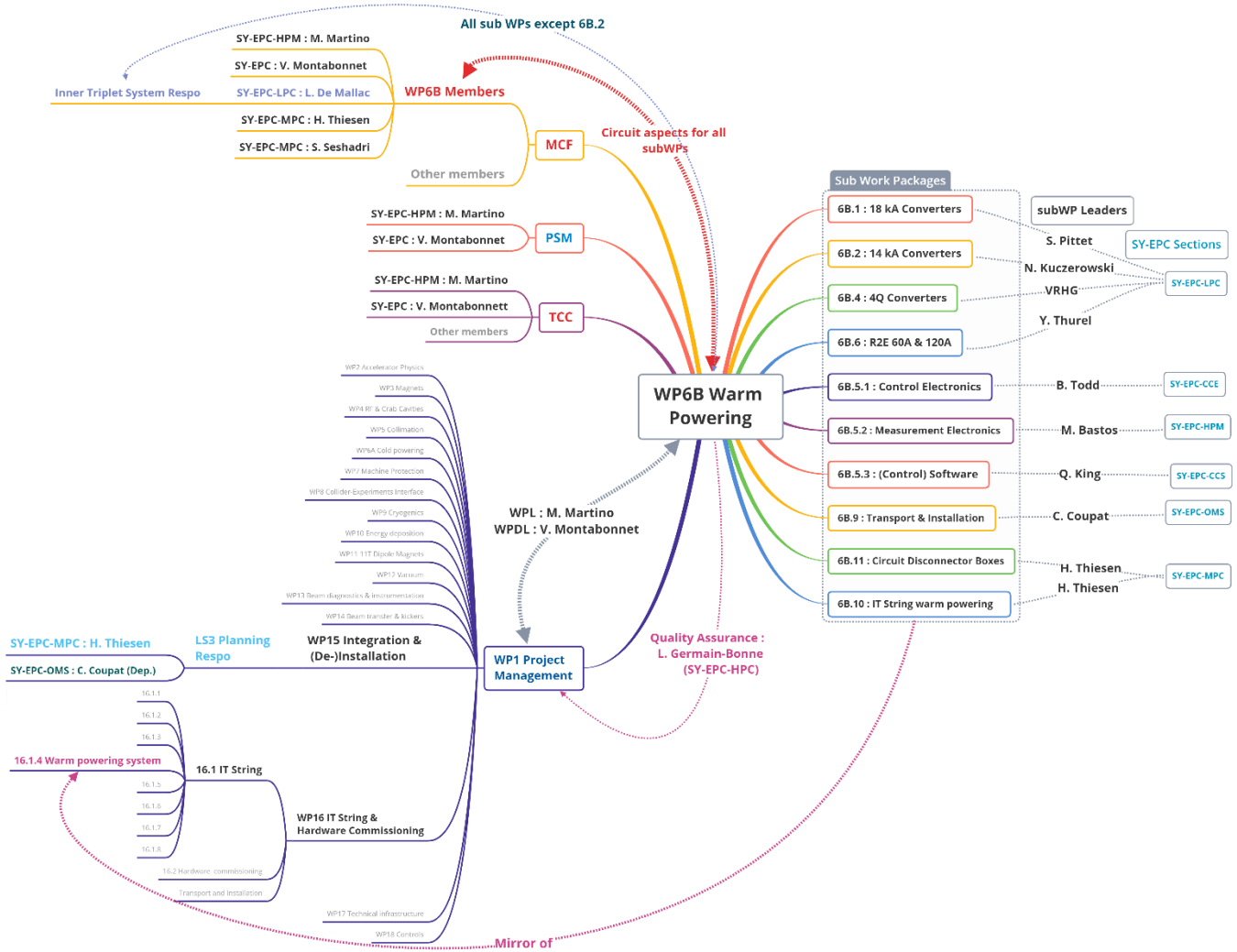
Warm Powering Status Report

Michele Martino – CERN
on behalf of WP6B

12th HL-LHC Collaboration Meeting – Uppsala – Sweden – September 20th 2022

WP6B – Who's who



HL-LHC [18kA; ±10V]: RPAFE$_{RQX}$ latest news

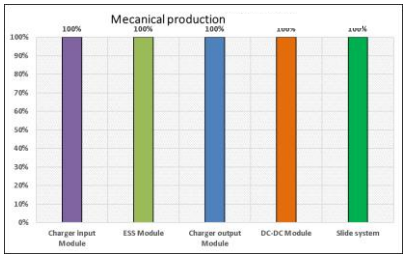
6B.1 Status

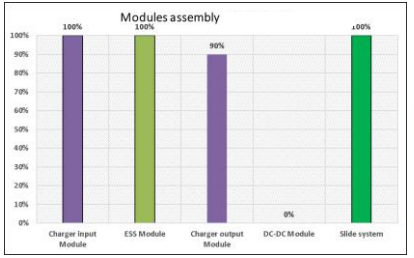
- Reminder: built of 9+1 2kA ±10V subs with Energy Storage System
  - 2kA sub validated by 03/2022 ✓ [TCC #126 02/21 and TCC#152 03/22]
- All collaborations are now completed ✓
  - EPFL – Switzerland 09/2020
    - High-Current Low-Voltage Power Supply for Superconducting Magnets (first Ph.D. dissertation discussed over zoom in Covid time at EPFL)
  - LIC-CONICET – Argentina 06/2022
  - UPV/EHU-APERT – Spain 08/2022
- Prototype for IT String is being assembled ✓
- New crowbar design presented at MCF #107 08/2022 ✓
  - Part of the **new** general **WP6B contribution** to **circuit protection** TDR Sec. 6B.4.5
  - ECR being drafted, approval foreseen by end of 2022

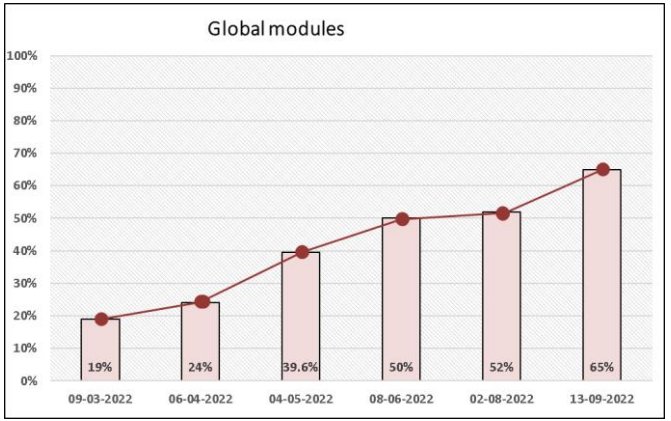
HL-LHC [18kA; ±10V]: RPAFE$_{RQX}$ Prototype

- All components have been delivered to CERN ✓
- Power modules assembly is progressing steadily: ≥ 65% [last week]

