HiLumi
HL-LHC PROJECT

Overview of the System Tests and Commissioning Plan for the HL-LHC IT String

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HL-LHC Magnet Circuit Instrumentation Day 2023

2023-06-20

Contents

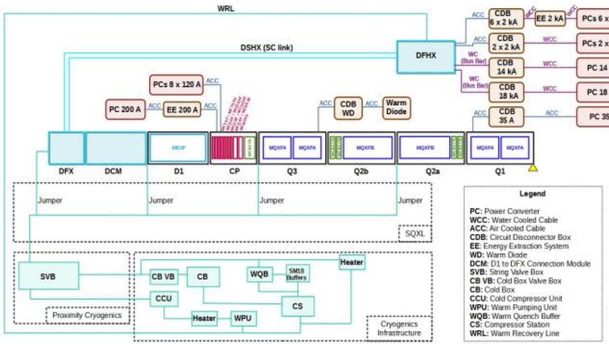
- Introduction
- Overview of the Individual Systems Tests (related to instrumentation)
- Hardware Commissioning Tests
- Control, Supervision and Analysis Software
- Conclusion

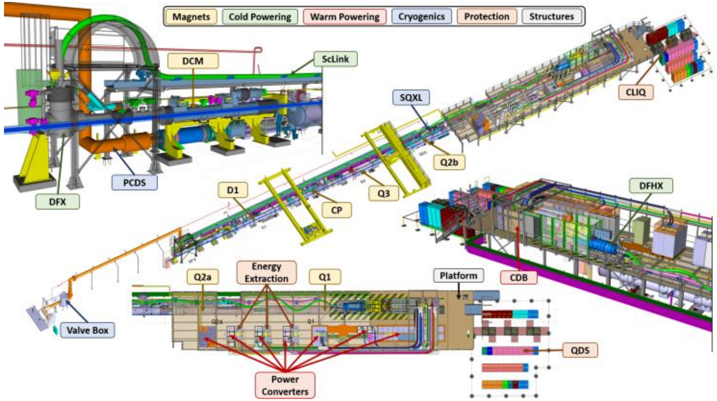
Introduction

Scope of HL-LHC IT String Validation Program

The *scope* of the HL-LHC 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 (magnets, magnet protection, cryogenics for the magnets and the superconducting link, magnet powering, vacuum, alignment, interconnections between magnets, and the superconducting link).

Reference of the HL-LHC IT String Scope [EDMS no. 1693312]



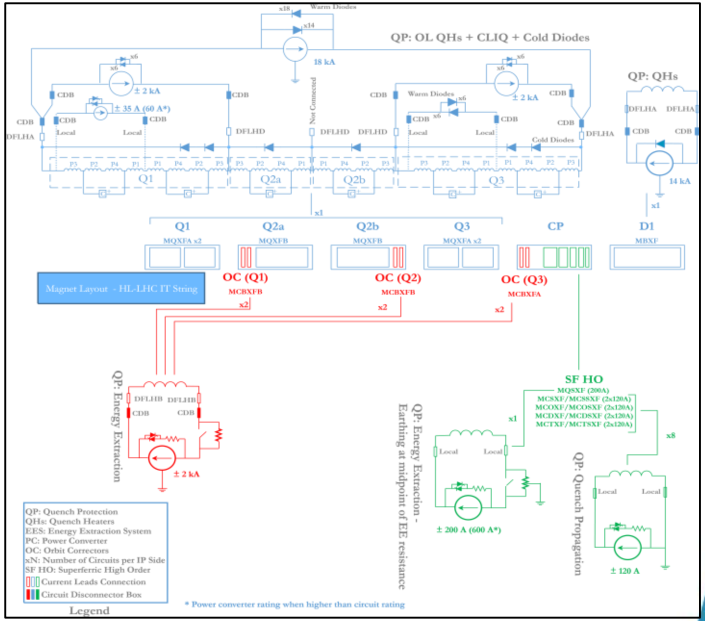


The HL-LHC IT **String** will deliver **the first complete experience** of installing and operating the HL-LHC IT zone

Drivers of the String Validation Program

Powering and Protection Scheme in the IT String

- Inner Triplet Circuit:
  - Rated 18 kA and 2 trims at 2 kA over Q1 and Q3 – powered through the SC Link
  - 1x 35 A for K-mod on Q1a – powered via local feeders on Q1
  - Protected by means of Quench Heaters, CLIQ and Cold Diodes
- RD1 circuit:
  - Individually Powered Dipole Circuit rated 14 kA
  - Protected by means of Quench Heaters
- RCBX Dipole Corrector Circuits:
  - 6 circuits for 3 nested magnets (V,H) rated at 2 kA
  - Protection by means of 150 mΩ Energy Extraction System
- High Order Correctors
  - Powered via conduction cooled cables/local powering
  - 8x 120 A circuits where magnets are self protected
  - 1x 200 A circuit protected via 1.4 Ω Energy Extraction



Overview of the Individual Systems Tests

Tests for Warm Powering

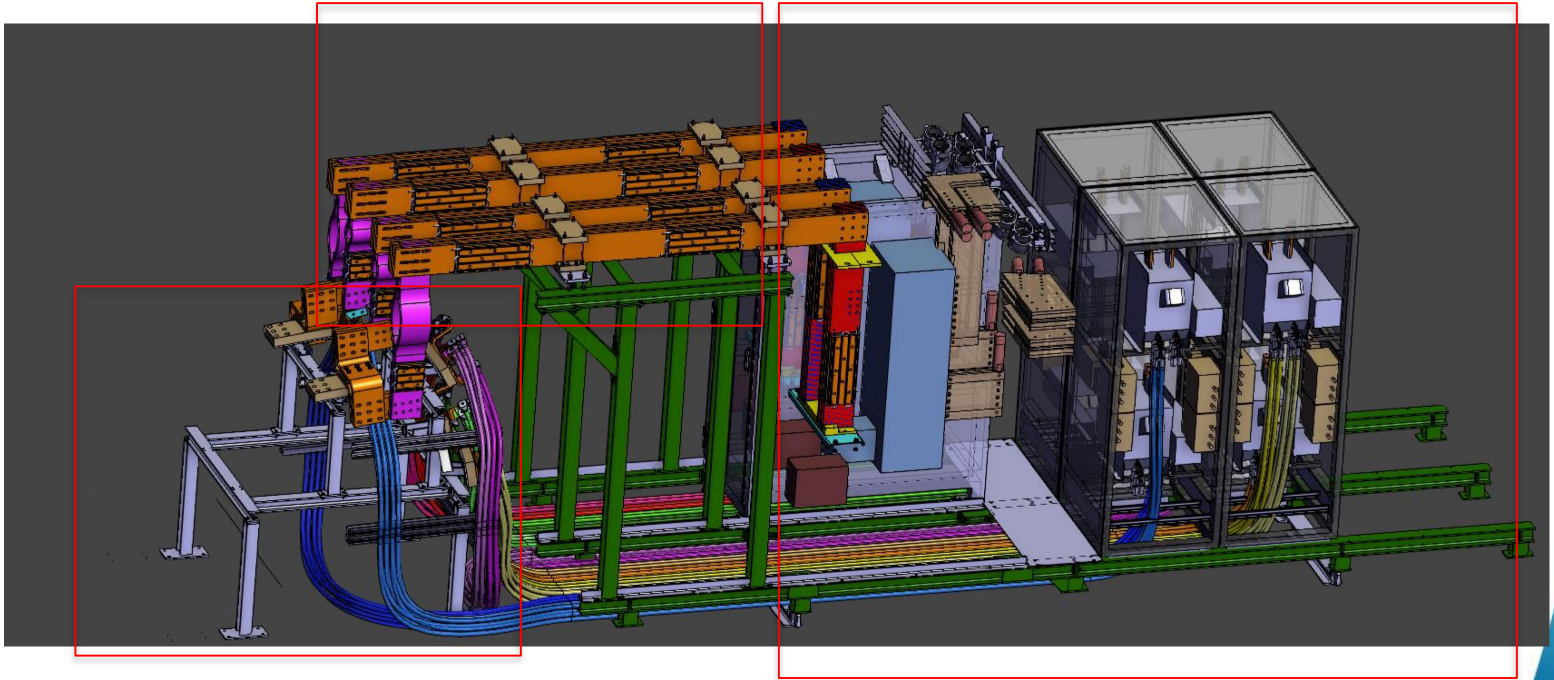
1. Control, Signal and Power Cables IST | Water Cooling Network IST | Electrical Distribution Network IST
2. Water Cooled Cables IST — LHC-XMS-OP-0002
3. Connection of the EES to Infrastructure | Connection of PCs and CDBs to Infrastructure | Connection of PIC to Infrastructure
4. HSE Inspection (Hydraulic and Electrical)
5. PC and CDBs IST | Energy Extraction IST — LHC-XMS-OP-0001, LHC-XMS-OP-0005
6. Short Circuit Tests (including PIC) — LHC-XMS-OP-0003

Short Circuit Tests in the HL-LHC IT String

- Short Circuit Connections in the IT String Test *LHC-XMS-OP-0003*
  - PIC, Water-Cooled Cables, Bus Bars, Power Converter and Energy Extraction System Validation with Relevant Instrumentation

