Heat transfer (inside) Cryocoolers and its impact

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THALES CRYOGENICS BV – EINDHOVEN

WORK PERFORMED IN DIFFERENT PROJECTS

BY DIFFERENT ENGINEERING TEAMS

CHMT WORKSHOP 04/05-11-2019

Contents

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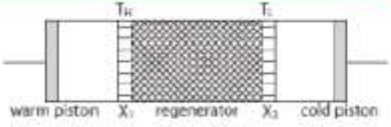
Used technologies by Thales Cryogenics

Compact systems

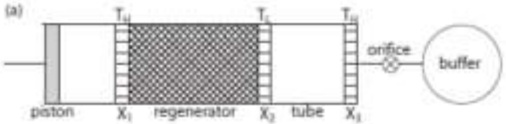
- Input power < 500 W
- Temperature range 30 … 150K

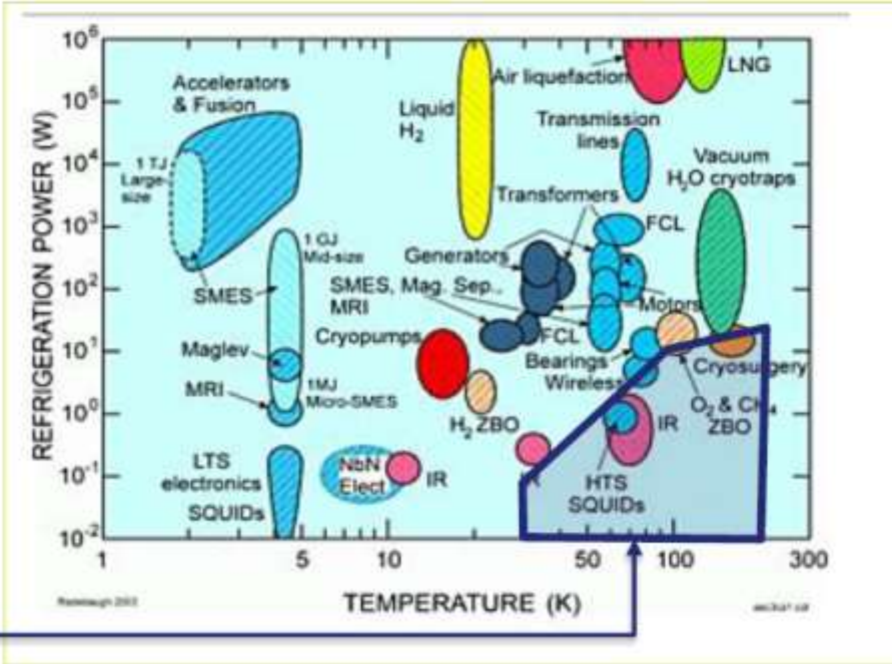
Used cooling principles

- Stirling Cycle



- Pulse Tube cycle



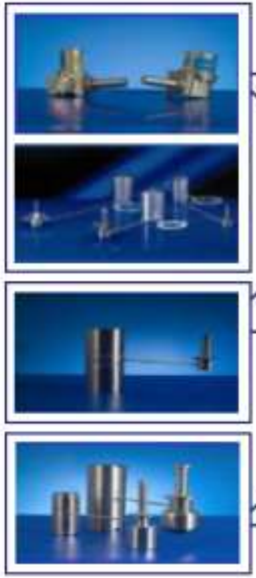


Courtesy of Ray Radebaugh

Main products perimeter

Type of coolers | **Market requirements** | **Typical applications**

145 gr, 150mW @ 90K @ 2 Wac



Contact seal coolers

"Flexure" coolers

Pulse Tube coolers

6000 gr, 9000mW @ 77K @ 200 Wac

Defense Markets (Stirling coolers)

High MTTF
Compact, robust & efficient

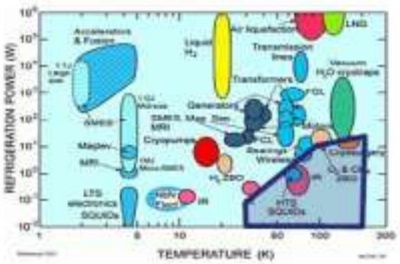
Commercial Markets (Stirling & Pulse tube)

High availability&
Cost effective solutions

Space Markets (Pulse tube coolers)

High availability
High efficiency
"No" vibrations
Reduction of (development) costs

Expected future market needs



Compactness (Gimbel applications)

Lower interference (IV/Audible noise/EMI)

More cooling Power/Lower Te

Lower NRC and RC costs

1

2

3

4

Depending on Application Area

We try to translate individual customer needs to cooler concepts that can be used for different customers and in different types of applications

Understanding of (Cryogenic) Heat and Mass transfer critical for utilization of cryocoolers

