



Development, Fabrication & Test of the Round, Multi-Layer REBCO Cables of the Cold Powering Systems of the HL-LHC

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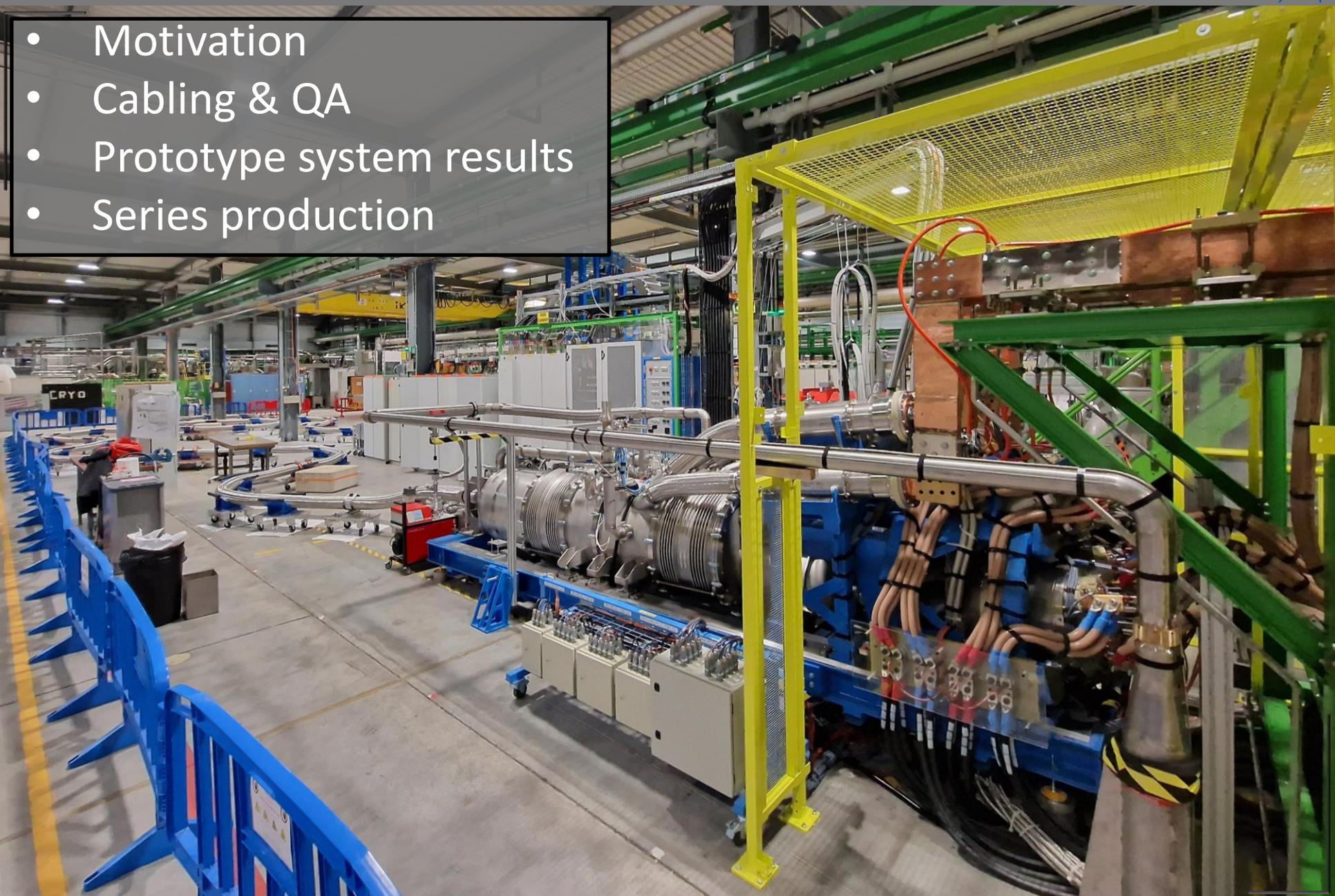
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Outline

