

Turbo Brayton for Space

Julien TANCHON

INNOVATIVE SOLUTIONS
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SYSTEM

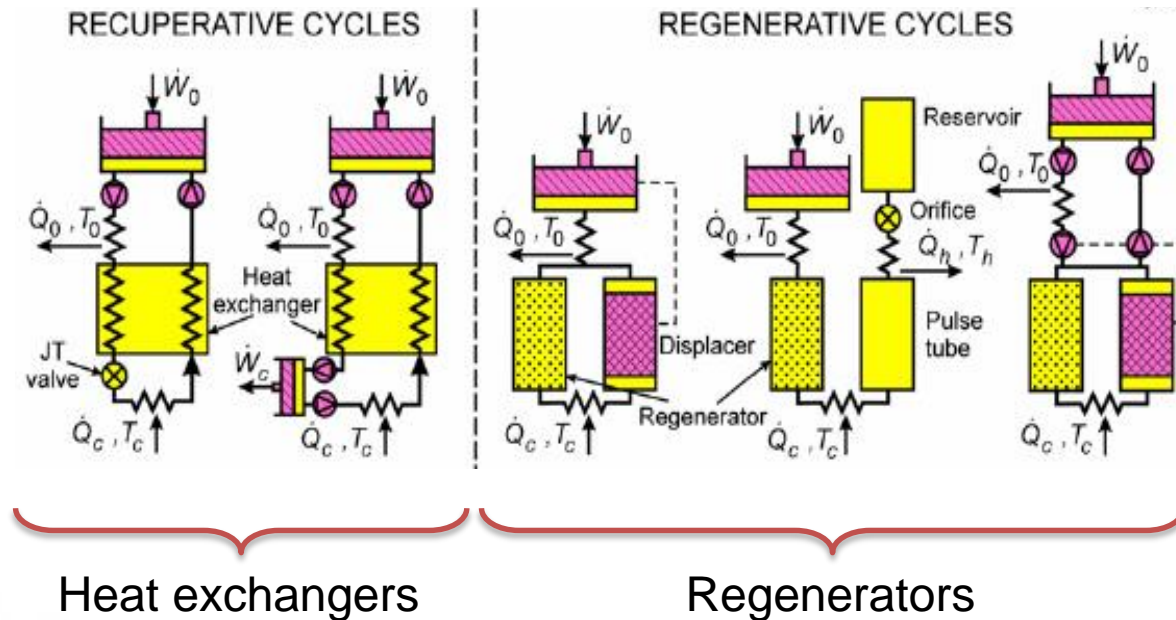
Objectives of the talk :

- A quick reminder of the thermodynamic cycles
- Review of the Turbo-Brayton cycles and general concept
- Interest of this technology for space applications
- Technologies implemented within Turbo-Brayton for space
- Examples of Turbo-Brayton activities

Thermodynamic cycles

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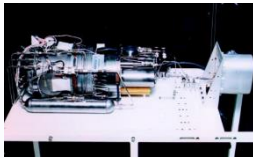
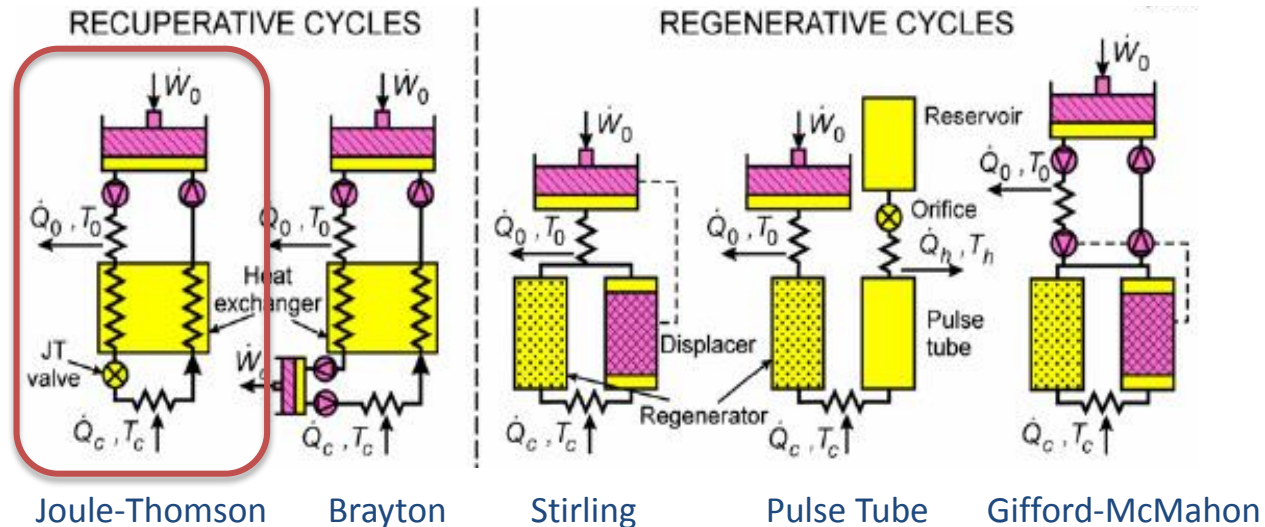
The main types of cryogenic coolers (or cryocooler) commonly used to achieve cryogenic temperatures are classified in 2 categories



Thermodynamic cycles

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The main types of cryogenic coolers (or cryocooler) commonly used to achieve cryogenic temperatures are:



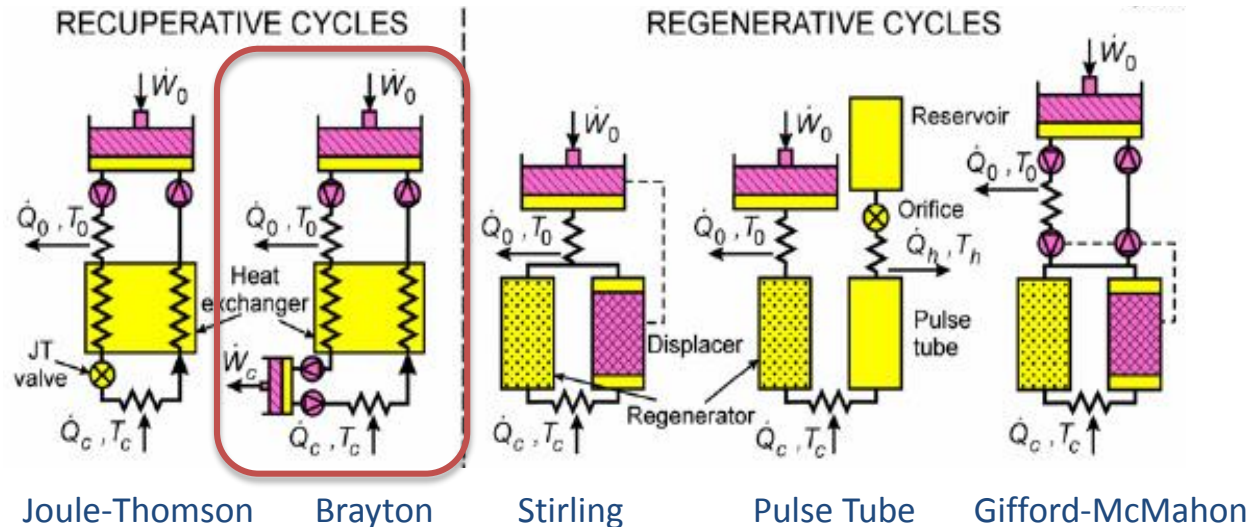
- Operating temperature range : 1.6K to 300K
- Cooling power range: from few mW up to hundreds of W
- Reduced thermodynamic efficiency due to isenthalpic expansion
- Multi-stage cooling possible
- High pressure compressor complexe

