Improving the Cool-down times for Third Generation Gravitational Wave Observatories

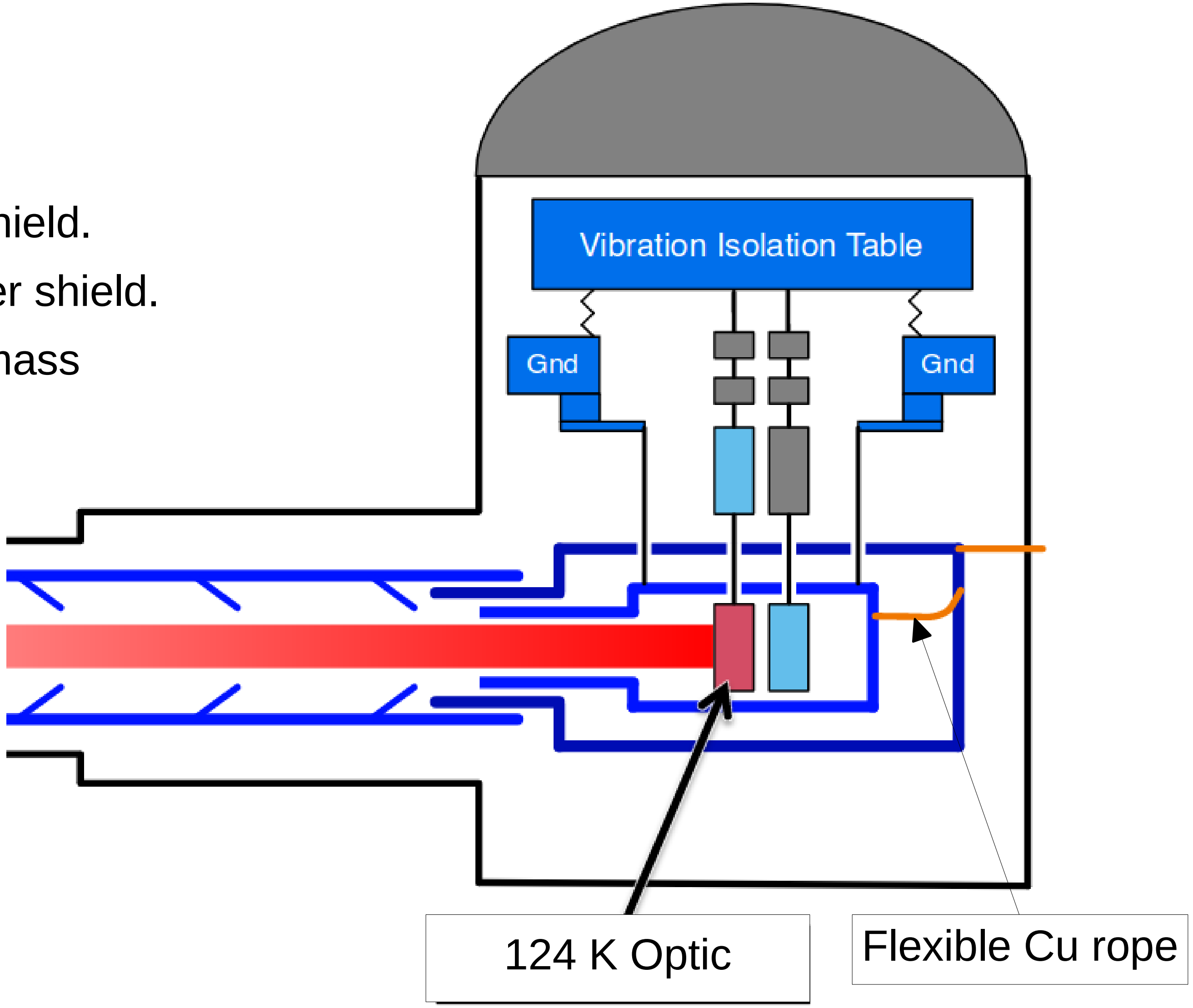
Edgard Bonilla,
On behalf of the Stanford LIGO Group

Outline

- Motivation

Voyager Technology

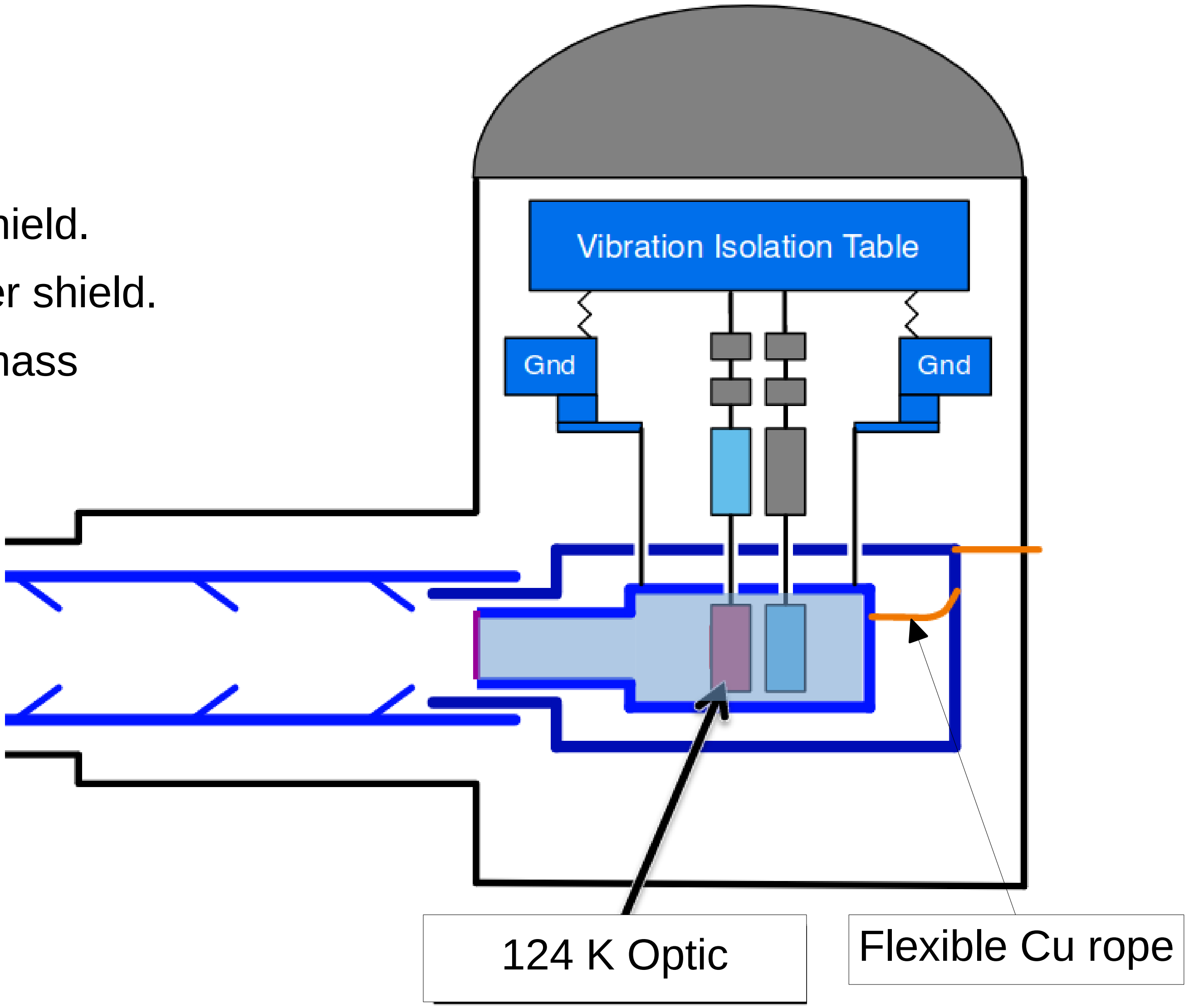
- Dual Cryo Shield.
- Active Isolation on the inner shield.
- Single Phase Coolant for Outer shield.
- Radiative Cooling of the test mass



Voyager Technology

- Dual Cryo Shield.
- Active Isolation on the inner shield.
- Single Phase Coolant for Outer shield.
- Radiative Cooling of the test mass

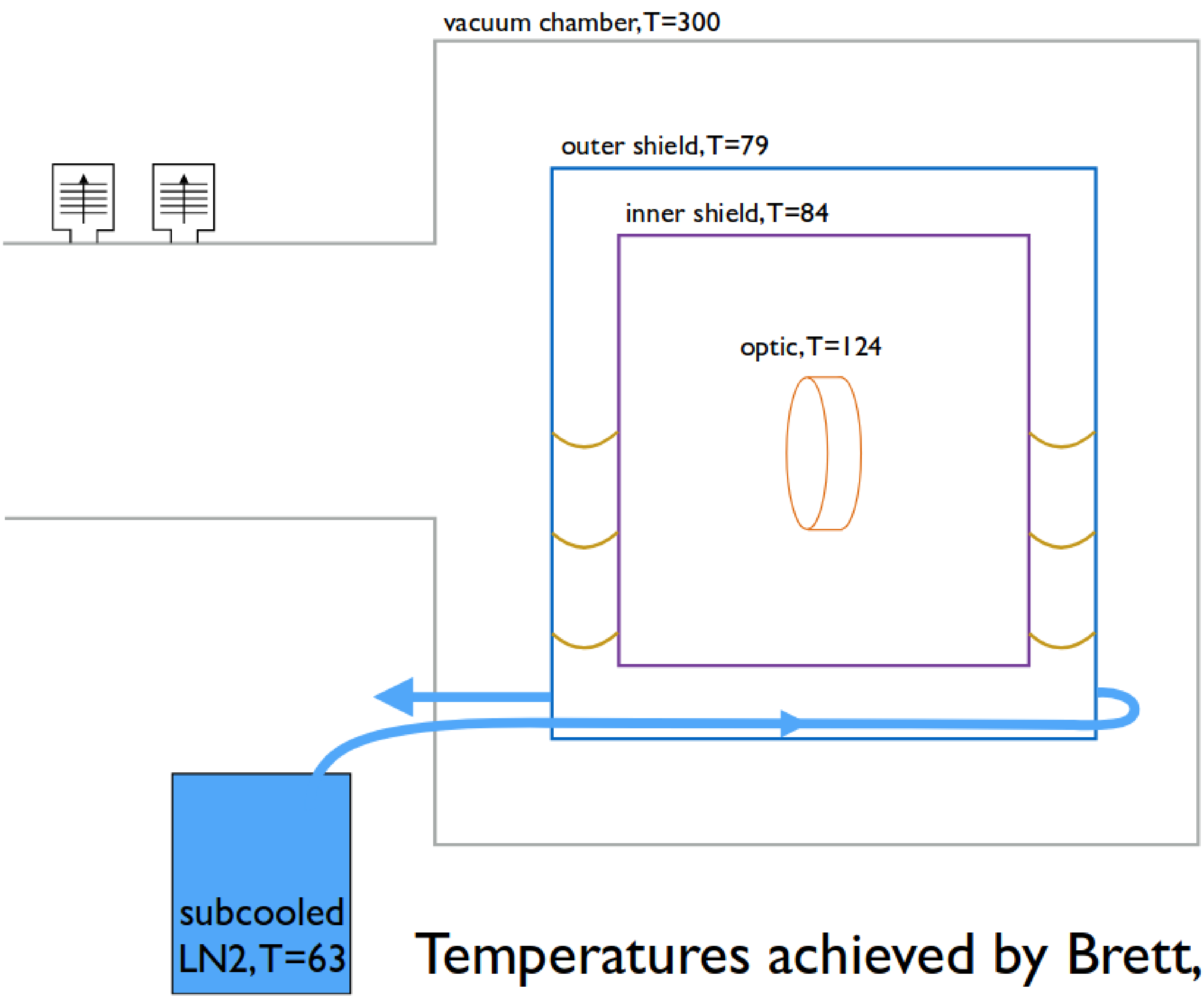
Next:
- Fast Cooldown time with exchange gas



Outline

- Motivation
- The idea.
  - Free Molecular flow heat transfer.

