APA Winder Upgrades

Dune UK Collaboration Meeting

July 2023

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(University of Liverpool)
(on behalf of the Daresbury Lab Factory Technical Team)

Factory Technical Team

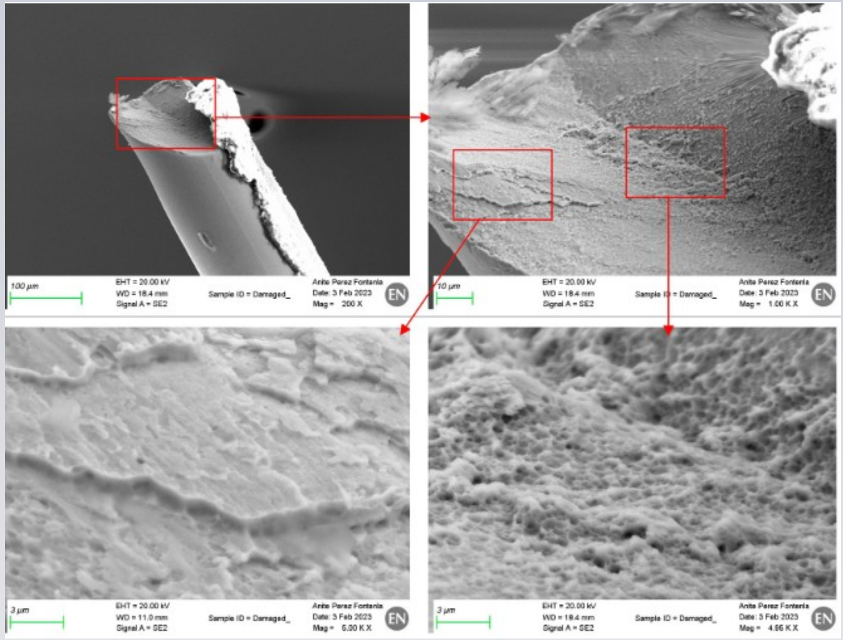
- David Sim (winder head mechanics, maintenance, servicing)
- Alan Muir (winder head design, mechanics)
- Philip Heath (controls engineer and software)
- Dan Salisbury (experience operator)
- Mike Lowe (electrical engineer)
- Krish Majundar (software and Database)
- Anyssa Navrer-Agasson (DWA)
- Sotiris Vlachos (QA process)
- Carlos Chavez (winder development, controls and software)

Winder development program

- Understand current problems
  - Safety, winder head and frame mechanics, maintenance, load-cell calibration, tension control system, winding recipes and calibration, winder control software, manual operator tasks, database and data management, tension measurement systems, ...etc.
- Find, propose and implement solutions to these problems
- Achieve main goals:
  - Improve safety: operators, machine, wire integrity
  - Proper preventive and total maintenance plans
  - Significant reduction of manual wire segments re-tension and manual replacement to less than 1%, or les 60 wires per APA (~6k wire segments)
  - Consistency and reliability across all 5 winder machines
  - Better efficiency and time reduction improvements across the overall winding process and wire tension testing process

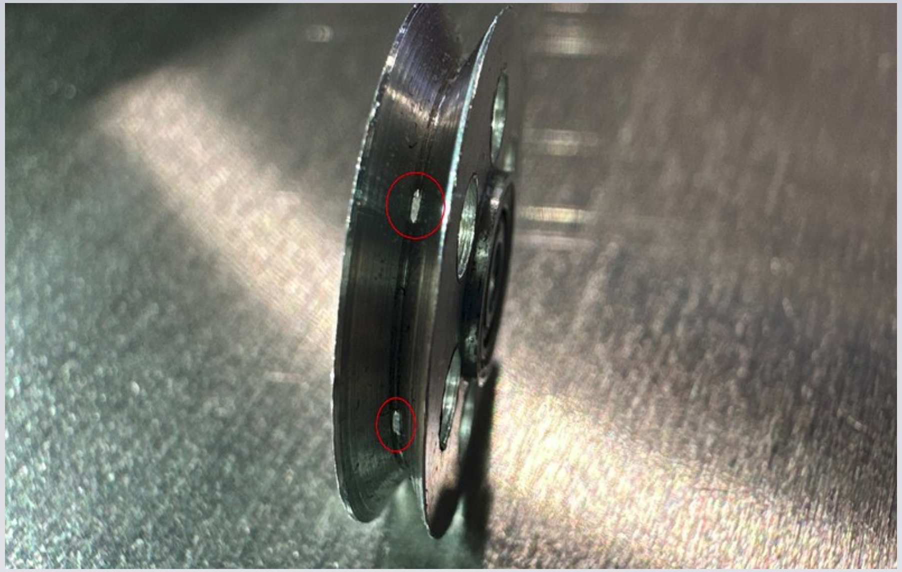
Broken wire on APA 3

- A V-layer wire on APA 3 in ProtoDUNE II broke
  - After the cold box tests in October and before late November when the first CE readout was done in the cryostat
  - Broken wire was removed from APA and analyzed
    - Report on EDMS
    - https://indico.fnal.gov/event/58720/
  - Cause of brake concluded to be most likely a fracture surface
  - Excessive tension applied on wires when winding?



Winder 2 pulley problem

- When winding G-Layer on APA 6 in early March
  - It was observed that a guide pulley has excessive wear and has broken through material of pulley possibly causing a "crinkled" effect on the laid wire.
- Several possible causes
  - Manufacturing problem and/or build up tolerances
  - Wire over tension (wearing off surface)
    - A high Set Point was used in this winder (#2)
    - Load cell calibration was not right



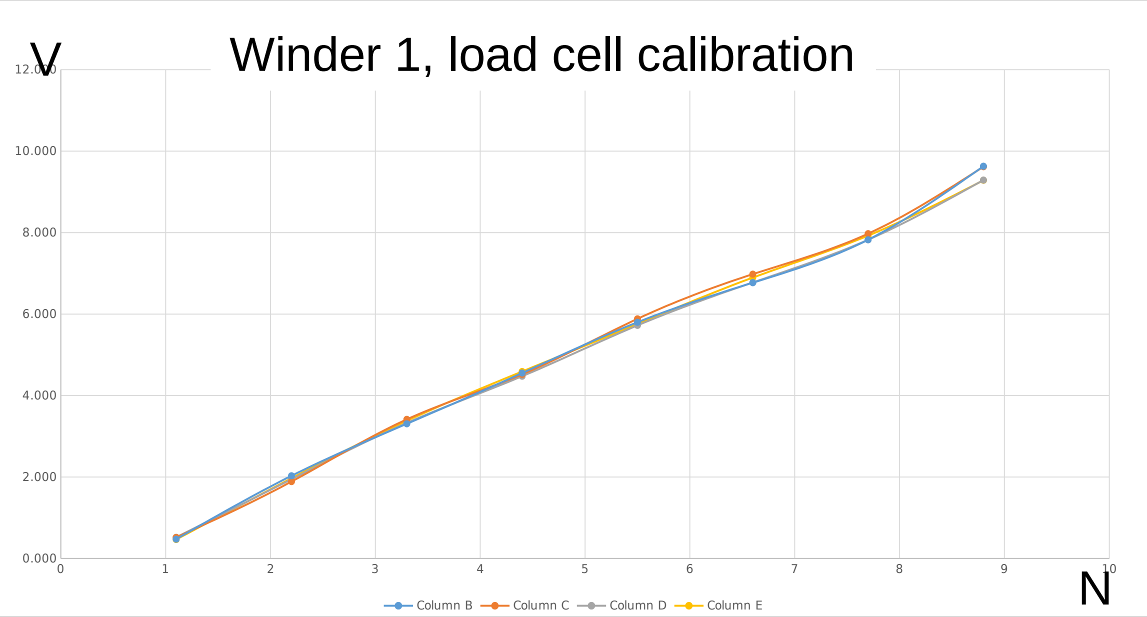
- Action taken
  - APA 6 scrapped and started again
  - New pulleys were designed and manufactured (more smaller holes, more material)
  - More regular inspections and replacement of pulleys (moving parts in the head)

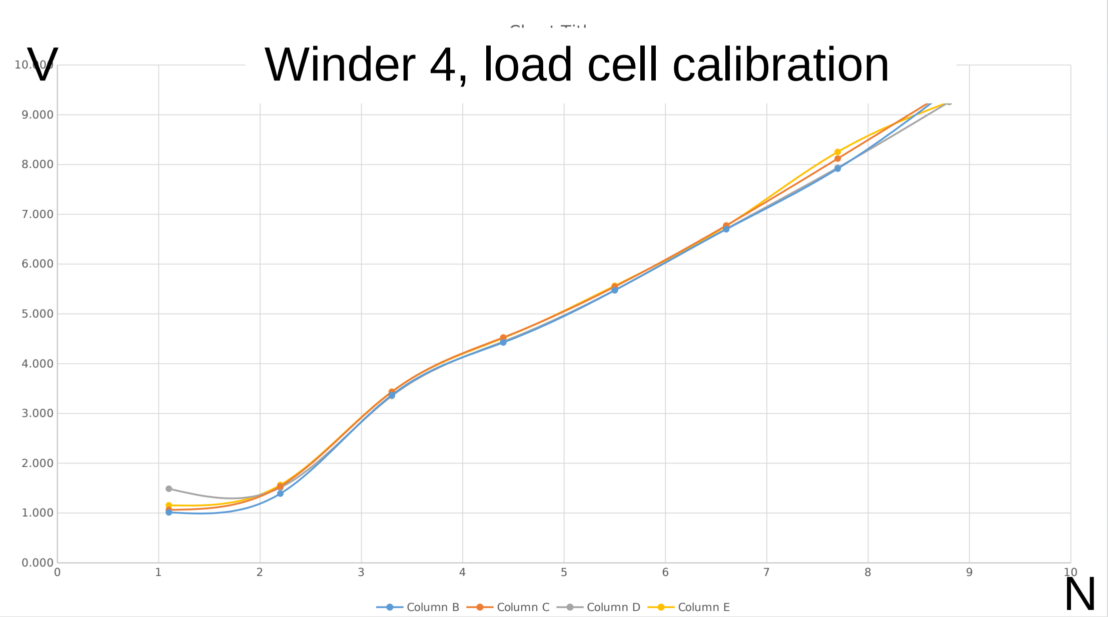
Wire tension system
(clear need for better understanding)

