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Presentation by J. Falter (TransMIT GmbH), at the KRYO 2013 Workshop, Oct. 8, 2013.

Efficient strategies towards low-loss damping of the intrinsic temperature oscillations in 4 K pulse tube coolers

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Outline

- **Motivation: Why using Pulse Tube Coolers (PTCs)**
- **Overview of TransMIT 4 K PTCs**
- **Some problems with using PTCs in highly-sensitive applications**
  (residual vibrations, temperature oscillations)
- **Methods for the damping of T-oscillations**
  (applications: sc voltage standards, THz-detectors in astronomy)

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Why Pulse Tube Coolers?

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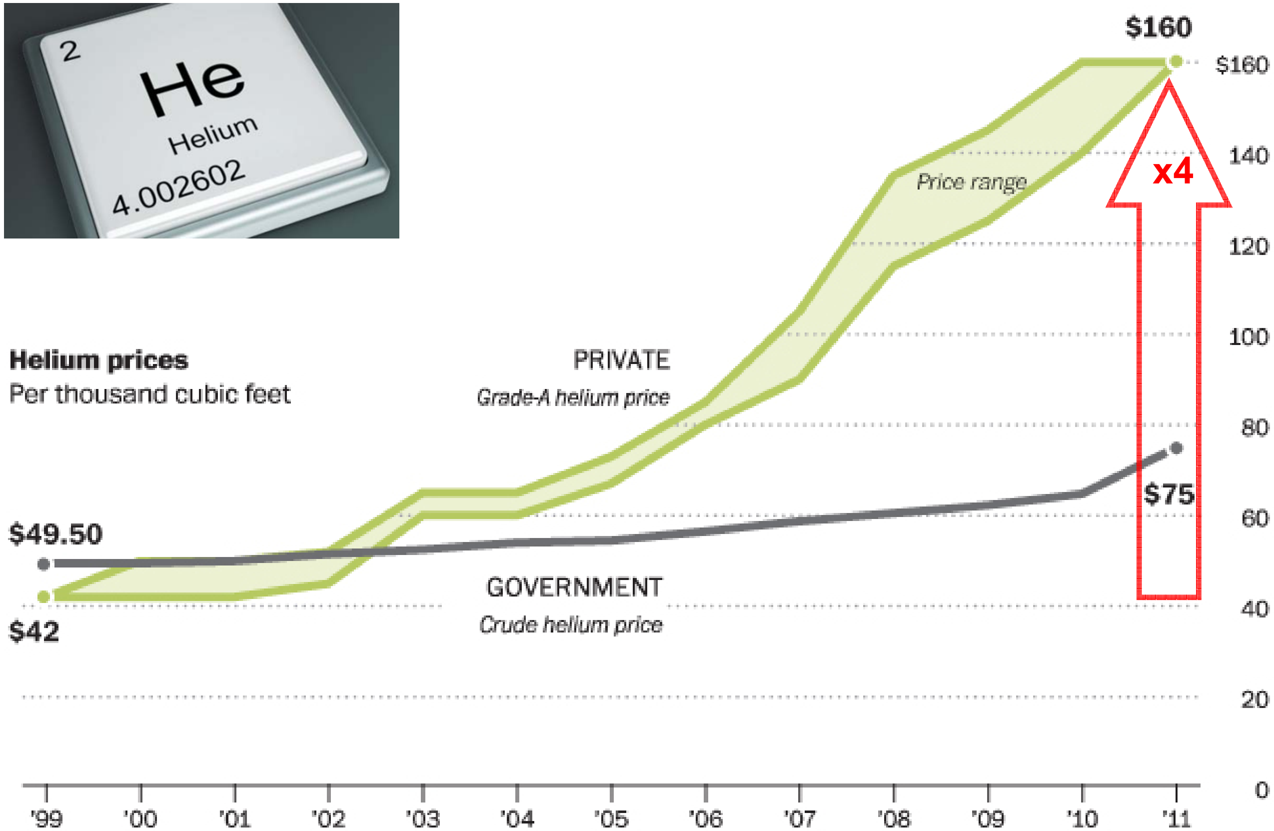

📖 Source: U.S. Geological Survey. Graphic: The Washington Post. Published on May 11, 2012

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Why Pulse Tube Coolers?

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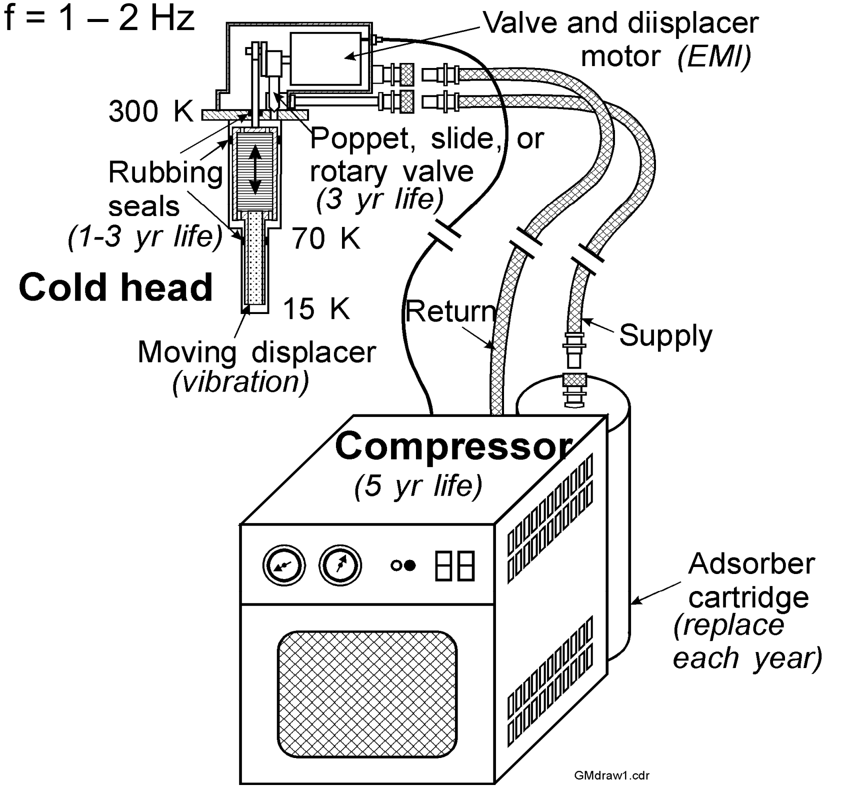
„Gifford-McMahon cooler“

