Sub-K cryogenics for QUBIC

For Technological Demonstrator (T.D.)

And

For Final Instrument (F.I.)

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Sub-systems

Sub-systems		Delivered...		Delivery date for...	
		By	To	T.D.	F.I.
Detection chain and 1K box		APC	APC	03/2017	09/2017
	TES Detectors	CSNSM	APC	12/2016	06/2017
Calibration sources		APC	APC	04/2017	Cf. TD
Simulations, Instrument Design, Data Analysis		APC	QUBIC	Completed	12/2016 for design
Optics Group					
	Filters	Cardiff	Roma / APC	12/2016	04/2017
	Horns (RF design)	Manchester	APC	Completed	Completed
	Horns (fabrication)	Milano	APC	Completed	11/2016
	Horns (tests)	Milano-Bicocca	APC	11/2016	05/2017
	Optical simulations	Maynooth	QUBIC	Completed	12/2016
	HWP	Cardiff	Roma	12/2016	Cf. TD
	Switches (RF design)	Cardiff	QUBIC	Completed	11/2016 (chokes)
	Switches (general design)	APC	Milano	Completed	12/2016
	Switches (fab + assembly + slow control + test)	Milano-Bicocca	APC	10/2016	03/2017
	Full Beam Source	Roma	APC	04/2017	Cf. TD
	Polarizer & Dichroic	Cardiff	APC	01/2017	05/2017
	Baffling	Roma	APC	05/2017	Cf. TD
	Combiner test	Roma	APC	04/2017	07/2017
	Mirrors (fabrication + tests)	Milano-Bicocca	APC	09/2016	05/2017
	Carbon Fiber Lamps	LAL		01/2017	Cf. TD
Cryostat & cryogenics		Roma	APC	04/2017	08/2017
	Cryogenic HWP Rotator	Roma	Roma	11/2016	Cf. TD
	1K and Sub-K Fridges	Manchester	Roma / APC	01/2017	Cf. TD
	Cryogenics Maintenance	CNEA CAB	QUBIC	-	Start 2018
Overall Slow control & Data Storage of Raw Data		IRAP	QUBIC	11/2016	Cf. TD
Mount		GEMA	On site	-	03/2018
Logistics & Site Development		IAR / ITEDA	On site	-	10/2017
Assembly, Integration and test of QUBIC module		APC	QUBIC	12/2017	04/2018
	Calibration and test of integrated instrument	LAL	QUBIC	12/2017	04/2018

Sub-systems

Cryogenic System						
Element	Identification	Availability	Interfaces with	Functional Test	Requirement Phase	Responsibility
Cryostat	CS1	05/17		Yes	P3-1	Roma
SubK He fridge	CS3	?		Yes	P3-1	Manchester
Heat switches	CS4	01/17		Yes	P3-1	Manchester
1K fridge	CS5	?		Yes	P3-1	Manchester

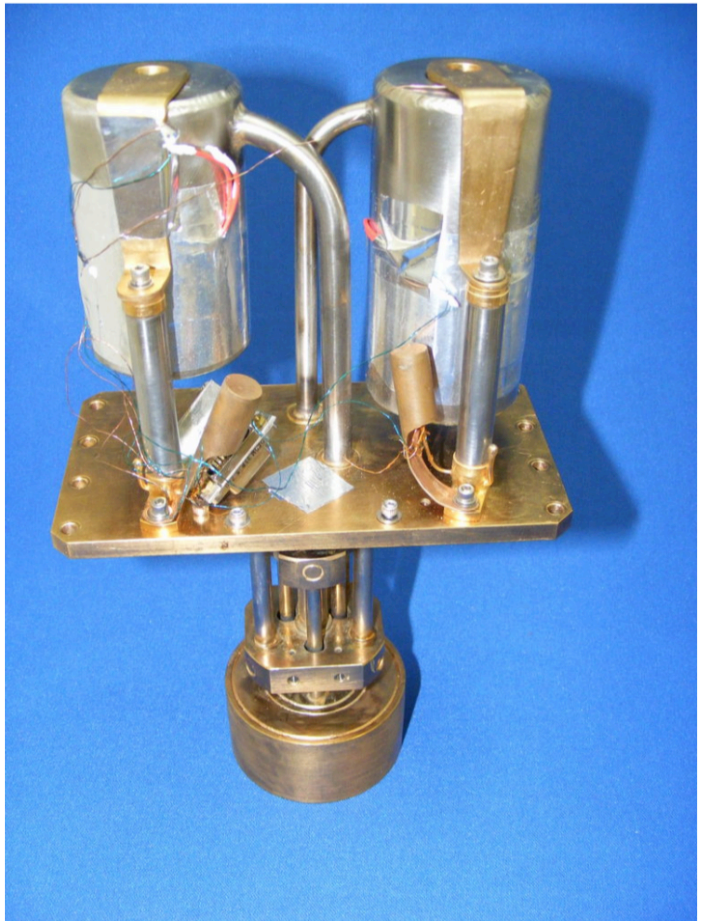
SubK He Fridge

SubK He fridge

4K cooling	Pulse Tube Cooler
Pulse Tube Cooler 4K cooling power	>1 W
Pulse Tube Cooler Electrical consumption	< 15 kW
Pulse Tube Cooler angle range	+/- 20 degrees
1K stage refrigerator	^{4}He sorption fridge
1K cooling power	>2 mW
detector stage refrigerator	^{3}He/^{4}He Sorption Cooler
detector stage cooling power	> 20μW
Instrument Diameter	< 1.6m
Instrument Height	< 1.8m
Instrument Weight	< 800 kg

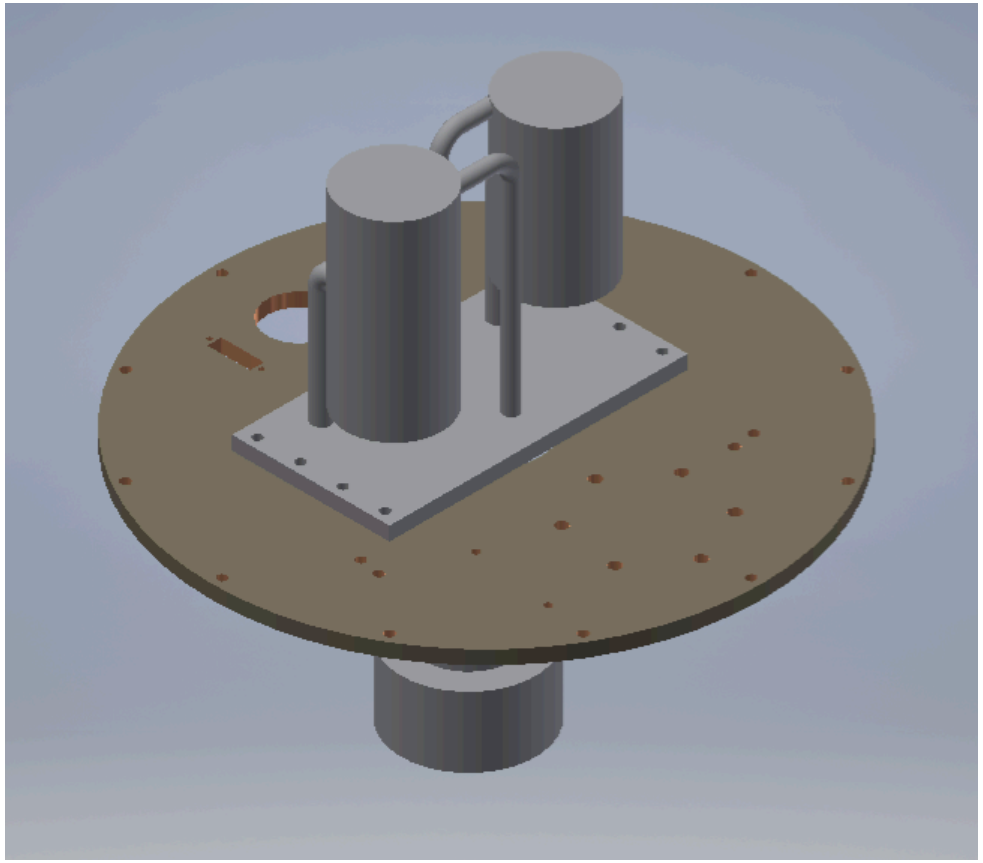
@ 320 mK

SubK He fridge



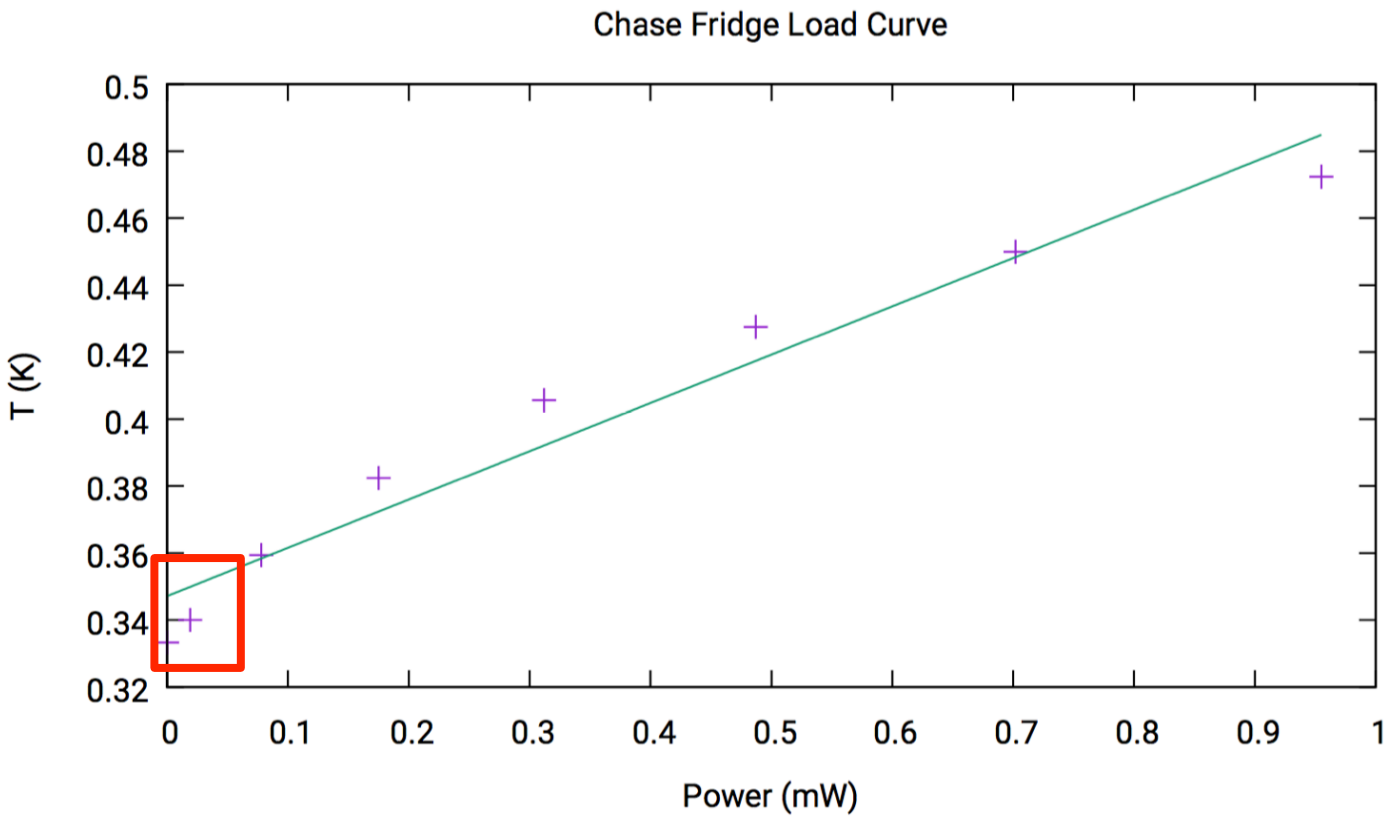
- Originally manufactured by Chase Cryogenics
- Recycled using 2x Chase minimal gap HSs
- 4 K plate mounting for condensers, also need to specify connector – microD ?
- Fridge is sealed - no helium charging required
- Status - currently in use on EPR experiment in Manchester, should be available Nov (will need redressing)

Mechanical interface



- Existing CAD model, footprint only
- We have interface pattern for 4 K stage
- More detailed model could be provided (if needed) when EPR experiment is finished

Load curve



- Existing load curve
- Curve needs characterising better in 0-30 uW range
- Temperature stability tests required - histogram to characterise
- Need to confirm condenser temperature - 4.2 K? Which PTC? Test!

Hold time and temperature

P_{load} (μW)	Days	Hours	Seconds	Joules	T (mK)
19.5	3.75	89.92	323700	6.31	336 mK
43.9	2.45	58.83	211800	9.29	349 mK

- Measurements done on EPR cryostat
- T_0 should be reduced
- Further testing after EPR required due to possible presence of parasitic loads
- Also suggested that precooling with 1 K fridge could be used to reduce T_0 – to be investigated
- However, we now need to know precooling requirement for focal plane

Status of the sub-system : blocking points and schedule

- What is the status of the sub-system ?
  - Design/manufacturing (home made/industry)/assembly/tests ? Final testing to start – load curve, hold time, temp stability. Finish by 12/16
  - When is this phase supposed to be finished ? 01/17

- If you are still designing the sub-system:
  - Which inputs / specifications / requirements, needed to finish the detailed design of your sub-systems, are not yet delivered ?
    - For D.T. Condenser temp, PTC? Is precooling of focal plane to 320 mK required? Warm up during recycling?
    - For F.I.
  - Which other working group should deliver these inputs (see annex 1 for list of main WP) ?
    - For D.T. Roma? APC?
    - For F.I.

- What time is still needed in order to (for D.T.) – assume that the above inputs are provided if needed - :
  - Finish the whole detailed design of D.T. ? None
  - Manufacture the sub-system ? None
  - Test the sub-system in your premises before delivery to APC / ROMA ? ~3 months

- Idem for F.I.

