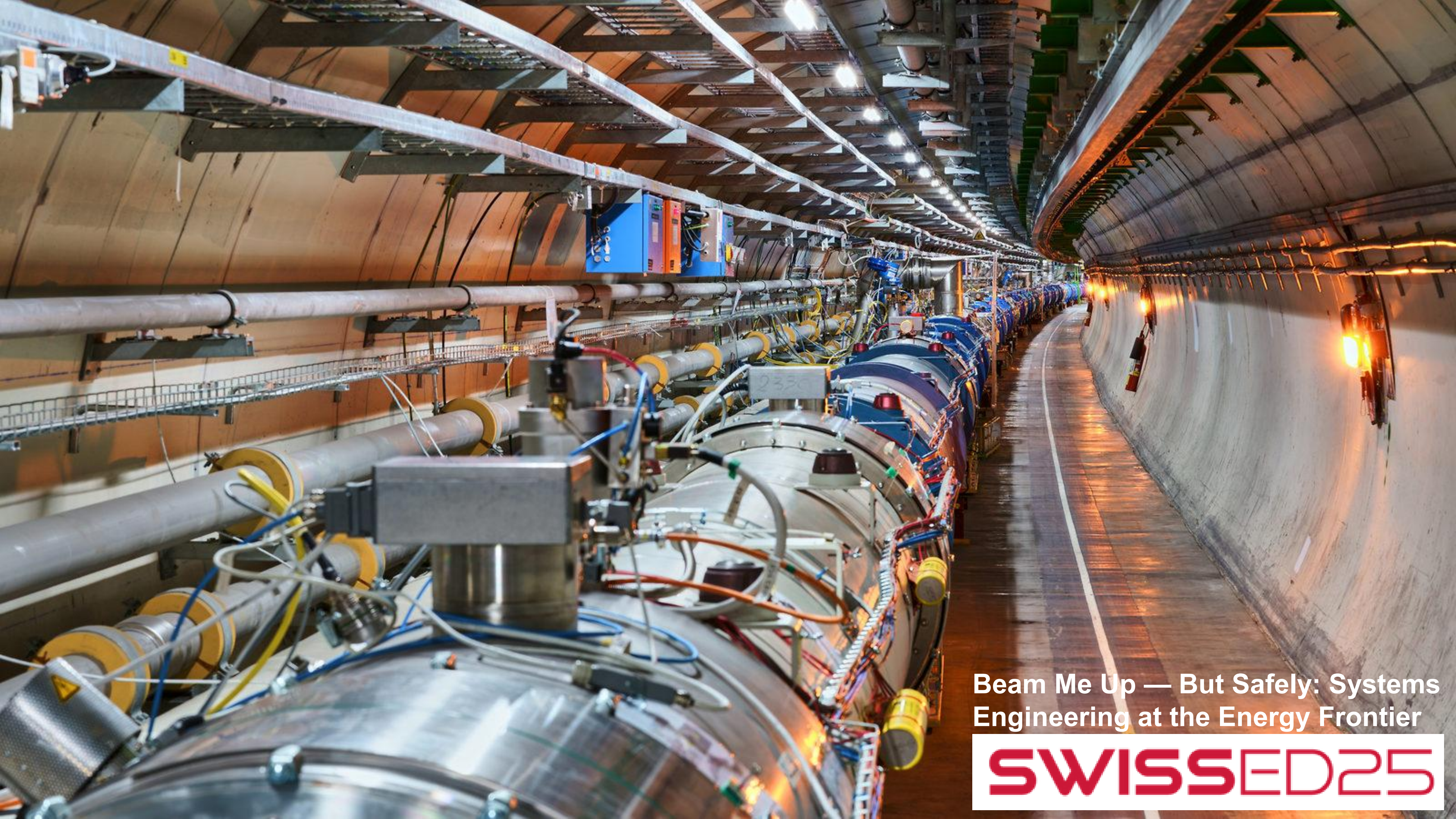


Beam Me Up — But Safely: Systems Engineering at the Energy Frontier

SWISSED25

Science for peace

CERN was founded in 1954 with 12 European Member States

CERN's annual budget is 1200 MCHF (equivalent to a medium-sized European university)

Employees:
2704 staff,
1181 graduates and fellows
Associates:
12 406 users, **1401** others

25 Member States

Austria – Belgium – Bulgaria – Czech Republic
Denmark – Estonia – Finland – France – Germany
Greece – Hungary – Israel – Italy – Netherlands
Norway – Poland – Portugal – Romania – Serbia
Slovakia – Slovenia – Spain – Sweden – Switzerland
United Kingdom

9 Associate Member States

Brazil – Croatia – Cyprus – India – Latvia – Lithuania
Pakistan – Türkiye – Ukraine

4 Observers

Japan – USA – European Union – UNESCO

~ 50 Cooperation Agreements

Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bahrain – Bangladesh – Bolivia – Bosnia and Herzegovina
Canada – Chile – Colombia – Costa Rica – Ecuador – Egypt – Georgia – Honduras – Iceland – Iran – JINR – Jordan
Kazakhstan – Lebanon – Malta – Mexico – Mongolia – Montenegro – Morocco – Nepal – New Zealand
North Macedonia – Palestine – Paraguay – People's Republic of China – Peru – Philippines – Qatar – Republic of Korea
Saudi Arabia – South Africa – Sri Lanka – Thailand – Tunisia – United Arab Emirates – Uruguay – Vietnam

Data as of 31 December 2024

A laboratory for people around the world

Distribution of all CERN Users by the location of their home institute

Geographical & cultural diversity
Users of **110 nationalities**
23.7% women

Member States (7704)

Austria 88 – **Belgium** 142 – **Bulgaria** 49 – **Czech Republic** 250
Denmark 50 – **Estonia** 27 – **Finland** 88 – **France** 856 – **Germany** 1260
Greece 101 – **Hungary** 84 – **Israel** 75 – **Italy** 1657 – **Netherlands** 174
Norway 88 – **Poland** 363 – **Portugal** 110 – **Romania** 110 – **Serbia** 42
Slovakia 72 – **Slovenia** 29 – **Spain** 448 – **Sweden** 103 – **Switzerland** 409
United Kingdom 1029

Associate Member States (602)

Brazil 141 – **Croatia** 35 – **Cyprus** 12 – **India** 158 – **Latvia** 22
Lithuania 21 – **Pakistan** 35 – **Türkiye** 151 – **Ukraine** 27

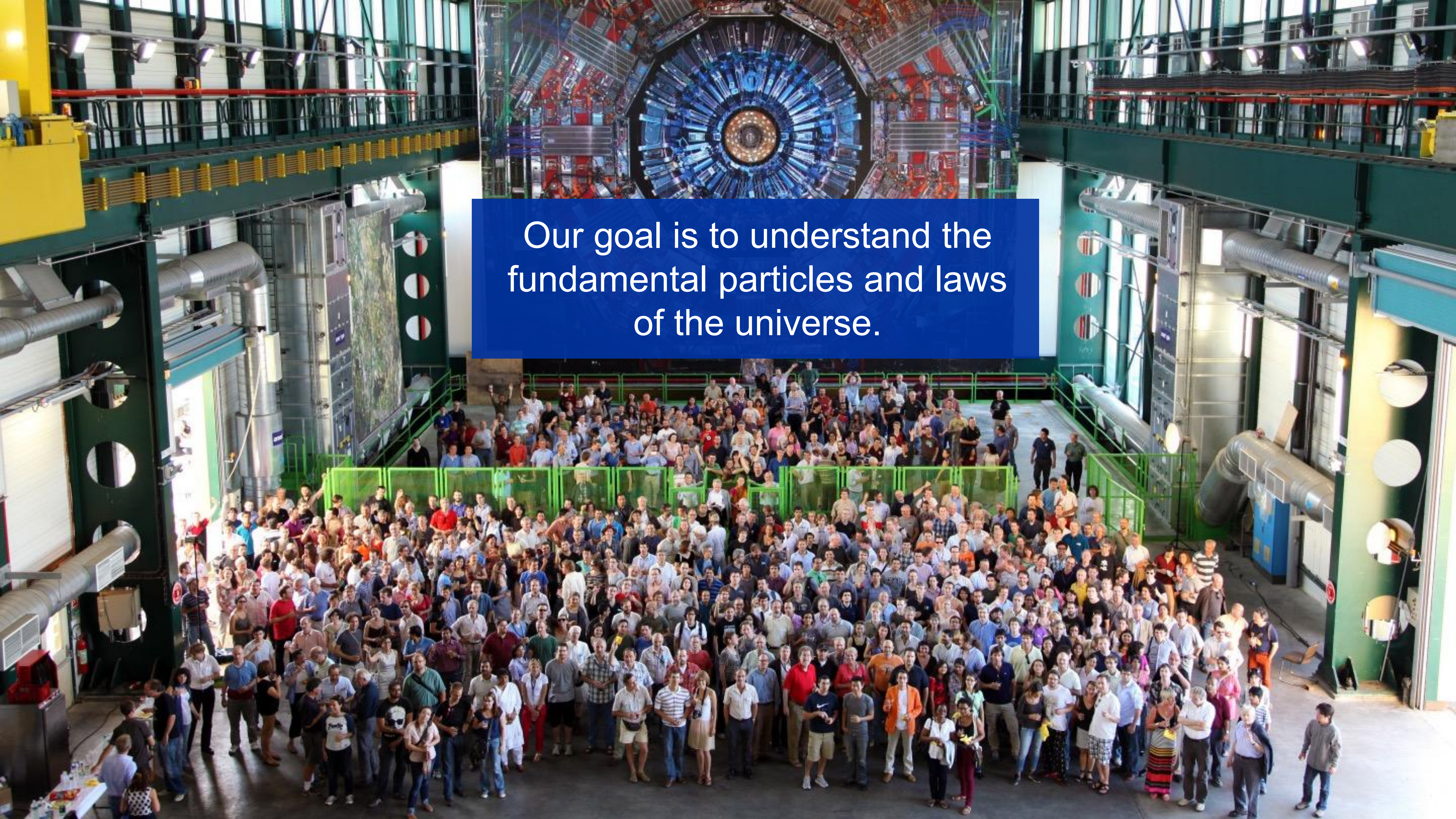
Observers (2330)

Japan 229 – **United States of America** 2101

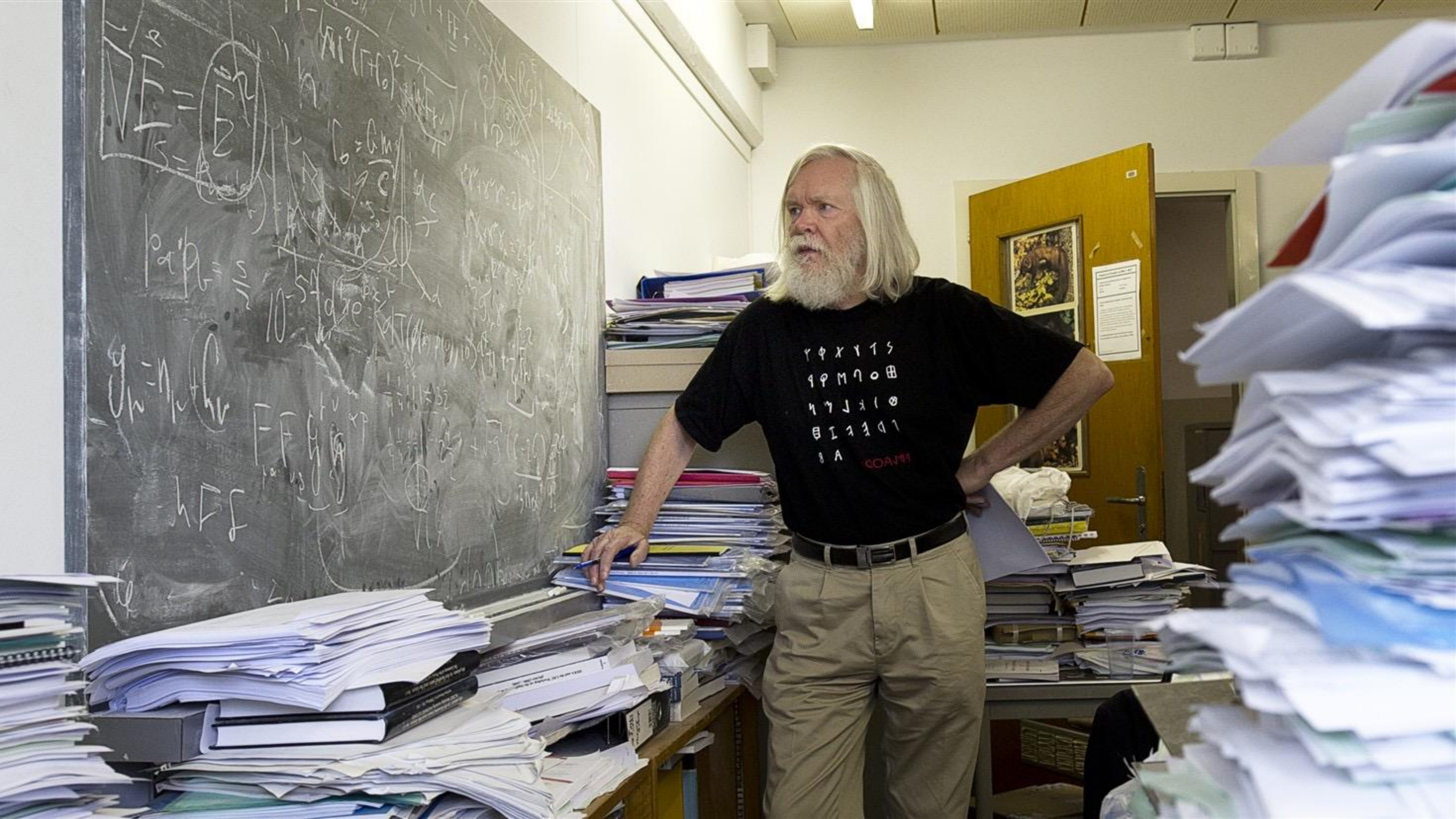
Cooperation Agreements (1770)

Albania 7 – **Algeria** 1 – **Argentina** 17 – **Armenia** 28 – **Australia** 31 – **Azerbaijan** 2 – **Bahrain** 10 – **Canada** 203
Chile 58 – **Colombia** 25 – **Costa Rica** 8 – **Cuba** 3 – **Ecuador** 4 – **Egypt** 22 – **Georgia** 36 – **Hong Kong** 17 – **Iceland** 3
Indonesia 8 – **Iran** 18 – **Ireland** 11 – **JINR** 305 – **Jordan** 2 – **Kazakhstan** 8 – **Kuwait** 2 – **Lebanon** 12 – **Madagascar** 1
Malaysia 1 – **Malta** 3 – **Mexico** 66 – **Montenegro** 4 – **Morocco** 22 – **New Zealand** 1 – **Nigeria** 1 – **Oman** 1 – **Palestine** 1
People's Republic of China 472 – **Peru** 3 – **Philippines** 1 – **Republic of Korea** 184 – **Saudi Arabia** 4 – **South Africa** 73
Sri Lanka 7 – **Taiwan** 49 – **Thailand** 17 – **Tunisia** 3 – **United Arab Emirates** 14 – **Vietnam** 1

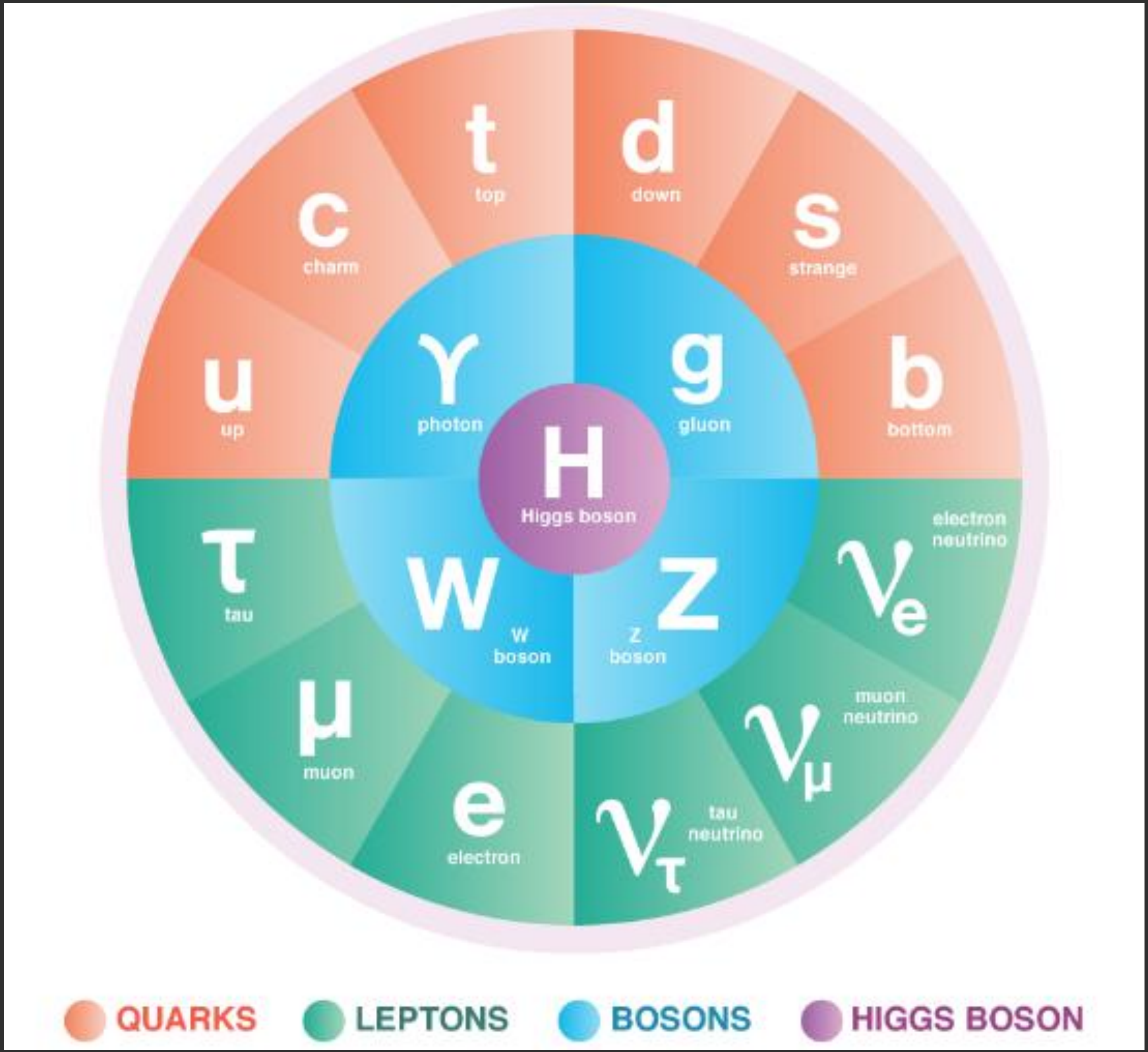
Data as of 31 December 2024

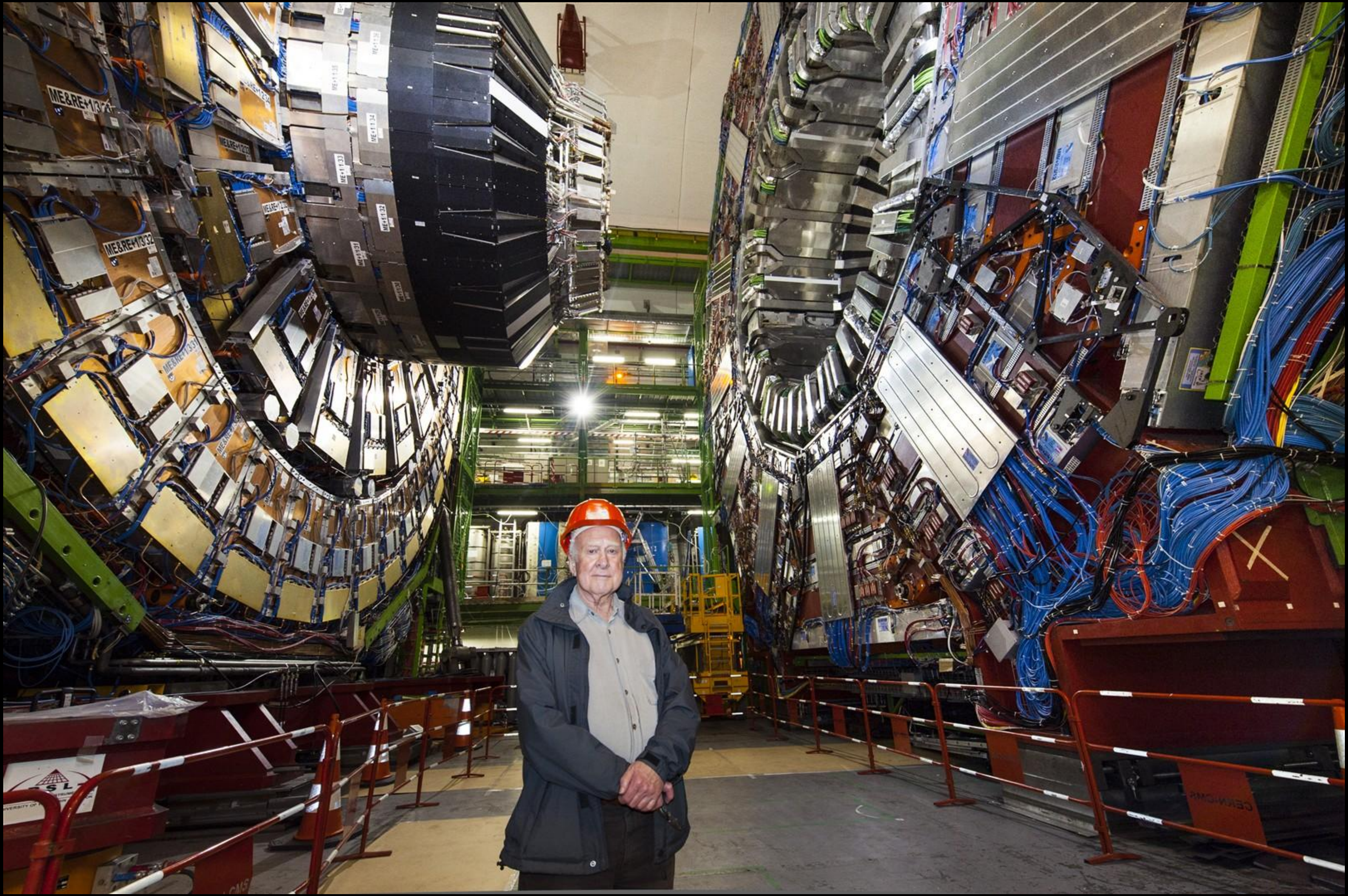


Our goal is to understand the fundamental particles and laws of the universe.



