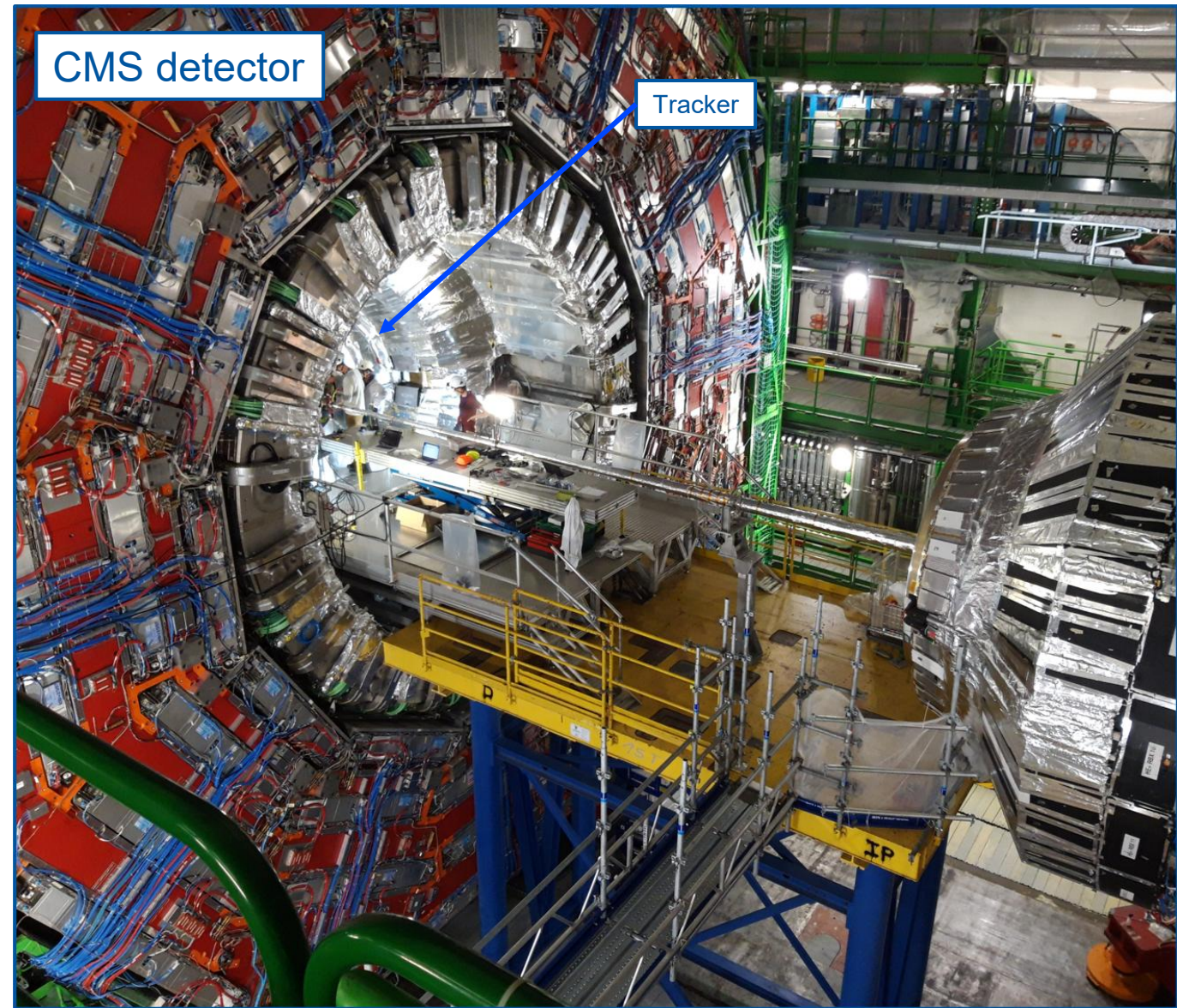


CMS Inner Tracker Service Cylinder Thermal Mockup

Joseph Moss 2025

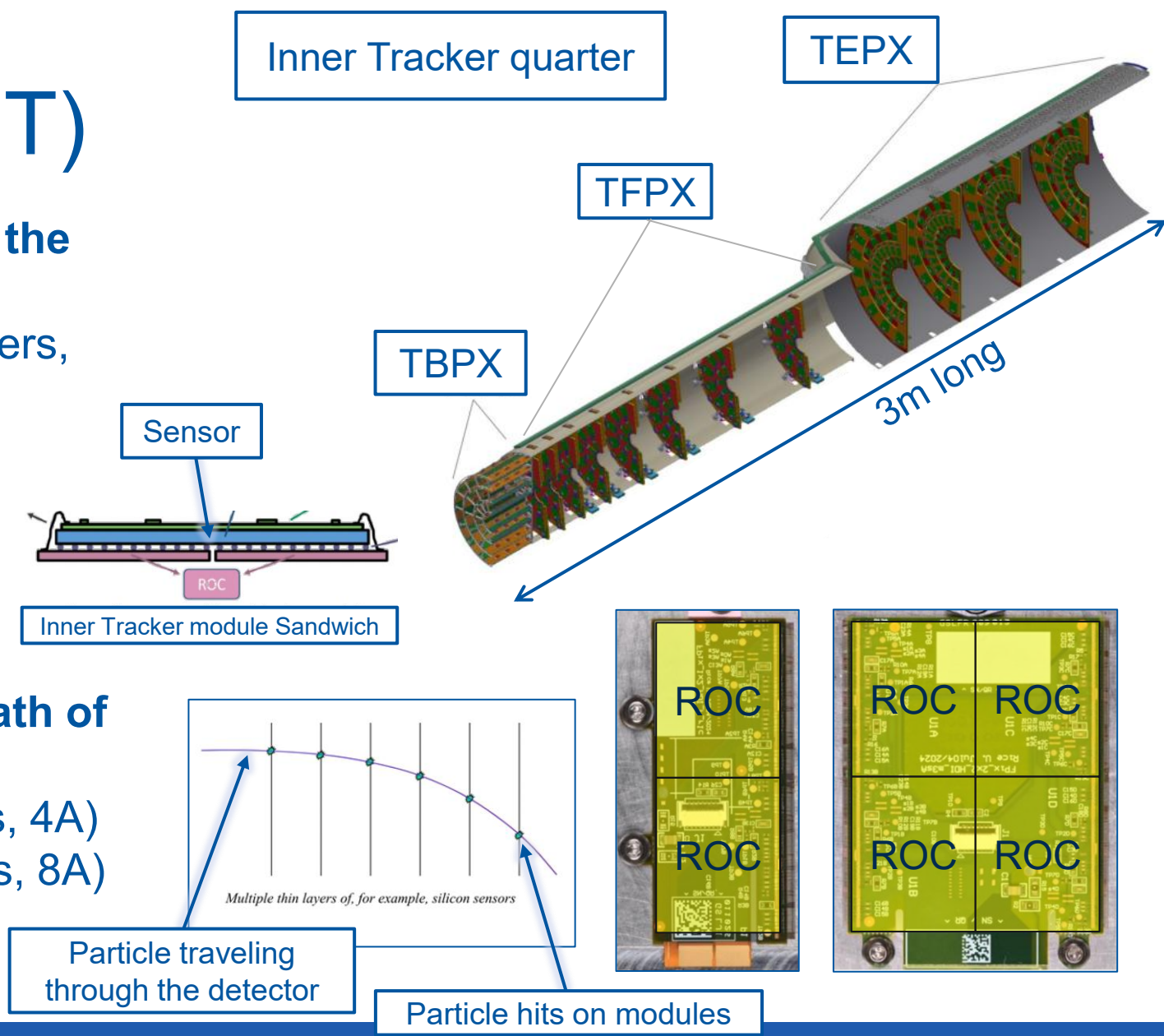
Introduction

- Who am I?
 - Joseph Moss
 - Mechanical engineering student from the University of Cambridge in the UK
 - Finished my bachelor's degree and have one year master's degree to complete this coming year.
 - Started at CERN on 30th June and will finish on 19th September.
- What have I been working on?
 - My project is looking into the thermal performance of the CMS Phase 2 Inner Tracker service cylinder.
 - This involves the design, assembly, and testing of a mockup of a segment of the inner tracker.



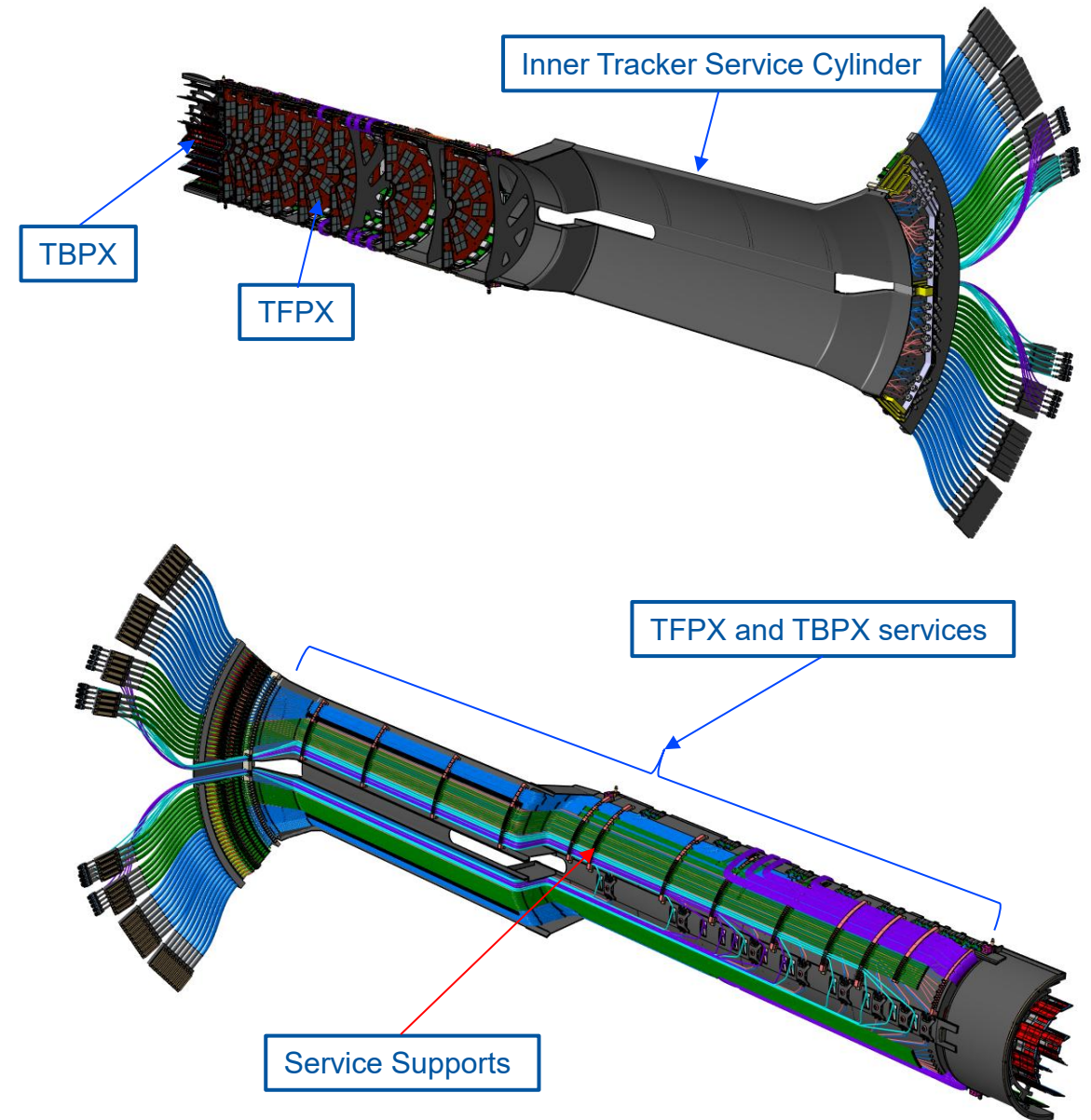
CMS Inner Tracker (IT)

- **Closest part of the CMS detector to the beam pipe**
 - Constructed from 4 identical quarters, rotated to populate a full detector
- **Comprises three sub-detectors:**
 - Tracker Barrel Pixel (TBPX)
 - Tracker Forward Pixel (TFPX)
 - Tracker Endcap Pixel (TEPX)
- **Populated with two types pixel modules sandwiches to track the path of particles**
 - 1x2 modules (two Read Out Chips, 4A)
 - 2x2 modules (four Read Out Chips, 8A)