6B.1 Status



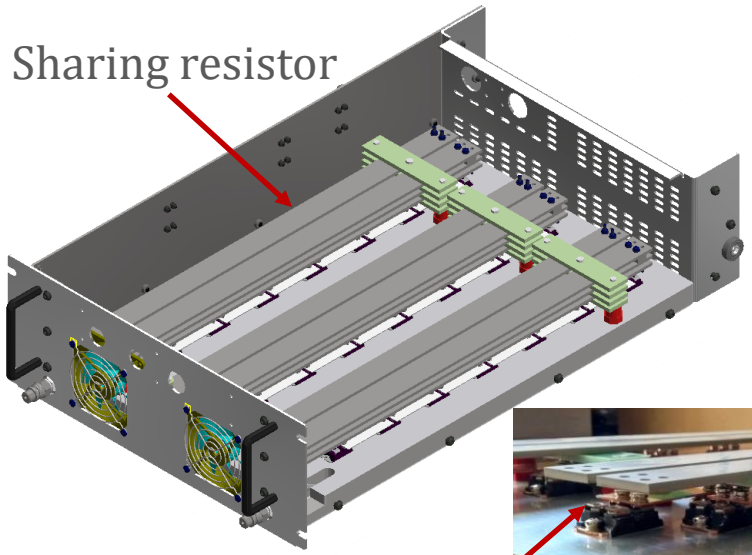


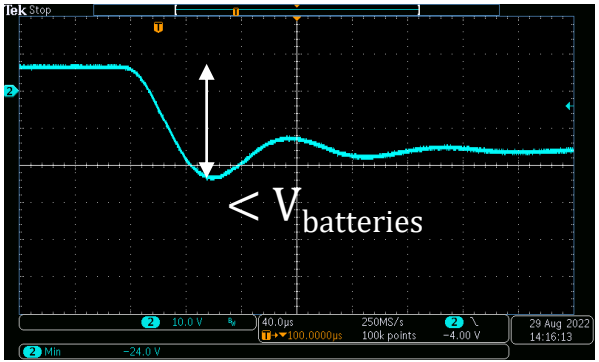


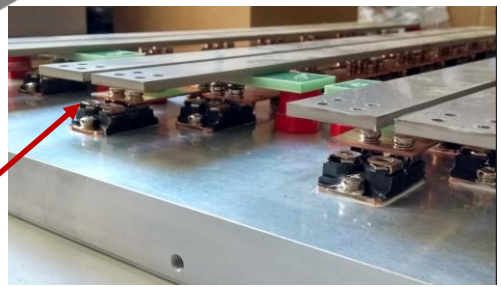
HL-LHC [18kA; ±10V]: RPAFE$_{RQX}$ Crowbar

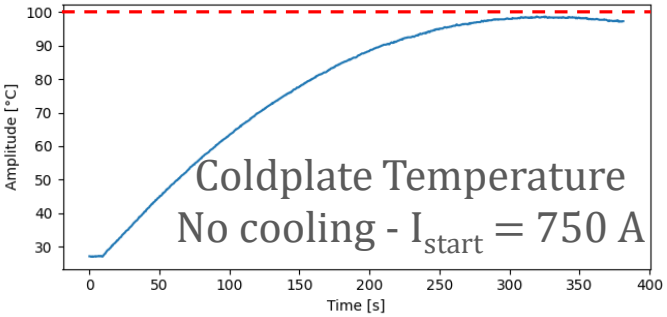
- Modular diode-based crowbar design with >10% redundancy
  - 28 modules – **650A-module** successfully validated (tested up to 750 A) ✓
- 1200 x2 power diodes for the IT String proto ordered ✓ expected end 2023

6B.1 Status



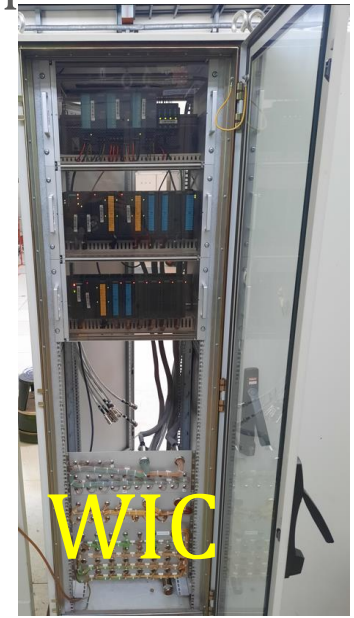






HL-LHC [14; 18] kA testbed: Completed ✓

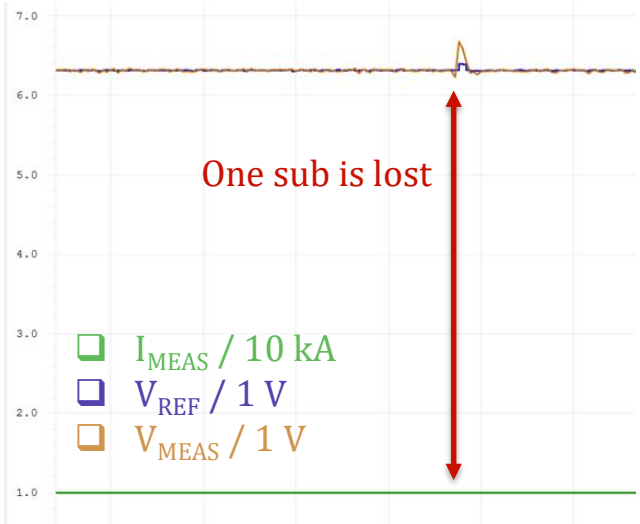
- Two different circuits to validate 14kA and 18kA Class 0 converters
- A **link** between the two to simulate energy recovery
  - 18kA converter feeding the 14kA freewheeling diodes
  - 14kA converter supplying the 18kA energy recovery system (modular testing)
- More than 7 tons of copper in total & dedicated WIC system



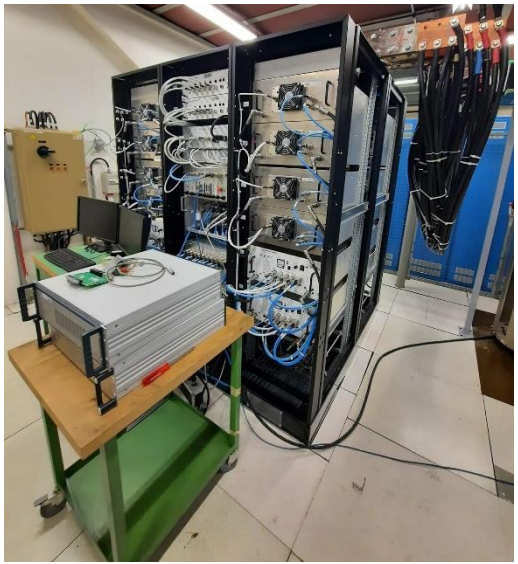
HL-LHC [14kA; 08V]: RPAFE$_{RD1/2}$ demo completed ✓

- [20kA; 08V] PC delivered to 6B.5.2 ✓ for Class 0 DCCT testing 08/2022
- **Achievement** for 6B.2: **validation of the full control of 9+1 2kA subs** ✓
  - Validation of electronics crate/boards + regulation software
  - Validation of N+1 redundancy [sudden lost of a sub not to affect the output current]
  - Basis for the mechanical integration of the 14kA [7+1 2kA subs]