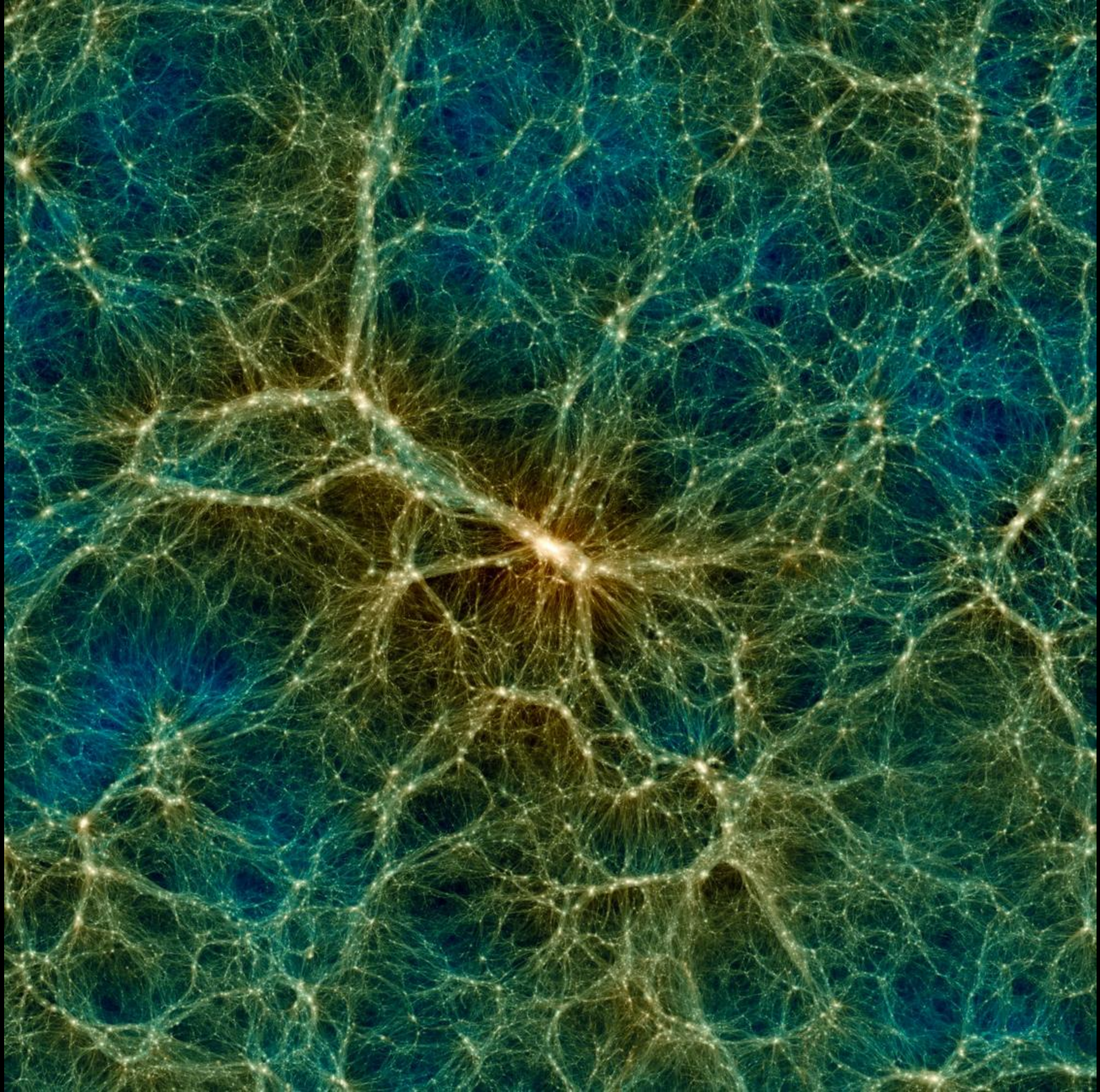

WE FOUND A NEW PARTICLE


t
top
d
down
c
charm
s
strange
u
up
γ
photon
g
gluon
b
bottom
H
Higgs boson
τ
tau
W
W boson
Z
Z boson
electron neutrino
ν_e
μ
muon
muon neutrino
ν_μ
e
electron
ν_τ
tau neutrino
QUARKS
LEPTONS
BOSONS
HIGGS BOSON

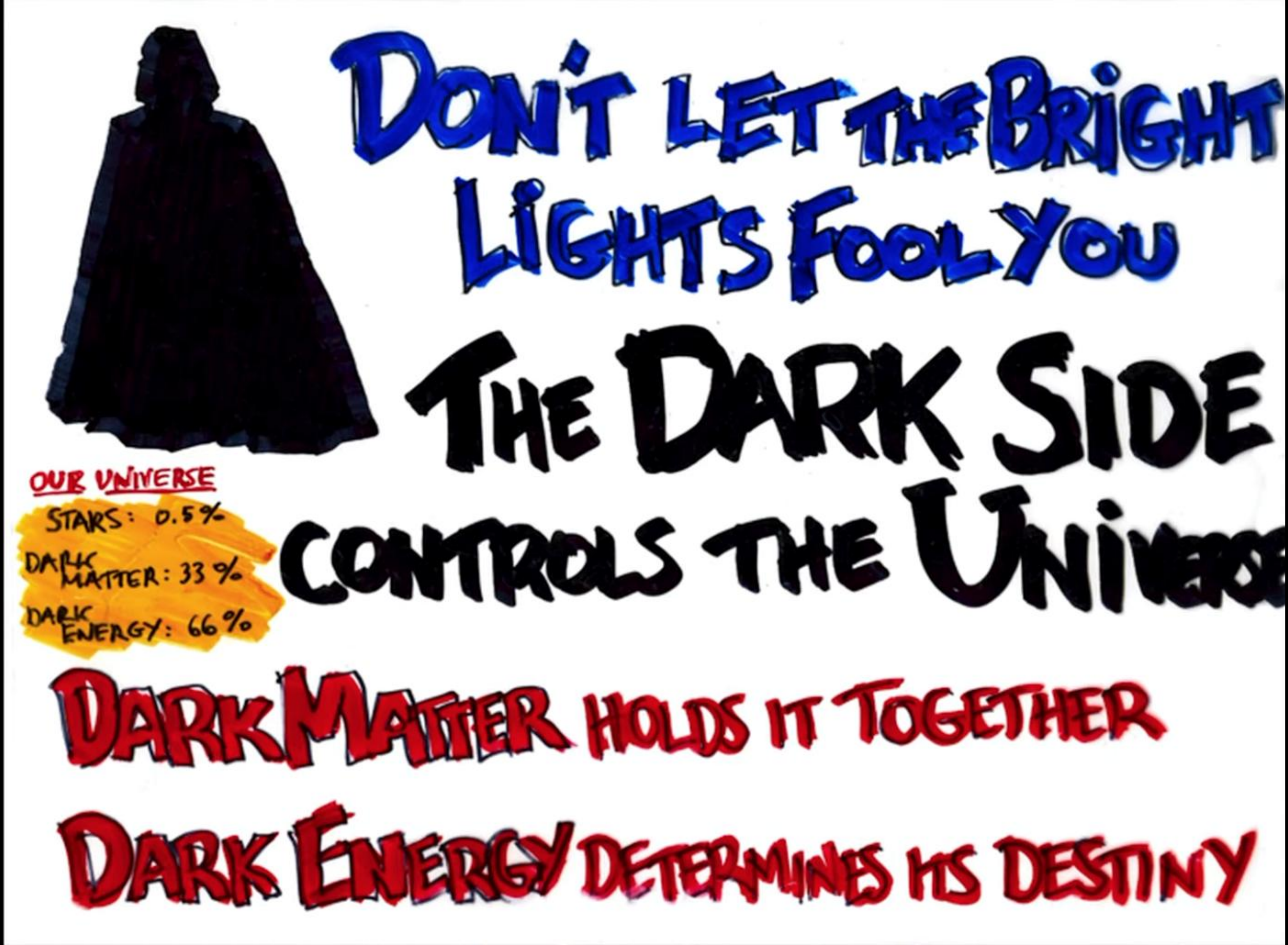

ME&RE+1/3/32


Who is Higgs?
Why did he freeze in the Universe?
Why do we exist?
Who is dark matter?
Who saved us from a complete annihilation?
Hitoshi Murayama
©Warner Bro.

Cosmic web of Dark Matter Decorated by Stars

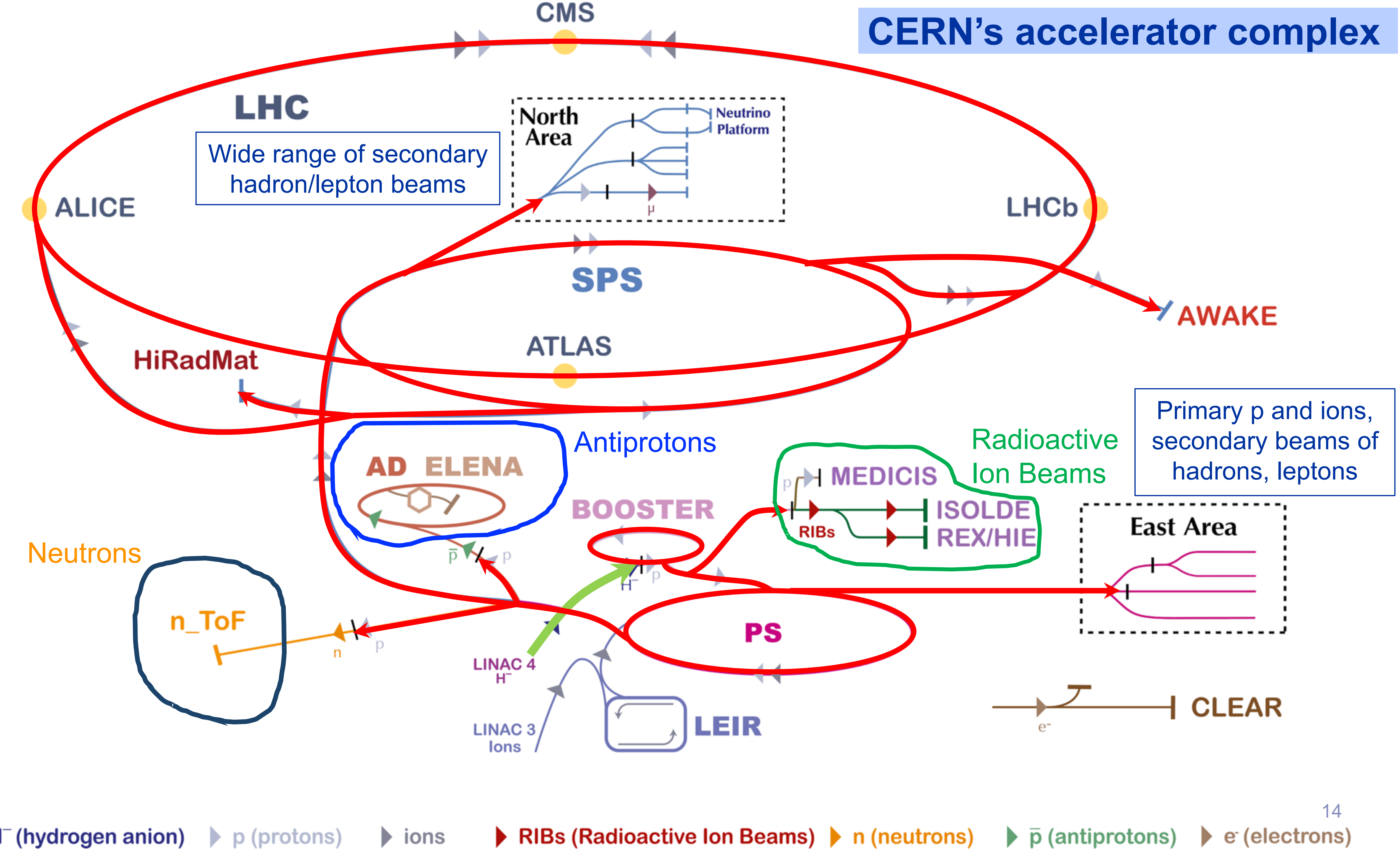


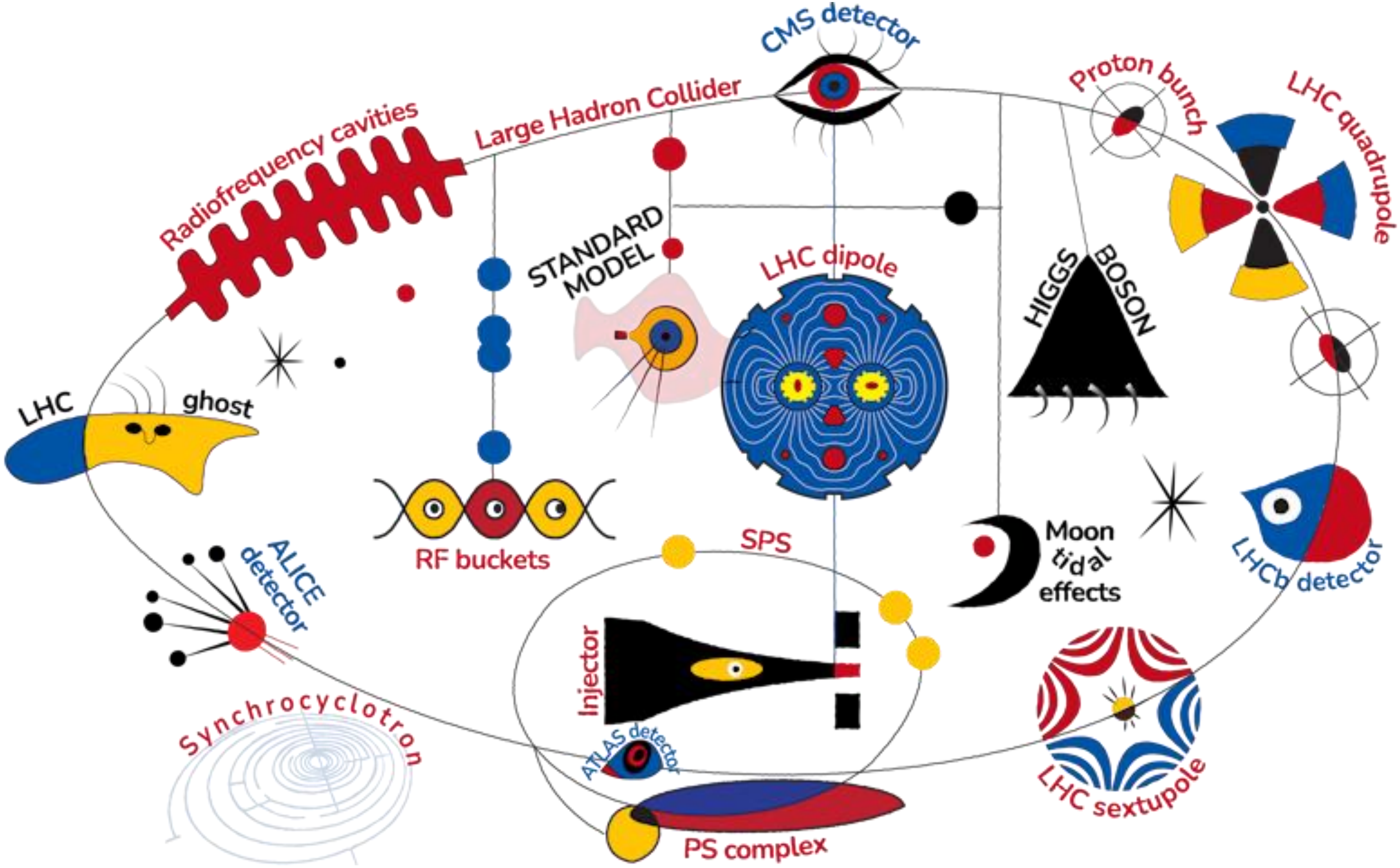
Simulation of the large-scale structure of the universe, showing dense clusters of galaxies, filaments, galactic walls and voids.
Credit: Uchuu project.



Michael Turner

CERN's accelerator complex




CMS detector
Large Hadron Collider
Radiofrequency cavities
Proton bunch
LHC quadrupole
STANDARD MODEL
LHC dipole
HIGGS BOSON
LHC
ghost
RF buckets
SPS
Moon tidal effects
LHCb detector
ALICE detector
Injector
Synchrocyclotron
ATLAS detector
LHC sextupole
PS complex

LHC - protons

E = 6.8 TeV
= 6,800,000,000 keV

v=0.999999991c

1.6e11 protons per bunch
2460 bunches per beam
4e14 protons per beam

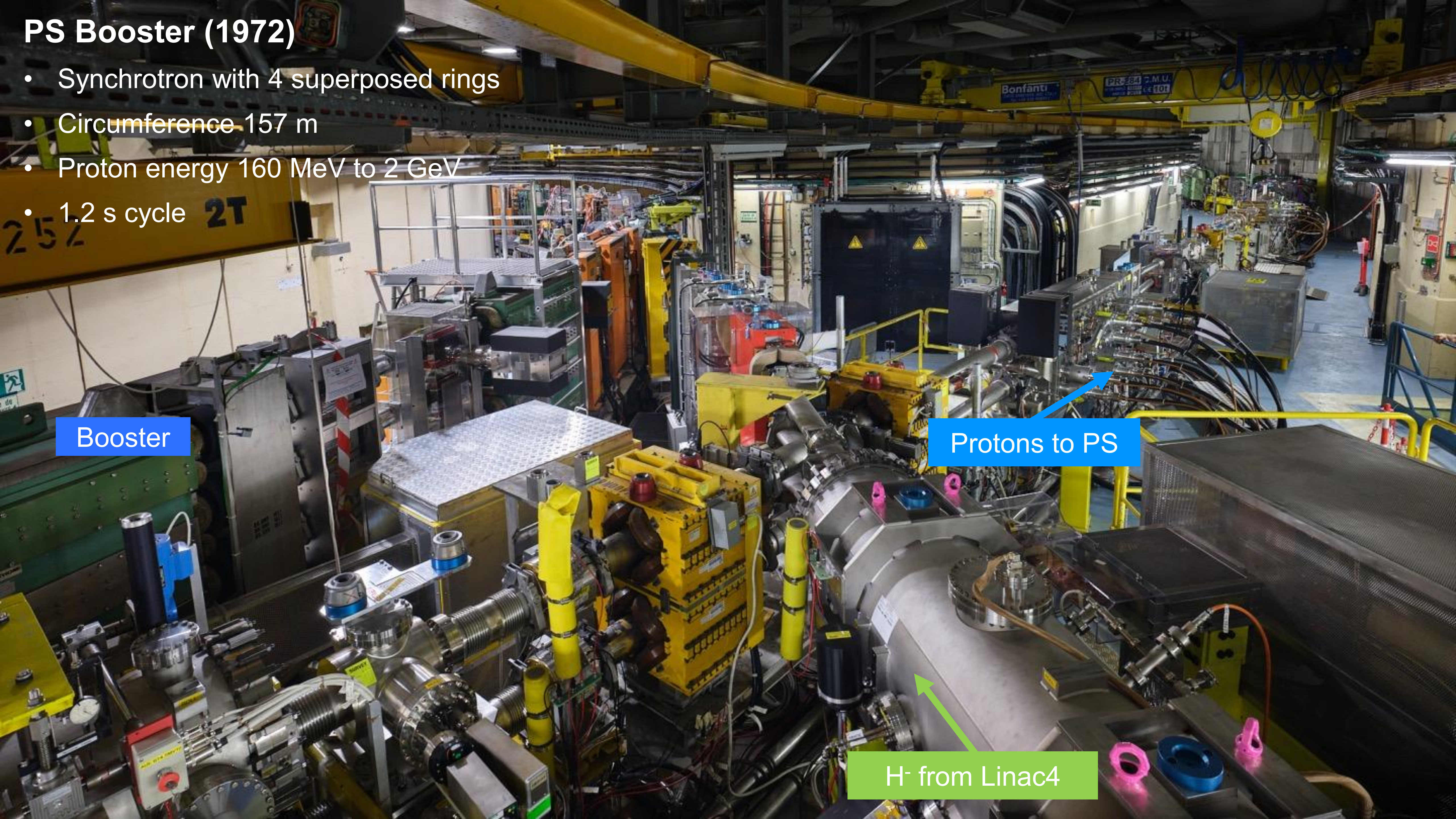
430 MJ - TGV at 170 kph

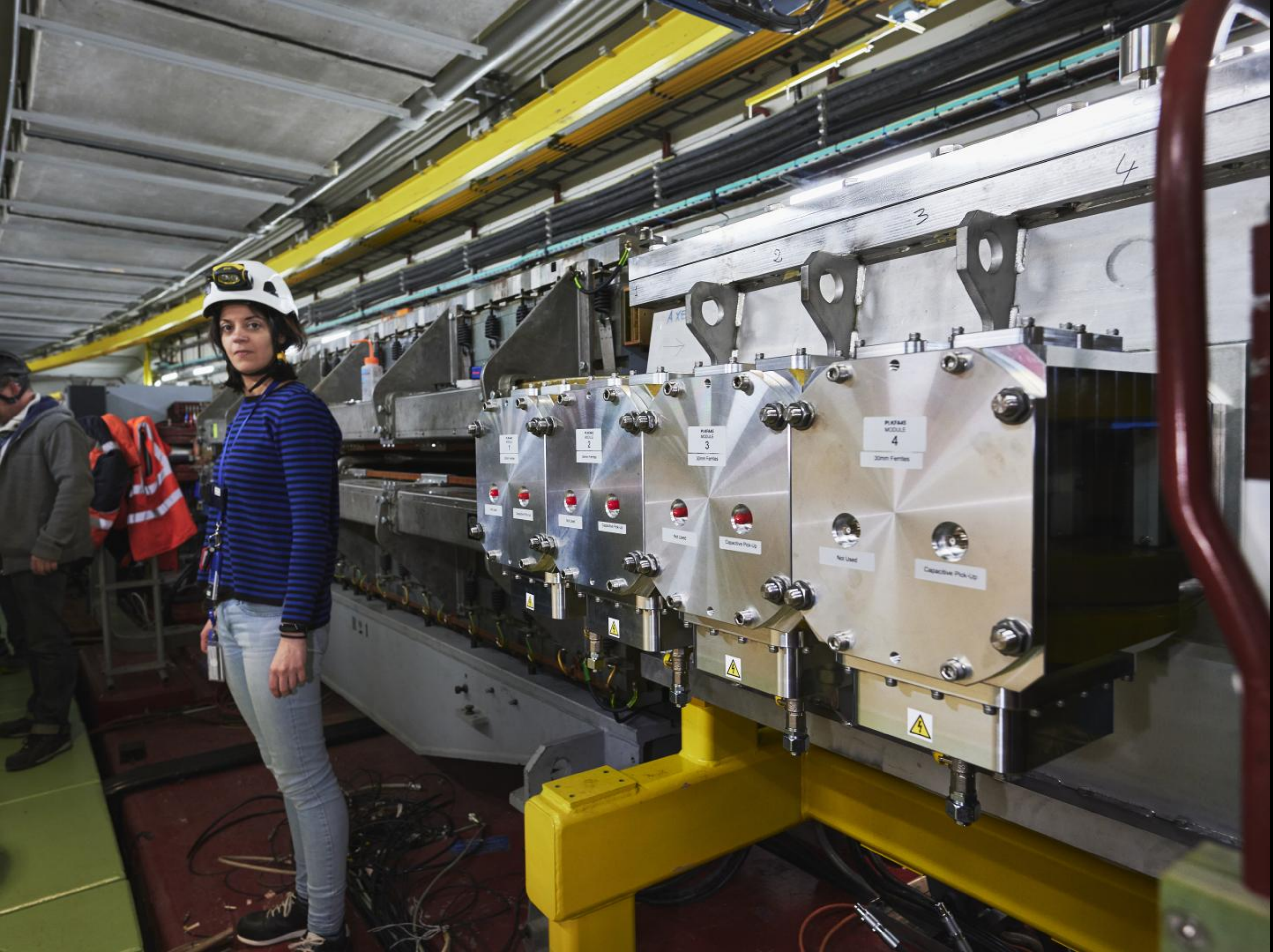
Linac4

- H^- ion source at 95 keV
- Accelerates beam up to 160 MeV
- 80 μs of beam every 1.2 s

PS Booster (1972)

- Synchrotron with 4 superposed rings
- Circumference 157 m
- Proton energy 160 MeV to 2 GeV
- 1.2 s cycle





