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Compact Cryocooler Developments at Thales Cryogenics

Thales Cryogenics, Eindhoven
Daniel Willems & Tonny Benschop

2022-06-14

Content of this presentation

Types of cryogenic coolers

How do they work

- Compressors
- Cold fingers (Stirling / Pulse-tube)

Optimization of performance

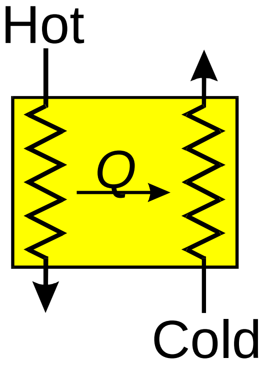
Application examples (focus on space projects)

Future requirements / studies

Types of coolers (linked to Heat exchangers)

RECUPERATIVE

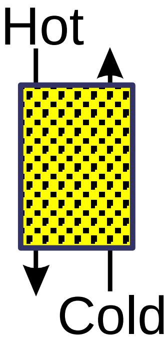
Separate channels with solid walls separating the continuous flow of hot and cold fluids. Fluids usually in counter flow.



Heat exchanger
=
Transfer of energy to Counter flow Medium
=
DC-flow

REGENERATIVE

A single flow channel filled with a matrix of finely divided material subject to alternating flows of hot and cold fluids.



Regenerator
=
Storage of energy in regenerator matrix
=
AC-flow

Pictures courtesy of Ray Radebaugh

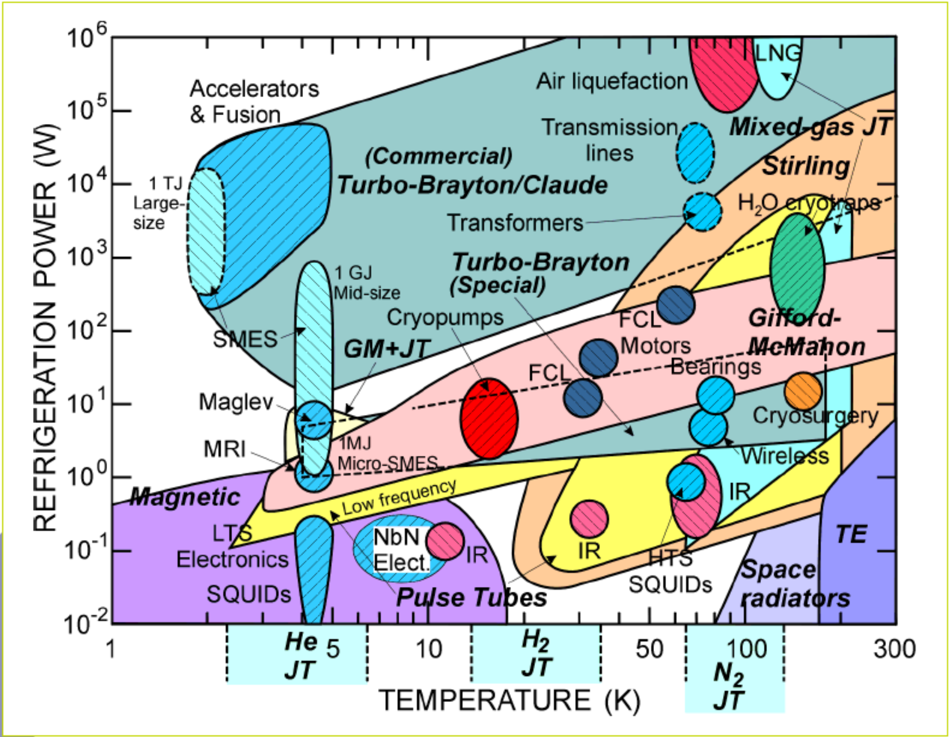
Types of cryogenic coolers woldwide

Types of coolers @Thales

- **Stirling cooler**
- GM / Pulse tube cooler
- **JT cryocooler**

Operating frequency

- JT
  - **Open system** (high pressure)
  - Closed cycle (gas mixtures)
- Stirling and Pulse Tube
  - **High frequency**
  - Low frequency



Pictures courtesy of Ray Radebaugh

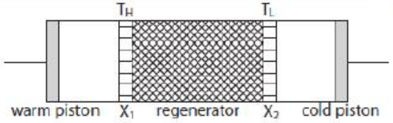
Focus on used technologies

Compact systems

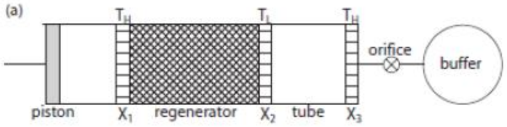
- Input power < 500 W
- Temperature range 30 … 150K

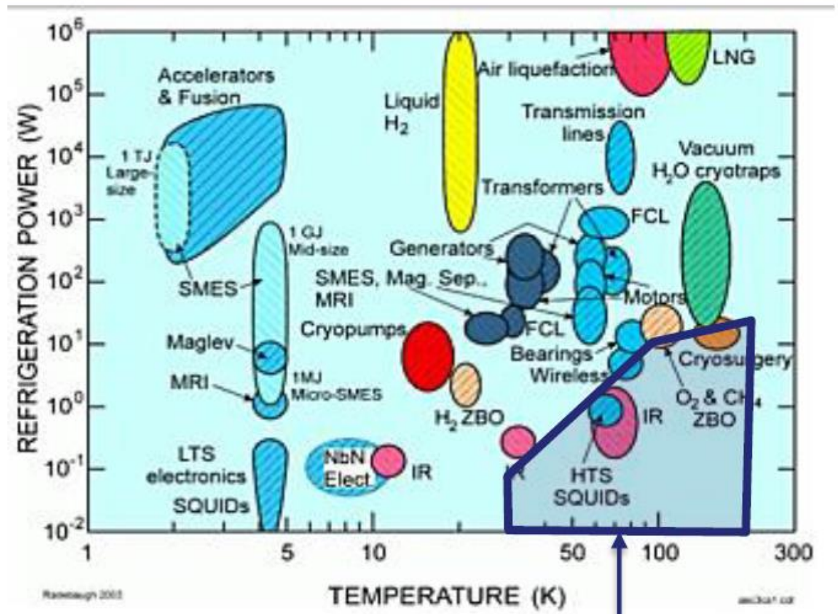
Used cooling principles

- Stirling Cycle



- Pulse Tube cycle

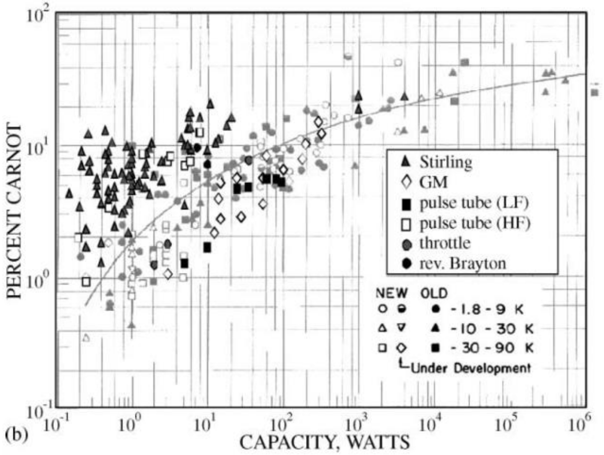




Pictures courtesy of Ray Radebaugh

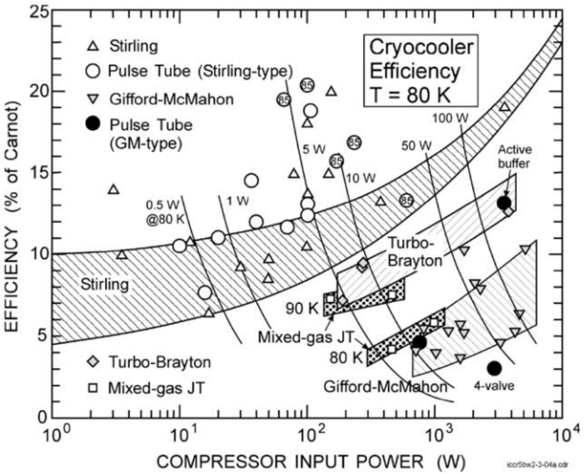
PRODUCT DESIGN REQUIREMENTS: Compact, Closed REGENERATIVE Cycle, No Maintenance, High Availability, Efficiency

Achieved efficiencies (study 2002 - 2009)



Low-power cryocooler survey, Cryogenics 42 (2002) 705–718
*H.J.M. ter Brake *, G.F.M. Wiegerinck*

$$\eta_{carnot} = \frac{T_{Low}}{T_{High} - T_{low}}$$



R. Radebaugh J. Phys.: Condens. Matter21(2009)

Conclusions:

- Producing extreme cold is consuming a lot of energy !!
- Stirling and Pulse Tube have the highest efficiency at low cooling capacities !
- How is this efficiency achieved? What is the efficiency achieved today?

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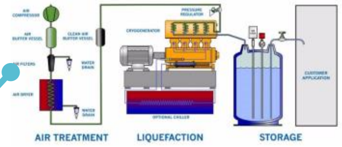
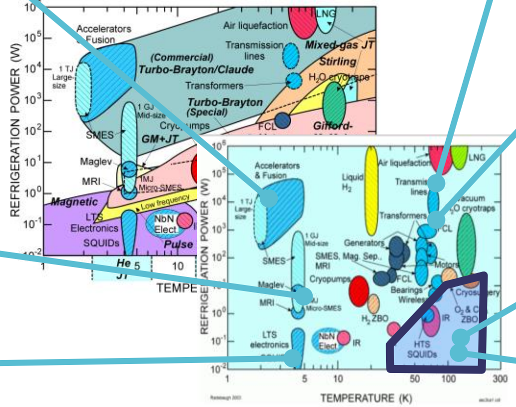
Pictures applications

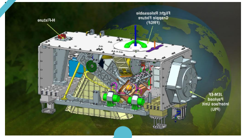
One of the eight 4.2K units @ CERN. Image CERN

Small liquefaction plant. Image: Cryotec



Principle of Air Liquefaction Image: Stirling Cryogenics (NL)





ECOSTRESS IR - Hyper Spectral analyzer: Image : NASA

3T MRI systems. Image Philips

4K Squid Brain imaging. Image: Elekta

Sophie Utlima, Hand held cooled IR/Visual camera. Image : Thales

FOCUS OF THIS PRESENTATION WILL BE ON SMALL REGENERATIVE CRYOGENIC COOLERS

Types of compressors

Types of compressors

Picture courtesy of Ray Radebaugh

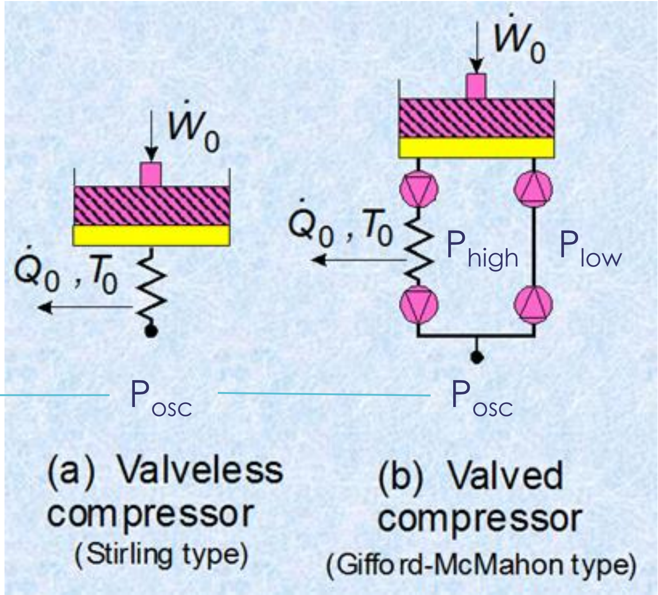
Compressors are used to created a pressure wave which will enable enthalpy flow from cold > warm side

Valve less compressor:

- Higher frequencies (> 20 Hz)
- Dedicated designs
- Limited input power (< 500 W)

Valved compressor:

- Lower frequencies (< 6 Hz)
- Significant pressure losses at valves
- Use of existing (lubricated compressors of air conditioning applications)
- High input power 1 .. 6 kW



Pictures courtesy of Ray Radebaugh

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Used medium in compact regenerative crycoolers

QUESTION 1:

Which type of working gas do you expect to be used inside Stirling cryocoolers ?

A: Nitrogen

B: Neon

C: Helium

Type of gas (ANSWER SLIDE)

Which type of gas is used inside the coolers ?

