DMRadio 50L
20mK stage

Maria Salatino – Stanford University

a CMB artisan in Chelsea's group

DMRadio Collaboration Meeting

August 5, 2024

20mK stage: requirements

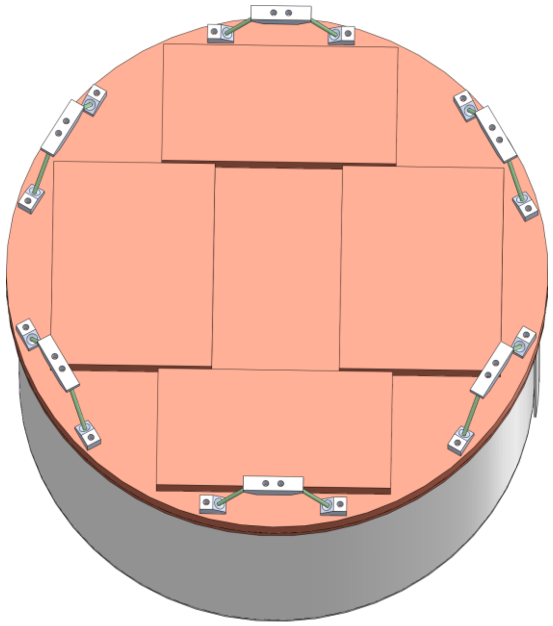
1. Maximize the experiment volume
2. Mechanically connected to but thermally insulated from the 1K stage
3. Cooled down by the MC cooling power transferred via the 20mK cold finger
4. Enclose the experiment volume
    1. Optically shielded by the radiation loads from 1K and higher temperature stages
    2. Magnetically shielded by the magnet magnetic field
    3. Allow to evacuate the air from the 20mK volume without adding extra radiative loads

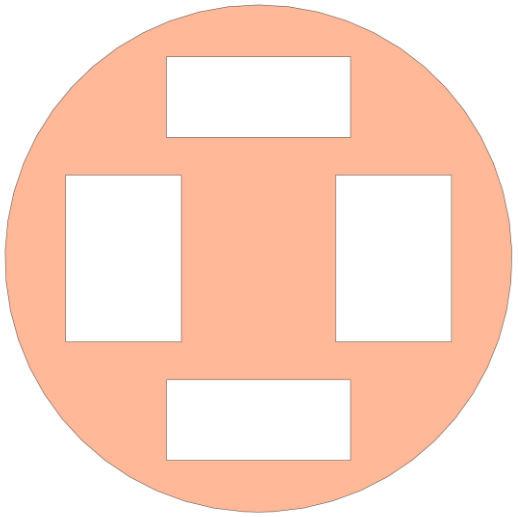
1. Maximize the experiment volume: the 20mK plate

- Diameter increased from 273 to 289mm
  - Constrained by the 4K ring ID
- Cu 10mm thick for improved thermal behavior

- Currently: full plate – adding ports would allow:
  - Running multiple experiments without re-fab the 20mK plate
  - The experiment(s) could be integrated independently from the 20mK plate and on the bench
  - No need to finalize all mechanical interfaces before 20mK plate fab
  - One smaller port for HK connectors/cables
  - Angular sector-shape ports have higher filling factor but are more expensive

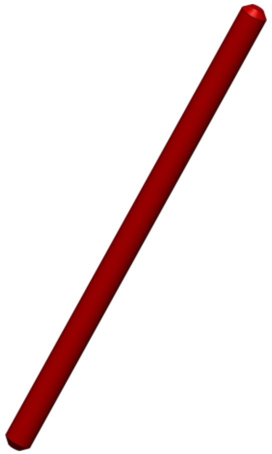
Example of possible ports dimensions:
105 mm x 46 mm
95 mm x 66 mm

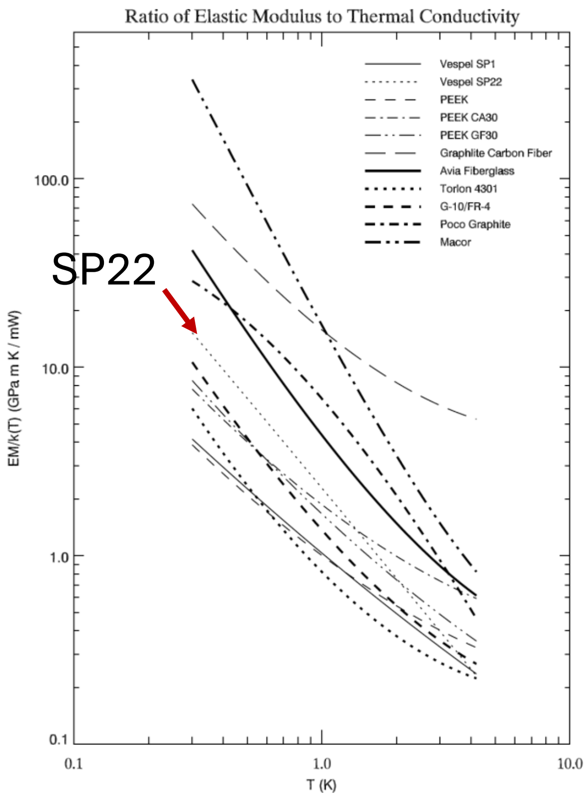


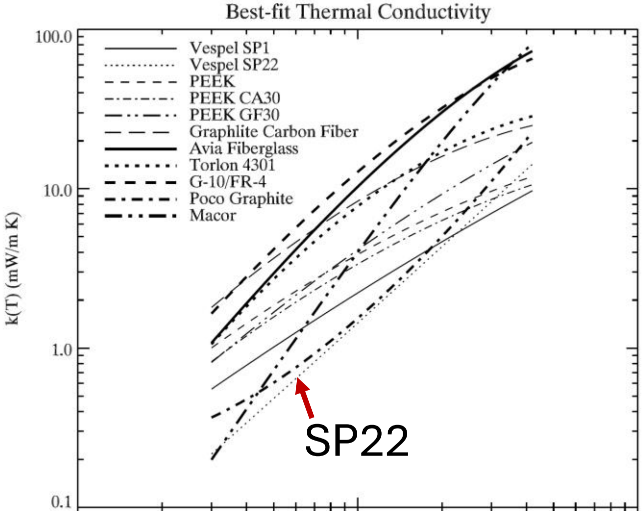


2. Mechanically connected to but thermally insulated from the 1K stage: vespel

- Vespel SP22 k < SP1 – Locatelli+ 1976
  - 5.7 uW/cm/K in [0-1]K
- 12 rods, 2mm diameter, 38mm long
  - Reasonable length for mechanical access to 20mK plate
  - Longer would make 20mK stage less stiff
  - **1.5 uW** thermal load
- AGOT graphite
  - 3x less thermally conductive in [0-1]K
  - Not available anymore
  - Replacement: k POCO AXM-5Q 10% > SP22 - Woodcraft+ 2003
- Macor
  - Very good at mK temps, not > 1K
  - Maybe for mounting experiment parts in the 20mK volume ?
- Additional refs:
  - Woodcraft+ 2013, k(T) plots. Olson 1993
  - Hartwig 1984: G10, Kevlar, carbon fibers properties versus chemical structure