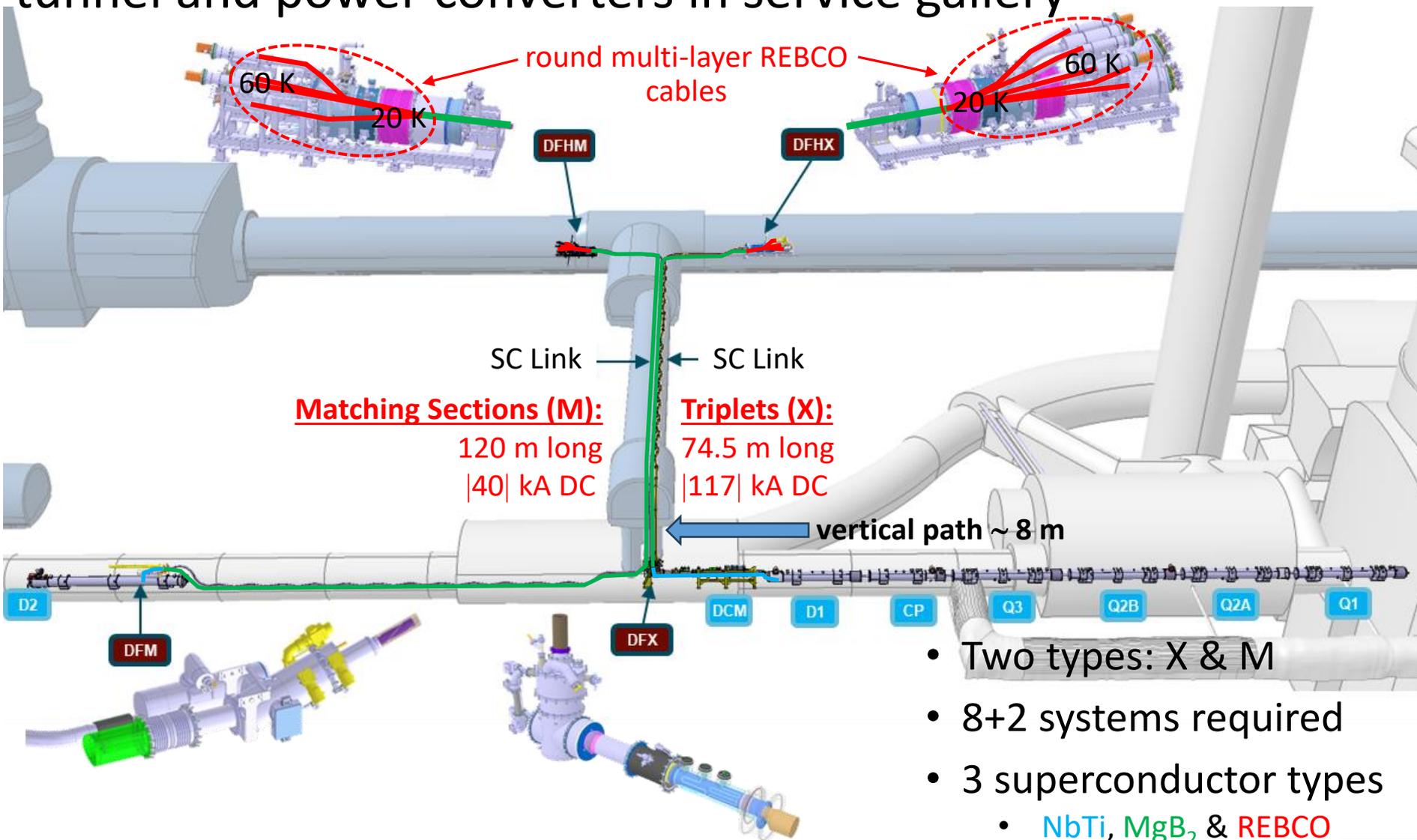


- Motivation
- Cabling & QA
- Prototype system results
- Series production



Motivation: HL-LHC Cold Powering

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



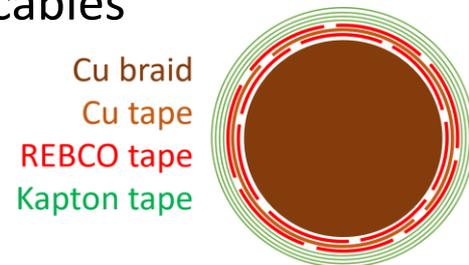
- Two types: X & M
- 8+2 systems required
- 3 superconductor types
 - NbTi, MgB₂ & REBCO

REBCO cable requirements:

- Zero cabling I_c degradation, isotropic bending to 600 mm radius
- $I_{nom} = 3 \text{ kA} / \text{cable} @ 60 \text{ K}, 0.5 \text{ T}$
- 5 kV gHe (300 K, 1.3 bar) compatible insulation
- Same cable for all circuits
 - 2 kA Corrector circuit: 1 cable
 - 2 kA Trim circuit (2 kA DC & 5 - 7 kA pulse): assembly of 2 cables
 - 15 kA & 18 kA circuits: assemblies 6 cables

Chosen REBCO cable type:

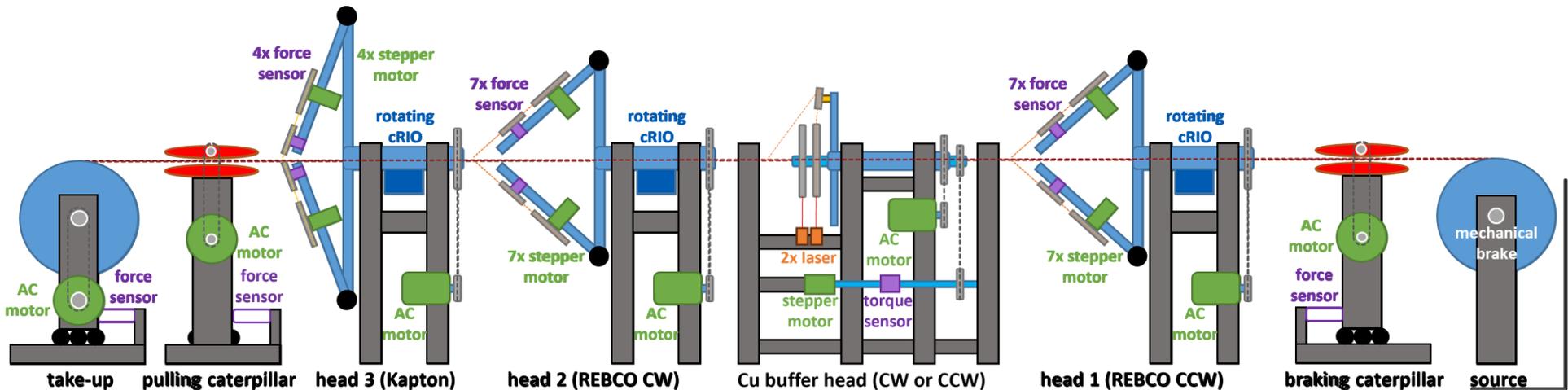
- 14 REBCO tapes helically wound on braided Cu core
 - 7 tapes / layer, 4 mm wide, 20 μm Cu, 50 μm substrate
 - 2 layers, opposing winding directions
- 12 mm x 0.1 mm Cu tape buffer between REBCO layers
- Outer Kapton tape insulation layer
 - 20 mm wide, 50 % overlap per tape
 - 2 tapes in same winding direction, 25 % overlap between tapes
- 42 cables per X-type & 20 cables per M-type system
 - cable lengths of 2.5 – 4.5 m, $\sim 1.15 \text{ km}$ total length



- Machine base functionality & control: 10.1109/TASC.2023.3249656

Upgrade of the HTS cabling machine:

- Improved safety features:
 - Force limiter on pulling caterpillar
 - Safety cages enclosing all heads
- Cu tape buffer head between REBCO heads
 - Coaxial head with double motorized axis:
 - outer: Cu tape deposition, AC motor in phase-lock control mode
 - inner: 2x Cu tape storage (CW & CCW), Cu tape tension control
 - Precise Cu tape tension control (stationary & in rotation)
 - speed of inner axis stepper motor PID controlled via FPGA
 - in-axis rotating torque sensor + Cu tape storage diameter measure lasers → calculate Cu tape tension → PID process input

