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TE-MSC

Results of the Cold Test of the first HL-LHC Cold Powering System

Superconductivity & Particle AcceleratorS 2024
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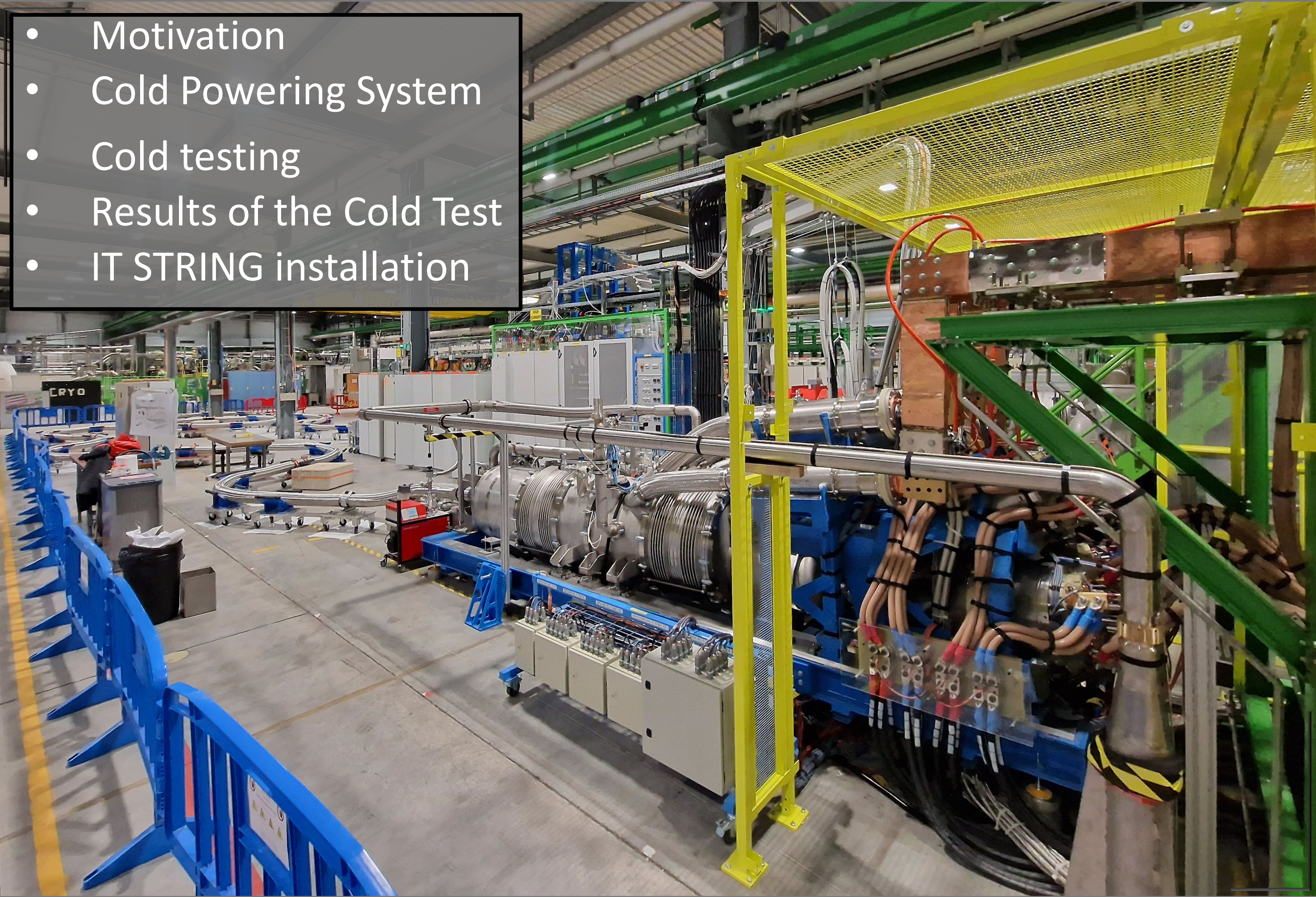
Outline

- Motivation
- Cold Powering System
- Cold testing
- Results of the Cold Test
- IT STRING installation



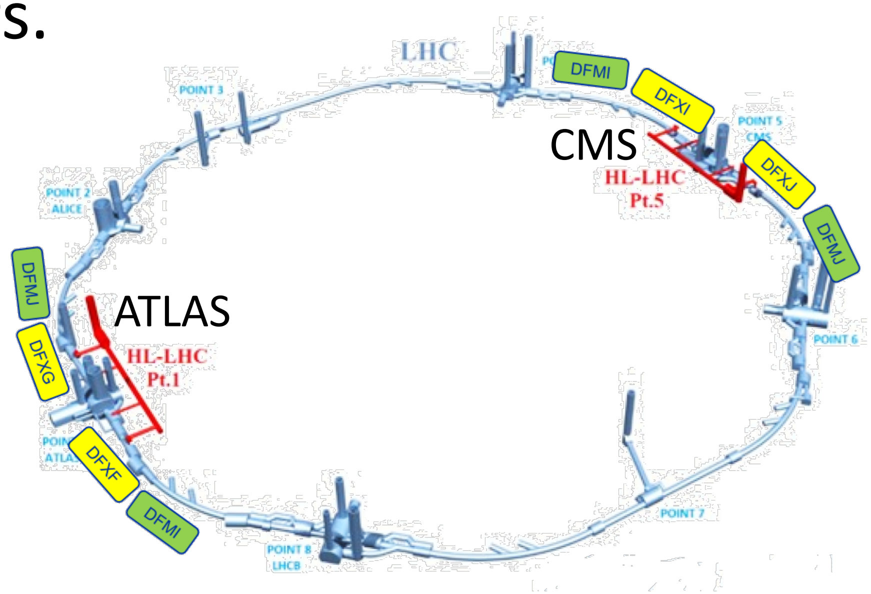
Motivation: The HL-LHC Project

Key objectives:

- **Extend** the **LHC lifetime** by another **decade**
- Implement hardware configuration to reach:
  - **Increase** of the **peak luminosity** by a **factor 5 – 7.5**
  - **Achieve** an **integrated luminosity** of **250 fb^{-1}** per year and **L_{int} = 3000 fb^{-1}** within twelve years
- **Exceed** the **expected luminosity reach** of the LHC lifetime by a **factor** of **10** within 10 years.

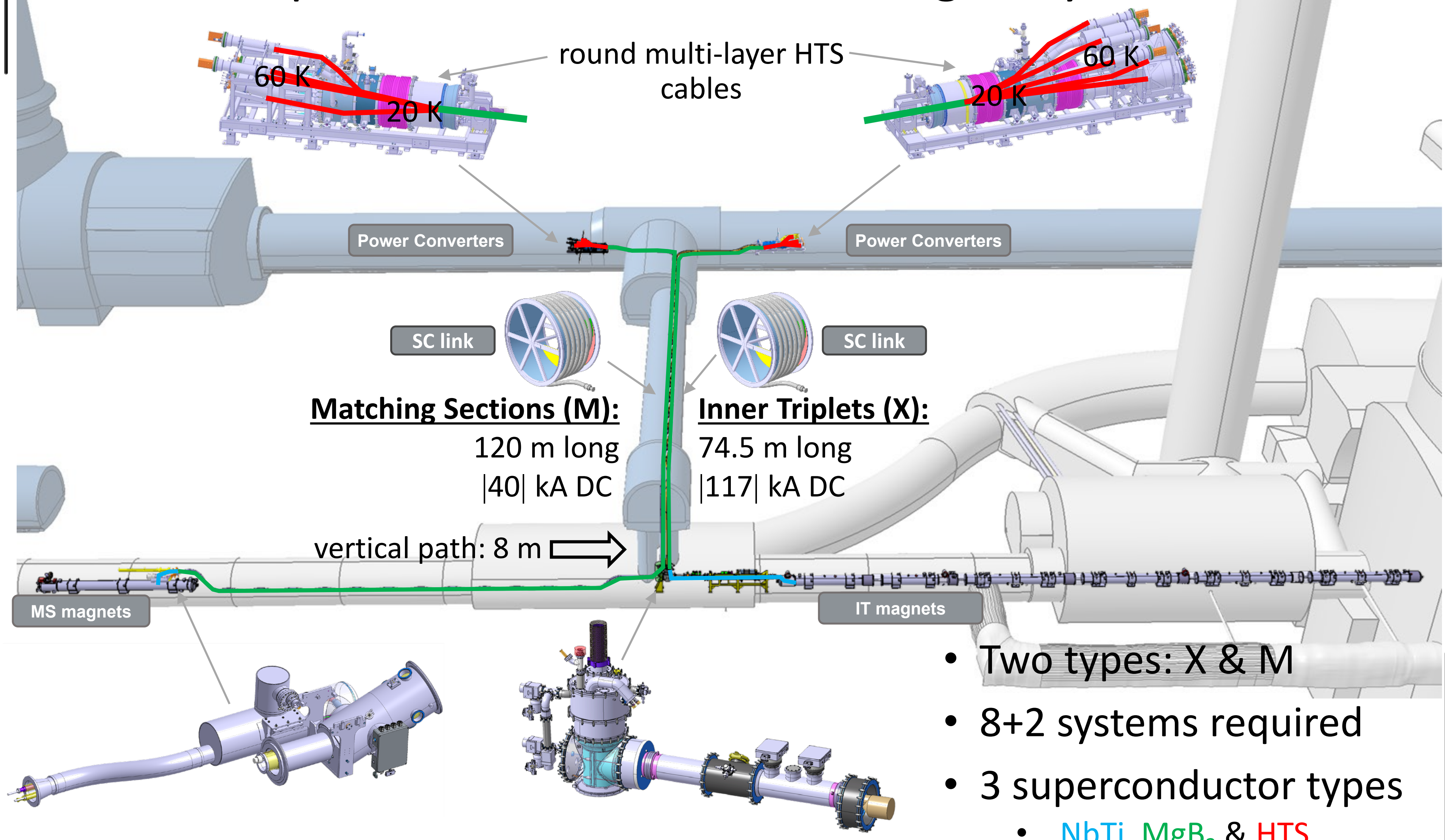
At ATLAS and CMS experiments:

- Improved **interaction region magnets** (e.g. MQXF)
- **Cold Powering** from service galleries to interaction region



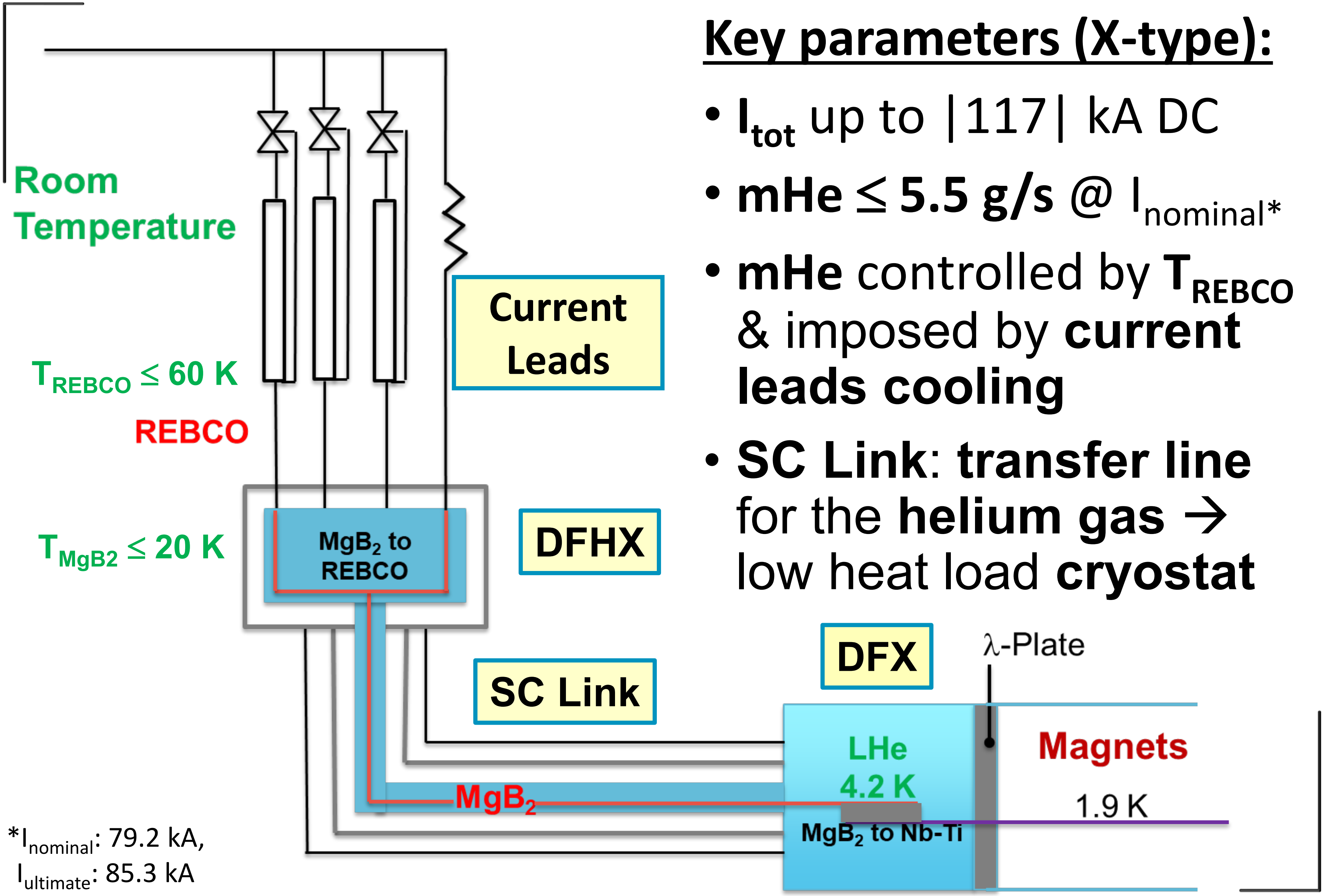
Motivation: HL-LHC Cold Powering

Key Function: Electrical connection between magnets in LHC tunnel and power converters in service gallery



- Two types: X & M
- 8+2 systems required
- 3 superconductor types
  - NbTi, MgB_2 & HTS

Motivation: HL-LHC Cold Powering



Key parameters (X-type):

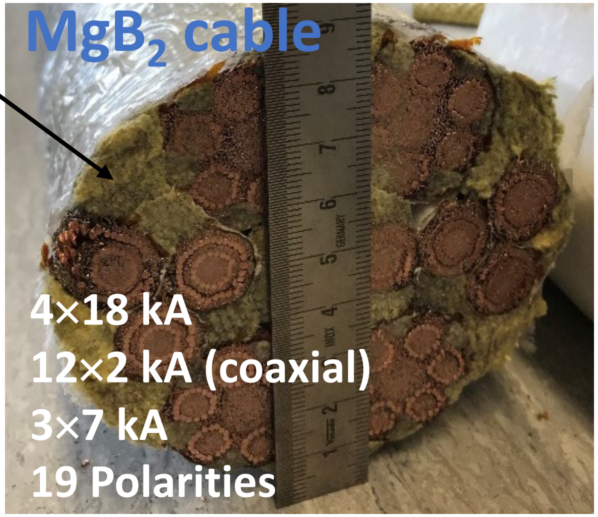
- I_{tot} up to |117| kA DC
- **mHe ≤ 5.5 g/s** @ $I_{nominal*}$
- **mHe** controlled by $\mathbf{T_{REBCO}}$ & imposed by **current leads cooling**
- **SC Link**: **transfer line** for the **helium gas →** low heat load **cryostat**