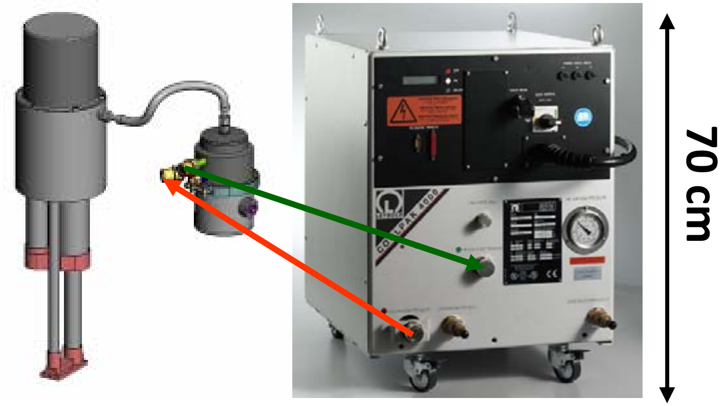


$P_{Compressor}$ = 2 -8 kW

Mass = 75-120 kg

Courtesy of R. Radebaugh (NIST)

„GM-type" PTC



No cold moving parts in the cold head →

-- No maintenance of cold head

-- Less vibrations and EMI

Disadvantage compared to GM-coolers:

-- Orientation dependence of performance (gravitation-induced convection)

-- Maintenance of compressor as for GM-coolers

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Pulse Tube Cooler Development in Giessen since 1993

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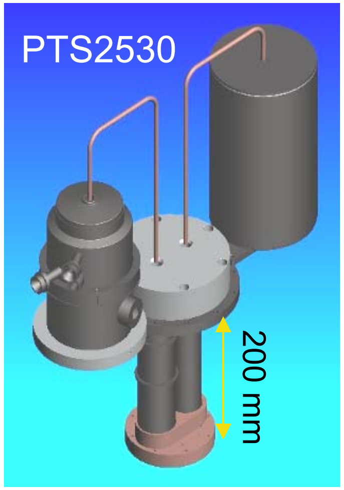
Gifford-McMahon (GM)-type PTCs
f = 1 - 4 Hz

1-stage PTCs for cooling at 20-100 K



Input power: 2 – 12 kW
Cooling power:
80 W @ 50 K (6 kW)
30 W @ 80 K (2 kW)

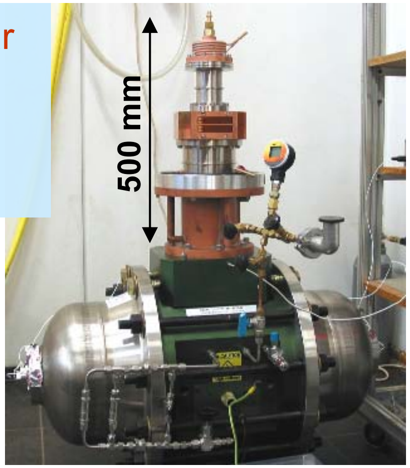
2-stage PTCs for LHe-temperatures

Input power: 2 – 7 kW
Cooling power:
0.2 – 1.2 W @ 4.2 K

1-stage Stirling-type PTCs
f = 40 - 60 Hz

With 50 - 200 W linear compressors
Cooling power: 1 – 9 W @ 80 K

With 10 kW linear compressor
Cooling power:
420 W @ 80 K



Additionally, under development: 2-stage STPTC versions for cooling below 30 K

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2-Stage 4 K PTC (PTD406)

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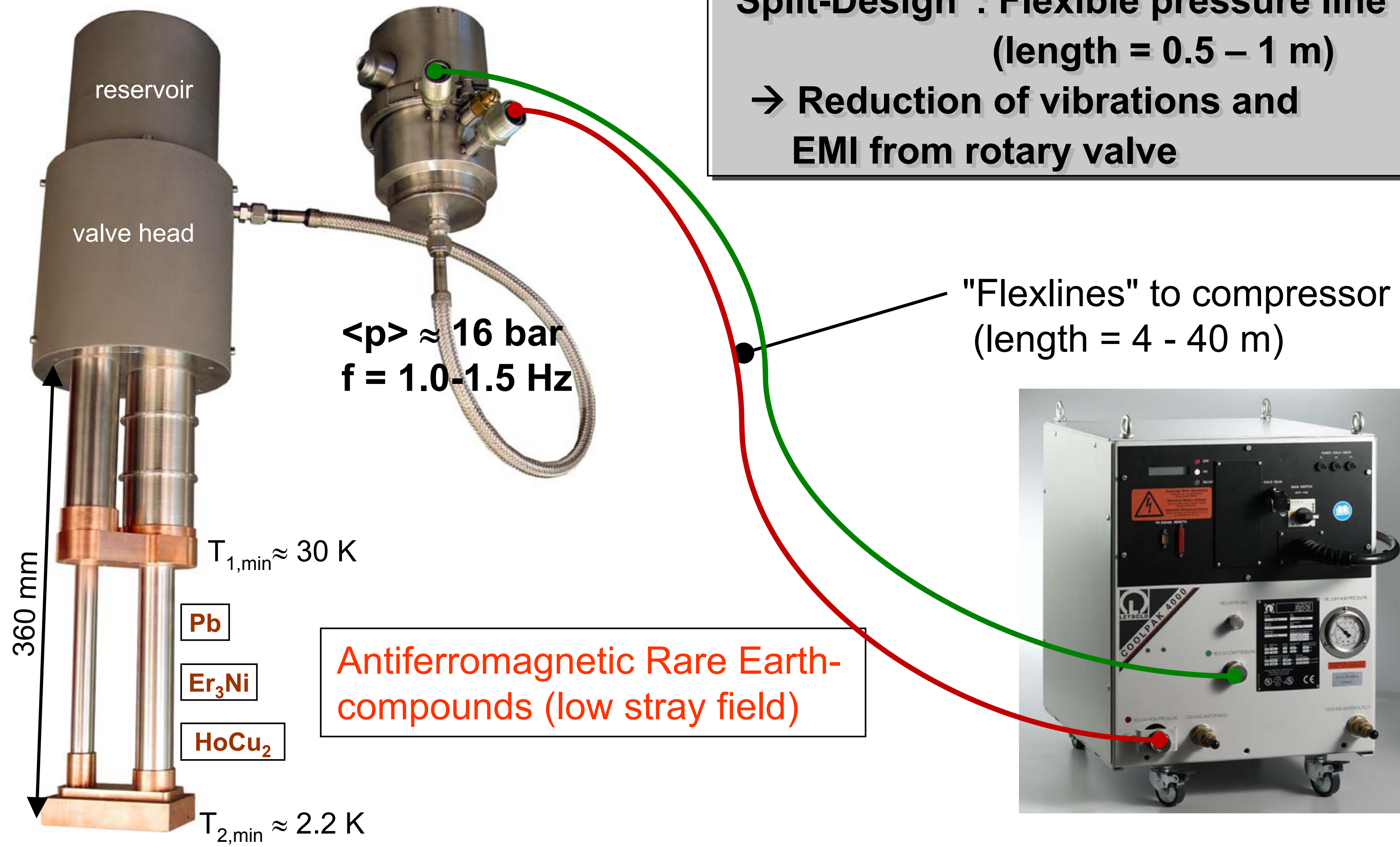
"Split-Design": Flexible pressure line (length = 0.5 – 1 m)