- Need to understand wire tension during winding process
  - Controlled pulling tests
  - Are we applying excessive tension on wires ?
    - In the past, it was observed that momentarily the tension applied could exceed the maximum output of the live tension system (~10 N, depending on the load-cell calibration and mechanics)
  - Needed better understanding load-cell calibration on winder head
  - Observe in detail winding process
    - Mechanical instabilities in the frame
    - Recipe movements (acceleration, deceleration, speed)
    - Live tension recording and analysis
    - Understand PID loop and corresponding tuning parameters

Understanding wire tension system

- Winder head mechanics
  - 23 moving parts: pulleys, sprockets, belt, spring, plunger, bearings, wire spool, brushed PMDC motor
  - Load cell location and fitting determine the linear operational range between hard stops
  - Each winder head behaves differently and tension system is non-linear
  - Need to perform load cell calibrations and tests under controlled conditions and understand them

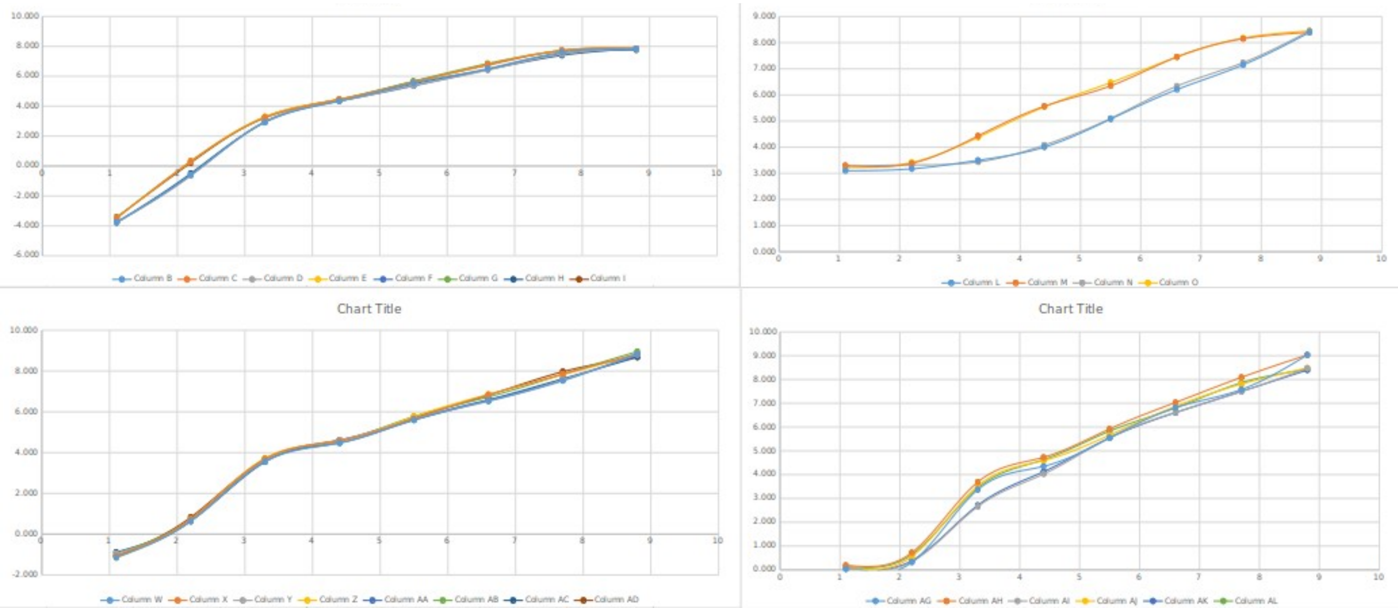




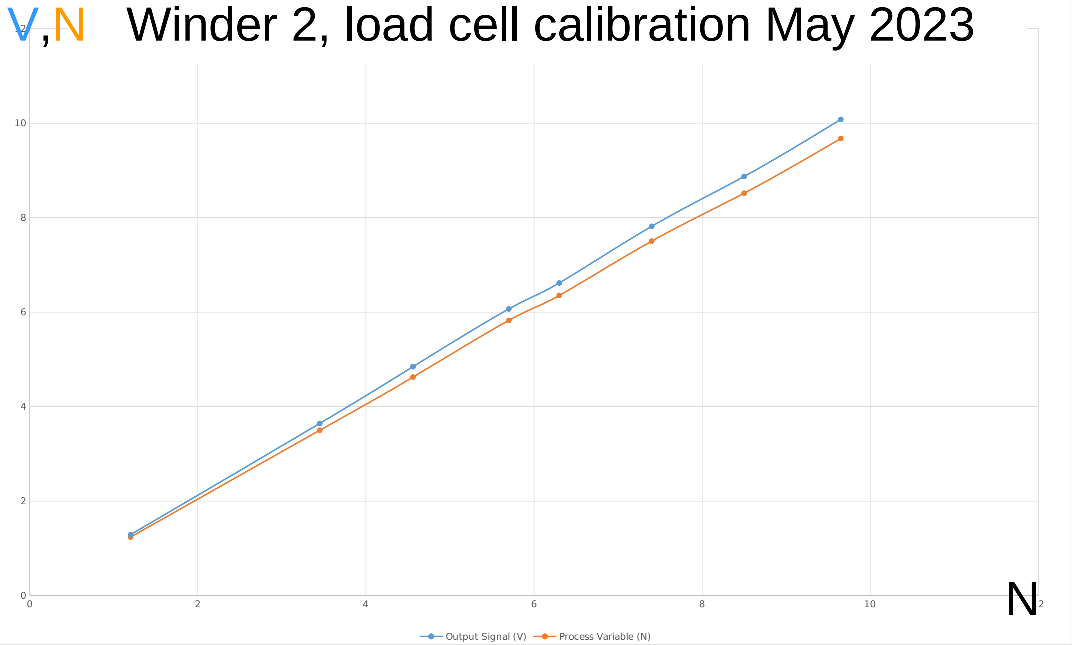
Winder 2 (load cell calibration)

- Winder 2 was chosen for development
  - Some problems with its performance (had the pulley worn off, APA 6 scrapped)
  - Load cell calibration was not right, several attempts showing it (Jan 2023)
  - After comparing with W#1 load cell location, it needed to be moved by 3 mm (May 2023)

Winder 2, load cell calibration attempts in January 2023

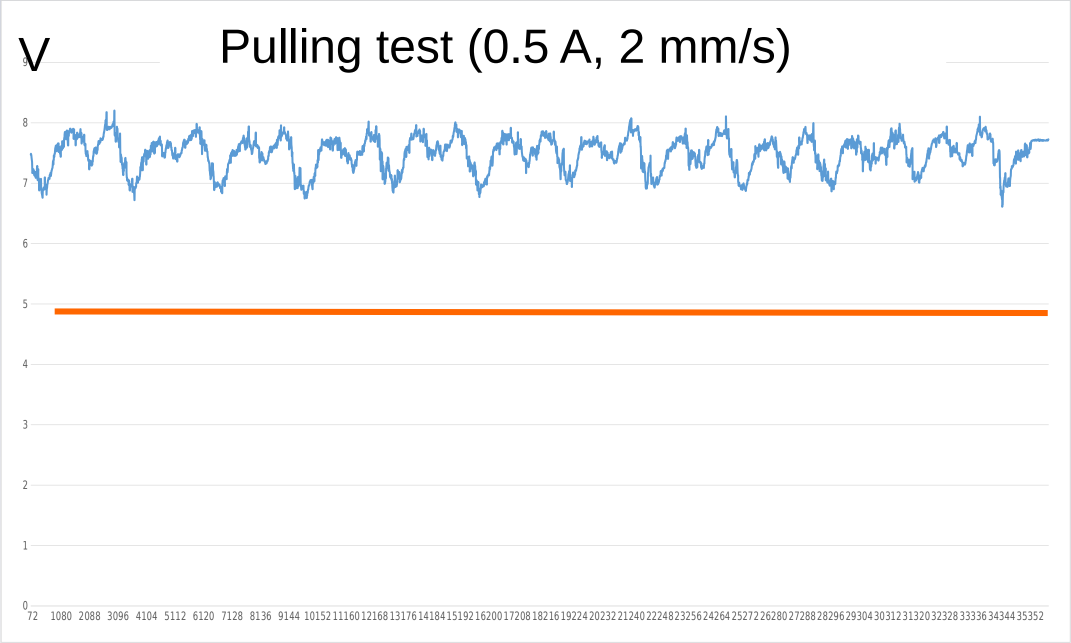


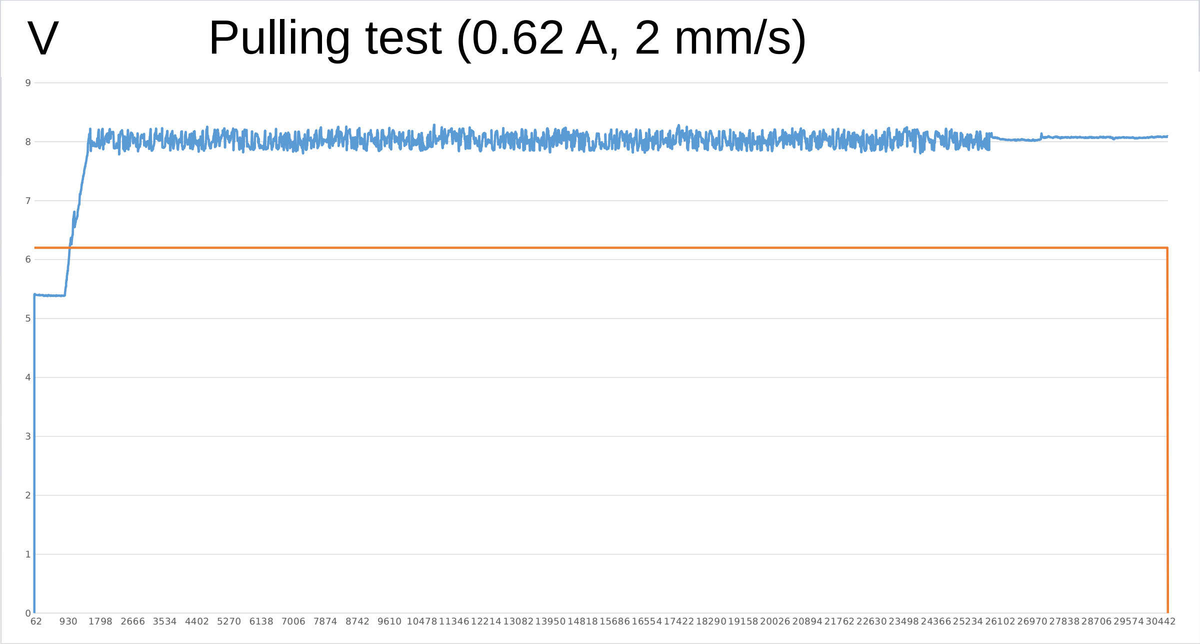
Winder 2, load cell calibration May 2023