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Thermodynamic cycles

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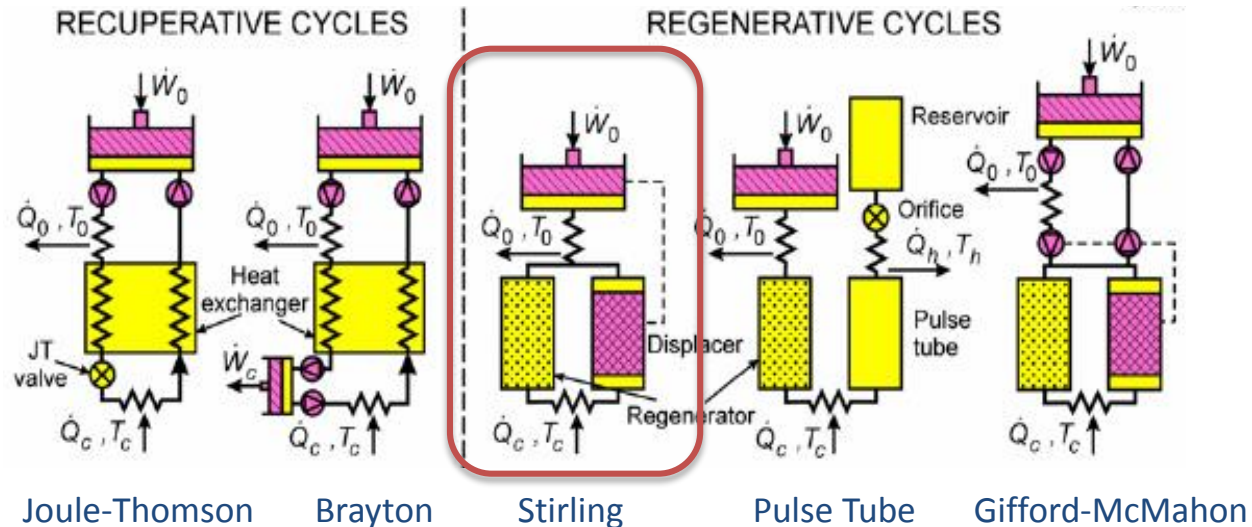
- Operating temperature range : 4K to 300K
- Cooling power range: from few mW up to kW
- High efficiency, particularly for high capacity cooler
- Very compact due to the motor compacity
- Important lifetime and reliability
- Distributed load and intermediate cooling stages
- Limit for manufacturing small compressor and turbine wheels

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Thermodynamic cycles

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The main types of cryogenic coolers (or cryocooler) commonly used to achieve cryogenic temperatures are:



AIRBUS
DEFENCE & SPACE

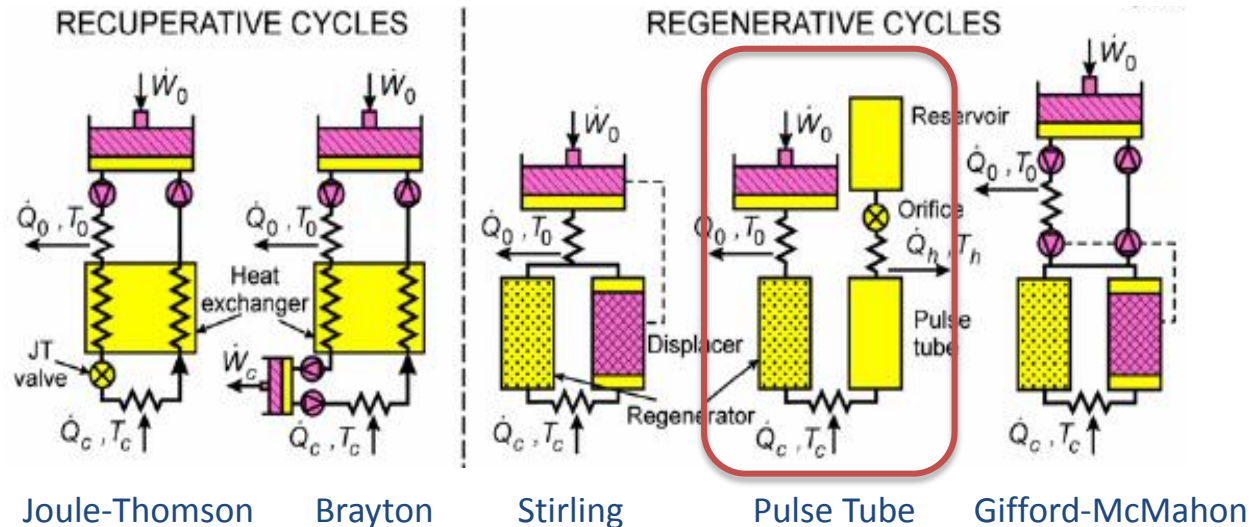
- Operating temperature range : 4K to 300K
- Cooling power range: from few mW up to tenths of W
- From one stage up to 3 stages
- Cold source punctual and not distributed
- System compact
- Important lifetime and reliability

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Thermodynamic cycles

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The main types of cryogenic coolers (or cryocooler) commonly used to achieve cryogenic temperatures are:



 **Air Liquide**

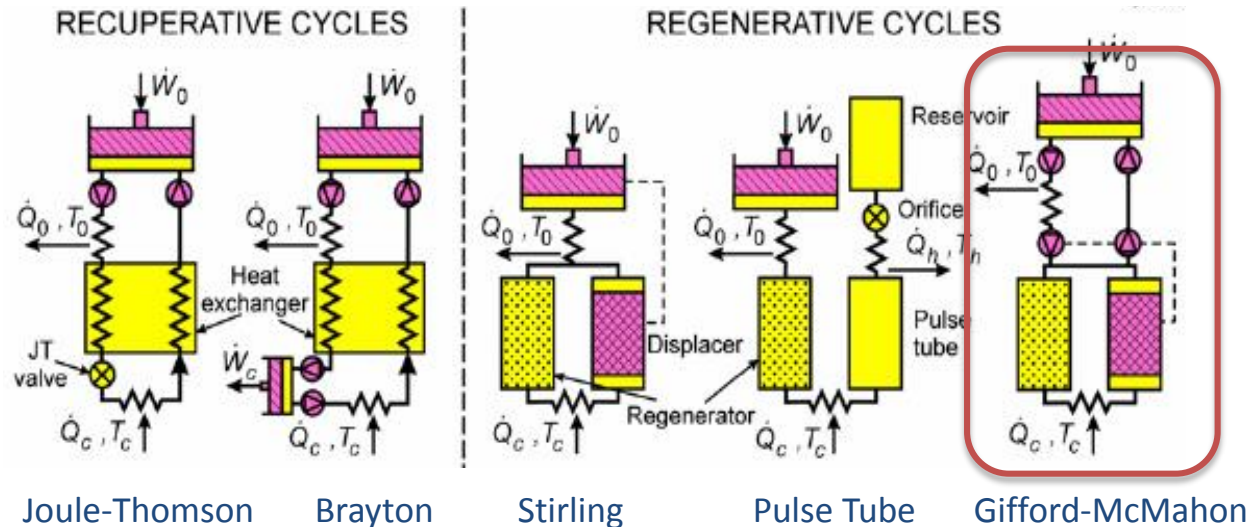
- Operating temperature range : 4K to 300K
- Cooling power range: from few mW up to tenths of W
- From one stage up to 4 stages
- Cold source punctual and not distributed
- System compact
- Important lifetime and reliability

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Thermodynamic cycles

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The main types of cryogenic coolers (or cryocooler) commonly used to achieve cryogenic temperatures are:



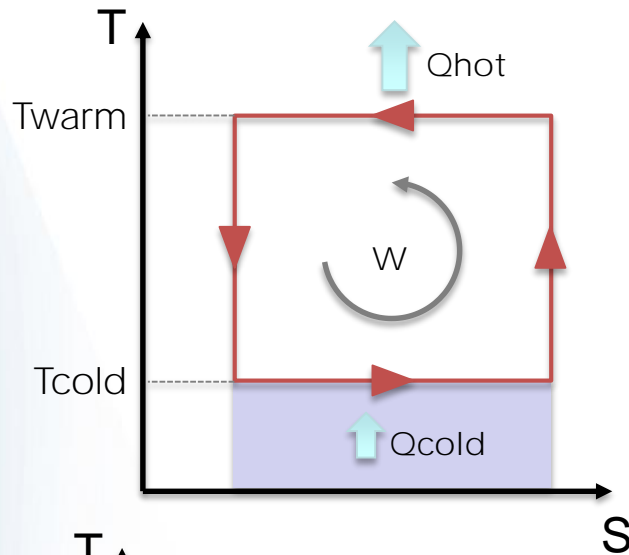
CRYOMECH
WORLD LEADERS IN CRYOREFRIGERATION FOR MORE THAN 50 YEARS

- Operating temperature range : 4K to 300K
- Cooling power range: from few mW up to hundreds of W
- Multi-stage cooling possible
- Cold heat exchanger punctual and not distributed
- Lubricated compressors from mass production of industrial air conditioning
- Important size due to low frequency operation and the need for oil separation unit