- Helium

Advantages

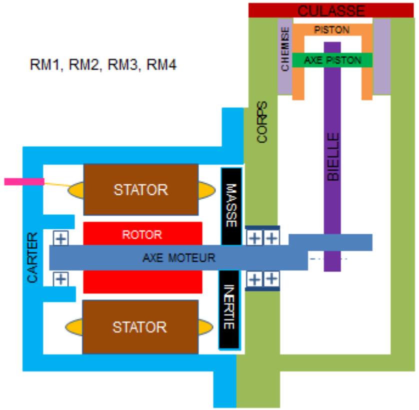
- Single atom gas : Highest Cp/Cv value > Highest temp increase at adiabatic compression $[T.P^{\frac{Cp}{Cv}-1} = C]$
- No condensation / freezing down to 4.2K
- Low viscosity > low flow losses
- High thermal conduction
- Safe to use

Disadvantages:

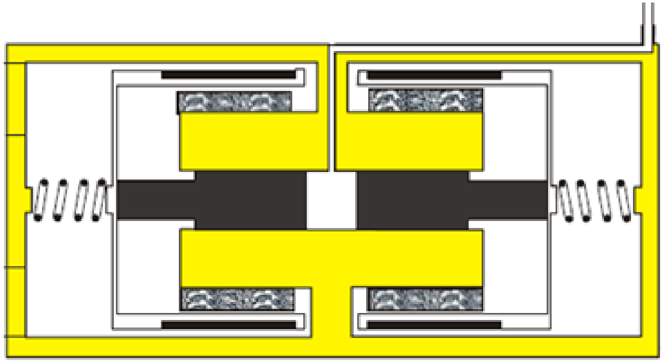
- Very small molecules > difficult to contain (no plastics, metal seals, welding)
- Becoming more and more expensive

Compressor types for High Frequency Coolers 20 .. 150 Hz

Crank shaft compressors



Linear compressor:

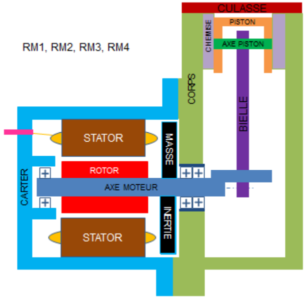


Question 2: Which concept is most efficient A: Crank shaft B: Linear

Question 3: Which concept has highest reliability A: Crank shaft B: Linear

Compressor types for (ANSWER SLIDE)

- Crank shaft compressors



- Linear compressor:

- Fixed volume variation
- Varying frequency
- Drive by (DC brushless) motor

+ High motor efficient / power density
+ Compact design (high power density)
- Lubrication required for ball bearings
- High side forces on pistons

- Variable volume variation
- Fixed operation frequency
- Drive in resonance by linear motors

+ Limited side forces on pistons
+ Balancing possible due to dual piston
- Lower motor efficiency
- Lower power density

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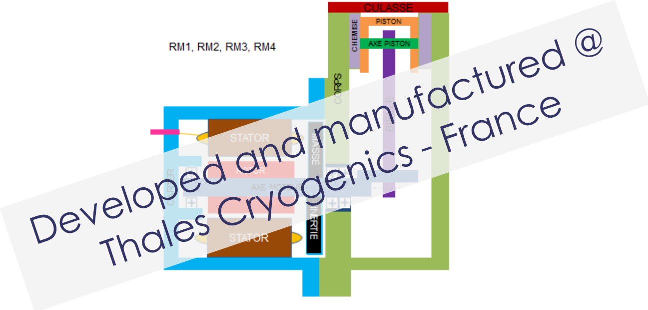
Compressor types for (ANSWER SLIDE)

Crank shaft compressors



- Fixed volume variation
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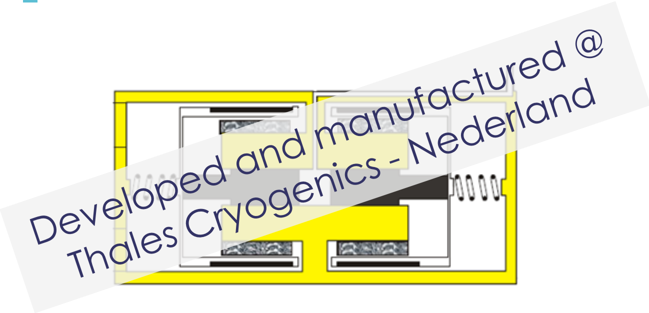
Linear compressor:



- Variable volume variation
- Fixed operation frequency
- Drive in resonance by linear motors

+ Limited side forces on pistons
+ Balancing possible due to dual piston
- Lower motor efficiency
- Lower power density

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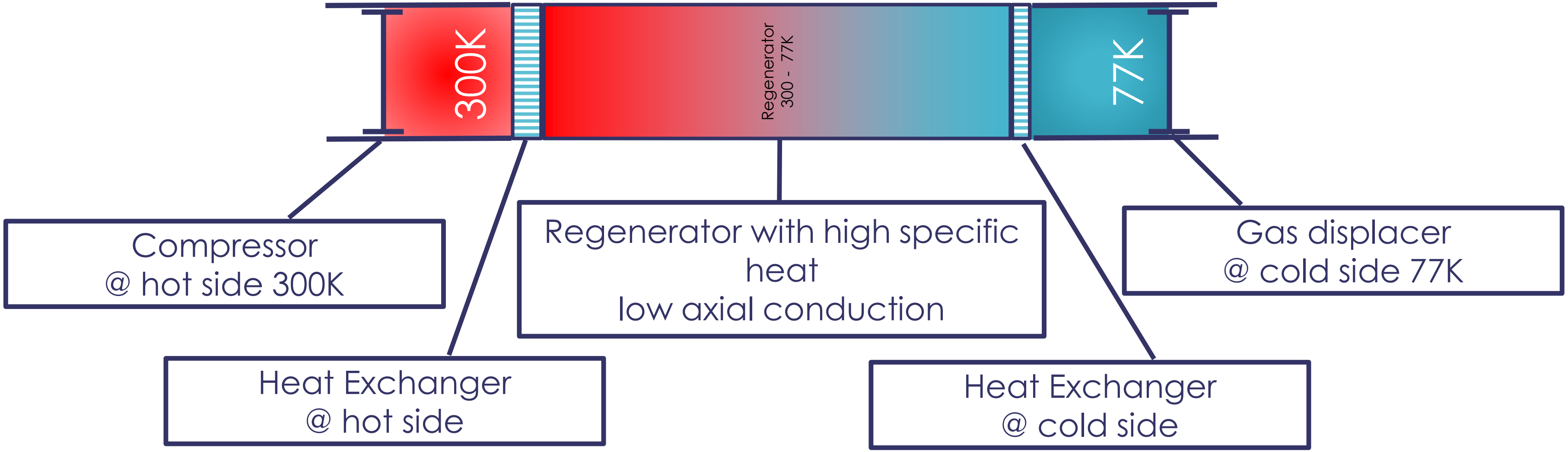
Cold fingers

THE STIRLING CYCLE
THE PULSE TUBE CYCLE

Cold production in regenerative cycles

- Lets focus on gas volume movement and temperature during one cycle in the system depicted below.



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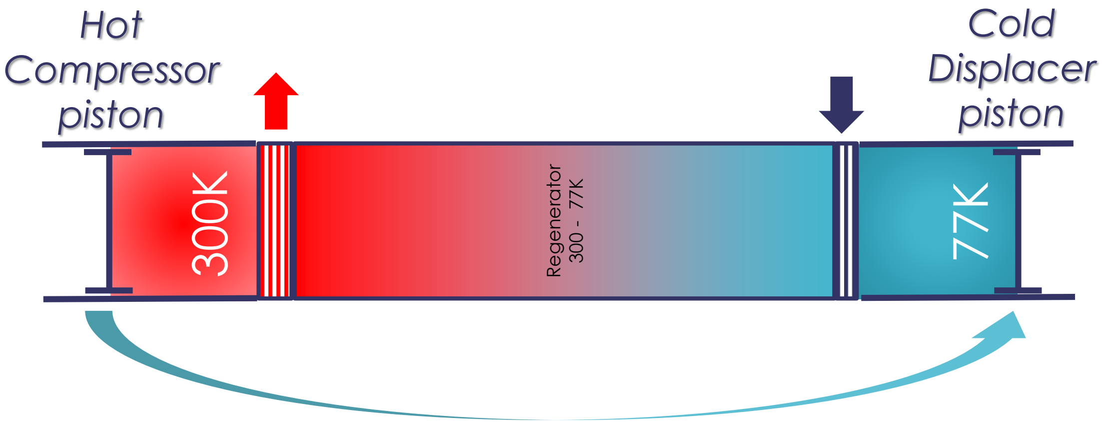
Cold production in regenerative cycles



Thus, correct synchronization between movement of pistons on hot and cold side is required to produce cold.

- Volume between pistons defines the pressure.
- Position of the pistons relative to regenerator defines amount of gas in compression and expansion space and the flow through the regenerator.

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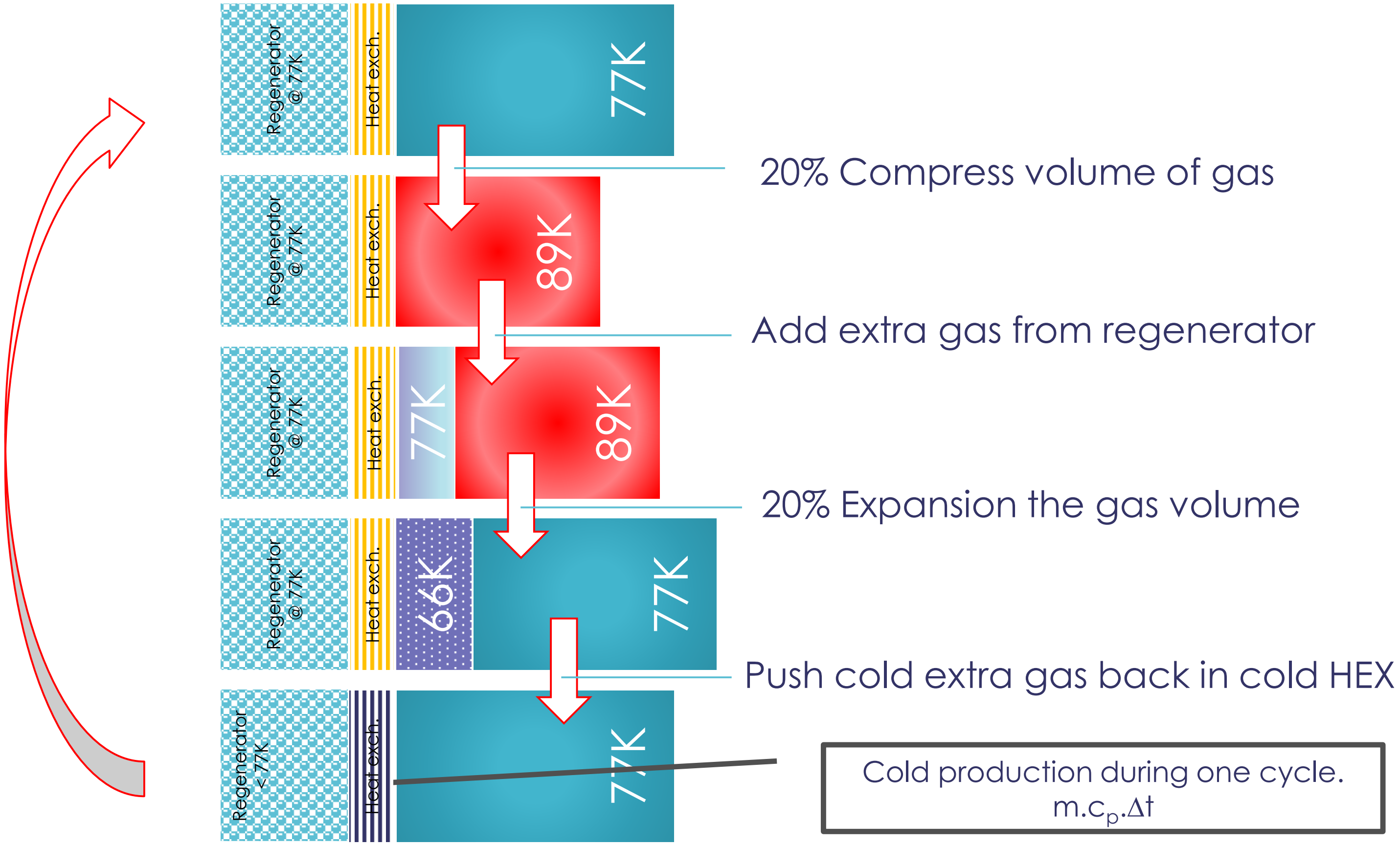
Cold production in regenerative cycles



Cold production during one cycle.
$m.c_p.\Delta t$

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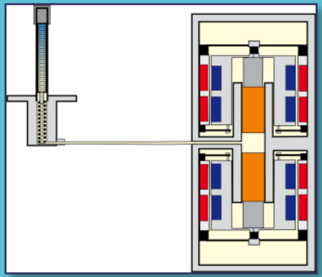
Cryocoolers

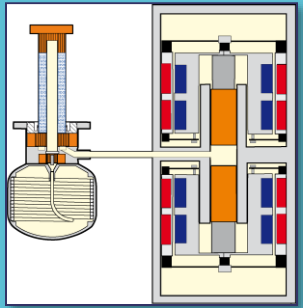
Cooler families defined by mechanical solutions for ‘displacement’ at cold end