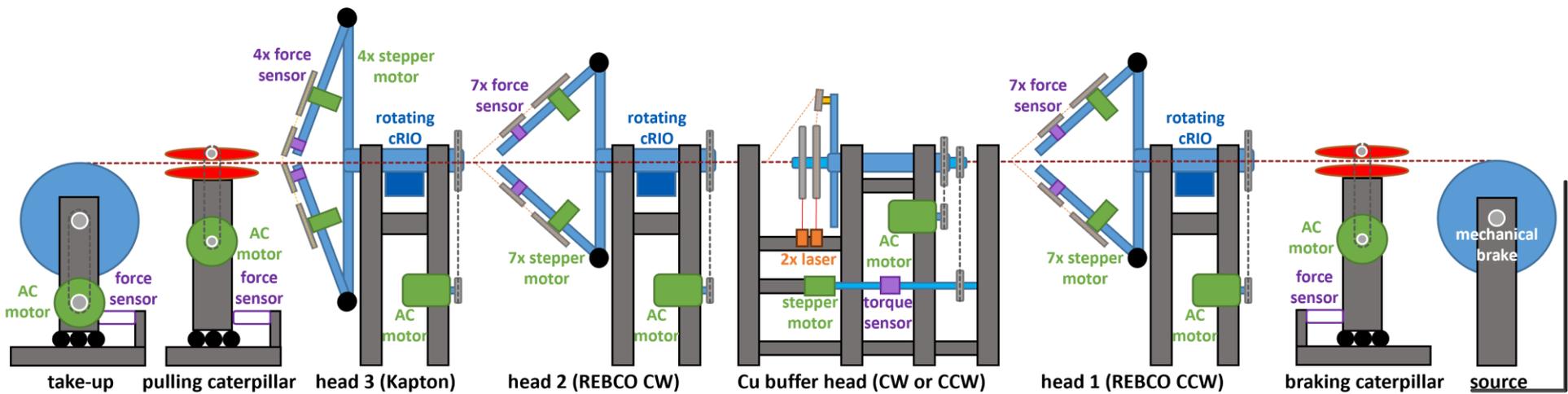
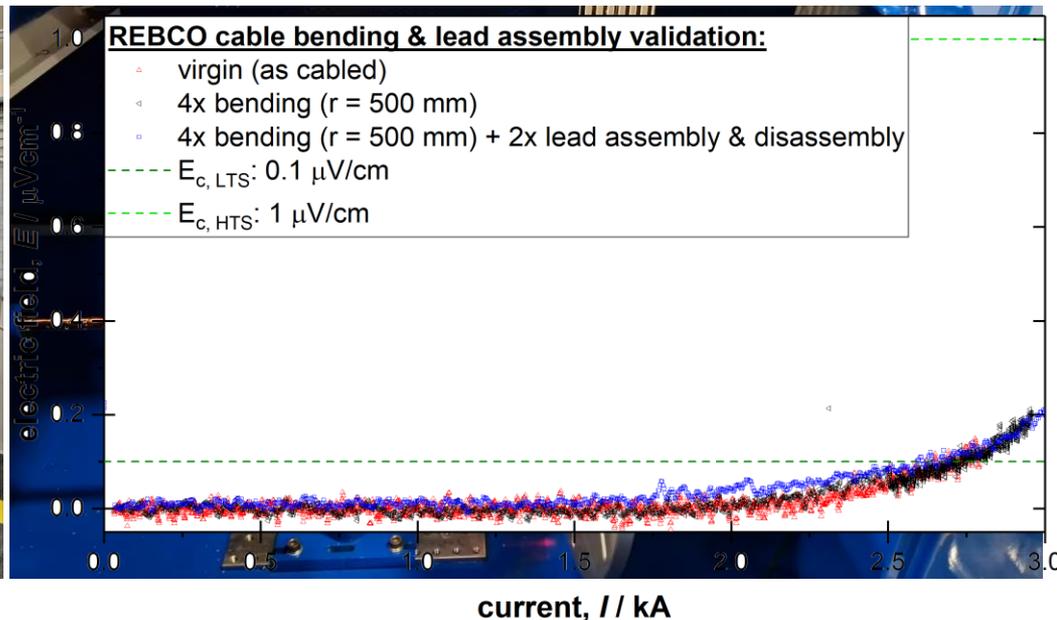


Cabling and QA



- Machine base functionality & control: 10.1109/TASC.2023.3249656

Upgrade of the HTS cabling machine:



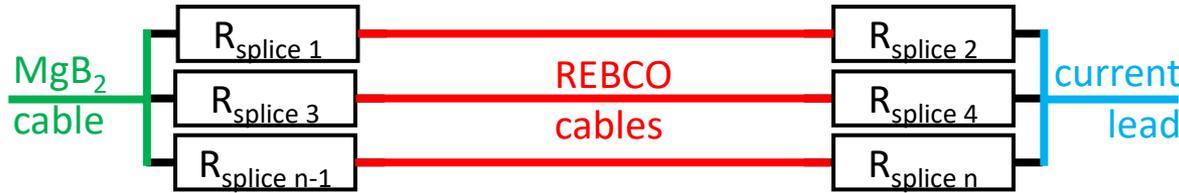
Cabling and QA

QA process:

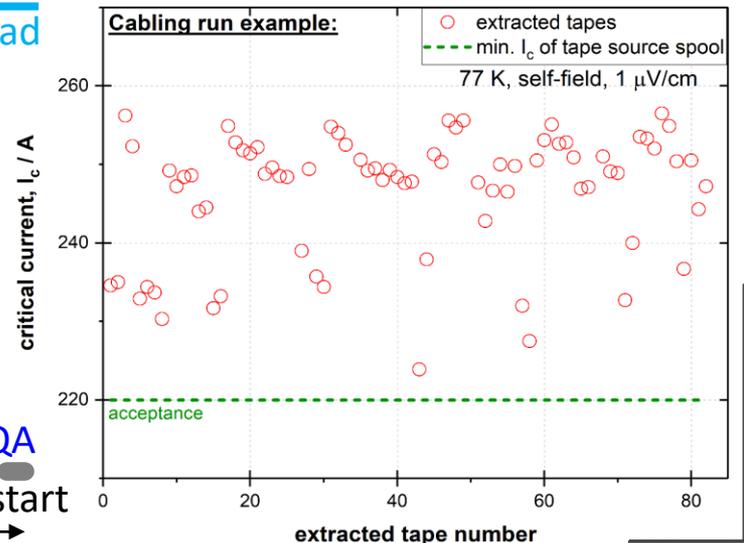
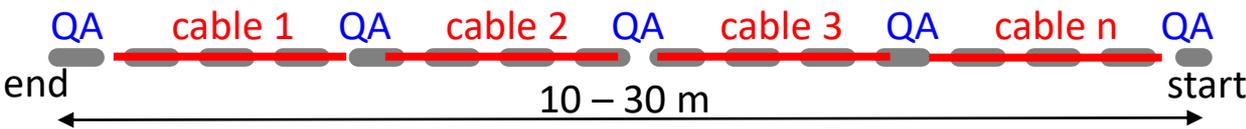
- Based on HL-LHC Nb₃Sn conductor & cabling QA
 - Verification measurements after REBCO spool reception
 - validate supplier I_c claim
 - Cabling qualification via extracted tapes
 - exclude cabling related I_c degradation
- R_{internal} homogenization within all parallel cables of a circuit essential for current distribution

Conductor acceptance

Cable acceptance



- Cabling runs are 10 m (initial) – 30 m (after machine upgrade)
 - Cut to into multiple cables of 2.5 – 4.5 m
 - Dedicated extracted tapes QA samples at extremities & between cables



R_{internal} homogenization:

- Target: std. deviation within 10 % of avg. value
- Example: 1st full X-type Cold Powering System (Prototype System)

• 2 kA Correctors:

- 164 ± 17 n Ω
- 145 ± 16 n Ω
- 164 ± 12 n Ω

• 15 kA:

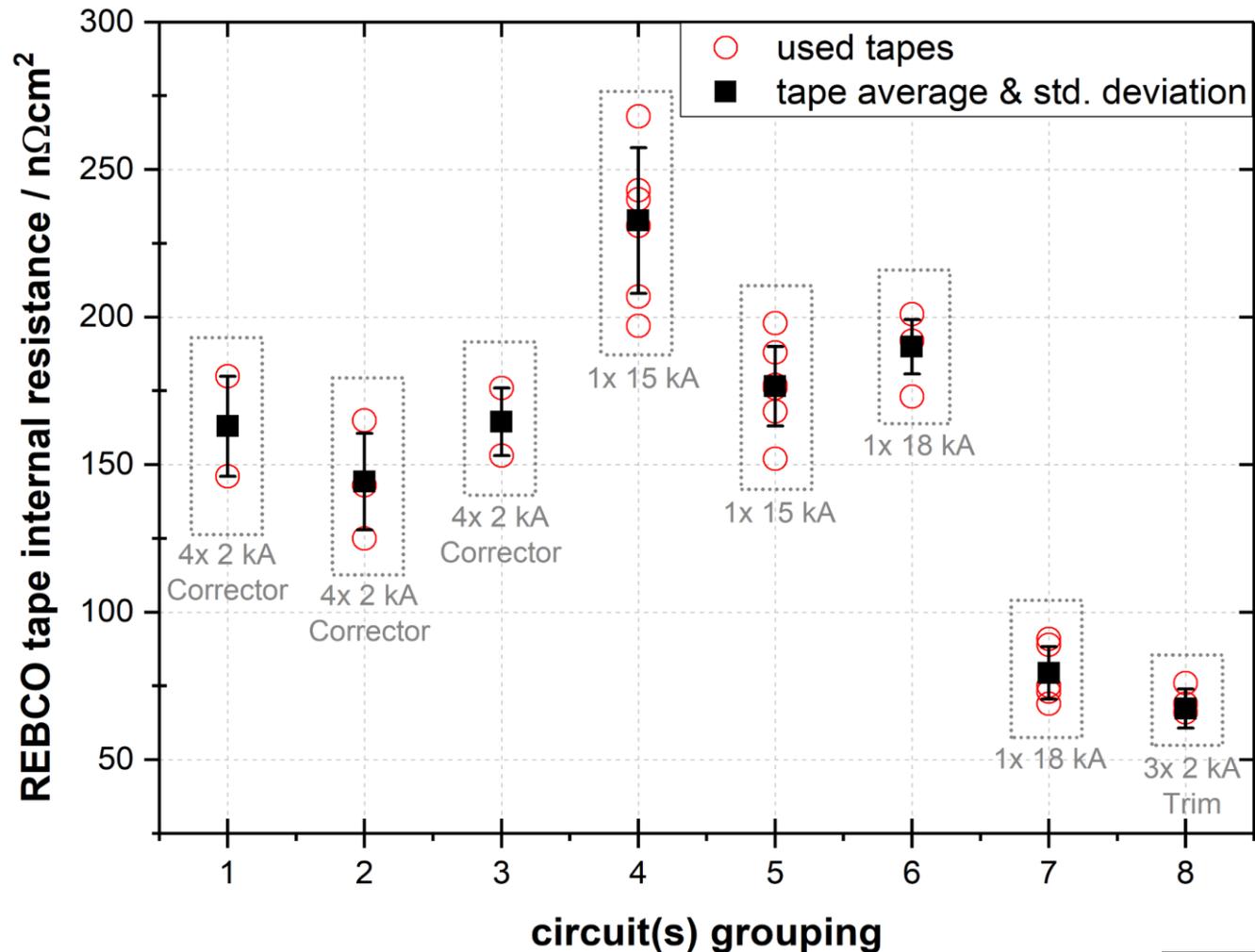
- 232 ± 24 n Ω
- 176 ± 14 n Ω

• 18 kA :

