Systematic Uncertainties in the lH2 Absorber

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Aims

Determine the systematic uncertainties of the lH2 absorber including:

- Warm absorber bore contraction as it is cooled
- Deflection of absorber windows due to pressure
- Effect of lH2 weight on the absorber windows
- Smoothness of absorber windows (thickness variance)
- Ortho/Para Hydrogen
- Change in lH2 density for varying temperatures/pressures
- Accuracy of temperature/pressure sensors

Information follows on from MICE note 155 by Michael Green and Stephanie Yang who investigated similarly in 2006

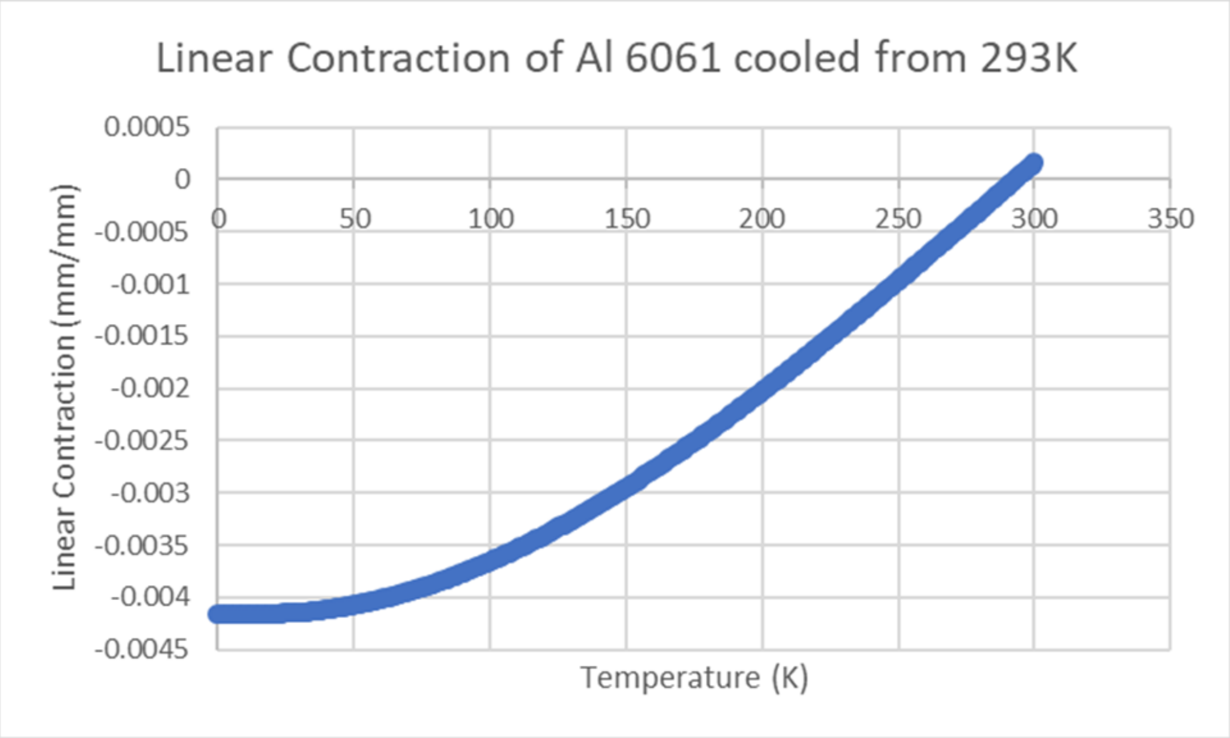
Absorber Vessel Contraction

As the vessel is cooled from room temperature, the linear contraction is:

$$\alpha = -4.1277 \times 10^{-3}\, T - 3.0389 \times 10^{-6}\, T^2 + 8.7696 \times 10^{-8}\, T^3 - 9.9821 \times 10^{-11}\, T^4$$

where

T = Operating Temperature



Line fit from data collated by NIST (US National Institute of Standards and Technology)

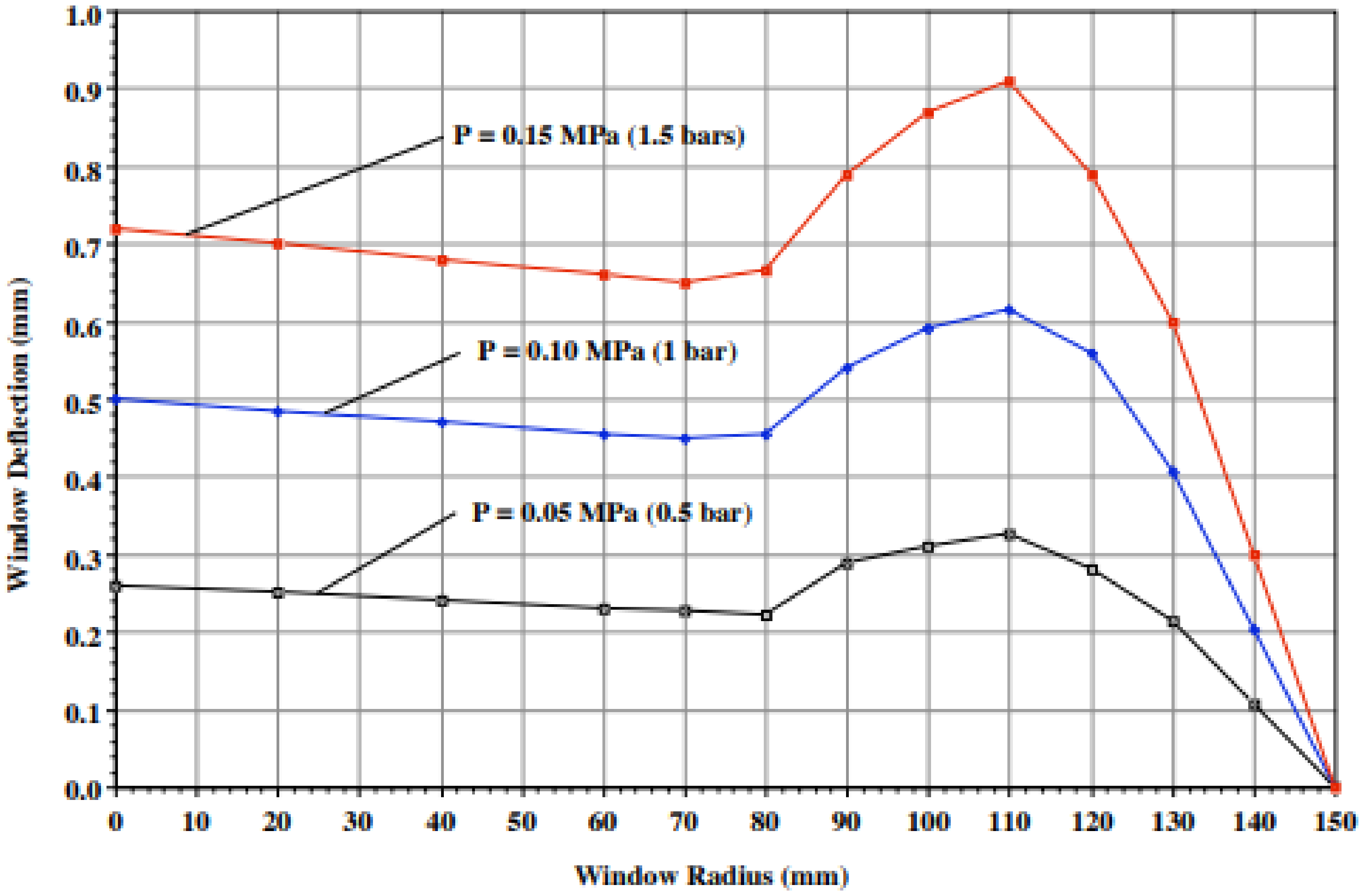
Al 6061 absorber contraction

- When cooled from 293K to the MICE operating temperature the vessel shrinks 0.415% along each plane (4% curve fit error)
- The vessel is held suspended in place meaning it is free to contract uniformly along each plane
- Vessel supports may rotate slightly on contraction
- However, a rotation as high as 0.5º would only result in a path length reduction of 0.0038% through the liquid Hydrogen

Central warm bore length contraction:

350mm * 0.00415 = 1.4525mm (±4%)

Deflection of Absorber Windows due to pressure



- ANSYS model from Green and Yang
- Uncertainty in deflection up to 20%, although they believe far smaller
- Linear expansion with pressure up to 2 Bar before window begins to yield
- Measured Mice operating pressure: 1085 ± 5 mBar

Deflection at window centre:

0.5374 ± 0.1098mm

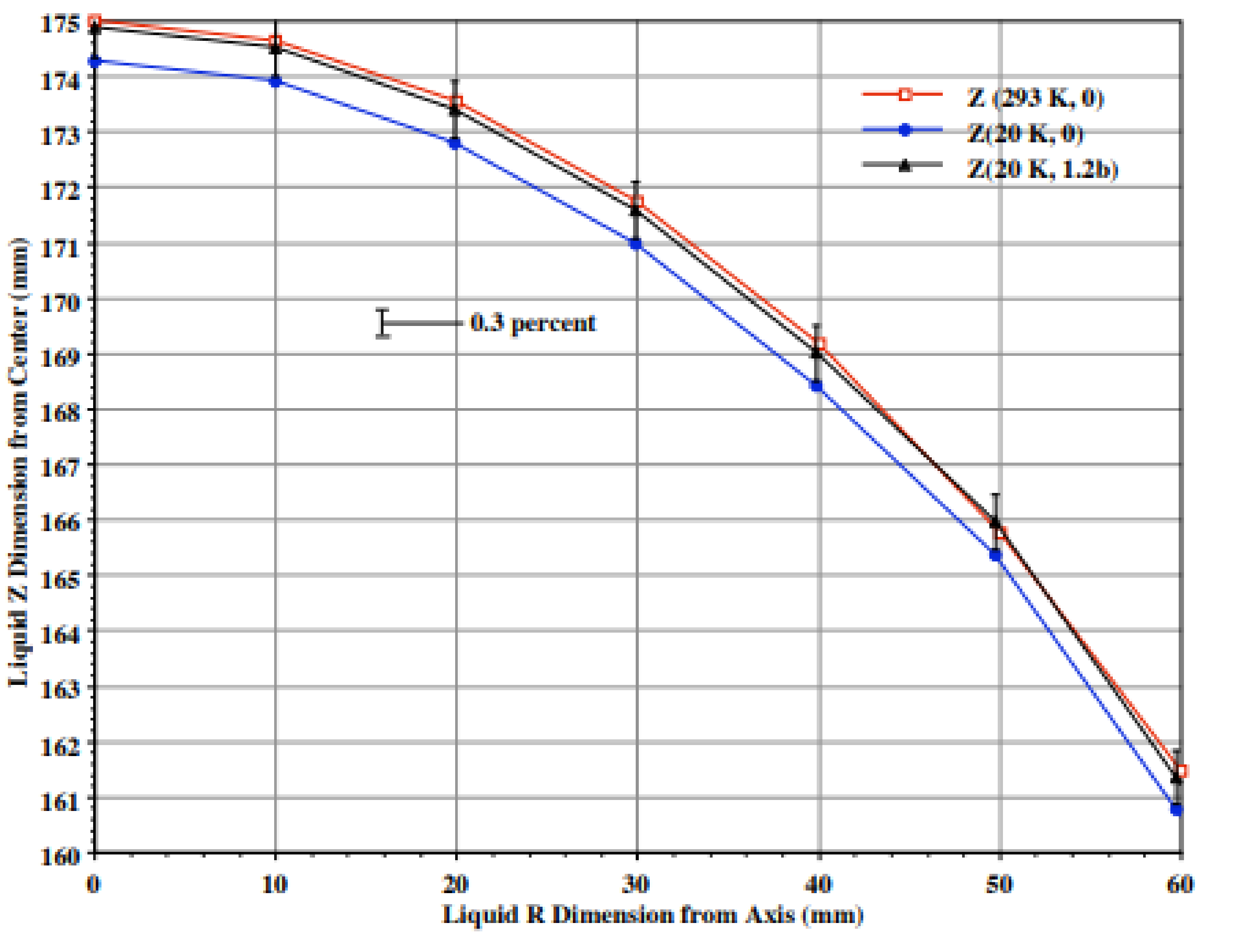
Deflection of absorber windows due to weight of lH2

- lH2 is not very dense => very light
- Approximate absorber vessel by a cylinder with flat windows
- Maximum pressure exerted on walls of cylinder at base

- $W = \rho g V = 70.8 * 9.81 * 0.022 = 15.28N$
- $P = F/A = 15.28 / (\pi * 0.15 * 0.15) = 216.17$ Pa

- A pressure of only 0.002 Bar at base of absorber where window is thickest
- At centre of absorber the pressure is 0.001 Bar which corresponds to a deflection of 0.005mm
- Weight is very small => negligible effect

Contraction and absorber window deflection combined



- Green and Yang data from 2006, based on 1.2 Bar operating pressure
- Actually ~1.085 Bar
- Contraction was 1.4525mm
- Deflection is 0.5374mm