- Do you think you can comply to the target schedule (see annex 2) ? Yes

Interfaces with other sub-systems

- List and describe needed interfaces with other systems. Mechanical
  - Electrical / Signal Thermometry and heaters
  - Vacuum
  - Thermal Condenser mating. Should use vacuum grease to maximise k
  - Etc…
- Are these interfaces currently frozen ? Yes for thermal, no for wiring

Test, Delivery, Assembly, Calibration Operations

- Tests of the sub-system in your premises before delivery at APC or ROMA:
  - What is the rationale for testing the sub-systems ? Validate cooling to 320 mK, temperature stability
  - Which specifications will be tested ? Heat lift, temp, hold time
  - What are the criterion for fail / pass ? 20 uW @ 320 mK, hold time > 24 hours

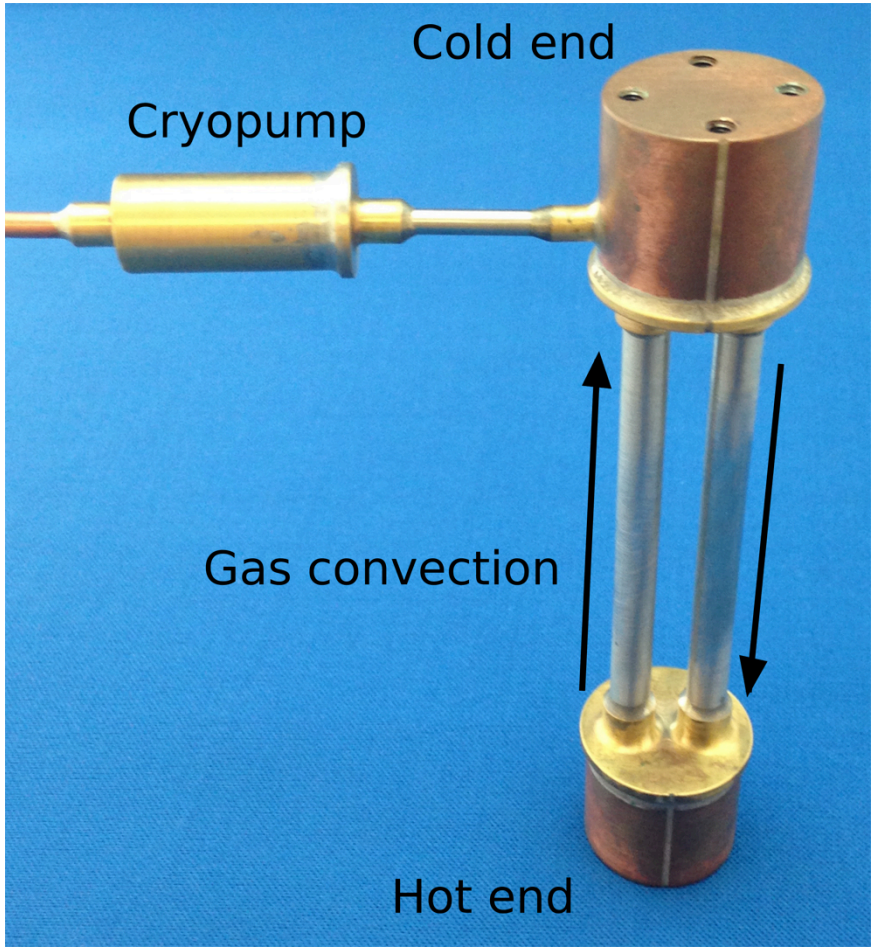
- Delivery to APC or ROMA:
  - Special care needed for the transportation and handling of the goods ? Yes – pressurized gas

- Assembly Operations in APC or/and ROMA:
  - Same questions as first point above. As above
  - + which other sub-systems should be integrated before yours? After yours ? Assembled after 1 K box, mount to 4 K
  - + Is there any specific material needed for assembly ? (see annex 3 for help) Leak checker, thermometry/heater readout
  - What are the test sequences needed to be performed during/after integration Leak test, check thermometry/heaters
  - + How many FTE will you send people at APC / ROMA for help during assembly ? 1-2

- Calibration Operations at APC:
  - Same questions as for Assembly operations. As above

Heat switches

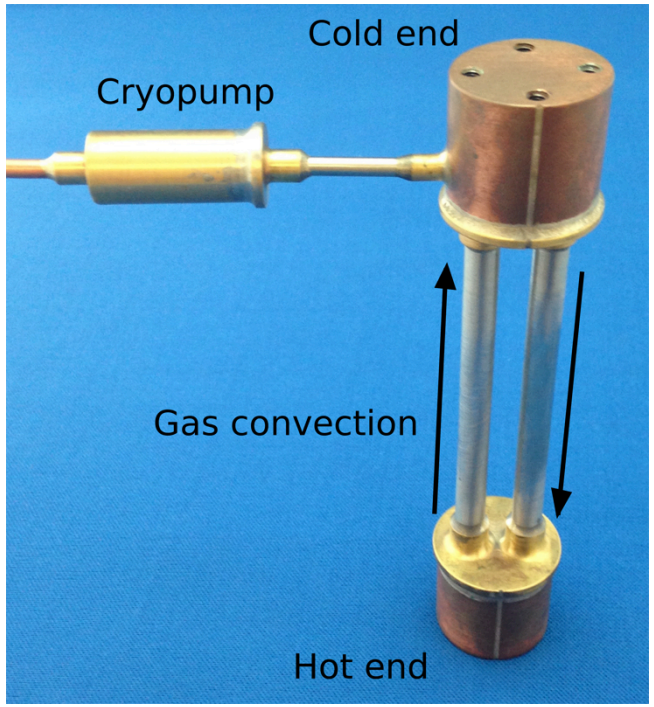
Convective HS



- Convective switches have so far shown better performance than minimal gap design
- Will be used to precool 1 K box to 4.2 K
- Also used for recycling 1 K fridge

Type	Location	No. Wire Pairs	Notes
Diode	Heat switch cryo pump	1	
Heater	Heat switch cryo pump	1	

Convective HSs



131 mm

Fridge HS

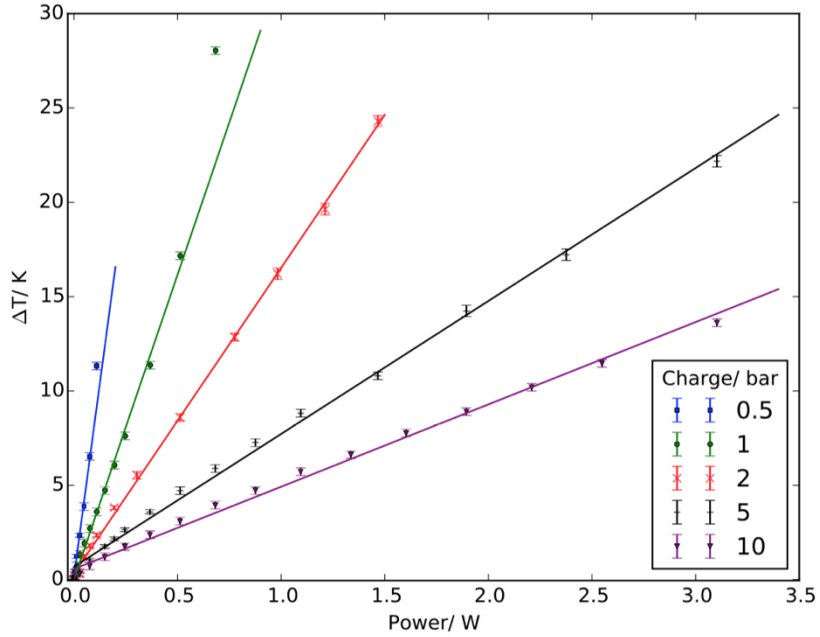
243.2 mm

Long HS

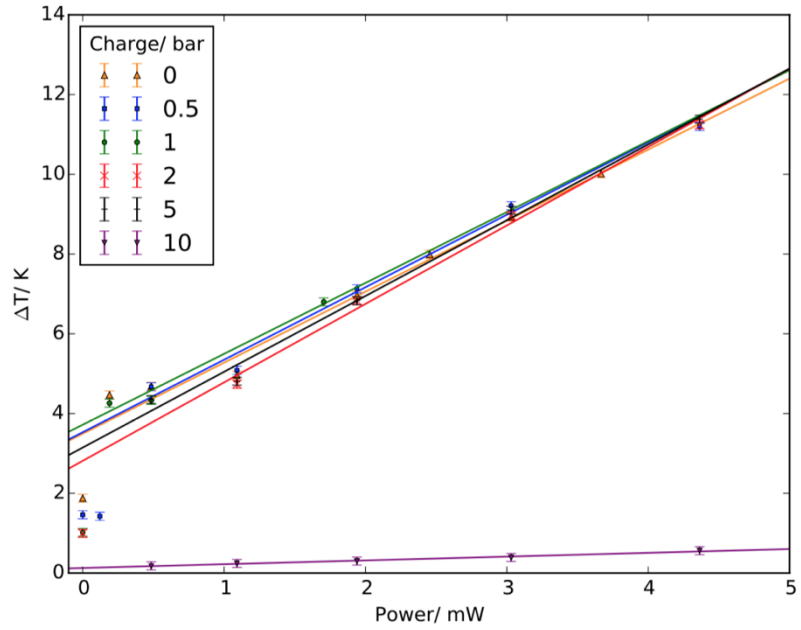
- Conductance to be defined?
- Number of switches - determined by cooldown time and performance
- Location to be defined
- Both sizes have been built
- Testing nearly complete – optimal charge tbd
- Interface bolt pattern fixed
- Commissioning requires charging, connection (heat gun) and leak testing

Fridge HS performance

Charge/bar	D_{on}/mWK^{-1}	D_{off}/mWK^{-1}	Ratio
0	-	0.51 ± 0.03	-
0.5	12.2 ± 0.4	0.55 ± 0.04	22 ± 2
1	32.1 ± 0.6	0.56 ± 0.09	57 ± 9
2	61.7 ± 0.6	0.51 ± 0.03	121 ± 7
5	141 ± 3	0.53 ± 0.03	270 ± 20
10	234 ± 4	10.6 ± 0.7	22 ± 2



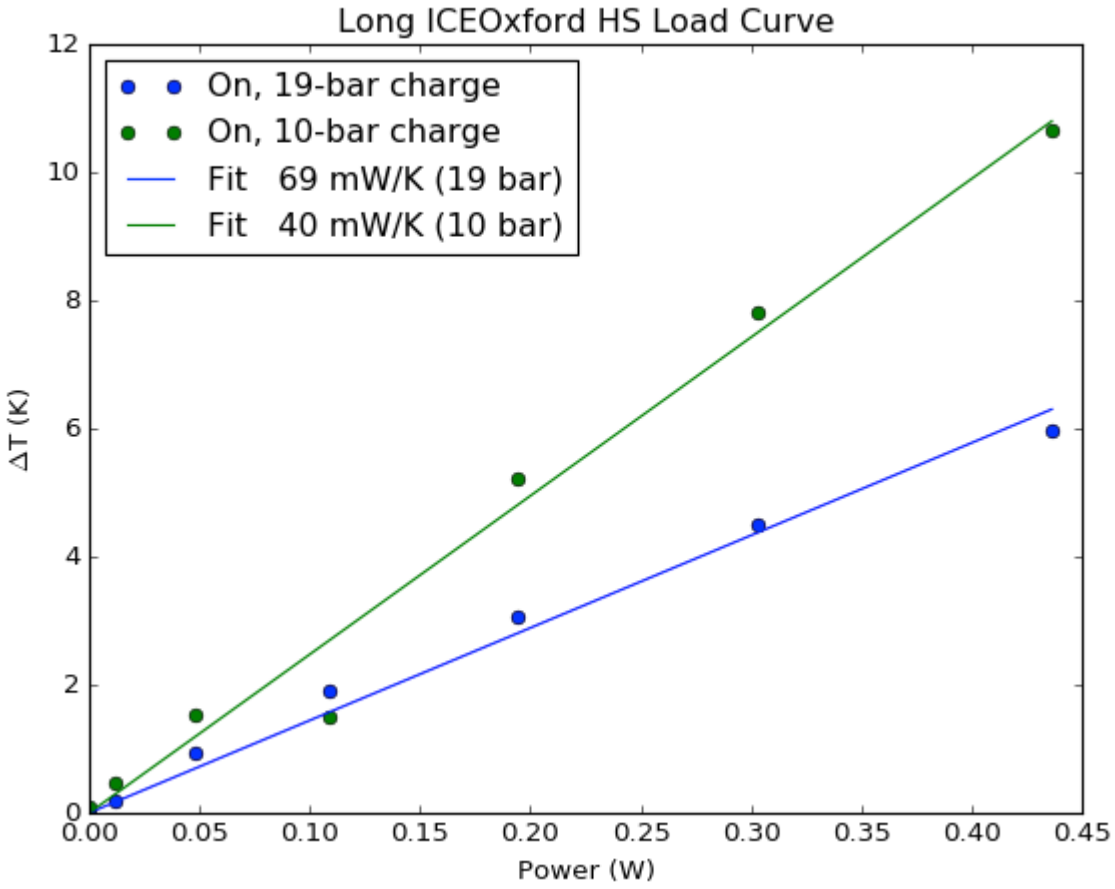
On



Off

Long HS performance

- Preliminary off conductance measurement of 52 uW/K, gives 166 uW heat leak from 4.2 to 1 K per switch
- May be reduced further using thinner walled tubes if required
- On conductance measured at 69 and 40 mW/K for 19 and 10 bar charges
- On conductance should inform cooldown time to 4 K



On

Status of the sub-system : blocking points and schedule

- What is the status of the sub-system ?
  - Design/manufacturing (home made/industry)/assembly/tests ? Both manufactured, fridge HS testing complete, long HS final testing to start. Further manufacture required for additional switches, although this is minimal
  - When is this phase supposed to be finished ? 01/17

- If you are still designing the sub-system:
  - Which inputs / specifications / requirements, needed to finish the detailed design of your sub-systems, are not yet delivered ?
    - For D.T. Location of switch(es), number, conductance. Copper straps used for connection?
    - For F.I.
  - Which other working group should deliver these inputs (see annex 1 for list of main WP) ?
    - For D.T. Roma?
    - For F.I.

- What time is still needed in order to (for D.T.) – assume that the above inputs are provided if needed - :
  - Finish the whole detailed design of D.T. ? None
  - Manufacture the sub-system ?
  - Test the sub-system in your premises before delivery to APC / ROMA ? ~ 3 months, including further manufacture and validation
- Idem for F.I.