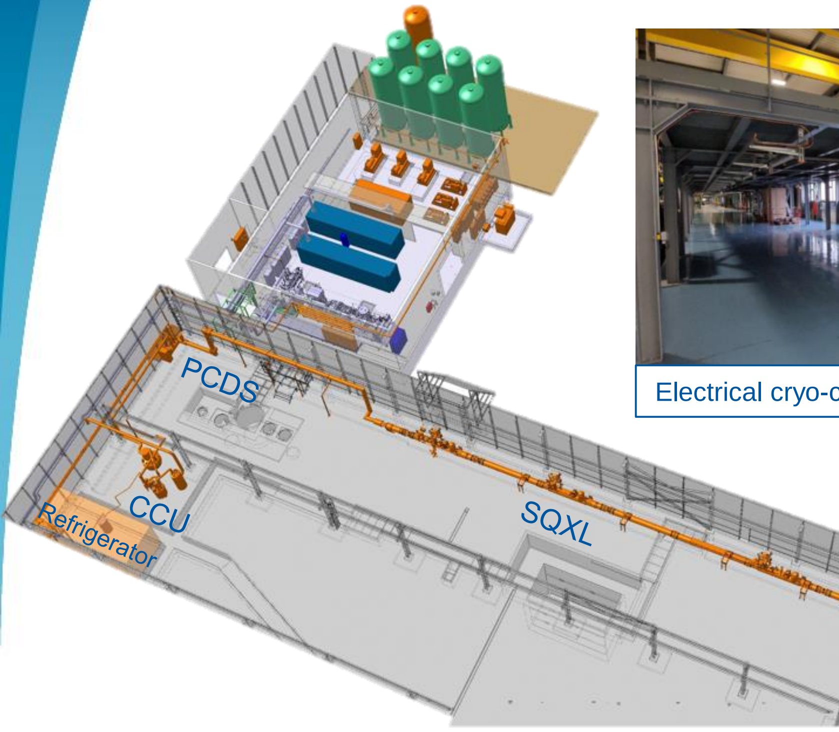
High Current Bus-bars

CDBs



DFHX Current Leads Connections Model

Commissioning of the Cryogenics without Magnets



Electrical cryo-cabinets installed in the HL-LHC IT String

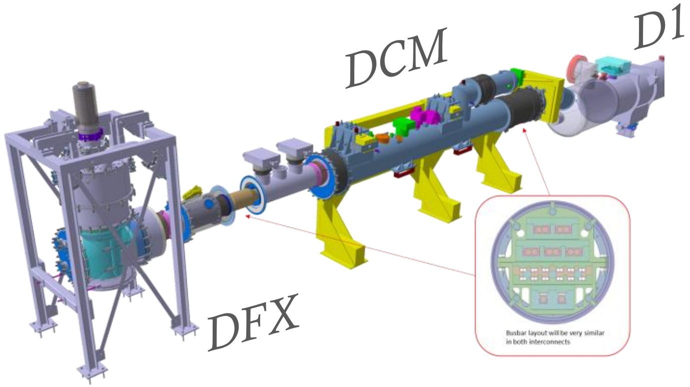
Objectives (EDMS no. 2620402) :

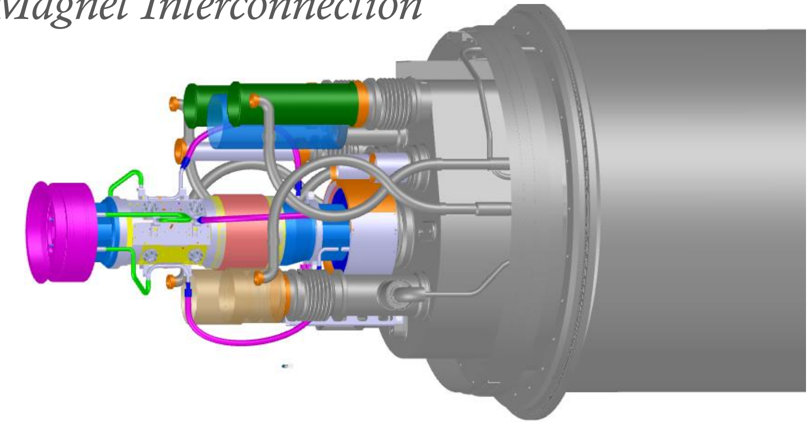
- Validate mechanical and thermal design (+ vacuum leak checks by TE-VSC)
- Verify the operation and calibration of the instrumentation at room temperature & cold conditions
- Tune the control loops to reduce commissioning time with magnets

Cryo Commissioning wo Magnets → Magnets Installation → Cryo Commissioning before Powering → IT String Validation Program

Courtesy of A. Perin

QC during Cold Powering and Magnet Installation





Electrical Quality Assurance (ElQA) tests are foreseen as defined in LHC-XMS-OP-0004 to check di-electrical withstand and continuity in connections (polarities, instrumentation, etc.) of cold powering and magnets during the interconnection phase.

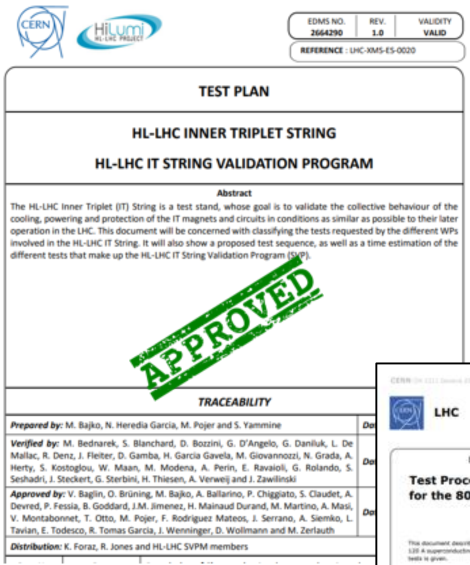
Instrumentation wires routed at room temperature are also di-electrically tests.

(See talk of Mateusz).

HWC of the HL-LHC IT String

MP3 from String Validation Program 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).

APPROVED

TRACEABILITY

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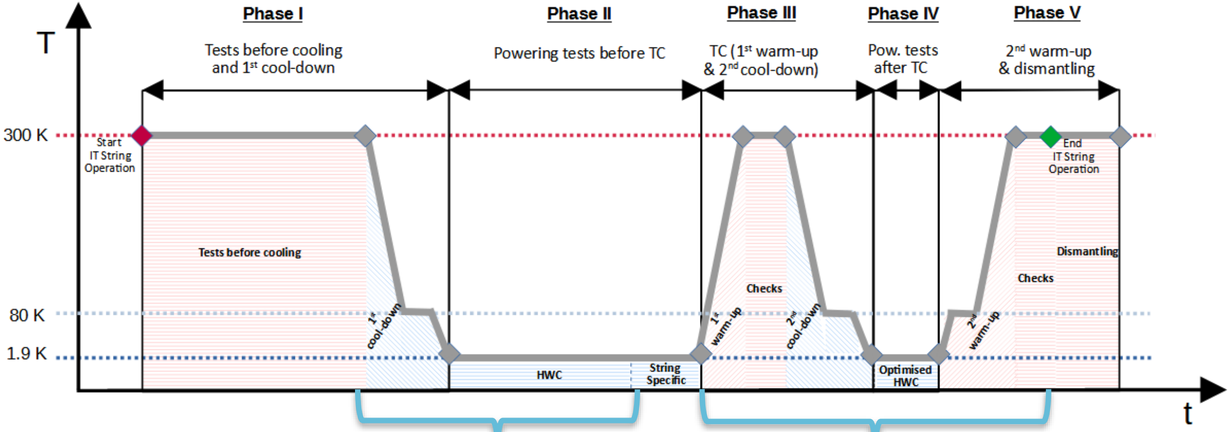
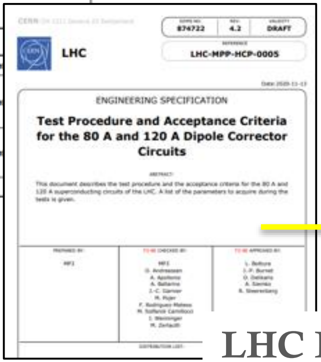



EDMS NO. 874722 | REV. 4.2 | VALIDITY DRAFT

LHC

LHC-MPP-HCP-0005

ENGINEERING SPECIFICATION

Test Procedure and Acceptance Criteria for the 80 A and 120 A Dipole Corrector Circuits

This document describes the test procedure and the acceptance criteria for the 80 A and 120 A superconducting circuits of the LHC. A list of the parameters to acquire during the tests is given.

First implementations of the HL-LHC procedures fully inspired from LHC procedures of similar circuits family

LHC HWC Procedures


HARDWARE COMMISSIONING PROCEDURE

HL-LHC INNER TRIPLET STRING

TEST PROCEDURE AND ACCEPTANCE CRITERIA FOR THE 2 KA RCBX CORRECTOR CIRCUITS

Abstract

This document describes the test procedure and the acceptance parameter specification for the 2 kA RCBX superconducting circuits of the HL-LHC Inner Triplet (IT) String test facility. A list of the parameters to acquire during the tests is also detailed.