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Thermodynamic cycles

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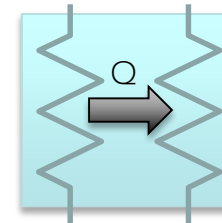
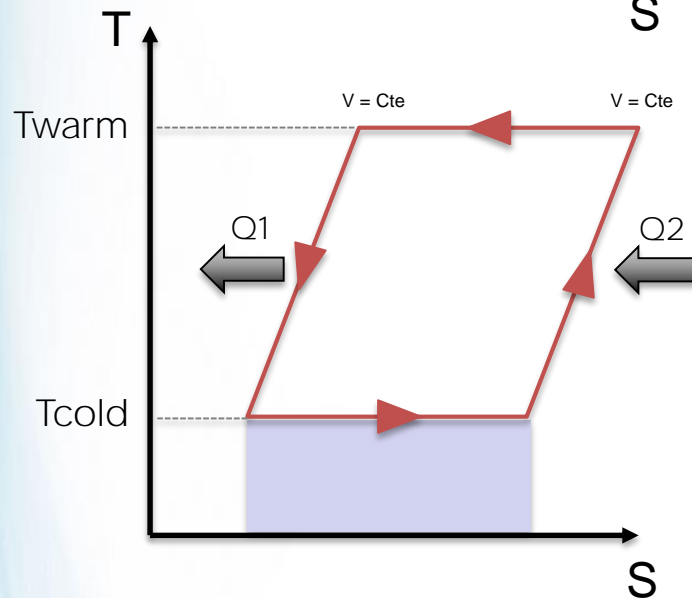
Carnot cycle is the "ideal" cycle to transfer reversibly the amount of heat Q_{cold} at T_{cold} to T_{warm} by the provision of a work W

Isothermal reversible compression/expansion phases
Adiabatic reversible transformation

Carnot cycle not « feasible » but similar cycles exist - Stirling cycle (or Pulse Tube)

Isothermal compression/expansion phases
Isochoric transformations

$Q_1 = Q_2$ but opposite directions



Recuperative cycles use a recuperator



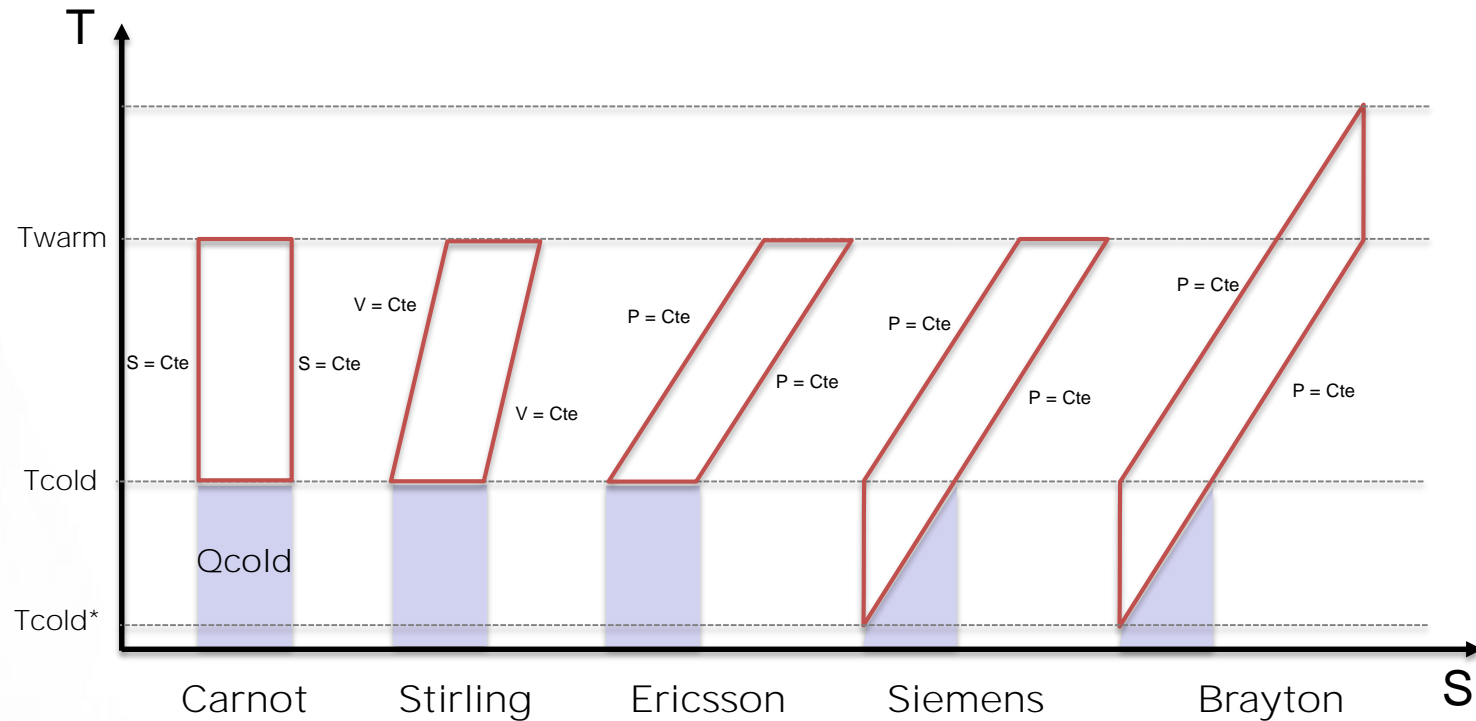
Regenerative cycles use a regenerator

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Thermodynamic cycles

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Brayton cycle



Carnot : 2 x Isothermal + 2 x Adiabatic

Stirling : 2 x Isothermal + 2 x Isochoric

Ericsson : 2 x Isothermal + 2 x Isobaric

Siemens : 1 x Isothermal + 2 x Isobaric + 1 Adiabatic expansion

Brayton : 2 x Adiabatic + 2 x Isobaric

$$\eta_{\text{Carnot}} = \eta_{\text{Stirling}} = \eta_{\text{Ericsson}}$$

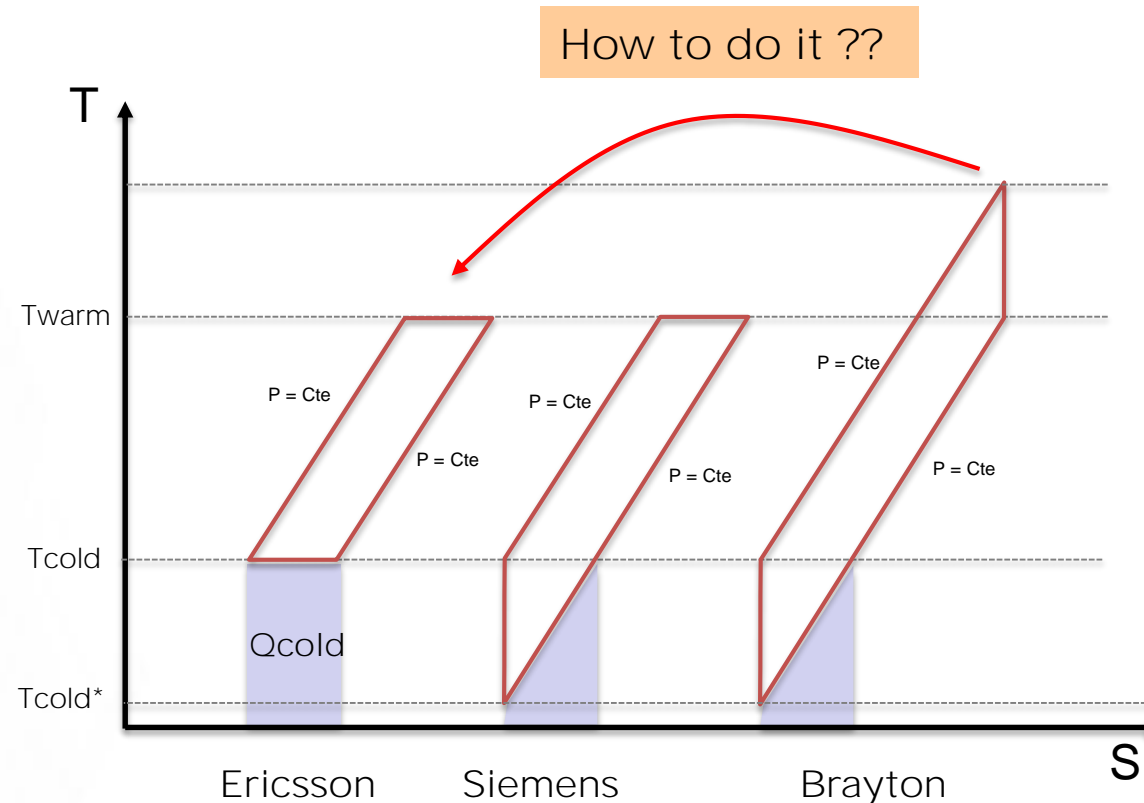
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Thermodynamic cycles

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Brayton cycle

Ericsson cycle is the ideal performances achievable for a Brayton
Need to tend towards Ericsson cycle to improve efficiency