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

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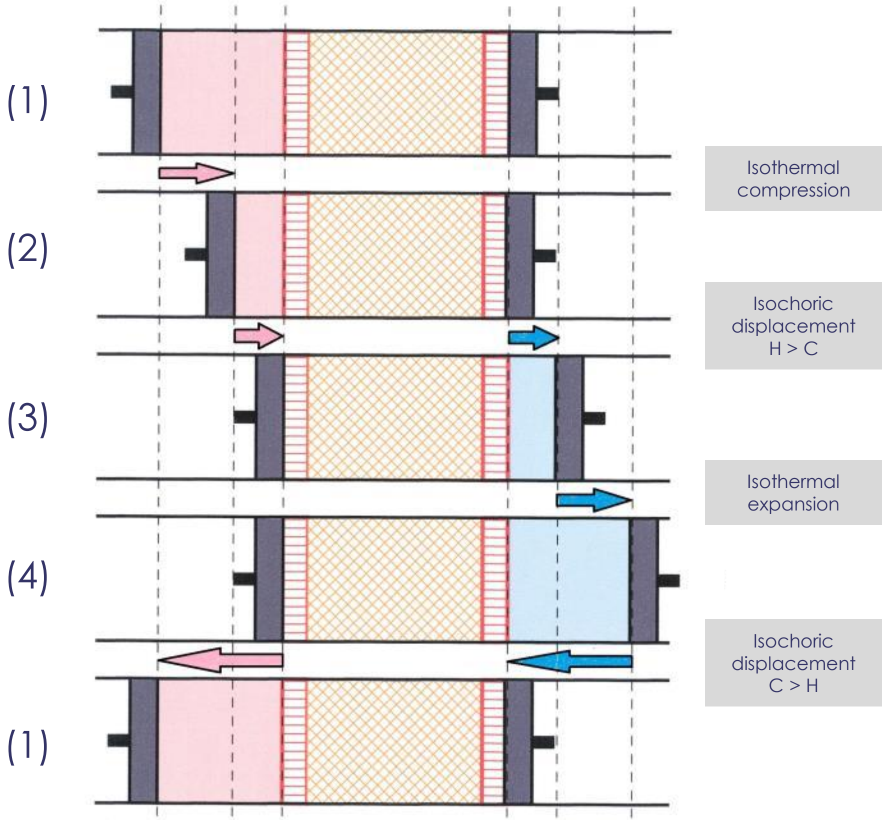
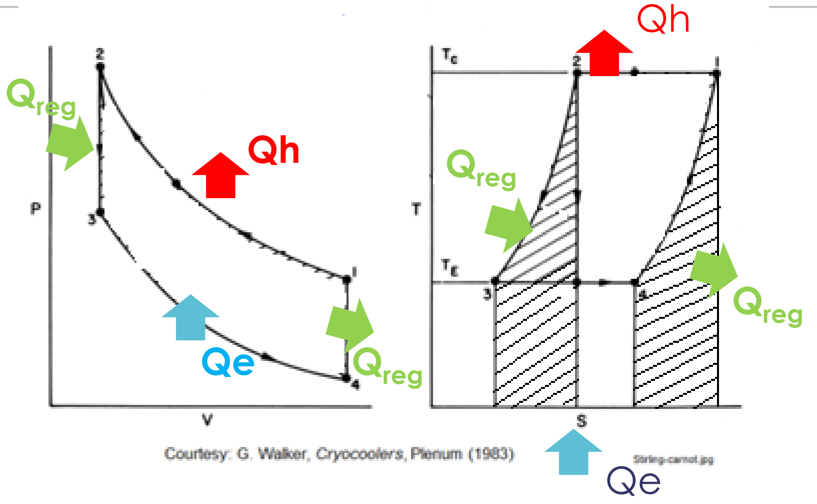
Stirling coolers

Stirling representation in PV and TS diagram





Courtesy: G. Walker, *Cryocoolers*, Plenum (1983)

Ideal Stirling:

2 isothermal, 2 isochoric phases

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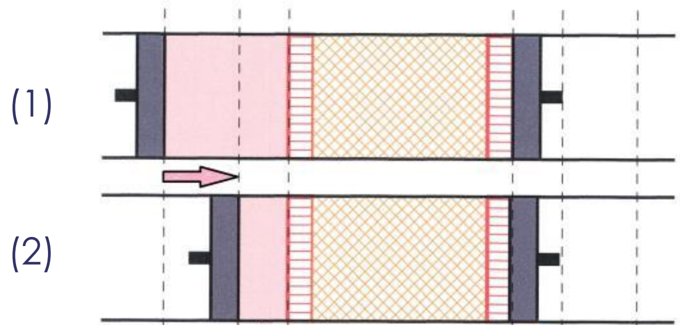
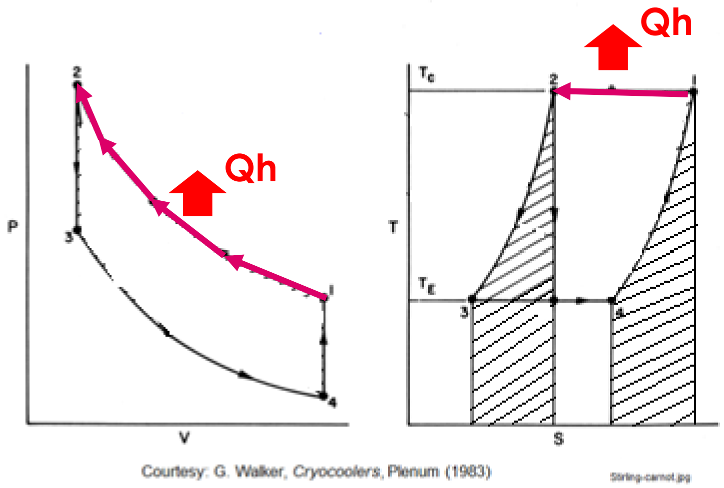
Stirling representation in PV and TS diagram (1 > 2)



Isothermal compression



Ideal Stirling:

2 isothermal, 2 isochoric phases

Ball park figures for ideal 1W cooler @ 77K :

- **Qh = 4 W**

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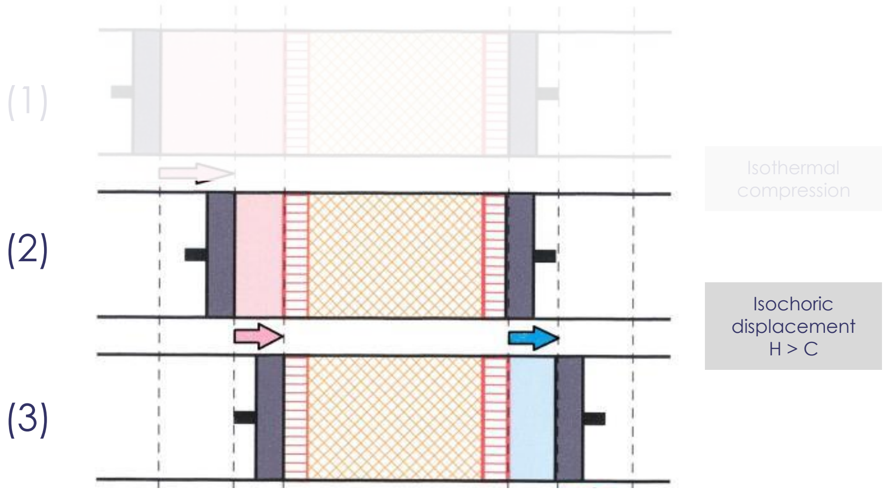
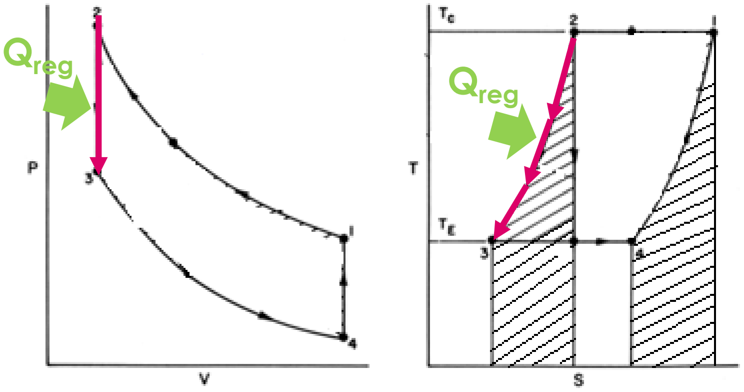
Stirling representation in PV and TS diagram (2 > 3)





Courtesy: G. Walker, *Cryocoolers*, Plenum (1983)

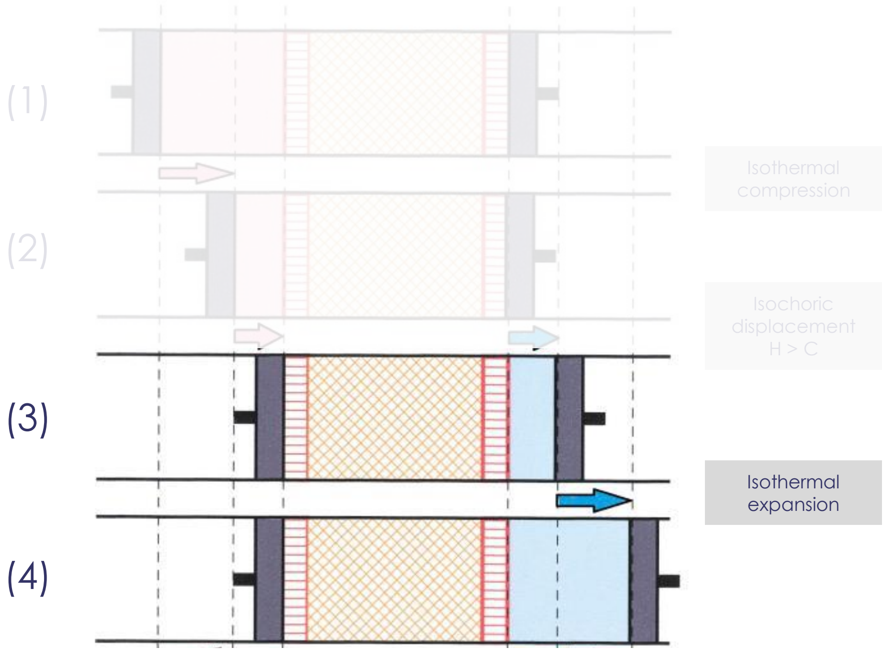
Ideal Stirling:

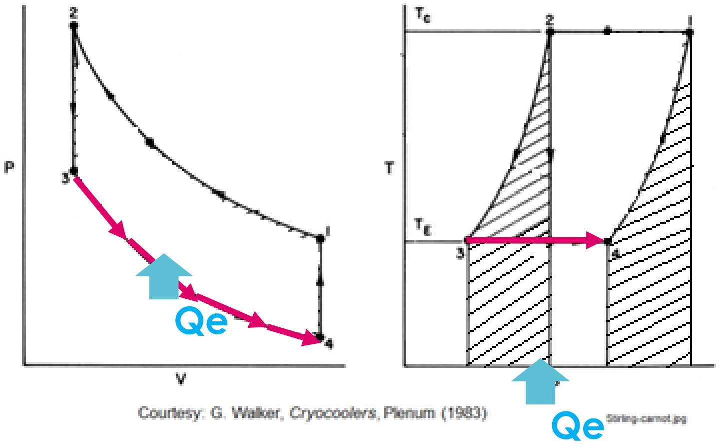
2 isothermal, 2 isochoric phases

Ball park figures for ideal 1W cooler @ 77K :

- **Qh = 4 W**
- **Qreg = 200 W**

Stirling representation in PV and TS diagram (3 > 4)





Courtesy: G. Walker, *Cryocoolers*, Plenum (1983)

Ideal Stirling:

2 isothermal, 2 isochoric phases

Ball park figures for ideal 1W cooler @ 77K :

- **Qh = 4 W**
- **Qreg = 200 W**
- **Qe = 1W**

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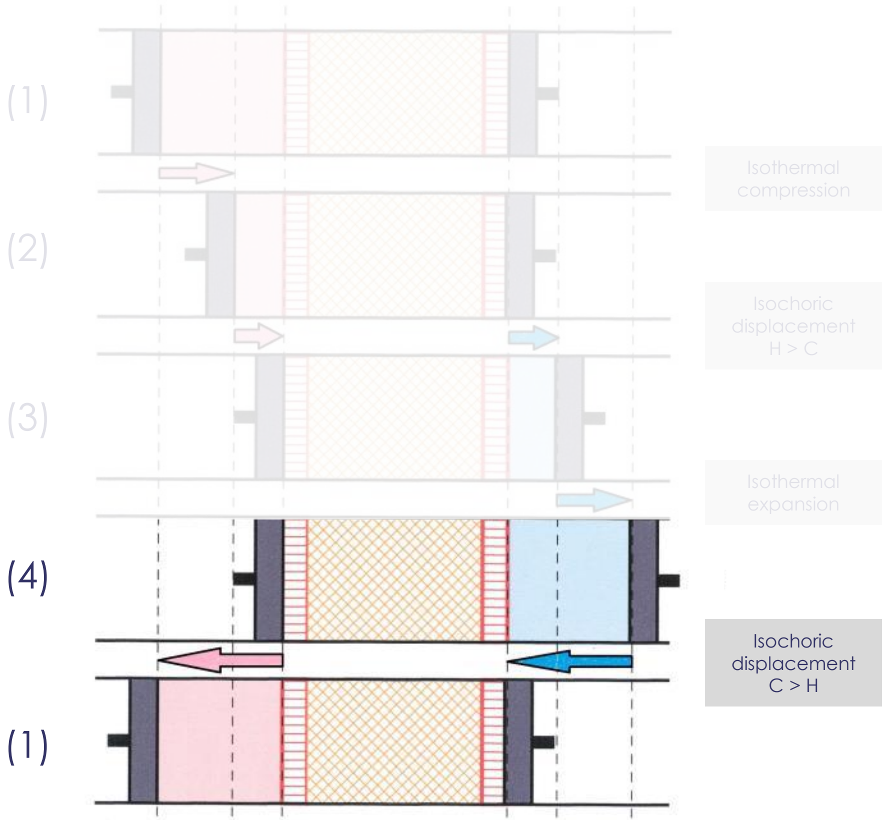
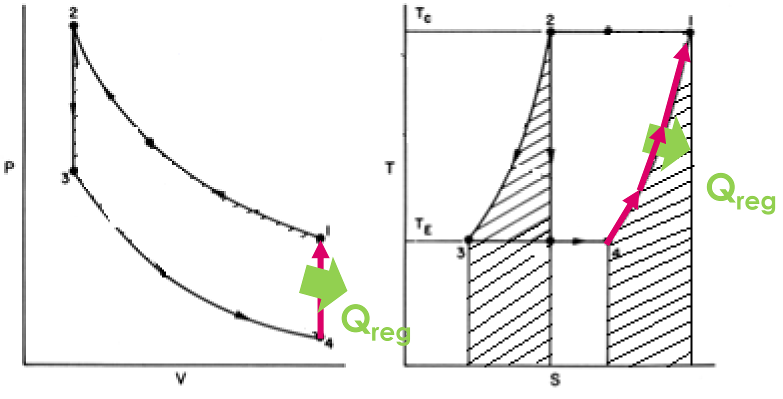
Stirling representation in PV and TS diagram (4 > 1)





Courtesy: G. Walker, *Cryocoolers*, Plenum (1983)

