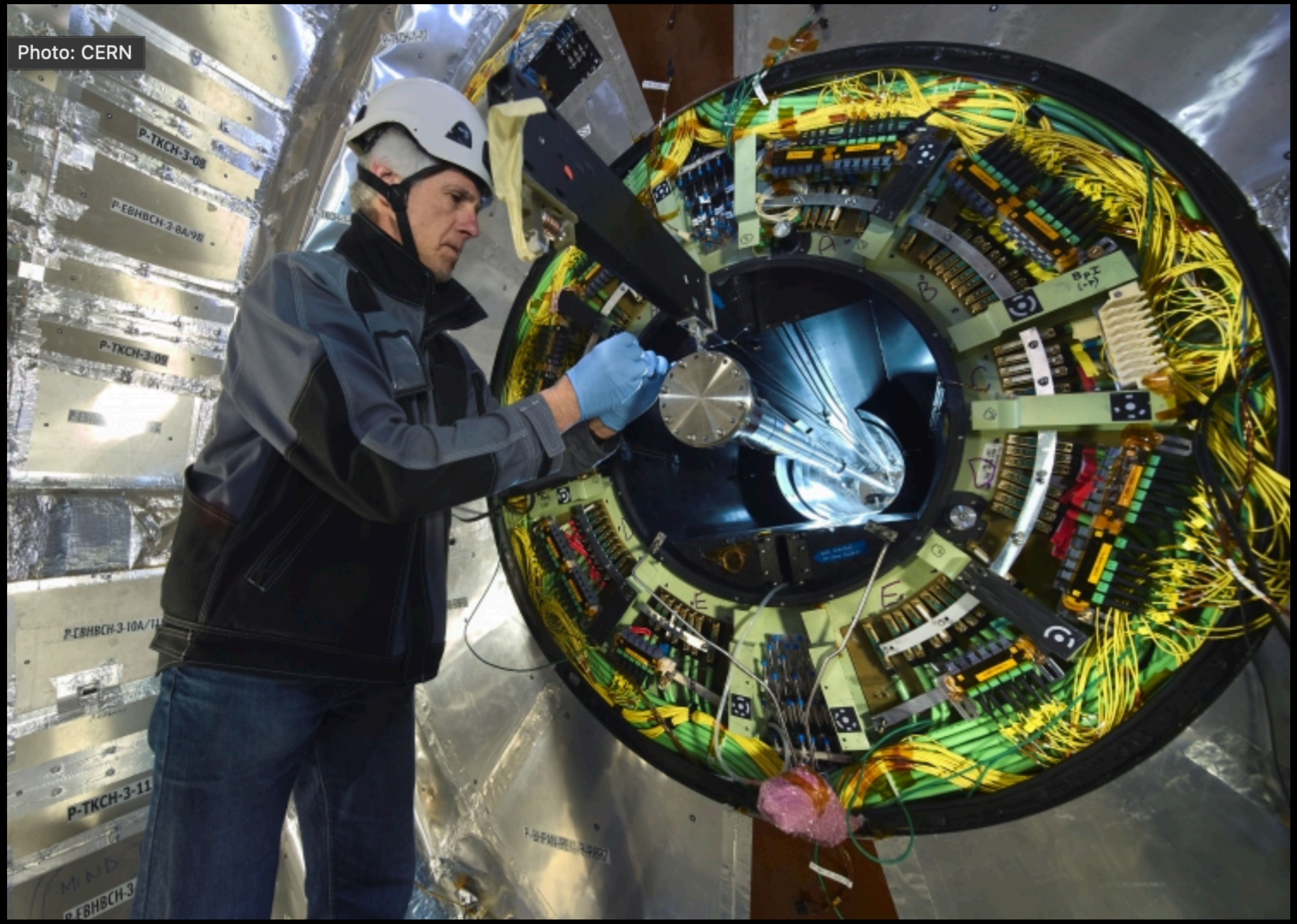
- Task:
  - Get 27 km of LHC magnets cooled down from room temperature
- Achieved by:
  - Injecting liquid He into a special cryogenic system surrounding the magnets
  - Gradually reduce temperature over several months as the He approaches liquid state
  - He becomes a liquid below 5 K
  - Naturally inert: no

