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Development, construction, and commissioning of a fully automated cabling machine for round multi-layer REBCO cables

2022-12-15: MSC-Seminar

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Acknowledgments:

G. Lenoir[*], J. Hurte[*], F. Girardot[*], S. Morisi[*], P. Koziol[+], the TE-MSC-SCD section, the EN-MME design office, the EN-MME & TE-MSC mechanical workshops

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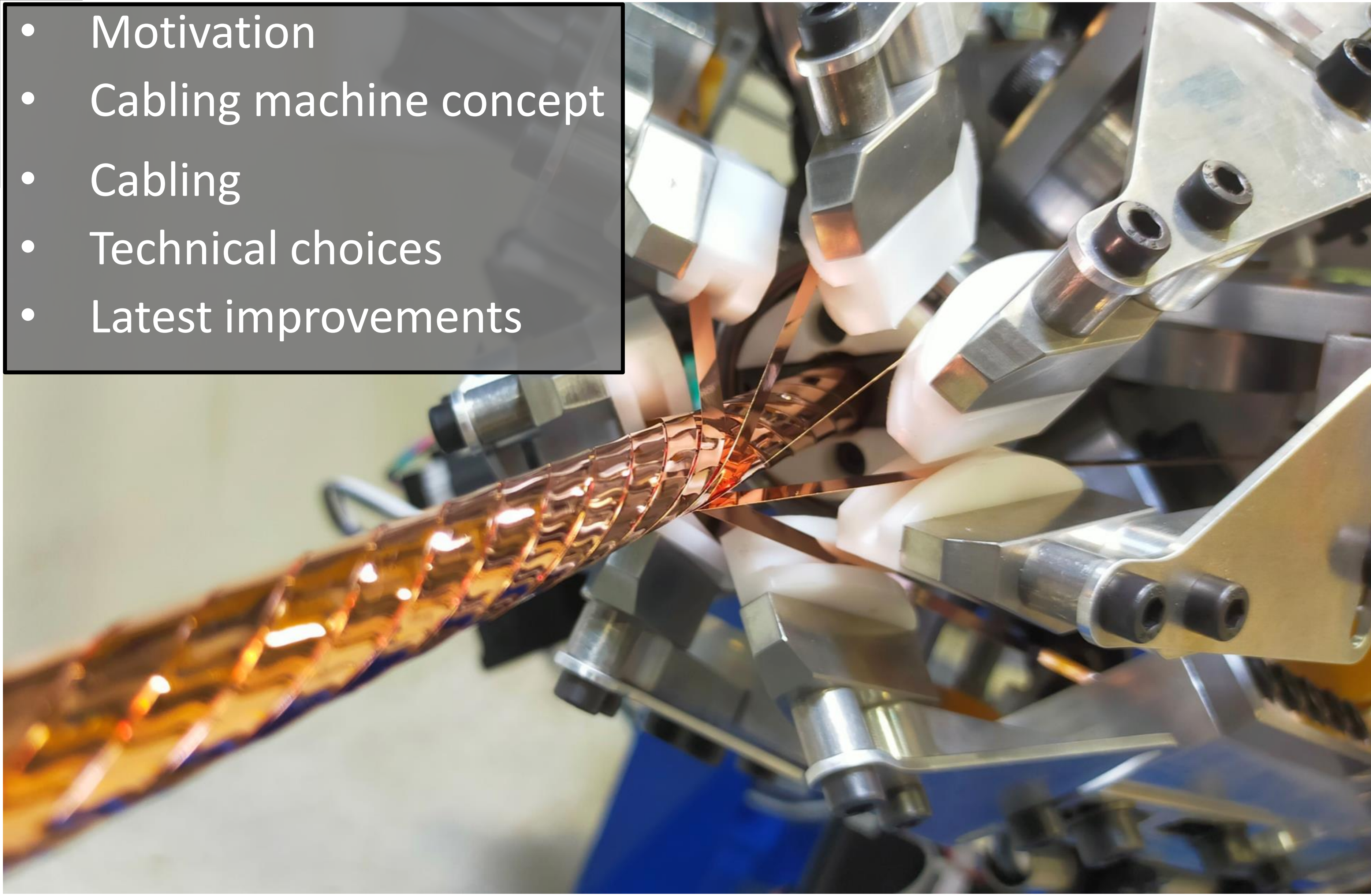
Outline

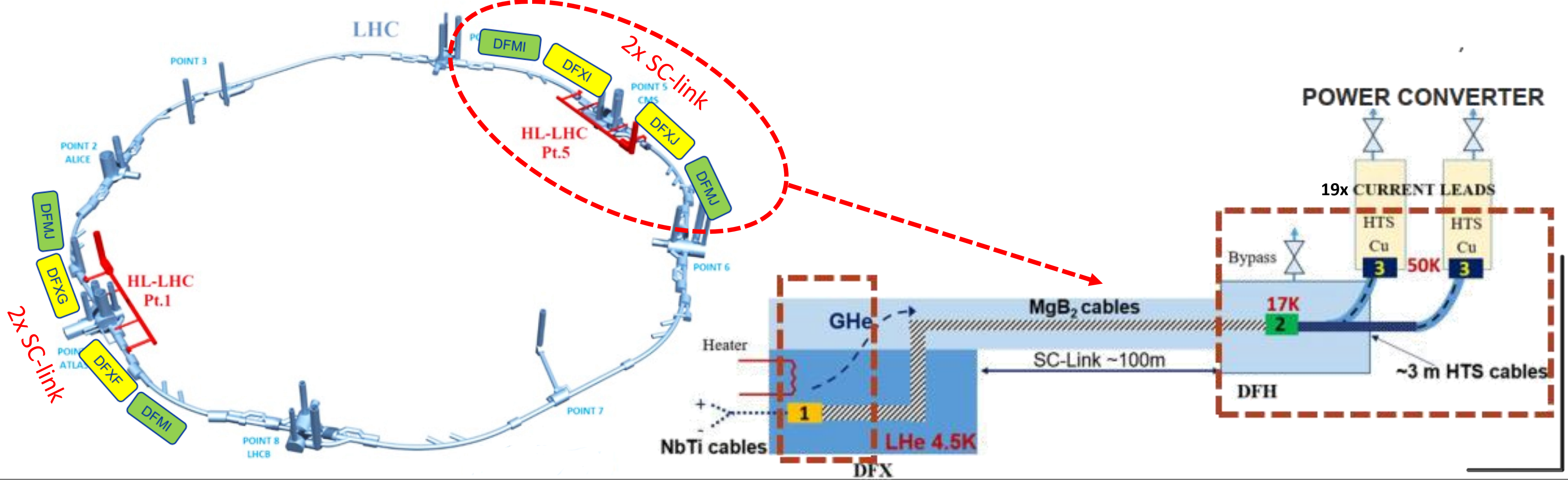
- Motivation
- Cabling machine concept
- Cabling
- Technical choices
- Latest improvements



Motivation: HL-LHC superconducting links

Cold powering system upgrade, part of HL-LHC:

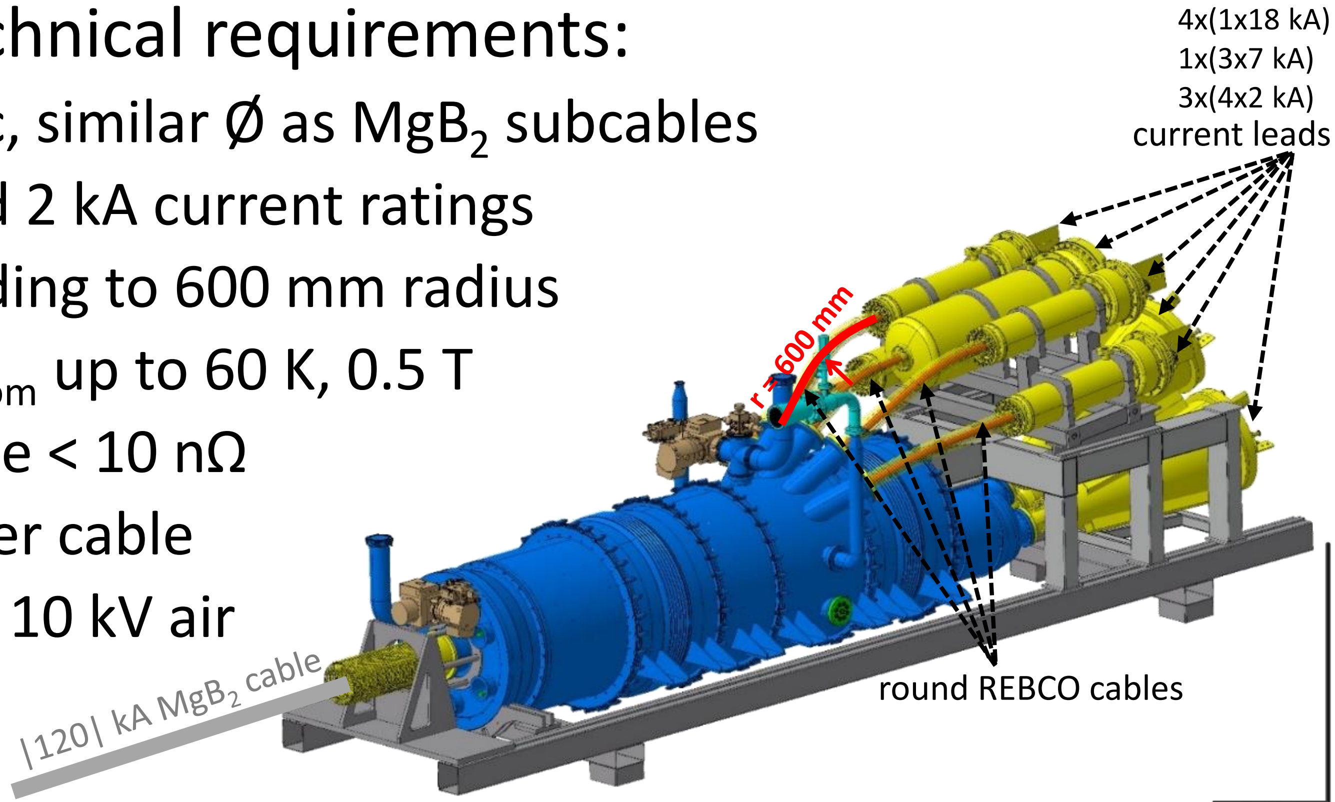
- 4 superconducting links connect magnets and power converters that are in gallery 10 m above the tunnel
  - multiple circuits per link, currents rated from 2 – 18 kA
  - MgB_2 cables in flexible cryostats connected to current leads through flexible REBCO cables
    - MgB_2 cables: 100 m long, He gas cooled (4.5 – 17 K)
    - REBCO cables: 2.5 – 4.5 m long, He gas cooled (17 – 50 K)



Motivation: HL-LHC superconducting links

Cold powering system upgrade, part of HL-LHC:

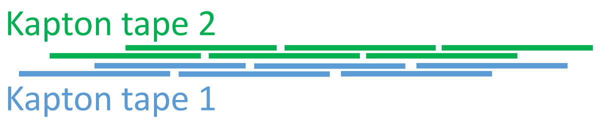
- |120| kA in a SC-Link MgB_2 cable, multiple isolated circuits
- Distributed into separate REBCO cables in horizontal distribution cryostat (DFH)
- REBCO cable technical requirements:
  - round isotropic, similar Ø as MgB_2 subcables
  - 18 kA, 7 kA and 2 kA current ratings
  - (multiple) bending to 600 mm radius
  - operation at I_{nom} up to 60 K, 0.5 T
  - splice resistance < 10 nΩ
  - > 80 mm^2 Cu per cable
  - > 3.5 kV gHe, > 10 kV air



Motivation: HL-LHC superconducting links

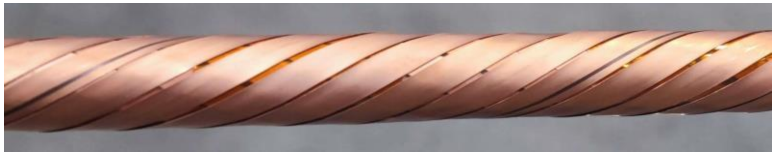
Chosen REBCO cable type:

- REBCO tapes helically wound on braided Cu core
  - 7 tapes / layer, 4 mm wide, 20 µm Cu stabilized, 50 µm substrate
  - 2 layers, opposing winding directions, REBCO towards outside
- Outer Kapton tape insulation layer
  - 20 mm wide, 50 % overlap per tape
  - 2 tapes in same winding direction, 25 % overlap between tapes



- Same cable for all circuits: I_{nom} = 3kA / cable @ 60 K, 0.5 T
  - 2 kA circuit: 1 cable
  - 7 kA circuit: assembly of 3 cables
  - 18 kA circuit: assembly 6 cables

3 kA round REBCO cable



- 310 REBCO cables needed for SC-Link
  - cable lengths of 2.5 – 4.5 m, ~1 km total length

Motivation: HL-LHC superconducting links

Why no use CORC® cables?

- Power transmission cable: large Cu section (> 80 mm^2), low splice resistance < 10 nΩ, good current sharing
  - large Ø (11.3 mm) braided Cu core
  - REBCO oriented towards outside
  - minimize no. layers (max. 3)

  → low J_e, high electrical stability
- SC-Link part of LHC cold powering
  - long term operation, zero cabling degradation required
  - same QC as other LHC magnet components

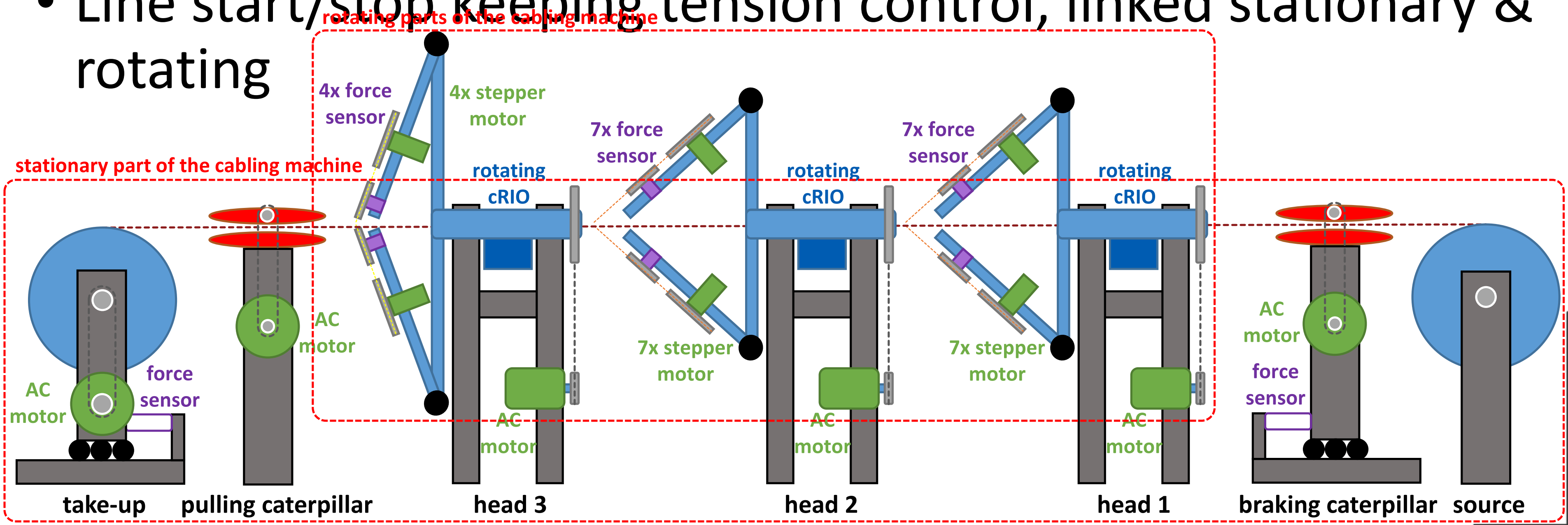
Development & construction of REBCO cabling machine:

- 100 % in-house (development, design, fabrication)
- 6 months development & design, 12 months construction
- Detailed data logging for quality control

Machine concept: general

Cabling machine concept:

- 150 – 300 N tension in the core, well controlled: < ±50 N
- Head rotations directly linked to linear core movement
- Precisely controlled tape tensions: < ±2 N deviation
- Individual adjustment of depositioning angle of each tape
- Line start/stop keeping tension control, linked stationary & rotating



Machine concept: general

Tension control methods:

- Brakes (mechanical, magnetic, electromagnetic)