Winder 2 (load cell calibration)

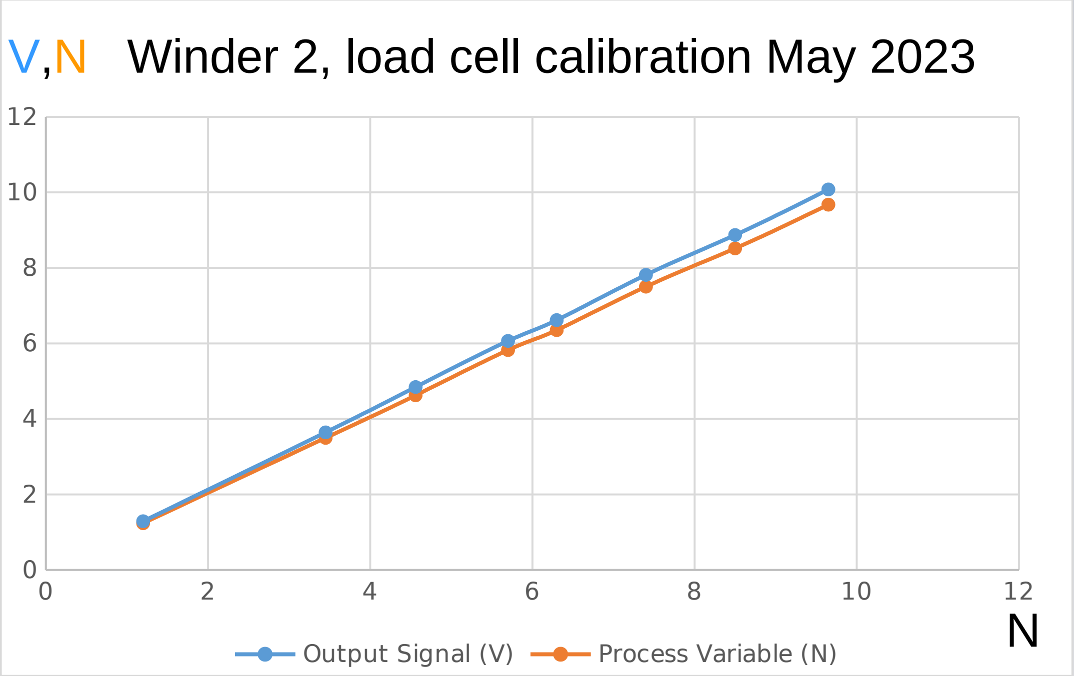
- Pulling test
  - Pulling wire from a fixed point for a fixed distance (1000 mm)
  - Driving motor at constant current (constant torque)
  - Moving at a constant low speed, the load cell amplifier output (in Volts) expose mechanical problems
  - In this particular case the smaller variations (at 6.2 A test) is a clear indication of the system hitting the high hard stop (at 8.3 V)
  - This prompted the compare the position of the load cell wrt winder 1 and 4 , then change its location and calibrate





Winder 2 (load cell calibration)

- Much Improved calibration
  - We now know the linear range reliably
  - We know the hard stop is beyond the max amplifier output of 10 V
  - The amplifier output is always slightly higher than the tension measured by load cell (in N), **10 V := 9.7 N**



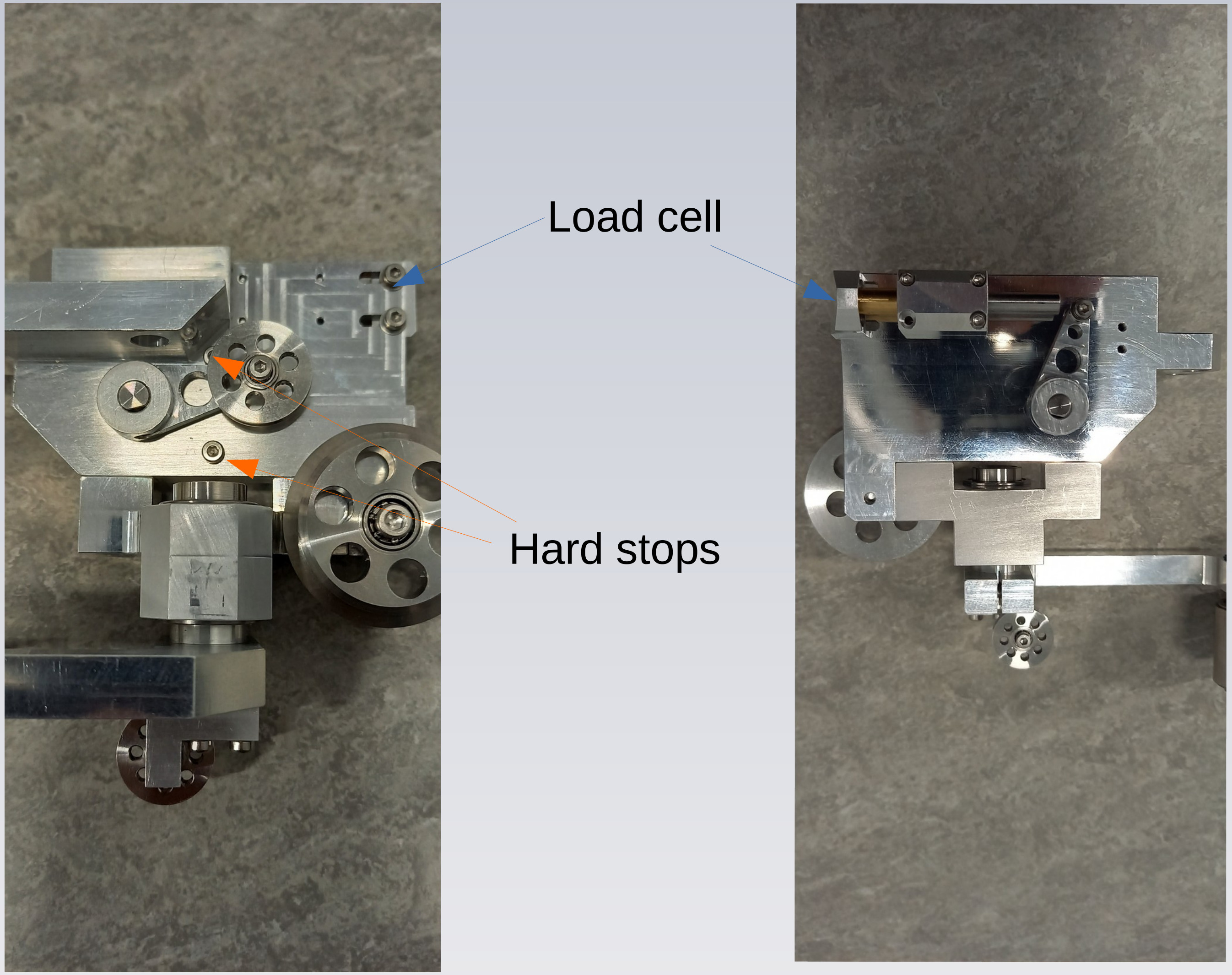
Nominal Wt. (N)	Output Signal (V)	Process Variable (N)	Notes
1.2	1.29	1.238	Still on the wire break switch
3.45	3.644	3.498	
4.56	4.845	4.625	
5.7	6.067	5.825	
6.3	6.617	6.353	
7.4	7.816	7.503	
8.5	8.872	8.517	
9.65	10.079	9.676	

Winder 2 Mechanical improvements

- Changes to old sprocket
  - Used to make substantial modifications to the manufacturers sprocket
  - Old sprocket used to have two pieces
    - Now only one
  - New design only has on single piece
  - The small sprocket for belt was clocked and showed run off
    - It was machined to reduce run off

Winder 2 Mechanical improvements

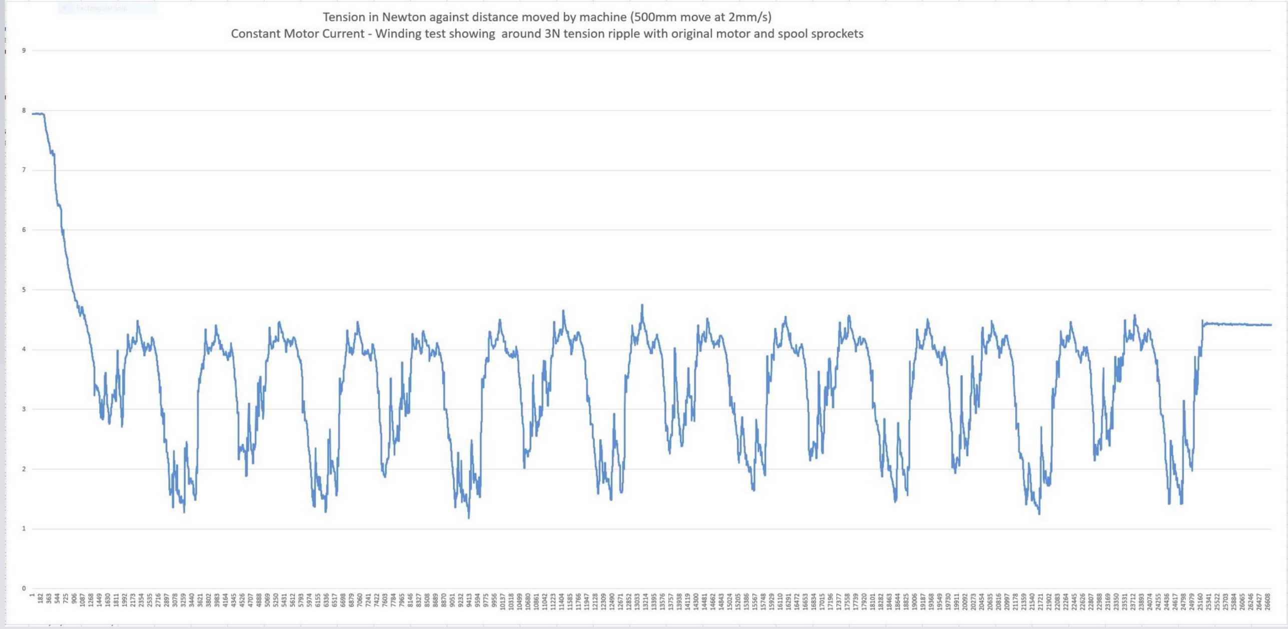
- Changes to load cell location
  - Moved load cell 3mm to match winder #1
  - Avoiding hitting the hard stop before 10 V output



