HL-LHC IT STRING

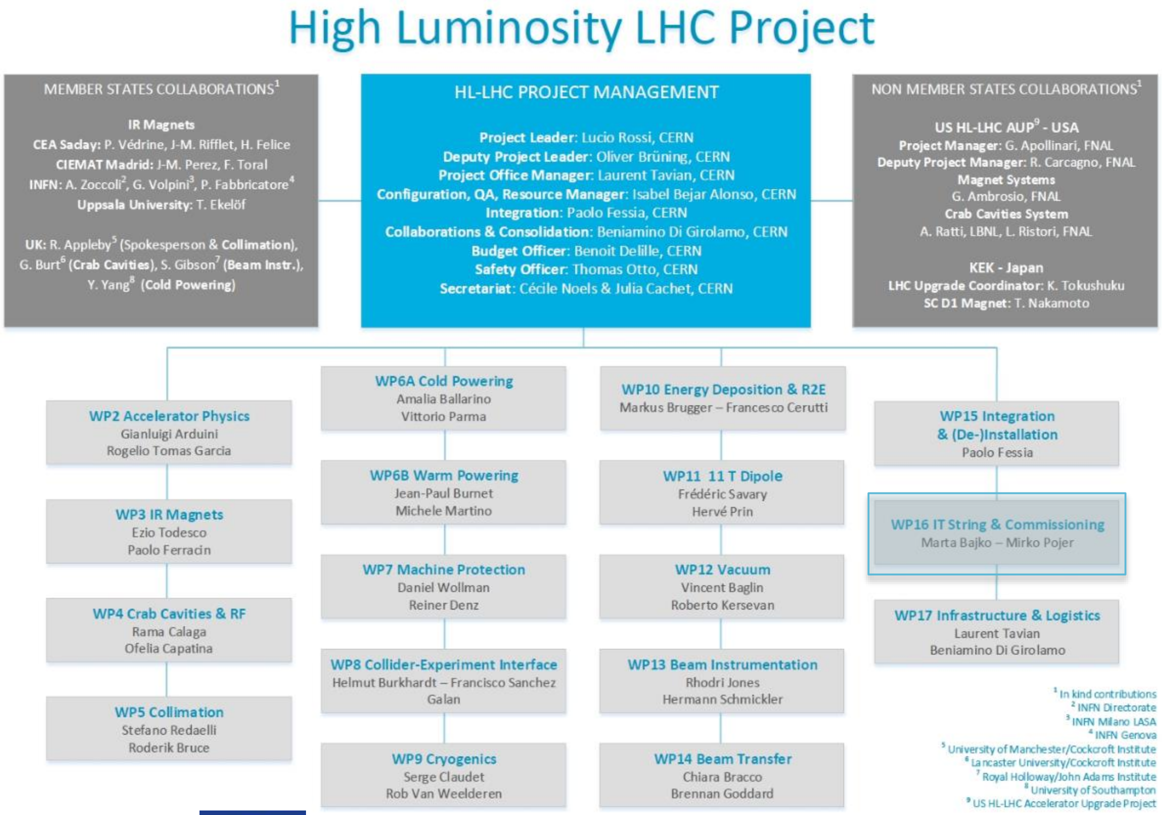
M. Bajko CERN

for TCC 15th September 2016

Outline of the presentation

- WP16 in the HL-LHC Structure and IT STRING Scope
- Brief return to the past
- Experience with LHC Triplet
- Relevance of HL-LHC IT String
- ID Card
- Main facilities of the IT String
- Organization of the work
- Limitations and solutions in space
- Limitations and solutions in time
- Status of the work

The HL-LHC IT STRING in the organigram



[…] **THE WP16** covers the coordination of the commissioning of the HL-LHC equipment as part of the accelerator system. […] The first important system test will be the Inner Triplet (IT) STRING test.

The IT STRING should comprises all magnets with their cold and warm powering and associated cryogenics systems from Q1 to D1 magnets including DFX. […] The IT STRING will have conditions as similar as possible to the operational ones and will constitute an integration and system test of the most critical part of the upgrade.

Ref. HL_WP16 Conceptual specification : https://edms.cern.ch/document/1586706/1

Ref. HL_WP16 IT STRING Mandate: https://edms.cern.ch/document/1513780/1

HiLumi HL-LHC PROJECT

CERN

The HL-LHC IT STRING SCOPE

INTRODUCTION
In the HL-LHC configuration, the Inner Triplet (IT) region of IR1 and IR5 of the present LHC will be heavily modified. In particular the Q1-Q2-Q3-D1 magnets will be completely different from the present LHC magnets, mainly due to the new technology they are based. In particular the
D1 magnet will be **superconductor** instead of normal conductors as is today in the LHC. The IT quadrupoles (Q1-Q3) will use **Nb_3Sn** superconductors instead of the **Nb-Ti** used by the present ones.
The powering of the magnets will be with **higher current** than the present LHC IR magnets and will be made via a **superconducting link.** The **protection** of the magnets based on Nb_3Sn superconductor technology will be **different** from the present ones (ex. Cliq and new QH) due to its particulate characteristics at low and medium field and the **high magnetic energy stored** in the magnets in operational conditions.
In addition, the **aperture will be much larger**, the cold mass configuration will be completely different and the **corrector package** will be **substantially modified** as configuration and technology, too.

[…]
MAIN GOAL
The HL LHC IT STRING will be a test stand to **STUDY and VALIDATE the COLLECTIVE BEHAVIOURE** of the different systems: magnets, magnet protection, cryogenics for magnets and superconducting link, magnet powering, vacuum, and interconnections between magnets and superconducting link, alignment.

Ref. HL-LHC IT STRING Scope https://edms.cern.ch/document/1693312/1

System architecture WP16

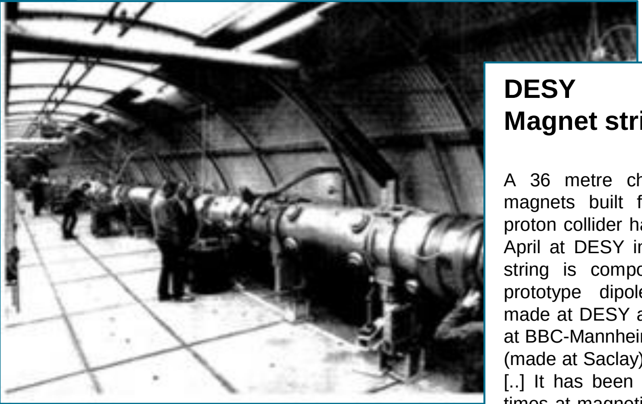
- IT STRING
  - Cryogenic System (CRG)
    - Cryogenic Cooling
    - Cryogenic Distribution
    - Controls Instrumentation and Software
  - Magnets Cryostats and Connections (MSC)
    - Magnets (Q1,Q2A,Q2B, Q3,CP,D1)
    - DFH
    - Magnet Interconnects
    - Controls Instrumentation and Software
    - Measuring Systems
  - Cold Powering System (MSC)
    - SC Link
    - Current leads (DFX)
    - Control Instrumentation and Software
  - Warm powering system (EPC)
    - Power Converters (EPC)
    - Warm Power Distribution (EL)
    - Control Instrumentation and Software
  - Magnet Protection System (MPE)
    - Protection Heater Supplies
    - Cliq System
    - Energy Extraction
    - PIC
    - Control Instrumentation and Software
  - Vacuum (VAC)
    - Hardware
    - Control, Instrumentation and Software
  - DAQ
  - Utilities
    - Civil Engineering (GS)
    - Network (Including Wfip)
    - Demineralized Water (EN CV)
    - Water Cooled Cables (EN EL)
    - Survey System (EN ACE)
    - Control Room(TE-MSC)
    - Transport and Handling EN-E)
  - Design and Integration
- Safety (HSE,HL LHC)

https://edms.cern.ch/document/1690890/1.0

Previous experience - past

In the past **STRINGs tests** were run for

SSC
Hera
Tevatron,
RHIC and
LHC



DESY
Magnet string tests

A 36 metre chain of superconductive magnets built for the HERA electron-proton collider has been under test since April at DESY in Hamburg. The magnet string is composed of three full-sized prototype dipole magnets (with coils made at DESY and mounted in cryostats at BBC-Mannheim) and two quadrupoles (made at Saclay).
[..] It has been quenched more than 20 times at magnetic fields between 1.8 and 5.8 tesla, the latter corresponding to a proton beam energy of 1010 GeV

CERN Courier, December 1987

Hi Marta – I checked with Erich Willen, who was head of the magnet division at the time. **In RHIC, a full cell has two dipoles and two quads. There were two full cell tests set up in trenches in the floor of the magnet building.** The second one successful (magnets reached operating current), but no report exists.

