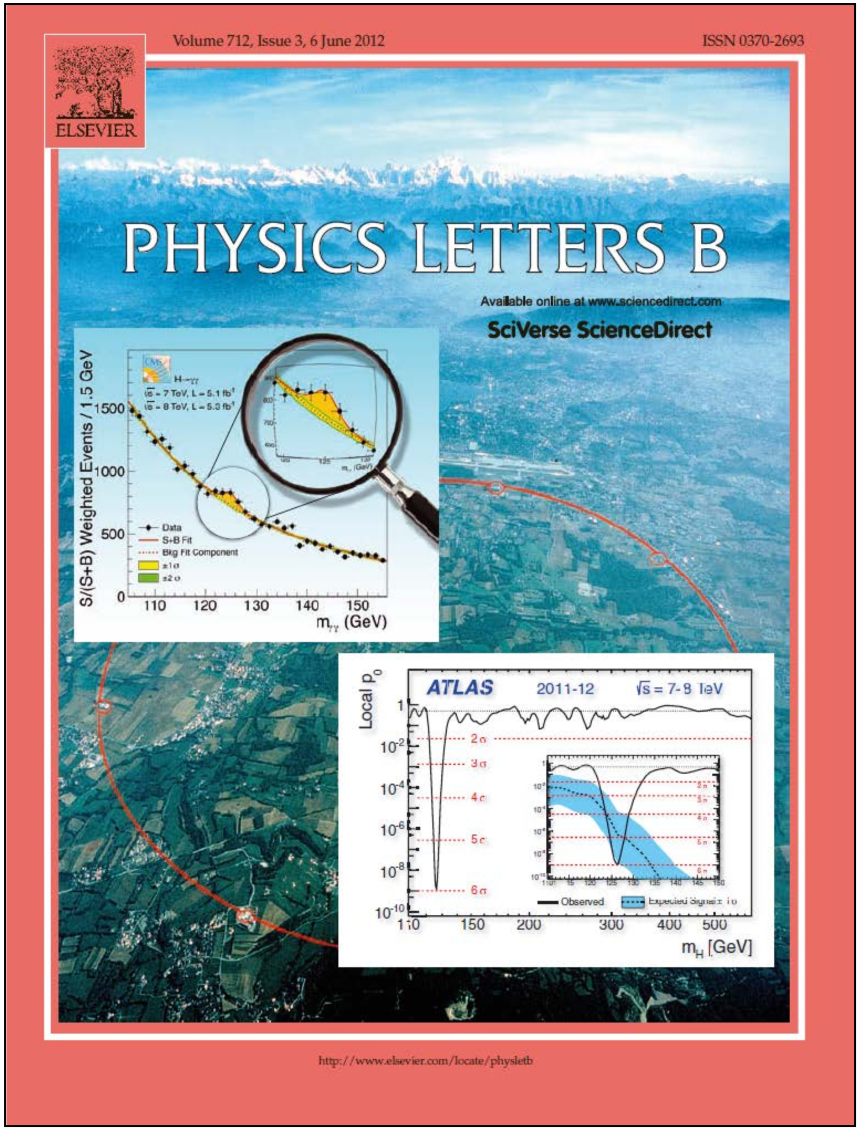
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2013
Invited presentation 1EPl A1 given at CEC/ICMC 2013

Cryogenics for the Large Hadron Collider (LHC): from construction to operation and future upgrades

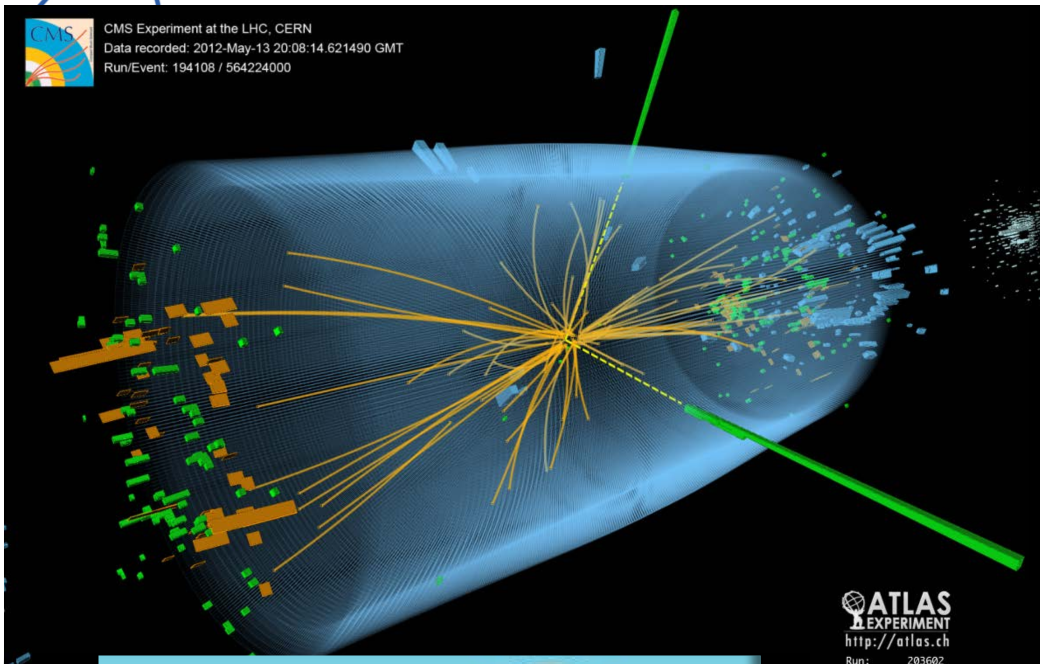
Philippe Lebrun
CERN, Geneva, Switzerland

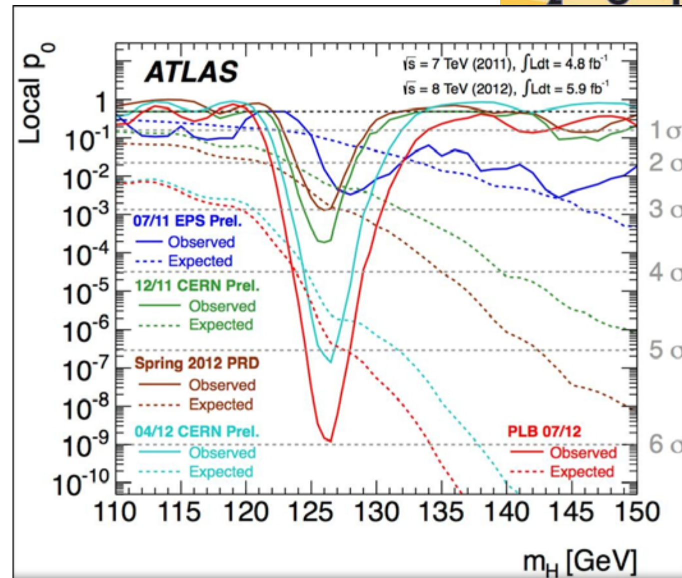
Cryogenic Engineering Conference / International Cryogenic Materials Conference
Anchorage, Alaska, 17-21 June 2013

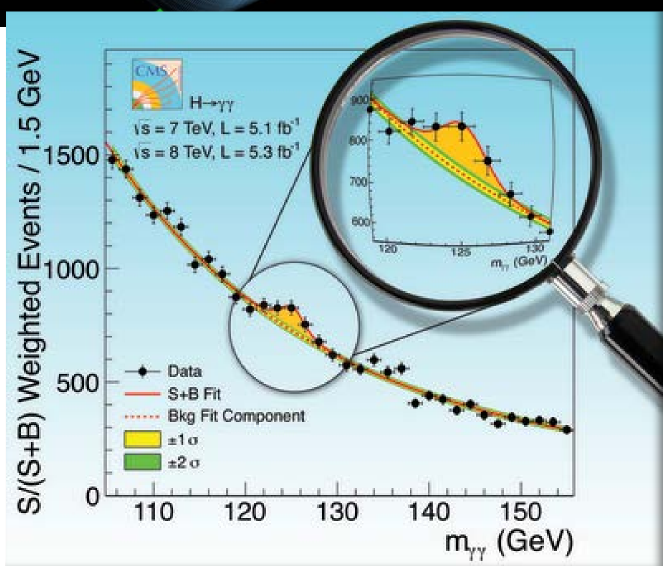
2012, a remarkable year for physics

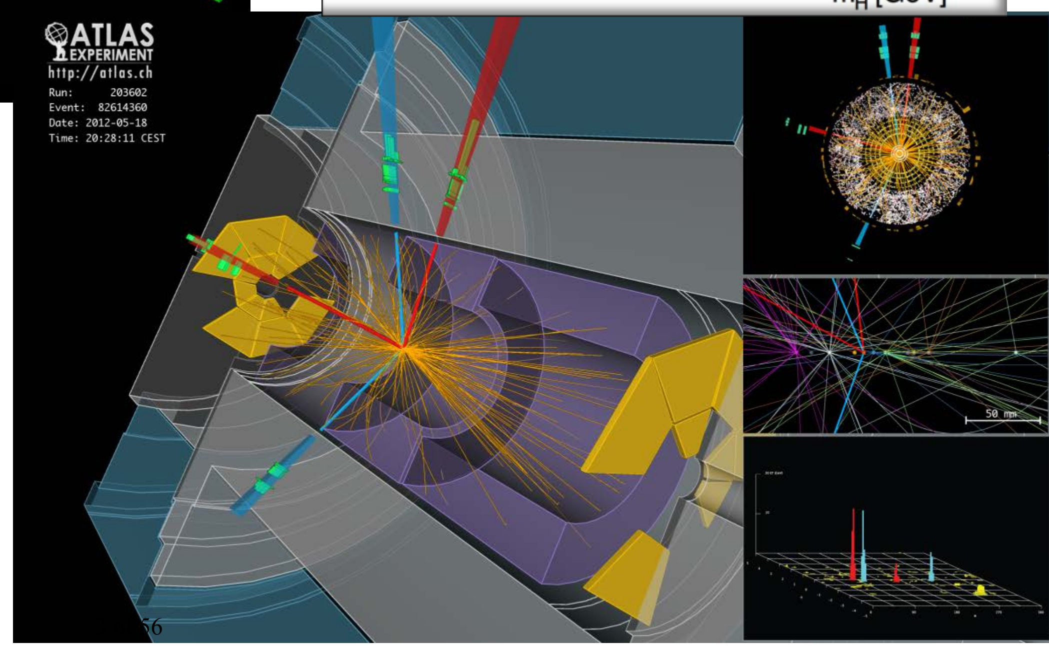


"CERN experiments observe particle consistent with long-sought Higgs boson"



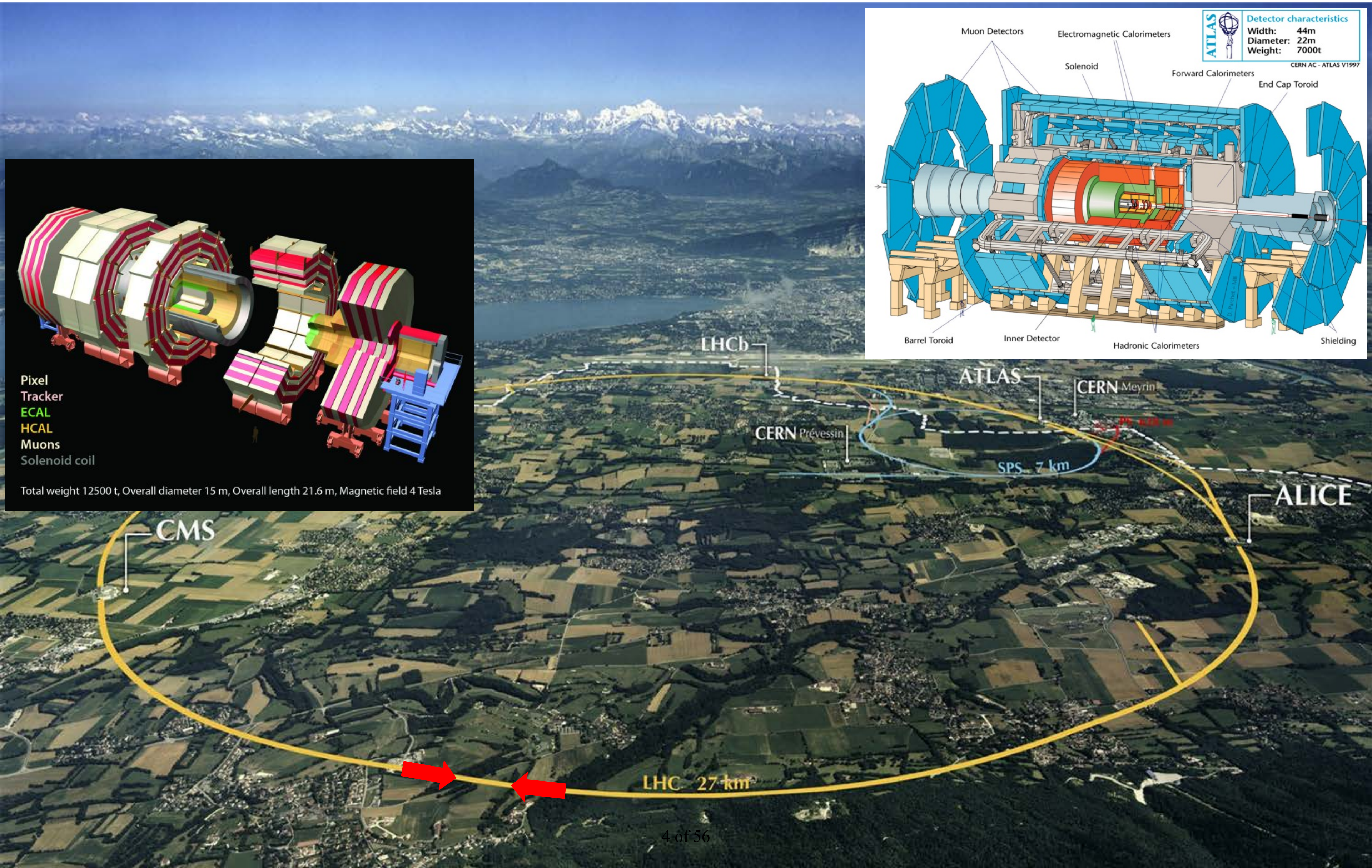






The largest scientific instrument in the world…

27 km in circumference

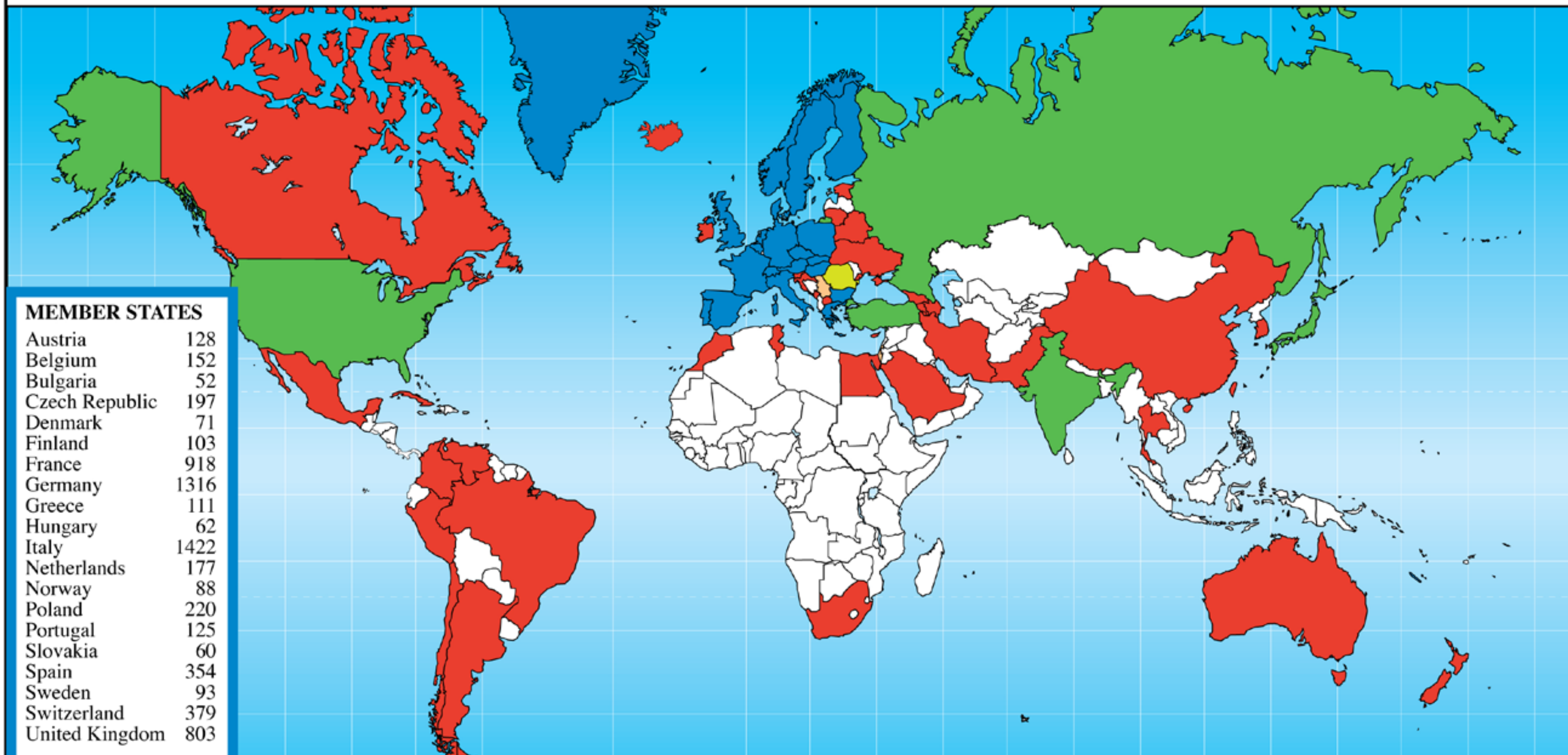


…serving the community of particle physicists

11’000 users from around the world

CEC / ICMC ANCHORAGE 2013

Distribution of All CERN Users by Location of Institute on 14 January 2013



MEMBER STATES

Austria	128
Belgium	152
Bulgaria	52
Czech Republic	197
Denmark	71
Finland	103
France	918
Germany	1316
Greece	111
Hungary	62
Italy	1422
Netherlands	177
Norway	88
Poland	220
Portugal	125
Slovakia	60
Spain	354
Sweden	93
Switzerland	379
United Kingdom	803

6831

OBSERVERS

India	146
Japan	238
Russia	883
Turkey	94
USA	1757

3118

CANDIDATE FOR ACCESSION

Romania	88

ASSOCIATE MEMBER IN THE PRE-STAGE TO MEMBERSHIP

Israel	63
Serbia	31

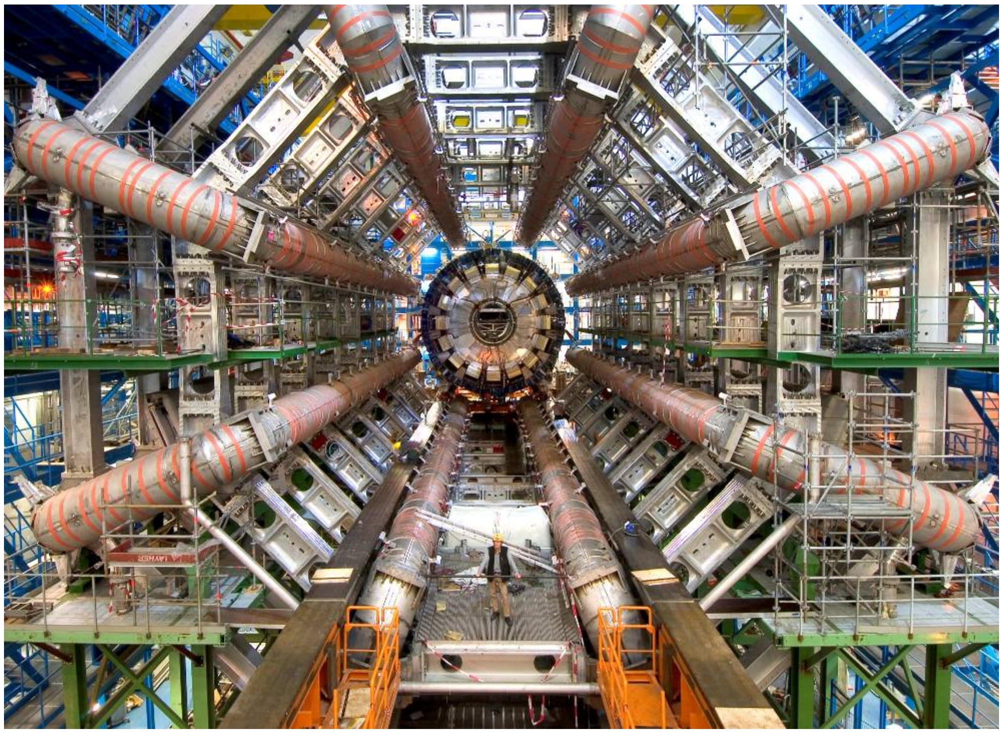
OTHERS

Argentina	19
Armenia	15
Australia	32
Azerbaijan	2
Belarus	22
Brazil	107
Canada	168
Chile	7
China	114
China (Taipei)	69
Colombia	10
Croatia	24
Cuba	3
Cyprus	7
Egypt	11
Estonia	17
Georgia	10
Iceland	4
Iran	23
Ireland	8
Korea	96
Lithuania	13
Malta	1
Mexico	41
Montenegro	1
Morocco	10
New Zealand	9
Pakistan	22
Peru	2
Saudi Arabia	3
Slovenia	30
South Africa	25
Thailand	5
T.F.Y.R.O.M.	2
Tunisia	1
Ukraine	25
Venezuela	1