→ Reduction of vibrations and EMI from rotary valve



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Working Principle of a PTC

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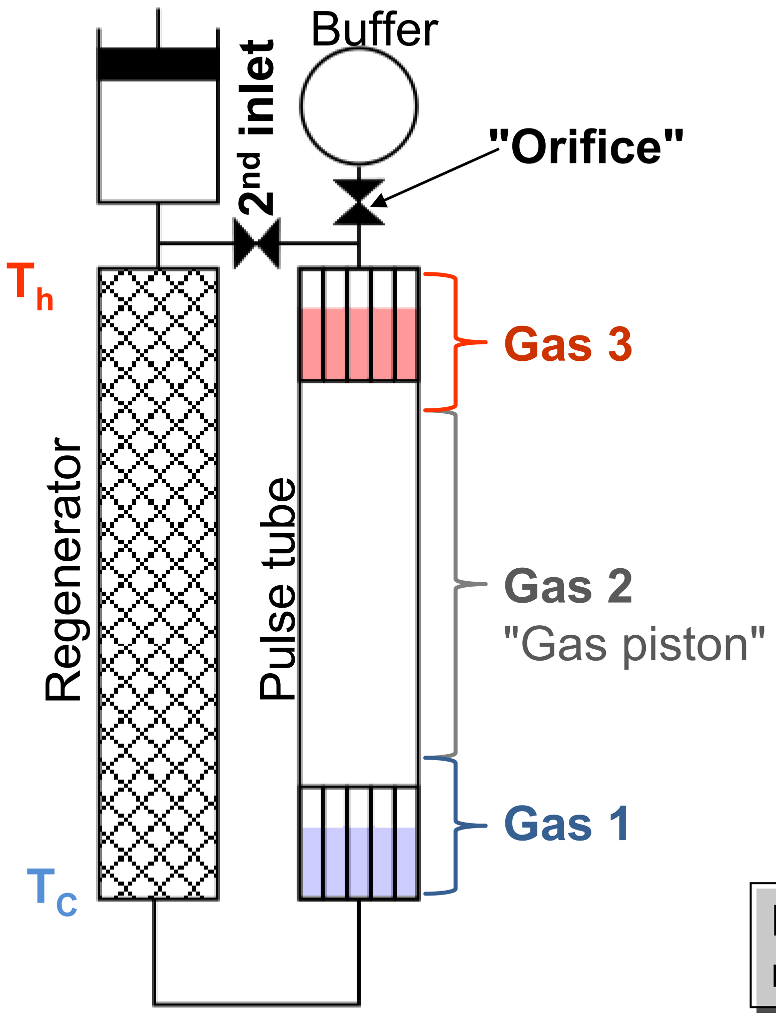
Schematic of single-stage PTC



- **Gas column in pulse tube can be divided in 3 parts:**
  - Gas 1: oscillates through the cold heat exchanger T_c and absorbs heat from the cooling load.
  - Gas 2: („invisible“) acts as piston that controls the movement of the upper and lower gas parts.
  - Gas 3: flows periodically through the warm heat exchanger T_h and releases heat to the ambient environment.

- Cooling power (ideal) is given by the expansion work per time of gas 1:

$$\dot{W} = f \oint p \cdot dV$$

Regenerator losses increase with (T_h-T_c) → multistage PTC needed for cooling below 10 K !

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PTD406C with SHI F-70H Compressor

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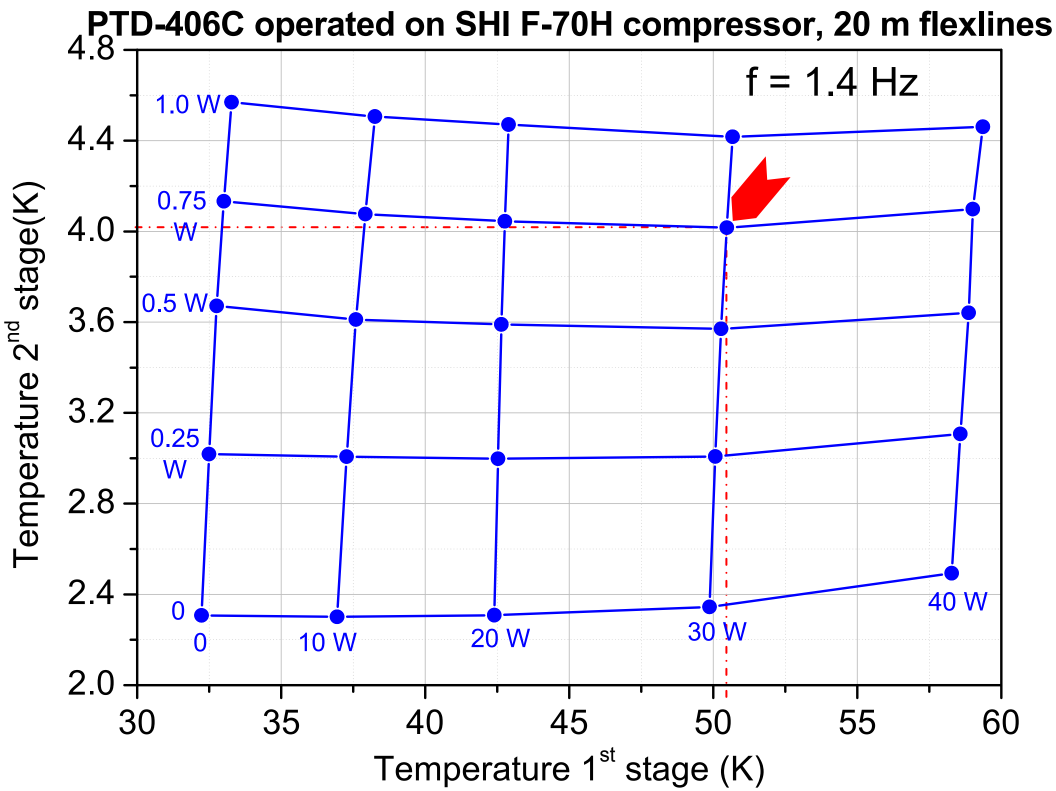
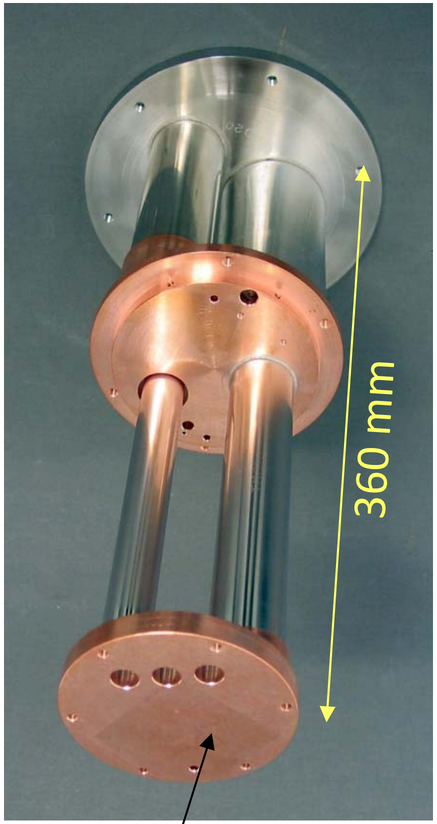