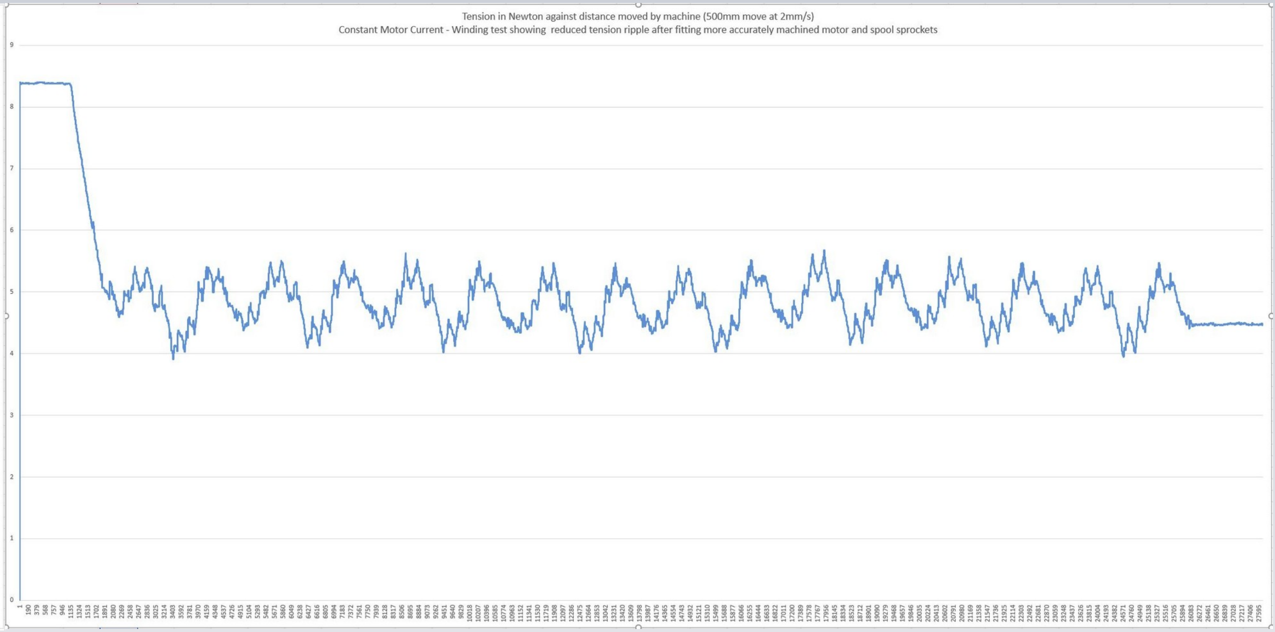
Winder 2 improvements

- Changes : new sprocket and new calibration

Before



After

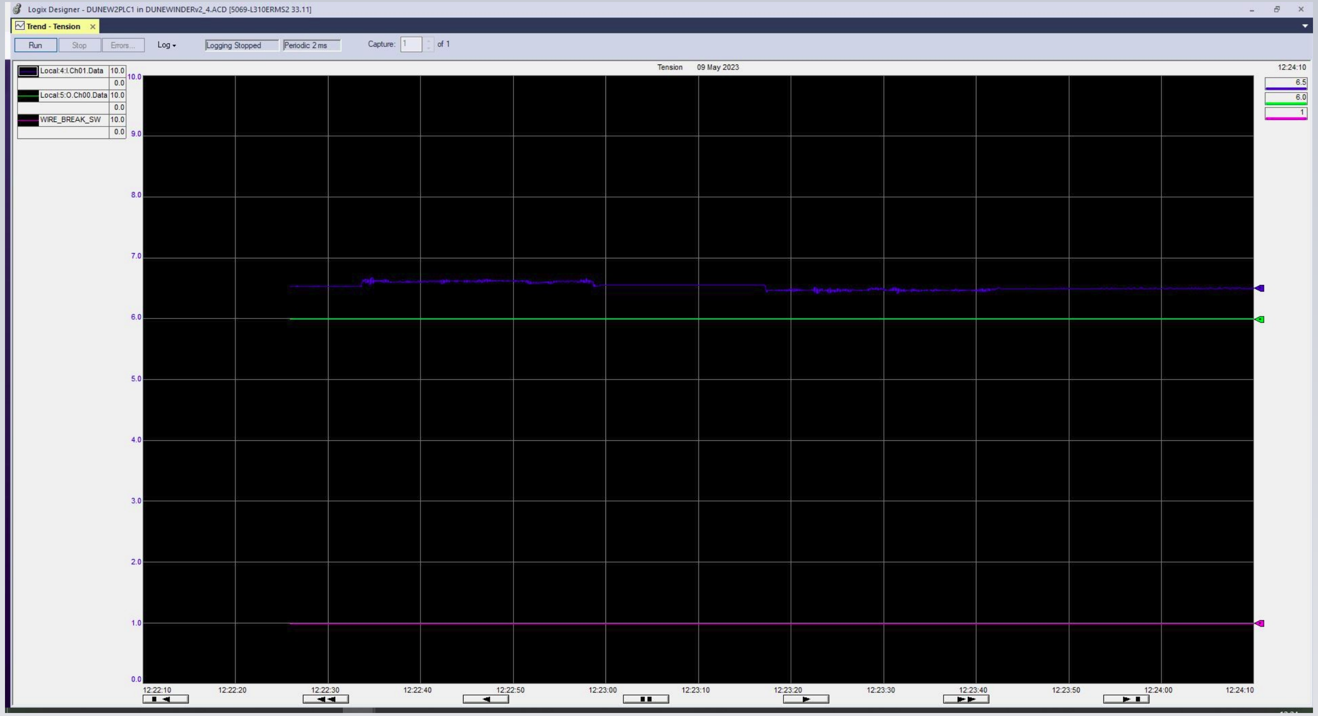


Winder 2, test 1

- Unwind to rewind test
  - Wire end is fixed to the winder frame and winding head is in constant current mode
  - Winder is moved horizontally
  - Large offset observed from unwind to rewind
  - A significant amount of ripple was observed, but from experience can be considered good, but there is room for improvement

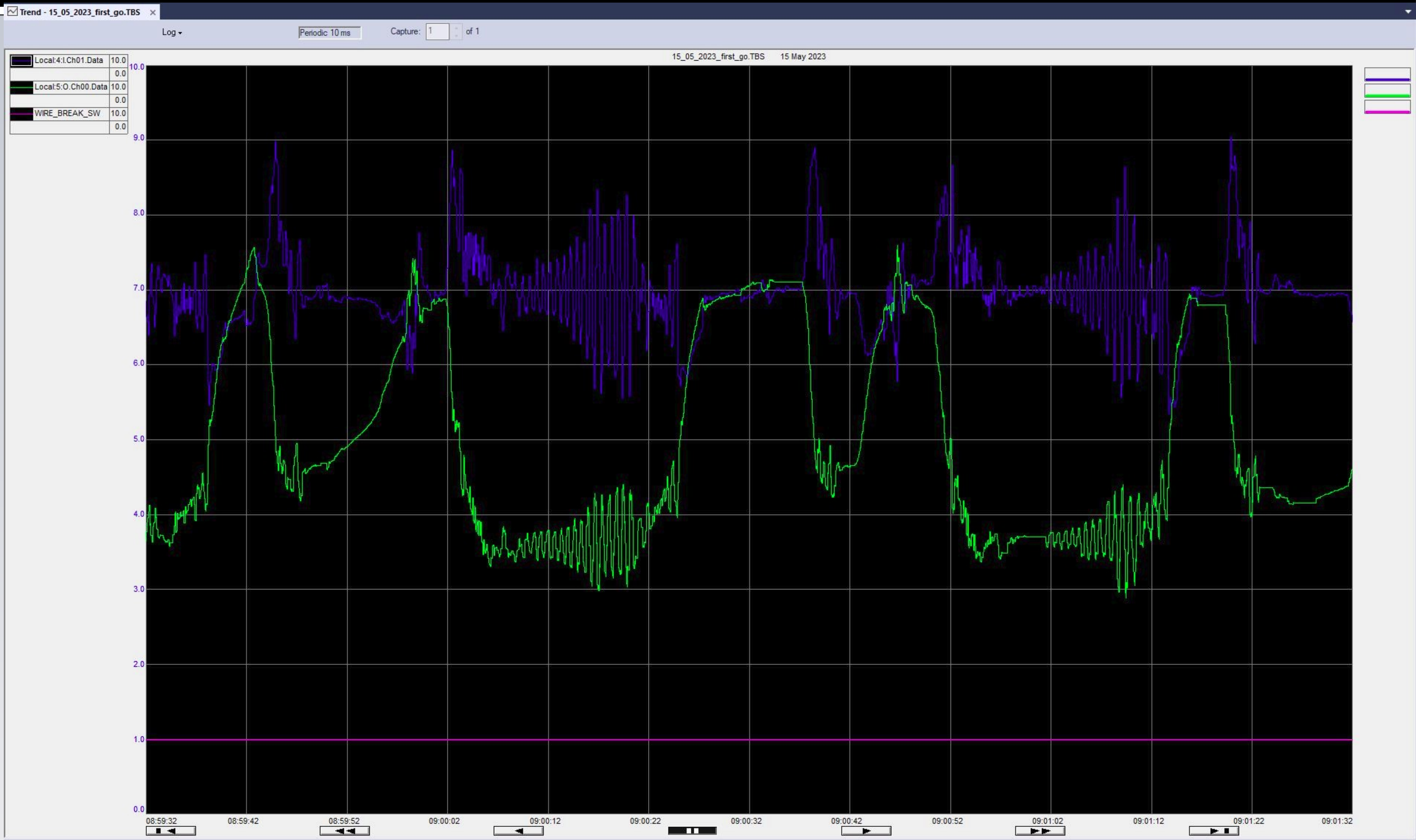
Winder 2, test 2

- Isolation test : pulleys and load cell
  - Section of wire cut. One end tied to winder frame. Wire is routed through all of the winding head including everything except the spool, timing belt, and motor. Other end has 6.5N weight hung.
  - Winder is moved up and down.
  - Small amount of offset from unwind to rewind,
  - Which indicates the offset seen on previous slides is from the spool, timing belt, or motor.
  - Almost no ripple was observed, which is very good