959

The superconducting magnets of ATLAS

Barrel toroid
8 coils 25 m x 5 m
Magnetic field 1 T
Stored energy 1.1 GJ



End toroid
Diameter 11 m
Magnetic field 1 T
Stored energy 0.5 GJ

Central solenoid
Diameter 2.5 m
Magnetic field 2 T
Stored energy 39 MJ

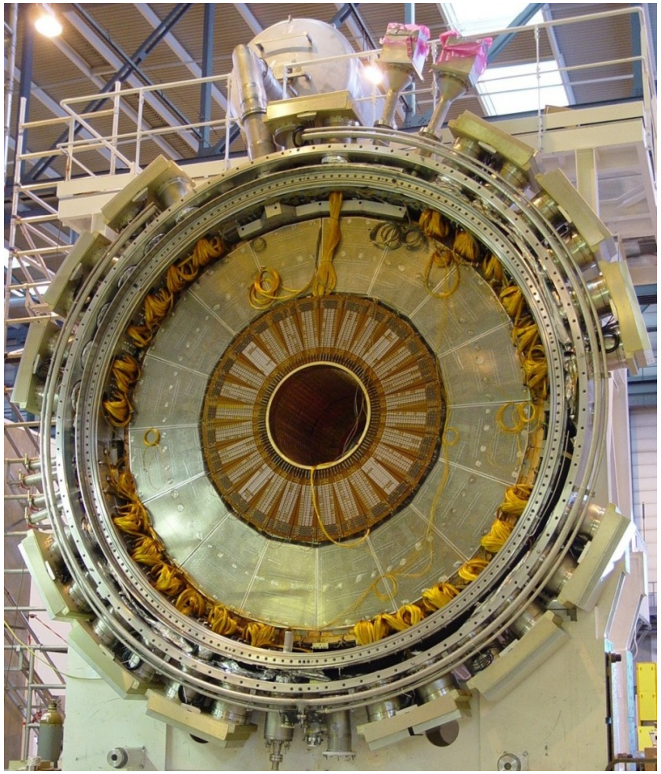
The liquid argon calorimeters of ATLAS

Barrel

120 t mass, 40 m^3 liquid argon

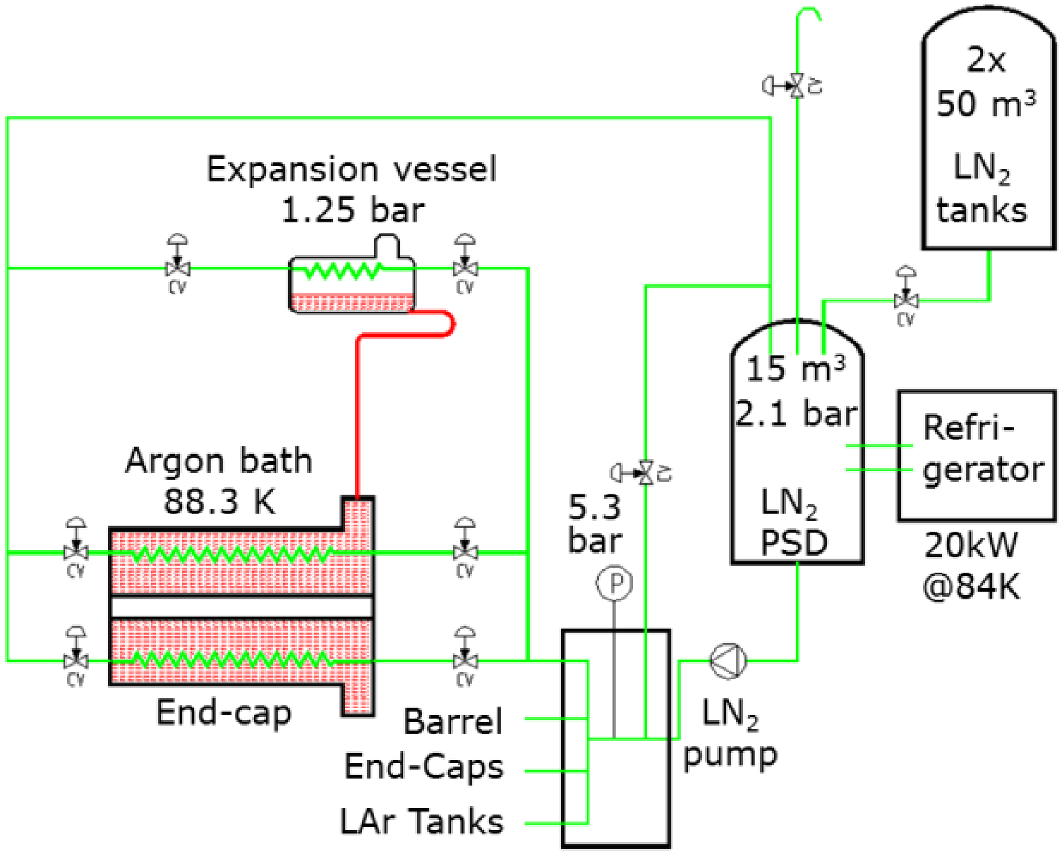
End cap

220 t mass, 19 m^3 liquid argon



C. Fabre

Cryogenics for ATLAS argon calorimeters



Temperature uniformity < 0.3 K

Temperature stability < 0.02 K

Argon purity between 0.1 and 0.3 ppm O_2 equivalent

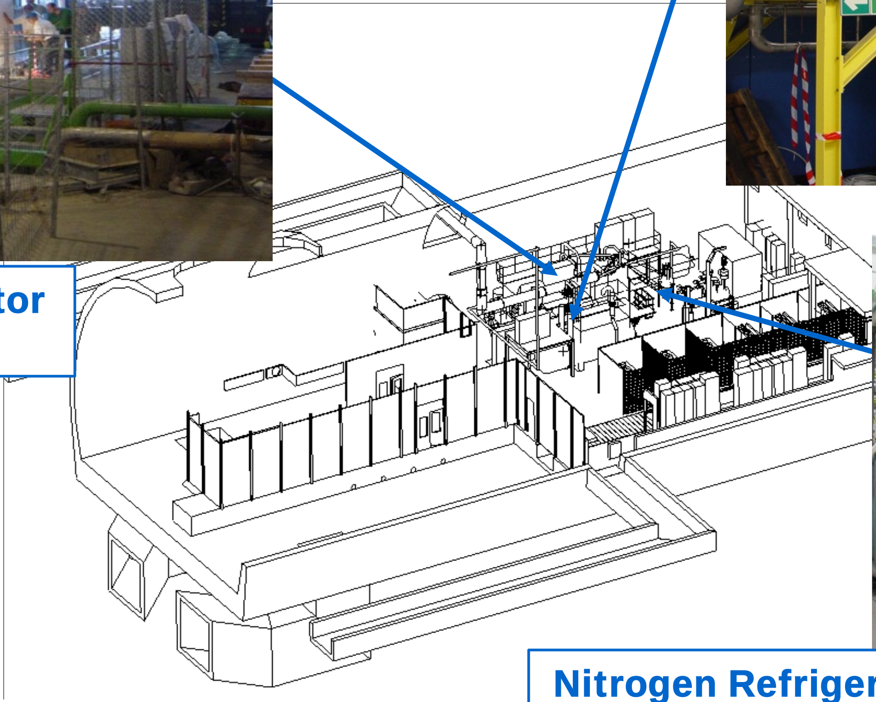
Operation 365/365

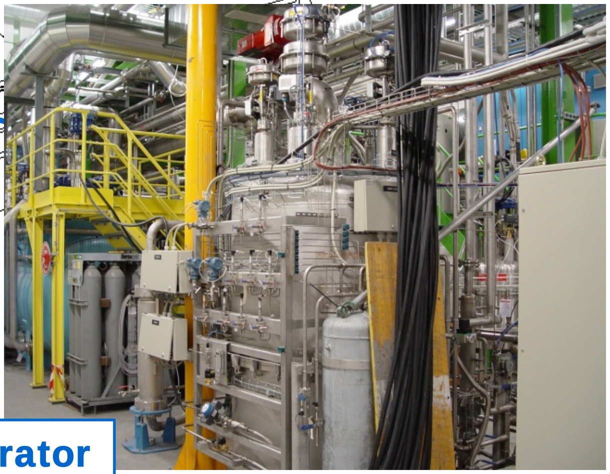
C. Fabre

ATLAS cryogenic refrigeration

He Shield Refrigerator
20 kW 40 - 80 K

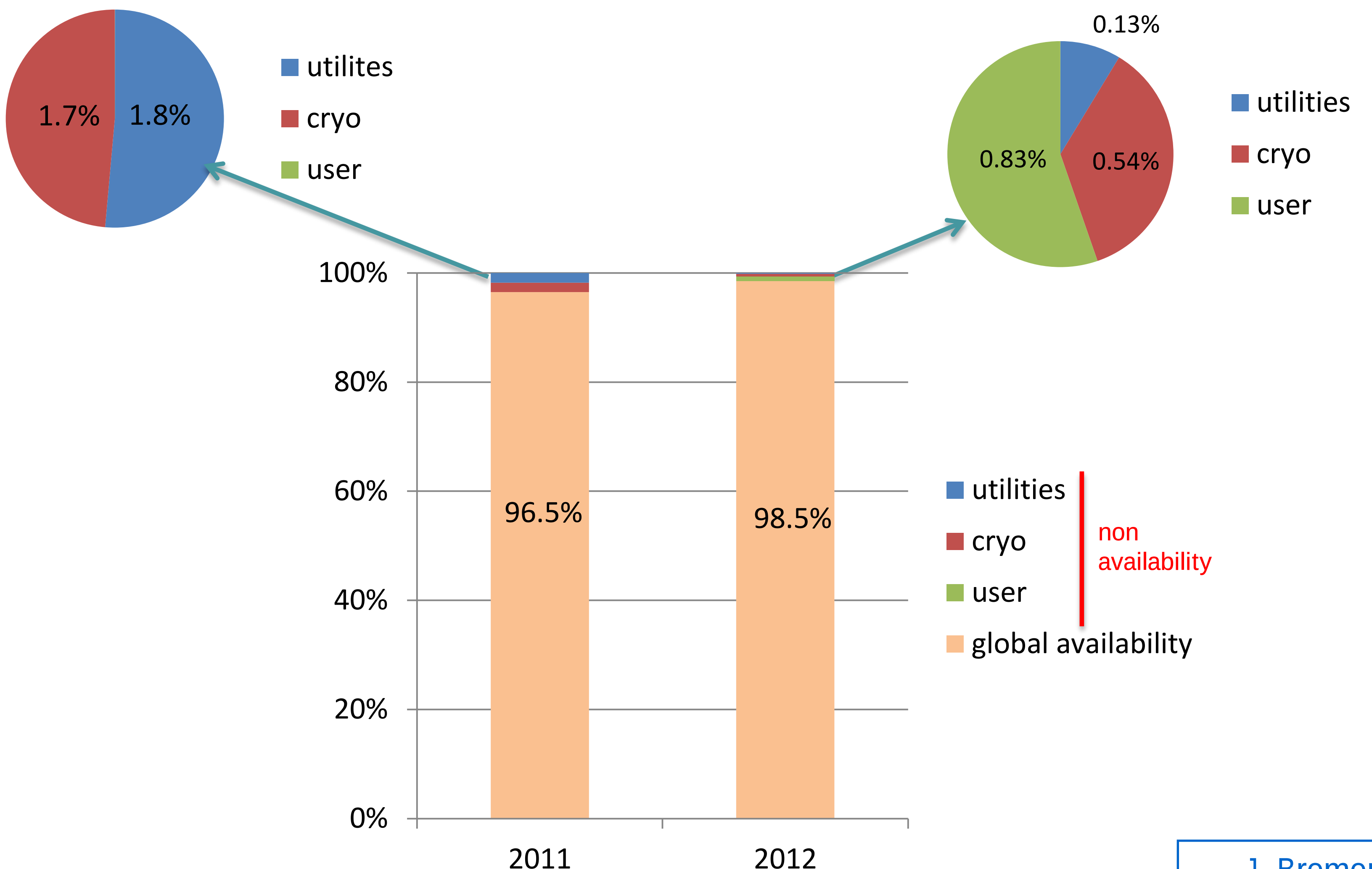
He Main Refrigerator
6 kW @ 4.5 K





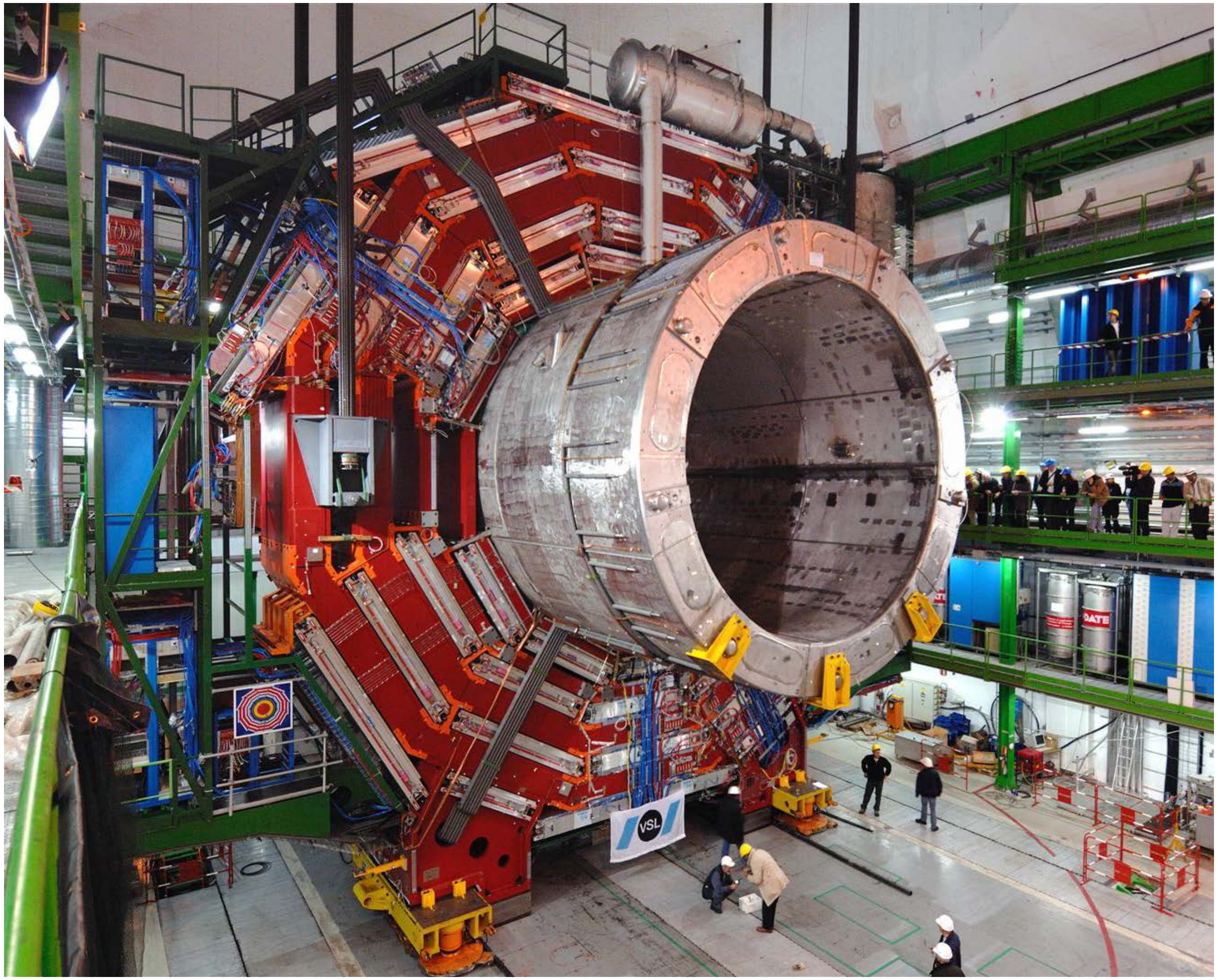
Nitrogen Refrigerator
20 kW @ 84 K

ATLAS cryogenics availability



J. Bremer

The superconducting solenoïd of CMS

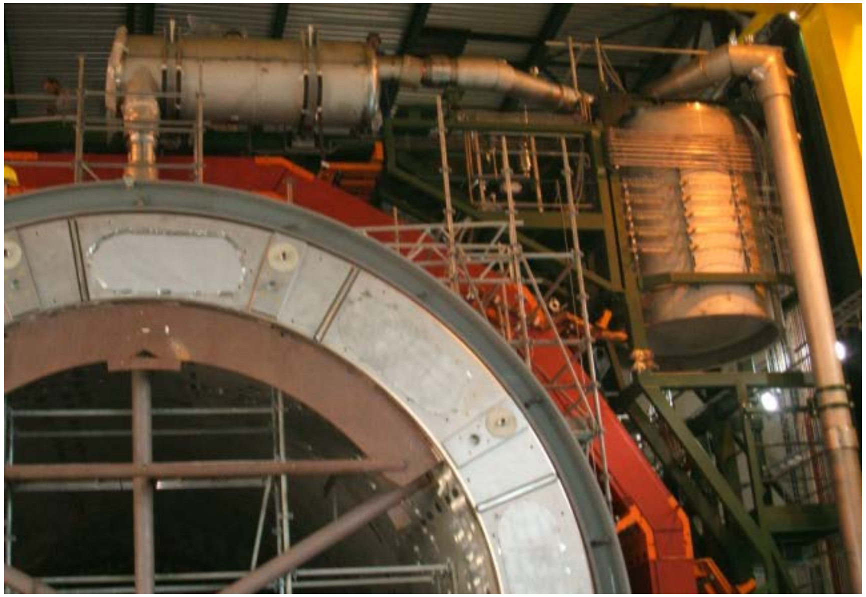


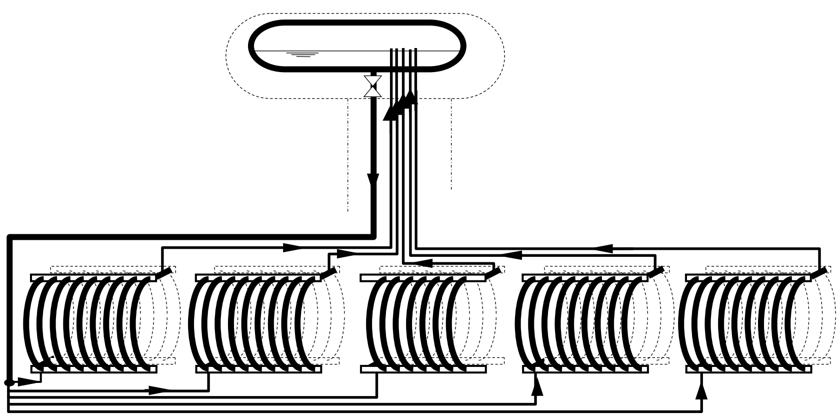
Operation temperature	4.5 K
Length	12.5 m
Diameter	6 m
Cold mass	225 t
Magnetic field	4 T
Stored energy	2.6 GJ