PS

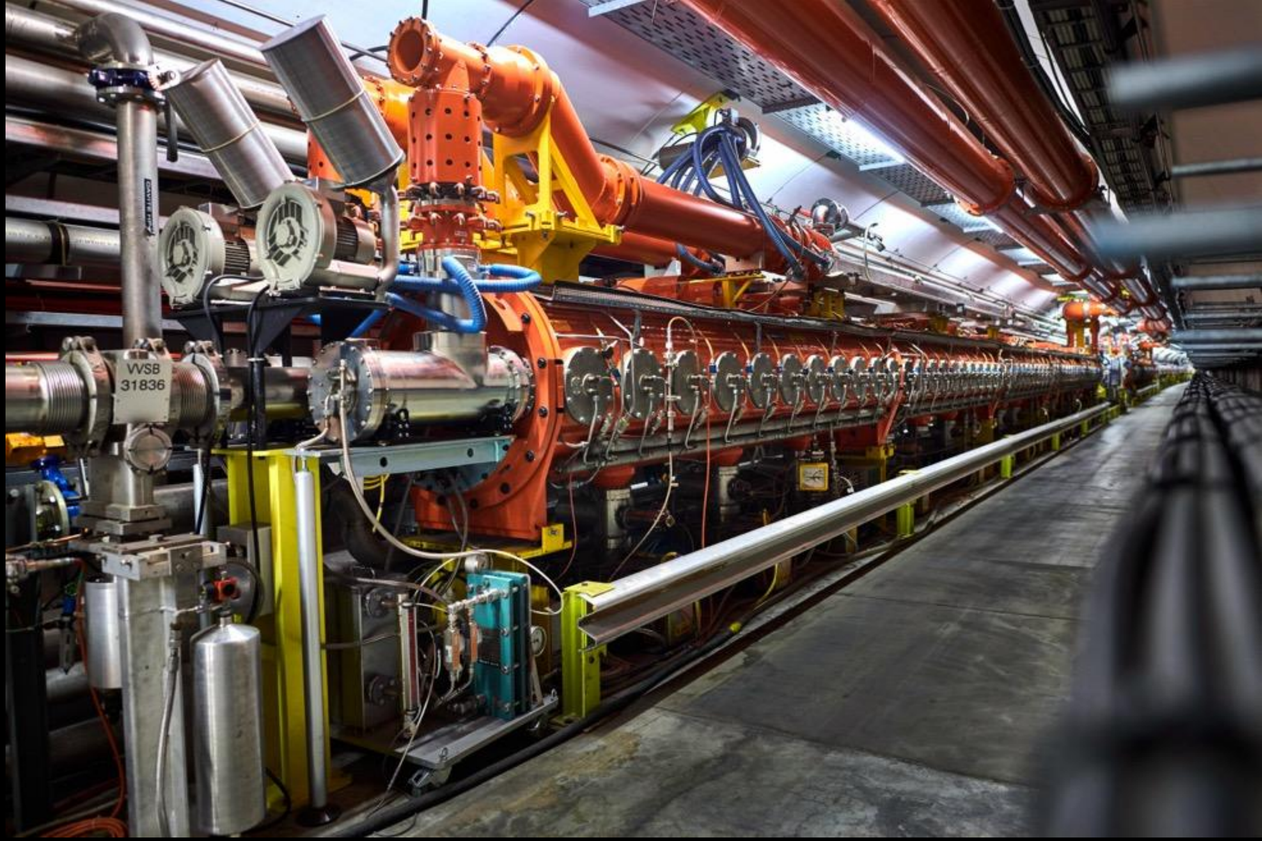
Proton Synchrotron

The oldest operating synchrotron at CERN (1959)

Circumference of 628 m

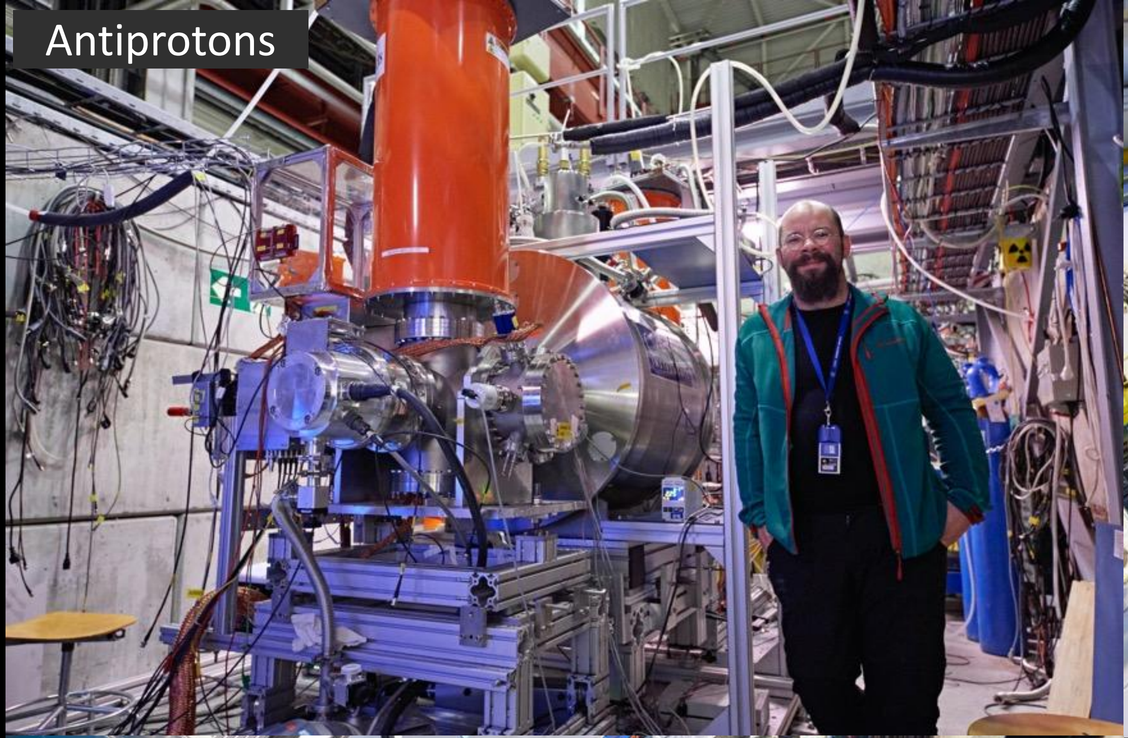
Increases proton energy from 2 GeV to max. 26 GeV

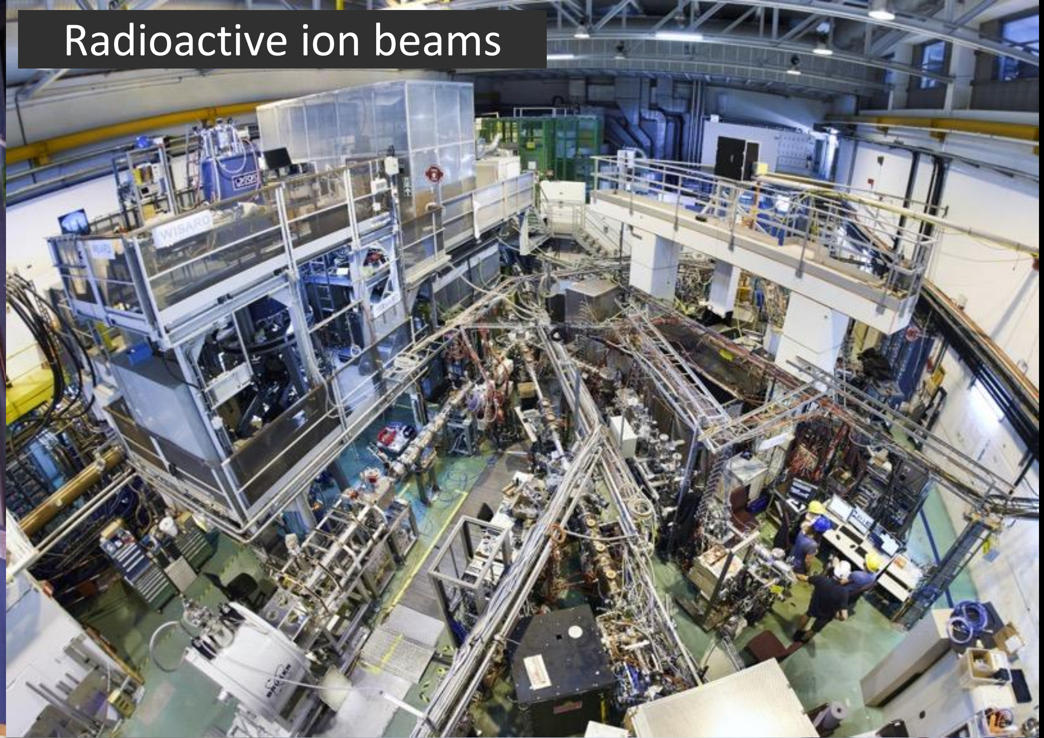
Cycle length ranges from 1.2 s to 3.6 s



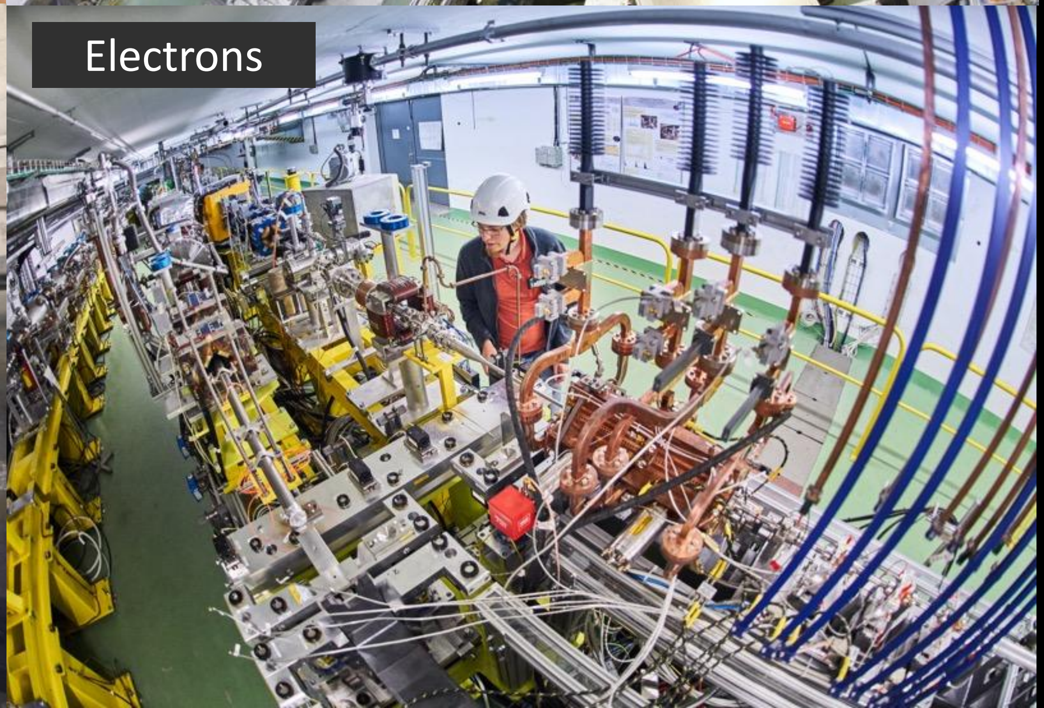
SPS (Super Proton Synchrotron) (1976)

- 6.9 km circumference
- Conventional warm magnets (2 T dipoles)
- Accelerates protons up to 450 GeV
- Serves the LHC, and North Area + HiRadMat and AWAKE

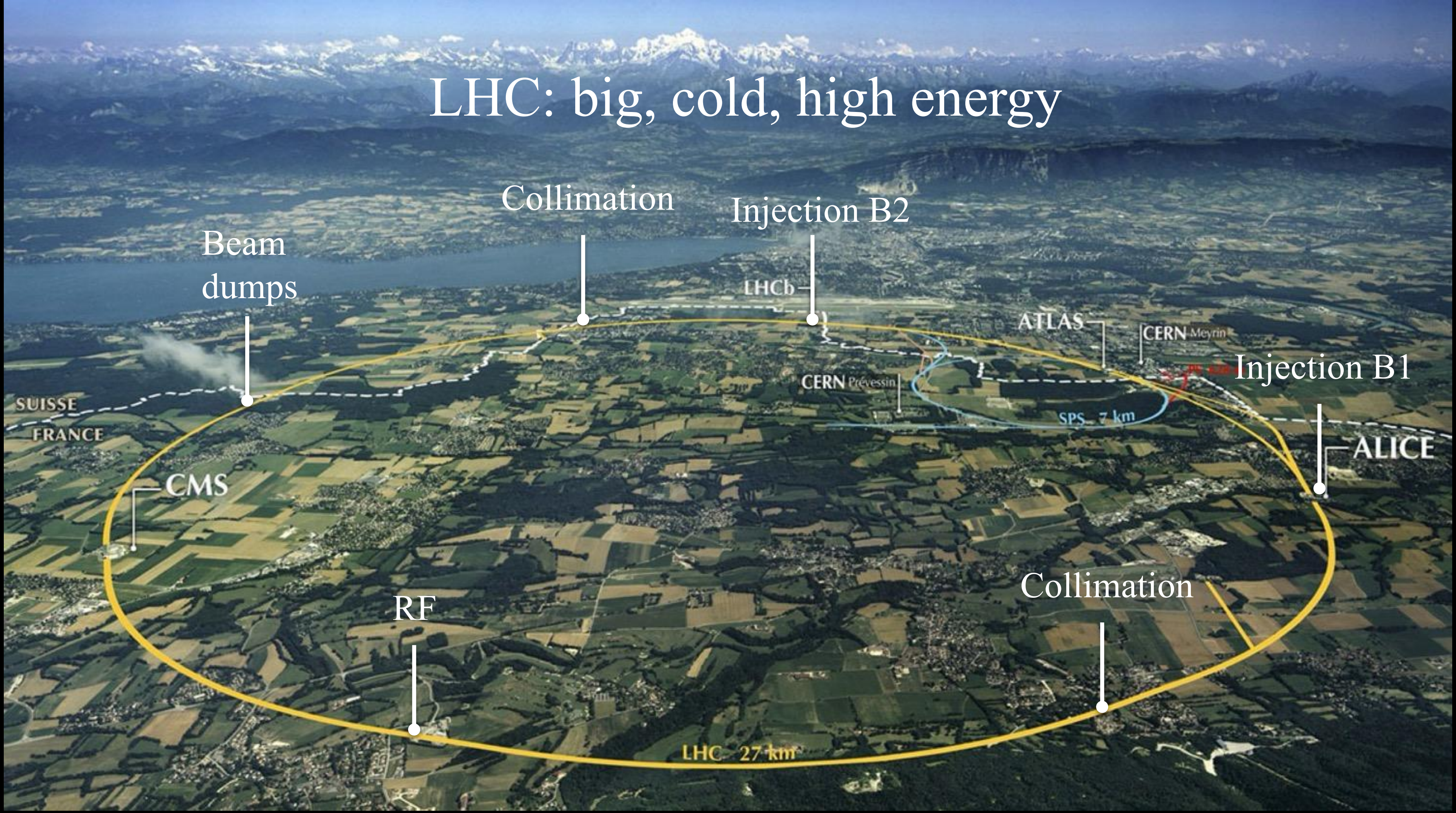

Antiprotons


Radioactive ion beams


Protons


Electrons

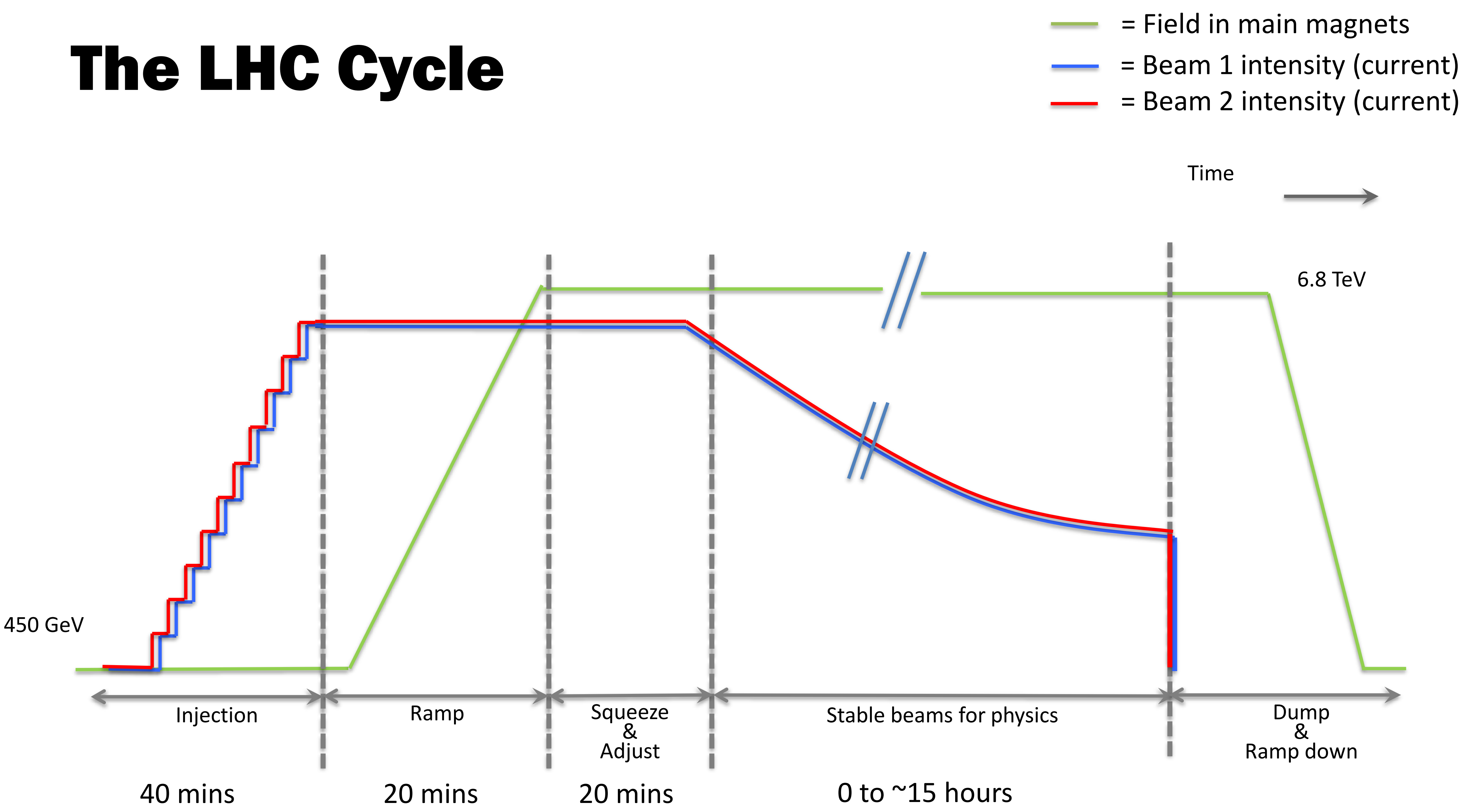
LHC: big, cold, high energy



1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

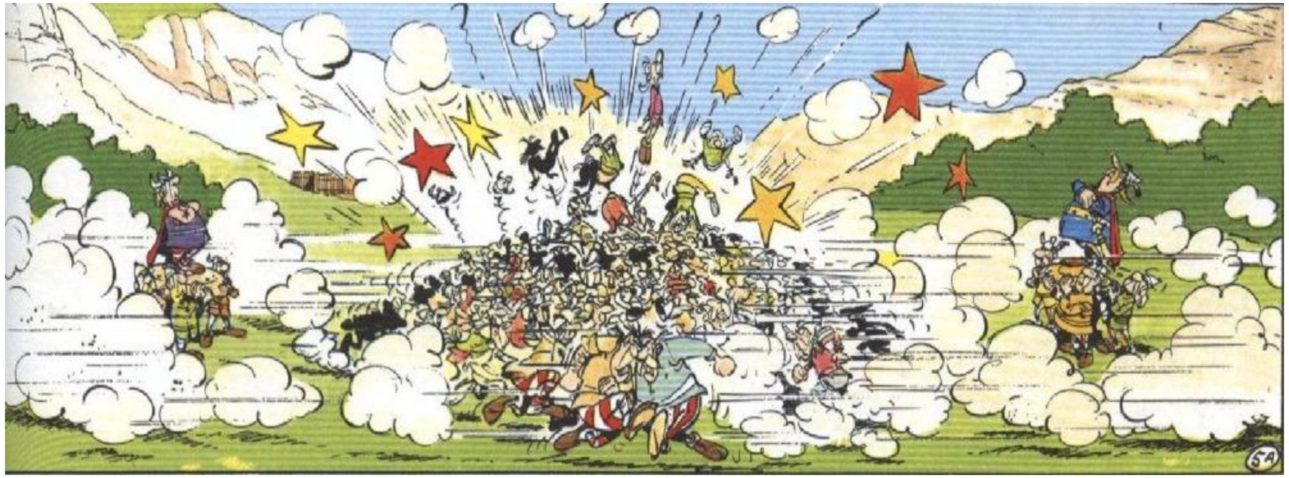
150 tonnes helium, ~90 tonnes at 1.9 K
400 MJ stored beam energy in 2025
1.3 GJ magnetic energy per sector at 6.8 TeV

