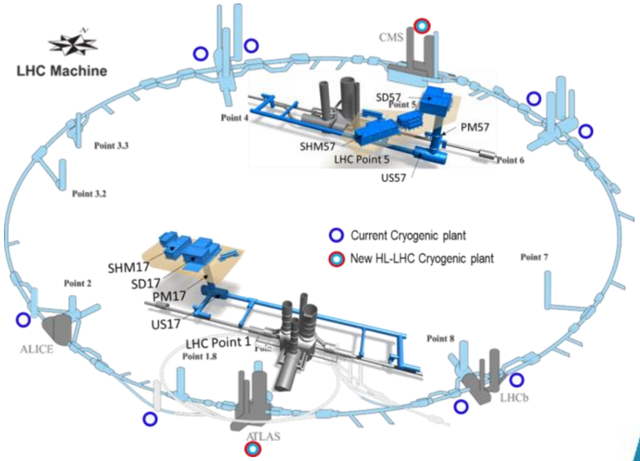
Industry Workshop on Cryogenics in Big Science, Paris, 16th to 17th April 2024

The cryogenic system for the High Luminosity upgrade of the Large Hadron Collider at CERN

A. Perin, S. Claudet, CERN, TE-CRG

Outline

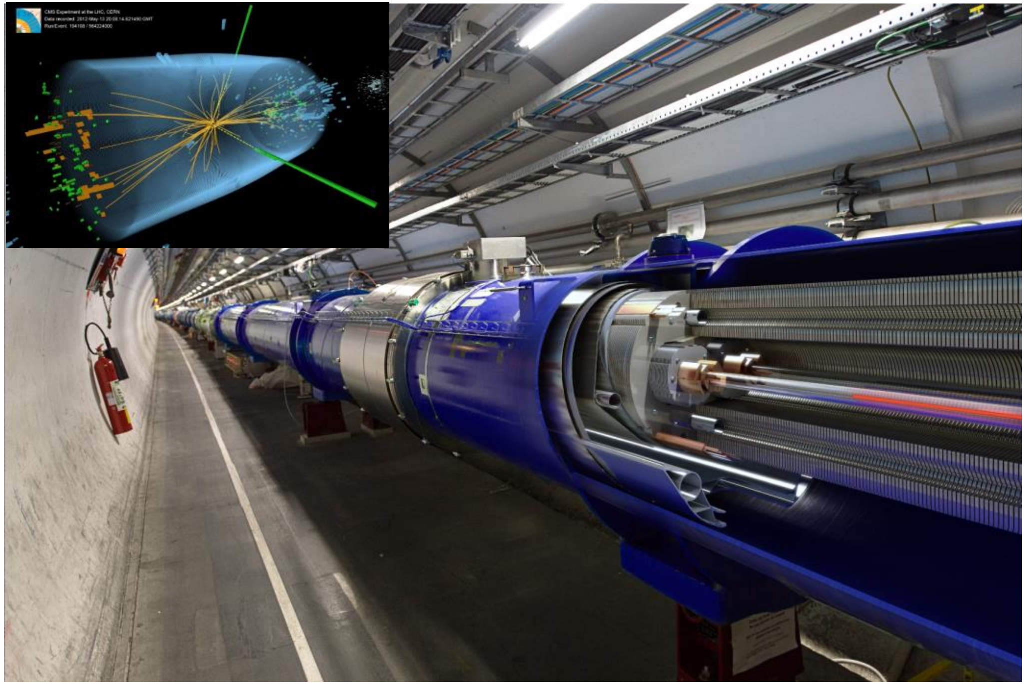
- The Large Hadron Collider (LHC) and the HL-LHC project
- HL-LHC Cryogenics scope and architecture
- Refrigerators and Cryogenic distribution line
- Complementary items
- Procurement and Schedule
- Summary



The Large Hadron Collider and its experiments

The LHC accelerator

proton-proton collisions at 2 x 7 TeV, 500 MJ stored energy in the beams



2007-2009: Cool-down and commissioning

2010-2012: Collisions and Higgs boson discovery

Picture July 2012

Since: many more Higgs bosons and all kind of physics.

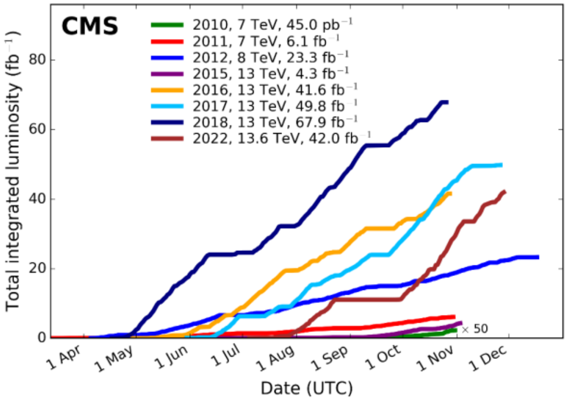
24 km of superconducting magnets (8.33T) @ 1.9K, 140t Helium

Why the High Luminosity LHC project ?

Many questions remain !

- Higgs properties [coupling]
- More than one Higgs?
- Beyond Standard Model Physics? Dark Matter & Dark Energy?

➔ Need **more Data and Statistics** !!



➔ The final focusing magnets will also need to be replaced because of radiation damage.

$$\frac{dR}{dt} = L\sigma_p$$

dR/dt : number of events per second
L : luminosity
σ_p : event production cross section

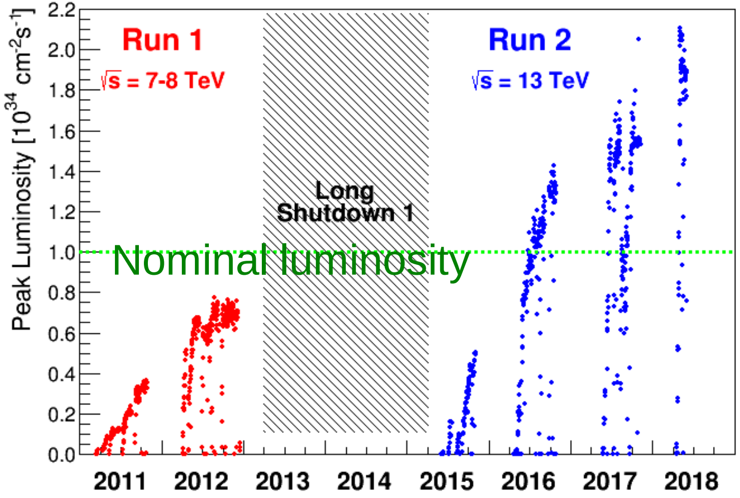
HL-LHC Goals

- Extend the LHC lifetime by 15+ years
- Prepare the machine for producing in that period 10 times more data as compared to the nominal LHC operation period

NB: doubling the accuracy for the experiments would require 4 times the data volume (over 20 Years of operation with current peak performance after end of Run 3)

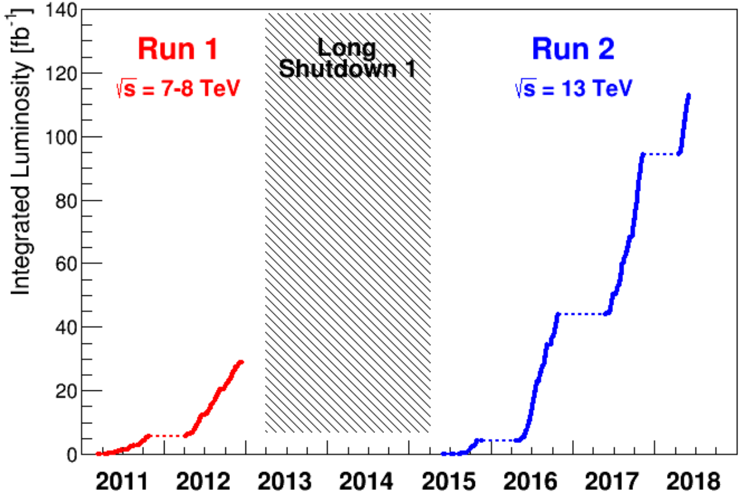
Basic performance indicators of a particle collider

Peak Luminosity
=> Performance



“ The potential of the facility”