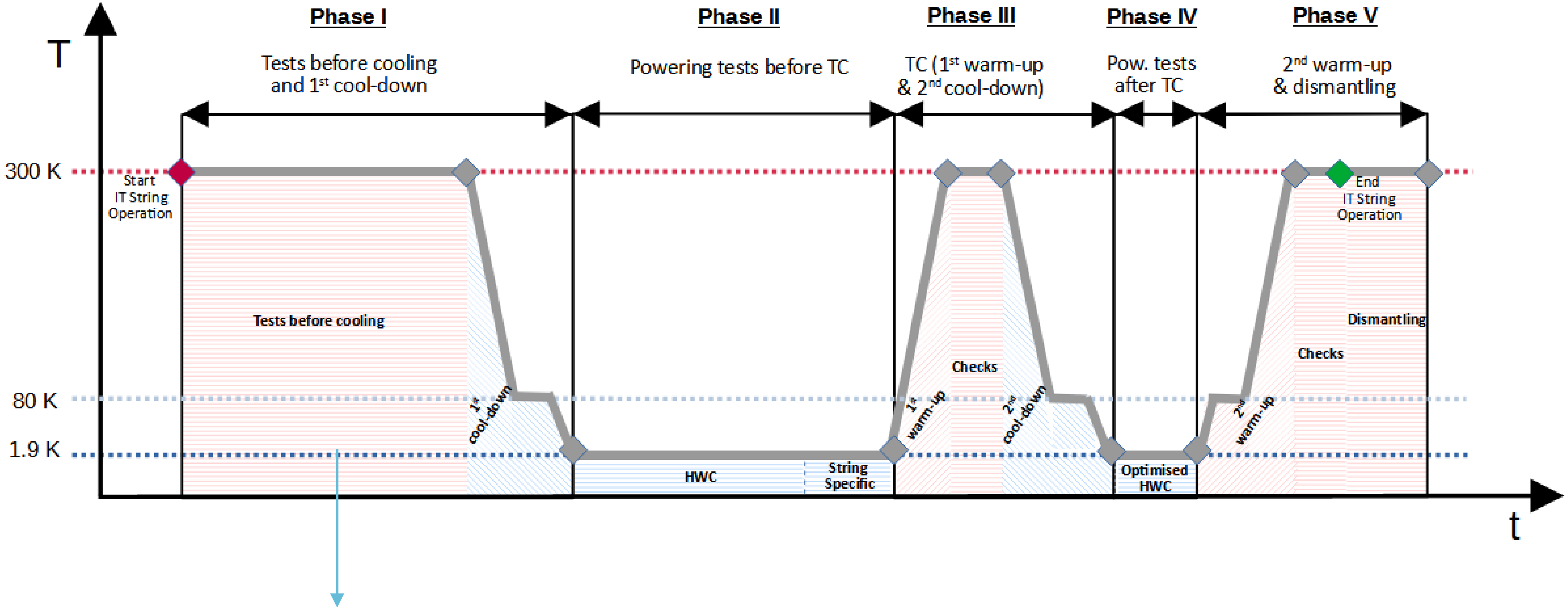
IN PROGRESS

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

LS3 HL-LHC HWC

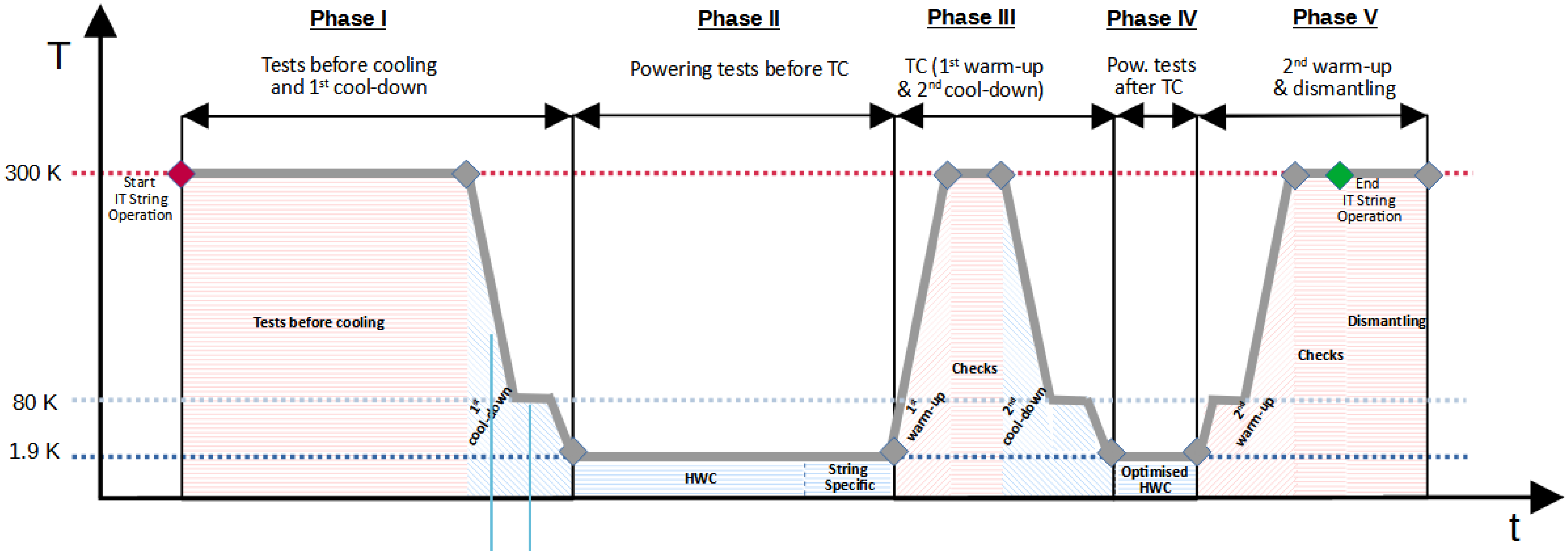
HL-LHC HWC Procedures

String Validation Program Phases



Pumping and Global Leak Tests for the Magnet and Cold Powering Vacuum	5 w
Cryogenics Pressure and Leak Tests and Insulation Vacuum Check	2 w
ElQA and Alignment Tests at Room Temperature	2 w

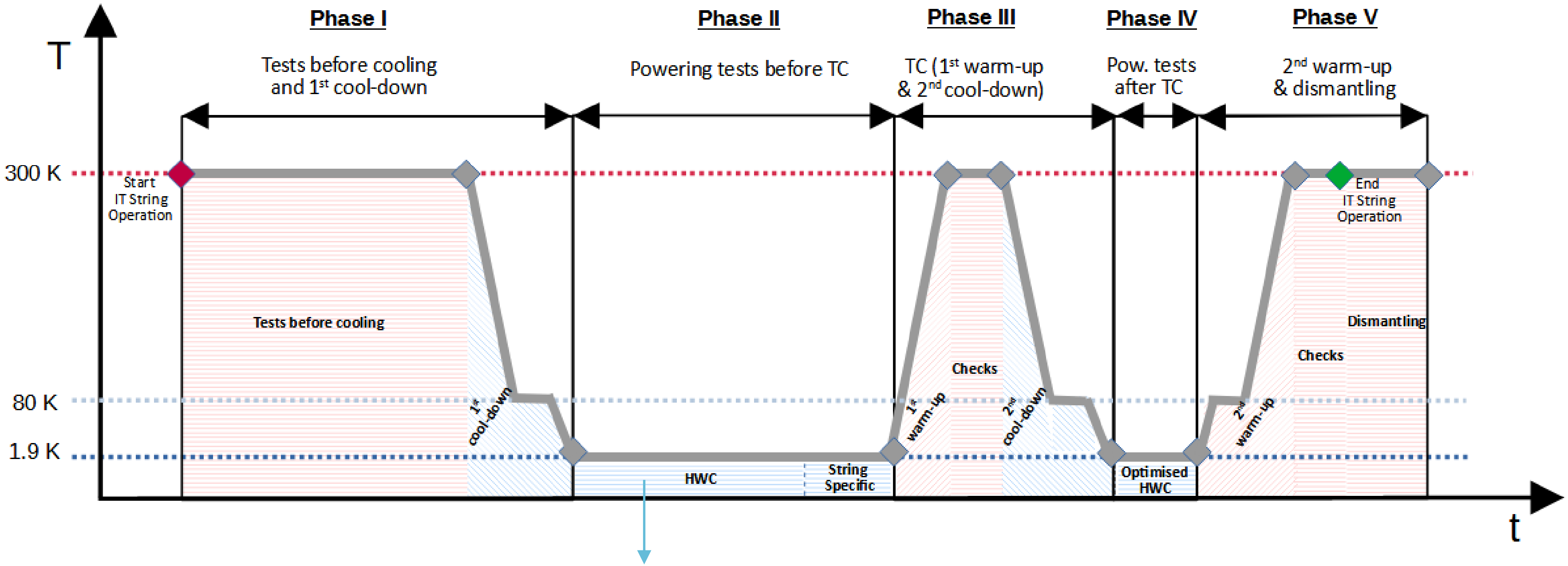
String Validation Program Phases



Alignment Checks and ElQA tests at 80 K (soundness of the instrumentation wires)	1 w