At a later time, the first sector of magnets (1/6 on one ring) was installed in RHIC, cooled, and reached operating current. I am unaware of a report on this test. The tests were generally successful, but there were still a couple of problems that were found and fixed only after the full machine was installed.

Peter

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Brookhaven National Laboratory
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Upton NY 11973-5000
(ph) 631 344 7687

CONSTRUCTION AND INSTALLATION OF THE SSC ACCELERATOR SYS
TEST CRYOGENIC SYSTEMS

T. Ankermann, M. Freeman, T. Kobel

Process Systems International, Inc., 20 Walkup Drive,
Westborough, Massachusetts 01581-5003 U.S.A.

The Superconducting Super Collider Laboratory is installing three cryogenic systems for refrigerating superconducting magnets to the temperature range of 4.5-2.5K. The first of these three systems is dedicated to the Accelerator System String Test (ASST) which simulates the conditions of the Main Ring for a string of five magnets. The second cryogenic system will be installed adjacent to the first, and together they will be used to service the first actual sector (one-tenth) of the Main Ring. The third cryogenic system will be used for magnet performance testing at the Magnet Test Laboratory (MTL) and includes test stands to support five magnet tests running in parallel. This paper describes the cryogenic refrigeration hardware which has been constructed and reports on the progress of the installation and the commissioning of the ASST, MTL and N15B Cryogenic Systems.

BERKELEY LAB

Title:
The SSC Full Cell Prototype String Test

Author:
McInturff, A.D.

Lawrence Berkeley National Labo
Lawrence Berkeley National Labo

***Abstract*—At the conclusion of the S string testing program in February, 1993, analysis revealed that several substantiv remained unresolved. These questions we voltages to ground (>2 kV) measured d conditions be substantially reduced, 2) magnetic elements that became resis controlled and 3) did the cryostats of th provide adequate insulation and isolatio refrigeration loads. To address these questions, a prototypical full cell of collider magnets (ten dipoles and two quadrupoles) was assembled and tested. At the conclusion of this testing there were definitive answers to most of the questions with numerical substantiation, the notable exception being the heat leak question. These answers and other results and issues are presented in this paper.**

THE LHC MAGNET STRING PROGRAMME :
STATUS AND FUTURE PLANS

F.Bordry, J.Casas-Cubillos, P.Cruikshank, K.Dahlerup-Petersen, F.Rodriguez-Mateos, P.Proudlock, G.Riddone, R.Saban, R.Schmidt, L.Serio, C.Wyss, CERN, Geneva, Switzerland.

Abstract

String 1, with one twin aperture quadrupole and three twin aperture 10-m dipoles (MB1, MB2 and MB3) powered in series and operating at 1.9 K, has recently been dismantled after four years of operation interrupted by technical stops and shutdowns for upgrading or exchanging equipment. Following the validation of the main LHC systems (cryogenics, magnet protection, vacuum, powering and energy extraction) the experimental programme was oriented towards the optimisation of the design and the observation of artificially induced fatigue effects.
The design study for String 2 has been completed. This facility, which will be commissioned in December 2000, is composed of two LHC half-cells each consisting of one twin aperture quadrupole and three 15-m twin aperture dipoles. A cryogenic distribution line housing

Model-based predictive control (MBPC) algorithms were investigated in order to obtain a narrower control band compared to standard PID control loops [5,6]. Preliminary results were encouraging but the temperature operational range was limited because only linear approximations of the process were used. Future developments are the implementation of non-linear models into the MBPC controller. Before being able to power the magnets an in-situ calibration of the temperature sensors was necessary. The observed reproducibility between sensors was better than 0.01 K and no degradation was measurable during the 4 years of operation.
The String was controlled and monitored [7] from a dedicated control room but could be controlled from any remote terminal with appropriate privileges. Over 600 process variables were archived during the lifetime of the String every second and, transients on voltage taps,

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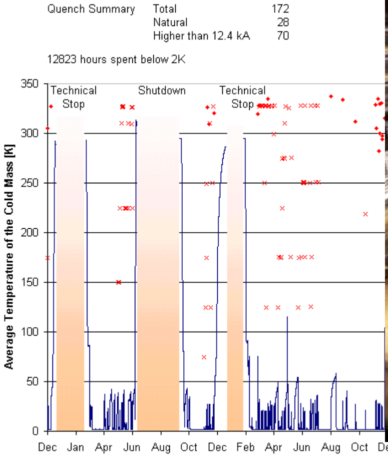
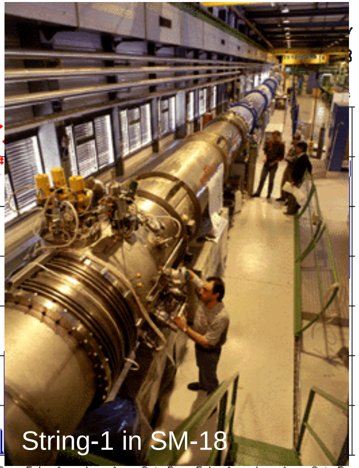
Previous experience @ CERN

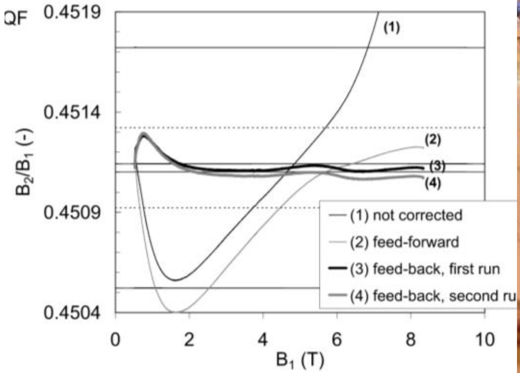
STRING-1 (1994-1998)
- One <u>half</u> LHC cell:
  - 3 MB (10 m) + 1 MQ
- Validation of:
  - Cryogenics (6 CD's)
  - Vacuum
  - Quench (172) and protection
  - Powering and energy extraction

STRING-2 (2000-2004)
- One <u>full</u> LHC cell
  - 6 MB (15 m) + 2 MQ + correctors
- Validation of:
  - Cryogenics,
  - Vacuum
  - Quench and protection
  - Powering
  - Accelerator relevant operation (e.g.tracking of MQ and MB)





String-1 in SM-18

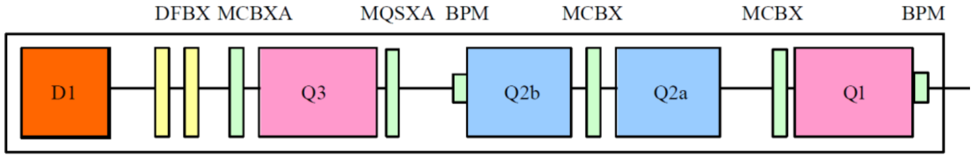


String-2 in SM-18

Courtesy of L. Bottura

Previous experience : LHC triplets

What we have learned from it?