Sketch for exchange gas discussion

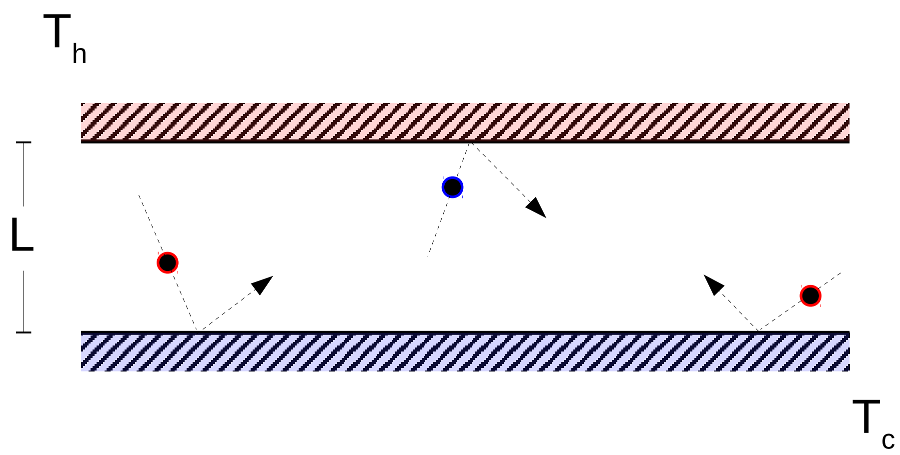


Temperatures achieved by Brett, Marcio, Edgard

Heat Conduction in Gases

Free Molecular

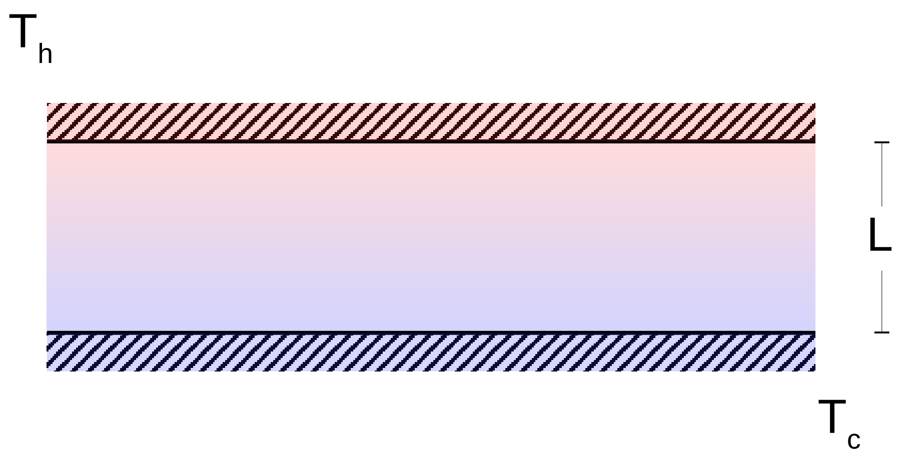
λ >> L



- Ballistic regime valid at low pressures
- Heat transfer independent of L
- Heat transfer linear with pressure

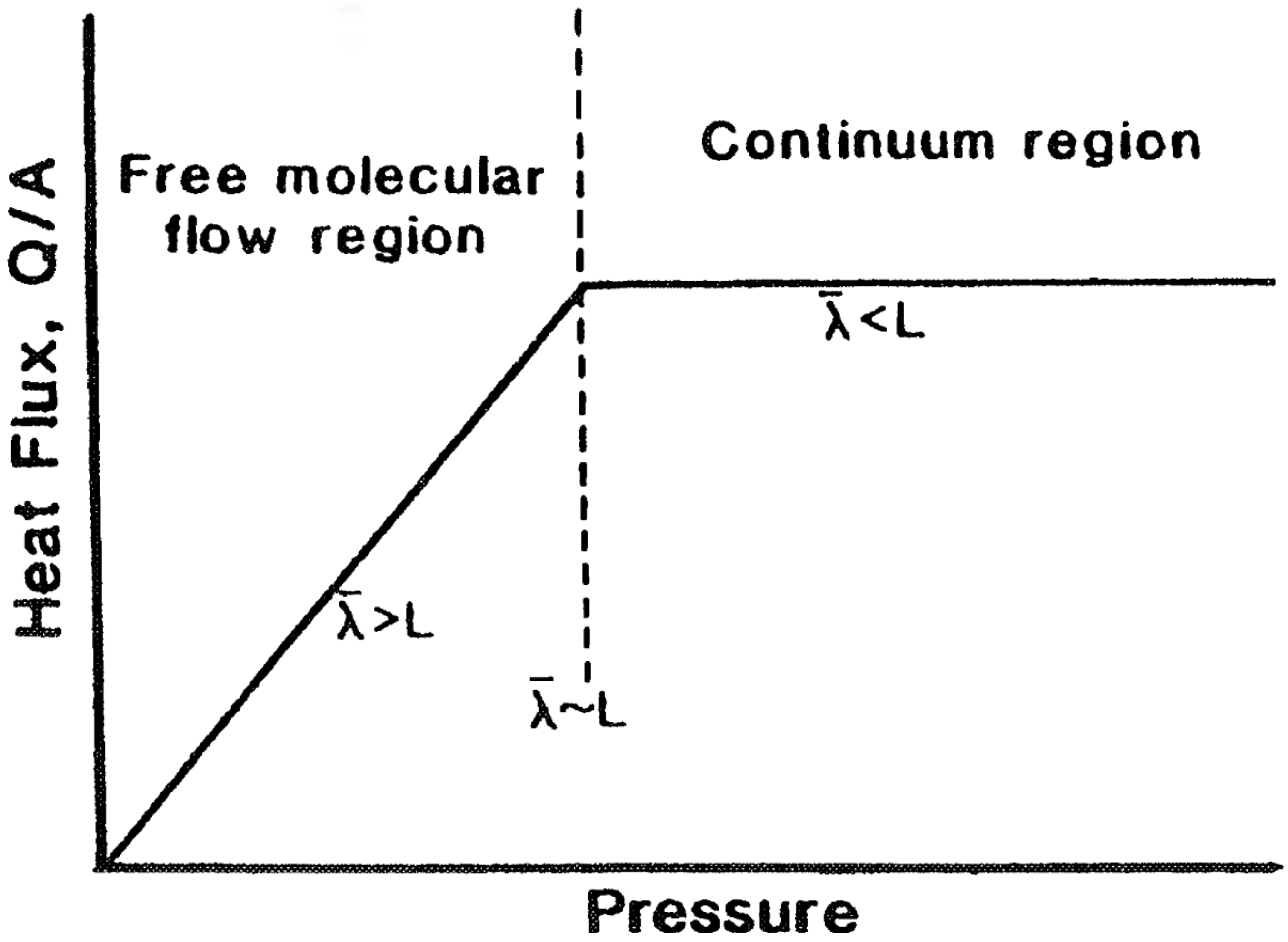
Continuous

λ << L

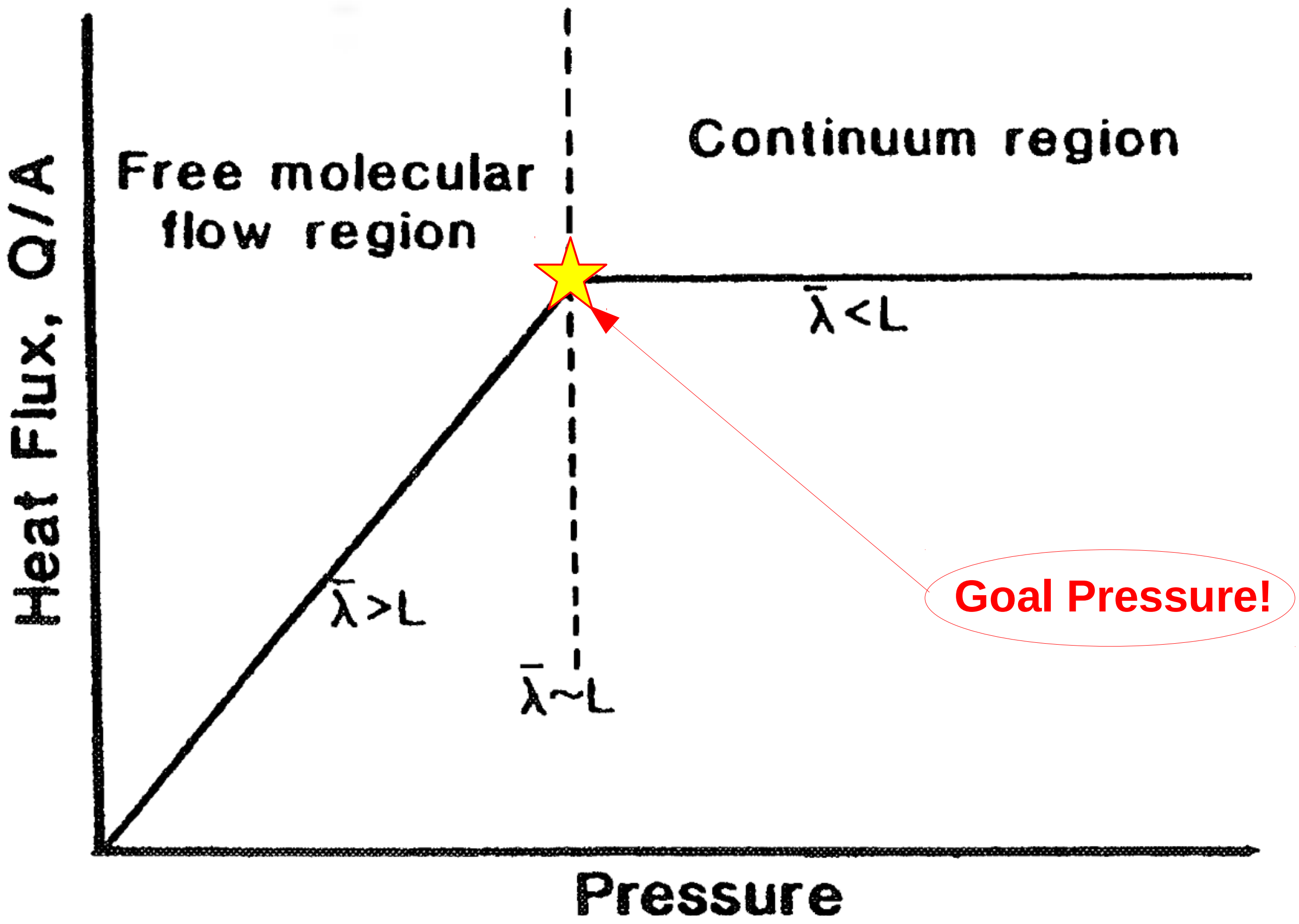


- Heat diffuses through gas bulk
- Heat transfer inversely proportional to L
- Heat diffusion is independent of pressure

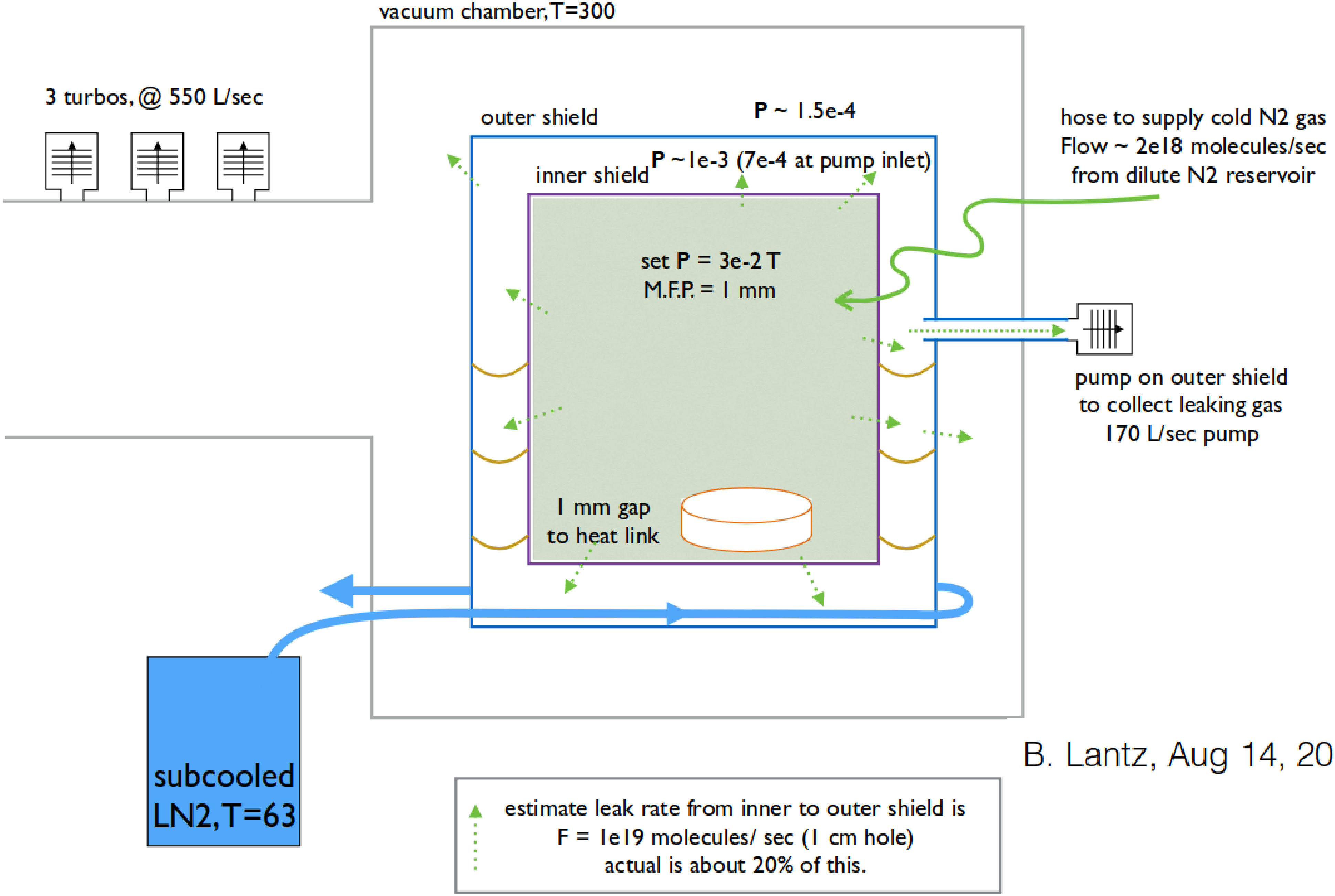
Heat Conduction in Gases



Heat Conduction in Gases



Plan to increase cooling rate:



B. Lantz, Aug 14, 2018

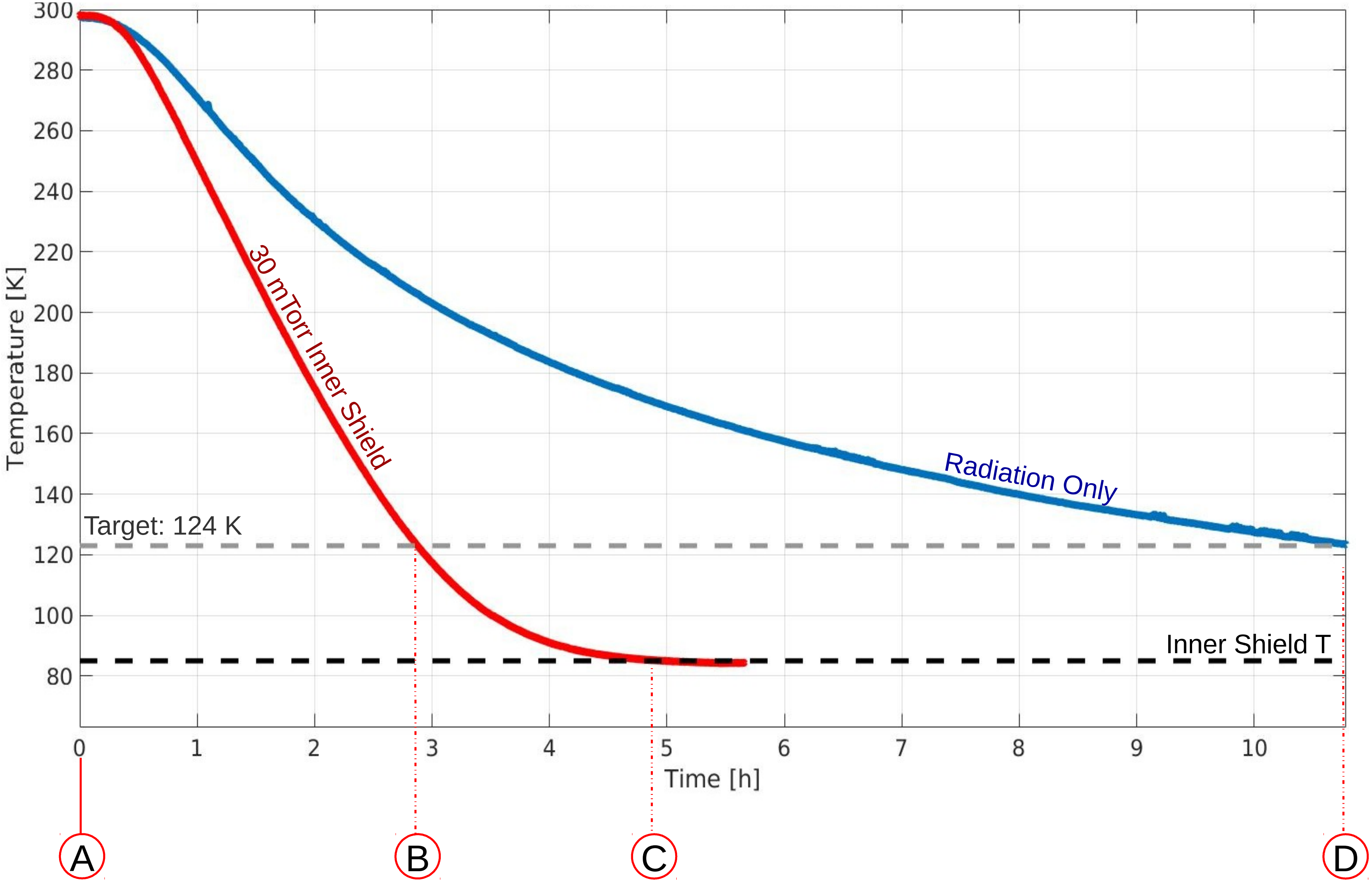
Experimental Questions:

- Can the gas injection speed up the cooldown without compromising other components?
- Is the choice of operating pressure ‘reasonable’?
- Can we model the results of our experiments?

Outline

- Motivation
- The idea.
  - Free Molecular flow heat transfer.
- Results
  - Cooldown time comparison
  - Theoretical Description

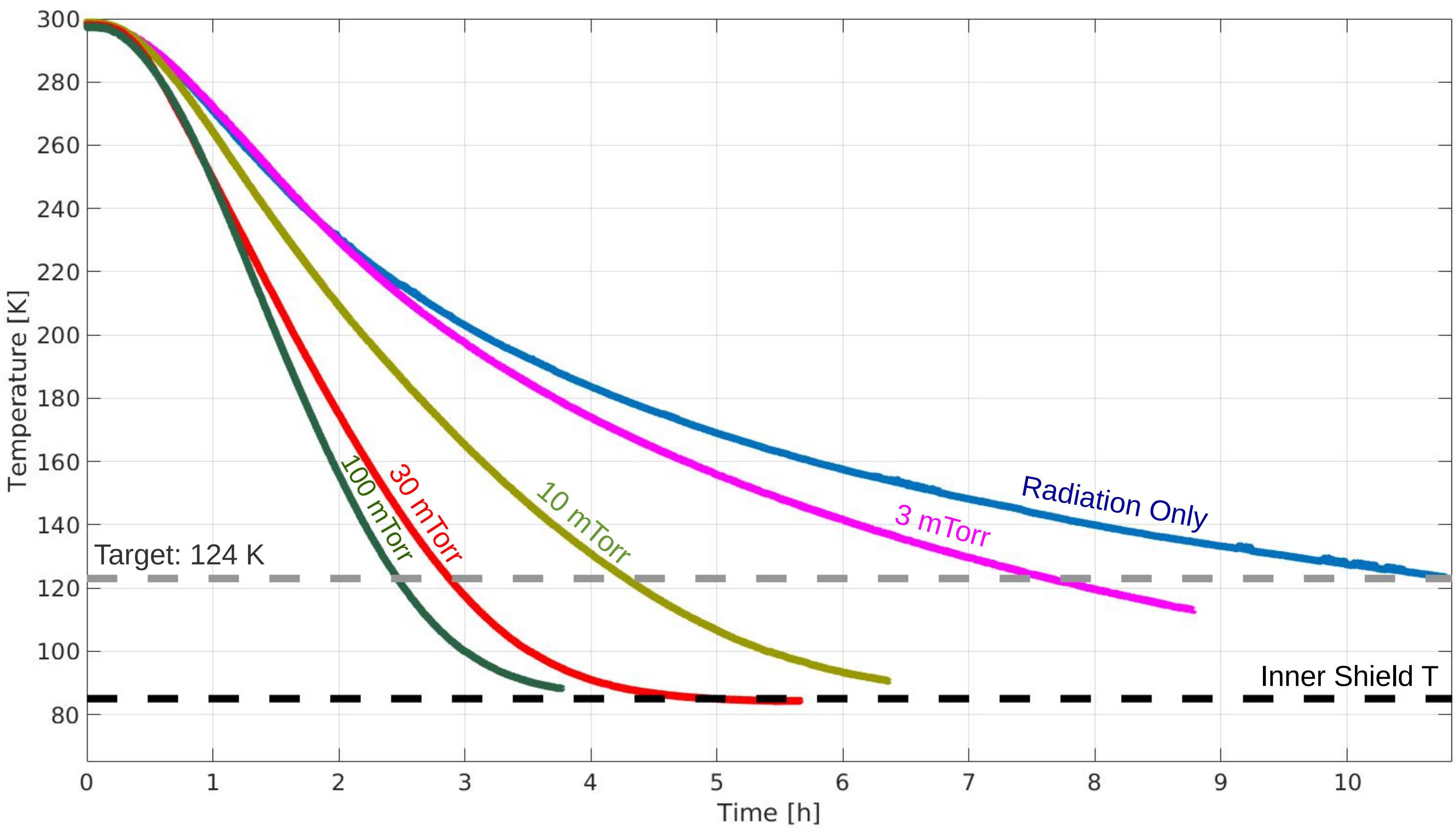
1 kg Silicon Mass results:



A: Start to flow LN2 on the shields (0 h)
B: Gas + Radiation achieves target (2.9 h)

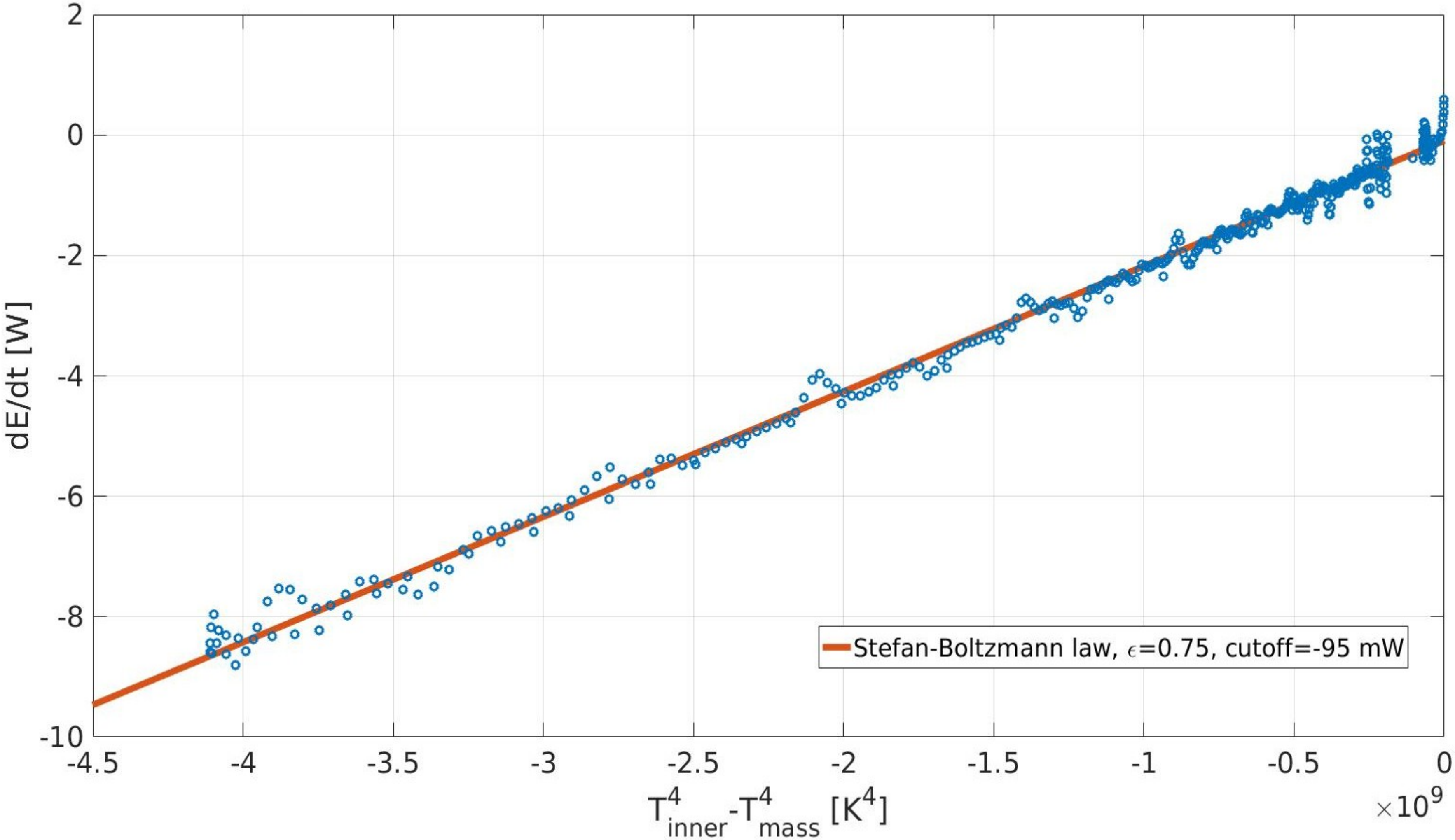
C: Gas+Radiation mass is at 86 K (4.9 h)
D: Radiation only mass achieves target (10.8 h)

1 kg Silicon Mass results:



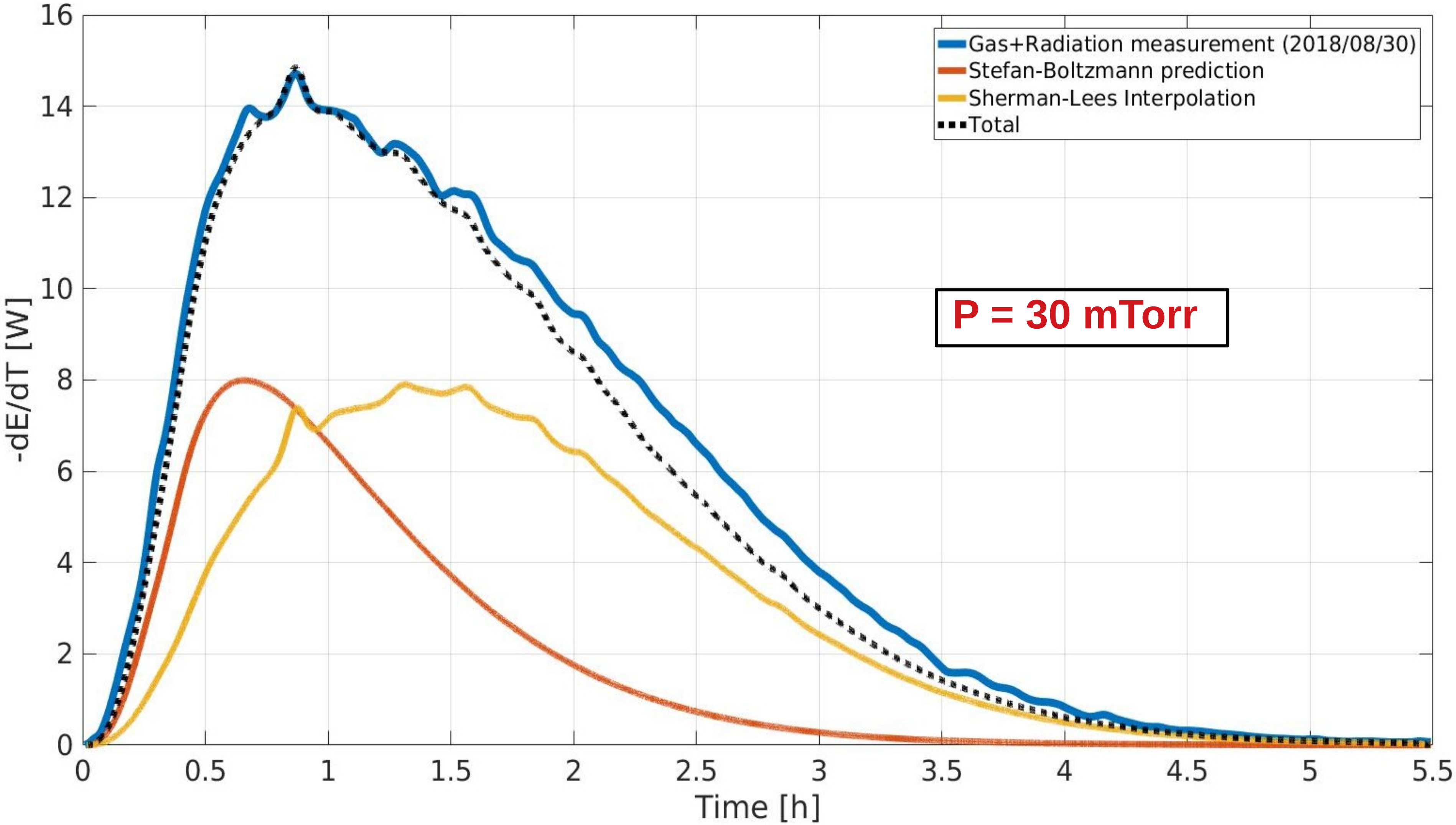
- Most of the improvement is made with the first ~10 mTorr
- The cooldown time improvement halts as we enter the continuous regime.