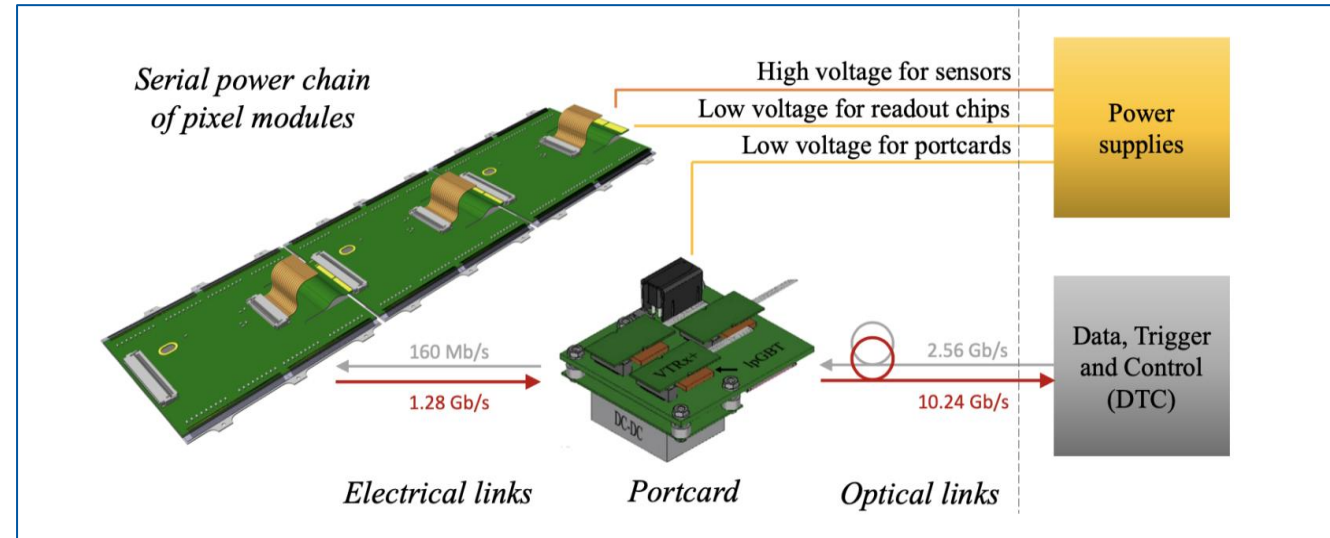
IT Service cylinder

- **Carbon fibre Service Cylinder acts as the backbone of the TBPX and TFPX detectors**
 - Must be radiation hard
 - Must minimise material budget (material choice+ quantity)
- **Services for TBPX and TFPX routed along the service cylinder**
 - Supported by dedicated service supports
- **Cover, not shown in the pictures, sits on top of the services and protects them during installation of the detector**

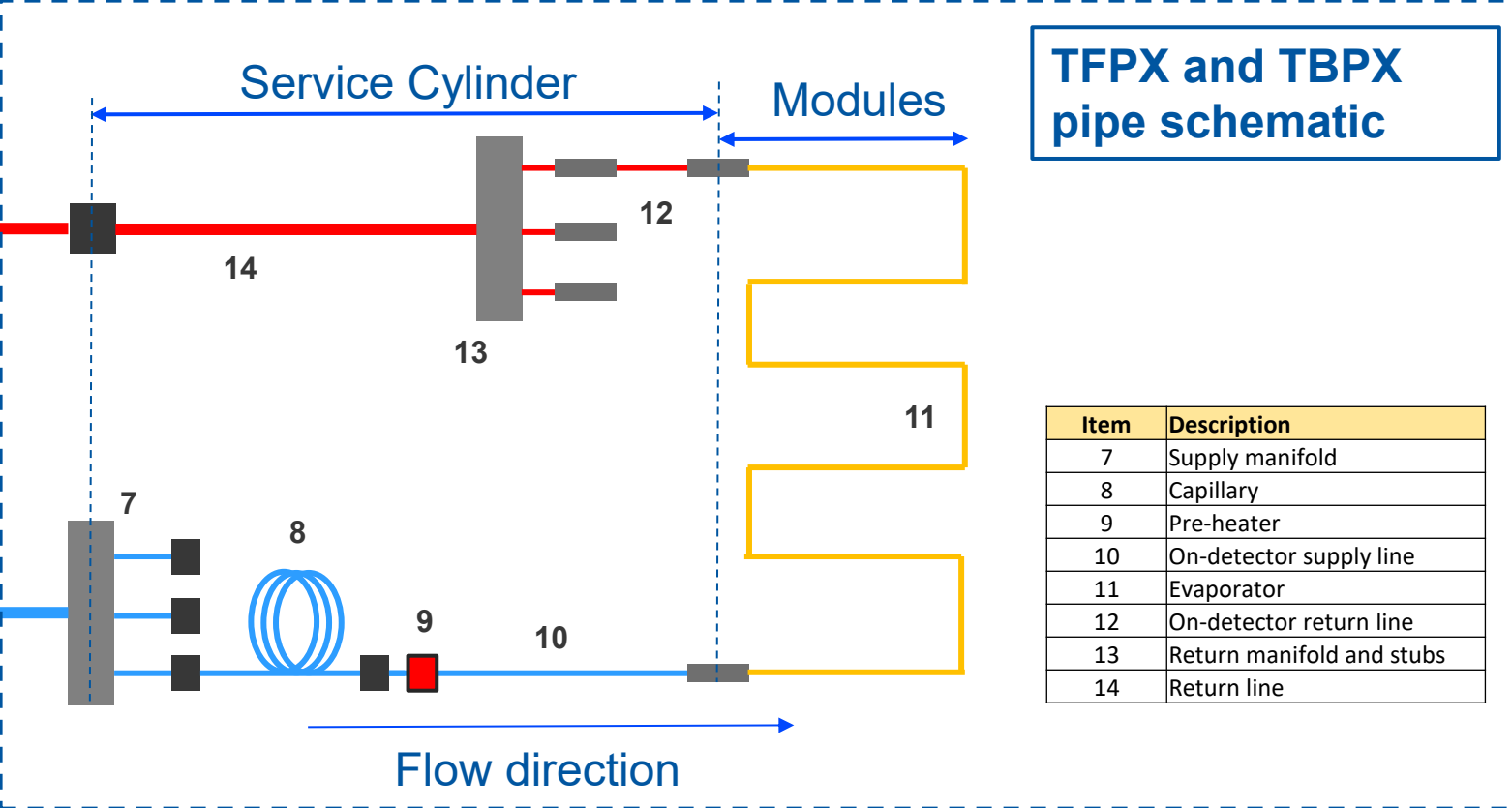


IT powering scheme

- **Inner Tracker utilises a Serial Powering (SP) scheme**
 - Multiple modules are powered in series by the same power supply and cabling
 - A constant current of 8A or 4A needs to be provided to a serial powering chain
 - Copper cladded aluminium (CCA) wires are used on the service cylinder
- **Other power services are required:**
 - Sensor bias voltage (High voltage)
 - Optoelectronics (portcard) power (Low voltage)
- **Total power dissipation of wires on the Service Cylinder around 3.45kW**
 - Mostly originates from the Serial Power chains

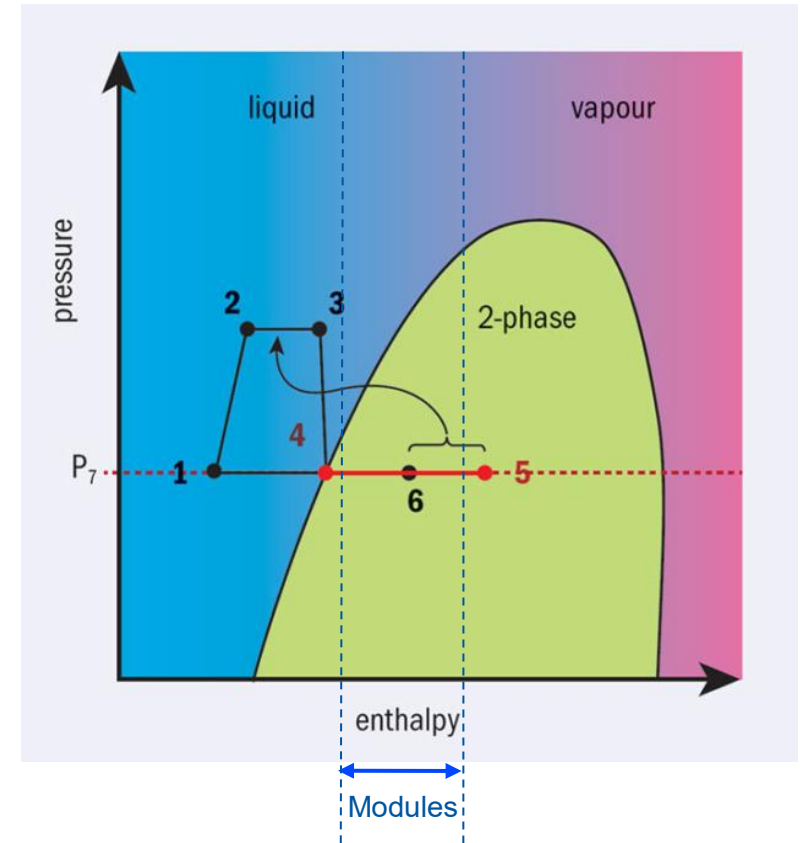


	cable power (worm + cold) [kW]	cold cable power [kW]	detector POWER [kW]	TOTAL POWER [kW]
TBPX	3.468	0.644	8.768	12.237
TEPX	8.423	1.386	19.221	27.644
IFPX	9.932	2.793	18.771	28.704
TOTAL	21.823	4.824	46.761	68.584



IT cooling scheme

2-Phase cooling schematic



- **Inner Tracker will utilize a 2-phase CO2 cooling system, targeting -35C on the modules**

- 2-phase cooling will ensure constant temperature of the modules (pipe 11)
- If energy (heat) is introduced into the cooling circuit before the evaporator, the cooling power available for the modules is reduced
- The cooled volume is flushed with -35C N2 dry-gas to avoid condensation on cold surfaces

Project objectives

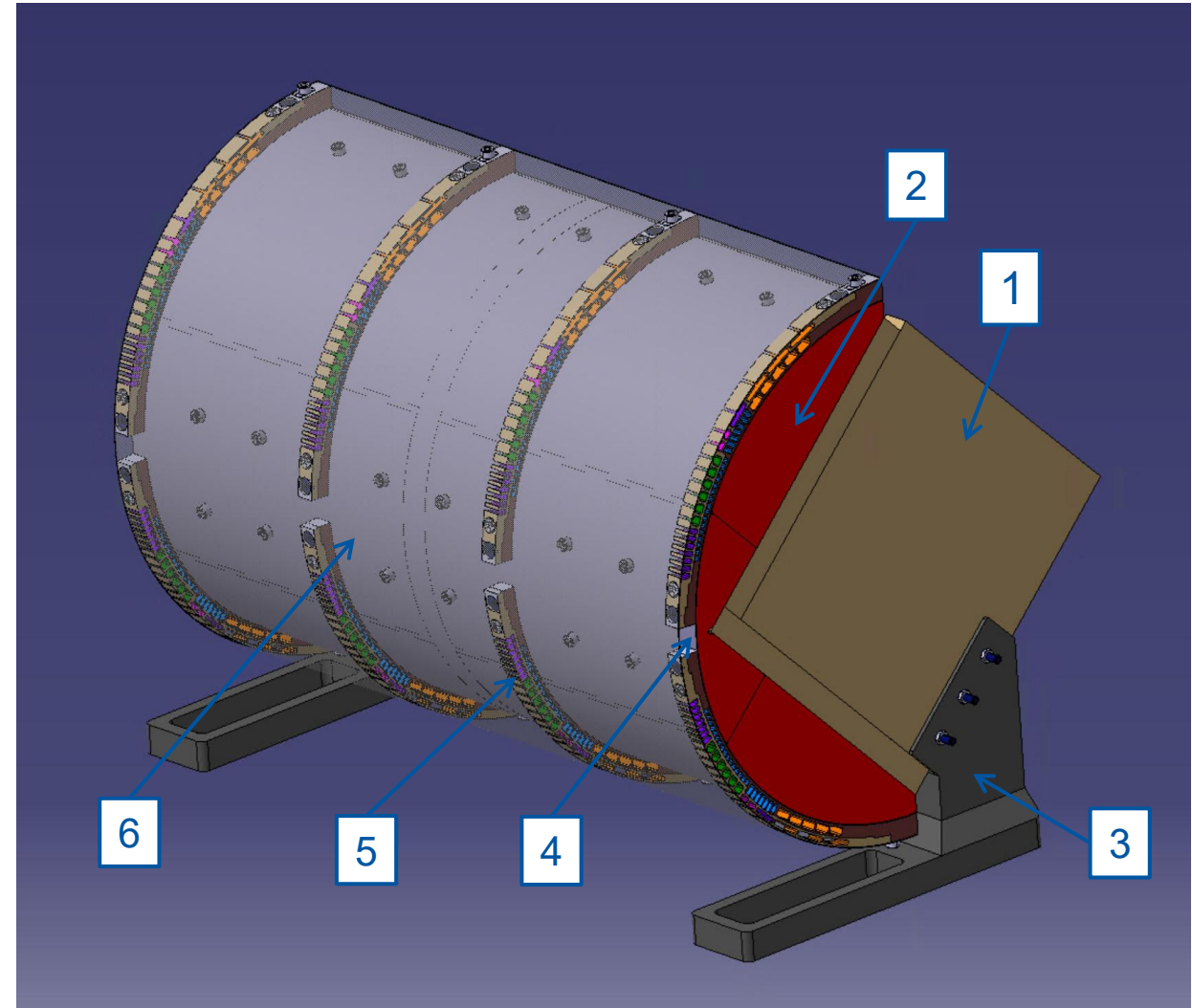
- Investigate the thermal performance of the service cylinder
 - Observe stable operating temperatures for SP-wiring
 - Understand heat pickup of the cooling system
 - Get a feeling on the thermal margins
 - Study the impact of different covers and insulations on heat transfer to surroundings and cooling system
- Design and build a 1:1 scale, 0.5m mockup of the Service Cylinder with service supports, and a cover.
- Populate the mockup with relevant services and resistance thermal detectors (RTDs).