*$I_{nominal}$: 79.2 kA, $I_{ultimate}$: 85.3 kA

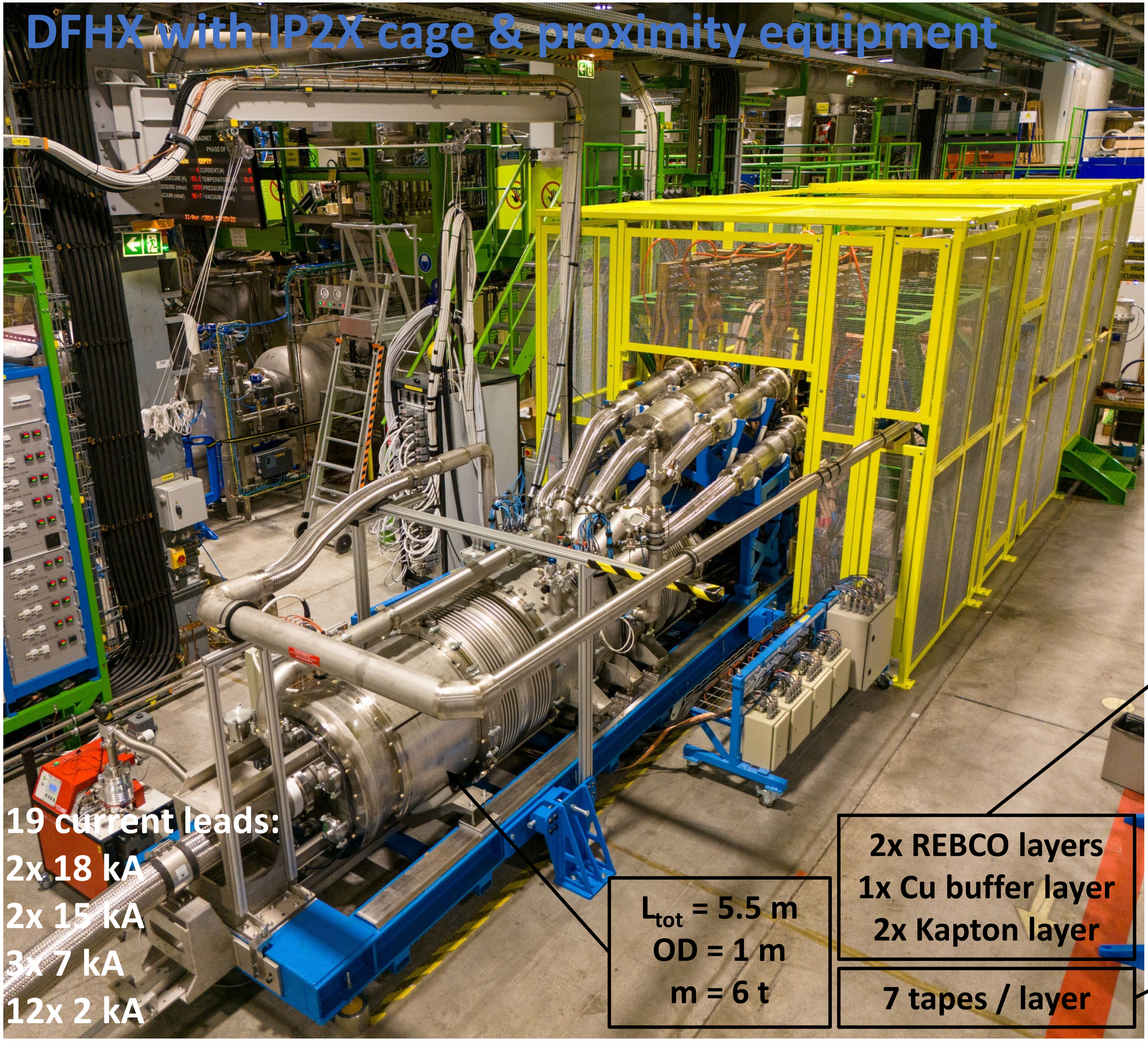
Cold Powering System: in SM-18

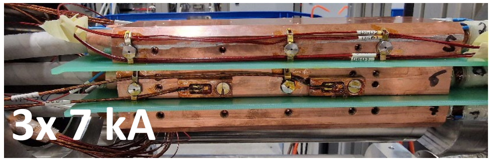
Instrumentation signals: 304 voltage taps and 105 temperature sensors

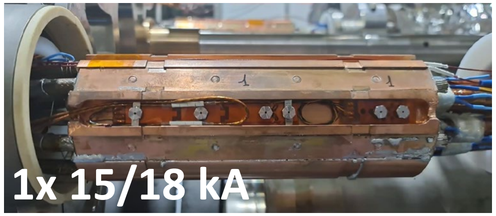
Cold Powering System: Superconducting Link