6B.2 Status

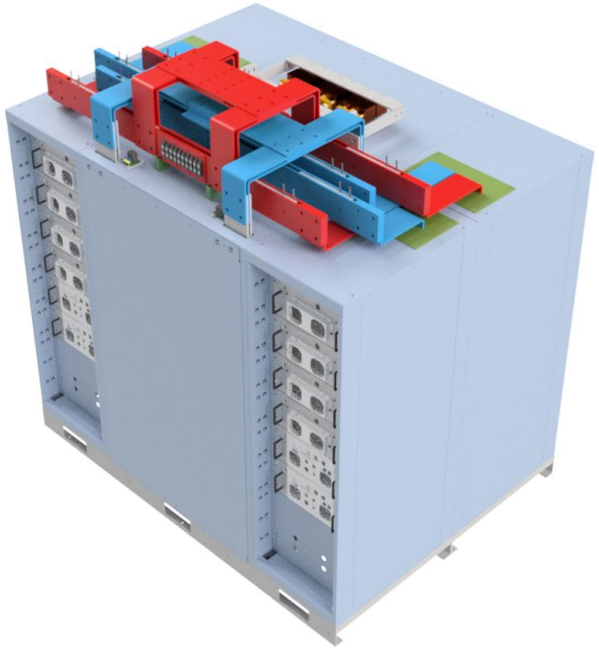


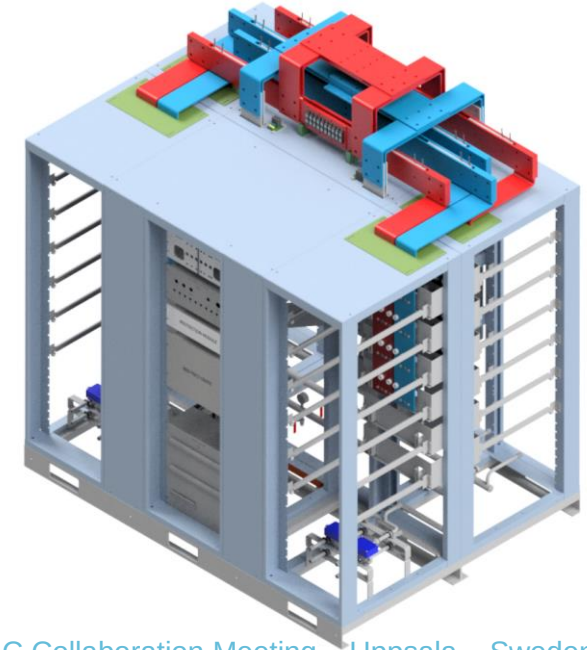
Converter installed in its final location **P-Hall** (bldg. 377)



HL-LHC [14kA; 08V]: RPAFE$_{RD1/2}$ steps ahead

- Prototype for the IT String being assembled
  - Mechanical frames production ongoing, expected by end of September 2022
  - Busbars and water cooling components already available at CERN ✓
  - Already tested power modules (from R2E LHC) ready for installation ✓





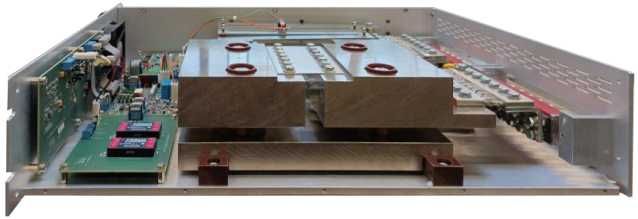
6B.2 Status

HL-LHC [±2kA; ±10V]: RPBAA$_{\text{IT OC}}$, RPBAB$_{\text{IT trims}}$

- Prototype (→ **pre-series**) successfully tested end of 2021 ✓

Power Module
400A

Auxiliary Supply Module



Protection Module

Power Rack

HL-LHC [±2kA; ±10V]: RPBAA$_{\text{IT OC}}$, RPBAB$_{\text{IT trims}}$

6B.4 Status

- Prototype equipment passed CE marking tests by 02/22
  - Safety: EN 52368-1 ✓ EMC: EN 61000-6

Voltage dip test

Radiated Immunity test

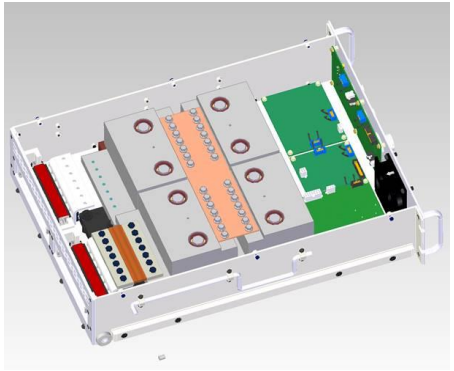
- **Contract** for **power modules + racks ongoing** ✓ [Jema Electrónica – Spain]
  - Pre-series: racks expected by 12/22 – modules by 05/23

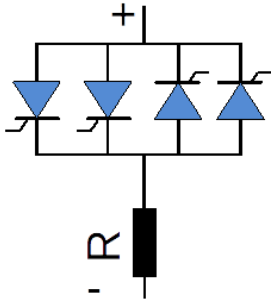
HL-LHC [±2kA; ±10V]: RPBAA, RPBAB Crowbars

6B.4 Status

RPBAA – OC circuits

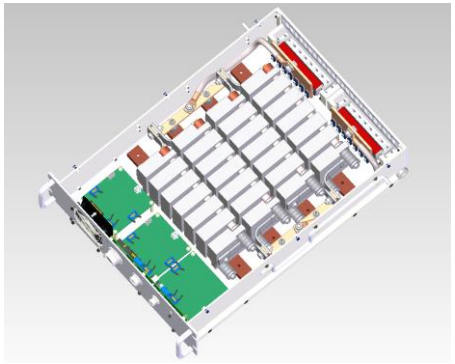
Redundant Design - Thyristor based

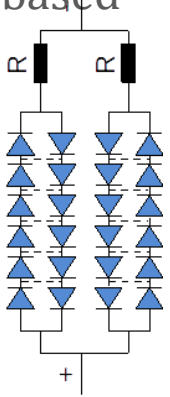




RPBAB – IT trims circuits

Redundant Design - Diode based



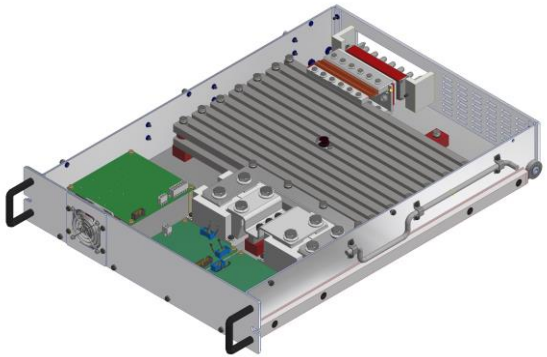


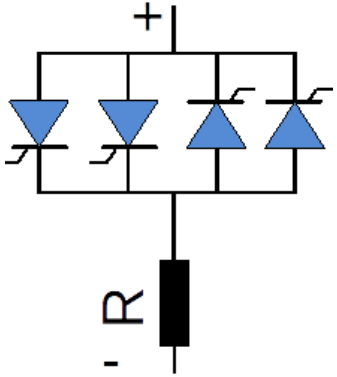
- Design completed 07/22 – Production started 08/22 ✓
  - Both expected at CERN by 12/22 [for successive installation in IT String]

HL-LHC [±600A; ±10V]: RPBMF D2 correctors

6B.4 Status

- Design (full PC) to be completed by end 2022
  - Built with 2 x 400A modules → fully redundant PC as $I_{nom} < 400A$
- 8 x 400A power modules prototypes ordered ✓ expected by 10/2022 [Estonia]
- Proto to be validated by mid 2023
- Redundant thyristor based crowbar design ongoing





European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

Price Enquiry

Tender Form

Production and Testing of
HL-LHC600A-10VPower Modules

(To be uploaded duly completed, signed and dated)