- Do you think you can comply to the target schedule (see annex 2) ? Yes

Interfaces with other sub-systems

- List and describe needed interfaces with other systems. Mechanical
  - Electrical / Signal Thermometry, heaters
  - Vacuum
  - Thermal Physical interface. Should use vacuum grease to maximise k. Are copper straps to be used?
  - Etc…

- Are these interfaces currently frozen ? Bolt pattern yes, copper no

Test, Delivery, Assembly, Calibration Operations

- Tests of the sub-system in your premises before delivery at APC or ROMA:
  - What is the rationale for testing the sub-systems ? Validate conductance
  - Which specifications will be tested ? Conductance
  - What are the criterion for fail / pass ? If spec (tbd) is met

- Delivery to APC or ROMA:
  - Special care needed for the transportation and handling of the goods ? No, if shipped unpressurized

- Assembly Operations in APC or/and ROMA:
  - Same questions as first point above. As above
  - + which other sub-systems should be integrated before yours? After yours ? After 1 K box, mounted on 4 K
  - + Is there any specific material needed for assembly ? (see annex 3 for help) Gas handling system, leak checker
  - What are the test sequences needed to be performed during/after integration Charge, leak test
  - + How many FTE will you send people at APC / ROMA for help during assembly ? 1-2

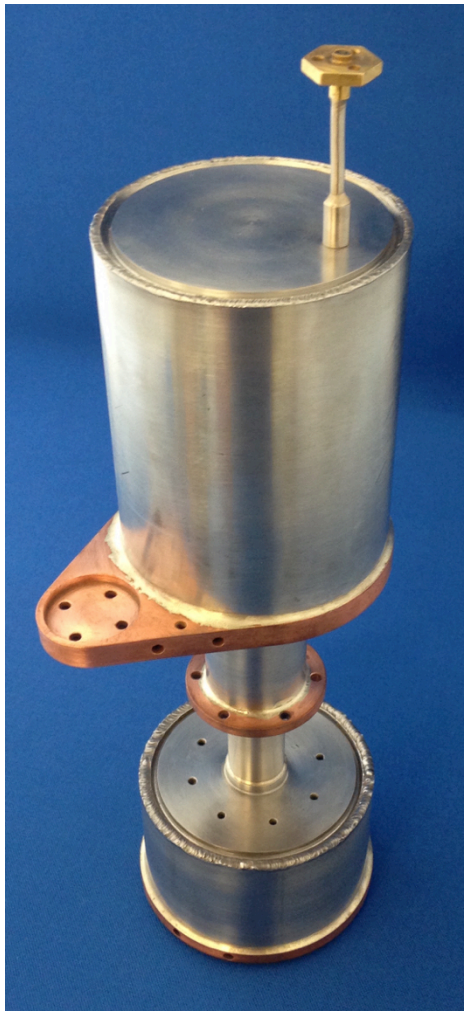
- Calibration Operations at APC:
  - Same questions as for Assembly operations. As above

1 K Fridge

1 K fridge

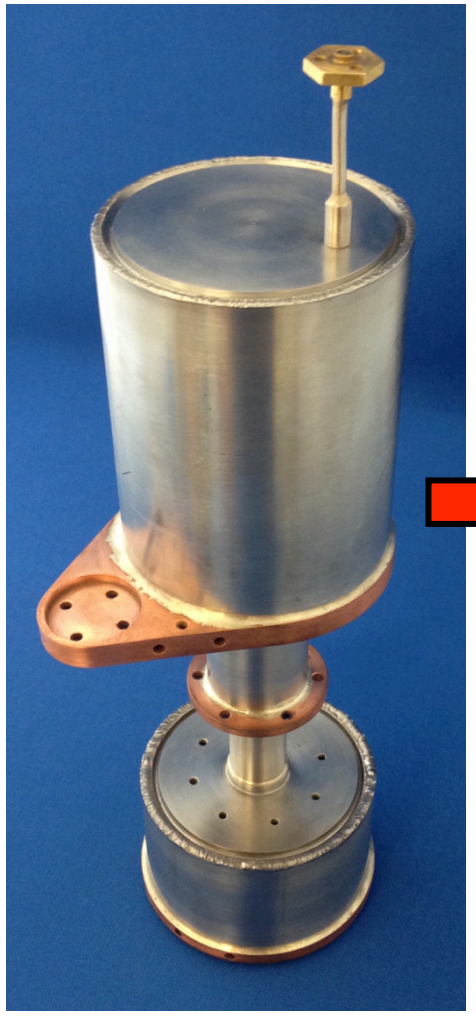
4K cooling	Pulse Tube Cooler
Pulse Tube Cooler 4K cooling power	>1 W
Pulse Tube Cooler Electrical consumption	< 15 kW
Pulse Tube Cooler angle range	+/- 20 degrees
1K stage refrigerator	^{4}He sorption fridge
1K cooling power	>2 mW
detector stage refrigerator	^{3}He/^{4}He Sorption Cooler
detector stage cooling power	> 20μW
Instrument Diameter	< 1.6m
Instrument Height	< 1.8m
Instrument Weight	< 800 kg

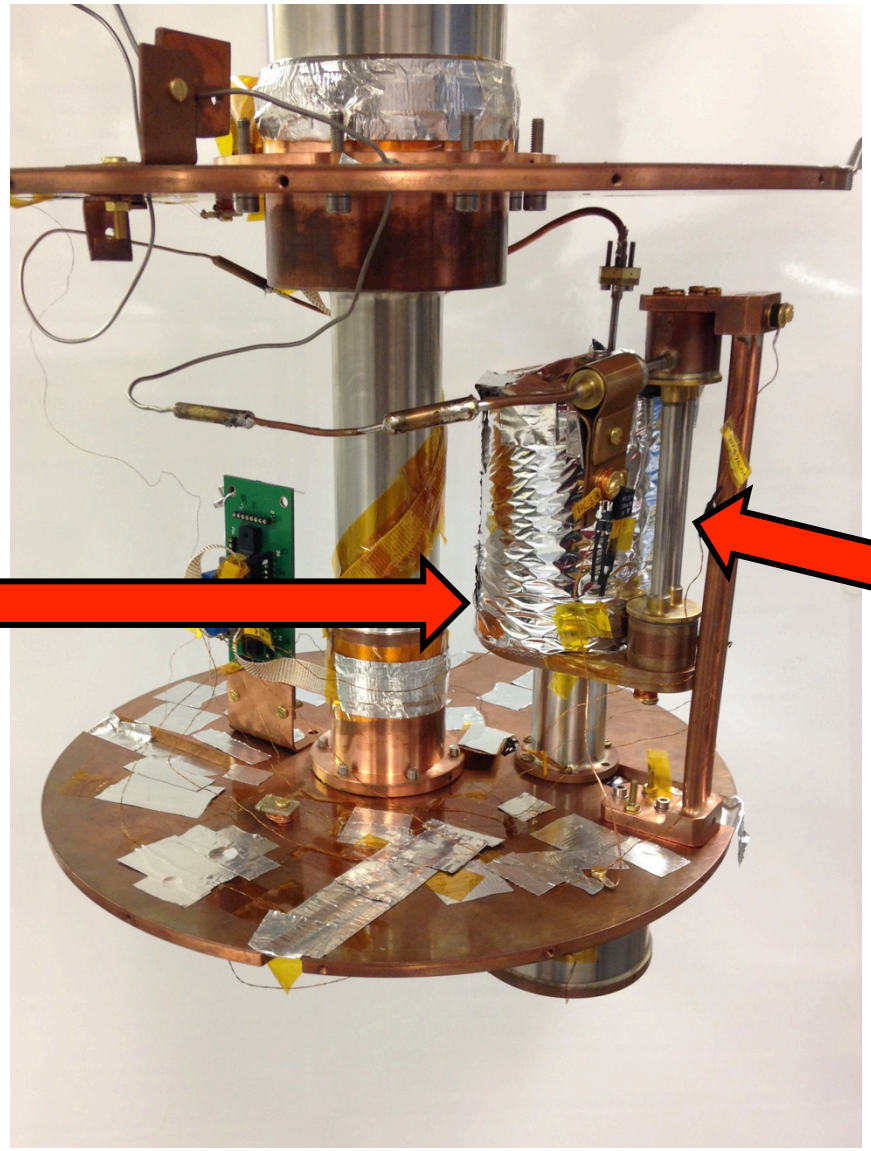
1 K fridge



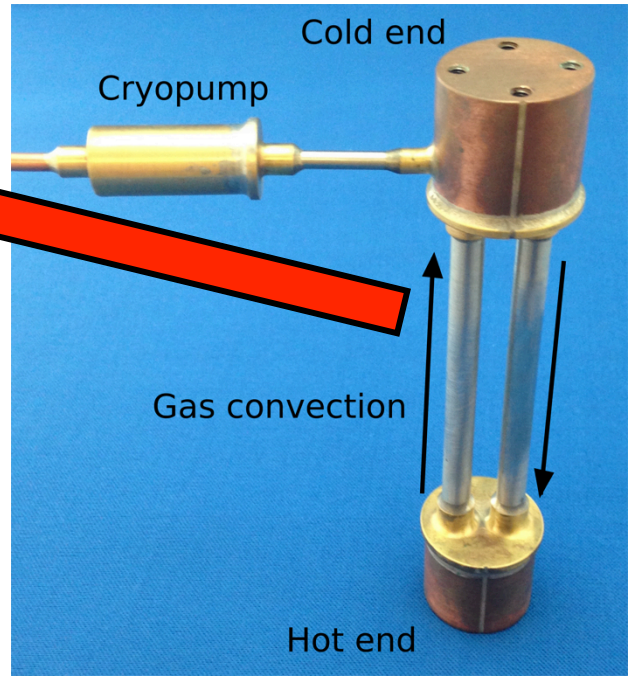
- High heat lift 1 K fridge designed for a separate project
- Design spec: 10 mW @ 1 K
- Suggested to use for QUBIC