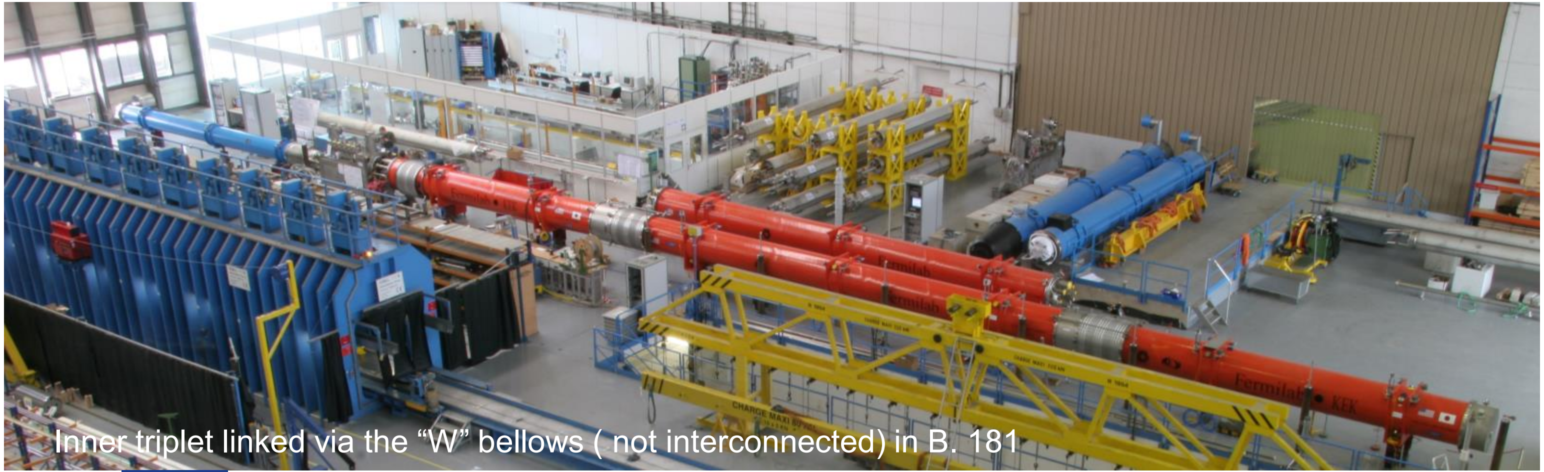


When pumping the vacuum magnets moved

STRING of Q1 Q2 Q3 (2005)

Validation of:

- ~~Cryogenics,~~
- (Insulation) vacuum
- ~~Quench and protection~~
- ~~Powering~~
- ~~Accelerator relevant operation~~


Inner triplet linked via the “W” bellows (not interconnected) in B. 181

Info from H. Prin

Previouse “InExperience”: LHC triplets

What we **could** have learned from a more complete IT STRING :

STRING of Q1 Q2 Q3 (2005)

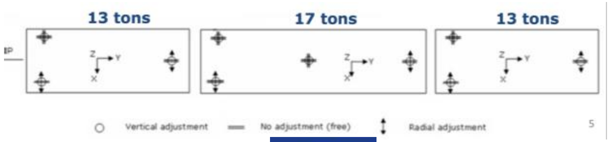
Validation of:

- Cryogenics,
- Vacuum
- Quench and protection
- Powering
- Accelerator relevant operation

The default of the heat X tube that collapsed during the pressure and leak test in the tunnel at < 10 bar. The NCR was due to a bad procedure of welding . Discovered in the tunnel and implied a serious intervention and so delay!
This NC hided the next one (see below)

The default of the spiders: a design problem in the supporting system of the cold mass, only being seen once interconnected and ready for cooling.

The spider (supporting system very good radially but not longitudinally) broke and an other serious intervention on this implied once again a delay !

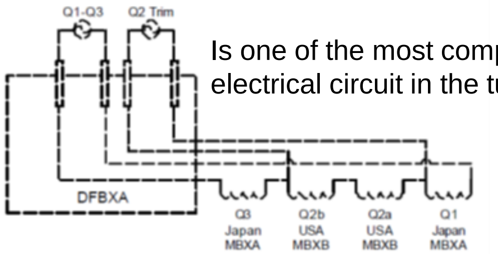


The supporting of the present triplet is largely hyperstatic and loads are not distributed as foreseen in the chain of the triplets. Some of the supports takes higher loads (load on Q2 central jack up to 17 t). The straps been installed to overcome the problem.

The alignment is also laborious.

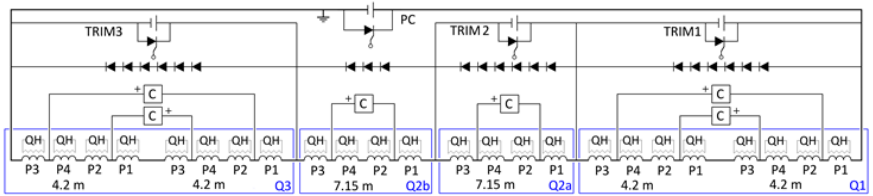
Info from H. Prin and L. Bottura

LHC vs HL-LHC triplet

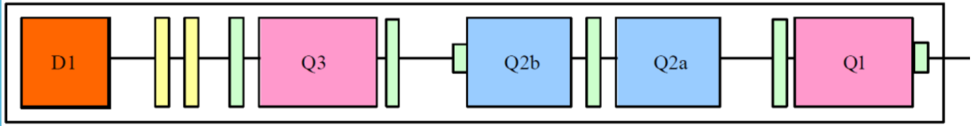


Is one of the most complex electrical circuit in the tunnel

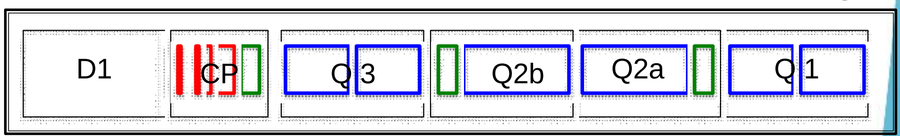
Quench analysis



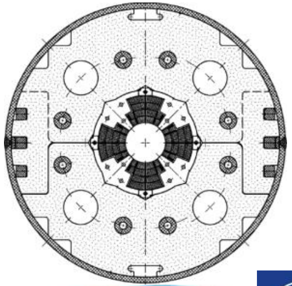
LHC



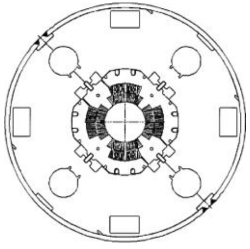
HL-LHC



MQXA



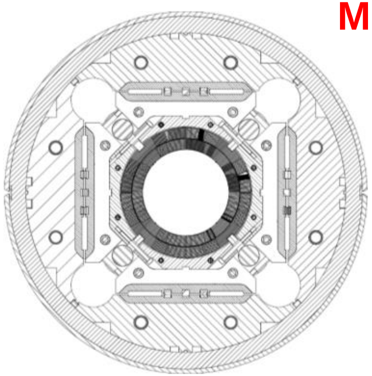
MQXB



Comparison of main magnet characteristics

- NbTi against Nb_3Sn technology
- 1.3-1.5 times the cold ass OD (to **630 mm)**
- 2.14 times the aperture: (to **150 mm)**
- ~ 4 times the e.m. forces in straight section
- ~ 6 times the e.m. forces in the ends
- 2- 4.8 times the stored energy (to **1.2 MJ/m**)

MQXF

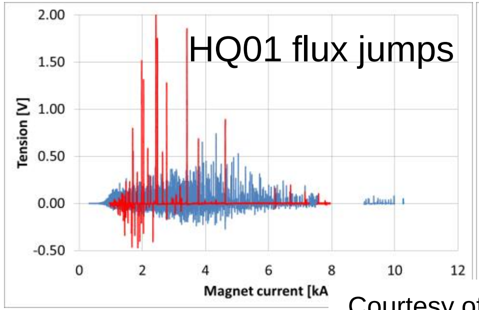


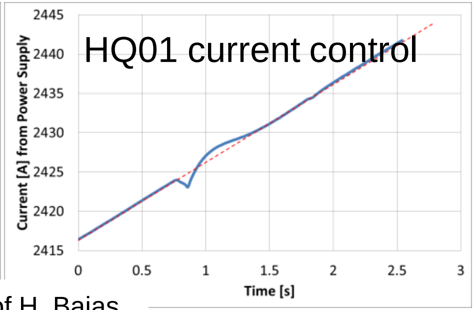
Courtesy of P. Ferracin and G. Willering and E. Ravaioli

Ex. of future experience to gain with IT String

Features related to Nb_3Sn :

- Flux jumps show up in Nb_3Sn magnets as a “noise”, both in the terminal and compensated voltage
  - The effect ***propagates from one spot*** along the cable length
  - Poles are coupled magnetically, attempting to reduce flux changes
- ***Flux jumps*** are random in location, amplitude and occurrence
- They can influence powering (1 ppm control) as well as the detect-ability of normal transitions