Bidder (Lead Firm in the case of a Group of Firms)
Name: TET ESTEL AS
Address: Kesali 6, 13619 Tallinn, Estonia
URL (If applicable): https://www.tet-estel.com/

Details of the Bidder's representatives in charge of this Bid:

For commercial and administrative matters		
Daria Arsenova	Tel	Email
In case of absence:	+372 6228 300	
Anton Kotovalov		daria@tet-estel.com
For technical matters	+372 6228 390	
Kirill Gavrilov	Tel	anton.kotovalov@tet-estel.com
In case of absence:	+372 6228 339	Email
Pavlo Sotula		kirill.gavrilov@tet-estel.com
	+372 6228 322	Email
		pavel.sotula@tet-estel.com

Date: 20.01.2022

PO-3344/SY/HL-LHC

R2E-LHC [±200A; ±10V]: RPBMD$_{SF\ 2^{nd}}$

- 400A power modules (R2E – LHC) produced and tested ✓ 11/2019
- Four racks (assembled with 200A DCCTs) produced, tested and ready for installation ✓ since 03/2022
- **First "series" Power Converters ready for HL-LHC** – 1x for IT String ✓

6B.4 Status

2 x

Control Electronics

6B.5.1 Status

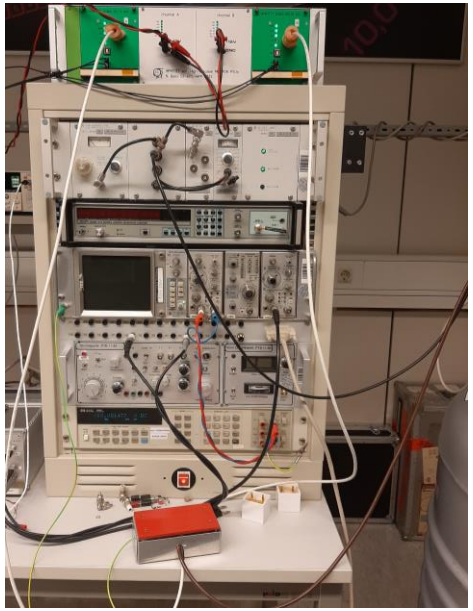
- ECR for FGC3.1 control approved in 10/21 [EDMS 212383]
- Procurement x LS3 is ongoing [facing long delivery time for some components]
- All electronics for IT String is ordered or already available ✓ except:
  - Inner Triplet PIC "concentrator" chassis [EDMS 2730935] exp. by 12/22
  - FPGA logic for 2 channels Class 0 external ADCs [optical link] exp. by 12/22
- HIL tester for IT decoupling control completed in 08/22 ✓

HIL IT decoupling control tester [Typhoon]

6B.5.2.1 ADCs – Class 0: HPM7177

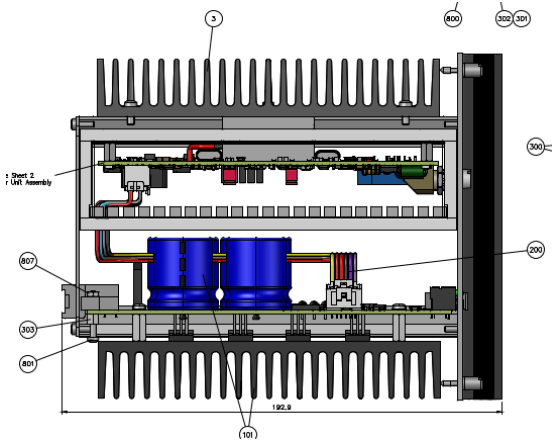
- HPM7177 [open hardware] fully validated in 2021 [EDMS 2520612] ✓
- MS4690 and IT4690 carried out in 2021 [EDMS 2579048, EDMS 2629302] ✓
- Pre-series production launched at the end of 2021 ✓– delivery end of 2022
- Independent EMC testing in 2022 ✓
- **Metrology validation** in **PTB** in 2022 (with **P**rogrammable **J**osephson **V**oltage **S**tandard) ✓

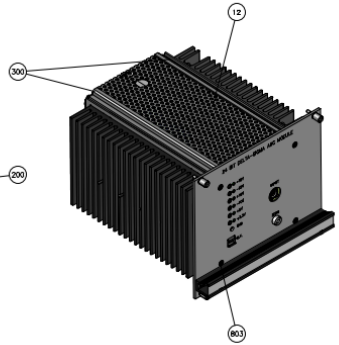
6B.5.2 Status

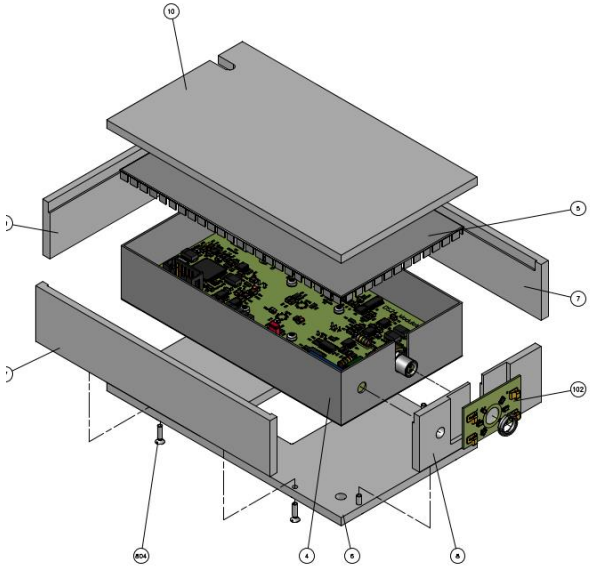


6B.5.2.1 ADCs – Class “0.5”: CERN DS24

- New DS24 (upgrade of DS22): prototype fully validated in 2022 [EDMS 2717543] ✓
- Ready for production ✓ Upgrade of LHC Dipoles in EYETS 24/25 [to be presented at LMC]

