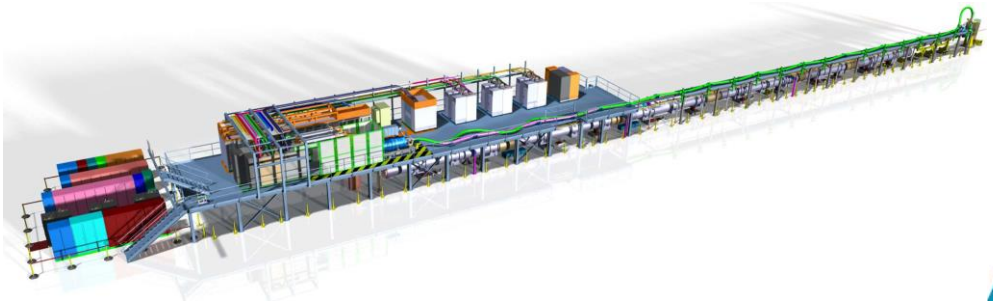
From HWC of the IT String to the HWC of the HL-LHC: Status and Preparation

S. Yammine on behalf of the MCF, MP3 and WP16

14th HL-LHC Collaboration Meeting, Genoa (Italy),
9th October 2024

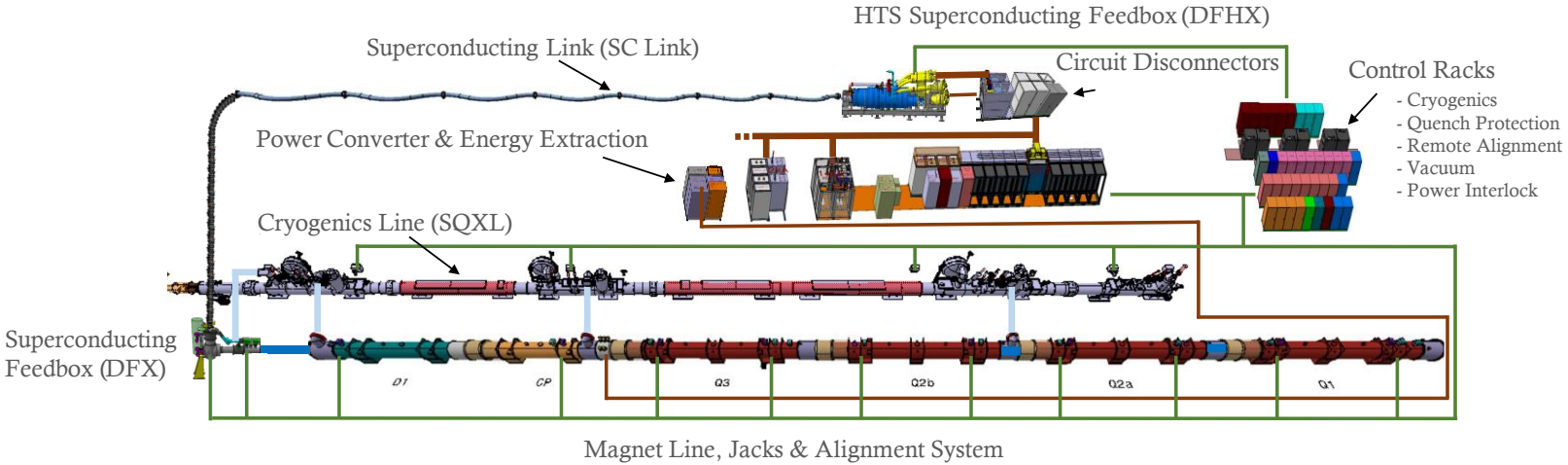


Outline

I. Introduction
II. String Validation Program
III. Quality Control and Quality Assurance
IV. Individual System and Short Circuit Tests
    a) Cryogenics System
    b) Alignment System
    c) Warm Powering Systems
V. Powering Tests for the Hardware Commissioning
VI. Takeaway Message