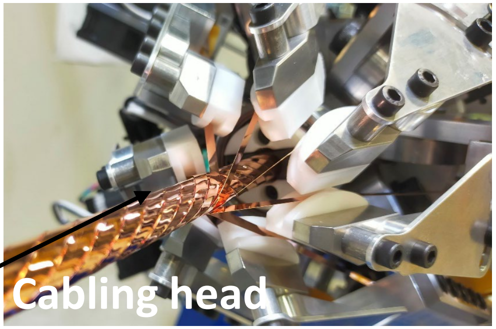


Cold Powering System: DFHX









Cold Powering System: DFX & vertical path

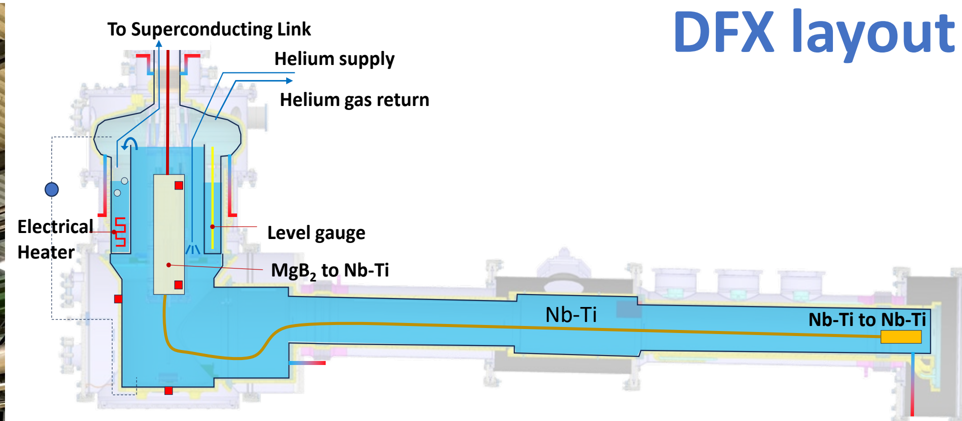
DFX

19x MgB_2-NbTi splices

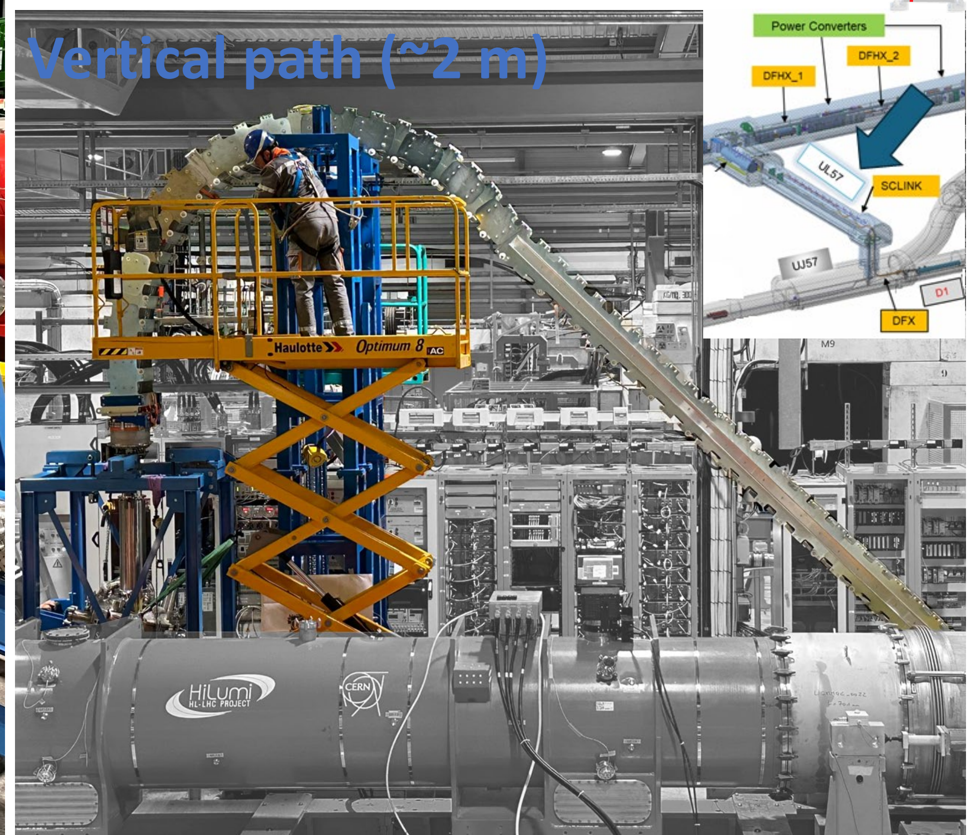
9x NbTi short circuits

He gas generation

DFX layout

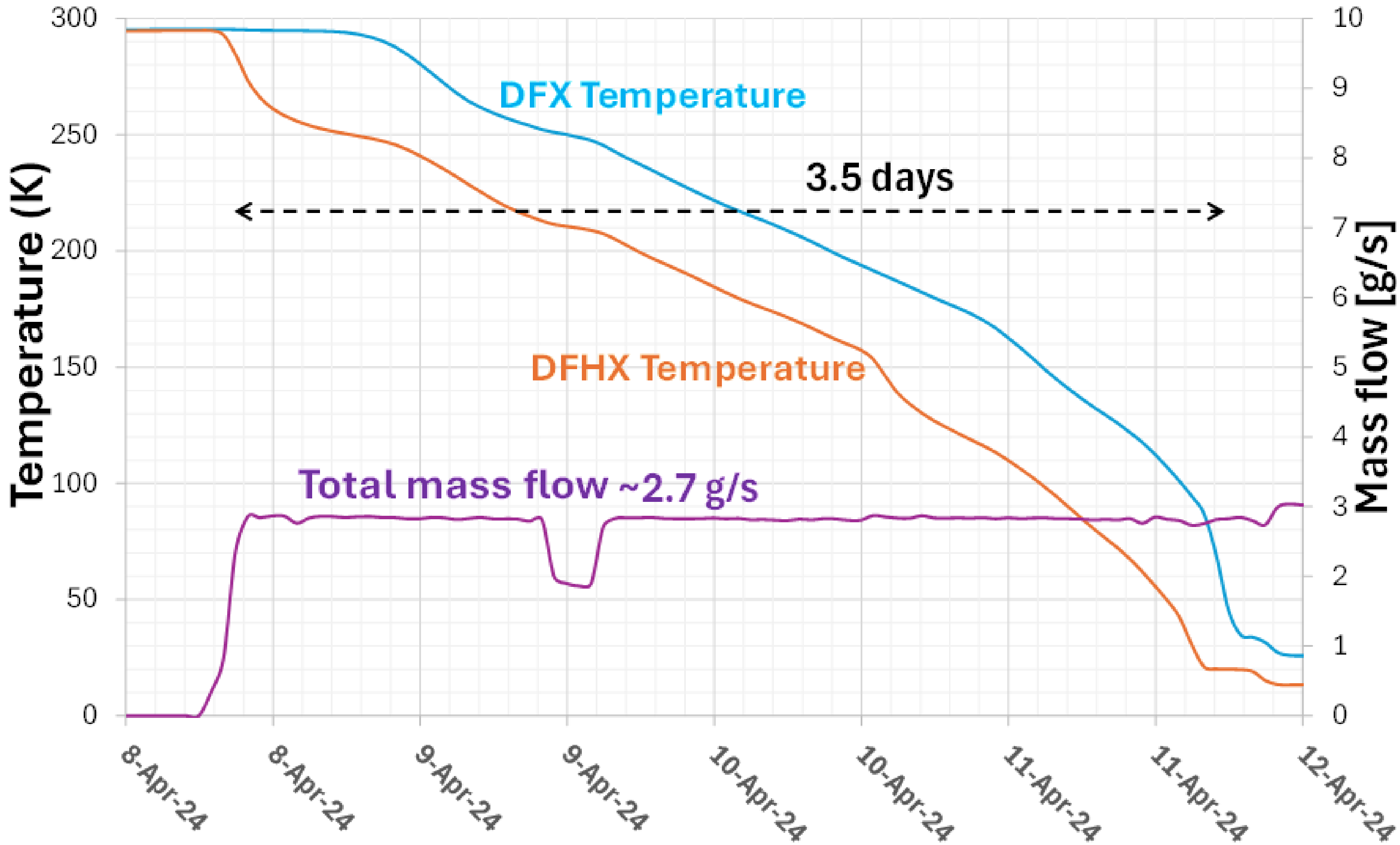


Vertical path (~2 m)



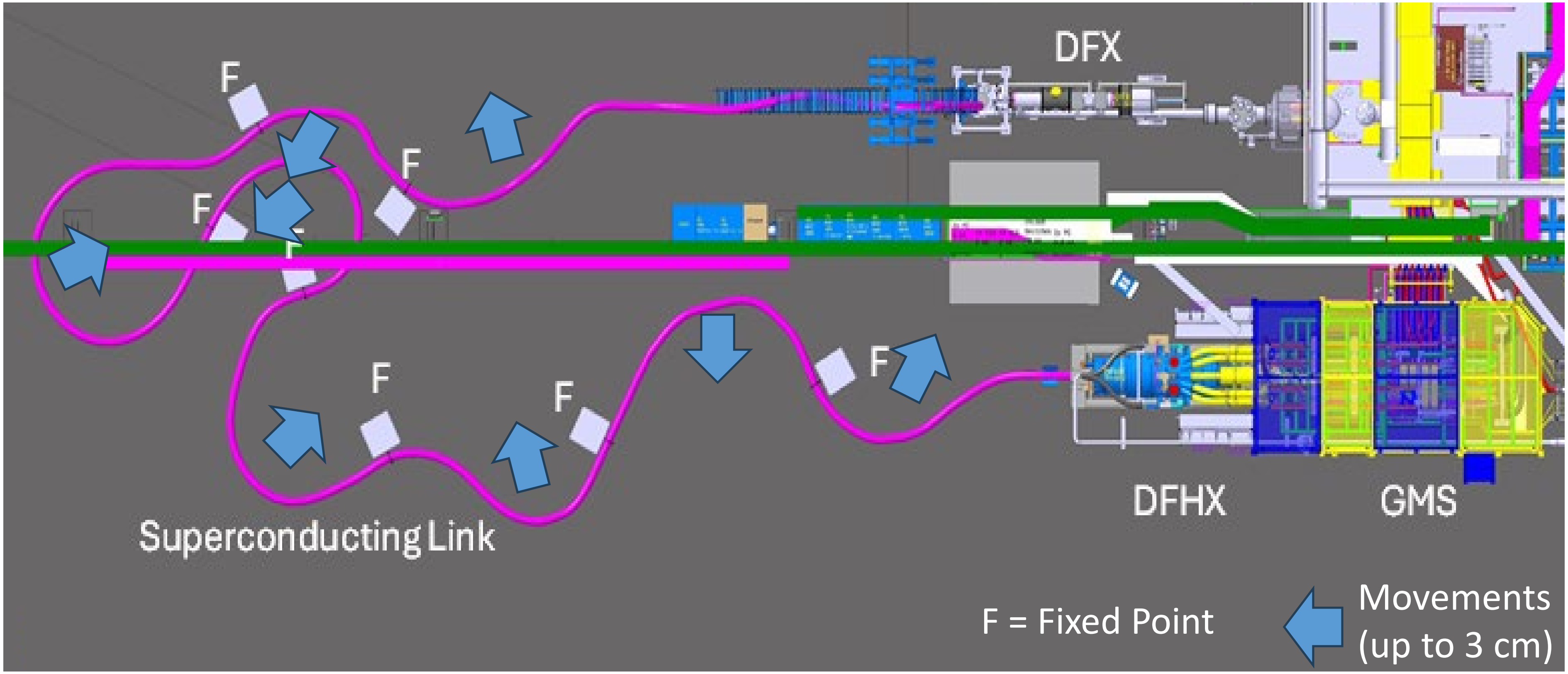
Cold Testing: Cool-down

- After **pressure test** (4.6 bara)
- And **leak test** (He leak rate < $1 \cdot 10^{-8}$ mbar·l · s^{-1})
- **Cool-down** to nominal cryogenic conditions (< 1 week)



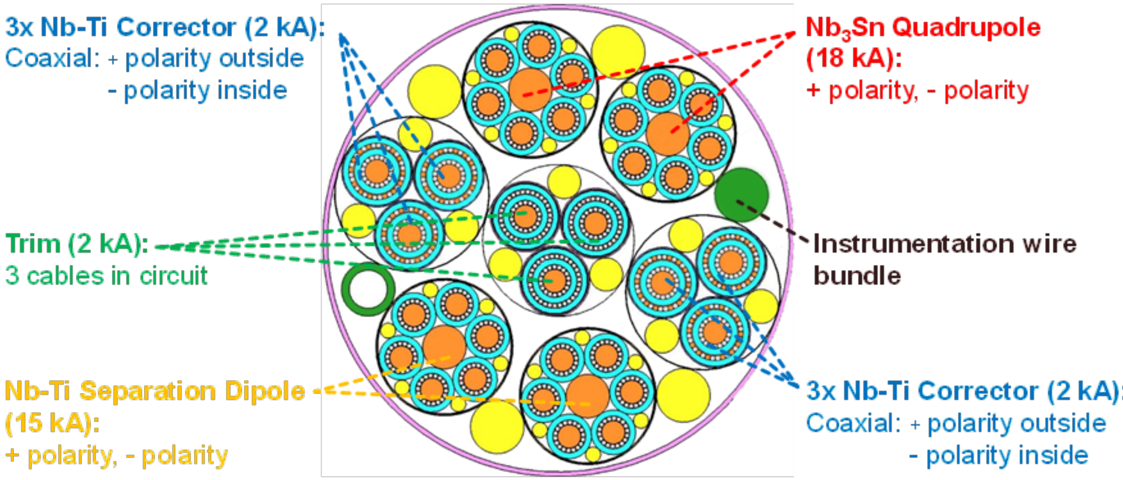
Cold Testing: Thermal Contractions

- **Waves** with **regular fixed points** to allow movement
- **Two thermal cycles** (RT → cryogenic conditions) **followed** by **powering** of all circuits
- **Repetitive performance**