- Combined :
- 1.4525 – 2(0.5374) = 0.3777mm

- Large error from ANSYS model:
- Combined 0.38mm +/- 0.28mm

Absorber window thickness variation

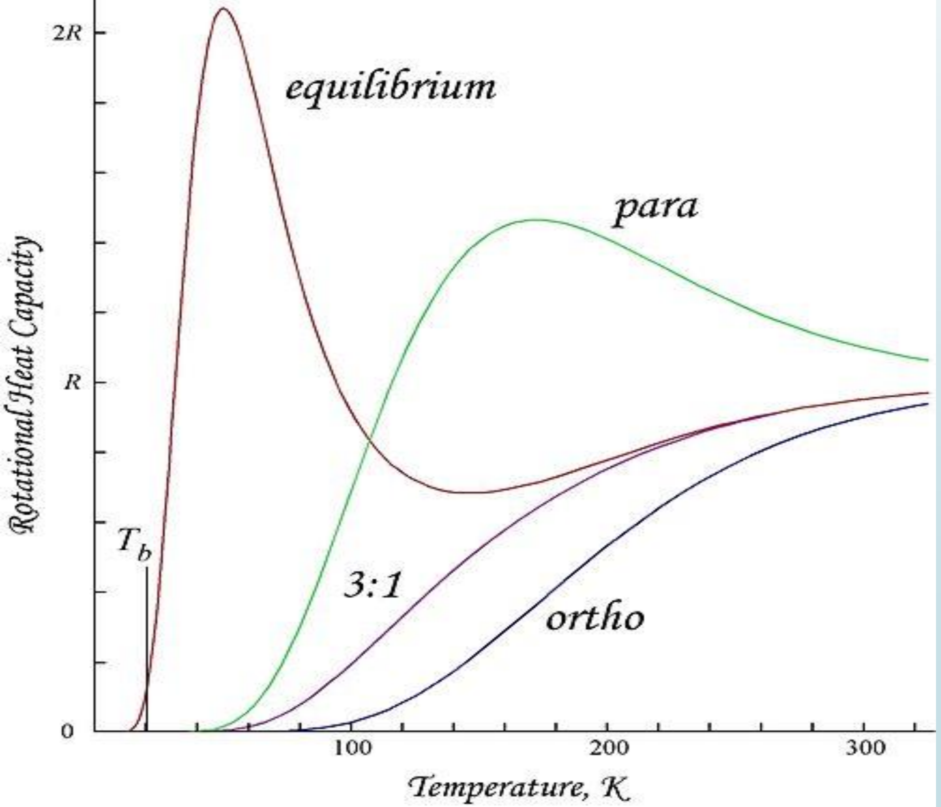
At centre of absorber	Measured (µm)	Design (µm)
Safety Window 1	197 ± 8	210
Absorber Window	174 ± 5	180
Absorber Window	184 ± 2	180
Safety Window 2	230 ± 9	210
Total	785 ± 24	780

Effect on Energy Loss:

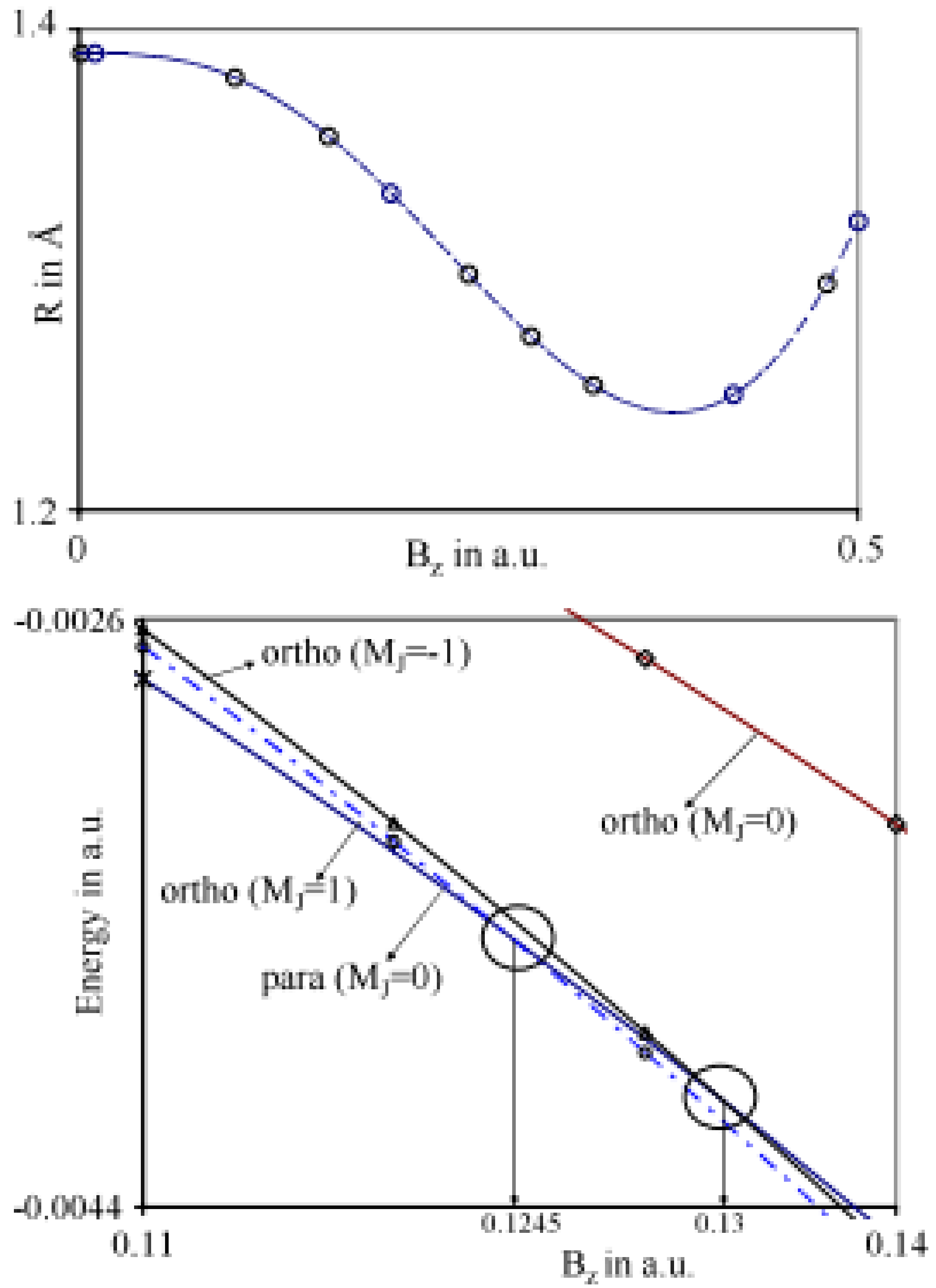
- A 200 MeV muon passing along the central axis of an empty absorber vessel will lose 0.345 MeV with an uncertainty of 0.01 MeV

Para and Orthohydrogen at MICE temperatures

	T (K)	p (MPa)	ρ (mol dm^{-3})
		Parahydrogen	
Critical point	32.938	1.283 77	15.556
Triple point	13.8033	0.007 042	38.215
		Normal hydrogen	
Critical point	33.19	1.315	14.94
Triple point	13.952	0.007 7	38.3



- Hydrogen composed of mixture of Parahydrogen and Orthohydrogen
- Differ by nuclear spin which causes a difference in properties e.g Heat capacity, Boiling temperature
- At room temperature Ortho to Para ratio 3:1
- At 20K (in equilibrium) over 99% Parahydrogen
- Ortho to Para conversion slow (1.9%/hr)
- MICE uses Hydrogen stored in bottles
- Bottles use catalyst during filling to ensure high Parahydrogen concentration to prevent boil-off from Ortho to Para conversion
- Properties of liquid Hydrogen in Absorber will be nearly identical to that of Parahydrogen

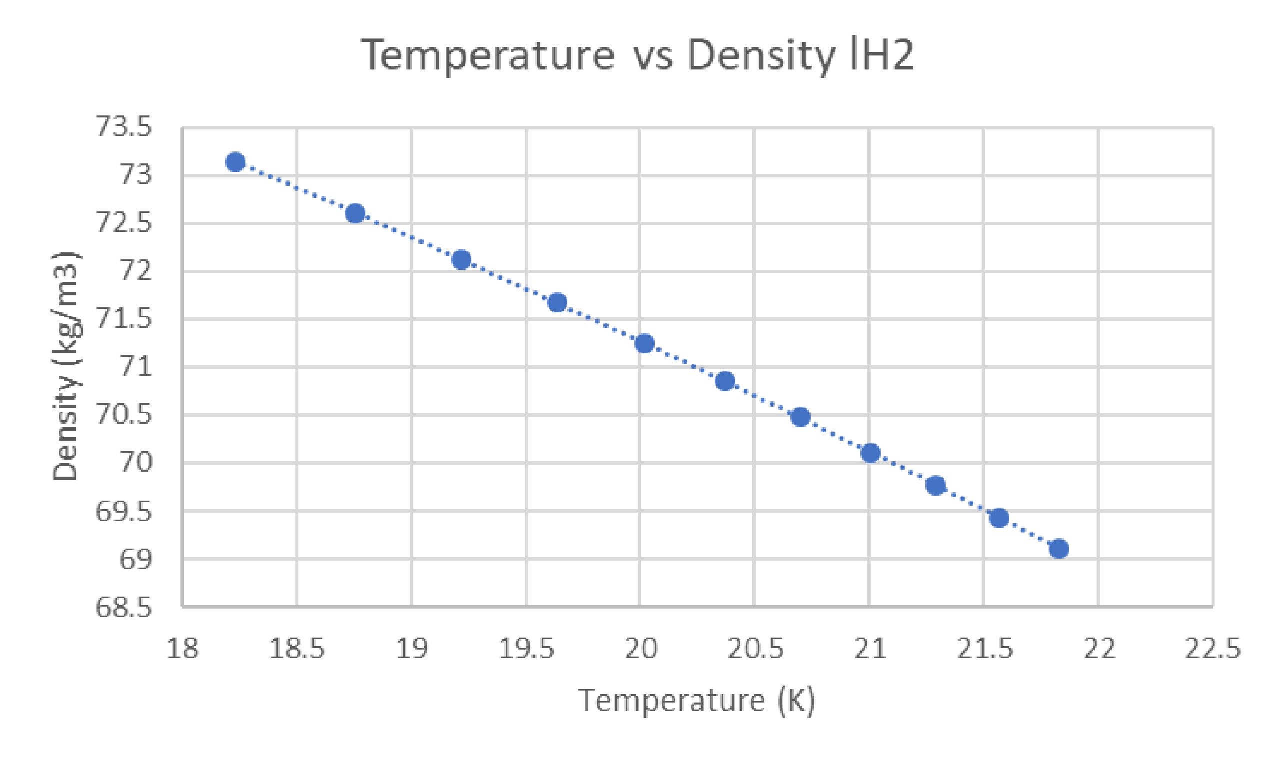


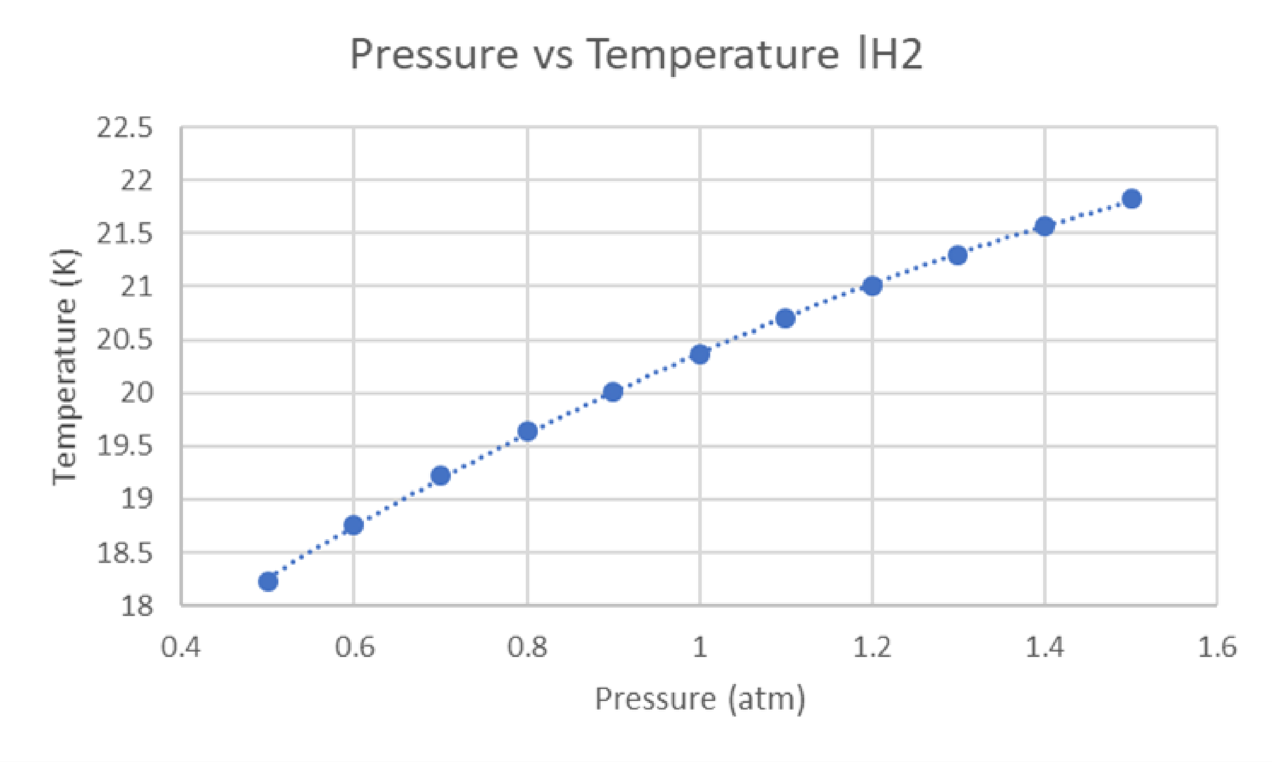
Para and Orthohydrogen in a magnetic field