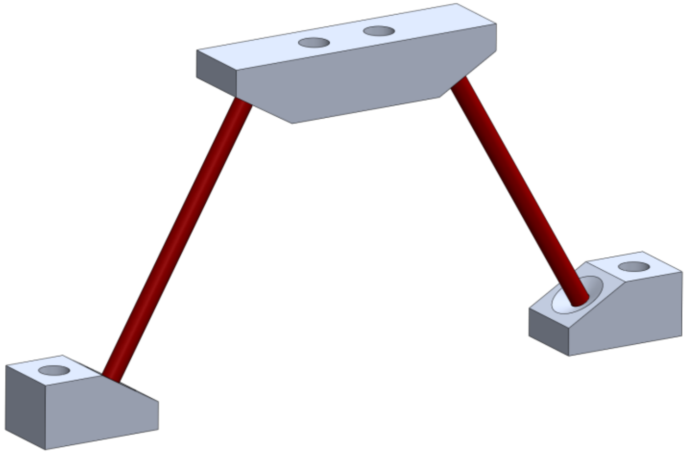






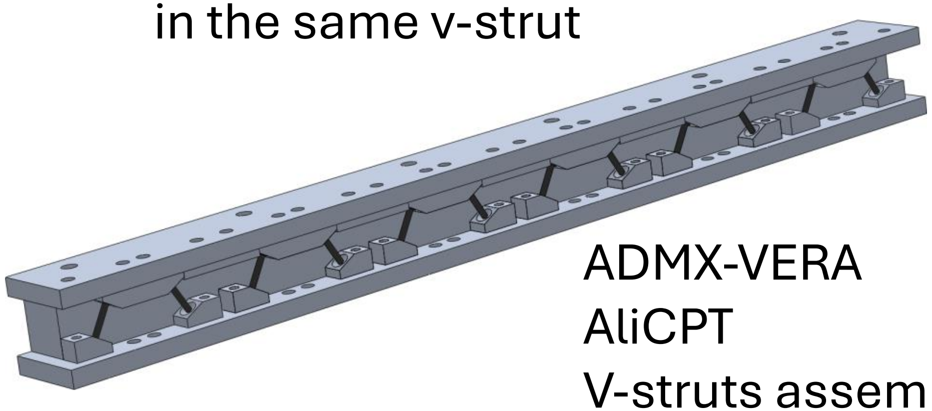
Runyan+ 2008

2. Mechanically connected to but thermally insulated from the 1K stage: vespel



- 6x *V-strut* Al6061 and vespel SP22 assembly
  - Mechanical design adapted from AliCPT
  - 2 screws rather than 1 on the top shoulder: better alignment / mechanical stiffness
  - Can accommodate rods of different lengths (i.e. thermal load)
- Glued with Stycast 2850FT
  - Lower thermal contraction than Stycast 1266
  - Close match to Al thermal contraction

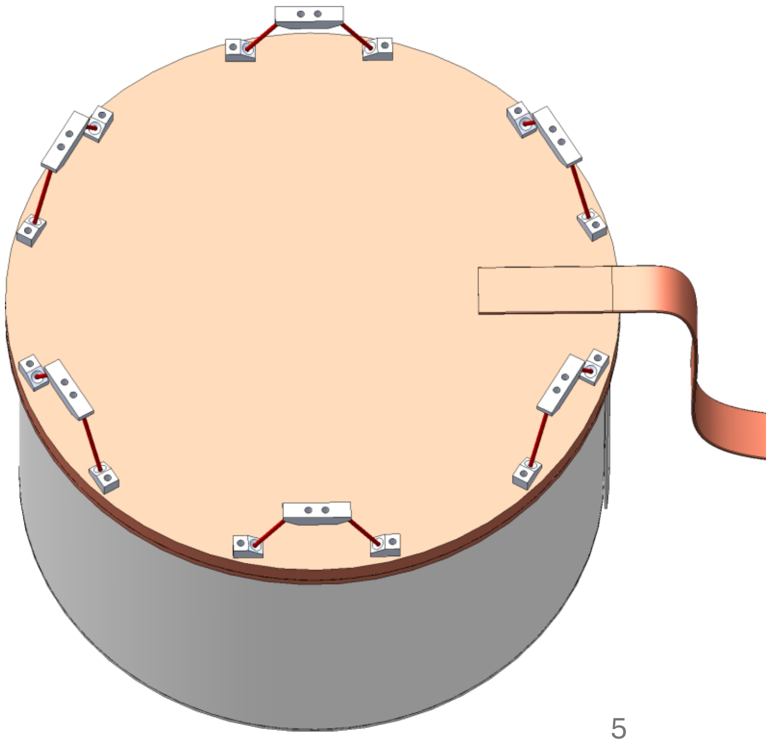
  Ventura 2006, Ekin 2006, SCUBA-2 Woodcraft+ 2009
- In a mechanical jig
  - Equal height among different assemblies
  - Perfect alignment among the Al parts in the same v-strut