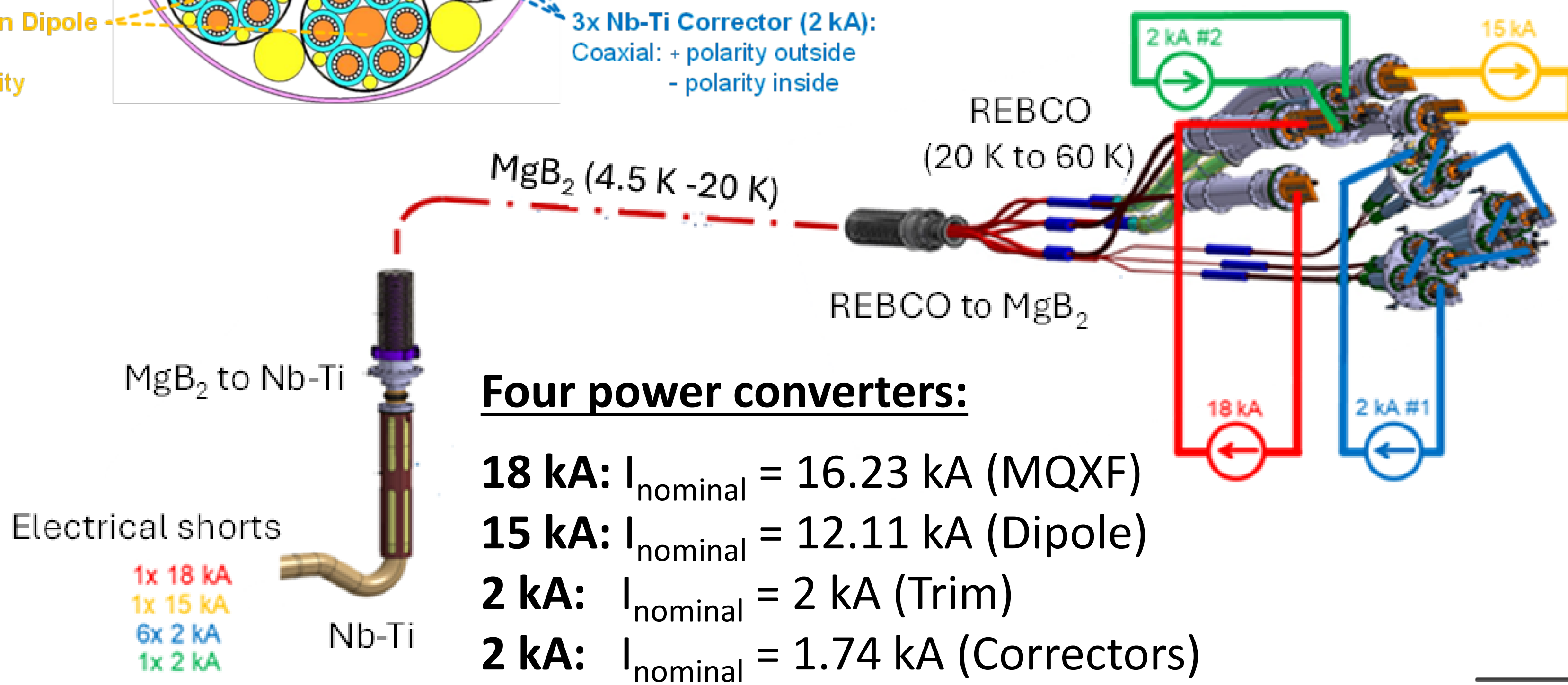


Cold Testing: Powering Scheme

- **+ & -** of each circuit in **shorted** @ 4.2 K
- **Similar circuits** connected **in series** @ RT



Maximum current delivered by the power converters: **94 kA**



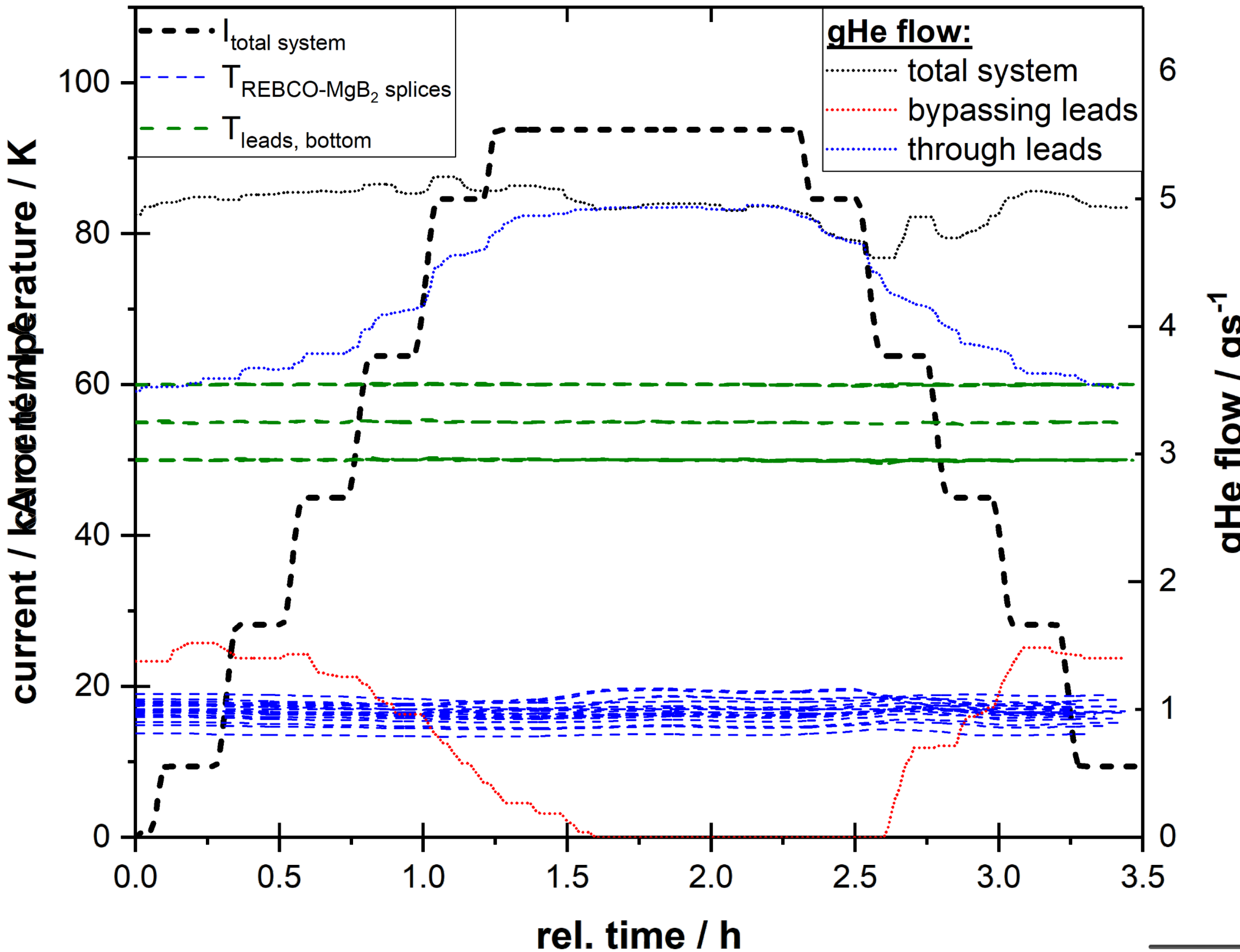
Four power converters:

18 kA: $I_{nominal}$ = 16.23 kA (MQXF)
15 kA: $I_{nominal}$ = 12.11 kA (Dipole)
2 kA: $I_{nominal}$ = 2 kA (Trim)
2 kA: $I_{nominal}$ = 1.74 kA (Correctors)

Results: Flow & temperatures

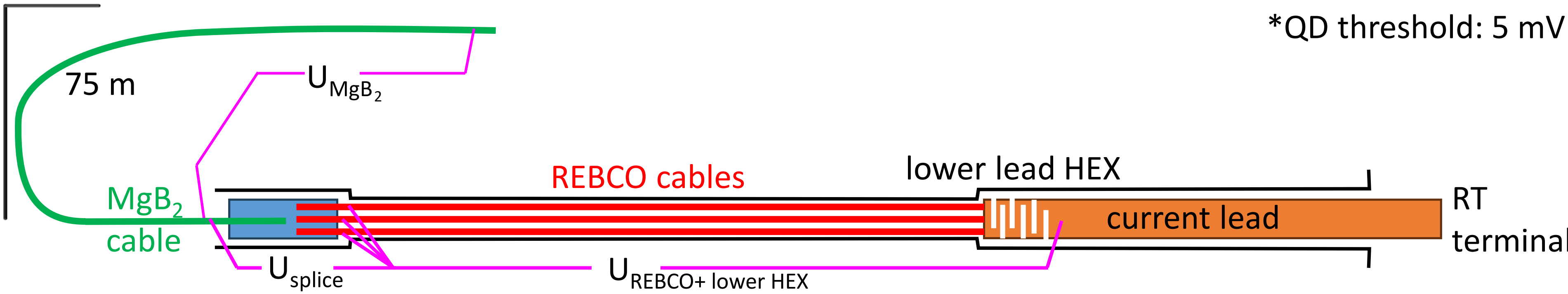
1st full X-type Cold Powering System successfully cold tested:

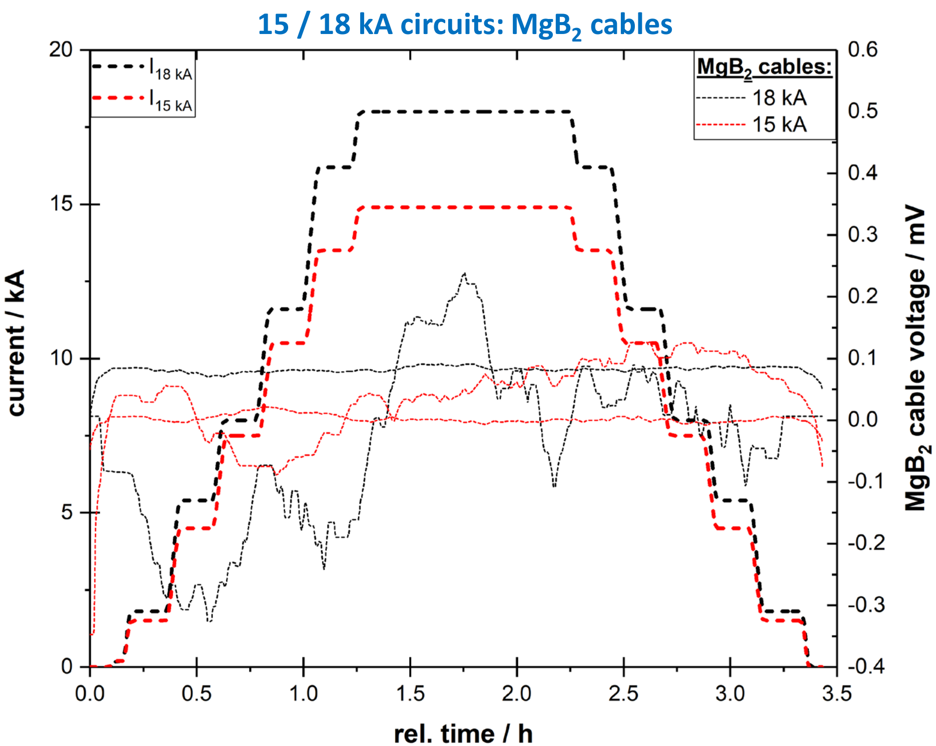
- Transported **94 kA @ 5.0 g/s gHe** flow
- **Within specifications:** 79.2 kA ($I_{nominal}$ of HL-LHC magnets) @ 5.5 g/s
- Avg. current lead **gHe flow: 50 mg·s^{-1}· kA^{-1}**
- REBCO cable splice & lead temp. stable
- Splice temp. limit: 25 K
- Lead temp. setpoints:
  - 18 kA: 50 K
  - 15 kA: 55 K
  - 2 kA: 50 – 60 K

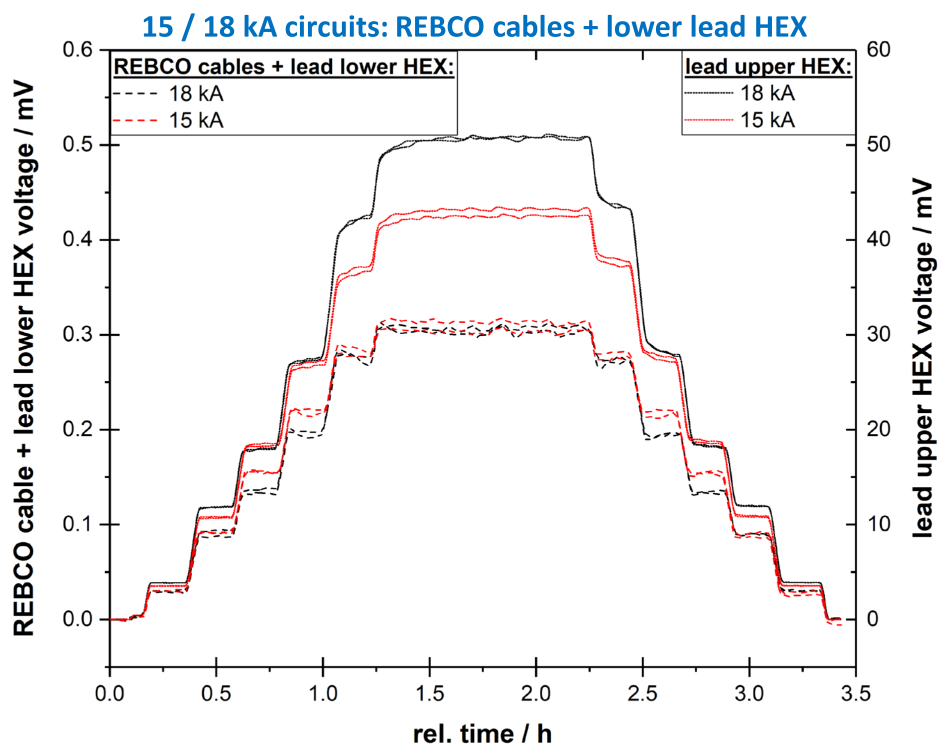


Results: Superconductor cables

*QD threshold: 5 mV



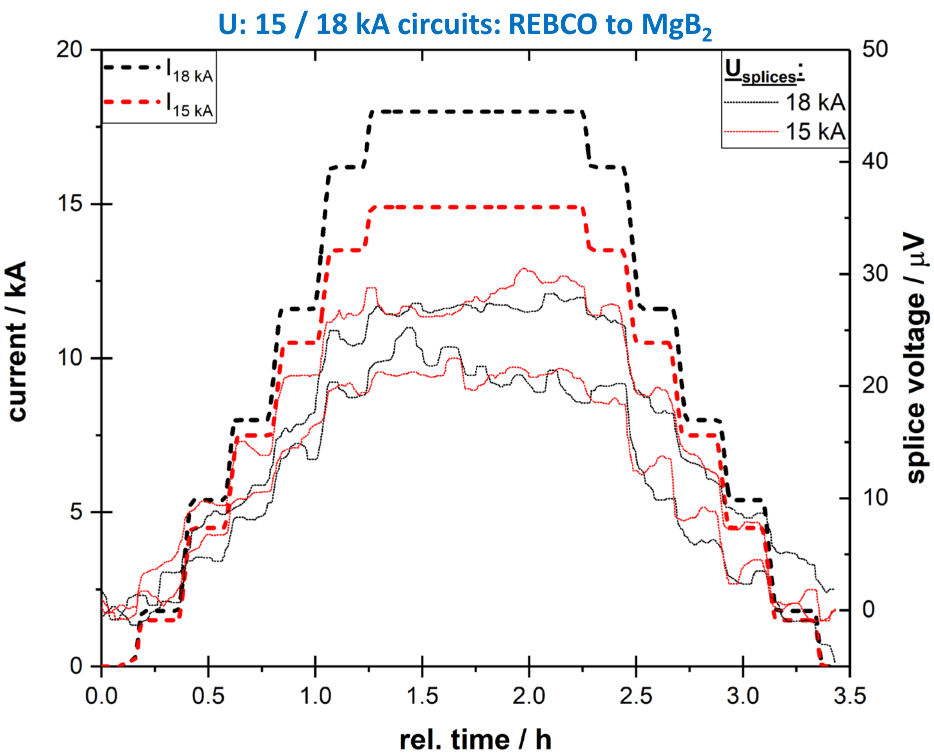


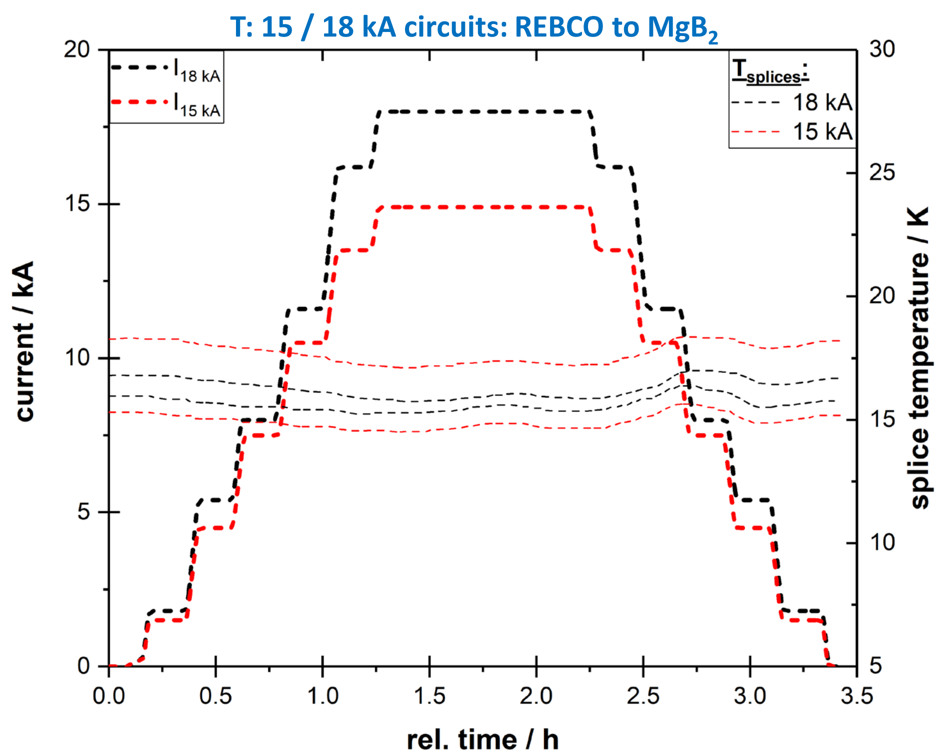


- **Stable, no transition**, x10 – x100 below QD threshold*

Results: Splices

Circuit	REBCO to MgB_2 splices (REBCO to MgB_2, GHe @ 20 K)		MgB_2 to Nb-Ti splices (MgB_2 to Nb-Ti, LHe @ 4.5 K)		Nb-Ti to Nb-Ti splices (Nb-Ti to Nb-Ti, LHe @ 4.5 K)	
	R_{splice} measured	R_{splice} expected	R_{splice} measured	R_{splice} expected	R_{splice} measured	R_{splice} expected
18 kA	1.4 ± 0.1 nΩ	1.5 - 2.2 nΩ	1.4 ± 0.1 nΩ	≤ 1.8 nΩ	0.9 ± 0.1 nΩ	≤ 2.0 nΩ
15 kA	1.7 ± 0.1 nΩ		1.4 ± 0.3 nΩ		0.9 ± 0.1 nΩ	
2 kA - Trim	4.3 ± 0.8 nΩ	4.5 - 6.5 nΩ	1.4 ± 0.2 nΩ	≤ 3.5 nΩ	1.2 ± 0.1 nΩ	
2 kA - Correctors	10.1 ± 1.1 nΩ	9.0 - 13.0 nΩ	2.4 ± 1.4 nΩ	≤ 6.0 nΩ	1.1 ± 0.3 nΩ	