  +: small & cheap, easy to implement, reliable

  -: only effective with machine running, no control during standstill

- Variable clutch on motor turning in opposite direction

  +: effective during machine run & standstill, easy to control

  -: bulky & expensive, large speed changes challenging

- Bi-directional motor speed modulation

  +: small & cheap, effective during machine run & standstill

  -: difficult to control, unforgiving to errors, fast response needed

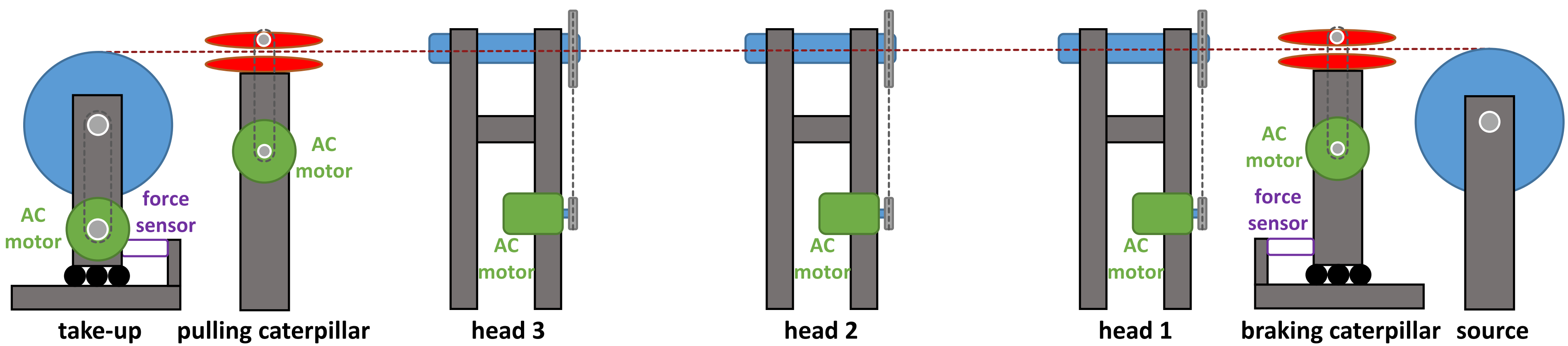
Implemented tension control system:

- FPGA controlled bi-directional motor speed modulation
  - 24-bit analog inputs, filtering & high speed PID control

Machine concept: stationary part

Functions:

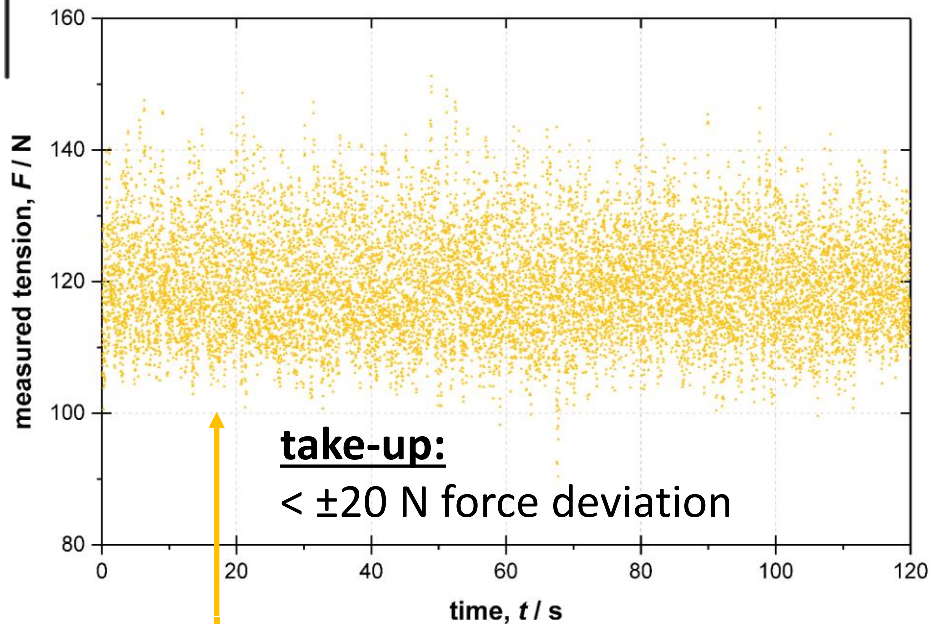
- Pulling caterpillar sets linear cabling speed
- Take-up & braking caterpillar control core tension
  - braking caterpillar in the cabling zone, take-up for reel-to-reel operation
  - rail mounted with force sensors, motor speed PID controlled
- Head motor speed linked to pulling caterpillar speed
  - directly coupled to pulling caterpillar encoder feedback



Machine concept: stationary part

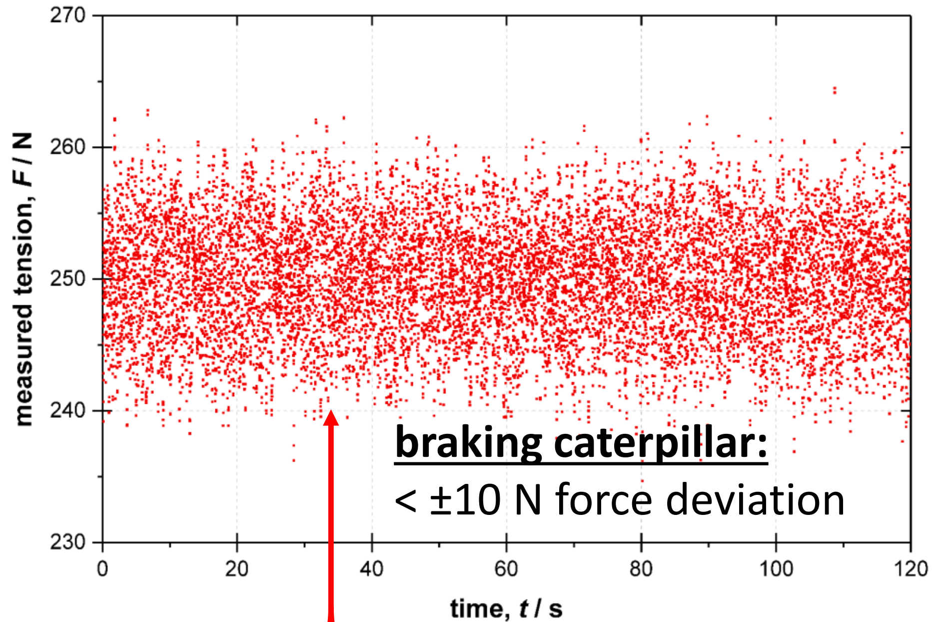
Precise core tension control:

Take-up: 120 N tension setpoint:

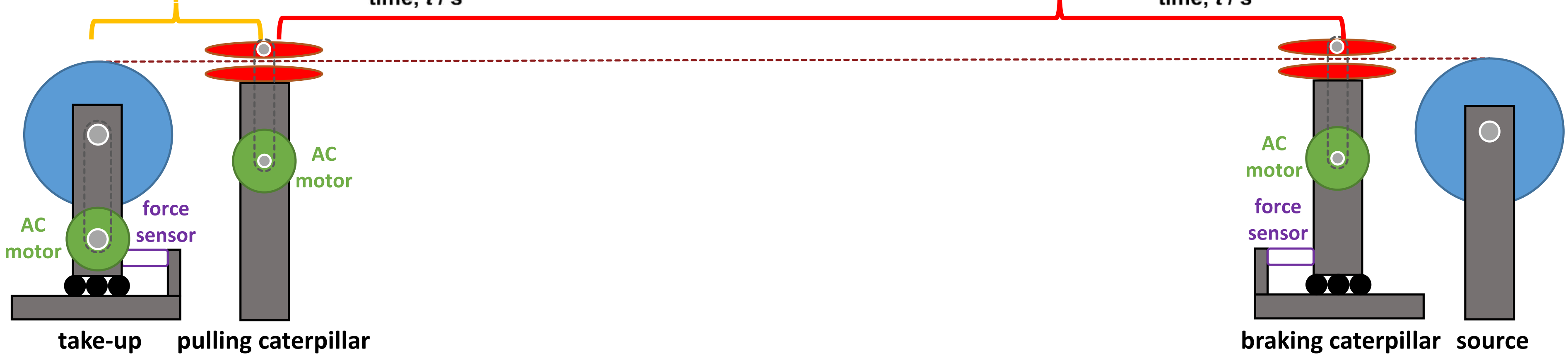


take-up:
< ±20 N force deviation

Breaking caterpillar: 250 N tension setpoint:



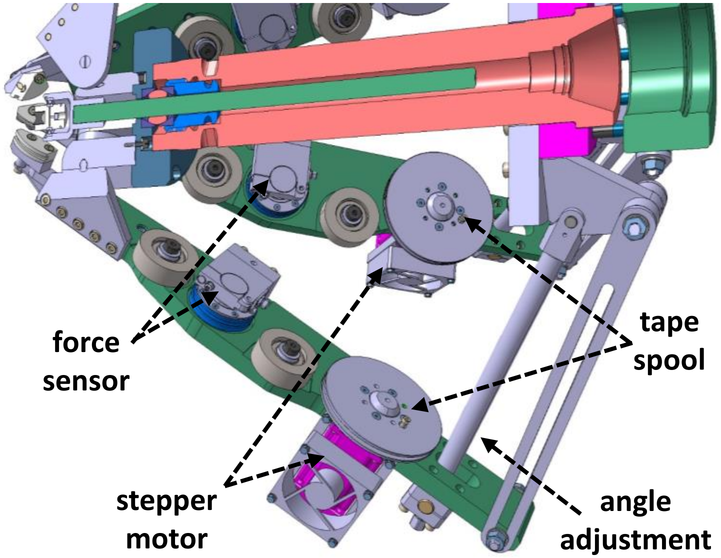
braking caterpillar:
< ±10 N force deviation



Machine concept: rotating parts

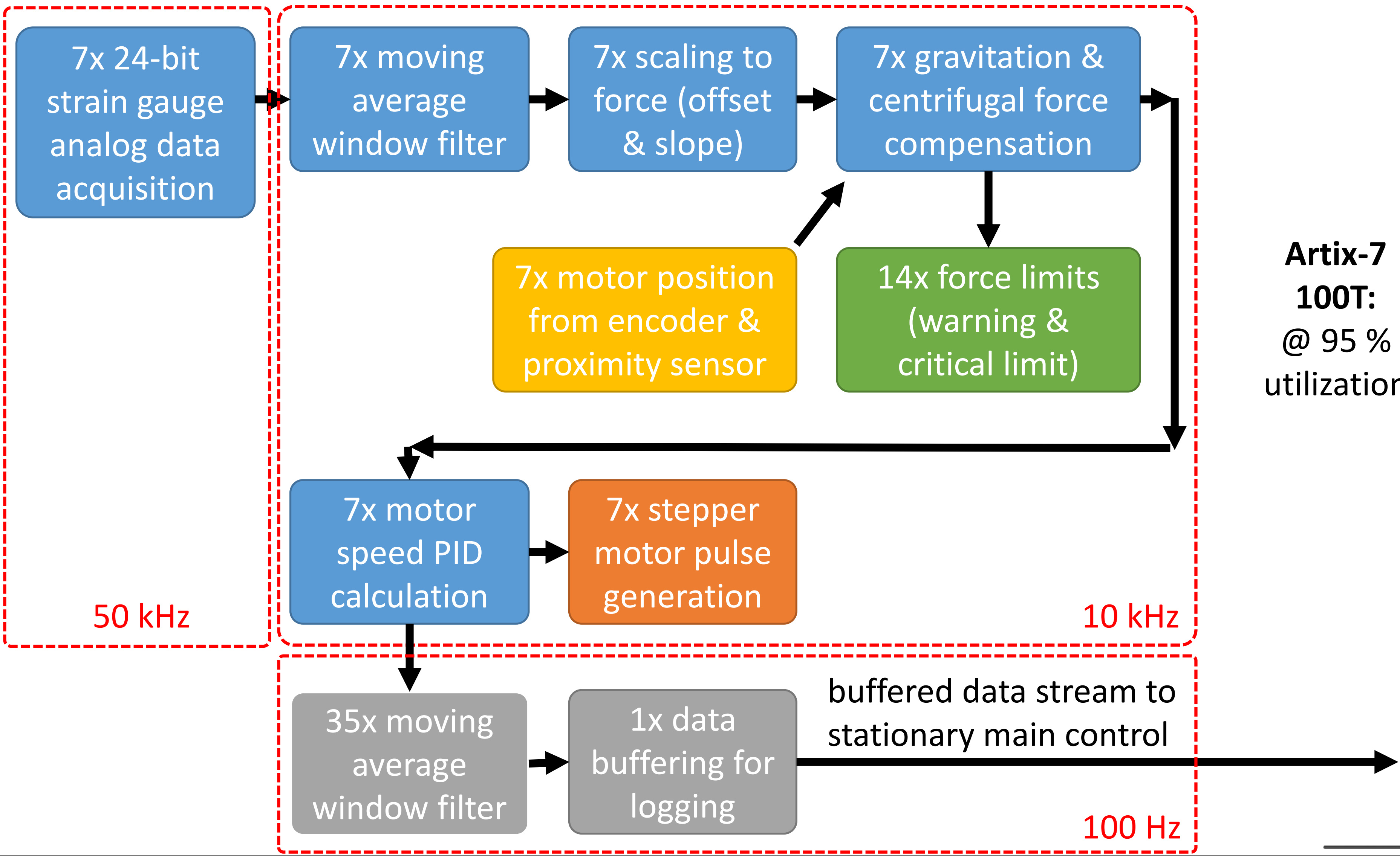
Functions:

- 50 N strain-gauge force cells to measure tape tension
- Stepper motors regulate tape tension, PID controlled
- Data acquisition, post-processing and PID control in FPGA
  - 50 kHz, 24-bit data acquisition with digital filtering, gravitation & centrifugal force compensation
  - 10 kHz PID calculation and motor ‘step’ & ‘direction’ generation
- Closed loop system
  - each cabling head runs indecently
  - buffered data exchange for logging with stationary main control system
- Rotating contacts: 30 V DC supply
- Each arm: precise angle adjustment