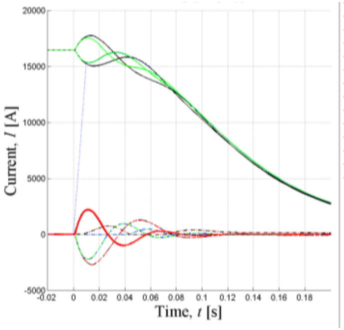




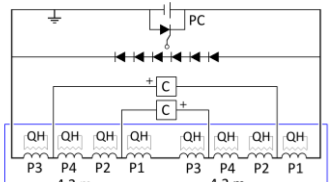
Courtesy of H. Bajas

Features related to the HL-LHC IT Circuit:

Cold masses powered and protected individually by ***cliq*** and quench heaters but once in a circuit the effect can propagate : the ***ringing***, the ***HV***. Return currents in the ***trim*** bus bars and main bus bars aswell as in the ***Sc link***

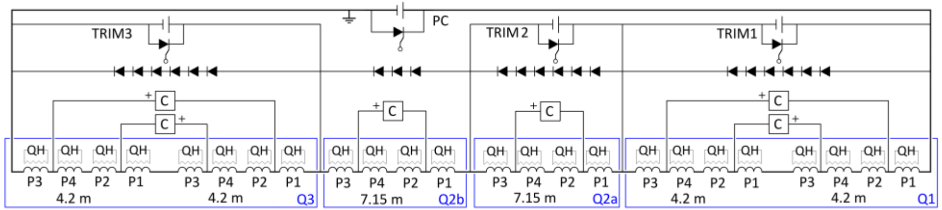


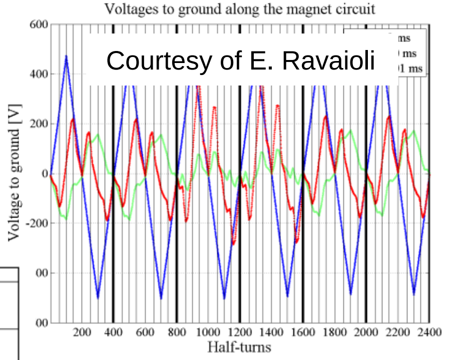
Cold mass test



All these aspects can be simulated **but test needs to validate the simulations**

Circuit test





Q1 Q2a Q2b Q3

Relevance for the HL-LHC IT STRING

The HL-LHC IT-String can provide relevant experience (same object as in the LHC), validation ("first time" test) and advanced operation information on:

- Magnet positioning, alignment, interconnection procedures (do not under-estimate)
- Mechanical behavior of the IT continuous cryostat (Q1 to DFX) and other components (DSH, DFH) under pressure, vacuum, cool-down, operation and warm-up
- Cryogenic behavior and operation under static (and dynamic) conditions
- Insulation and beam vacuum static (and dynamic) behavior
- Powering behavior of the system with Sc links, dynamic response (and associated field quality), interaction of circuits
- Cross talk between magnets in operation and during a quench, detection, propagation and protection of the complete superconducting circuit

These aspects, especially the **collective behavior**, can only be tested in a representative test, a so-called STRING

GOALS in parallel: **Develop methods, techniques** / **Develop tooling** / **Develop procedures** for definition of **Installations** / **Test** / **Operation** to support **HWC and OP of HL-LHC**

ID Card of HL-LHC IT-String

- Test Facility name: HL-LHC IT STRING
- Test Facility location: SM18 (b. 2173)
- Test date: 2021-2023
- Operational temperature: 1.9 K
- Operational current: 108% $I_{nominal}$ = 18 kA?
- Magnets: Q1, Q2a, Q2b, Q3, CP, D1
- Cold powering: SC link (60 m or 110 m) HTS leads DFH and DFX,
- Warm powering: 1 x PC 18 kA , 3 Trim Q1-Q3, 6 x 2 kA , 1 x 12 kA, 9 x 0.1 kA
  Water cooled cables
- Protection: CLIQ , QH and EE

[…] a **FULL INTEGRAL TEST** of the equipment from **Q1 till D1** including the **DFX** is foreseen in the HL-LHC project, in CONDITION AS SIMILAR AS POSSIBLE to the operational one.

The IT STRING of the HL-LHC will be composed by systems previously tested individually at least in nominal operational conditions.

HL_WP16 Conceptual specification :
https://edms.cern.ch/document/1586706/1

Main Facilities needed for the HL-LHC IT STRING

UPGRADE DRIVEN BY the recommendation enabling to carry out the full test programme with no contraints

CRYOGENIC COOLING PRODUCTION: **+ 35 g/s LHe to 60 g/s**

NEEDS essentially for the running of the HL LHC IR STRING in parallel with magnet testing

DEMINERALISED WATER PRODUCTION: **+ 150 m^3/h**

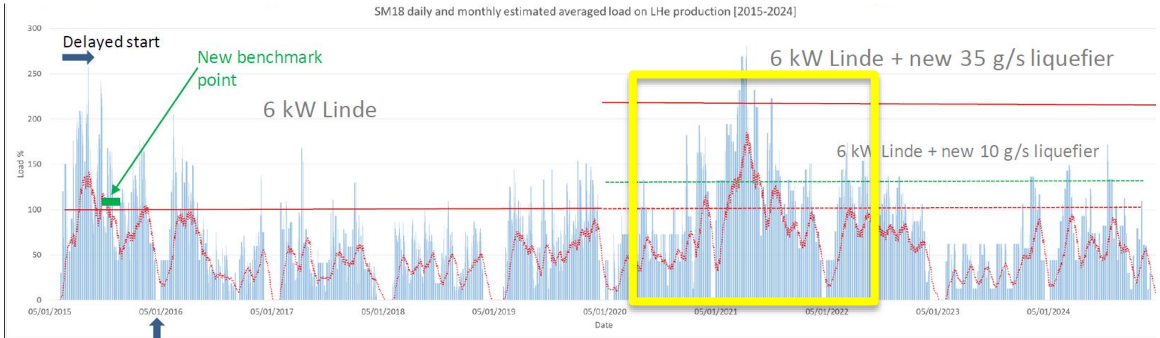
NEEDS FOR DEMINERALISED WATER ENTIRELLY COMING FROM MAGNET operation

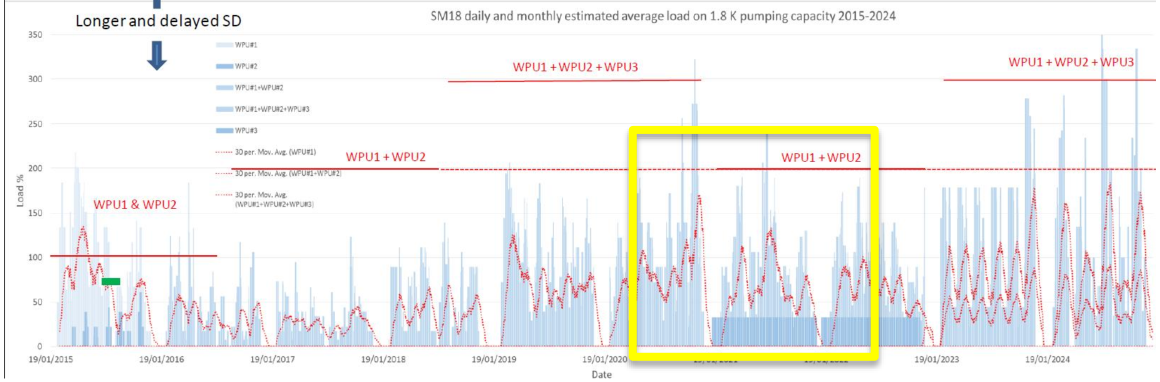
POWERING FROM THE NETWORK: **3 MVA**

NEEDS FOR NEW OR MODIFIED PC COMING FORM MAGNETS and IR STRING

SM18-UPG project of the TE department under the responsibility of V. Mertens:
the upgrade of all necessary services to cover the needs for the test stands operation (this includes the HL-LHC STRING as a test stand of a ***complete*** *system).*

Test stands : cryogenics upgrade





An additional **35 g/s liquefier** (thus bringing the **total production capacity for LHe at 4.2 K to 60 g/s)**

The existing total pumping capacity in SM18 at **1.8 K is 12 g/s**, **combining** the capacity of **WPU1 and 2**.
If need for IR STRING a dedicated 3rd WPU shall be installed.