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Cryocoolers technologies

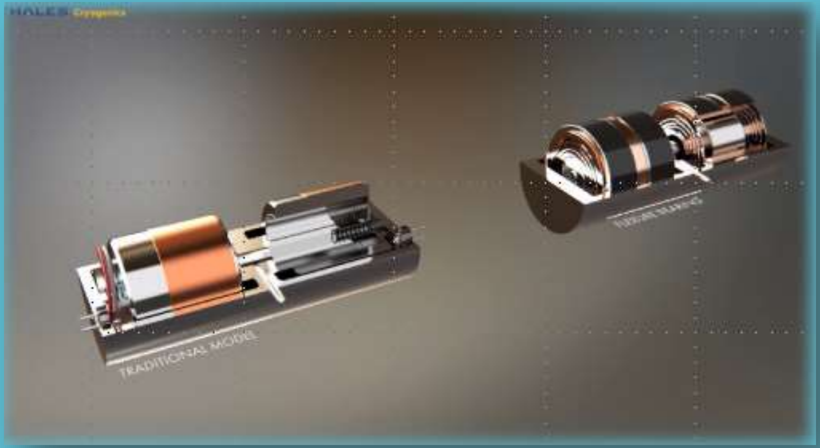
Cooler families defined by mechanical solutions

Compressor (pressure wave generation)

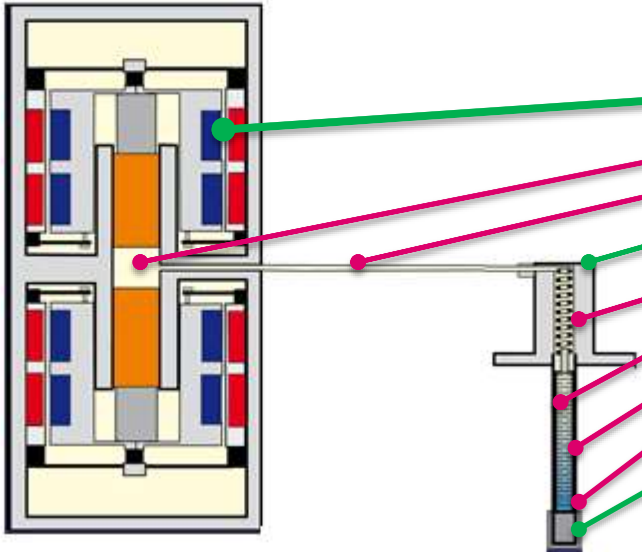
- Linear compressors with contact seal bearings or flexure bearings

Cold finger (cold generation)

- Stirling cooler: Moving displacer
  - Main failure mode is displacer seal wear
- Pulse-tube coolers: No moving parts in cold side of the cooler
  - Higher reliability
  - Lower induced vibrations
  - Lower overall efficiency



Transfer of Electrical power > Cooling power



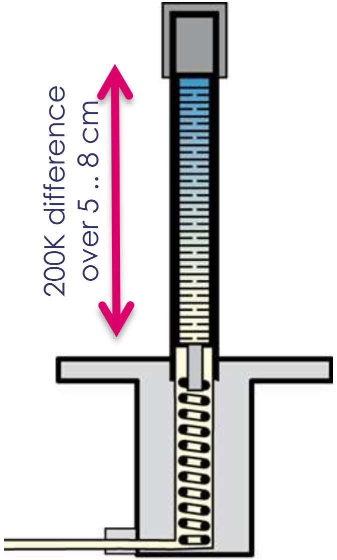
ROM values for standard Stirling cooler
6 W @ 77K / 293 K

Order of magnitude figures (Stirling cooler)	**Watt**
Input power	**150**
Pneumatic power	100
Flow losses split pipe	5
Transition to cooling power (77-293)	**17**
Impact heat transfer warm side (20K)	-0.84
Regenarator losses	-7.00
Thermal conduction along CF	-0.81
Impact heat transfer cold side (10K)	-1.60
Nett cooling power	**6.69**

Overall Efficiency ≈ 13% of Carnot


90
100
110
120
130
150
160
0

Cold finger / Loss of efficiency



Loss effects cold finger:

- Conduction losses (walls / regenerator)
- Flow losses (pressure drop)
- DT at cold and warm end DT
- Finite heat capacity regenerator

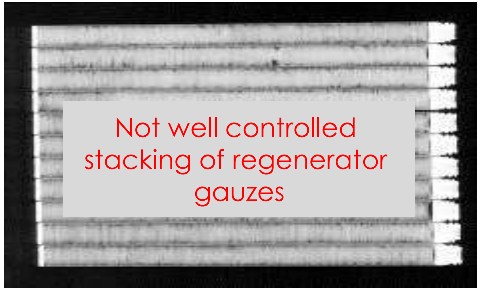
Example of ≈ 1 @ 77K Watt cooler:

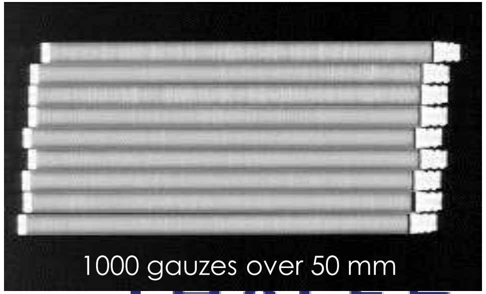
Cooling power = Cold production – Losses
(0.8 W = 3.7 W – 2.9 W)