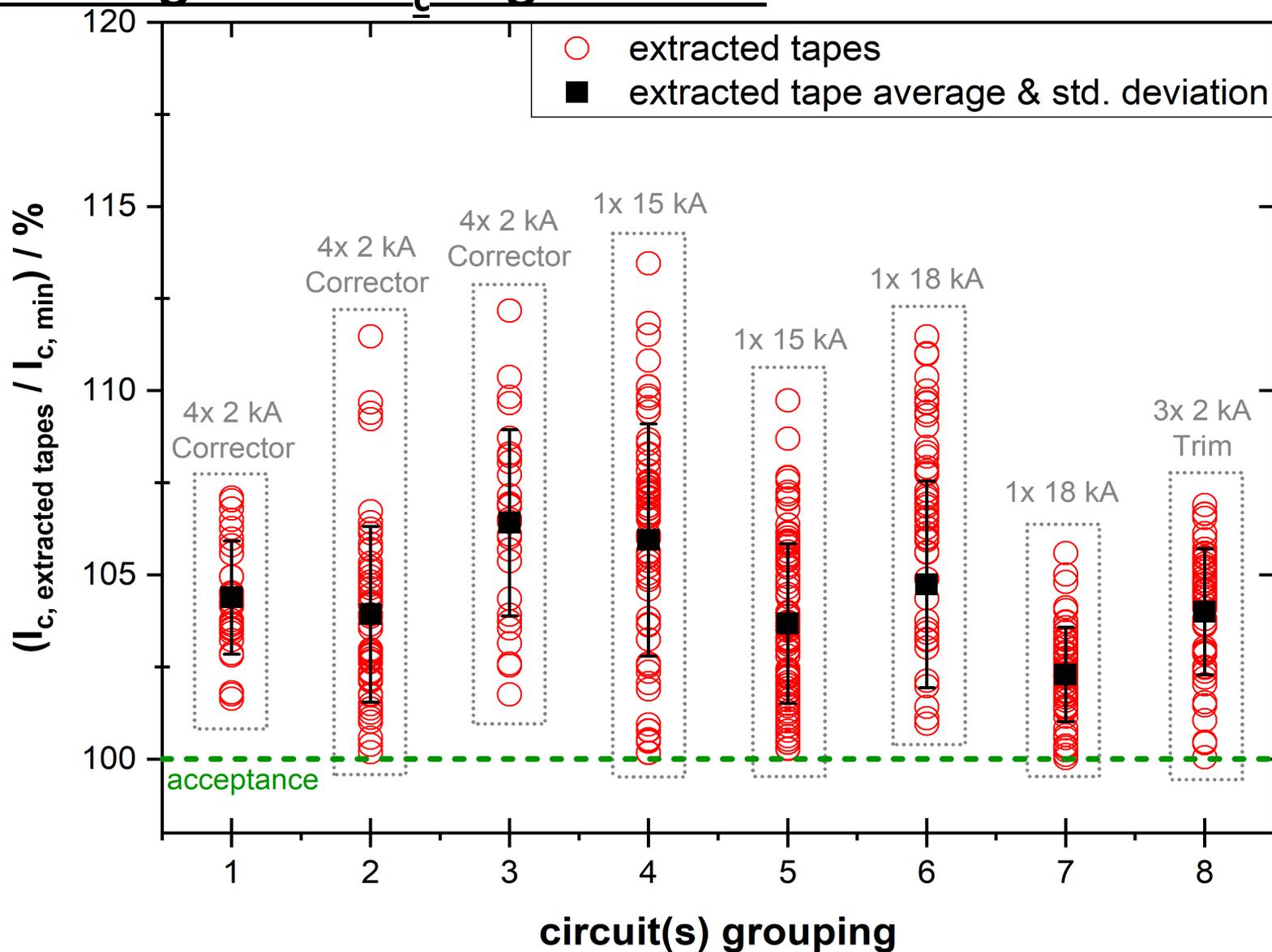
- 190 ± 10 n Ω
- 80 ± 9 n Ω

• 2 kA Trim:

- 67 ± 7 n Ω



No cabling related I_c degradation:

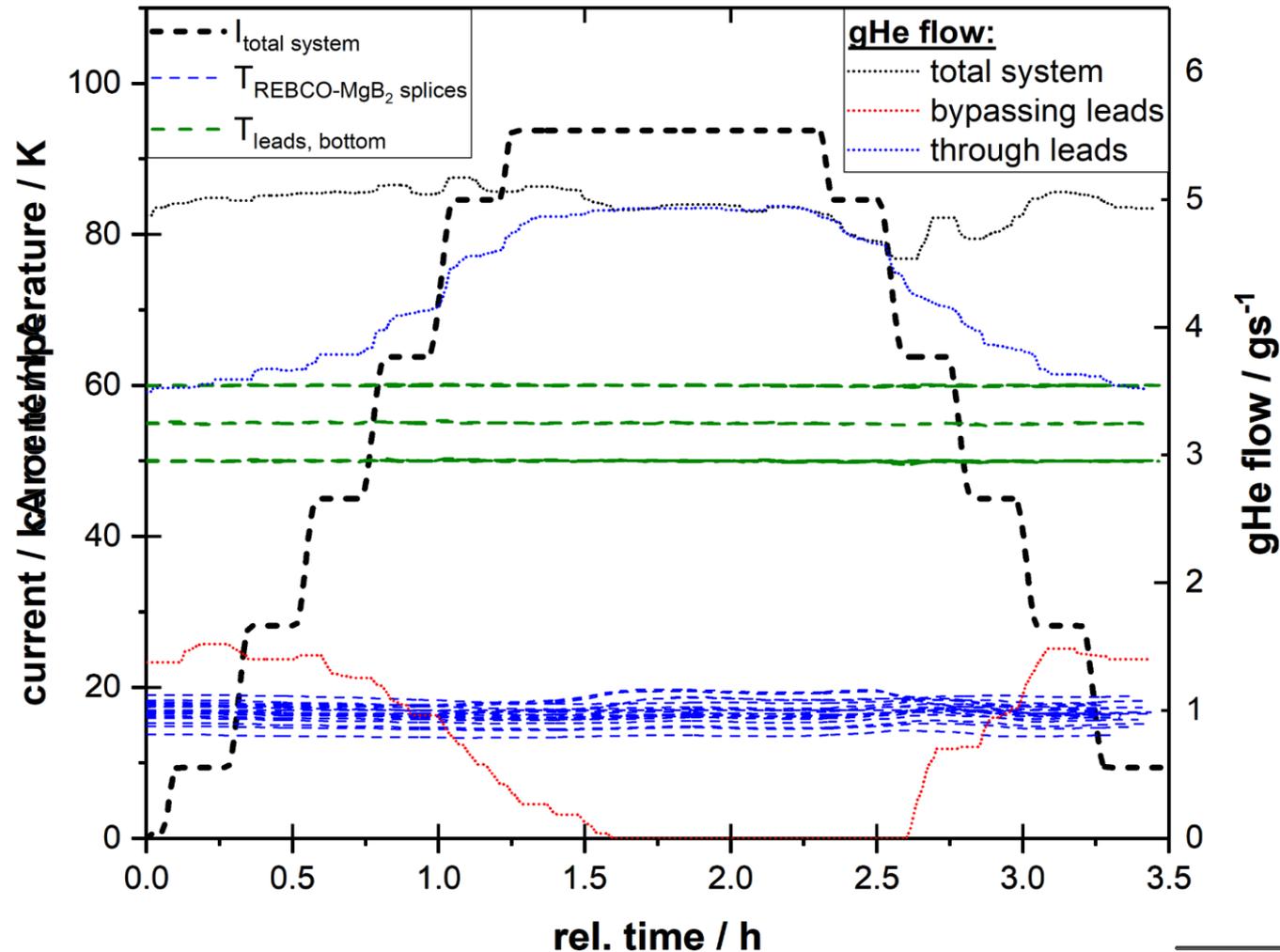


Prototype System: Cold test results



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

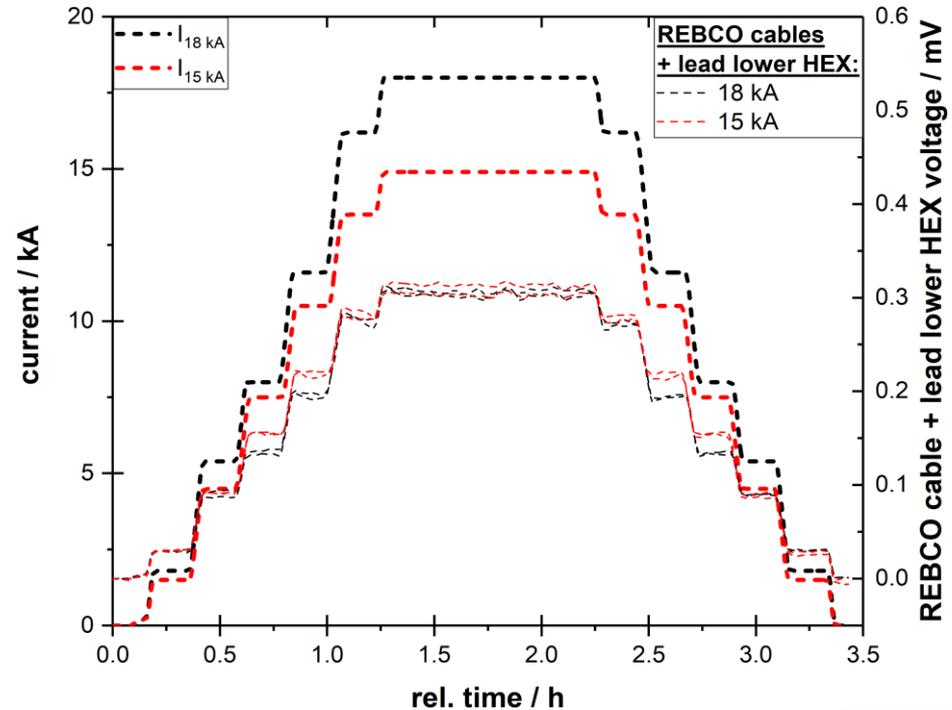
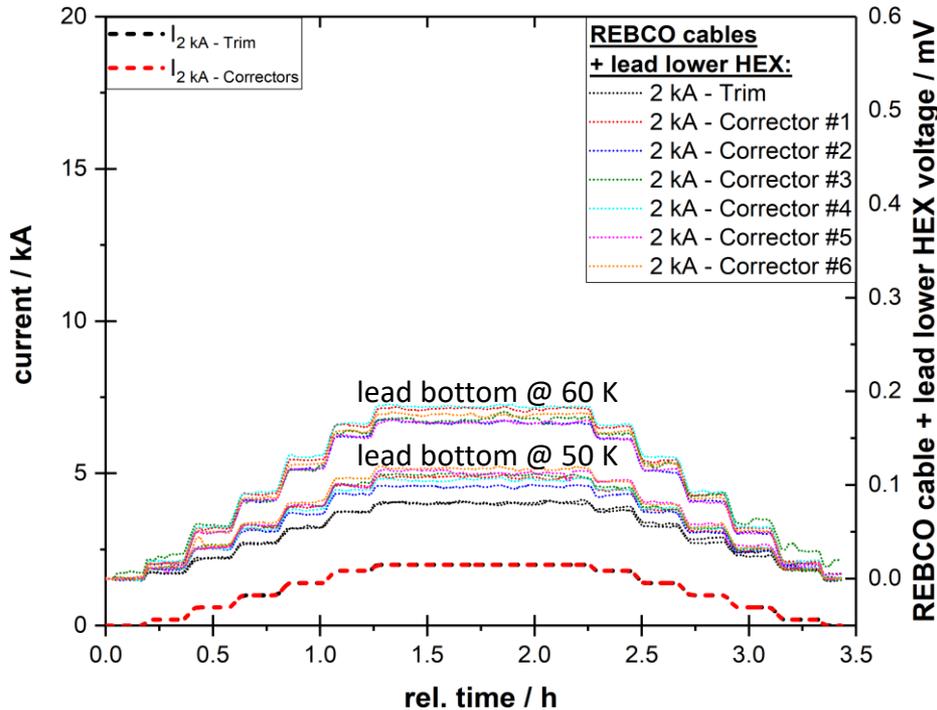
- Transported 94 kA @ 5.0 g/s gHe flow
- Within specifications: 79.2 kA (I_{nominal} of HL-LHC magnets) @ 5.5 g/s
- REBCO cable splice & lead temp. stable
- Splice temp. limit: 25 K
- Lead temp. setpoints:
 - 18 kA: 50 K
 - 15 kA: 55 K
 - 2 kA: 50 – 60 K



Prototype System: Cold test results

REBCO cables:

- REBCO cables + lower lead heat exchangers & protected together (LHC tunnel configuration):
 - ≤ 0.3 mV voltage drop, x10 below QD threshold (5 mV)
 - Voltages stable, driven by lead bottom temperature



Prototype System: Cold test results

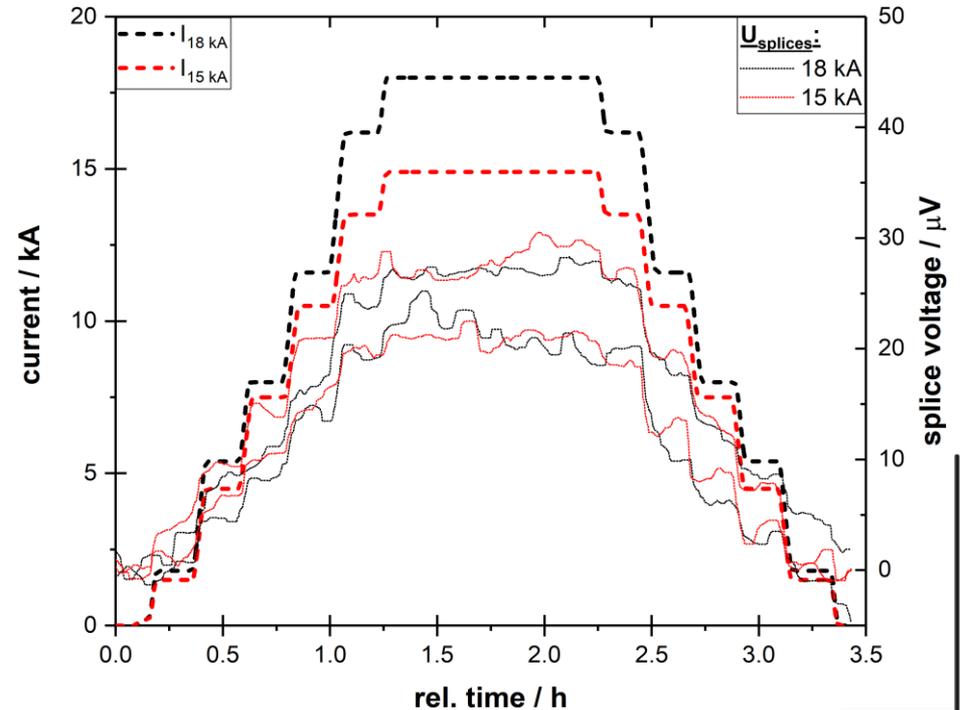
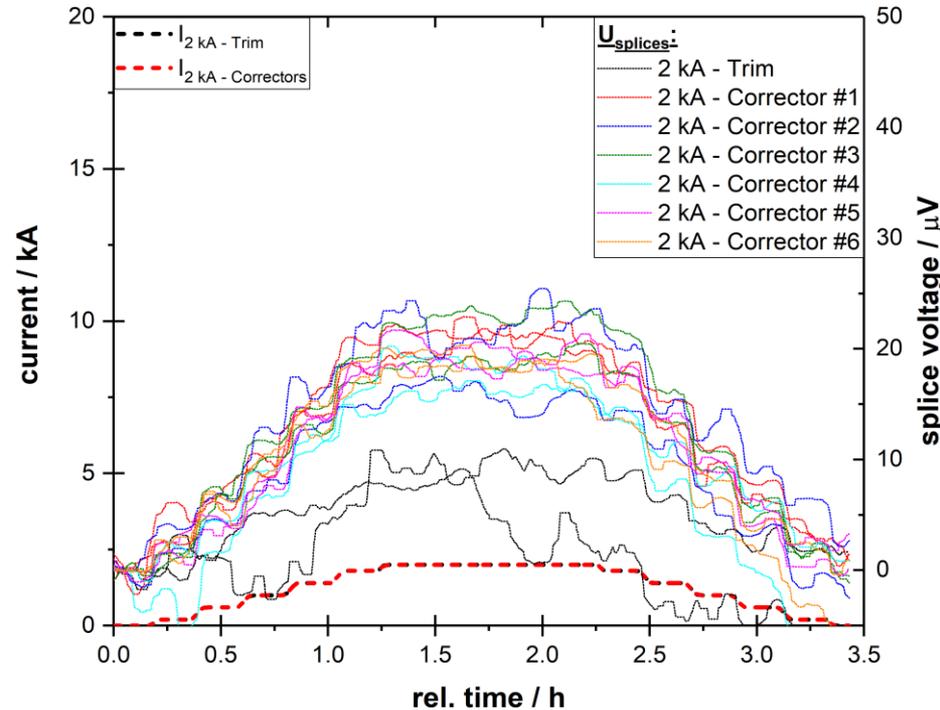