Indirect-cooled coil, Al stabilized

CMS cryogenics

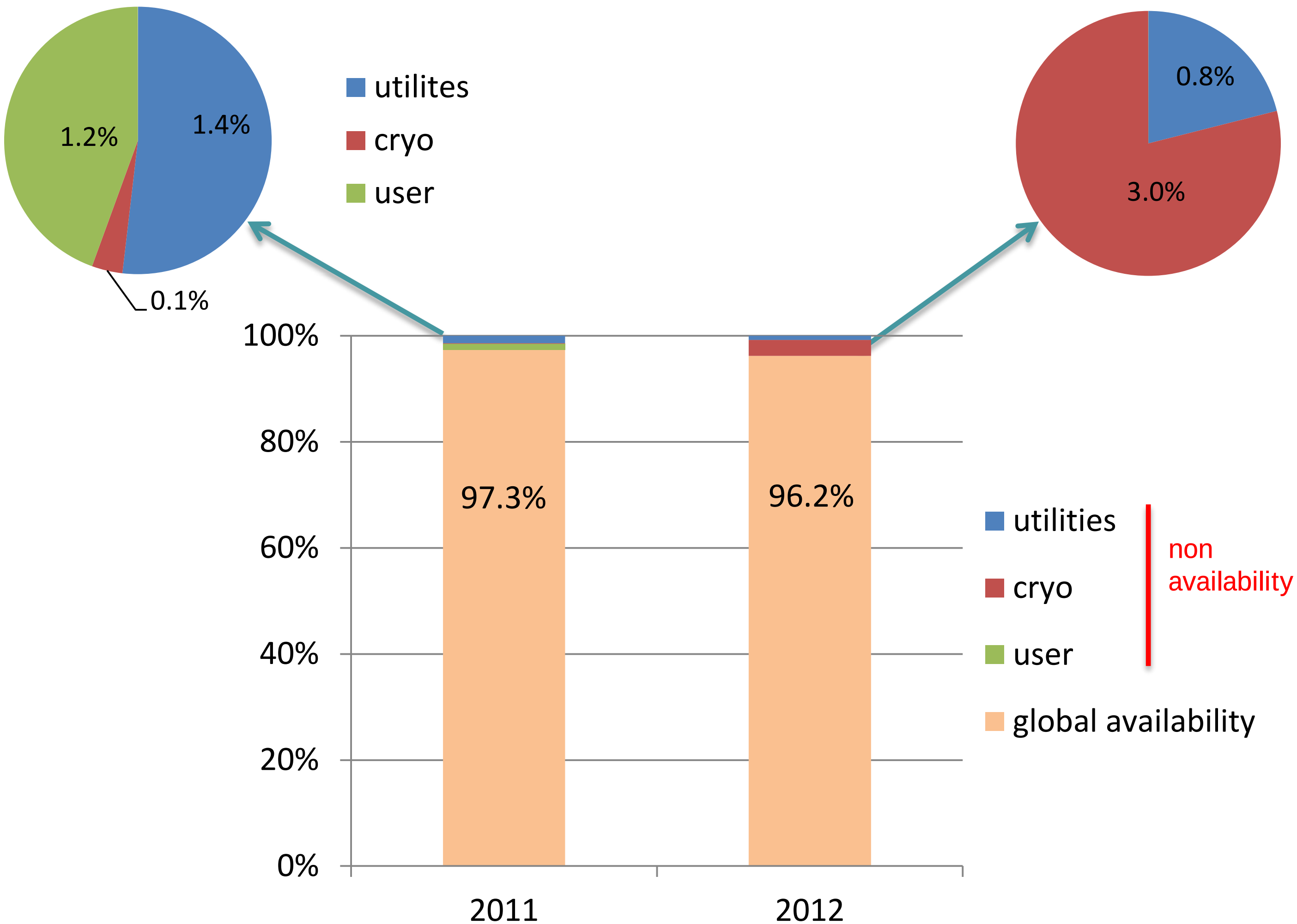
Two-phase thermosyphon cooling





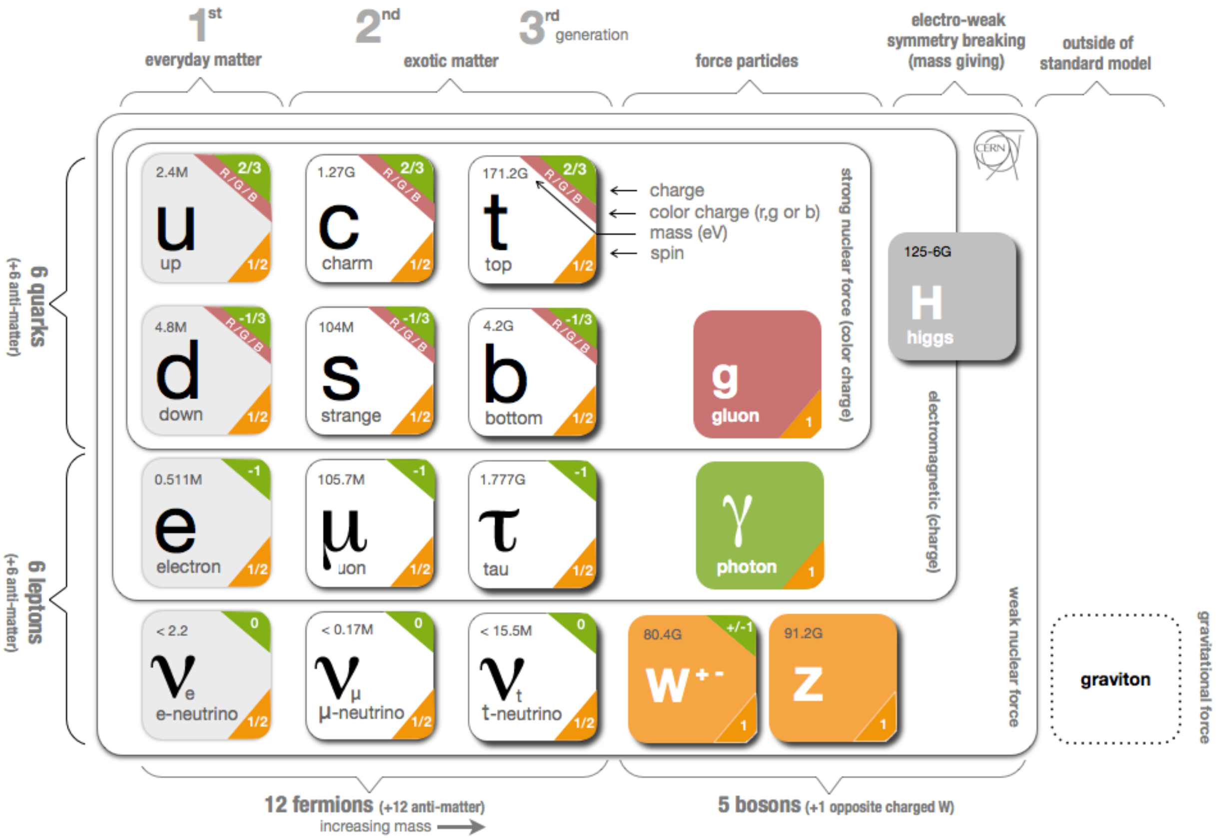
1.5 kW @ 4.5 K helium refrigerator

CMS cryogenics availability



J. Bremer

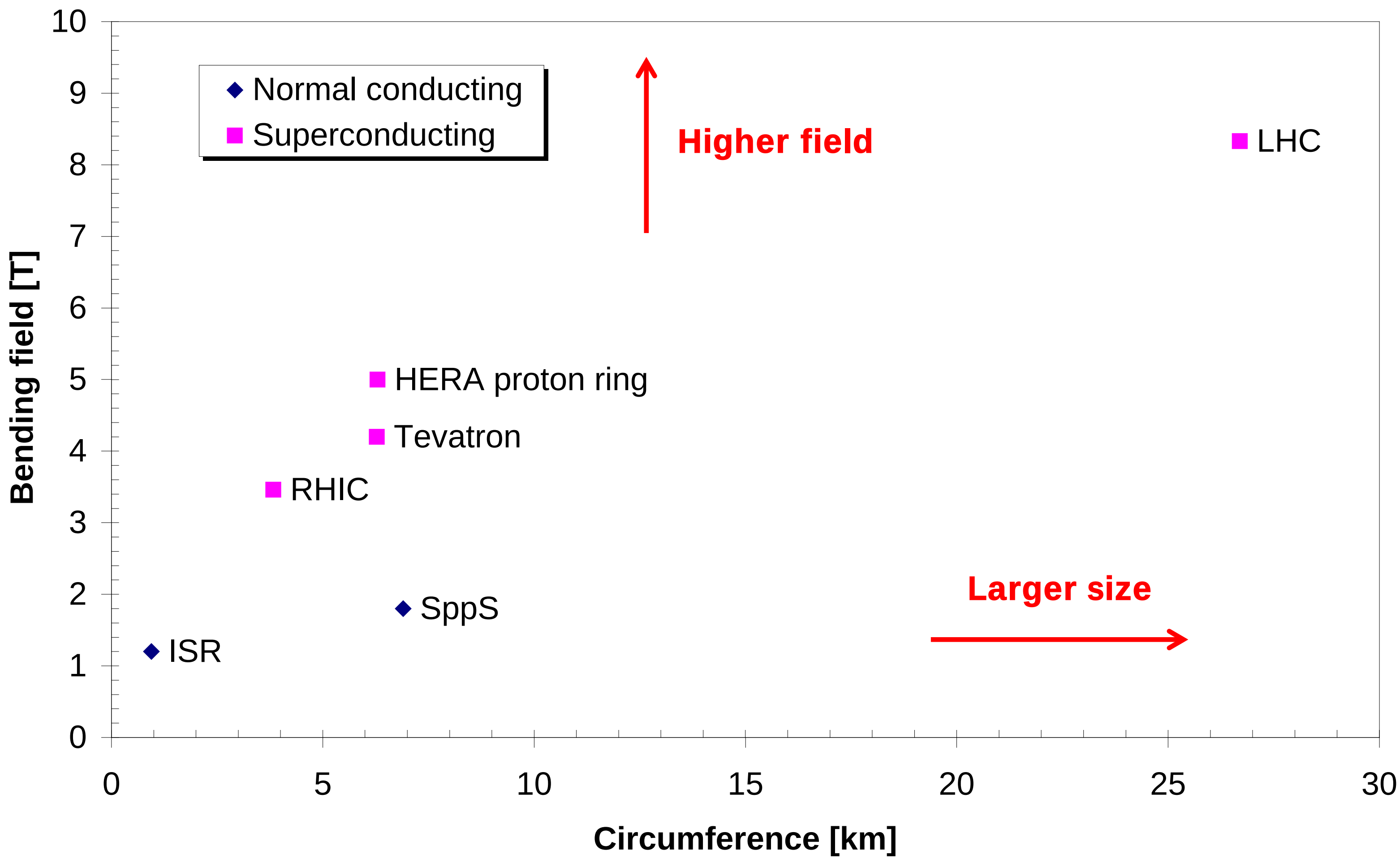
The Higgs boson completes the Standard Model ...but does not answer all questions!



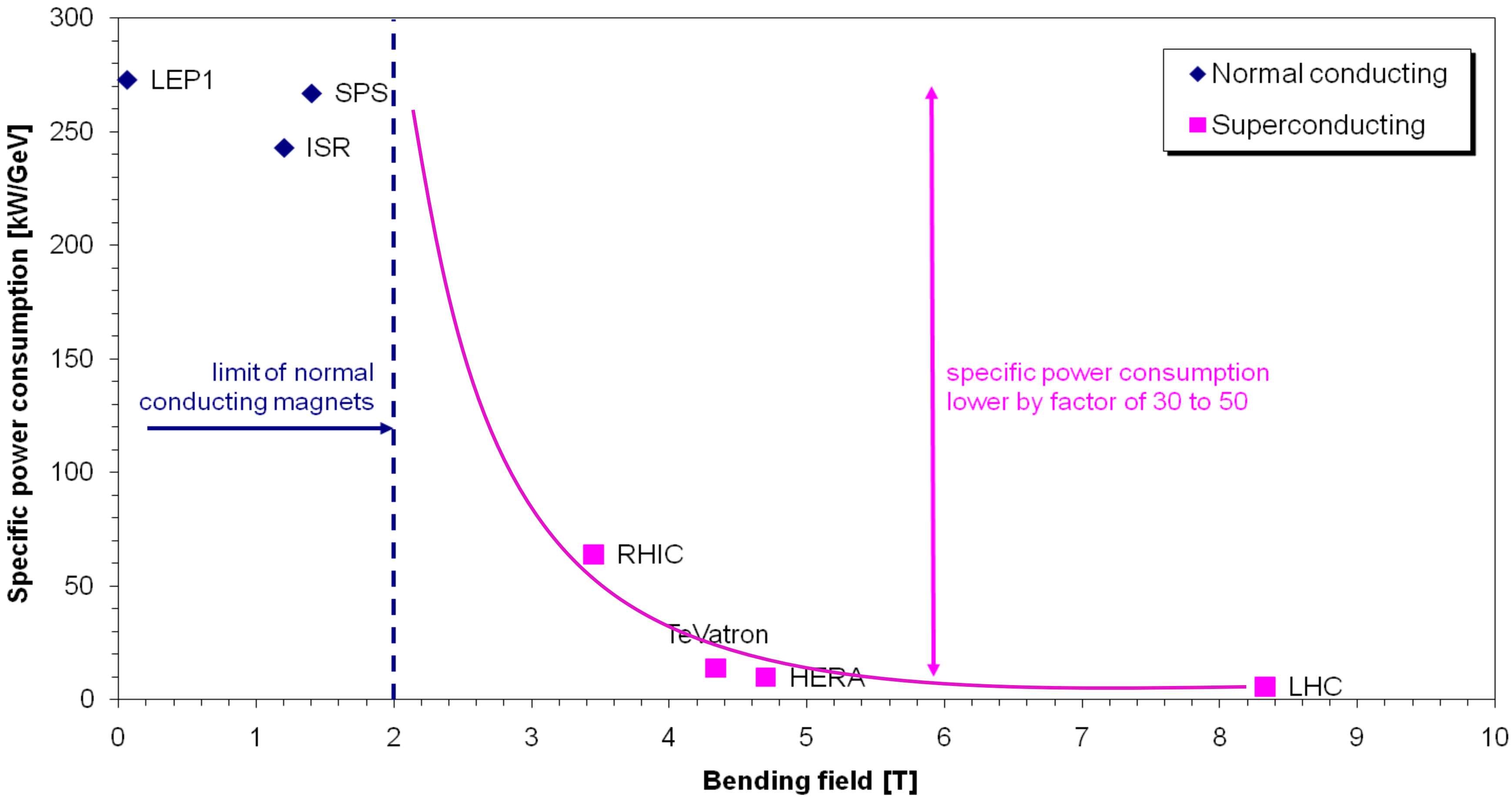
- Does this description of nature remain valid at energies >> 1 TeV?
- How should it be modified to account for unexplained phenomena (matter-antimatter asymmetry, «dark» matter in the universe, cosmological inflation, quantum gravity)?

Workhorses of discovery: hadron colliders

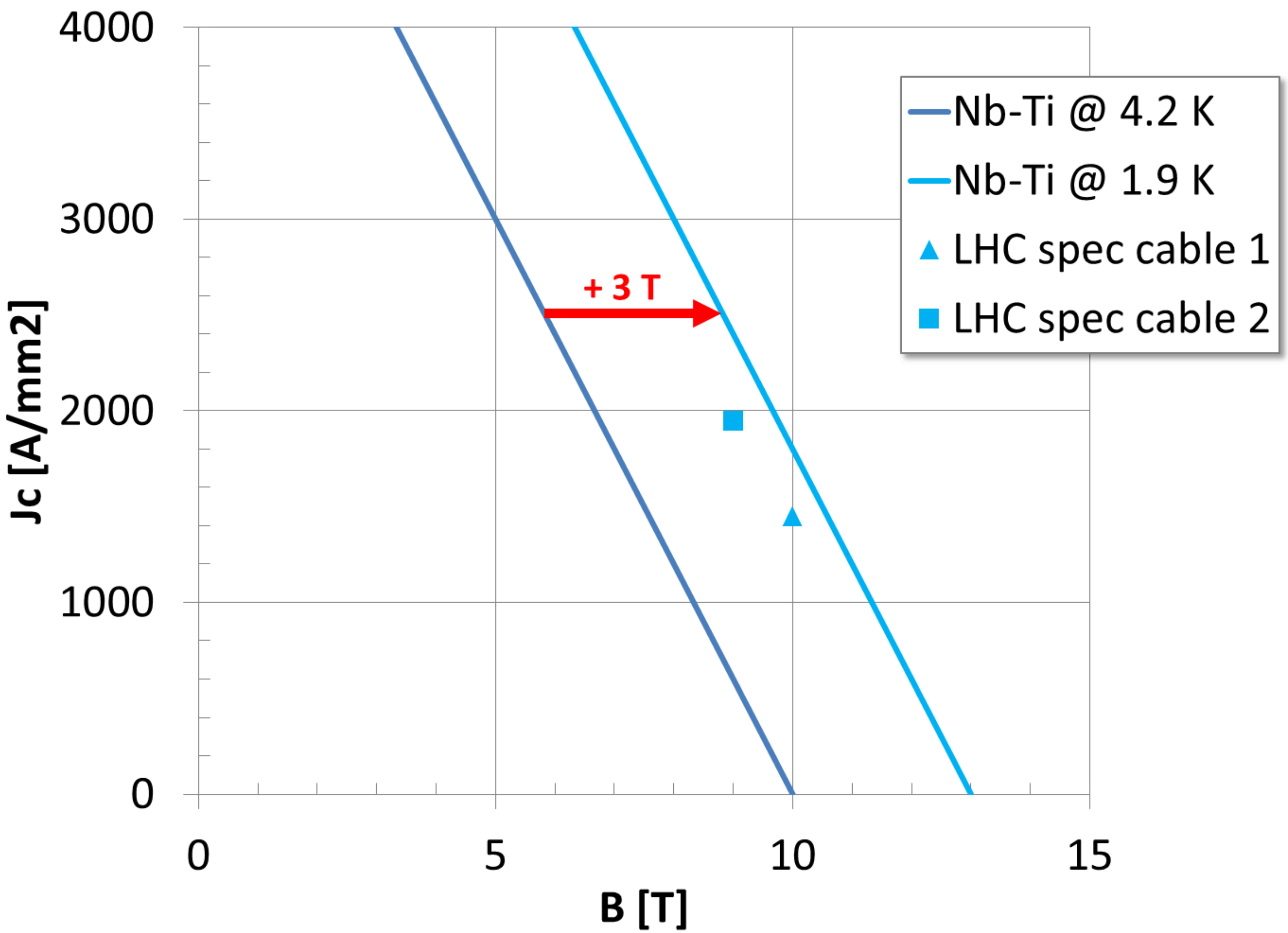
Progress in technology helps contain increase in size!



Specific power consumption of particle colliders
Superconductivity and high fields allow strong reduction of the power bill!



Superfluid helium cooling enhances performance of Nb-Ti superconductor

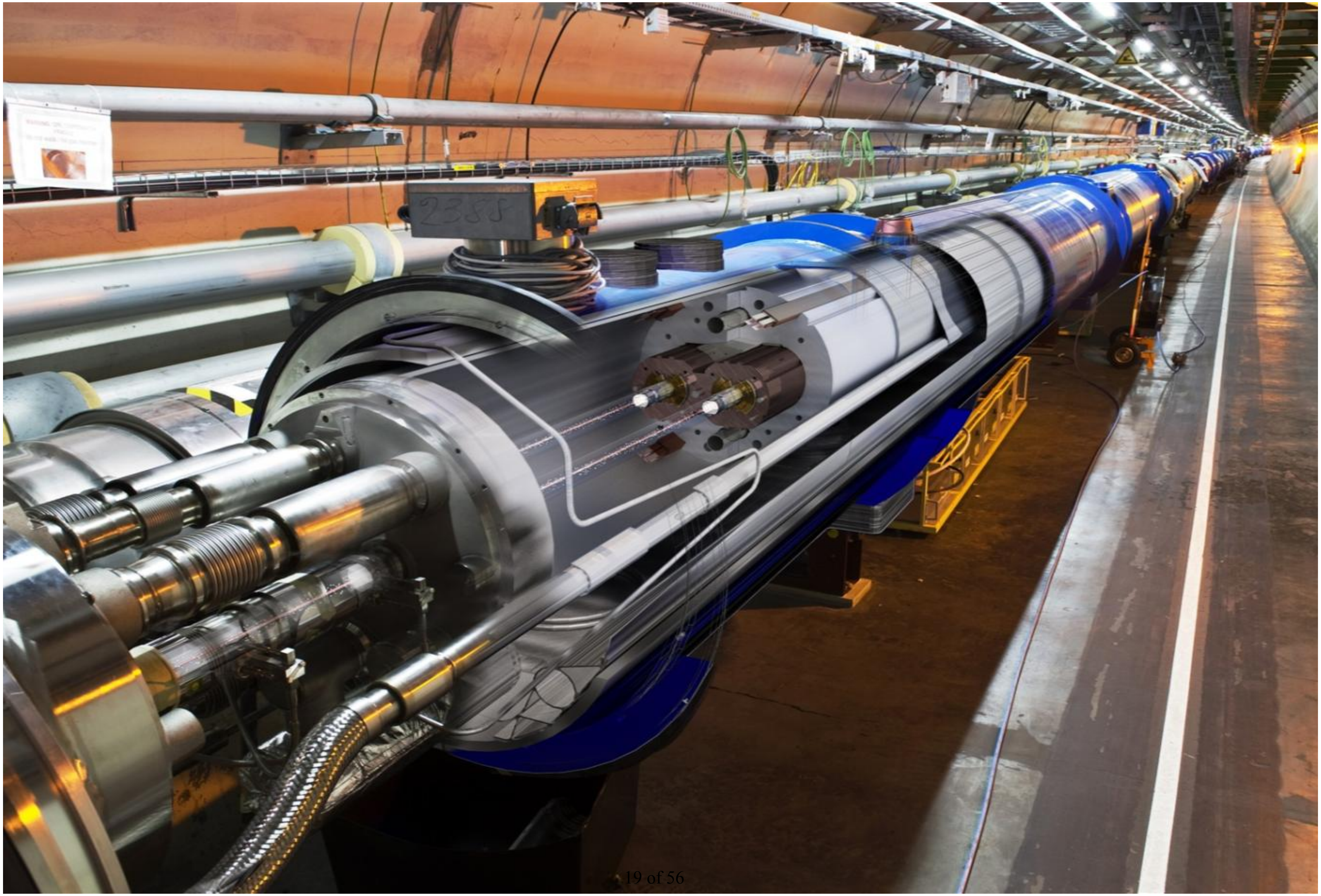


View of the LHC in tunnel

23 km of superconducting magnets
1232 dipoles, 474 quadrupoles, 7612 correctors

Twin-aperture superconducting dipoles

B_{nom} = 8.33 T, I_{nom} = 11850 A



Industrial solutions for a 23 km cryostat

Thermal budget ~ 0.2 W/m @ 1.9 K

Low heat inleak GFRE support post

Aluminium extrusion for thermal shield, with built-in cooling channel

1EOrC3-01 – Tuesday 10h30

Does one need a 4.5 K screen in cryostats of superconducting accelerator devices operating in superfluid helium?

Prefabricated MLI blankets around thermal shield and cold mass

Cryogenic tests of magnets at CERN

- On all magnets
  - Mechanical integrity and leaktightness after cooldown
  - Electrical integrity after cooldown and under helium
  - Integrity of instrumentation and protection systems
  - Quench performance at 1.9 K
- On a sample of the total production
  - Magnetic measurements
    - Transfer function, field quality at 1.9 K
    - Cold-to-warm correlations
    - Geometry and magnetic axes
    - Dynamic effects

Interconnections in tunnel

65’000 electrical joints

Induction-heated soldering

Ultrasonic welding

Very low residual resistance

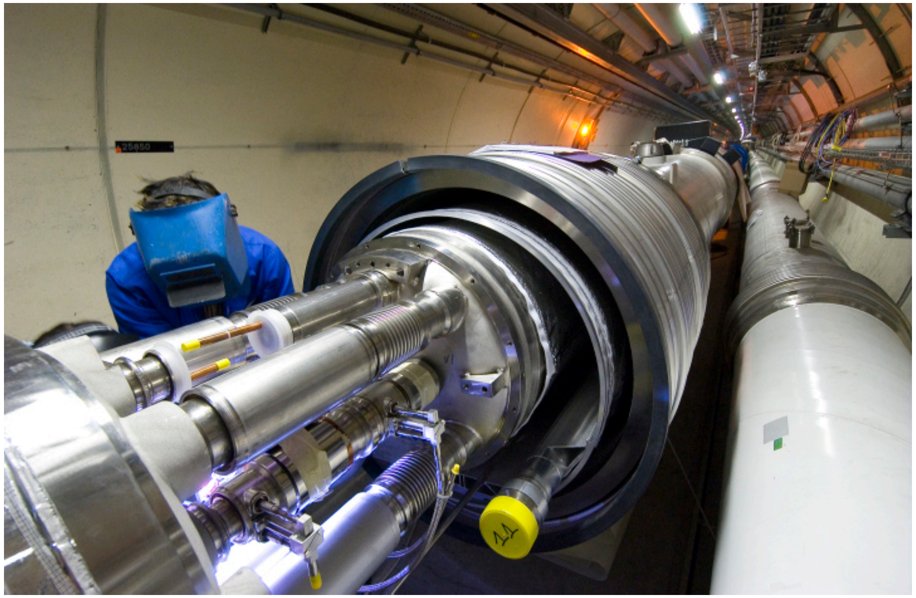
HV electrical insulation

40’000 cryogenic junctions

Orbital TIG welding

Weld quality

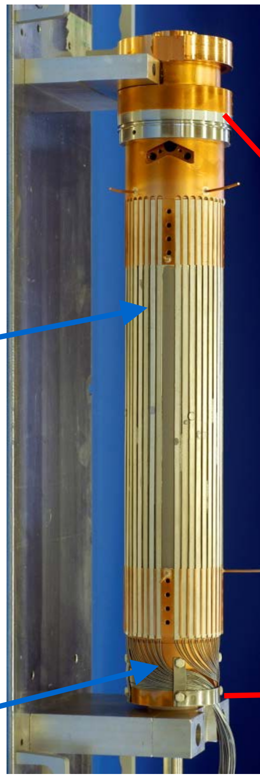
Helium leaktightness



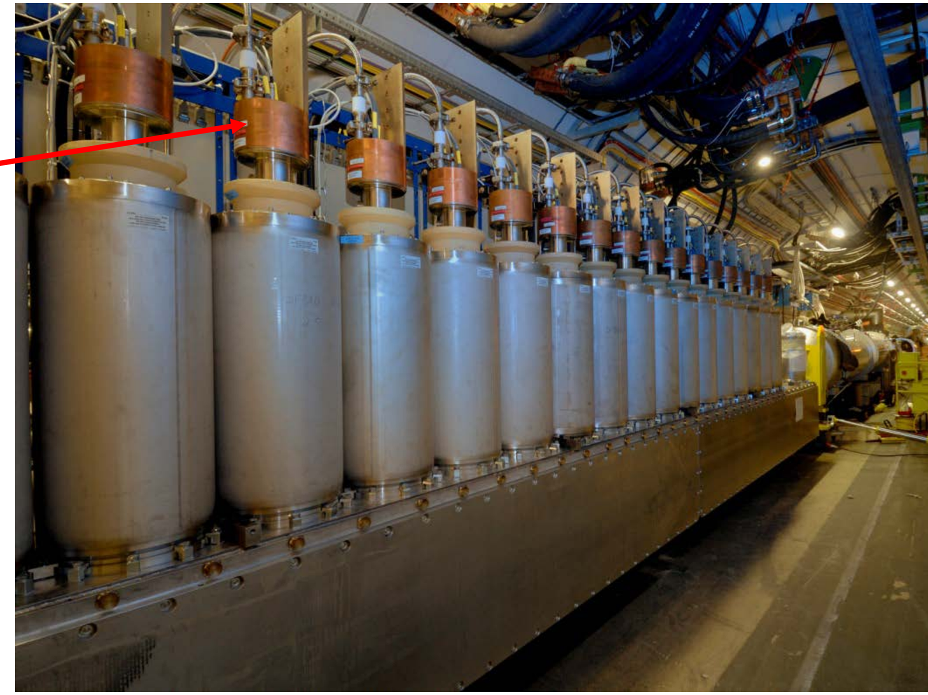
Current leads using HT superconductors

13 kA HTS current lead

BSCCO 2223 tapes



Nb-Ti wires



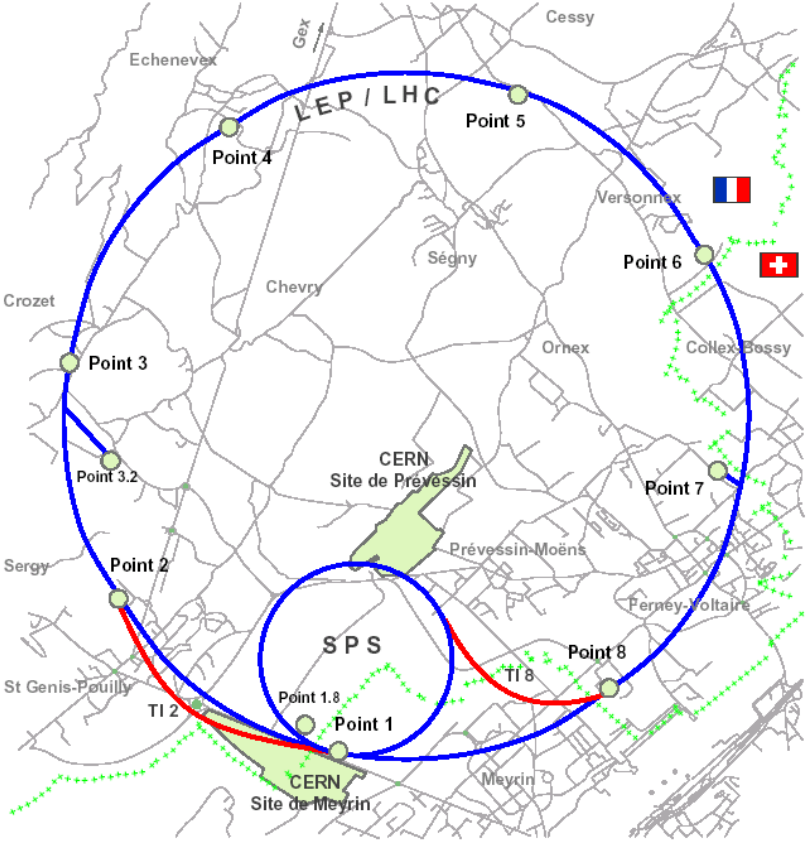
Sum of currents into LHC ~ 1.7 MA, i.e. need current leads for 3.4 MA total rating