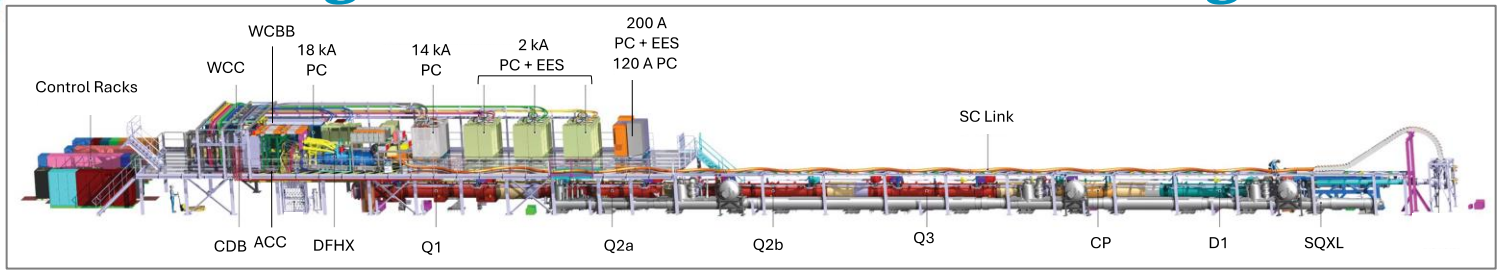
Introduction

HL-HLC IT String Systems and Scope

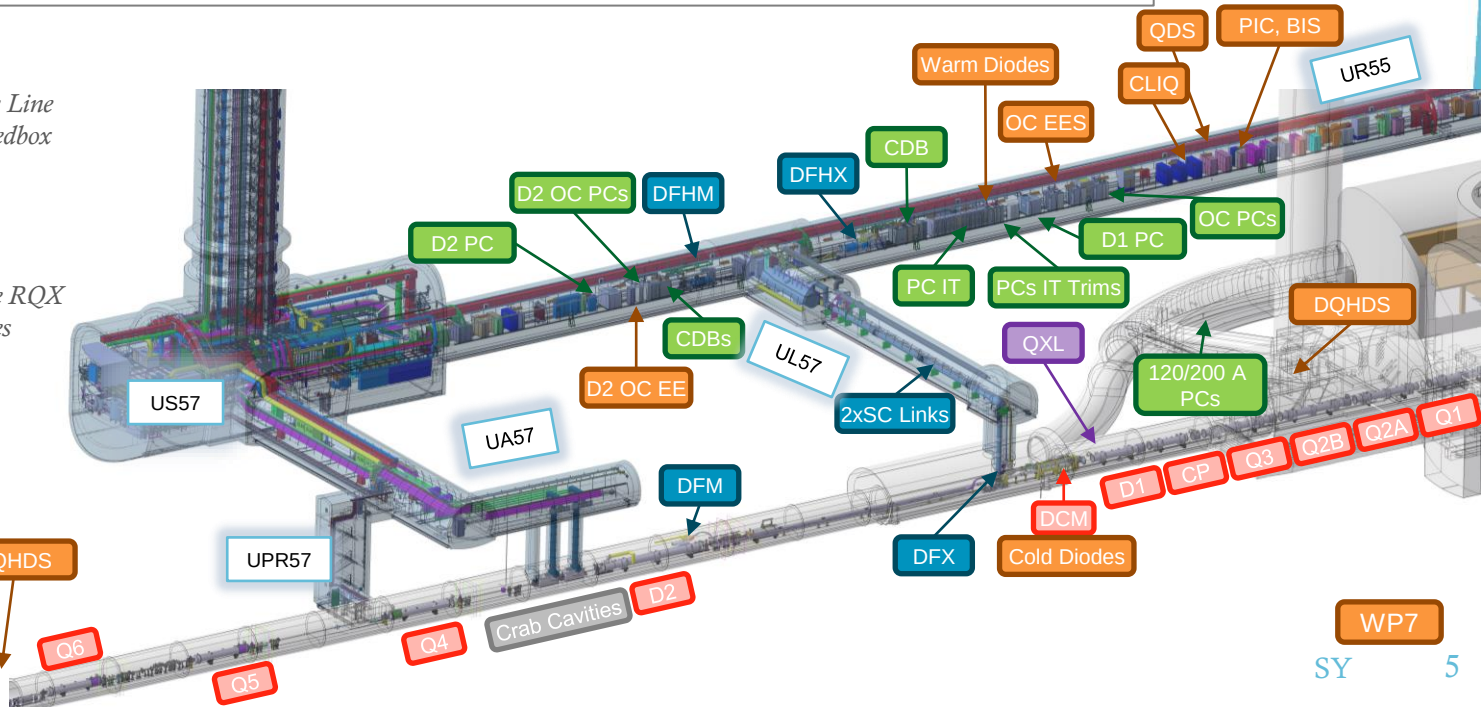


- Scope of the IT String is to represent, as best as reasonably achievable in a surface building, the various operation modes to **study and validate the collective behaviour** of the different systems of the HL-LHC's IT zone.
- Another key motivation is to test and optimize the **QC plans, IST, SCT and Powering Test procedures** to prepare to a smooth LS3
- Few differences w.r.t. tunnel configuration: SQXL includes more instruments, no beam-position monitors, no slope, beam-screens and beam vacuum excluded, etc.

Integration - HL-HLC IT String vs. HL-LHC

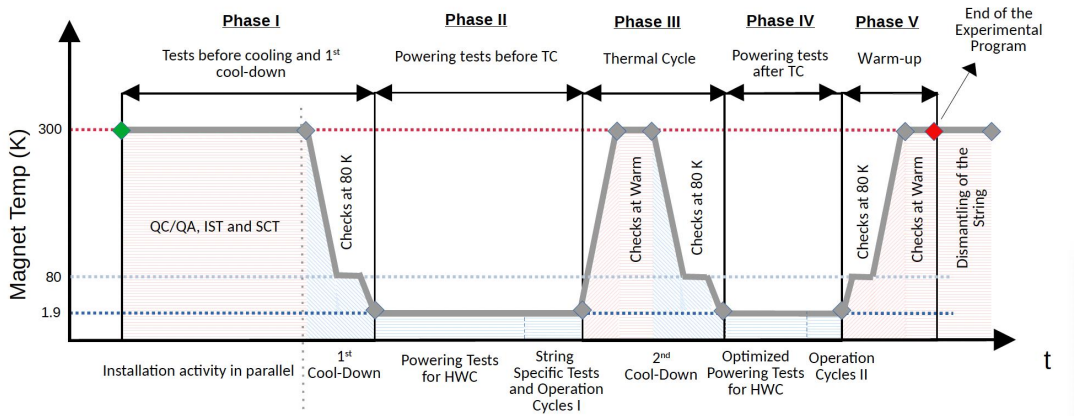


WCC: Water-Cooled Cables
SQXL/QXL: String/Tunnel Cryogenic Line
DFHX/DFX: HTS/LTS Electrical Feedbox
SC Link: Superconducting Link
CDB: Circuit Disconnector Boxes
PC: Power Converter
EES: Energy Extraction System
CLIQ: Quench Protection System for the RQX
DQHDS: Quench Heater Power Supplies



String Validation Program

HL-LHC IT String Validation Program



HL-LHC IT String Validation Program
EDMS no. 2664290

String Specific Tests :
- *Cryogenics bayonet heat exchanger tests*
- *Crosstalk studies*
- *Flux jump measurements*

Operation Cycles :
- *Powering endurance tests*
- *FRAS with and without current in magnets*
- *Powering cycles in synergy with BE-OP*

IST for:
- *Cryogenic system*
- *Warm powering*
- *Quench protection*
- *Full Remote Alignment System (FRAS)*
- *Magnet mechanical transfer function*

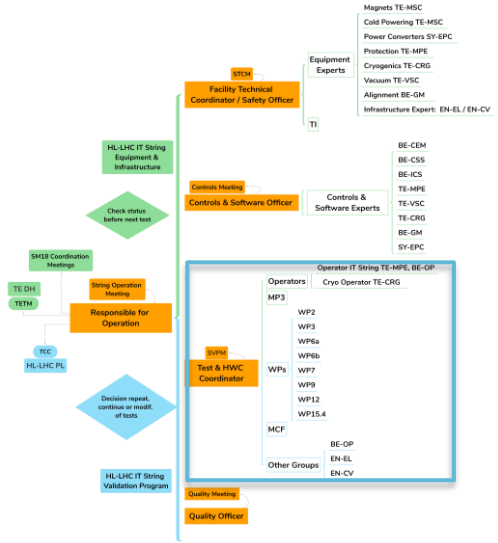
QA/QC:
- *Electrical quality assurance*
- *Continuity and polarity control*
- *Pressure and leak tests*

Powering Tests for HWC:
- *QPS IST*
- *Powering tests from low to higher energy circuits:*
  - *PC performance (control loops, energy recovery)*
  - *Quench detection and protection*
  - *Performance of the link with magnets*
  - *Cryogenics operation during ramps and after quenches*
  - *Movement of magnets after quenches and thermal cycle*