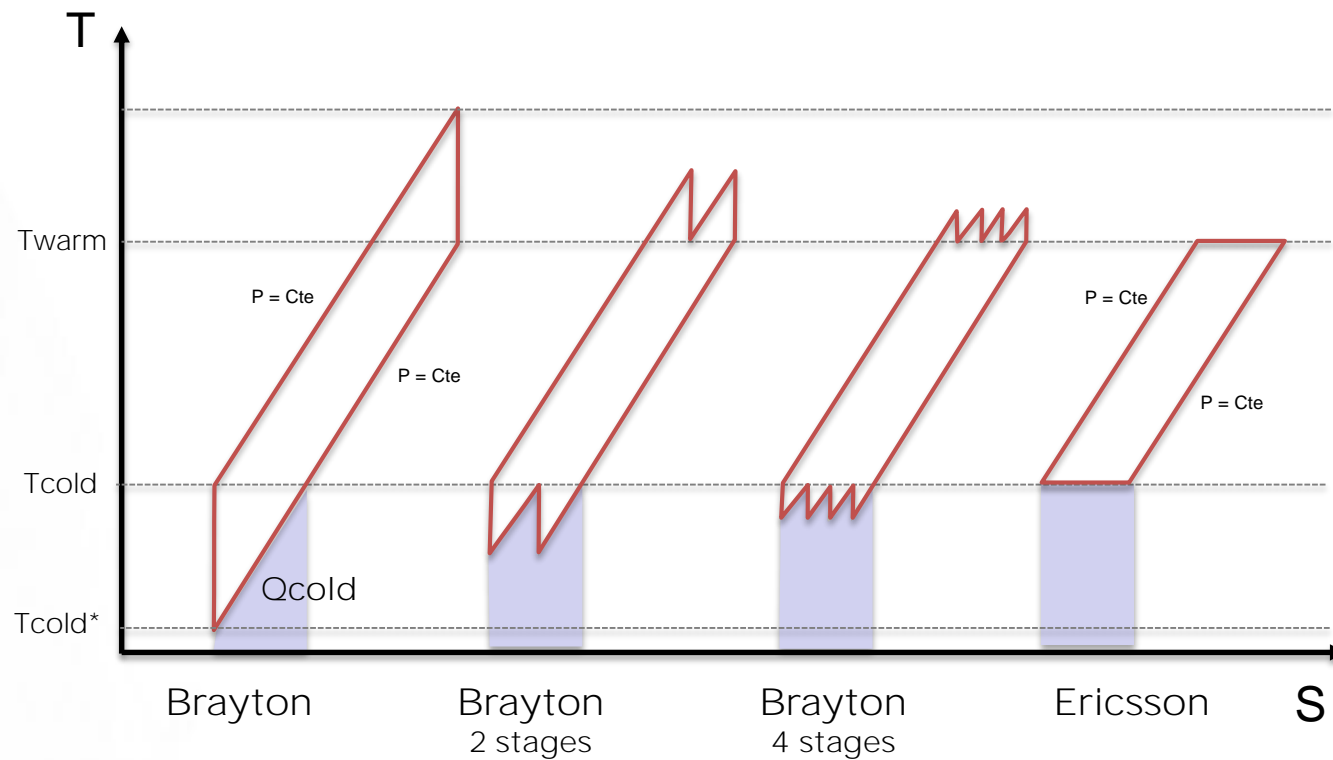
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Thermodynamic cycles

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Brayton cycle

By a succession of transformations
Multiple compression and expansion



Allows to recover efficiency but with a higher complexity

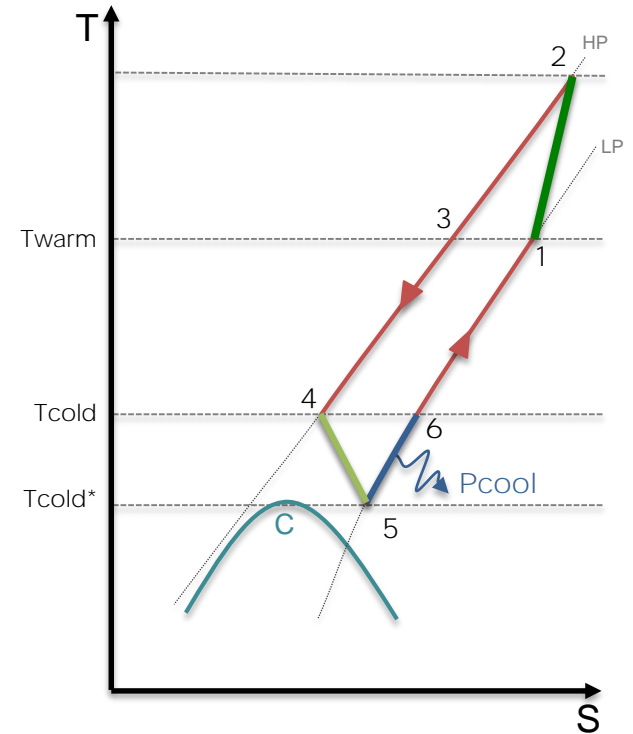
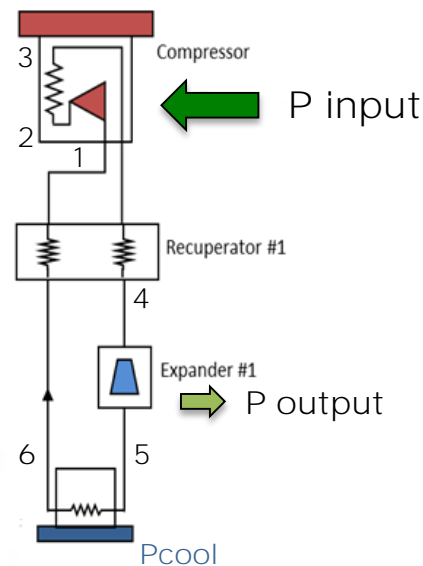
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Review of the Turbo-Brayton cycles and general concept

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Turbo-Brayton cycle

A Turbo-Brayton cooler is operating on a Brayton cycle, using turbomachines technology for the compressors and turbines



- 1 - 2 : Compression through centrifugal compressor
- 2 - 3 : Cooling at room temperature
- 3 - 4 : Precooling through recuperator
- 4 - 5 : Expansion in a turbine (centripetal) - Mechanical work to be extracted
- 5 - 6 : Warming in the cold heat exchanger (cooling power)
- 6 - 1 : Warming at room temperature (using heat flux from 3-4)

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Review of the Turbo-Brayton cycles and general concept

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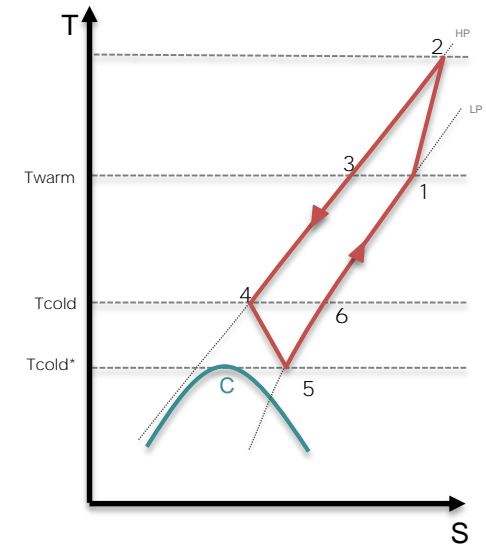
Turbo-Brayton - Choice of the working fluid

Fluid **MUST** be in vapor state all along the cycle

The fluid is selected in function of the operating temperature

The criteria are:

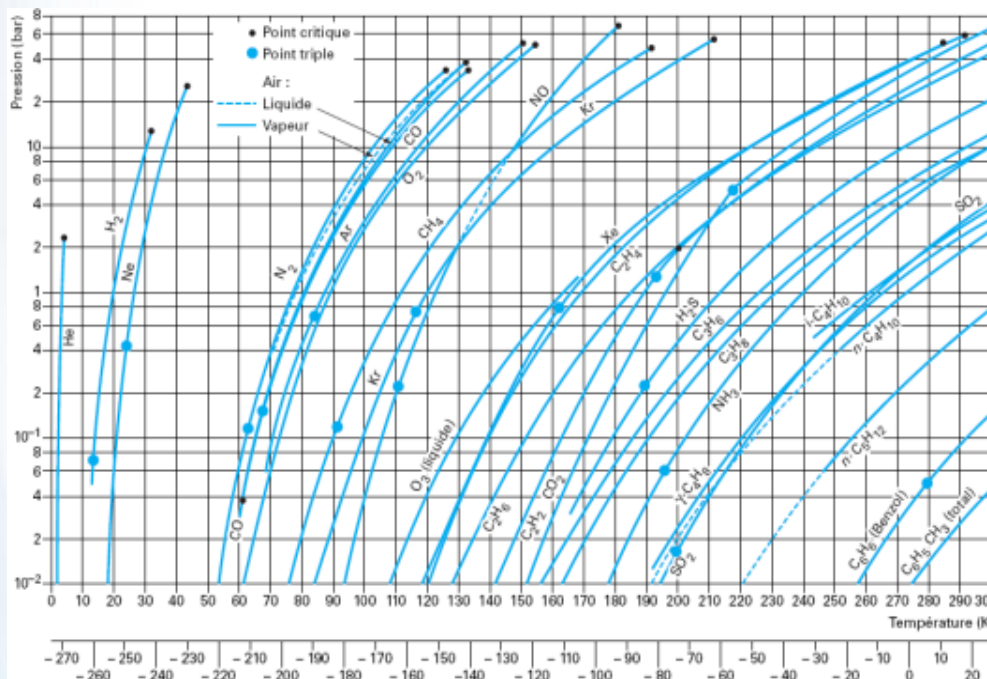
- Pressure ratio
- Temperature rise during compression
- Thermal properties of the gas (for recuperator efficiency)