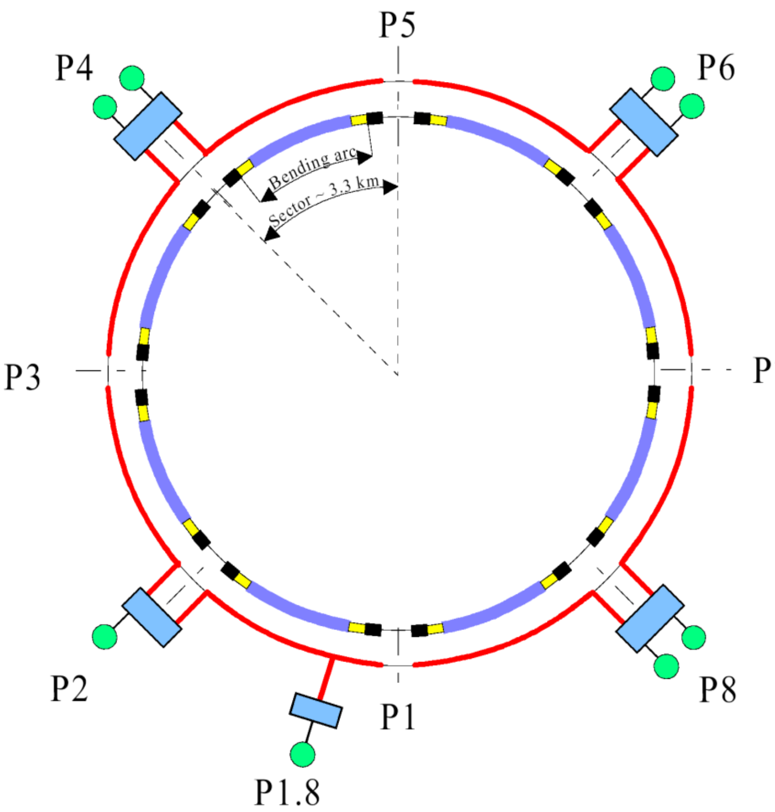
Economy ~ 3400 W in liquid helium ~ 5000 l/h liquid helium

⇒ capital: save extra cryoplant

⇒ operation: save ~ 3.2 MW

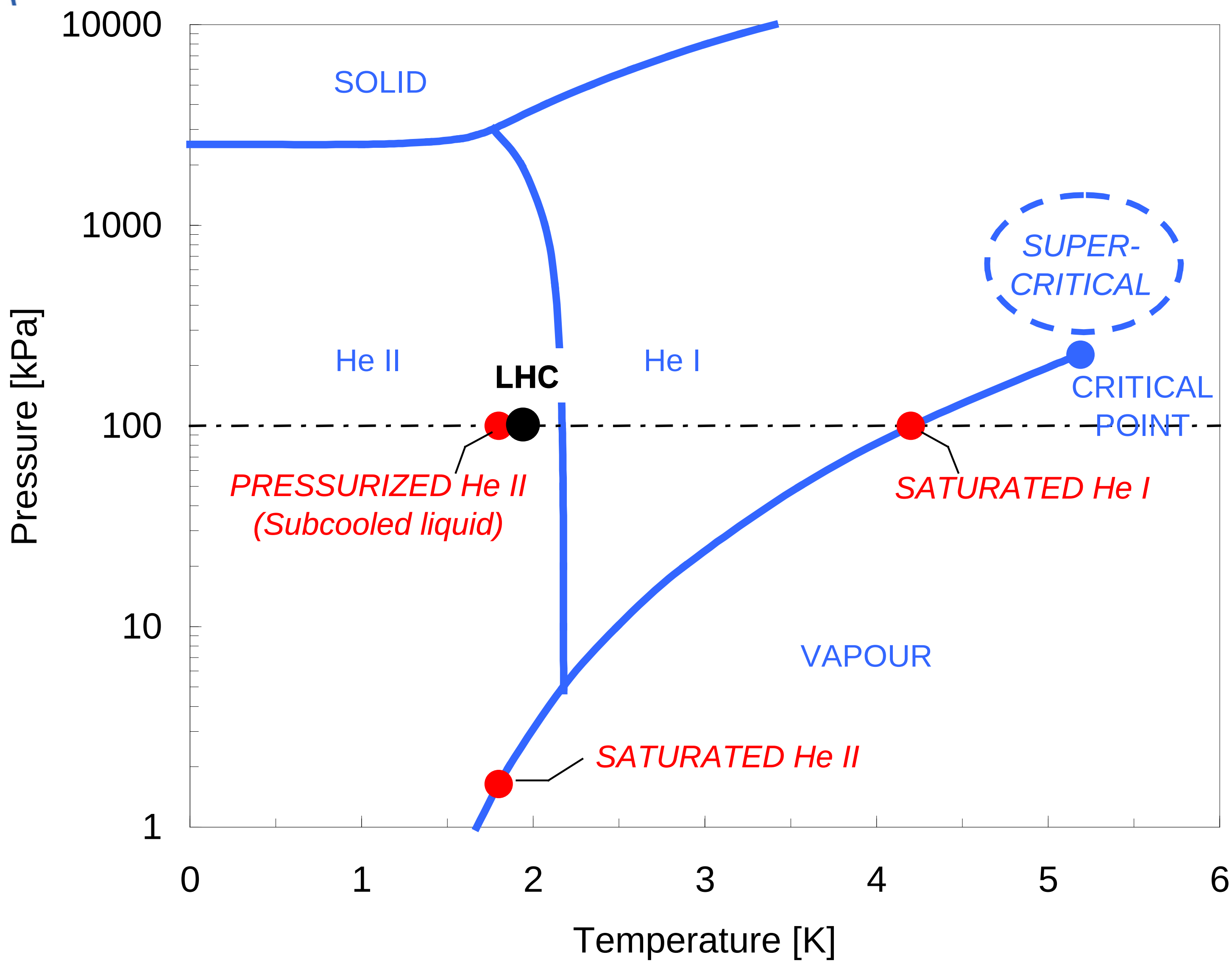
Layout of the LHC cryogenic system





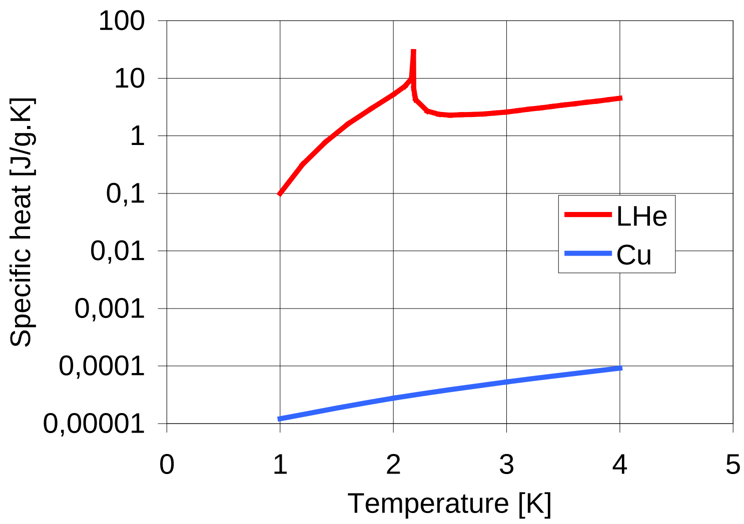
- 5 cryogenic islands
- 8 cryogenic plants, each serving adjacent sector, interconnected when possible
- Cryogenic distribution line feeding each sector

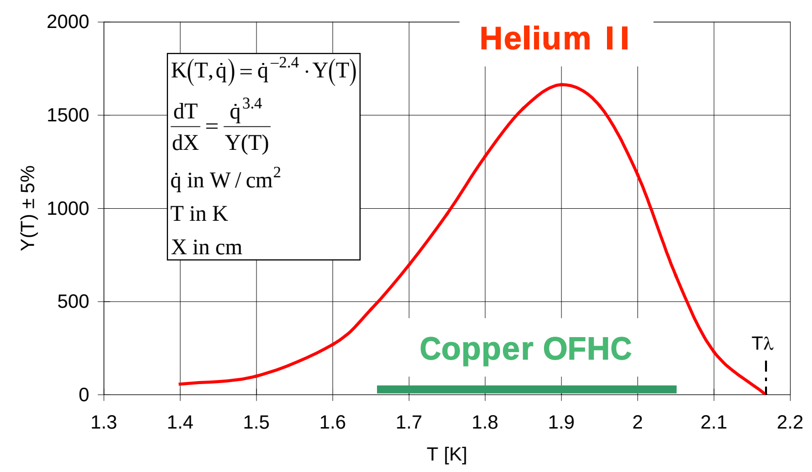
Superfluid helium as a technical coolant



Thermophysical properties of superfluid helium and engineering applications

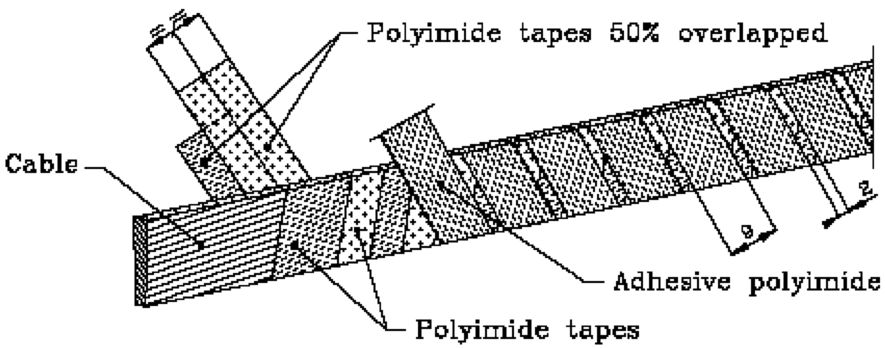
- **Temperature** < 2.17 K
  ⇒ superconductor performance
- Low effective **viscosity** *⇒ permeation*
  - 100 times lower than water at normal boiling point
- Very high **specific heat** *⇒ stabilization*
  - 10^5 times that of the conductor by unit mass
  - 2×10^3 times that of conductor by unit volume
- Very high **thermal conductivity**
  ⇒ heat transport
  - 10^3 times that of OFHC copper
  - Peaking at 1.9 K
  - Still, insufficient for transporting heat over large distances across small temperature gradients

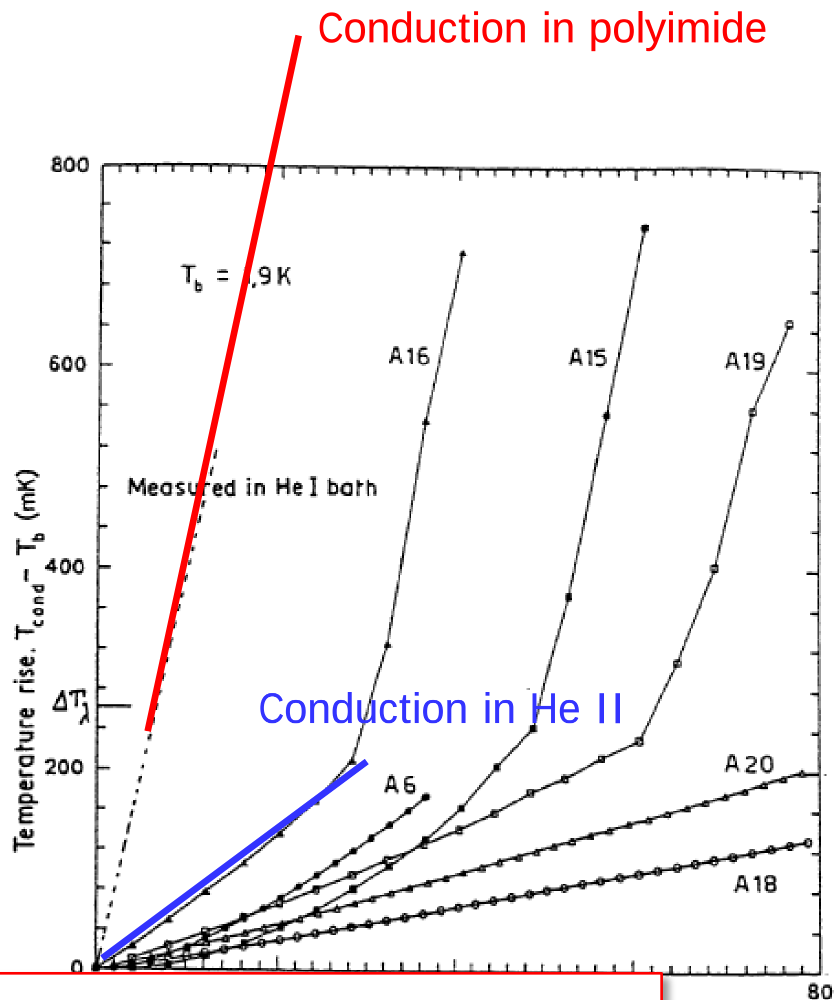




Heat transfer across electrical insulation of LHC superconducting cable

Double wrap with partial overlap maintains porosity and percolation paths in electrical insulation of superconducting cable



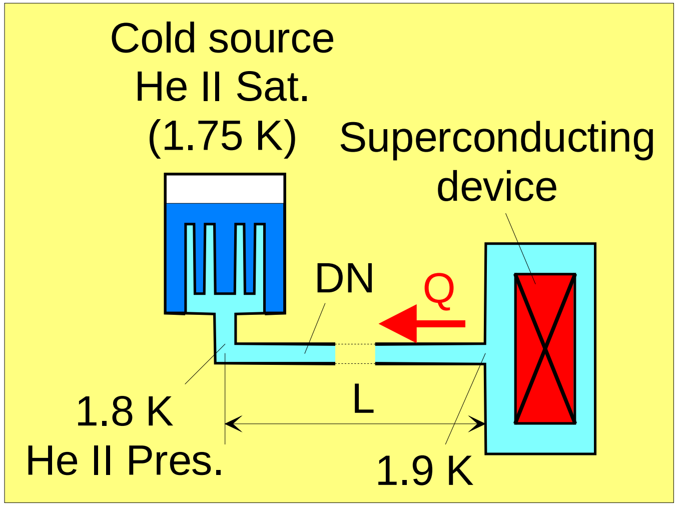


1EOrF2-02 – Tuesday 17h15

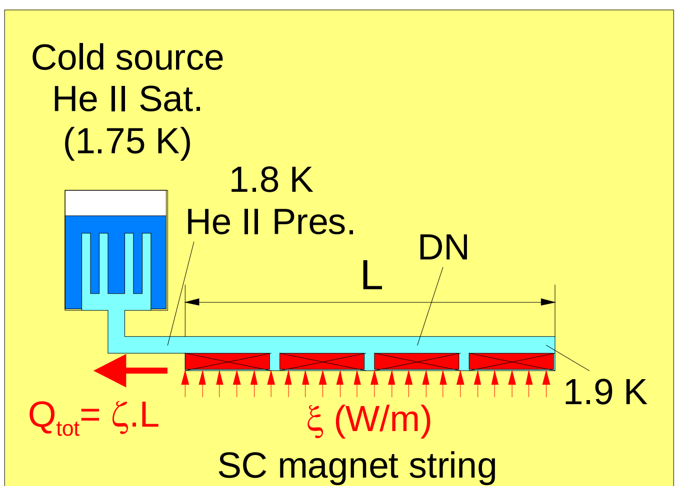
Experimental study of He II heat transfer in micro-channels