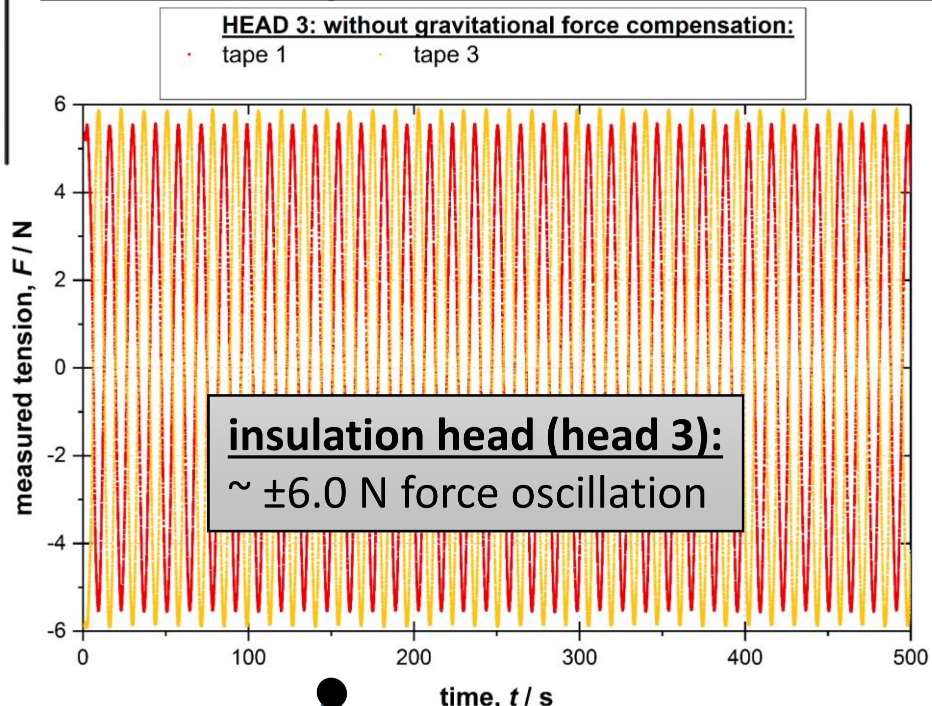


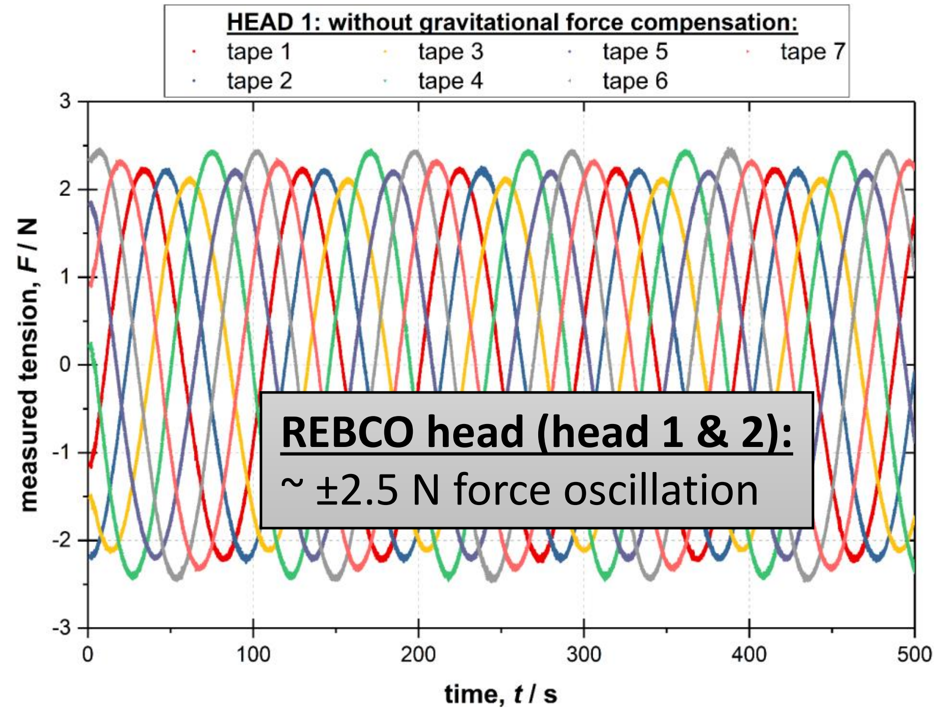
Machine concept: rotating parts

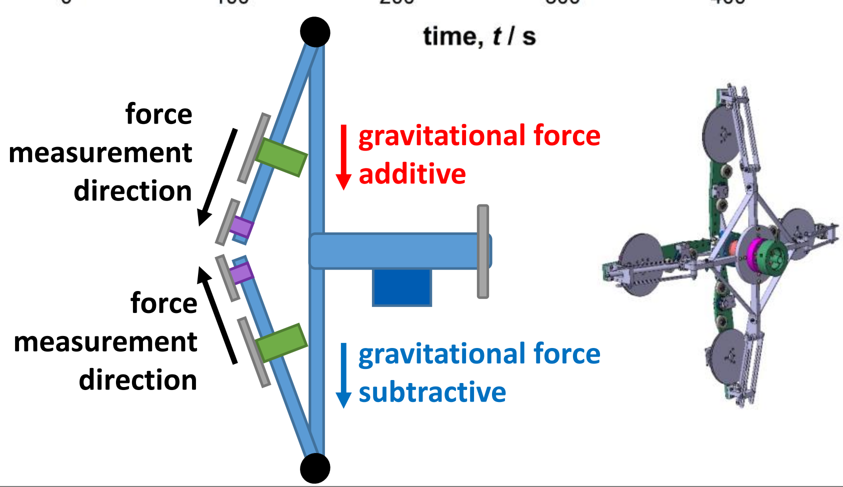
FPGA based data acquisition & tape tension control:

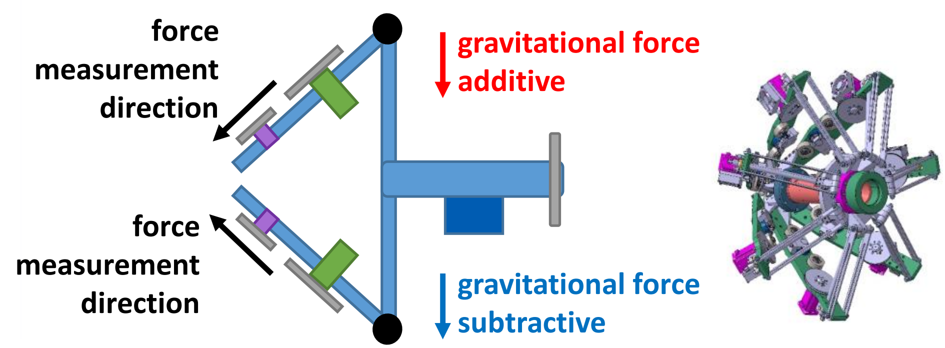


Without gravitational force compensation:



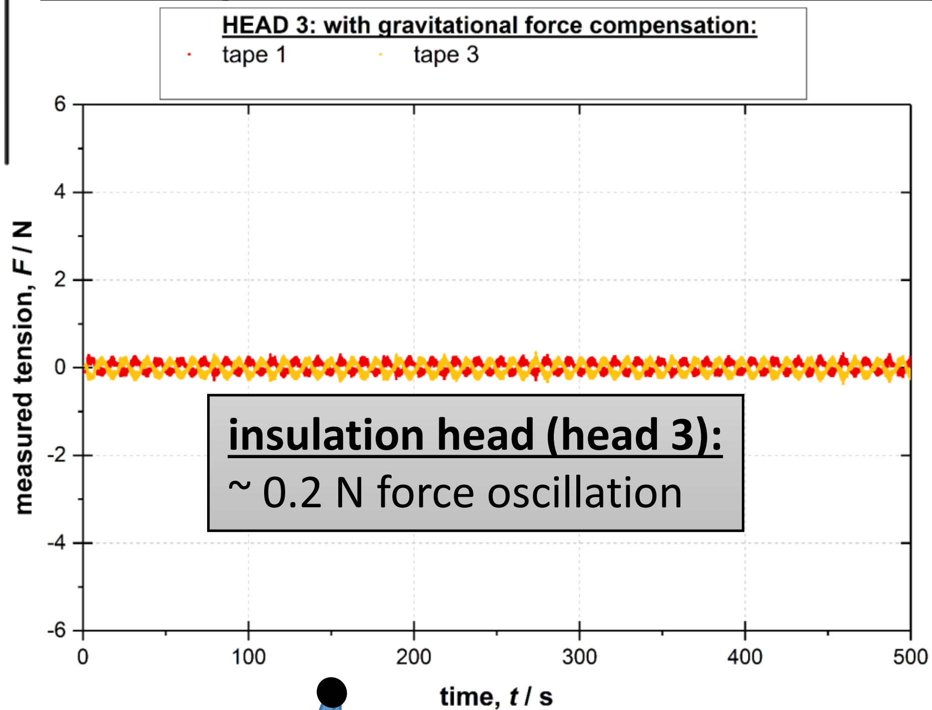


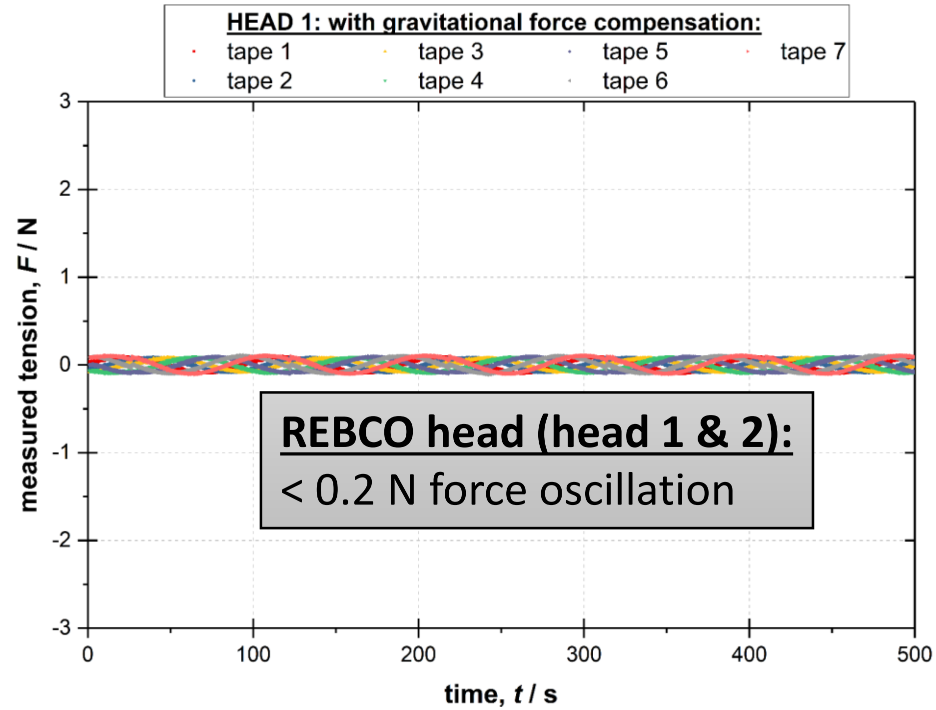


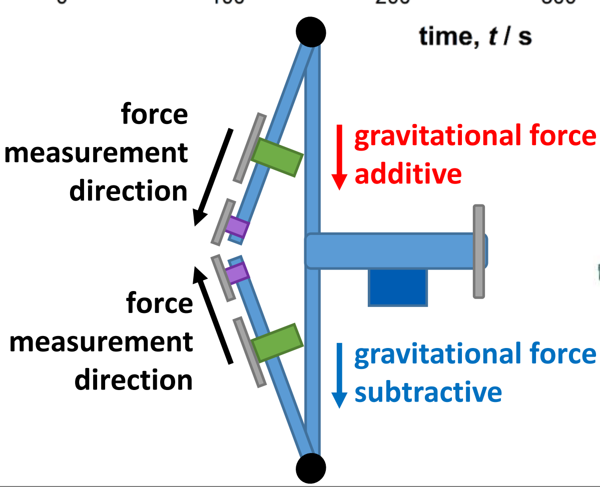


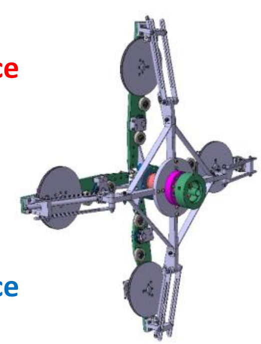
Machine concept: rotating parts

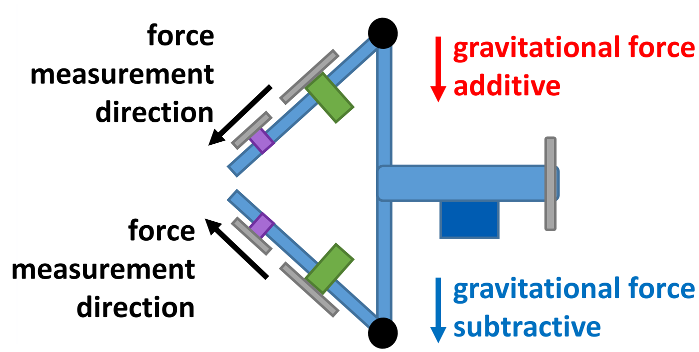
With gravitational force compensation:

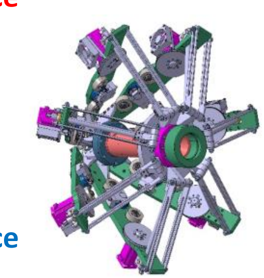






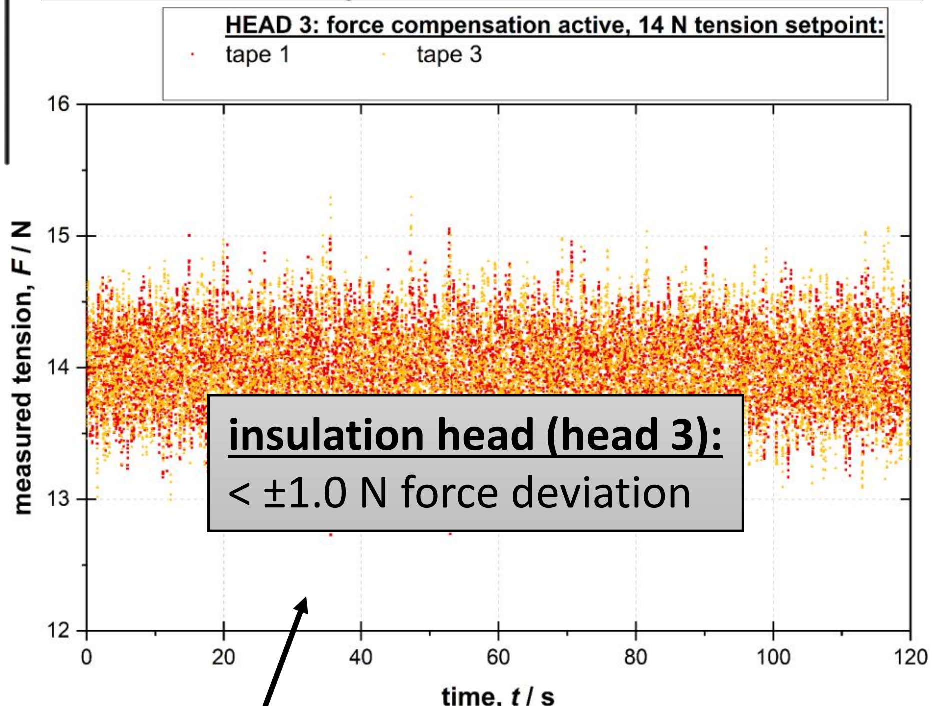


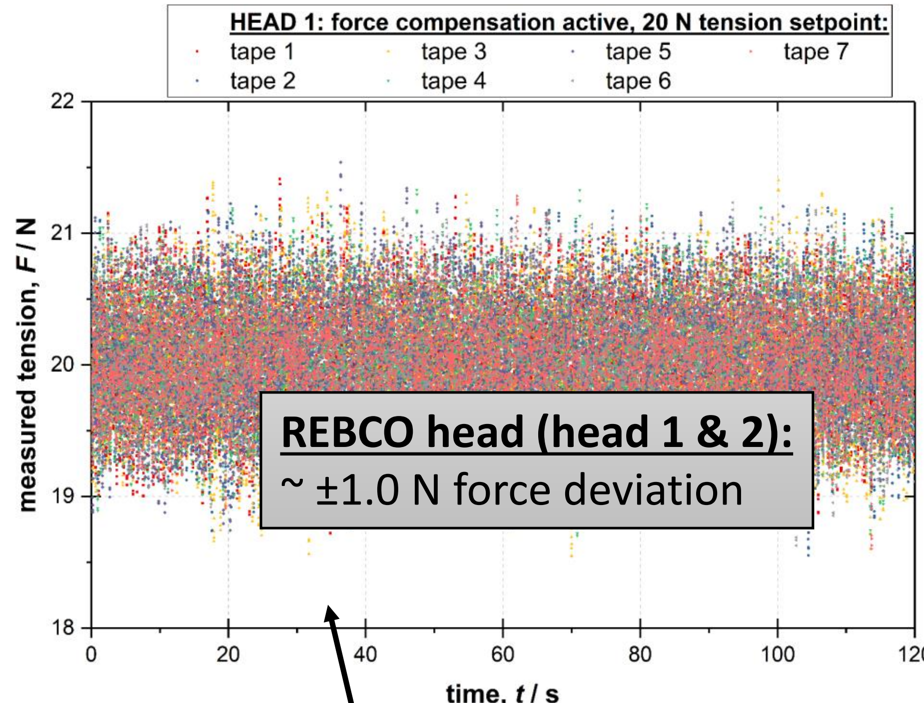


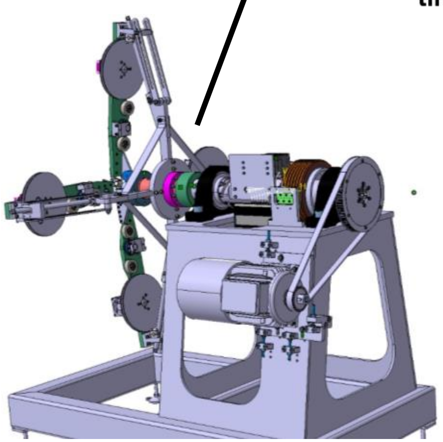


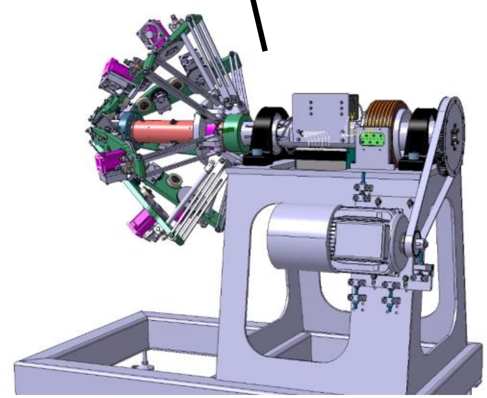
Machine concept: rotating parts

Precise tape tension control:





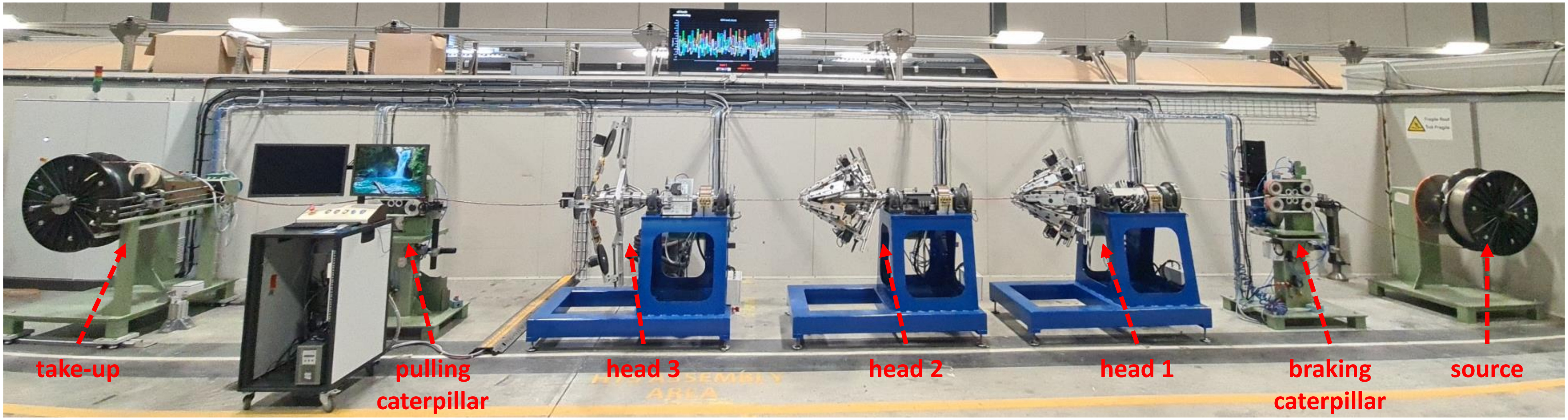




Cabling

Cabling parameters:

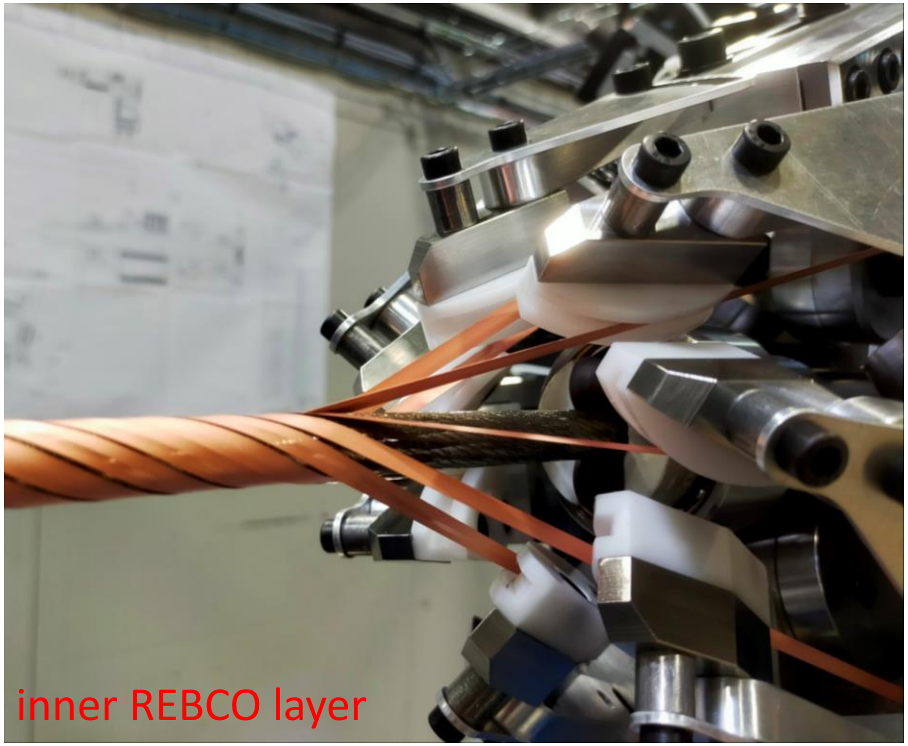
- Cabling parameters optimized through characterization of tapes extracted from cables
  - 250 N core tension, 120 N take-up tension
  - head 1: 20 N tape tension (inner REBCO layer)
  - head 2: 12 N tape tension (outer REBCO layer)
  - head 3: 14 N tape tension (Kapton tape insulation)
- Zero cabling related critical current degradation observed



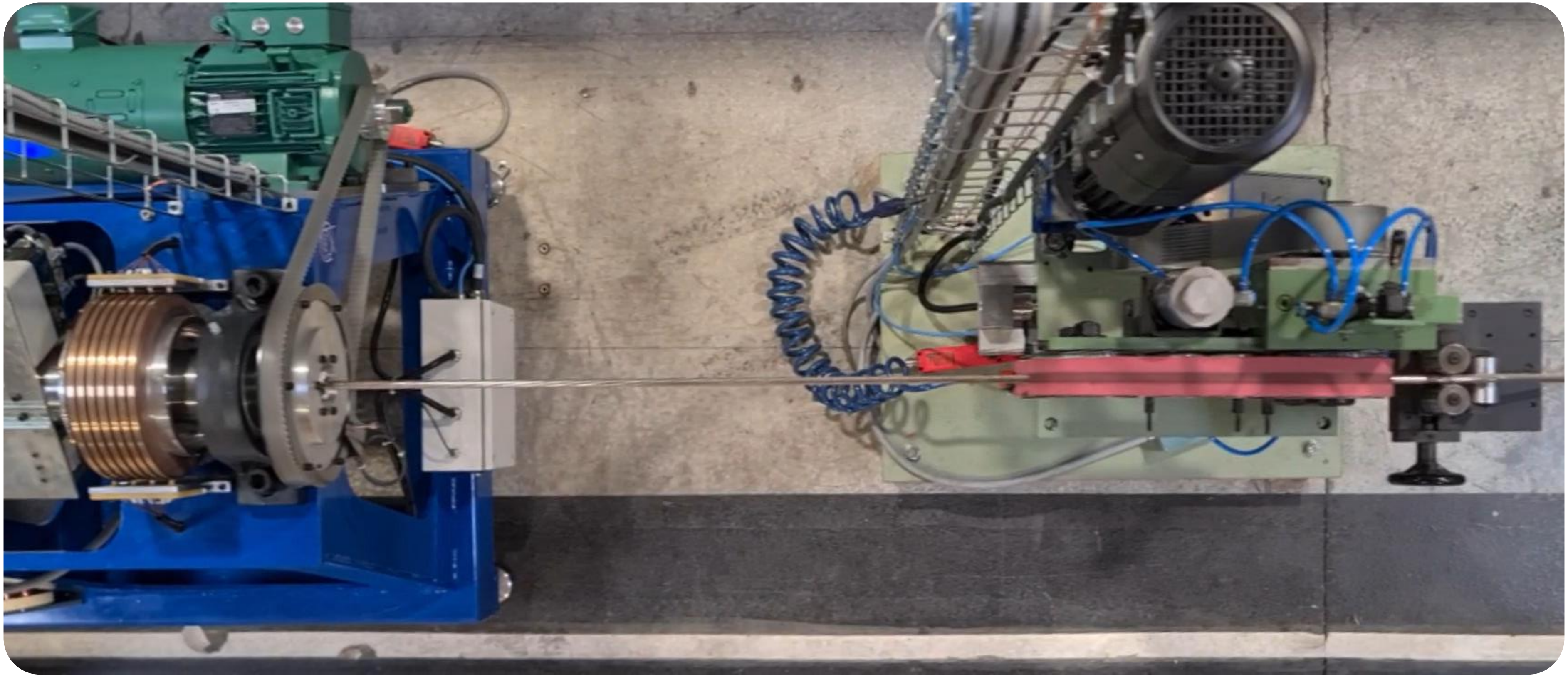
Cabling

Cable performance:

- Splice resistance reproducible & within expectations
  - 2 – 3 nΩ for Superox tape and 4 – 8 nΩ for Superpower tape
- Several unit lengths have been successfully cabled
  - cables work reliably, verified with extracted tape measurements



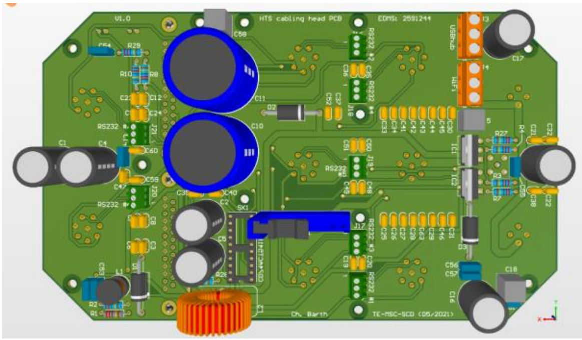
Cabling



Technical choices: cabling head motors

- 7x ‘PANdrive’ Smart Stepper Motor from ‘Trinamic’
  - stepper motor with integrated driver
  - controlled via TTL step & direction pulses
    - 50 KHz max. step frequency, 2 µs pulse length
  - setup via TTL RS232 serial interface
    - number of steps & micro-step resolution
    - max. current & hold current limits
  - ~200 CHF for 3.1 Nm model, ~600 CHF for 7.0 Nm model