Integrated Luminosity
=> Qualification – Global availability - Time

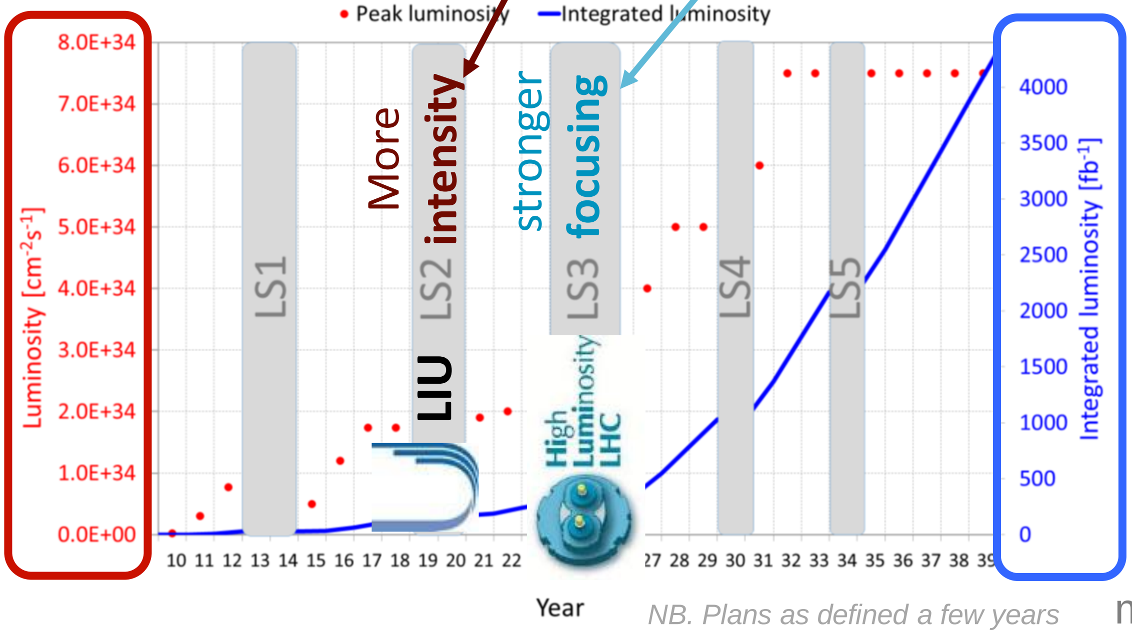


“What allows science” (statistics)

Towards higher collision rates

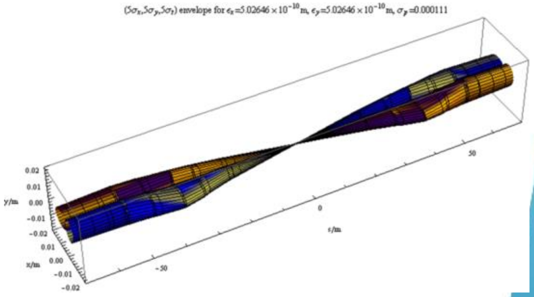
New discoveries and precision measurements need integrated luminosity !!!

Luminosity = f * N^2 / $4\pi\sigma^2$ → Need for more protons in a smaller cross section !!!



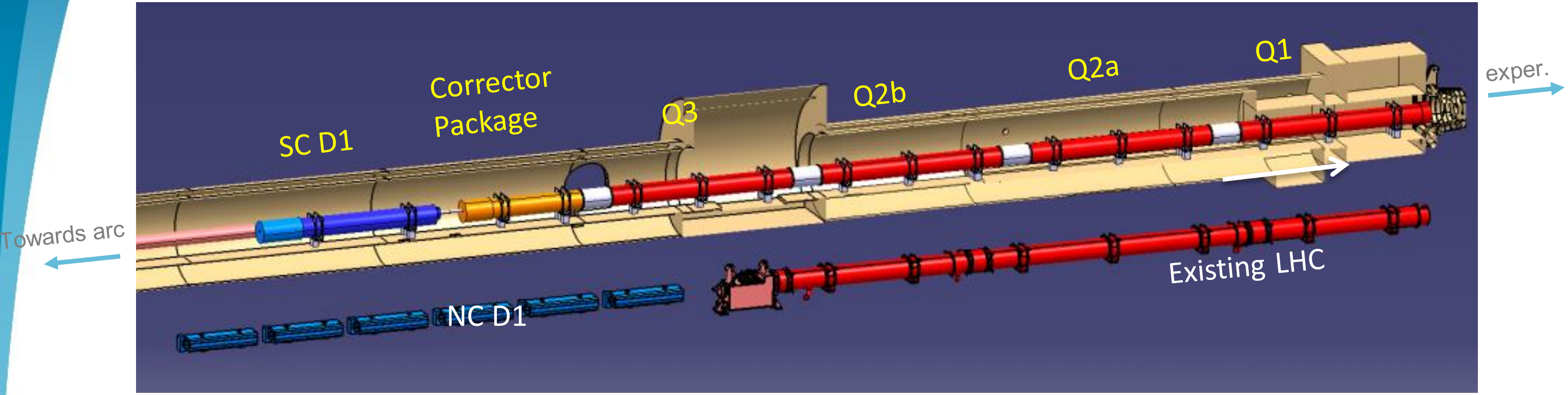
NB. Plans as defined a few years ago, timing not up-to-date

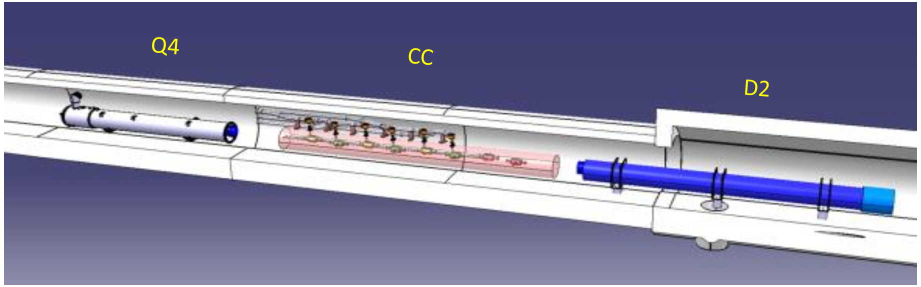
Target for physics: doubling integrated Luminosity for each new run



more powerful final focusing !