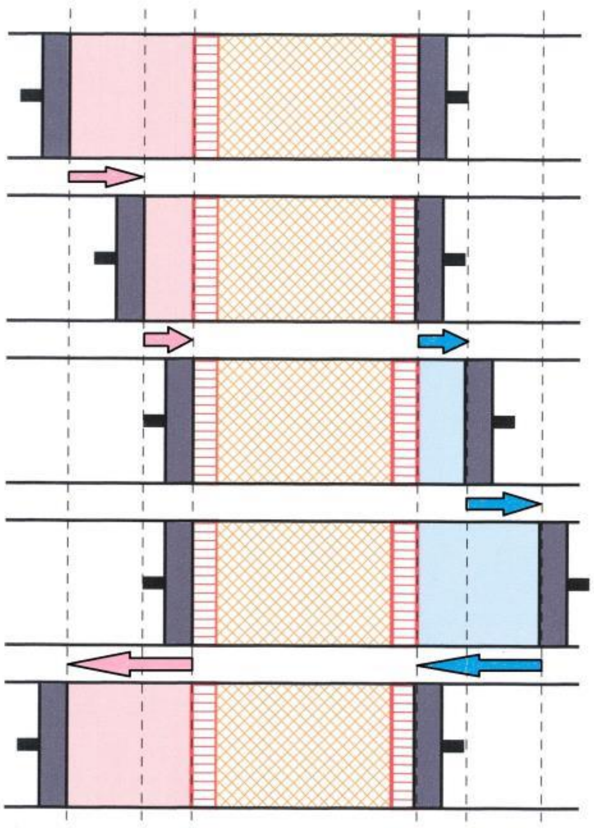
Ideal Stirling:

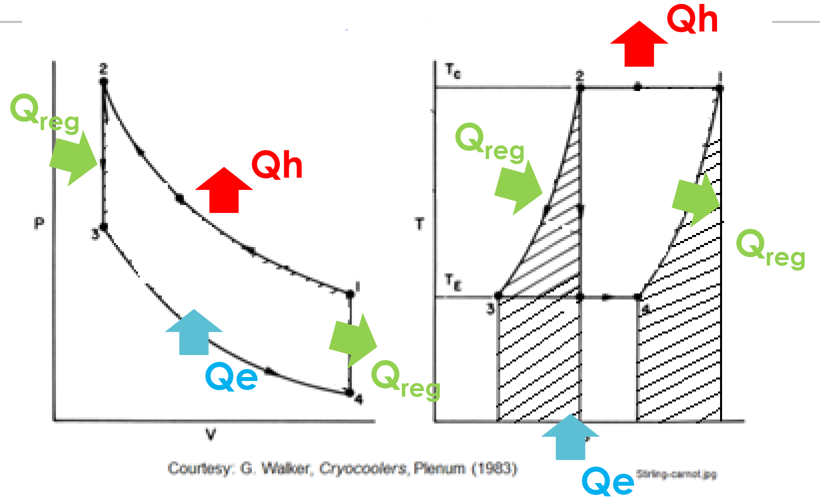
2 isothermal, 2 isochoric phases

Ball park figures for ideal 1W cooler @ 77K :

- **Qh = 4 W**
- **Qreg = 200 W**
- **Qe = 1W**
- **Qreg = 200 W**

Stirling representation in PV and TS diagram (Full cycle)





Ideal Stirling:

2 isothermal, 2 isochoric phases

Ball park figures for ideal 1W cooler @ 77K:

- **Qh = 4 W**
- **Qreg = 200 W**
- **Qe = 1W**
- **Qreg = 200 W**

3W work required to generate the cold

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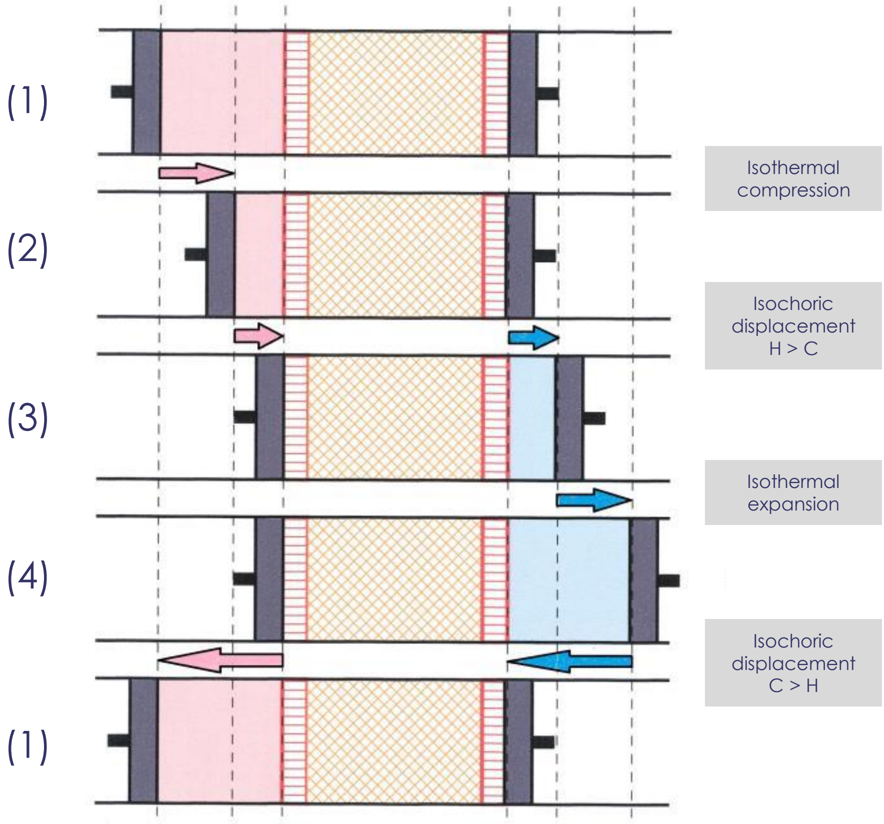
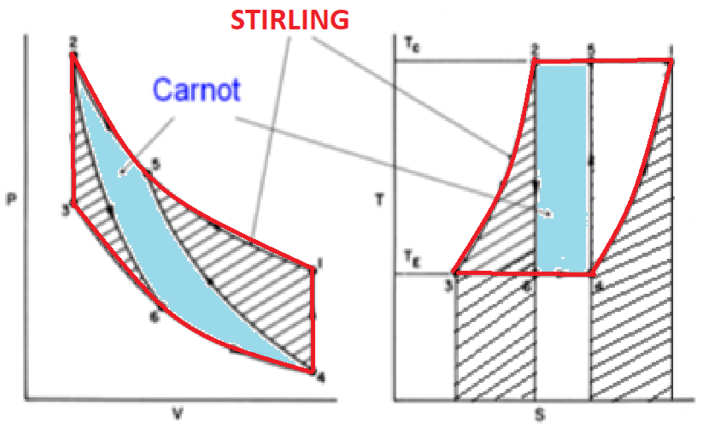
Stirling Cycle is an ideal thermodynamic cycle





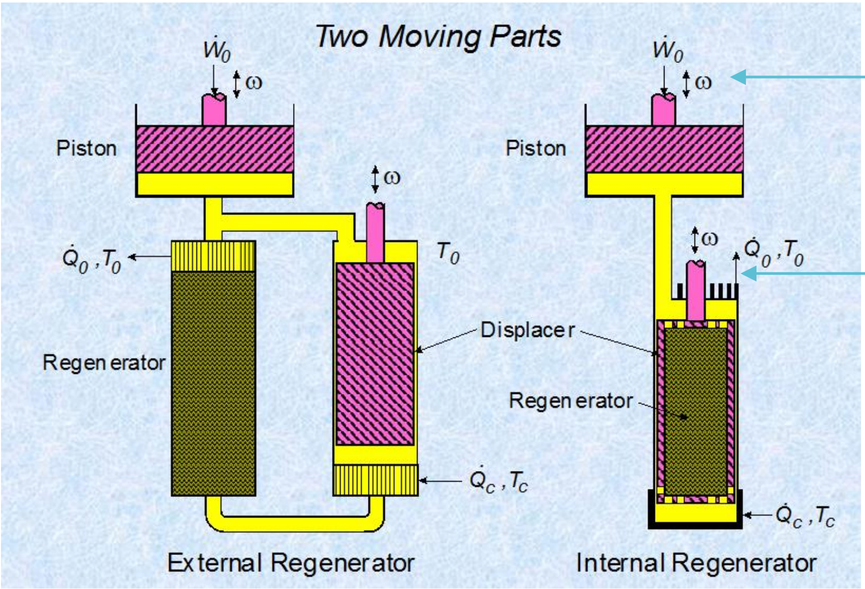
Courtesy: G. Walker, Cryocoolers, Plenum (1983)

Ideal Stirling cycle:
2 isothermal, 2 isochoric phases

Ideal processes >> No entropy generation
Efficiency ideal Stirling = Ideal Carnot

Ideal Carnot cycle:
2 isothermal, 2 isentropic phases

Stirling coolers – how to drive the cold side displacement?



Stroke and phase difference between compressor and displacer of importance for cold production.

Instead of a cold-side piston, a so-called displacer is used

"Larger" systems
> 100 W @ 77K cooling
Displacer and Regenerator different components

"Smaller " systems
< 100 W @ 77K cooling
Displacer and Regenerator combined components

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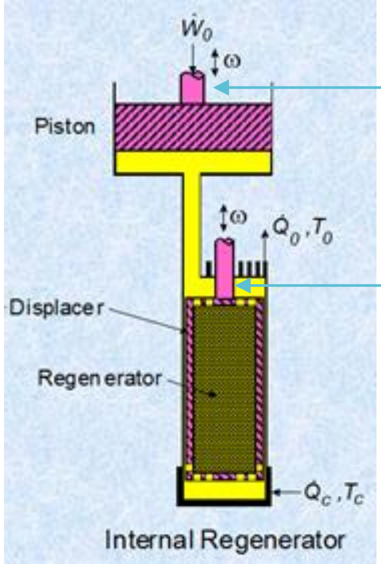
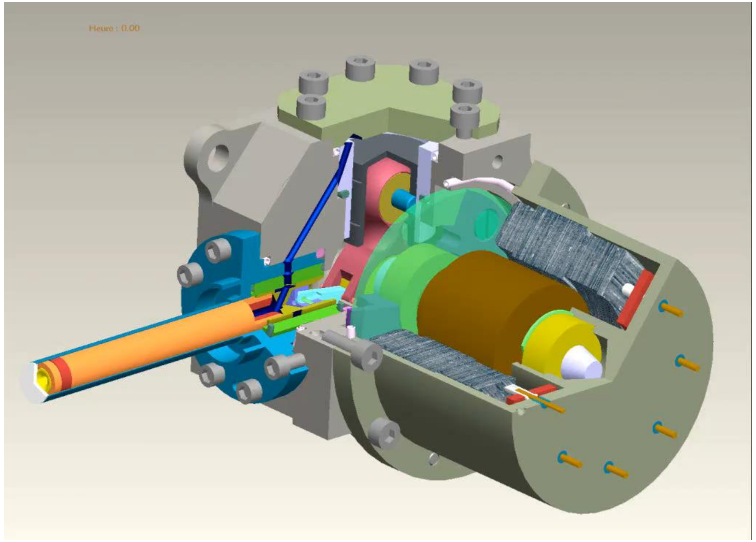
Creating the correct phase difference in Rotary coolers



Piston and displacer connected to same drive shaft with fixed phase difference.



Mechanical driven displacer/regenerator ensures correct phase difference between pressure and volume variations

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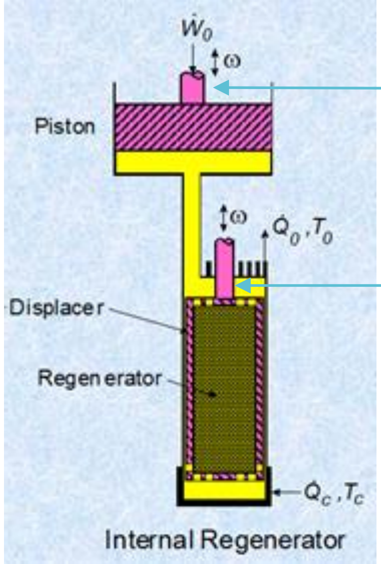
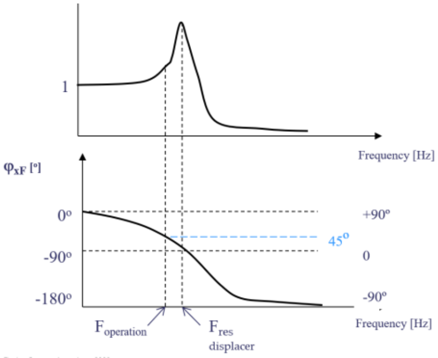
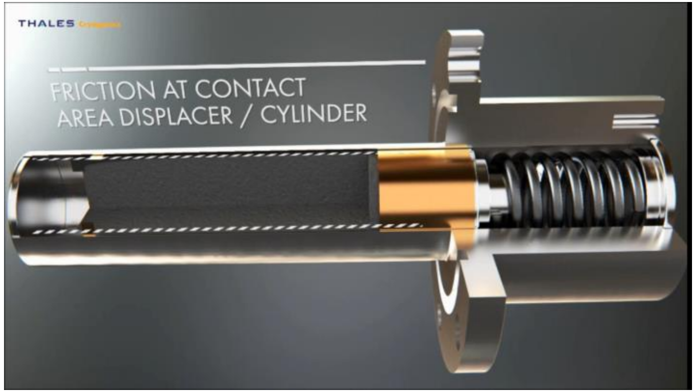
Creating the correct phase difference with free displacer coolers



Piston and displacer NOT connected to same drive shaft phase difference and amplitude defined by dynamics. (DP displ | Resonance Fre displ) (2e order damped mass-spring system)





Free displacer/regenerator are driven by the pressure drop over the displacer.
The correct phase difference is obtained by tuning of the resonance frequencies