Low γ
High molar mass (low r)
High Lambda

Monoatomic gas are preferred

Helium, Neon or Helium / Neon mixture are commonly used in TurboBrayton cryocoolers



Interest of this technology for space applications

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Operating frequency above 2500Hz with, low-mass and precision balanced rotors

Gas bearings provide contactless operation (no wear, no friction)

Inherently vibration-free below 1kHz
No vibration cancellation electronics is required
No damping structure and launch locking

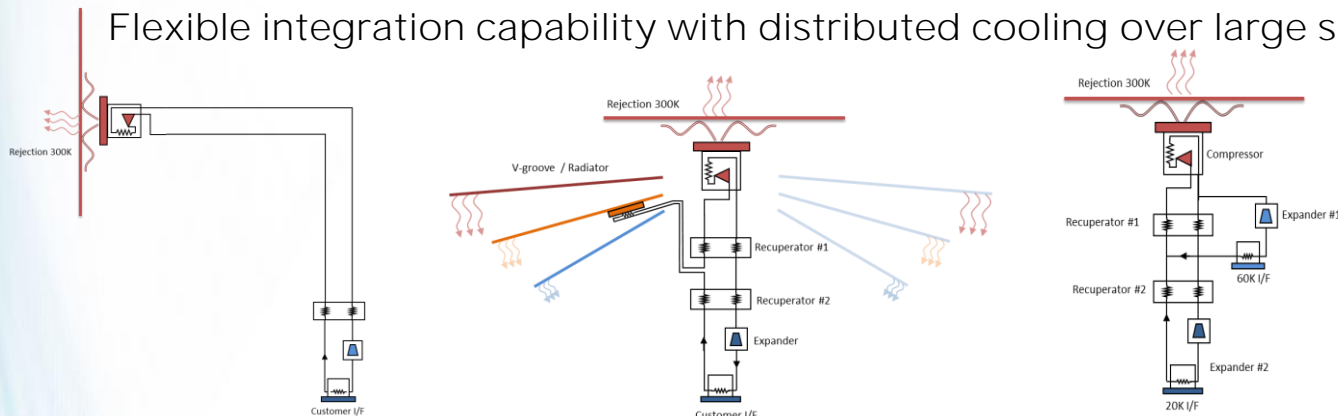
Compatible with >10 years lifetime requirements

High efficiency and operating all along the 4K-300K temperature range

Passive thermal control of the cooler (heat switch function of the redundant cooler)

Possibility to implement precooling using radiators

Flexible integration capability with distributed cooling over large surfaces



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Interest of this technology for space applications

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Exported vibrations

Critical bandwidth for visible instruments: 0 - 1000 Hz

Vibrations generated by mechanical systems are critical (< 50mN all axis)

Conventional mechanical cryocoolers required:

- ✗ Complex integration
- ✗ Complex active vibration control electronics

and

- ✗ Residual vibration level not cancelled on transverse axes
- ✗ Need of passive dampers (or active vibration cancellation) at upper level (instrument level)



Air Liquide



Turbo-Brayton cooler operates far away this critical frequency range

- ✓ Inherently vibration-free below 1kHz, in all axes and without electronic control
- ✓ Vibrations lower than 10mN demonstrated, in all axes

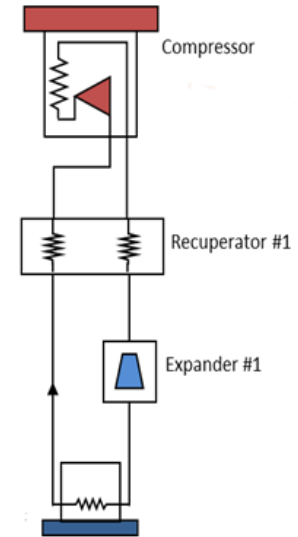
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Technologies implemented within Turbo-Brayton for space

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Turbo-Brayton - Main components

- A centrifugal compressor
- An “aftercooler”
- A recuperator
- An expander
- A cold heat exchanger



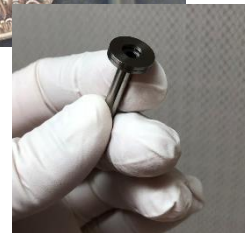
Centrifugal compressor



Aftercooler



Recuperator



Turbine

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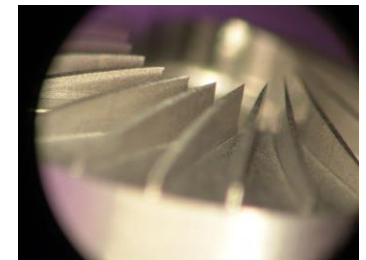
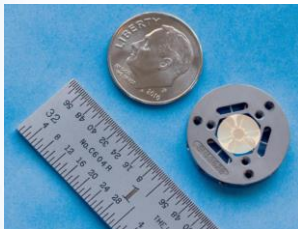
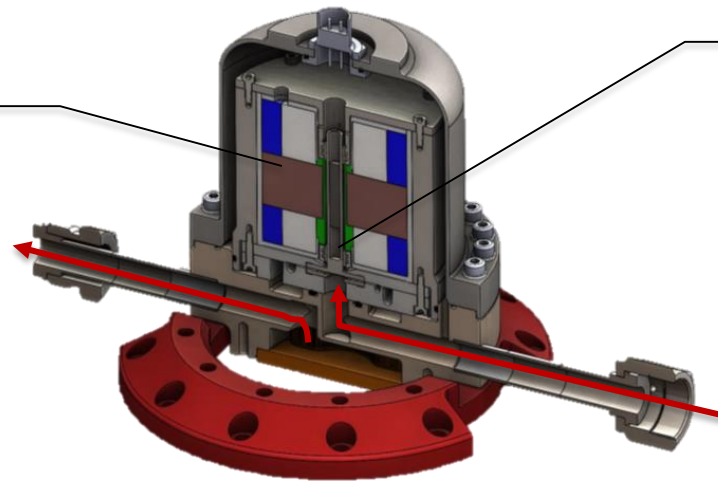
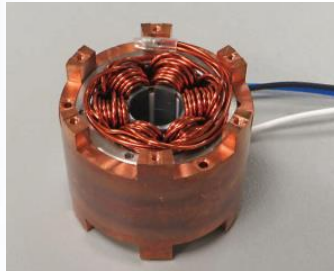
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Centrifugal compressor

A centrifugal compressor convert kinetic energy in pressure rise

The gas flow is accelerated using the blades of impeller and its speed increase the total pressure



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Technologies implemented within Turbo-Brayton for space

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Centrifugal compressor

What are the main challenges in a high speed centrifugal compressor?

- To run a small shaft at a very high speed : 150.000 to 500.000 rpm
- To operate for 10 years lifetime (or more)
- To be efficient (low input power)

It requires:

- High performance bearings
- High efficiency high speed motors
- A robust rotor dynamic design
- An optimized thermo-hydraulic design

Technologies implemented within Turbo-Brayton for space

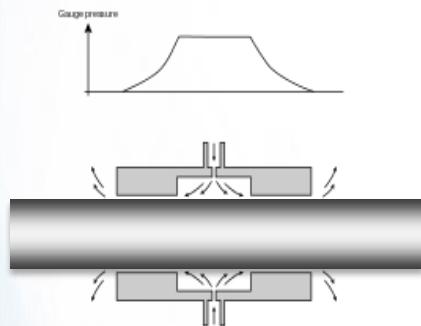
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Centrifugal compressor

High performance bearings

- Considering lifetime and reliability issue, ball bearings are not an option
- Only contactless bearings are useful
- The main technologies are:
 - Hydrostatic gas bearing : use of HP source to generate a lifting force on the shaft
 - Hydrodynamic gas bearing : use the rotation speed of the shaft to create a local overpressure to lift the shaft
 - Magnetic bearings : use of a magnetic field to levitate the shaft