Testing

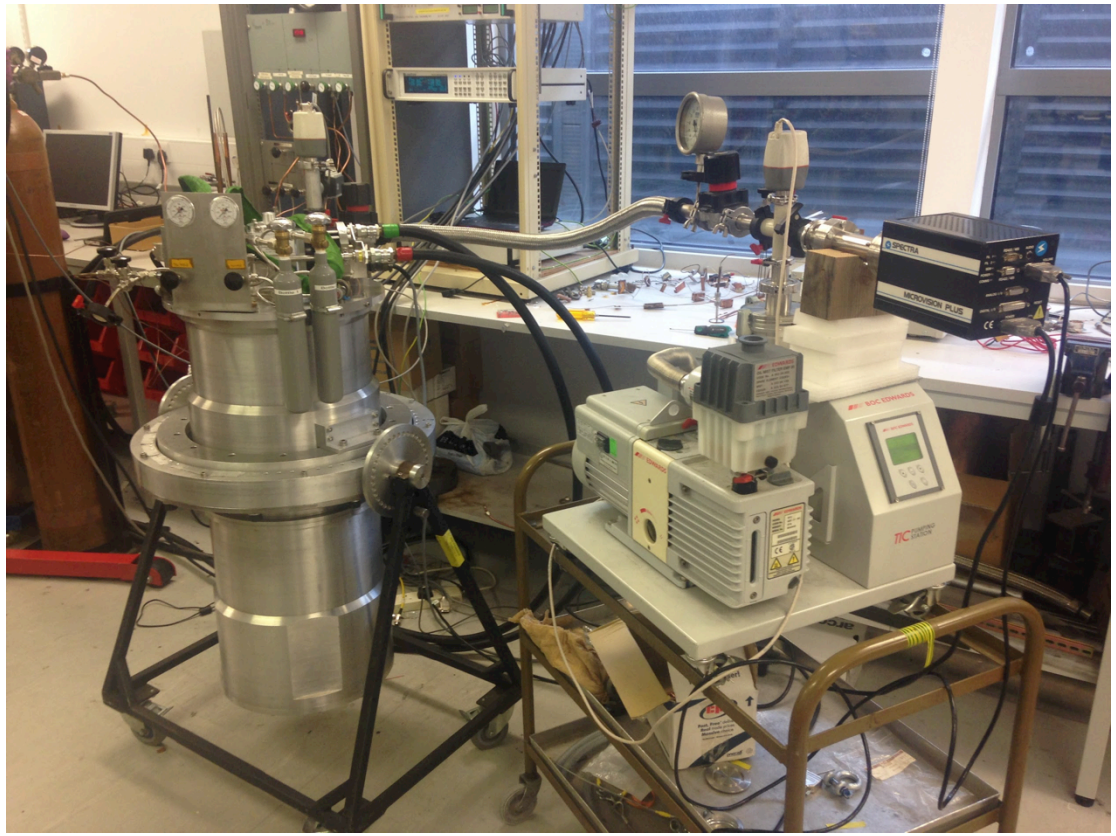




Gas lines using soft soldered brass collars and bolted indium seal



Testing

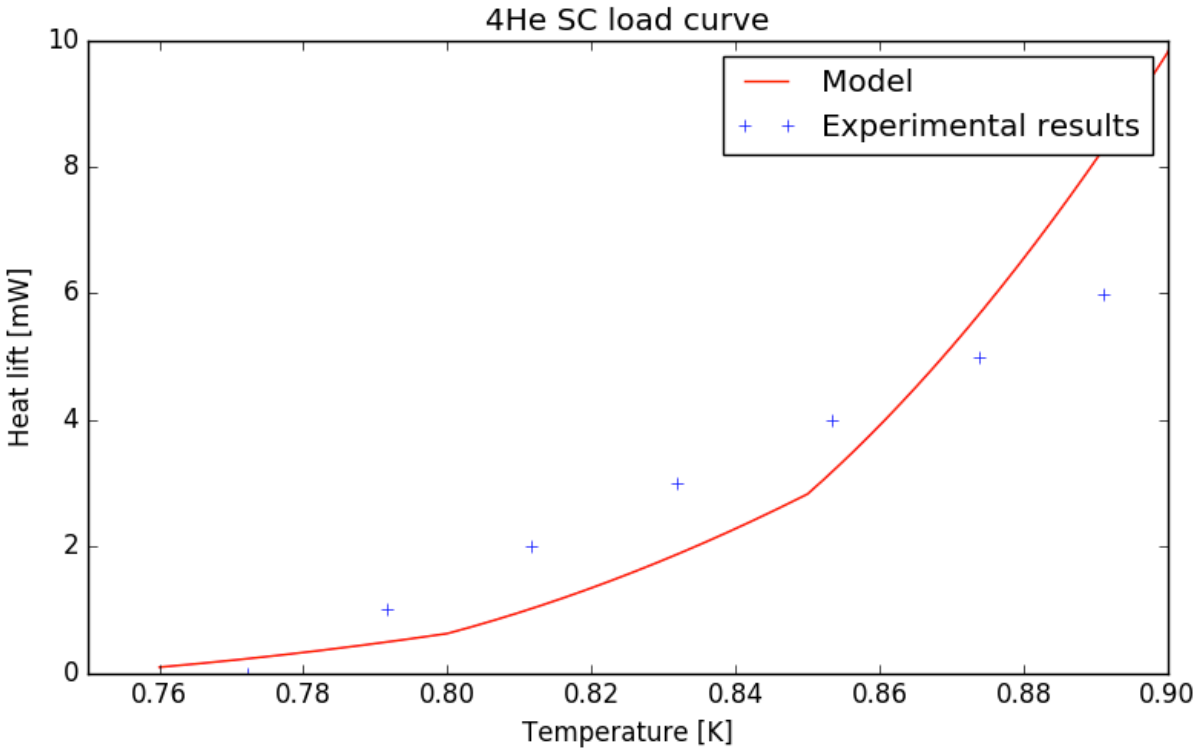


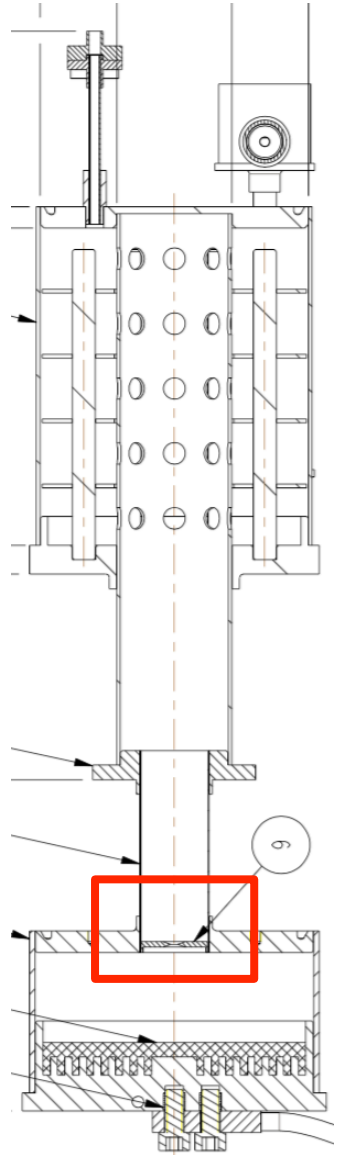
- Achieved min temp of 656 mK!
- Pump operation verified
- Condenser operation verified - can now define mating with 4 K
- Pumping line verified
- Integration of HS verified
- Indium seal verified

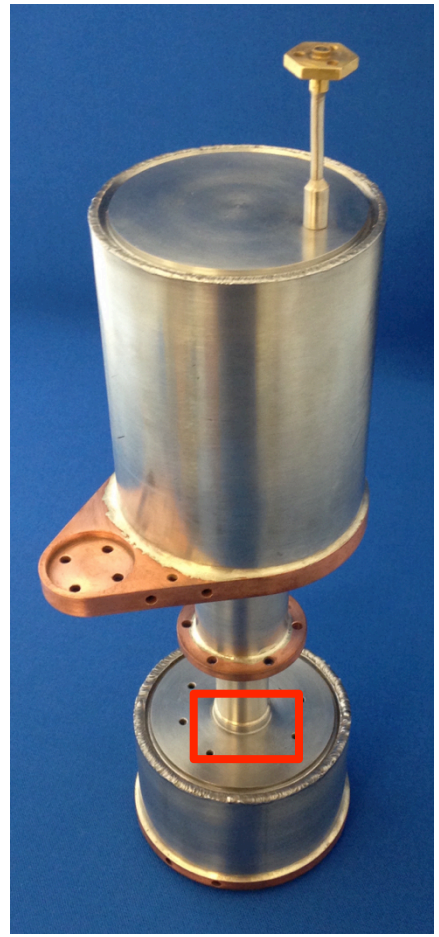
Load curve

Agrees reasonably well with model below 900 mK

Complicated by intermediate flow regime near orifice



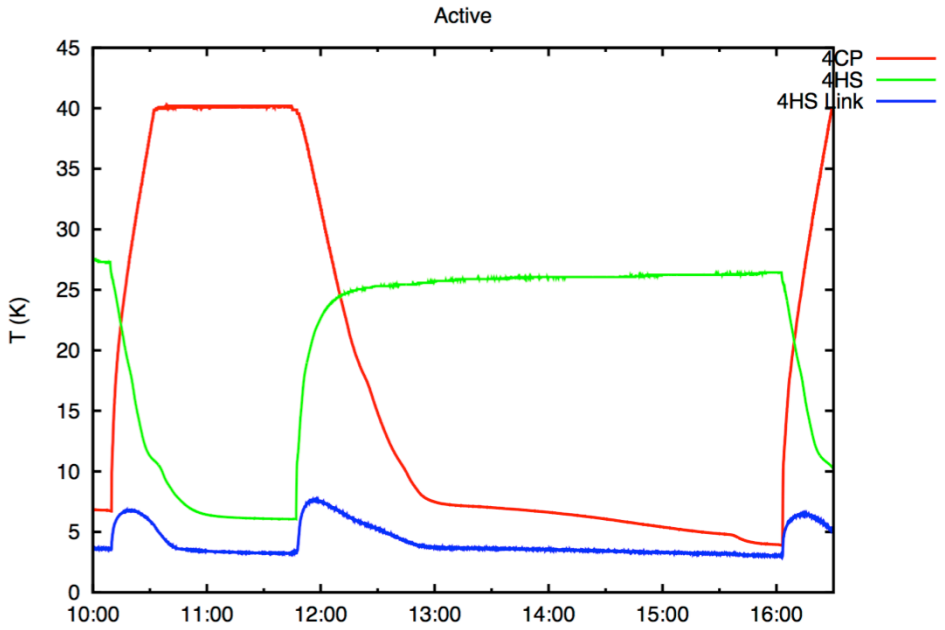


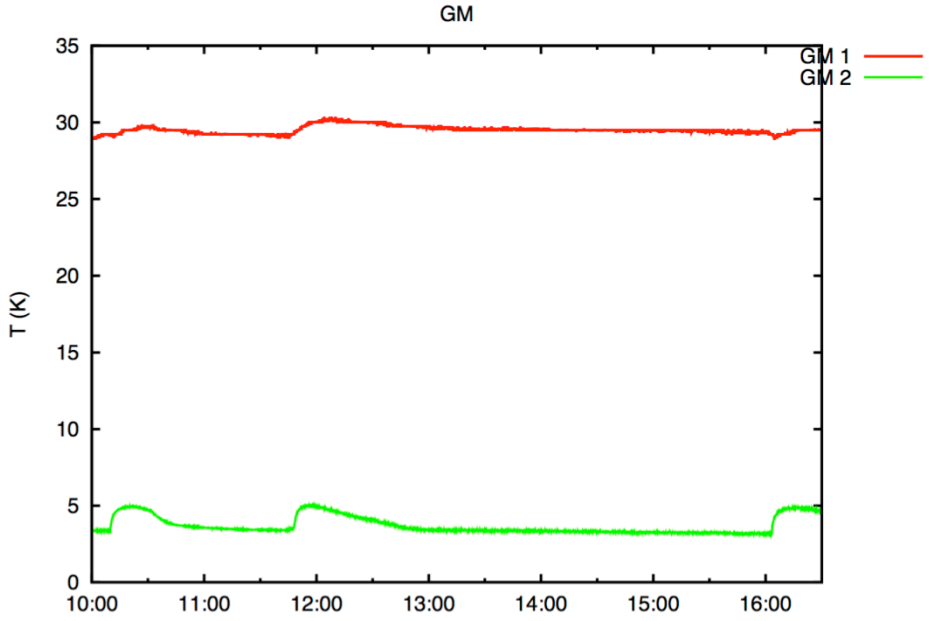


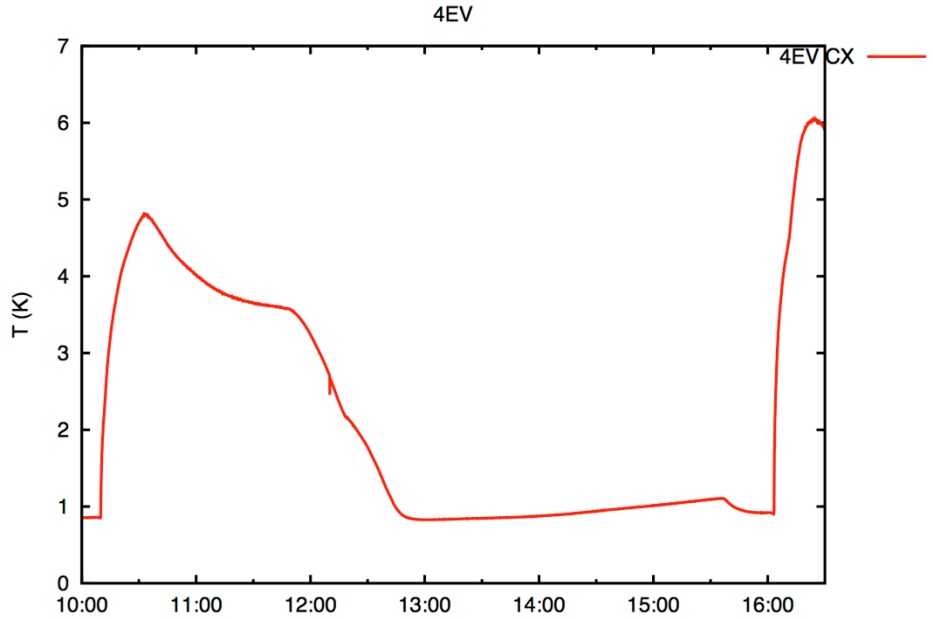
Cycle

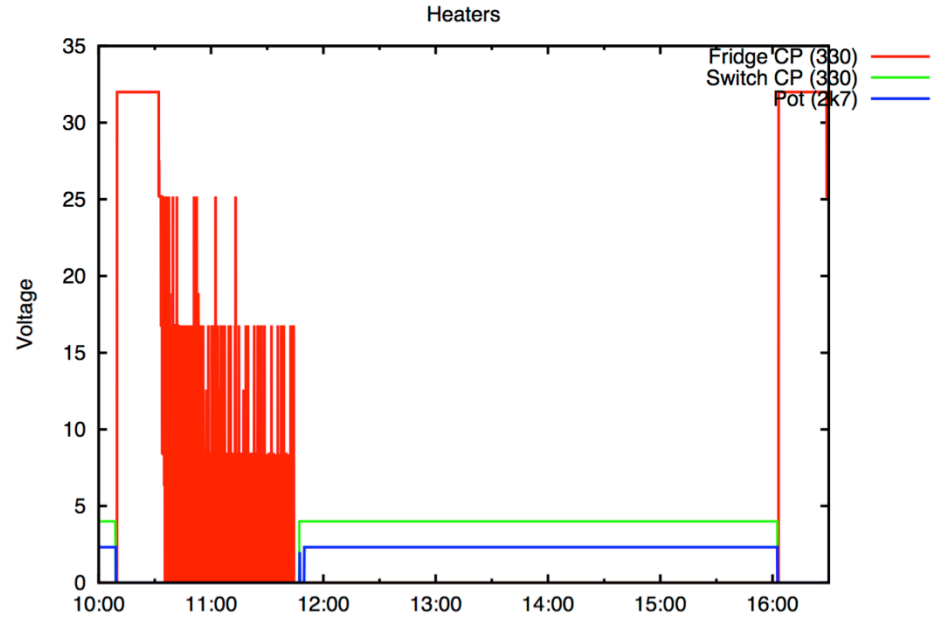
Controlled using XML scripts, PID used for CP thermostat

Example here shows 3 mW load, initial charge of 1.55 mol (comparable to QUBIC operation)