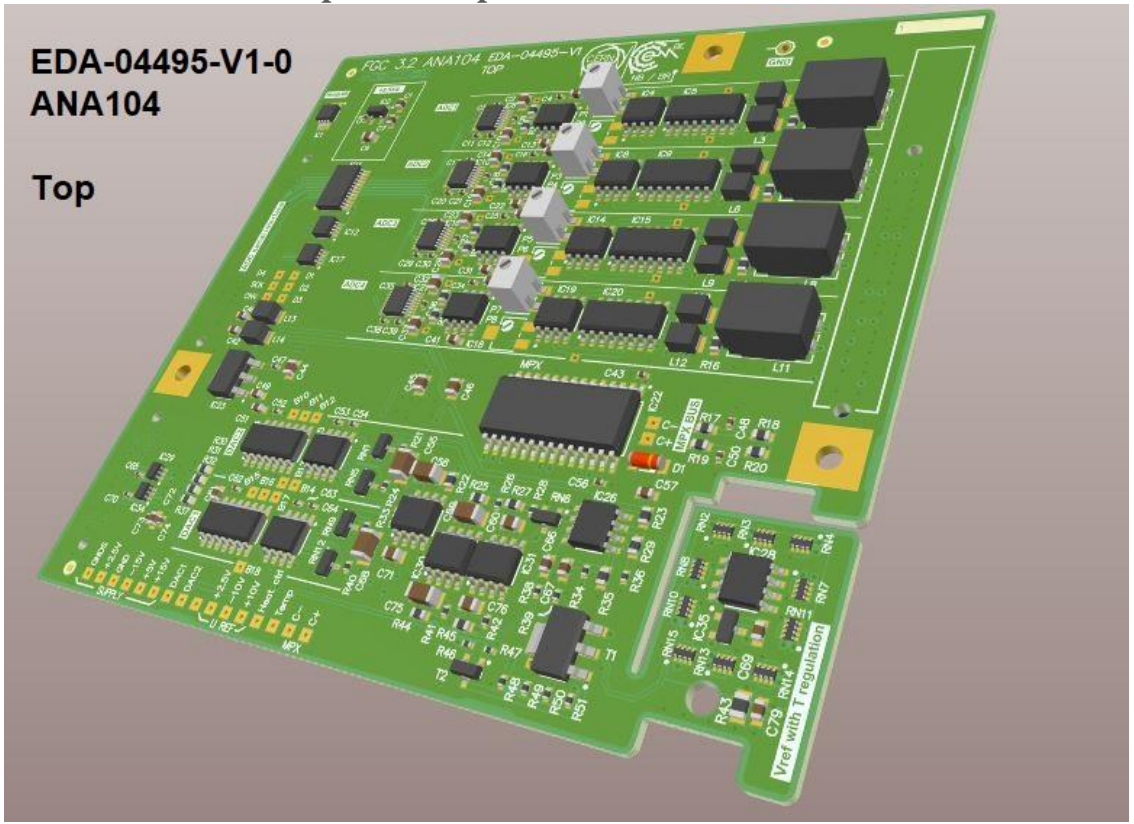






6B.5.2.1 ADCs – Class 3: ANA 104

- **ANA104** (**FGC internal ADC**): prototype validated in 2022 [EDMS 2424037] ✓
- Ready for production ✓ Component procurement has started ✓



6B.5.2.2 DCCTs – Class 0

- **Class 0 DCCTs** (18kA & 14kA) **prototypes validated** ✓ [EDMS 2687320, EDMS 2687321]
- Pre-series production ongoing ✓ delivery expected by May 2023

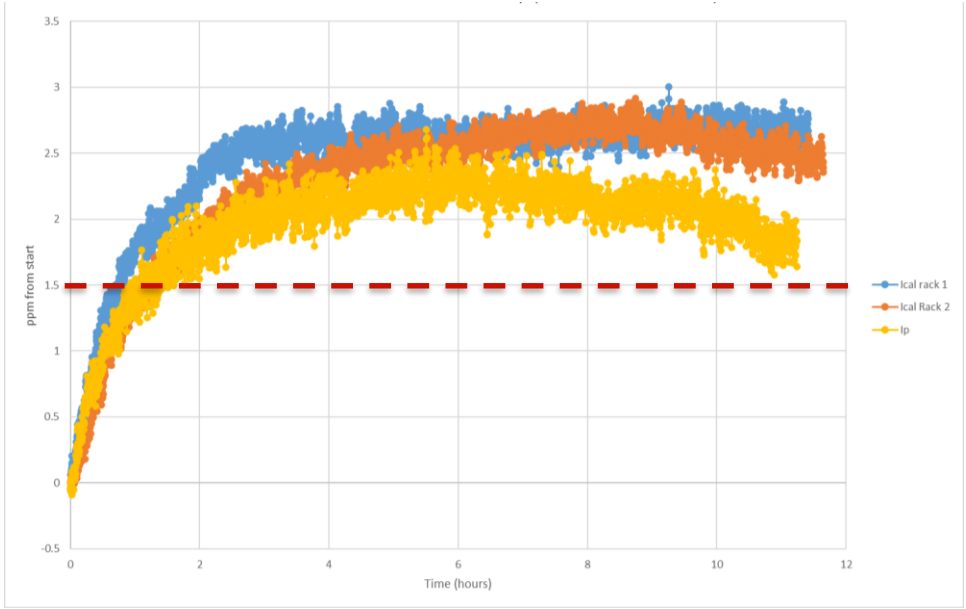
EMC testing

18kA performance testing

6B.5.2.2 DCCTs – Class 2

- Class 2 DCCTs (2kA) prototypes **validation ongoing**
- Stability performance not yet within specs: **2.5 ppm achieved** vs **1.5 ppm required**
- Intense work is ongoing with the manufacturer to improve it
- **Delivery to IT String** is currently estimated **by September 2023**

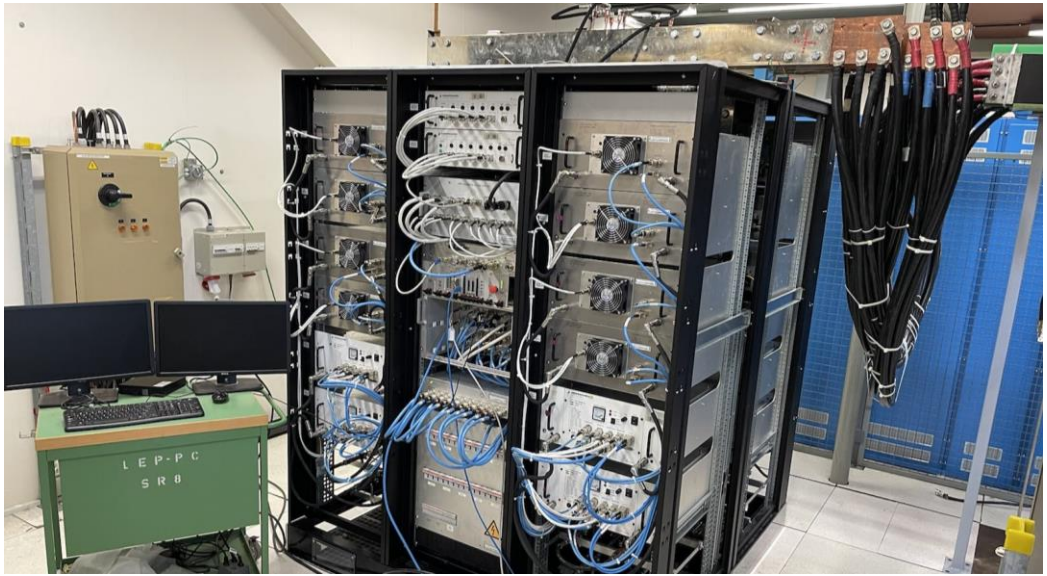
6B.5.2 Status



12h drift after 0A to I_{nom} step [excluding first 5 min]