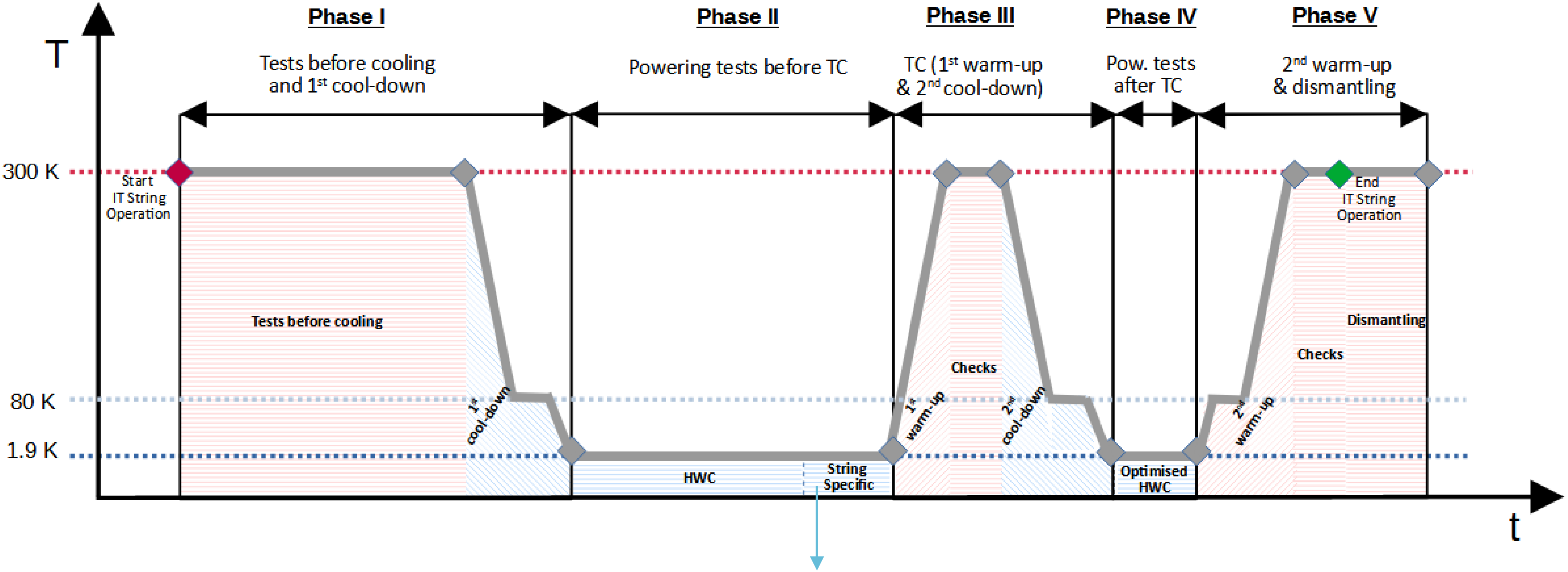
Cool-down Current Leads Heating System checks Cryogenics Instrumentation checks and control tuning	2 w

String Validation Program Phases



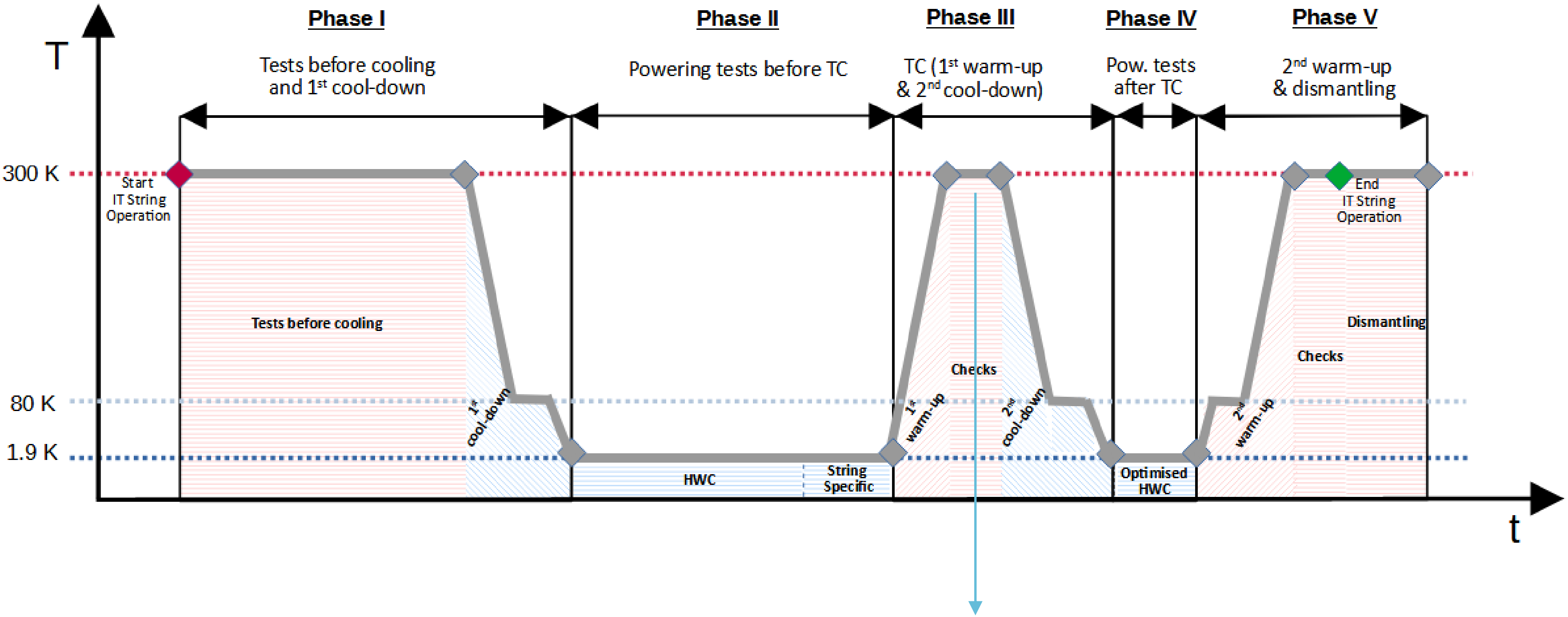
Static Cryogenics Measurements and Controls Tuning	4 w
ElQA and Alignment Tests at Nominal Conditions	1 w
Protection System IST and PIC1 Tests	3 w
HWC Powering Tests for 120A + 200A Circuits (I_{nom})	2 w
HWC Powering Tests for RCBX -2 kA- Circuits (I_{nom})	3 w
HWC Powering Tests for RD1 -14 kA- Circuit (I_{nom})	2 w
HWC Powering Tests for RQX -18 kA- Circuit (I_{nom})	11 w
Powering of Grouped Circuits	1 w

String Validation Program Phases



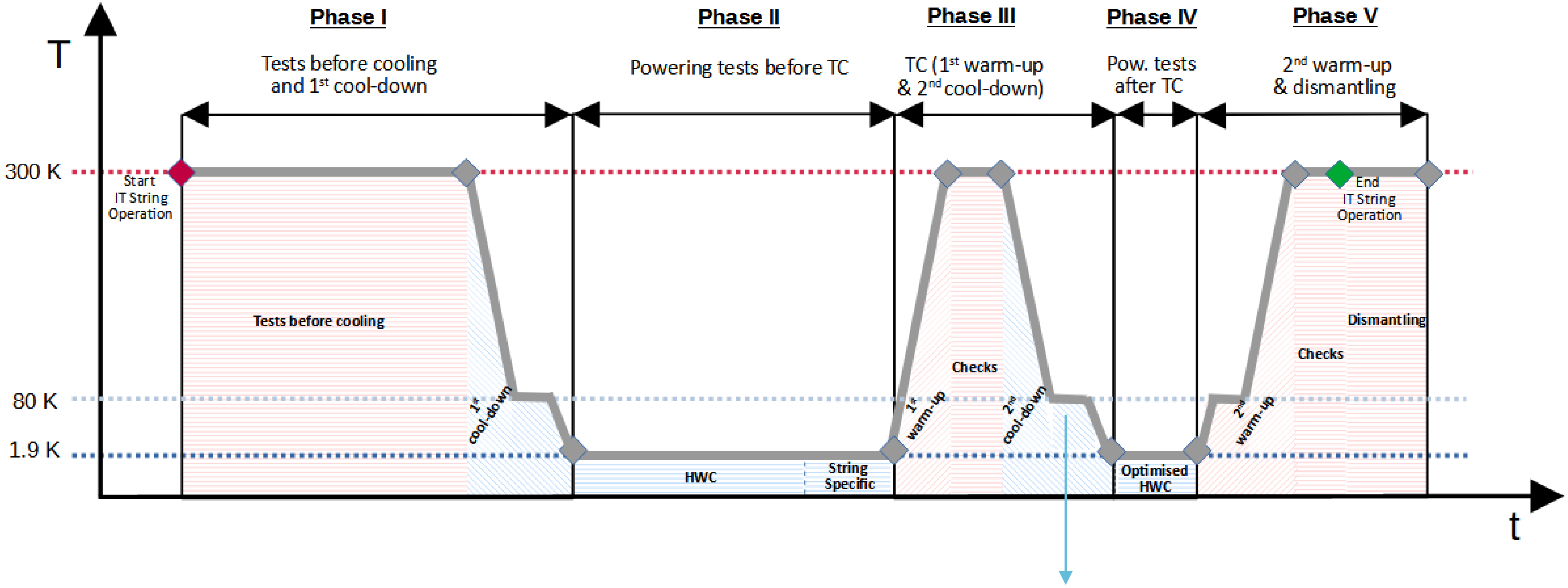
Bayonet Heat Exchanger Test	1 w
Cross Talk Studies	4 w
Operation Powering Cycles and Noise Measurements	3 w
Flux Jump Measurements	3 w
Powering Cycle Endurance Test	3 w