Design considerations for mockup

- Carbon fibre vs aluminium service cylinder
 - Access to a fitting carbon fibre service cylinder was not possible within project timescales
 - Aluminium chosen for mockup service cylinder:
 1. Ease of manufacture and installation
 2. Availability and lead times
 3. Well known thermal conductivity and diffusivity
 - Drawbacks of using aluminium
 - Thermal conductivity and diffusivity of aluminium notably higher than carbon fibre
 - Wires expected to reach a lower stable temperature with an aluminium service cylinder than with a carbon fibre service cylinder
 - Possible hot-spots on the cylinder won't be as noticeable since the heat will diffuse more effectively through an aluminium cylinder
- CO2 2-phase cooling vs lab chiller
 - Chiller chosen for cooling the mockup since it will be easier to analyse of the heat pickup
- Services to include in the mockup:
 - Only include SP wires
 - Cooling tubes

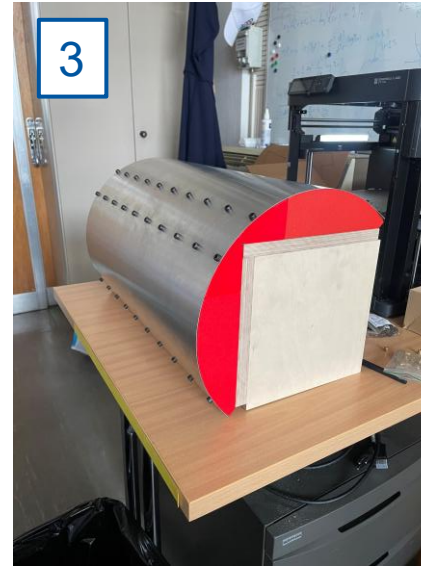
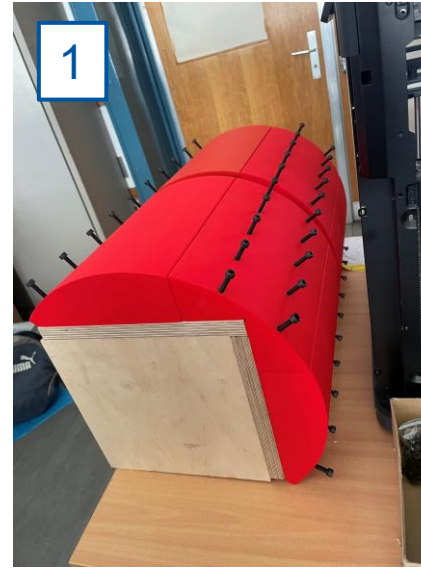
Mechanical Design

- Designed the mockup assembly using CATIA
 - Real detector design used as a reference
 - Model stored on SmarTeam and to be uploaded to PLM
- The mockup comprises the following components:
 1. Wooden base structure fastened together with wood screws
 2. Series of 3D printed parts with threaded inserts to form a mould for the service cylinder skin to lay on.
 3. 3D printed mounting feet
 4. Aluminium sheet metal Service cylinder
 5. 3D printed service supports which attach to the service cylinder and the cover
 6. Aluminium sheet metal cover



Mechanical Assembly

1. Assembly of wooden base and 3D printed cylindrical mould
 2. The service cylinder formed onto the base with bolts
 3. Service Cylinder skin fully installed
 4. Service supports and mounting feet installed
- Cover to be installed after services are installed

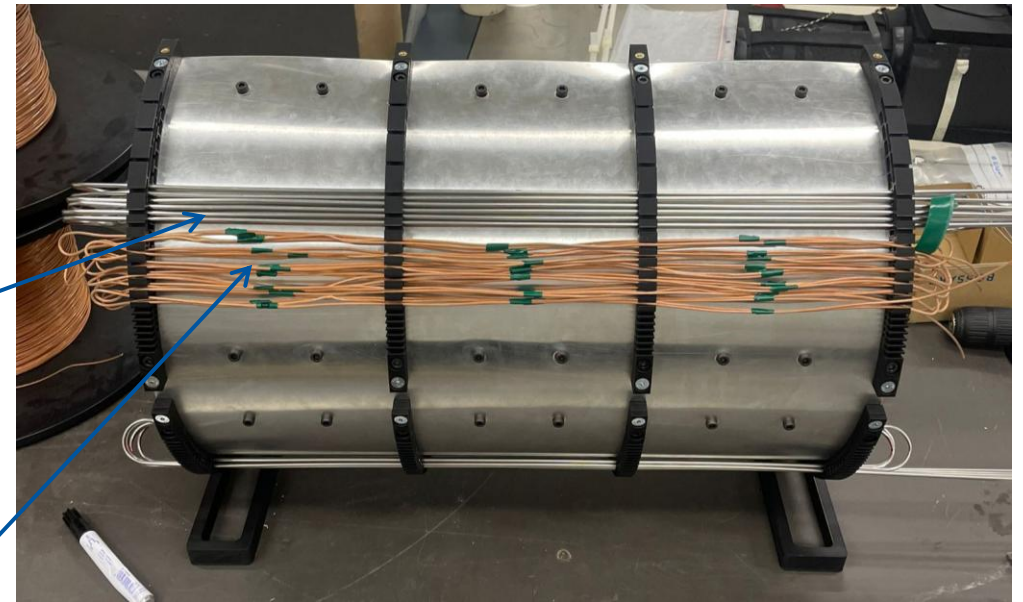


Service routing

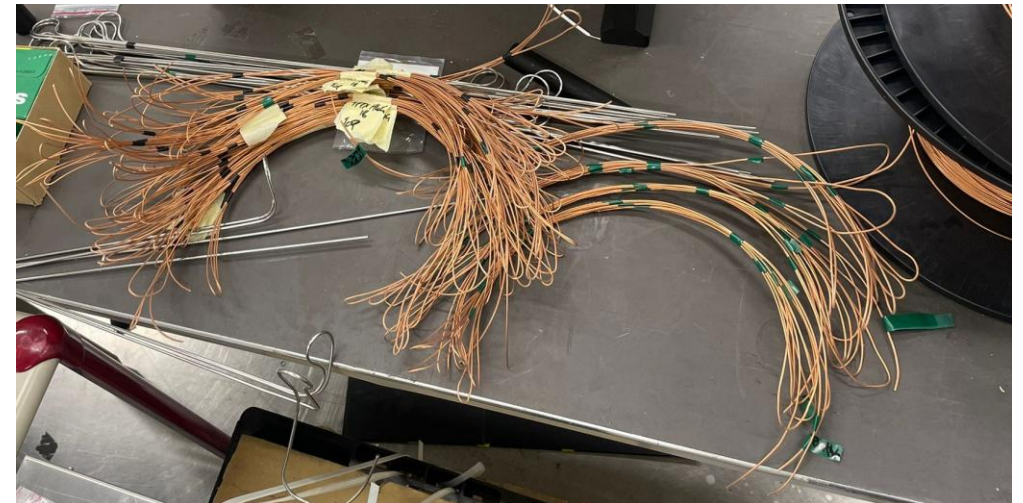
- Cooling pipes and serial power CCA wires routed back and forth with the packing currently specified for the new inner tracker
- 3mm OD, 2.5mm ID, cold-drawn seamless stainless steel tubes
- 2 channels of serial power wires
 - AWG18 wire carrying roughly 4A
 - AWG16 wire carrying roughly 8A

Single set of cooling pipes

Single set of SP wires



Wire	Area(mm2)	Actual current (A)	Current density (A/mm2)
AWG18	0.82	3.9	4.76
AWG16	1.31	7.2	5.50



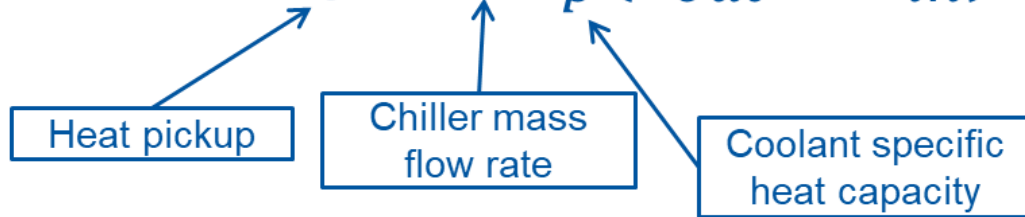
Thoughts on the testing environment

- Testing in free air, testing in a box, testing in a fridge
 - Free air testing allows the setup to dissipate heat to surrounding air, similar to the real detector being flushed with cold air, but is less repeatable and less controlled
 - An isothermic box would provide a more controlled environment, but is less representative of the real detector environment
 - A fridge would provide a "flushed" air environment, but might skew results to the optimistic direction
- Aiming to test in an isothermic box with cold dry gas flow with free air testing as a backup

Ideas for analysis

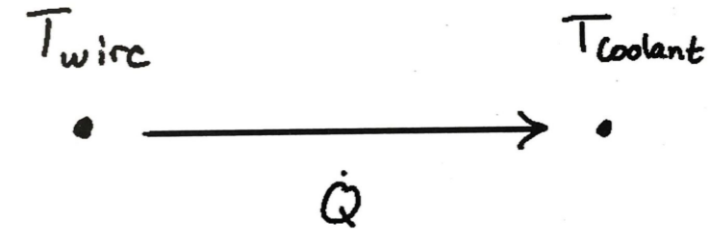
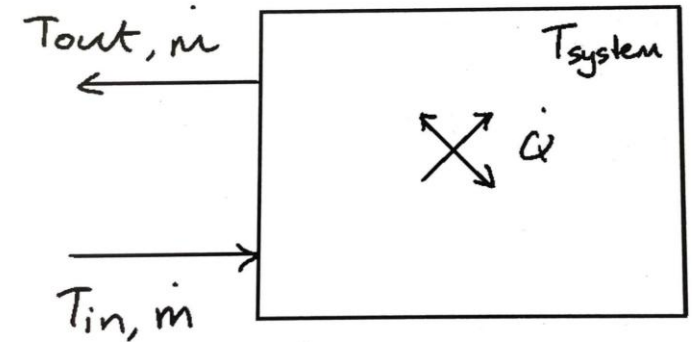
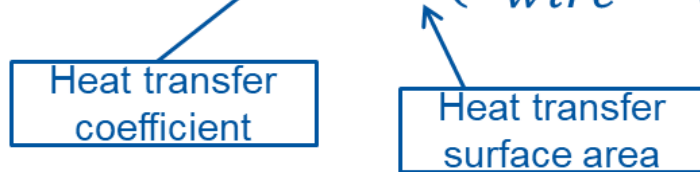
- Heat pickup from cooling pipes