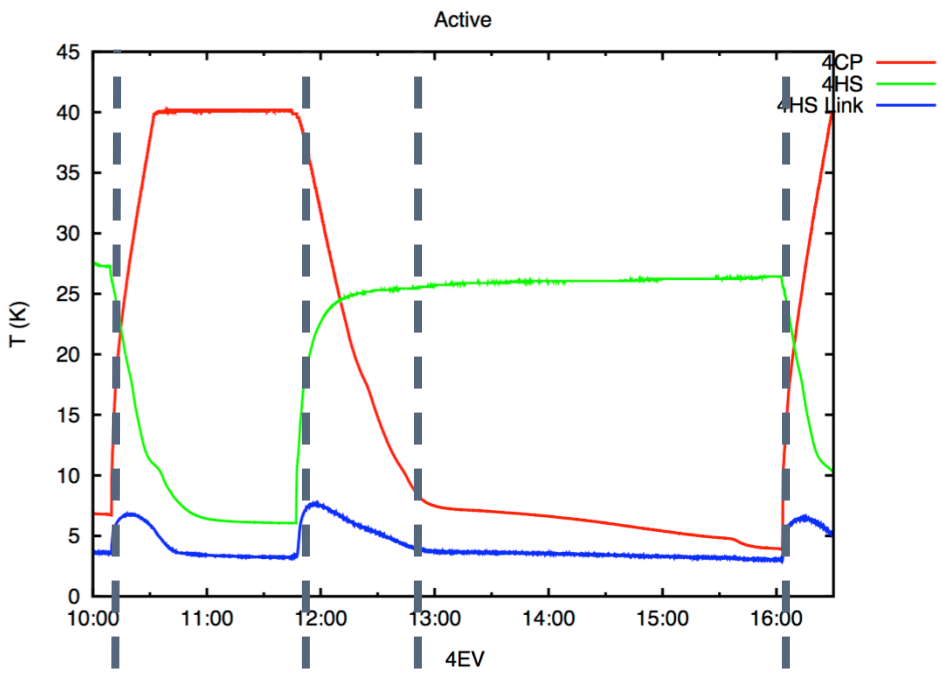


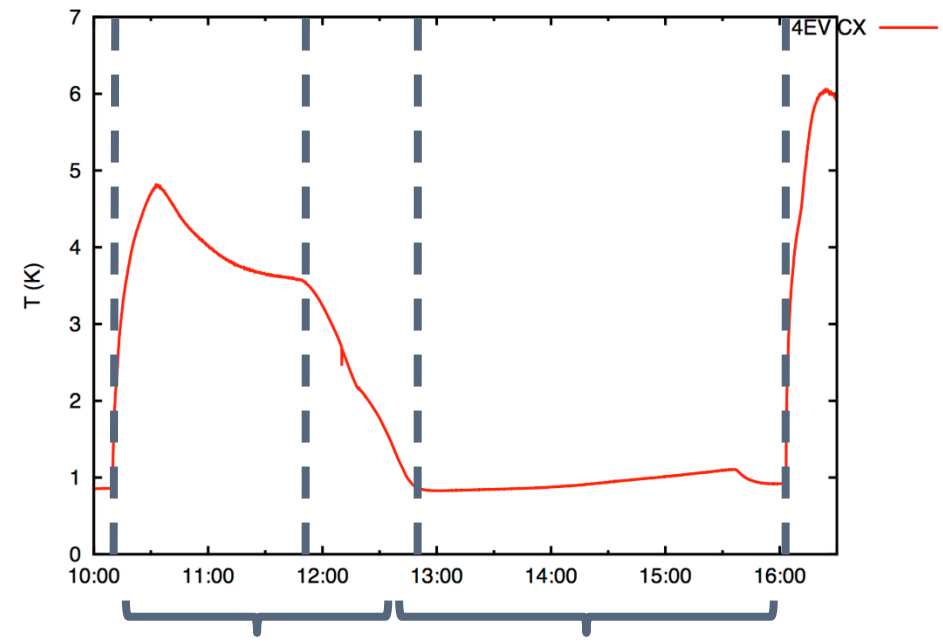




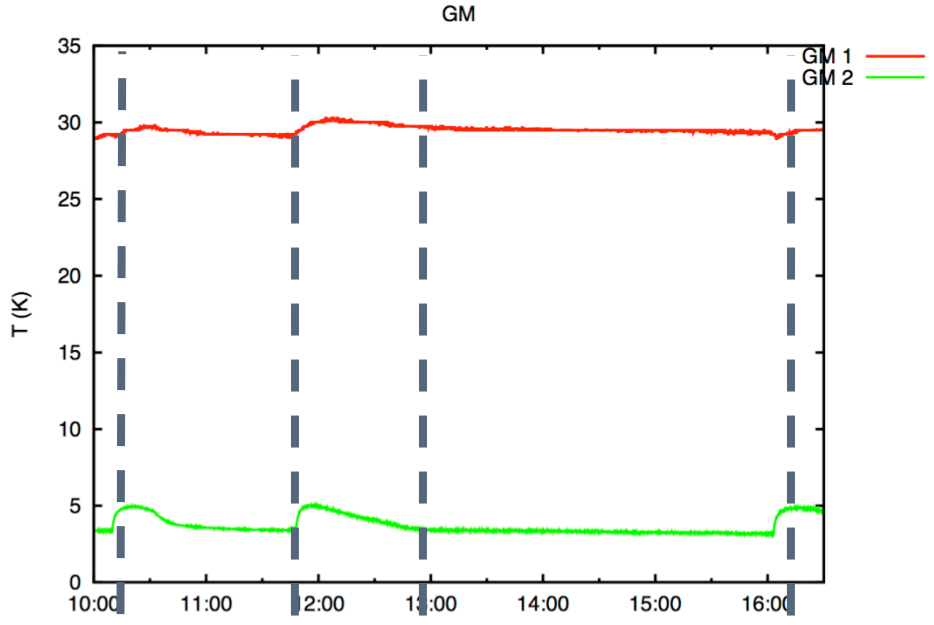


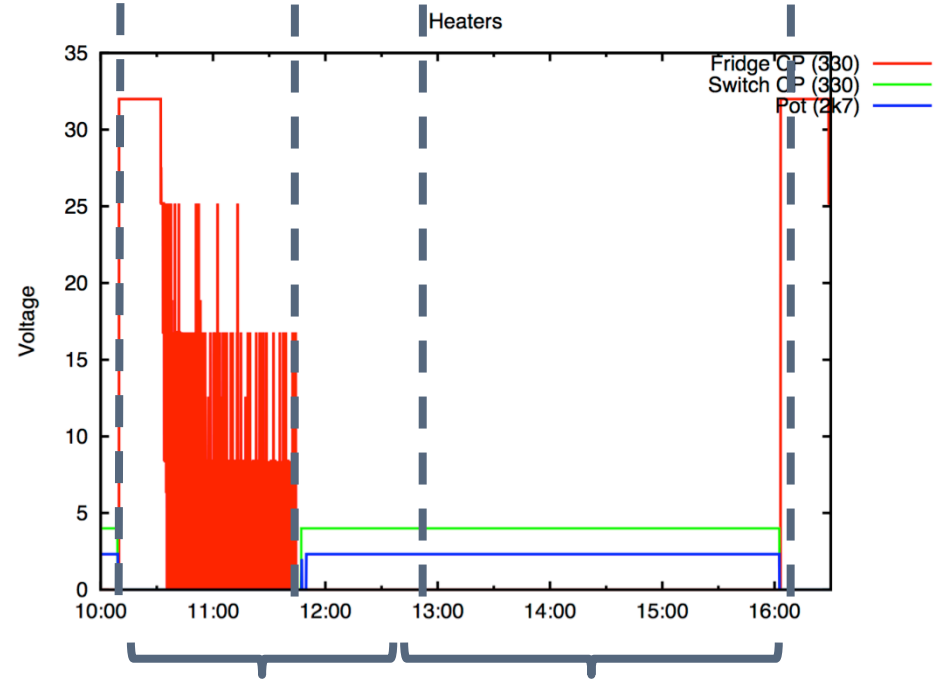
Cycle





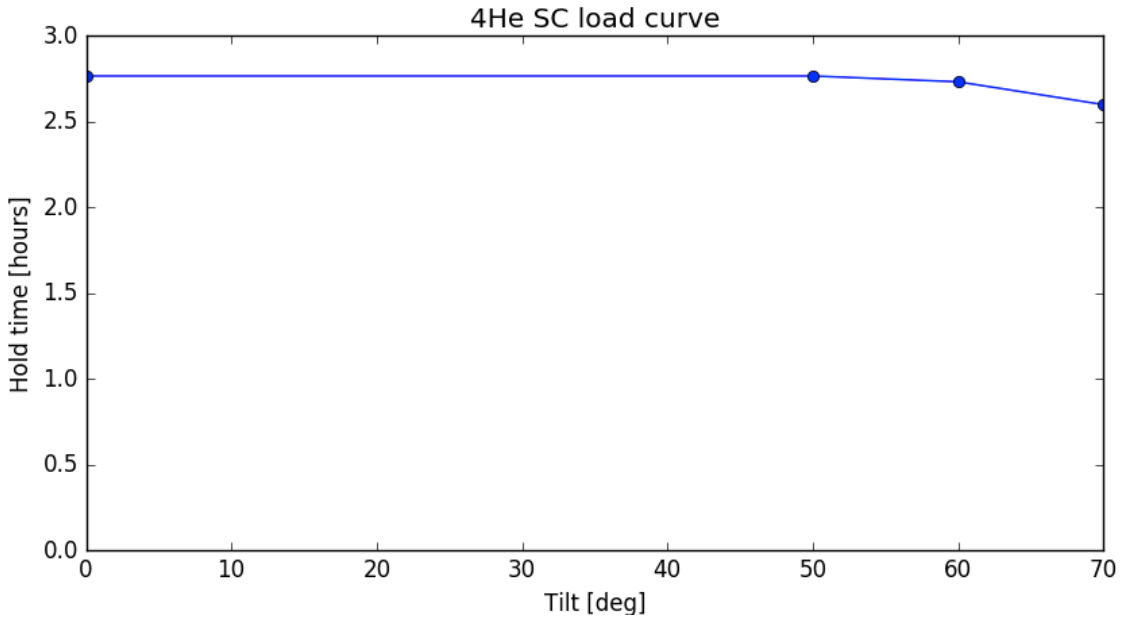
Recycling Cooling





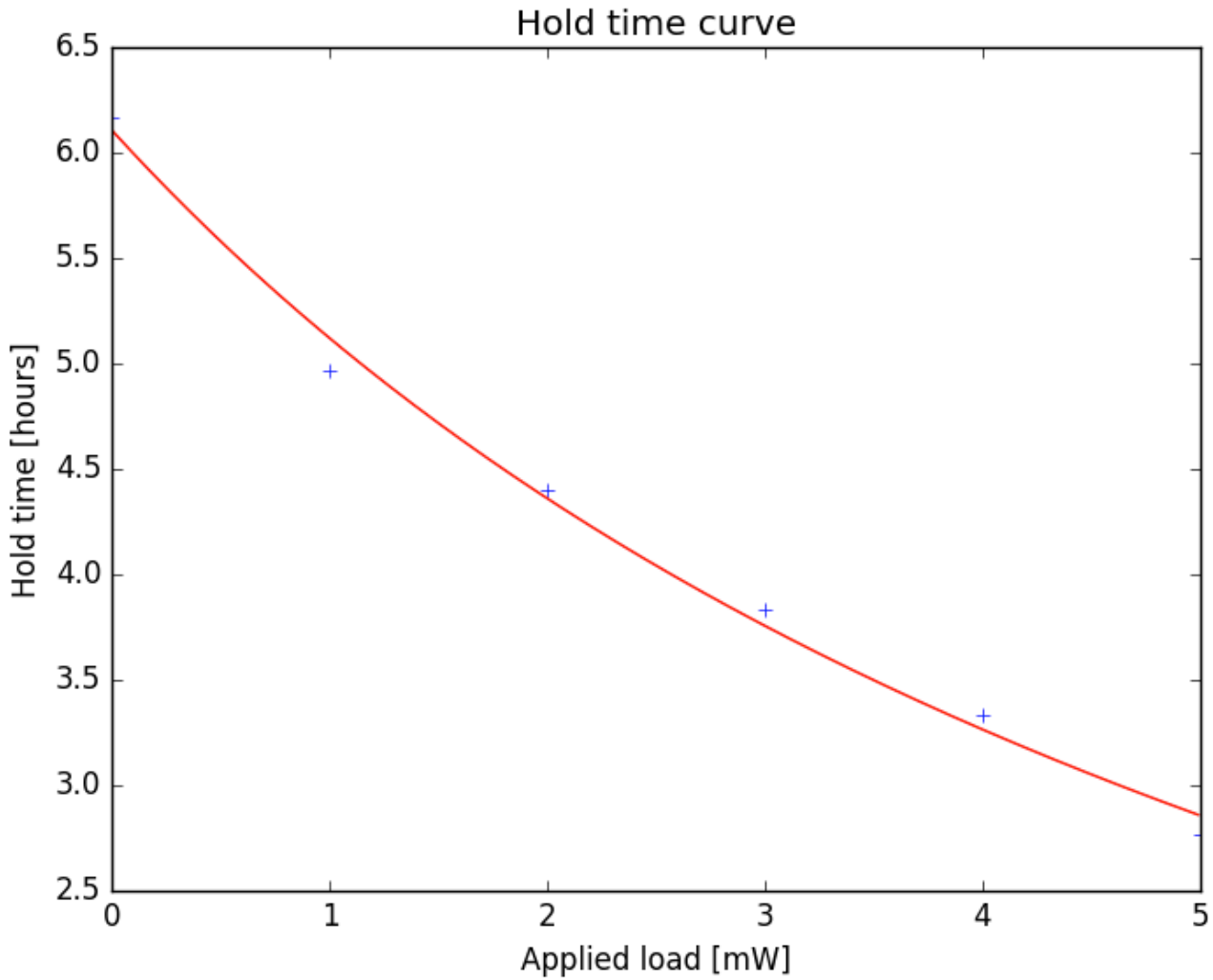
Recycling Cooling

Tilt tests



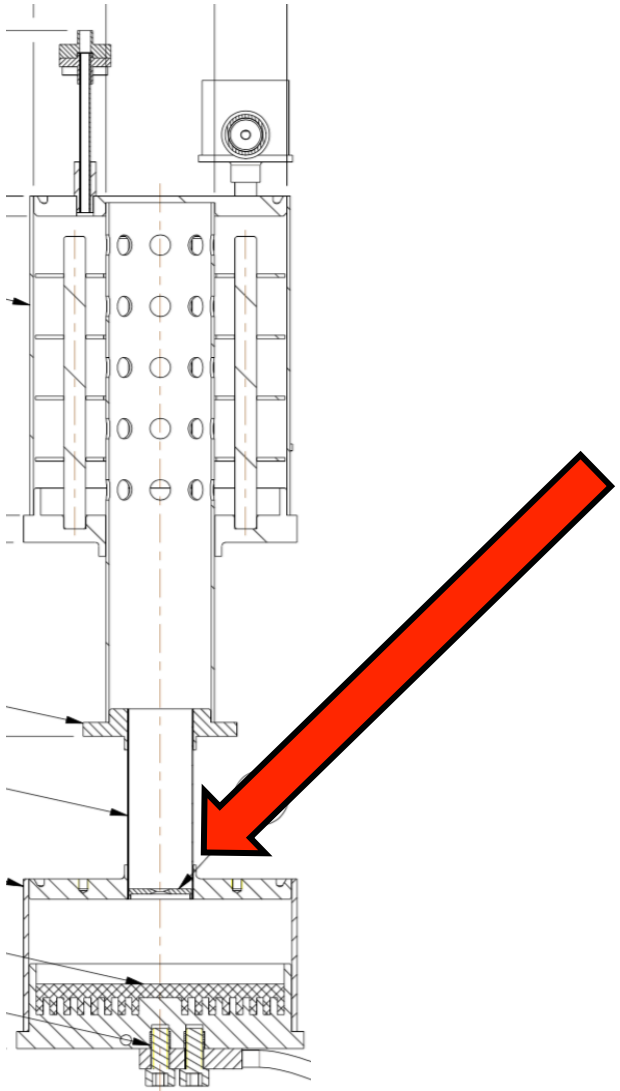
- Hold time unaffected by tilt up to 50 deg from vertical
- Only minor degradation in performance up to 70 deg
- Hence, no concern for QUBIC operation ± 20 deg