String Validation Program Phases



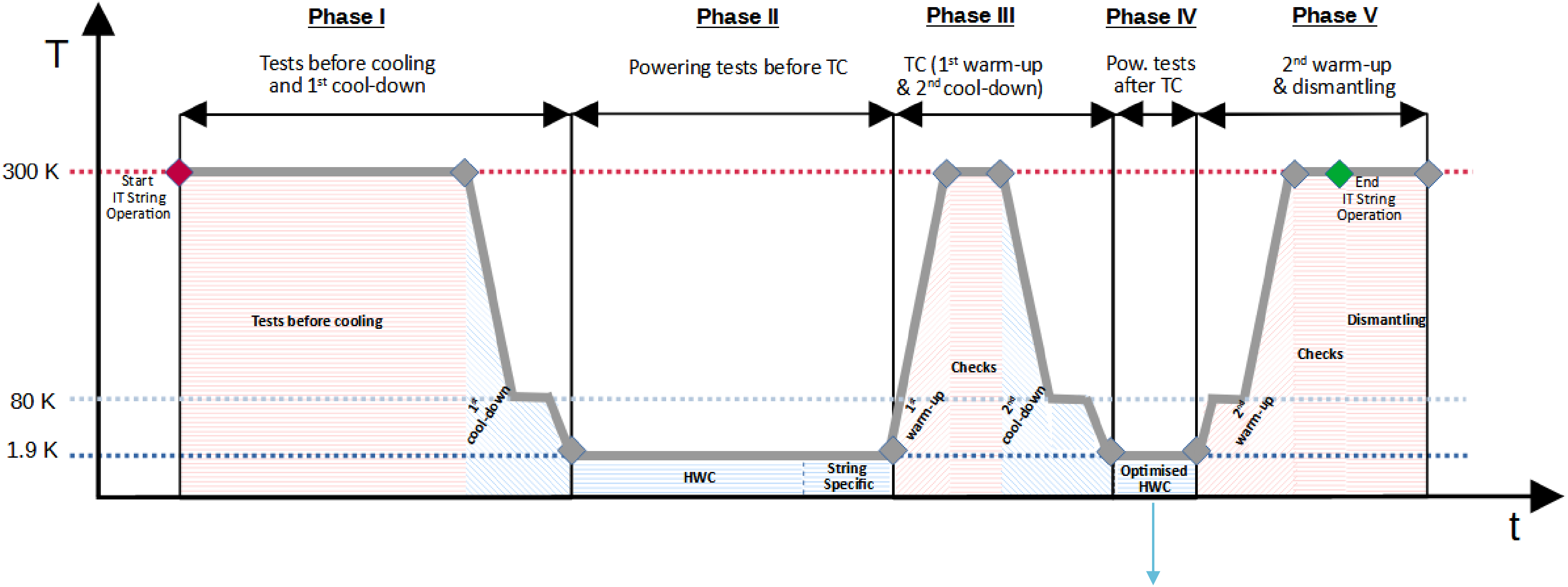
ElQA and Alignment Tests at Room Temperature Global Leak Test to Re-validate Leak Tightness	1 w

String Validation Program Phases



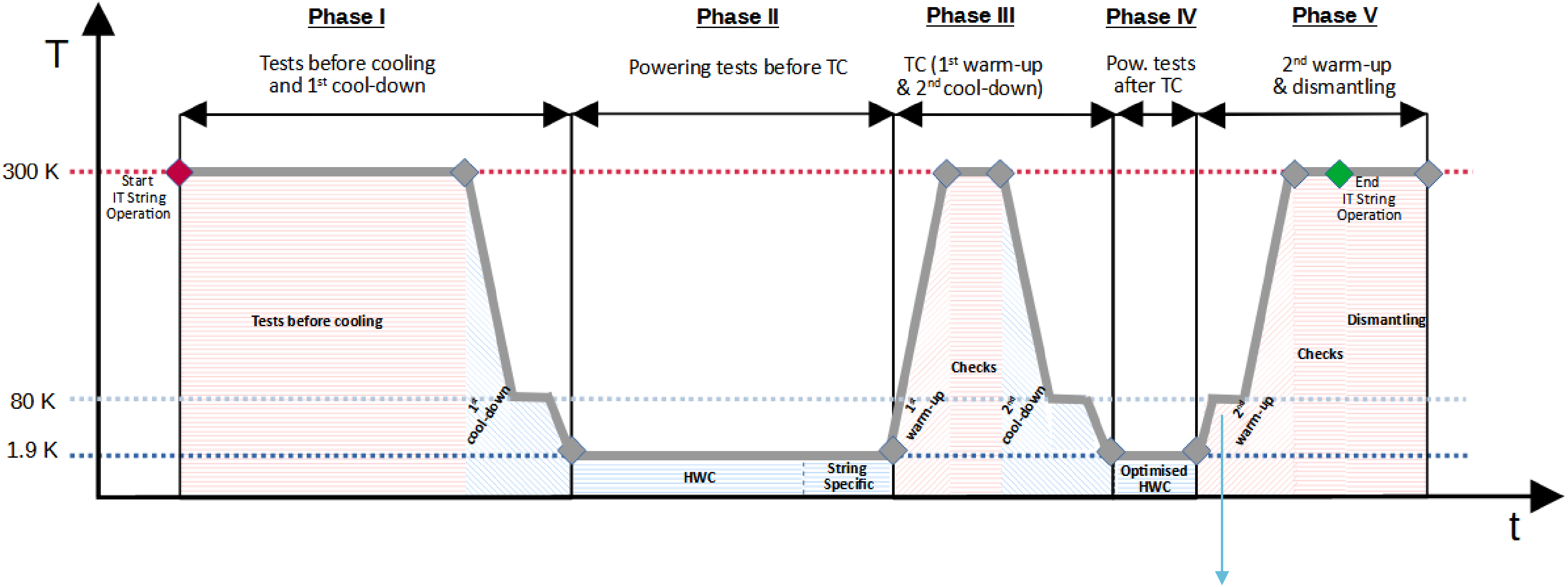
ElQA and Alignment Tests at 80 K	1 w

String Validation Program Phases



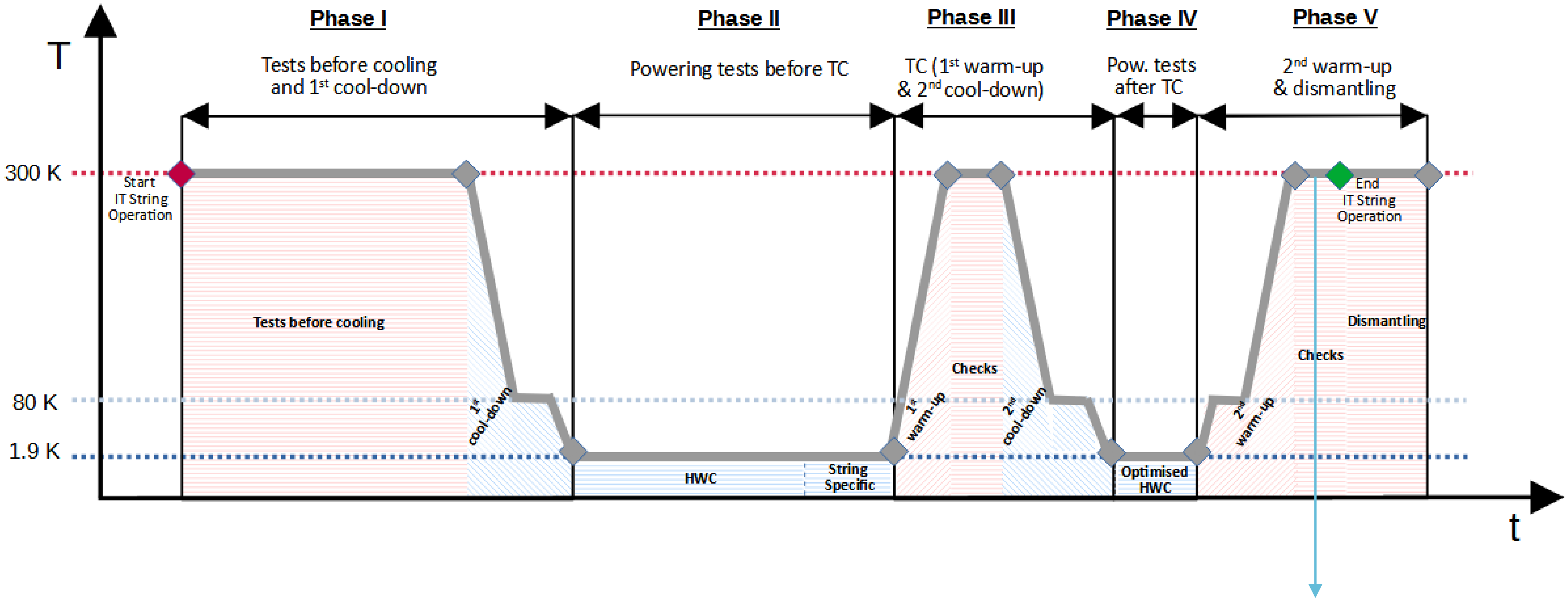
Protection System IST and PIC1 Tests	3 w
HWC Powering Tests for 120A + 200A Circuits (I_{nom})	1 w
HWC Powering Tests for RCBX -2 kA- Circuits (I_{nom})	1 w
HWC Powering Tests for RD1 -14 kA- Circuit (I_{nom})	1 w
HWC Powering Tests for RQX -18 kA- Circuit (I_{nom})	4 w
Powering of Grouped Circuits	1 w
Final ElQA Tests at Nominal Conditions	1 w