Steady-state conduction in He II p from 1.9 to 1.8 K

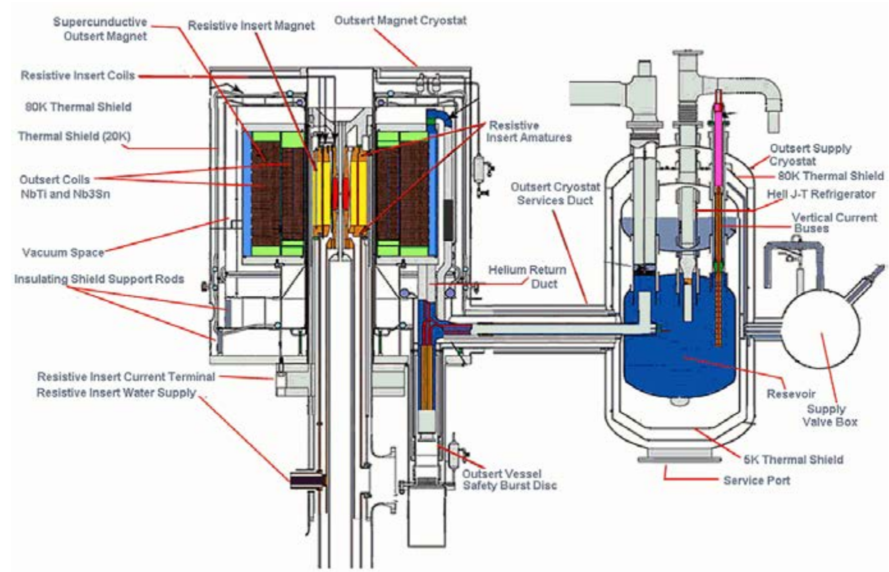
Lumped heat load

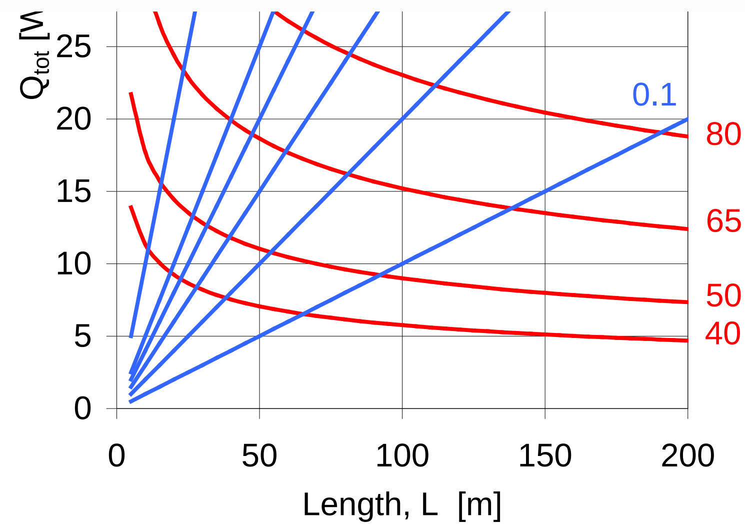


Linear distributed heat load



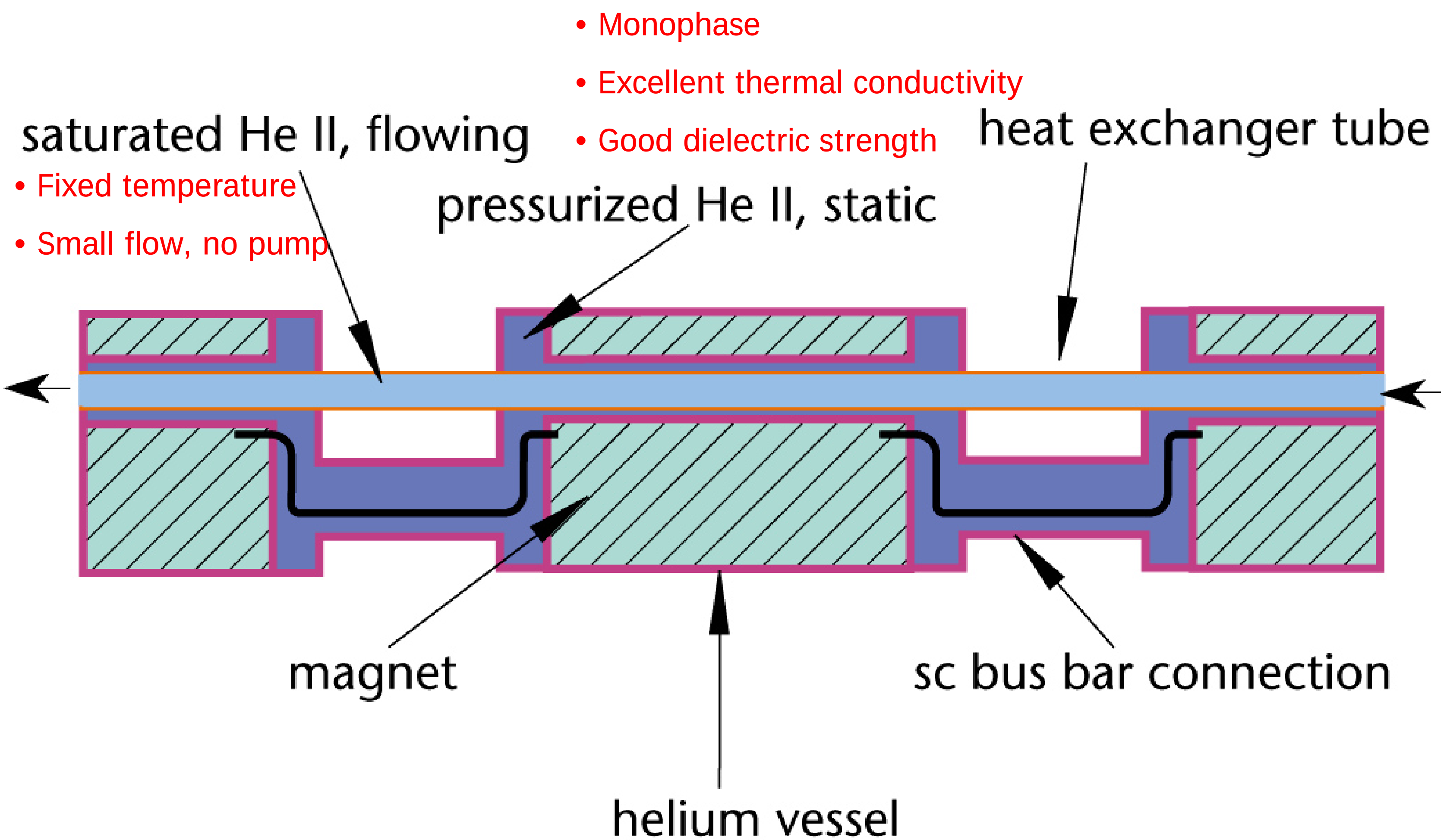
45 T hybrid magnet at NHMFL



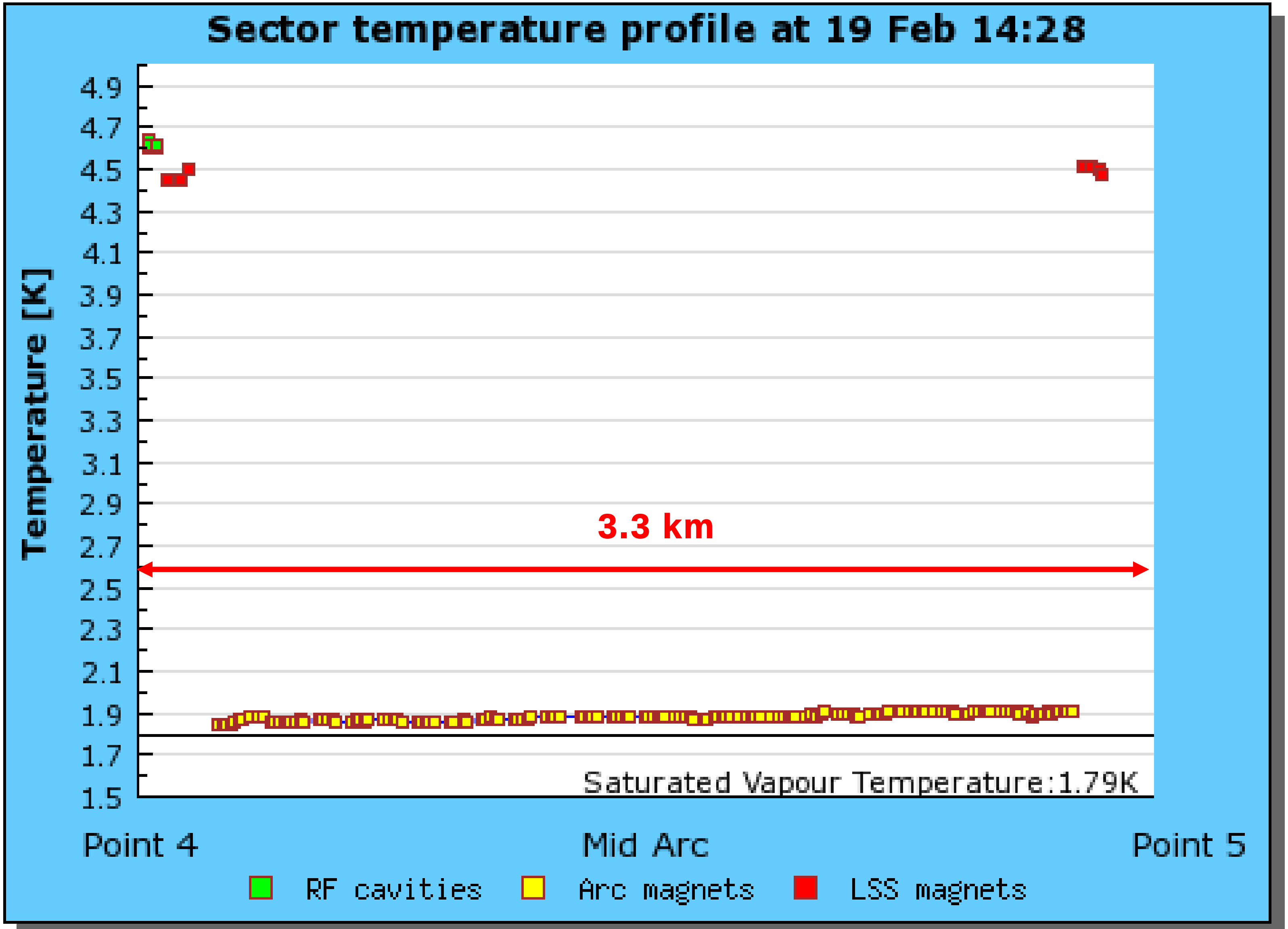


Magnet string cooling with superfluid helium

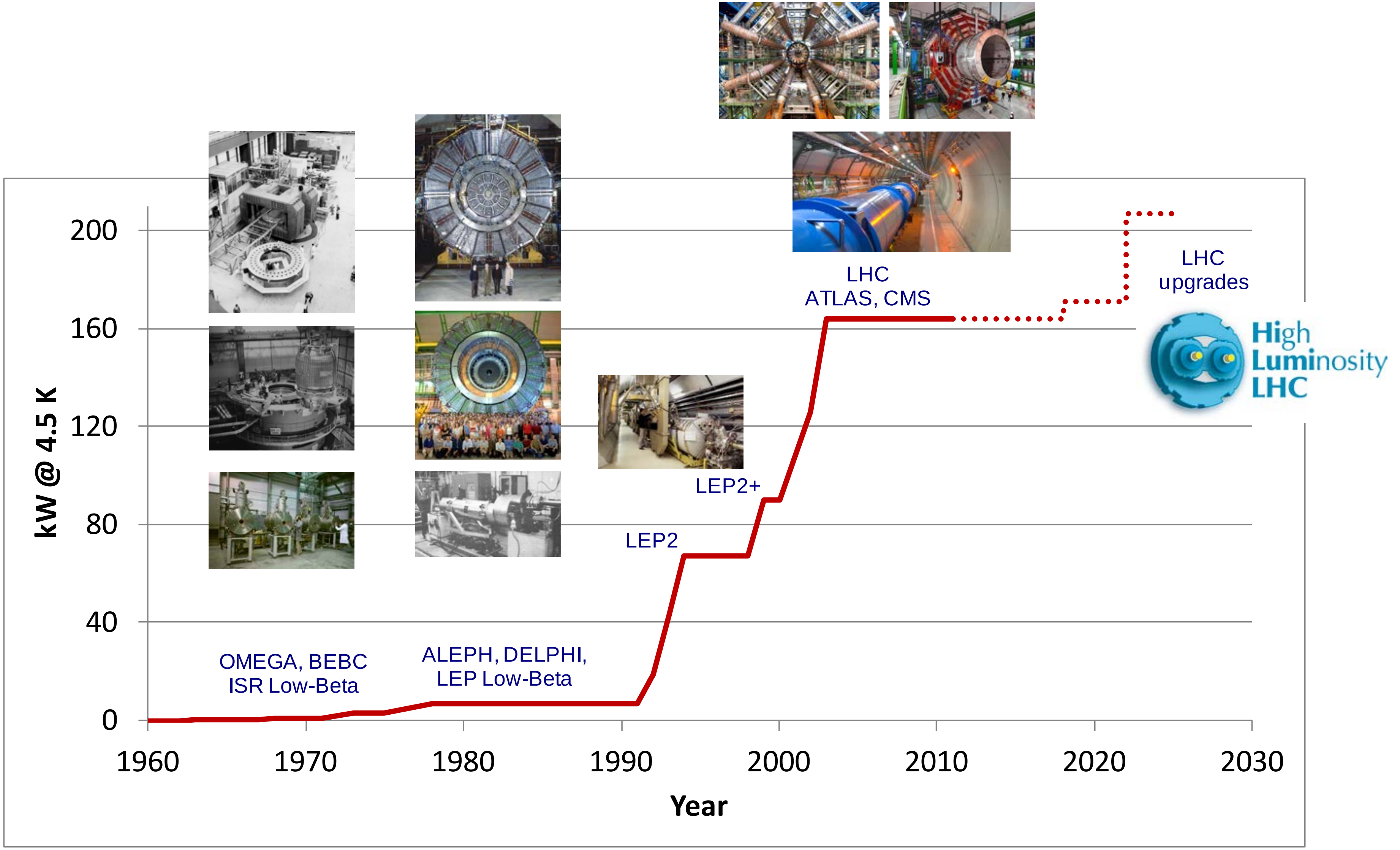
Getting the best of helium transport properties



Magnet temperature profile in LHC sector

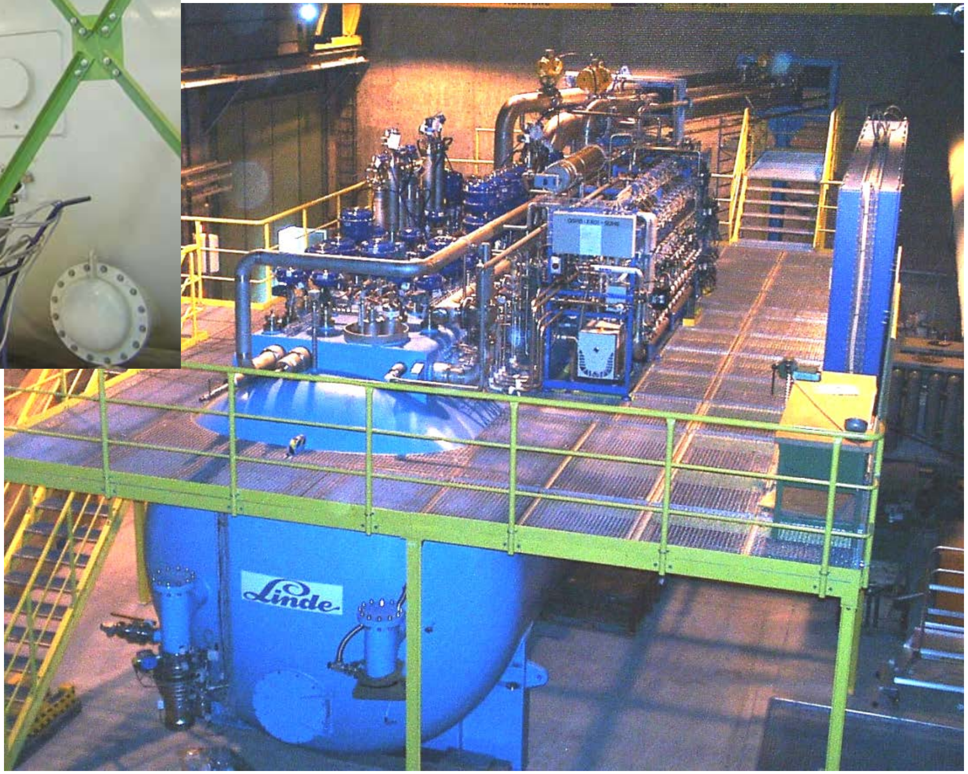


Cryogenic helium refrigeration capacity at CERN



18 kW @ 4.5 K helium refrigerators

33 kW @ 50 K to 75 K
23 kW @ 4.6 K to 20 K
41 g/s liquefaction



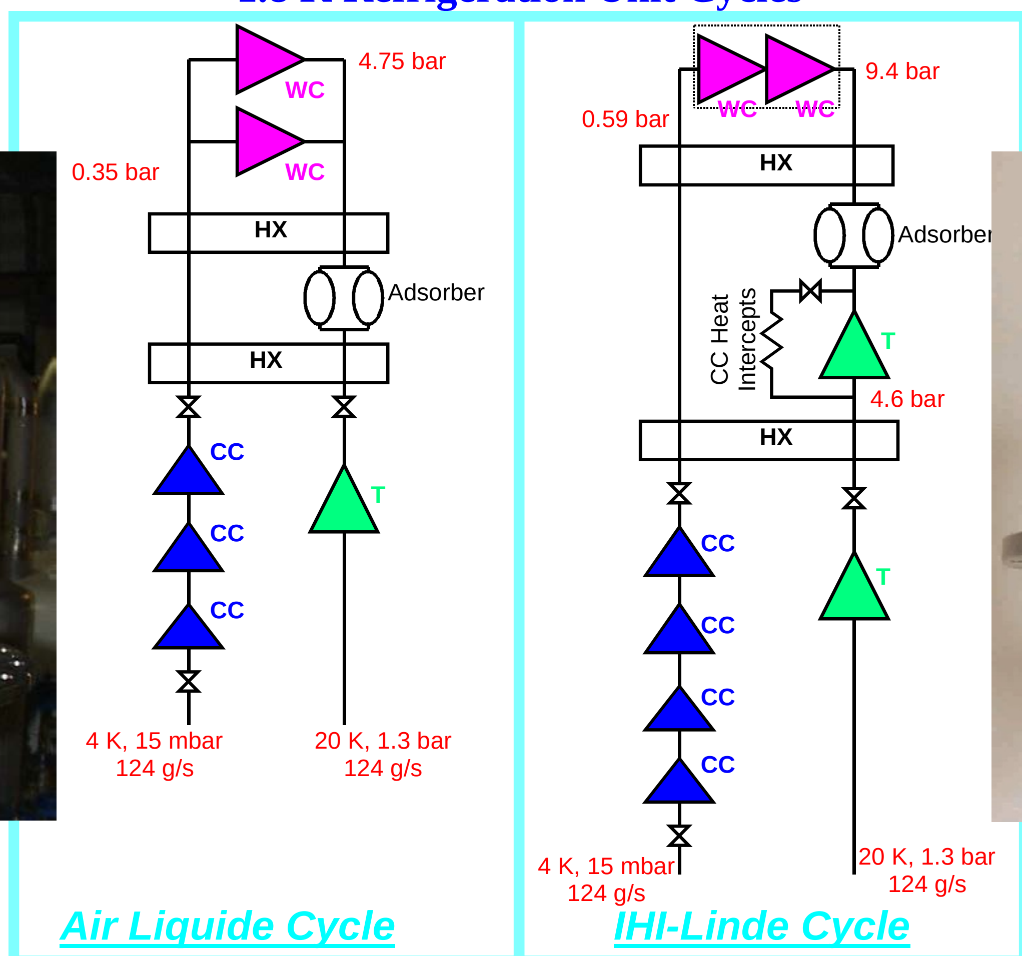
High thermodynamic efficiency

COP at 4.5 K: 220-230 W/W

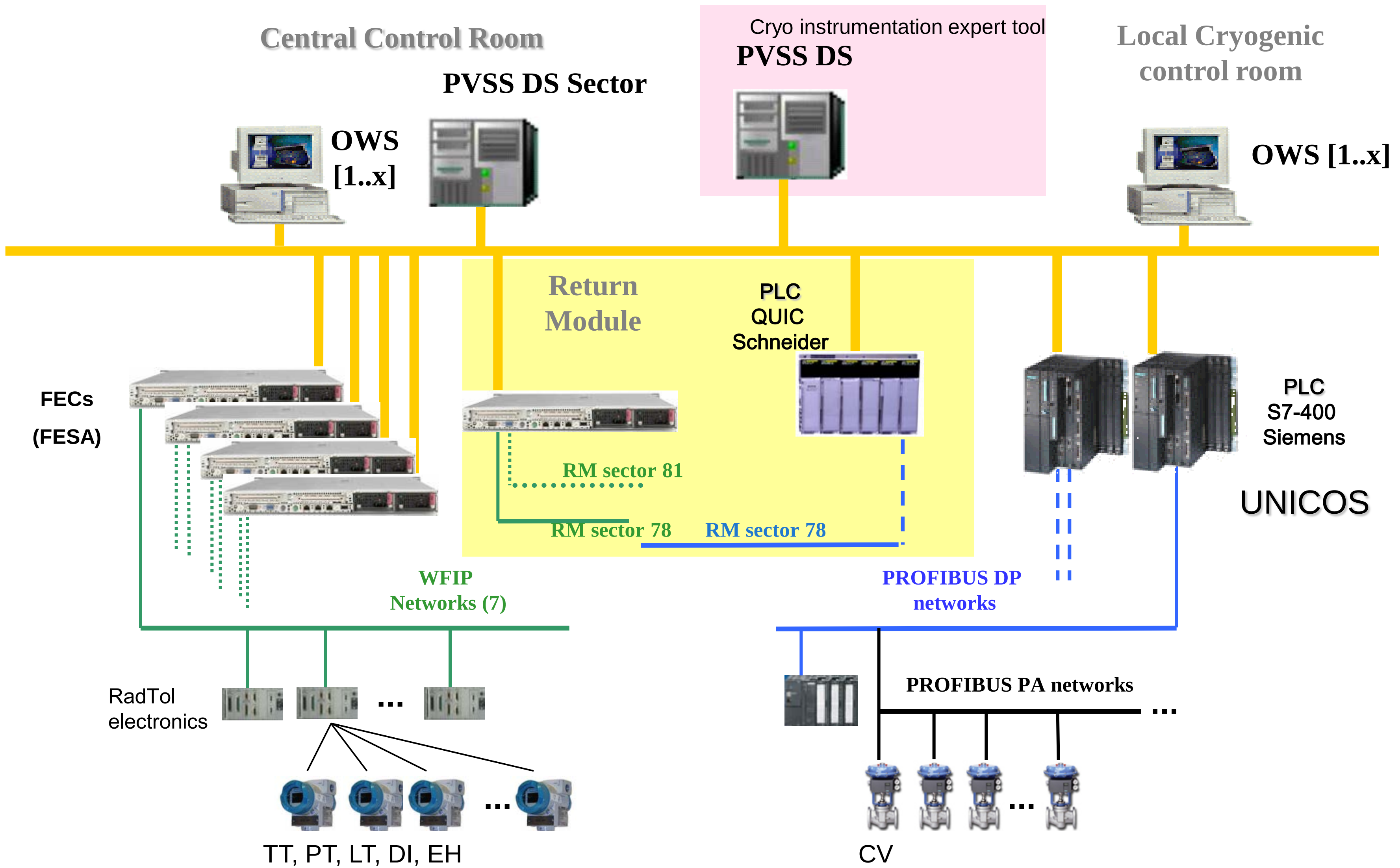
2.4 kW @ 1.8 K refrigeration units

Cold hydrodynamic compressors with active magnetic bearings, rotational speed 100-800 Hz

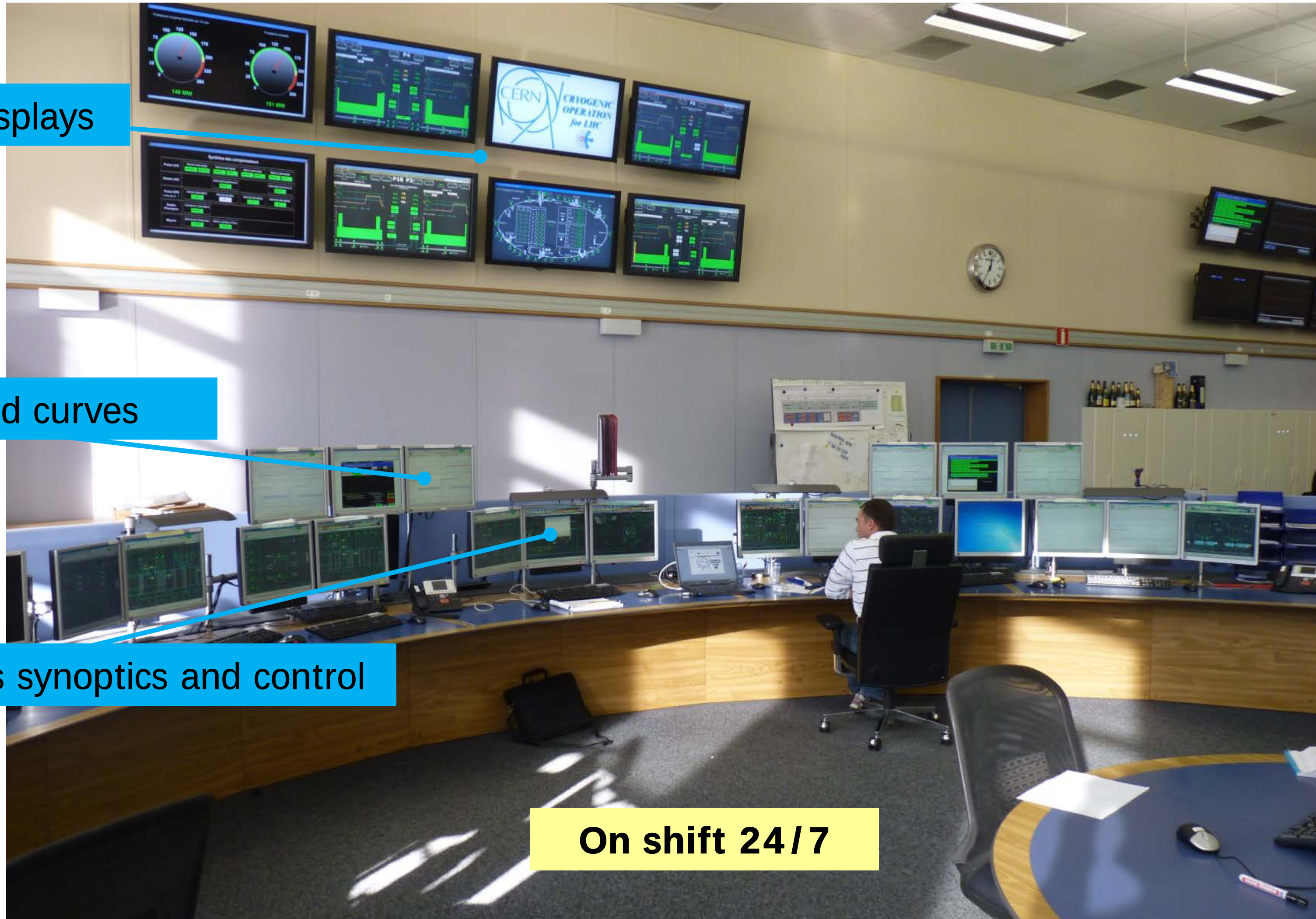
1.8 K Refrigeration Unit Cycles



Controls for LHC cryogenics
21300 AI, 7000 AO, 18400 DI, 4200 DO
4700 analog control loops