Simultaneously available cooling powers with F-70H:

2^{nd} stage: **0.75 W @ 4.02 K (0.87 W @ 4.22 K)**

1^{st} stage: **30 W @ 51 K**

Input power: **7.0 kW**



PTD406**C** has same dimensions as PTD406 but cold platforms are **C**oncentric.

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Performance of TransMIT 4 K PTCs

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Model (remote rotary valve)	$P_{Compressor}$ (stationary)	Typ. cooling power 2nd and 1st stage	T_{min}	Cool down time to 4 K
PTD4200	2.0 kW	0.25 W @ 4.2 K 1 W @ 57 K	< 2.8 K	< 120 min
PTD4200-4kW	3.8 kW	0.5 W @ 4.2 K 5 W @ 55 K	< 2.6 K	< 75 min
PTD406 / PTD406C	5.7 kW	0.7 W @ 4.2 K 10 W @ 47 K	< 2.4 K	< 65 min
PTD411	7.1 kW	1.17 W @ 4.2 K 20 W @ 53 K	< 2.4 K	< 65 min
Cryomech PT415*)	9.2 kW	1.5 W @ 4.2 K 40 W @ 45 K	2.8 K	60 min
Sumitomo SRP-082B*)	7.0 kW	1.0 W @ 4.2 K 40 W @ 45 K	< 3.0 K	< 80 min

*) Integral rotary valve !

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Possible Application Problems

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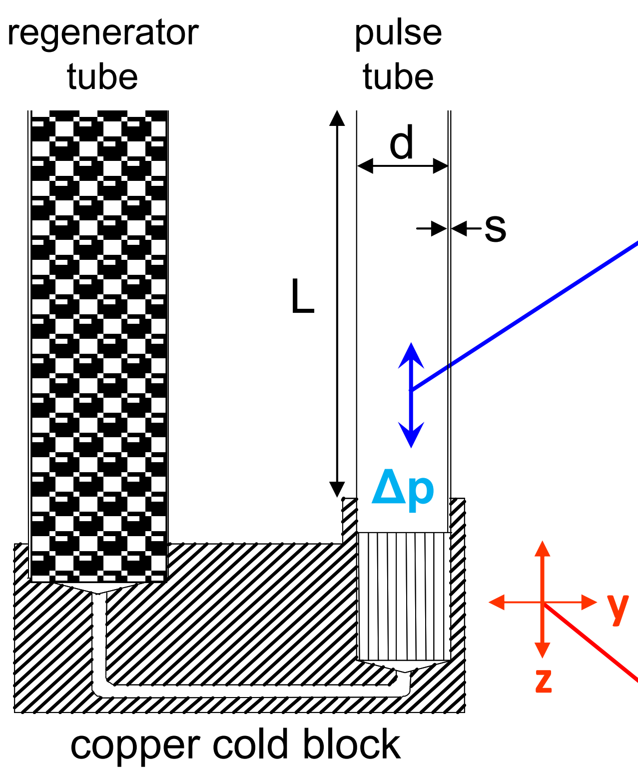

- **Temperature oscillations:**
  from periodic expansion *(adiabatic)* of the working fluid ($He_{(g)}$)

$$\Delta T = \frac{\alpha_V T}{\rho C_p}\Delta p$$

Volume expansion coefficient:
$\alpha_V = 1/V\,(dV/dT)_p$

mainly a problem near 4 K

- **Mechanical vibrations:**
  periodic elastic deformation („breathing“) of the thin-walled tube with the pressure oscillation (s: wall thickness; d: diameter)

$$\frac{\Delta L}{L} = E^{-1}\frac{d}{2s}\Delta p$$

(E: Young´s modulus)

problematic for sensitive measurements

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„Compact“ 4 K PTC (PTD4200) for Cryoelectronics

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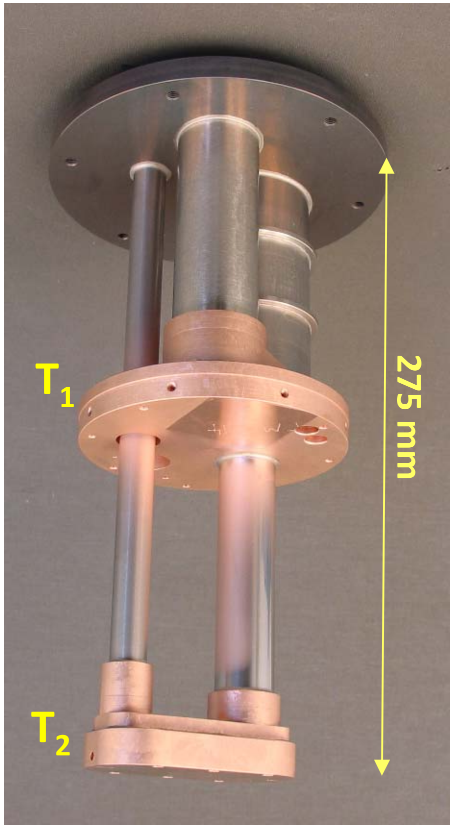
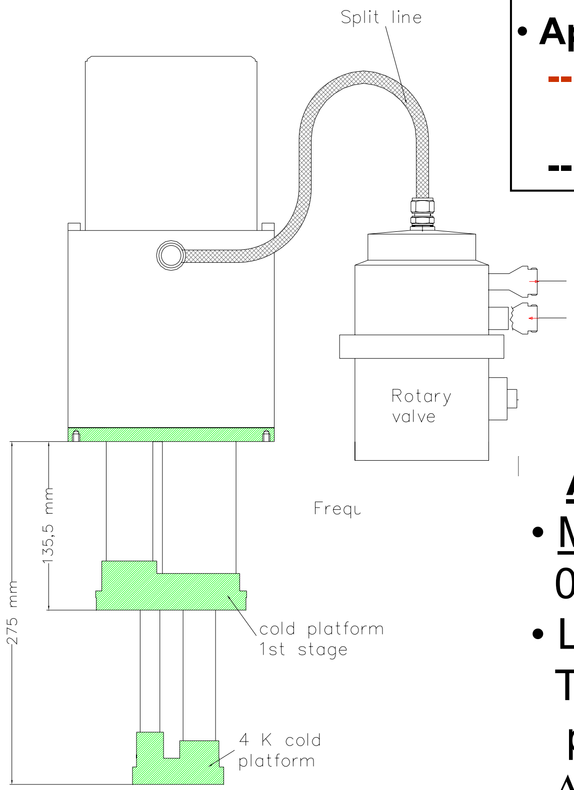
PTD 4200





