Special thanks to Roberto Saban for fruitful discussions
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 IT STRING in the organigram

High Luminosity LHC Project

WM6A Cold Powering
Amalia Ballarino
Vittorio Parma

WP6B Warm Powering
Jean-Paul Brunet
Michele Martinou

WP7 Machine Protection
Daniel Wulliman
Reiner Dero

WP8 Collider-Experiment Interface
Helmut Burhardt – Francisco Sanchez Galan

WP9 Cryogenics
Serge Claudef
Rob van Weelden

WP10 Energy Deposition & RVE
Markus Brugger – Francesco Cerutti

WP11 11 T Dipole
Frederic Savary
Hervé Prins

WP12 Vacuum
Vincent Bagli
Robero Krenevian

WP13 Beam Instrumentation
Rohini Jones
Hermann Schmickler

WP14 Beam Transfer
Chiara Braccio
Brennan Goddard

WP15 Integration & (De-)Installation
Paolo Tessara

WP16 IT String & Commissioning
Marta Bajko – Mirko Pojer

WP17 Infrastructure & Logistics
Laurent Savari
Beniamino Di Girolamo

Ref. HL_WP16 IT STRING Mandate: [https://edms.cern.ch/document/1513780](https://edms.cern.ch/document/1513780)

Ref. HL_WP16 Conceptual specification: [https://edms.cern.ch/document/1586706/1](https://edms.cern.ch/document/1586706/1)

[...] **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 comprise 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.
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$_3$Sn 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$_3$Sn 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 BEHAVIOUR 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
Comparison of main magnet characteristics

- NbTi against Nb$_3$Sn 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)

Is one of the most complex electrical circuits in the tunnel

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

Marta Bajko for the TE-TM June 2016
Hi Marta - I was not able to find a document about the first FERMILAB above-ground string test (not the one in the tunnel with beam). But I can briefly describe it from memory.

At a location called B-12 […] a half-cell consisting of four prototype Tevatron dipoles and a quadrupole, and eventually a full cell of 8 dipoles and two quads, was fully cooled with liquid helium and power tested.

One interesting and memorable result of those tests was that an arc to the helium bellows, rupturing the bellows and sending helium into the insulating vacuum space, resulted in pressurization of the vacuum space and displacement of the magnet string by almost a meter. I still have in my office a bent 1-inch threaded rod from a support stand in that incident. […]

Kind regards,
Tom

Tom Peterson
tommy@fnal.gov
630 840 4458

STRING tests were run for Tevatron, Hera, SSC, RHIC

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

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[…] 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
Previous experience @ CERN

- One half LHC cell:
  - 3 MB (10 m) + 1 MQ
- Validation of:
  - Cryogenics
  - Vacuum
  - Quench (120)
  - Powering and energy extraction

- One full LHC cell
  - 6 MB (15 m) + 2 MQ + correctors

THE LHC MAGNET STRING PROGRAMME:
STATUS AND FUTURE PLANS


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,
Previous experience: LHC triplets

What we have learned from it?

STRING of Q1 Q2 Q3 (2005)

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

When pumping the vacuum magnets moved

Info from H. Prin

Inner triplet linked via the “W” bellows (not interconnected) in B. 181
Previouse “InExperience”: LHC triplets

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

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

STRING of Q1 Q2 Q3 (2005)

Validation of:

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

Marta Bajko for the TE TM June 2016
**Ex. of future experience to gain with IT String**

Features related to Nb$_3$Sn:
Flux jumps show up in Nb$_3$Sn 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.

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 as well as in the *Sc link*.

---

**Cold mass test**

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

**Circuit test**

---

*Marta Bajko for the TE TM June 2016*
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
- Crosstalk between magnets in operation and during a quench, detection, propagation and protection of the complete superconducting circuit

These aspects, especially the collective behaviour, 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: 2020-2022
- Operational temperature: 1.9 K
- Operational current: $108\% I_{\text{nominal}} = 18\text{ kA}$?
- 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
NEEDS essentially for the running of the HL LHC IR STRING in parallel with magnet testing

DEMINERALISED WATER PRODUCTION: + 150 m³/h
NEEDS FOR DEMINERALISED WATER ENTIRELY COMING FROM MAGNET operation

POWERING FROM THE NETWORK: 2 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 IT STRING a dedicated 3rd WPU shall be installed.