“*Filling the entire accelerator requires 130 metric tons of helium, which we received from our supplier at a rate of around one truckload every week*” — Laurent Tavian, the group leader of the CERN cryogenics team

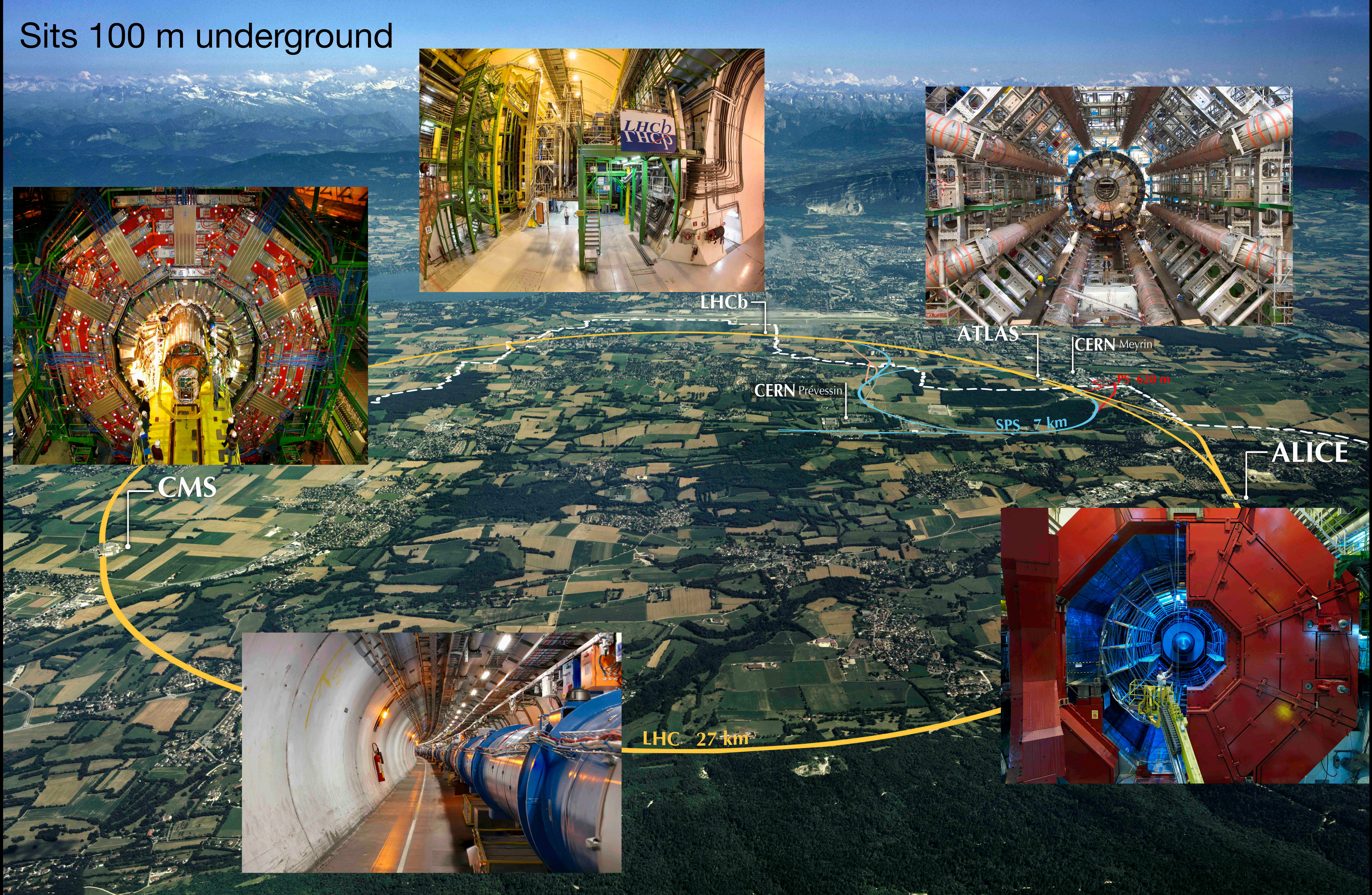
Filling the first liquid-helium truck for external storage