Also included in the HL-LHC HWC

Coordination of the String Validation Program

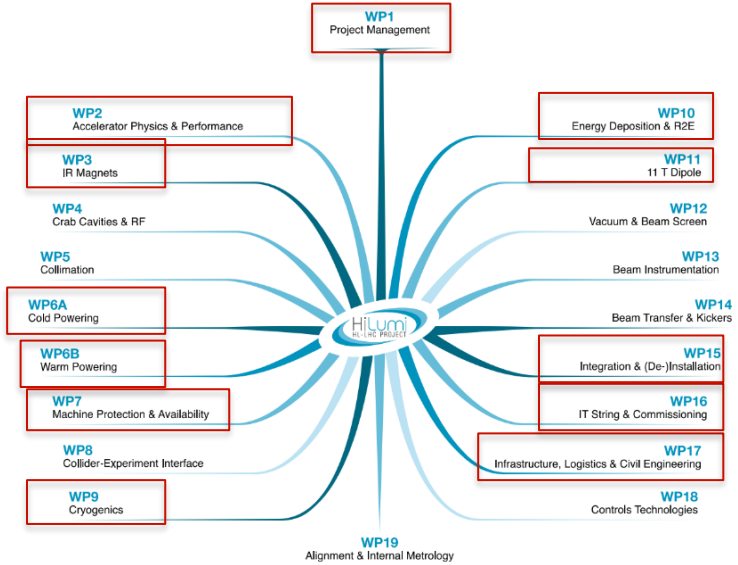
From EDMS no. 2956328



String Validation Program Meetings

Test plan, procedure and results are documented and systematically reported in the concerned forums (MCF, SVPM, MP3 and TCC)

See talk of R. Piccin talk – THU AM



HL-LHC Magnet Circuit Forum (link) as forum to discuss the HL-LHC circuits systems;

LHC Magnet Circuits, Powering and Performance Panel - MP3 - (link) as responsible of the HWC powering procedures

Quality Control and Quality Assurance

Electrical Design Criteria for HL-LHC IT String and HL-LHC

EDMS No.	Title
1963398	HL-LHC Electrical Design Criteria for the HL-LHC Inner Triplet Magnets
2060633	HL-LHC Electrical Design Criteria for the High Order Corrector Magnets
2187266	HL-LHC Electrical Design Criteria for the D1 Dipole
2363905	CIEMAT - MCBXF - ELECTRICAL DESIGN CRITERIA
2363906	IHEP - MCBRD - ELECTRICAL DESIGN CRITERIA
2363904	INFN - MBRD - D2 - ELECTRICAL DESIGN CRITERIA
2824470	Electrical Design Criteria for the HL-LHC Circuit Components operating at Room Temperature
2826527	Electrical Design Criteria for the HL-LHC Superconducting Link System
3002227	HL-LHC Electrical Design Criteria for the D1-DFX, D2-DFM Interconnection modules and Superconducting busbars in HL-LHC Line N1 and Line N2

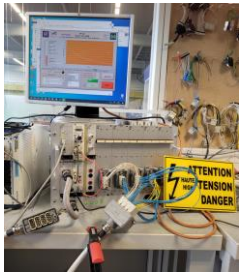
Collaborative work with Work Packages, CERN's ElQA team and HL-LHC Magnet Circuit Forum

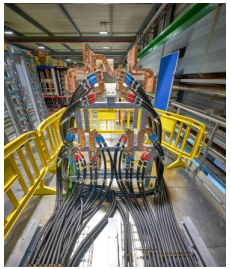
Electrical Tests during Installation

Scope:

- Electrical Design Criteria (EDC) documents specify voltage withstand requirements during lifetime
- During installation, RT and SC components connected to the magnet circuits are electrically tested

Warm Powering and Cables



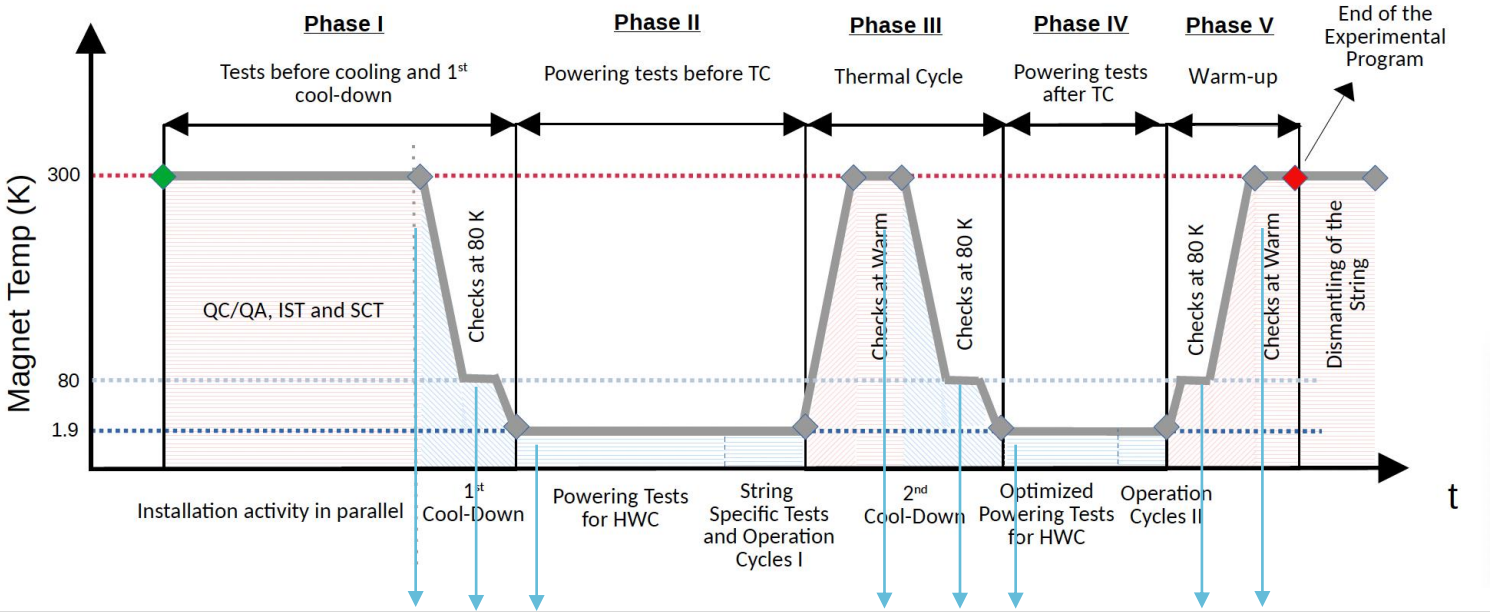


SC Link tests at RT (gHe conditions)

Magnet tests at Warm

More information in G. West talk – THU AM

Electrical Tests on Full System



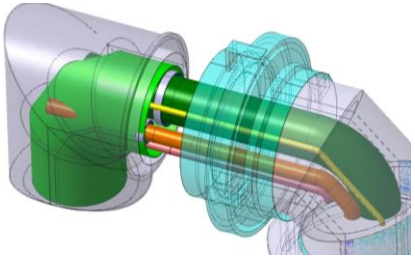
ElQA Tests on Full System depending on conditions as defined in EDC Documents

More information in G. West talk – THU AM

Pressure and Leak Tightness Tests

Scope:

- Pressure tests are applied to pressurized systems based on NF-EN-13480 for metallic pipes
- Each system is tested for leak tightness: installation vacuum to helium (10^{-9} mbar.l/s) and to air (10^{-8} mbar.l/s)



Clam Shells for magnet interconnections

Leak Tightness of the SC Link + DFHX

Leak Tightness of the String QXL (SQXL)