Foreseen for 2019

Ref. L. Serio
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 m³/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

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.

Antoine Kosmicki EN ACE integration
Estrella Vergara EN ACE planning

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
Serge Pelletier EN-HE
Adriaan Rijllart EN STI

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.

Jean Philippe Tock is deputy of HL-LHC STRING
And ….I am looking after a Scientific Secretary…
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

Power converters (depends on final topology)

Switches and dump resistors (depends on final requirements)
Boundary conditions in SM18

THE SUPERCONDUCTING MAGNET TEST STAND AT CERN in SM18

What boundary conditions we considered?
Conflict or synergy in space and time

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.

Overlap with Vertical cryostats
Overlap Sc link test stand and STRING
IT String and Sc link test stand: solution 1

The drawback is:
1. DFX is not tested and the valve box should be able to deliver He gas or
2. DFX is not a standard HL LHC design but is equipped with a vacuum barrier

The advantage is:
1. Warm powering system is not doubled
2. Vertical test stand is less crowded
3. Local cryogenics is shared

Power converters
(depends on final topology)

Switches and dump resistors
(depends on final requirements)
IT String and Sc link test stand: solution 2

The advantage is:
1. Warm powering system is not doubled
2. Vertical test stand is less crowded
3. DFX is standard and systematically tested with DSH

Power converters (depends on final topology)

Switches and dump resistors (depends on final requirements)
IT String and SC link test stand: solution 3

The advantage is:
1. Warm powering system is not doubled
2. DFX is standard and systematically tested with DSH
3. We re-use the exiting equipment: no stop in the testing of Sc link
4. The two system integration are separated

Power converters (depends on final topology)

Switches and dump resistors (depends on final requirements)
Options in space: where we are today?

Cooling side

Powering side

Extremity
Options in space: where we are today?

PROS AND CONS

INTEGRATION/Criteria

<table>
<thead>
<tr>
<th>Warm powering</th>
<th>Cryogenics</th>
<th>DFX individual test</th>
<th>Independent design SC link IT String</th>
<th>Re-using of exiting Feed Box</th>
<th>Conflict with vertical test stands</th>
<th>Modification of standard equipment</th>
<th>Safety exits</th>
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Marta Bajko for the TE TM June 2016
2.11. String Tests

The string tests were proposed to be taking place in 2 phases, arriving relatively late in the project. We strongly support the string test and its realization in 2 phases.

**PHASE 1** STRING can start in 2020 with prototypes but Q3 will missing

**PHASE 2** Complete STRING with series magnets can not start before mid 2021 due to late arrival of the 1st series of D1
SOLUTION 1: the earliest possible

21-23 March, 2016, CERN Geneva

[...]

2.11. String Tests

[...]

We recommend [...] All required effort should be provided to realize the first phase as early as possible.

PHASE 1 STRING can start in 2020 with prototypes but Q3 will missing

Switches and dump resistors (depends on final requirements)
Comparison of solutions in Time

**SCHEDULES/CRITERIA**

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<td>Complete experience</td>
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<td>Overlap with LS2</td>
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**Notes:**
- **Phase 1** STRING can start in 2020 with prototypes but Q3 will be missing.
- **Phase 2** Complete STRING with series magnets cannot start before **mid 2021** due to late arrival of the 1st series of D1.
Current status of the work

- Integration ongoing with all elements that we know today
- Estimate of budget (4.5 MCHF) has 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 manpower management support will be required
- Few WPs gave already a wish list for the complete test plan
Thanks for your attention
## Alternatives

### INTEGRATION/CRITERIA

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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$_3$Sn), 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

**Installations 2** support **HWC OP**

**Test**

**Operation**

**X**

**definition of**
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, H₂, CO, CO₂ 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)