- $\dot{Q} = \dot{m}c_p(T_{out} - T_{in}).$



- Heat transfer coefficient

- $h = \frac{\dot{Q}}{A(T_{wire} - T_{coolant})}$



CMS IT thermal mockup tests

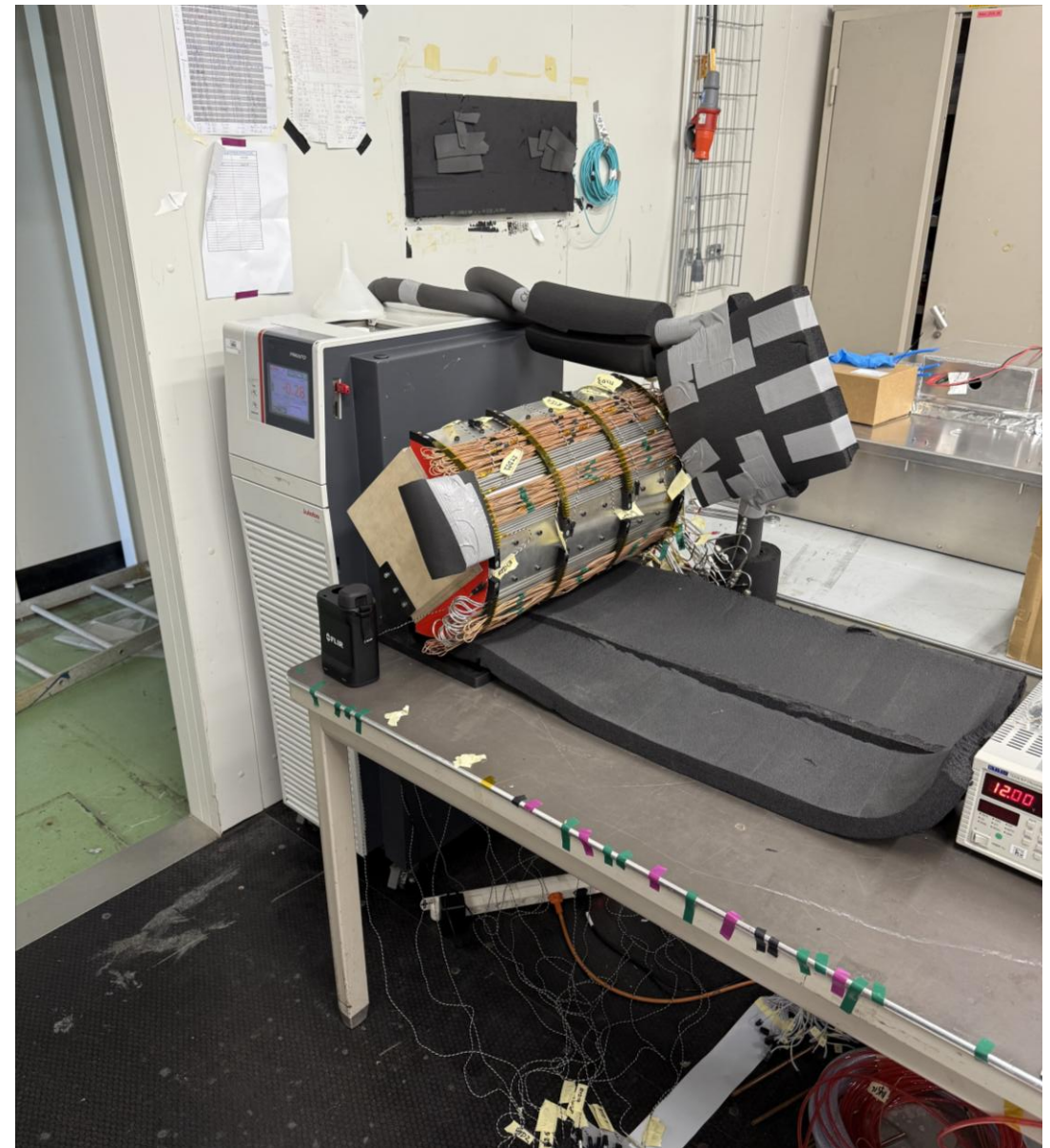
16.9.2025

Joseph Moss

Data in Sharepoint: [LINK](#)

Setup and equipment

- TFPX Service Cylinder mockup
 - As presented here: [LINK](#)
 - CAD: ST1A60214_01
- Julabo A80 two stage ethanol chiller
 - Capable of operating -45C to +40C
- Two lab power supplies
 - 8A (for AWG16 wires)
 - 4A (for AWG18 wires)
- mTRS readout system
 - 24 RTD sensors
- FLIR E75 thermal camera
- Setup run at current loads varying up to full detector power and measured:
 - Supply voltage
 - Supply current
 - Supply power
 - Temperatures



Thoughts on setup

- **Isothermic box did not arrive on time for testing**
 - Running the tests at 0-degrees to mimick the delta temperature between the detector and the ambient in real conditions inside CMS
- **Real CMS operating conditions:**
 - Detector at -35C, Ambient at -15C
- **Test operating conditions:**
 - Coolant at 0C, Ambient at 20C

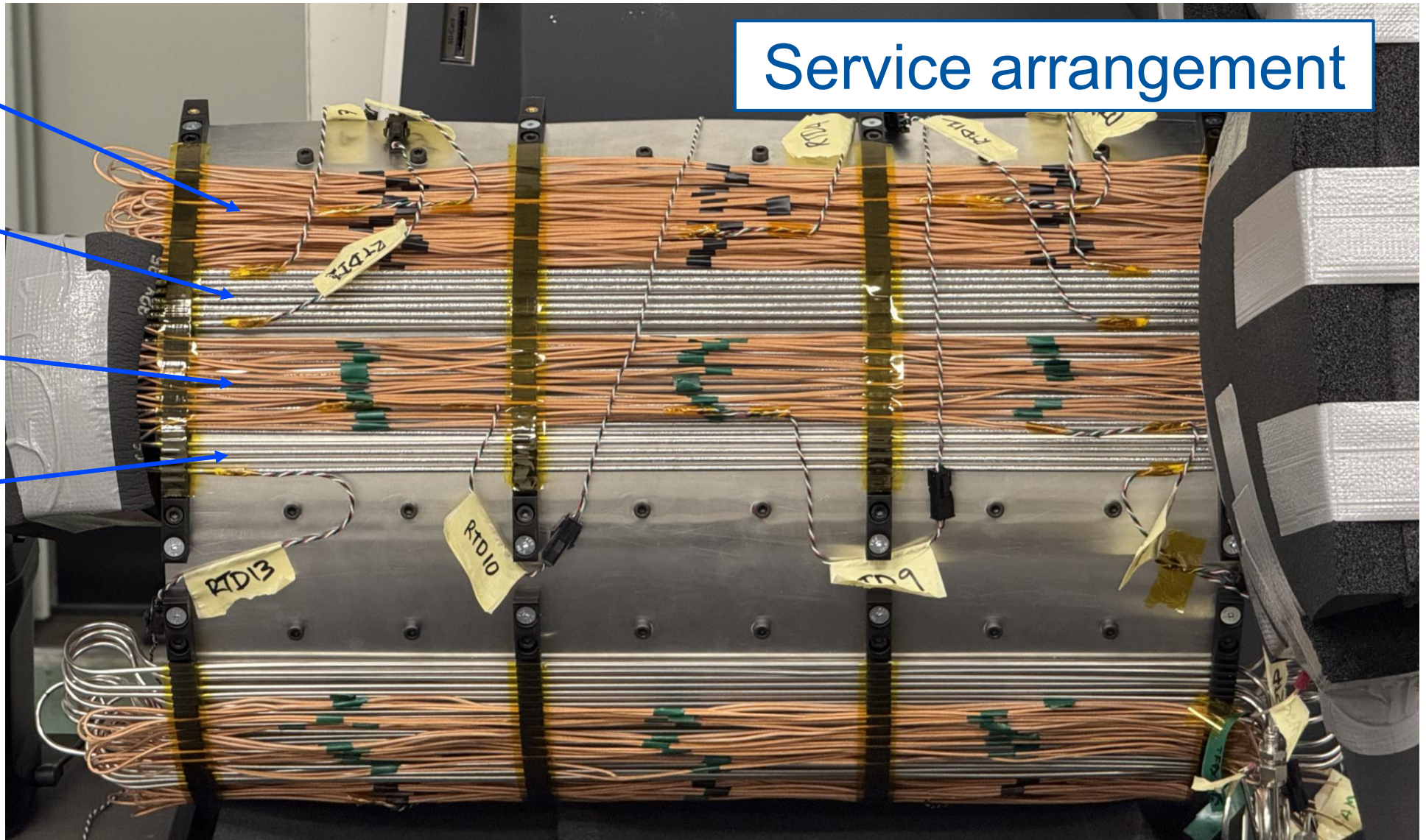
TFPX wires

TBPX pipes

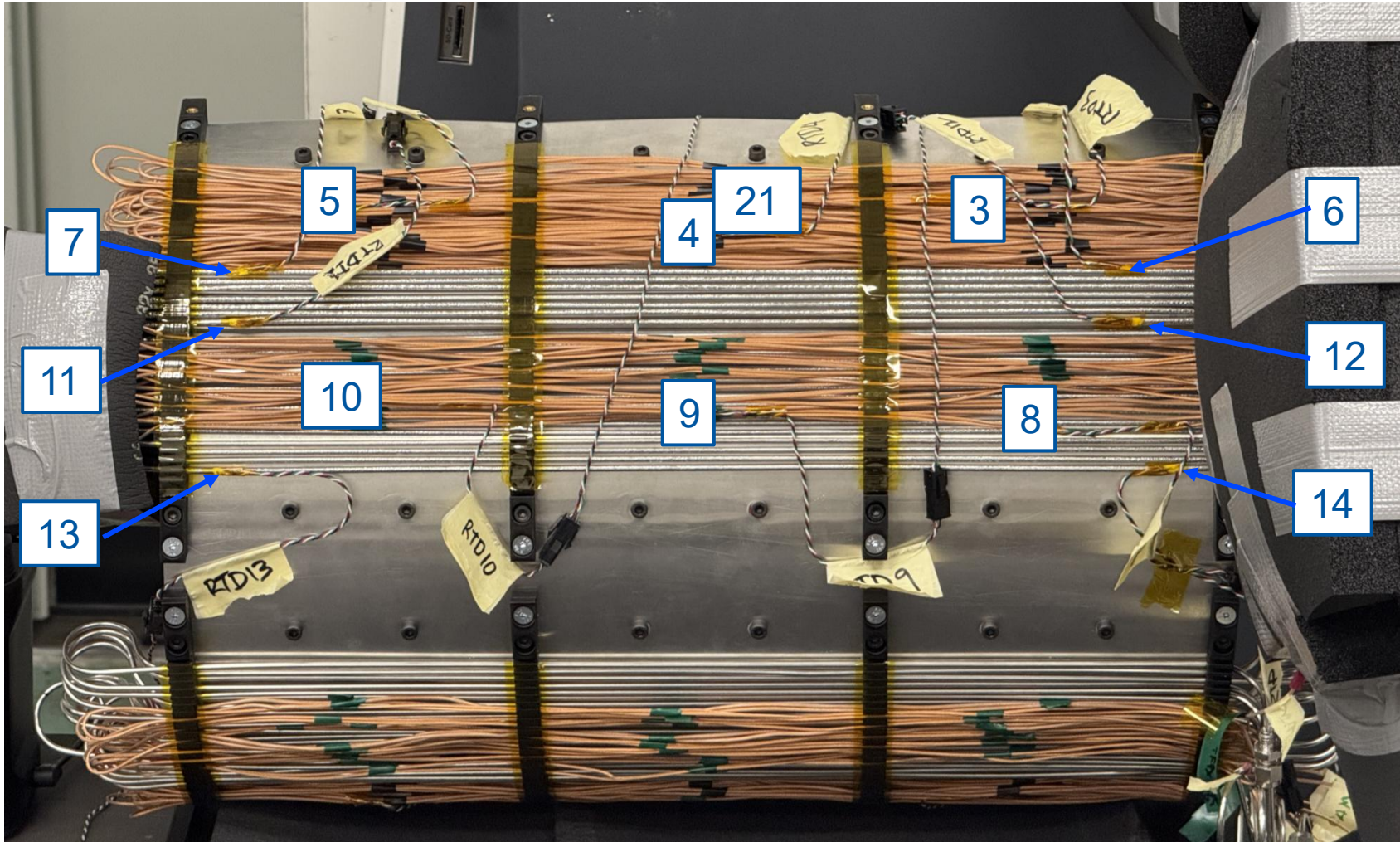
TBPX wires

TFPX pipes

Service arrangement



RTD positions



Wire RTDs

- 1: AWG 16 wire in
- 2: AWG 18 wire in
- 3: TFPX wire bundle
- 4: TFPX wire bundle
- 5: TFPX wire bundle
- 8: TBPX wire bundle
- 9: TBPX wire bundle
- 10: TBPX wire bundle