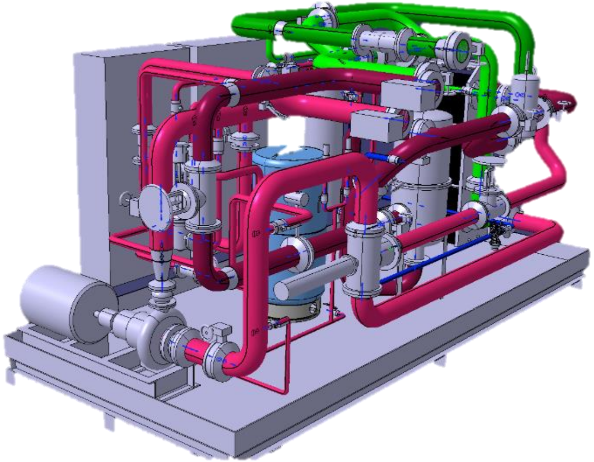
Ref. L. Serio

Foreseen for 2019

Test stands : demineralized water production

The demands for the magnet test stations, including the IT String, will rise to a peak need to 1.7 MW (142 m^3/h).

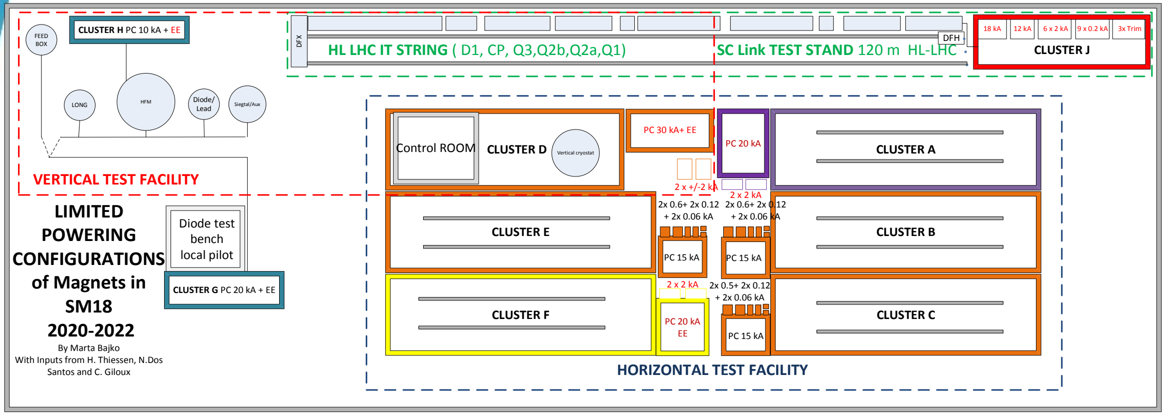
In the past SM18 had a demineralised water station with a thermal capacity of 800 kW limiting the operation to two test stands



Operational from April 2016

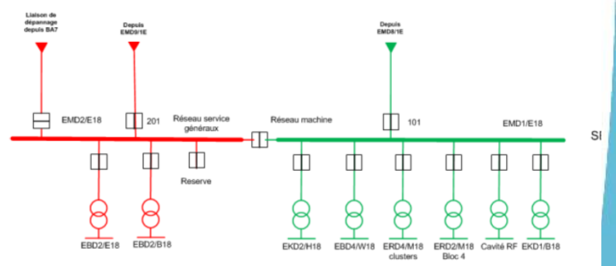
Ref. A. J. Broche

Test stand : electrical powering



- 18 kV power consumption and margin

EMD201/E18		EMD101/E18	
Power available	18 MVA	Power available	18 MV
Maximum measured load	6.75MVA	Maximum measured load	7.85 M



Foreseen for 2019

ERD2/M18: 920 kVA	ERD4/M18: 2200 kVA	EMD1/E18: 1600 kVA	CLUSTER J: 1000 kVA	nCLUSTER F: 950 kVA
1 MVA	2 MVA	1.6 MVA	1 MVA	1 MVA
CLUSTER G 20 kA CLUSTER H 10 kA	CLUSTER D 25 kA sCLUSTER D(E) 15 kA CLUSTER B 14 kA CLUSTER C or E 14 kA	CLUSTER A 20 kA CLUSTER A 2x 2 kA	CLUSTER J	nCLUSTER F 20 k nCLUSTER F 2x 2

TEST STAND	...	...pacity by ...nnection [...MVA]
		2
Horizontal		2
IT STRING		3
Vertical		2

To allow some flexibility and margin with new requests that are not formulated yet, the proposal is to **INSTALL a TRANSFORMER OF a 3 MVA CAPACITY**

The new transformer will feed HL-LHC IT STRING (Cluster J) and the new Cluster F with the 20 kA power converter.

Ref. C. Giloux, F. Formenti, N. Dos Santos

How we are organised for the work?

Integration and Construction

- Regular meetings every 3 weeks: Friday afternoon in SM18
- The team is made of persons appointed by the GLs.

<u>Antoine Kosmicki EN ACE integration</u>
<u>Estrella Vergara EN ACE planning</u>

Hugues Thiesen, Samer Yamine TE-EPC
Jean-Claude Guillaume EN-EL
Amalia Ballarino, Andre Jacquemod TE MSC
Vittorio Parma TE MSC
Ezio Todesco TE MSC
Herve Prin TE MSC
Luigi Serio, Serge Claudet +… tbd during summer 2016 TE CRG
Markus Zerlauth TE MPE
Felix Rodriguez Mateos TE MPE (Mr. Circuit)
Patrick Viret TE MSC (TSO B. 2173)
Paul Cruikshank, Cedric Garion TE VAC
Carlos Arregui Rementeria HSE
Dominique Missiaen EN ACE
Helene Mainaud Dourand EN ACE
Serge Pelletier EN-HE
Adriaan Rijllart EN

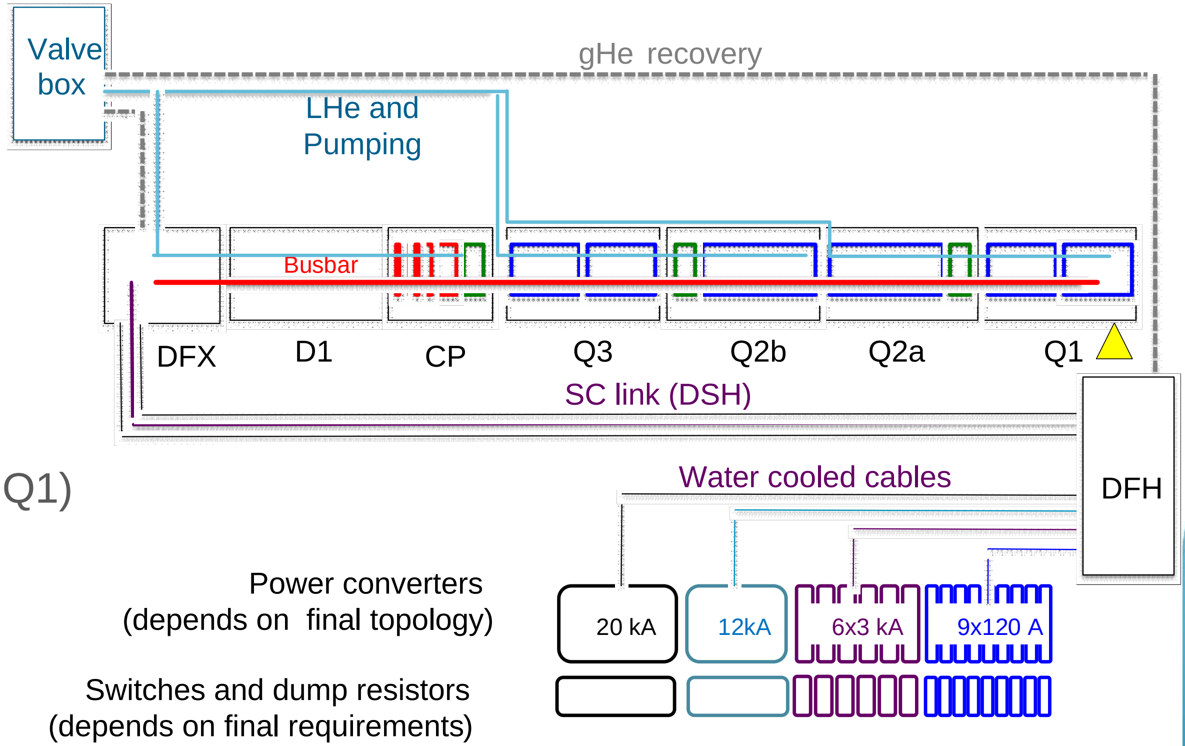
Test plan and results

- Meetings to define the test plan to be reported to the HL-LHC TCC . ….later regular reports on the results .
- The team is made of the concerned WP leaders and HL-LHC and TE management.