Final focusing: from LHC to HL-LHC



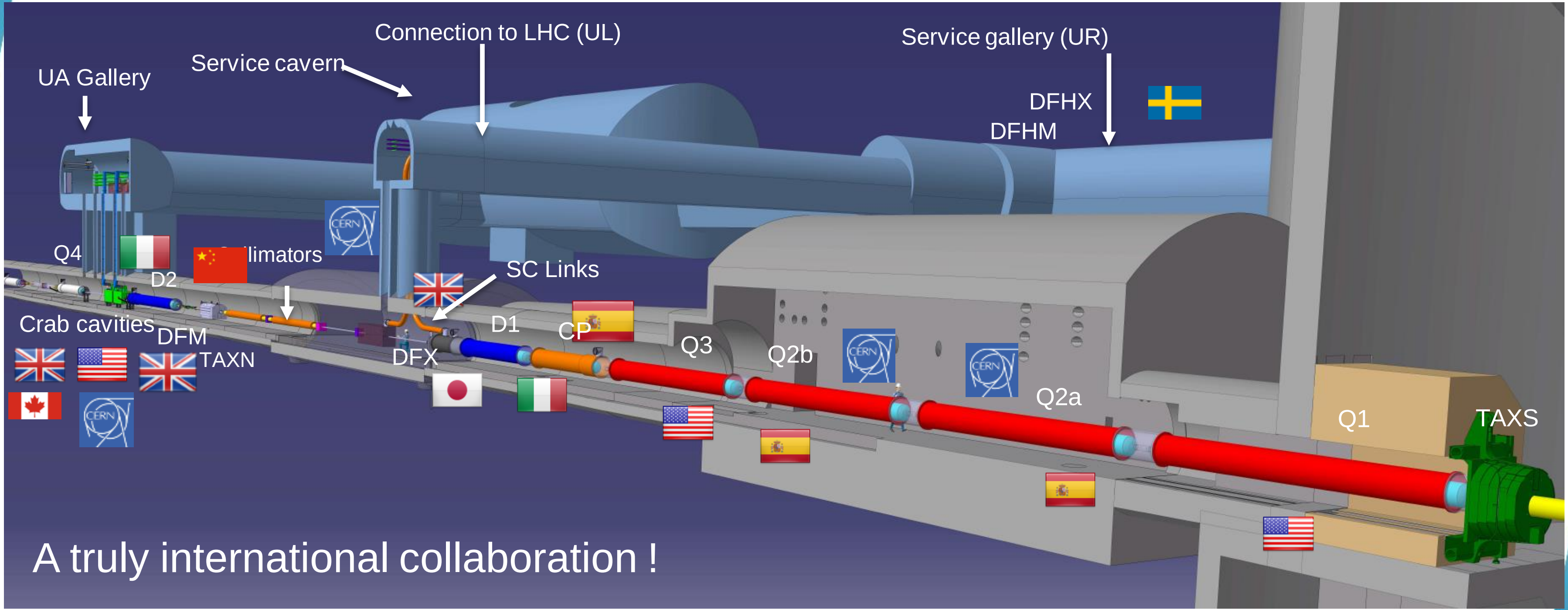


HL-LHC relies on:

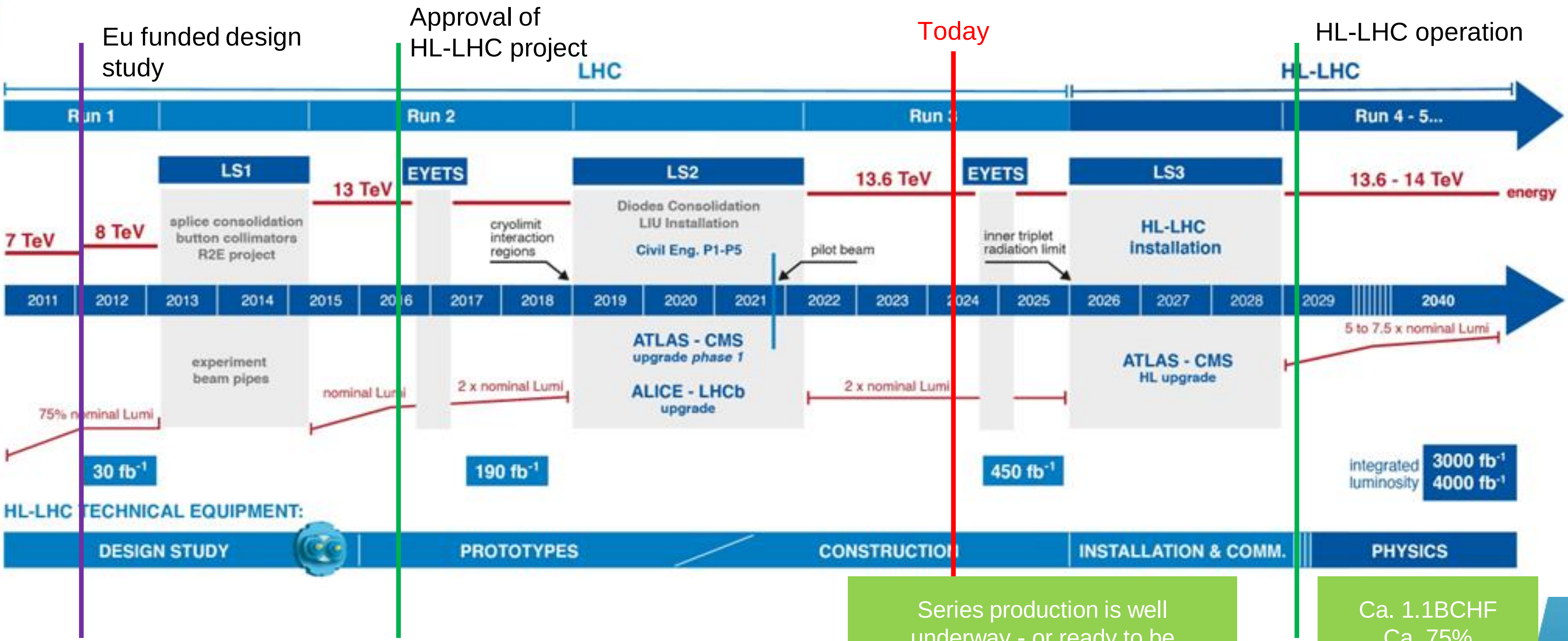
- more powerful final focusing quadrupoles, associated recombination dipoles
- crab cavities.

Local heat loads expected x5 w.r.t LHC !

Overview of underground configuration at IP5



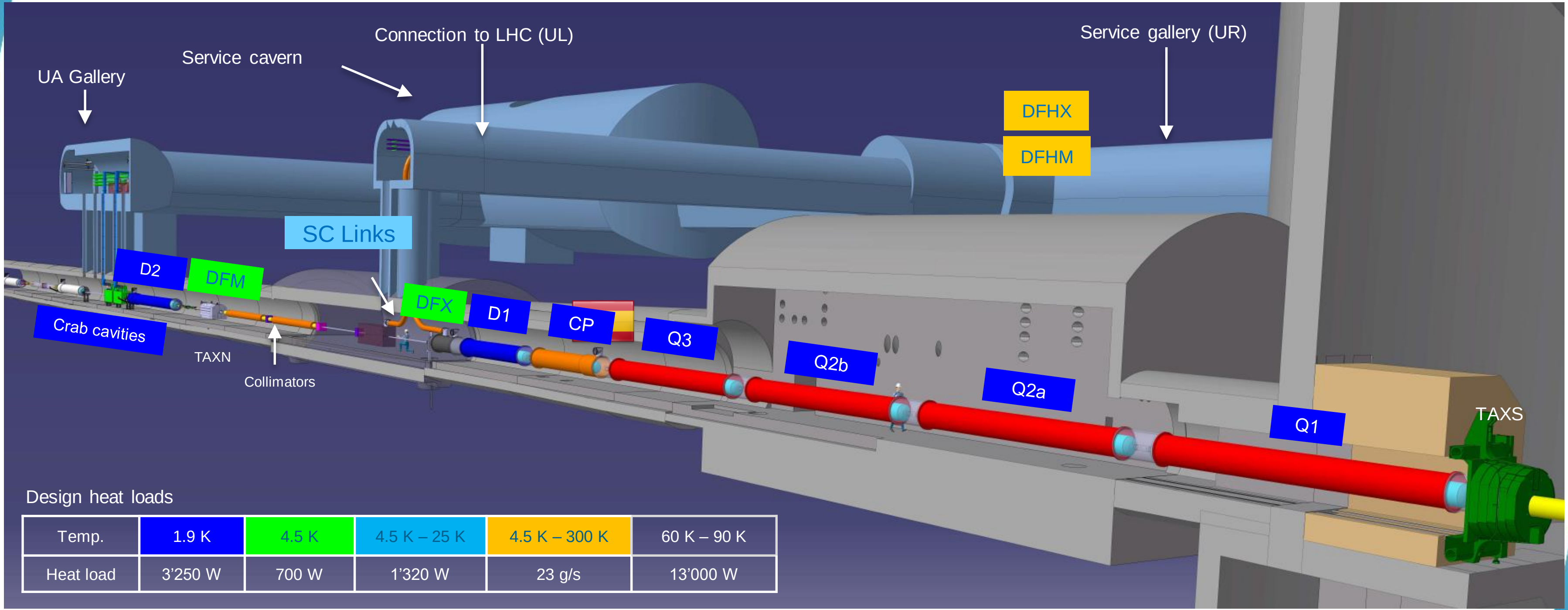
Timeline of LHC and HL-LHC



Series production is well underway - or ready to be launched - for all components!