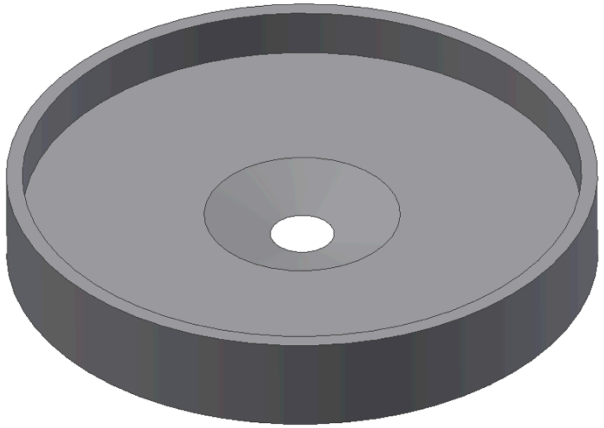
Hold time tests for 2 mW

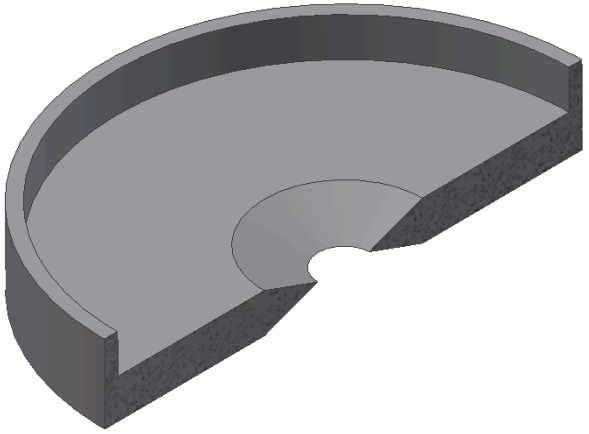


- Charged w/ 1.55 mol
- Hold time of ~4 hours @ 2 mW
- Orifice didn't behave as desired
- Likely due to fabrication issues

Current orifice design







- 2 mm punched
- Knife edge

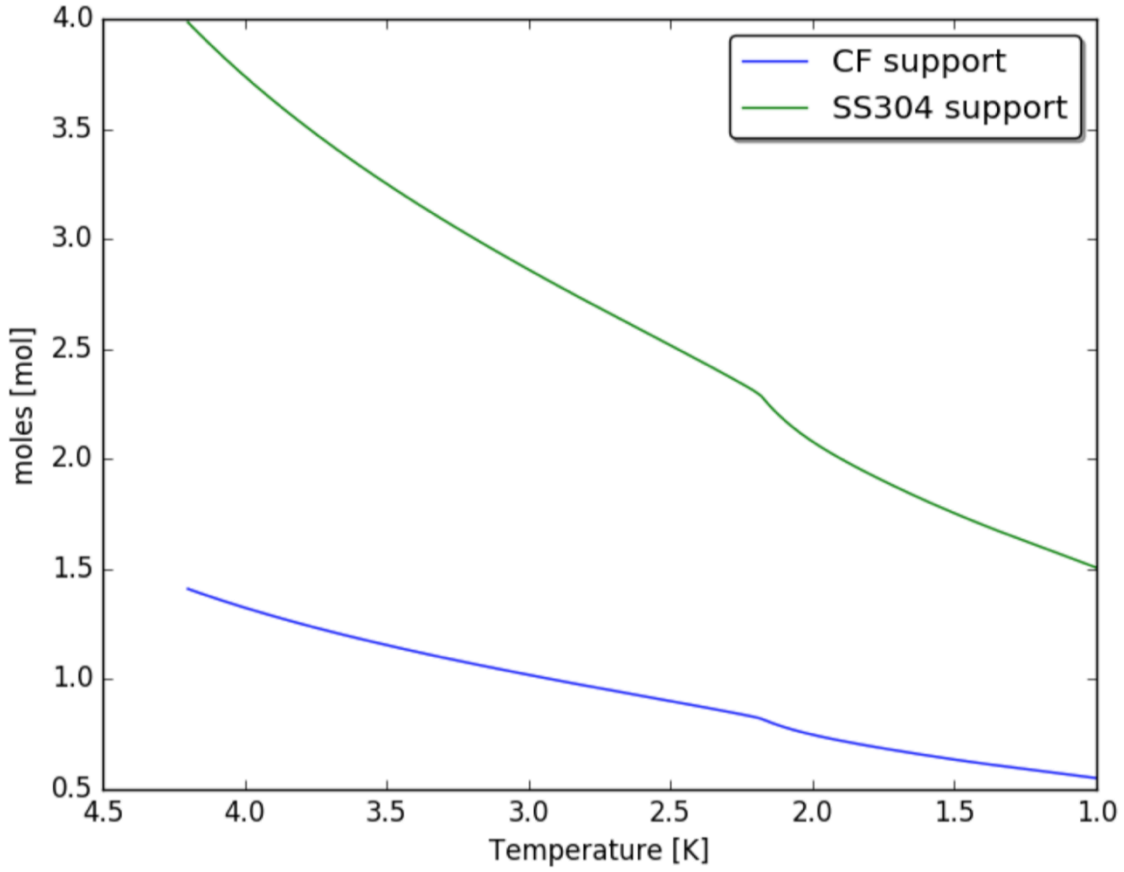
Orifice redesign

- Alternative fabrication method used on a different fridge appears (from preliminary testing) to be functioning much better, ~24 hour hold time
- It is therefore planned to undertake series of orifice tests to improve hold time of fridge
- Ready early next year?

1 K fridge wiring

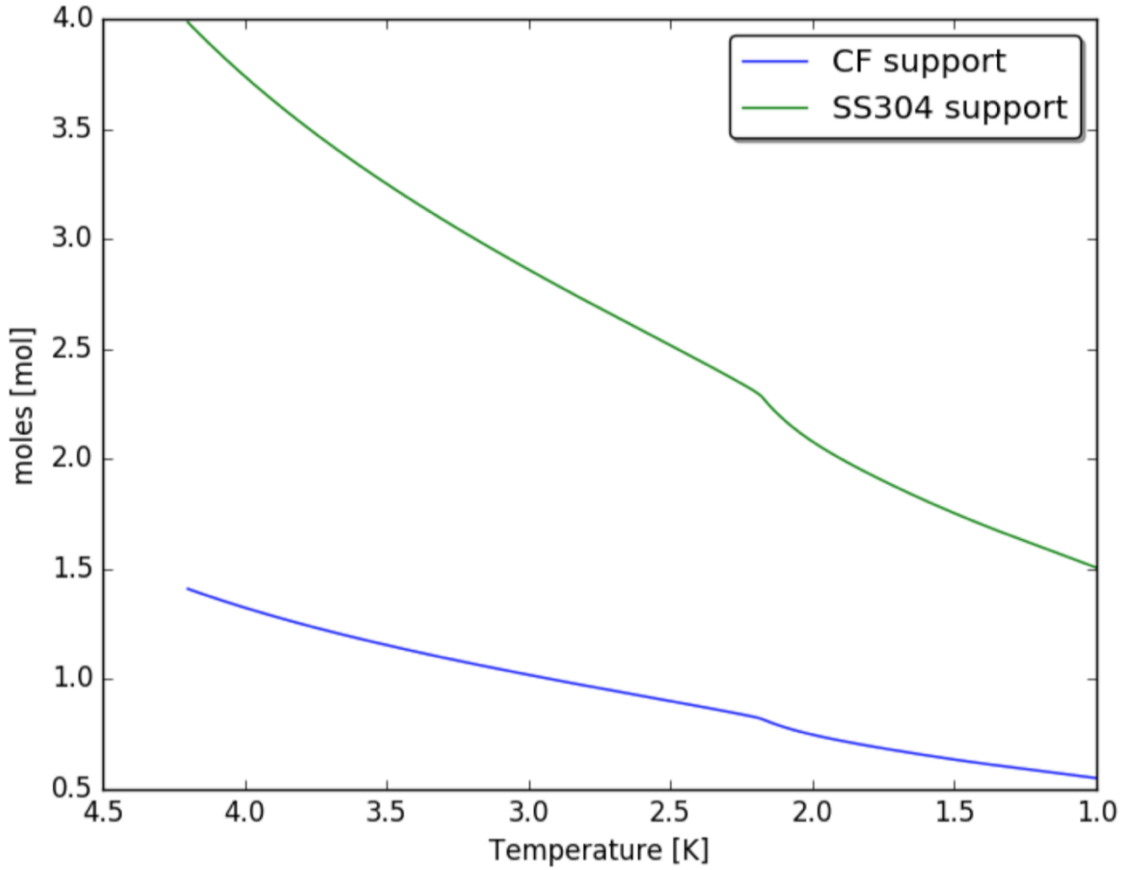
Type	Location	No. Wire Pairs	Notes
Diode	^{4}He heat switch	1	
Heater	^{4}He heat switch	1	
Diode	^{3}He heat switch	1	
Heater	^{3}He heat switch	1	
Diode	^{4}He cryo pump	1	
Heater	^{4}He cryo pump	1	
Diode	^{3}He cryo pump	1	
Heater	^{3}He cryo pump	1	
RTD	Cold stage	2	Optional
RTD	Intermediate stage	2	Optional
Heater	Cold stage	1	Optional

Charge required



- For cool down + 24h hold
  4 mol ⇒ 200 bar @ 300 K
  1.5 mol ⇒ 75 bar @ 300 K
- Should be charged in Roma, possibly using expansion volume

Charge required



- For cool down + 24h hold
  ~~4 mol ⇒ 200 bar @ 300~~ K
  1.5 mol ⇒ 75 bar @ 300 K
- Should be charged in Roma, possibly using expansion volume

Commissioning

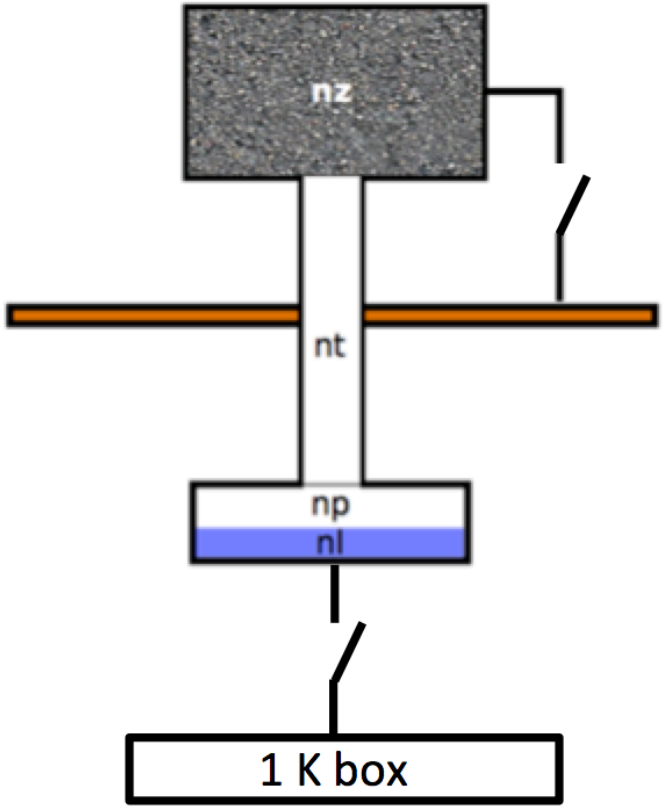
- Bake out, requires resistor (heater) and power supply
- Solder charging lines
- Leak test (requires helium leak detector)
- Check gas connection (using heat gun and bubble up)
- Charge (requires expansion volume ~1 L, gas handling system)

Cryogenic cycle for 1 K box

- 123 J to cool box from 4.2 to 1 K (17 hours @ 2mW)
- SS supports give 168 J/day (2 mW), CF give 43 J/day (0.5 mW) (Other loads negligible)
- Concern over warm up to 4.2 K each cycle - recyling fridge will effectively create HS to 4 K)
- If so, 24 hours to cool back to 1 K - very inefficient
- Thermal model needed to confirm - could be done now?

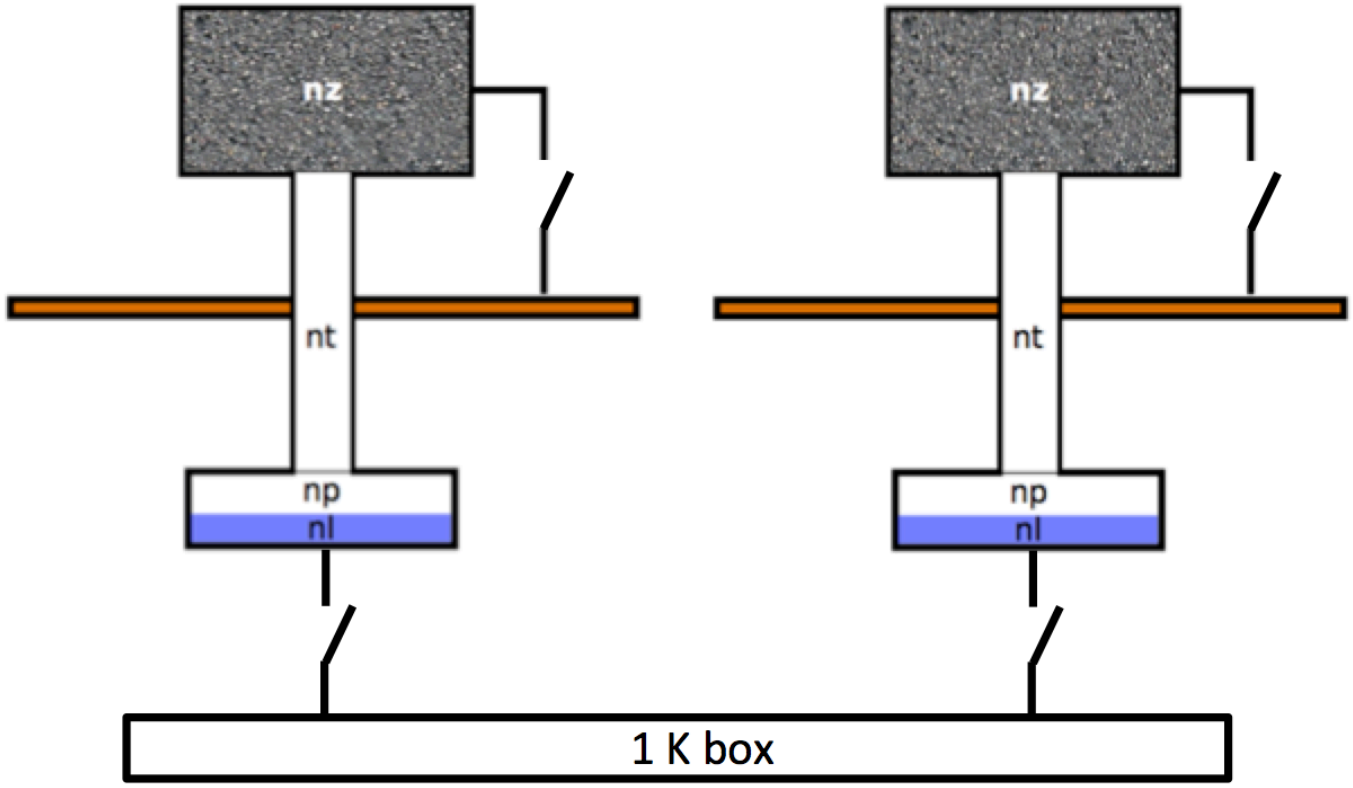
Cryogenic cycle for 1 K box

- Suggested to use 1x HS to isolate 1 K box?