- **Designed for 2 kW compressor**
- **Applications in Cryoelectronics**
  - **-- 4 K cooling of Josephson voltage standards** *(IPHT Jena / Supracon AG)*
  - **-- Precooling of THz-detectors** *(IPHT Jena)*

Advantages:

- More compact: Cold head volume ≈ 0.6 × volume of PTD406
- Lower vibrations and lower T-oscillations because of smaller p-p pressure variation: $\Delta p \approx 6$ bar p-p with 2 kW compressor
- Only single-phase wall power needed

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Cooling Performance of PTD4200

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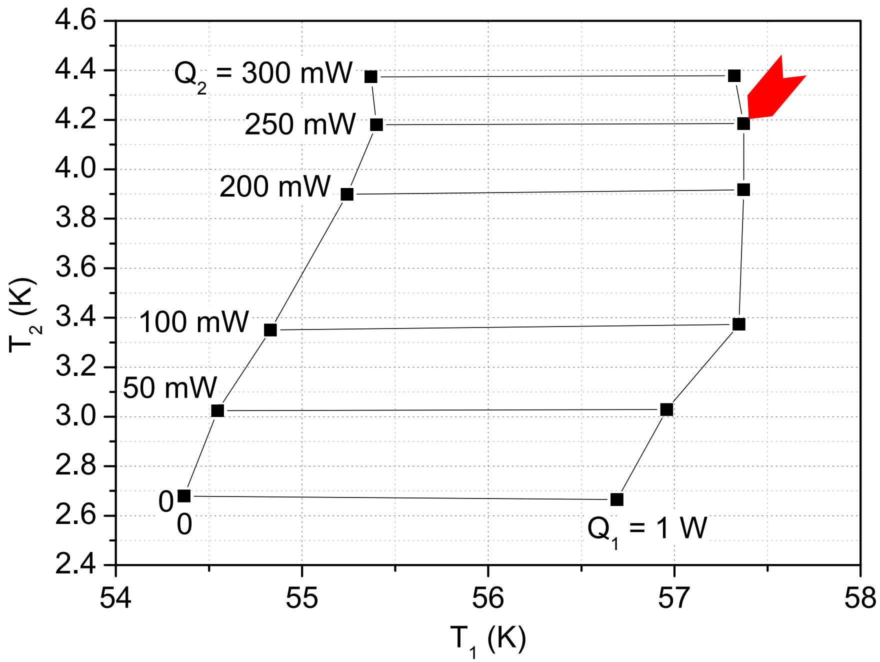
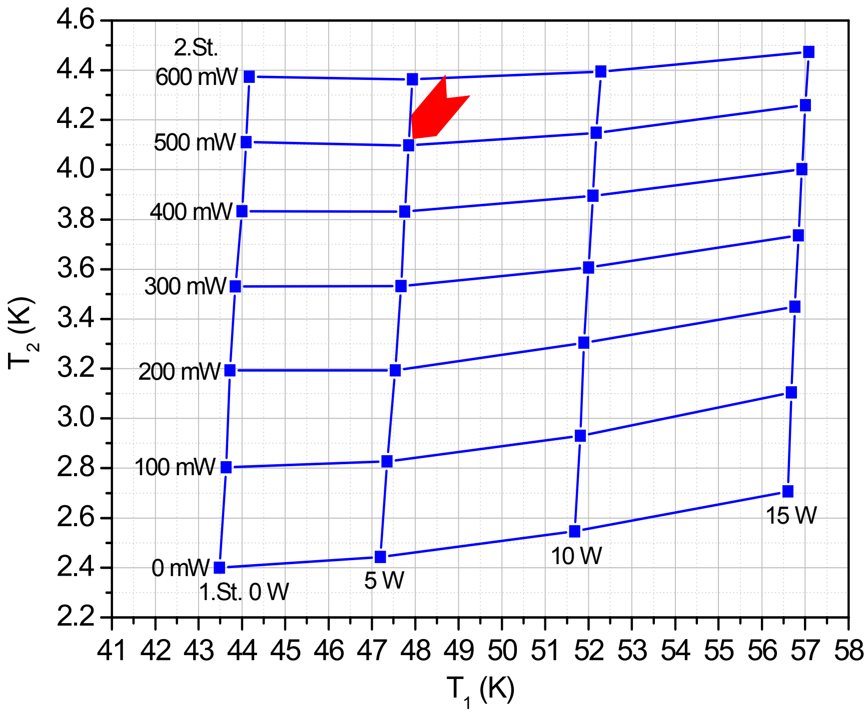
2 kW compressor (Leybold CP2000A)



- Simultaneous cooling powers: 250 mW @ 4.20 K and 1.0 W @ 57 K with 2 kW electric input COP (4.2 K) = 1.25 × 10^{-4}

4 kW compressor (Leybold CP4000)



- Simultaneous cooling powers: 500 mW @ 4.10 K and 5 W @ 48 K with 4 kW electric input

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Vibration Spectra of a PTC: PTD4200 (2 kW and 4 kW)