Ca. 1.1BCHF
Ca. 75% committed

What needs to be cooled

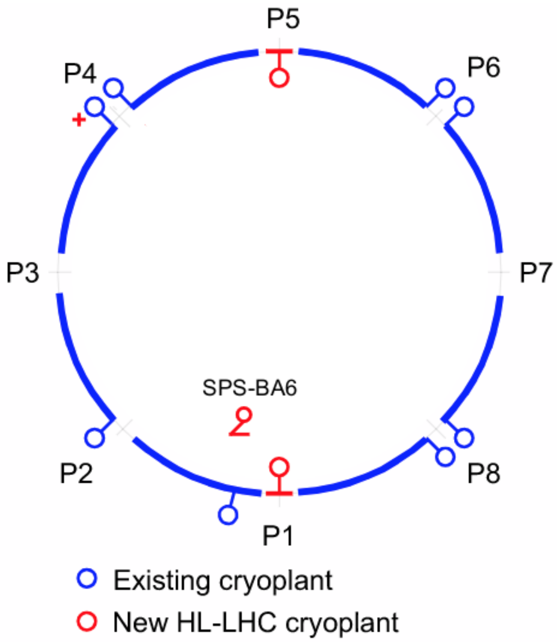


Design heat loads

Temp.	1.9 K	4.5 K	4.5 K – 25 K	4.5 K – 300 K	60 K – 90 K
Heat load	3’250 W	700 W	1’320 W	23 g/s	13’000 W

SC magnets beam screens are cooled at 60-90 K

HiLumi-Cryogenics, Global scope overview

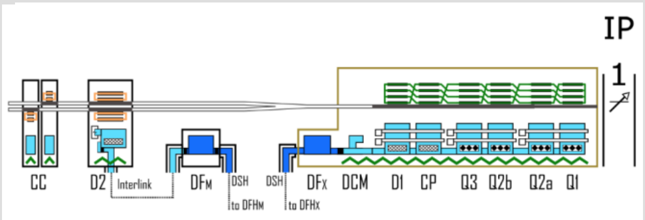


P1-P5: 2 new cryoplants (~14 kW @ 4.5 K incl. 3.25 kW @ 1.9 K) and 2 x 750m cryo-distribution for high-luminosity insertions

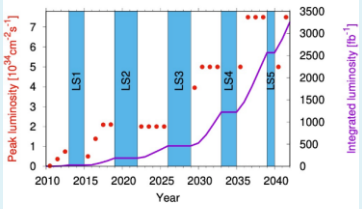
To provide adequate cooling for:

P4: upgrade (+2 kW @ 4.5 K) of an existing LHC 18 kW @ 4.5K cryoplant (completed)
SPS-BA6: SRF test facility with beam primarily for Crab-Cavities (completed)

P1-P5 machine devices



HL-LHC performance



HL-LHC P1/P5 Cryogenic architecture

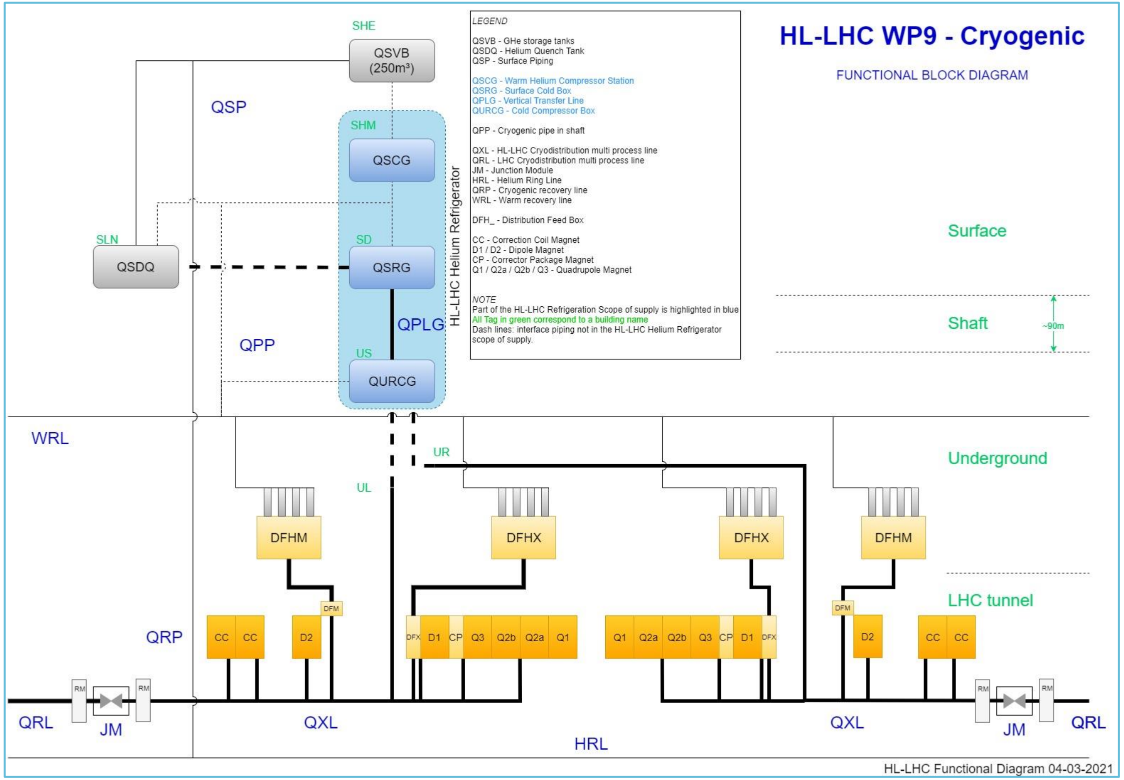
QSCG : Compressor station providing gaseous helium **20 bara**

QSRG : 4.5K refrigerator providing supercritical helium at **3 bara and 4.6 K**

QPLG : Vertical transfer line (~100 m height)

QURCG : Cold compressor box providing cooling capacity at **1.8 K**

Users at tunnel level

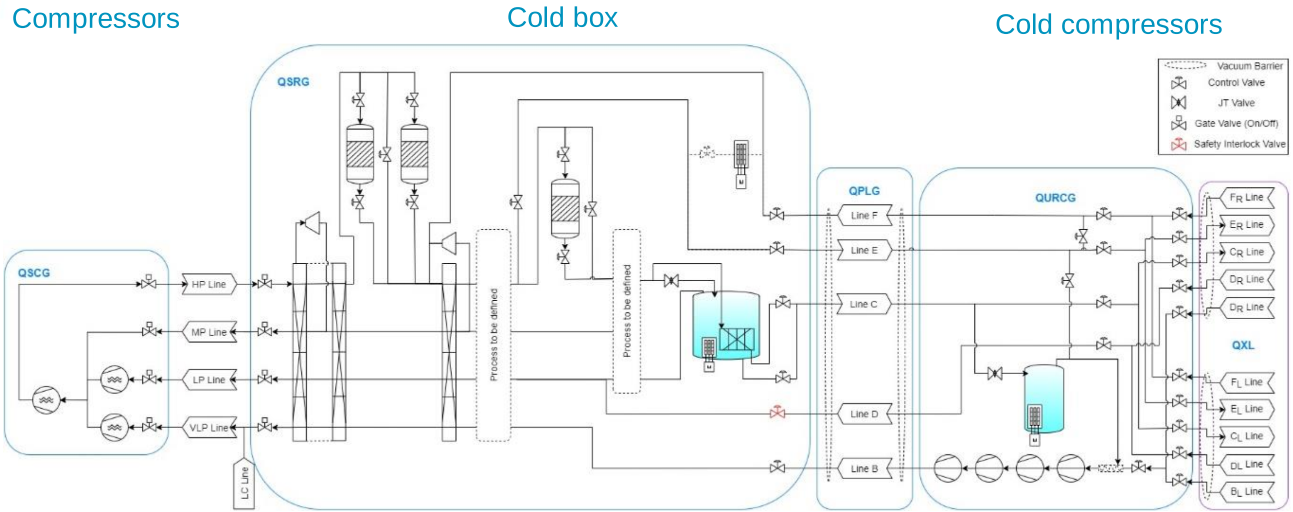


QSVB : 2x 250 m^3 storage tanks

QXL : Distribution line distributing C,E and returning B,D,F
- 70 m for the common branch
- 270 m for the long branch
- 60 m for the short branch

RM/JM : Return module and junction module at extremities for transient handling and back-up