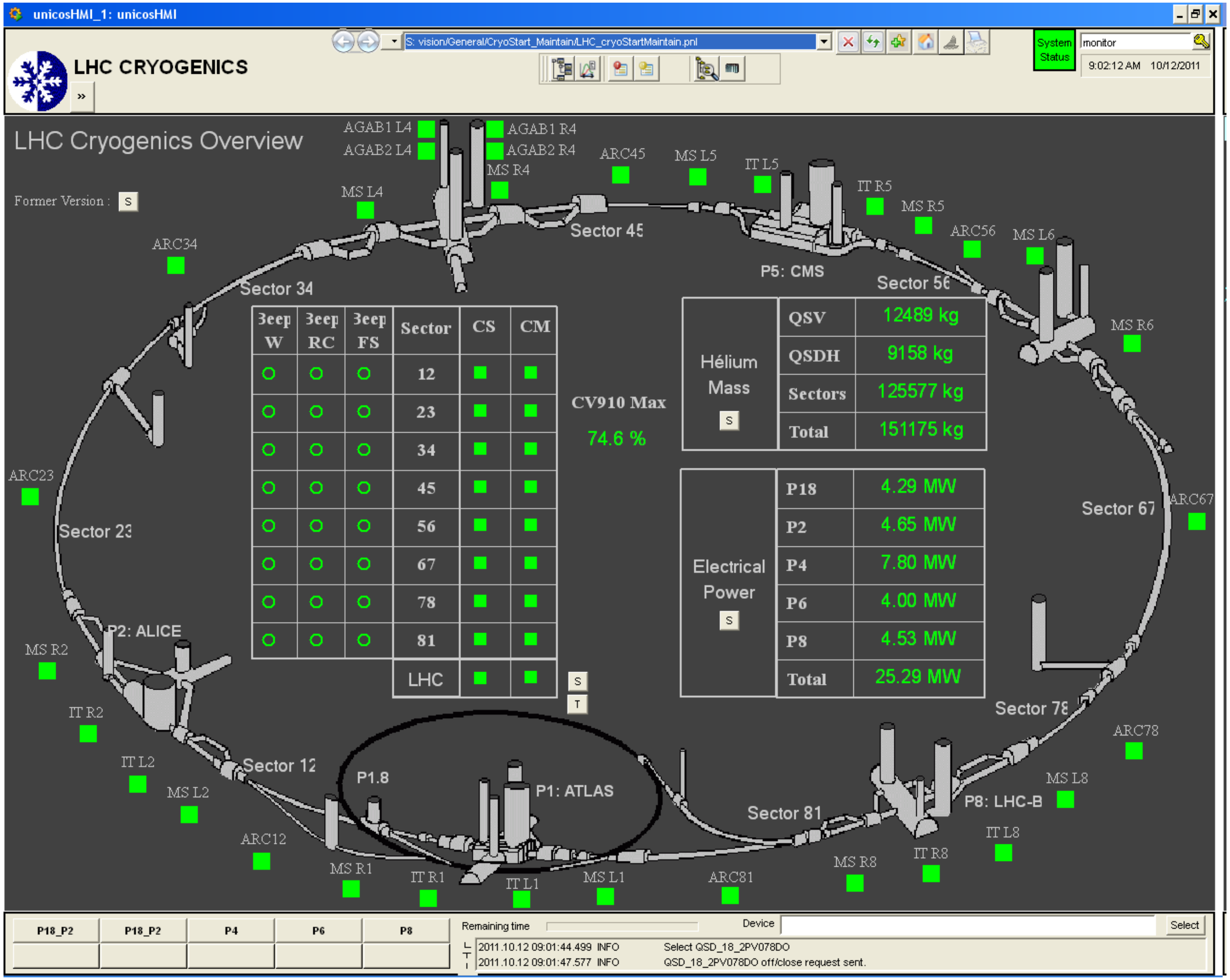


Cryogenics in CERN Accelerator Control Centre



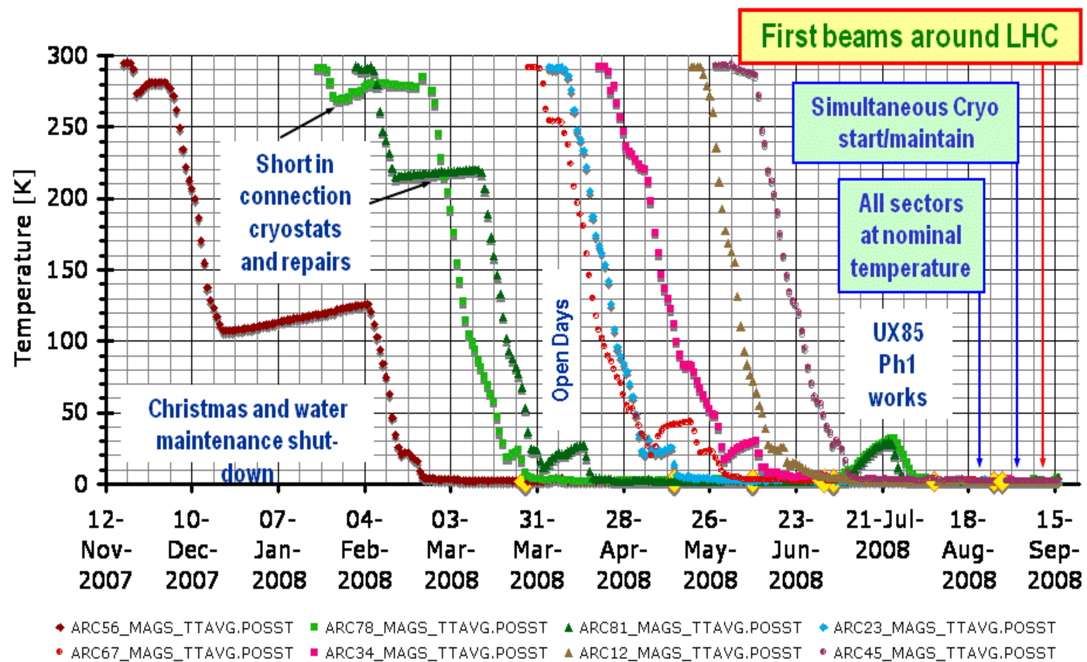
S. Claudet

Display of cryogenic operation indicators



Precooling 37’500 t magnets with 10’000 t liquid nitrogen

Cooldown to 80 K: 600 kW per sector
with up to ~5 tons/h liquid nitrogen

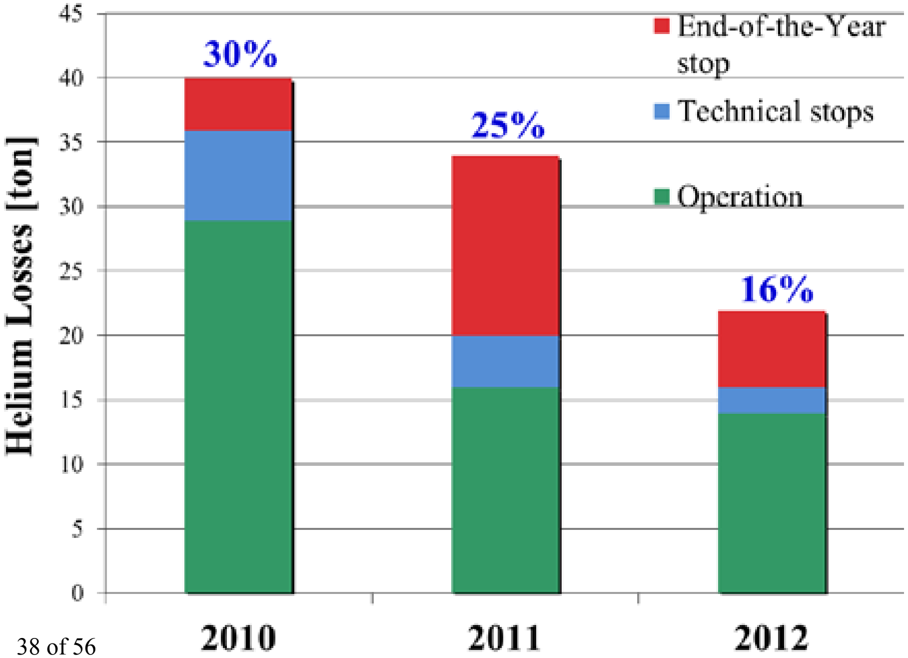


Helium inventory management

Total He inventory of LHC accelerator: 135 tons
On-site storage: 125 tons
« Virtual » storage contract: 60 tons

Storage capacity GHe @ 2 MPa, Tambient:
- 58 x 250 m^3 tanks
- 40 x 80 m^3 tanks

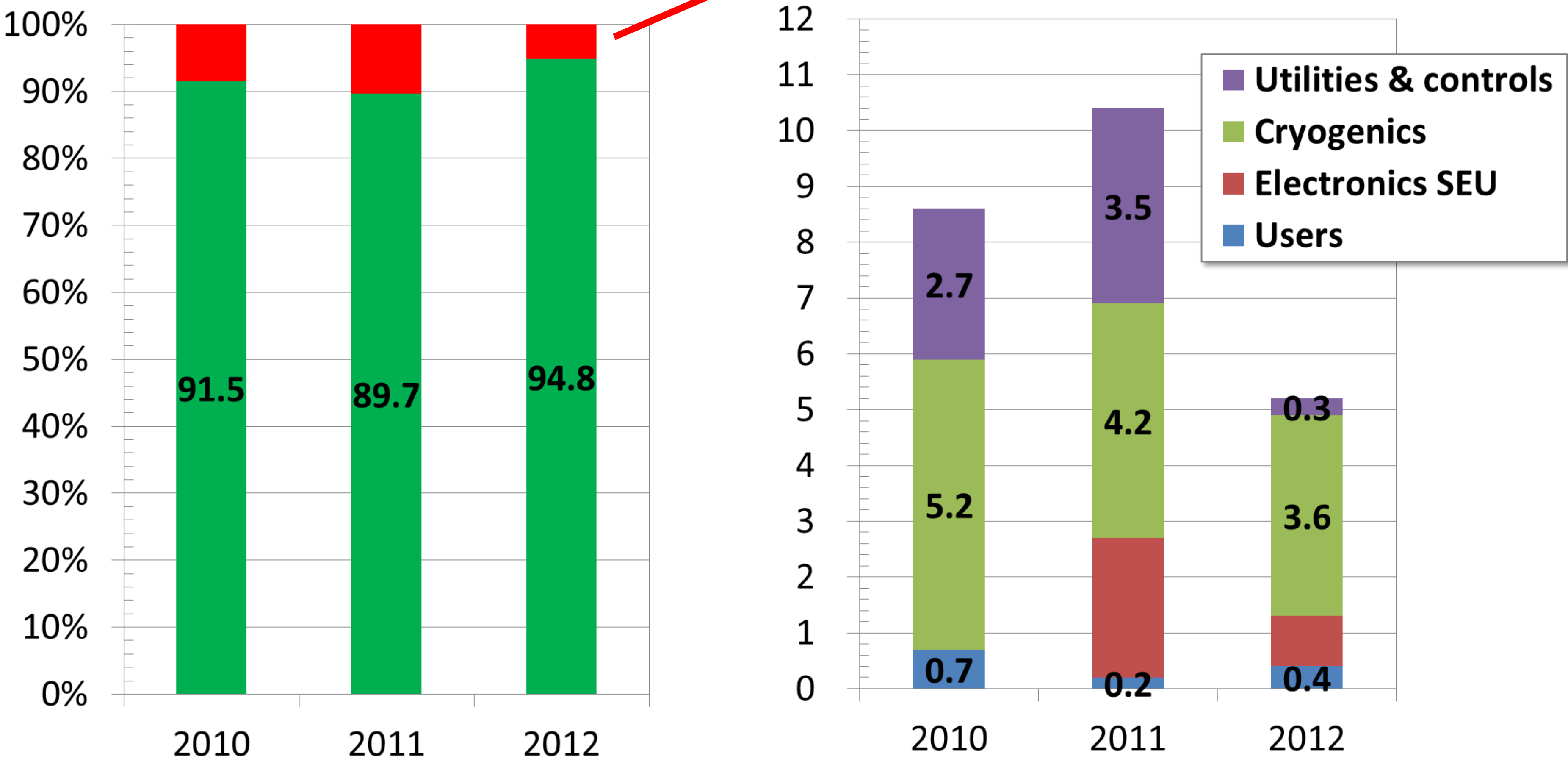
Storage capacity LHe @ 0.1 MPa, 4.5 K:
- 6 x 120'000 liter vacuum-insulated vessels



Availability of LHC cryogenics

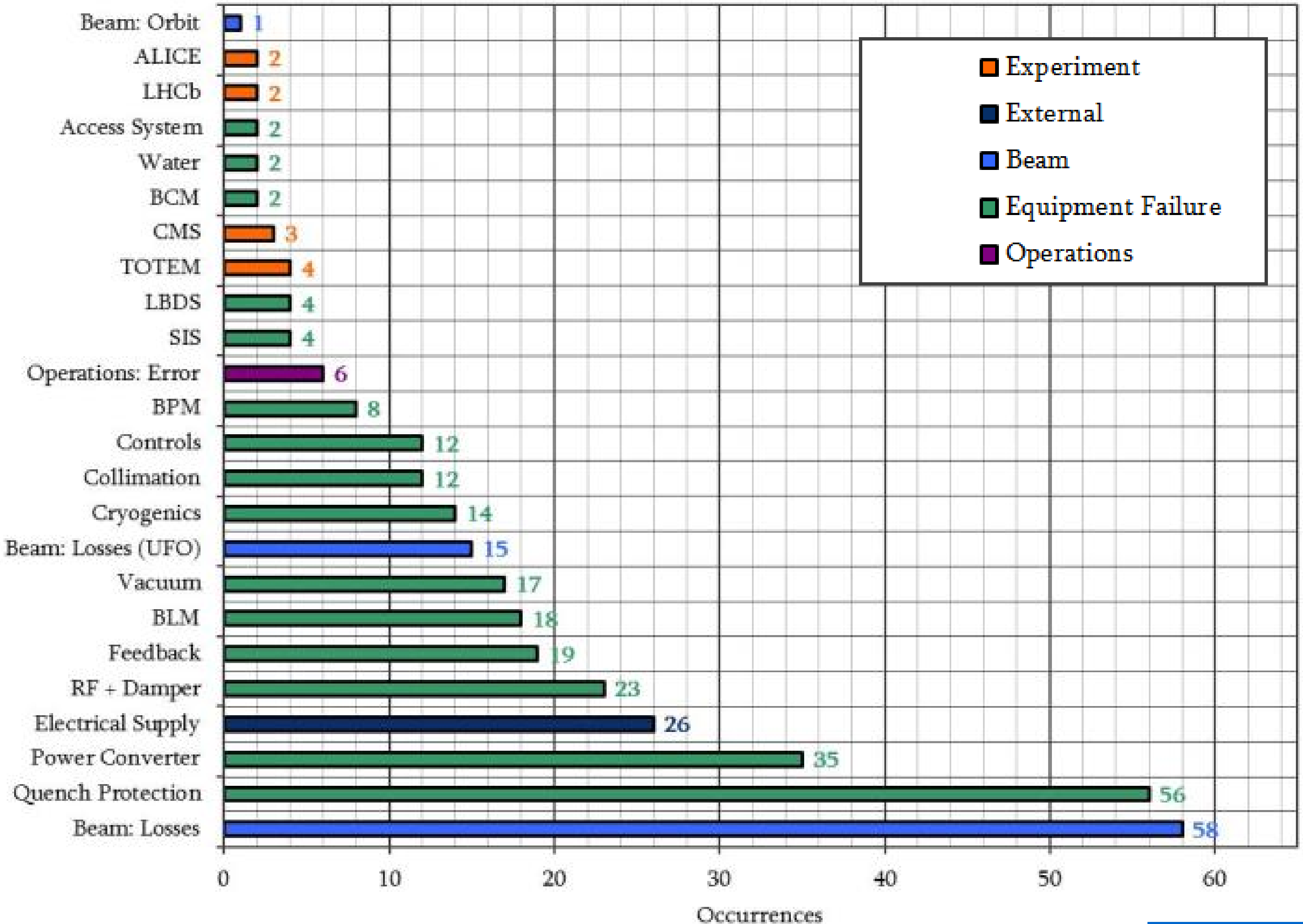
Overall availability [%]

Sources of unavailability [%]