String Validation Program Phases



ElQA and Alignment Tests at 80 K	1 w

String Validation Program Phases



ElQA and Alignment Tests at Room Temperature Global Leak Test to Re-validate Leak Tightness	1 w

Focus on 2 kA Corrector Circuit Powering Tests

LHC 600 A (Reference)	Step for HL-LHC IT String	Test Description
PCC	PCC	Power Converter Configuration
PIC2	PIC2	PIC tests
PCS	PLI1.s1	Splice Mapping @ 500 A
PLI3.b1	PLI1.b1	EE from QDS @ 500 A
	PLI1.d1	Powering Failure @ 500 A
	PLI1.e1	SPA @ 500 A
	PLI2.s1	Splice Mapping @ 1 kA
	PLI2.c1	FPA @ 1 kA
	PLI2.d1	Powering Failure @ 1 kA
	PLI2.e1	SPA @ 1 kA
PNO.d3	PNO.d1	Training and Powering Failure
PNO.b1	PNO.b1	EE from QDS @ ±I_PNO
PNO.a3	PNO.a1	Bipolar Cycle @ ±I_PNO
PNO.x1	PNO.x3	Combined Powering

HL-LHC IT String Circuit Commissioning Tests

- LHC-XMS-OP-0004 (v.0.1) ELQA QUALIFICATION OF SUPERCONDUCTING CIRCUITS IN THE HL-LHC IT STRING
- LHC-MPP-HCP-0005 (v.4.2) Test Procedure and Acceptance Criteria for the 80 A and 120 A Dipole Corrector Circuits
- LHC-MPP-HCP-0003 (v.5.4) Test Procedure and Acceptance Criteria for the 600 A Circuits
- LHC-XMS-OP-0006 (v.0.1) Test Procedure and Acceptance Criteria for the 2 kA Corrector Circuits (RCBX) in the HL-LHC IT String
- LHC-XMS-OP-0007 (v.0.1) Test Procedure and Acceptance Criteria for the Separation Dipole Circuit (RD1) in the HL-LHC IT String
- LHC-XMS-OP-0008 (v.0.1) Test Procedure and Acceptance Criteria for the Inner Triplet Circuit (RQX) in the HL-LHC IT String
- LHC-XMS-OP-0009 (v.0.1) Parameters for the HL-LHC IT String Circuit Powering Tests

IN PROGRESS

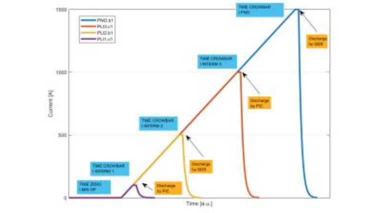
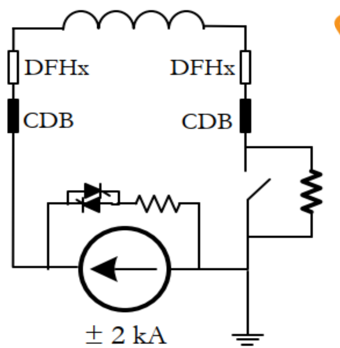


Figure 7 - Current during energy extraction discharges.

Table 6 – Analysis of PLI1.B1, PLI2.C1 and PNO.B1 tests.

Type of analysis	Criteria
Verify EE discharge.	Status flags of the EE are OK. Discharge voltage is within calculated value ± 10%.
Check EE discharge resistance temperature	Monitor of thermocycle of the resistors. Temperature criteria to be defined after first tests.
Determine commutation time (Time from PC Stop to U_DUMP increase)	1ms < T_delay_ee < 3 ms

IT Orbit Corrector (MCBXFA/B)

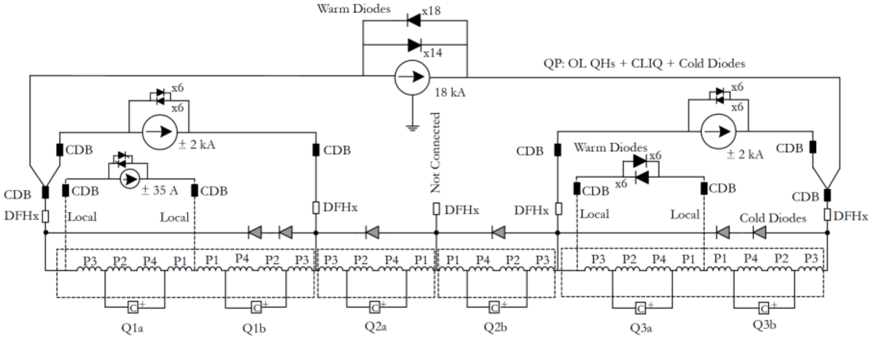


Example : Steps for 2 kA Circuits

Powering Tests and Acceptance Criteria for the 2 kA RCBX Circuits

LHC-XMS-OP-0006, EDMS no. 2771111

Case of the the HL-LHC Inner Triplets



Step	Test Description	Number of Tests
IST.QPS	Individual CLIQ Discharge at 0 A	6
IST.QPS	Combined CLIQ Discharge at 0 A	1
IST.QPS	Combined QHs discharge at 0A, 300V	1
IST.QPS	Combined QHs discharge at 0A, 900V	1
IST.QPS	Combined CLIQ + QHs discharge at 0A	1

Test at 0 A (1/4)

Step	Test Description	Main Current(kA)	Trim Q1 Current(kA)	Trim Q3 Current(kA)
PCC	Power Converter Configuration	-	-	-
PIC2	PIC check with SB current	-	-	-
PLI1.s1	Splice Mapping	2	-1	-1
PLI1.d1	Powering Failure	2	-1	-1
PLI1.f1	QPS Provoked Quench	2	-1	-1
PLI1.d2	Powering Failure	2	1	1
PLI1.f2	QPS Provoked Quench	2	1	1
PLI1.f3	QPS Provoked Quench	2	1	-1
PLI1.f4	QPS Provoked Quench	2	-1	1
PLI1.f5	QPS Provoked Quench	2	0	0
PLI1.g1	Manual Triggering of Q1a CLIQ Unit	2	0	0
PLI1.g2	Manual Triggering of Q1b CLIQ Unit	2	0	0
PLI1.g3	Manual Triggering of Q2a CLIQ Unit	2	0	0
PLI1.g4	Manual Triggering of Q2b CLIQ Unit	2	0	0
PLI1.g5	Manual Triggering of Q3a CLIQ Unit	2	0	0
PLI1.g6	Manual Triggering of Q3b CLIQ Unit	2	0	0

Tests at 2 kA (2/4)