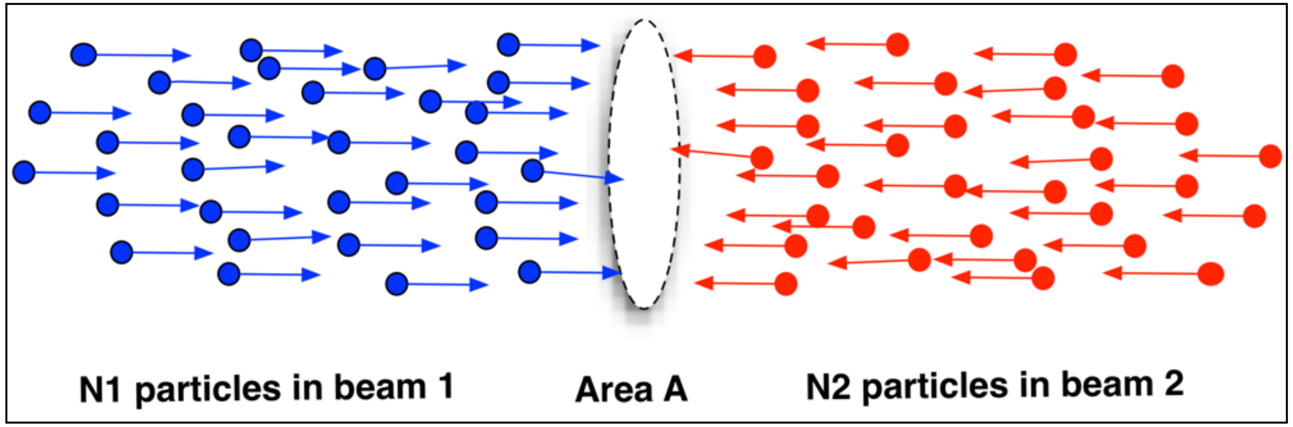
The LHC Cycle



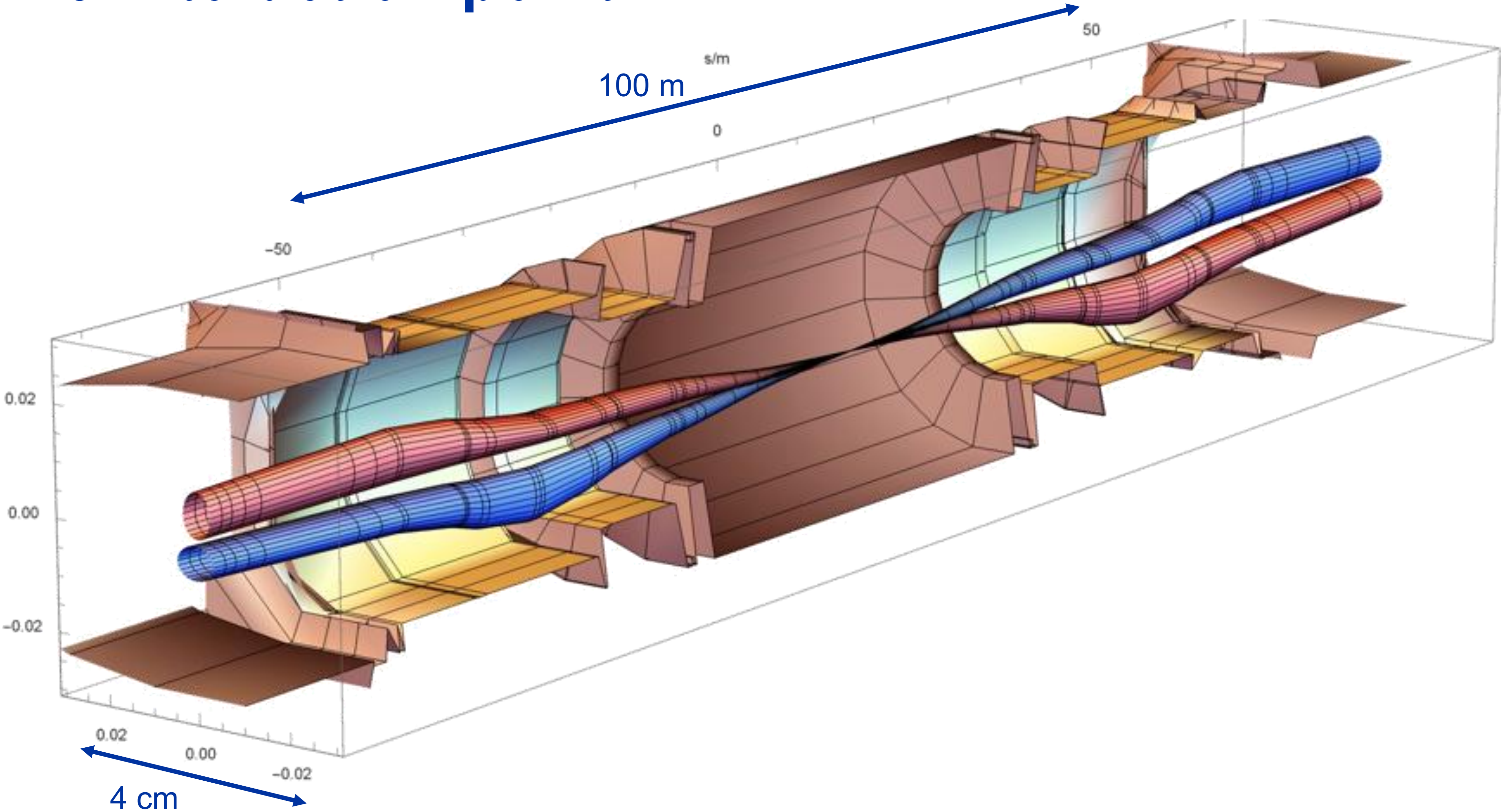
Aim of the Game

To deliver the maximum number of collisions at the maximum beam energy for maximum physics reach



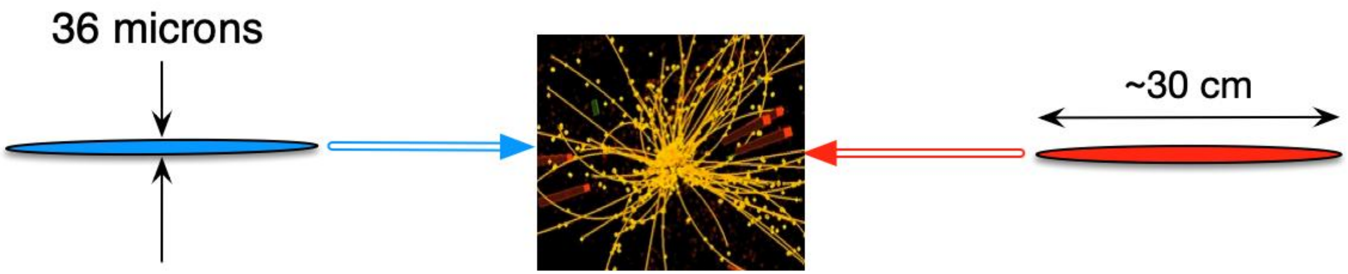


LHC interaction point



Collisions in the LHC

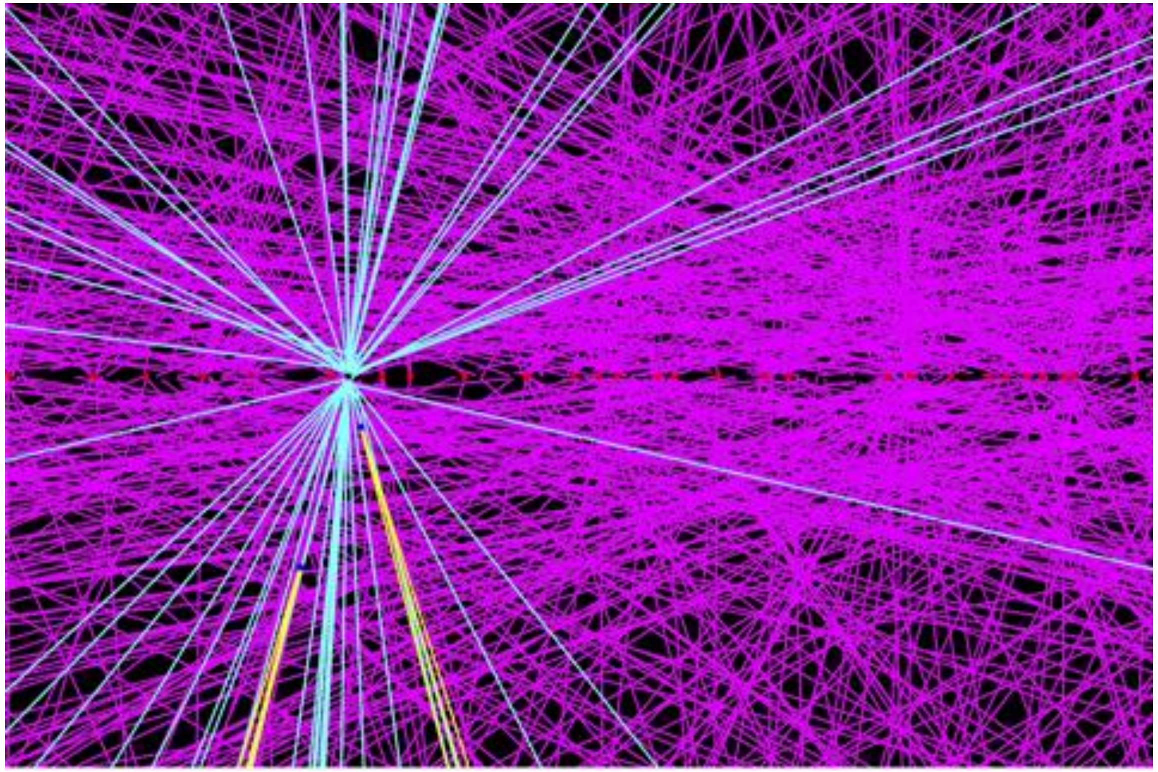
1.6e11 protons a bunch
~64 p-p collisions per bunch crossing



revolution frequency - 11,245 turns per second
2460 bunches

~1800 million collisions per second

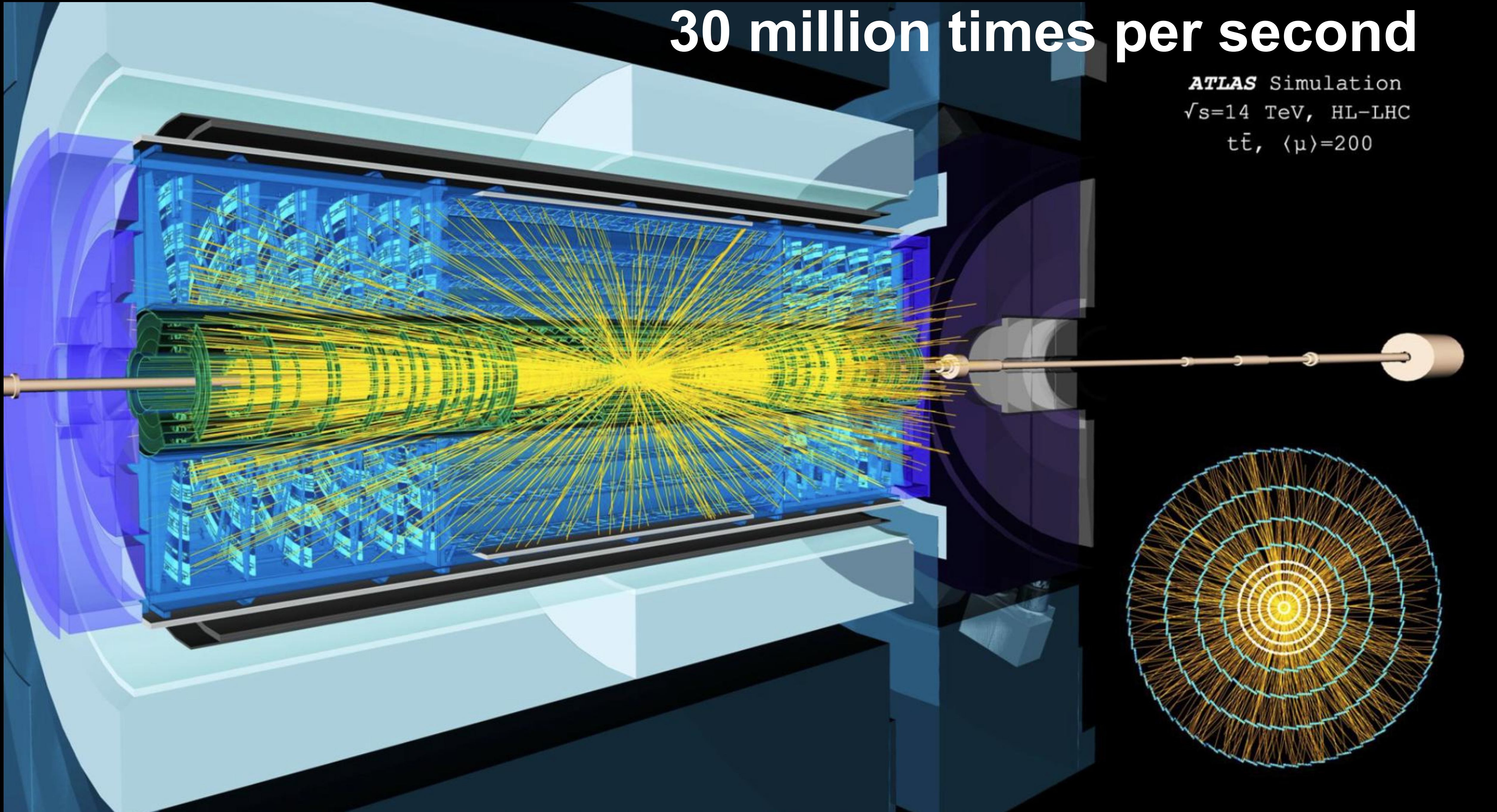
→ 1 Higgs every 2 seconds



real CMS event with a pile-up of ~50

[LHC Page 1]

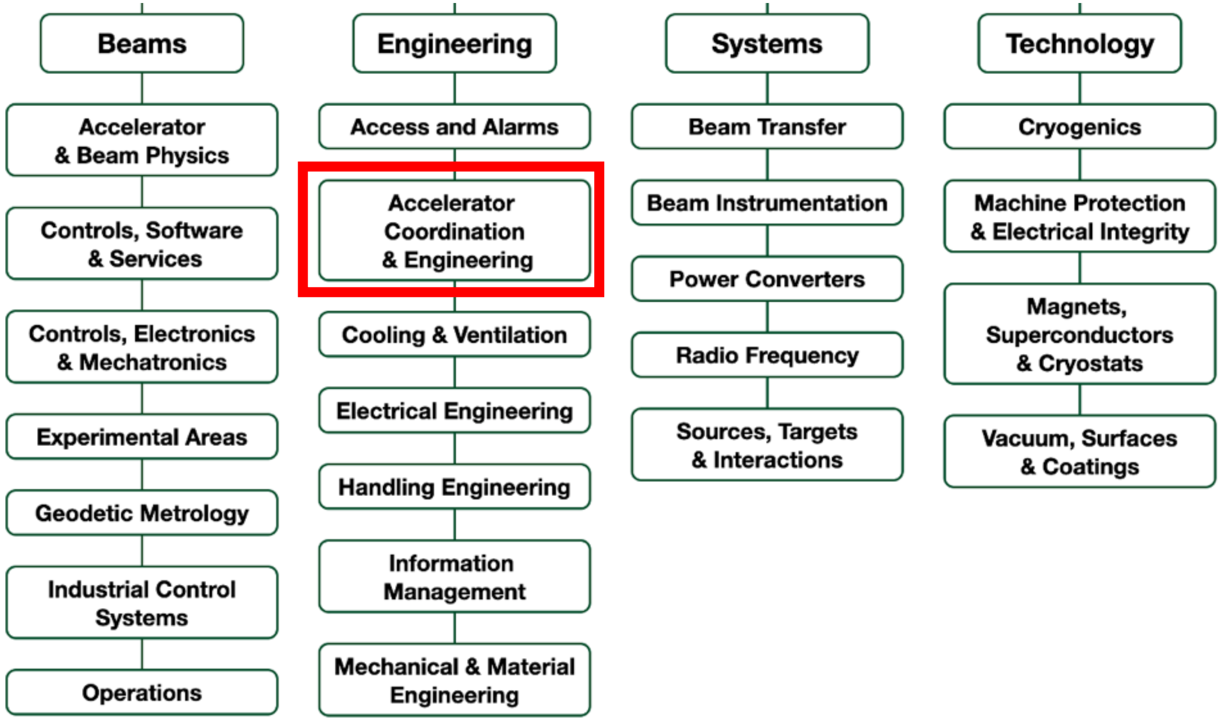
30 million times per second



Display of a simulated ttbar event with μ = 200 (1600 tracks) in the ATLAS ITk


CERN

Accelerator side organization



Operates, maintains, consolidates, upgrades the accelerator complex and associated technical infrastructure

- 1300 staff
- 538 fellows/graduates
- 446 associates
- Contract personnel

Strong compartmentalization

Full complex coverage in one group

Ancient to modern accelerators

Specialized in-depth expertise within group

Specialized facilities and labs within group

Centralized engineering support

Centralized workshops and facilities

Major new developments via projects matrixing into the groups

HIGH LUMINOSITY LHC PROJECT

MEMBER STATES COLLABORATIONS[1]

Spain - CIEMAT
SC Orbit Corrector MCBXF: J-M. Perez, F. Toral

Italy - INFN
SC HO Correctors & SC D2 Magnet: S. Malvezzi[2], M. Statera[3], S. Farinon[4]

Sweden - Uppsala University
Magnets & CC Test, Cold Powering DFHM/X: T. Ekelöf, M. Olvegård

United Kingdom
Collimation: R. Appleby[5] (Spokesperson)
SRF RFD & DQW CC Cryomodules: G. Burt[6], N. Templeton[7]
Beam Instrumentation: S. Gibson[8], C. Welsch[9], P. Burrows[10]
Cold Powering DFM/X: Y. Yang[11]

HL-LHC PROJECT MANAGEMENT

WP1 - CERN

Project Leader: Oliver Brüning
Deputy Project Leader & Configuration Office: Markus Zerlauth
Monitoring & Control Office: Giovanna Vandoni
Collaborations Office: Emmanuel Tsesmelis
Procurement, Documentation, Quality & Risk Office: Hector Garcia Gavela
Integration & Installation Office: Paolo Fessia & Davide Bozzini
Schedule Officer: Paolo Fessia
Safety Office: Thomas Otto & Christelle Gaignant
Communications & Outreach Office: Cécile Noels & Florence Thompson
Project Support & Secretariat: Cécile Noels

NON MEMBER STATES COLLABORATIONS

USA
DOE HEP Link: S. Rolli, J. Kao
US HL-LHC AUP[12]: G. Apollinari [13], V. Lombardo [13], G. Sabbi [14]
Q1/Q3 Magnet System: G. Ambrosio[13]
Q1/Q3 CM & Cryostats: S. Feher[13]
Dressed RFD CC System: L. Ristori[13]

Japan - KEK
SC D1 Magnet, QHPS & CC Powering: T. Nakamoto

China - IHEP
SC Orbit Corrector MCBRD: Q. Xu

Russia
Crystals: O. Fedin[15]

Canada - TRIUMF
RFD CC Cryomodules: O. Kester, B. Laxdal

Work Packages

WP2 Accelerator Physics
Rogelio Tomas Garcia
Nicolas Mounet

WP3 IR Magnets
Susana Izquierdo Bermudez
Delio Duarte Ramos

WP4 Crab Cavities & RF
Rama Calaga
Ofelia Capatina

WP5 Collimation
Stefano Redaelli
Antonio Perillo Marcone

WP6A Cold Powering
Amalia Ballarino
Yann Leclercq

WP6B Warm Powering
Michele Martino
Valérie Montabonnet

WP7 Machine Protection & Availability
Daniel Wollman
Reiner Denz

WP8 Collider-Experiment Interface
F. Sanchez Galan
Oliver Boettcher

WP9 Cryogenics
Vanessa Gahier - Antonio Perin

WP10 Energy Deposition & R2E
Francesco Cerutti - Ruben Garcia Alia

WP11 11 T Dipole[16]
Diego Perini

WP12 Vacuum & Beam Screen
Vincent Baglin
Giuseppe Bregliozzi

WP13 Beam Instrumentation
Raymond Veness
Thibaut Lefevre

WP14 Beam Transfer & Kickers
Chiara Bracco
Anton Lechner

WP15 Integration & (De-)Installation
Paolo Fessia
Davide Bozzini

WP16 IT String & Commissioning
Marta Bajko - Mirko Pojer

WP17 Infrastructure & Logistics
Henry de Maynard
Silvia Grau

WP18 Controls Technologies
Javier Serrano
Grzegorz Daniluk

WP19 Alignment & Internal Metrology
Helene Mainaud Durand
Mateusz Sosin

[1] In kind contributions
[2] INFN Milano Biccoca
[3] INFN Milano LASA
[4] INFN Genova
[5] University of Manchester

[8] Royal Holloway/John Adams Institute
[9] University of Liverpool/Cockcroft Institute

[12] US HL-LHC Accelerator Upgrade Project (BNL, FNAL, LBNL, SLAC
[13] FNAL

[16] Descoped from the project

Aspects of Systems Engineering at CERN

Systems Management

- Systems engineering at CERN involves a **holistic approach (!)** to manage the interconnected technical infrastructure that supports its particle accelerators and experiments.

Infrastructure Design & Maintenance

- This includes the design, installation, operation, and maintenance of crucial systems like cooling, ventilation, access, alarms, and electrical power.

Project Management:

- Project Management Institute (PMI) standards and methodologies
- openSE framework

Safety and Risk Management

Engineering Data Management

- manage engineering information using tools like CAD and Product Lifecycle Management (PLM) systems to maintain data integrity and traceability for technical installations.

Technology (briefly!)

Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry.

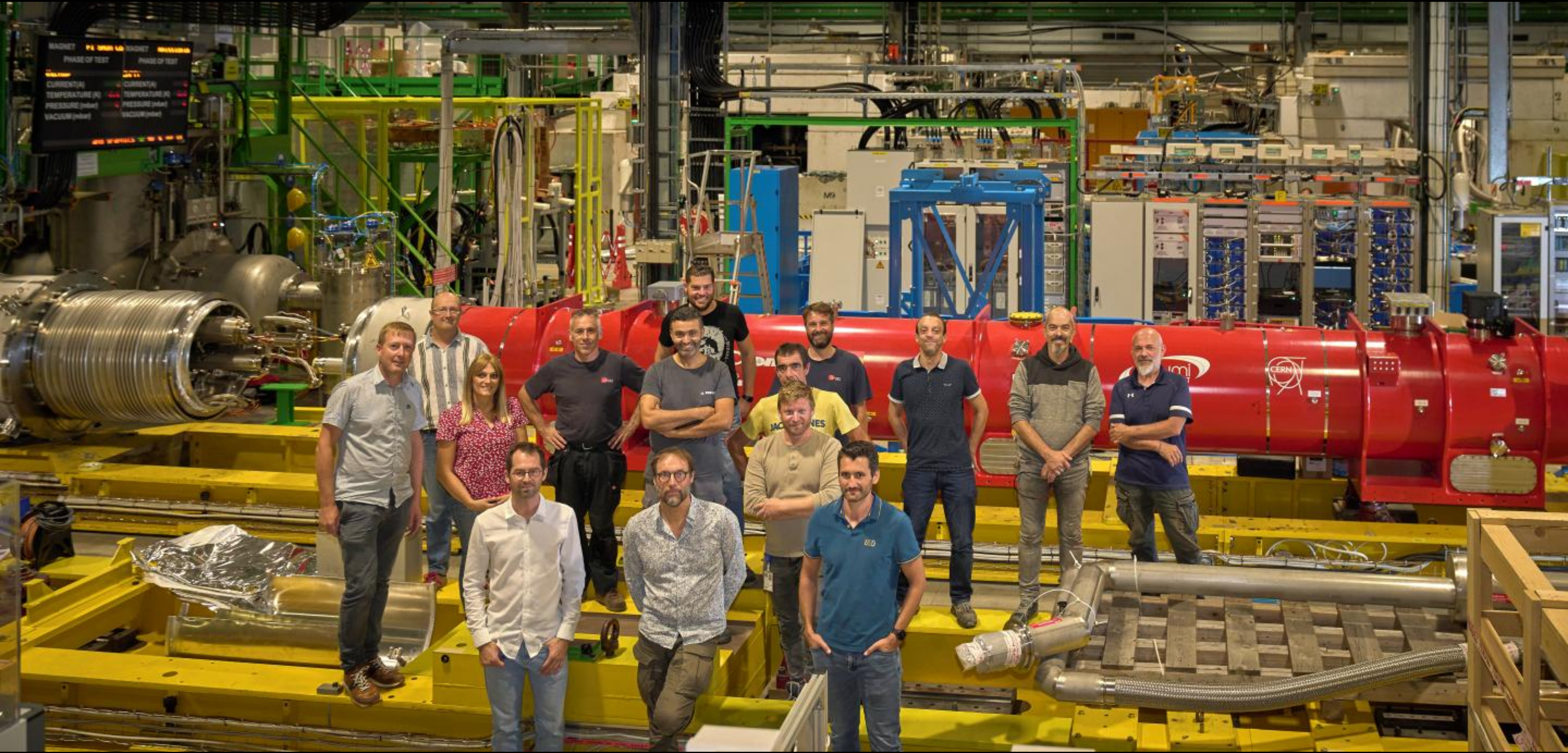
The technologies under consideration include high-field magnets, high-temperature superconductors, high-gradient accelerating structures etc. etc.