Main losses:

1. **Regenerator design**
2. **Heat exchanger designs**
3. **Conduction losses**

Wire thickness = 1/10 of human hair
10 wires per mm

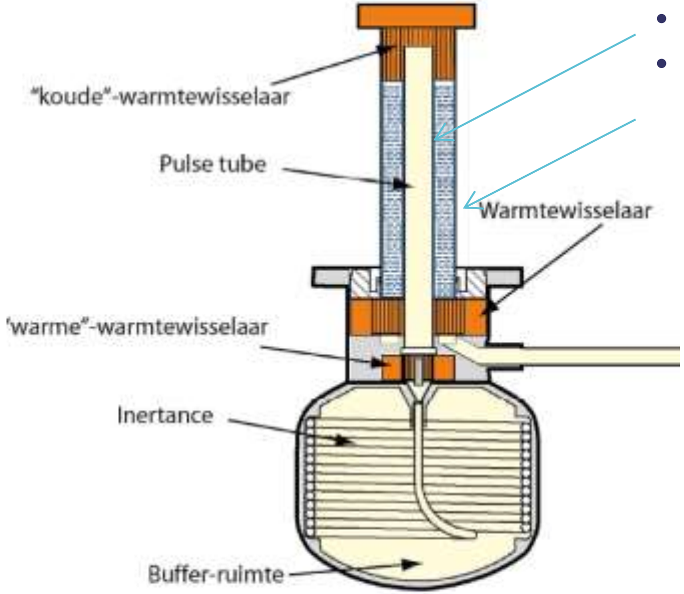


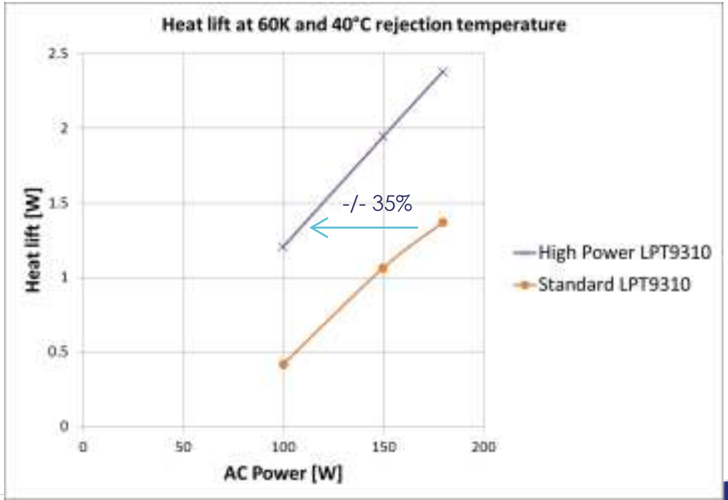


Optimization of regenerator material for 60K operation

Optimization of regenerator matrix for PT coolers @ 60K required for use in JPL-NASA ECOSTRESS mission

- **Use of different StSt wire mesh geometries in the regenerator**
- **Use of Ti6Al4V tubing to reduce conduction losses**

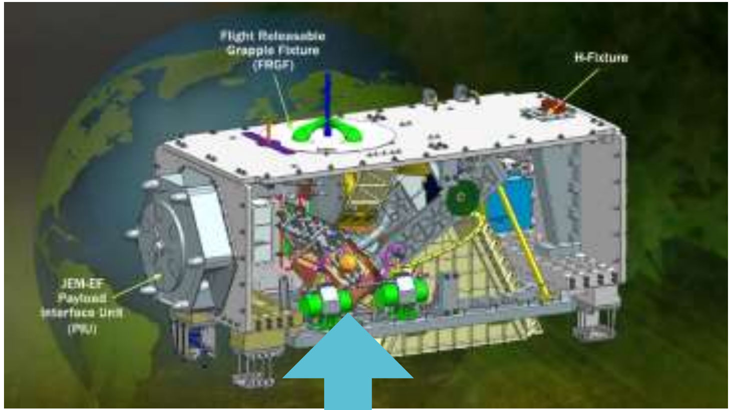


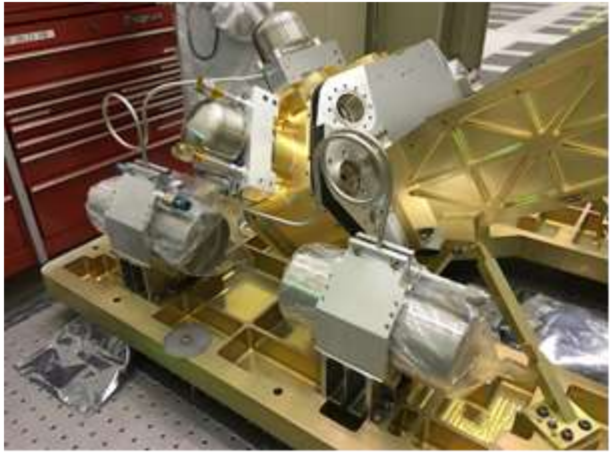


Use of improved 60 K PT cooler

System concept of ECOSTRESS

- **Design based on standard 4W @ 77K PT cooler**
  - 2 coolers to keep sensors below 65 K
  - 1 cooler used at 120K for shield cooling
- **Improved performance @ 65 K required due to limited available power budget from ISS.**
- **Distance between compressors and PT > 80 cm**