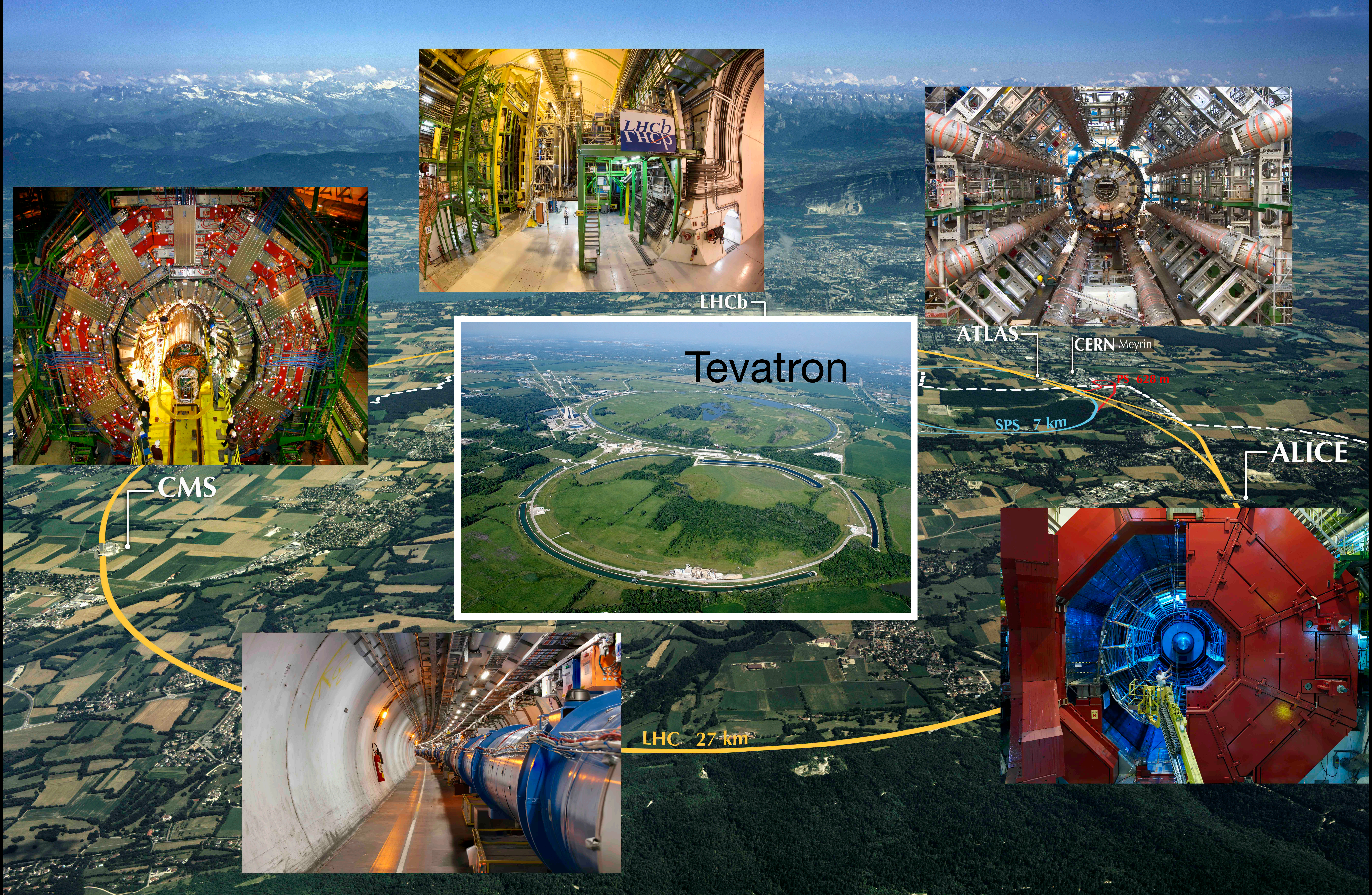
The LHC beams and the vacuum

- Inside the LHC, two particle beams travel at the speed of light in opposite directions
- Housed inside beam pipes
- Beam pipes kept at ultrahigh vacuum
- Emptier than interstellar space
- Largest vacuum system in the world - 104 km of piping



Sits 100 m underground




LHCb
Tevatron
ATLAS
CERN Meyrin
PS 628 m
SPS 7 km
ALICE
CMS
LHC 27 km


LHCb
ATLAS
CERN Meyrin
PS 628 m
SPS 7 km
ALICE
CMS
LHC 27 km
LIGO
End-station @ 4 km