Cryogenic process



Impeller of an LHC cold compressor stage

14kW@4.5K equivalent

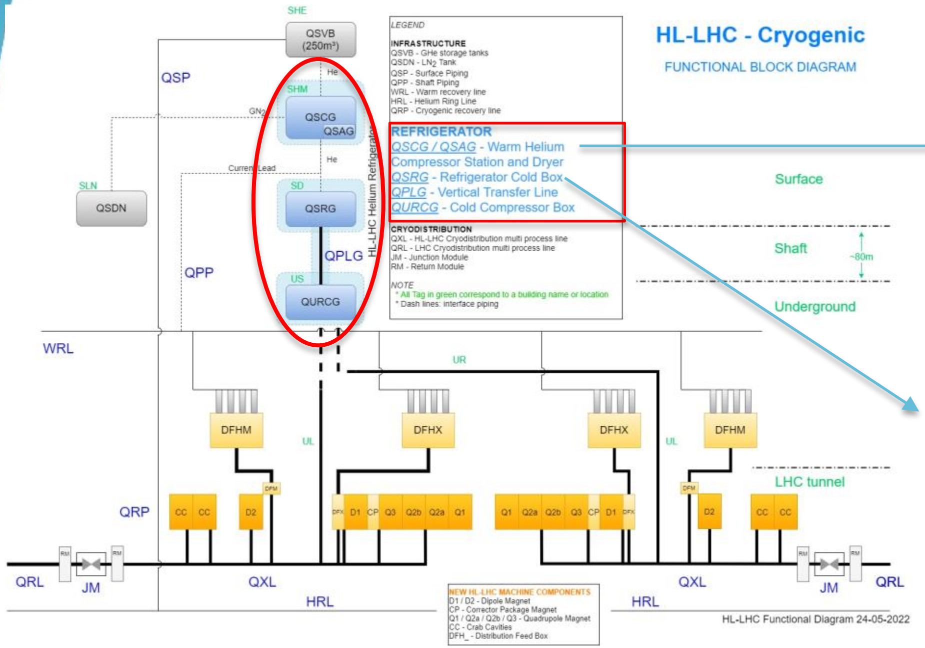
including 3.25kW@1.9K

Operating modes heat loads

Temp. level OP mode	1.9 K	4.5 K	4.5 K – 25 K	4.5 K – 300 K	60 K – 90 K
Max.	3’760 W	-	1’320 W	23 g/s	13’000 W
Design	3’250 W	700 W	1’320 W	23 g/s	13’000 W
Turndown	1’100 W		700 W	10 g/s	6’000 W

Helium Refrigerators at LHC P1 and P5 for HL-LHC

P1-P5 Cryogenic Architecture



Helium Refrigerators

2 x 14kW@4.5K, including 3.25kW@1.9K

LHC Helium Refrigerators
similar capacity required
for P1 and for P5,
in addition to 8 existing ones

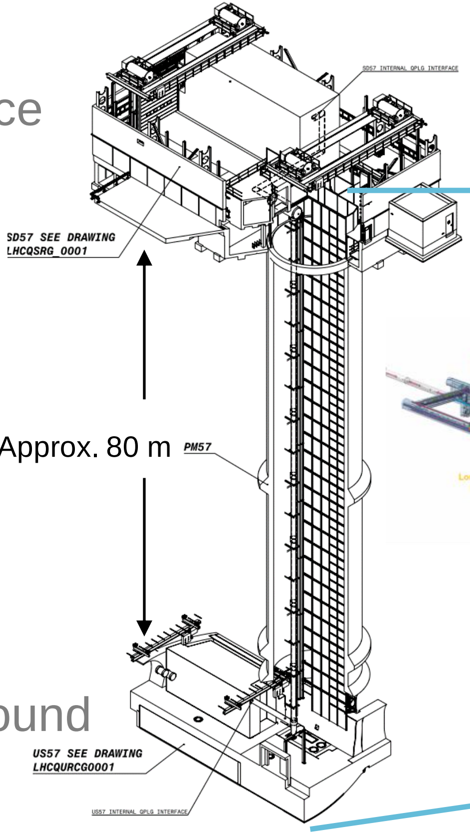
Compressor station
(100t, 4MW input power)

Cold boxes from world-wide leading industries:
(>100t, Heat exchangers, expansion turbines, valves, controls)

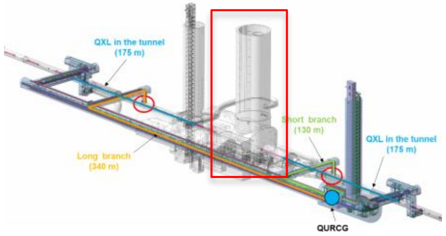
Tendering: Q1-2022, contract Q3-2022

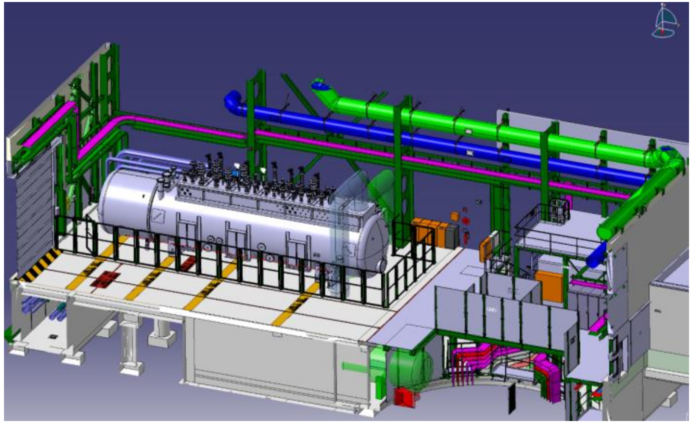
Helium Refrigerators at LHC P1 and P5 for HL-LHC