Courtesy of W. Maan

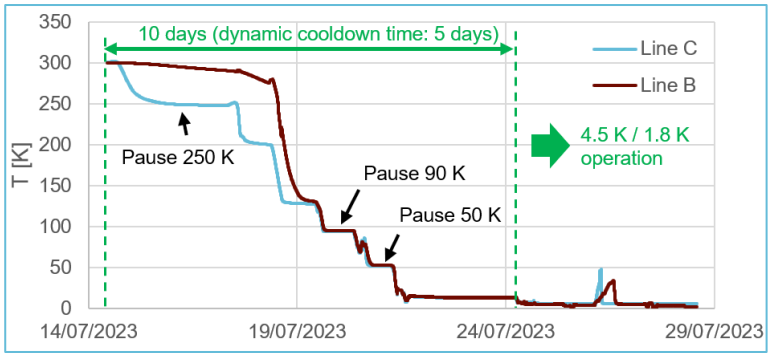
Individual System and Short Circuit Tests (applying to both IT String and HL-LHC)

Test Procedures for HL-LHC IT String (and HL-LHC)

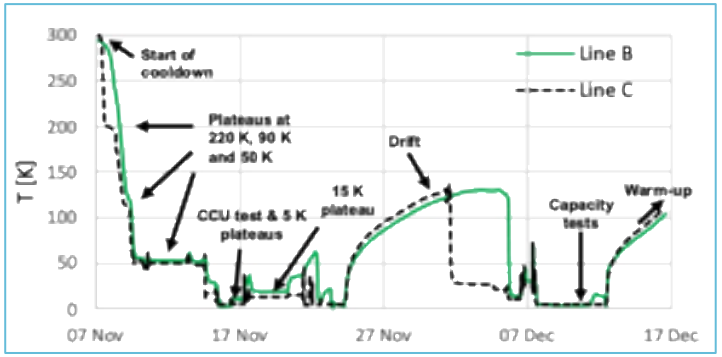
Type	Test Procedure	EDMS no.	Doc. Status	Activity Status in String
IST	Energy Extraction Systems in the HL-LHC IT String	2744520	Released	Done in Q1 24
IST	Water-Cooled Cables in the HL-LHC IT String	2744521	Released	Done in 23
IST	PC and the Circuit Disconnector Boxes in the HL-LHC IT String	2767662	Released	Done in Q1/2 24
IST	Full Remote Alignment System in the HL-LHC IT String	2783832	Draft Version (to be launched soon)	Start in Q4 24
IST	Quench Heater Power Supplies in the HL-LHC IT String	3118980	Eng. Check	Start in Q4 24
IST	CLIQ in the HL-LHC IT String	3118978	Under Approval	Start in Q4 24
IST	Quench Detection and Supervision System in the HL-LHC IT String	2912337	To be done	Start in Q4 24
IST	Cryogenic System in the HL-LHC IT String - Phase 1a	2910866	Released	Done in Q3 23
IST	Cryogenic System in the HL-LHC IT String - Phase 1b	2974487	Released	Done in Q4 23
SCT	HL-LHC Inner Triplet String Short Circuit Tests	2744522	Released	Done in Q1/2 24

Collaborative work with Equipment Owners and String Validation Program members

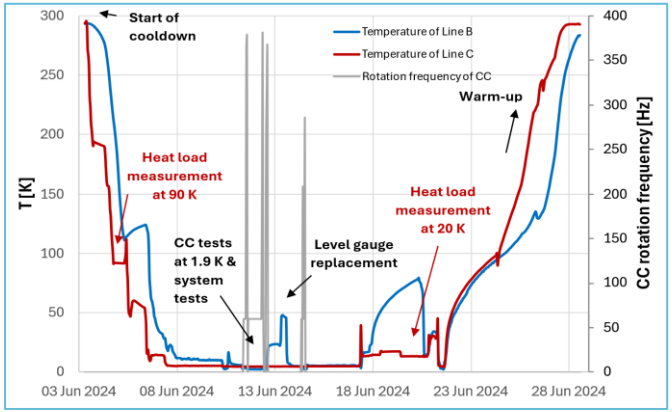
Commissioning of the Cryogenics – Phase 1 without Magnets



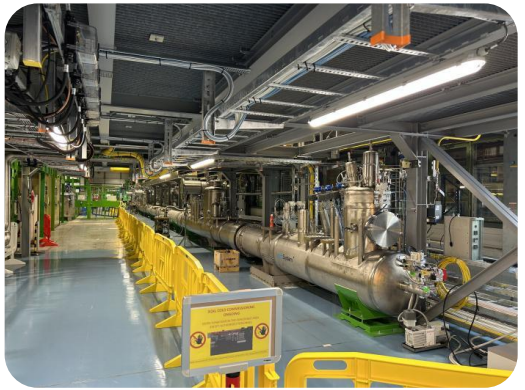
Phase 1a



Phase 1b



Phase 1c



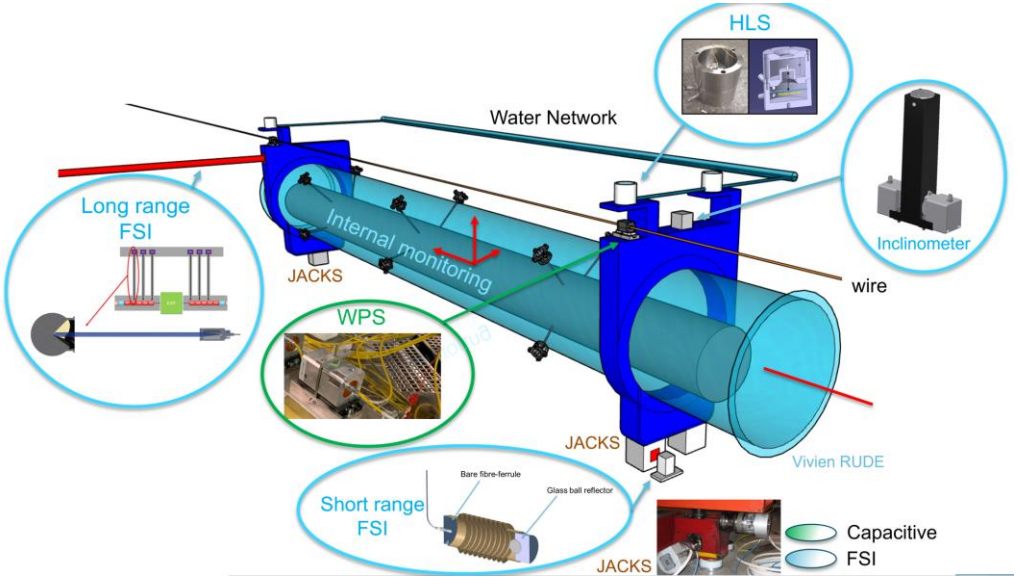
Example of the SQXL in the HL-LHC IT String

Courtesy of A. Onufrena et al.