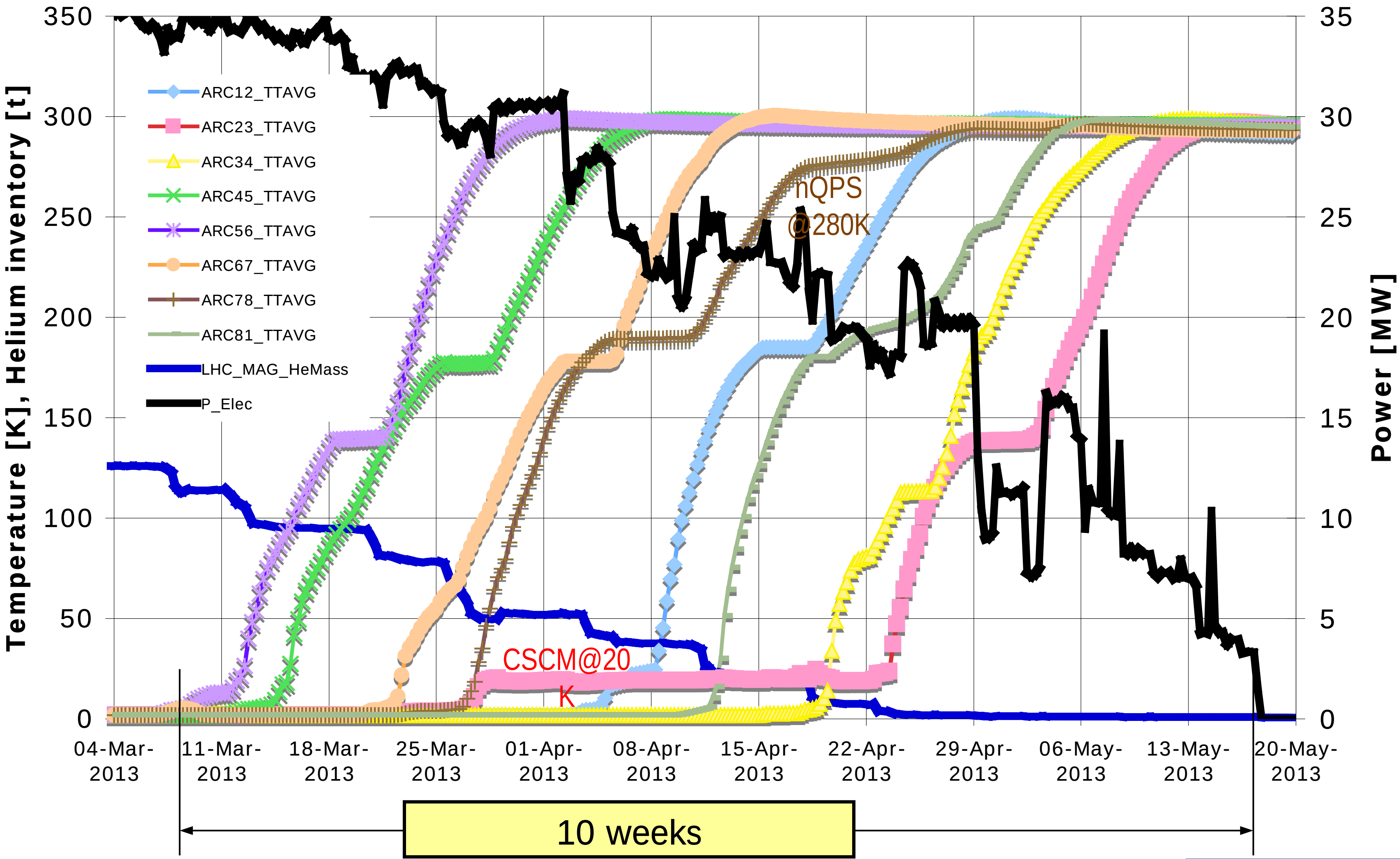
S. Claudet

Sources of beam dumps at 4 TeV



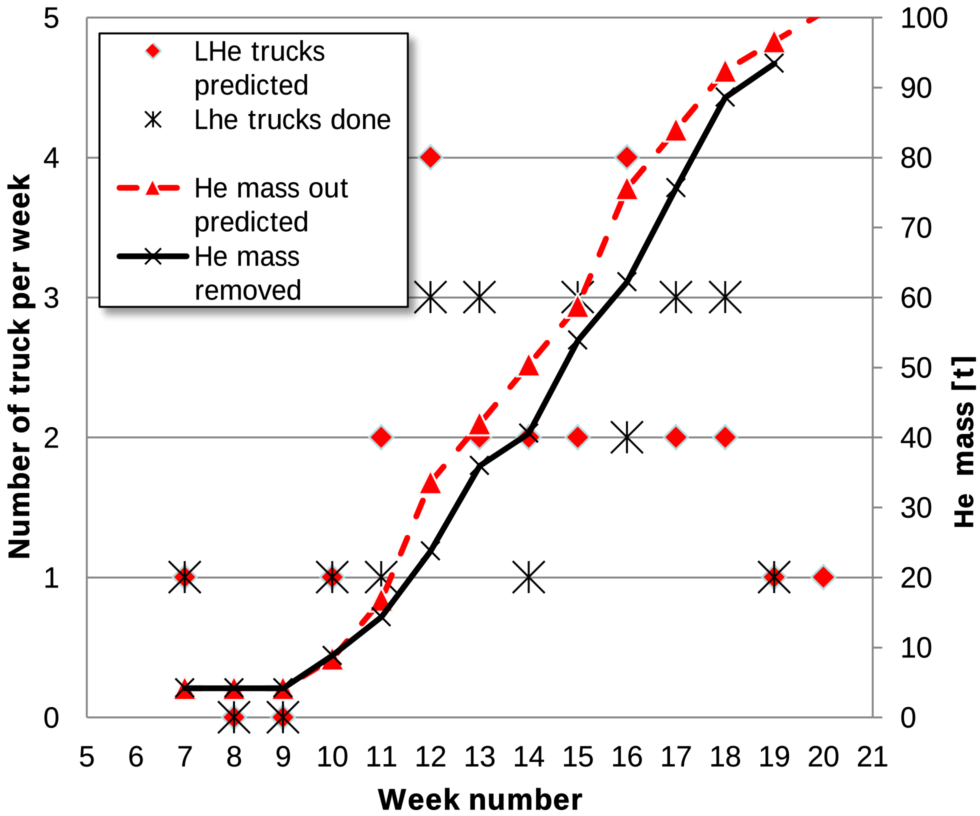
M. Zerlauth

LHC warm-up Spring 2013



S. Claudet

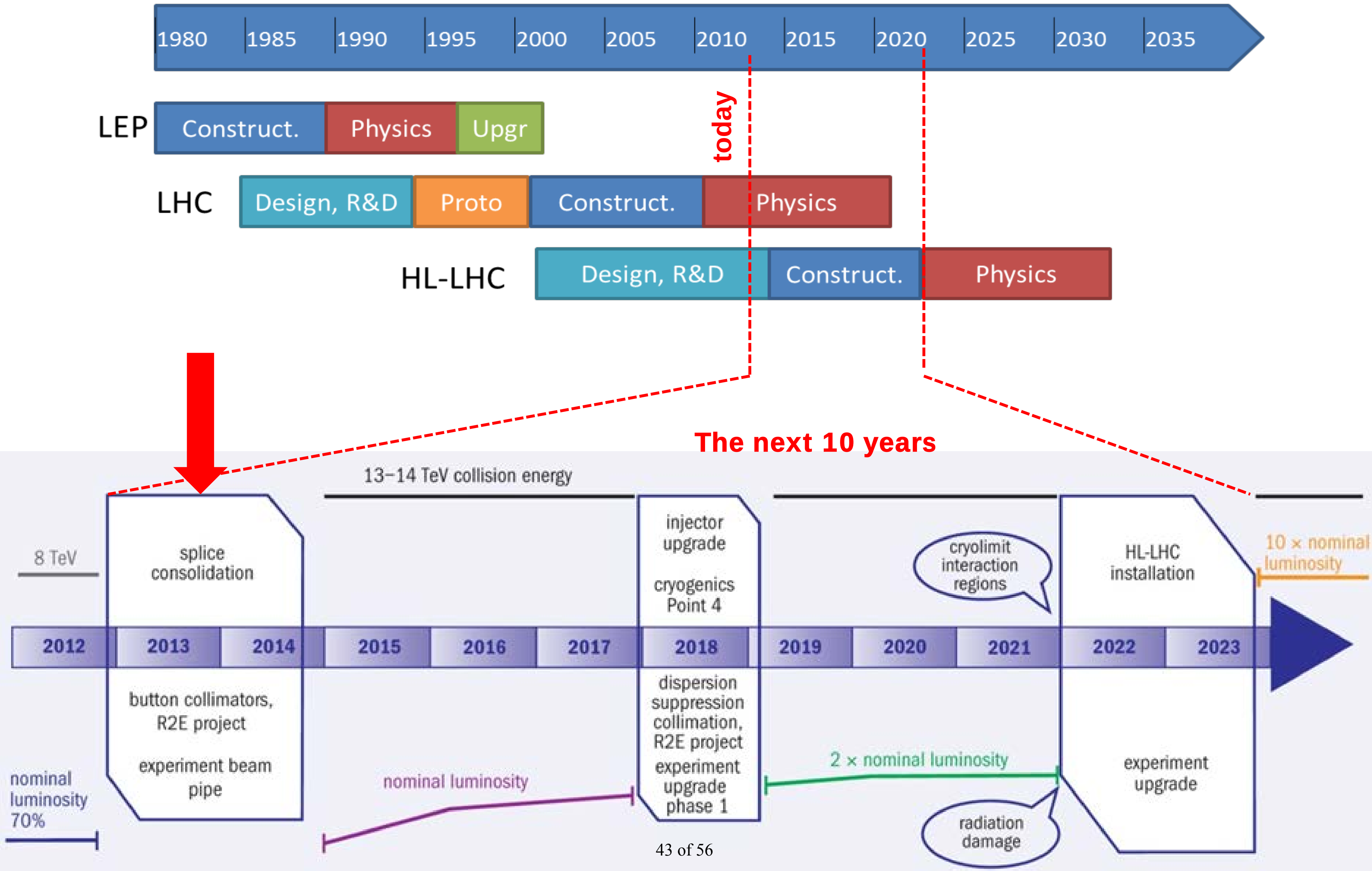
He «virtual storage» 2013-2014



- **Spring 2013**: 93.5 t He extracted from LHC, reliquefied and «virtually stored» in standard containers (22 truckloads) put back on the market
- **Spring 2014**: LHC refill foreseen at ~2 truckloads/week

S. Claudet

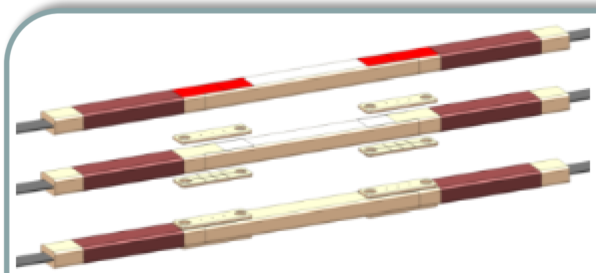
A roadmap for exploiting the full potential of LHC



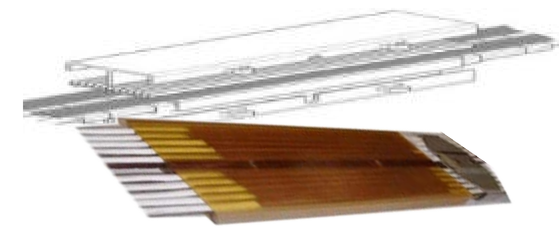
First long shutdown

Superconducting magnet & circuit consolidation

- Interconnections
  - Total magnet-to-magnet interconnects: 1695
  - Total high-current splices: 10’170
  - Splices to be re-done ~ 1500
  - Shunts to be applied > 27’000 (all splices)



✓ Consolidated dipole magnets bus splice

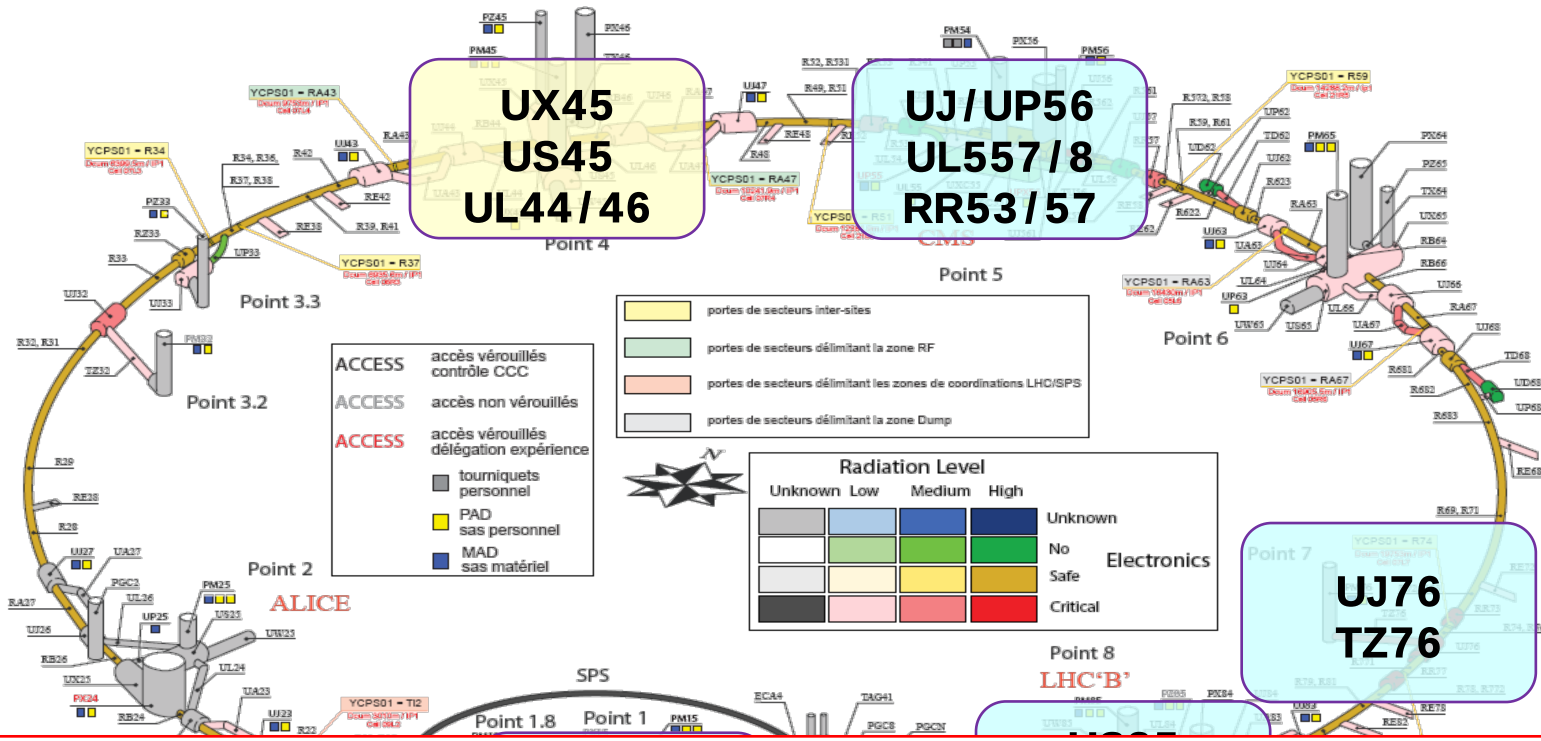


✓Consolidated electrical insulation system

- Magnets to exchange: 19
- Electrical feedbox consolidation
- DN200 relief plate installation on cryostats

First long shutdown
Radiation to electronics

- More than 100 electronic racks relocated in radiation-protected areas
- Installation of additional shielding
- Upgrades of critical systems: power converters, quench protection

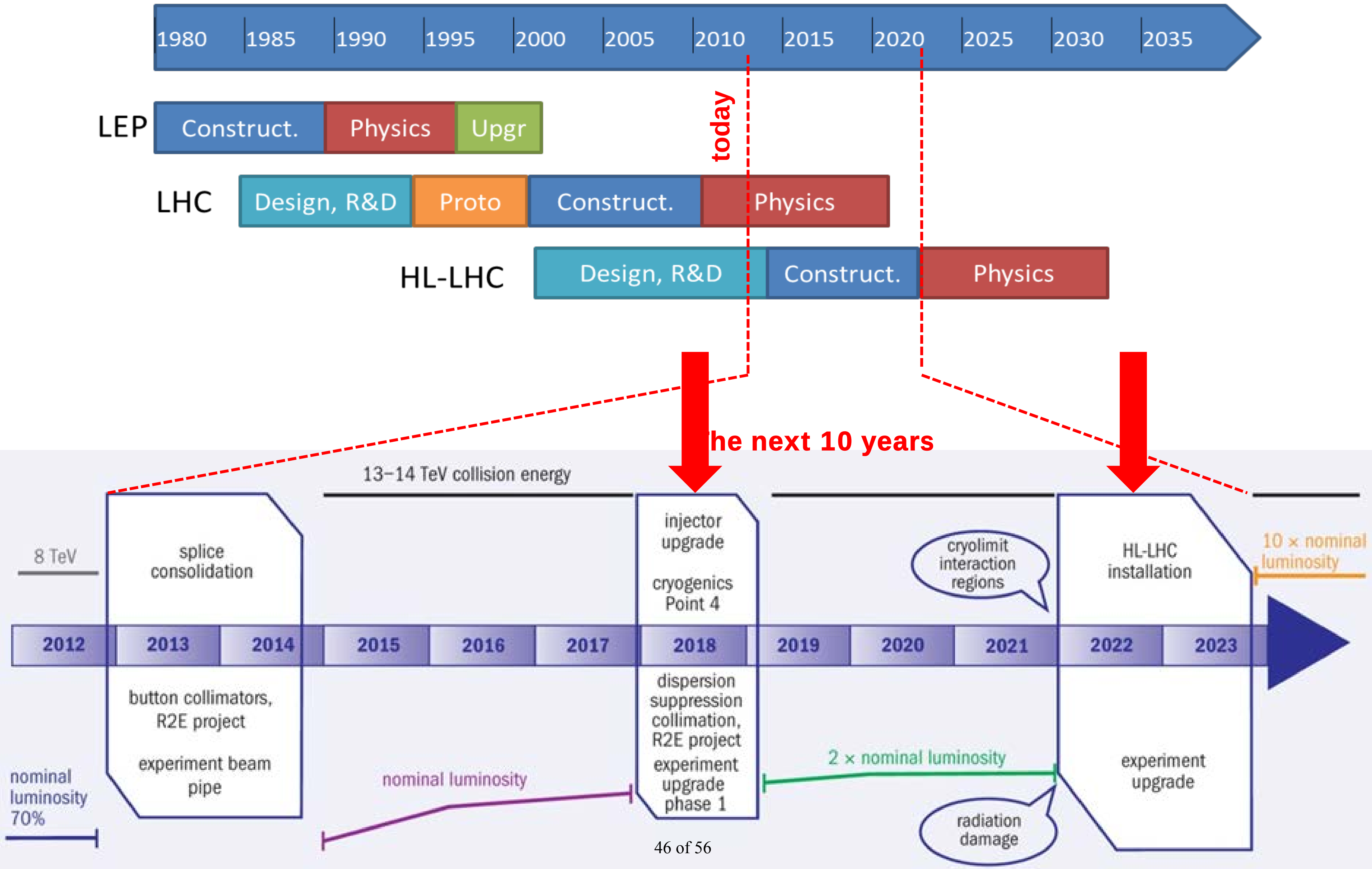


1EOrC6-03 – Tuesday 11h00

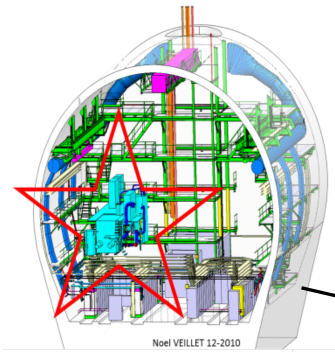
Analysis of the failures and corrective actions for the LHC cryogenics radiation-tolerant electronics and its field instruments

ATLAS

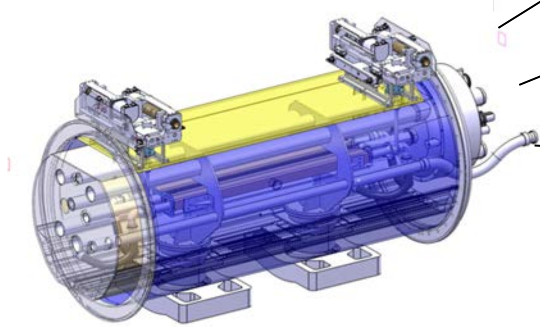
The HL-LHC project



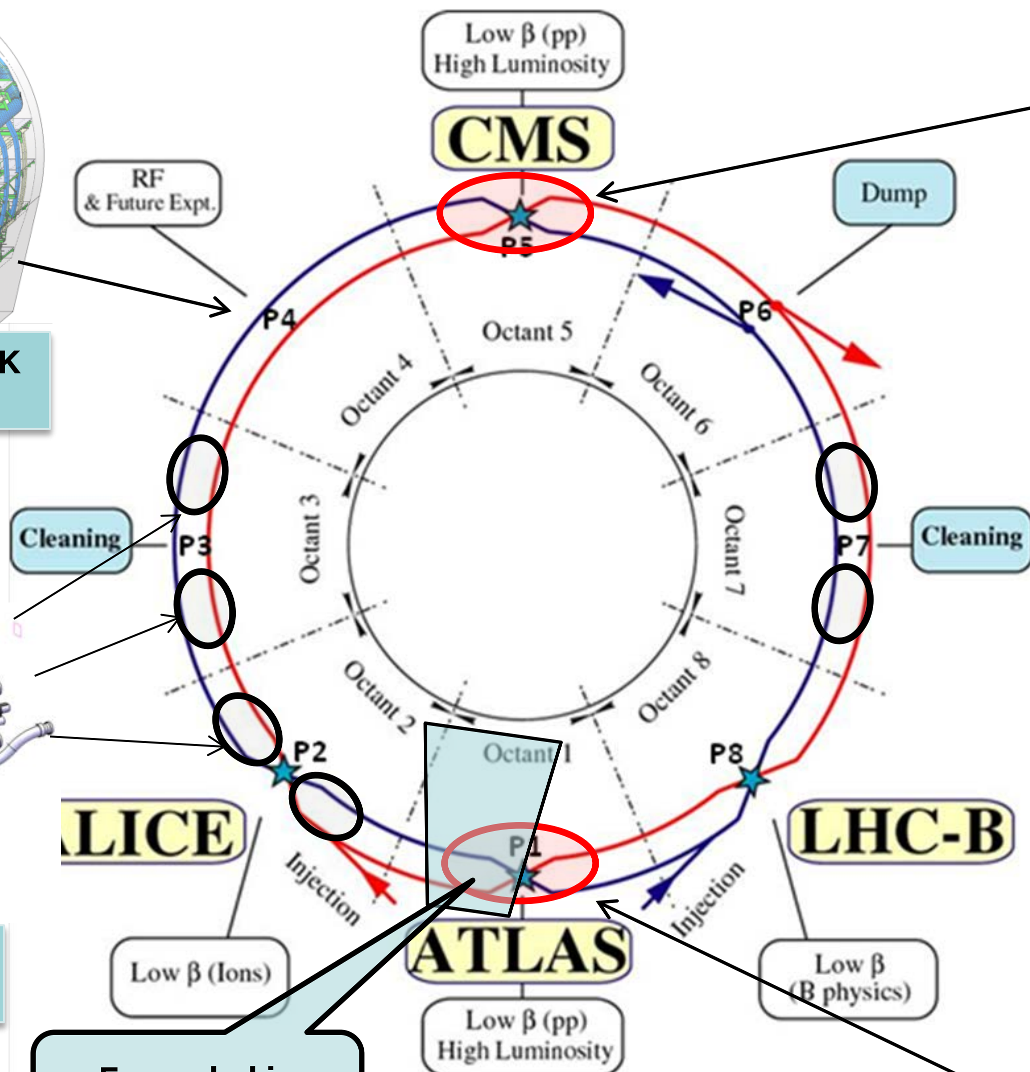
HL-LHC project
Changes around the ring



6.5 kW @ 4.5K cryoplant



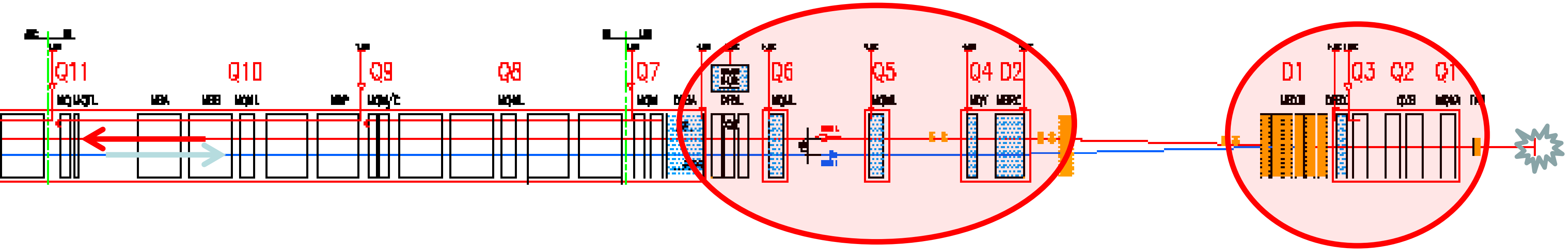
11 T dipoles with cryocollimator



Expanded in next slide

2 x 18 kW @ 4.5K cryoplants for IRs

HL-LHC Project
Changes to the Interaction Regions



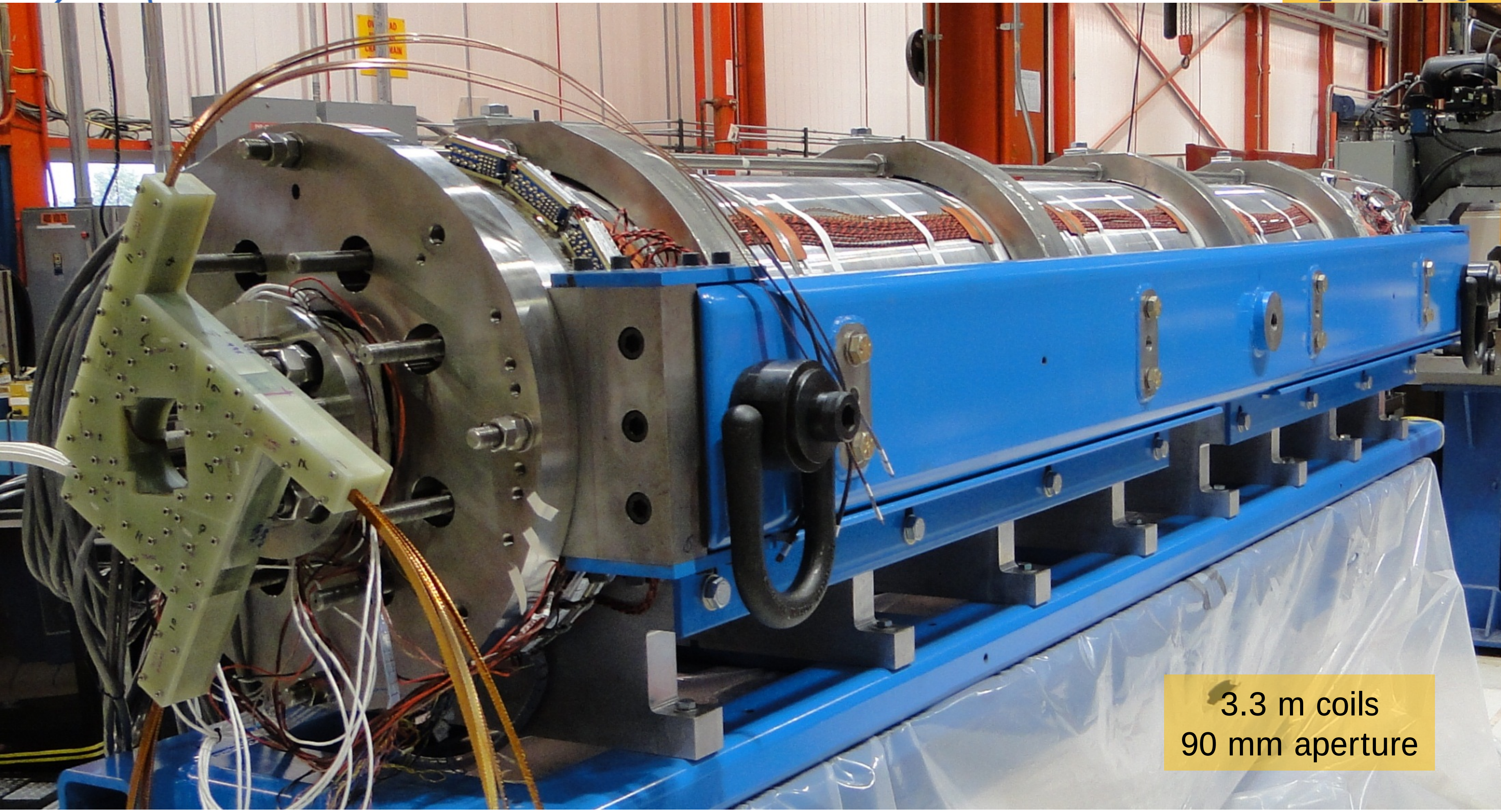
2. Deep changes in matching section: magnets, collimators and SC RF «crab cavities»