- Para to Orthohydrogen ratio at low temperatures in a magnetic field investigated by Misra and Panda
- Magnetic field strength affects bond length
- Crossover where Parahydrogen is no longer the lowest energy state at 0.1245 a.u.
- Equivalent to 29257.5 Tesla
- 10,000 times greater than MICE
- At low T and B still over 99% Parahydrogen

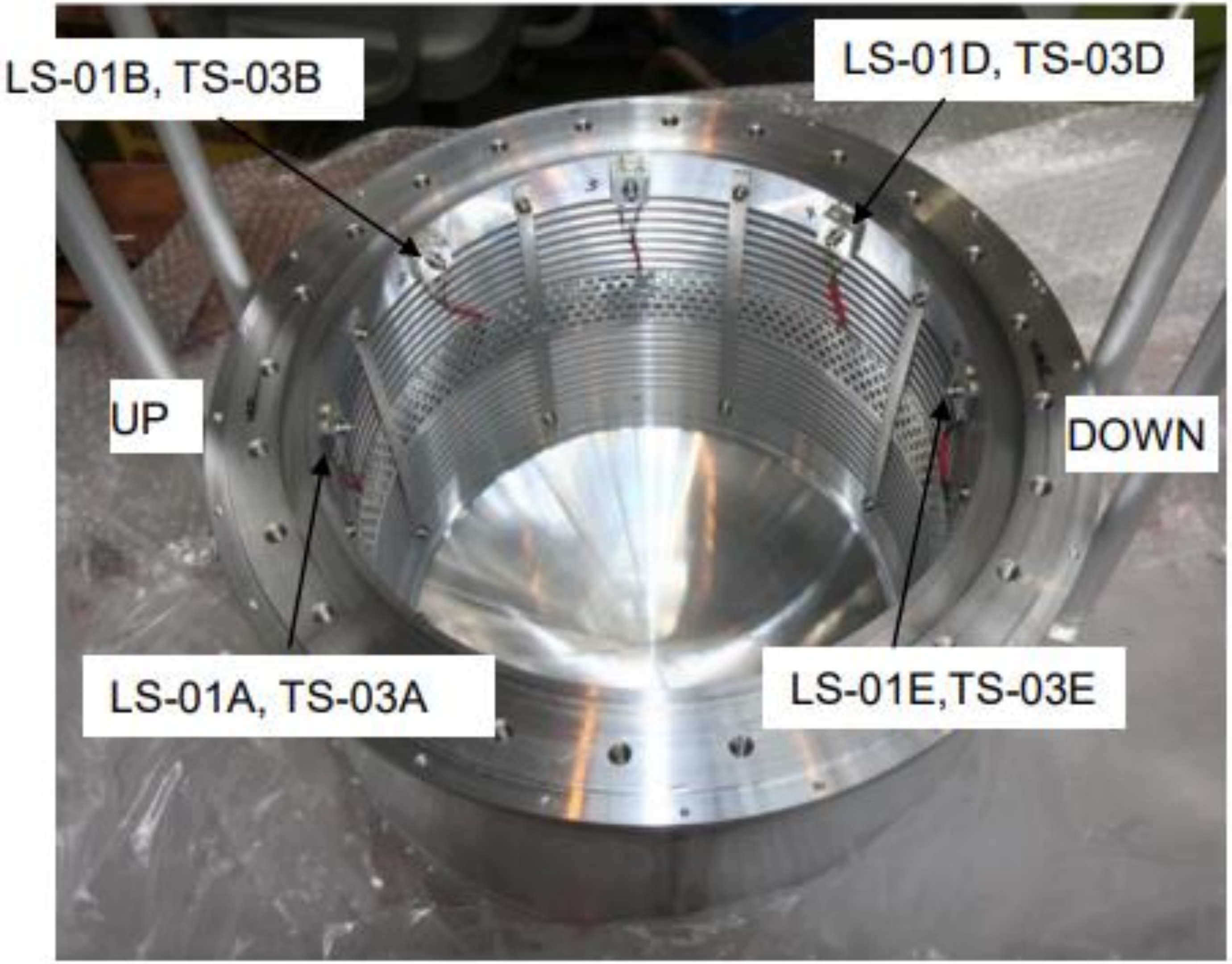
Saturation Properties of lH2

- Density of lH2 changes at varying temperatures and pressures
- Changes the energy lost by a muon travelling through the absorber
- Accuracy of temperature and pressure sensors determines the uncertainty in the density of lH2





lH2 absorber body and sensors



- 8 sensors in 4 pairs
- 4 Level sensors determine liquid height in vessel, can also read temperature (labelled LSA, LSB, LSD and LSE)
- 4 temperature sensors, just for temperature (labelled TSA, TSB, TSD and TSE)
- Manufacturer Uncertainties:

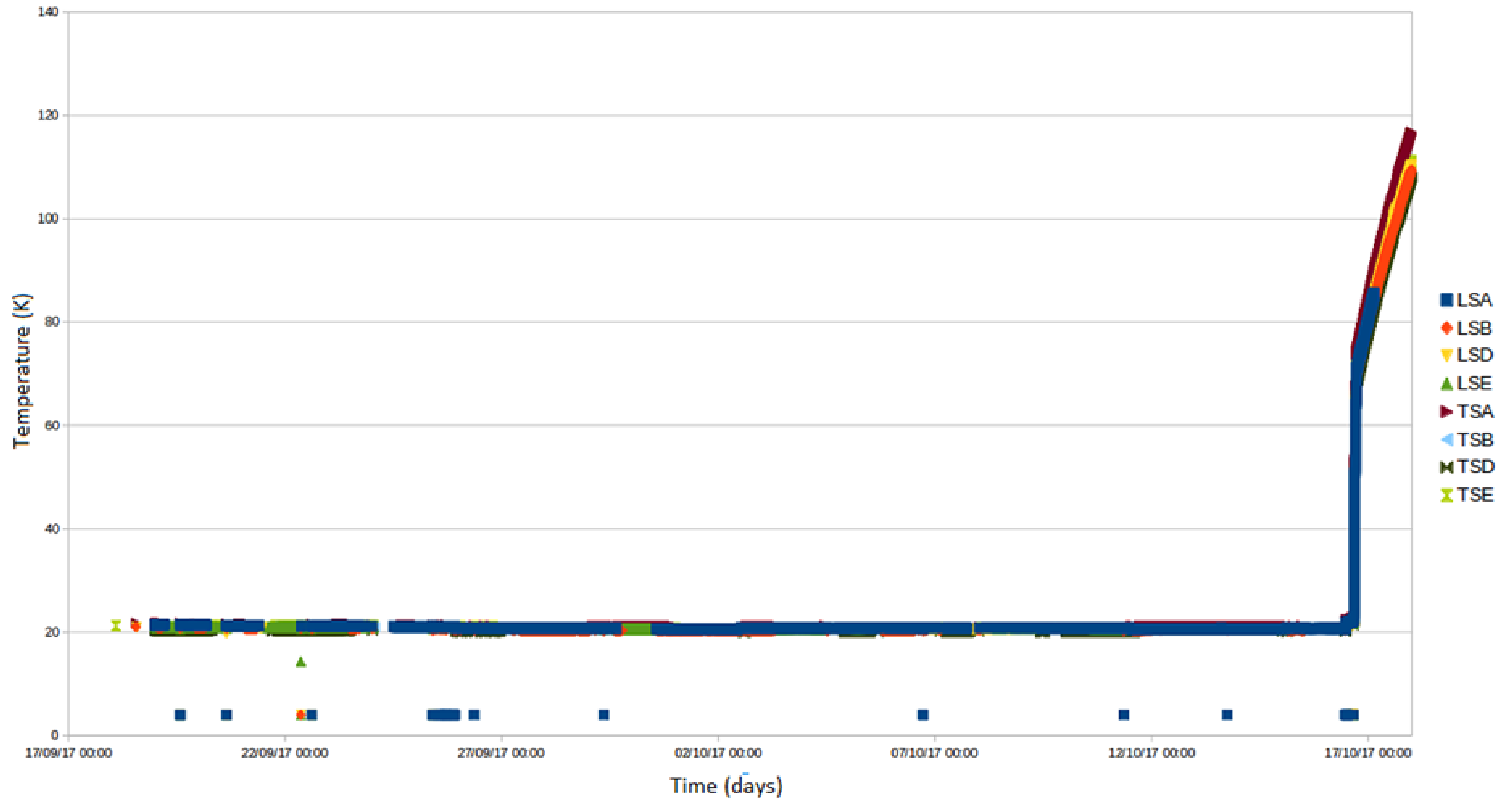
  ± 9mK Sensor accuracy

  ± 12mK long-term stability

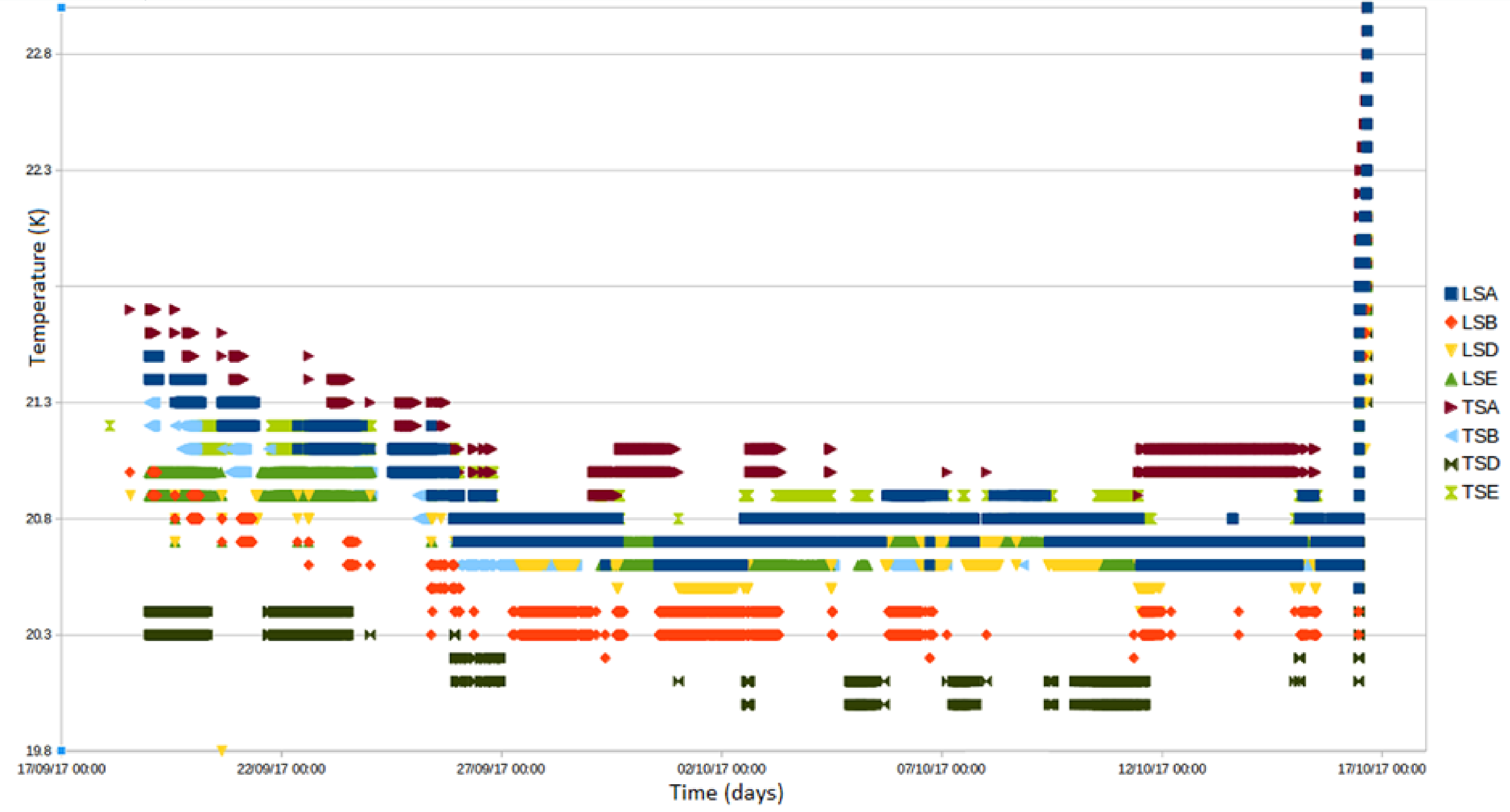
  0.04% (ΔT/T) at 2.5T magnetic field

  equivalent to ± 8mK at 20K

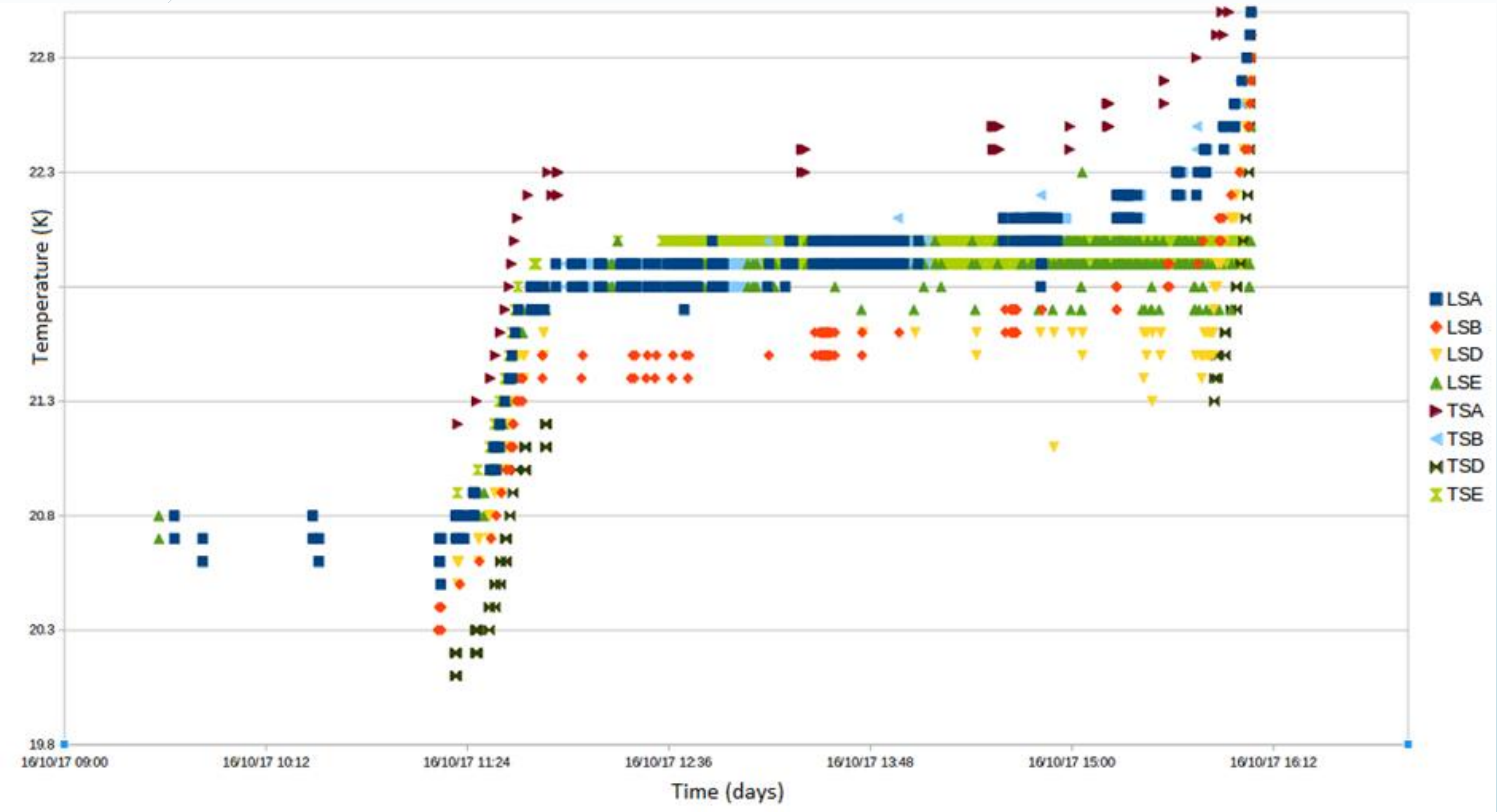
Temperature readings from cooldown and liquefaction to boil-off and venting



Temperature readings from cooldown and liquefaction to boil-off and venting



Temperature readings during boil-off



Temperature sensors (Cernox 1050 SD)

- Sensors recorded data to 0.1K resolution, capable of far greater
- Limited to 0.1K resolution for data storage considerations
- Temperature reading cut off after first decimal place, with the latter digits discarded, introduces error as not rounded
- Reading recorded up to every 4 seconds, if a change in reading has occurred
- During steady state period sensors agreed to within 1 Kelvin (constant pressure at 1085 mBar and steady temperature)
- Time Periods as long as days with no temperature reading during steady state

Time weighted temperature readings

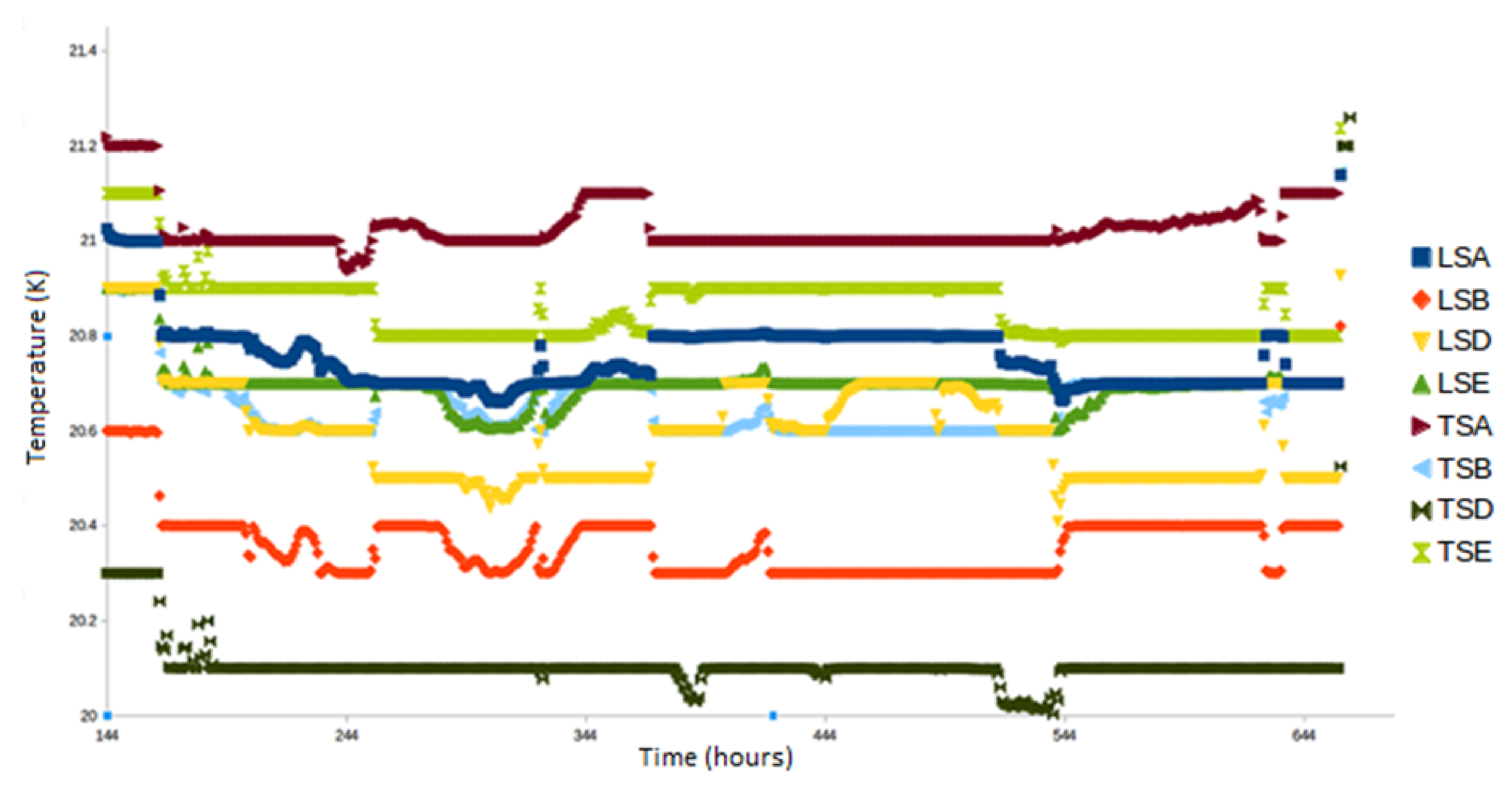
- Will calibrate sensors based on boiling temperature
- A temperature reading is only recorded when a 0.1 K temperature step occurs
- First create temperature readings at equal moments in time weighted by time for all eight sensors

$$T_{average} = \frac{T_{previous}\Delta t_{first} + \sum_i T_i \Delta t_i + T_{last}\Delta t_{last}}{t_{interval}}$$

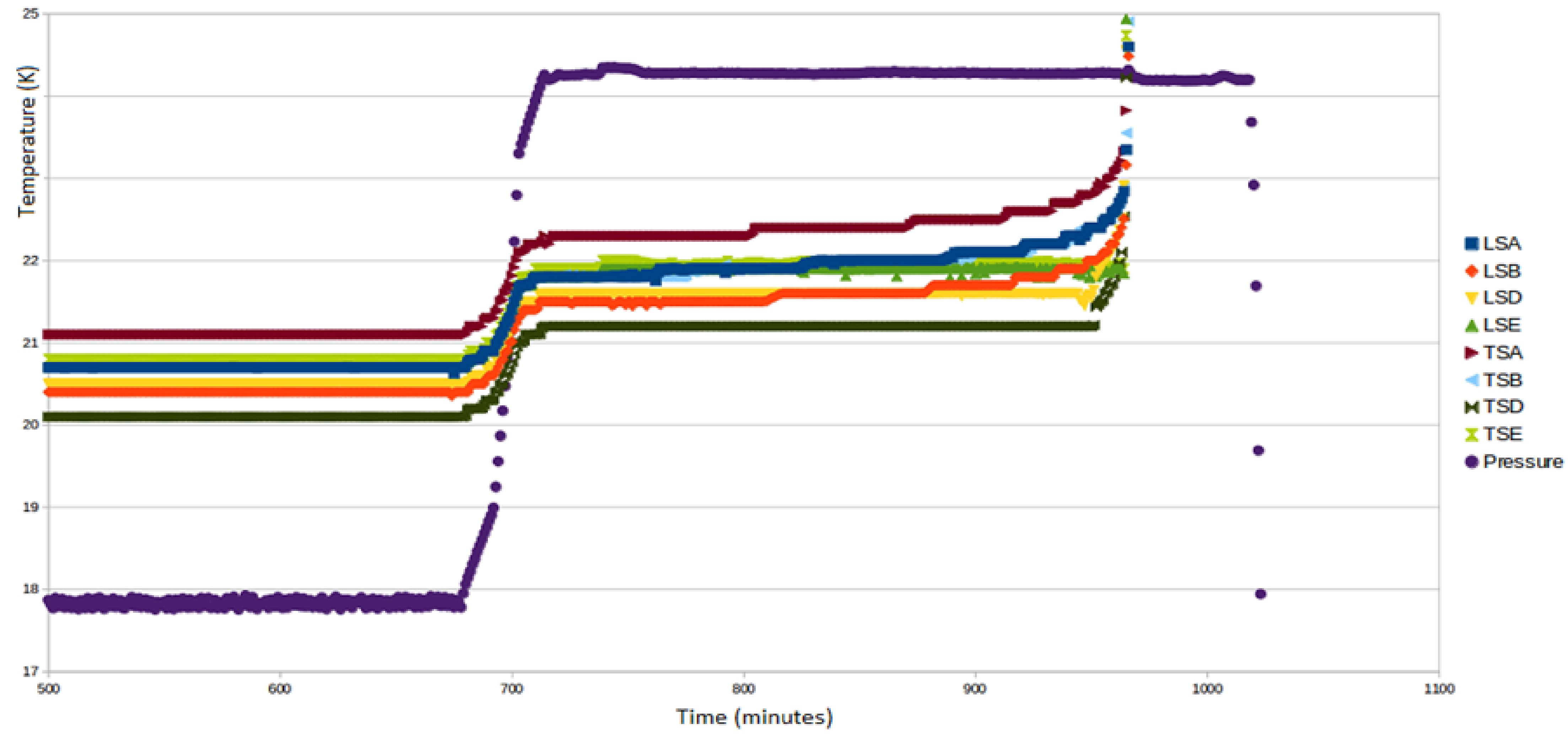
$$t_{interval} = \Delta t_{first} + \sum_i \Delta t_i + \Delta t_{last}$$

Where $T_i \Delta t_i$ refers to the time period at that temperature, Δt_{first} from the start of the interval to the first reading, and Δt_{last} from the last reading to the end of the interval