Commissioning of the Fully Remote Alignment System

FRAS components to be tested:

- Wire Positioning System
- Hydrostatic Levelling system
- Inclinometers
- Longitudinal monitoring
- Cold mass monitoring
- Motor adapters
- Load and environmental sensors
- Software control and data flow
- Protection layers



Courtesy of M. Sosin, V. Barbarroux et al.

IST procedure for the HL-LHC IT String is being drafted by WP19

LHC-XMS-OP-0010, EDMS no. 2783832

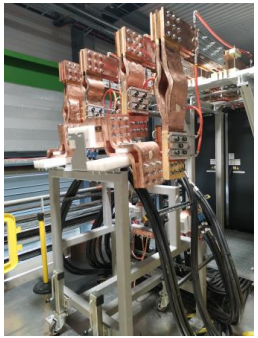
Sequence for Warm Powering IST and SCT

1. Control, Signal and Power Cables QC
   Water Cooling Network QC
   Electrical Distribution Network QC
2. Water Cooled Cables IST — *LHC-XMS-OP-0002*
3. Connection of Systems to Infrastructure (Power Cables, Electrical Distribution and Water Cooling)
4. HSE Inspection (Hydraulic and Electrical)
5. Power Converter and CDB IST
   Energy Extraction System IST
   LHC-XMS-OP-0001
   LHC-XMS-OP-0005
6. Short Circuit Tests (with PICv2) — *LHC-XMS-OP-0003*

- Interlock checks
- PIC loop checks
- Extraction discharges
- Heat-run tests at ultimate current (~7.5 TeV)

Warm Powering Infrastructure in the IT String

HL-LHC power converters with same layout as in the HL-LHC



Air-cooled cables and DC connection model

Circuit disconnector boxes

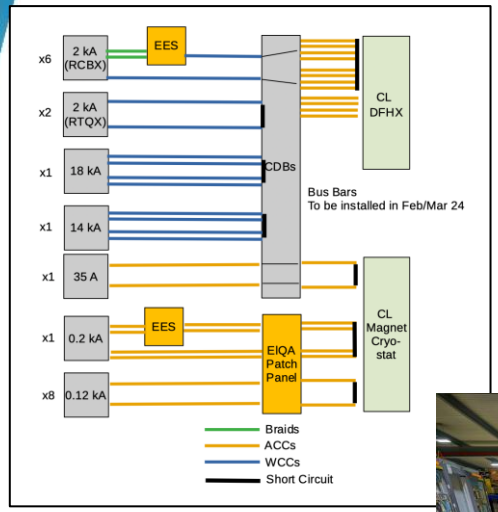
PICv2

HL-LHC energy extraction systems

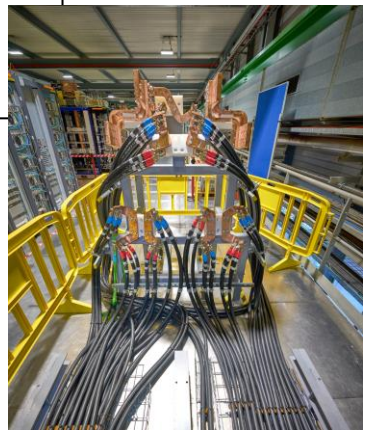
Water-cooling network and water-cooled cables

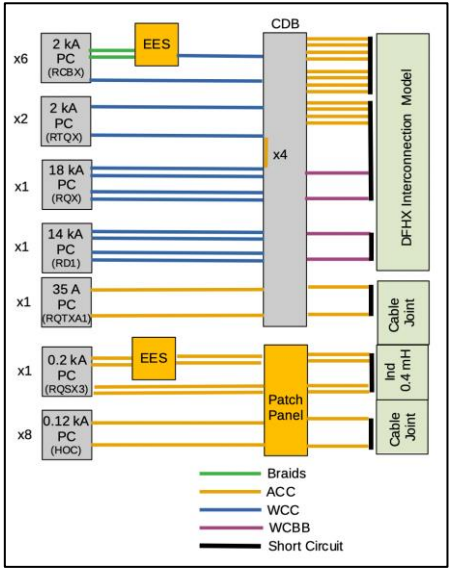
AC infrastructure

Short-Circuit Test Configuration in the String

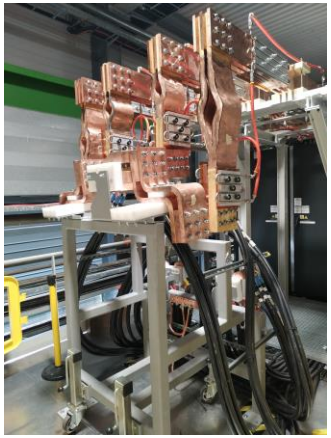


Phase 1 - Jan 2024





Phase 2 - May 2024



More information in H. Thiesen's talk – THU AM and the upcoming talk on IST and SCT in the same session

Powering Tests for the Hardware Commissioning (applying to both IT String and HL-LHC)

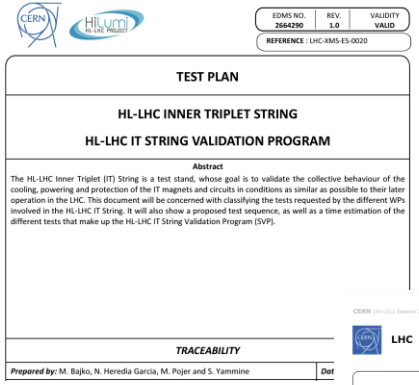
Test Procedures for HL-LHC IT String and HL-LHC

Type	Test Procedure and Acceptance Criteria	EDMS no.	Doc. Status	Activity Status in String
HWC	ElQA Qualification of the Superconducting Circuits in the HL-LHC IT String	2746933	Draft Version	Start in Q4 24
HWC	Interlock Tests of the HL-LHC IT String Circuits	2797308	In preparation - planned for Q1 25	Start in Q4 25
HWC	Powering of the HL-LHC Inner Triplet (RQX)	2771115	In Preparation - planned for end of 24	Start in Q4 25
HWC	Powering of HL-LHC Separation Dipole (RD1)	2771114	Under Approval	Start in Q4 25
HWC	Powering of the HL-LHC IT Orbit Correctors (RCBX)	2771111	Under Approval	Start in Q4 25
HWC	Powering of the HL-LHC 200 A RQSX3 Circuit	2922509	Eng. Check	Start in Q4 25
HWC	Powering of the HL-LHC High Order Corrector (120 A) Circuits	2922510	Eng. Check	Start in Q4 25
HWC	Parameters for the HL-LHC Circuit Powering Tests	2771118	Eng. Check	Start in Q4 25
HWC	Parameters for the HL-LHC Quench Detection System	2920923	In Preparation - planned for Q1 25	Start in Q4 25

Collaborative work with Work Packages, MP3, HL-LHC Magnet Circuit Forum and String Validation Program members