- ✓ Easy to produce
- ✗ Need high pressure source
- ✗ Large flow rate bypassed



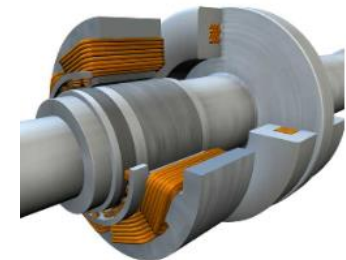
Hydrostatic bearing

- ✓ Completely passive
- ✓ Robust technology
- ✗ Difficult to produce



Hydrodynamic bearing

- ✓ Easy to implement
- ✗ Extremely complex system



Magnetic bearing

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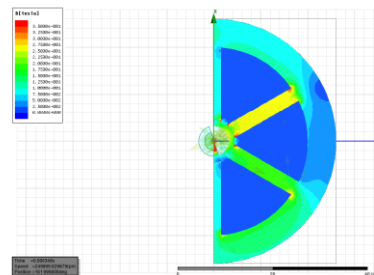
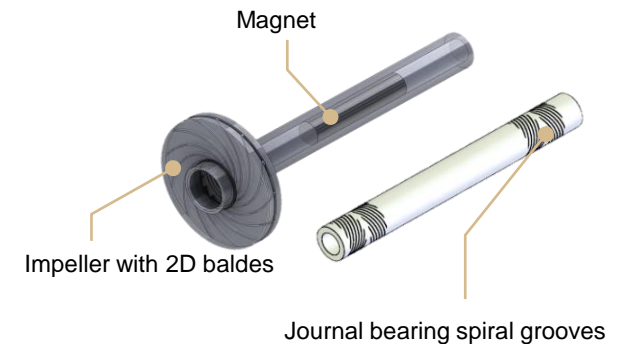
Technologies implemented within Turbo-Brayton for space

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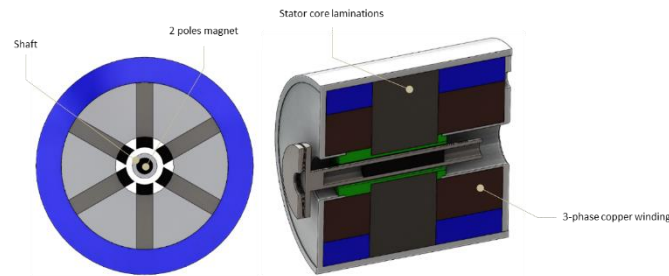
Centrifugal compressor

High efficiency high speed motor

- The motor of the centrifugal compressor is integrated in the compressor
- Most of the time, the magnet is inside the shaft
- Management of high frequency losses is a challenge
- > 96 % efficiency achieved on our motor



FEM 3D modelling



CAD design



300krpm, 180W motor

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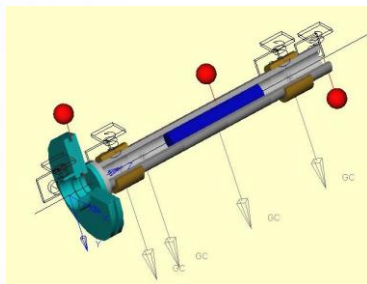
Technologies implemented within Turbo-Brayton for space

INNOVATIVE SOLUTIONS

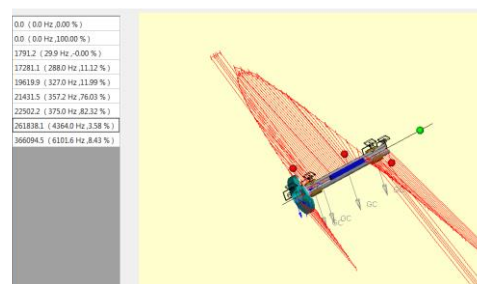
Centrifugal compressor

A robust rotor dynamic design

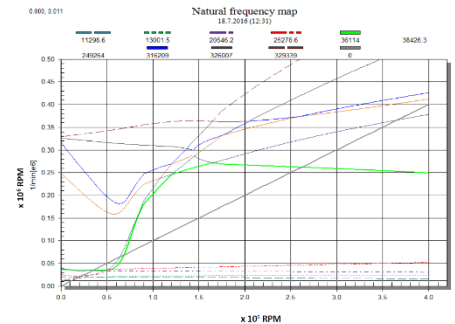
- The rotor dynamic consists :
 - to design the rotor structure (bearing location and dimensions, thrust bearing, shaft diameter)
 - to insure that no bending mode will appear along the operating frequency range
 - to check the bearing stability for the different operating conditions



Rotor dynamic model



Mode shape



Campbell diagram for stability

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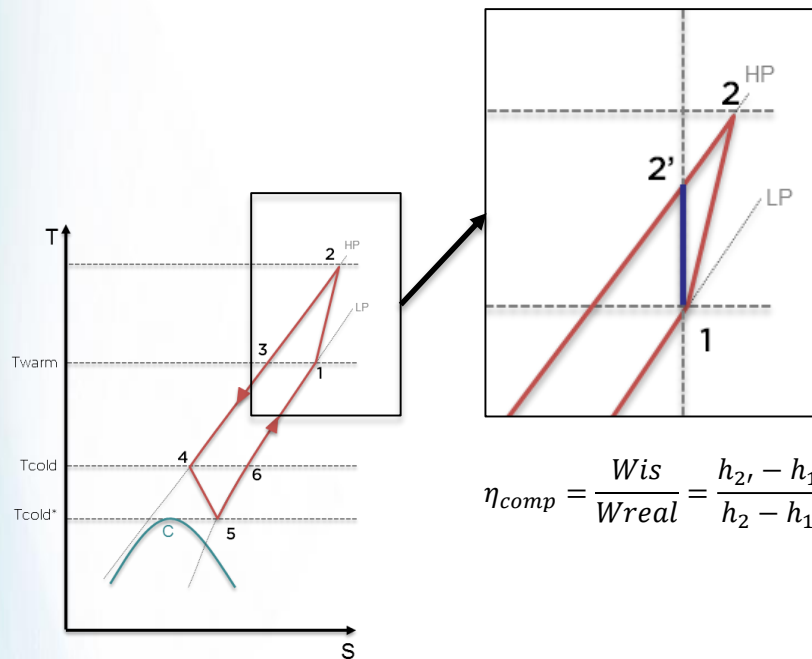
Technologies implemented within Turbo-Brayton for space

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Centrifugal compressor

An optimized thermo-hydraulic design

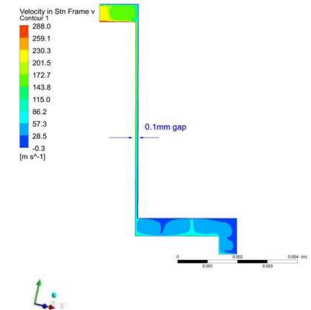
- The thermohydraulic optimization consists to improve the isentropic efficiency of the compressor
- Aerodynamic features can be optimized by changing the machine tool paths for impeller and diffuser
- CFD modelling to optimize the performances and to evaluate losses



$$\eta_{comp} = \frac{W_{is}}{W_{real}} = \frac{h_{2'} - h_1}{h_2 - h_1}$$

Isentropic efficiency definition

Velocity
Streamline 3
276.6
207.5
138.3
69.2
0.0
[m s⁻¹]



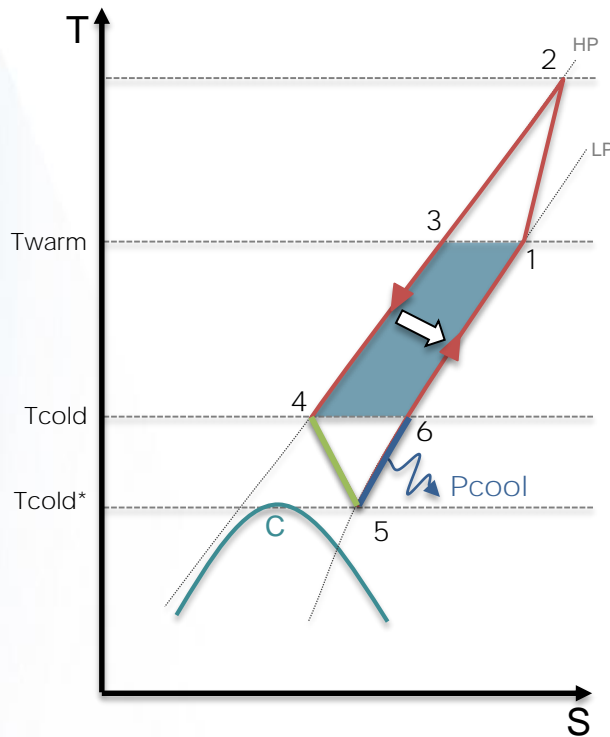
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Technologies implemented within Turbo-Brayton for space