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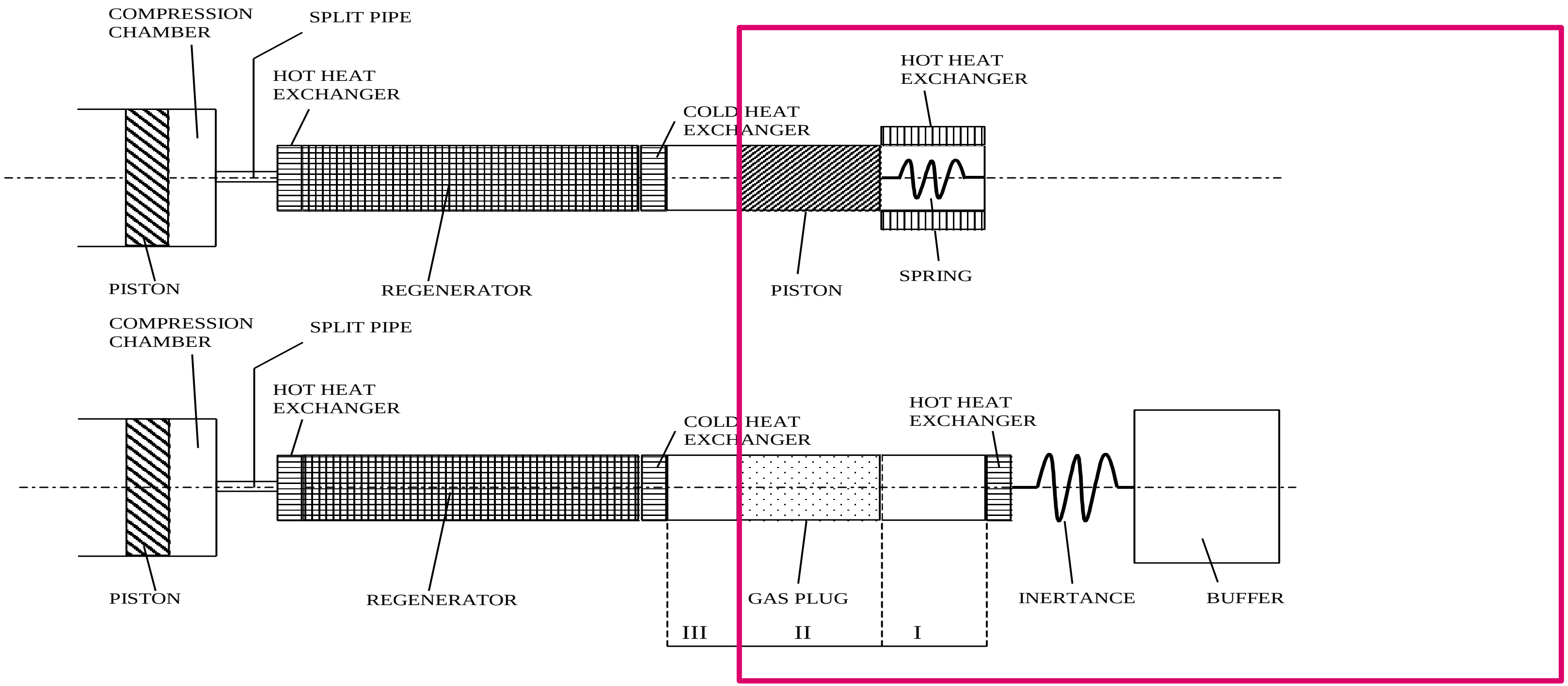
Pulse tube cooler

Comparison Stirling >> Pulse Tube cooler



Displacer replaced by gas plug and phase shifter (inertance/buffer)

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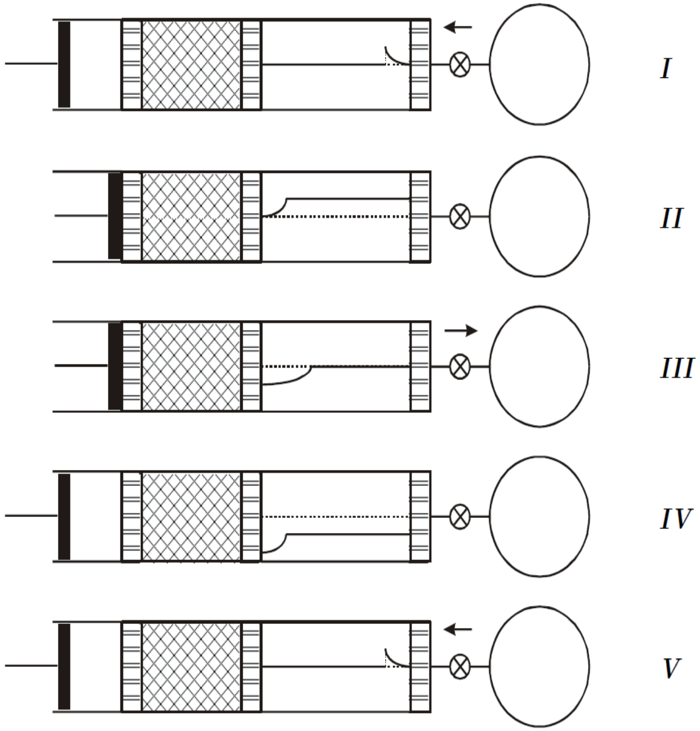
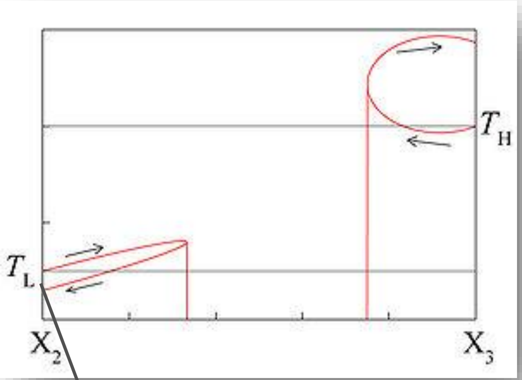
Operating cycle in a pulse-tube cooler

Mass flow in pulse-tube coolers



Trajectory of particle at cold and *warm side* within the pulse tube



Cold production during one cycle.
$m.c_p.\Delta t$

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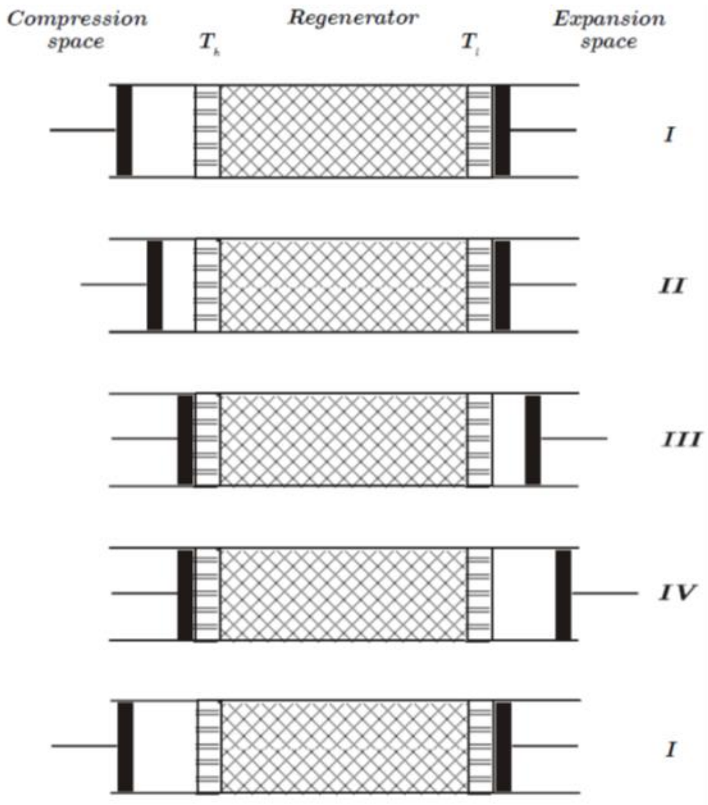
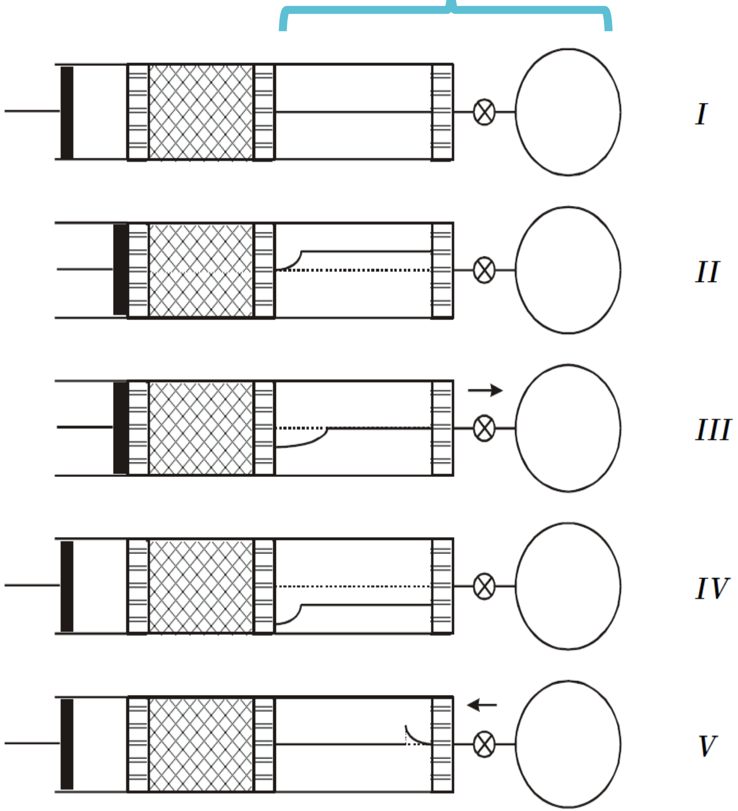
Synergies between Stirling and Pulse tube cycle



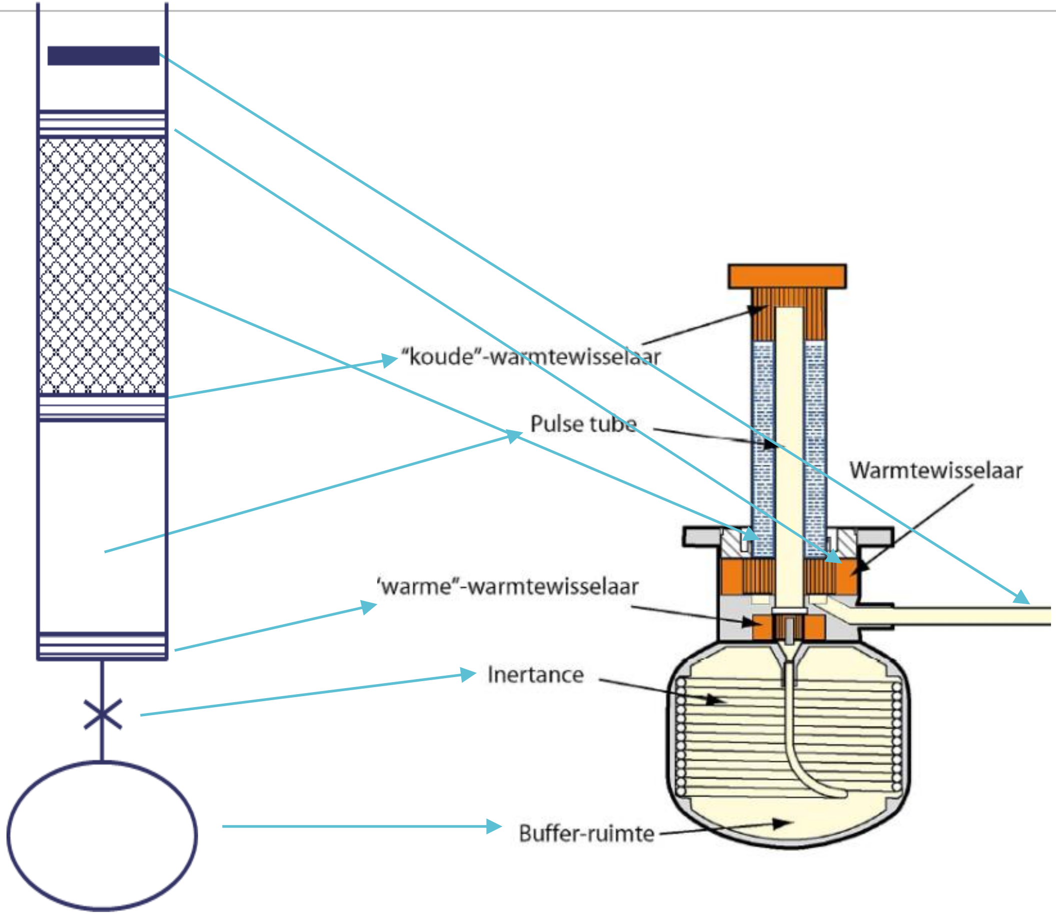
Schematic Stirling representation

PT, orifice and buffer replace displacer piston



Schematic Pulse-tube representation

Cross section of typical Pulse Tube cold finger



Today most PT-coolers are co-axial due to ease of integration. Although this definition is more restrictive in design optimizations

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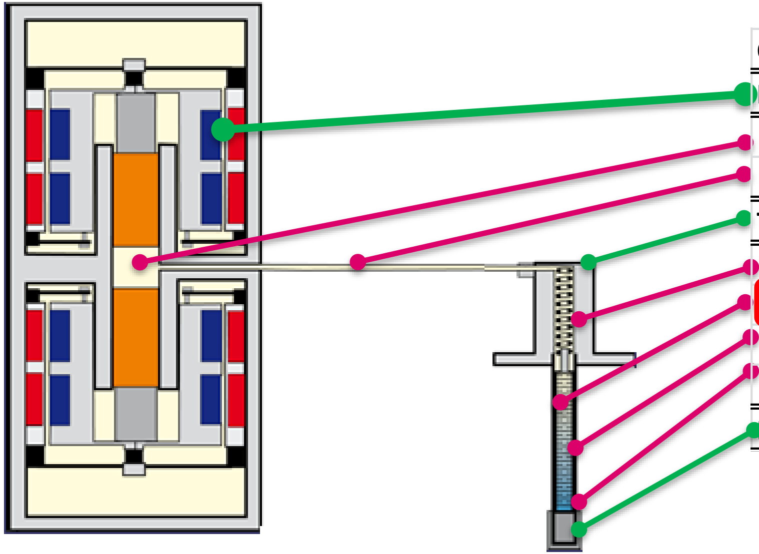
Op

Optimisation of coolers

WHICH PARAMETERS ARE CRITICAL FOR THE EFFICIENT TRANSFER OF ELECTRICAL POWER TO COOLING POWER

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
Regenerator 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

Regenerator losses are typically the highest losses in recuperative cooling cycles

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The regenerator losses are quantitively the highest losses in a recuperative coolers (70% of the losses)

Question:

- What are the required properties for the material used inside the regenerator

A. Specific heat per mass [J/(kg.K)]
B. Specific heat per volume [J / (m3.kg)]
C. Thermal conduction of the material [W/(m.K)]
D. Surface area for heat exchange [m^2/m^3]

Regenerator material

Regenerator material needs to have:

- High heat capacity per unit volume unit
- High thermal conduction into the material (to use the full heat capacity of the material)
- Low thermal conduction over the temperature gradient to avoid conduction from hot to cold side

Conflicting req.