M. Pojer is deputy of HL-LHC STRING

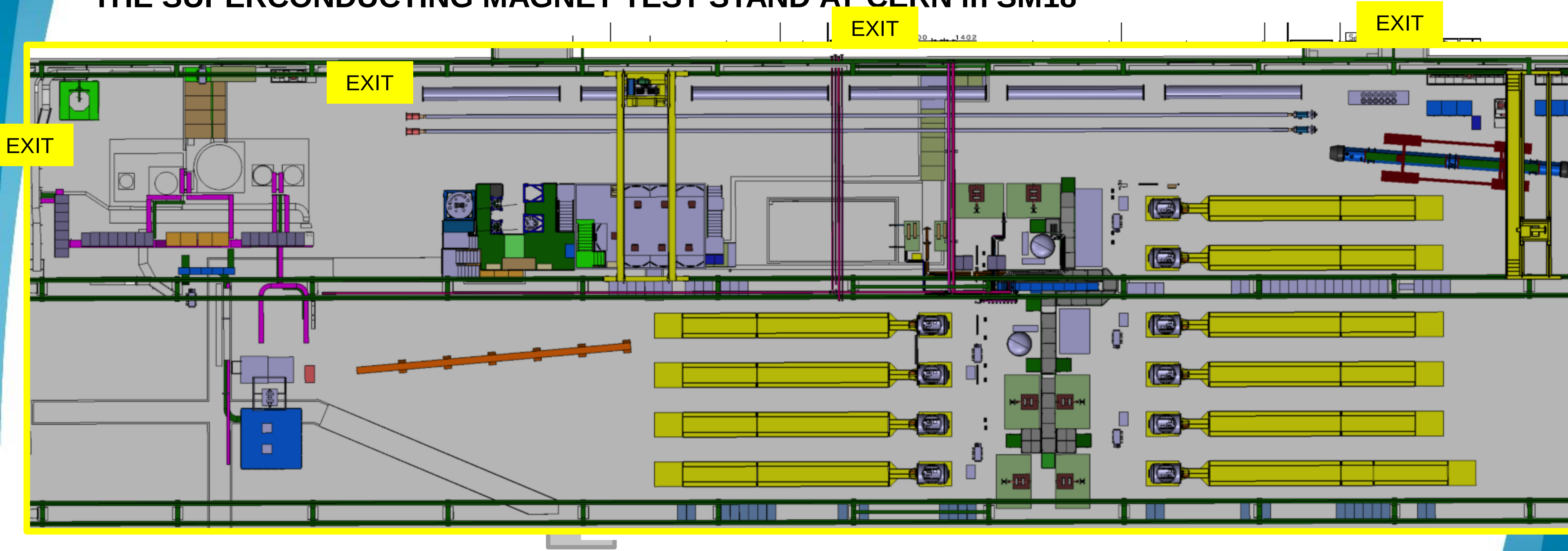
Main components and schematics

- Power Converters (PC)
- Water Cooled Cables (WCC)
- Current Leads (CL and DFH)
- Superconducting Link (DSH)
- Connection Module (DFX)
- Magnets (D1,CP,Q3,Q2a,Q2b,Q1)
- EE and Protection
- Interlock and DAQ systems



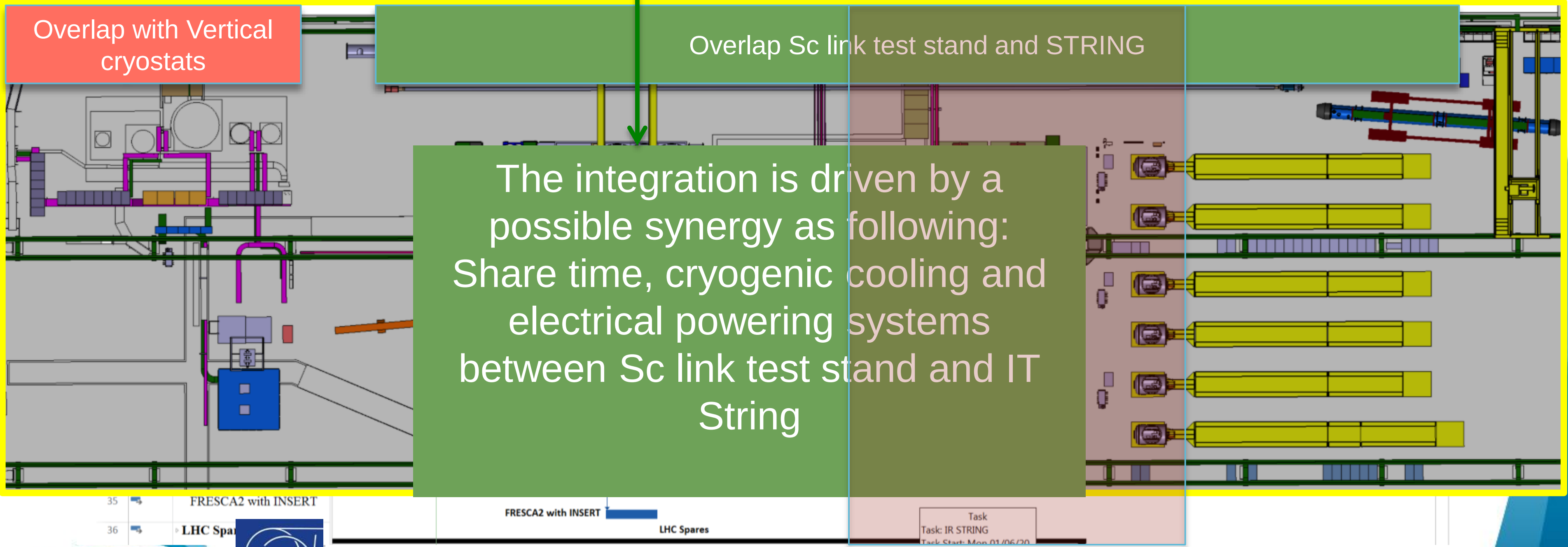
Limitations in space in SM18

THE SUPERCONDUCTING MAGNET TEST STAND AT CERN in SM18



Conflict or synergy between test stands

Vertical test cryostat | SC link test stand (110m) | IT String (80 m) | Horizontal benches