Cryogenic cycle for 1 K box

- Even more efficient to use 2x HS - could give continuous 1 K with 2x fridges, 2x switches
- Also would mean that fridges meet spec without redesign required (already have second fridge manufactured, ready for prelim testing)
- However, increased number of components, wires



Other operational considerations

- Choice of cryogenic cycle will determine time scale
- Final testing criteria will also depend on this
- Condenser temp will determine condensation efficiency - 4.2 K from PTC? Need to know
- Dedicated PTC for (both?) fridge(s) to allow for temperature spikes?
- Alternatively, reduce conductivity of switch, although this will increase recycling time
- Will be shipped uncharged, helium fill in Roma?
- May be charged and sealed (crimp and solder cap) for placement into cryostat

Status of the sub-system : blocking points and schedule

- What is the status of the sub-system ?
  - Design/manufacturing (home made/industry)/assembly/tests ? Fridge built, tested. Orifice testing and modification required, further testing
  - When is this phase supposed to be finished ? 01/17

- If you are still designing the sub-system:
  - Which inputs / specifications / requirements, needed to finish the detailed design of your sub-systems, are not yet delivered ?
    - For D.T. Condenser temp, dedicated PTC? Continuous system or single shot? HS on evaporator?
    - For F.I.
  - Which other working group should deliver these inputs (see annex 1 for list of main WP) ?
    - For D.T. Roma?
    - For F.I.

- What time is still needed in order to (for D.T.) – assume that the above inputs are provided if needed - :
  - Finish the whole detailed design of D.T. ? 2 months (including orifice testing runs)
  - Manufacture the sub-system ? 5 weeks
  - Test the sub-system in your premises before delivery to APC / ROMA ? 2 weeks

- Idem for F.I.

- Do you think you can comply to the target schedule (see annex 2) ? Yes

Interfaces with other sub-systems

- List and describe needed interfaces with other systems. Mechanical
  - Electrical / Signal Thermometry/heaters
  - Vacuum
  - Thermal Condenser mating. Grease used to maximise k
  - Etc… Gas lines to charge depending on charge/hold time requirement?

- Are these interfaces currently frozen ? Condenser yes, gas lines no

Test, Delivery, Assembly, Calibration Operations

- Tests of the sub-system in your premises before delivery at APC or ROMA:
  - What is the rationale for testing the sub-systems ? Validate operation of orifice
  - Which specifications will be tested ? Hold time
  - What are the criterion for fail / pass ? Dependent on continuous/single shot operation

- Delivery to APC or ROMA:
  - Special care needed for the transportation and handling of the goods ? No if unpressurized

- Assembly Operations in APC or/and ROMA:
  - Same questions as first point above. As above
  - + which other sub-systems should be integrated before yours? After yours ? Assembled after 1 K box, mount to 4 K
  - + Is there any specific material needed for assembly ? (see annex 3 for help) Leak checker, gas handling system
  - What are the test sequences needed to be performed during/after integration Bake out, leak test, connection check
  - + How many FTE will you send people at APC / ROMA for help during assembly ? 1-2

- Calibration Operations at APC:
  - Same questions as for Assembly operations. As above

Management

ATRIUM and Documentation

- SubK fridge
  - Load curve, hold time results to be uploaded in due course
  - Interface dimensions
- Heat switches
  - Conductance results to be uploaded in due course
  - Interface dimensions
- 1 K fridge
  - Load curve, hold time results to be uploaded in due course
  - Interface dimensions

Budget (excluding salaries)for T.D. + F.I.

	Spendings (type and amount)	Funding (source and amount)	Status of funding (granted / under examination)
2016			
2017			
2018			

Covered by department consolidated grant

Manpower

Name and responsibility	% FTE 2016	% FTE 2017	% FTE 2018
COPPI	20	20	20
MAY	20	20	20
McCULLOCH	20	20	20
MELHUISH	5	5	5
PICCIRILLO	5	5	5
TOTAL FTE	70	70	70

Risks analysis

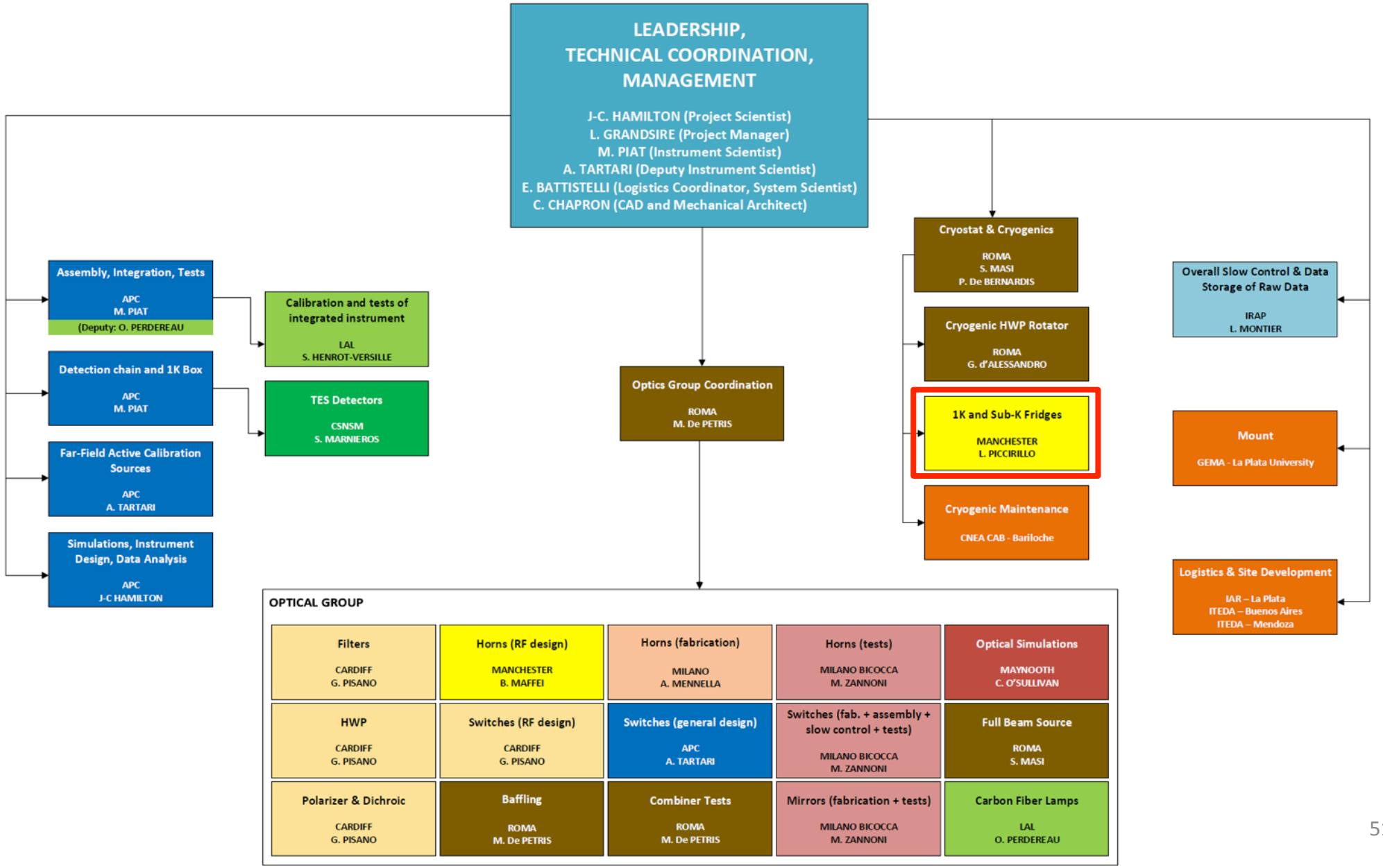
- Delays in testing schedule for subK fridge
- Delays in testing of orifice
- Performance of orifice, impact on hold time

Final thoughts

- Several performance parameters still to be defined
- Thermal model to be built
- Recycling - switches on 1 K fridges? Cryogenics program needs defining asap
- Given system complexity, debugging will be needed!