System has been fully operational for one year.
ECOSTRESS mission extended with one year

https://ecostress.jpl.nasa.gov/

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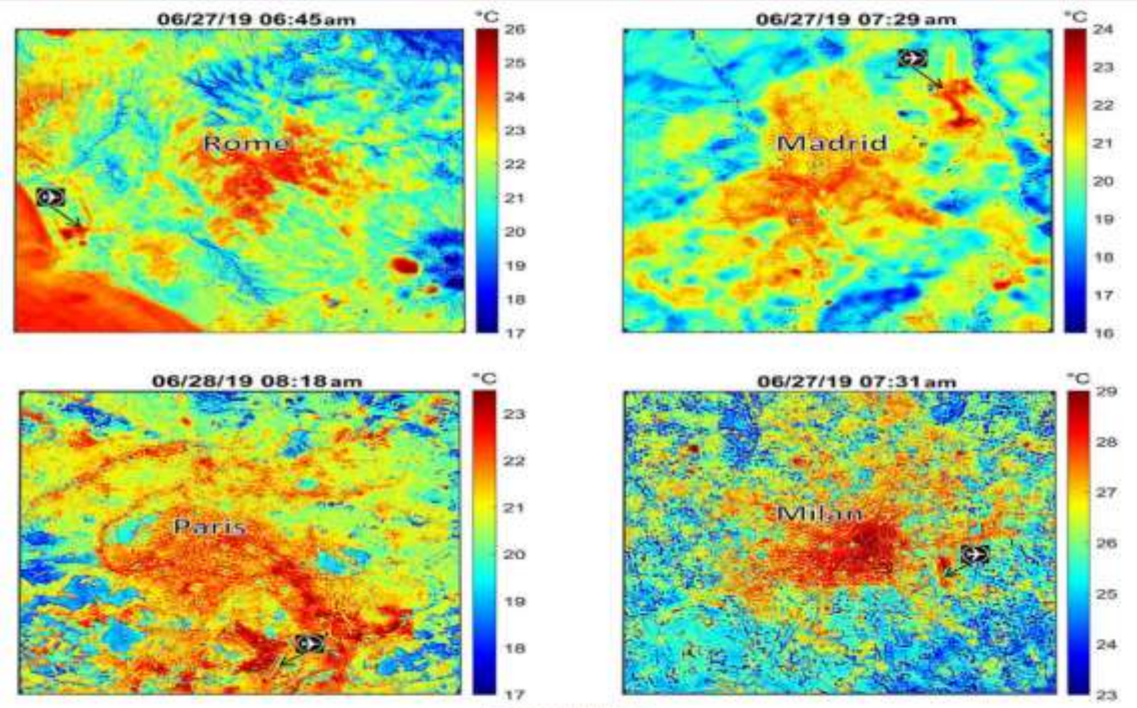
Pictures produced by ECOSTRESS



European Heat Wave

ECOSTRESS land surface temperature images of four European cities acquired in the early mornings of June 27 and 28, 2019,

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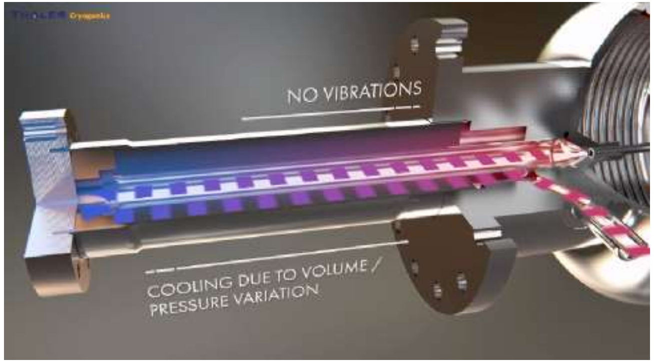
Impact of internal heat exchangers



		20 °C		77K	
	Pwr	77K	87K	20°C	30°C
9340	≈150W	7.695	9.186	7.695	7.367
	≈ 75W	4.561	5.722	4.140	3.887
9310	≈150W	3.515	4.694	3.515	3.085
	≈ 75W	1.606	2.390	1.606	1.276

dQe/dTe		dQe/dTamb	
0.149	1.9%	-0.033	-0.43%
0.116	2.5%	-0.025	-0.61%
0.118	3.4%	-0.043	-1.22%
0.078	4.9%	-0.033	-2.05%

**Impact of heat transfer gas > wall of cold finger is critical.
Especially for higher cooling powers.**

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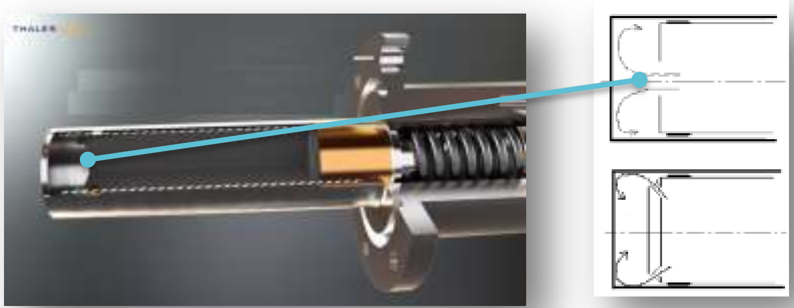
Impact of outflow of regenerator on cooling power

Impact of extra convective gas flow on the top of the regenerator.