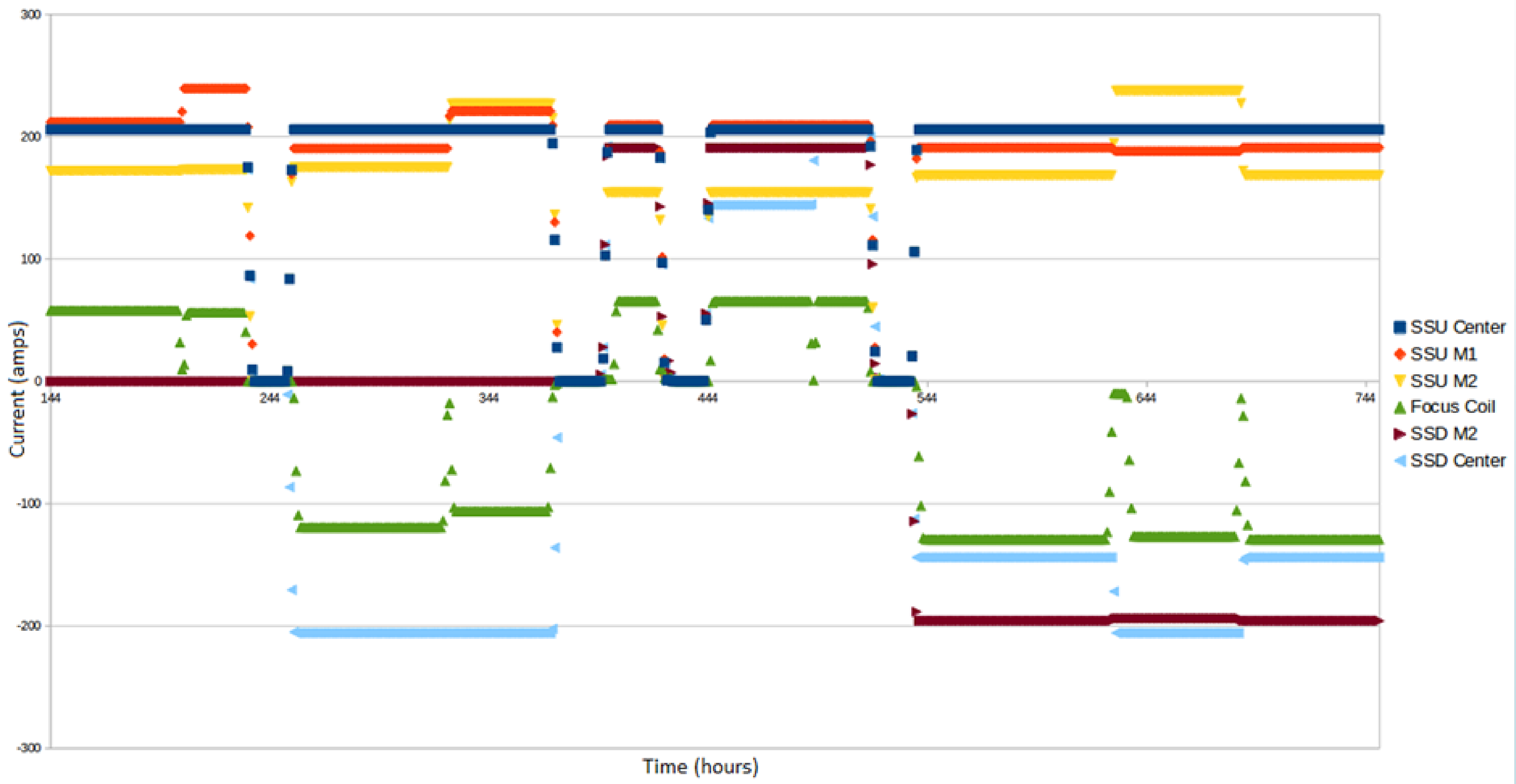
Time averaged temperature readings



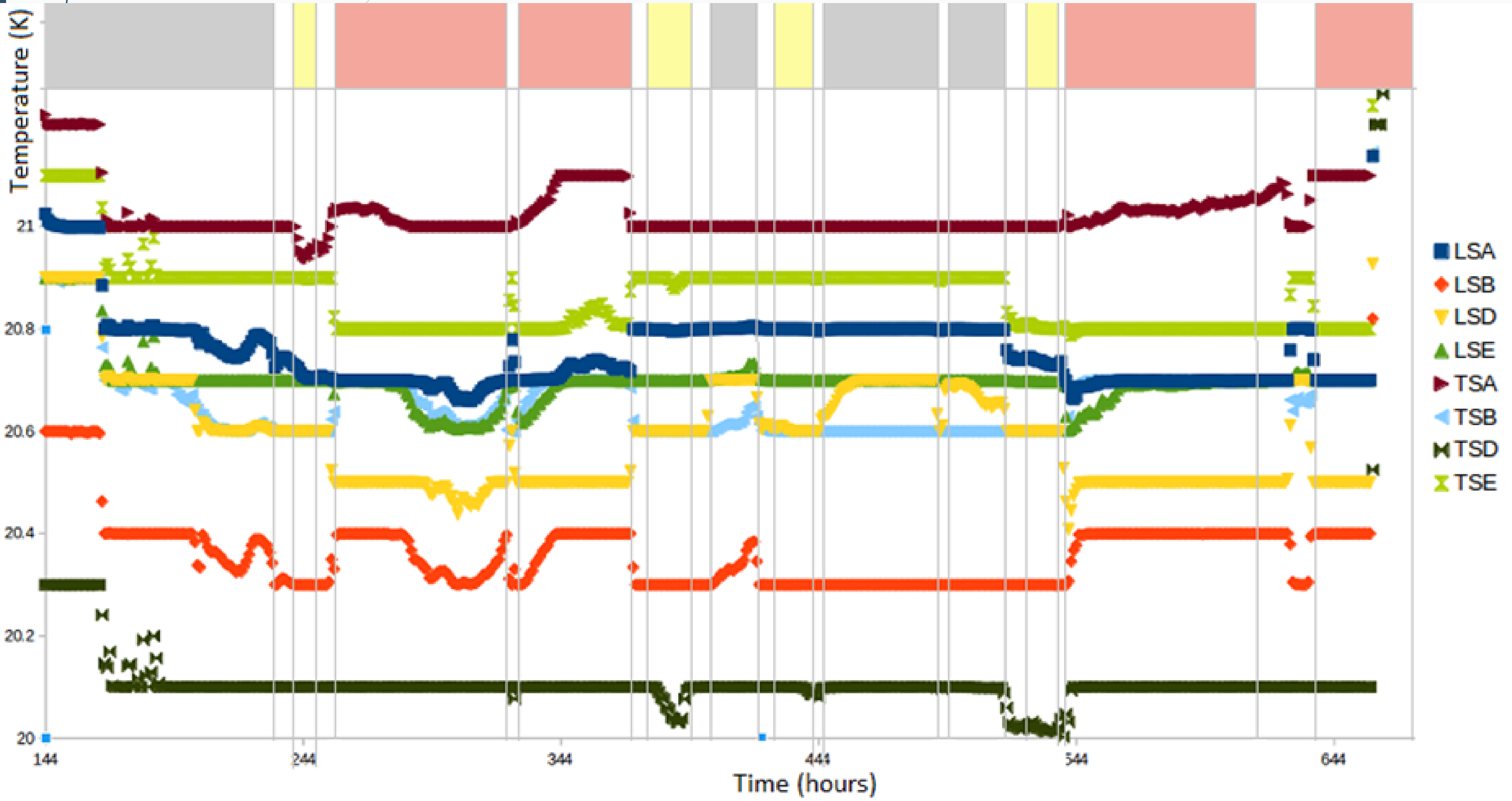
Time averaged temperature and scaled pressure readings during boil-off



Magnet currents (flip as negative)

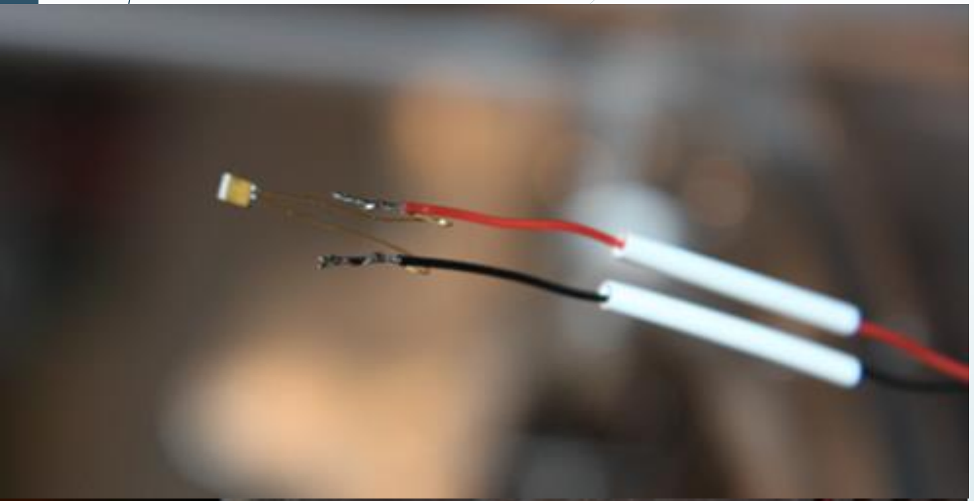


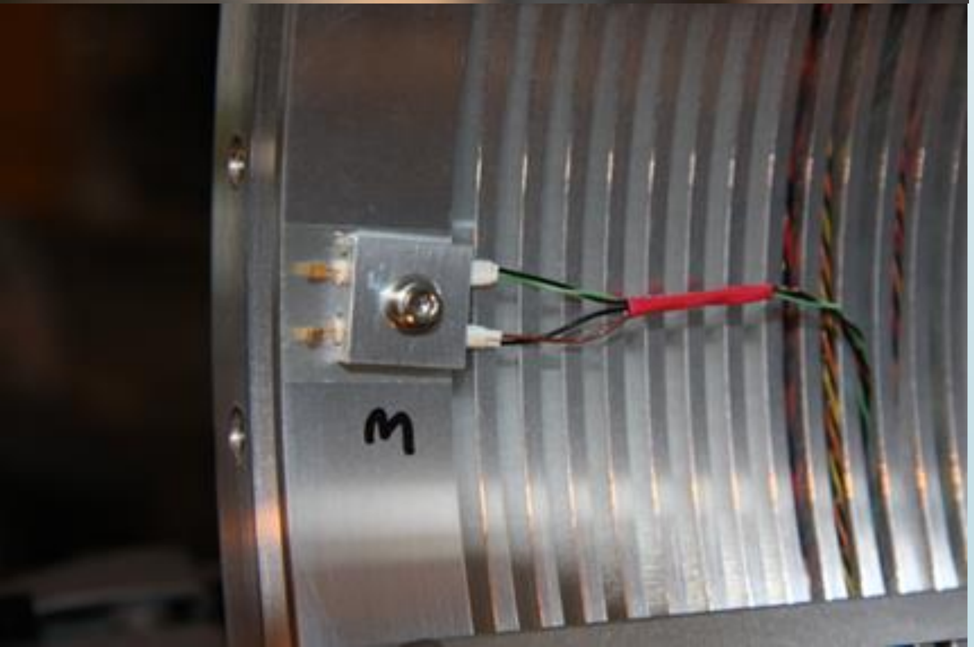
Temperature Readings and magnetic field



- Grey areas are solenoid mode
- Red areas are flip mode
- Yellow areas are no magnetic fields
- White areas when no run data was being taken and the magnets were ramped up and down

Magnetic field effects on sensors





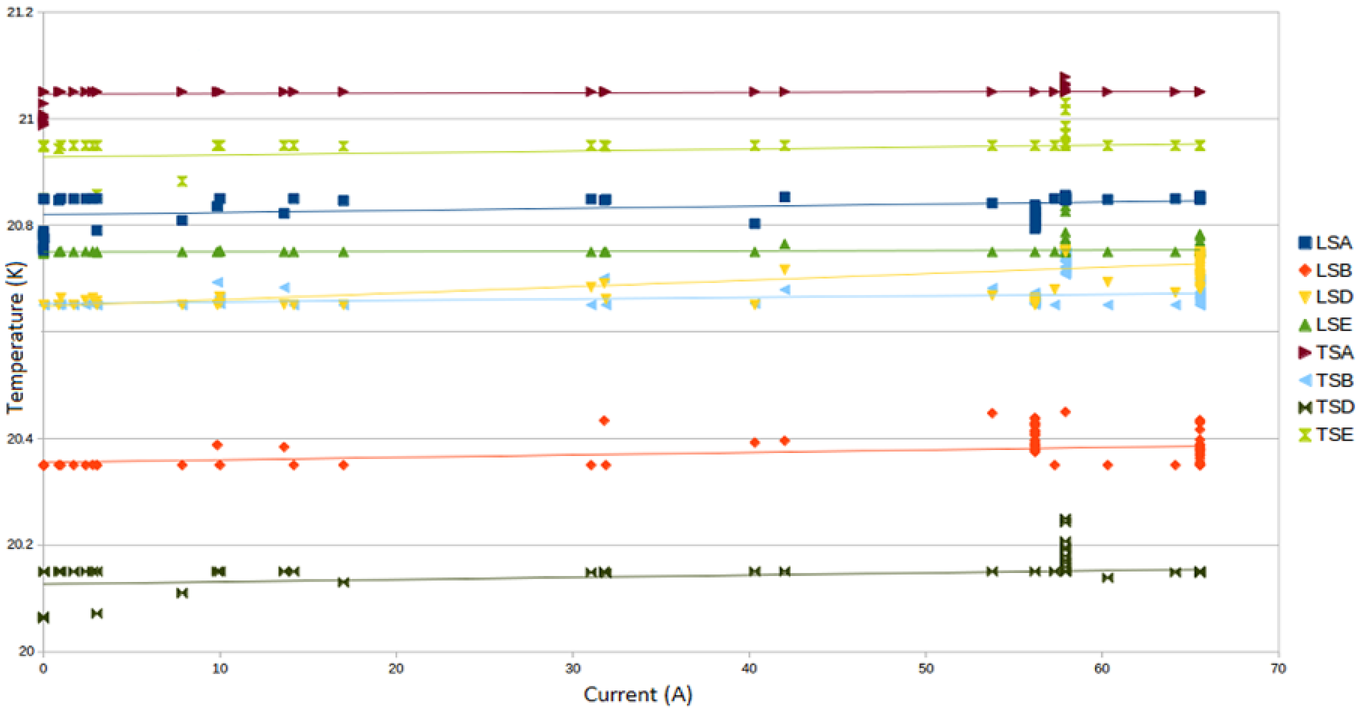
- 0.1K steps in temperature for some sensors when the magnets are on.
- Other sensors may also step in temperature, but can't be seen due to the 0.1K resolution
- Steps can occur in the opposite directions for some sensors
- Difficult to tell if orientation plays a factor as the sensors may move slightly when the vessel is cooled and filled with liquid Hydrogen
- Manufacturer claims orientation of sensors has no effect