Radiative Cooling Verification:



- Effective emmisivity of 0.75 is around the expected value for our prototype.
- Nonzero Cutoff likely due to test mass spacers.

Heat transfer with Exchange Gas:



- The Exchange gas contribution to the heat transfer exceeds the radiative for most of the experiment.
- The expected heat transfer rate underestimates the experimental results.

Conclusions

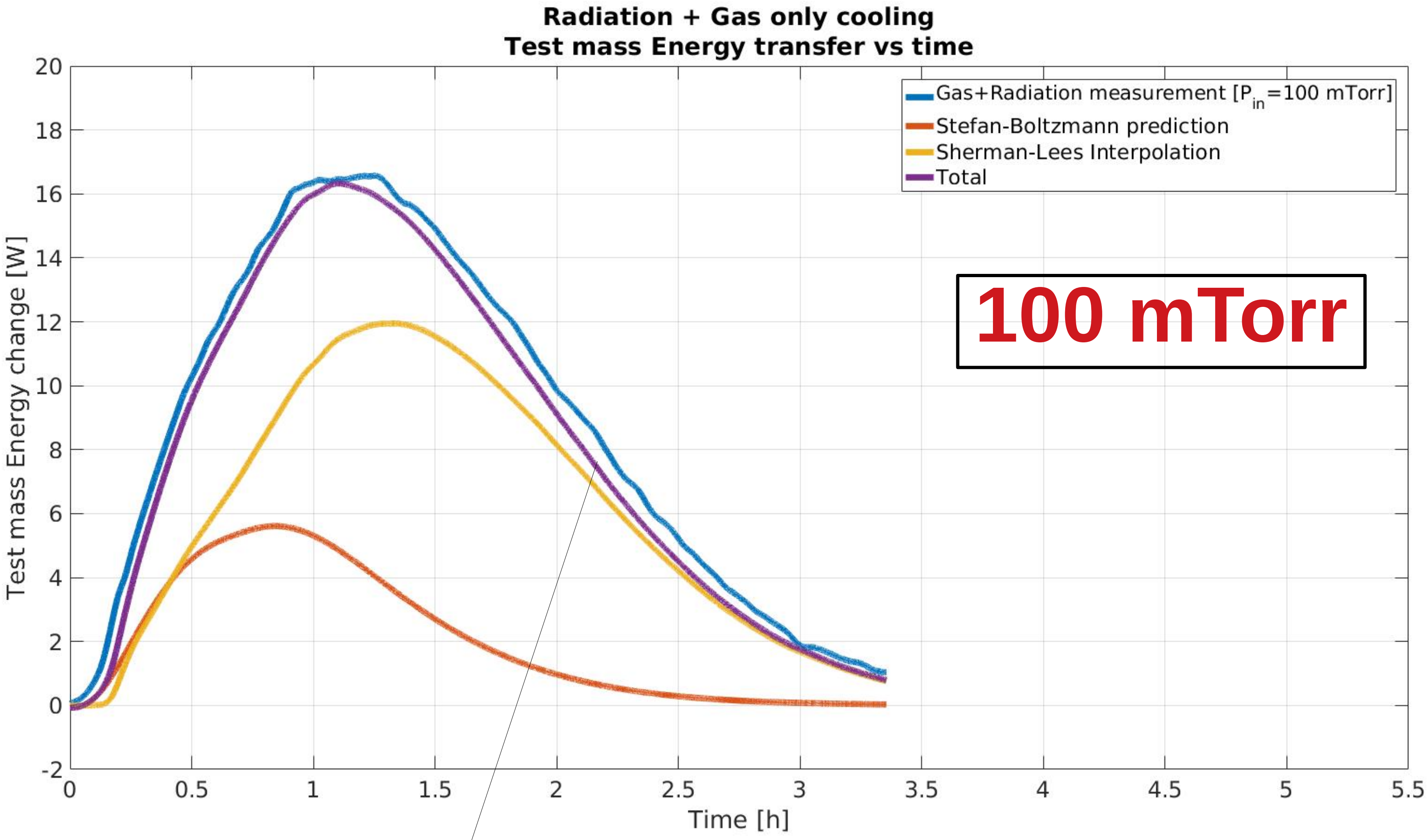
- The cooldown time was reduced by a factor of 3.5 in our prototype at 30 mTorr.
- This mechanism does not compromise the rest of the vacuum chamber or its components.
- The design is compatible with the requirements for LIGO Voyager.
- We can get a theoretical lower bound estimate of the cooldown rate.

Future Work

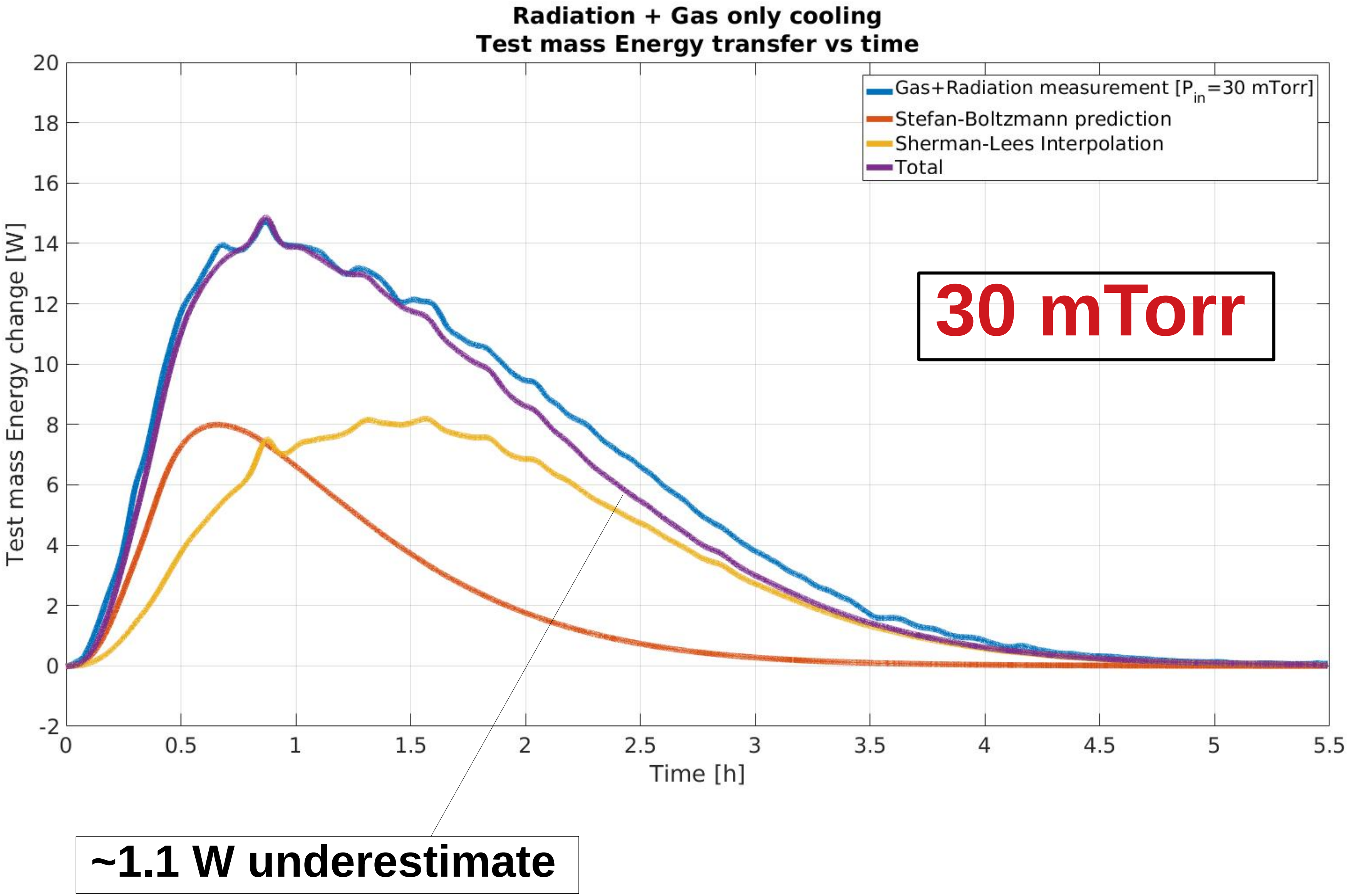
- Design/Test an in vacuum gate system to work with the exchange gas.

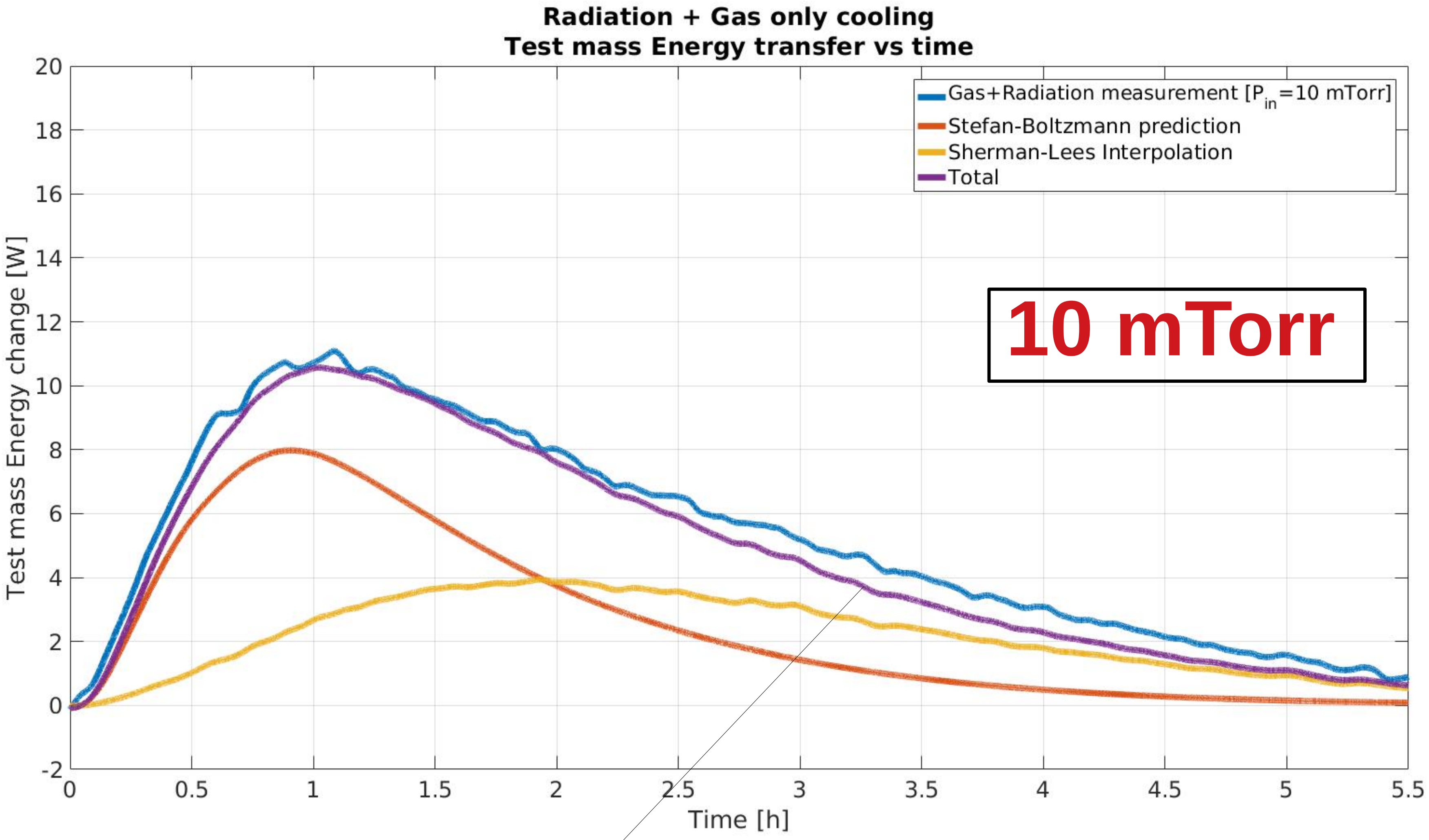
Useful References:

- Total variation derivative:
  - Chartrand, Rick. "Numerical differentiation of noisy, nonsmooth data." ISRN Applied Mathematics 2011 (2011).
- Heat conduction in gases:
  - Bird, G. A. "Molecular Gas Dynamics and the Direct Simulation of Gas Flows (Oxford Engineering Science Series)." Clarendon, (1994).