Backup slides

Annex 1: list of main-sub-system and WP leaders

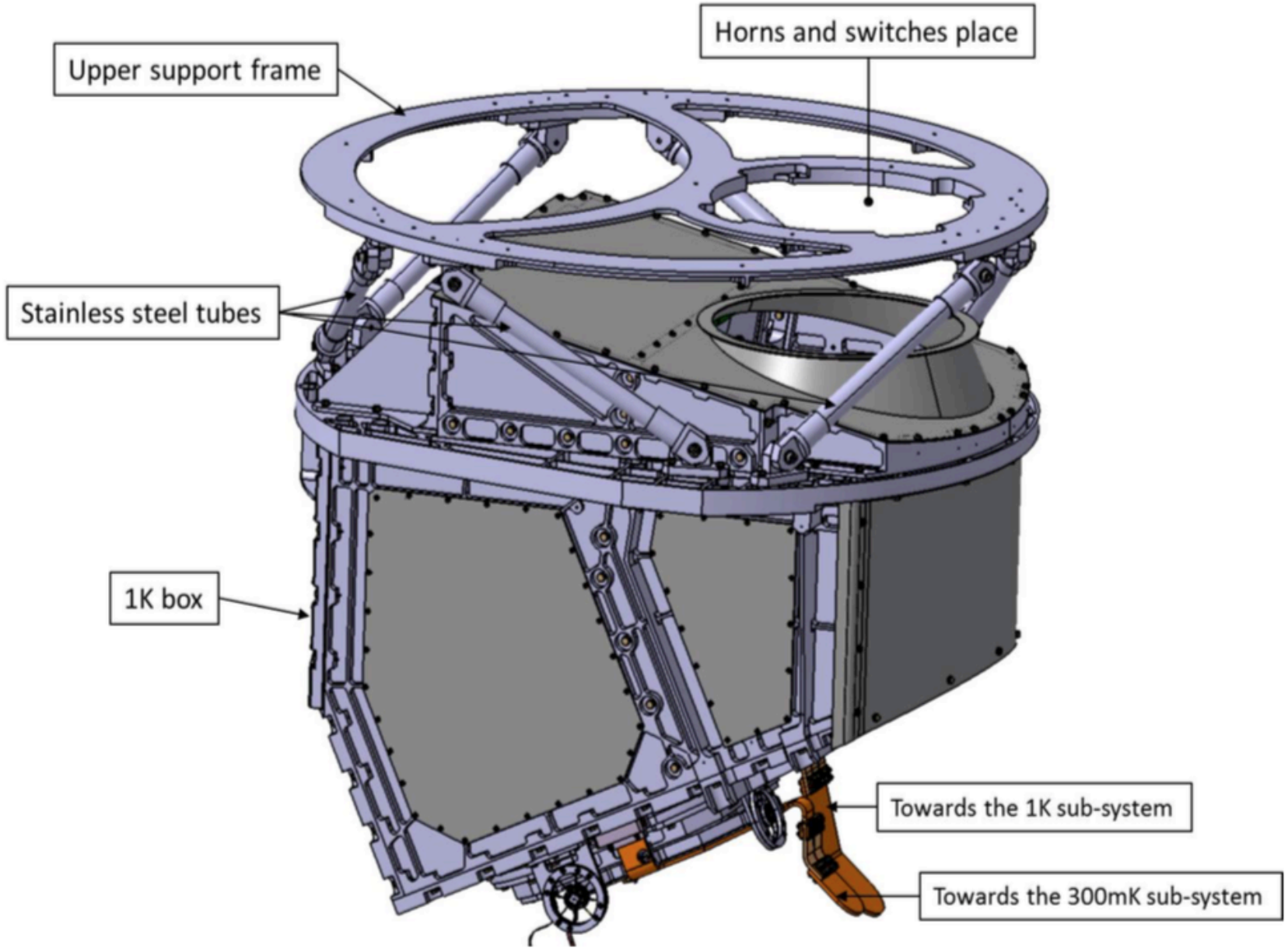


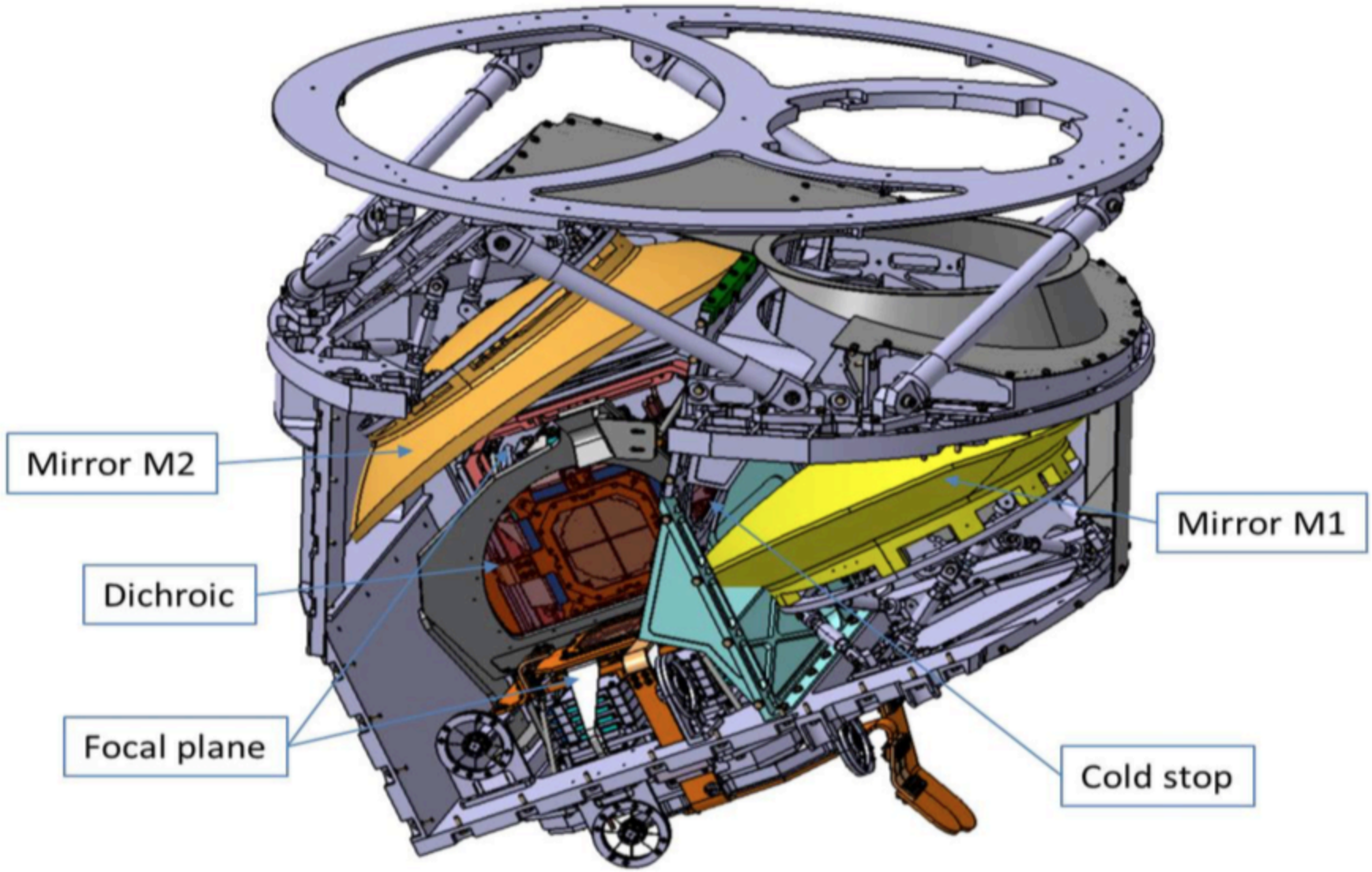
Annex 2 : Target schedule

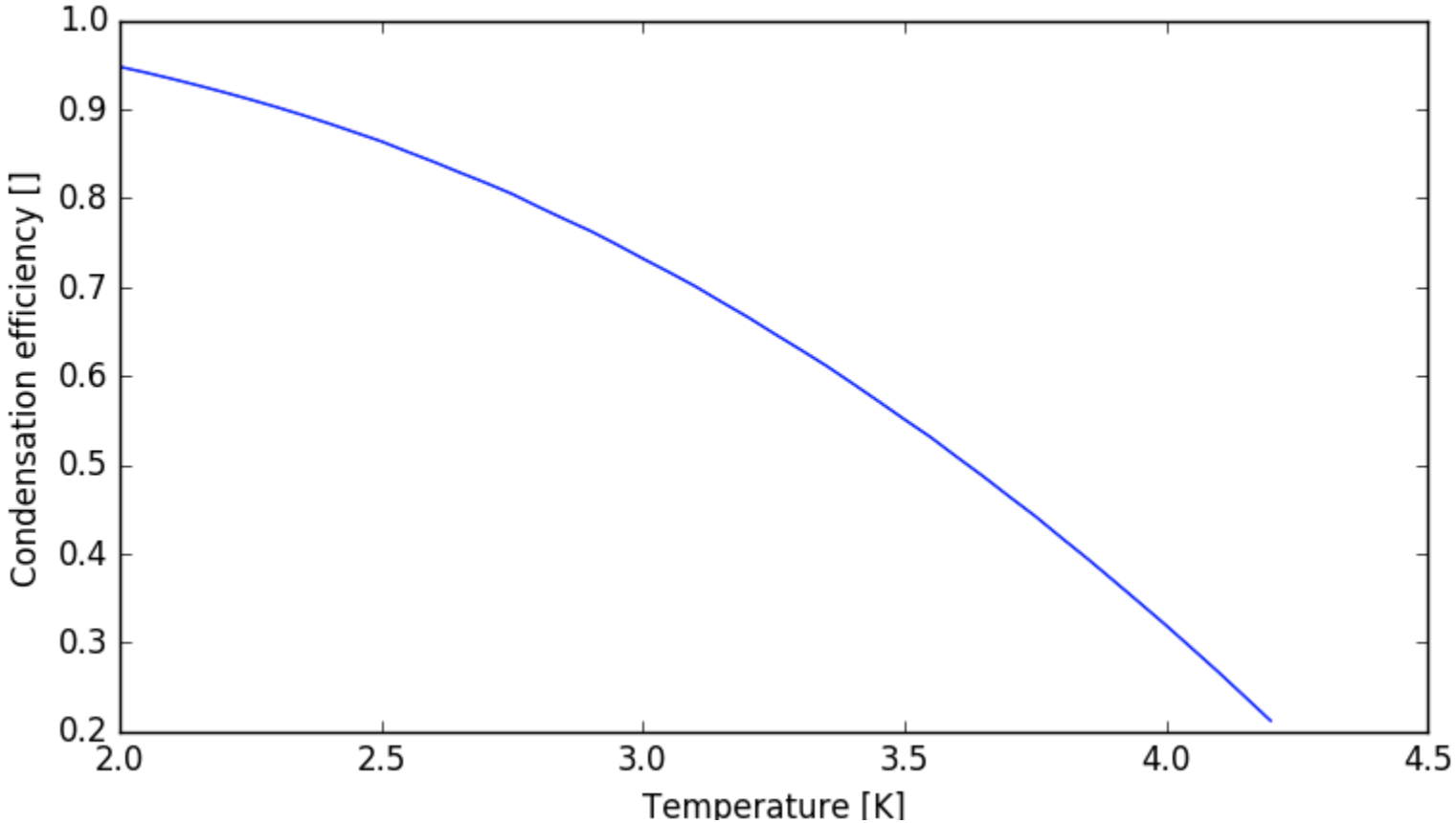
Sub-systems		Delivered…		Delivery date for…	
		By	To	T.D.	F.I.
Detection chain and 1K box		APC	APC	03/2017	09/2017
	TES Detectors	CSNSM	APC	12/2016	06/2017
Calibration sources		APC	APC	04/2017	Cf. TD
Simulations, Instrument Design, Data Analysis		APC	QUBIC	Completed	12/2016 for design
Optics Group					
	Filters	Cardiff	Roma / APC	12/2016	04/2017
	Horns (RF design)	Manchester	APC	Completed	Completed
	Horns (fabrication)	Milano	APC	Completed	11/2016
	Horns (tests)	Milano-Bicocca	APC	11/2016	05/2017
	Optical simulations	Maynooth	QUBIC	Completed	12/2016
	HWP	Cardiff	Roma	12/2016	Cf. TD
	Switches (RF design)	Cardiff	QUBIC	Completed	11/2016 (chokes)
	Switches (general design)	APC	Milano	Completed	12/2016
	Switches (fab + assembly + slow control + test)	Milano-Bicocca	APC	10/2016	03/2017
	Full Beam Source	Roma	APC	04/2017	Cf. TD
	Polarizer & Dichroic	Cardiff	APC	01/2017	05/2017
	Baffling	Roma	APC	05/2017	Cf. TD
	Combiner test	Roma	APC	04/2017	07/2017
	Mirrors (fabrication + tests)	Milano-Bicocca	APC	09/2016	05/2017
	Carbon Fiber Lamps	LAL		01/2017	Cf. TD
Cryostat & cryogenics		Roma	APC	04/2017	08/2017
	Cryogenic HWP Rotator	Roma	Roma	11/2016	Cf. TD
	1K and Sub-K Fridges	Manchester	Roma / APC	01/2017	Cf. TD
	Cryogenics Maintenance	CNEA CAB	QUBIC	-	Start 2018
Overall Slow control & Data Storage of Raw Data		IRAP	QUBIC	11/2016	Cf. TD
Mount		GEMA	On site	-	03/2018
Logistics & Site Development		IAR / ITEDA	On site	-	10/2017
Assembly, Integration and test of QUBIC module		APC	QUBIC	12/2017	04/2018
	Calibration and test of integrated instrument	LAL	QUBIC	12/2017	04/2018

Annex 3: examples of possibly needed major tools or utilities

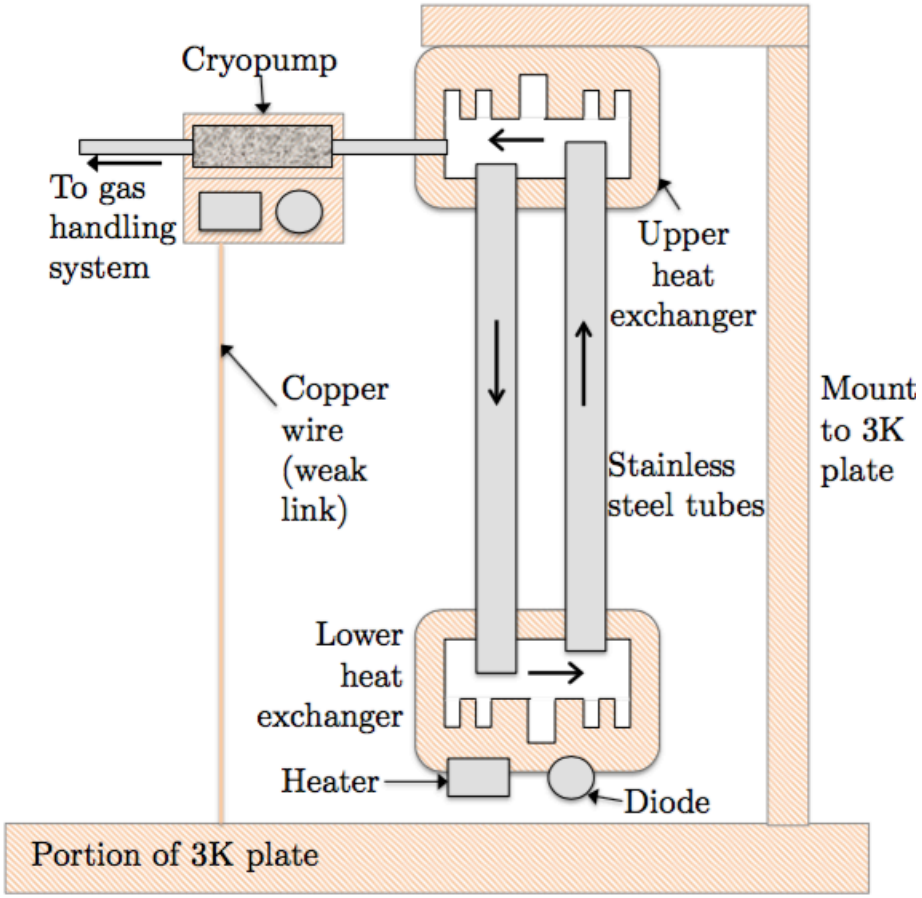
- High voltage (380 V) power
- Cold water
- Liquid or gaseous N2 / He
- Compressed air
- Clean air laminar flow / clean room / conditioned air
- Assembly Hall
- Mechanical workshop
- IT network or Wifi
- Chemicals
- ESD equipments
- Crane or heavy handling systems
- Metrology systems (Faro, MMT, Laser…)
- VNA
- Calibration source
- Mount (or fake)
- Vacuum systems (including degassing)
- Acquisition systems
- Computers / data acq. systems
- Electrical test with probe station


Horns and switches place
Upper support frame
Stainless steel tubes
1K box
Towards the 1K sub-system
Towards the 300mK sub-system

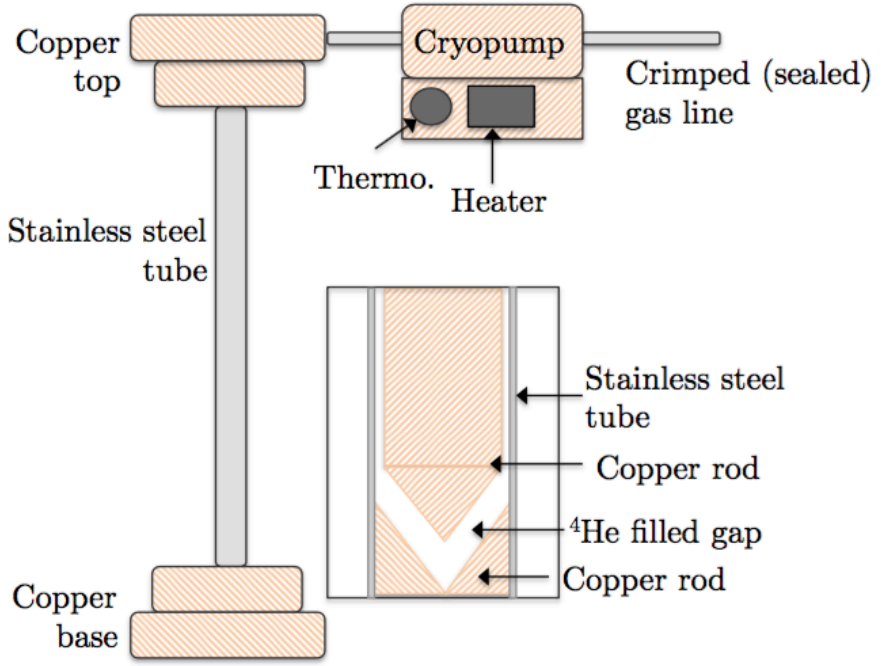

Mirror M2
Dichroic
Focal plane
Mirror M1
Cold stop


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Condensation efficiency []
2.0
2.5
3.0
3.5
4.0
4.5
Temperature [K]

Courtesy: Philippa McGuinness



Convective HS



Minimal gap HS