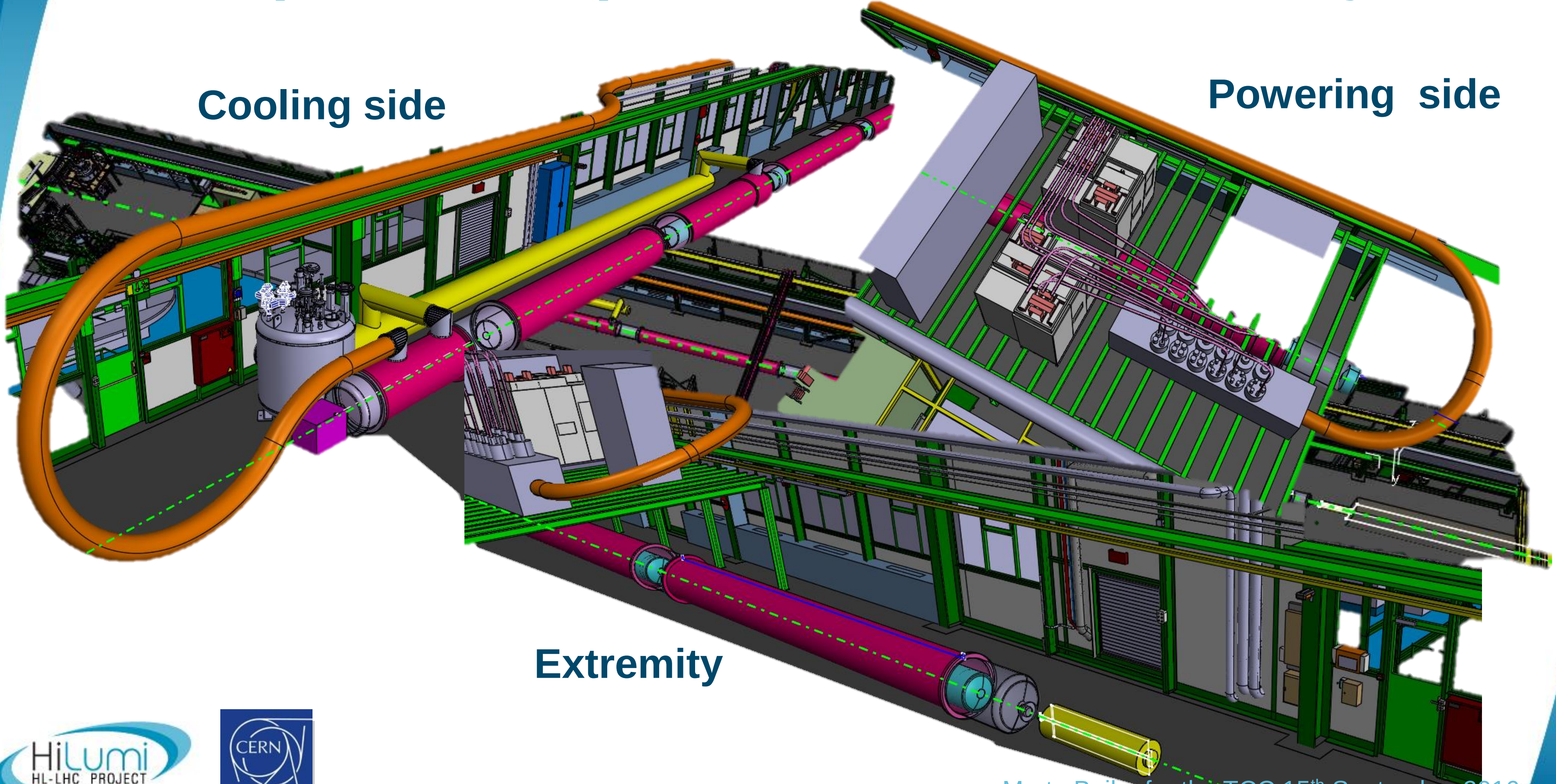


Overlap with Vertical cryostats

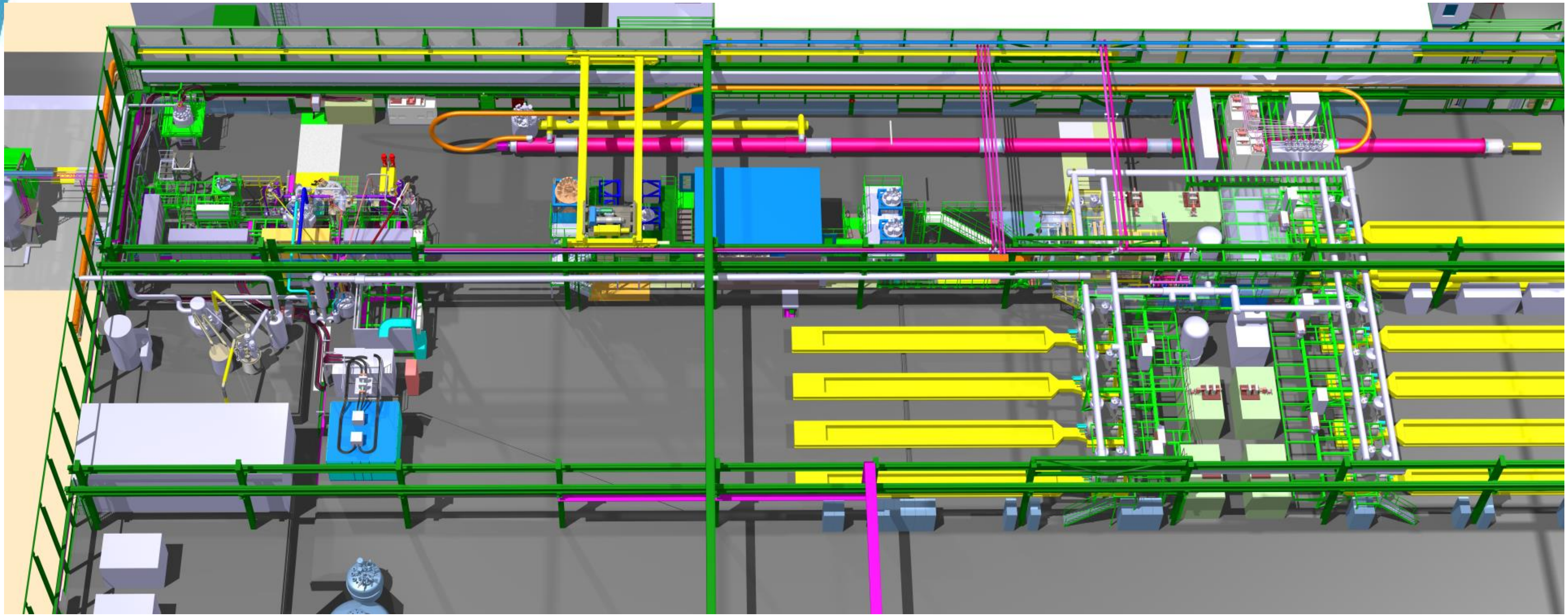
Overlap Sc link test stand and STRING

The integration is driven by a possible synergy as following: Share time, cryogenic cooling and electrical powering systems between Sc link test stand and IT String