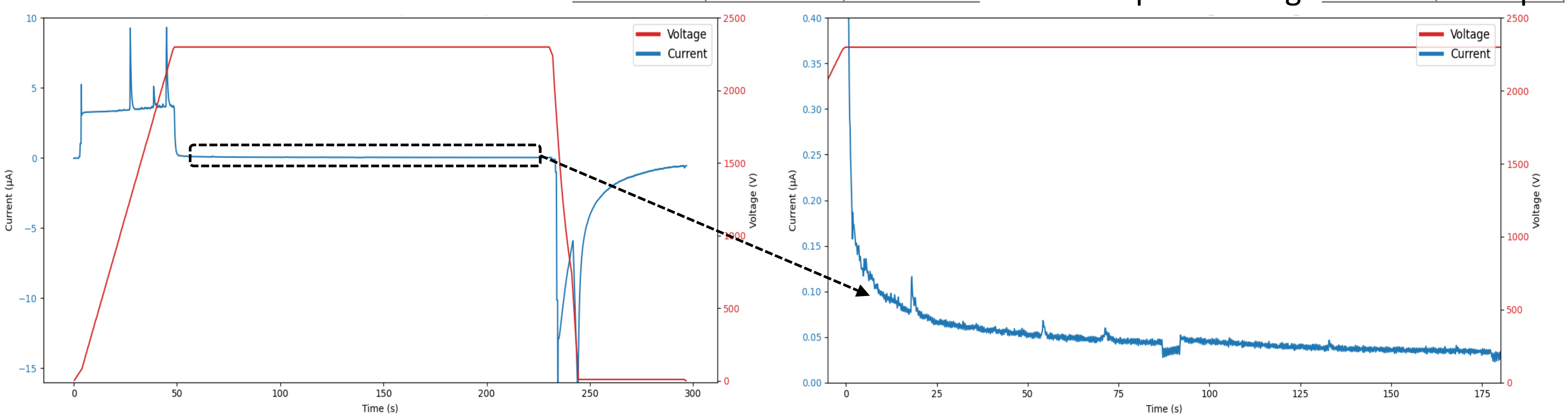
- **Stable**, T_{splice} **independent** of **current** (± 1 K)

Results: High Voltage Tests

- At nominal operating conditions & warm gHe
- HV between all circuit combinations and ground

Circuit	Voltage / kV	Time / s	Conditions	Plateau leakage current / nA	Test passed
18 kA	2.3	180	NOC	32*	Yes
15 kA	2.3	180	NOC	104*	Yes
2 kA - Trim	2.3	180	NOC	42*	Yes
2 kA Corrector #1	2.3	180	NOC	20*	Yes
2 kA Corrector #2	2.3	180	NOC	25*	Yes
2 kA Corrector #3	2.3	180	NOC	35*	Yes
2 kA Corrector #4	2.3	180	NOC	24*	Yes
2 kA Corrector #5	2.3	180	NOC	24*	Yes
…ector #6	2.3	180		*	Yes

*accepted leakage current: ≤ 10 µA



- **HV** tests successfully **passed**, NOC leakage x100 below limit

Results: Transient behavior

Successfully validated:

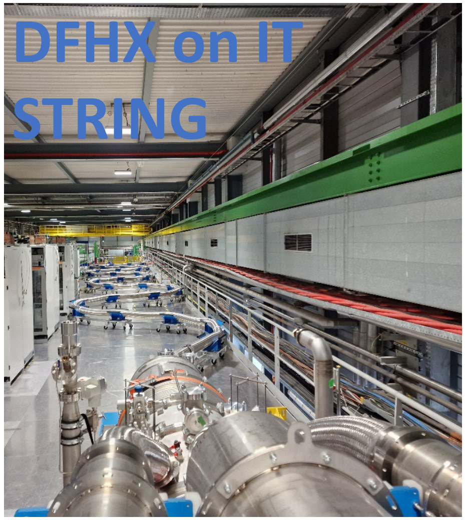
- Cryogenic requirements:
  - Capability of **operating without** liquid **helium supply** during **10 minutes** with MgB_2-Nb-Ti splices immersed in liquid helium
  - Ability to produce up to 10 g/s gHe with DFX
- Electrical requirement:
  - Circuit cross-talk (< 50 µH coupling) allowing 100 A/s ramps
  - **Quenches** of 2 kA - Corrector circuits **do not trigger QD** of any of the **other circuits**
    - Very low inductance (0.03 µH) due to coaxial layout

Circuit	Test current (kA)	Ramp rate (A/s)	Inductive coupling (µH)			
			18 kA	15 kA	2 kA - Trim	2 kA - Correctors
18 kA	18	100	31.0*	8.1	15.0	2.3
15 kA	15	100	0.1	0.1*	18.0	0.03
2 kA - Trim	2				*	
2 kA - Correctors	2	50	0.03	0.03	0.02	1.5*

*self inductance

IT String installation

- **Transportability** of Cold Powering system **demonstrated**
- System **deployed** on **IT STRING**
- DFX rebuilding & proximity equipment installation ongoing



Summary & Conclusion

- The **first Cold Powering System for the HL-LHC Triplets** has been **successfully validated**:
  - Cryogenic, electrical and mechanical **performance** all **met design** parameters
  - **Robustness** of system in different operating modes was proven
- The system transferred |**94**| **kA*** in **DC** mode with 5.0 g/s gHe:
  - **MgB_2 @ 20 K** (Operation of MgB_2 cable possible up to 29 K)
  - **REBCO cables @ 60 K** (Operation of REBCO cables possible up to 70 K)
  - **→ ~ 10 K temperature margin**
- Spooling & **transportability** (incl. crane) **demonstrated**
- **Components industrialized** after intensive R&D at CERN
- Systems in **advanced** phase of **series production**
- **Installation** in the **LHC underground** is planned to start **2027**

*$I_{nominal}$: 79.2 kA, $I_{ultimate}$: 85.3 kA

- Thank you for your attention -

HL-LHC Cold Powering: 94 kA @ 5.0 g/s gHe

Results: Superconductor cables

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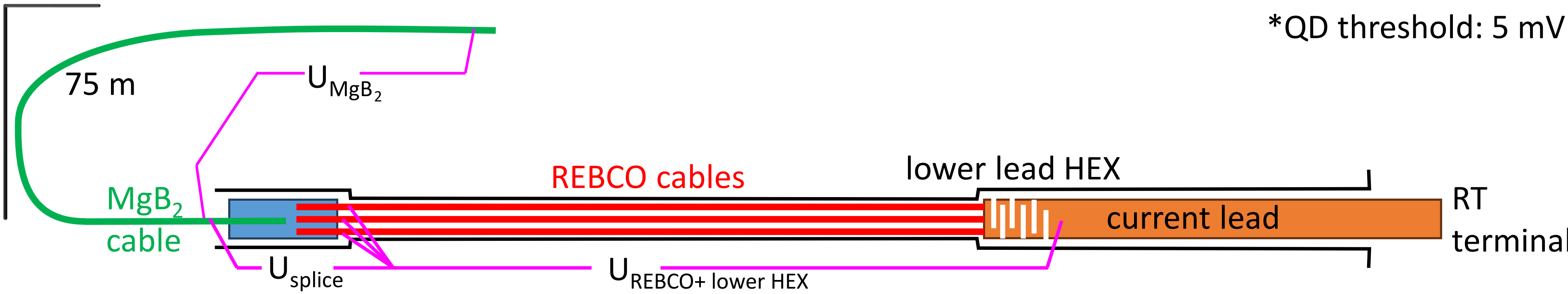