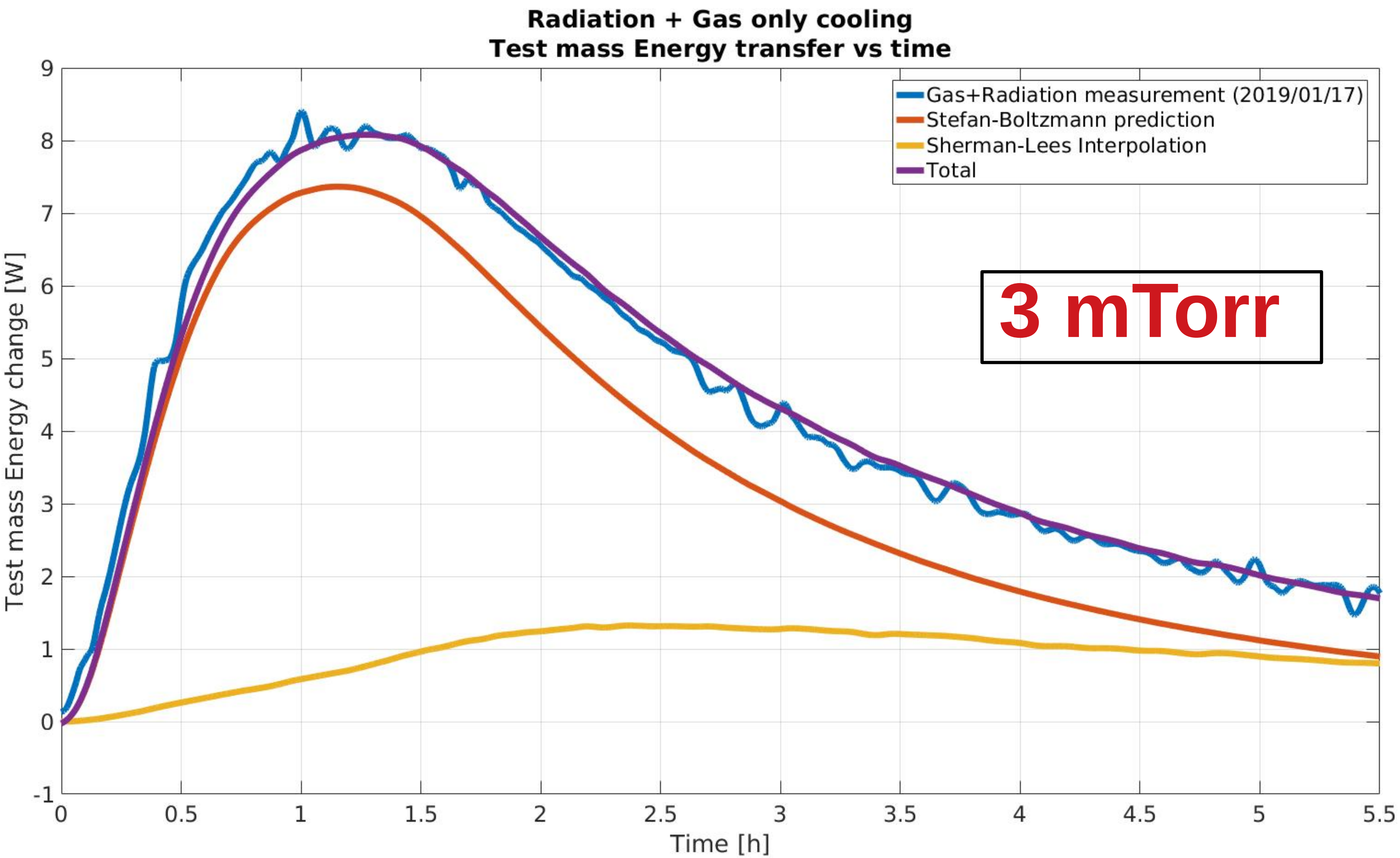


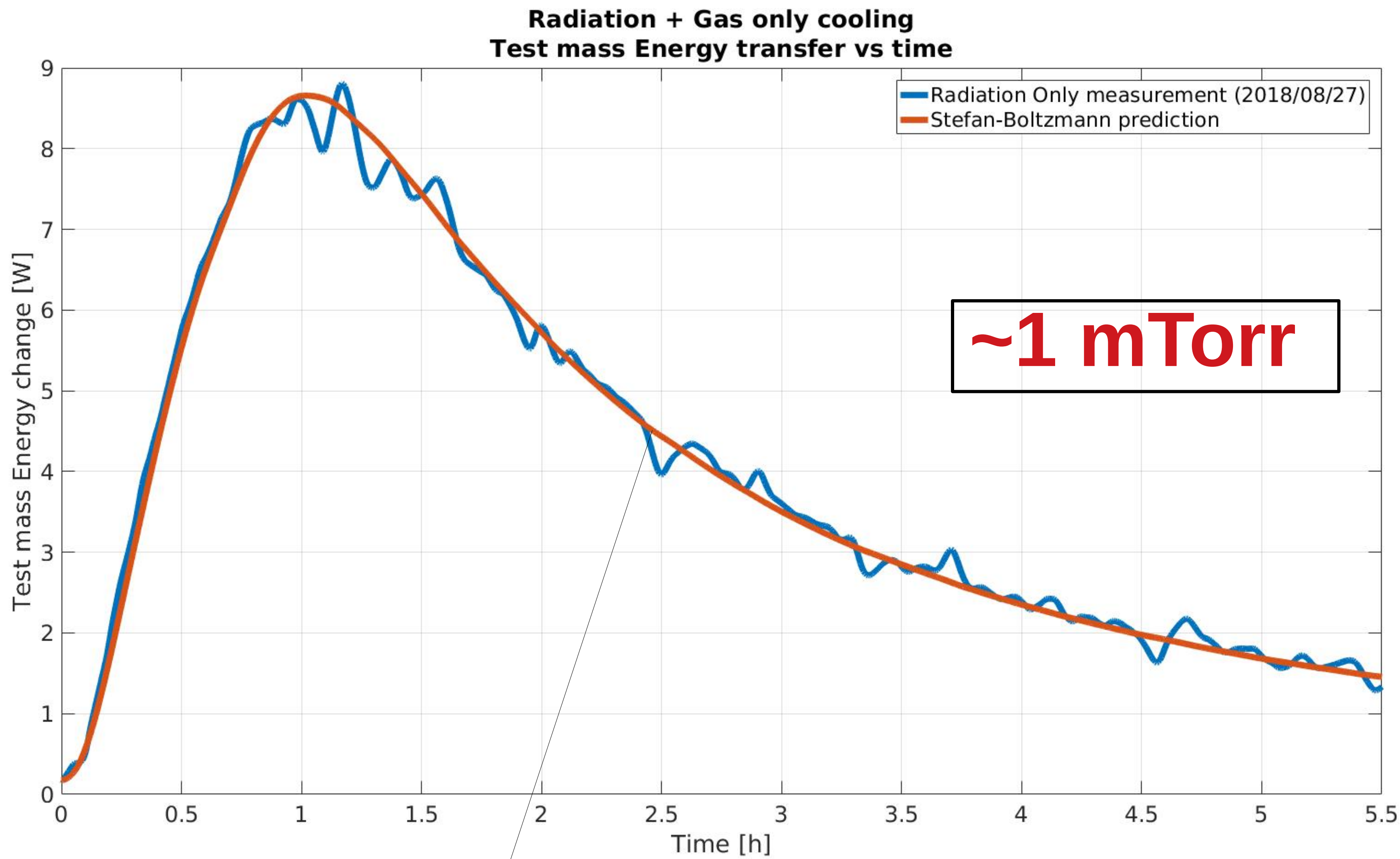
~0.8 W underestimate


Radiation + Gas only cooling
Test mass Energy transfer vs time
Gas+Radiation measurement [P_in=30 mTorr]
Stefan-Boltzmann prediction
Sherman-Lees Interpolation
Total
Test mass Energy change [W]
Time [h]
20
18
16
14
12
10
8
6
4
2
0
-2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
30 mTorr
~1.1 W underestimate