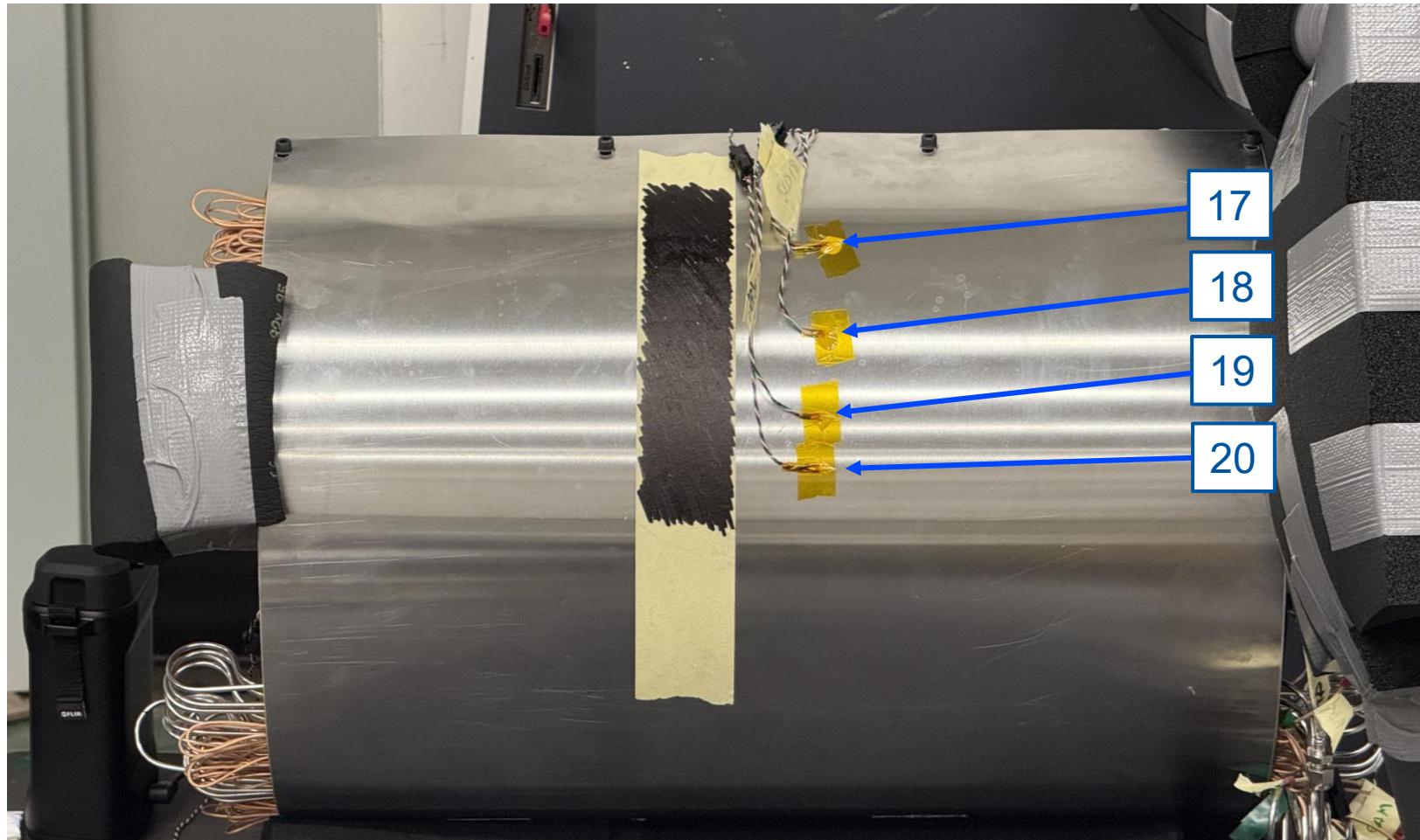
Cooling RTDs in flow order

- 23: Chiller supply
- 6: TBPX 1
- 7: TBPX 2
- 11: TBPX 3
- 12: TBPX 4
- 13: TFPX 1
- 14: TFPX 2
- 24: Chiller return

Extra

- 21: Warmest point
- 22: Room ambient

RTD positions cont.

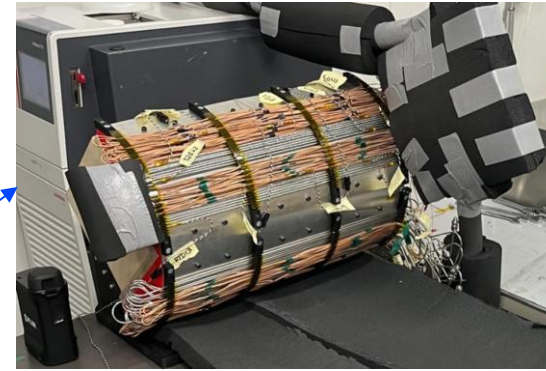


Cover RTDs

- 17: TFPX wire bundles
- 18: TBPX pipes
- 19: TBPX wire bundles
- 20: TFPX pipes bundle

Tests performed

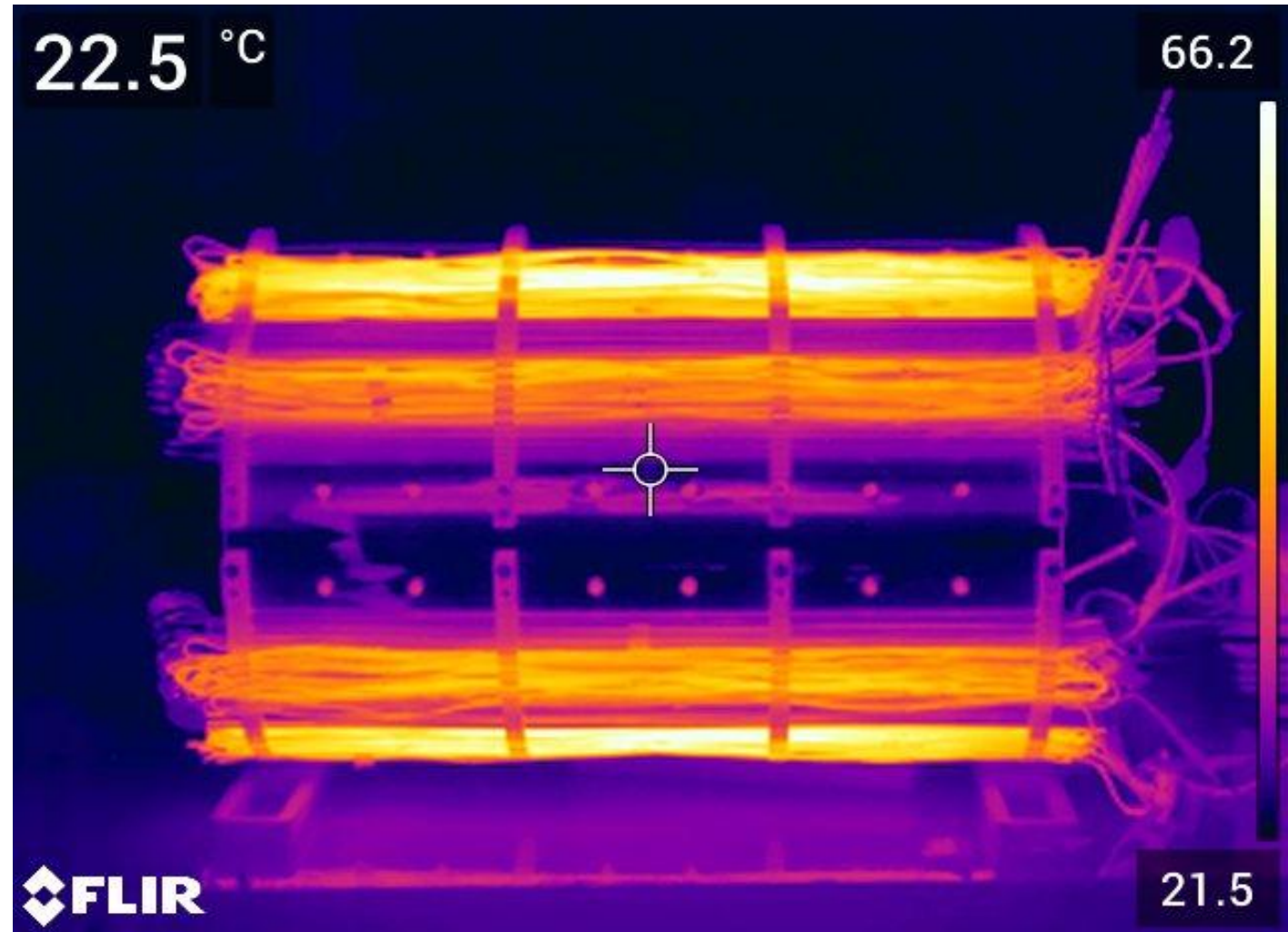
- Preliminary tests with no cooling using thermal camera
- Run 1: No cover
- Run 2: Cover
- Run 3: Cover with insulation



Preliminary test

Preliminary tests: No cooling, thermal camera

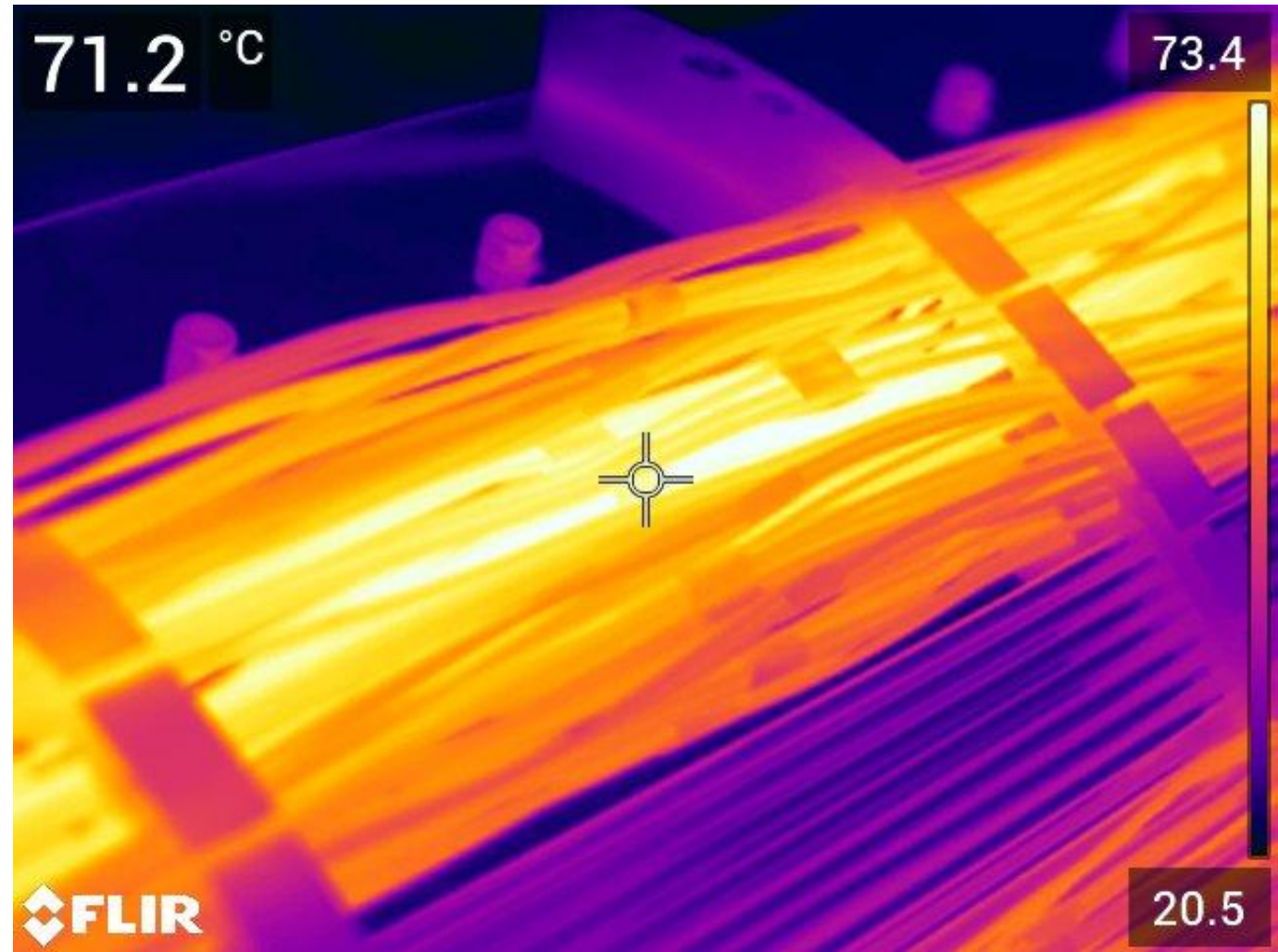
- Setup function test and initial impressions
- Larger bunches of wires reach higher temperatures
- Significant temperature delta above ambient conditions



Thermal image of setup at full power load. No cooling

Preliminary tests: No cooling cont.