- High surface area for optimal heat transfer between gas and regenerator matrix
- Low pressure drop over the regenerator to limit dissipation /losses

Conflicting req.

- Affordable

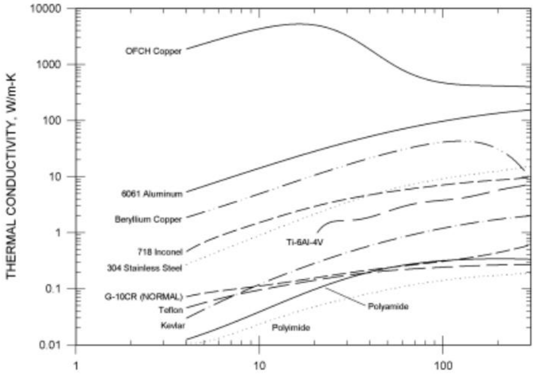

Figure 1. Thermal conductivity of various materials.

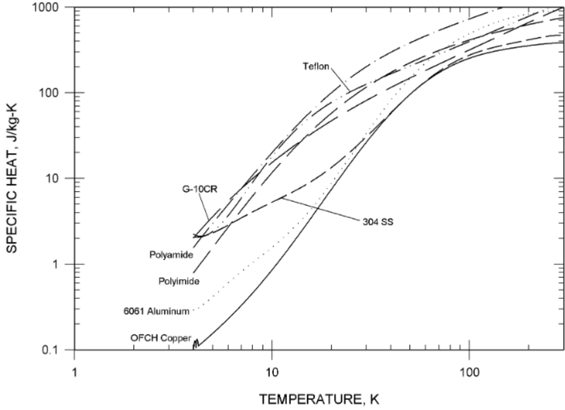

Figure 2. Specific heat of various materials.
Data presented by NIST, ICC 11 2000

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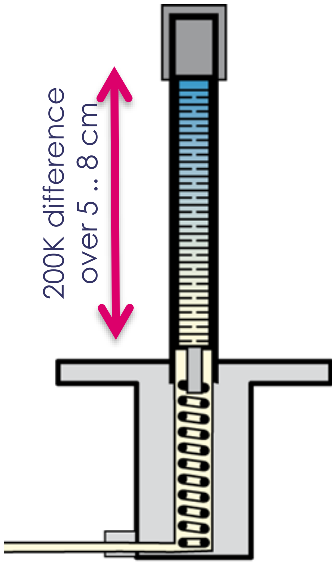
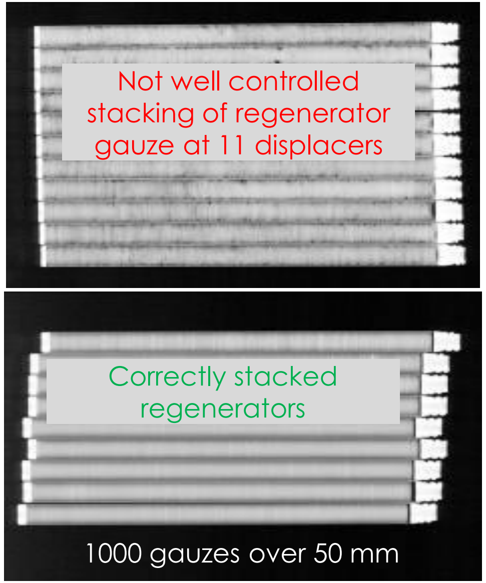
Cooler optimization 1/3

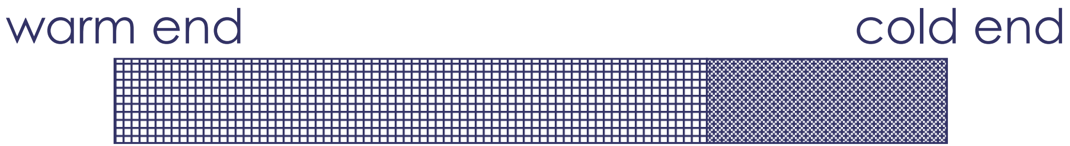


- Regenerator material: Stainless steel woven wire gauzes
  - Best compromise between heat capacity and thermal conductivity (and cost…)
  - Find best geometry (conflicting requirements): wired diameter and fill factor
  - Stack evenly to ensure smooth flows
- Use low-thermal conductivity materials where needed
  - Stainless steel or Titanium for tubing
- Surface area
  - Increase heat transfer on cold and warm side

Wire thickness (25µm)= 1/4 human hair
10 wires per mm



Cooler optimization 2/3 -> finding the best regenerator design?



performance @ 25 W_{pdV} / *warm part / cold part*	**calculated regenerator loss**	**calculated pressure drop over regenerator**	**measured pressure drop over regenerator**	**measured lowest tip temperature**
LOW / MED filling factor	2472 mW	0.85 bar	0.60 bar	80 K
MED / MED filling factor	2114 mW	1.10 bar	0.95 bar	75 K
LOW / HIGH filling factor	1896 mW	0.97 bar	0.82 bar	72 K

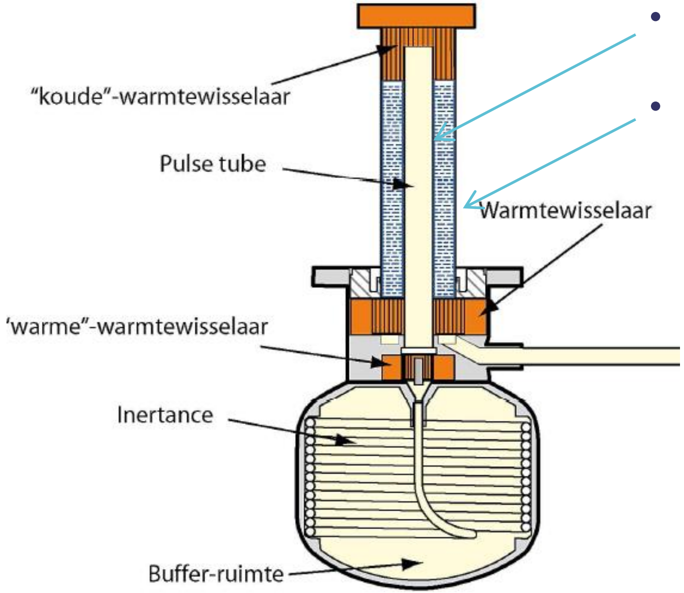
- Low filling factor : not enough heat capacity to reach low temperature
- Medium filling factor : pressure drop (mainly over warm part) too high
- Mixed regenerator : high filling factor only where it is needed

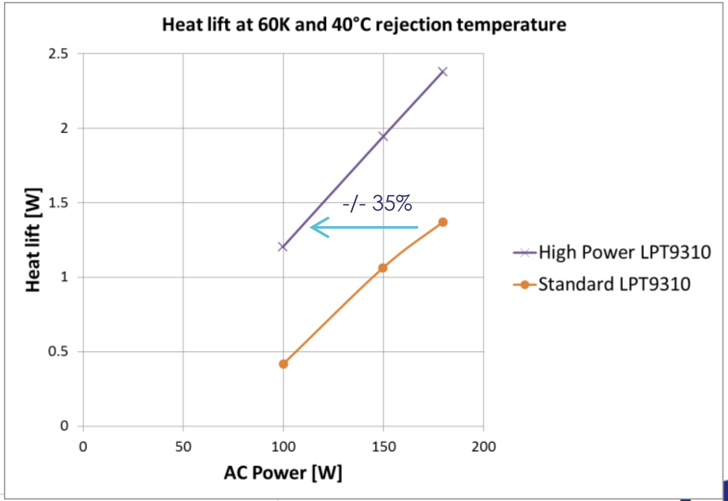
Design of regenerator is balancing act between the different losses

Cooler optimization 3/3 – Sometimes a trade-off is needed

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
  Higher filling factor @ cold side
- Use of Ti6Al4V tubing to reduce conduction losses





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Cryocoolers technologies

Cooler families defined by mechanical solutions

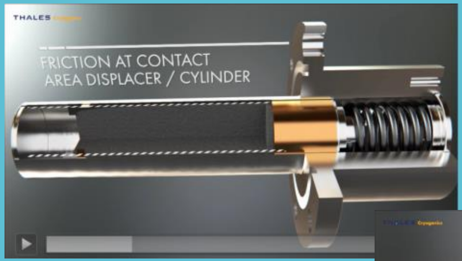
Stirling cooler: Moving displacer

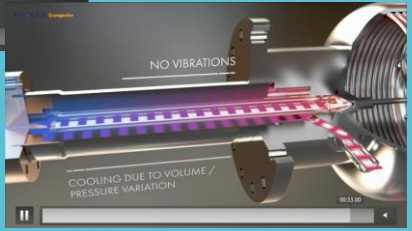
- Main failure mode is displacer seal wear

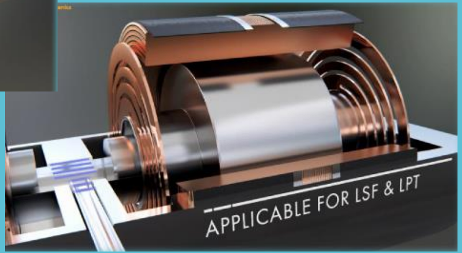
Pulse-tube coolers: no moving parts in cold side of the cooler

- Higher reliability
- Lower induced vibrations

Linear compressors with contact seal bearings or flexure bearings







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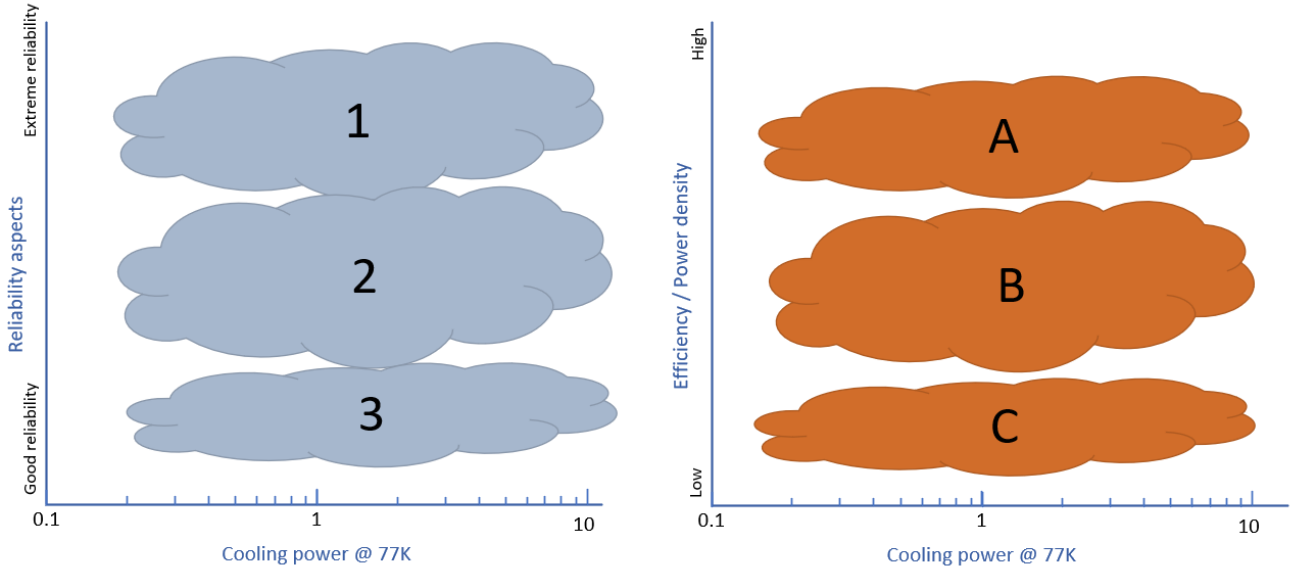
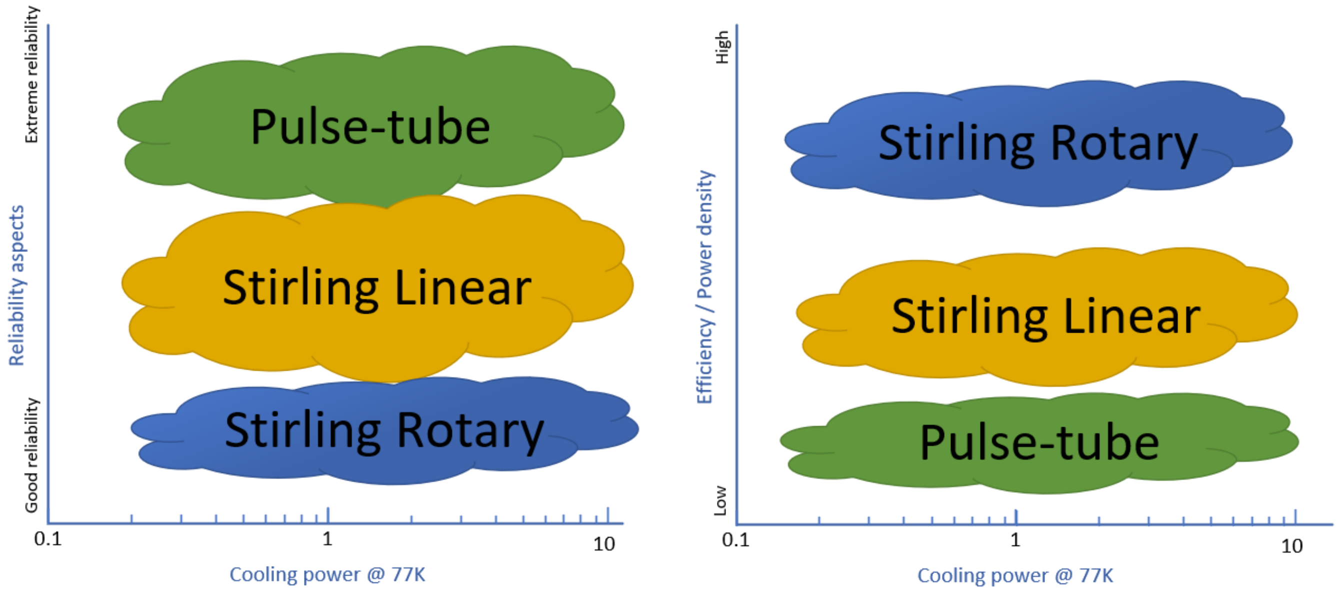
Positioning of the different cooler technologies