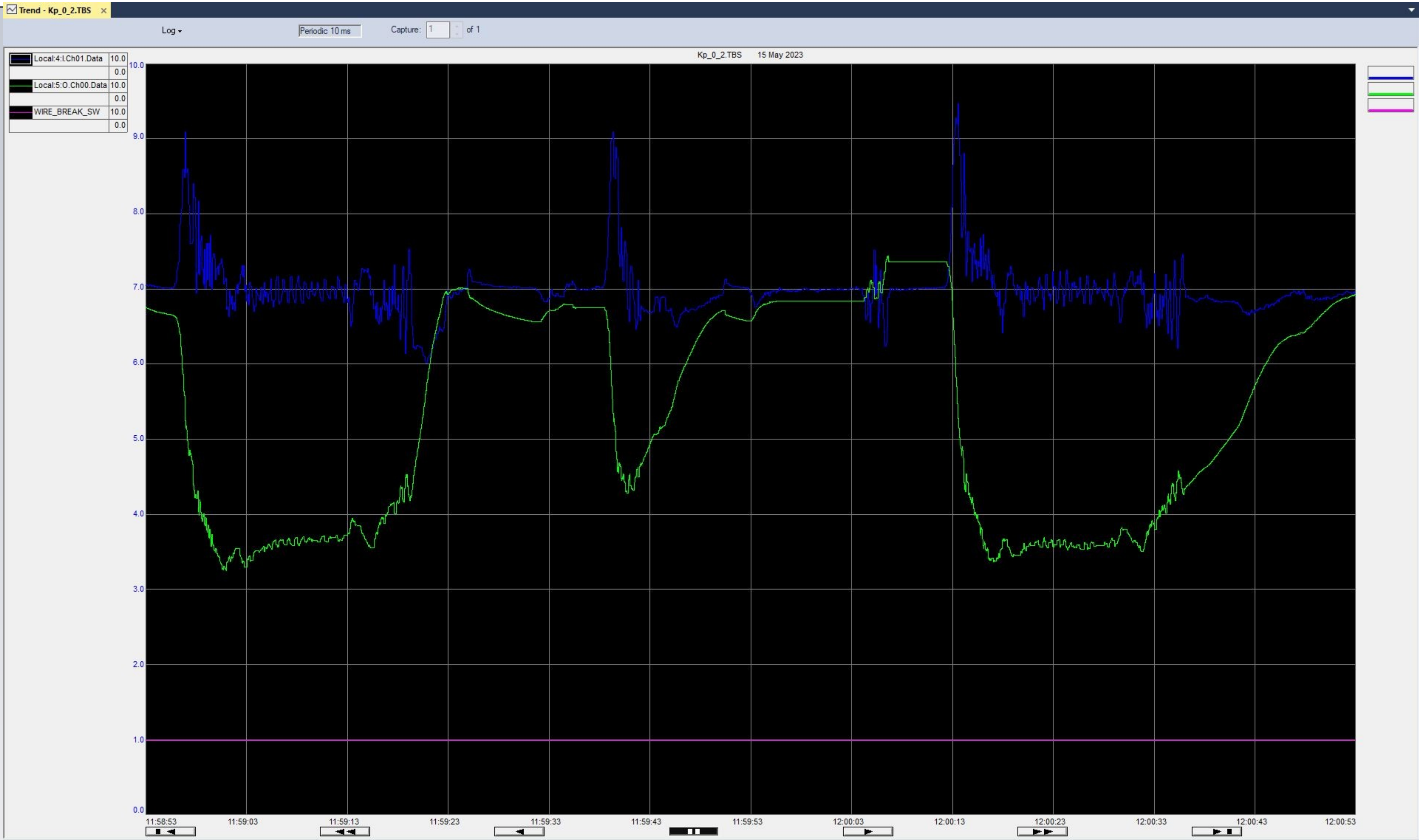
Winder 2, before PID loop tuning

- APA 6 X-Layer winding
  - Before PID loop tuning
  - Quick build up of oscillations when laying the long wire horizontally
  - Peaks observed when laying the wire during the first tenths of milliseconds during acceleration, also when moving head from Side A to B and vice versa.
  - Need for PID loop tuning



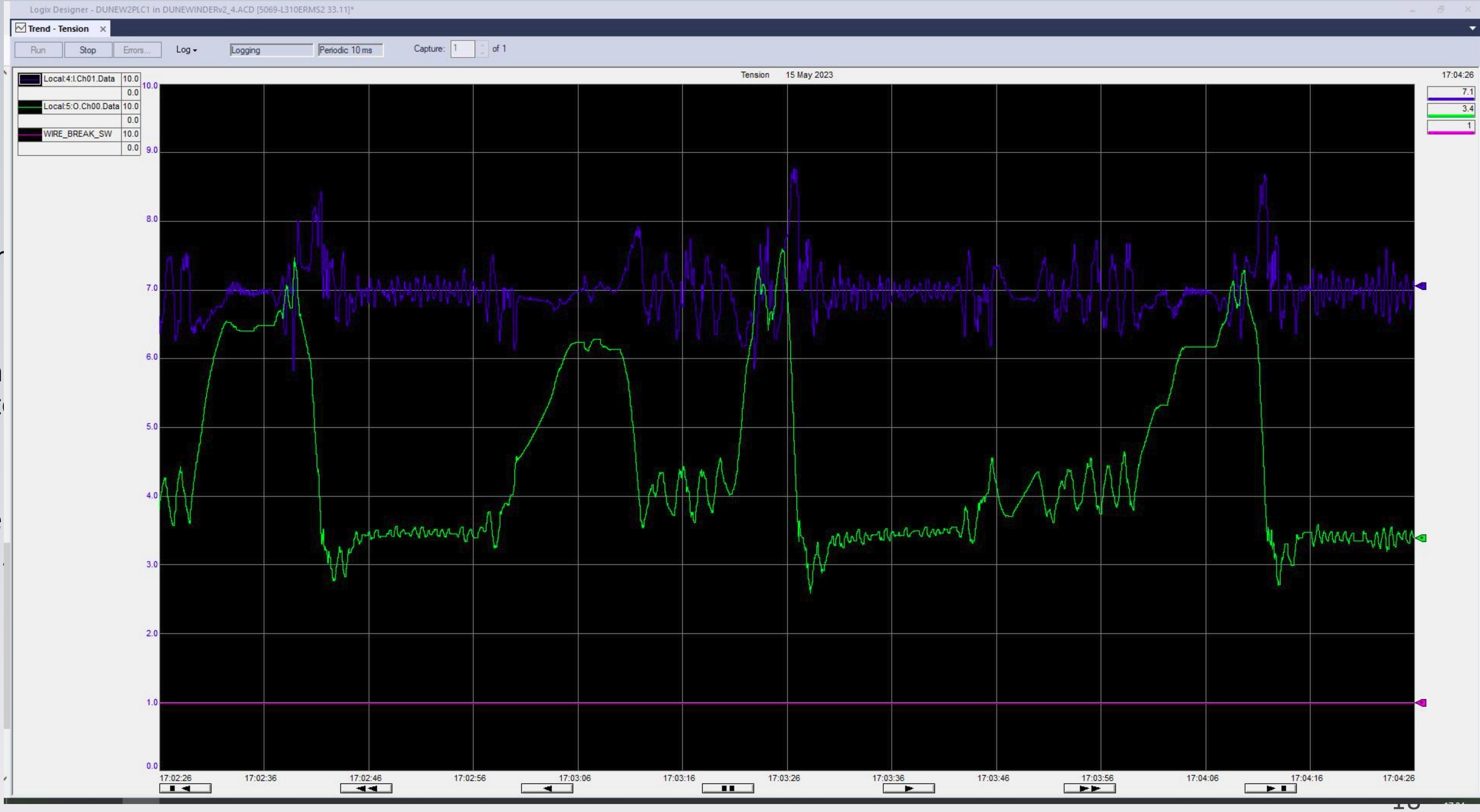
Winder 2, after PID loop tuning

- APA 6 X-Layer winding
  - After PID loop tuning
  - Oscillations when laying the long wire horizontally under control
  - Peaks observed when laying the wire during the first tenths of milliseconds during acceleration only when moving head from Side A to B and vice versa.
  - Need for change in winding recipe



Winder 2, after change in recipe

- APA 6 X-Layer winding
  - After Change in recipe
  - Slowing down the transfer head movement only
  - Oscillations on the long wir horizontally under control
  - Peaks now much reduced when laying the wire when moving head from Side A t B and vice versa.
  - Next is to adjust the set point to reduce the numbe of wires needed re-tension and aiming to be closer to the target tension.