- Hottest point in the bundle of TFPX wires at the top of the cylinder
- Maximum temperature observed with thermal camera is roughly 75 degrees.
 - Max wire operating temperature is 100 degrees
- Ambient temperature roughly 20 degrees
- Temperature delta of roughly 55 degrees (quite high)



Characterisation of heat transfer (no cooling)

- Once the system has reached steady state, all heat from the wires is being transferred to the surroundings. The heat transfer is modelled with the following equation:

$$\dot{Q} = \underbrace{h_r(T_w^4 - T_a^4)}_{\text{Radiative heat transfer}} + \underbrace{h_c(T_w - T_a)}_{\text{Conductive and convective heat transfer}}$$

$\dot{Q}$ = Heat output of SP wires
 T_w = Maximum wire temperature
 T_a = Ambient temperature
 h_r = Radiative heat transfer coefficient
 h_c = Conductive and convective heat transfer coefficient

$$\frac{\dot{Q}}{T_w - T_a} = h_r \frac{T_w^4 - T_a^4}{T_w - T_a} + h_c$$

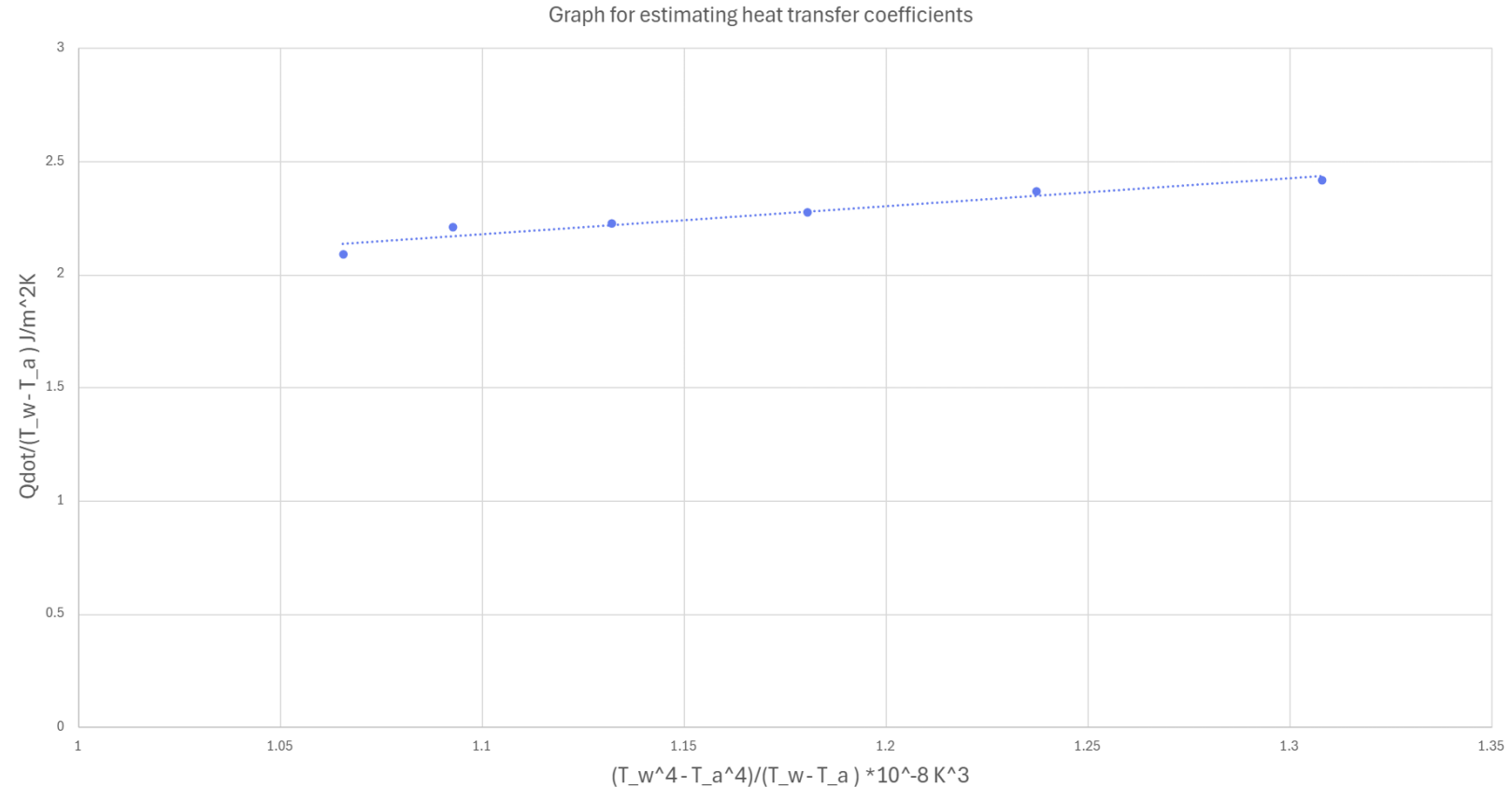
$$y = m x + b$$

Equation of straight line
(assuming heat transfer
coefficients are constant)

- If heat transfer coefficients are known, the proportion of the heat which is transferred by radiation and conduction/ convection can be calculated.

Calculation of heat transfer coefficients

- Linear trend observed with an R^2 value of 0.935 indicating that the HTC's are constant over varying power loads
- Values:
 - Radiative HTC:
 $1.22 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$
 - Conductive/convective HTC:
 $0.831 \text{ W/m}^2 \text{ K}$
- Heat transfer is roughly 60% radiation and 40% conduction and convection
- Can expect the temperatures to increase with a cover



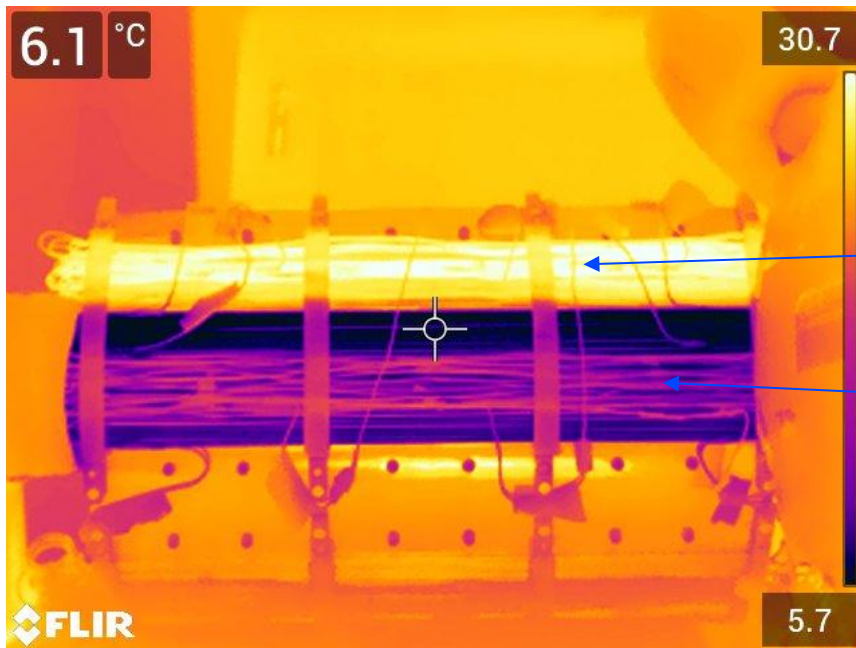
RTD runs (fresh data from 15.9.2025)

Run 1, No cover

- Chiller parameters
 - Coolant temp: 0deg
 - Pump pressure: 2 bar
- Running top half of the cylinder



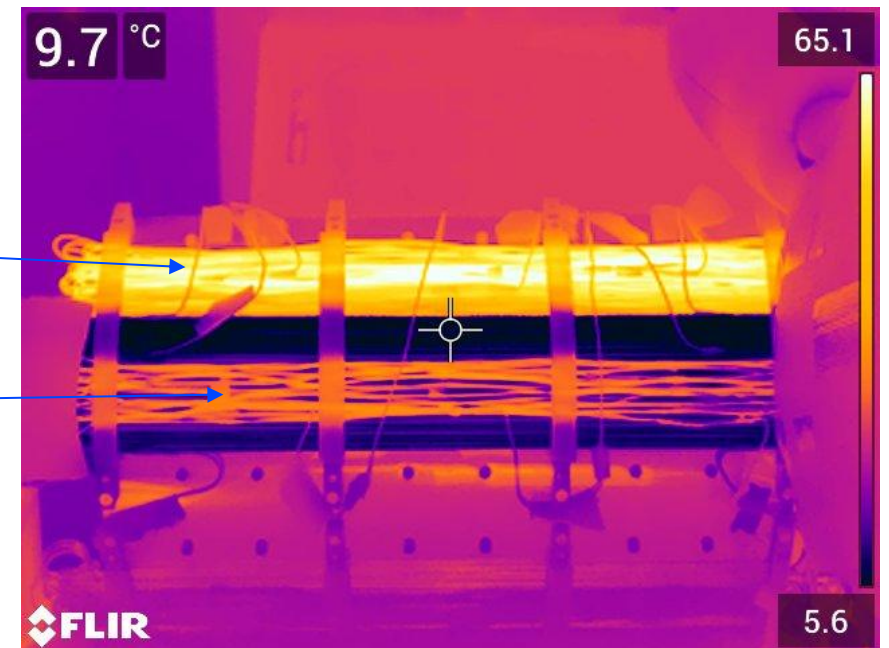
Run 1: With cooling, no cover



Half current load

TFPX wires

TBPX wires



Full current load

- TFPX wires reach much higher temperature than TBPX wires
- TBPX wires in direct contact with pipes at significantly lower temperature than those which don't

Run 1 wire temperature plot

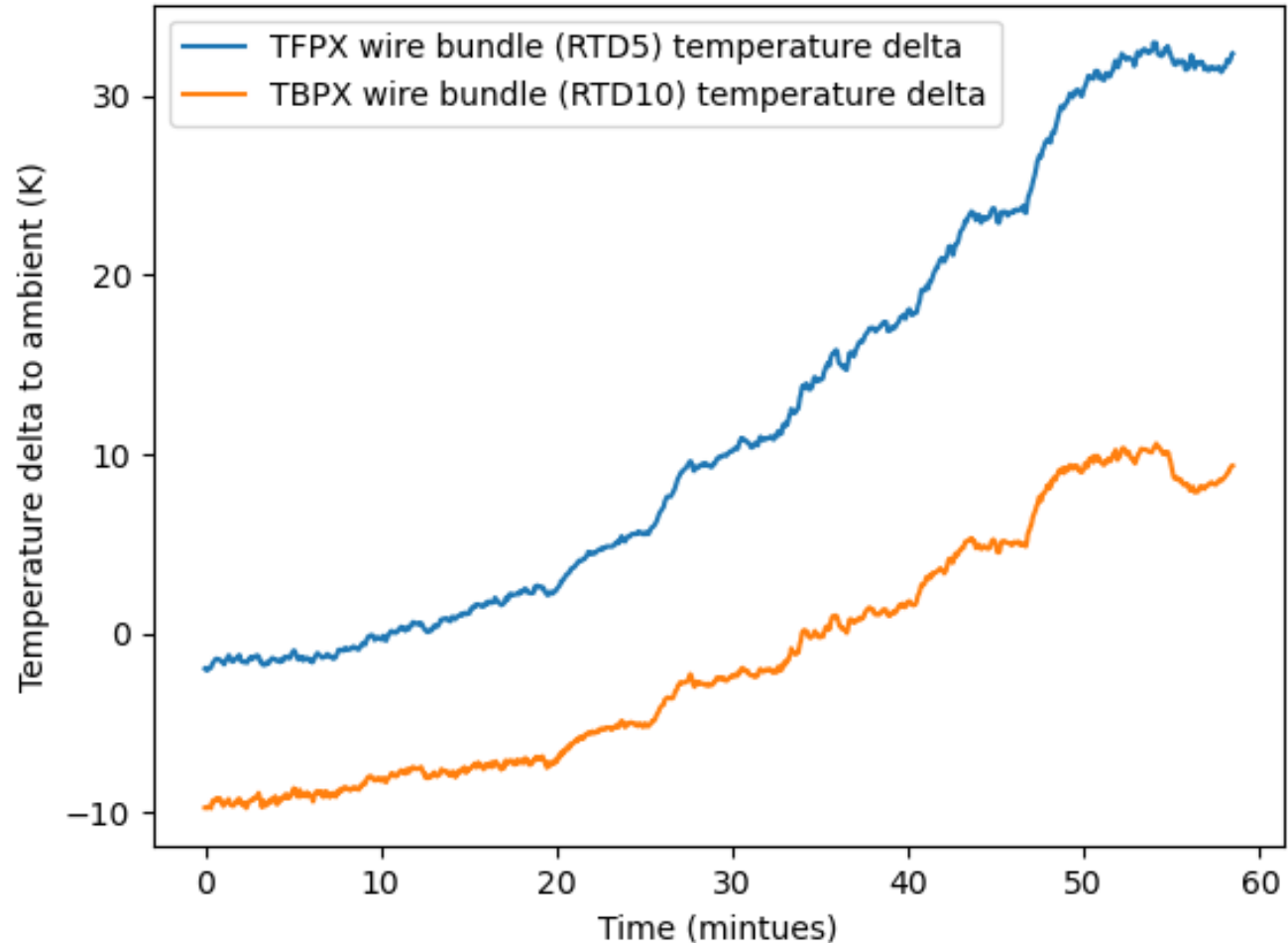
TFPX wires in proximity of TBPX pipes run much warmer