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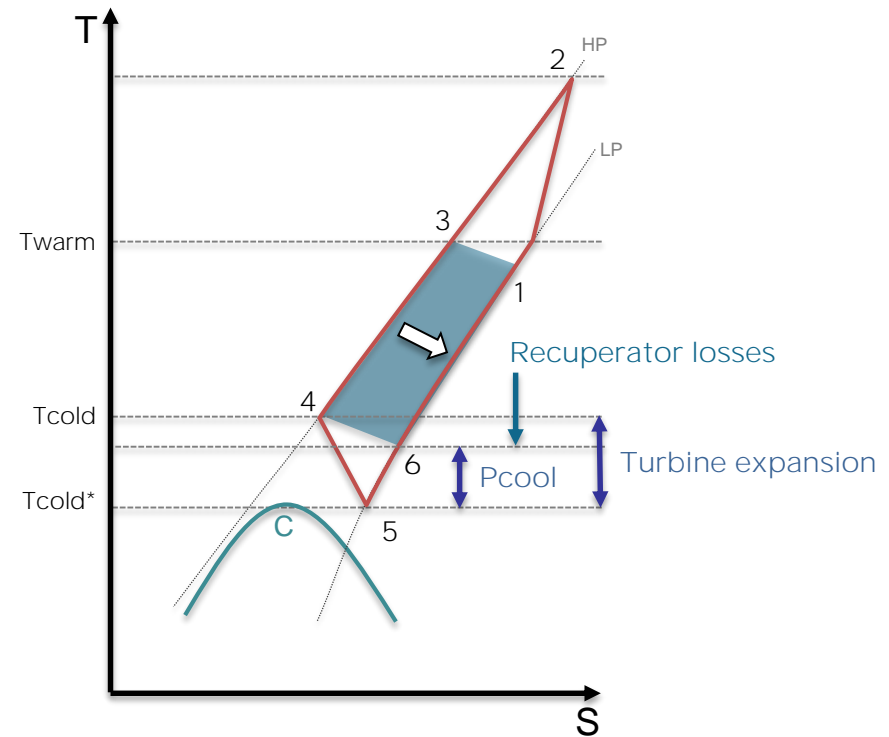
Recuperator

The recuperator is one of the most critical components regarding cooler performances



For a perfect recuperator: $T_6 = T_4$ and $T_1 = T_3$

In this case $P_{cool} = Q_m * (h_6 - h_5)$



For a real recuperator : $T_6 < T_4$

To go down to 80K, Efficiency > 97% required

To go down to 40K, Efficiency > 98% required

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Technologies implemented within Turbo-Brayton for space

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Recuperator

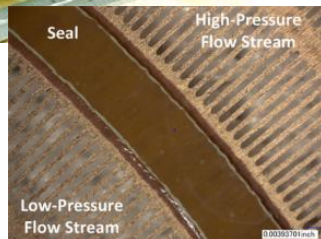
The recuperator is one of the most critical components regarding cooler performances

Furthermore the pressure drops need also to be minimized to improve the turbine expansion work and the axial conduction as low as possible

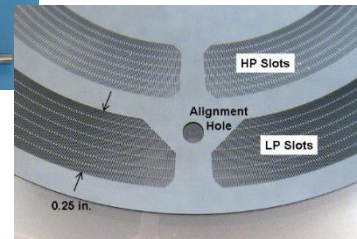
Finally, the recuperator needs to be compact and robust to mechanical loads

Several technologies are used for space systems:

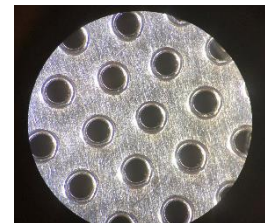
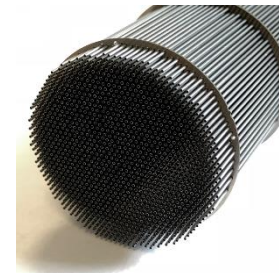
- Microchannels HX
- Microtubes



Microchannel copper plate



Microchannel Silicon plate



Microtubes

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Technologies implemented within Turbo-Brayton for space

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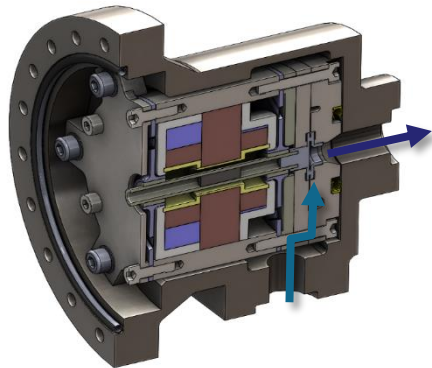
Turbine

A cryogenic expander (turbine) expands the gas to provide cooling effect

This expansion is “isentropic” and expansion work needs to be extracted

The expansion work is :

- Extracted by an cryogenic alternator - or turbo-alternator
- Extracted by an hydraulic break (second impeller operating as a compressor) and transfer to a secondary loop
- Recovered by the centrifugal compressor if they are mounted on the same shaft



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Technologies implemented within Turbo-Brayton for space

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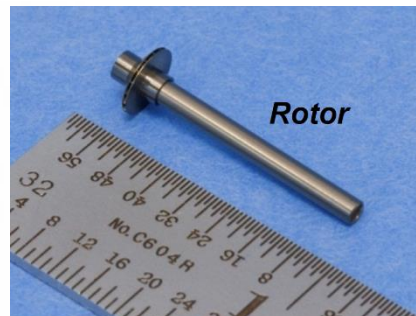
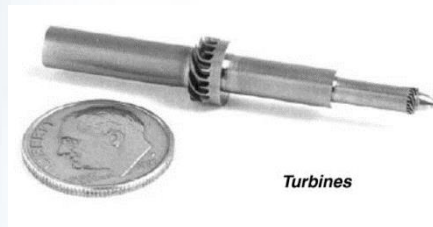
Turbine

The challenges for the expander are the same than for compressor, except that it is:

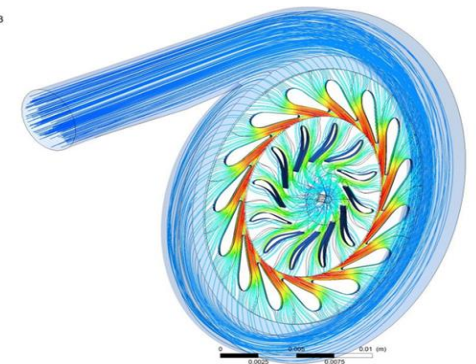
- Smaller, due to density effect
- Operating at cryogenic temperature !

So some technologies like the **magnetic bearing** or some **materials** for the motor or other **internal components**, can't be used in the cryogenic expander

The **thermal stability** over the temperature range is also extremely critical (particularly for hydrodynamic gas bearings)



Velocity
Streamline 3
97.1
72.9
48.6
24.4
0.2
[m s⁻¹]

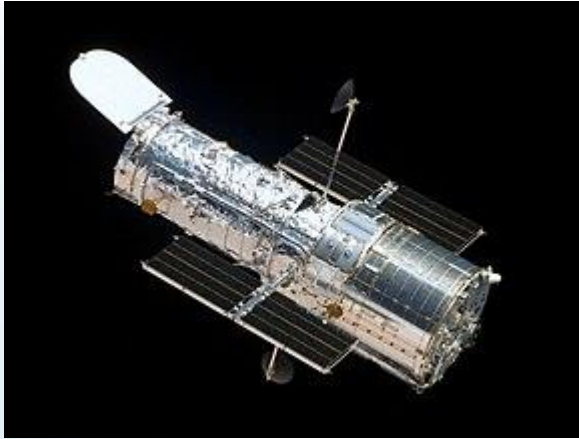


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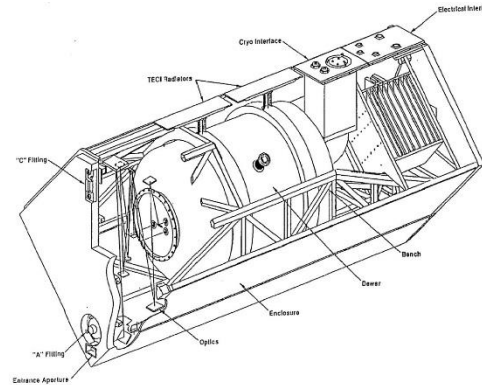
Examples of Turbo-Brayton activities

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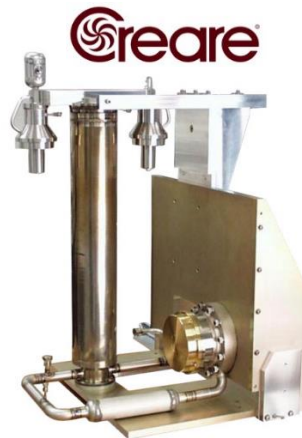
First turbo-Brayton in space