Mid-station @ 2 km
4 km (2.5 mi.)

Key Parameters

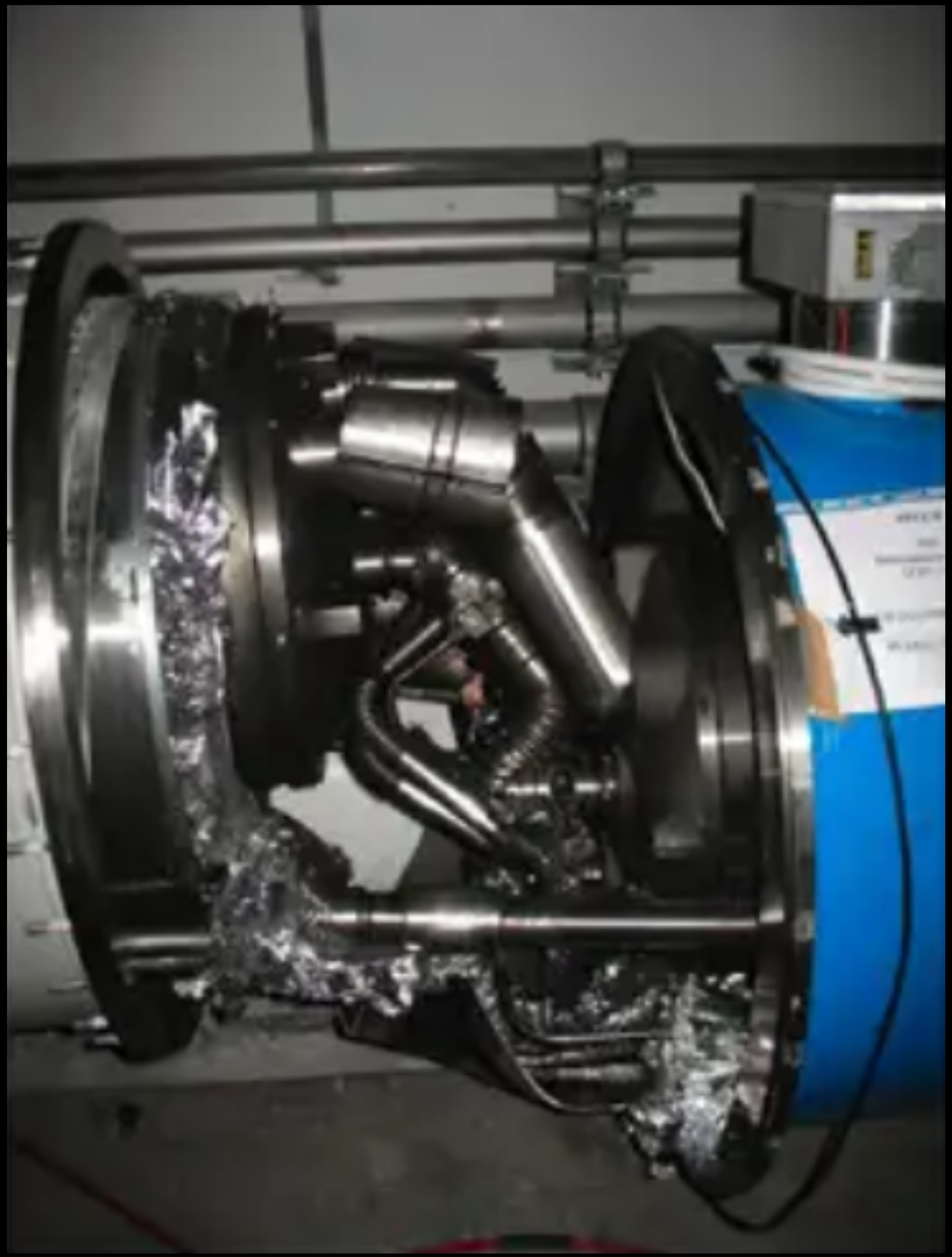
Parameters	Tevatron	LHC (nominal)
Circumference	6.28 km (2*PI)	27 km
Beam energy	980 GeV	7 TeV
Number of bunches	36	2808
Protons per bunch	275 X 10^9	115 X 10^9
Stored proton beam energy	**2.1 MJ**	**732 MJ**
Main dipoles	780	1232
Bend field	4.2 T	8.3 T
Main quadrupoles	~200	~600
Operating temperature	4.2 K (liquid He)	1.9 K (superfluid He)
Number of collisions per second	10 million	1 billion