- Starting at ambient temperature
- Reaching a maximum of 30C above ambient
- Delta of 30C

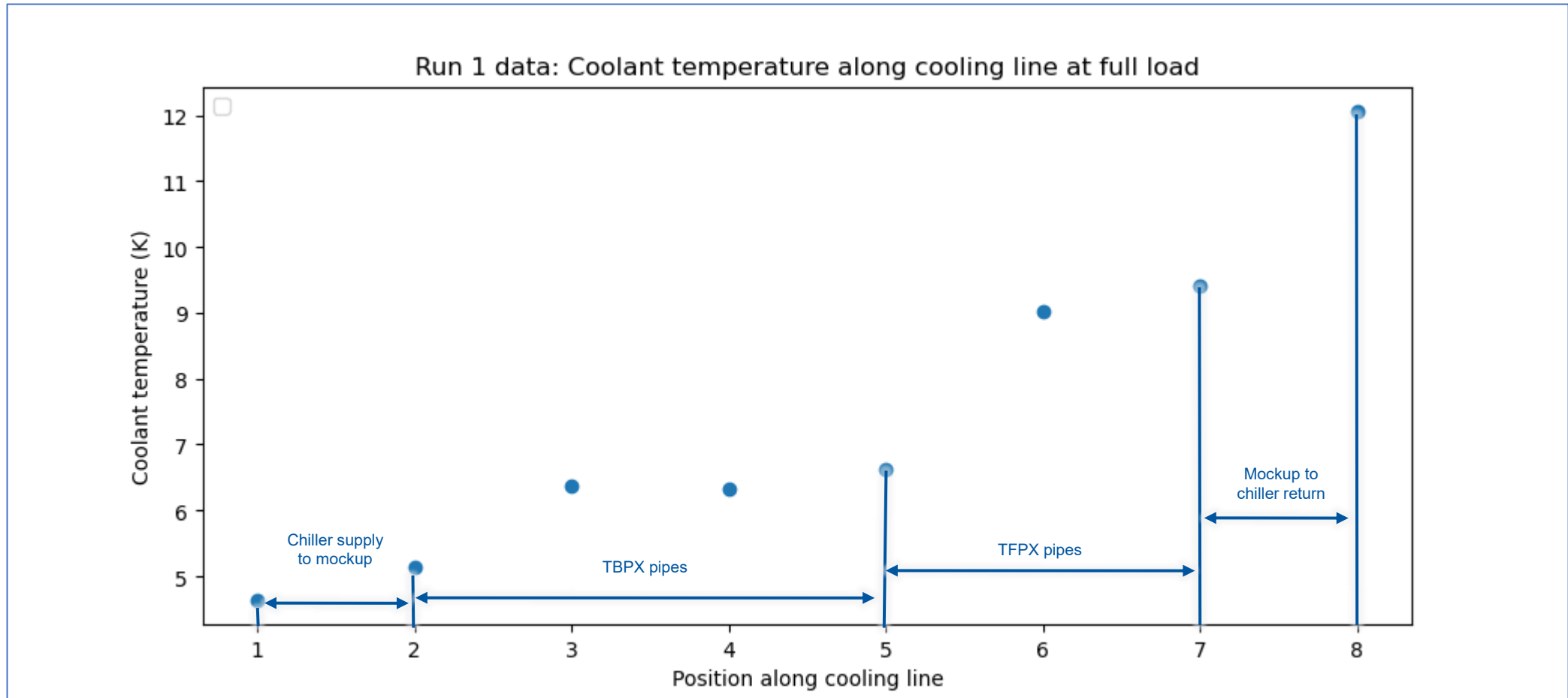
TBPX wires on top of TFPX cooling pipes run cool

- Starting at 10C below ambient
- Reaching max 10C above ambient
- Delta of 20C

Run 1 data: TFPX and TBPX wire bundle temperature deltas

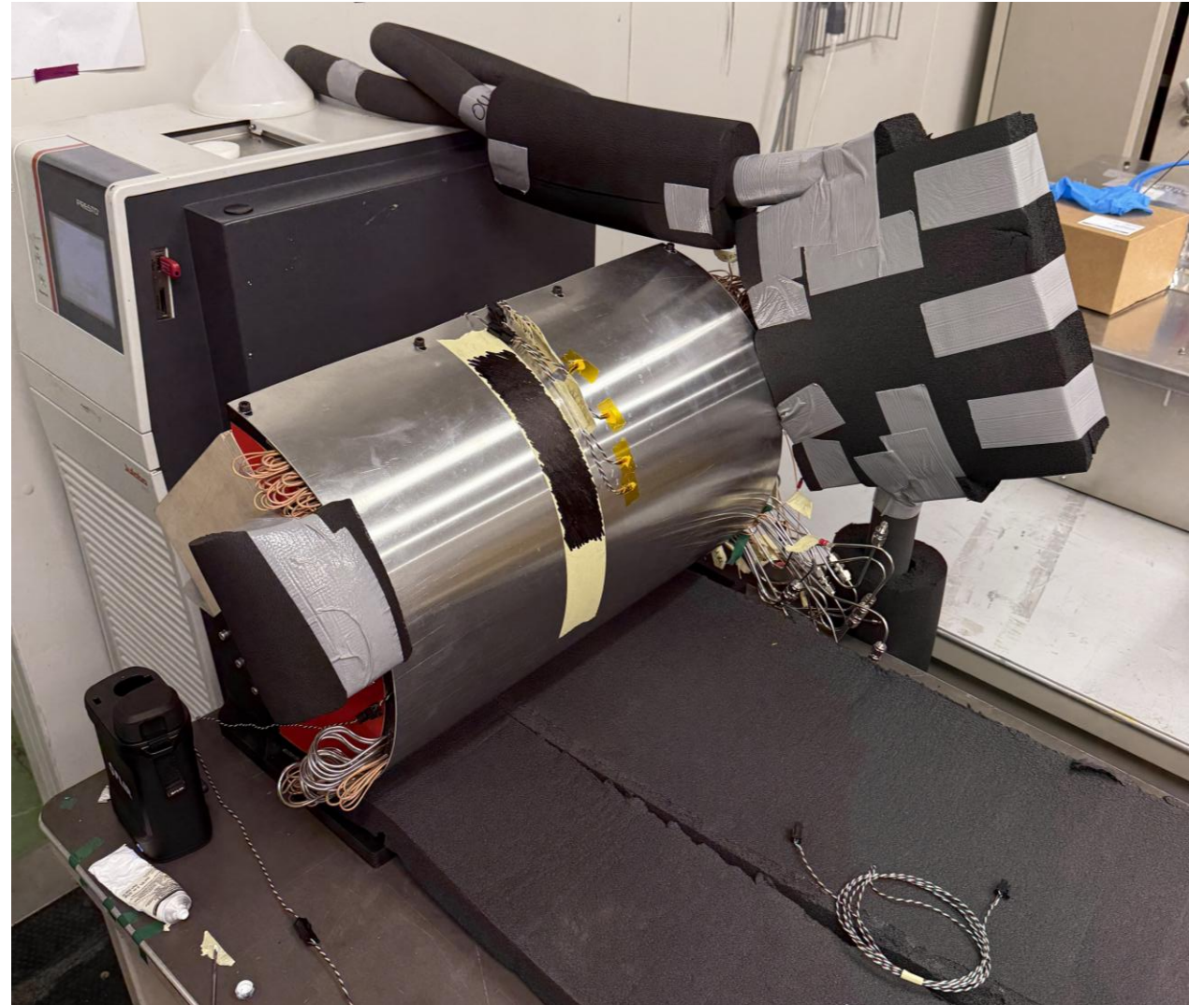


Run 1 coolant plot

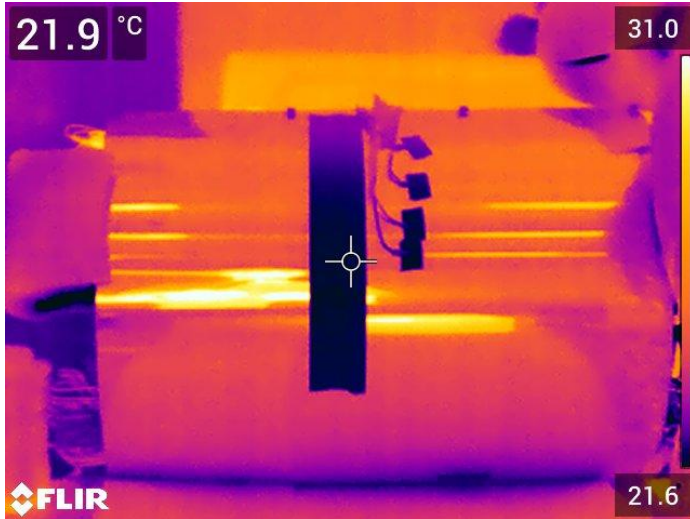


Run 2, Cover

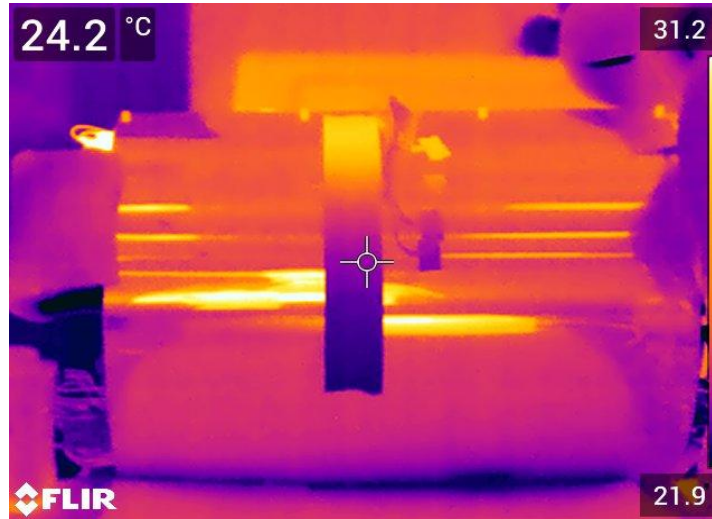
- Chiller parameters
 - Coolant temp, 0deg
 - Pump pressure, 2bar
- Running top half of the cylinder