The different compact cooler technologies could be positioned based on Reliability / Efficiency



Question 4: Where do we position the different technologies:
Rotary Stirling (..|..) / Linear Stirling (..|..) / Linear Pulse-tube cooler (..|..)

Answer on question 4:



Answer:

Rotary Stirling (3|A) / Linear Stirling (2|B) / Linear Pulse-tube cooler (1|C)

Application areas

Overview of Thales Cryogenics Product Line Perimeter

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

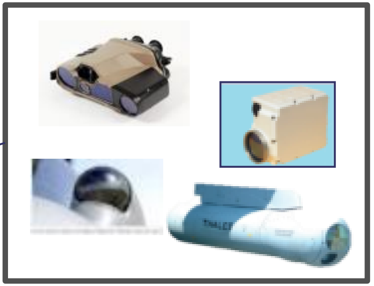

Contact seal coolers


"Flexure" coolers


Pulse Tube coolers

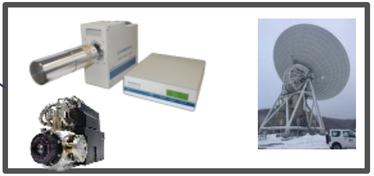
Defense Markets (Stirling coolers)

Compact, robust & Efficient
New (IR-) detectors



Commercial Markets (Stirling & Pulse tube)

Extreme **reliability** &
Cost effective solutions



Space Markets (Pulse tube coolers)

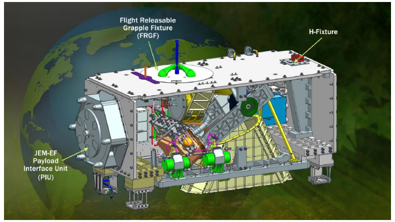
Extreme reliability
High efficiency
"No" vibrations
Reduction of (development) costs

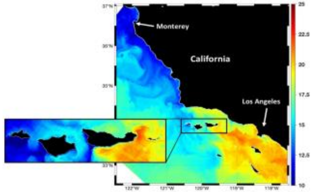
Our markets and examples of applications

IR today still the biggest identified market
for compact Cryocoolers

Markets

- IR-detectors
  - Military
  - Civil applications
- New technologies requiring cooling 30 .. 150K
- Medical systems
- Superconductive systems (non RF)
  - SQUID / SQIF's
  - Superconductive bearings
- Superconductive devices RF devices
  - Low Noise Amplifiers (RF domain)
  - Superconductive filters (RF domain)
- Space
- Germanium sensors
- Zero boil-off





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Question:

- What is the most important requirement for space coolers

  A. Reliability / Robustness
  B. Efficiency
  C. Induced vibrations
  D. Costs

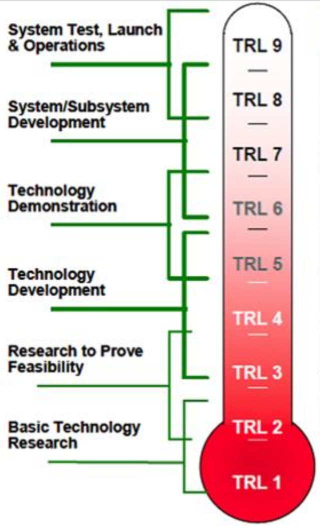
- What are the costs of a typical space cooler for a 5 year mission:

  A. < 50 kEur
  B. 50 < .... < 250 kEur
  C. 250 < .... < 500 kEur
  D. > 500 kEur

Space cooler examples

3 showcases with different TRL, complexity and price level

- Ecostress mission (JPL-NASA)
  Status - TRL 9
- 30..50K development (TRP ESA)
  Status – TRL 6
- Athena cooler development
  Status – TRL 4



Technology Readiness Levels[1]	
9	Actual system "flight proven" through successful mission operations
8	Actual system completed and "flight qualified" through test and demonstration (Ground or Flight)
7	System prototype demonstration in a space environment
6	System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

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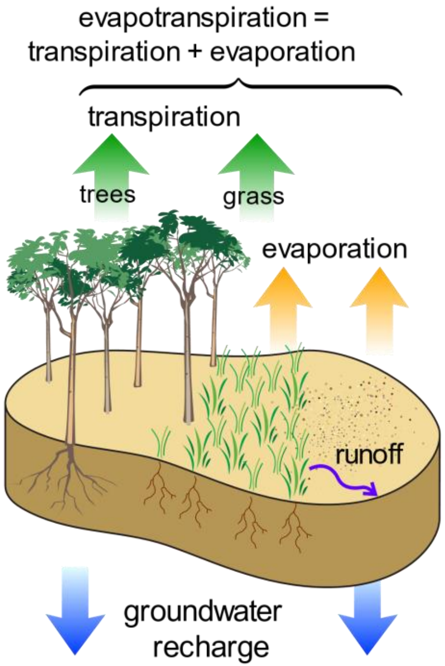
ECOSTRESS MISUION

ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station

Measurements of EVOTRANSPIRATION



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ECOSTRESS instrument design and project

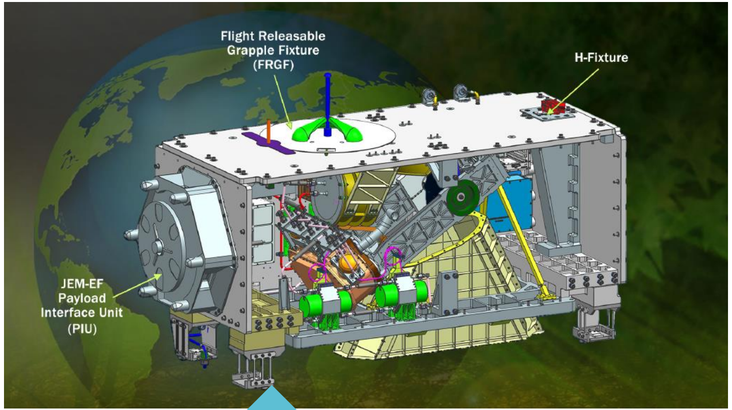
Cooling requirement:

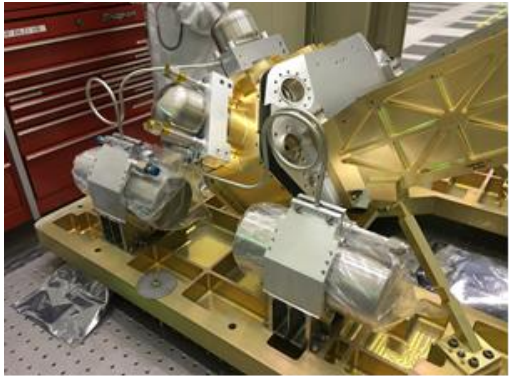
- 1 cooler needed for cold shield cooling (115K)
- 2 coolers to keep the sensors (< 65 K)

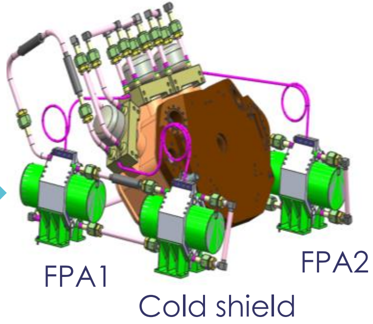
Pressure on costs and energy budget

Mission lifetime 1 year (“Class D”)

Choice for upgraded Civil PT coolers







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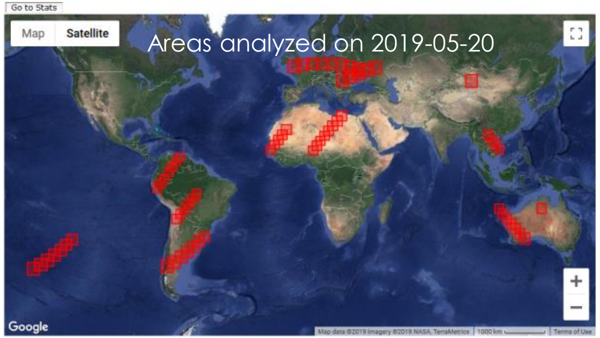
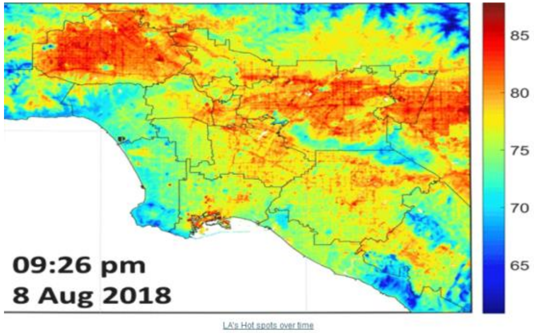
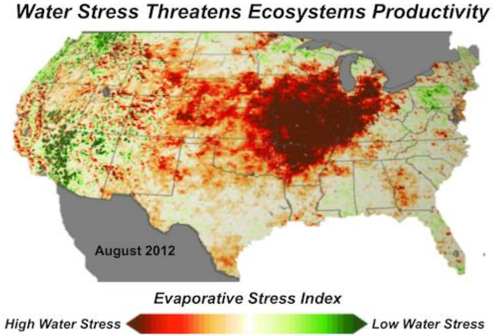
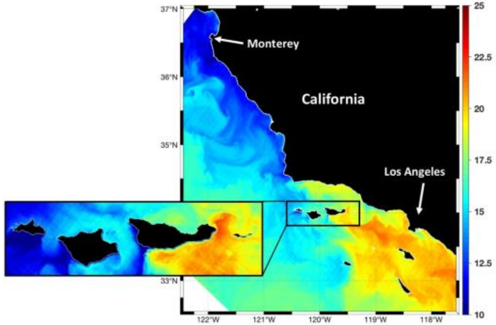
ECOSTRESS mission









Although originally 1 year mission system is already operational for 3 years.

No degradation at cooler level witnessed ☺

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30..50K ESA Techical Research Program (2015 .. 2018)

Goal

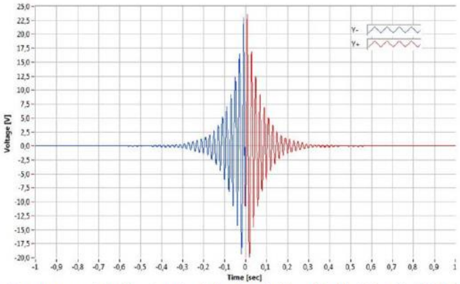
- Develop a thermal structure able to cool 2 IR detectors to temperatures below 50K with 2 redundant coolers suitable for space missions
- Coolers should be able to provide cold at two temperature levels:
  - 350 mW at 30 K and 1200 mW at 100 – 120 K

  OR
  - 800 mW at 35 – 40 K and 1500 mW at 100 – 130 K

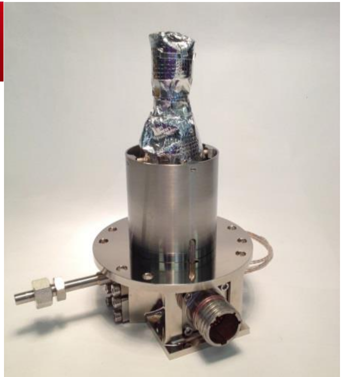
Consortium:

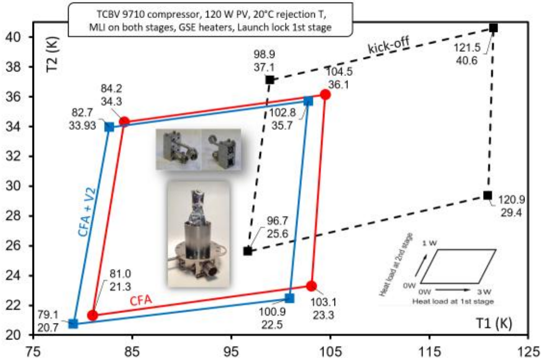
- Thales Cryogenics : Compressor + Program management
- CEA-SBT (Fr) : 2 stage PT development
- Absolut System (Fr) : Mechanical strucuture and thermal connections