6B.5.2.3 DCCT Test Infrastructure

- 20kA and 6kA Power Converters installed and commissioned 08/2022 ✓



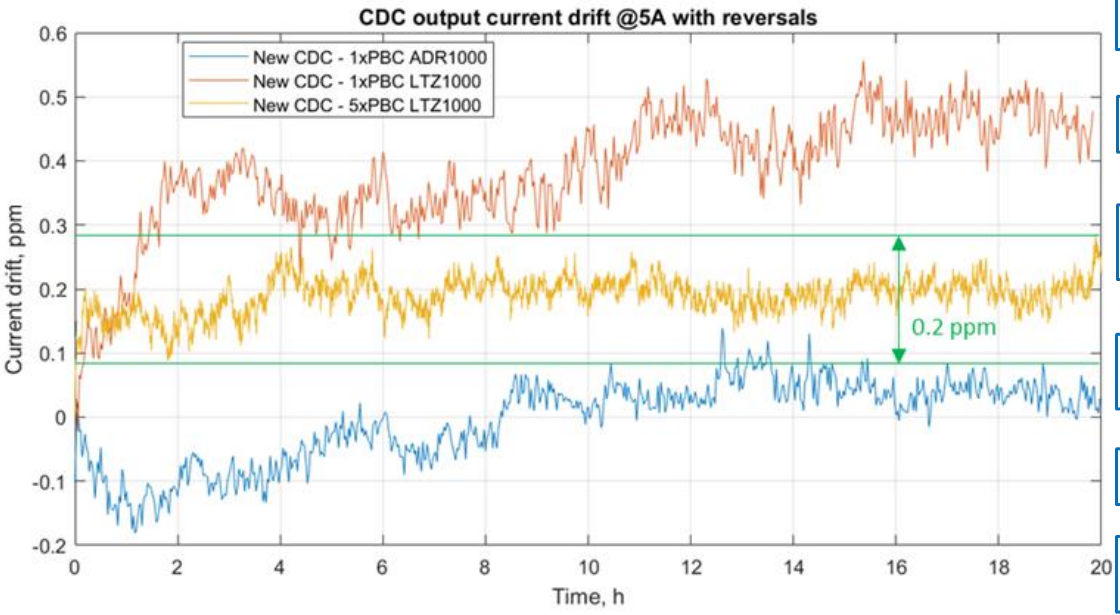
20kA Power Converter [“14kA demo” from 6B.2]

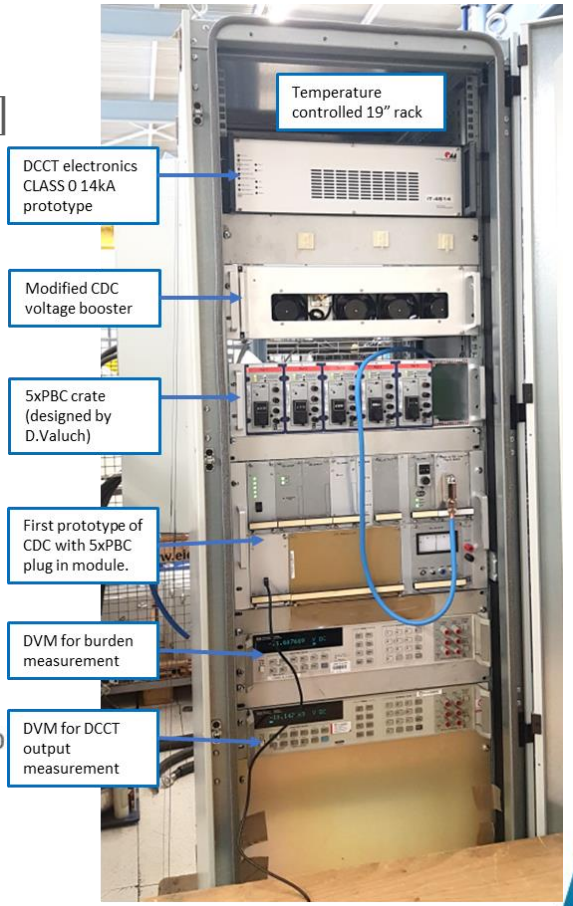
6kA Power Converter

6B.5.2.3 DCCT Test Infrastructure

- CERN DCCT CALIBRATOR prototype validated 07/2022 ✓
  - **Drift better than 0.2 ppm** peak-peak **over 20 hours**
  - Finalization is ongoing [TECH student arriving 10/22]

6B.5.2 Status

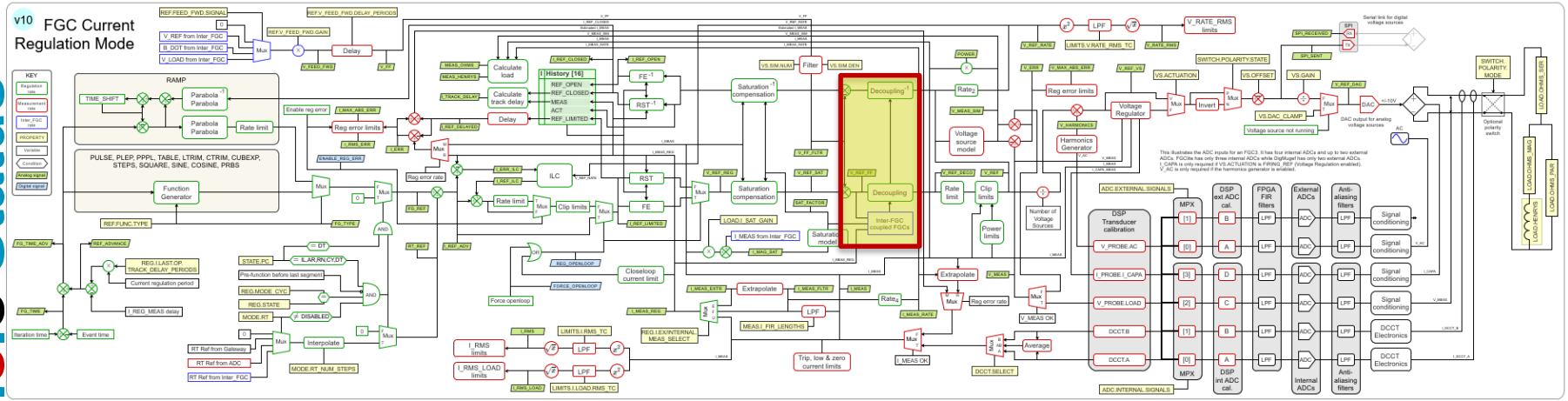




Control Software

6B.5.3 Status

- IT decoupling control library is ready since end of 2020 ✓



- Validation by means of HIL tester expected by Q1 2023
  - during IT String testing it will be seen if MQXF saturation needs to be taken into account [after 10/24]

R2E-LHC [60; 120]A: $RPLBC_{120A}$ & RPLAC / D_{60A}

- 3 different converters $RPLBC_{R2E}$ 120A, $RPLAC_{R2E}$ 60A, RPLAD $35A_{60A}$
- **2** common **building blocks**: **P**OWER **M**ODULE – **C**ONTROL & **P**ROTECTION **M**ODULE
  - DM 1 special crowbar module (up to 3.5 kA for Q1a KT modulation)
- **High synergy** leading to cost optimization ✓
  - R2E 60A & 120A: **500 Gy** current target - first design phase completed ✓
  - Modules of all three types are currently under construction ✓