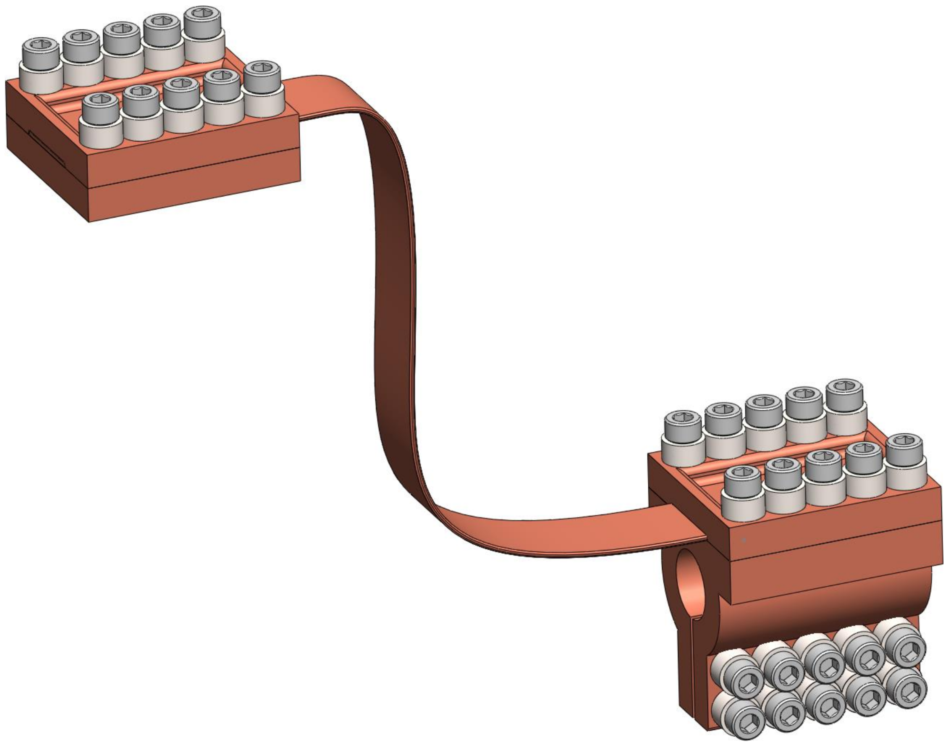
ADMX-VERA
AliCPT
V-struts assembly jig

Angular clock:
- Maximize clearance for
- Mechanical Stiffness near

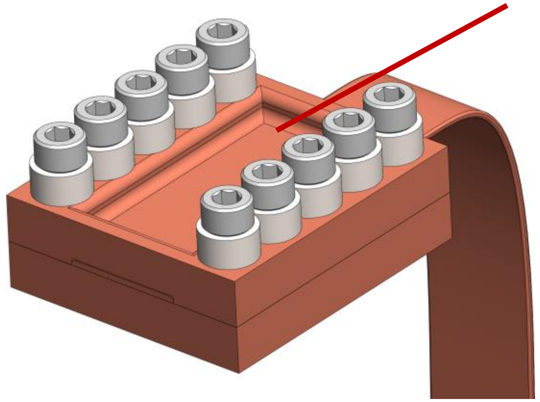
20mK side heatstraps



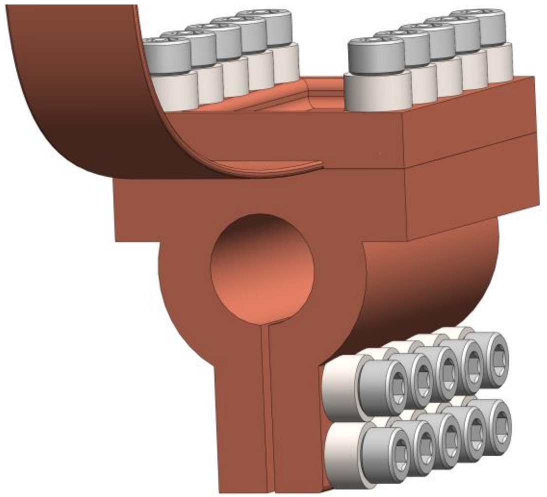
3. Cooled down by the 20mK cold finger: heatstraps assembly



- High purity Cu foil array or braids **e-beam welded** between Cu flanges
  - 25mm wide
  - # foils/braid numbers (thermal performance) easy to tune
- shaft-collar style clamp
  - Mechanical connection to 20mK cold finger
  - Prevent mechanical stress
- Array of M6 screws for high clamping force
- **Ti spacers** compensate thermal contraction mismatch Cu-SS screw - Keith Thompson, AliCPT
  - Ekin 2006 – Invar washers
- Thermal performance limited by 20mK cold finger performance



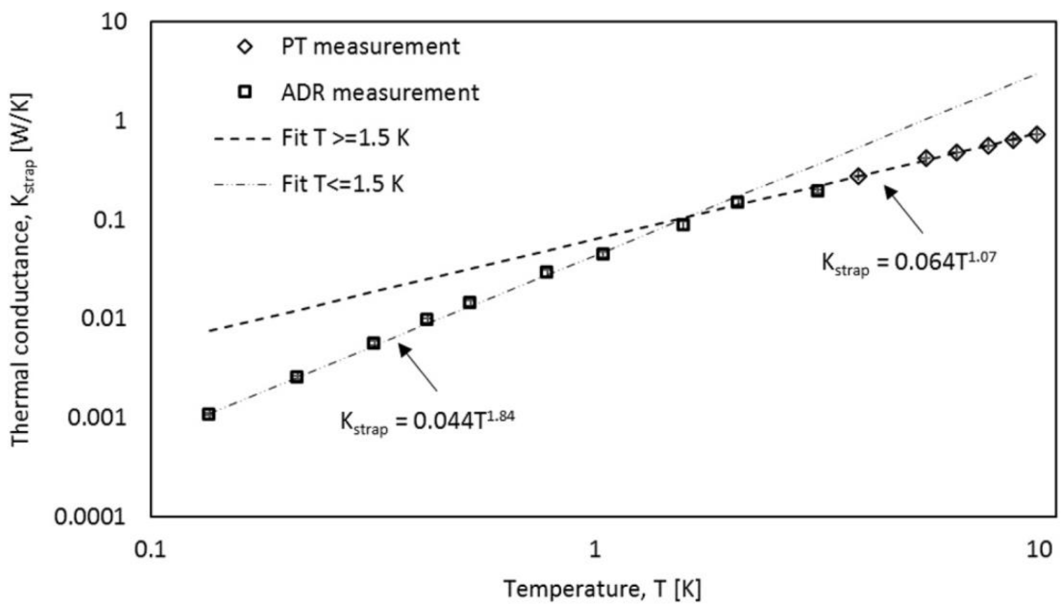
Cutouts to reduce weight



Light weight cutouts possible

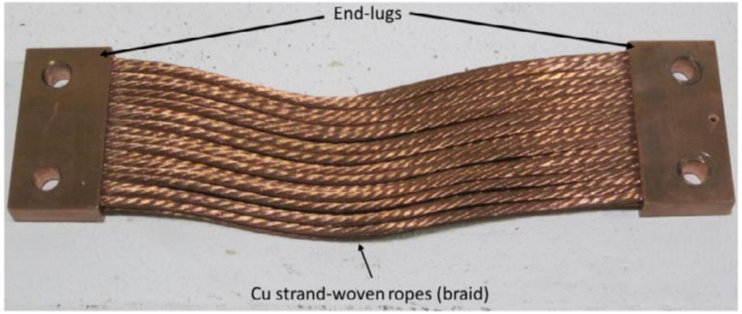
ID clamp needs to be checked – before welding- against OD cold finger to avoid tolerance gap/mismatches

3. The importance of e-beam welding 1/2



1.5K

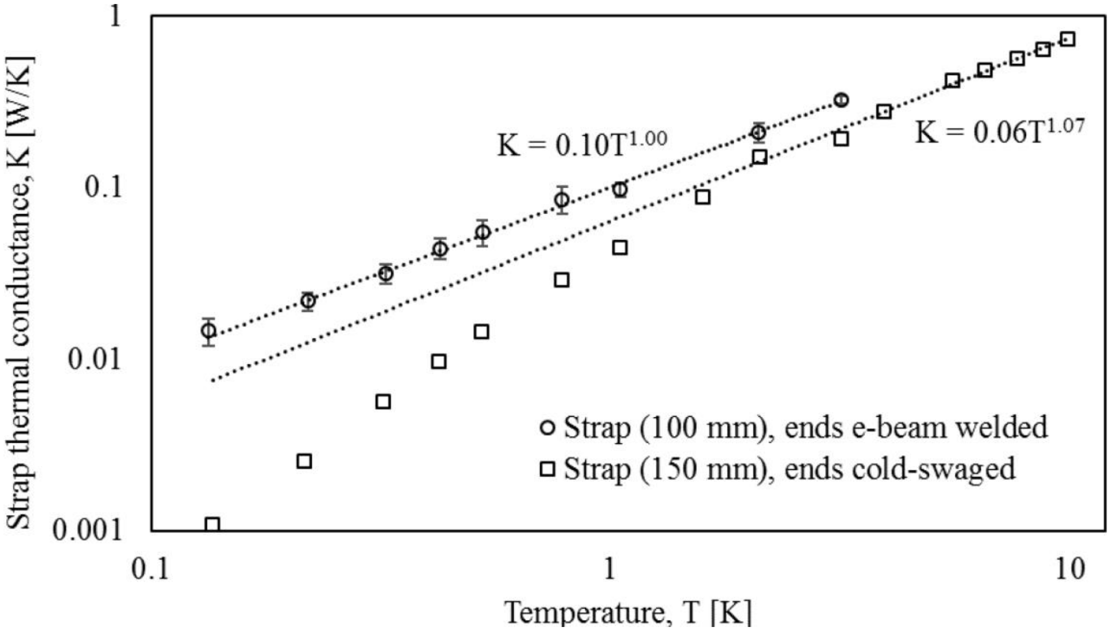
$T^{1.84}$	T
Pressed joints	braid
Heat conductance: phonons	Heat conductance: electrons