From String Validation Program Phases to HL-LHC HWC

HL-LHC IT STRING Validation Program Document
(Goals and Methods)
LHC-XMS-ES-0020, EDMS no. 2664290


EDMS NO. 2664290 | REV. 1.0 | VALIDITY VALID
REFERENCE : LHC-XMS-ES-0020

TEST PLAN

HL-LHC INNER TRIPLET STRING

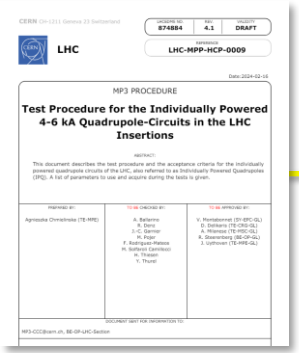
HL-LHC IT STRING VALIDATION PROGRAM

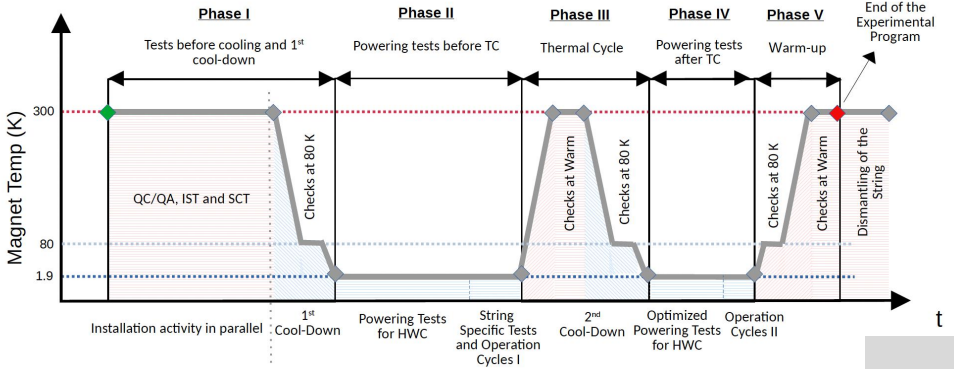
Abstract

The HL-LHC Inner Triplet (IT) String is a test stand, whose goal is to validate the collective behaviour of the cooling, powering and protection of the IT magnets and circuits in conditions as similar as possible to their later operation in the LHC. This document will be concerned with classifying the tests requested by the different WPs involved in the HL-LHC IT String. It will also show a proposed test sequence, as well as a time estimation of the different tests that make up the HL-LHC IT String Validation Program (SVP).

TRACEABILITY

Prepared by: M. Bajko, N. Heredia Garcia, M. Pojer and S. Yammine


LHC
LHC-MPP-HCP-0009
MP3 PROCEDURE
Test Procedure for the Individually Powered 4-6 kA Quadrupole-Circuits in the LHC Insertions



First implementations of the HL-LHC procedures inspired from LHC procedures


HARDWARE COMMISSIONING PROCEDURE

HL-LHC INNER TRIPLET STRING AND HL-LHC

TEST PROCEDURE AND ACCEPTANCE CRITERIA FOR THE SEPARATION DIPOLE CIRCUIT (RD1)

Abstract

TRACEABILITY

Final version of HL-LHC procedures ready to validate for the HL-LHC HWC

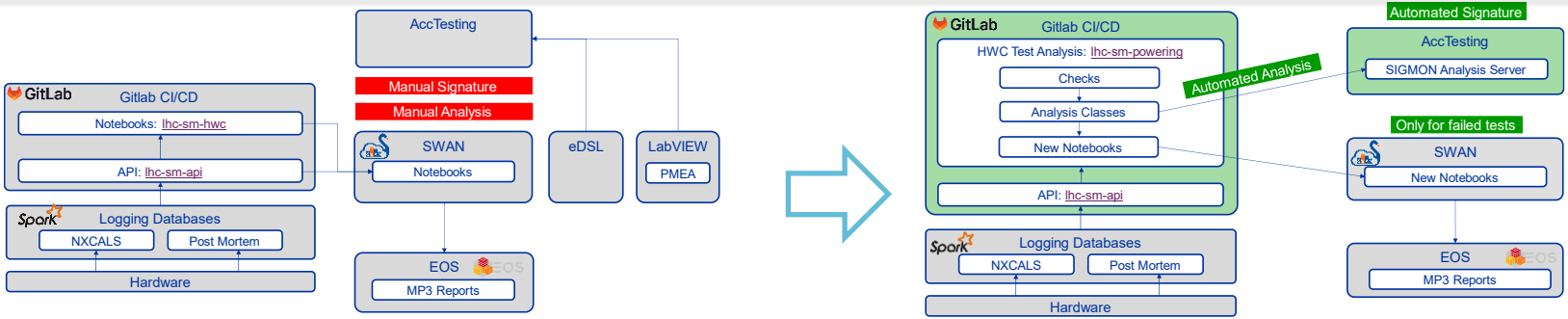
LS3 HL-LHC HWC

LHC HWC Procedures

HL-LHC HWC Procedures
https://edms.cern.ch/project/CERN-0000231253

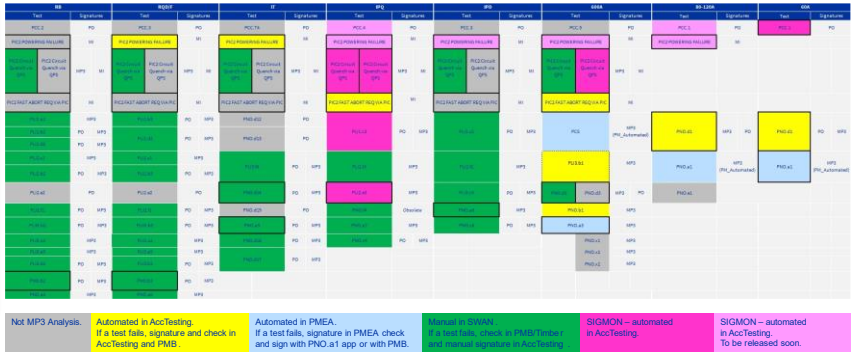
MP3 Ongoing Work on LHC HWC Powering Tests