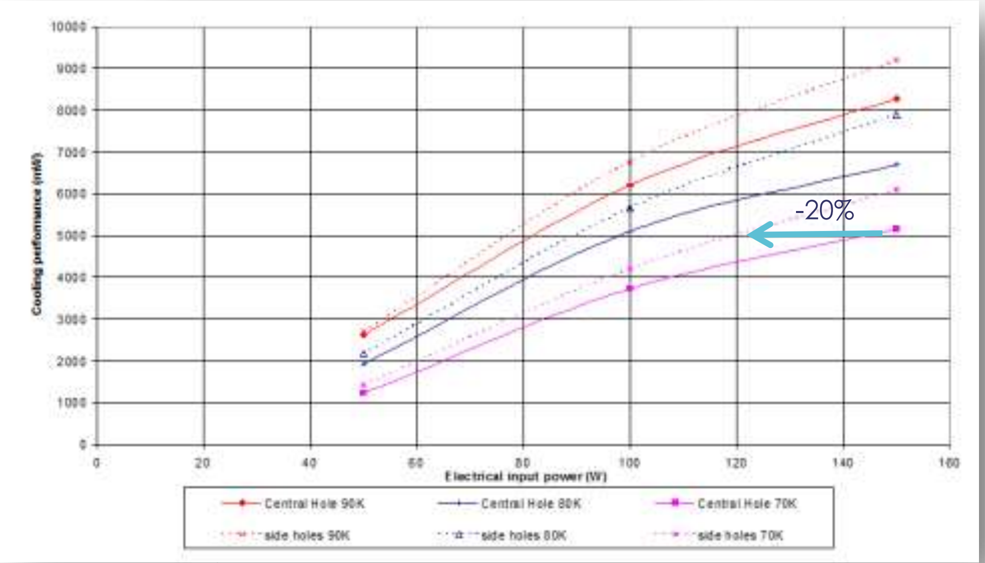


Idea:

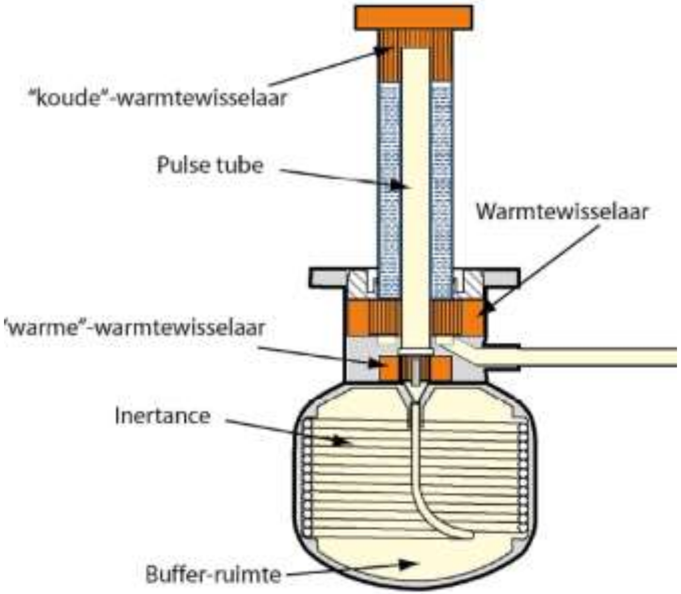
- Use side holes at displacer to improve heat transfer gas inside cold finger to wall.

Effect:

- Better heat transfer coefficient leads to a better overall efficiency
- Significant improvement (20%) of cooling power (@ higher loads)



Cross section of typical Pulse Tube cold finger



Implementation of heat exchangers in PT coolers is "easier" due to mass flow through heat exchangers. Copper slit heat exchangers (EDM machining) are being used.

Some case study for system integration aspects

1) PT system for cooling on electron microscope

2) Simulation of dynamical behavior in applications

3) Thermal links in 2 stage space cooler

Cooling of X-ray sensor on Electron Microscope

System requirement

- Continuous active cooling of High purity X-ray germanium sensor to 110K
- Full system directly connected to electron microscope structure (@ 500k magn.)
- No visual distortion of image accepted
- Availability 5 years of operation.