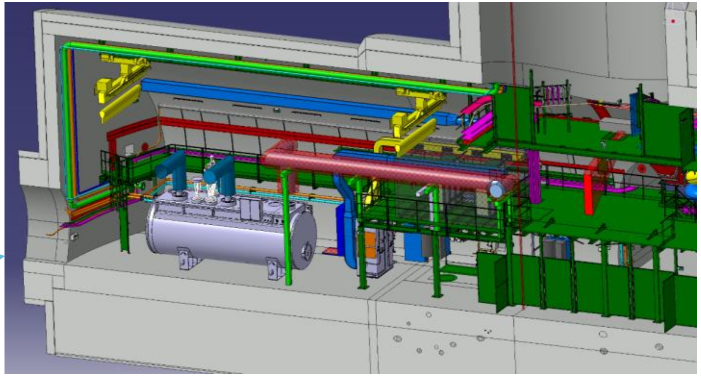
Surface



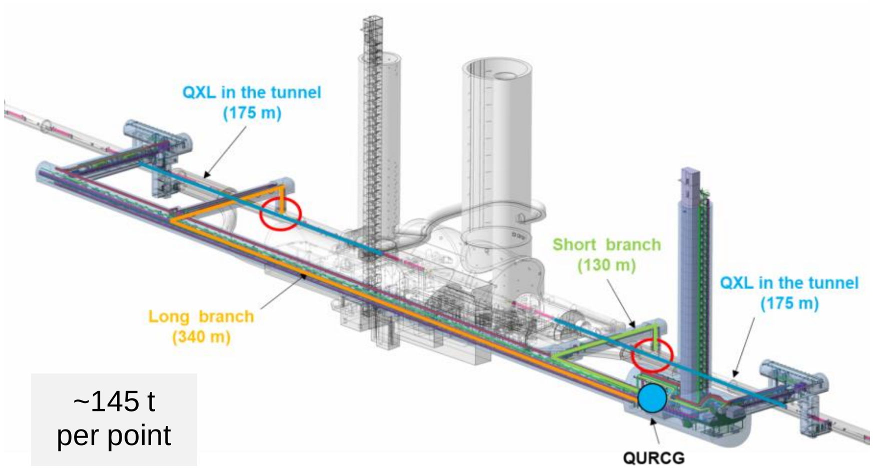
Underground



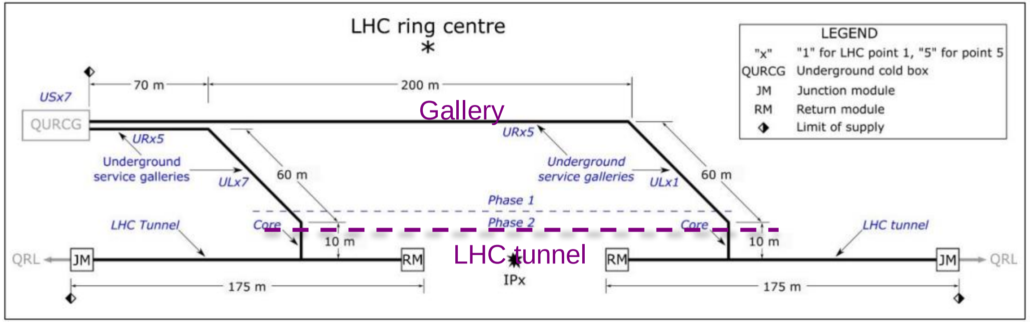




Cryogenic distribution line at P1 and P5



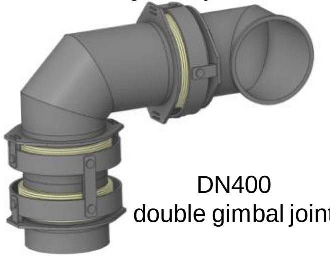
~145 t per point

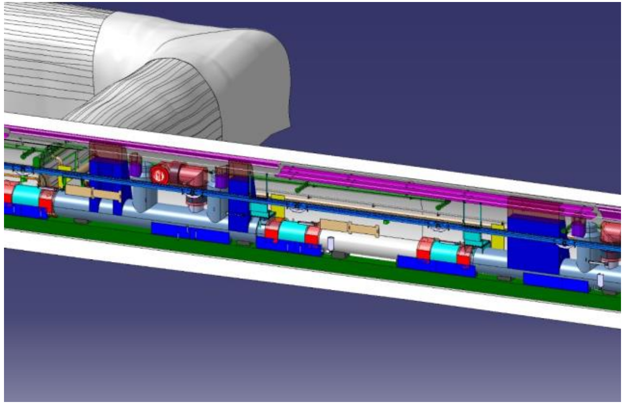


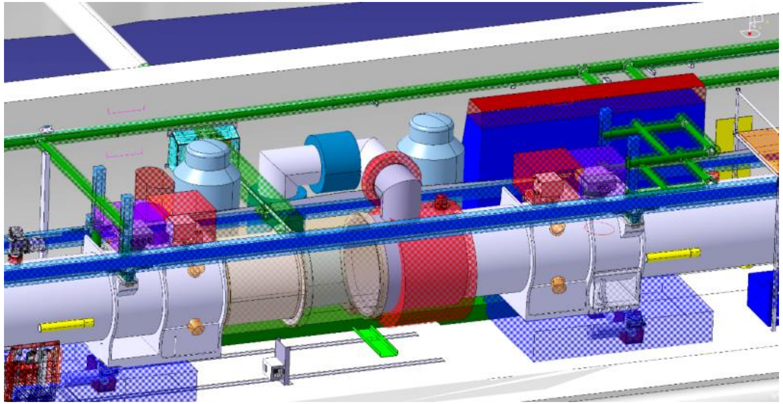
- 2 x 750 m, 5 process pipes, vacuum insulated lines
- Lines diam. 40 - 273 mm, 650 mm - 800 mm

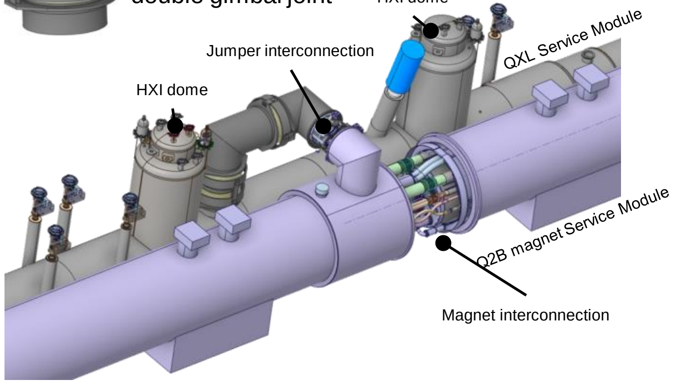
Tendering: Q1-2022, contract Q3-2022

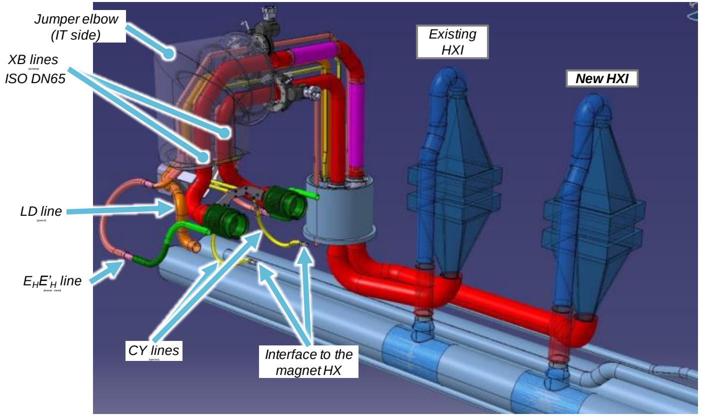
Cryogenic distribution line at P1 and P5: some details









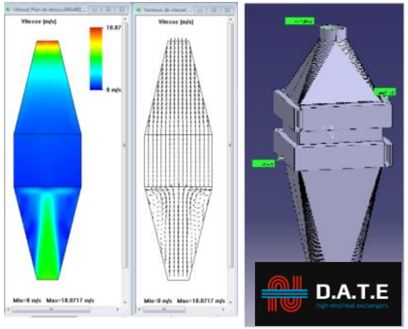


Some specific developments

A selection based on items developped for LHC or specifically for HL-LHC

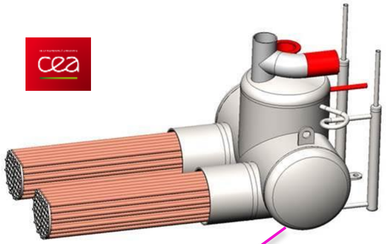
Subcooling Heat exchangers

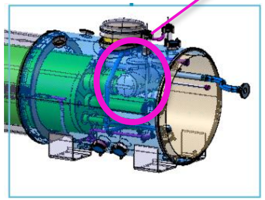
Block ~ 20 x 30 cm, L_tot ~ 1m



HeII Heat exchangers

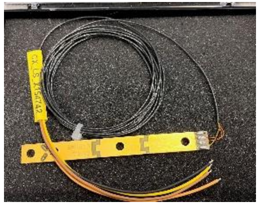
Cu + SS, L_tot ~ 1m





Instrumentation

Accuracy few mK @ 1.9K



Long block

Short block

Specific procurement aspects

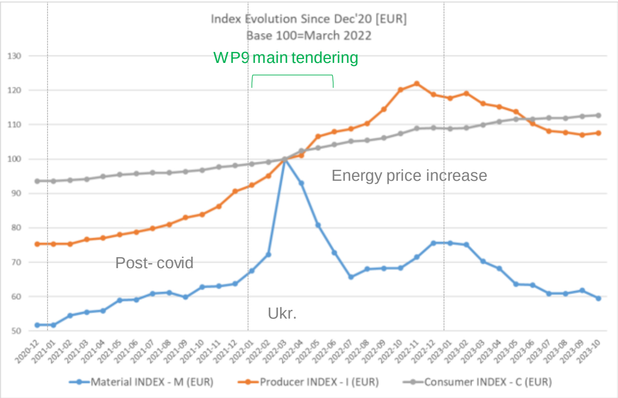
Tendering process for refrigerators

- Q2-Q3 2020: Market Survey **to qualify firms**
- Q1-Q2 2021: **Process & feasibility studies** (minimised risk of mis-understanding)
- Q4-21 - Q2-22: **Invitation to Tender** (extended). A set of requirements (performance, technology) to allow industry to provide the optimum for a given scenario
- **Adjudication: CAPEX + OPEX (10 years)**
- Capacity tests at CERN (bonus/malus)
- Special provisions to take into account large variations of material costs