Courtesy of A. Chmielinska

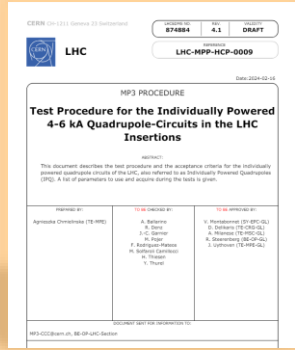


HWC Powering Test Analysis Architecture

HL-LHC circuits to be added



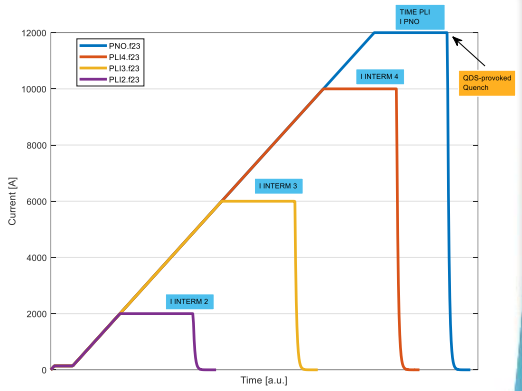
Progress for LHC circuits as of July 24



Updated LHC procedures in preparation

Example of the HL-LHC RD1 Test Procedure

Test	Current level	Test description	HL-LHC IT String	LS3,4,5 HWC	Warm up > 90 K	TS > 3 Wk
PCC.23	I_PCC	Power converter configuration	x	x	x	
PIC2	I_MIN_OP	Power interlock controller check	x	x	x	x
PLI1.c23	I_INTERM_1	Fast power abort via PIC at intermediate current 1	x	x		
PLI2.d23	I_INTERM_2	Powering failure at intermediate current 2	x	x		
PLI2.f23	I_INTERM_2	QDS provoked quench at intermediate current 2	x	x		
PLI3.e23	I_INTERM_3	Slow power abort via PIC at intermediate current 3	x			
PLI3.c23	I_INTERM_3	Fast power abort via PIC at intermediate current 3	x	x	x	
PLI3.f23	I_INTERM_3	QDS provoked quench at intermediate current 3	x			
PLI4.s23	I_INTERM_4	Splice mapping till intermediate current 4	x	x	x	
PLI4.d23	I_INTERM_4	Powering failure at intermediate current 4	x	x		
PLI4.f23	I_INTERM_4	QDS provoked quench at intermediate current 4	x			
PNO.c23	I_PNO+I_DELTA	Fast power abort after a current plateau at I_PNO+I_DELTA	x	x	x	
PNO.f23	I_PNO	QDS provoked quench at I_PNO	x			
PNO.a23	I_PNO	Current cycle to I_PNO with splice measurement	x	x	x	x
Total no. of Steps			14	10	6	2



Type of analysis	Acceptance Criteria
Check heater voltages (U_HDS_1, U_HDS_2, U_HDS_3, U_HDS_4), heater currents (I_HDS_1, I_HDS_2, I_HDS_3, I_HDS_4) and decay time constants (τ_HDS_1, τ_HDS_2, τ_HDS_3, τ_HDS_4) during the discharge	Compared with reference signals: U_HDS: ±5% τ_HDS: ±5% I_HDS: ±5%
Check the heater delay from the quench signal	t_delay (Start of HDS discharge with respect to quench signal being issued) is within ±5 ms
Check the earth current during the quench	Agreement of I_EARTH(t) to reference curve[*] within a tolerance of 10%.
[*] The reference signal is the last successful test that was approved in collaboration with the experts.	

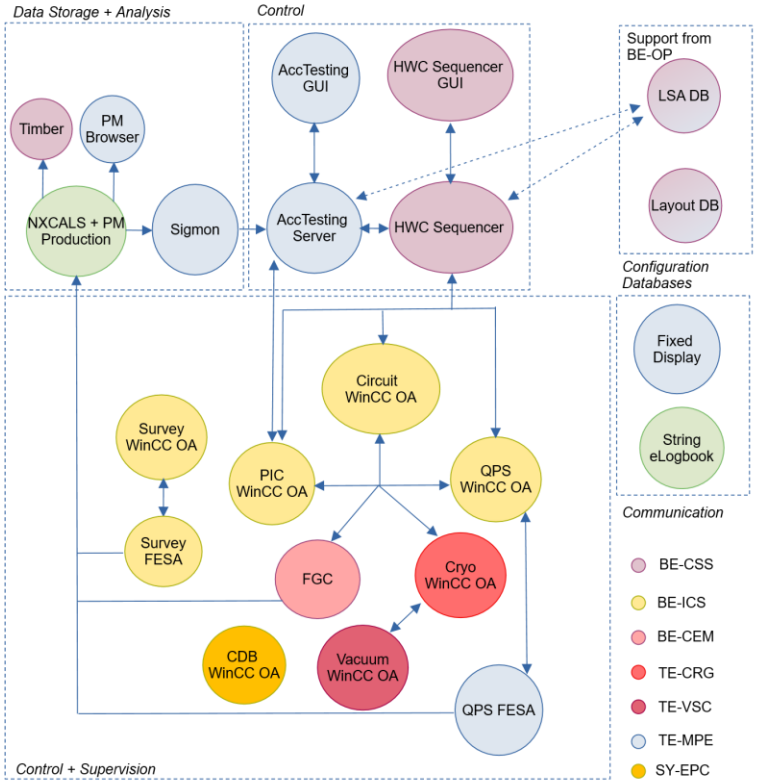
Discharge Curves and Acceptance Criteria

Powering Tests and Acceptance Criteria for the 14 kA RD1 Circuit

LHC-XMS-OP-0007, EDMS no. 2771114

HWC Controls, Analysis and Supervision SW

- Control, analysis and supervision software development for the HL-LHC IT String and the HL-LHC is in line with the LHC software and the HL-LHC new hardware:
  - HL-LHC circuit families
  - New Tests in AccTesting based on procedures
  - Sequences in HWC Sequencer
  - New software for PICv2
  - Supervision for HL-LHC QDS
  - New QPS: EES, CLIQ and DQHDS
  - FRAS and survey system
  - New circuit synoptic
  - Etc.



More information in S. Blanchard's talk

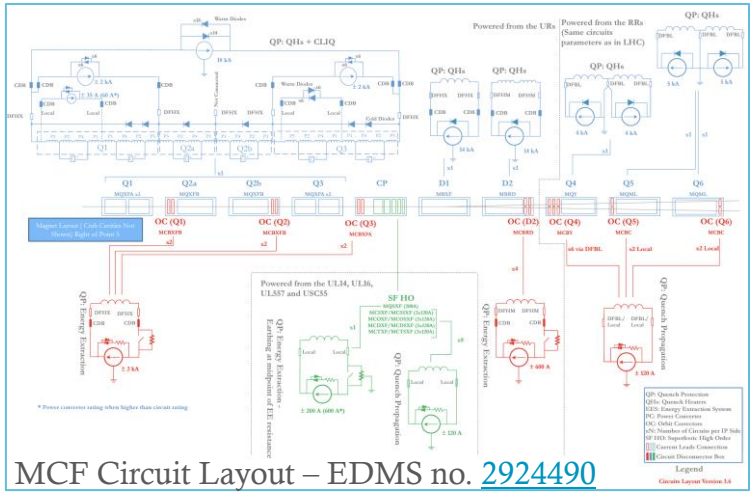
Extension of the IT String to HL-LHC – WP16 HWC Mandate

- **HL-LHC Hardware Commissioning phase encompasses the commissioning of all equipment that will be installed in the insertion regions** and the new service areas:
  - **New (or modified) superconducting circuits and related systems** (power converters, circuit protection, cryogenics and technical infrastructures),
  - **Other equipment, like Crab Cavities, beam instrumentation, FRAS and collimators, to prove their functionalities and reliability.**
- Concerning the **equipment other than the superconducting circuits**, their commissioning will be full responsibility of the equipment owners. WP16 will help coordinating the interaction with other stakeholders and the interference with the commissioning of the superconducting circuits and the integration in the LHC operational environment.