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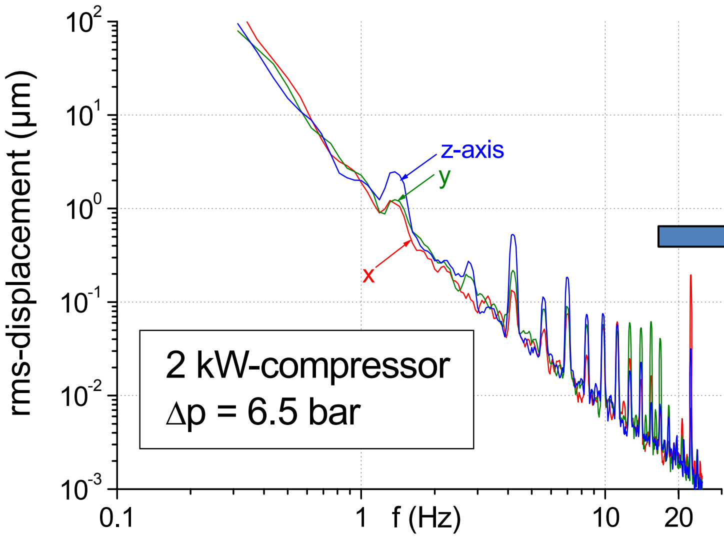
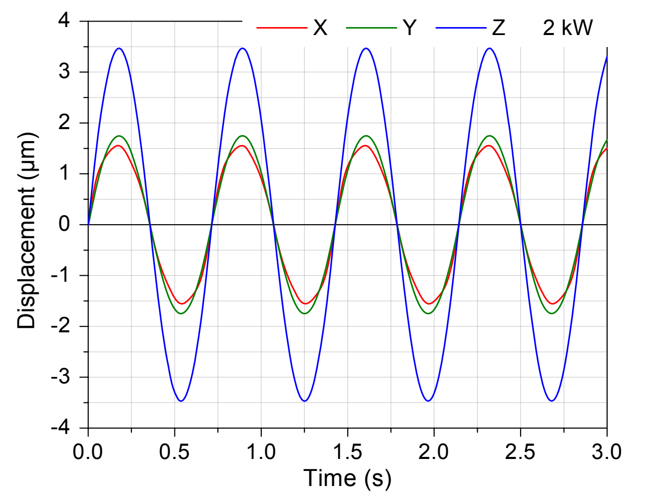
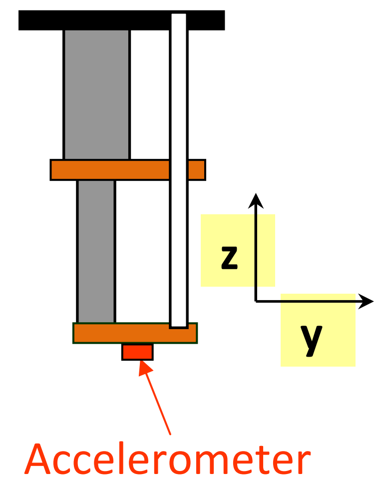
PTD4200, f = 1.4 Hz, $T_2 \approx 0$ °C

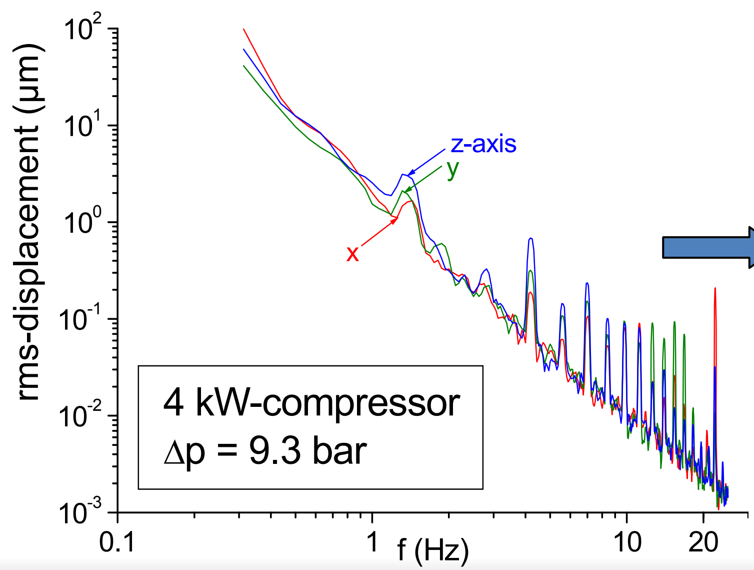


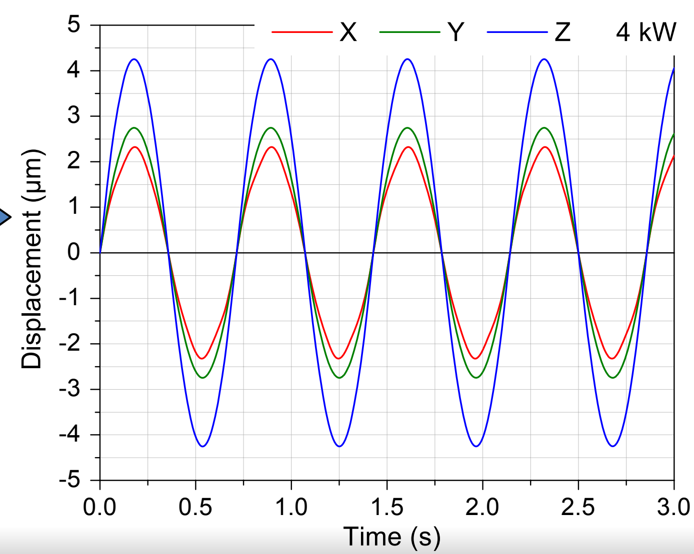
Mechanical vibrations:



2 kW-compressor:
x : ± 1.6 µm
y : ± 1.8 µm
z: ± 3.4 µm







4 kW-compressor:
x : ± 2.3 µm
y : ± 2.7 µm
z: ± 4.4 µm

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4 K PTC for Laser-Interferometer (ESA/PTB)