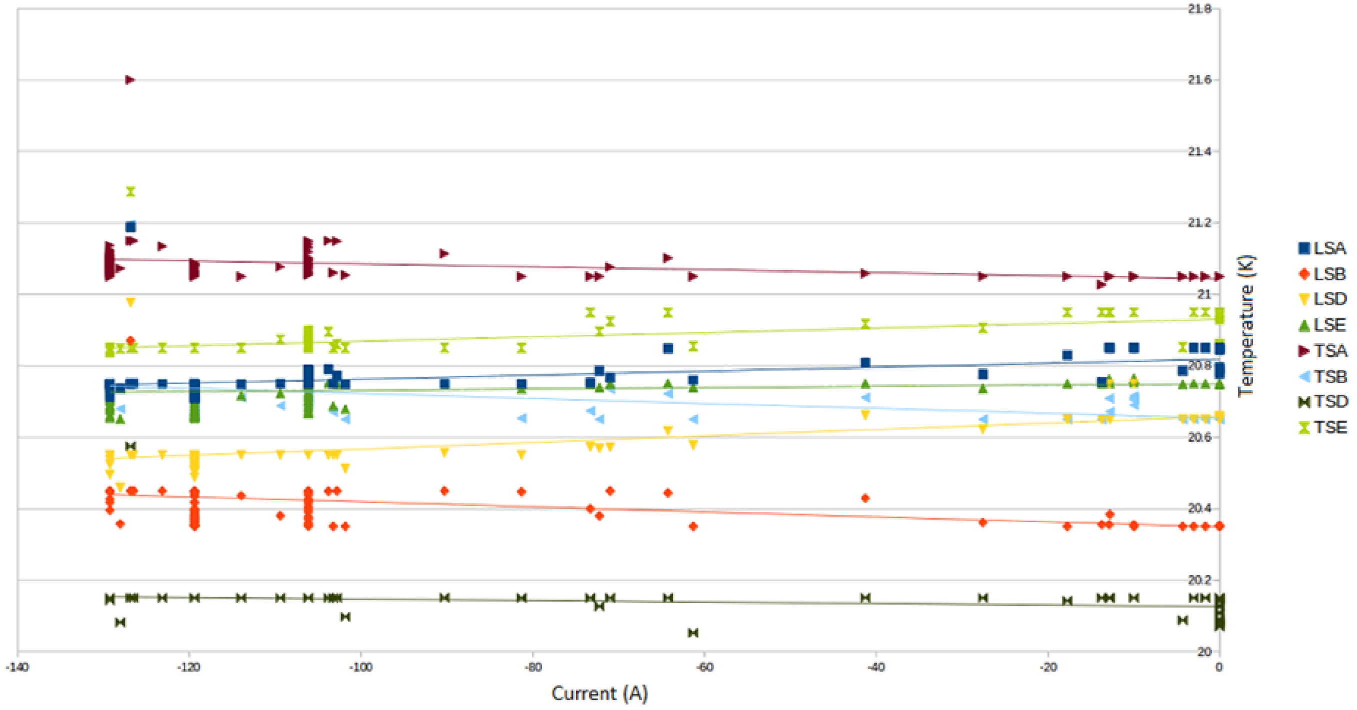
Temperature Calibration

Calibration based on the boiling temperature makes corrections for the focus coil current, cut-off of values and temperature scaling factor

$$T_{corrected} = \frac{T_{reading} + c_{cut-off} - c_{magnet} I}{c_{Temperature}}$$

Where $c_{cut-off}$ is 0.05, c_{magnet} are two magnet correction coefficients for each sensor (one for solenoid and one for flip mode), I is the focus coil current and $c_{Temperature}$ is the temperature scaling factor





Magnet coefficients

- Plot temperature against current for straight (top left) and flip mode (bottom left)
- Line of best fit gives magnet correction coefficient
- Limited by 0.1K resolution

Magnet and temperature coefficients

Mode	LSA	LSB	LSD	LSE
Straight	3.9424E-4	4.6810E-4	1.2207E-3	5.7725E-5
Flip	5.5024E-4	-7.0037E-4	9.0778E-4	1.8262E-4
Mode	**TSA**	**TSB**	**TSD**	**TSE**
Straight	7.1284E-5	2.8417E-4	4.2315E-4	3.7478E-4
Flip	-4.2225E-4	-6.9633E-4	-2.0447E-4	6.2125E-4

Scaling Factor	LSA	LSB	LSD	LSE
$T/T_{Vaporisation}$	1.010581837	0.989245608	1.003371485	1.008424313
Scaling Factor	**TSA**	**TSB**	**TSD**	**TSE**
$T/T_{Vaporisation}$	1.027755673	1.003697746	0.9784283	1.015526132

Magnet correction coefficients from line of best fit as magnets are ramped

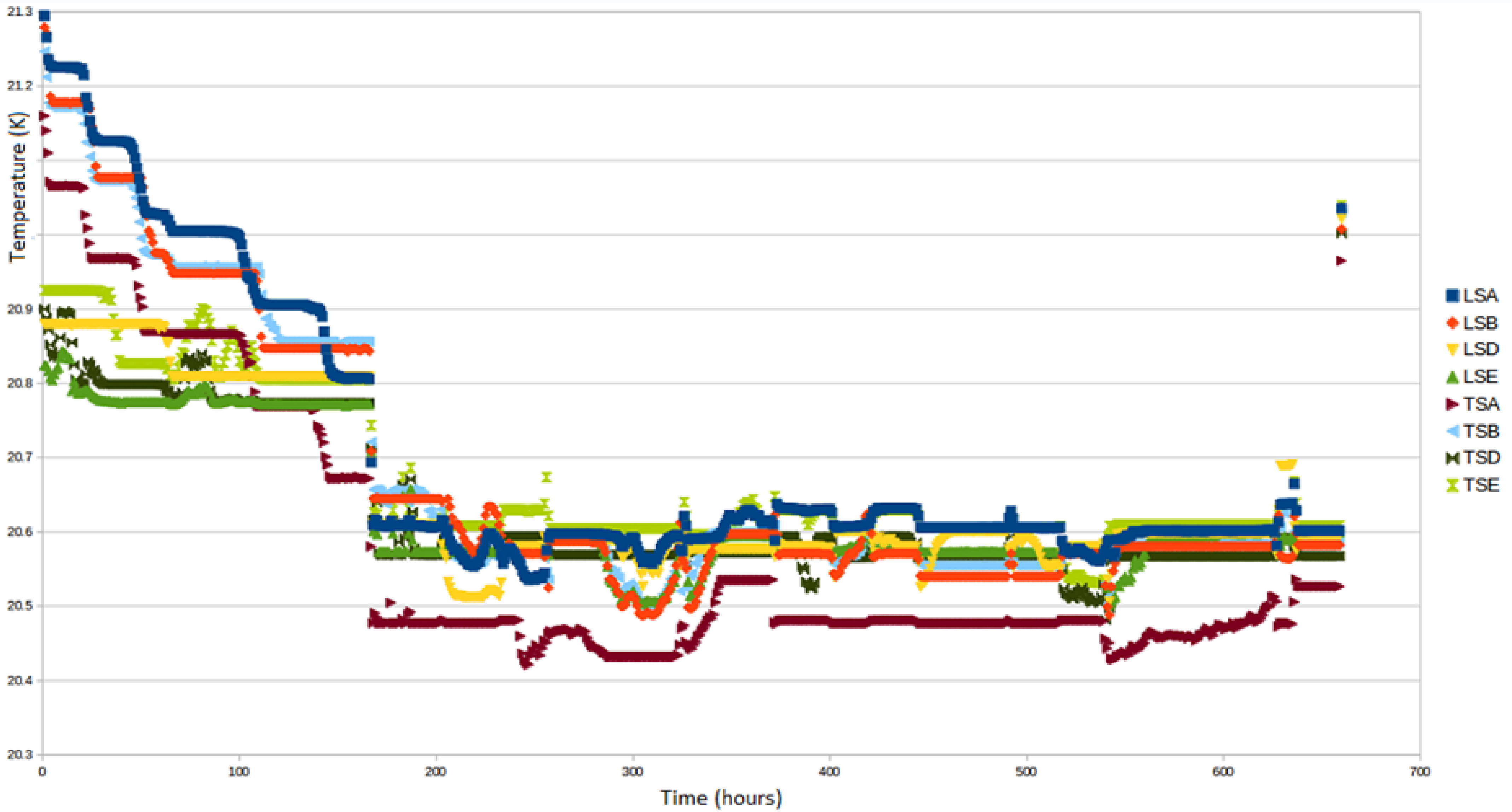
Temperature scaling factor calculated after cut-off and magnetic field corrections are applied (boil-off takes place in flip mode)

Boiling temperature changes with pressure.

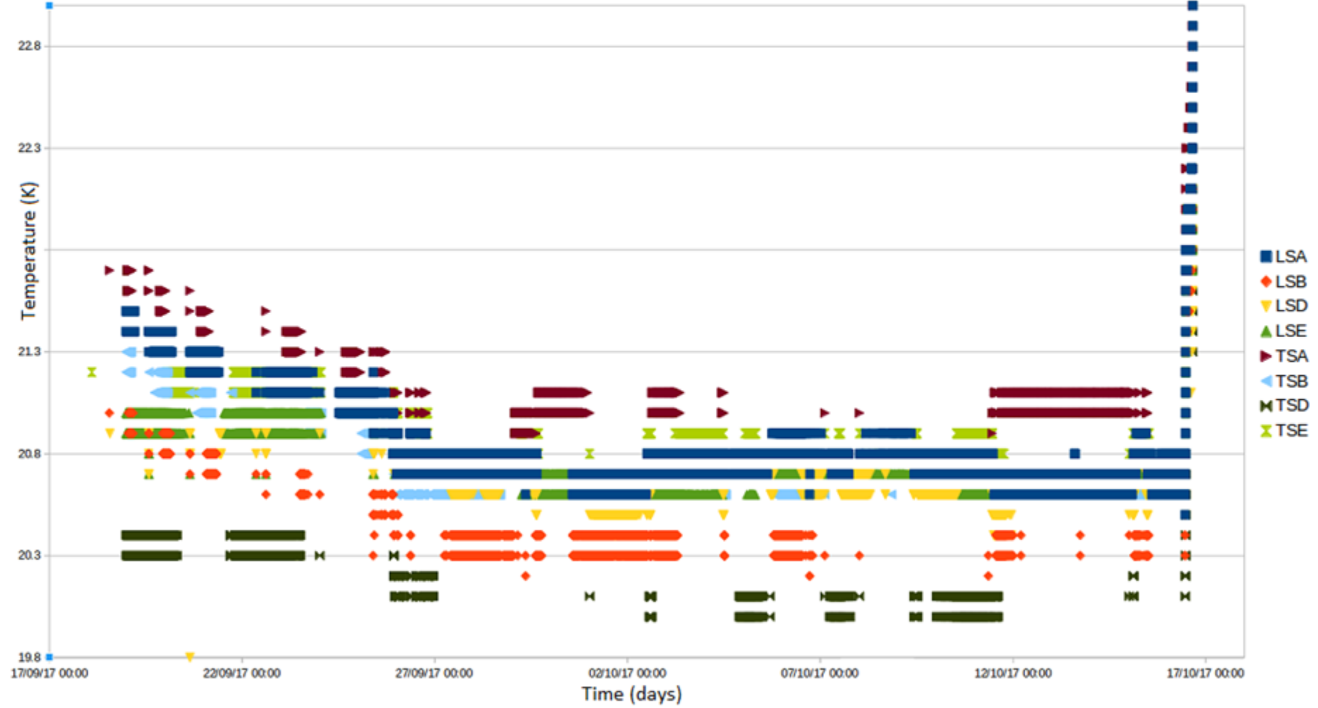
Pressure sensors have ± 5 mBar uncertainty

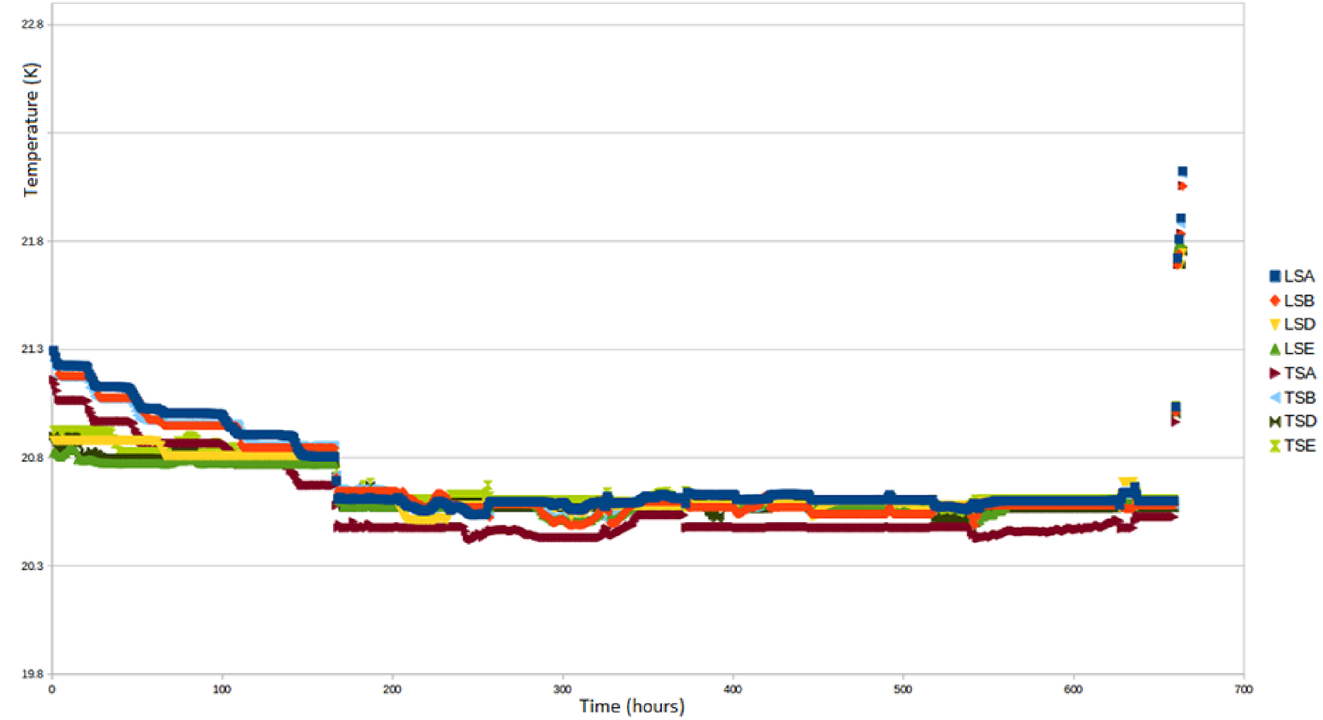
=> 0.014K uncertainty in boiling temperature at 1505 mBar