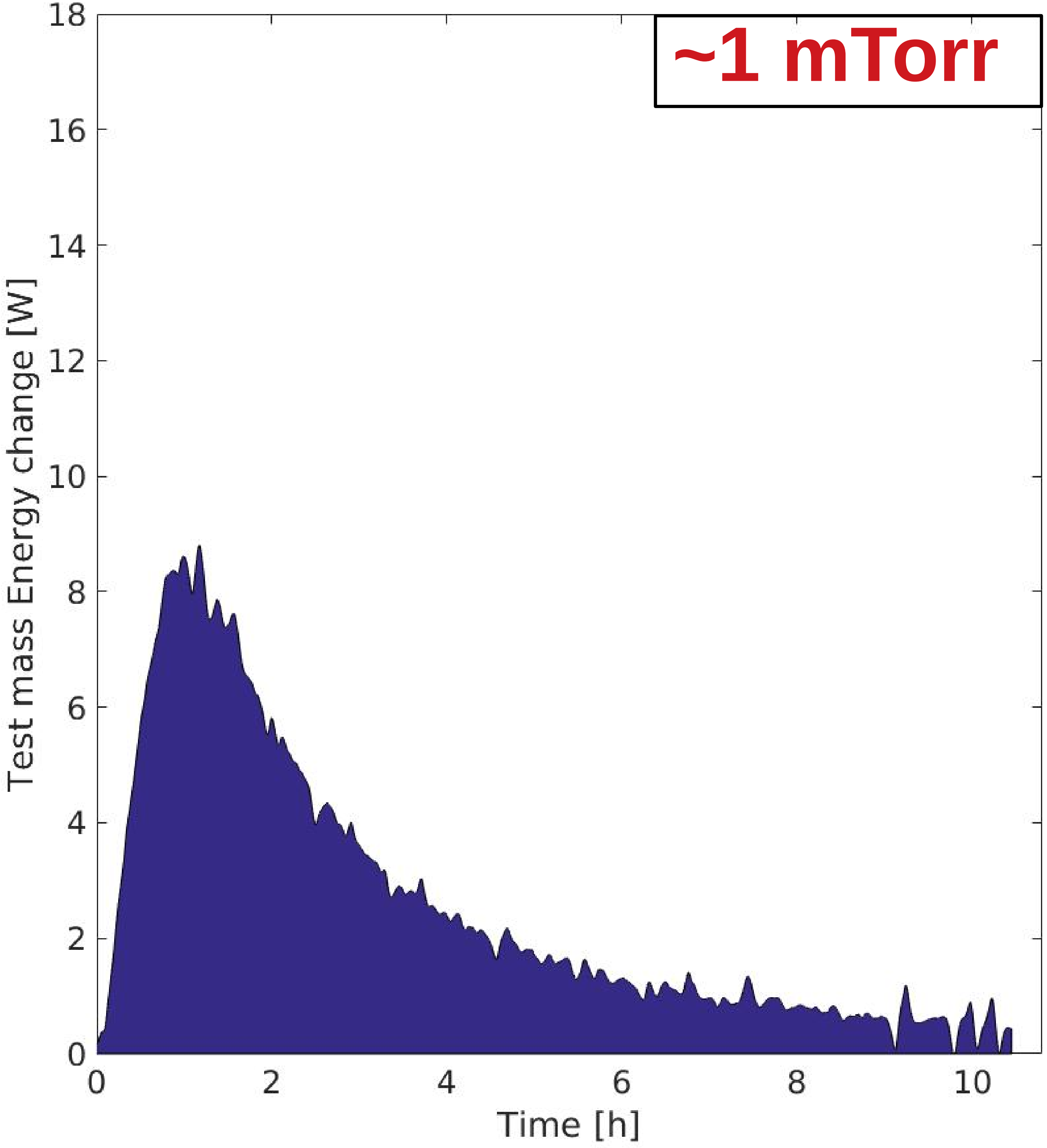


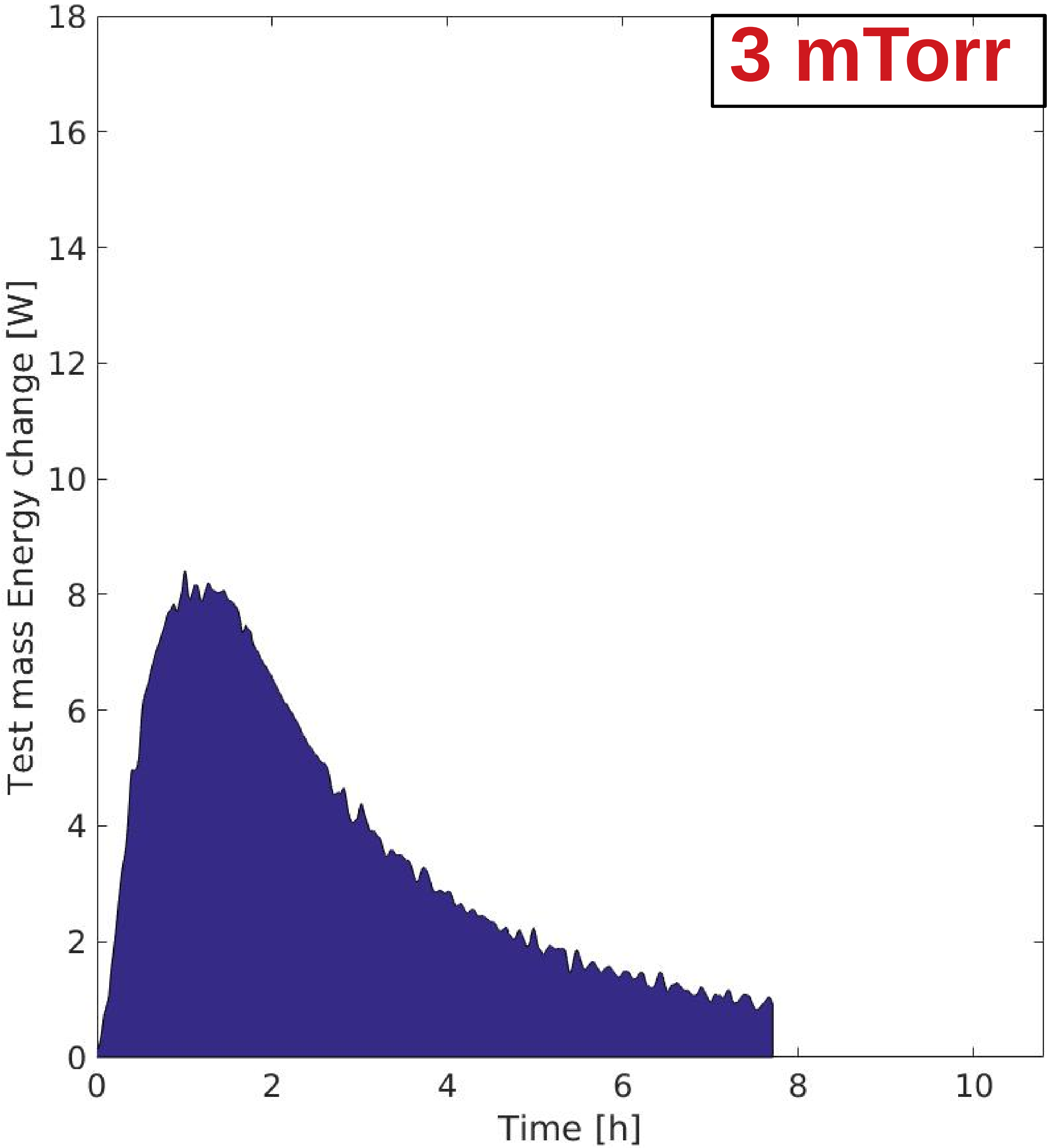
~0.8 W underestimate

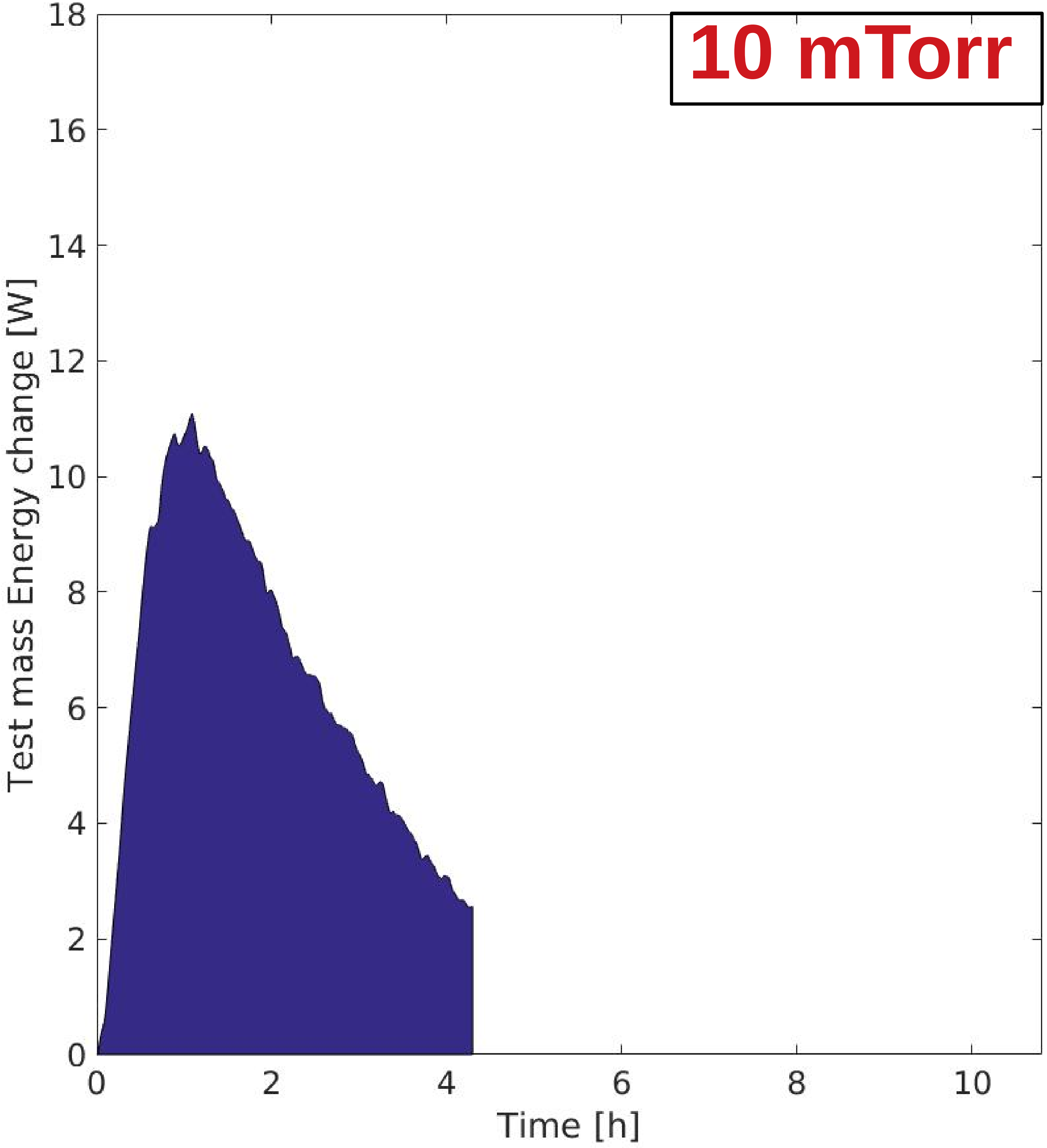

Radiation + Gas only cooling
Test mass Energy transfer vs time
Gas+Radiation measurement (2019/01/17)
Stefan-Boltzmann prediction
Sherman-Lees Interpolation
Total
3 mTorr
Test mass Energy change [W]
Time [h]
9
8
7
6
5
4
3
2
1
0
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5