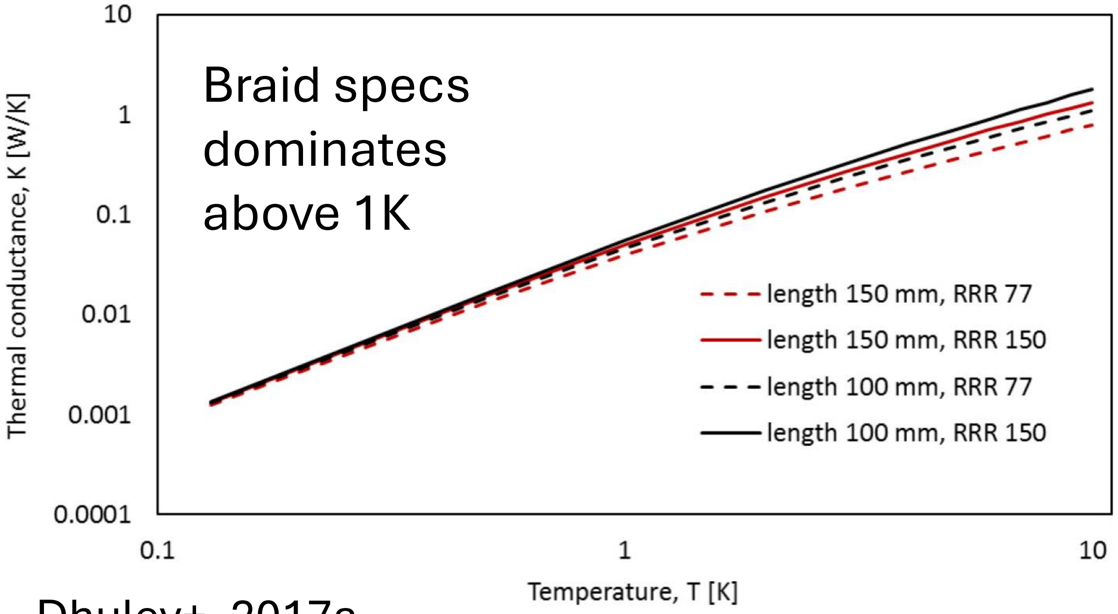
- Pressed Cu braid
- k decreases below 1K

Dhuley+, 2017a

T^2: native oxide layer
Ekin,2006



3. The importance of e-beam welding 2/2



Dhuley+, 2017a

1. e-beam welding:
- Electronic conduction ~~phonon~~
- Thermal conductance ∝ to T

2. Big screws (> M5)
- Reduce contact resistance
- Improve thermal contact
- high pressure contacts (> 1MPa): heat conductance ∝ to pressure

3. Au plating
- no oxide layer which decreases thermal conductance. Didschuns+, 2004

Let me e-beam weld,
gold plate and strongly tight you

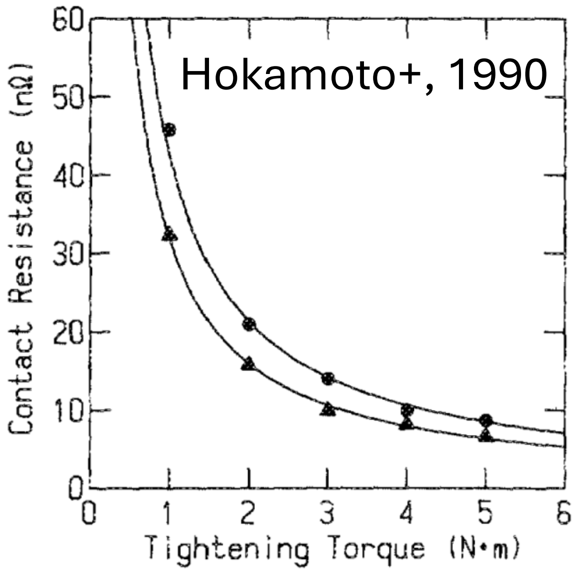


TABLE II. The contact resistance of several types of screw-fastened joints.

Inserted material	Surface treatment of copper disks	Tightening torque t_q (N m)	Contact resistance R_c (nΩ)
···	sanded(#100)[a]	4.0	29.9
···	sanded(#400)	4.0	15.1
···	polished(#3000)	4.0	34.4
···	gold plated[b]	4.0	10.0
···	gold plated	5.0	8.7
silver paste[c]	polished(#3000)	5.0	7.6
silver paste	gold plated	5.0	14.4
indium[d]	polished(#3000)	5.0	5.3
indium	gold plated	5.0	4.0
gold foil[e]	gold plated	4.0	28.2

3. Big screws

Experimentally thermal conductance prop to pressure
Ekin,2006

$$\dot{q}_{\text{pressed solid/solid contact (T)}} = \dot{q}_{\text{pressed solid/solid contact (100 lb, 4.2 K)}} (F / 445 \text{ N})\, (T / 4.2 \text{ K})^{y}$$

Screw and bolt sizes

Screw[a] size—Number of threads per inch	Major diam. [inches (mm)]	Nearest standard metric size	Maximum[b] load (SS bolts) [lbf (kN)]
1/4–20	0.2500 (6.350)	M6 × 1.0	1 910 (8.49)
1/4–28	”	”	2 180 (9.71)
5/16–18	0.3125 (7.938)	M8 × 1.25	3 150 (14.0)
5/16–24	”	M8 × 1.0	3 480 (15.5)
3/8–16	0.3750 (9.525)	M10 × 1.5	4 650 (20.7)

- 10x M6 screws, 40mK
- Assuming 2 10^{-2} W/K thermal conductance Au/Au pressed contacts (Ekin2006)
- Ideal G heatstraps: 3.8 W/K

Because of the cold finger geometry and the fact that this is not a direct Au/Au contact, I expect G heatstraps to be much lower than estimated above