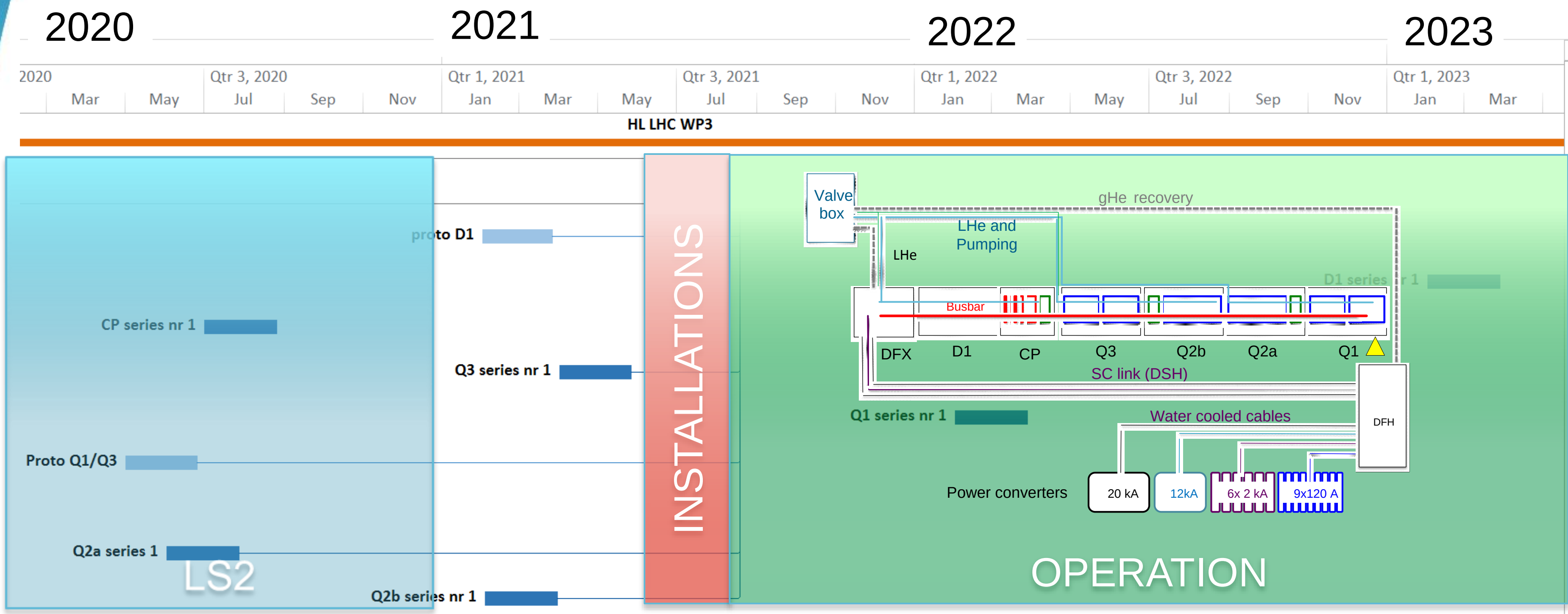
Options in space: where we are today



The latest proposal for integartion

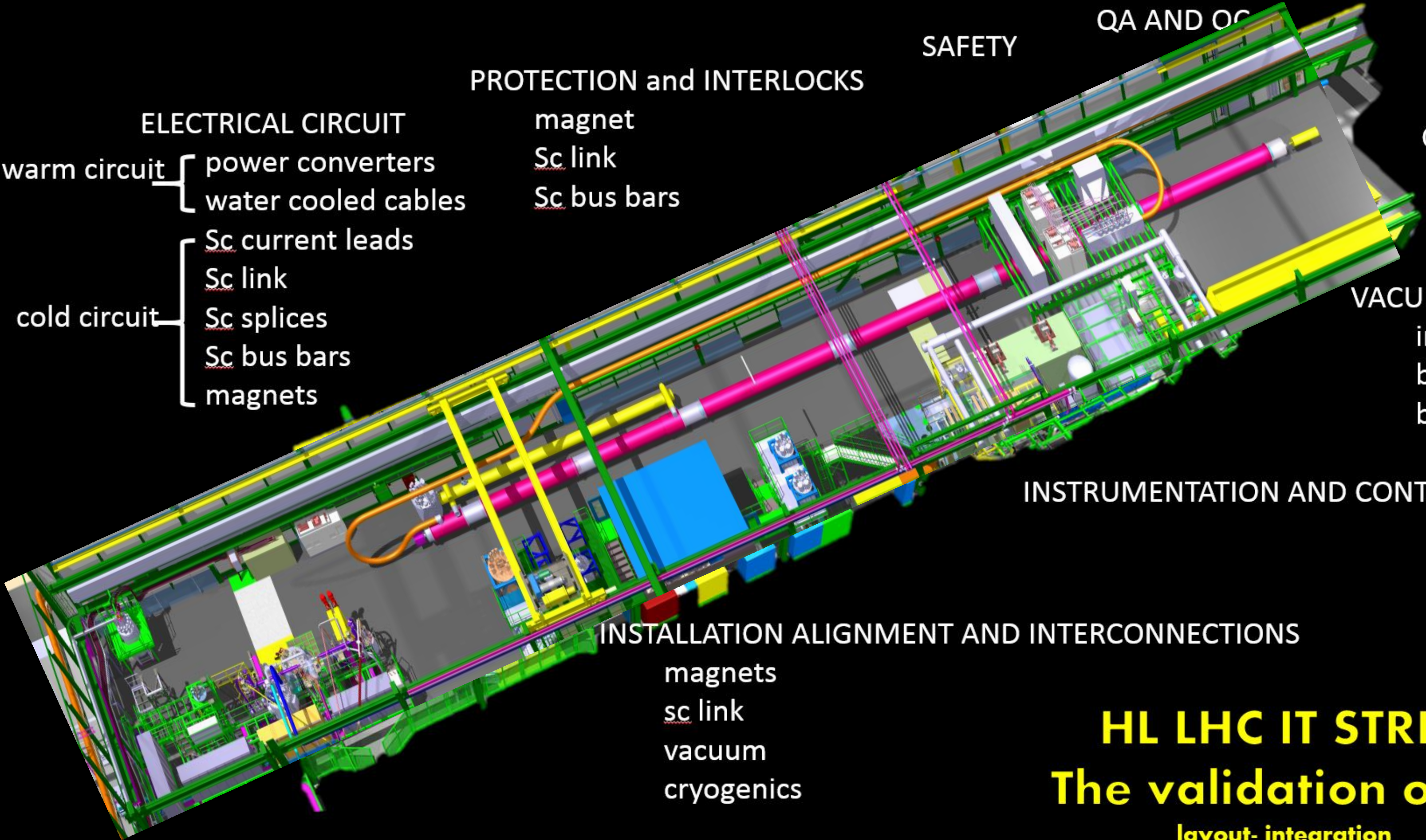


IT STRING the earliest possible?



Current status of the work

- Integration ongoing with all elements that we know today
- Estimate of budget (4.5 MCHF) have been done and now is under verification by the members of the integration team. The strategy is that
  - All main components usable in the HL-LHC are part of the WP (prototypes or series)
  - All components that are not usable in the HL-LHC are to be payed by the WP16 budget
  - All services are assured within the SM18 UPG project (financed by both TE dep and HL-LHC project)
- Estimate of manpower has been done and now is under verification by the members of the integration team
- In case of missing man power management support will be required
- Few WPs gave already a wish list for the complete test plan



QA AND QC

SAFETY

PROTECTION and INTERLOCKS
- magnet
- Sc link
- Sc bus bars

ELECTRICAL CIRCUIT
- warm circuit
  - power converters
  - water cooled cables
- cold circuit
  - Sc current leads
  - Sc link
  - Sc splices
  - Sc bus bars
  - magnets

OPERATION
- field reference
- tracking

VACUUM
- insulation
- beam
- beam screen

INSTRUMENTATION AND CONTROL

INSTALLATION ALIGNMENT AND INTERCONNECTIONS
- magnets
- sc link
- vacuum
- cryogenics

HL LHC IT STRING TEST

The validation of a system

layout- integration
installation sequence and procedures
the collective behaviour of components

Thanks for your attention

HL LHC STRING preliminary TEST PLAN

Validation of a layout- integration
Validation of installation sequence and procedures
Validation of a system (of components)
Validation of their collective behaviour

Quench: provoked, natural, holding current, propagation, detection, protection, clic, dump, switch
Cryogenics: cooling- warming speed (Nb_3Sn), heat load, recovery after quench, pressure, temperature, shielding
Integration: layout, interconnections, systems around (racks, cables trays, control cables et), total weight
Powering: bus bar, connections, current leads, power distribution at warm and at cold, converters, water cooled cables
Electrical integrity: splice resistance, electrical insulation
Interlock
Vacuum: leak detection, beam screen
Instrumentation , DAQ systems, DB , QA, QC: specific or not to string
Alignment

GOALS in parallel:

Develop methods, techniques
Develop tooling
Develop procedures

X definition of

Installations
Test
Operation

2 support

HWC
OP

MPE goals of HL-String test

- Validation of interlock loops and quench loops (for potential improvement of topology/diagnostics)
- Validation of final versions of the interlocks, quench detection system (QDS) and controls interfaces (including new phenomena as flux jumps,…)
- Validation of CLIQ layout and magnet protection for full magnet string
- Validation of transient effects and electromagnetic coupling in full magnet string + sc link during normal operation and during protective actions (CLIQ/heater firing). Verification of simulation models with obtained measurements.
- Validation of EE systems for IT corrector magnets (600A, 2kA)
- Validation of IST procedures for protection equipment
- ELQA procedures for full string
- Validate fully automated analysis of faults + automated/remote fault recovery (QDS, MP3 and Software)
- Transient heat load test (studies of beam/UFO induced quenches)
- Note:
  - Validation of the 11T topology should follow the same approach, using already on the test beds configurations as close as reasonably possible to the final LHC installation
  - String test and LS2 have a significant overlap, which might cause manpower issues for the hard- and software sections of MPE

VAC goals of HL-String test

- String (2019 -):
- Beam screen:
  - Quench
  - Thermal contraction
  - Heat loads to the cold mass (supporting system)
  - Flow induced vibrations
- Interconnections:
  - Assembly procedure and tooling for the PIM installation and beam screen cooling circuit
  - Measurements of the displacements at cold, during cool down and warm-up
  - Behaviour of the RF fingers
- Insulation vacuum:
  - Leak tests
  - New O'ring or seals
- Beam vacuum:
  - Pump down time before cool down
  - Static vacuum gas analysis
  - He, H_2, CO, CO_2 propagation tests with a-C coating at different beam screen operating temperature in the range 40 – 70 K
  - Study impact of quench and beam screen temperature on vacuum levels along the line and at cold warm transitions (with possibly dedicated vacuum gauges located at interconnects)