Challenging, highly technical domain

- Large scale mass production to bespoke
- High performance – precision engineering, precise metrology, material quality
- Control: precision, synchronization, feedbacks, timing
- Harsh environment – radiation, humidity, EMC, temperature, beam
- Reliability and availability
- Affordability
- Sustainability
- Engage industry whenever possible

Targets
Beam Incepting Devices
Beam dumps
Collimators
Beam instrumentation
Radiofrequency
Low temperature superconductors
High temperature superconductors
Cryostats
Superconducting magnets
Resistive magnets
Vacuum
Coatings
Cryogenics
Power converters
Rad-hard electronics
Precison timing
Robotics
Pulsed Power Engineering
Kickers
Septa
Fast electronics
Controls

CERN staff sitting on the first PS main magnet at the École de Physique 1955

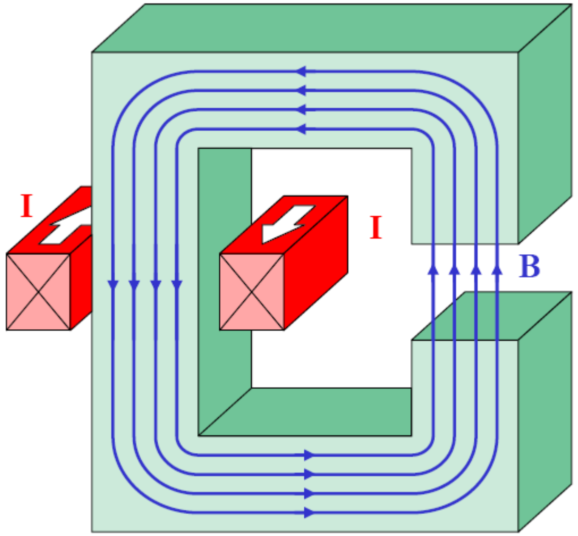


CERN staff in front of one of the first High Luminosity LHC Nb_3Sn quadrupoles 2023

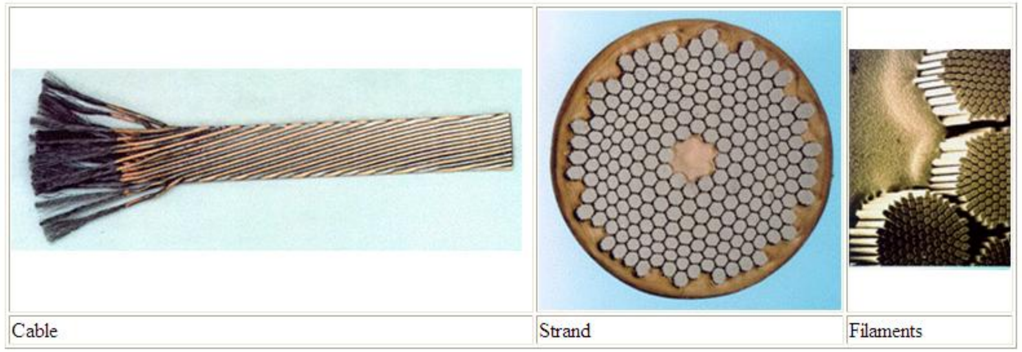
Why use Superconductivity?

- **Iron Yoke Magnets**
  - Good to reduce current required as iron guides magnetic field
  - But iron saturates at around 2 T
    - For an accelerator with fixed magnetic field

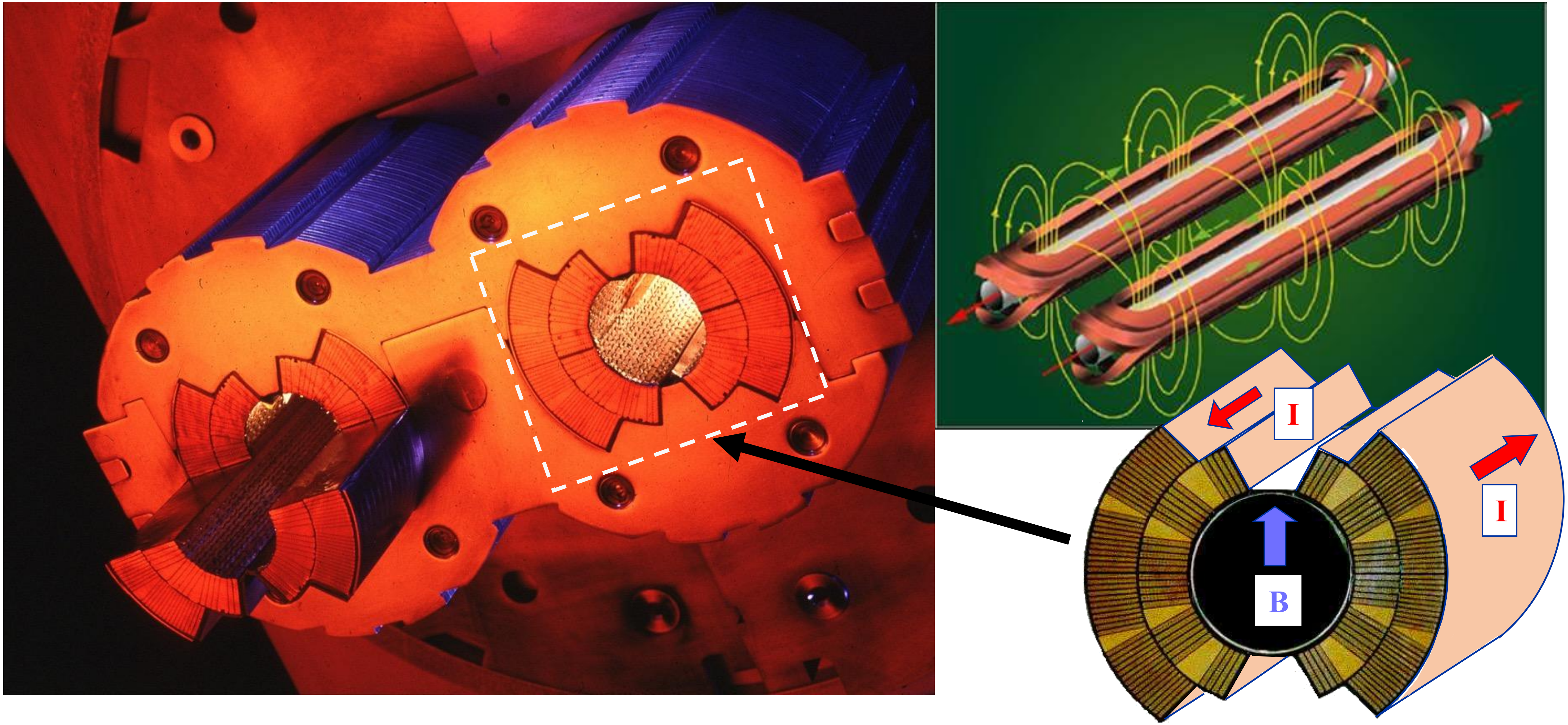
      Increasing the energy = increasing the size

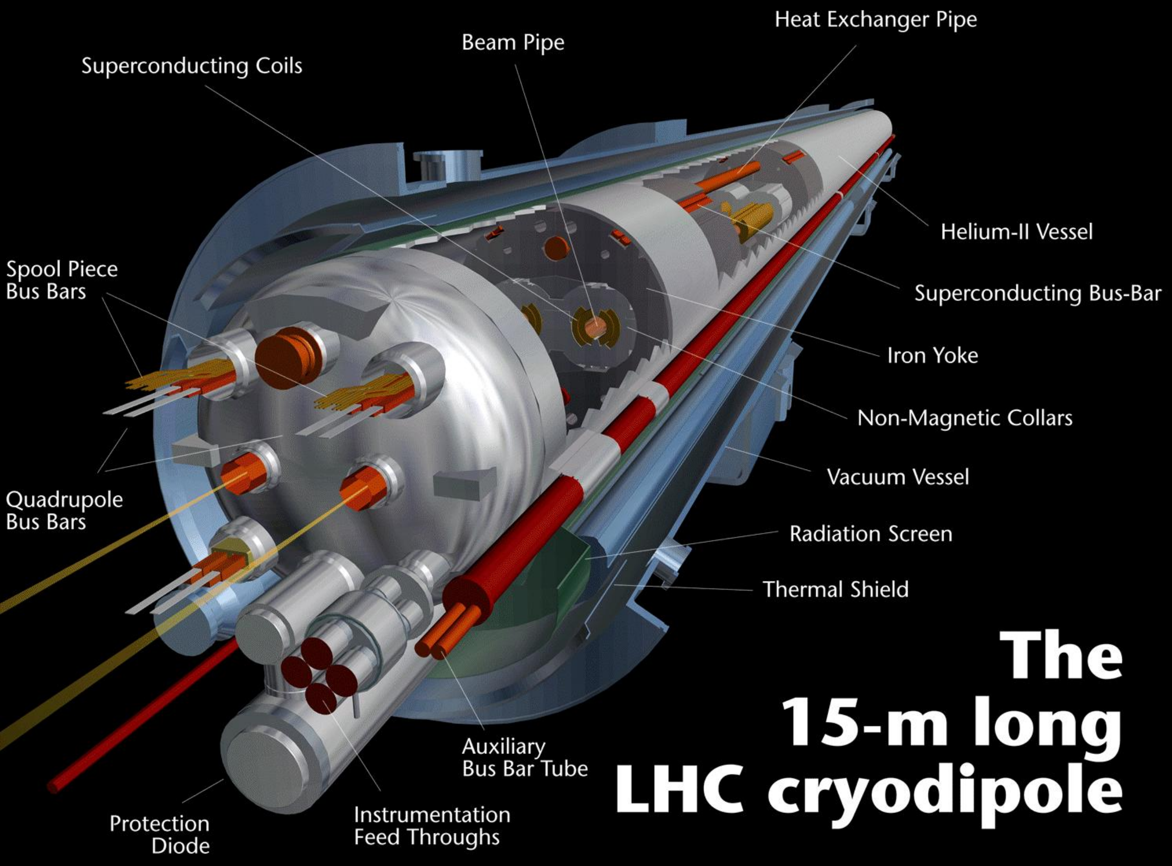


- **Superconducting Magnets**
  - Virtually lossless (no resistance)
  - Can carry very high currents to create high magnetic fields
    - Up to 8 T for the LHC magnets @ 13000 Amperes
  - BUT the wire needs to be cooled to near absolute zero
  - NbTi technology used for the LHC magnets



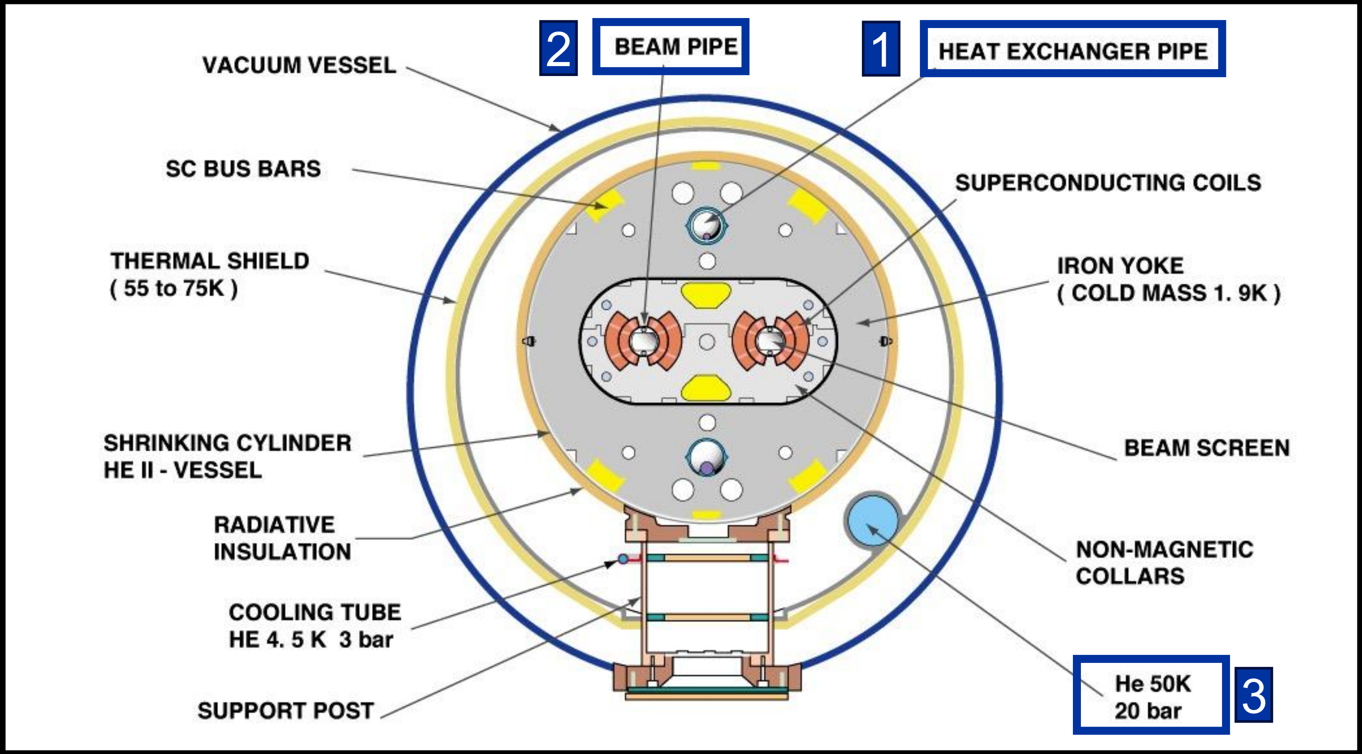
LHC Dipole Magnets





The 15-m long LHC cryodipole

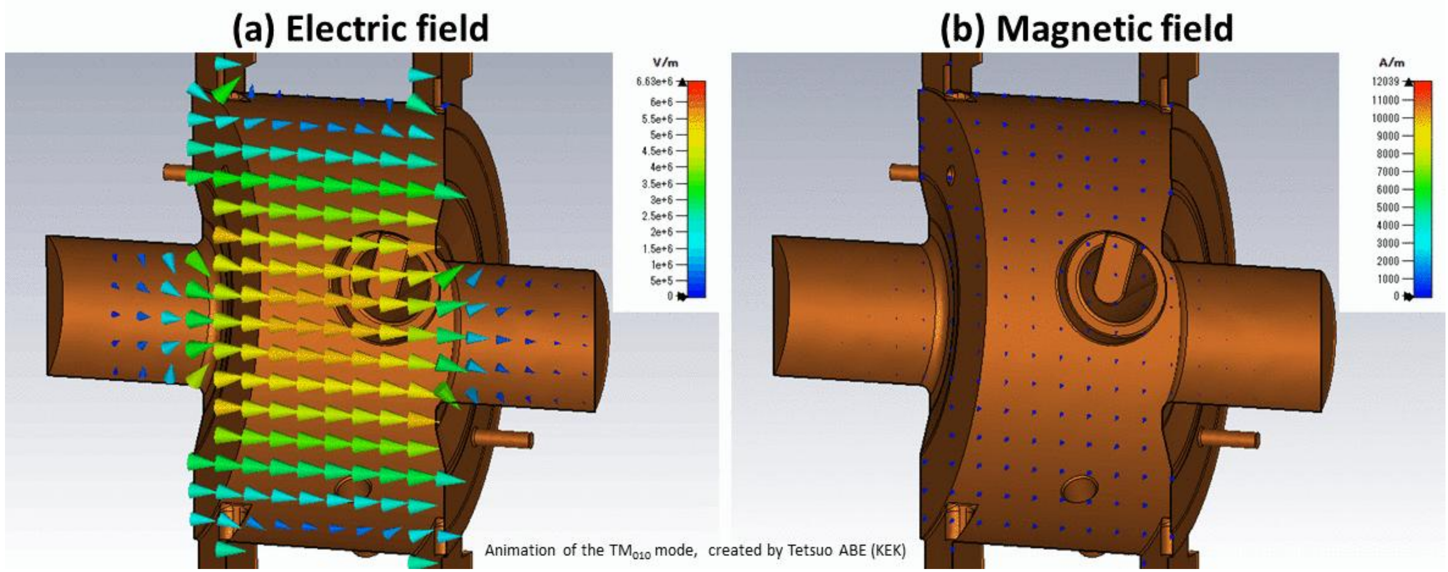
x 1232



Superconducting Acceleration Cavities

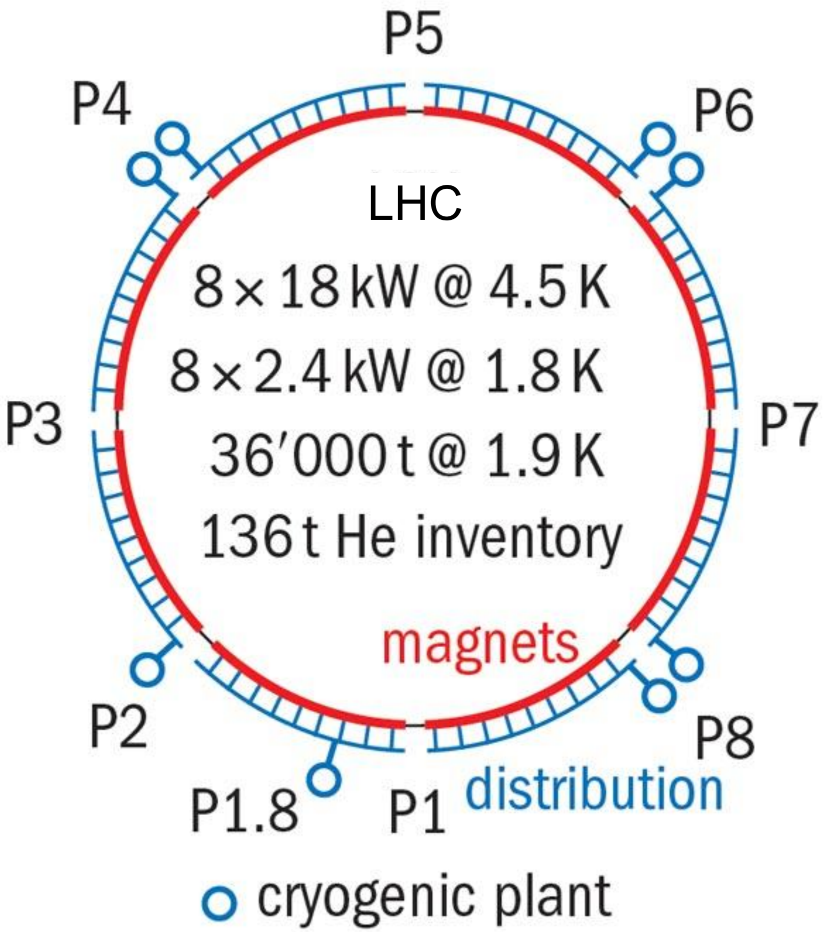
Superconducting radio frequency (SRF)

- Ultra-low electrical resistivity of superconducting material allows an RF resonator to store energy with very low loss over a narrow bandwidth so that nearly all the RF power goes to the beam



Q-factor ~1×10^{10}

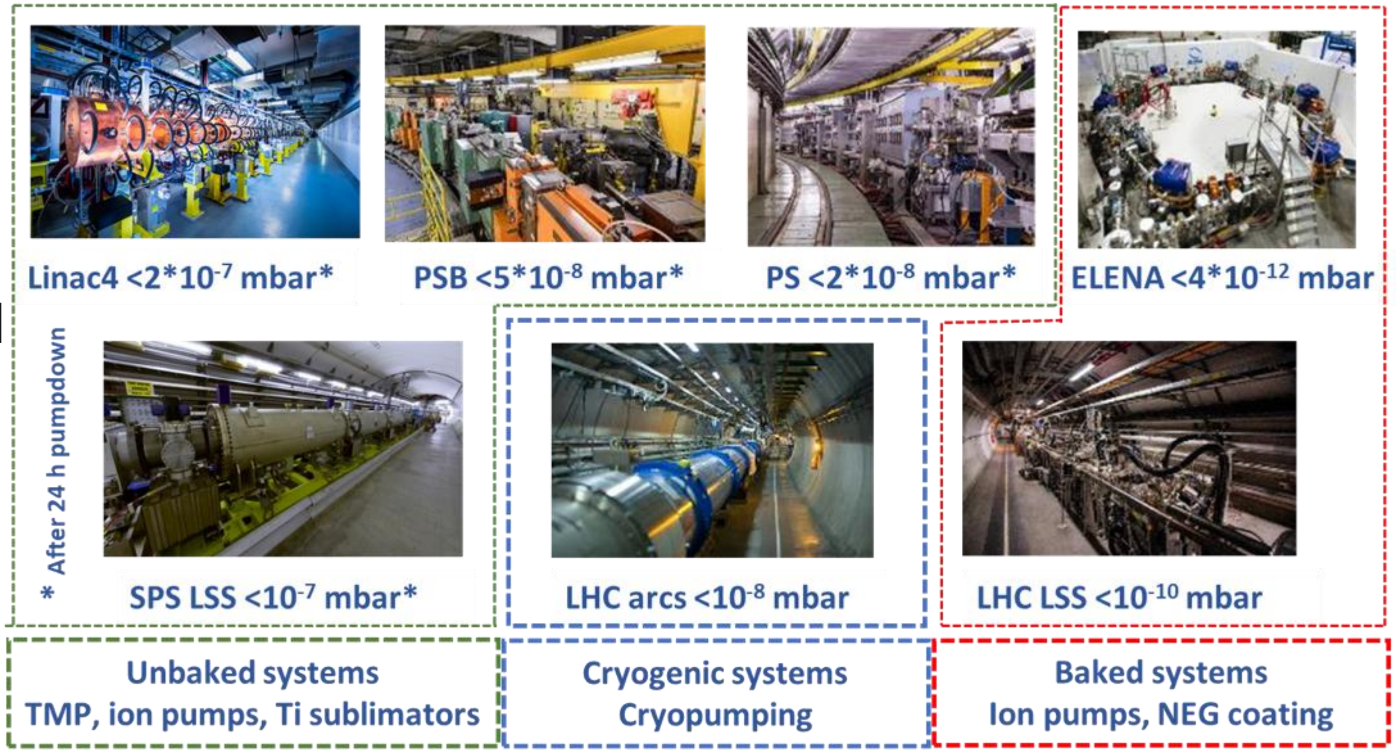
Cryogenics

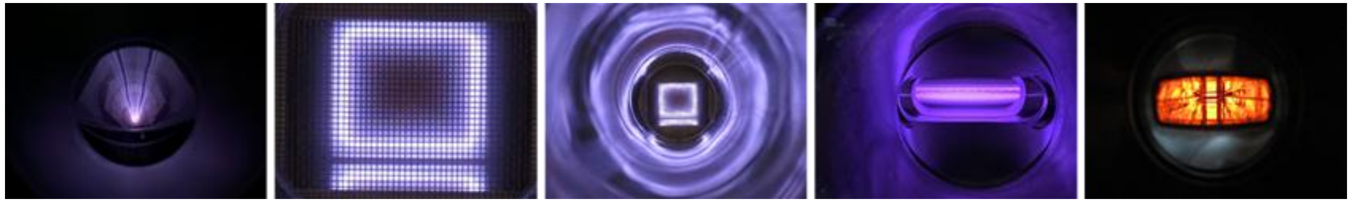

P5
P4
P6
LHC
8 × 18 kW @ 4.5 K
8 × 2.4 kW @ 1.8 K
36′000 t @ 1.9 K
136 t He inventory
P3
P7
magnets
P2
P8
P1.8
P1
distribution
cryogenic plant


Compressor unit of
4.5 K refrigerator

Largest Beam Vacuum System Worldwide

- **65 km UHV/XHV lines**
  - Multiple technologies used
- **Coatings and Plasma Processing an integral technology to obtain required vacuum with high intensity particle beams**
  - Thin film coating: evaporation, diode and magnetron sputtering
  - All types of materials including Nb, A15, amorphous-Carbon and Non-Evaporable Getter (NEG) coatings
  - Plasma and laser processing of surfaces
  - Removal of hydrocarbon contamination
  - Numerical simulations