Taking into account unpredictable cost evolutions

- For long duration and when significant impact of cost of materials. “Shared risk” approach compliant with CERN purchasing rules.
- Itemized price adaptation according to recognized European price indices for Materials (M), Producer (I) and Consumer (U) with specific weights (A, B, C) depending on the type of supply.

$$P = P_0\left(K + A\frac{M}{M_0} + B\frac{I}{I_0} + C\frac{U}{U_0}\right)$$



Main Contractors

Most main contracts have been placed in 2022-2023

Last large activity under definition: removal and reconfiguration of 1 km of existing LHC cryogenic distribution system

Refrigerators: contract signed in November 2022
Selection of single supplier for the two refrigerators

Linde Kryotechnik AG

Linde Engineering Dresden

with major partners identified

ENERPROJECT

AQUAGAS

Cryoworld

KASAG

PBS

Cryogenic distribution: contract signed in December 2022

KrioSystem
CRYOGENICS IS OUR PASSION

4x 250 m^3 storage tanks: contract signed in July 2023

A.SILVA MATOS
METALOMECÂNICA

Masterplan of HL-WP9-Cryogenics

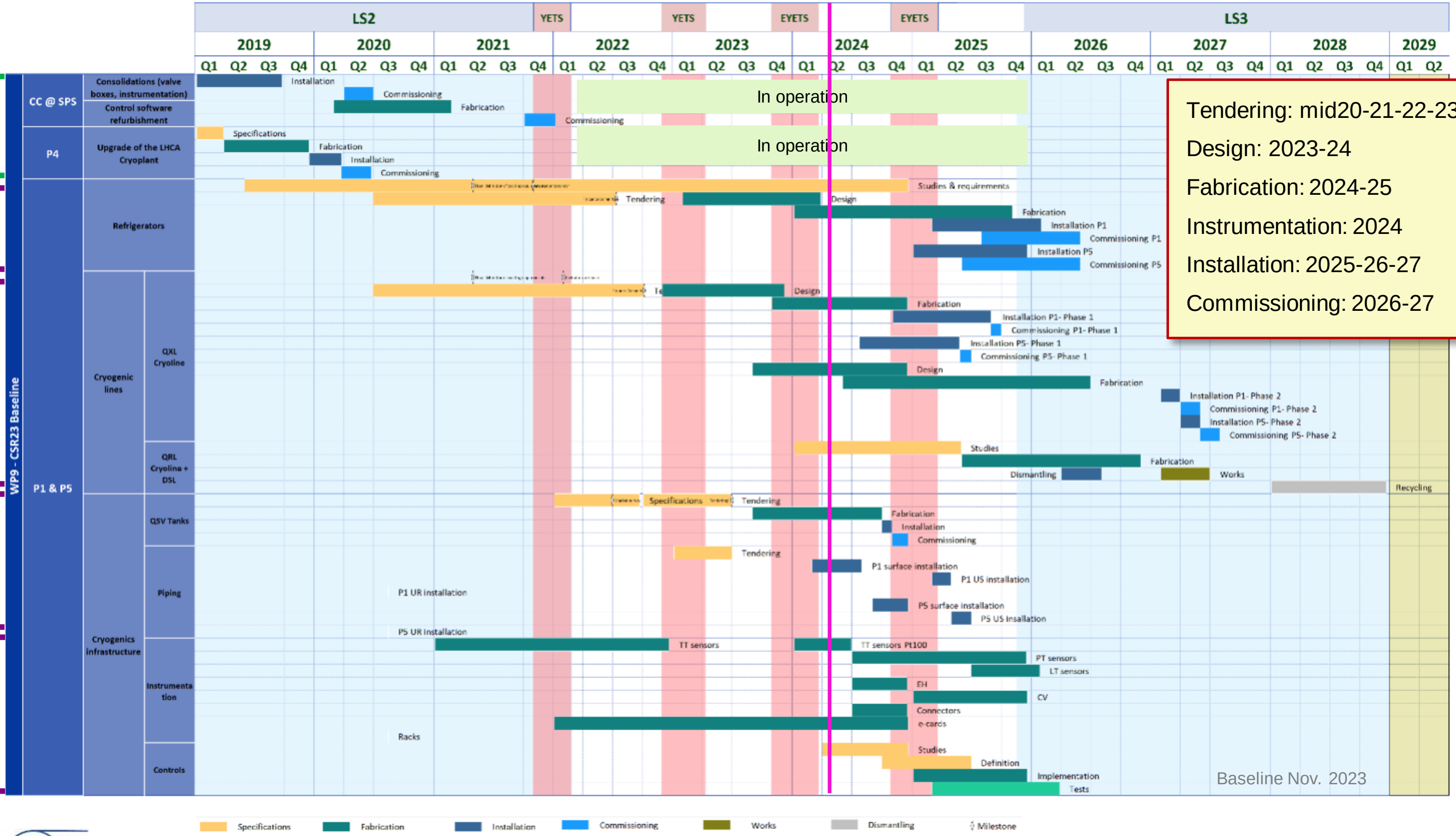
Completed

Refrigerators

Cryolines

Tanks, piping

Instrum.
and controls



Tendering: mid20-21-22-23

Design: 2023-24

Fabrication: 2024-25

Instrumentation: 2024

Installation: 2025-26-27

Commissioning: 2026-27

HiLumi HL-LHC PROJECT CERN

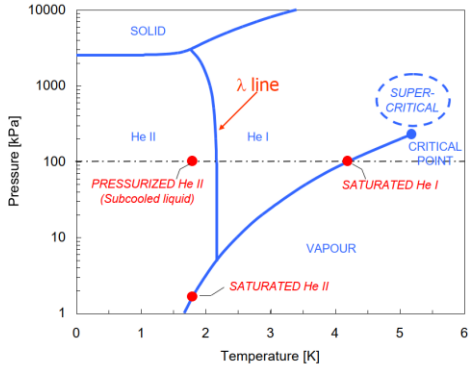
Summary

- The High Luminosity LHC project is a major upgrade of the Large Hadron Collider that will increase its lifetime by 15+ years and will increase its integrated luminosity for the ATLAS and CMS experiments by a factor of 10 over this time period.
- The new final focussing configuration for HL-LHC will generate a significant additional heat load at 1.9 K, therefore requiring two new cryoplants and cryogenic distribution at IP1 and IP5.
- A detailed review of the heat loads was performed, allowing to confirm the refrigeration capacity with final tuning of the global cryogenic architecture.
- Major tenders (Refrigerators, cryogenic distribution line) are completed and the project is now in the execution phase.
- The objective is to commission the refrigerators in 2026, cool-down magnets and CC in 2028 for operation with beams to resume in 2029 for a decade of new physics results !

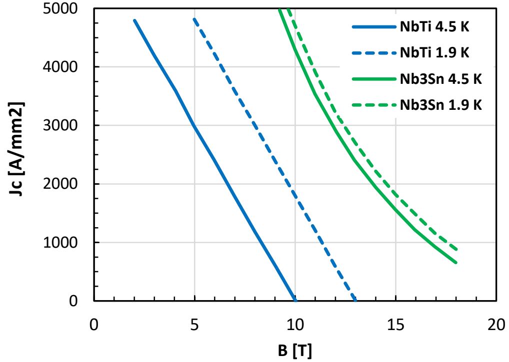
Helium cryogenics and superconductors

Magnets and RF “crab” cavities use superconducting materials

- Superconducting properties improve with lower temperatures
- The requirements for the new focusing quadrupole magnets for HL-LHC imposes Nb_3Sn Magnets (LHC used NbTi magnets) and 1.9 K.
- Pressurized HeII (superfluid) technology developed from LHC for the magnets.
- The niobium “crab” RF cavities will operate at 2 K, saturated helium pressure.