- Powered through rotating contact with 30 V DC (30 A)
  - custom PCB (8x 210 µm) for power & signal distribution
  - integrated voltage regulators
  - voltage stabilization



Technical choices: cRIO (NI ‘C’-Series)

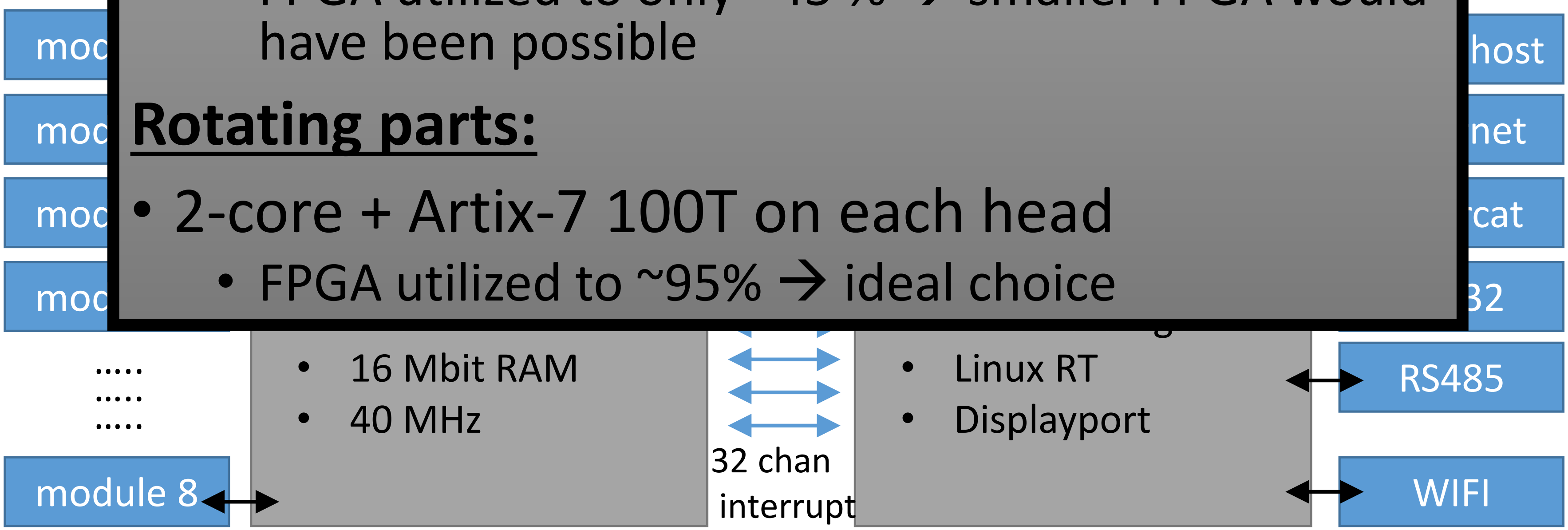
- Compact, 5 g rotation, shock & vibration proof
- Flexible (almost any kind of modules), easy to program
- Always contains FPGA + x64 Linux RT controller

Stationary part:

- 4-core + Kintex-7 325T as central control system
  - FPGA utilized to only ~45 % → smaller FPGA would have been possible

Rotating parts:

- 2-core + Artix-7 100T on each head
  - FPGA utilized to ~95% → ideal choice



Technical choices: Control systems

Stationary part:

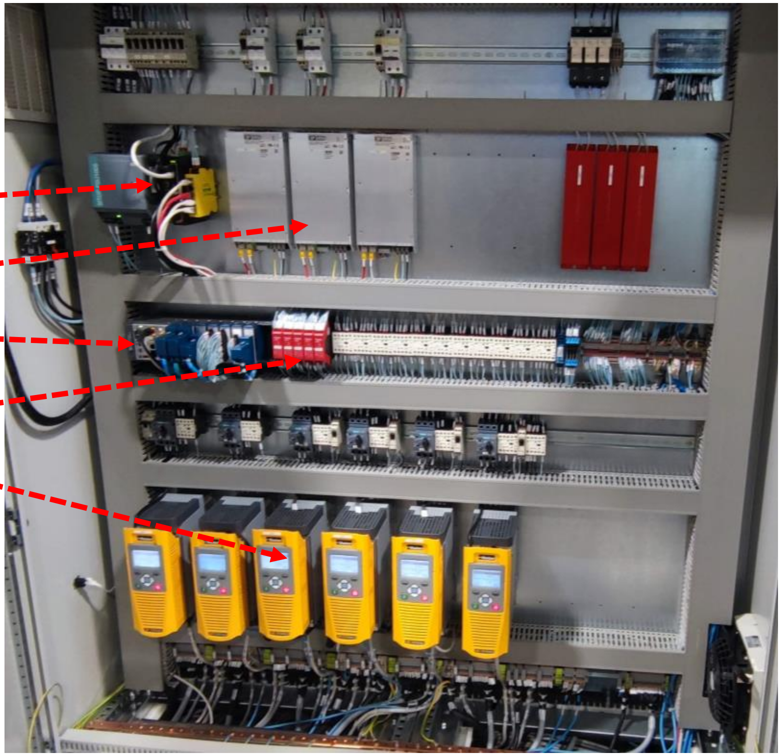
Wi-Fi communication with cabling heads

30 V DC, 30 A supplies for cabling heads

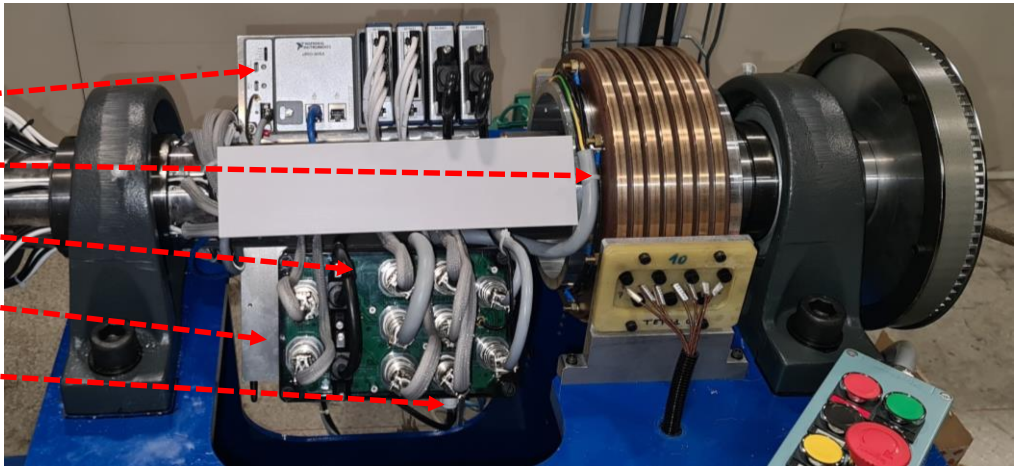
'main cRIO' (central control system)

'safe' machine security modules

inverters for industrial AC motors



Cabling head:



'rotating cRIO' (head control system)

rotating contact, 30 V DC, 30 A

custom PCB in electronic box

integrated USB – RS232 (TTL) converters

Wi-Fi communication with stationary part

Latest improvements: machine security

- Safety cages around each cabling head constructed
  - automatically locked during machine run, interlocked
- Rigid barrier in front of the machine in preparation

→ Machine security inspection by HSE planed early 2023

Latest improvements: cabling

Cable stabilization:

- Cu tape layer 'buffer' between REBCO layers for enhanced cable stability (electrical & mechanical)
  - dedicated depositioning head constructed & integrated
  - fully commissioned, will be used for SC-link HTS cables

Cable inspection:

- In-line 10 kV insulation tester installed & integrated
  - will be used for SC-link HTS cables

Cable protection:

- Pulling caterpillar force sensor as tension limiter

Summary

- Round REBCO cables optimized for power transmission
  - 14x 4 mm wide tapes in 2 layers, opposing winding directions
  - 1x 12 mm Cu buffer, 2x 20 mm wide Kapton tape insulation

- Round REBCO cables work reliably, no cabling degradation

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- Thank you for your attention -

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