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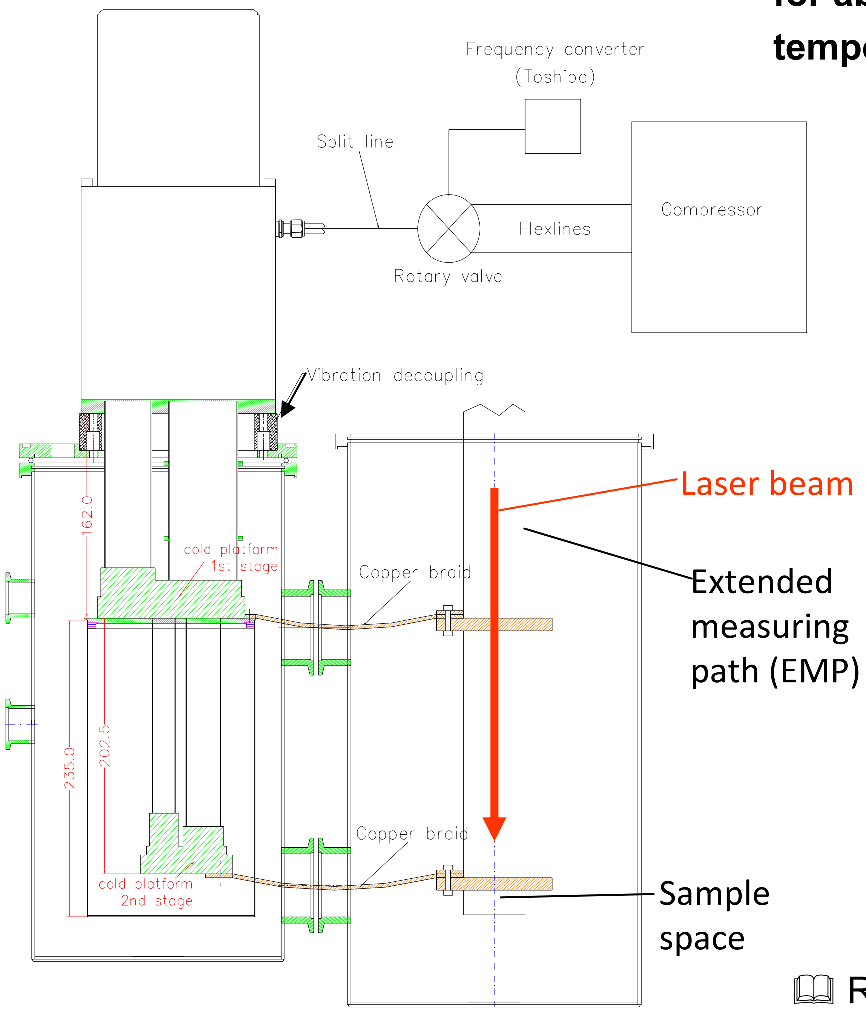
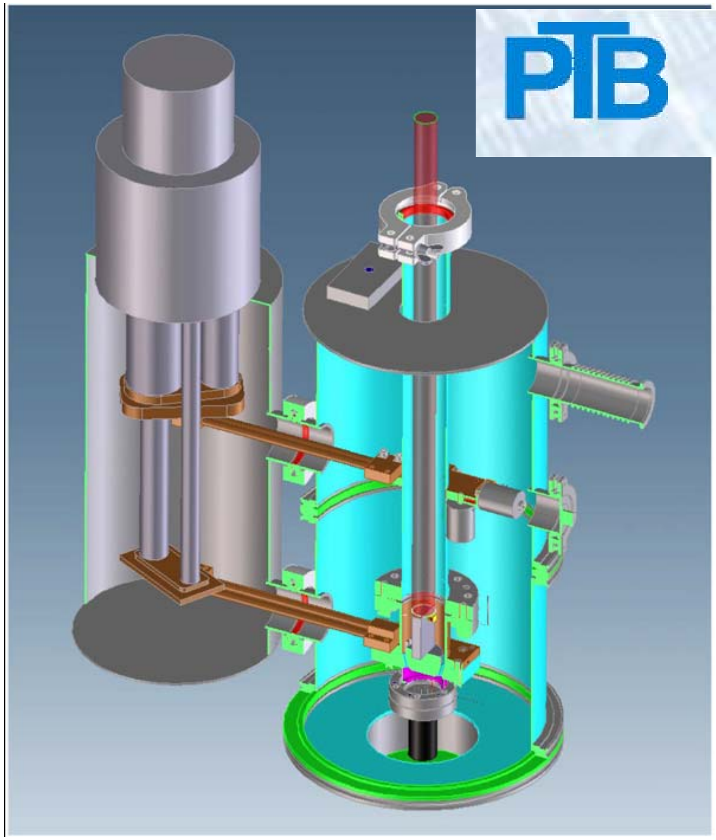
ESA/PTB/TransMIT project "Ultra Precision Interferometer for absolute length measurements down to cryogenic temperatures" (08/2010-01/2012)





📖 R. Schoedel et al., Meas. Sci. Technol. **23** (2012) 094004

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Countermeasures against Mechanical Vibrations of PTCs

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Further reduction of vibrations:

- by increasing the wall thickness s of the stainless steel tubes:
  $\Delta L/L \sim E^{-1} (d/2s)\, \Delta p$
- by decreasing the compressor input power, i.e. Δp
- by mechanical decoupling of the cold platform !

All methods are at the cost of available cooling power !

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Low-Noise Cooling of Josephson Voltage Standards

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Application: Primary 1 V and 10 V standards in electronics industry and metrological institutes

ipht jena

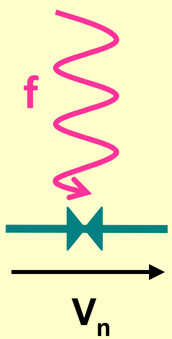
supracon

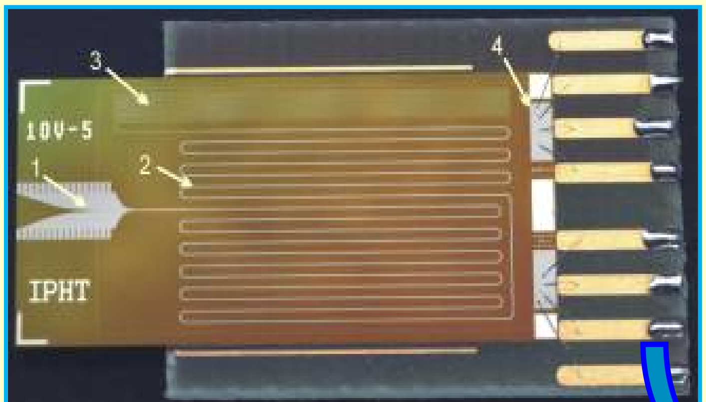
Synchronisation of Josephson oscillations by microwave radiation:

$V_n = n \cdot \Phi_0 \cdot f$ (n = 1,2,3,…)