1 stick of dynamite releases 2.1 MJ of energy 🧨

Powering the LHC

- CERN uses 1.3 terawatt hours of electricity annually
  - Enough power to fuel 300,000 homes for a year
- At peak usage, $1/3^{\text{rd}}$ energy used to power the nearby city of Geneva in Switzerland
- Glitch free stable power needed
- Powered by two different national grids
  - 1,000 high-voltage circuit-breakers
  - Modernization of electrical installations continuously underway

The accident — in 2008



- A quench developed in one of the dipole magnets
  - Local transition in the coil material from the superconducting to the normal conducting state, known as a quench.
- Led to the melting of an electrical connection
- Failure damaged the plumbing
- Vaporized the liquid He
- Several magnets heated up

https://spectrum.ieee.org/analyzing-the-lhc-magnet-quenches

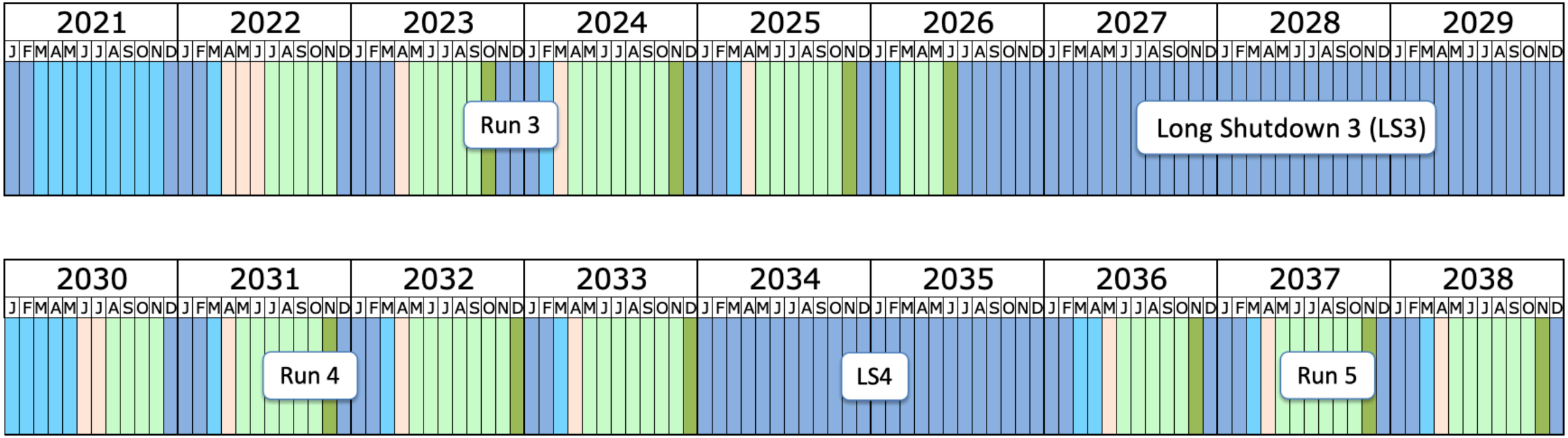
The accident — in 2008

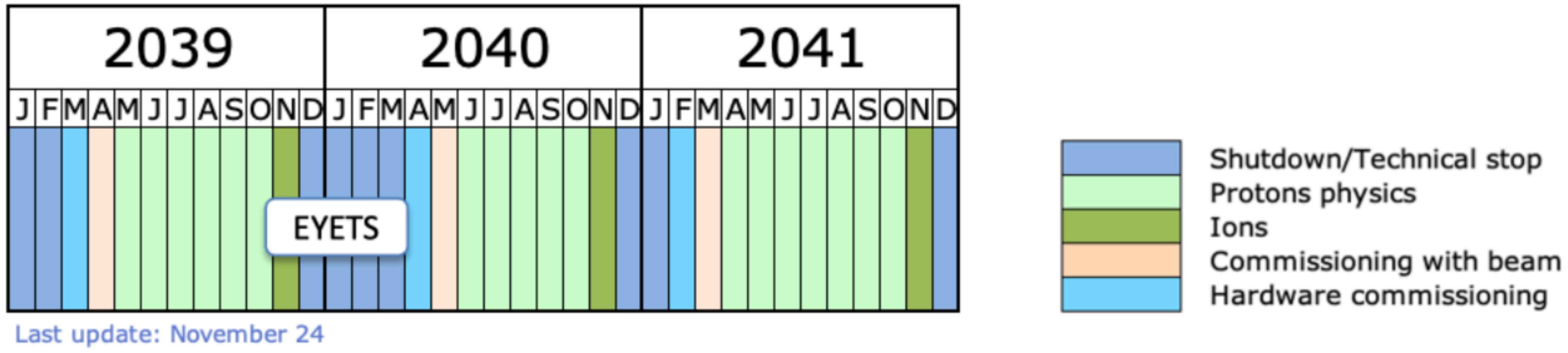
- Magnet supports dislocated from the ground by the increased pressure

Key milestones

- 10 September 2008: LHC first beam
- **23 November 2009**: LHC first collisions
- **30 November 2009**: world record with beam energy of 1.18 TeV
- **16 December 2009**: world record with collisions at 2.36 TeV and significant amount of data recorded
- **March 2010**: first beams at 3.5 TeV (19 March) and first high energy collisions at 7 TeV (30 March)
- **8 November 2010**: LHC first lead-ion beams
- **22 April 2011**: LHC sets new world record beam intensity
- **5 April 2012**: First collisions at 8 TeV
- **4 July 2012:** Announcement of the discovery of a Higgs-like particle at CERN
- **28 September 2012**: Tweet from CERN: "The LHC has reached its target for 2012 by delivering 15 fb^{-1} (around a million billion collisions) to ATLAS and CMS"
- **14 February 2013**: At 7.24 a.m, the last beams for physics were absorbed into the LHC, marking the end of Run 1 and the beginning of the Long Shutdown 1
- **8 October 2013**: Physics Nobel prize to François Englert and Peter Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

LHC Upgrade Schedule





Longer term LHC schedule

Update September 2024:

Short YETS 25/26
Extend Run 3 to end June 2026
Start LHC LS3 July 2026
Start final Hardware Commissioning January 2030
First beam June 2030
LS3 - beam to beam: 3 years 11 months, 47 months