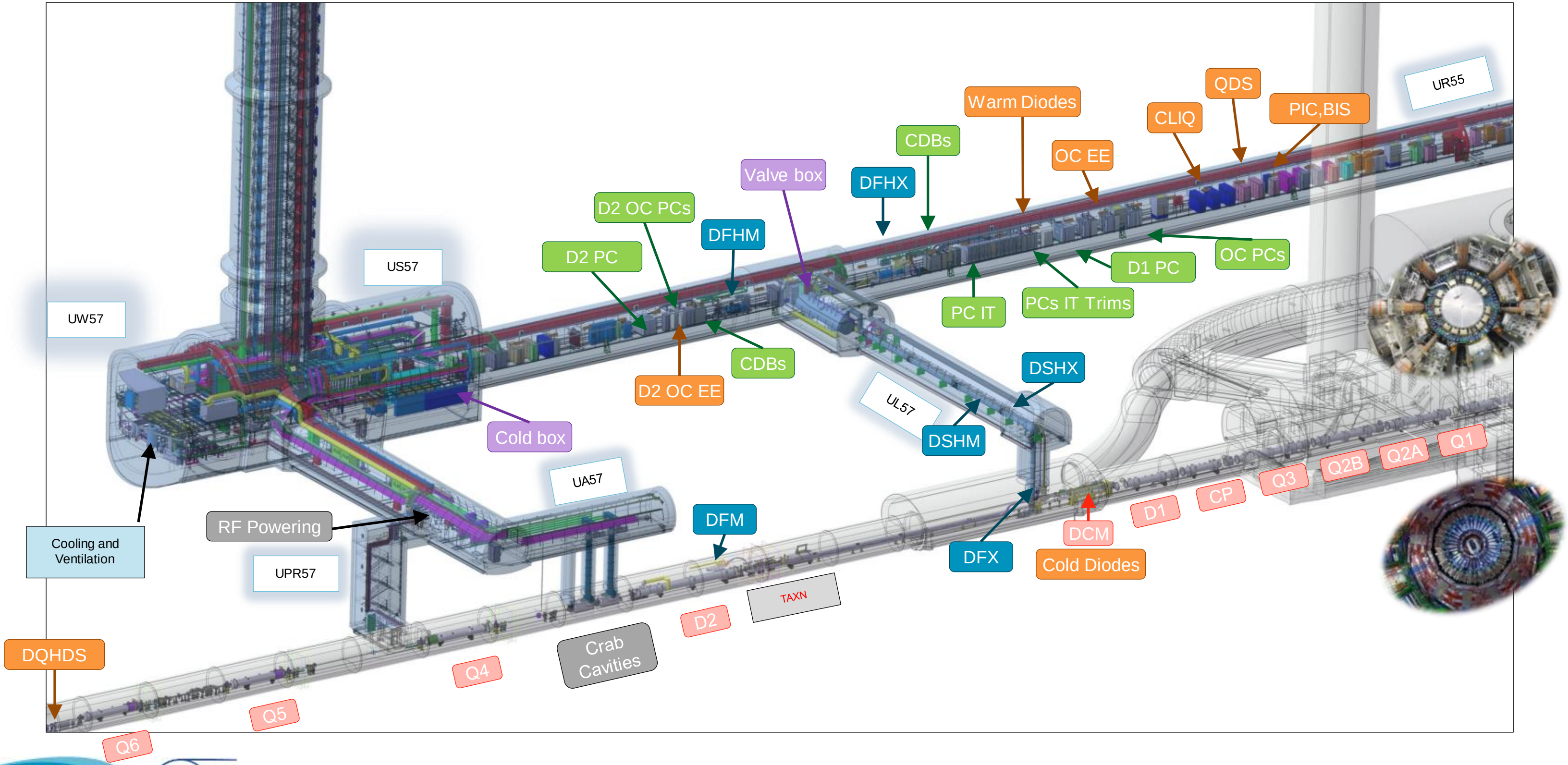


Phase diagram of helium

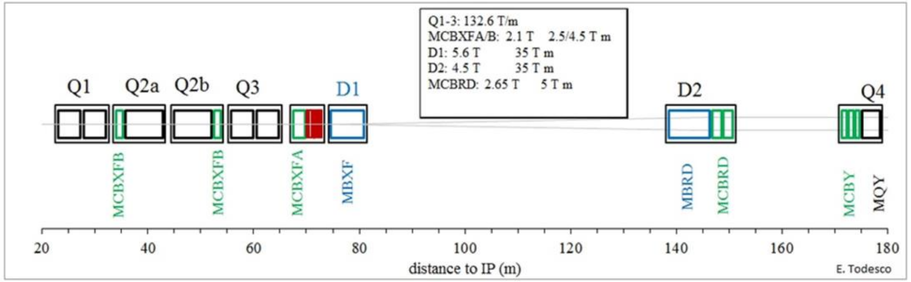


Critical current density of technical superconductors

View with the technical galleries



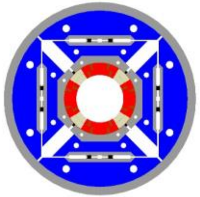
Cryogenics for the HL-LHC magnets



Layout of the HL-LHC magnets

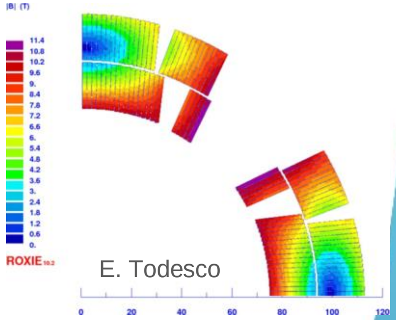
- The main quadrupole magnets in the “triplet” will have a peak field of 12.1 T and need Nb_3Sn superconducting cables.
- Tungsten Beam screens at 60 K – 80 K will be used to absorb most beam induced power from collisions.
- The triplet magnets and D2 will operate at 1.9 K in pressurized helium. Heat load up to 1.3 kW at 1.9 K for each triplet.
- Powering will be performed with MgB_2 SC links (4.5 K – 20 K) and HTS current leads (20 K - 300 K) (liquefaction heat load).

18 kA HL-LHC current leads. A. Ballarino.



MQXF magnet cross-section

E. Todesco

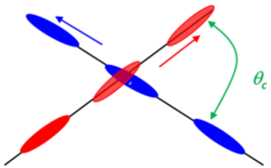


E. Todesco

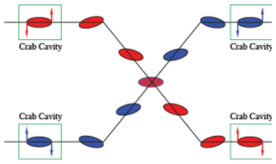
MQXF cross-section, field map at nominal current

MQXF magnet main data (E. Todesco)
Nominal Gradient 132.6 T/m
Aperture diameter 150 mm
Peak Field 11.4 T
Current 16.2 kA
Stored Energy 4.9 MJ (1.17 MJ/m)

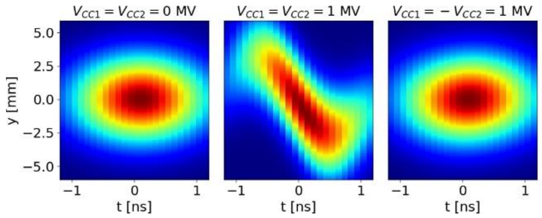
The SC RF "crab" cavities for HL-LHC



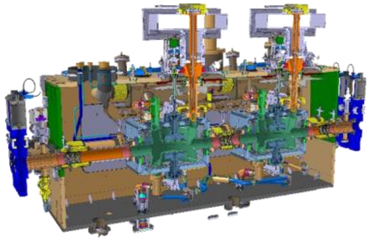
Colliding beams (no CC)



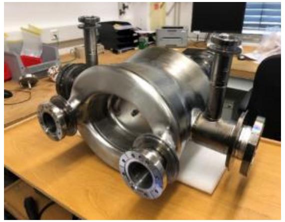
Colliding beams (with CC)



Prototype bunch tests in SPS BA6



DQW Cryomodule



Double Quarter Wave (DQW) RF cavity

RF dipole (RFD) cavity

- RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" and then luminosity is maximized
- Crab cavity maximizes the lumi and can be used also for luminosity levelling: if the lumi is too high, initially you don't use it, so lumi is reduced by the geometrical factor. Then they are slowly turned on to compensate the proton burning
- The cavities operate at 400 MHz, up to 3.4 MV design voltage/cavity, 40 kW RF input power.
- The Crab Cavities are made of Niobium and **operate at 2 K in a saturated HeII bath**.

Pictures & illustrations R. Calaga

New HL-LHC buildings already completed

Civil Engineering @ LHC P1 Sept. 2022

SHM – Compressor Station

SD – Refrigerator Cold Box

US – Cold Compressors Box