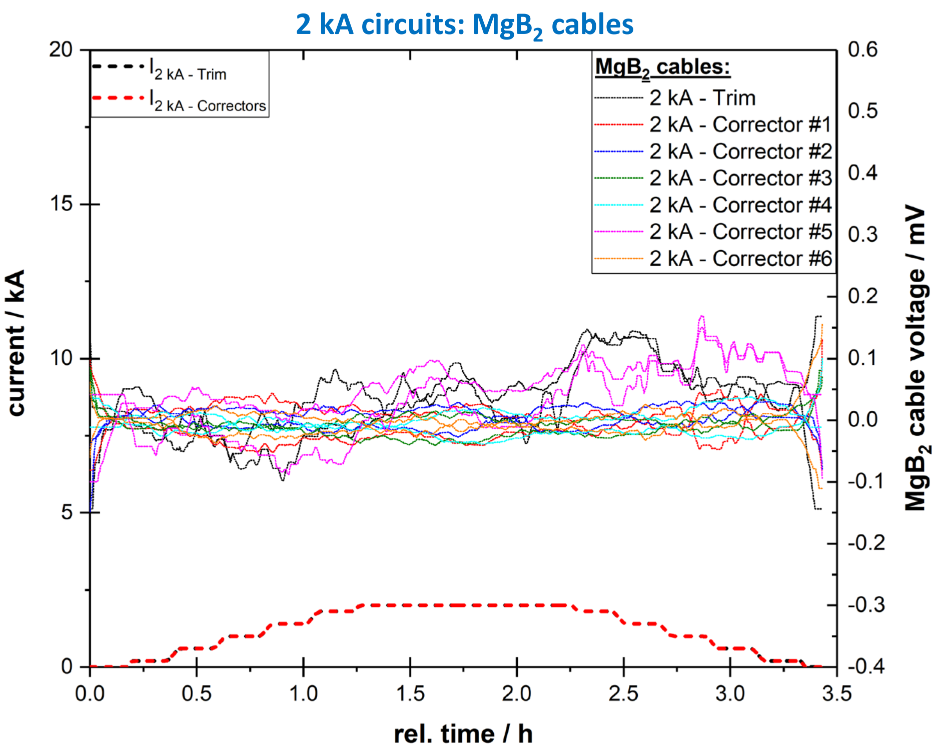

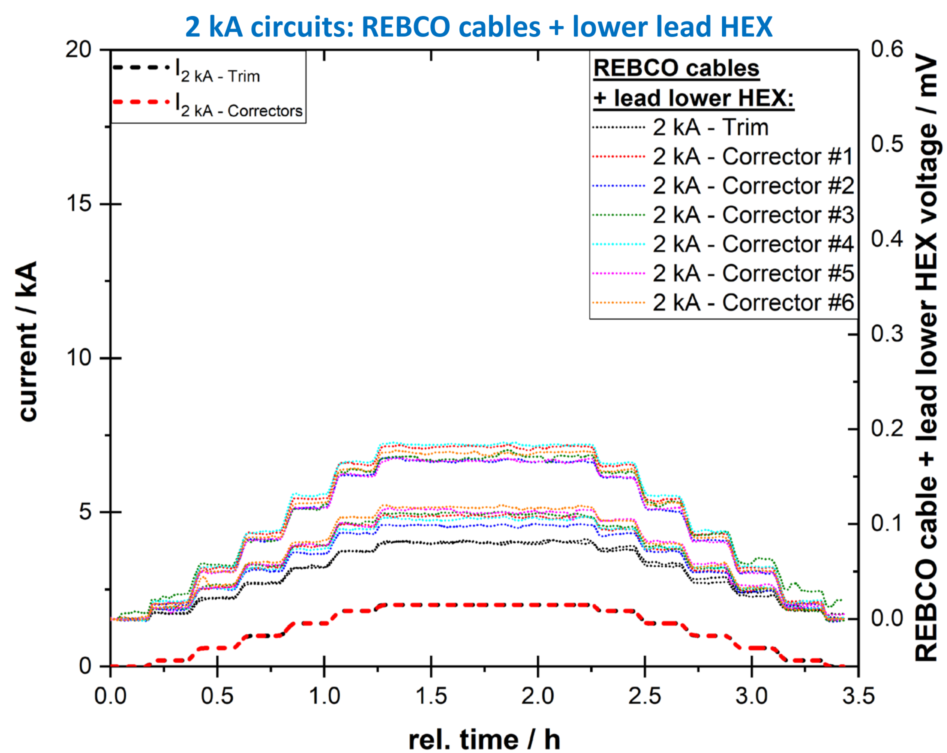

- **Stable, no transition**, x10 – x100 below QD threshold*

Results: Splices

REBCO to MgB_2, GHe @ 20 K — MgB_2 to Nb-Ti, LHe @ 4.5 K — Nb-Ti to Nb-Ti, LHe @ 4.5 K

Circuit	REBCO to MgB_2 splices		MgB_2 to Nb-Ti splices		Nb-Ti to Nb-Ti splices	
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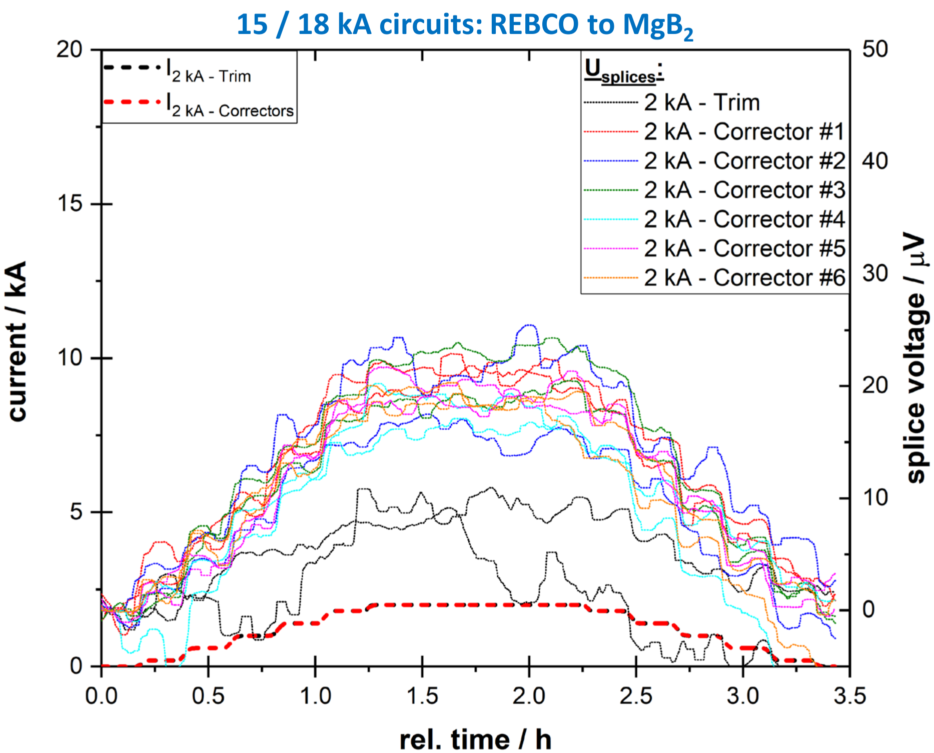

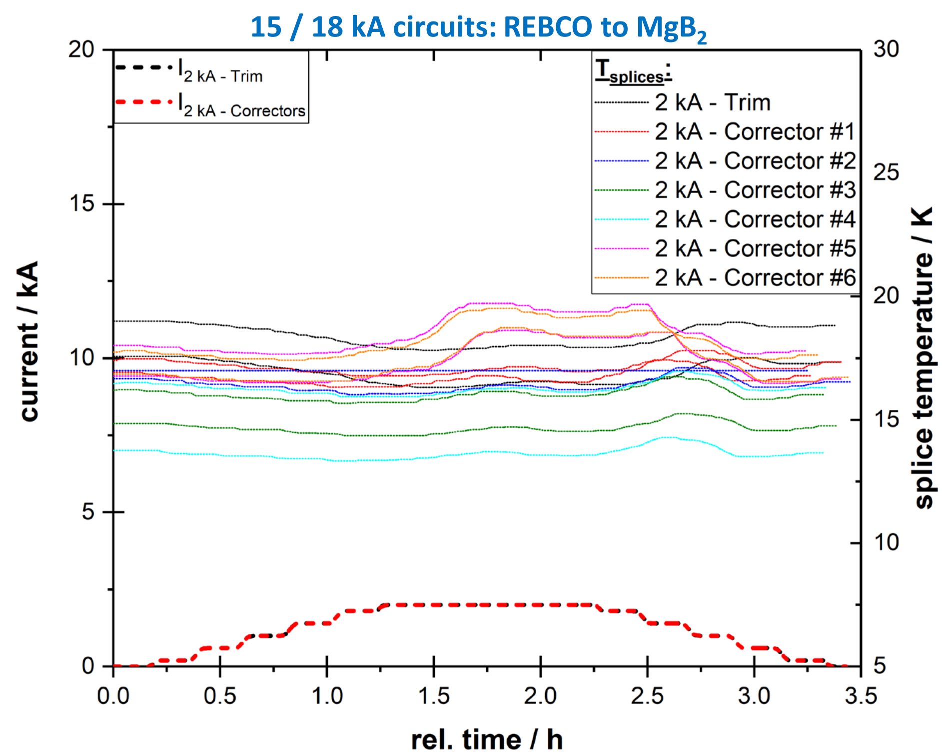

- **Stable**, T_{splice} **independent** of **current** (± 1 K)