6B.6 Status

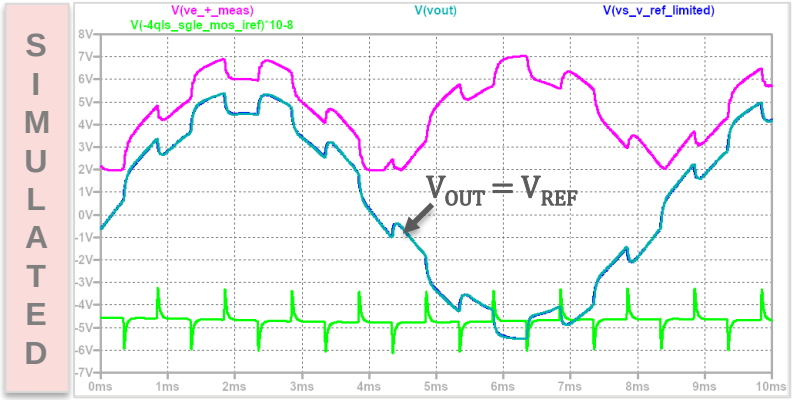
PM rated 60A

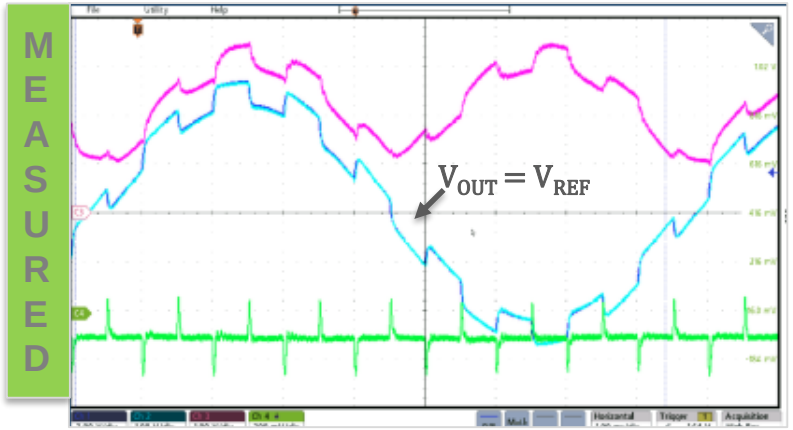
CPM

DM Module for RPLAD

R2E-LHC [60; 120]A: $RPLBC_{120A}$ & RPLAC / D_{60A}

- Simulated & measured **performance** of $PM_{Voltage\ Source}$ **fully satisfactory** ✓





6B.6 Status

- All **highly critical components tested** under radiation (R2E Team)
  - Degradation was measured and is now integrated in components models ✓
  - **Support of R2E team @ CERN** is **crucial** (heavy campaign) ✓
  - **570 000** components ordered (75% of critical semiconductors) ✓
  - Shortage on components is **currently mitigated** (but some delivery in Q3 2024)

R2E-LHC [60; 120]A: RPLBC$_{120A}$ & RPLAC / D$_{60A}$

6B.6 Status

Current sensor radiation qualification [campaign @ PSI]

Tested

0	0	Low	TBD (safe/design & vs its use)	TBD (safe/design & vs its use)	NPN Transistor	D44H11G	TO220	Σ			Σ	
0	0	Low	TBD (safe/design & vs its use)	TBD (safe/design & vs its use)	PNP Transistor	D45H11G	TO220	Σ			Σ	
0	0	Low	OK (Tested)	OK (Tested)	NPN Transistor	BCP56-16	SOT223	Σ			Σ	
0	0	Low	OK (Tested)	OK (Tested)	PNP Transistor	BCP53-16	SOT223	Σ			Σ	
0	0	Low	OK (Tested)	OK (Tested)	NPN Transistor	FMMT491TA	SOT23	Σ			Σ	
0	0	Low	OK (Tested)	OK (Tested)	PNP Transistor	FMMT591	SOT23	Σ			Σ	
0	0	Low	TBD (safe/design & vs its use)	TBD (safe/design & vs its use)	Bridge Rectifier	26MT160	D-34A	Σ			Σ	
2	2	High	TBD (Unknown & to be tested)	TBD (Unknown & to be tested)	Current Sensors	BJHCS-K3-100A HAS 100S	20mm x40mm x10mm	Σ			Σ	
2	2	High	OK (Tested)	OK (Tested)	Phase Sh. PWM	UC2875N (UC1875J (SP))	DIP20	Σ			Σ	
2	2	High	OK (Tested)	OK (Tested)	Op. Amplifiers	OPA2192 OPA1611,	SO8	Σ			Σ	
1	1	Med.	OK (Tested)	OK (Tested)	Analog Switches	SW06GSZ (DG444/5)	SOIC16	Σ			Σ	
0	0	Low	OK (Tested)	OK (Tested)	Comparators	LM193	SO8	Σ			Σ	
0	0	Low	OK (Tested)	OK (Tested)	Volt. Reference	TL1431, (TL431, TL431LI)	SOT23	Σ			Σ	

"Live" documentation on R2E components qualification

R2E-LHC [60; 120]A: RPLBC$_{120A}$ & RPLAC / D$_{60A}$

6B.6 Status

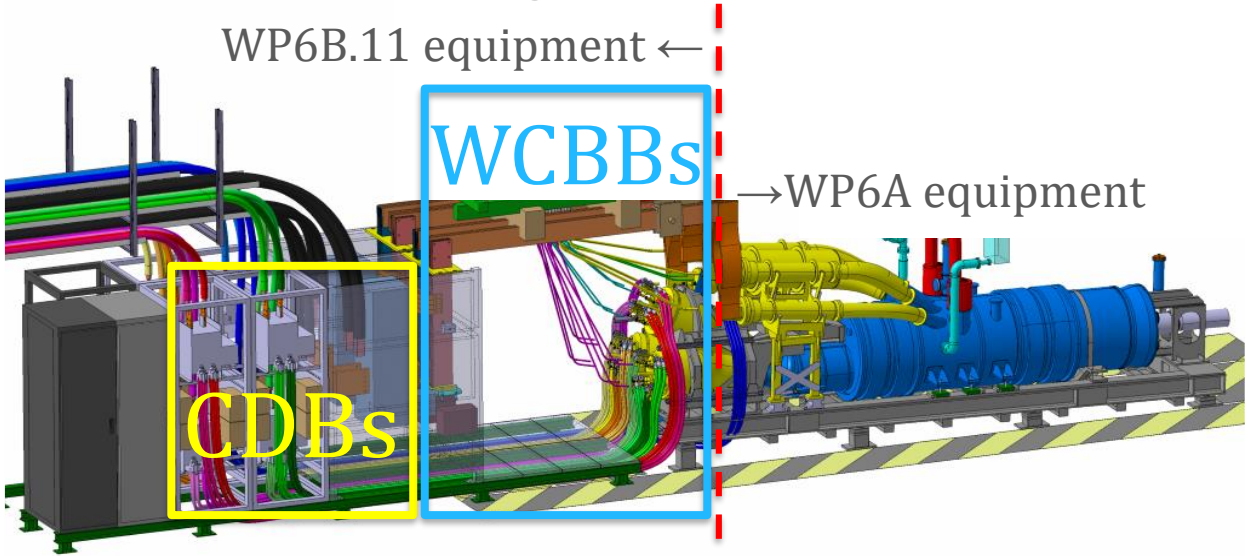
- Work on power rack started for
  - RPLBC [120A] in RRs
  - and RPLAD [35A] in URs + SM18 $_{\text{IT String}}$
  - Design well advanced taking into account operational aspects
  - including CDB like operations for lock-out tag-out:
    - Disconnection, Earthing, Short circuits (for tests)

Easy to “earth” circuit or disconnect it from converter side

CDBs & WCBBs

6B.11 Status

- Deliverables:
  - **C**ircuit **D**isconnector **B**oxes for circuits ≥ 600A
  - **W**ater **C**ooled **B**us **B**ars for circuits ≥ 14 kA
  - ECR for WCBBs recently approved ✓ 06/22 [EDMS 2453935]
    - Technical (and status) info tomorrow at MCF parallel session – talk: S. Seshadri
    - deliverables for Run4 might come as in-kind contribution - discussion ongoing ✓