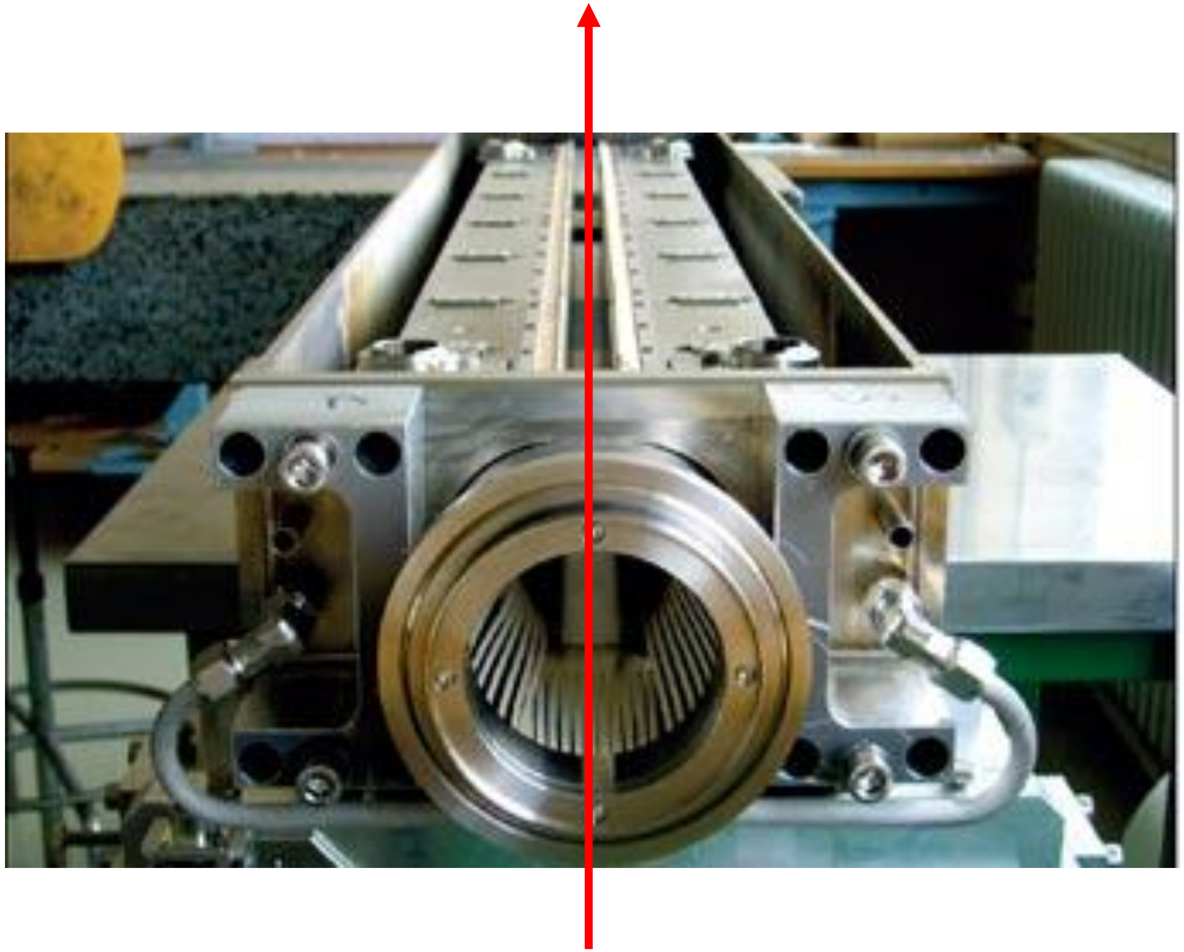
Collimation

Take out any protons than wander too far off axis

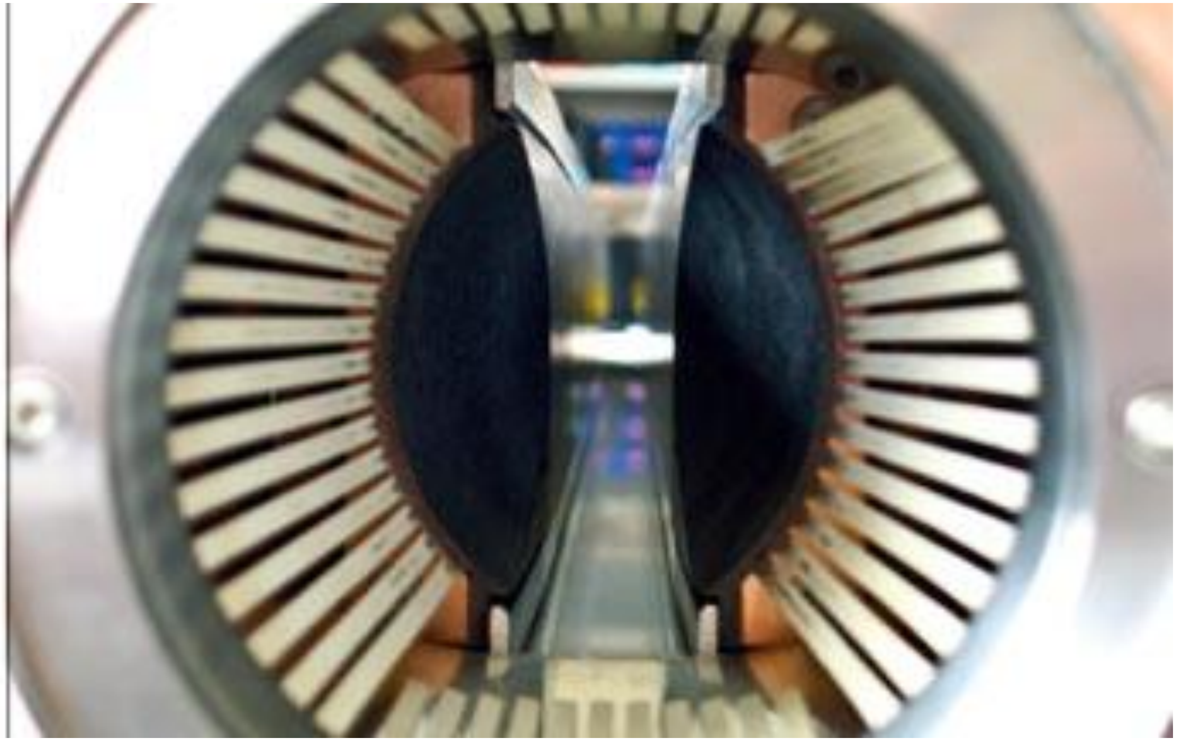
110 collimators/absorbers in the machine

Material:

- Molybdenum-Carbide Graphite (MoGr)
- Carbon Fibre Composite
- Cu-coated graphite
- Copper-Diamond



430 MJ



HW GROUP: COLLIMATORS_VISTAR_B1 | Beam Mode: STABLE | Energy: 6799 GeV | 11-09-2025 12:43:31

IR1

L (mm)	IR1	R (mm)
4.42	TCTPH.4L1.B1	-8.77
7.68	TCTPV.4L1.B1	-8.18
13.16	TCL.4R1.B1	-11.43
13.77	TCL.5R1.B1	-15.24
1.42	TCL.6R1.B1	-1.78

IR2

L (mm)	IR2	R (mm)
7.10	TCTPH.4L2.B1	-7.82
6.64	TCTPV.4L2.B1	-9.86
40.00	TDISA.A4L2.B1	-40.02
40.00	TDISB.A4L2.B1	-39.99
39.98	TDISC.A4L2.B1	-40.00
20.50	TCDD.4L2	-20.48
29.48	TCLIA.4R2	-29.50
24.81	TCLIB.6R2.B1	-24.98
19.92	TCLD.A11R2.B1	-20.00

IR3

L (mm)	IR3	R (mm)
3.36	TCP.6L3.B1	-4.24
2.65	TCSG.5L3.B1	-3.23
1.31	TCSG.4R3.B1	-2.71
2.07	TCSG.A5R3.B1	-3.26
2.01	TCSG.B5R3.B1	-3.93
5.81	TCLA.A5R3.B1	-5.92
4.45	TCLA.B5R3.B1	-6.41
4.97	TCLA.6R3.B1	-5.10
4.35	TCLA.7R3.B1	-2.75

IR5

L (mm)	IR5	R (mm)
10.77	TCTPH.4L5.B1	-11.87
4.64	TCTPV.4L5.B1	-2.43
11.44	TCL.4R5.B1	-14.49
12.37	TCL.5R5.B1	-15.82
1.12	TCL.6R5.B1	-2.05

IR6

L (mm)	IR6	R (mm)
3.17	TCDQA.A4R6.B1	
3.33	TCSP.A4R6.B1	-4.03

IR7

L (mm)	IR7	R (mm)
1.03	TCP.D6L7.B1	-0.85
1.42	TCP.C6L7.B1	-1.17
1.39	TCP.B6L7.B1	-0.80
1.57	TCSG.A6L7.B1	-1.41
64.75	TCPCV.A6L7.B1	Closed
1.84	TCSG.B5L7.B1	-1.84
1.86	TCSG.A5L7.B1	-1.85
1.05	TCSG.D4L7.B1	-1.36
65.01	TCPCH.A4L7.B1	Closed
22.99	TCSG.B4L7.B1	-22.98
1.74	TCSPM.B4L7.B1	-1.58
1.70	TCSG.A4L7.B1	-1.63
1.54	TCSG.A4R7.B1	-1.84
1.97	TCSG.B5R7.B1	-1.86
1.94	TCSG.D5R7.B1	-1.89
23.00	TCSG.E5R7.B1	-22.99
1.79	TCSPM.E5R7.B1	-2.04
22.99	TCSG.6R7.B1	-22.98
2.30	TCSPM.6R7.B1	-2.60
2.19	TCLA.A6R7.B1	-1.08
3.04	TCLA.B6R7.B1	-2.20
3.98	TCLA.C6R7.B1	-1.35
3.04	TCLA.D6R7.B1	-0.28
1.50	TCLA.A7R7.B1	-1.89

IR8

L (mm)	IR8	R (mm)
6.99	TCTPH.4L8.B1	-2.41
3.41	TCTPV.4L8.B1	-7.05

TI2

L (mm)	TI2	R (mm)
1.56	TCDIV.29011	-2.19
4.76	TCDIH.29049	-3.67
2.21	TCDIH.29206	-3.30
3.79	TCDIV.29233	-3.18
2.86	TCDIH.29464	-3.16
7.91	TCDIV.29508	-5.54

Collimation hierarchy (σ)

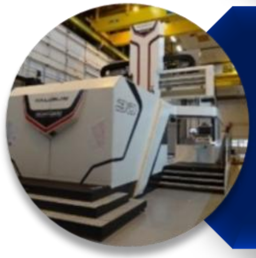
TCP.7	5.1
TCS.7	6.4
TCS.6	7.3
TCDO.6	7.3
TCT.1&5	8.5
TCLA.7	10.0
TCT.8	11.5
TCP.3	15.0
TCS.3	18.0
TCL4.1&5	18.0
TCLA.3	20.0
TCL6.1&5	21.1
TCL5.1&5	34.8
TCT.2	37.0
TCLD.2	Out
TCPC.7	Out

HL-LHC 2023 HIGHLIGHTS
HL-LHC 2023 HIGHLIGHTS
HL-LHC 2023 HIGHLIGHTS

Mechanical and Material Engineering group

Design

- Design Office
- Engineering Unit
- Mechanical Measurements Laboratory
  - 40+ designers and 15+ engineers



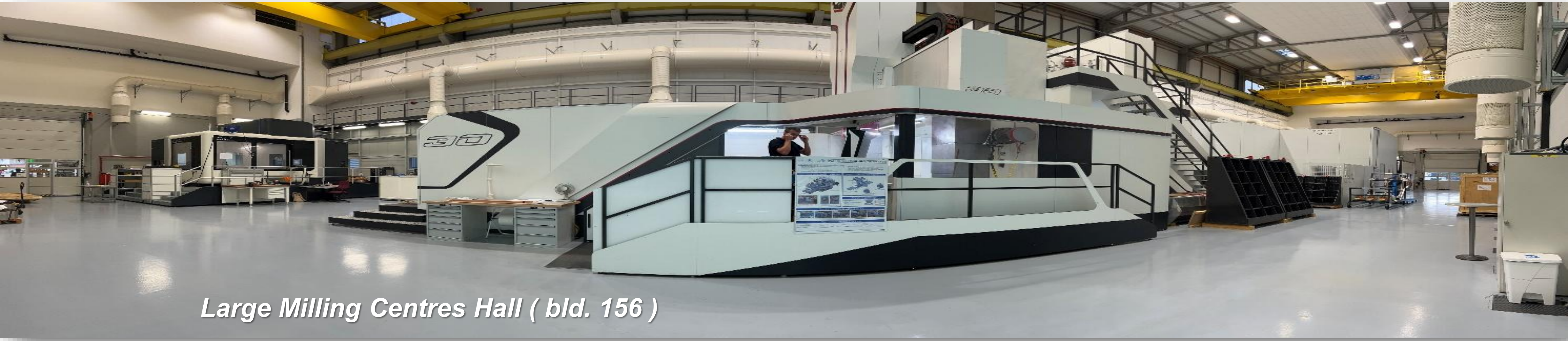
Fabrication

Mechanical Workshop & Technical Subcontracting unit

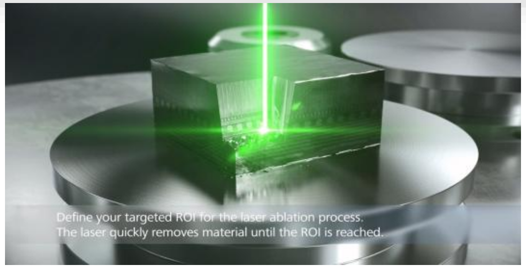
Materials

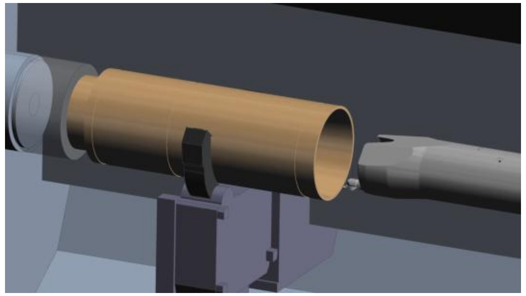
- Material science consultancy
  - Metallurgical analyses, microscopy including FIB, Mechanical tests
- NDT: UT, radiography, microtomography
- Metrology: 350 m^2 Lab., several CMM

Main Workshop assets “state-of-the-art technologies“


Large Milling Centres Hall (bld. 156)

345 assets | Cutting-edge capabilities





The approach

- Transform processes using next-gen tech: CAE, IoT, **Digital Twins**
- Engineer smart, efficient, and sustainable solutions
- Build future-ready infrastructure and **upskill teams**
- **The winning formula**: pairing fresh engineering minds with the seasoned hands of experienced technicians

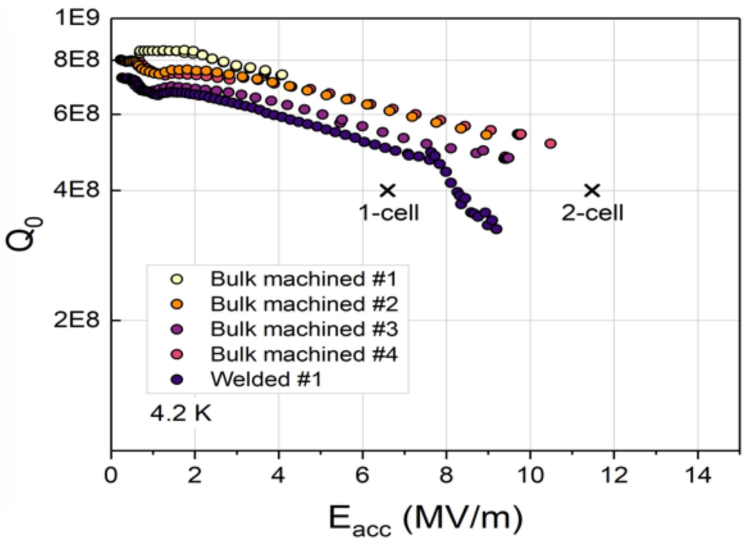
Developments: Superconducting RF (SRF) fabrication

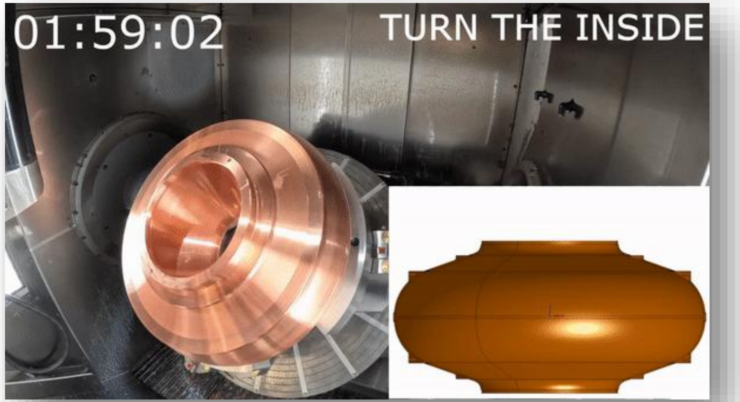
Seamless cavities & large subcomponents

Provide a **scalable, industry-ready solution** aligned with future needs

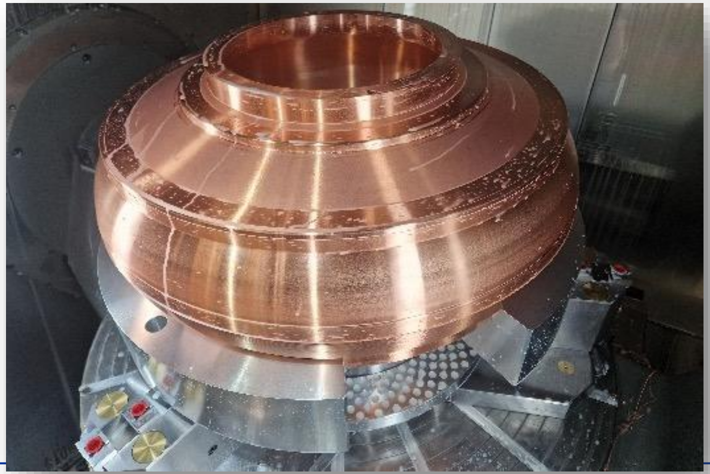
- Optimal surface and shape conformity, **boost our understanding** & coatings development
- Reduce multi-technology (**costs**, welds, subcomponents qty)
- Obtain unconventional geometries

1.3 GHz





400 MHz

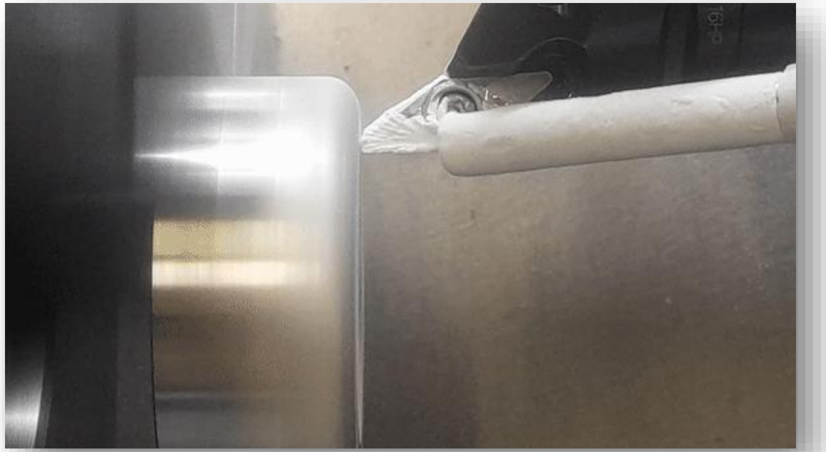


Strategic impact through technological excellence

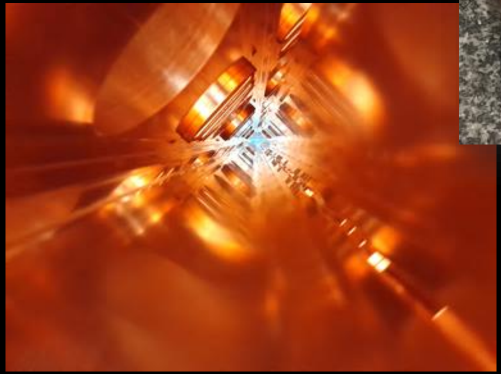
HL-LHC Crab Cavities

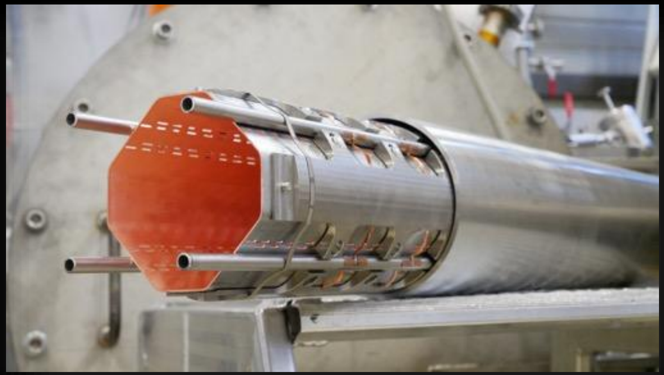
Last year's development in fabrication technologies:

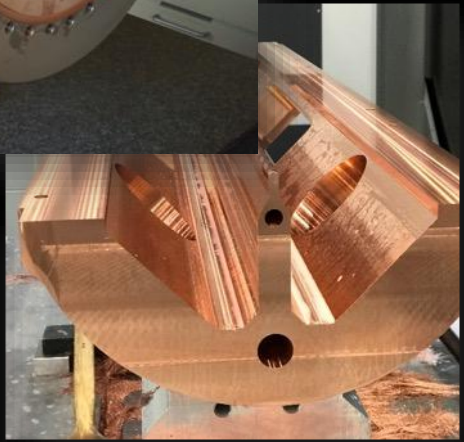
- **Breakthroughs in high-purity Nb fabrication** for SRF systems
- **Global tech transfer** of MME capabilities to key industry and research partners
- Enabled **next-gen technology adoption**, powering global innovation
- **CERN & MME recognized as global leaders** in SRF fabrication and innovation



LINAC4 Radio Frequency Quadrupole:
High-precision components



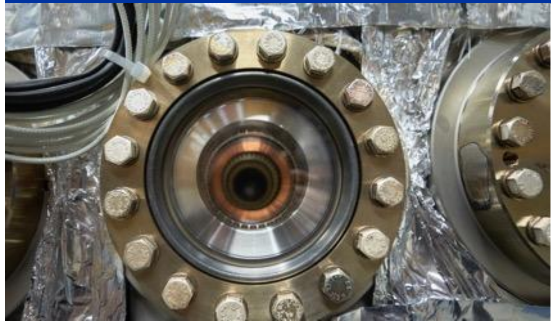




CERN and industry: what we buy and develop together

Civil engineering
- Construction
- Renovation of buildings
- Metallic structures
- Earthworks
- Roads

Electrical engineering and magnets
- Transformers
- Switchboards and switchgear
- Cables
- Automation
- Power supplies
- Magnets



Information Technology
- Computing systems
- Servers
- Software
- Network equipment
- Personal computer equipment

Mechanical engineering and raw materials
- Machining
- Sheet metal work and arc welding
- Special fabrication techniques
- Raw materials, finished and semi-finished products (plates, pipes, etc.)
- Offsite engineering and testing