Corrected temperature readings

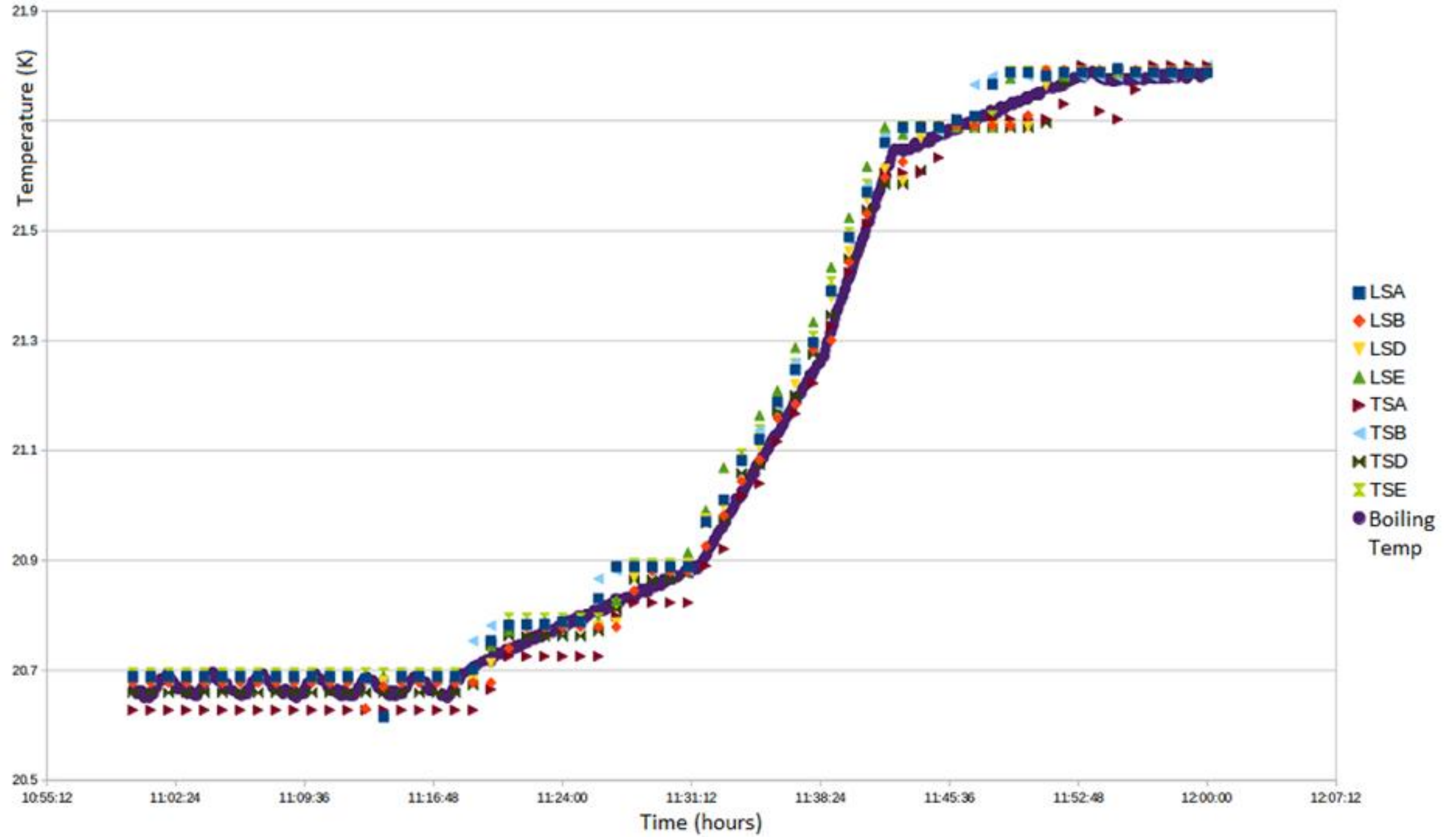


Comparison before and after calibration





Boiling temperature at a given pressure



Temperature Uncertainties

- 0.1 K resolution
- 0.29 mK sensors (9mK accuracy + 12 mK stability + 8mK magnetic field, although likely greater)
- Calibration: at 1.505 Bar boiling temperature is 21.692K but can only read 21.65K (21.6K cut-off plus 0.05 cut-off correction) i.e. off by 0.042K
- 0.016K during steady state from 5mBar pressure sensor uncertainty
- 0.014K uncertainty in Boiling point temperature at boiling point pressure

- Collectively add up to a minimum of 0.2K

Uncertainty on Energy Loss

- During steady state 20.5K ± 0.2K at 1085 ± 5 mBar

  => Density 70.54 ± 0.24kg/m^3
- Along Central Axis: 349.6 ± 0.3mm of lH2

  0.785 ± 0.024mm of Aluminium

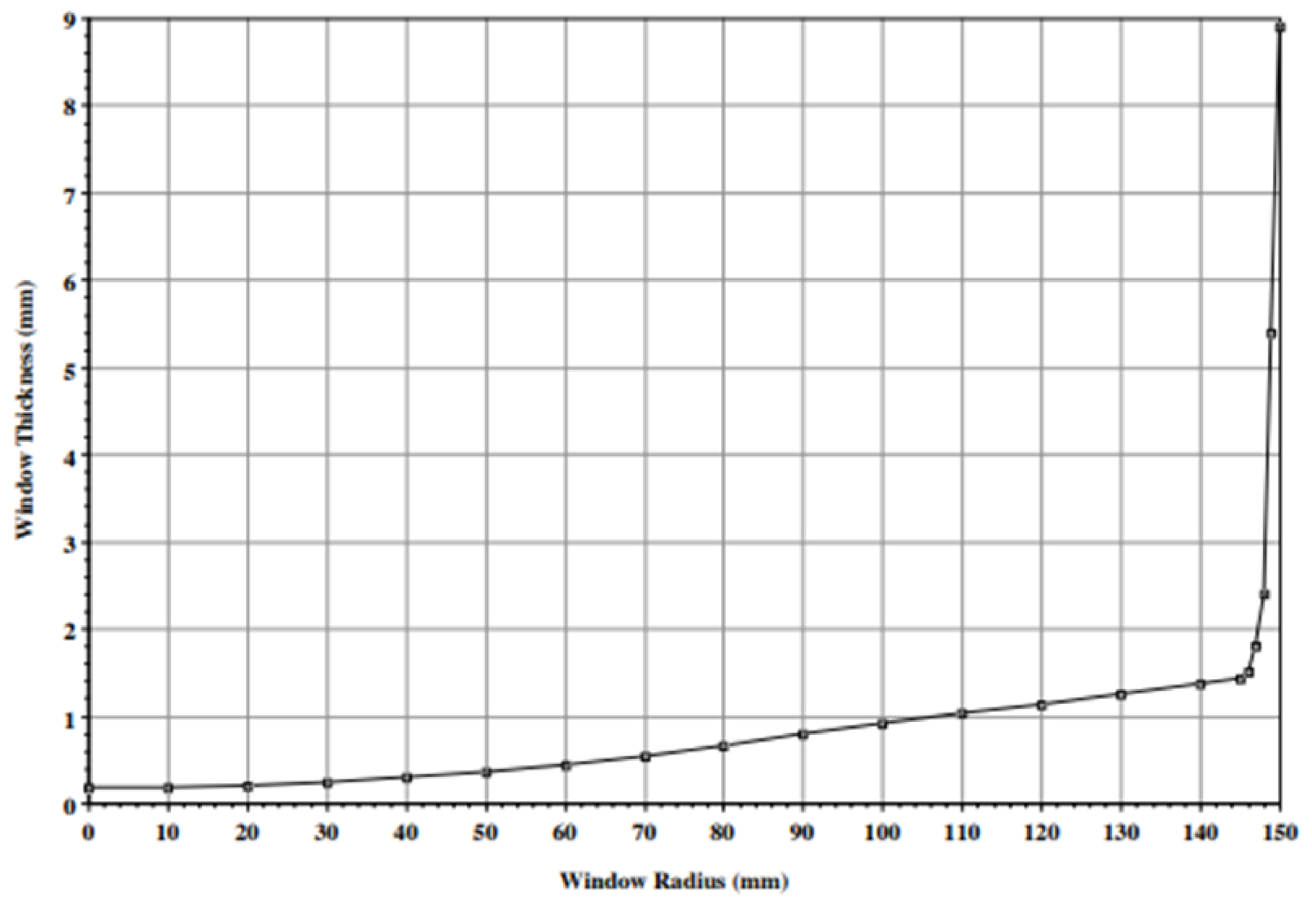
A 140 MeV muon will lose 10.88 ± 0.06 MeV

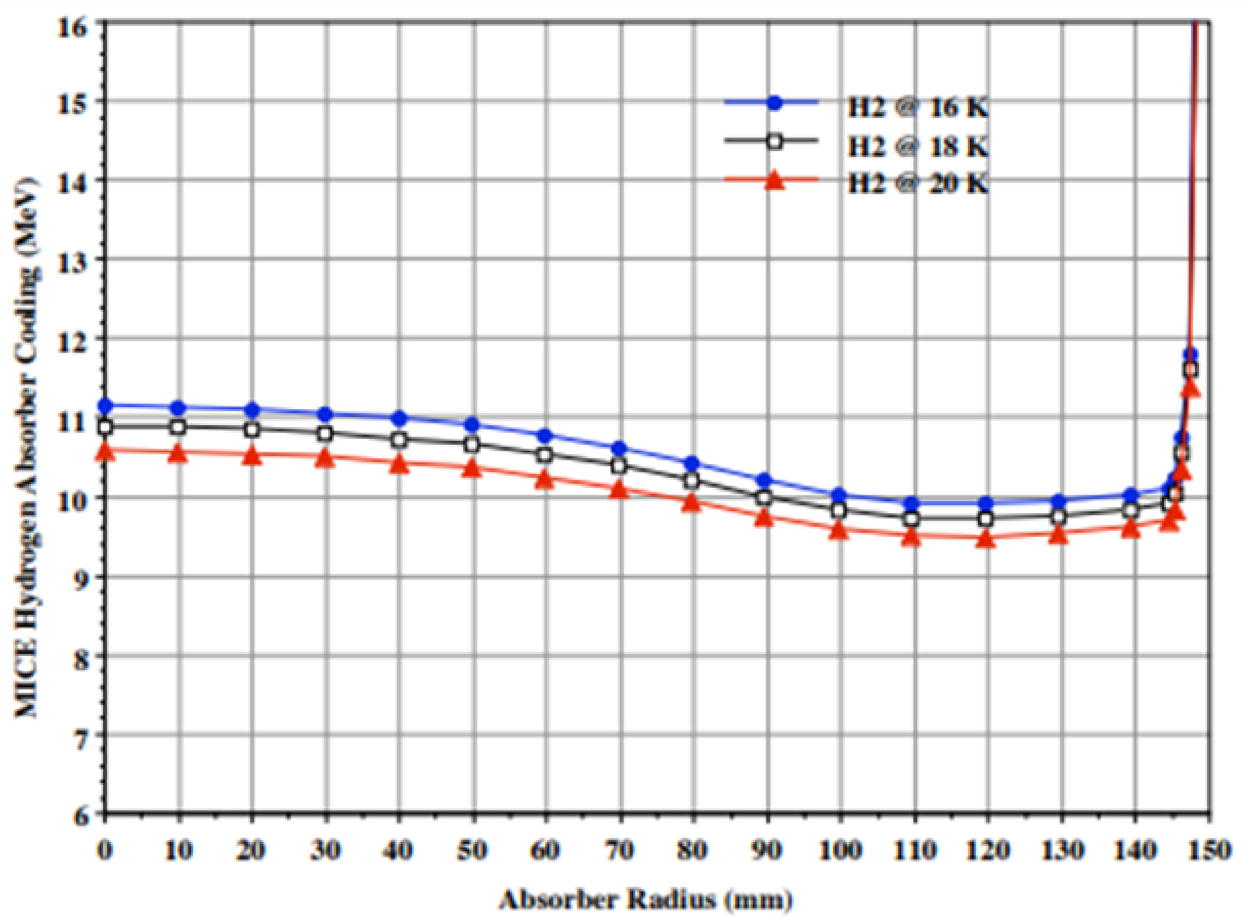
A 200 MeV muon will lose 10.44 ± 0.05 MeV

In terms of Energy Loss, all these uncertainties add up to a 0.51% systematic uncertainty on the mean Energy Loss

The End

Extra Slide


Window Thickness (mm)
Window Radius (mm)
0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150