My rules to improve the thermal behavior

1. Material purity – increase k

2. Annealing – increase k
   anneals structural lattice defects, Pobell2006

3. Threaded inserts/helicoils – thread realibility for soft materials (annealed Cu)

4. Big screws and thick plate
   co' n'M3 te posso solo' monta' er termometro

5. Sand paper/flatness – improve heat conductance
   depend on material asperities

5. E-beam welding – k: electronic conduction
   intuitively: melting together two parts of the same material

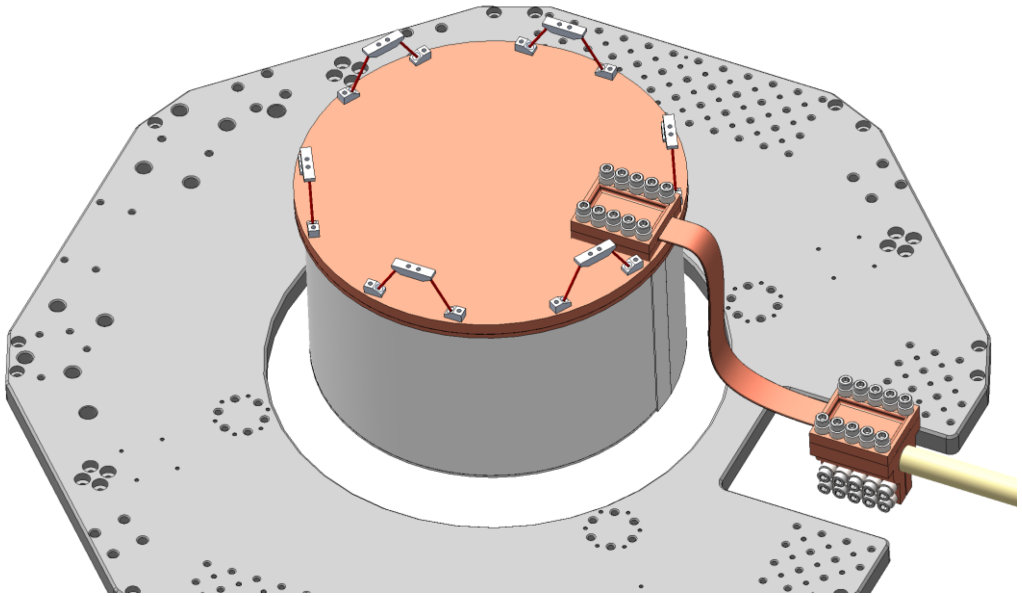
7. Au plating – prevent oxide layer

8. Low thermal contraction spacers – high clamping force at T cryo

9. Lock washers – keep clamping force over cryogenic cycles

(Rome dialect) = with a M3 screw I can only mount a thermometer

3. heatstraps assembly

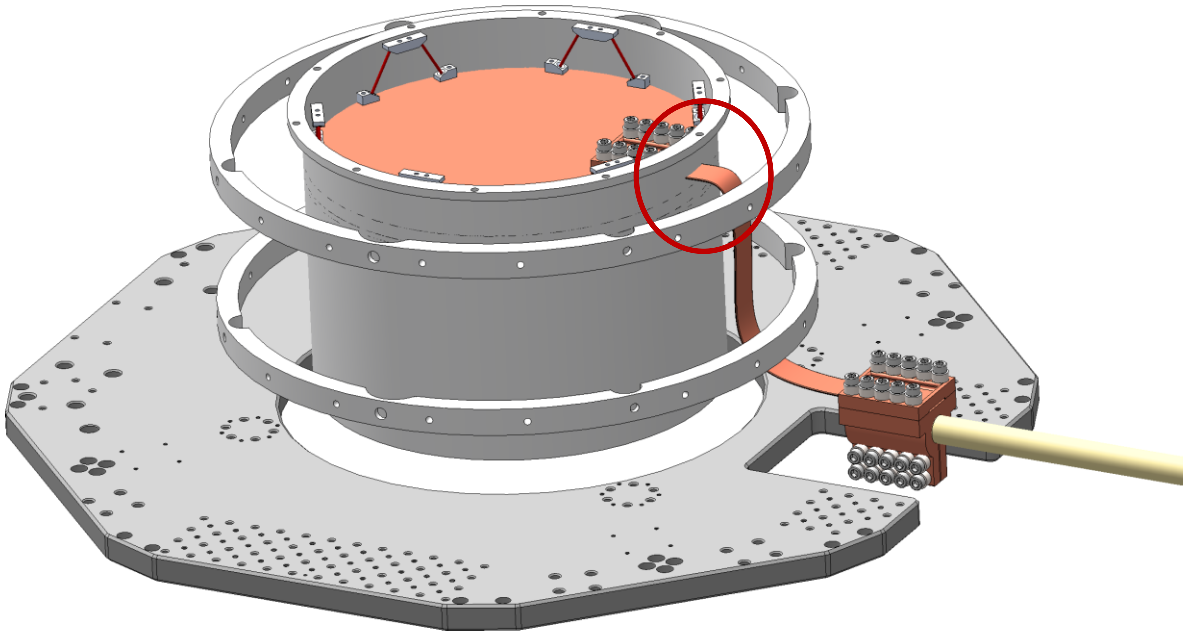


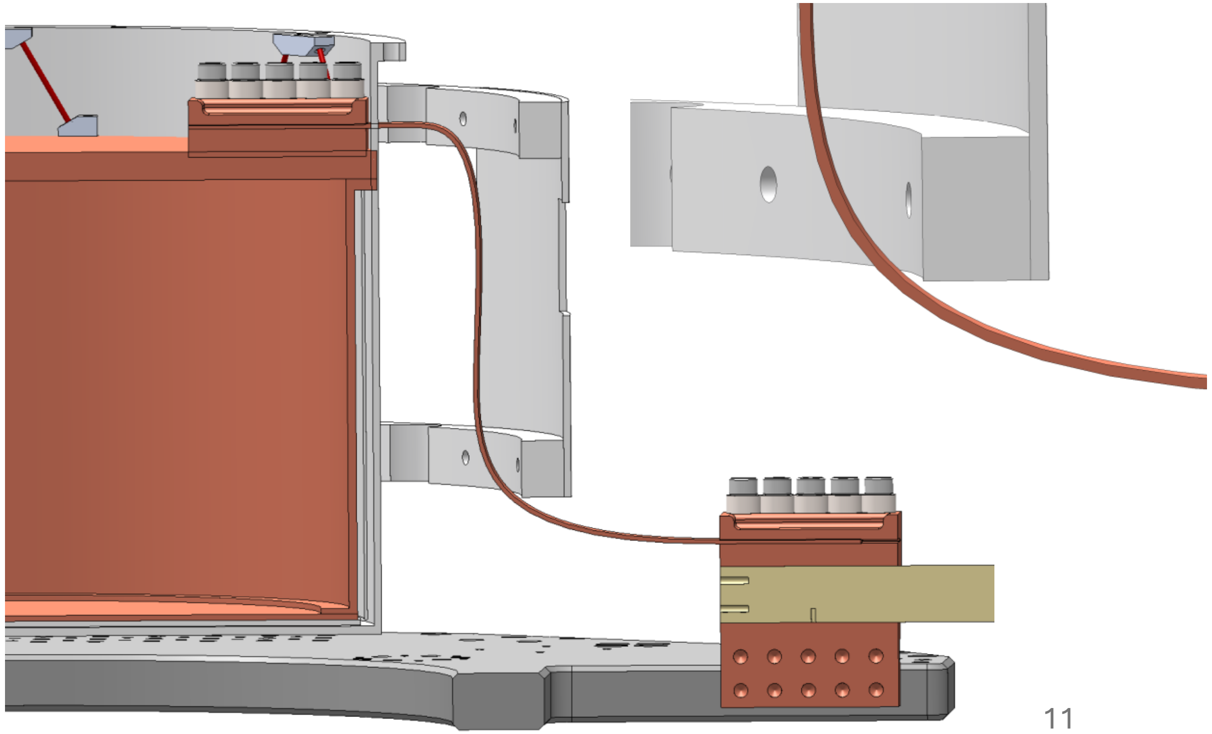
- No interference with the shear plate and rings
  - but add kevlar strings to better drive heatstraps shape