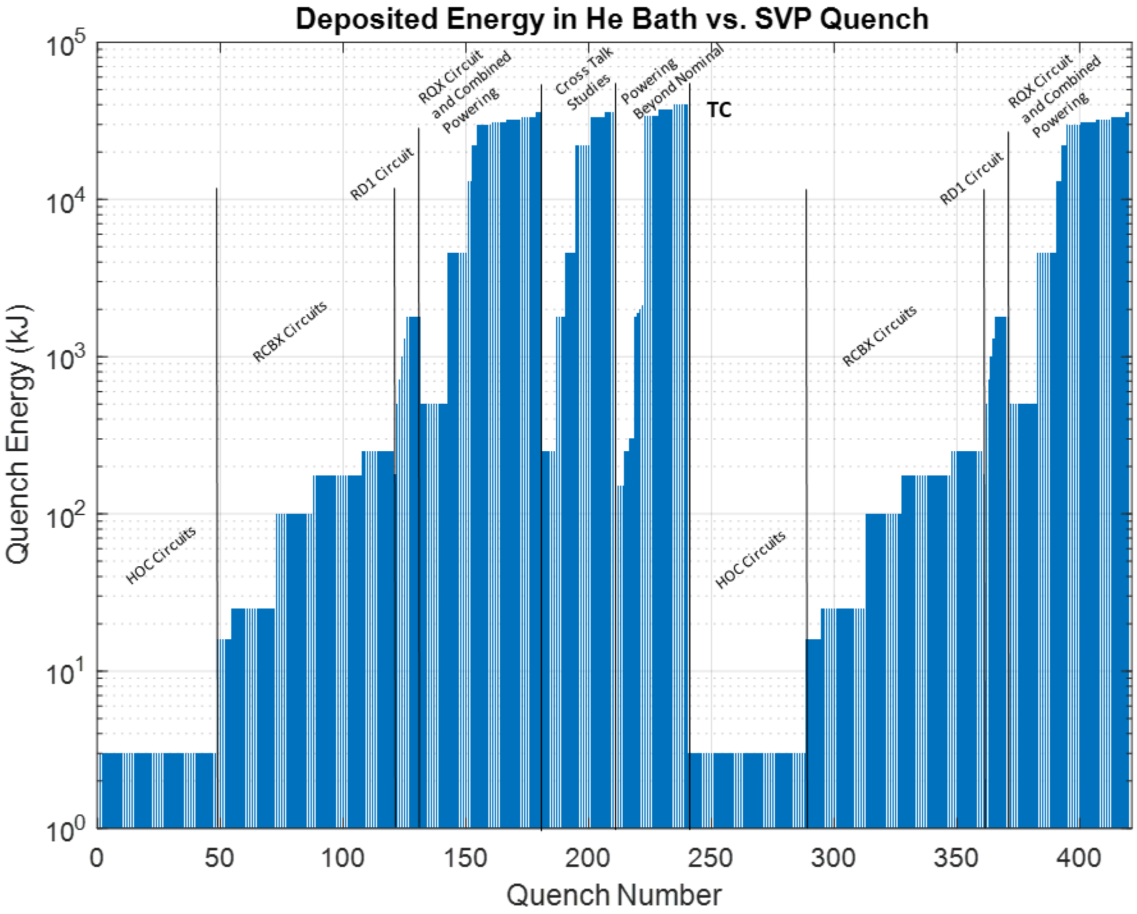
Step	Test Description	Main Current(kA)	Trim Q1 Current(kA)	Trim Q3 Current(kA)
PLI2.s1	Splice Mapping	6	1	1
PLI2.d1	Powering Failure	6	1	1
PLI2.f1	QPS Provoked Quench	6	1	1
PLI2.d2	Powering Failure	6	-1	-1
PLI2.f2	QPS Provoked Quench	6	0	0
PLI1.g1	Manual Triggering of Q1a CLIQ Unit	6	0	0
PLI1.g2	Manual Triggering of Q1b CLIQ Unit	6	0	0
PLI1.g3	Manual Triggering of Q2a CLIQ Unit	6	0	0
PLI1.g4	Manual Triggering of Q2b CLIQ Unit	6	0	0
PLI1.g5	Manual Triggering of Q3a CLIQ Unit	6	0	0
PLI1.g6	Manual Triggering of Q3b CLIQ Unit	6	0	0

Test at 6 kA (3/4)

Step	Test Description	Main Current(kA)	Trim Q1 Current(kA)	Trim Q3 Current(kA)
PLI3.f1	QPS Provoked Quench	10	-2	-2
PLI3.f2	QPS Provoked Quench	10	2	2
PLI3.f3	QPS Provoked Quench	10	-2	2
PLI3.f4	QPS Provoked Quench	10	0	0
PLI3.g1	Manual Triggering of Q2b CLIQ Unit	10	0	0
PLI4.f1	QPS Provoked Quench	13	-2	-2
PLI4.f2	QPS Provoked Quench	13	2	2
PLI4.f3	QPS Provoked Quench	13	2	-2
PLI4.f4	QPS Provoked Quench	13	0	0
PLI4.g1	Manual Triggering of Q1a CLIQ Unit	13	0	0
PNO.a1	Current Cycle	16.23	0	0
PNO.d1	Powering Failure	16.23	-2	-2
PNO.f1	QPS Provoked Quench	16.23	-2	-2

Test at 10 kA, 13 kA and Nominal Current (4/4)

Overview of Number of Quenches in the HWC

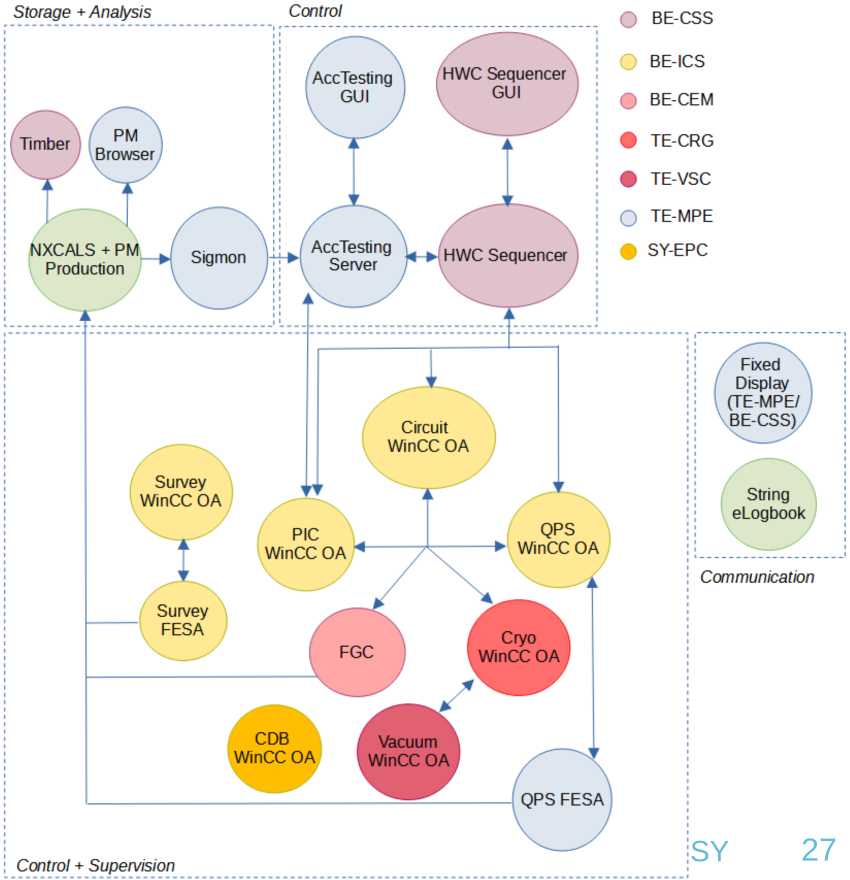


Control, Supervision and Analysis Software for HWC

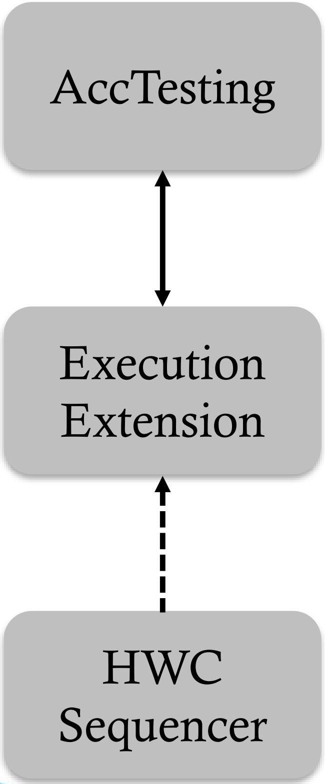
HL-LHC IT String Control, Analysis and Supervision Software