H2 @ 16 K
H2 @ 18 K
H2 @ 20 K
MICE Hydrogen Absorber Cooling (MeV)
Absorber Radius (mm)
6
7
8
9
10
11
12
13
14
15
16
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40
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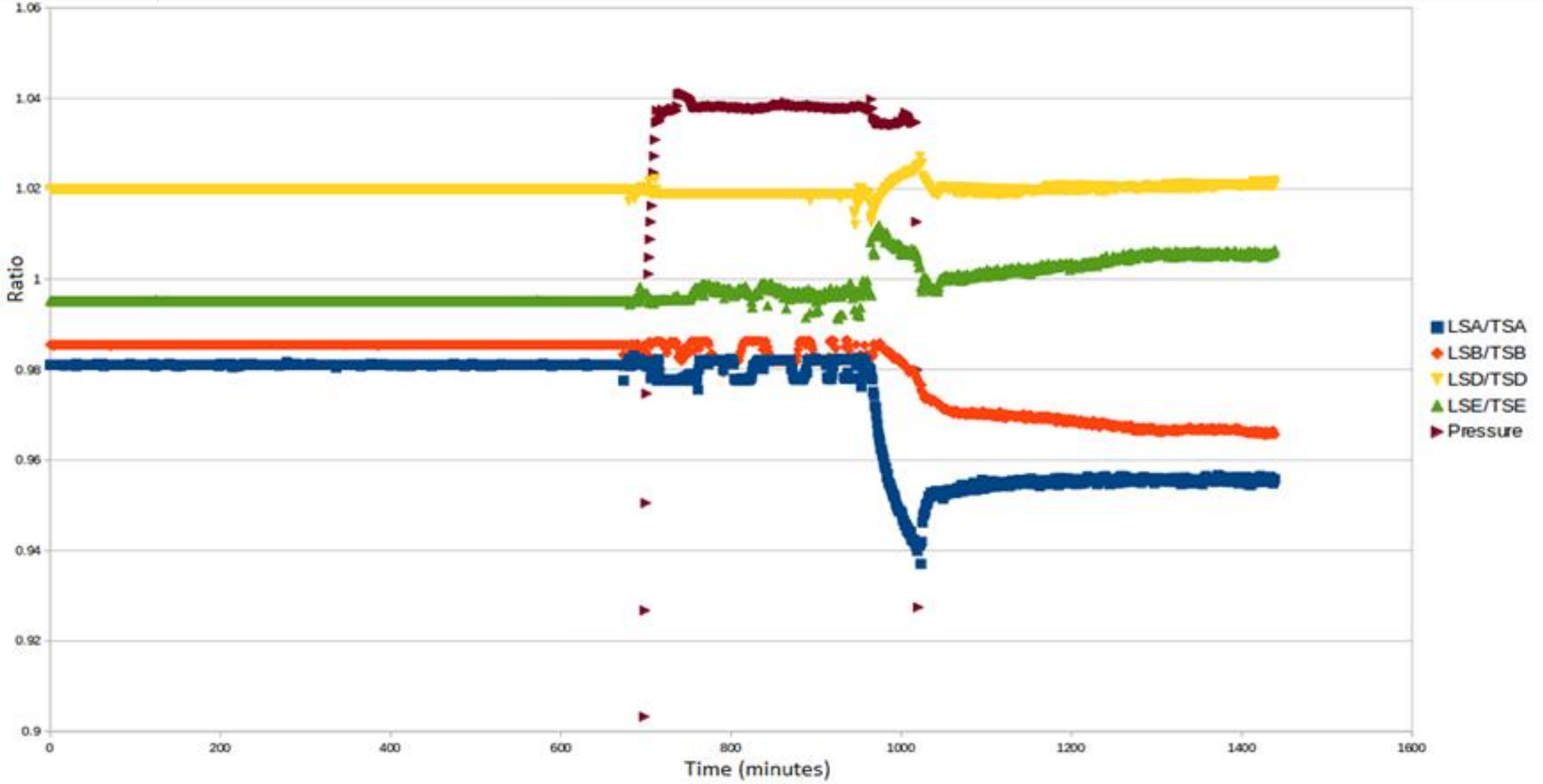

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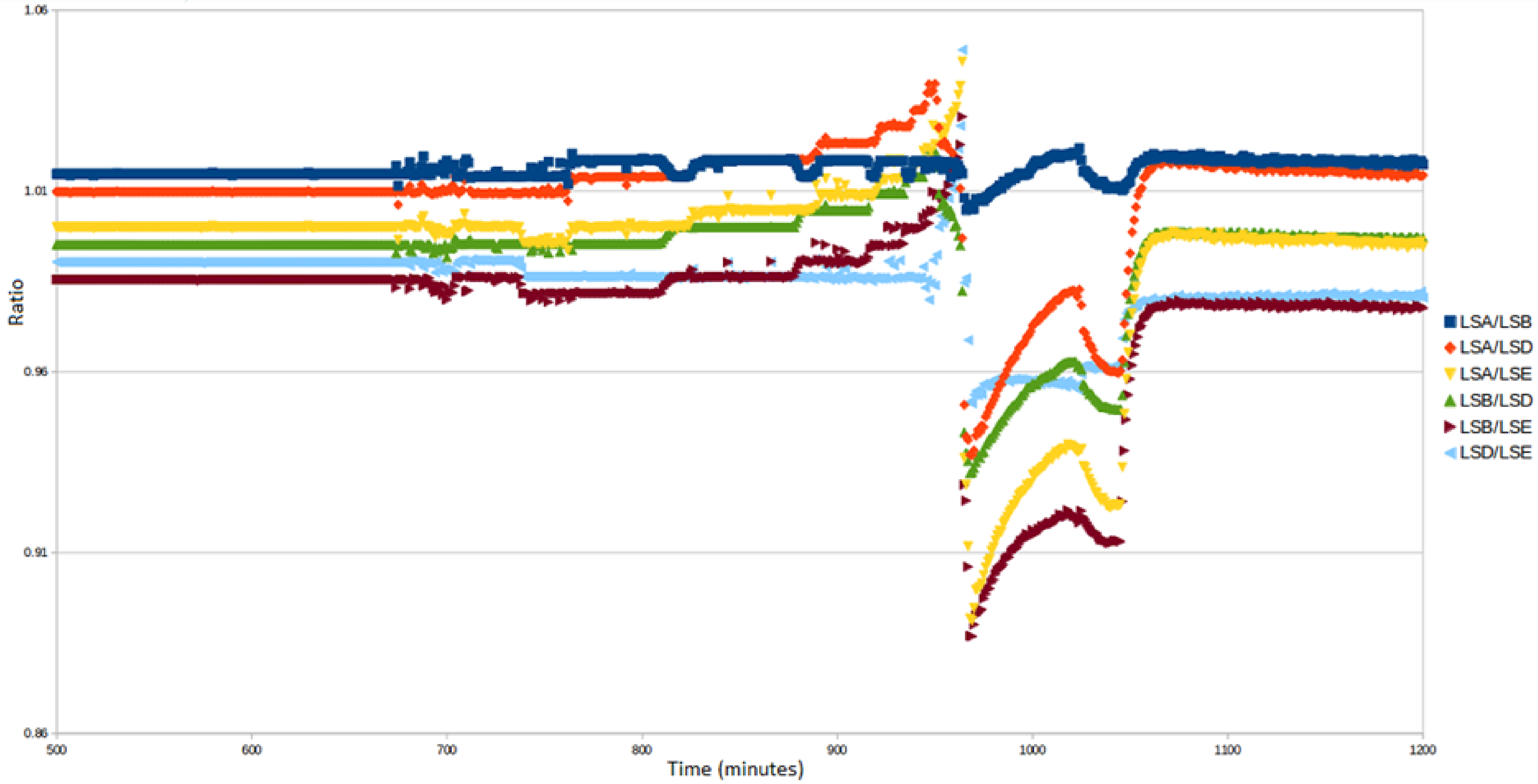

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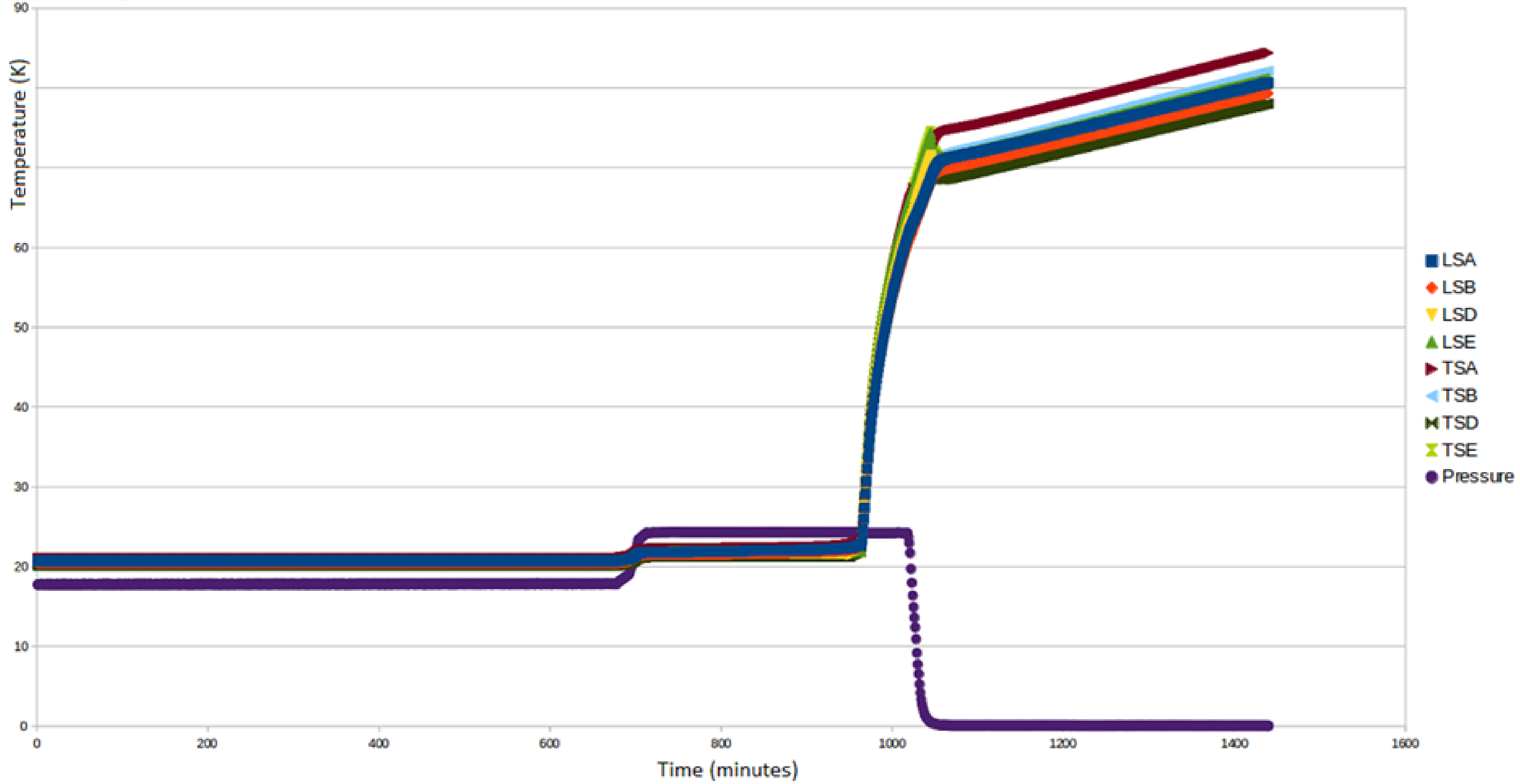

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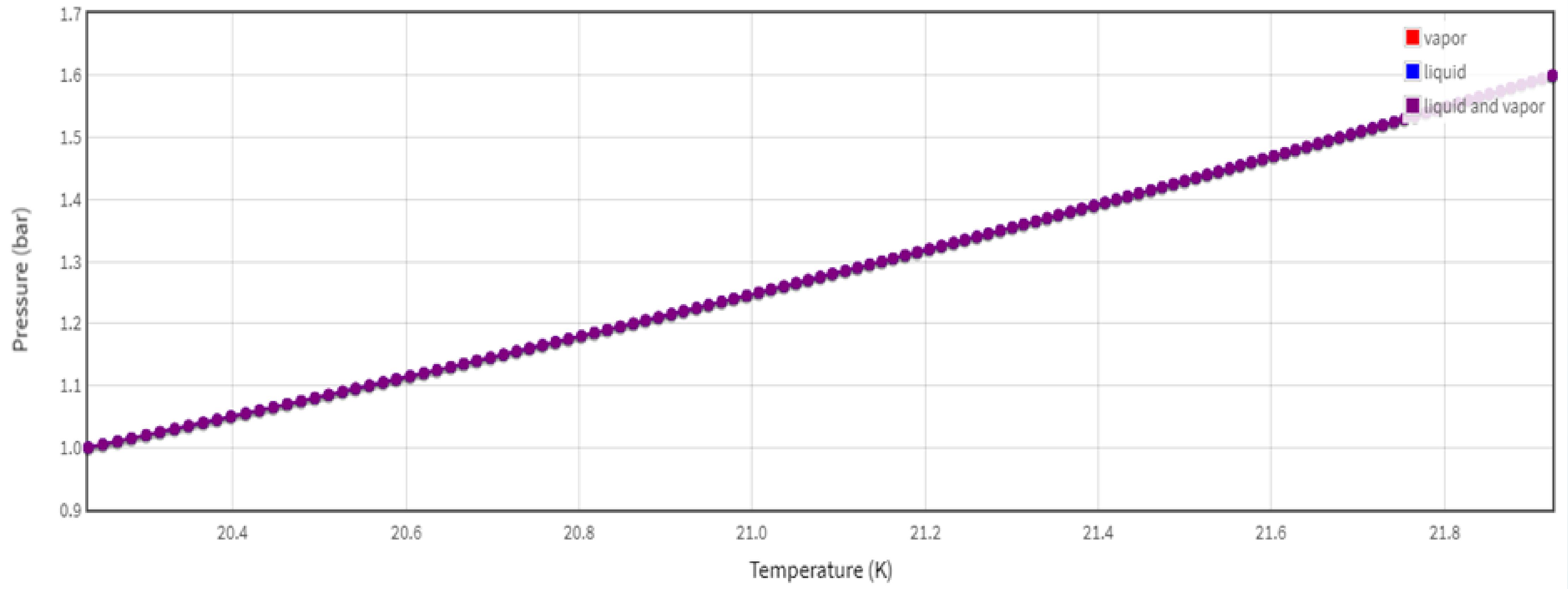

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