1. New magnets in the IRs and interface to detectors; relocation of Power Supplies via use of SC links

1EPoE1-04 – Tuesday (Poster)
Cooling options for the LHC high-luminosity upgrade final focusing magnets

Development of high-field magnets

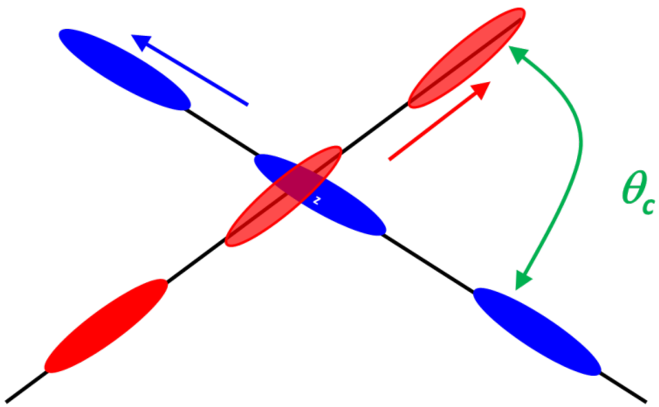
LARP long Nb_3Sn quadrupole

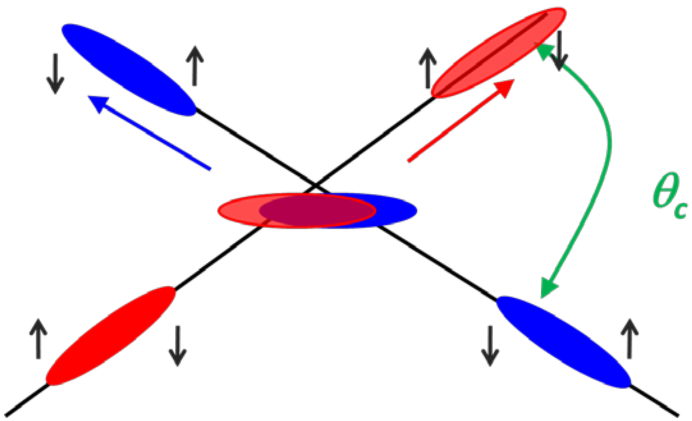


Target:
200 T/m gradient at 1.9 K

LQS03: **208 T/m** at 4.6 K
210 T/m at 1.9 K
1st quench: 86% s.s. limit

Development of SC «crab» cavities



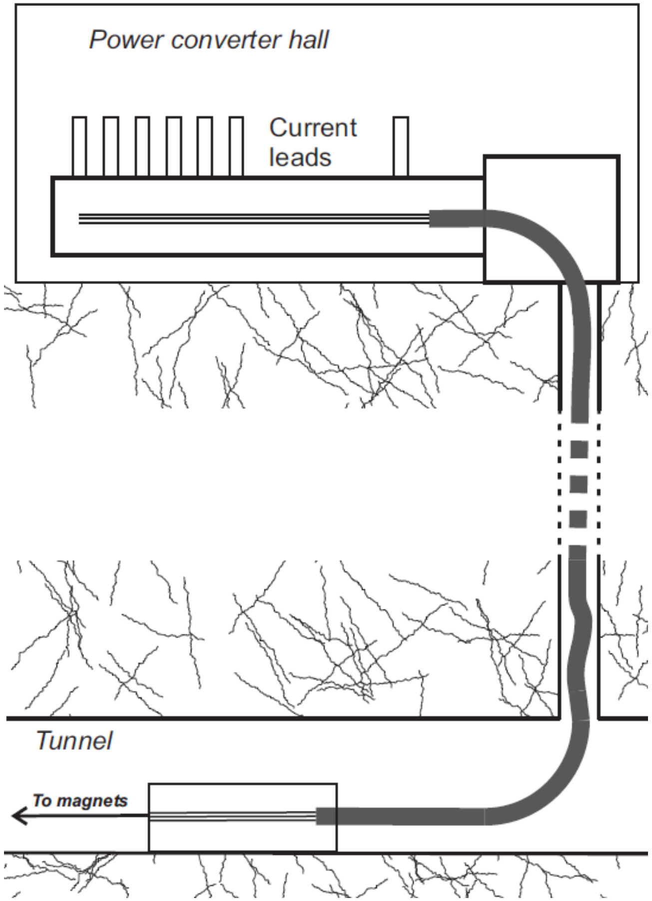


Brookhaven National Laboratory (USA)

Old Dominion University & Jefferson Lab (USA)

Cockroft Institute & Lancaster University (UK)

SC links for HL-LHC



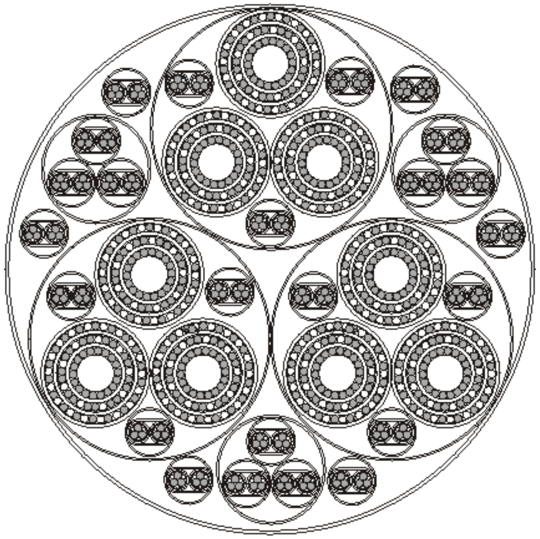
Compound SC cable using MgB_2 wires

27 cables 6000 A

48 cables 600 A

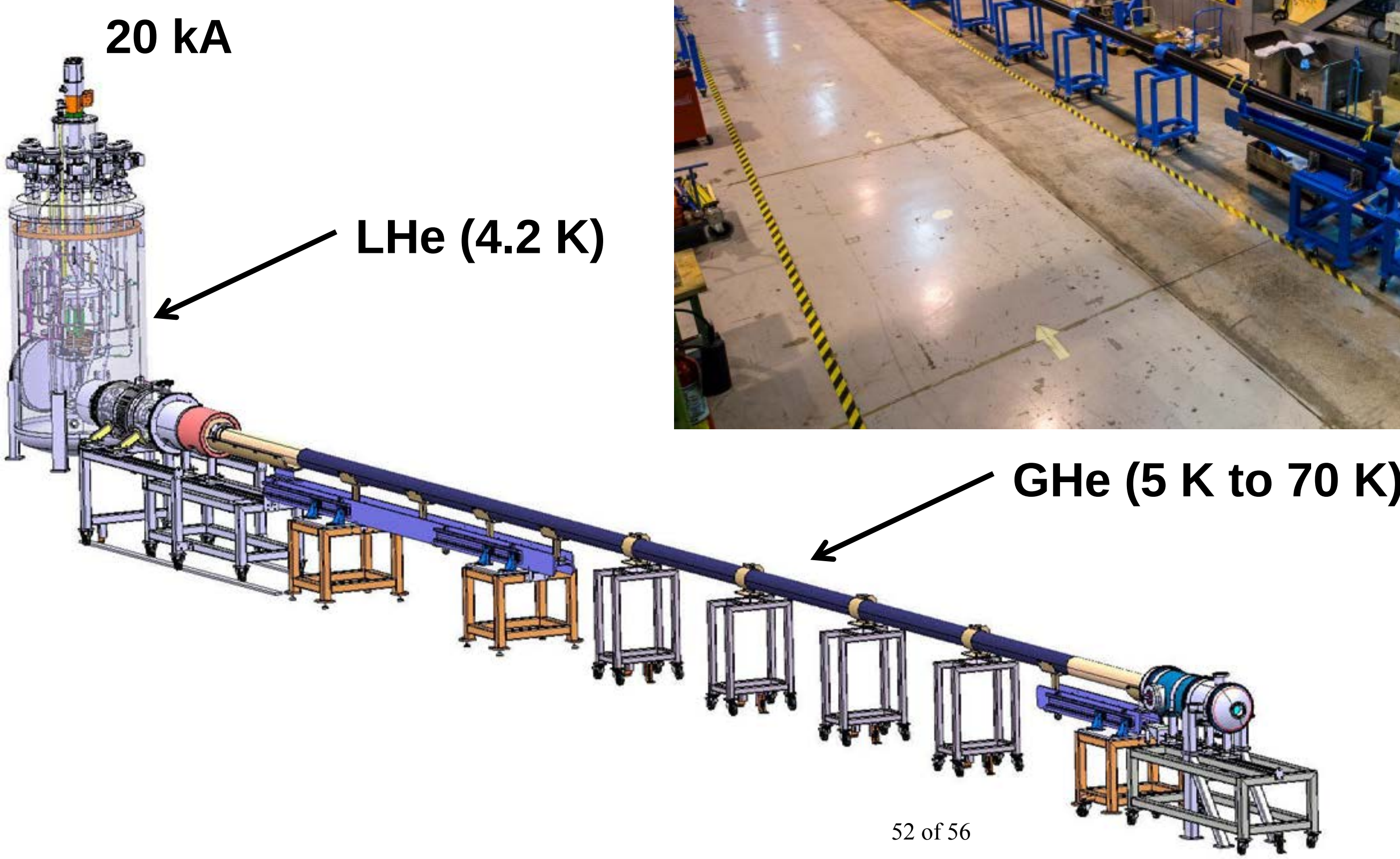
Itot = 190 kA (~2 × 95 kA)

Total length of conductor ~1000 km



A. Ballarino

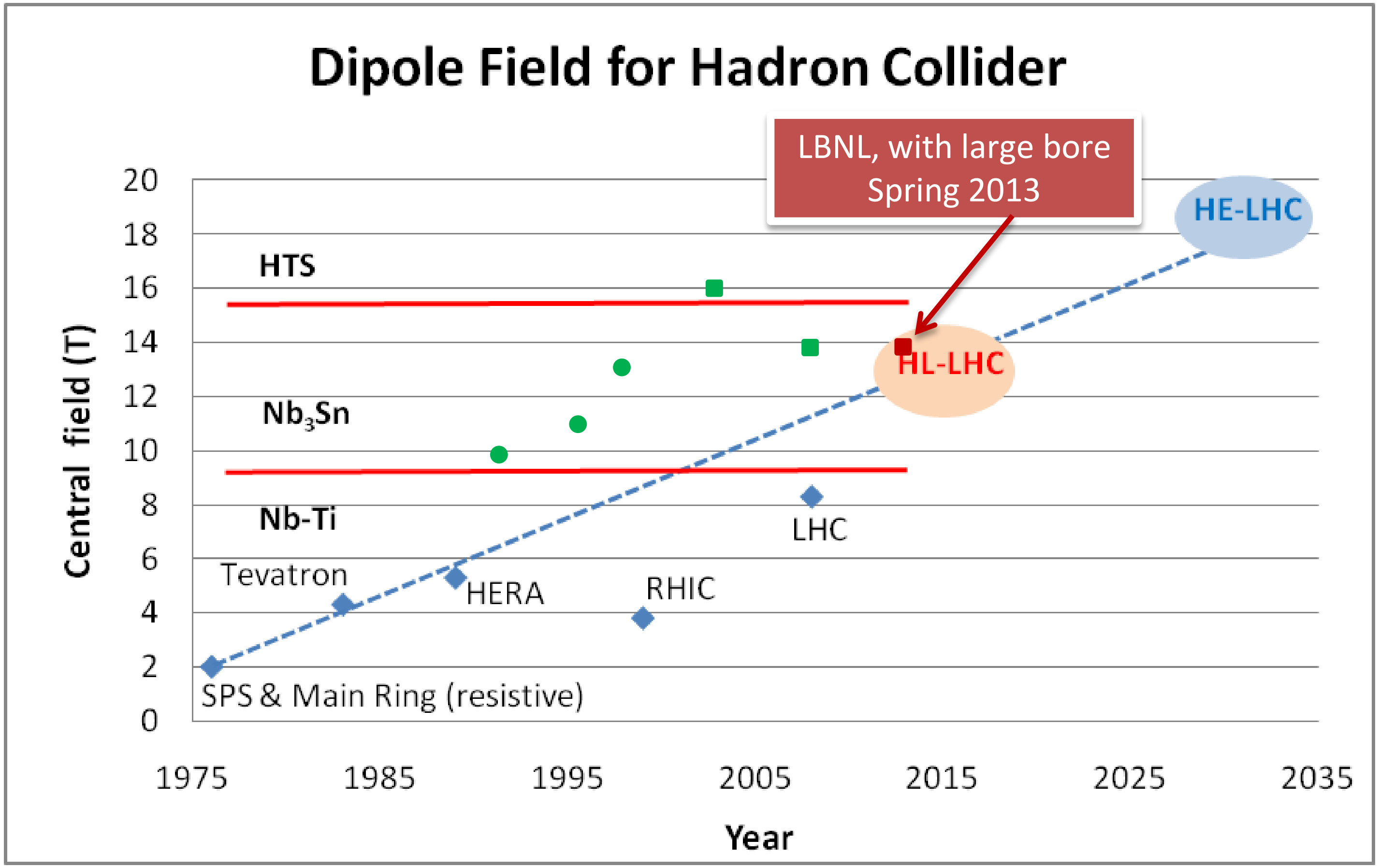
Test station for SC links



A. Ballarino

LHC beyond 2030

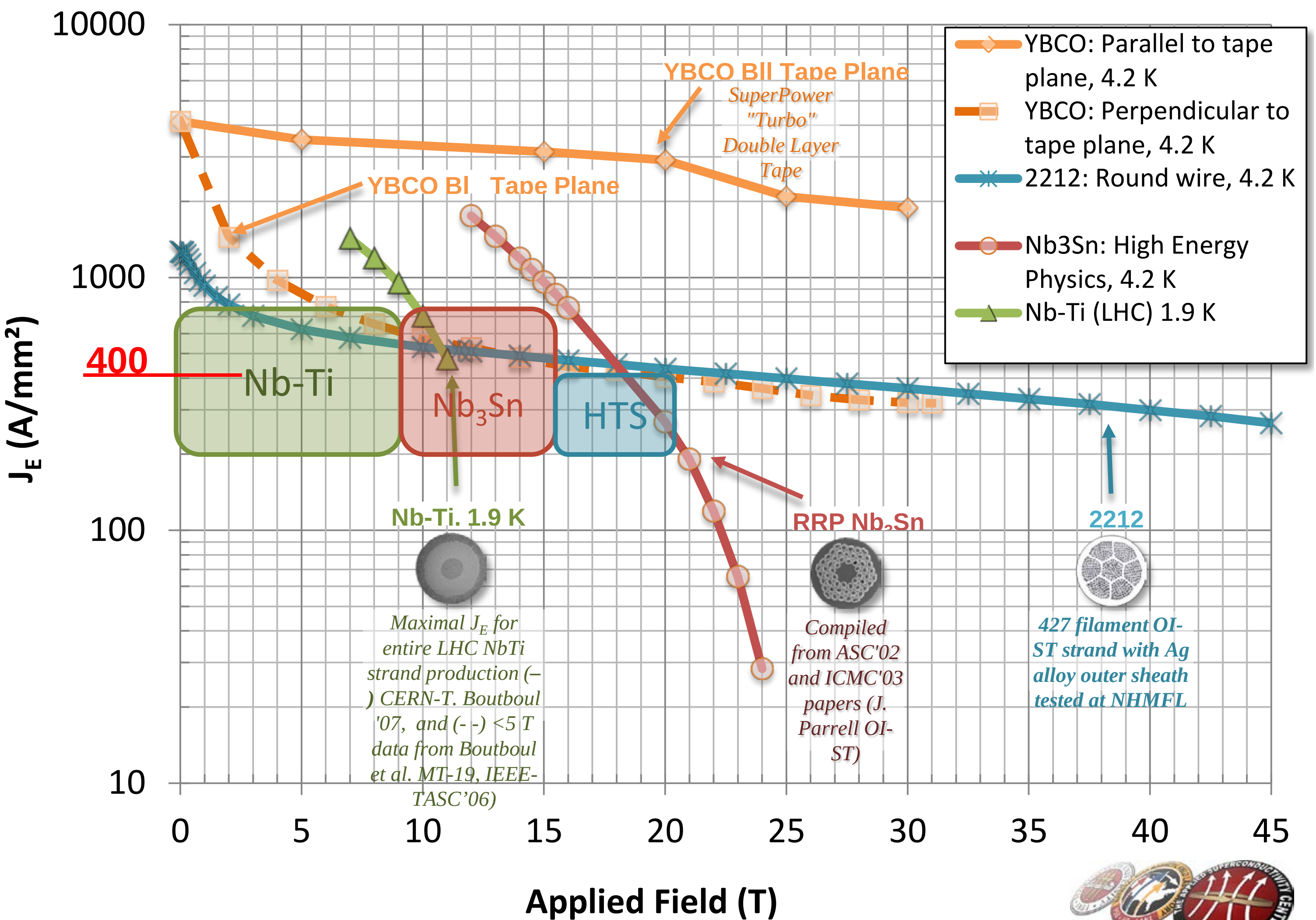
Key technology: very high-field magnets



◆ Nb-Ti operating dipoles ● Nb3Sn cosϑ test dipoles ■ Nb3Sn block test dipoles

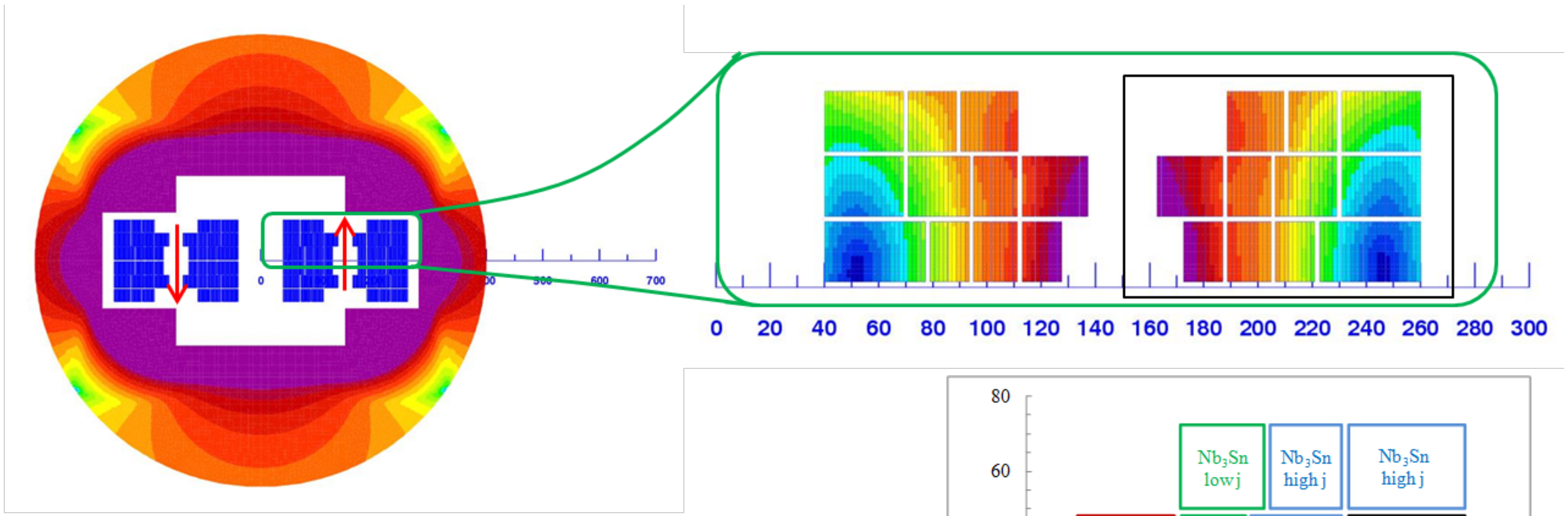
L. Rossi

Staging of superconductors minimizes use of (expensive) HTS

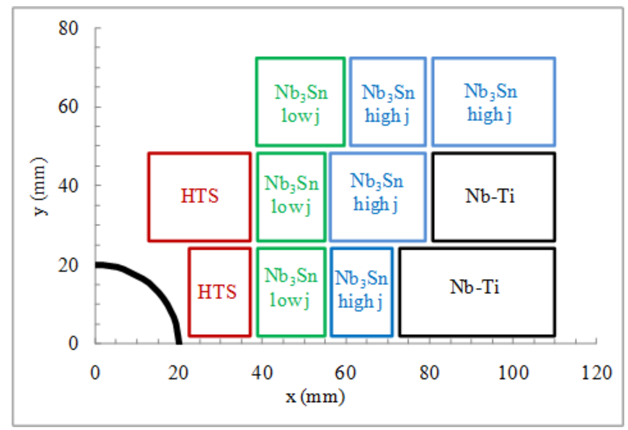


Conceptual design for a 20 T twin dipole

Nested coils using multiple superconductors



Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380



Would yield 33 TeV collision energy in LHC tunnel, 100 TeV in new 80 km tunnel

Magnet design very challenging: 300 mm inter-beam; anticoils to reduce stray flux; multiple powering in the same magnet for field quality

L. Rossi & E. Todesco

Conclusions

- The LHC, the largest application of high-field superconducting magnets and superfluid helium cryogenics, has been running smoothly up to **8 TeV** collision energy
- After three years of operation delivering an integrated luminosity of 30 fb^{-1}, the discovery of a **Higgs boson** is the first major physics result, calling for further studies of the properties of this new particle
- Exploitation of the **full potential** of the LHC is the first priority of the European Strategy for Particle Physics, recently updated and approved by the CERN Council
- 2013-2014 will be occupied by a **long shutdown** primarily devoted to consolidation of the magnet interconnections, in order to ultimately reach **14 TeV** collision energy
- The **luminosity upgrade** program HL-LHC, developing along several parallel lines including high-field magnets using Nb_3Sn and SC RF «crab» cavities, will enable to deliver 3000 fb^{-1} by 2035
- These technological developments open the way for **possible energy upgrade** with collision energy around 30 TeV using 16 to 20 T magnets in the same tunnel, or up to 100 TeV in a new ~80 km tunnel