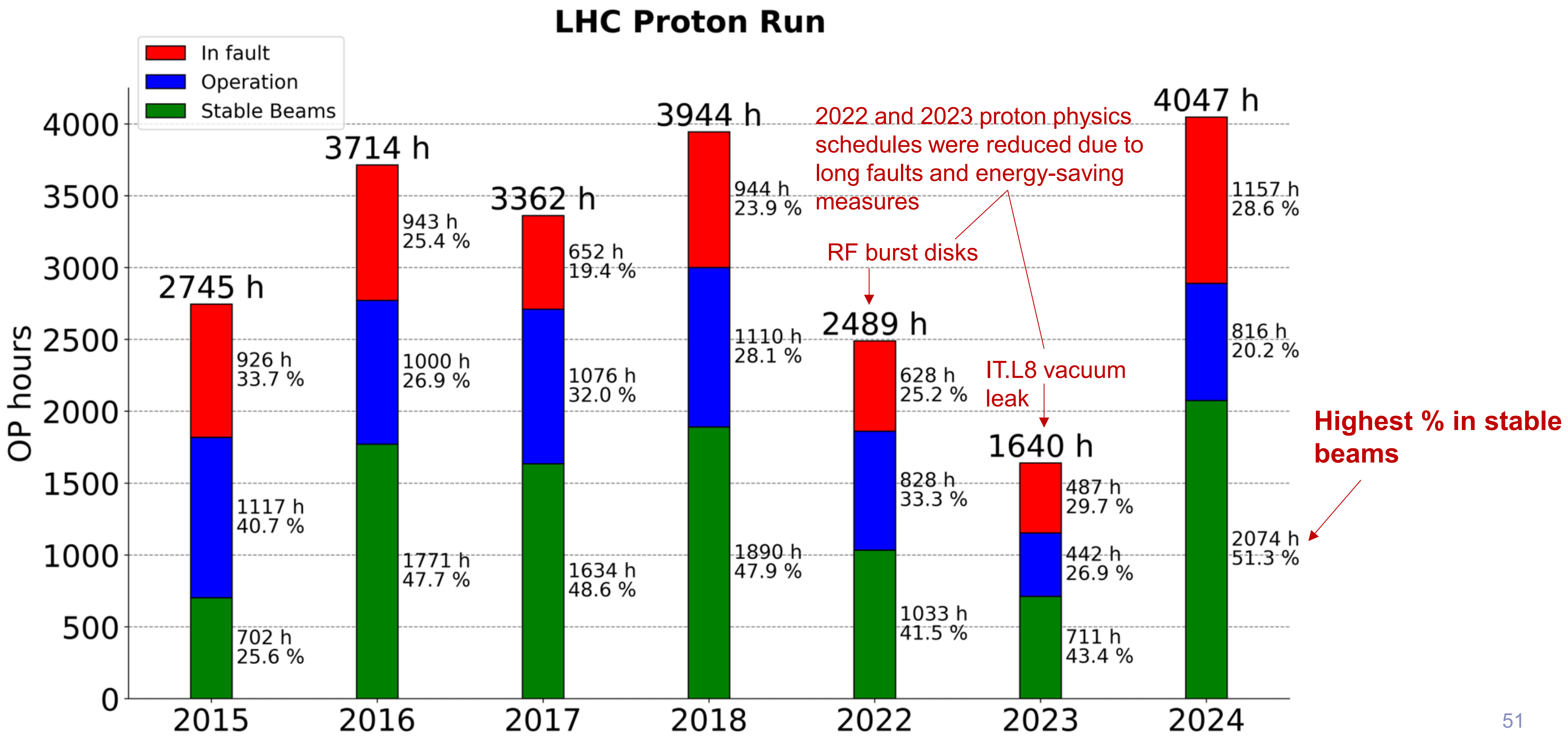
> 500 MCHF from CERN budget spent annually to purchase supplies and services mainly from high-tech industry in Member States

Electronics and radiofrequency
- Electronic components
- PCBs and assembled boards
- LV and HV power supplies
- Radiofrequency plants
- Amplifiers

As well as
- Cryogenic and vacuum equipment
- Optics and photonics
- Particle and photon detectors
- Health and safety equipment,
- Transport and handling equipment
- Office supply, furniture
- Industrial services on the CERN site

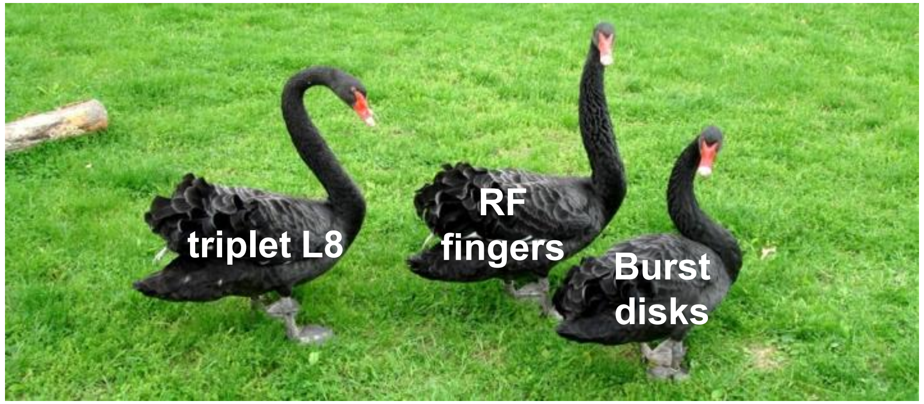
What could possibly go wrong?

A lot…



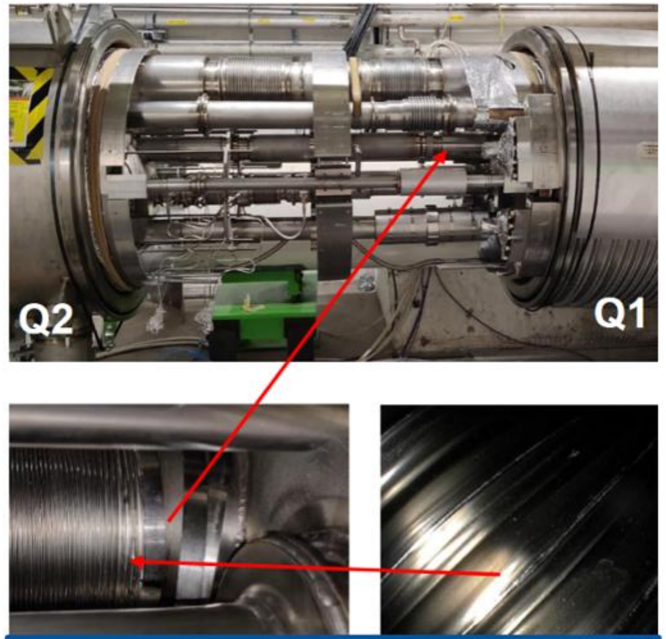
LHC Proton Run
In fault
Operation
Stable Beams
OP hours
4000
3500
3000
2500
2000
1500
1000
500
0
2015
2016
2017
2018
2022
2023
2024
2745 h
926 h
33.7 %
1117 h
40.7 %
702 h
25.6 %
3714 h
943 h
25.4 %
1000 h
26.9 %
1771 h
47.7 %
3362 h
652 h
19.4 %
1076 h
32.0 %
1634 h
48.6 %
3944 h
944 h
23.9 %
1110 h
28.1 %
1890 h
47.9 %
2489 h
628 h
25.2 %
828 h
33.3 %
1033 h
41.5 %
1640 h
487 h
29.7 %
442 h
26.9 %
711 h
43.4 %
4047 h
1157 h
28.6 %
816 h
20.2 %
2074 h
51.3 %
2022 and 2023 proton physics schedules were reduced due to long faults and energy-saving measures
RF burst disks
IT.L8 vacuum leak
Highest % in stable beams

2022/23



"*black swans*" on the rise?

Edge welded bellow – helium leak



damaged bellow in IT.L8

Non-conformity

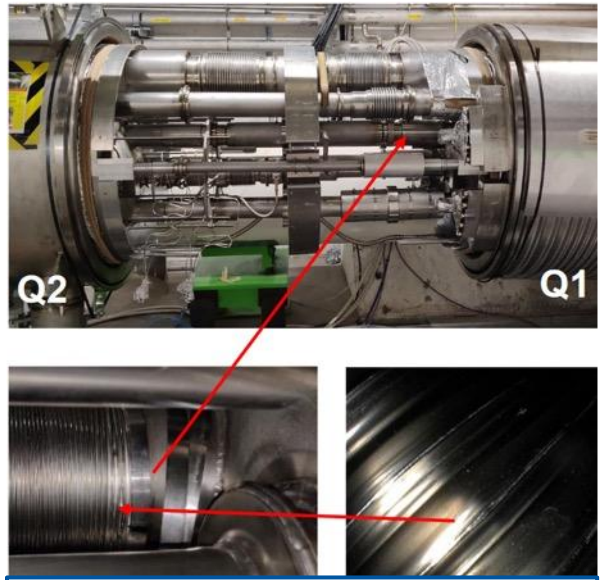
Example of damaged RF finger of A4L1 warm module

Unannounced change/ part out of spec.

installed RF burst disk type

July 2023: IT.L8 vacuum leak (inner triplet quads IP8)

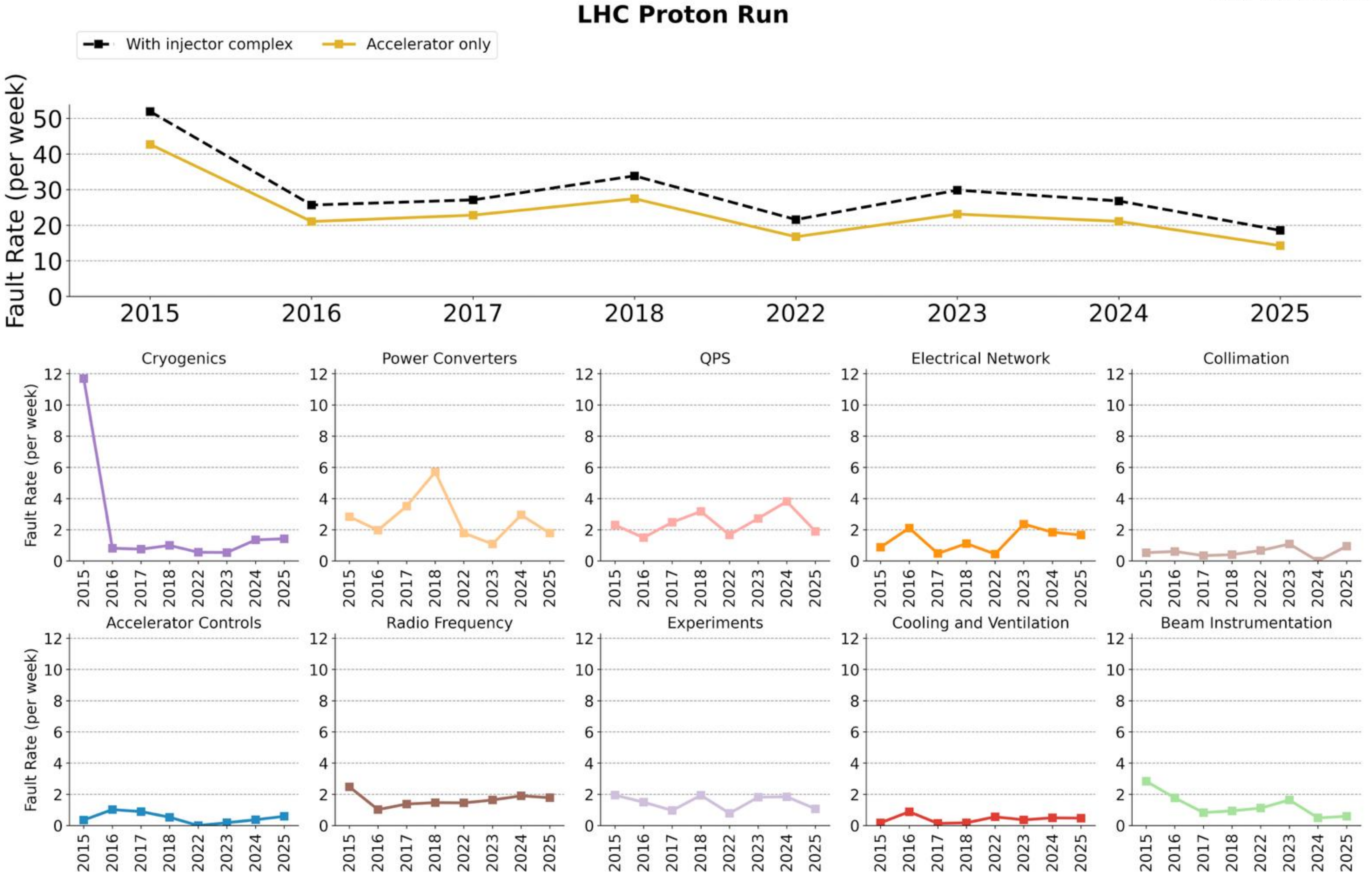
Description & Root Cause	Due to electrical network glitch, the **quench heaters of a few LHC magnets correctly triggered**, including the ones of the IT.L8. As expected, the pressure inside the cold masses increased up to 18 bars but **provoked a leak in an edge-welded bellow of the Q1-Q2 interconnection**. The pressure in the vacuum vessel degraded, preventing the running of the LHC and demanding the bellow repair. It was found that a few bellow convolutions were partially blocked.				
Impact	~50 days total impact on physics runs				
Wear-Out or Aging phenomenon?	**Beam intensity related?**	**Random Hardware Failure?**	**Due to modifications or upgrades?**	**Inadequate specification?**	**Production non-conformity?**
Possibly (mechanical fatigue due to partially blocked convolutions)	No	No.	No	**Yes** (bellow guiding shell)	No
Mitigation strategy & status	IT.L8: in-situ repair & mitigation by adapting bellow protection Others: none until LS3 (would need complete warm-up for mechanical repair)				
Outlook	**Similar events possible** on triplets and mainly in Q1-Q2 interconnection until LS3. Inspection not possible without warm-up, which would pose a significant risk due to a thermal cycle of irradiated triplets. Consolidation of IP2 and IP8 proposed in LS3 (IP1 and IP5 replaced by HL upgrade).				



damaged bellow in IT.L8

repaired interconnect

Knocked us out for 50 days – could have easily been longer


LHC Proton Run
With injector complex
Accelerator only
Fault Rate (per week)
Cryogenics
Power Converters
QPS
Electrical Network
Collimation
Accelerator Controls
Radio Frequency
Experiments
Cooling and Ventilation
Beam Instrumentation
2015
2016
2017
2018
2022
2023
2024
2025

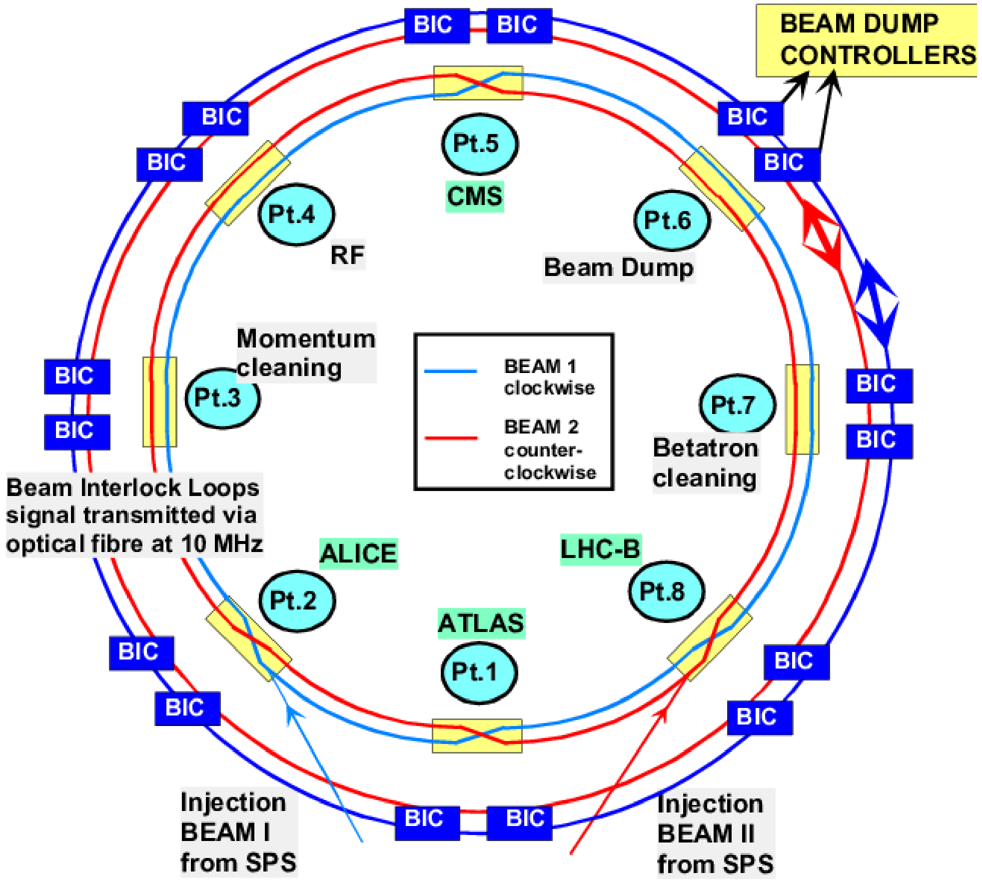
Operational Risk

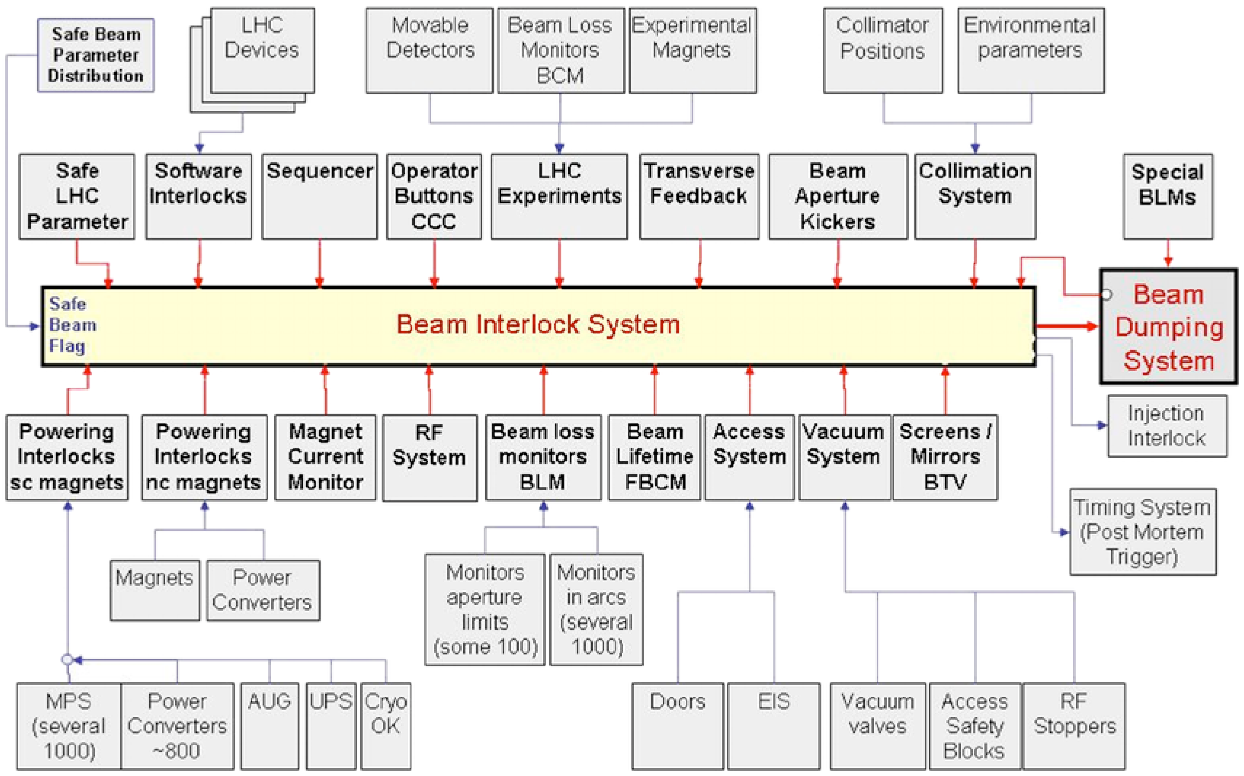
Complexity at Scale:

- Thousands of interconnected components (RF, cryogenics, vacuum, power, magnets, beam instrumentation…)
- Handling tight coupling of complex systems with clear and present danger
- LHC = >400 MJ stored energy in beams + >10 GJ in magnets

Layered Protection:

- Strong **machine protection architecture** (beam interlocks, hardware & software permits)
- **SIL-rated systems** (e.g. Beam Dump System – SIL 3 equivalent)
- Extensive **fault detection**
- **Post operation checks after every execution – good as new**
  - **IPOC – internal operation check – how did the system behave?**
  - **XPOC – external operation check – how did the beam behave?**





Beam Interlock System

Beam dump system – point 6

Video 2’10”

Operational Risk

Incident Response & Learning:

- Formal **post-mortem reviews**
- Systematic logging and diagnostics
- Operational procedures evolve (fast) from real experience
- Fault tracking helps drives targeted improvement and consolidation

Machine Protection Panels (MPP & restricted MPP):

- Cross-domain expert oversight
- Review changes, new features
- Oversees systematic requalification, intensity ramp-up after stops etc.
- Acts as institutional memory and guardians

What like a beam can undeceive?

Organisational Robustness and Risk Culture

Well-Structured Operational Roles:

- 24/7 CCC operation, with clear handovers and system expert on-call coverage
- Run Coordinators, technical coordination, expert teams embedded in daily operations

Integrated Risk Governance:

- Operations coordination groups (e.g. LMC, CCC daily meetings)
- Sector readiness reviews (e.g. LS3, annual cold-checkouts, machine tests)

Cross-Disciplinary Safety Awareness:

- Strong personnel safety culture, reinforced by access rules, radiation protection, training
- Common understanding of “what can go wrong”

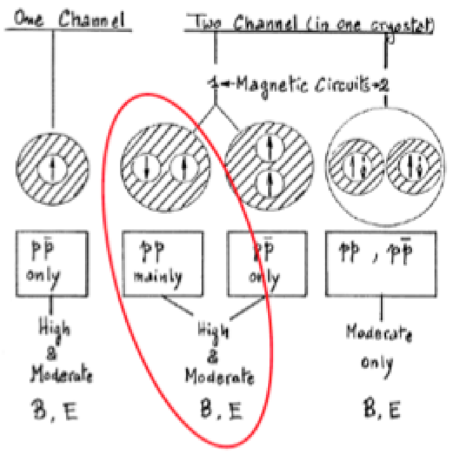
“Operational Humility”:

- Dry runs, phased intensity increases, checklists

Plus a lot of dedication, commitment, and expertise

And some things that
should not have been
forgotten were lost.
History became legend,
legend became myth.