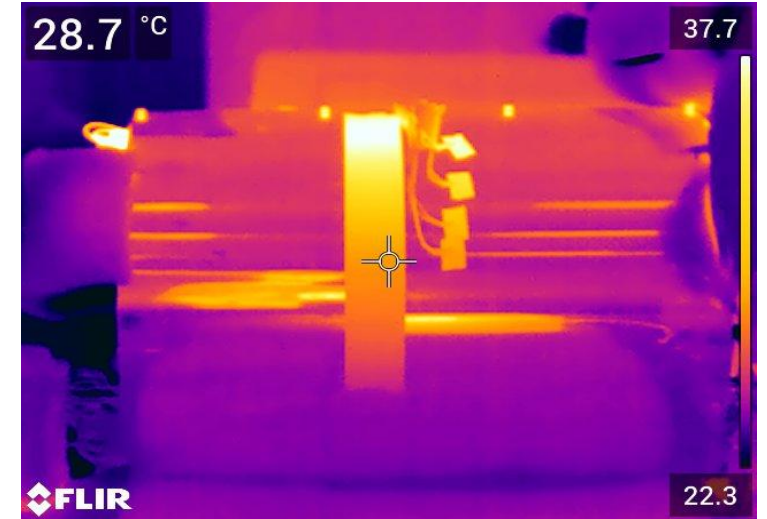
Run 2: With cooling and cover



Half current load



$\frac{3}{4}$ current load



Full current load

- Line of masking tape added to allow FLIR camera to measure temperatures on the surface of the cover
- Significant temperature gradients observed on cover
- Note that aluminium is much more conductive than carbon fibre. Temperature gradients on detector cover will be more severe

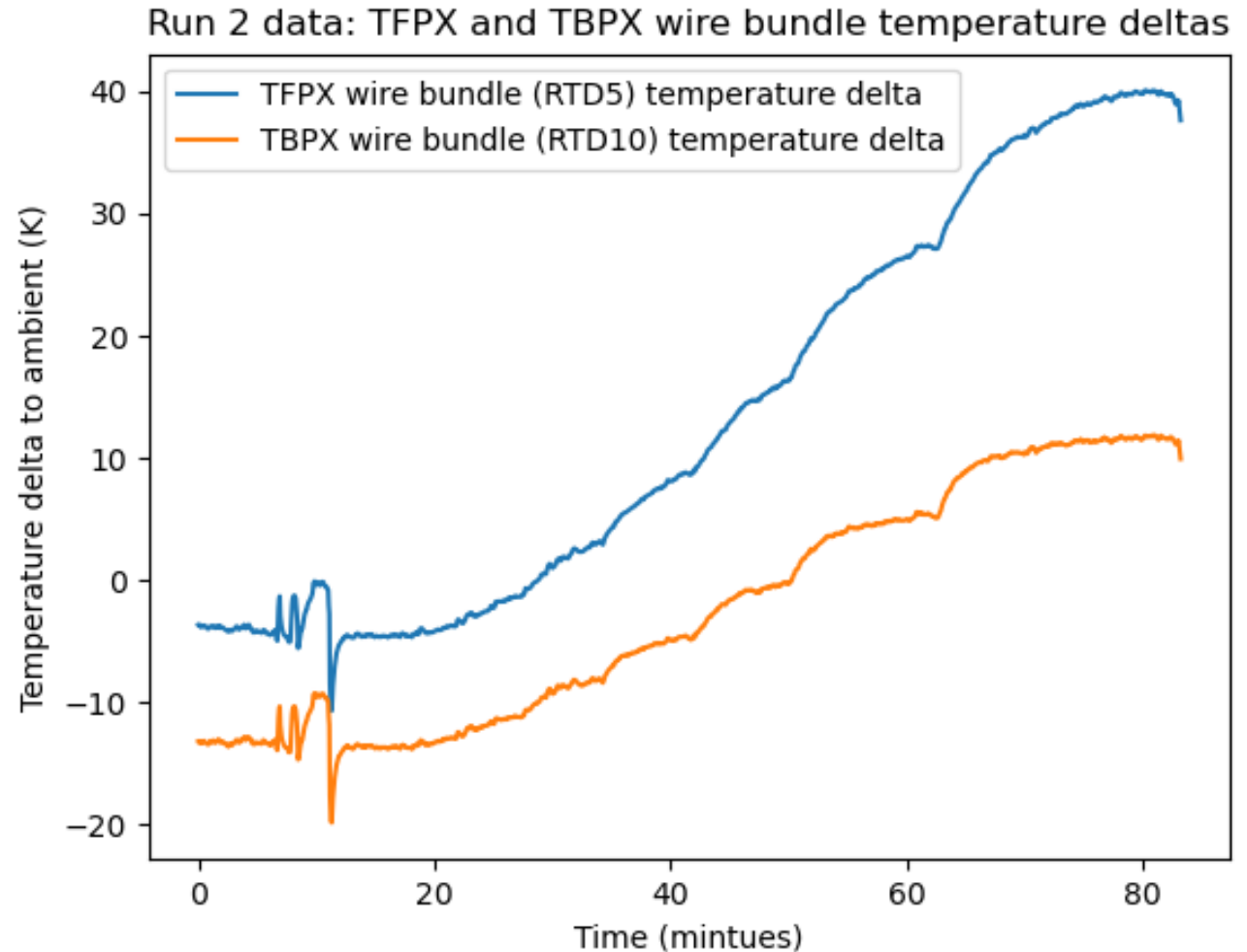
Run 2 wire temperature plot

TFPX wires in proximity of TBPX pipes run much warmer

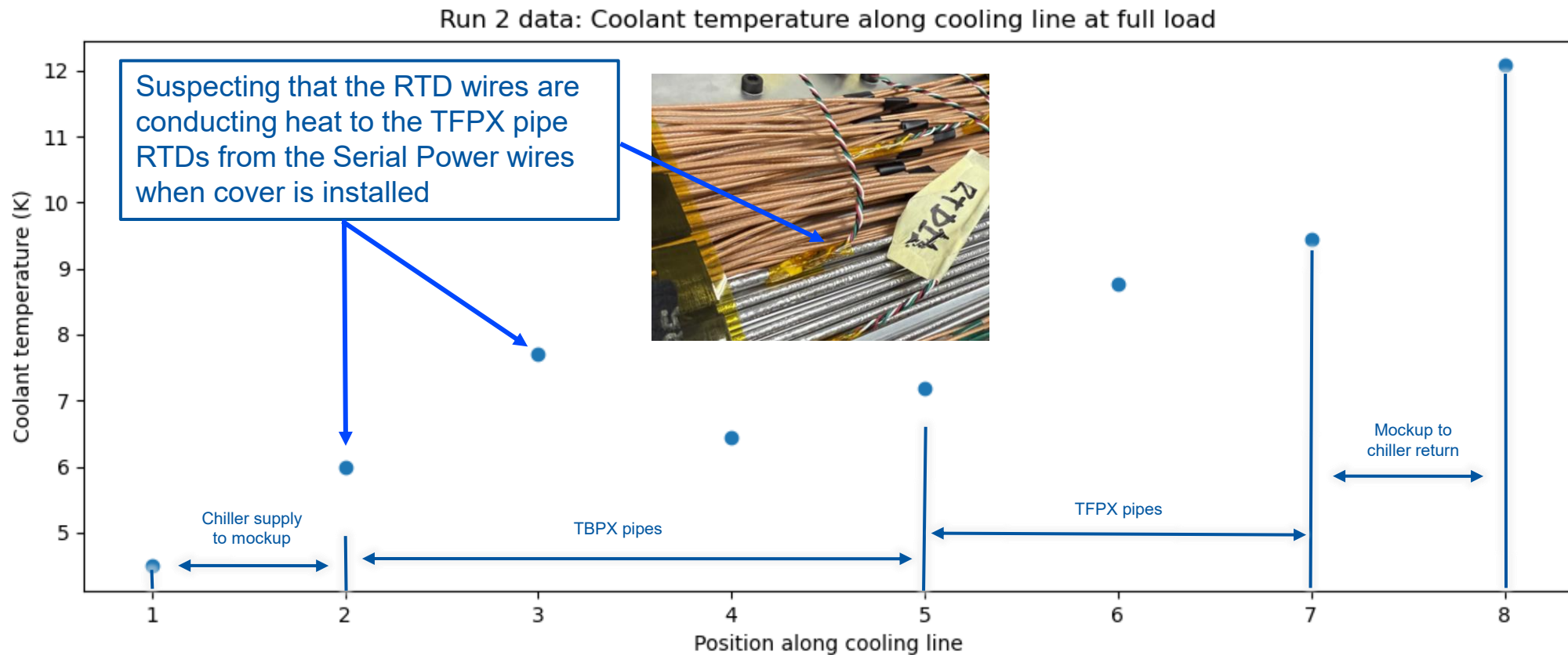
- Starting at 5C below ambient
- Reaching a maximum of 40C above ambient
- Delta of 45C

TBPX wires on top of TFPX cooling pipes run cool

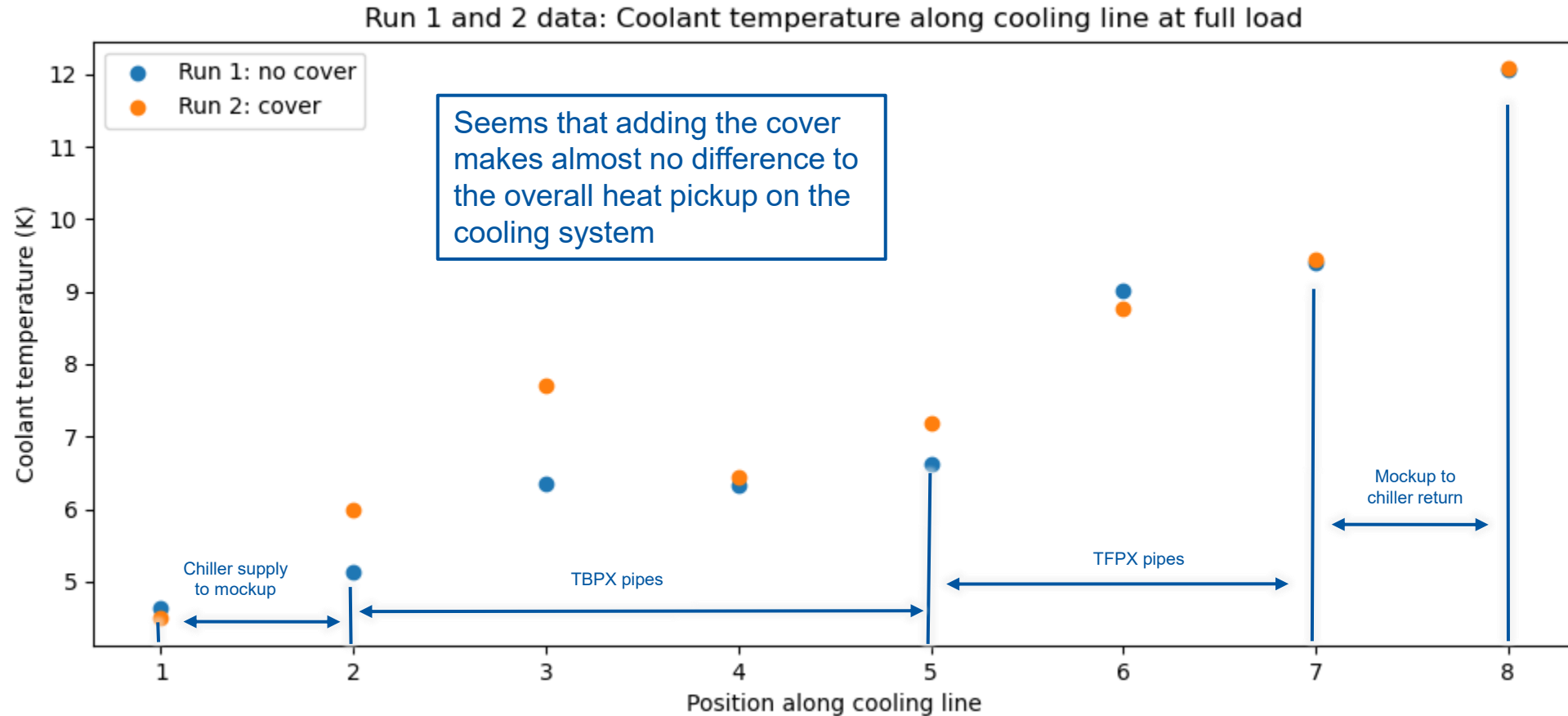
- Starting at 15C below ambient
- Reaching max 10C above ambient
- Delta of 25C



Run 2 coolant plot



Run 1 and 2 coolant plots overlap



Conclusions

- **Only wires that are in extremely close proximity to the pipes stay at reasonable temperatures**
 - TBPX wires stay cool due to proximity of TFPX cooling pipes
 - TFPX wires get very hot as no cooling pipes are in the proximity
 - Adding the cover seems to emphasize the effect when under load
- **Some concerns follow:**
 - The mockup is using a highly conductive Service Cylinder and Cover
 - Results will only get worse when switching to the real TFPX Service Cylinder

Next steps

- Analyse data from RTDs for runs 1, 2, and 3
- Repeat preliminary tests with RTDs to recalculate HTC's from heat transfer model
- Expand heat transfer model to take cooling into account
- Source a flow meter to calculate heat pickup