Winder 2, APA 6 X-Layer

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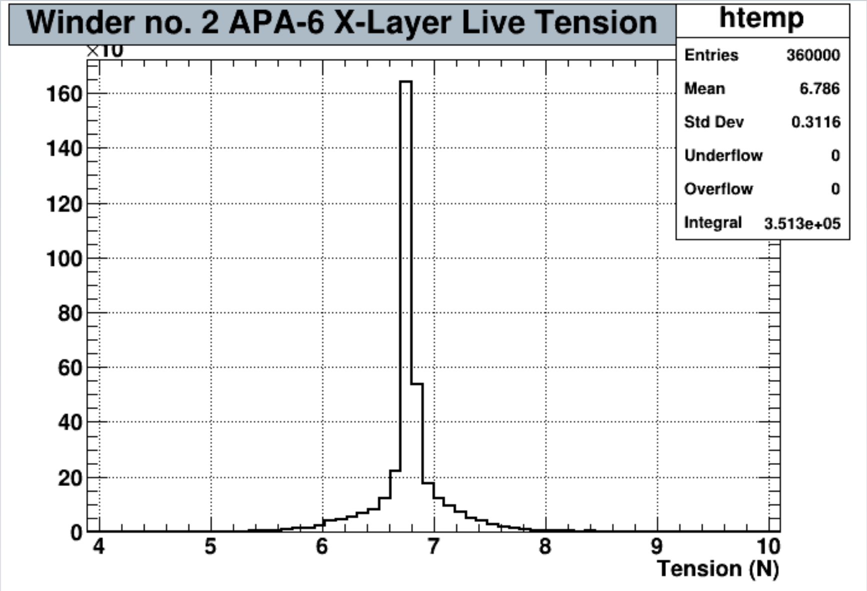
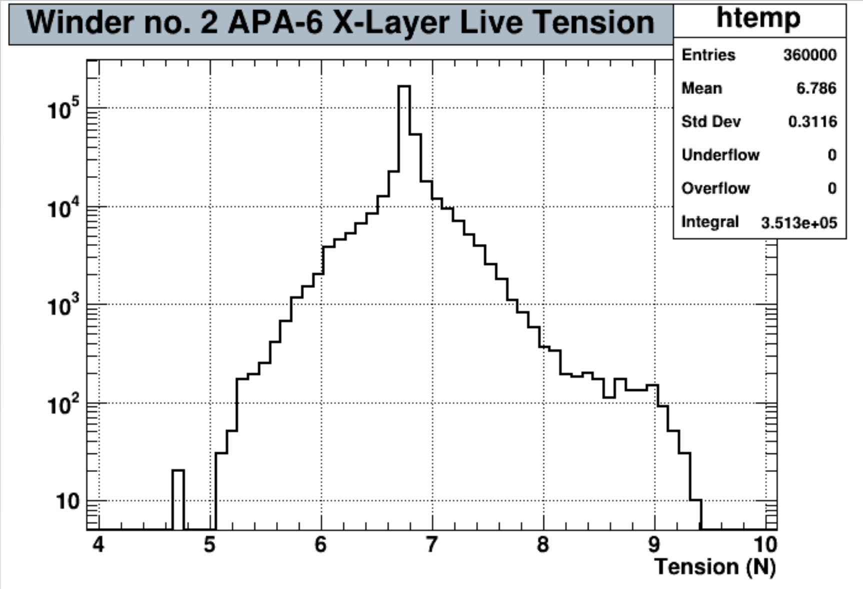
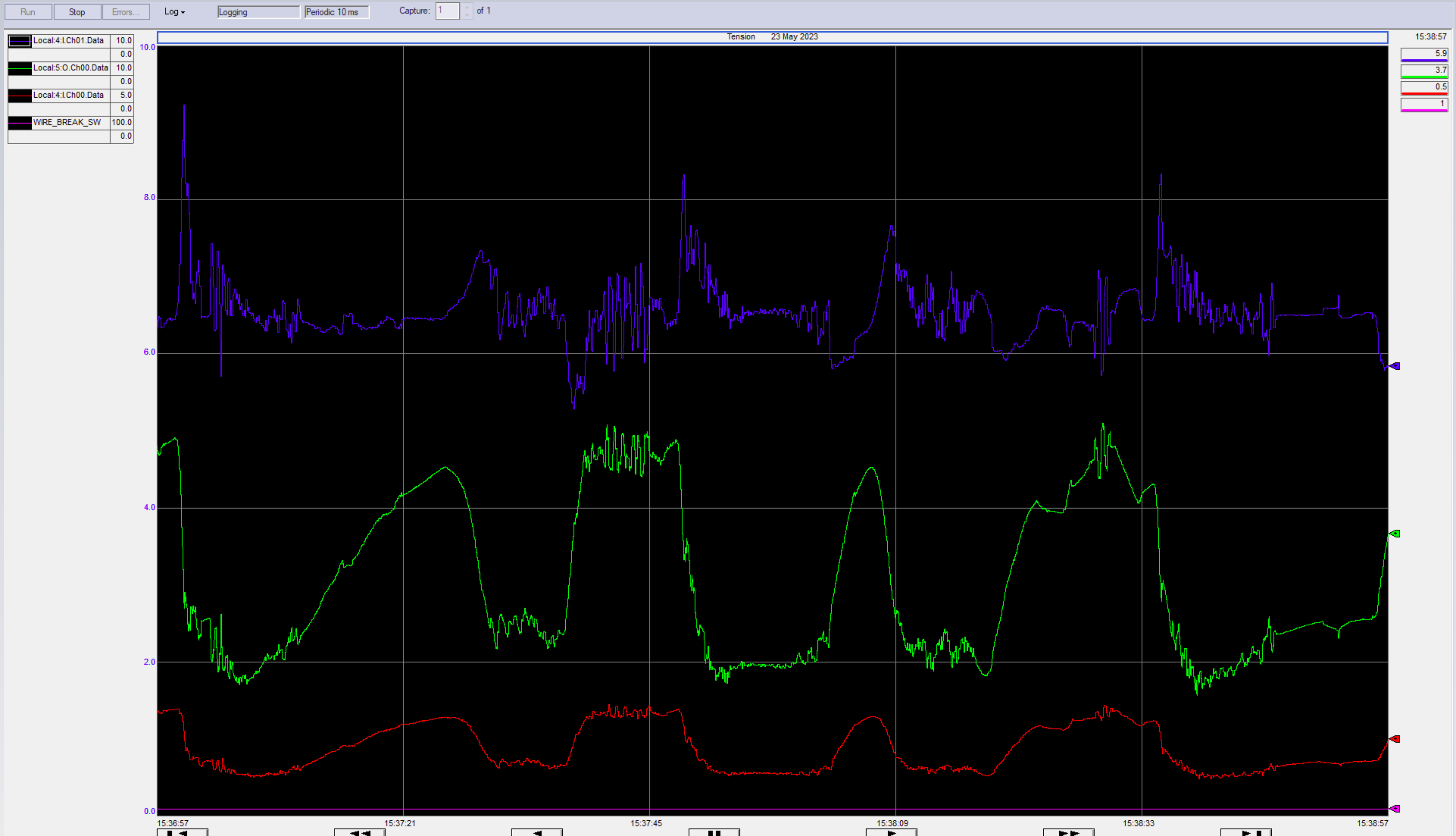


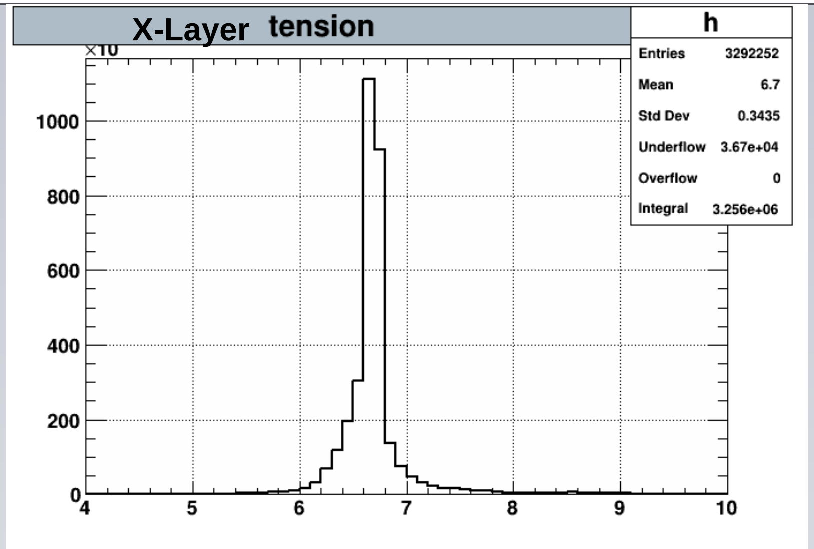


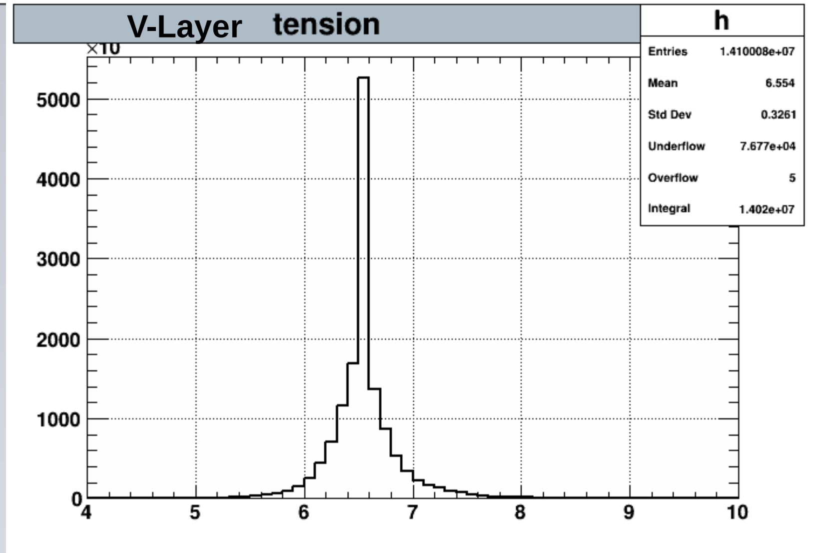
Winder 1, APA 8 U-Layer(Timed)

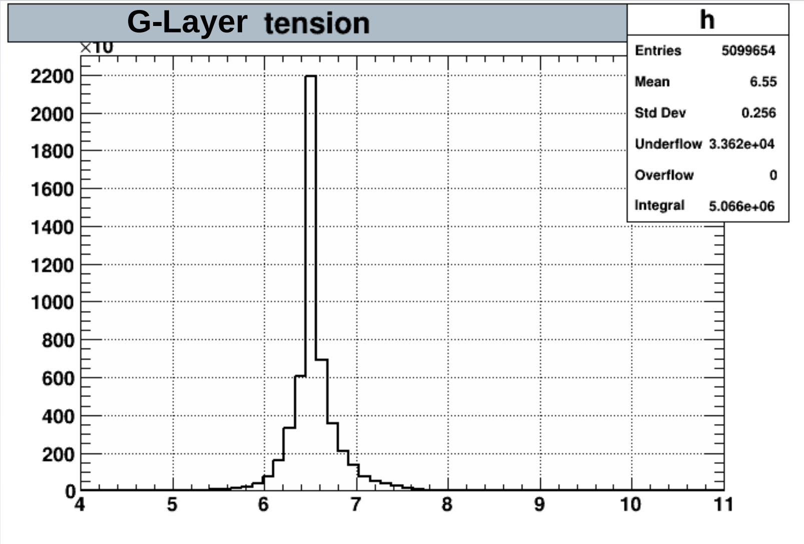
- APA 8 U-Layer winding
  - Shows controlled behavior
  - Not hitting hard stop
  - No exceeding max load cell amplifier output