Technical choices made:

- **Reliability** : Pulse tube technology + Flexure Bearing compressors
- **No vibrations:** Pulse tube cold finger + AVR @ Compressor + Flex support comp.
- **Efficiency:**
  - Direct mount of HPGe sensor at tip of cold finger
  - Hermetically sealed high vacuum dewar system
  - Forced air cooling supported by heat pipes and Peltier Cooler for Cold finger

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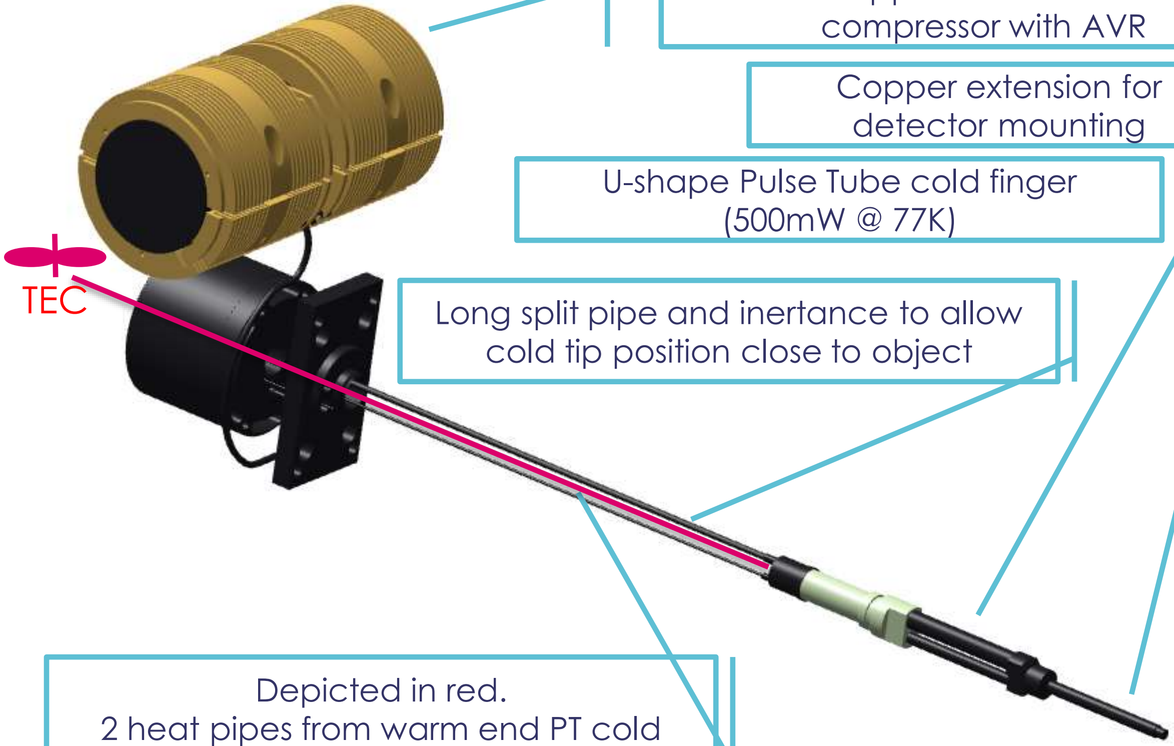
System set-up PT cooler for electron microscope



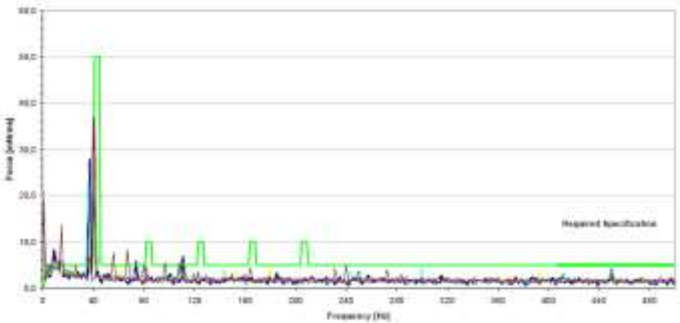
Dual opposed Piston flexure compressor with AVR

Copper extension for detector mounting

U-shape Pulse Tube cold finger (500mW @ 77K)

Long split pipe and inertance to allow cold tip position close to object

Depicted in red.
2 heat pipes from warm end PT cold finger to TEC cooler below compressor