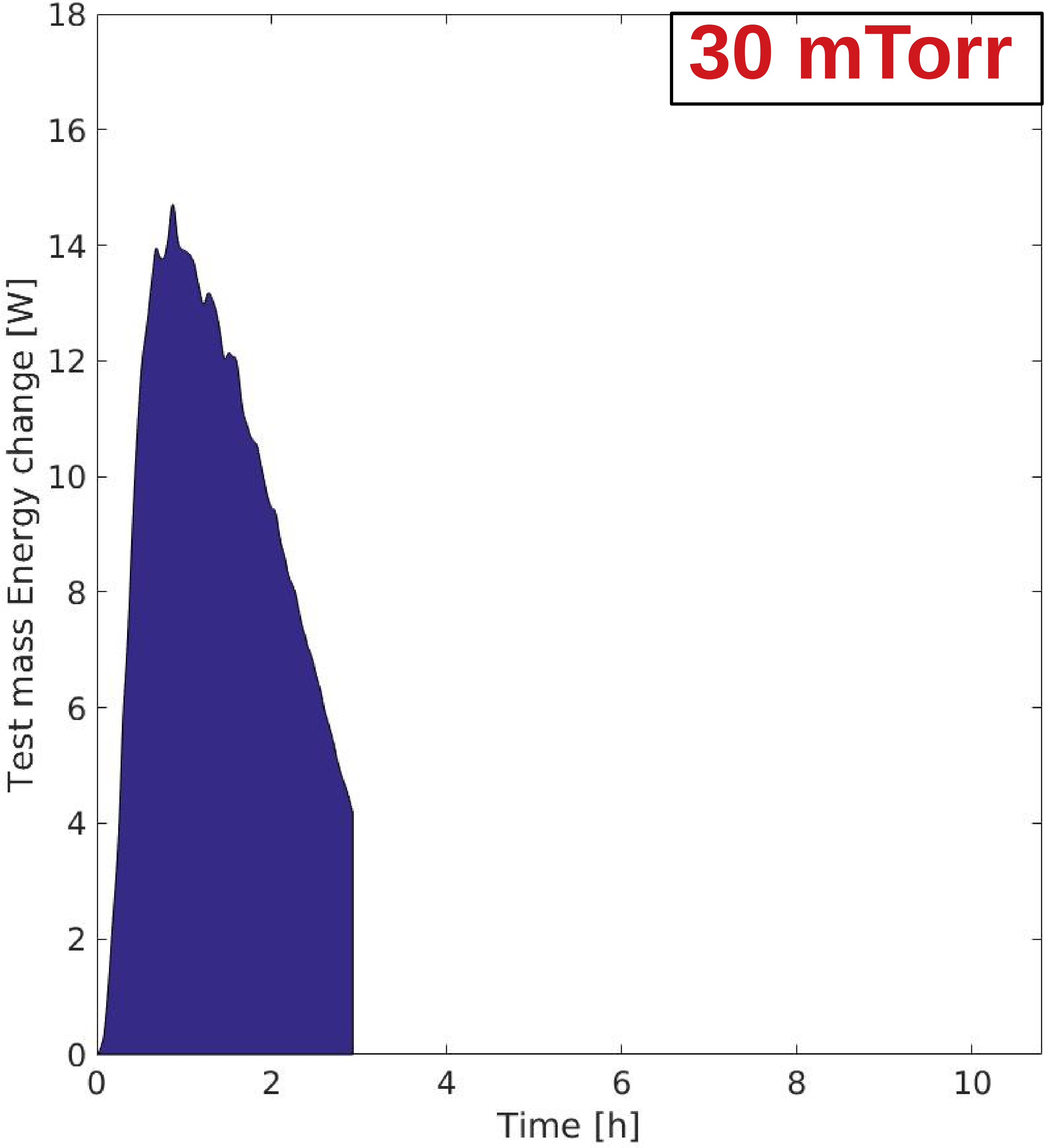


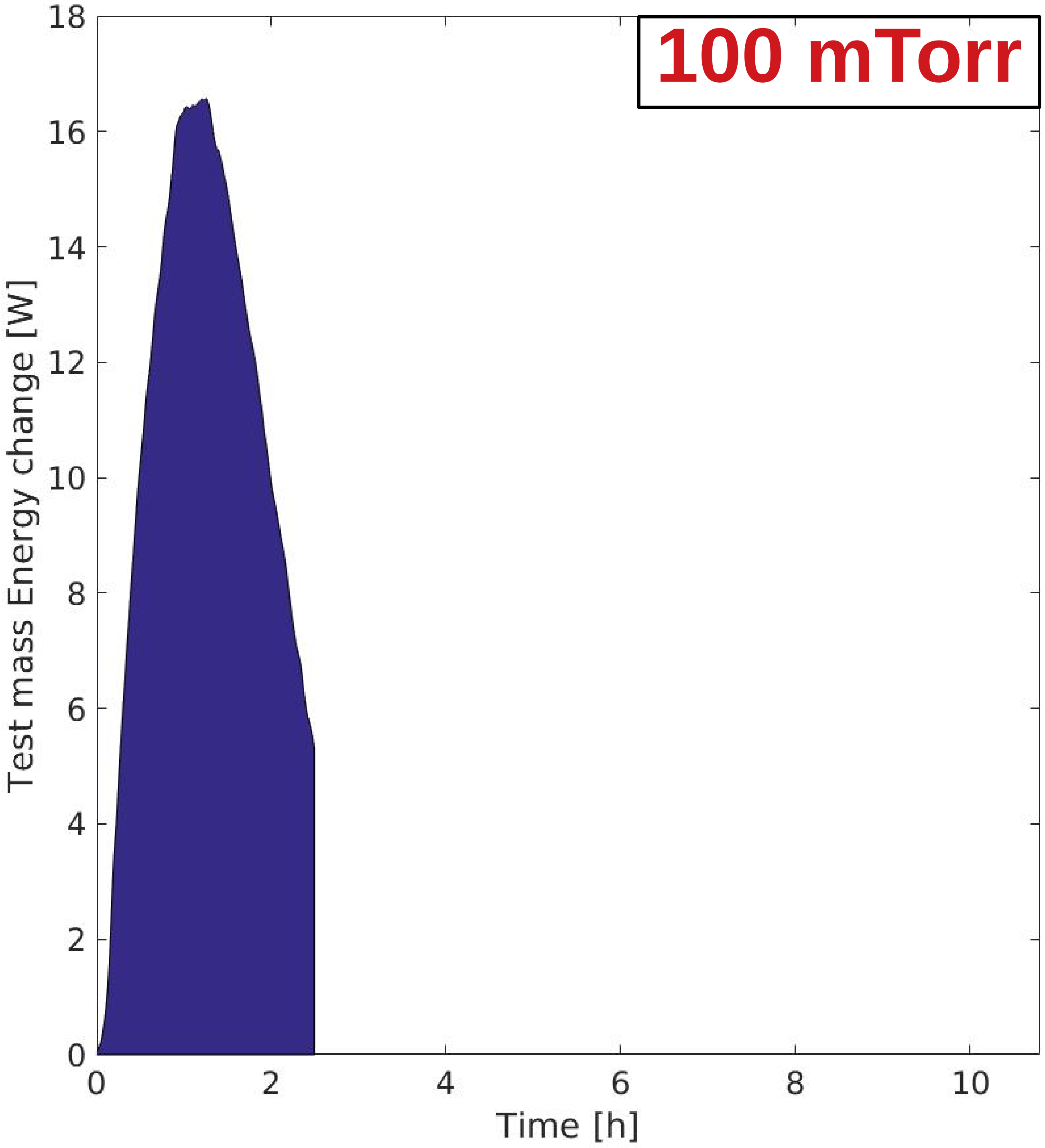
Fit with Stefan-Boltzmann's Law

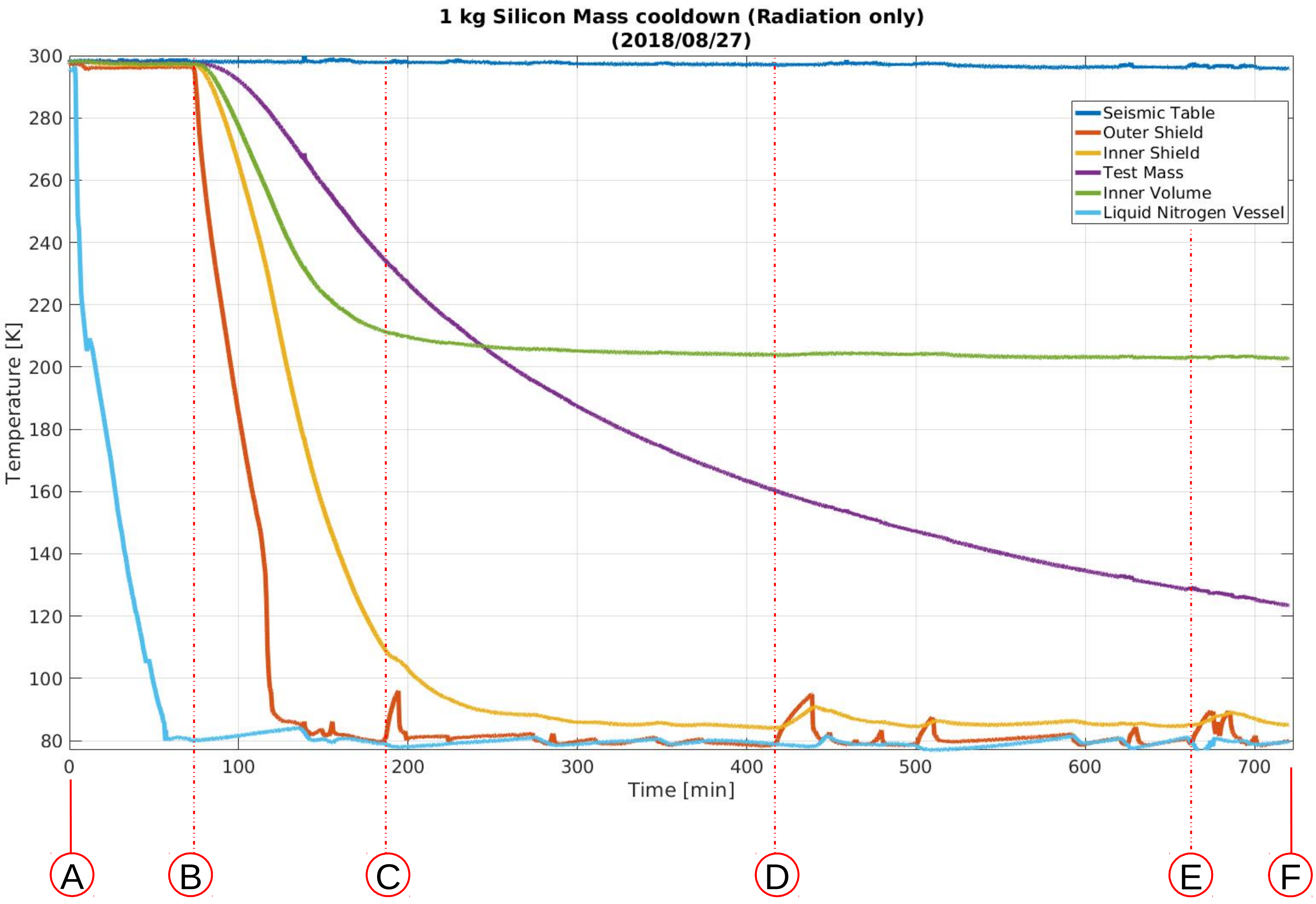

~1 mTorr
Test mass Energy change [W]
Time [h]
0
2
4
6
8
10
12
14
16
18
0
2
4
6
8
10


3 mTorr
Test mass Energy change [W]
Time [h]
0
2
4
6
8
10
12
14
16
18
0
2
4
6
8
10


10 mTorr
Test mass Energy change [W]
Time [h]
0
2
4
6
8
10
12
14
16
18


30 mTorr
Test mass Energy change [W]
Time [h]
0
2
4
6
8
10
12
14
16
18
0
2
4
6
8
10


100 mTorr
Test mass Energy change [W]
Time [h]
0
2
4
6
8
10
12
14
16
18



A: Start to fill LN2 vessel (0 min)

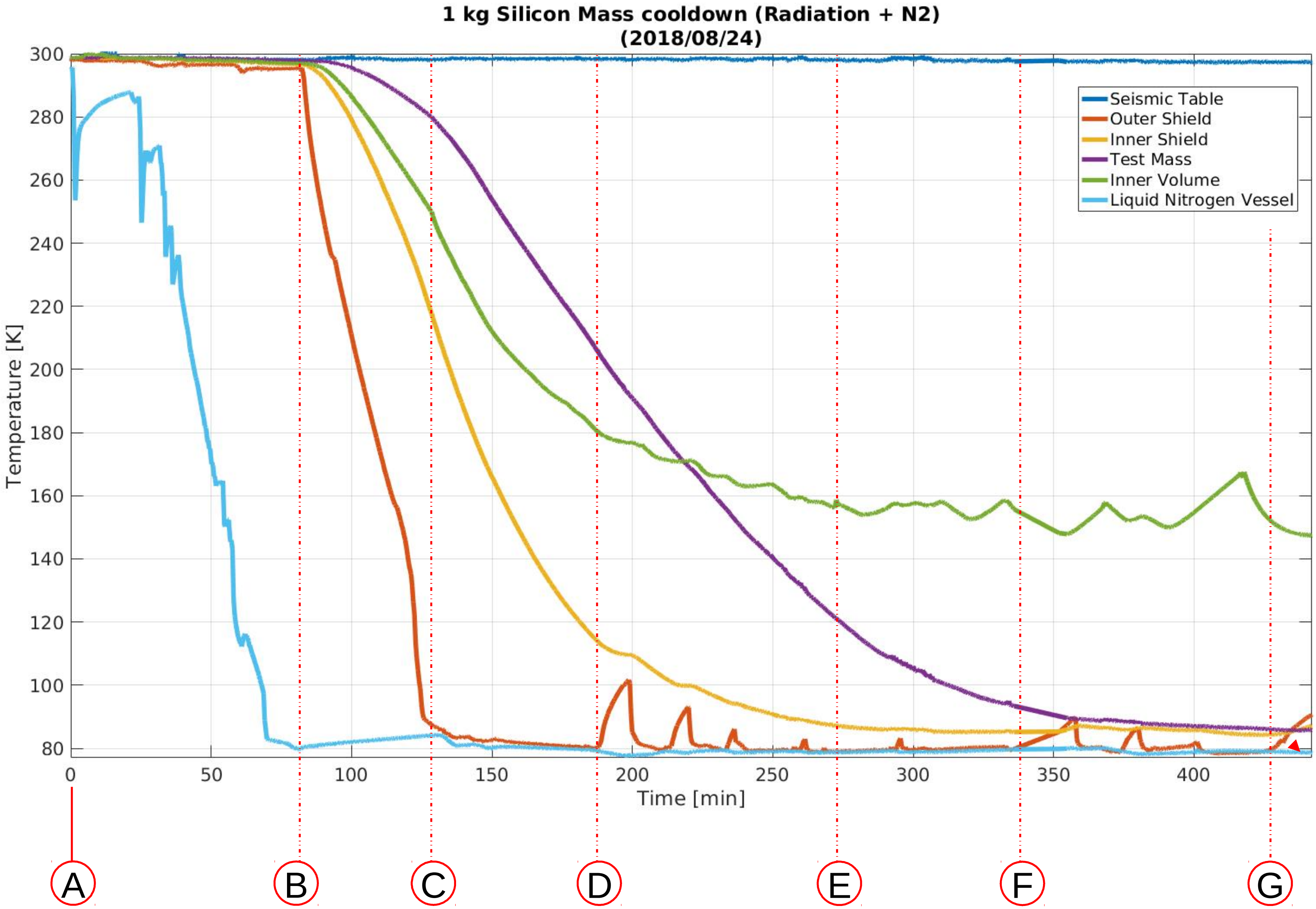
B: Start to flow LN2 on the shields (73 min)

C: Vessel is full, switching dewar (180 min)

D: Experiment unattended, finding new dewar (415 min)

E: LN2 vessel is empty (660 min)

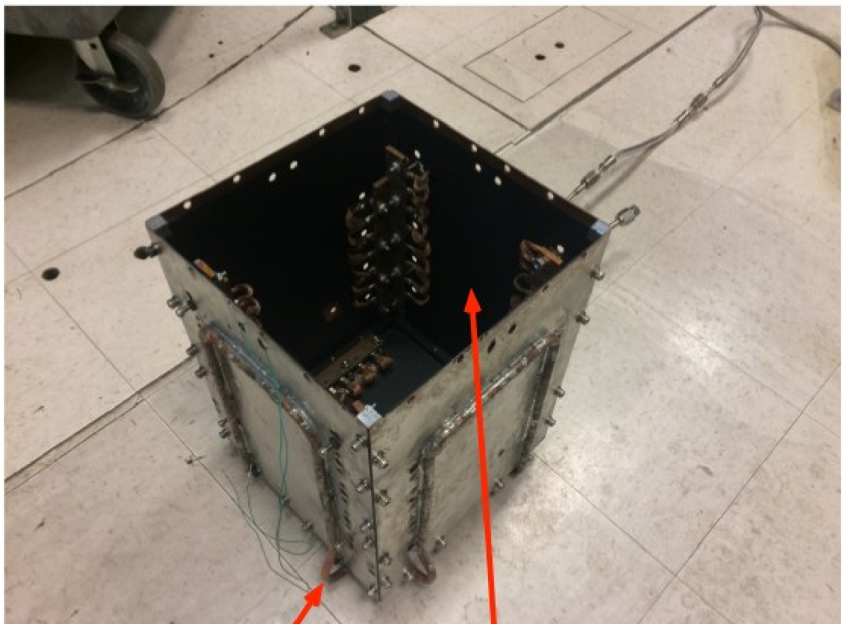
F: Target Achieved (720 min)

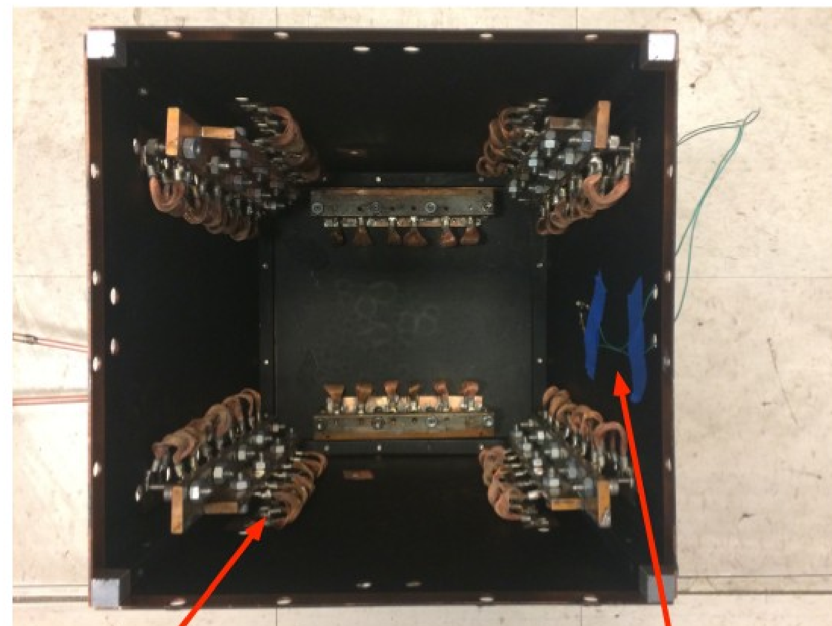


A: Start to fill LN2 vessel (0 min)
B: Start to flow LN2 on the shields (82 min)
C: Start gas injection (129 min)

D: Vessel is full, switching dewar (180 min)
E: Target Achieved (270 min)
F: False Stop (335 min)
G: T~86 K, True Stop (425 min)