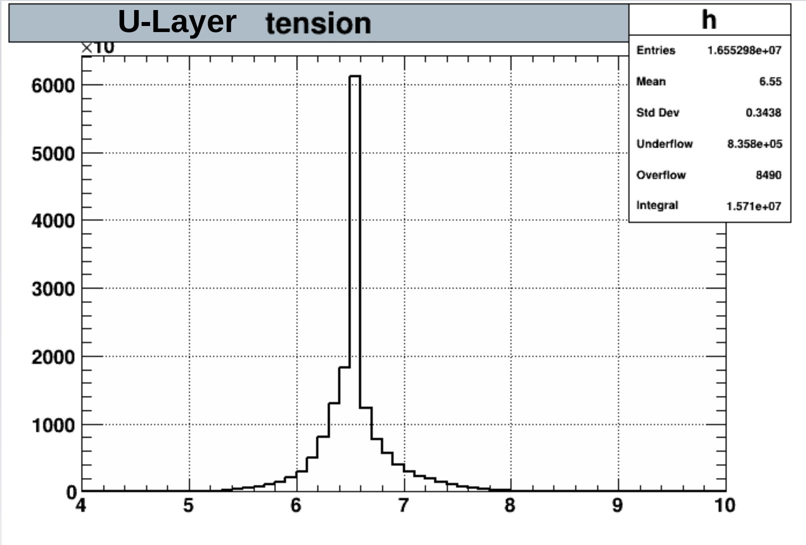


Winder #1 APA 8
Live wire tension measurements



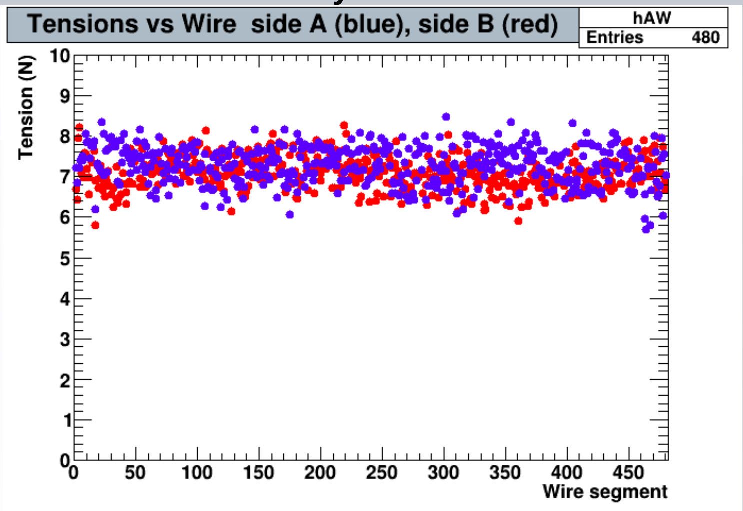




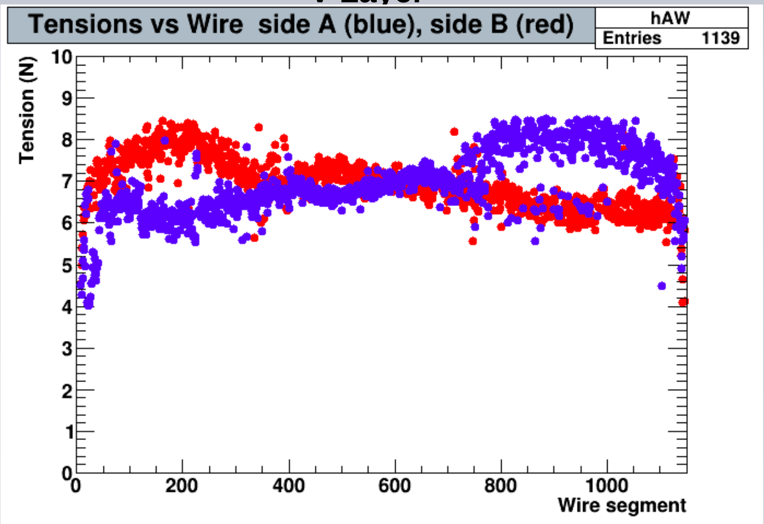


Winder #1 APA 8
Tension measurements with Laser system

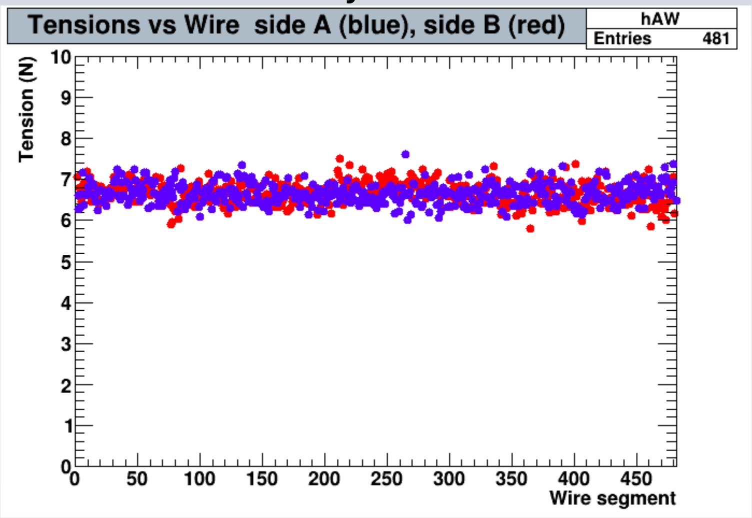
X-Layer



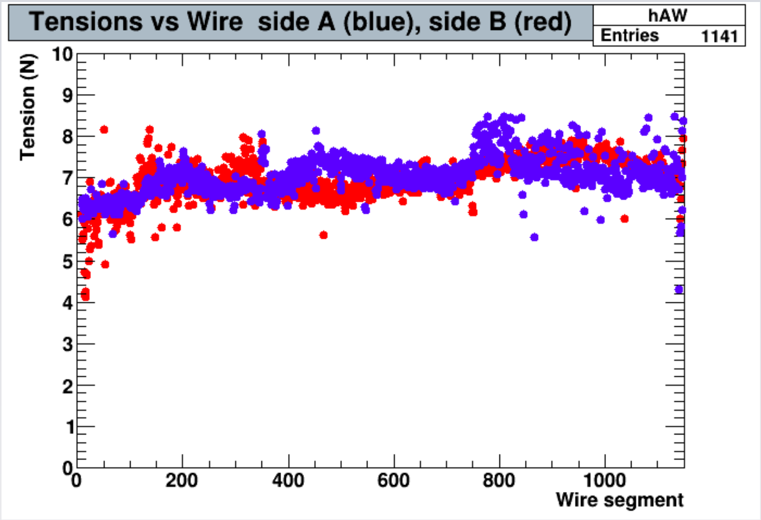
V-Layer



G-Layer



U-Layer



Winder Development Upgrade Tasks

- Mechanical improvements on the winder head and to the winder machines
- Develop a Preventive Maintenance plan (PM), for both winder head and winder machine
- Upgrades, changes and maintenance to the whole winder controls software, this is, the PLC software for hardware control, the Python back-end and its JavaScript GUI, this is the software used by the operators for winding APAs.
- Improvements and maintenance to the tension control system parameters (PID Loop tuning).
- Calibration of the load-cell and amplifier of each winder machine/head permutations and its regular updates throught the whole production. Standardize electrical wiring on each winder machine and winder head to be able to exchange heads on different winders as required by the factory operational needs.
- Implementation of a monitoring system for the indication of structural degradation and the predictive maintenance of structural components (CHASM system currently under RTO).
- Automation of tension measurement procedure with Laser Interferometter.
- DWA for tension measurement system.
- Automation of winder Calibration procedure using Cognex camera and its pattern recognition capabilities.
- Installation of Camera monitoring system for winding process with pattern recognition capabilities to aid the operator during winding process.
- Construction Database development and analysis software for tension data, its automation and data handling.

Summary

- Identified most problems in the winding process
- Have a plan to improve the winding process by improving on:
  - Integrity of the wire (making sure the wire is far from plasticity regime)
  - Efficiency (automation and monitoring of some task, improve on speed)
  - Quality (wire tension within specs)
  - Keep on understanding of the tension system
    - But will keep measuring and looking to uncover any blind spots

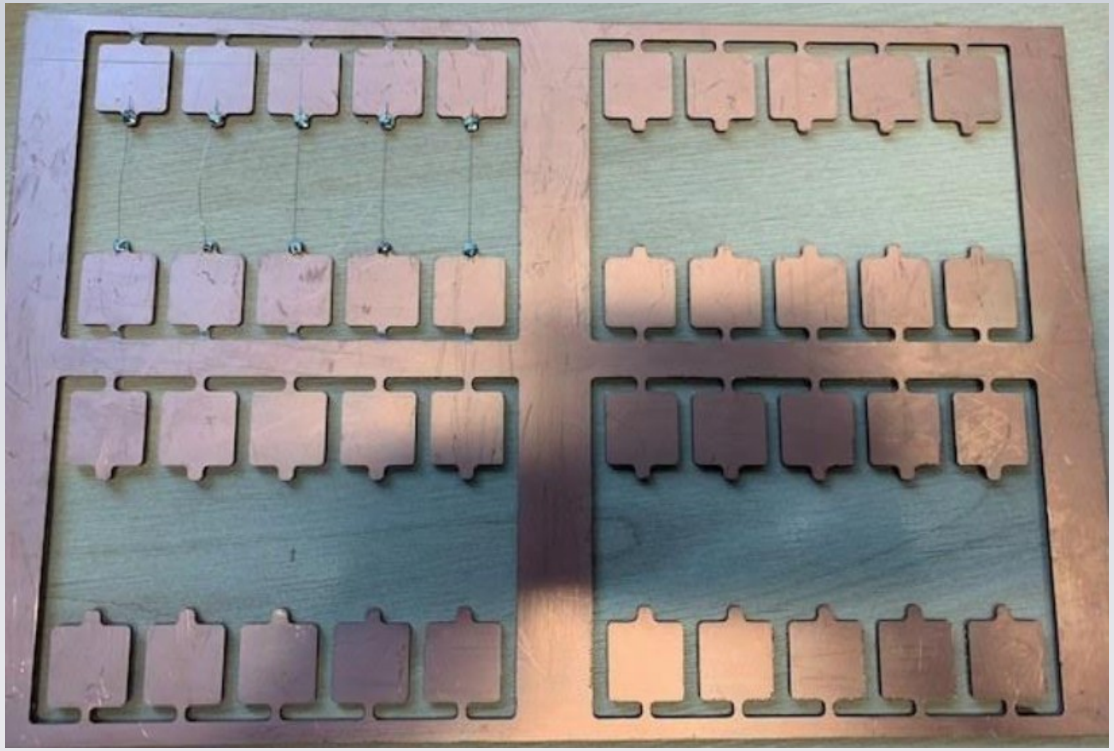
- Already working on its implementation

THANKS

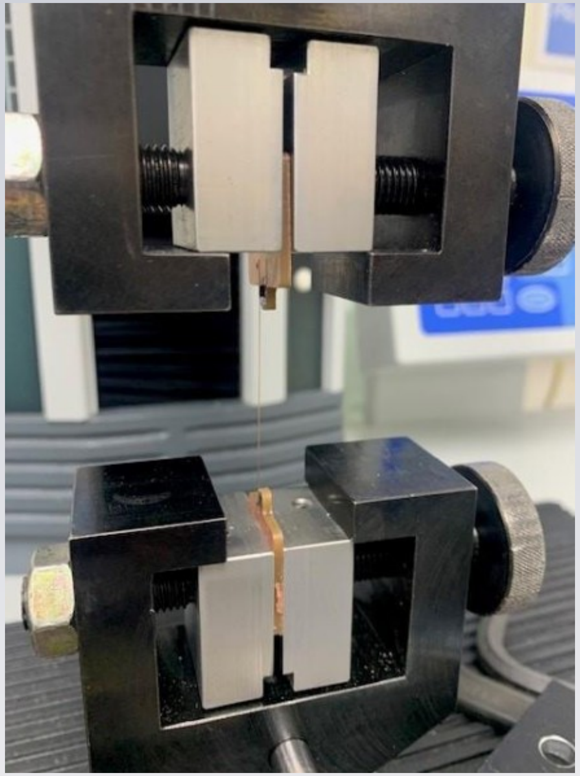
Wire tensile strength analysis

Tim Jones (Liverpool)