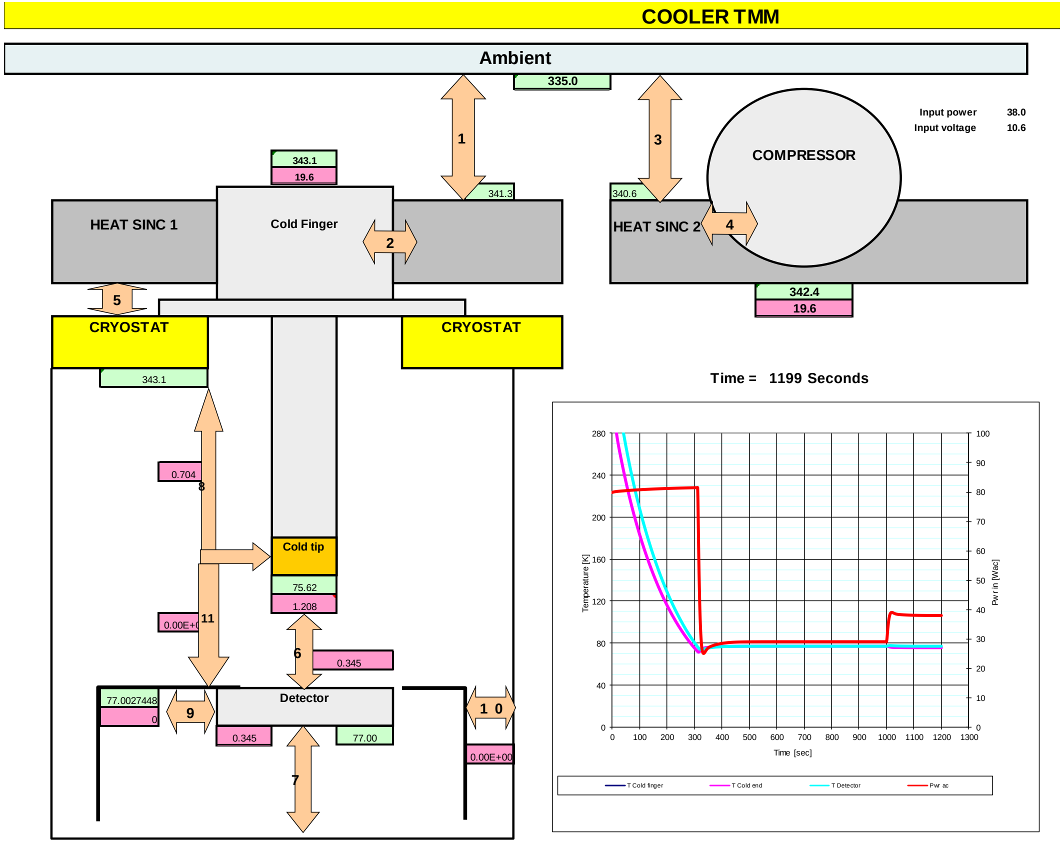


Thermal management

Thermal simulations

Thermal conductions

Thermal simulation of dynamical behavior cooler in application

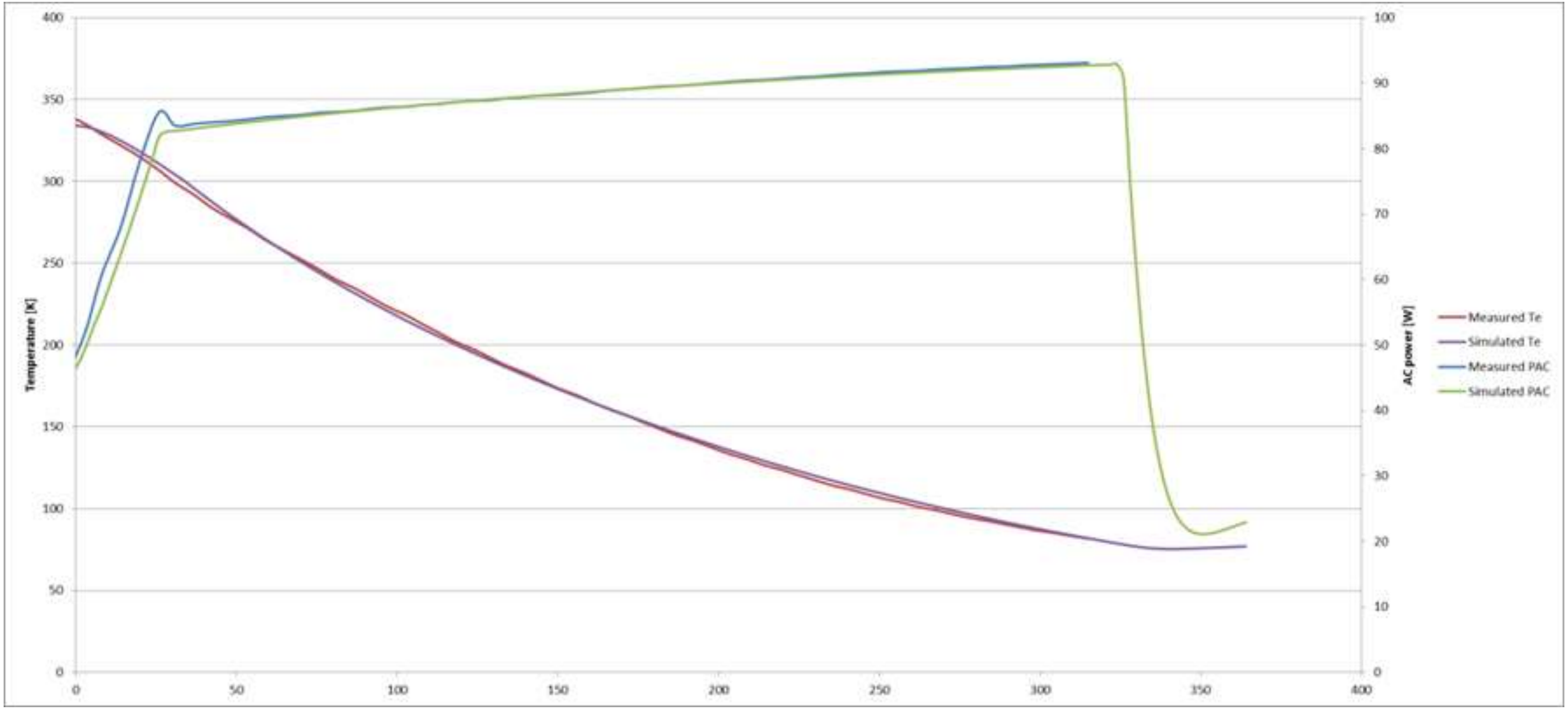


Cooler fit data	Used Fit 9599
Fit amb. Temp range	
a1	0.80010
a2	0.00194
a3	-0.76462
a4	0.00084
a5	-34.67816
a6	-0.03458
a7	8.59736
a8	9.98605
a9	-7.08612
Mass Cold Finger (kg)	0.0060
Meas dome losses 23C	0
Meas dome losses 71C	0
Dome losses at Tamb	0
Pmax	85.000
Vmax_warm	15.800
Vmax_koud	15.800
Slow start tijd	0
Vmax	15.5
Vmin	4.000
R_dyn 293 K	3.00
R_dyn at 77K	2.95
slope	0.00
Dyn impedance (Te)	2.95
Tamb (°C)	68.1
Te (K)	75.6
Power (W)	38.0
Uinput (V)	10.6
Qe (W)	1.208
Qe (W)_corrected	1.208
Corr factor 1	0
Corr factor 2	1

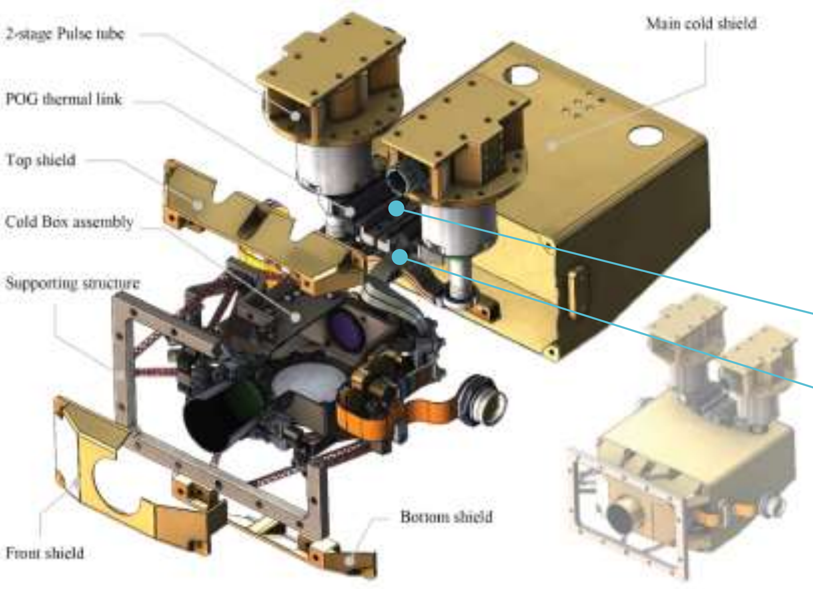
9 parameters describe cooler performance as function of Te, Tamb and Vac

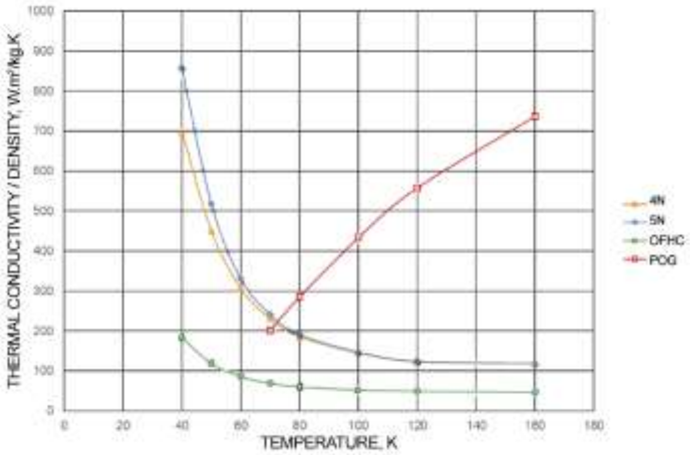
Used software THERMXL: www.esatan-tms.com

Comparison of simulated and actual performance



30 .. 50 K sensor system for ESA





AL 5N for 2nd stage thermal link

POG for 1st stage thermal link

Compressor not shown

ICC-19: Manufacturing and Testing of a Flight-Like Cryostat for 30-50K Two-Stage Pulse Tube Cooler, J Tanchon et.al

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Conclusions

- Full understanding of heat and mass transfer is required for the design and optimization of cryocoolers 40 .. 150K.

- Critical for correct system performance is:
  - Regenerator design
  - Combination of parts with low and high thermal conduction
  - Heat transfer gas > wall > interface plate (at cold finger)
  - Thermal interfacing to the overall system (cold and hot side)

- Several case studies have been discusses, each with its own criticalities.

QUESTIONS