To do:

- 1K shield: cutout for heatstrap installation
- Kevlar strings from 1K plate to discharge the weight load of the heatstraps on the 20mK cold finger

  1.8kg



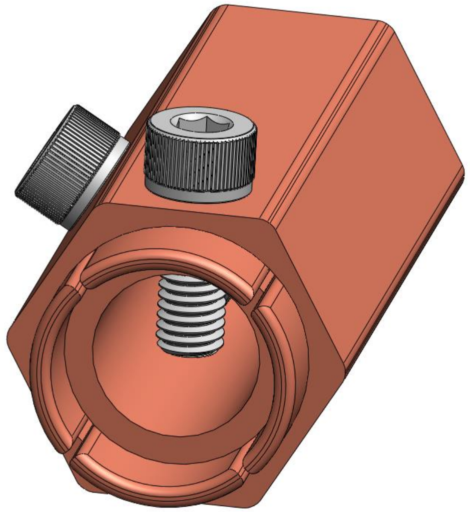


3. heatstraps assembly: alternative design 1

- A Cu rig with e-beam welded Cu braids/foils mounted on the 20mK cold finger with M6 screws on an alternate pattern
- Hex-shape: flat sides for better clamping force
- Cons: not enough material on the 20mK cold finger for adequate clamping force

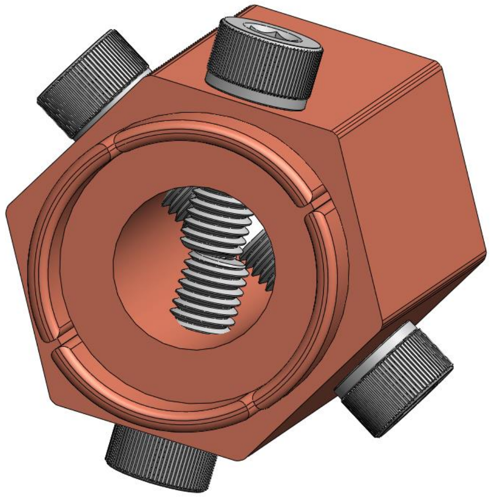
- Rings dimensions depend on braid/foils width

- Foils/braids from the ring to all overlap on top of each other
  - Avoid braid spreads and mechanical interference with shear rings/panels
  - Keep Cu heatstrap plate on the 20mK plate with a small footprint
    - Avoid experiment space reduction



4x 20mm wide
2.5mm thick
braids

470g Cu hex-assy



4x 25mm wide
2.5mm thick
braids

740g Cu hex-assy

3. heatstraps assembly: alternative design 2 and 3ish

- Cu foils/braids e-beam welded **directly** on the 20mK cold finger
    - machining away the Au plating for the necessary area
- This will simplify the design, reduce the assembly weight and remove one thermal interface
    - The less thermal interfaces, the better

- Make a new longer cold fingers that reduces the length of the Cu heatstraps
    - Simpler heatstraps path
    - Less prone to mechanical interference with shear assembly

3. Cu foil or braid?

$$T_{end} = \sqrt{\frac{2 l P}{A k_0} + T_{ini}^2}$$

- **Assume 16uW** 20mK thermal load (?)
- Weaker dependance on l
- Limited by T_{ini} (cold finger)

- Risegari+, 2004: k Cu [30-150]mK
- Cu foil from Goodfellow
- electronic contribution: k = a T
- 0.53 < a < 1.7 W/cm/K^2 (purity/RRR, annealing)

- purity/RRR Cu foil > Cu braid
  - Maybe process of twisting wires to make the braid itself
  - Foil tends less to decrease RRR due to bending/handling Cu braid
- Typically 25um thick, 50 foils
- Impractical/difficult to work with a large number of foils
  - Align, press inside the Cu flange for e-beam welding

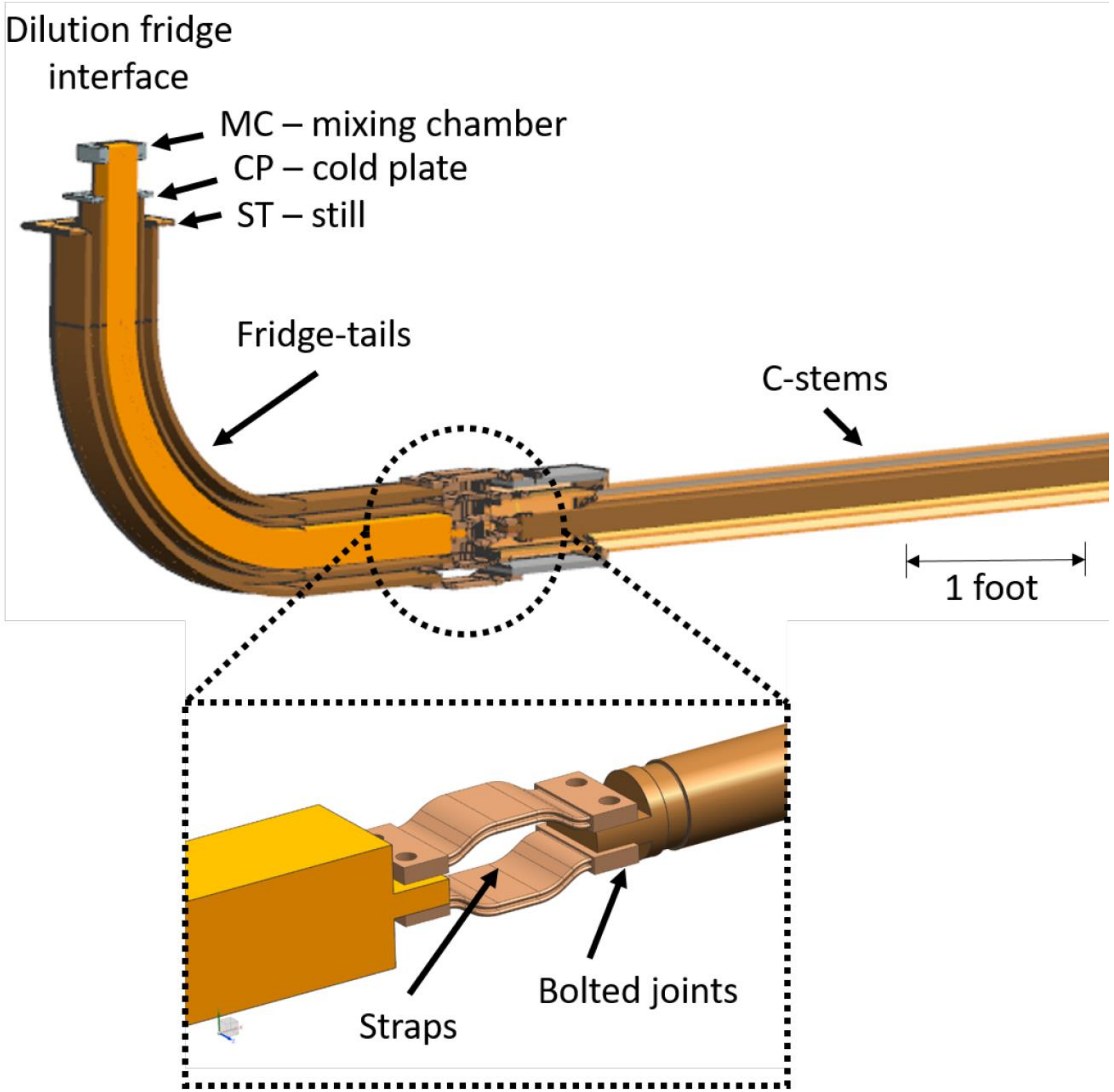
- For same geometry: foil performs better than braid

preliminary

- 4x Cu braids, 25mm wide
  2.5mm thick, ½ filling factor
  240mm long
  0.73 W/cm/K^2 (RRR > 40)
  T_{end} = 46mK