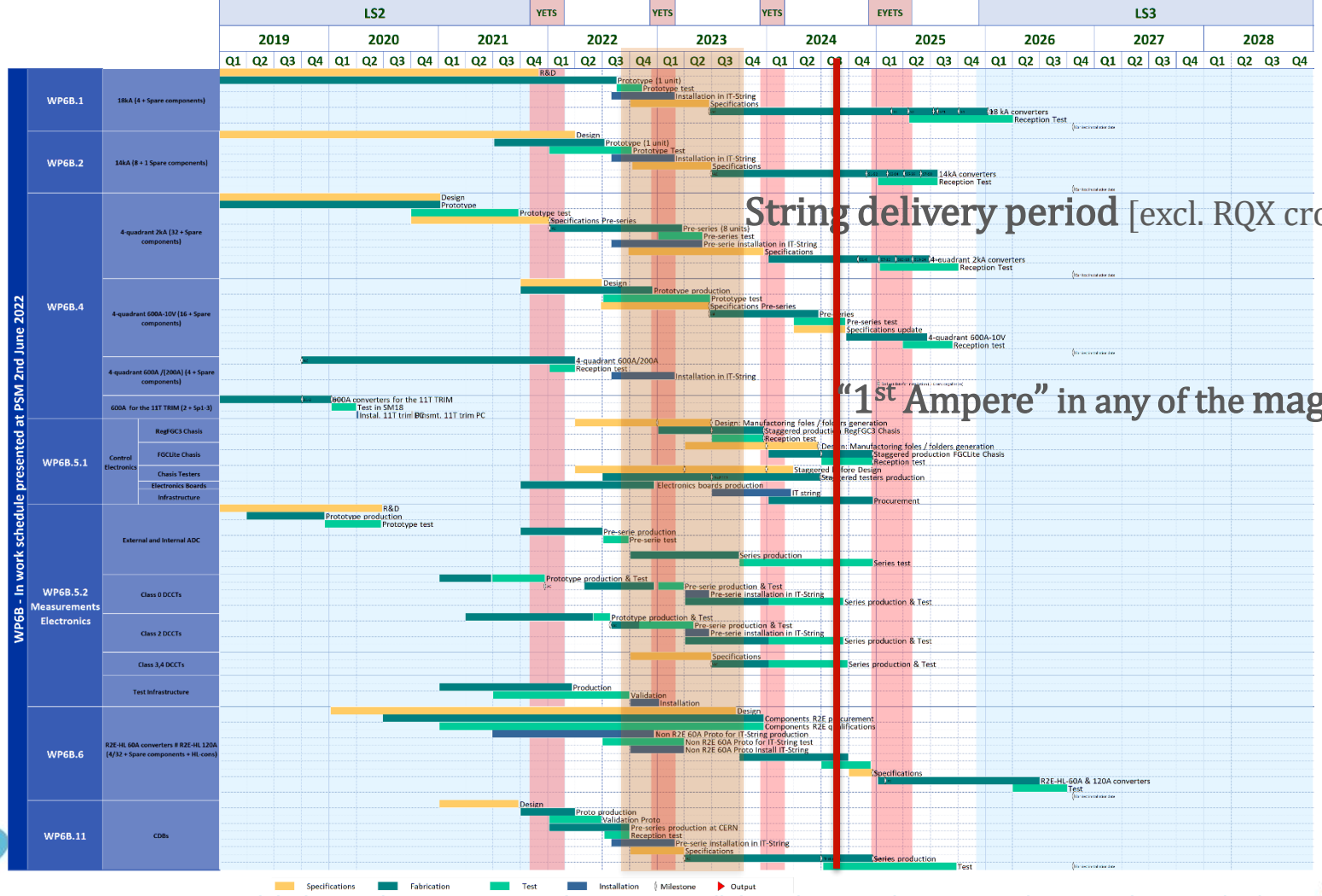
CDBs

6B.11 Status

- Power Racks
  - Mechanical design completed in 2021 ✓ - Prototypes finalized by 06/22 ✓
  - Pre-series for IT String being assembled for installation during 10/22 ✓
- Control rack
  - Design finalized in 06/22 ✓
  - Contract for pre-series being finalized for delivery end of 01/23

Contract in 2023 for Series Production in 2024

Conclusion



String delivery period [excl. RQX crowbar]

"1st Ampere" in any of the magnets

Thank you for your kind attention

Credits to: V. Montabonnet, S. Pittet, N. Kuczerowsi, V. R. Herrero Garcia, B. Todd, M. Cerqueira Bastos, Q. King, Y. Thurel, C. Coupat, H. Thiesen

Spare Slides

Scope and deliverables: Power Converters

WBS	Eq. Code	Magnet Circuit	Ratings *precision class*	Deliverables
6B.1	HCRPAFE	Inner Triplet Mains	[18 kA; ±10 V] *class.0*	06 (***04**: operation*)
6B.2	HCRPAFF	D1-D2	[14 kA; 8 V] *class.0*	10 (***08**: operation*)
6B.4	HCRPBAA	Inner Triplet Correctors	[±2 kA; ±10 V] *class.2*	37 (***32**: operation*)
	HCRPBAB	Inner Triplet Trims	[±2 kA; ±10 V] *class.2*	
	HCRPMBF	D2 Correctors	[±600 A; ±10 V] *class.3*	32 (***22**: operation*)
	HCRPMBD$_{R2E}$	SF 2nd Order (±200 A)	[±600 A; ±10 V] *class.3*	
	HCRPMBE$_{R2E}$	11 T Trim (±250 A)	[±600 A; ±10 V] *class.3*	
6B.6	HCRPLBC $_{R2E}$	SF High Order	[±120 A; ±10 V] *class.4*	36 (***32**: operation*)
	HCRPLAD	Q1a Trim (±35A)	[±60 A; ±10 V] *class.4*	06 (***04**: operation*)
	HCRPLBC $_{R2E}$	LHC Correctors + Q4-Q5-Q6 Correctors	[±120 A; ±10 V] *class.4*	100 (***92**: operation*)
	HCRPLAC $_{R2E}$	LHC Correctors	[±60 A; ±10 V] *class.4*	154 (***144**: operation*)

*** : deliverables other than operational converters are given as "equivalent" units; they do not represent "full converters" (protos/spares in different phases, spare parts, etc.).**

Scope and deliverables: complements

WBS	Equipment	Deliverables for 381* Power Converters (*338: operation*)
6B.5.1	**Control Electronics**	Modular & high-reliability control electronics for all WP6B power converters based on **FGC3.1** & **FGCLite** R2E
6B.5.2	**Current High Precision Measurement**	Current measurement equipment for all WP6B power converters - Development of **ultra-precision** HL-LHC **Class 0** (DCCTs, ADCs,…) - Test and calibration infrastructure
6B.5.3	**Software**	Software production for IT decoupling control and IT current monitoring system
6B.9	**Transport & Installation**	Manage all activities and deliverables concerning Transport and Installation of the 338 operational converters (+ relative spare units/parts). It includes both INDSERV and MATERIAL.
6B.10	**Warm Powering of IT STRING**	Management of all activities and deliverables to successfully provide “warm powering” for the IT String, including operation during 2025 and coordination for de-installation
6B.11	**Circuit Disconnector Boxes**	**CDBs** for all **32** HL-LHC circuits powered from URs (including PLC controls and spare units). CDBs for the IT String **WCBBs** for the **12** HL-LHC circuits : 18 kA and 14 kA

*** : deliverables other than operational converters are given as “equivalent” units.**