Cryo Shield Prototype





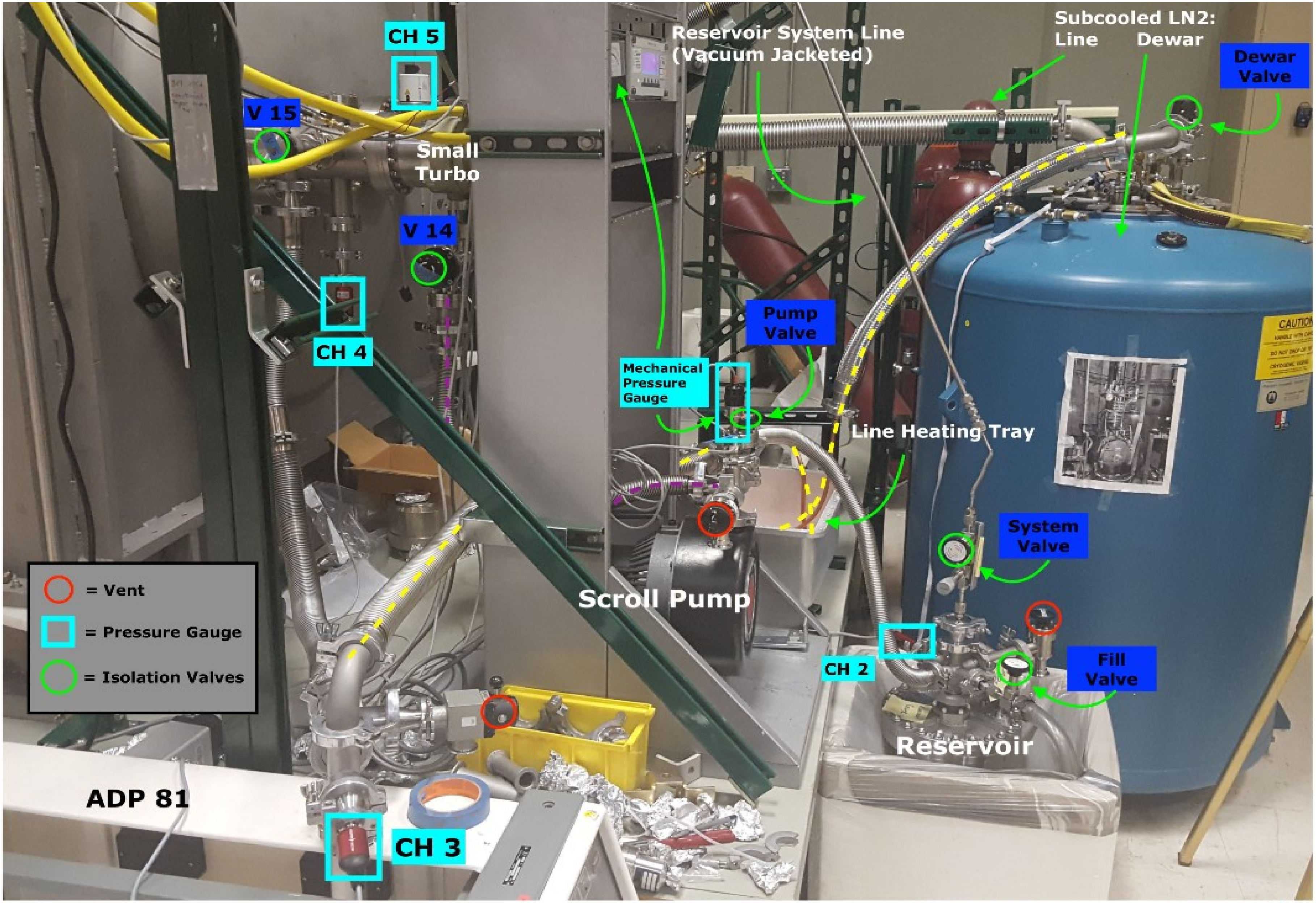
Liquid nitrogen pipe

Black paint

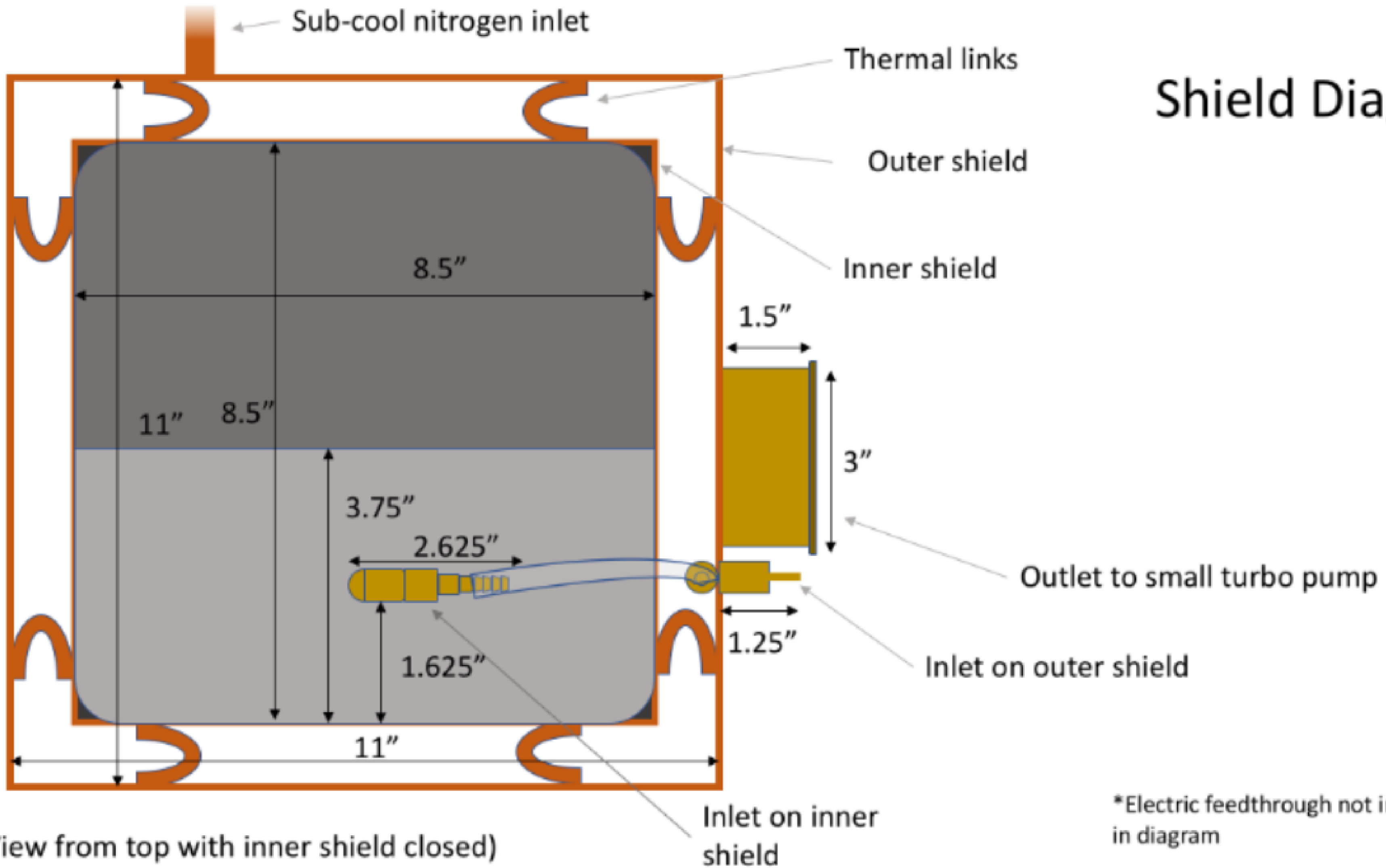
Flexible copper ropes for conductively cooling the inner shield

Silicon diode temperature sensor

Some of the plumbing:



Shield Diagram

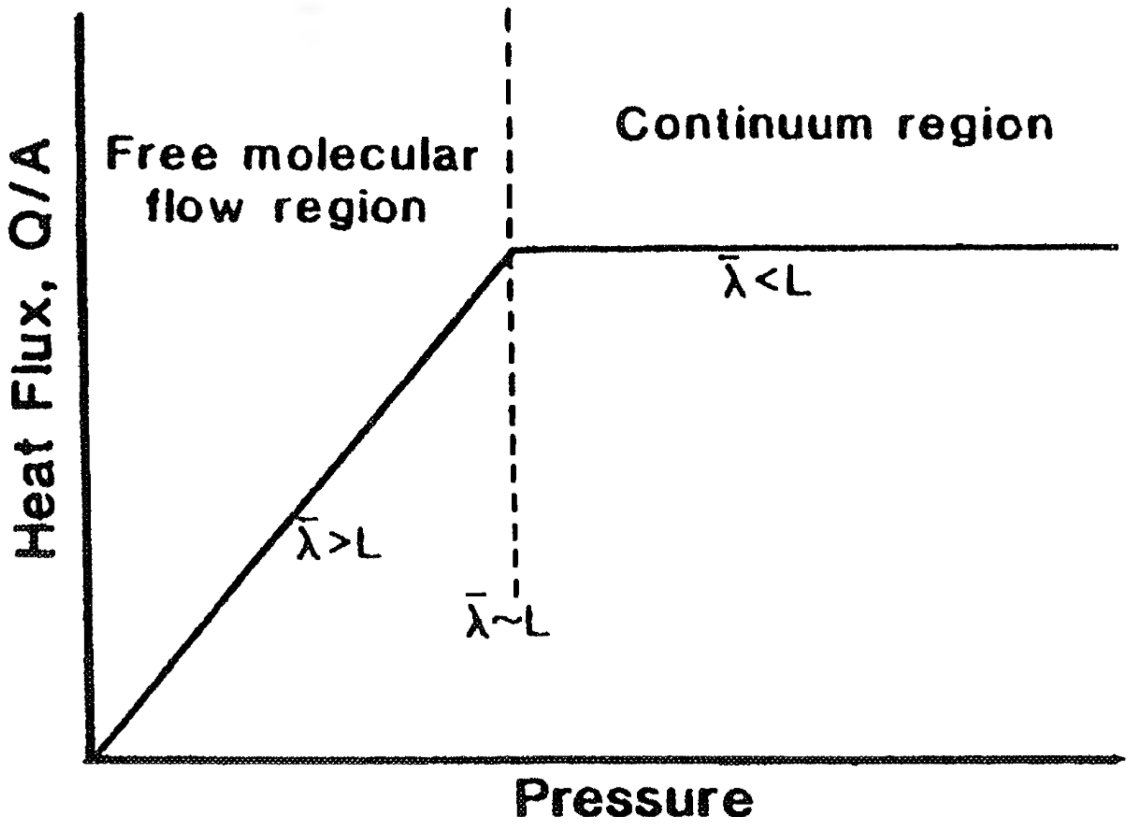


(View from top with inner shield closed)

*Electric feedthrough not included in diagram

J. Salone 08/02/18

Heat Transfer Regimes



Free-Molecular:

$$q_{FM} = -\alpha \left(\frac{8k_B}{\pi m}\right)^{1/2} \left(1 + \frac{\zeta}{4}\right) P(T_h^{1/2} - T_c^{1/2})$$

Continuum:

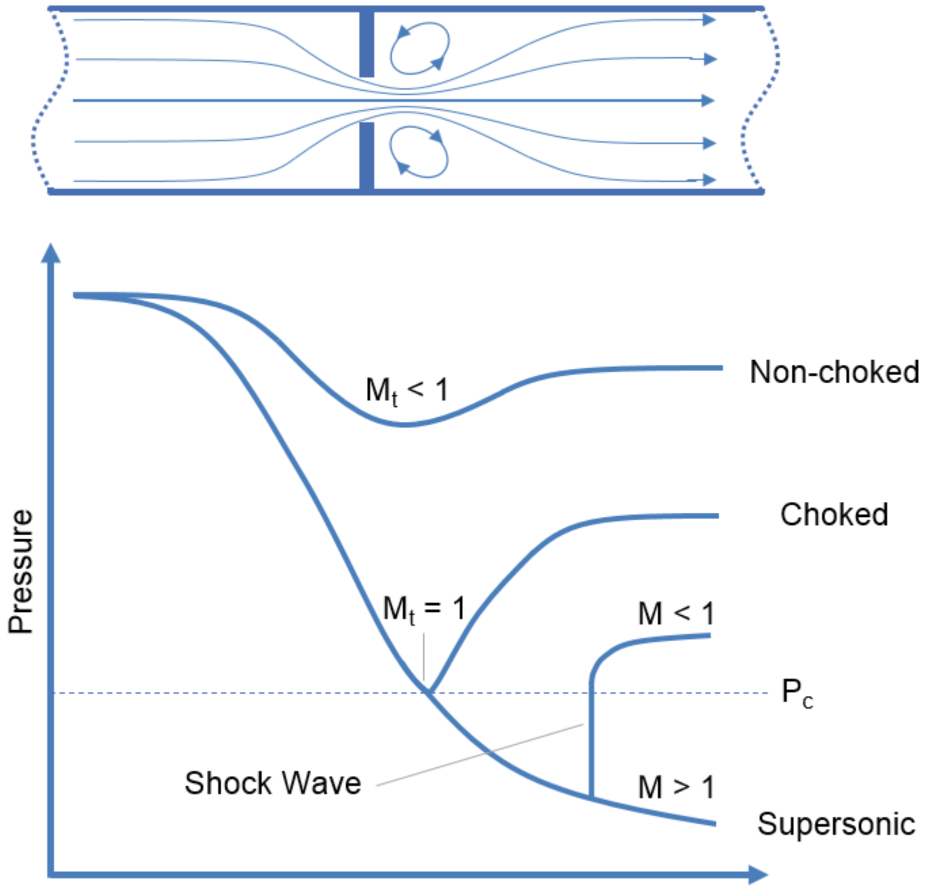
$$q_C = -\frac{1}{L} \int_{T_c}^{T_h} K(T)dT$$

Transition:

$$\frac{1}{q_T} = \frac{1}{q_C} + \frac{1}{q_{FM}}$$

Sherman-Lees Interpolation

Choked Flow



$$\frac{p^*}{p_0} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}}$$

$$\dot{m} = C_d A \sqrt{\gamma \rho_0 P_0 \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$