Courtesy of M. Pojer based on WP16 Mandate

Extension of the IT String to HL-LHC – WP16 HWC Mandate

- For the **superconducting circuits**, the HWC activity will pursue the preparation work to include the remaining circuits in close collaboration with MCF and MP3:
  - D2 and correctors (not included in the HL-LHC IT String),
  - Q4 swapped corrector planes at points 1 and 5/ Q4 and Q5 translated towards non-IP sides with modified DSL,
  - Q10 including the sextupole at pts 1/5
- HWC activity will ensure the execution of detailed procedures for the qualification of the HL-LHC superconducting circuits and the protection functionalities (including their IST and SCT campaign).



MCF Circuit Layout – EDMS no. 2924490

Circuits for HiLumi	Magnet Type	Circuit Name	Number of circuits per IP side	Total number of circuits	I_nominal (7 TeV) [kA]	I_ultimate [kA]	L per circuit at nominal current [mH]	R per circuit [mΩ]	PC quad number	Required Precision Class of PCs	Required ramp rate from beam dynamics [A/s]	Maximum ramp rate** [A/s]	Required acceleration rate from beam dynamics [A/s2]	Maximum Acceleration rate** [A/s²]
Inner Triplet	Trim Q1	-	RTQX1	1	4 (IR1/5)	2	2	69	1.35	4	2	2.09	2.09	0.16	0.16
	Trim Q1a	-	RTQX1	1	4 (IR1/5)	0.035	0.035	34.5	226.16	4	4	3.32	3.32	0.35	0.35
	Trim Q3	-	RTQX3	1	4 (IR1/5)	2	2	69	1.2	4	2	2.09	2.09	0.11	0.11
	Orbit correctors Q1/2 - Horizontal/Inner	MCBXFB	RCBXH[1,2]	2	8 (IR1/5)	1.74	1.864	58.4	2.37	4	2	15	15	5	5
	Orbit correctors Q1/2 - Vertical/Outer	MCBXFB	RCBXV[1,2]	2	8 (IR1/5)	1.43	1.532	124.8	2.42	4	2	15	15	5	5
	Orbit correctors Q3 - Horizontal/Inner	MCBXFA	RCBXH3	1	4 (IR1/5)	1.593	1.709	107.1	1.99	4	2	15	15	5	5
	Orbit correctors Q3 - Vertical/Outer	MCBXFA	RCBXV3	1	4 (IR1/5)	1.34	1.441	232.3	1.98	4	2	15	15	5	5
	Superferric, order 2	MQSXF	RQSX3	1	4 (IR1/5)	0.174	0.197	1530	14.31	4	3	2.42	2.42	0.48	0.48
	Superferric, order 3, normal and skew	MCSXF / MCSSXF	RCS[S]X3	2	8 (IR1/5)	0.099	0.112	213	54	4	4	1.4	1.4	0.28	0.28
	Superferric, order 4, normal and skew	MCOXF / MCOSXF	RCO[S]X3	2	8 (IR1/5)	0.102	0.115	220	54	4	4	1.4	1.4	0.28	0.28
	Superferric, order 5, normal and skew	MCDXF / MCDSXF	RCD[S]X3	2	8 (IR1/5)	0.092	0.106	120	54	4	4	1.4	1.4	0.28	0.28
	Superferric, order 6	MCTXF	RCTX3	1	4 (IR1/5)	0.085	0.097	805	54	4	4	1.4	1.4	0.28	0.28
	Superferric, order 6, skew	MCTSXF	RCTSX3	1	4 (IR1/5)	0.084	0.094	177	54	4	4	1.4	1.4	0.28	0.28
D1	Separation dipole D1	MBXF	RD1	1	4 (IR1/5)	12.11	13.231	24.84	0.31	1	0	12	12	2	2
D2	Recombination dipole D2	MBRD	RD2	1	4 (IR1/5)	12.33	13.343	27.46	0.13	1	0	12	12	2	2
	Orbit correctors D2	MCBRD	RCBRD[V,H]4	4	16 (IR1/5)	0.394	0.422	920	1.36	4	3	2	2	1	1
Q4	Individually powered quad Q4 (4.5K)	MQY	Same Circuit Paramters for Q4 in IR1/5 as in the LHC, Correction Plane Swapped by Turning and Swaping of Q4 Magnets												
	Orbit correctors Q4 (4.5K)	MCBY													
Q5	Individually powered quad Q5 (4.5K)	MQML	Same Circuit Paramters for Q5, Q6 and Correctors in IR1/5 as in the LHC; Q5 moves to ~10 m towards arc												
	Orbit correctors Q5 (4.5K)	MCBC													
Q6	Individually powered quad Q6 (4.5K)	MQML													
	Orbit correctors Q6 (4.5K)	MCBC													
Q10	Individually powered quad Q10 (1.9K)	MQML	RQ10	2	8 (IR1/5)	5.39	5.83	21	0.4	1	2	16.167	16.167	2	2
	Orbit correctors Q10 (1.9K)	MCB	RCB[V,H]10	2	8 (IR1/5)	0.055	0.06	6020	45.8	4	4	0.5	0.5	0.25	0.25
	Lattice Sextupole (1.9K)	MS	RS[D,F][1,2]	2	8 (IR1/5)	0.55	0.6	432	7.5	4	4	5***	5	1***	1
Q5	Individually powered quad Q5 (4.5K)	MQY	RQ5	2	4 (IR6)	3.61	3.9	74	0.4	1	2	10.83	10.83	2	2
	Orbit correctors Q5 (4.5K)	MCBY	RCBY[V,H]5	2	4 (IR6)	0.088	0.1	5270	34.4	4	4	0.67	0.67	0.25	0.25

Beam Dynamics - WP2 | Magnets - WP3 | Cold Powering - WP6a | Power Converters - WP6b | Protection - WP7 | Warm Connections - WP17-WP6b | IT and D2 Bus Bars - Spl

MCF Circuit Parameters Table – EDMS no. 2924490

Takeaway Message

- 2023 and 2024 have seen the first operational experience of the IT String. The team is looking forward to more exciting results in the months to come.
- Individual system and short circuit tests have been successfully executed and the cryogenic and warm powering systems are fully qualified without magnets in the IT String and provide a strong basis for the same tests in the tunnel.
- Lessons learnt passed onto the teams involved.
- Finalization of the procedures for the circuit powering is underway for IT String tests in 2025-2026 and will be optimized for the HL-LHC.

Thank you for your attention