- 4x Cu foils array, 25mm wide
  1.25mm thick
  240mm long
  1.7 W/cm/K^2 (RRR ≃ 120)
  T_{end} = 40mK

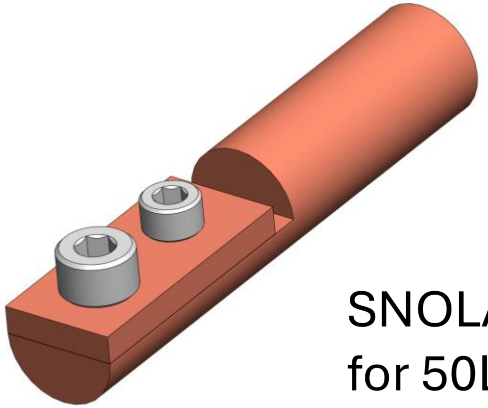
3. SuperCDMS SNOLAB cold finger vs 50L



Hollister+, 2017
Dhuley+, 2017a

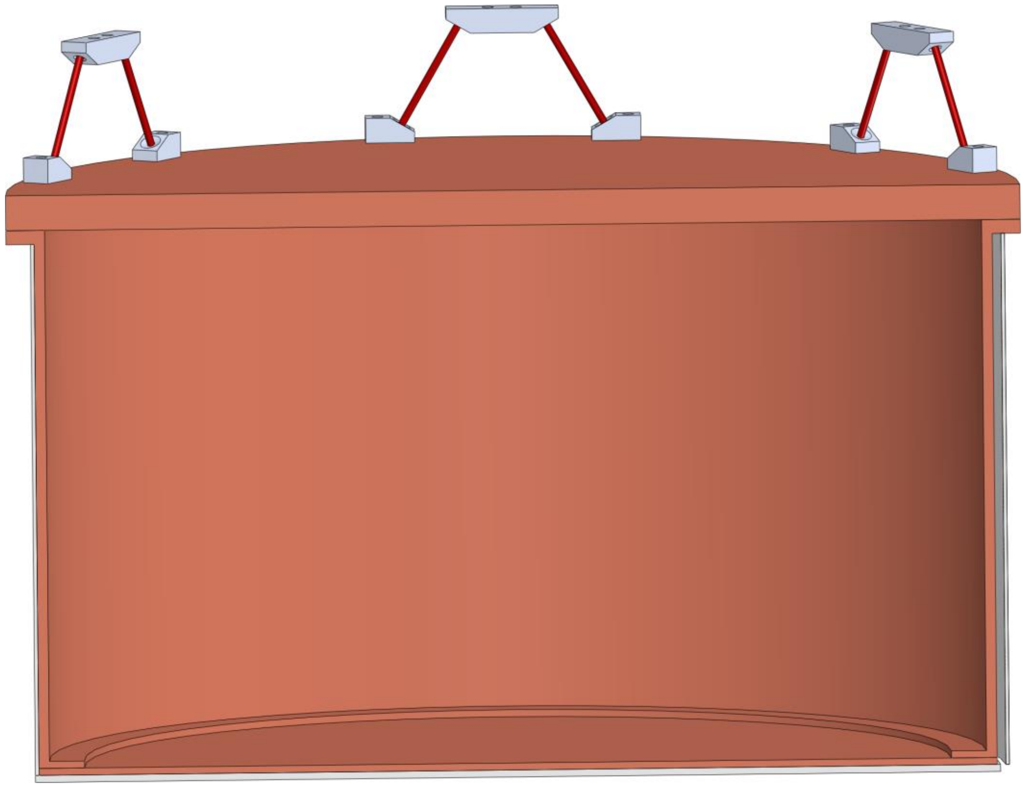
SuperCDMS SNOLAB design

- OD 45mm-ish
- Elegant
- Simple
- Does not work for 50L since the OD is only 20mm
  - Cut away material
  - Not enough clamping force/screws



SNOLAB design
for 50L cold finger

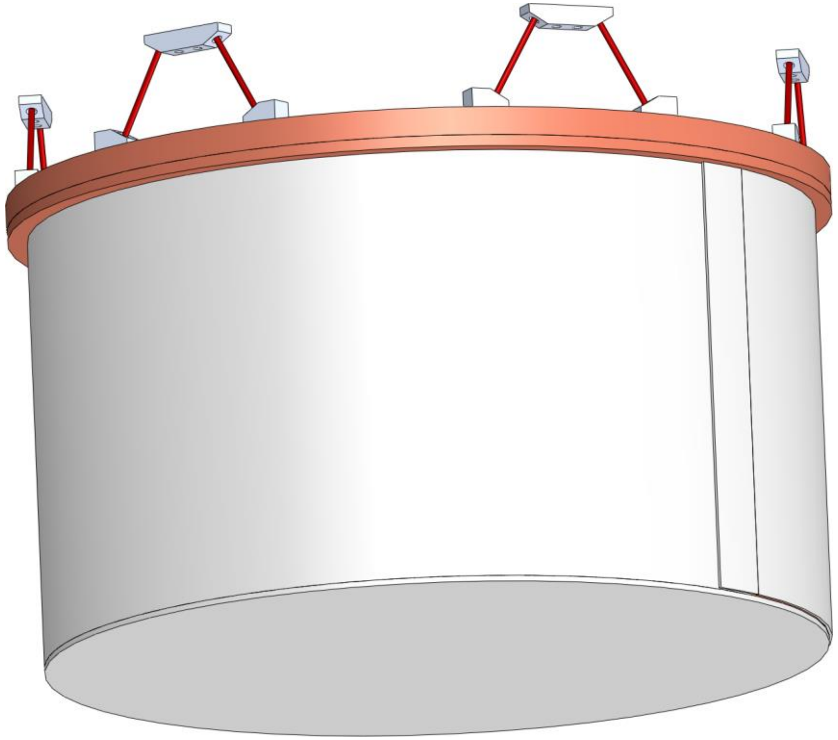
4. Enclosed experiment volume



A magnetic shield
Nb foil wrapped around 20mK shield
or welded together with a bottom cover

- Can permanently live on the 20mK shield
- Ideally: shield as close as possible to your experiment
- Can be combined with another one at 1K/4K with different material