- standard test tokens manufactured from a 1.6mm thick FR4 double-sided copper-clad PCB panel



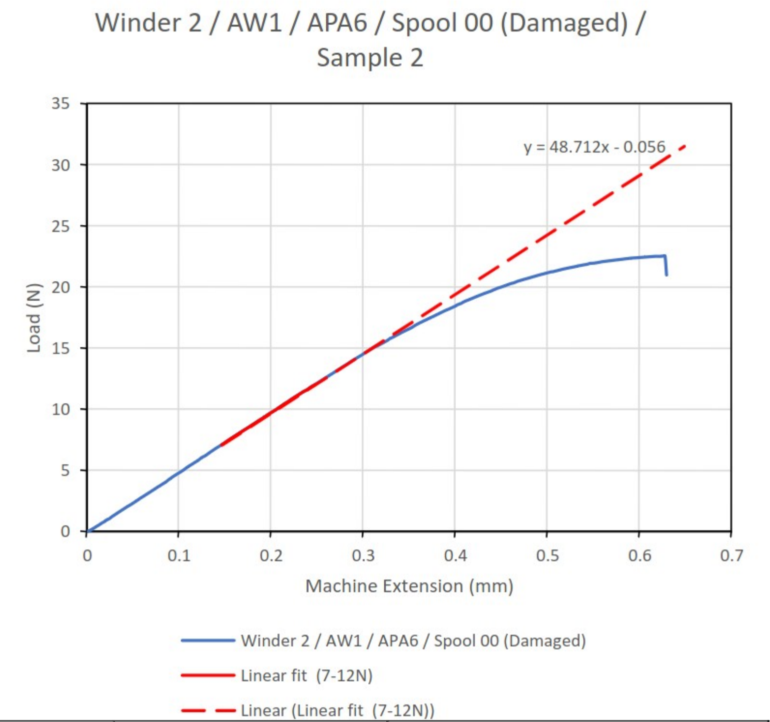
- The tests were all performed using a Lloyd Instruments LRX+ 5kN Universal Materials Tester equipped with a 100N load cell.



Wire tensile strength analysis
(spools: 1 LFA, 3 AW1)

- Yield point is the point on a stress-strain curve that indicates the limit of elastic behavior and the beginning of plastic behavior

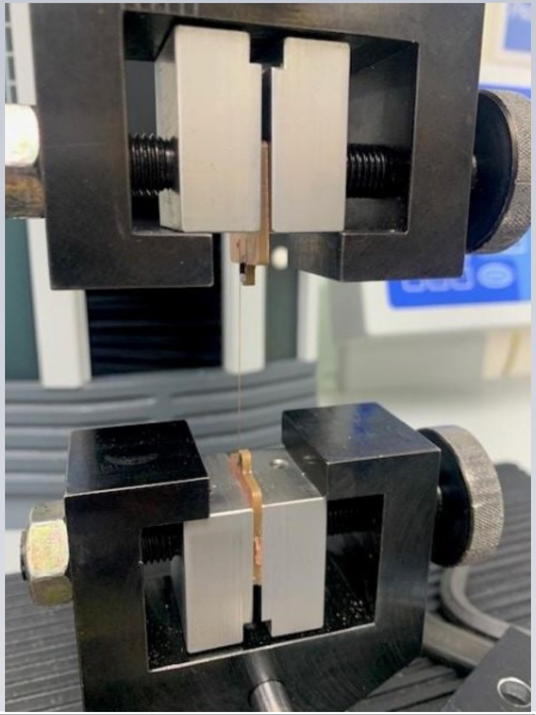
- Below the yield point, a material will deform elastically and will return to its original shape when the applied stress is removed



		LFA/PSL Spool #61		Winder 1 / AW1 / APA5 / Spool 31		AW1 Spool 00		Winder 2 / AW1 / APA6 / Spool 00 (Damaged)	
		Sample 4	Sample 5	Sample 1	Sample 2	Sample 2	Sample 3	Sample 1	Sample 2
(N)	**Load at 0.2% Yield**	23.06	25.34	18.152	21.795	17.355	19.017	21.143	21.294
(N)	**Load at break**	23.90	26.20	19.252	23.536	19.017	23.227	22.645	22.509
(MPa)	**Stress at 0.2% Yield**	1305	1434	1027	1233	982	1076	1196	1205
(MPa)	**Stress at Break**	1353	1483	1089	1332	1076	1314	1281	1274

Wire breaks observations

(spools: 1 LFA, 3 AW1)



- The PCB end-tabs are not properly positioned such that the wire emerges from the soldered region at an angle and that this creates a ‘kink’ in the wire as it is pulled, raising the stress and promoting early failure
  - Tried to minimise this by aligning the edge of the PCB tab with the front edge of the clamps (see photo of sample in materials tester above)
- The act of soldering has affected the strength of the wire (more tests ongoing)
  - MATWEB indicates an ‘Ageing temperature’ of 260 °C for (one form of) Cu Be
  - We currently use 340 °C for AW1 wire (320 °C LFA)
- There is a significant discontinuity in the stress in the wire between the soldered and free regions and this rapid change in stress leads to early failure
  - The standard geometry for test tokens for tensile testing is the ‘dog-bone’ in which there is a gentle reduction in the sample width between the clamped and free regions.

		LFA/PSL Spool #61		Winder 1 / AW1 / APA5 / Spool 31		AW1 Spool 00		Winder 2 / AW1 / APA6 / Spool 00 (Damaged)	
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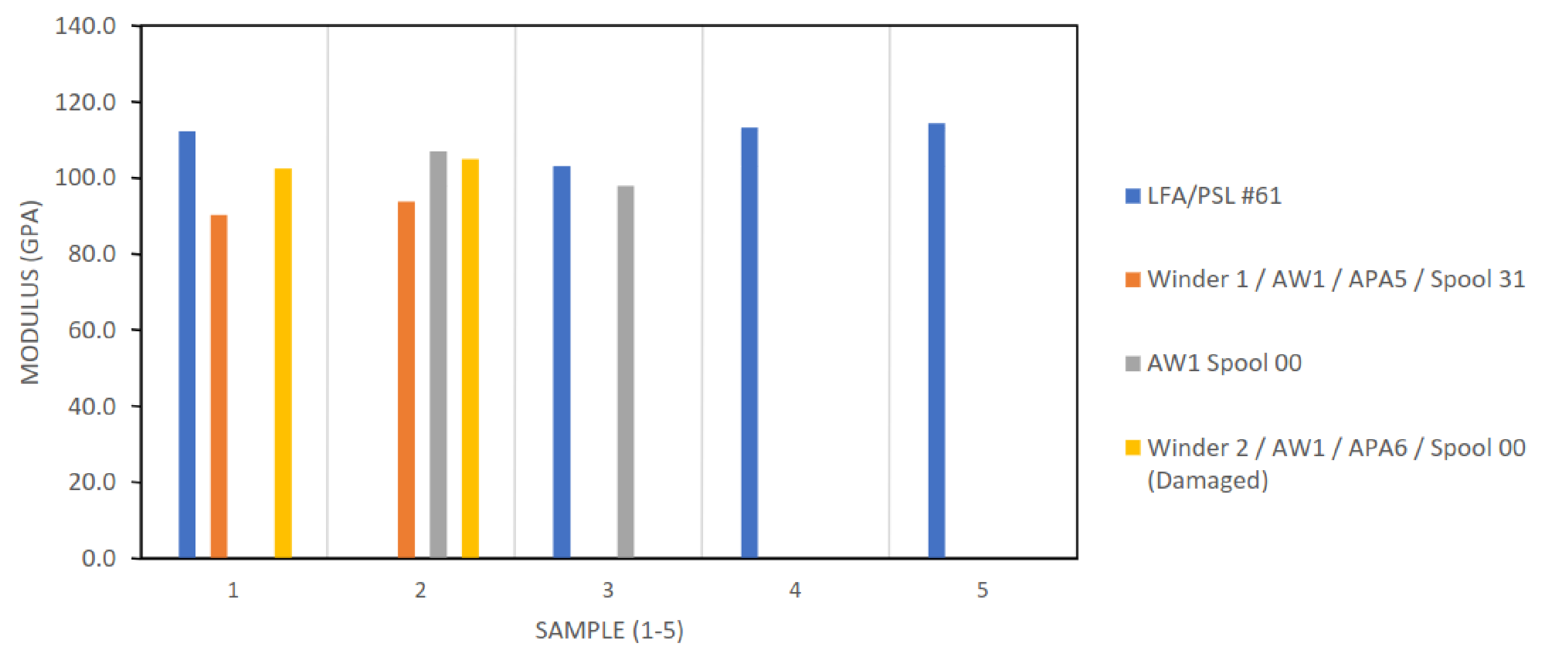
Wire tensile modulus

- Comparison of all tensile moduli measured for a total of 10 samples from 4 different batches of wire
- Tester measures stiffness, but need to correct for machine stiffness too
- 5 or 6 tests per sample
- Range of test 7N – 12N (going up to 15N)
- The Corrected Stiffness is calculated from the reciprocal subtraction of the apparent stiffness measured with the steel bar. The Modulus is calculated by multiplying the Corrected Stiffness by the ratio of Sample Length (33 mm) / Cross-sectional area (0.01767 mm2) and putting in the right factors of 1000



Wire Batch	Samples	Average Modulus	STDEV
LFA/PSL #61	4	110.8	5.1
Winder 1 / AW1 / APA5 / Spool 31	2	92.2	2.4
AW1 Spool 00	2	102.5	6.4
Winder 2 / AW1 / APA6 / Spool 00 (Damaged)	2	103.8	1.7

Winder #1 APA 8
Live wire tension measurements