Conception

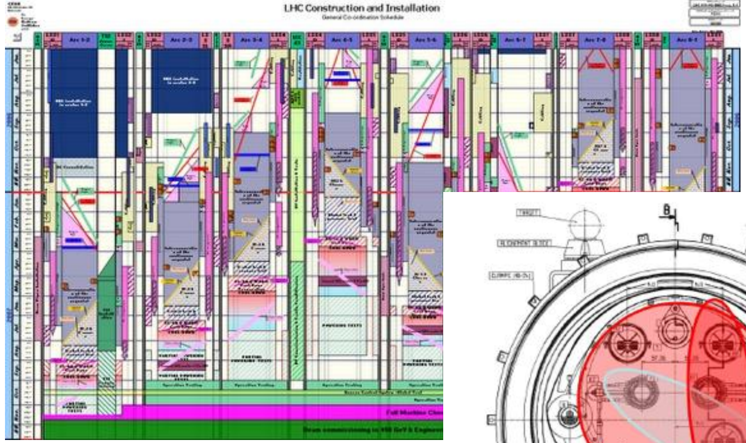


Initiation

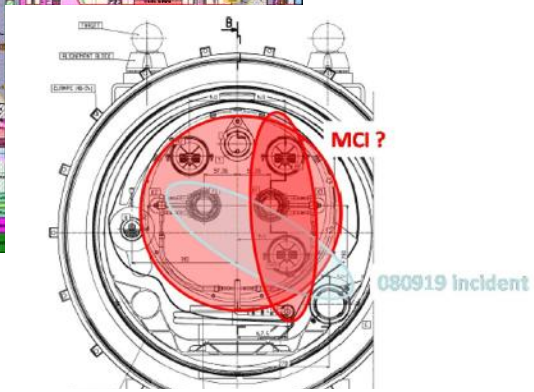
LHC approved by the Elders

Rival stumbles

SSC cancelled



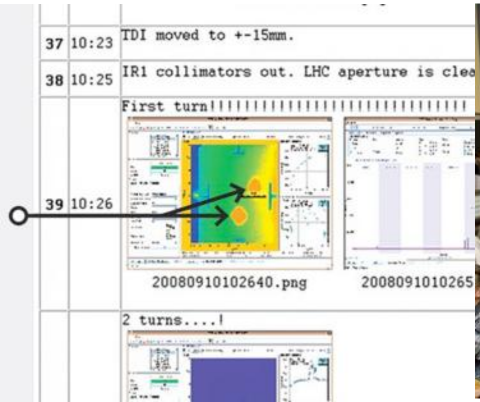
Birth – overdue



Withdrawal from community for mediation and preparation

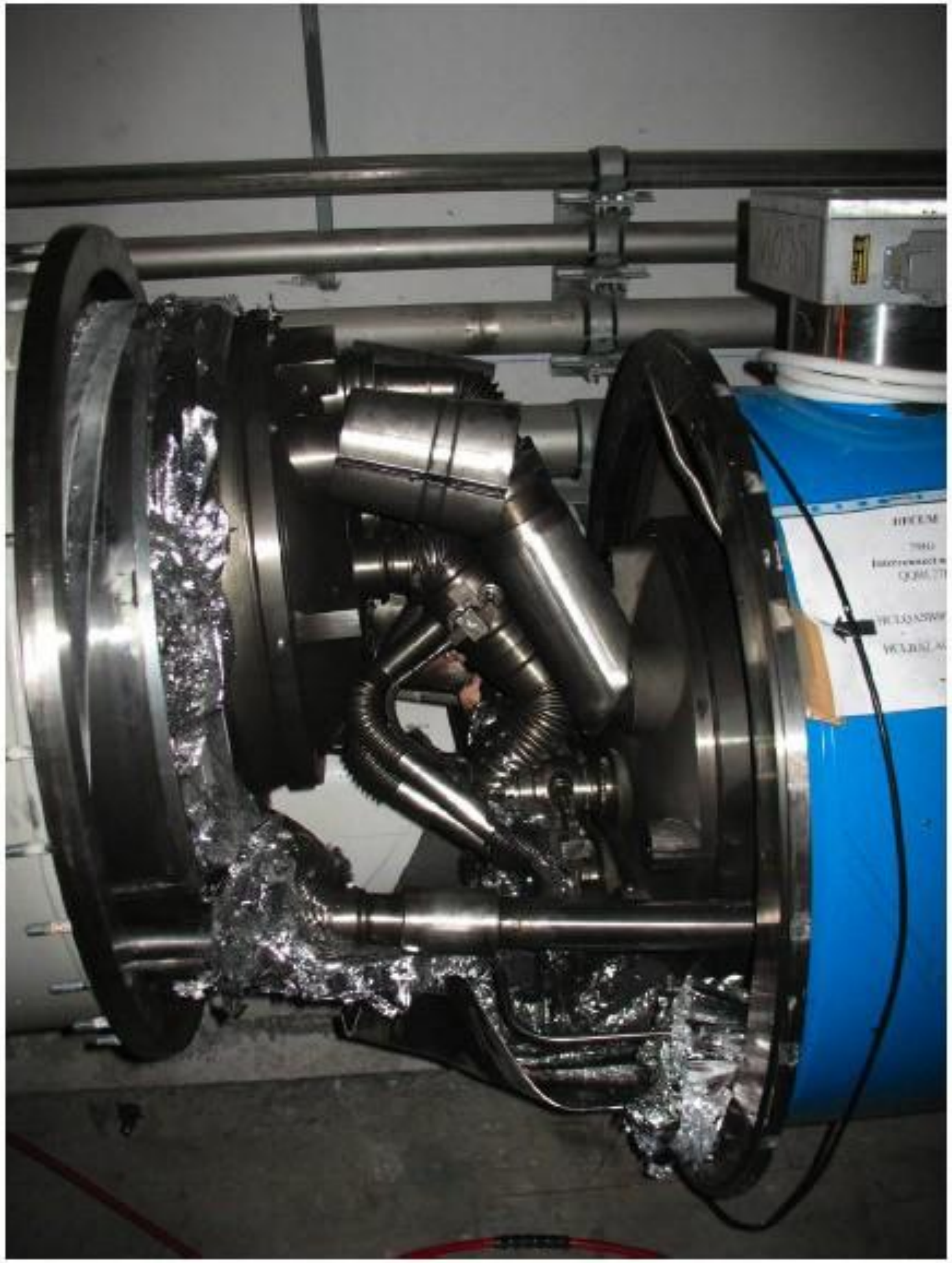
1984 // 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10

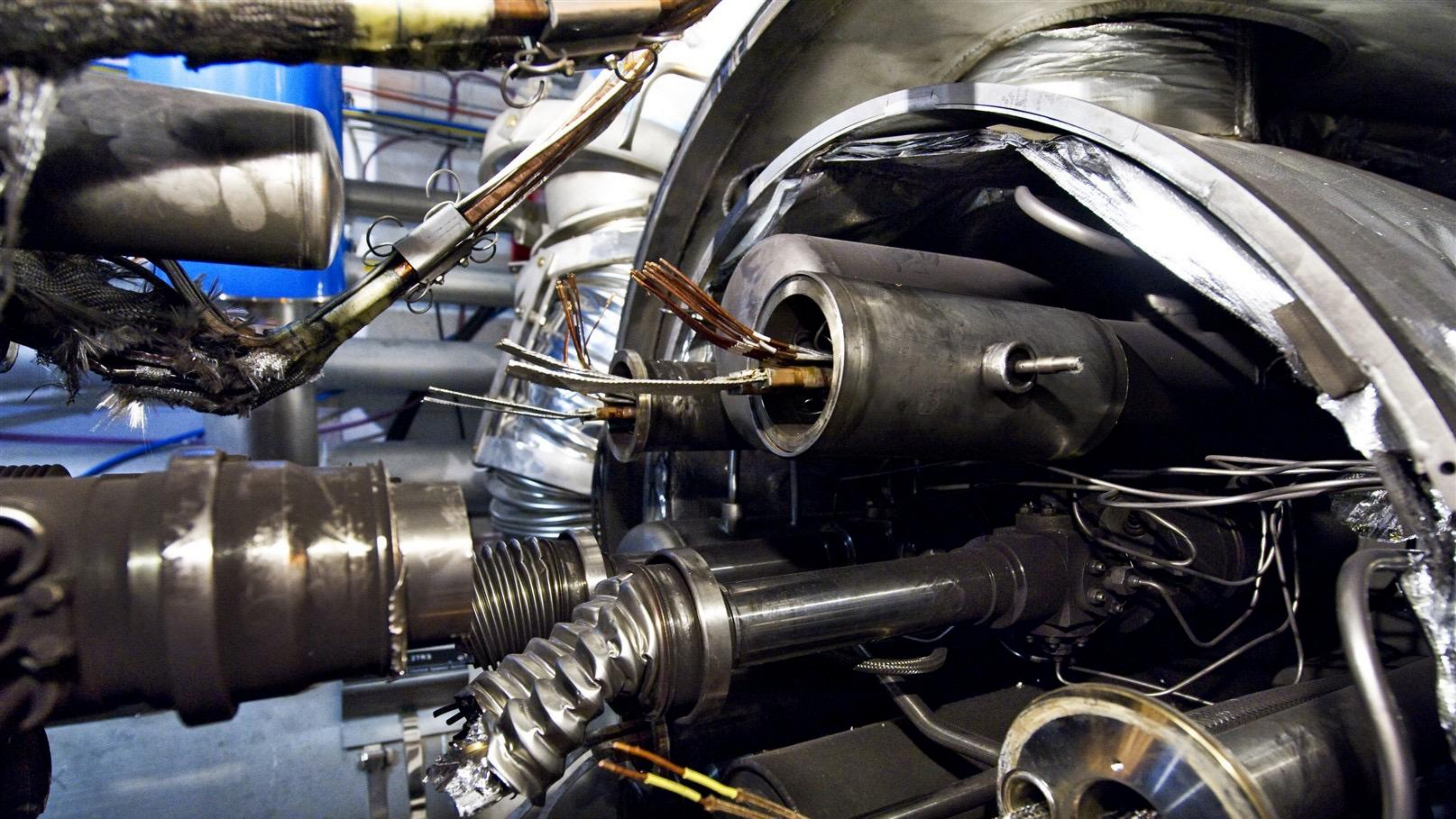
Hubris (?) September 10, 2008

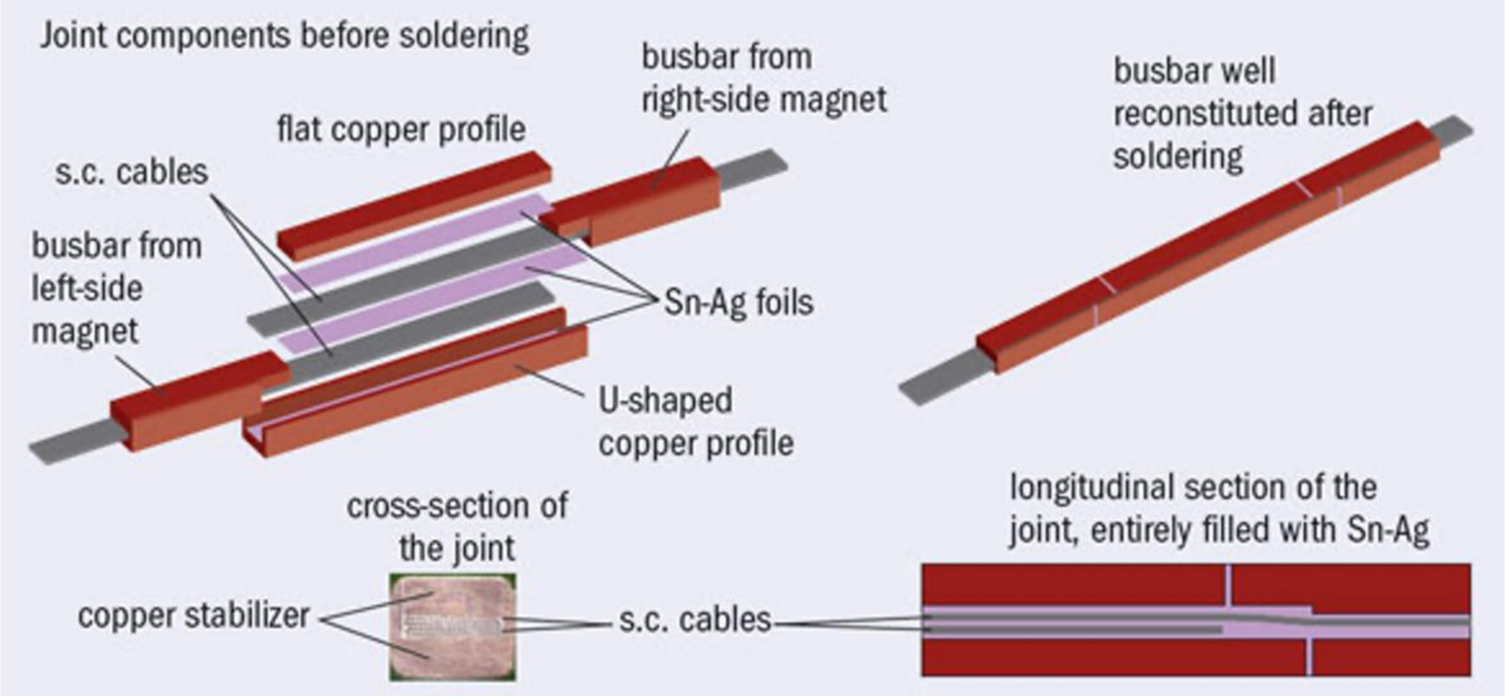


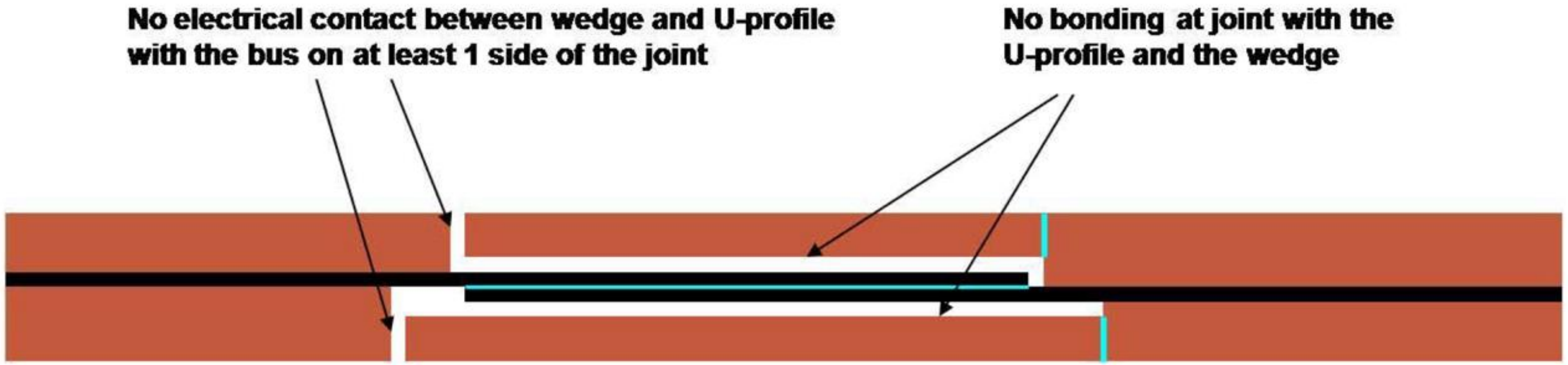
Nemesis September 19, 2008

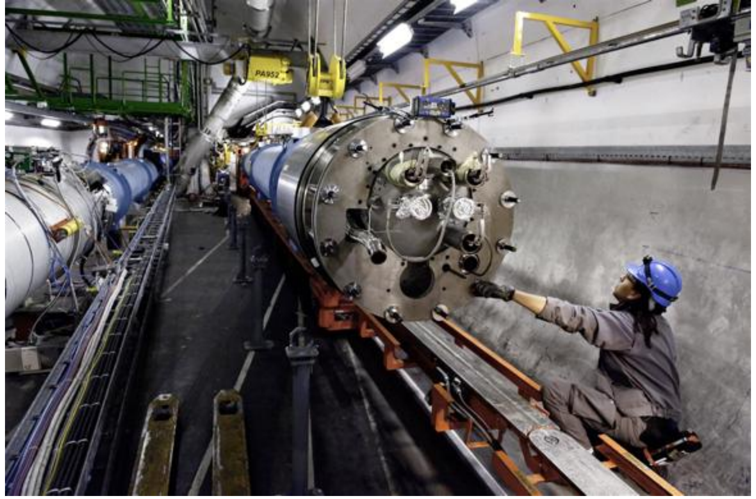
LHC



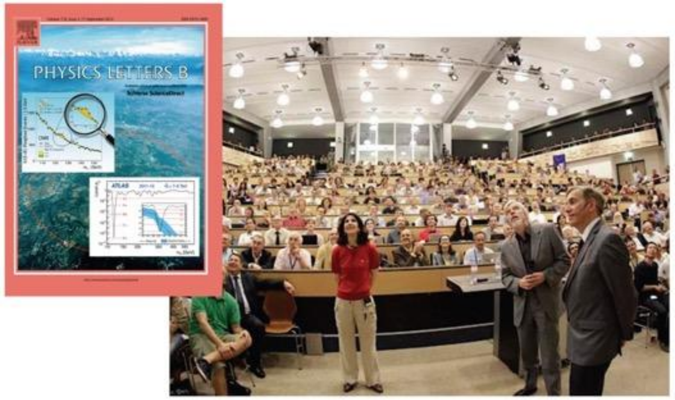

Joint components before soldering
busbar from
right-side magnet
flat copper profile
s.c. cables
busbar from
left-side
magnet
Sn-Ag foils
U-shaped
copper profile
busbar well
reconstituted after
soldering
cross-section of
the joint
copper stabilizer
s.c. cables
longitudinal section of the
joint, entirely filled with Sn-Ag


No electrical contact between wedge and U-profile
with the bus on at least 1 side of the joint
No bonding at joint with the
U-profile and the wedge



Trial/descent in the underworld

Apotheosis and atonement



4 July, 2012

November 29, 2009

Resurrection and rebirth

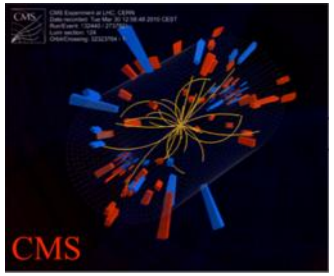
2009 | 2010 | 2011 | 2012 | 2013

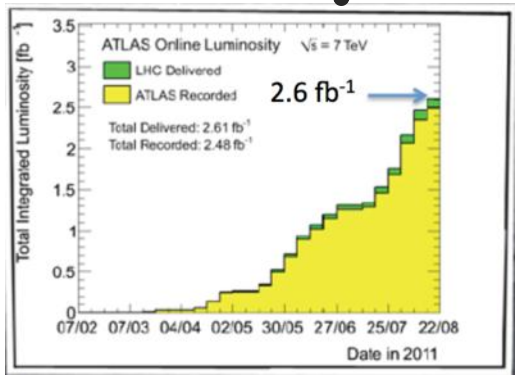
Ascension

Heroic subplot

March 30, 2010

First collisions at 3.5 TeV

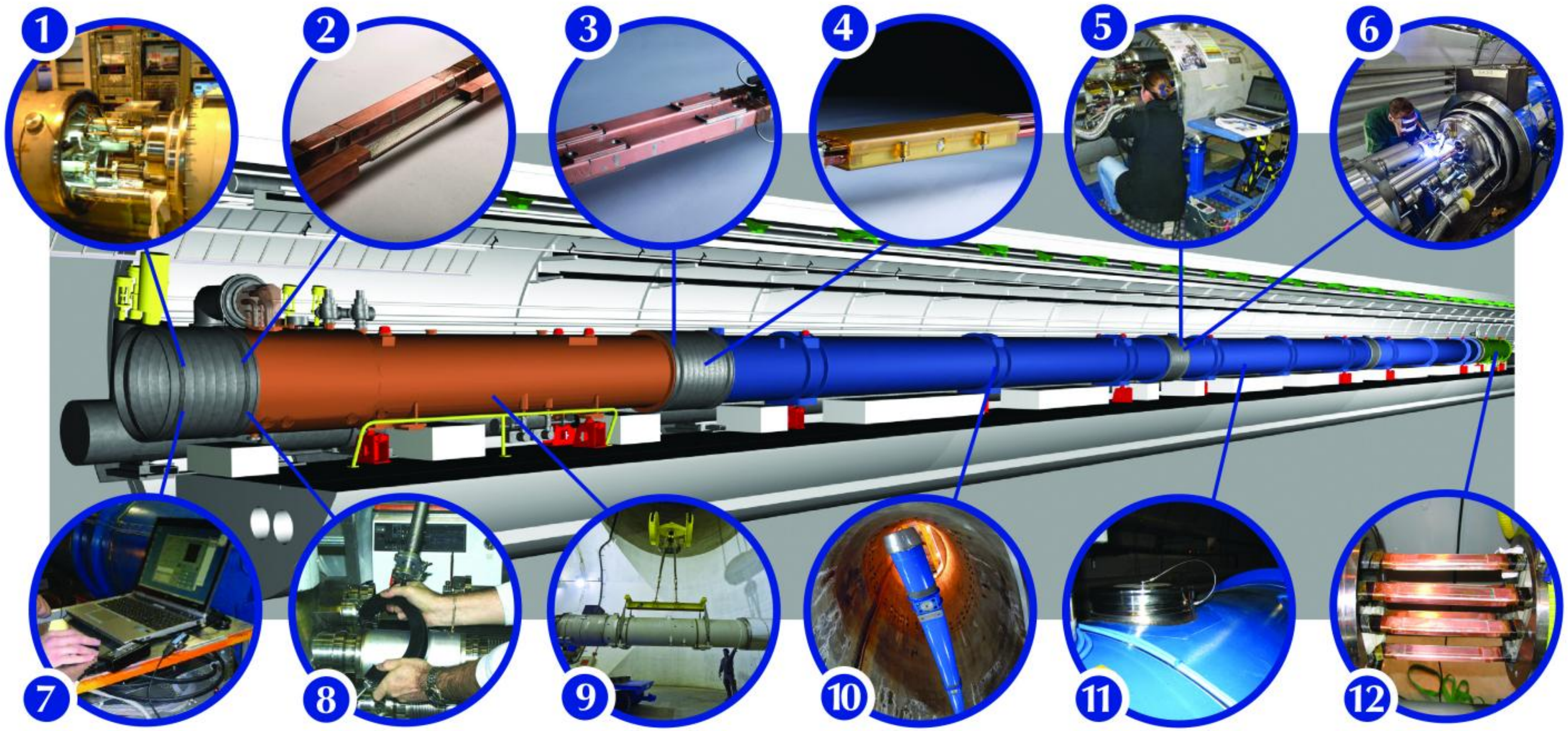




(Pb ion run)

The main 2013-14 LHC consolidations

1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 3000 of these splices
3. Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines



7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 3 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

Lesson: Quality control is vital during production and installation!

Knowledge is hard-won and easily lost

Outline

Basic Mechanical Engineering

Design

Mechanics and Structures 1 and 2
Engineering Materials
Steels 1
Non-Ferrous Materials
Steels 2
Design for Additive Manufacturing
Plastics and Composite Materials
Computational Tools 1 and 2
Fabrication Summary

Fabrication

Additive Manufacturing
Welding 1
Vacuum Brazing
Welding 2
Surface Treatments and Coatings
Forming

Testing

Physical Properties and Testing
NDT
Mechanical Testing
Mechanical Measurements
Introduction to Metrology
Measurement Uncertainty
Alignment and Metrology

Detectors & Accelerators

Standards and Safety
Intro to Design for Accelerators
Technology Highlights of High Energy
Accelerator Projects
Colliders
Beam Instrumentation
Beam Intercepting Devices
Cryostats and Cryomodules
Digital Twins for Accelerators and Detectors
Vacuum Systems for Accelerators
Undulators

Hands-On

Design
Materials and NDT
Mechanical Measurements
Metrology
Fabrication

Magnets

NC Magnets
SC Magnets

RF

RF Applications
RF Power and Couplers
Detector Magnets and Structures

Beyond HEP

Mechanics of Golf
Einstein Telescope
VDL
Differ
IBS
Sioux
Large Structures for Fusion Technology
Sustainable and Affordable Design

CAS on Mechanical Engineering:
https://indico.cern.ch/event/1326947/

"Mini-CAS" on Mech. Engg. (video lectures):
https://indico.cern.ch/event/958382/

Culture

CERN - mission driven – demands and passions and commitment is high

It all has to work, system issues can be very visible! But it's not a blame culture.

When stuff does go wrong, strong communal response.

Talent pipeline is encouraging with quiet revolution in tools, code etc. over the last decade

Work together - enjoy a relaxed open, collegiate, meritocracy based culture – interesting cultural variations!

Meeting culture, communications

- morning operations meetings – open to all
- high level committees – low on ceremony

Celebrate together! Share the prizes.


A
A

Closing remarks

Interesting position in engineering space

Permission to innovate (tacitly at least!) – no competitors

Have to develop well working prototypes into real, working systems. This is motivating! And occasionally terrifying.

In house systems engineering approach…

Some elements are required:

- Imagination/vision/passion
- A willingness to pool ideas and resources
- Openness to the requirements of others
- Multi-generational highly skilled engineers -
- Organisation, tenacity, patience

Time and resources ultimately pay off

"So yes… we do beam them up. But only because of the systems, **and the people**, that keep it safe."


ATLAS
EXPERIMENT