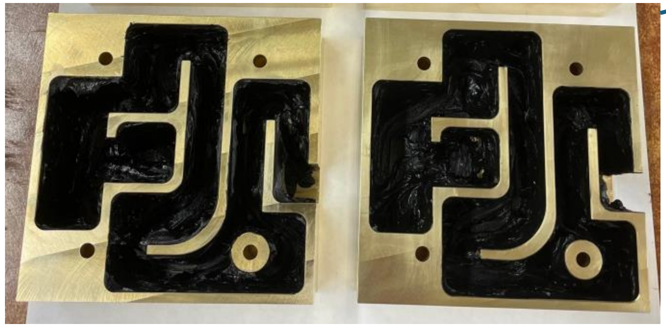
20mK shied:
150mm tall, 267mm OD
total experiment volume

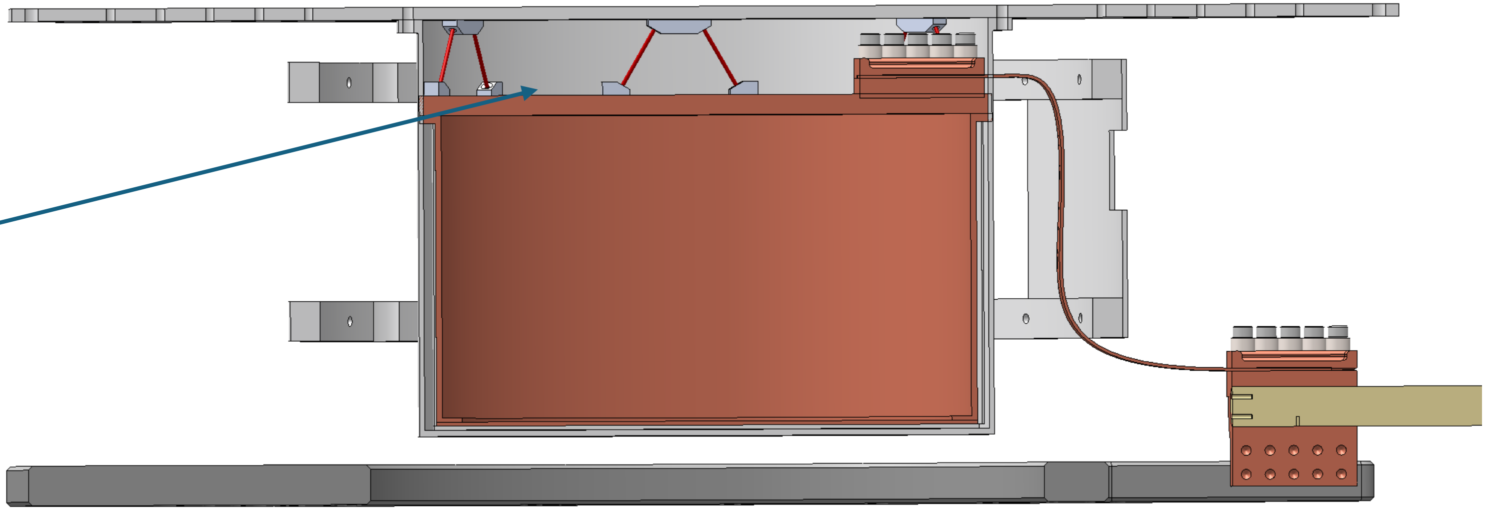


4. Enclosed experiment volume

- Superinsulation to reduce the radiative load from higher temp stages
- Air evacuated from the 20mK volume via an hole on the 20mK plate and a *meander*
  - The meander prevents radiative leaks

AliCPT meanders design: Keith Thompson





To do - timeline

- Work presented = result of just few days of work

- To do
  - Vespel v-struts
    - Thermomechanical FEA

  - Heatstrap assembly
    - Tune the design based on heatstraps geometry (foil number, width, etc etc)
    - Tune the flexible part considering the thermal contraction of the mechanical components involved
    - Tune Cu flanges design based on optimal e-beam process
      - Required minimum Cu thickness for efficient e-beam
      - excess material can be cut away
    - Kevlar, or similar material, support design for discharging assembly weight from the cold finger

Summary

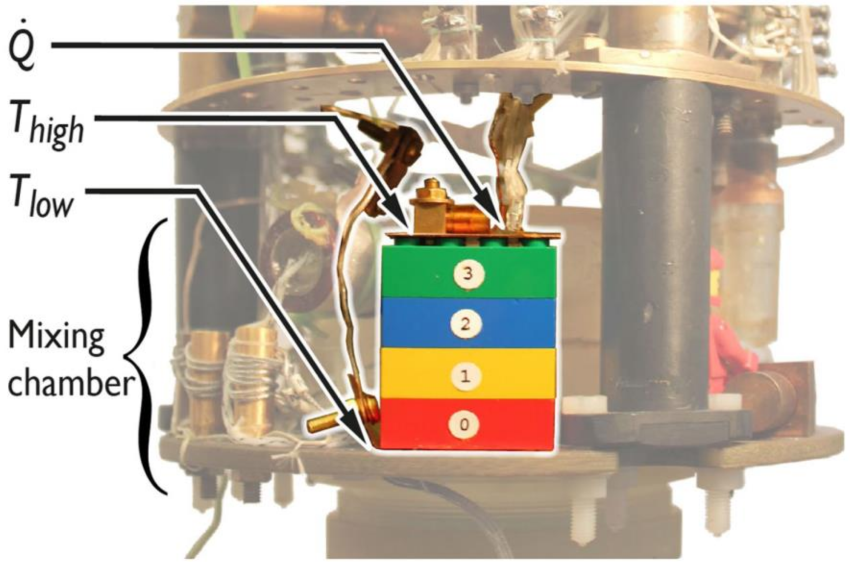
- Heatstraps assembly
  - No major mechanical interference
  - Some design options to be discussed
  - Well established technology

- V-strut assemblies
  - Different material available, choice driven by lowest thermal conductivity
  - Reliable specs at mK temp --- chosen a brand name material

LEGO® Block Structures as a Sub-Kelvin Thermal Insulator

J. M. A. Chawner, A. T. Jones, M. T. Noble, G. R. Pickett, V. Tsepelin & D. E. Zmeev*

We report measurements of the thermal conductance of a structure made from commercial Acrylonitrile Butadiene Styrene (ABS) modules, known as LEGO® blocks, in the temperature range from 70 mK to 1.8 K. A power law for the sample's thermal conductivity $\kappa = (8.7 \pm 0.3) \times 10^{-5}\, T^{1.75 \pm 0.02}\, \mathrm{W K^{-1} m^{-1}}$ was determined. We conclude that this ABS/void compound material provides better thermal isolation than well-known bulk insulator materials in the explored temperature range, whilst maintaining solid support. LEGO blocks represent a cheap and superlative alternative to materials such as Macor or Vespel. In our setup, $<$400 nW of power can heat an experimental area of 5 $\mathrm{cm^2}$ to over 1 K, without any significant change to the base temperature of the dilution refrigerator. This work suggests that custom-built modular materials with even better thermal performance could be readily and cheaply produced by 3D printing.



… if we don't get the vespel rods in time we can just go to the Lego store at Hillsdale shopping center….