Hubble telescope



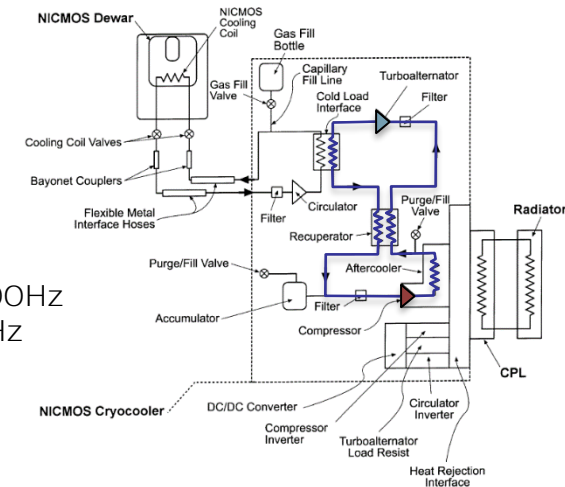
NICMOS IR camera



NICMOS turbo Brayton

Input power 315W
Cooling power 7 W@72K

Compressor operating at 7000Hz
Expander operating at 3500Hz



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NCC packaged for Extra Vehicular Activity (EVA)

Examples of Turbo-Brayton activities

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MELFI - « Minus Eighty degrees Laboratory Freezer for ISS »

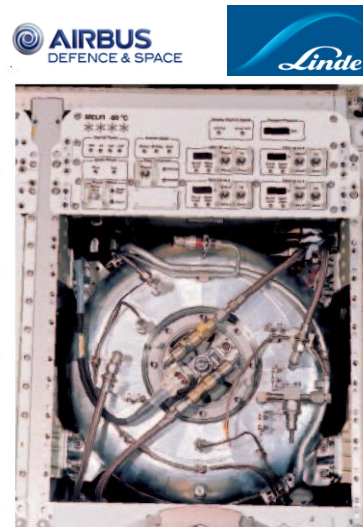
Freezer on-board ISS for storage and fast-freezing of life science and biological samples



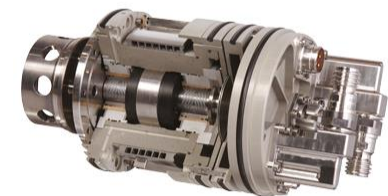
MELFI on-board ISS

Input power 800W
Cooling power 100W @ -80°C

Compressor/expander operating at 1500Hz



MELFI cooler



MELFI cartridge

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**ABSOLUT
SYSTEM**

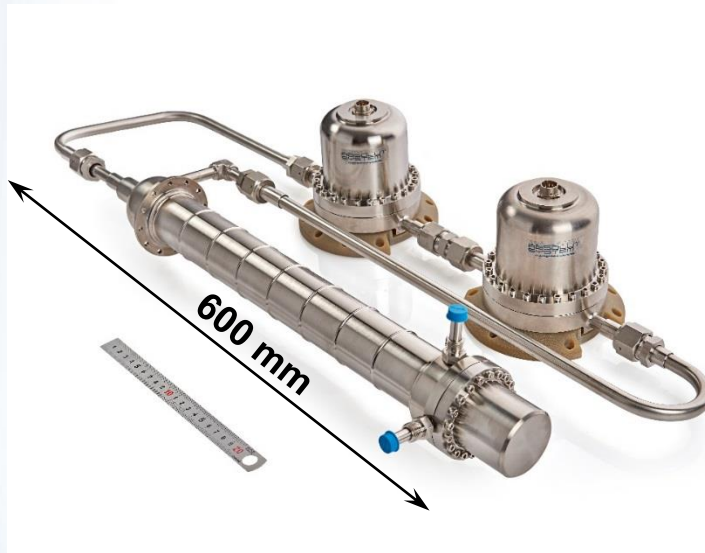
Examples of Turbo-Brayton activities

40-80K Vibration free cryocooler

Development for ESA to offer a vibration free solution for EU projects

Objectives are:

- To design, manufacture and test an EM of a “Vibration-Free” cooler
- To provide active cooling of $> 1\text{W}@40\text{K}$ with less than 180W input
- To generate less than 10mN exported vibration between $0\text{-}1000\text{Hz}$ (3-axis)
- To limit the rejection radiator surface at 1m^2



Centrifugal compressor
@Ambiant
Operating at 4200Hz

Turbo-alternator @40 K
Operating at 1500 Hz



Microtube recuperator
 $300\text{-}40\text{K}$ with integrated
Turbo-alternator



Monolythic shafts with
hydrodynamic gas bearing



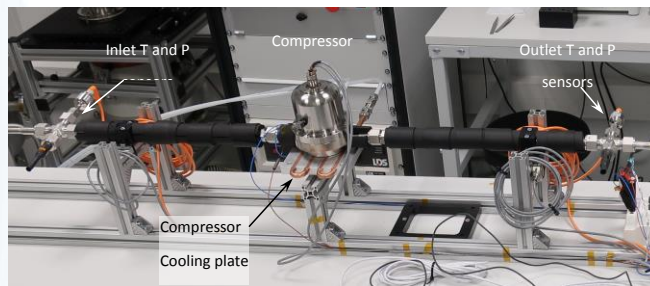
EM under testing
Cooling power expected:
 $3\text{W}@40\text{K}$ or $10\text{W}@80\text{K}$

Examples of Turbo-Brayton activities

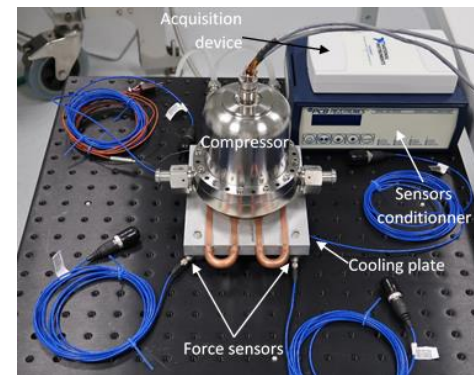
40-80K Vibration free cryocooler

Individual test of components

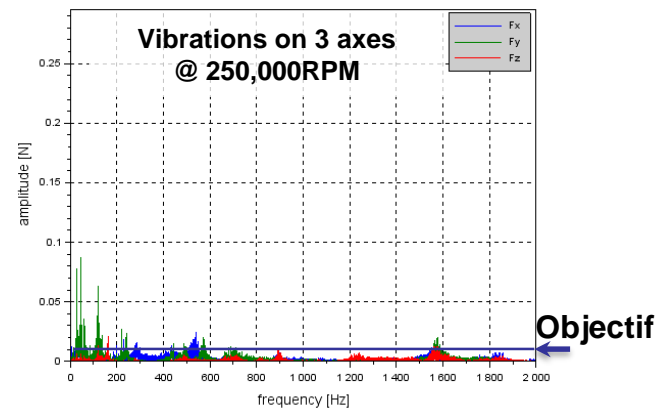
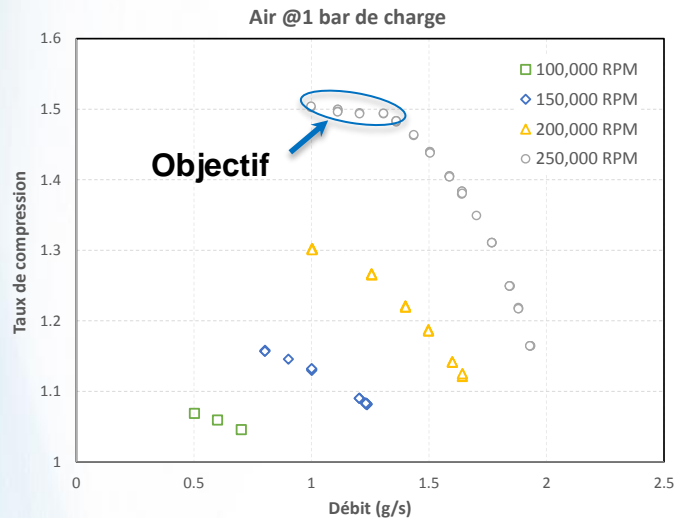
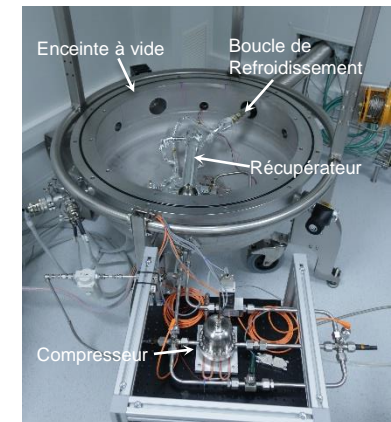
Compressor test bench



Exported vibrations test bench



Recuperator test bench



Thanks for your attention