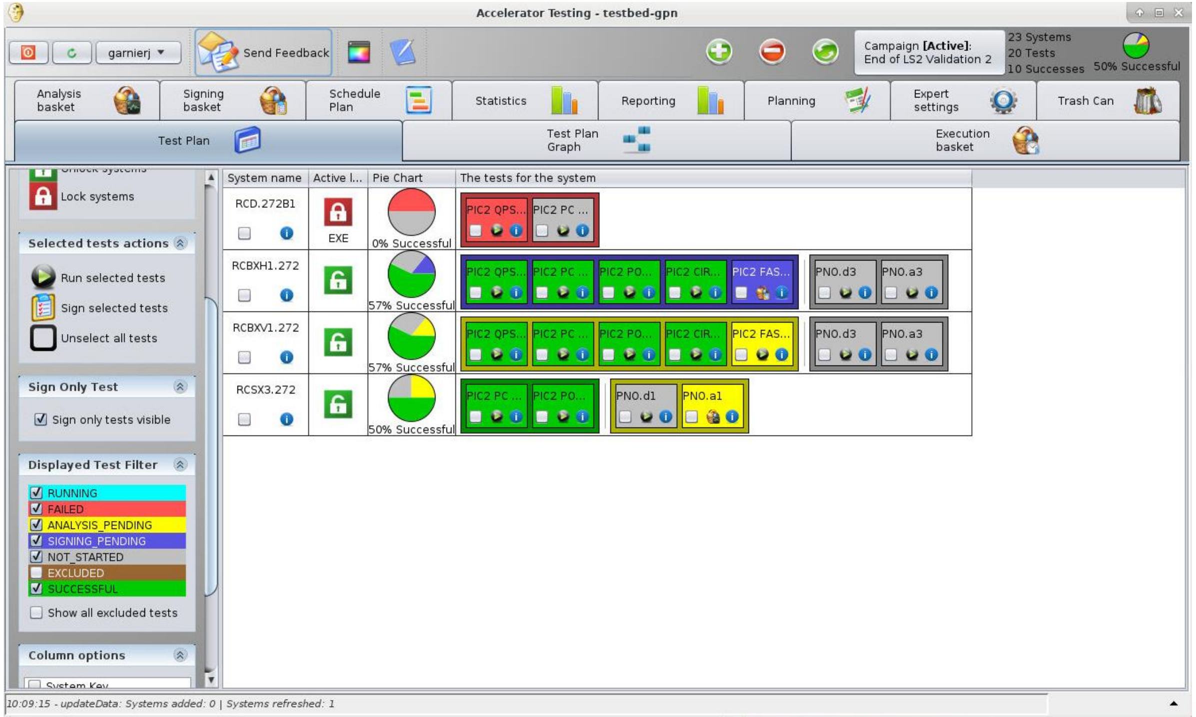
Software for the HL-LHC IT String

- ***Roadmap** set for the **full lifetime of the String Operation** (HWC tests, String-Specific tests, etc.)*
- *The software architecture chosen **to be as close as possible** to the LS3 implementation of **the software for HL-LHC HWC***
- Engineering Specifications is prepared (EDMS no. [2806419](2806419))



Execution of the HWC Powering Tests





*As done in the case of **the HL-LHC HWC***

MP3 Analysis of the HWC Powering Tests

- Analysis tools in the framework of Sigmon (Signal Monitoring – link), and in Jupyter Notebooks for MP3 (development already started for HWC 2021) and will continue in 2023-24 for the HL-LHC IT String

HL-LHC Inner Triplet	14 kA IPD	2 kA	200 A	80-120A
New Procedures	New Procedures Based on LHC IPDs	New Procedures Based on 600 A Circuits with EE	New Procedures identical to 600 A circuits with EE	New Procedures identical to 80-120 A circuits for LHC

Relevant QDS, cryogenics and other instrumentation signals will be checked by MP3 members after each test

SWAN Interactive notebooks

Analysis of a PNO.c6 HWC Test in an IPD Circuit

Superconducting beam separation dipoles of four different types are required in the Experimental Insertions (IR 1, 2, 5 and 8) and the RF insertion (IR 4). Single aperture dipoles D1 (MBX) and twin aperture dipoles D2 (MBRC) are utilized in the Experimental Insertions. They bring the two beams of the LHC into collision at four separate points then separate the beams again beyond the collision point. In the RF Insertions two types of twin aperture dipoles, each type with two different aperture spacings are used: D3 (MBRS) and D4 (MBRB). The D3 and D4 magnets increase the separation of the beams in IR 4 from the nominal spacing 194 mm to 420 mm. D2 and D4 are the twin apertures magnets with common iron core for both apertures. D3 is a twin apertures magnet with independent iron cores for each aperture.

The MBRC dipole consists of two individually powered apertures assembled in a common yoke structure.

- MBX – D1
  Single aperture of the magnet powered with one power supply.
- MBRC – D2
- MBRB – D4
  Apertures B1 and B2 of the magnet are powered in series with one power supply.
- MBRS - D3
  Apertures B1 and B2 of the magnet are powered in series with one power supply but series connection done in the DFBA.

Magnets in the Circuit	Temperature	Position	General information
MBX (D1)	1.9 K	RD1.R2, RD1.R8	I Nominal: 5800A, I_Ultimate: 6100A
			L tot: 26 mH, L per aperture: 26 mH
			max(di/dt): 17.453 A/s
MBRC (D2)	4.5 K	RD2.L1, RD2.R1, RD2.L5, RD2.R5	I Nominal: 4400A, I_Ultimate: 4670A
		RD2.L2, RD2.R2, RD2.L8, RD2.R8	I Nominal: 6000A, I_Ultimate: 6500A
			L tot: 52 mH, L per aperture: 26 mH
			max(di/dt): 18.147 A/s
MBRS (D3)	4.5 K	RD3.L4, RD3.R4	I Nominal: 5520A, I_Ultimate: 6000A
			L tot: 26 mH, L per aperture: 26 mH
			max(di/dt): 18.147 A/s
MBRB (D4)	4.5 K	RD4.L4, RD4.R4	I Nominal: 5520A, I_Ultimate: 6000A
			L tot: 26 mH, L per aperture: 26 mH
			max(di/dt): 18.147 A/s

This section is a copy of a document created by Alexandre Erokhin (https://twiki.cern.ch/twiki/pub/MP3/General_Info_IPD/separation_dipole.pdf)

PNO.C6 – FAST POWER ABORT AT NOMINAL CURRENT AND LEAD TEST

The aim of this test is to verify the correct performance of the current leads at operational current and evaluate the converter and magnet performance after a fast power abort from nominal current.

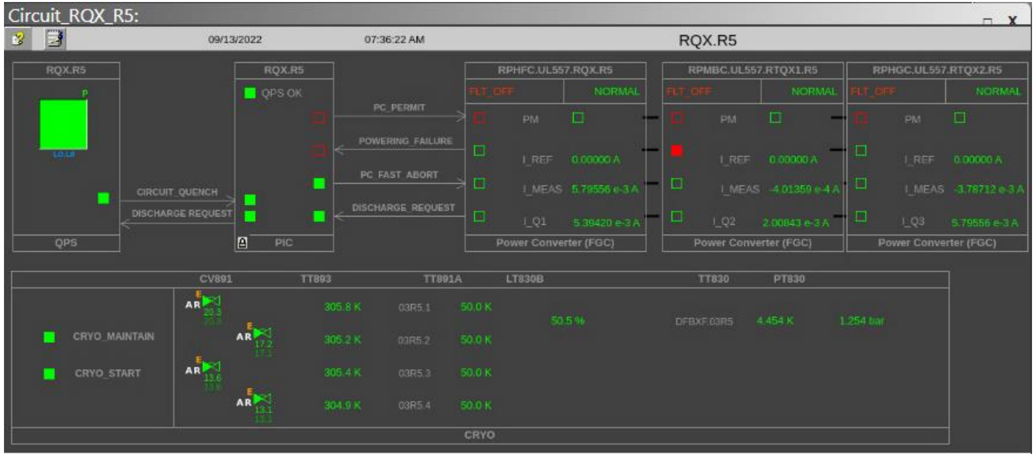
IPD currents during PNO.c6. Note: the actual parameters are listed in Appendix 1.

Offline analyses are listed below:

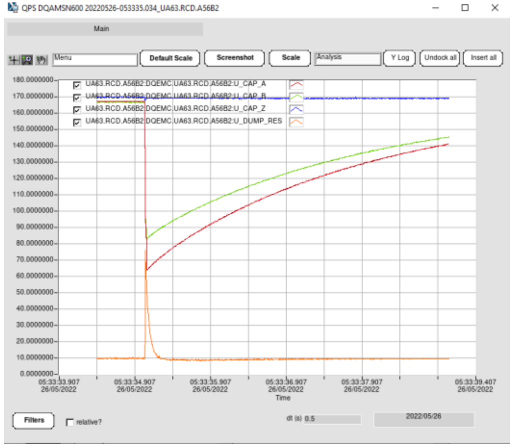
Responsible	Type of Analysis	Criteria
PC	Analysis of the current and waveform decay.	Agreement of V_MEAS(t) and I_MEAS(t) to the theoretical decay curve withing a tolerance of 10 %.
MP3	Check if QPS tripped, i.e. QPS PM event was created (it is not expected).	
	Check if FGC PM event was created (it is expected).	
MP3	Calculate splice resistances (**not possible due to limited logging resolution**)	R_{max} < 5 nOhm
MP3	Check DFB regulation	$T_{top,HTS}$ = temperature at 0 A current +/- 4K
		$T_{top,Cu}$ = temperature at 0 A current +/- 10K
MP3	Quench analysis (in case of a quench)	The signals have to be compared to the reference signals, and should agree within the limits given below:
	Check heater voltages (U_HDS_1, U_HDS_2) during the discharge, and their decay time constant	U_HDS: +/- 5%
		τ_HDS +/- 5%
	Check the heater delay from the quench signal	t_delay +/- 5 ms

source: Test Procedure and Acceptance Criteria for the Separation Dipoles Circuits, MP3 Procedure, https://edms.cern.ch/document/874885 (Please follow this link for the latest version)

Supervision and Analysis Tools



Circuit Synoptic



Post Mortem Browser, Logging (Timber), etc.

And many more tools to include the HL-LHC IT String Systems

Conclusions

Conclusions

- String Validation Program has been defined in 2022 and contains the IST and HWC steps for a complete commissioning, with several steps already ongoing

- HL-LHC IST and HWC represent and will prepare the steps to be done for the tunnel in LS3

- The defined steps are based on the experience from LHC

- Software for the IST and HWC are identical to the ones used for the tunnel

Thank you for your attention