REBCO cable splices:

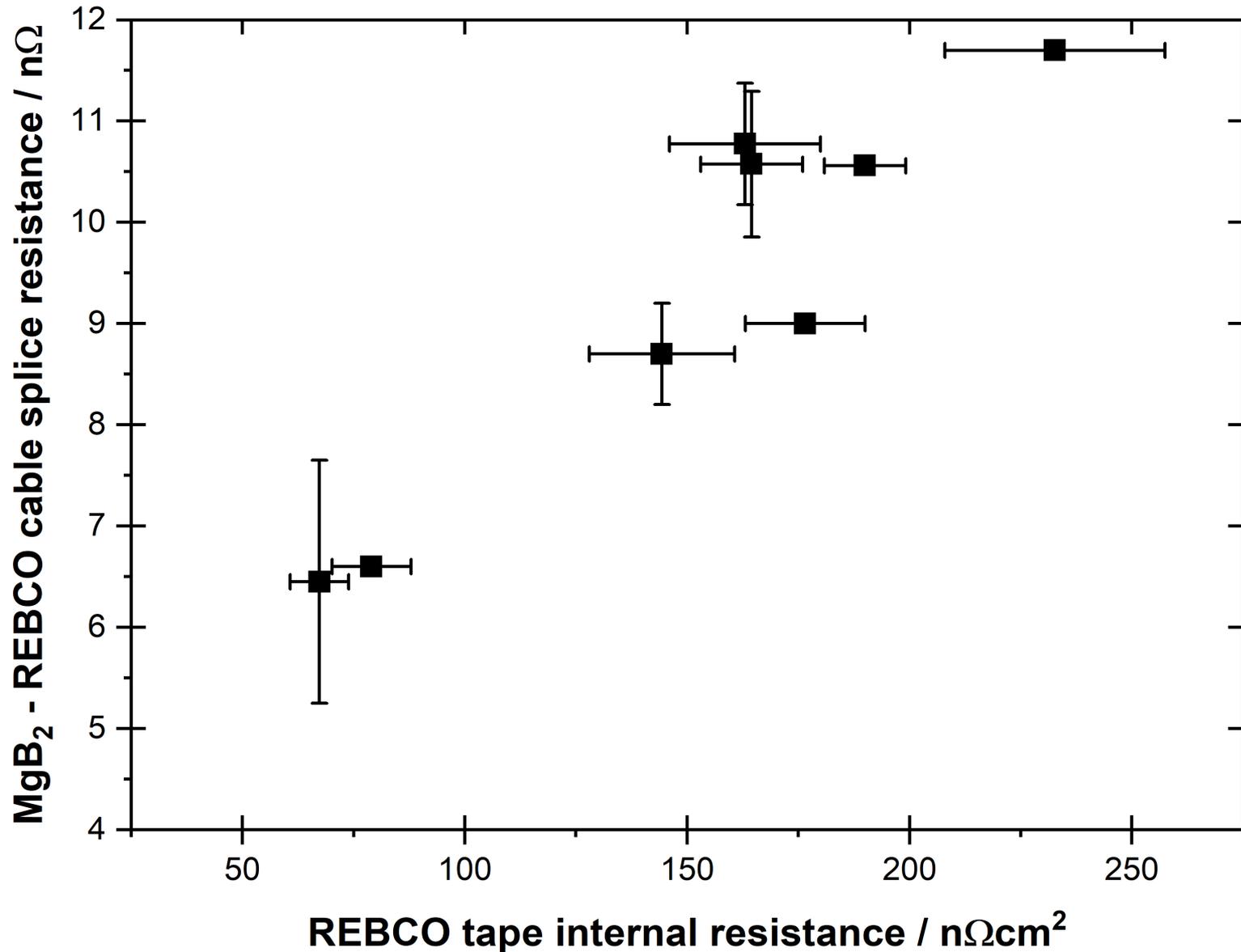
- REBCO-MgB₂ splices protected individually
 - $\leq 30 \mu\text{V}$ voltage drop, x100 below QD threshold (5 mV)
 - Voltages stable, splice resistances linear & within expectations
 - 2 kA Correctors: 8.1 – 11.8 n Ω (expected 9 – 13 n Ω)
 - 2 kA Trim: 3.5 – 5.1 n Ω (expected 9 – 13 n Ω / 2)
 - 15 kA & 18 kA: 1.1 – 2.0 n Ω (expected 9 – 13 n Ω / 6)

Expected R_{splice} values from FRESCA tests:

- MgB₂ cable: 5 n Ω
- REBCO cable: 4 - 8 n Ω



REBCO cable splices vs REBCO tape internal resistance:

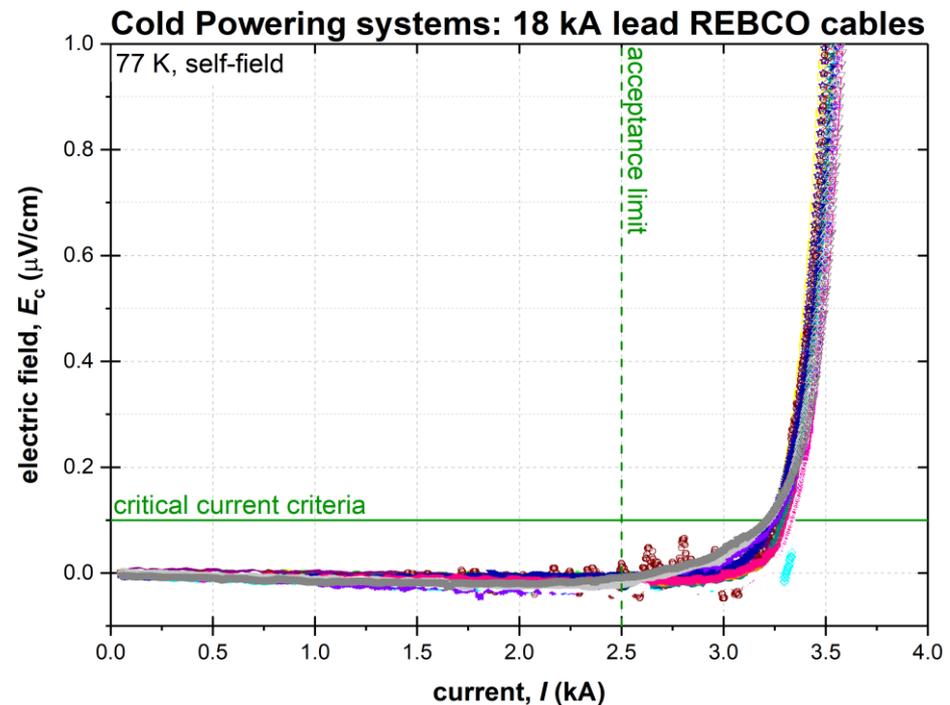
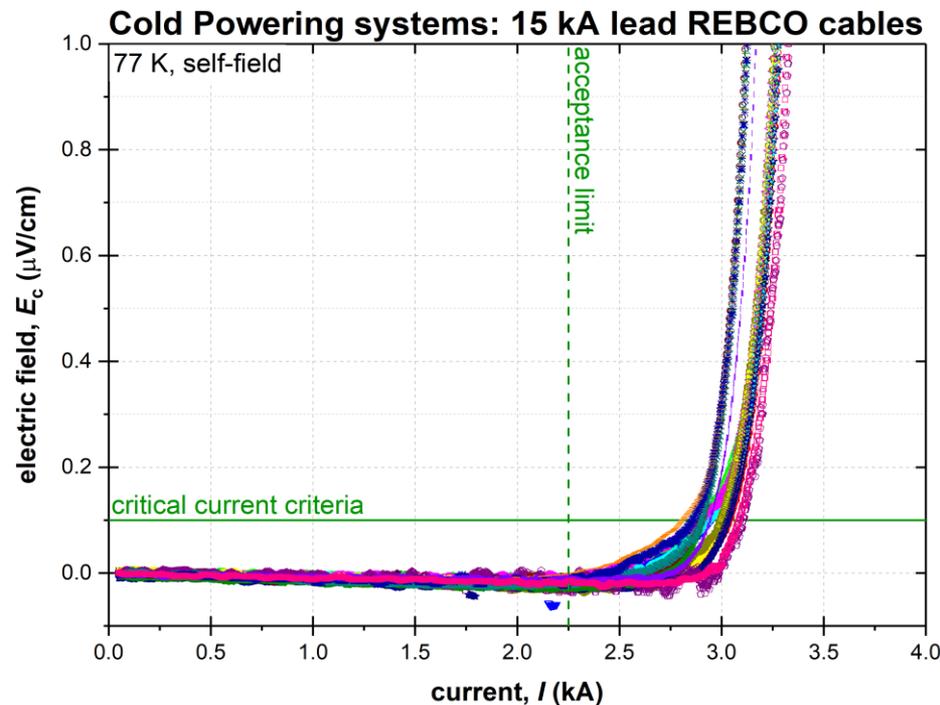


REBCO cable series production



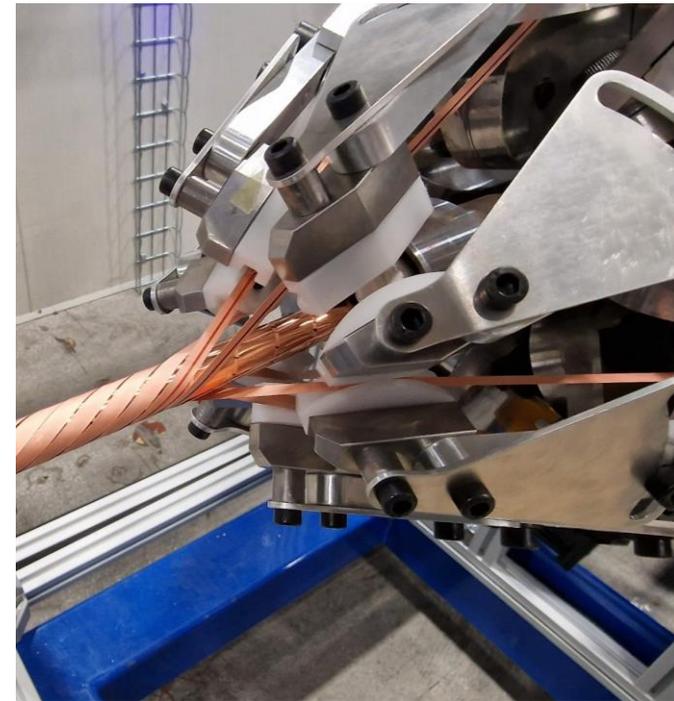
Production status & QA:

- 108 out of 310 cables produced & qualified (~415 m out of 1.2 km)
- I_c of each cable measured in LN₂ as additional QA
 - Qualification using 0.1 $\mu\text{V}/\text{cm}$ (as LTS cables)
 - No resistive slope subtracted



HL-LHC Cold Powering:

- Cabling & QC capabilities established for Cold Powering System series production
- 108 out of 310 REBCO cables produced & qualified
- Cu buffer tape between REBCO layers for degradation free cabling and bending ($r = 500$ mm)
- 1st full Cold Powering System successfully tested
 - Transported 94 kA with 5 g/s gHe flow
 - REBCO cables & splices stable, voltages x10 – x100 below QD limits
- $R_{\text{tape, internal}}$ correlates to cable R_{splice}
→ homogenization essential in the case of parallel cables





- Thank you for your attention -

REBCO cables for the HL-LHC Cold Powering: 94 kA @ 50 – 60 K