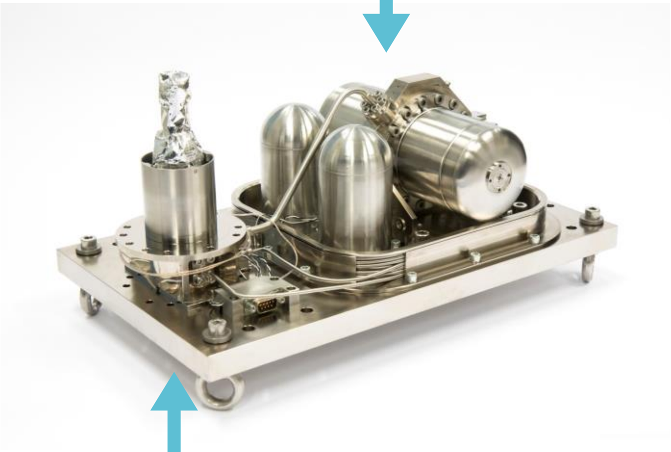
The used cooler definition



Ring down graph in the horiznatal orientation (Left: 13x; Right: 13x)







Environmental testing 30 .. 50K

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The complexity of the cold box

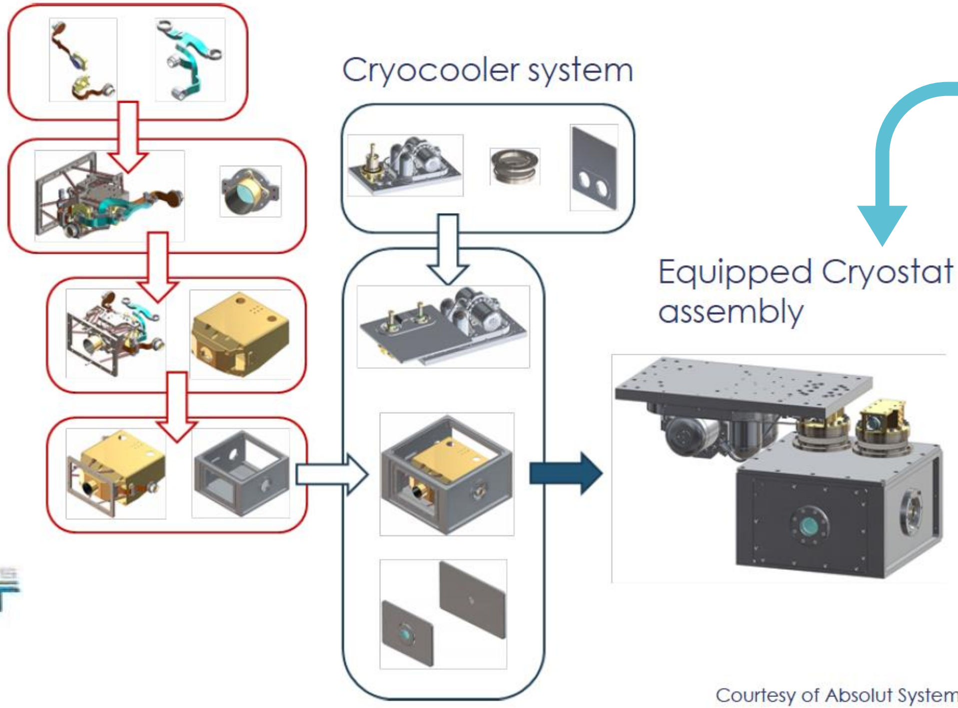
Cold box equipment

Cold box assy and support structure

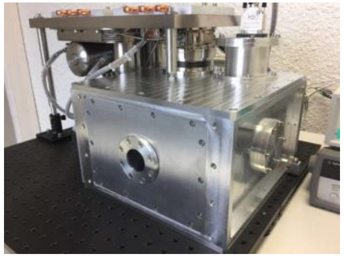
Optical bench assembly

Cryostat assembly

INNOVATIVE SOLUTIONS
ABSOLUT SYSTEM



Courtesy of Absolut System



System at TRL6 level, awaiting actual flight programs of ESA

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Athena mission (LARGE mission of ESA) TRP with potential launch 2031

Description of spacecraft and XIFU instrument

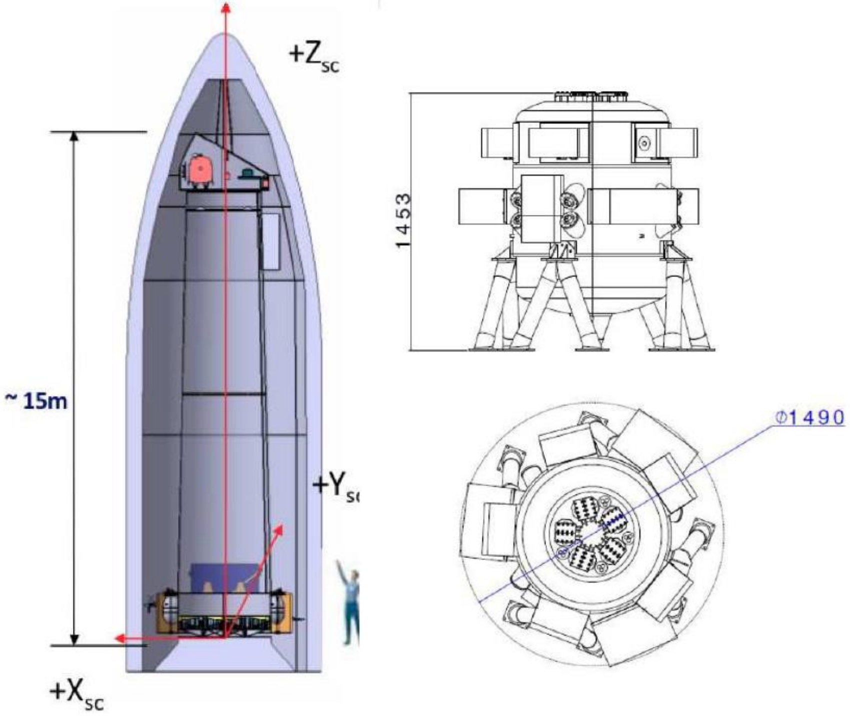
cnes

Main dimensions of spacecraft

- ≈ 15 m
- ≈ $7 tons$
- L2 orbit
  - Launch planned ≈ 2031 by ARIANE64

Main dimensions of XIFU

- ≈ 1.5 m high (Dewar)
- ≈ 1.5 m in diameter (Dewar)
- ≈ 800 kg (instrument)
- Electrical consumption ≈ $3000W$



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Extreme low temp / Complex Cryochain

Focus on Focal Plan Array

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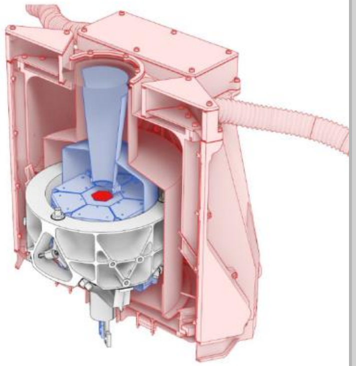
Subsystem under SRON responsibility

Insure magnetic, mechanic, electric and thermal environment for detector

- Thermal needs
  - $< 2.2mW@1.7K$ *(pink part)* for
    - Cold electronics dissipation (SQUID)
    - Dissipation of Impedance adaptation of signal harness
  - $< 5\mu W@300mK$ *(grey part)* due to
    - Conductive loads of mechanical support on Kevlar between 2K and 50mK structure
  - $< 0{,}5\mu W@50mK$ *(blue part)* due to
    - Dissipation in detector
    - Dissipation cold electronics (SQUID)
    - Conductive loads from 300mK
- Composed by 2 faraday cage (@2K and @50mK)



Complex Cryochain using different cooling technologies from different suppliers/countries
(NL (Thales) / Fr (ALaT,CEA) / Japan (JAXA) / UK (RAL))

Cryochain

cnes

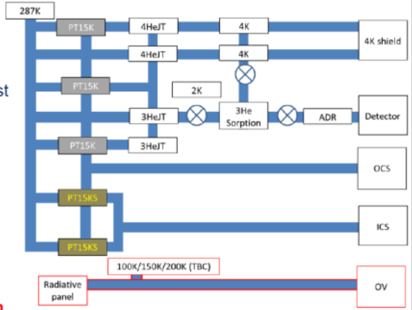
Cryogenic chain

Outer vessel cold by dedicated radiative panel

- Outer vessel close to 200K (TBC)

Active cooling for lower temperature

- 5x15KPulse Tube coolers (ESA / ALAT)
  - All 5 PTs used for OCS cooling and JTs pre-cooling on 1st precooling stage (~80 K)
  - 2 PTs for ICS cooling
  - 3 PTs for JT-precooling on 2nd precooling stage
- 2x4KJT coolers (JAXA)
- 2x2KJT coolers (JAXA or RAL)
- 1 sub-K cooler (CEA hybrid cooler)



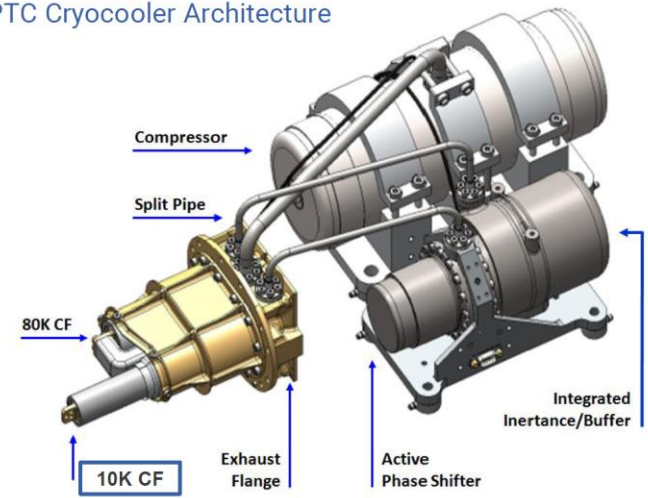
"No single point failure "philosophy" has a strong impact in sizing of cryochain

Open

Contribution of Thales Cryogenics

- **Thales Cryogenics: Supply of flexure bearing compressors.**
- **Connected to 2 stage PT cold finger (ALaT)**
- **Use of the compressors:**
  - 1st compressor used as pressure wave generator (500 W input power)
  - 2nd compressor used as phase shift controller for the 2nd stage PT to achieve better efficiencies compared to passive inertance / buffer.
- **5 coolers required for Athena mission**

Hi-PTC Cryocooler Architecture



The cooler delivers @ 300W input:
5000mW @ 100K (1st stage)
400mW @ 15K (2nd stage)

Weight of the cooler = 18 kg

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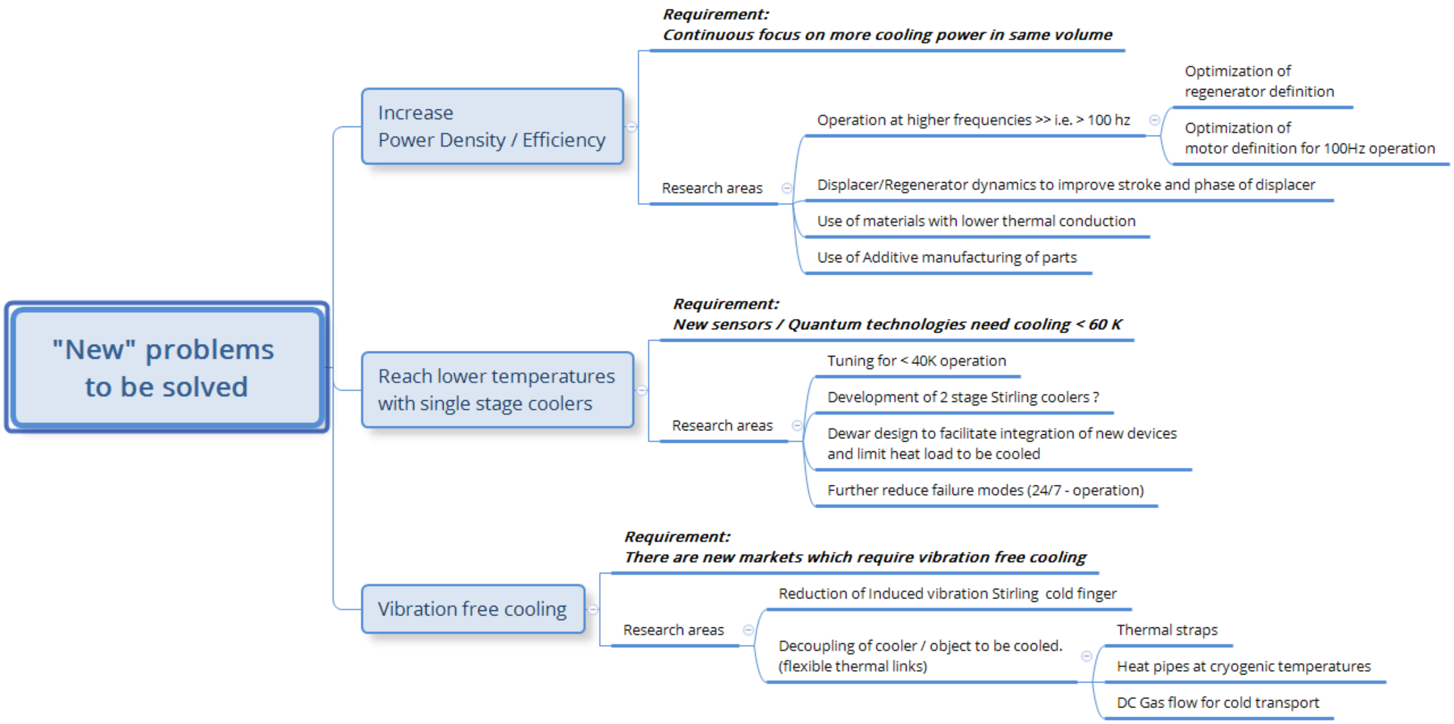
Future developments



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RELIABLE
SYNERGY
ROBUST
AFFORDABLE