$\Phi_0 = h/2e$

$= 2.0678\ldots\ \mu V/GHz$

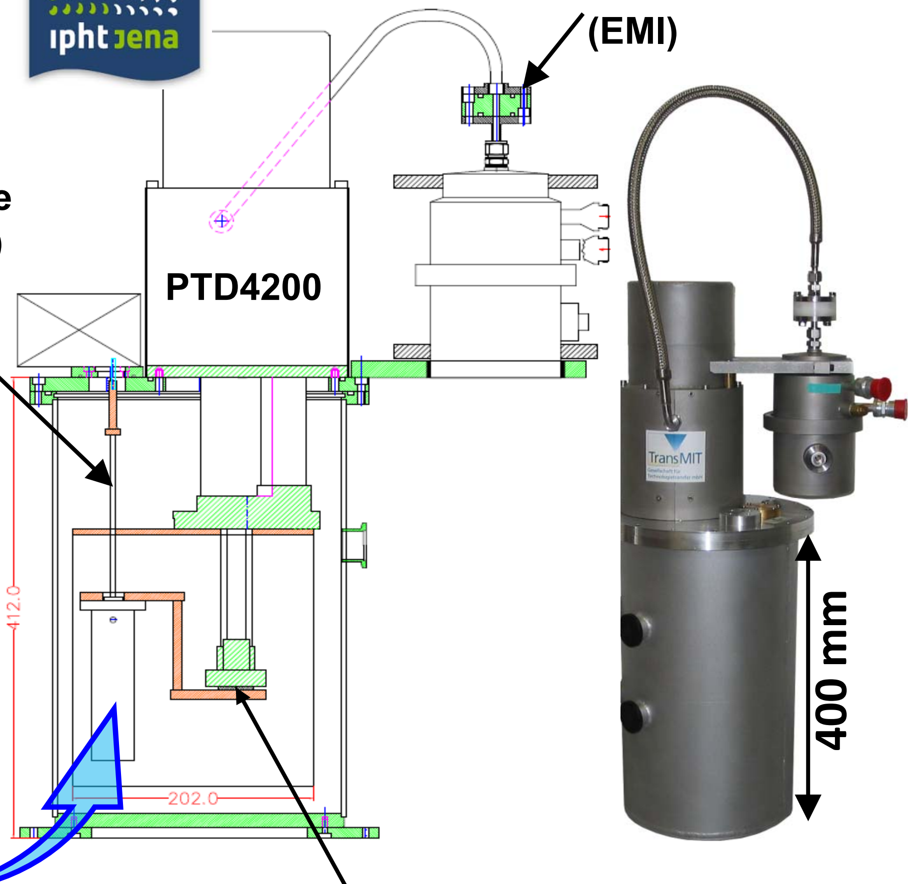




10 V-standard chip
(20,000 Nb junctions in series)
Photo: Courtesy of M. Schubert, IPHT Jena

Electr. insulation (EMI)

Dielectric wave guide (≈ 75 GHz)



Josephson-chip in cryoperm-shield at ≈ 3.8 K

Damping plate (T-oscillations: ΔT < 20 mK)

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Damping of T-oscillations for improving the accuracy of voltage standards

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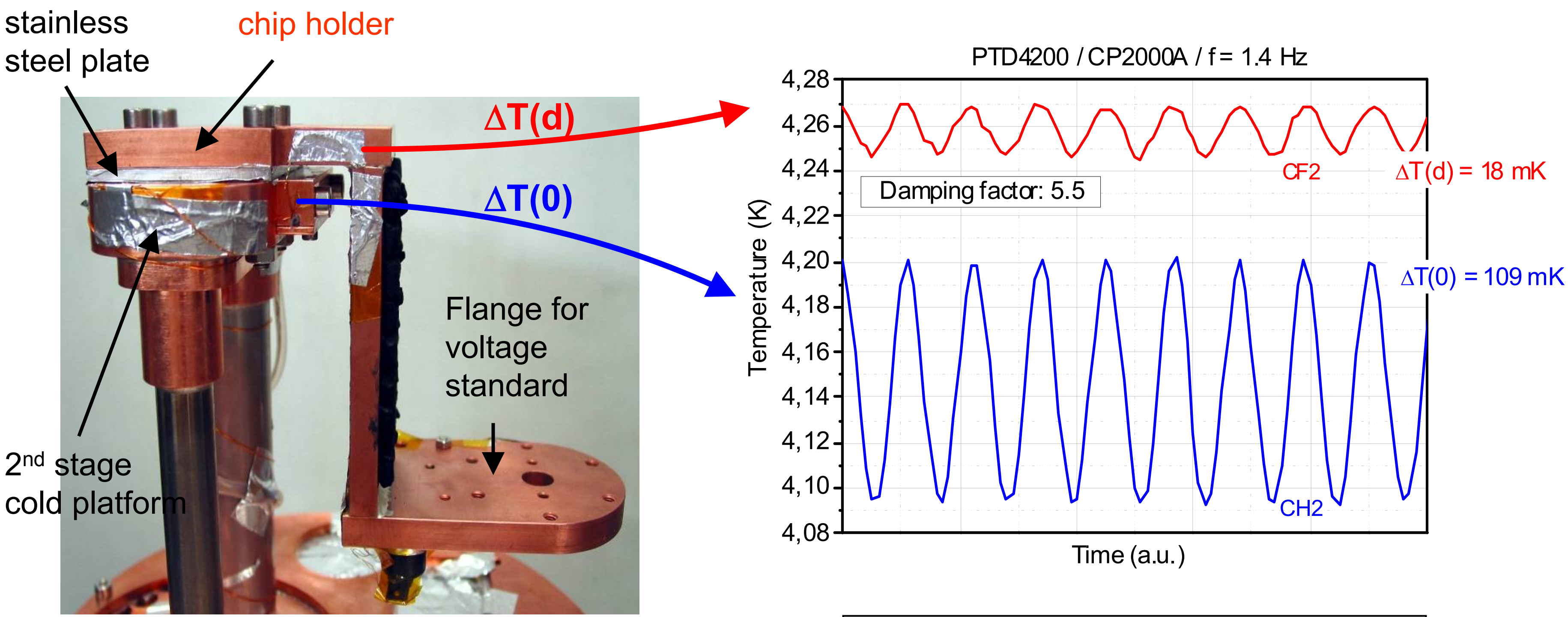

Stainless steel plate (thickness d ≈ 3 – 5 mm)
for damping of T-oscillations

$\Delta T(d) = \Delta T(0) \exp[-d/\delta_{th}]$, $\delta_{th} = [a/(\pi f)]^{1/2}$
with thermal diffusivity $a = \lambda/(\rho c_p)$

$\delta_{th}(4\ \mathrm{K}, 1.4\ \mathrm{Hz}) = 1.9$ mm for stainless steel

Draw back: Low thermal conductivity λ of stainless steel leads to a loss of cooling power.
Method only suitable for moderate (< 100 mW) heat loads from the device to be cooled !!

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Damping of T-oscillations by a metal plate sandwich

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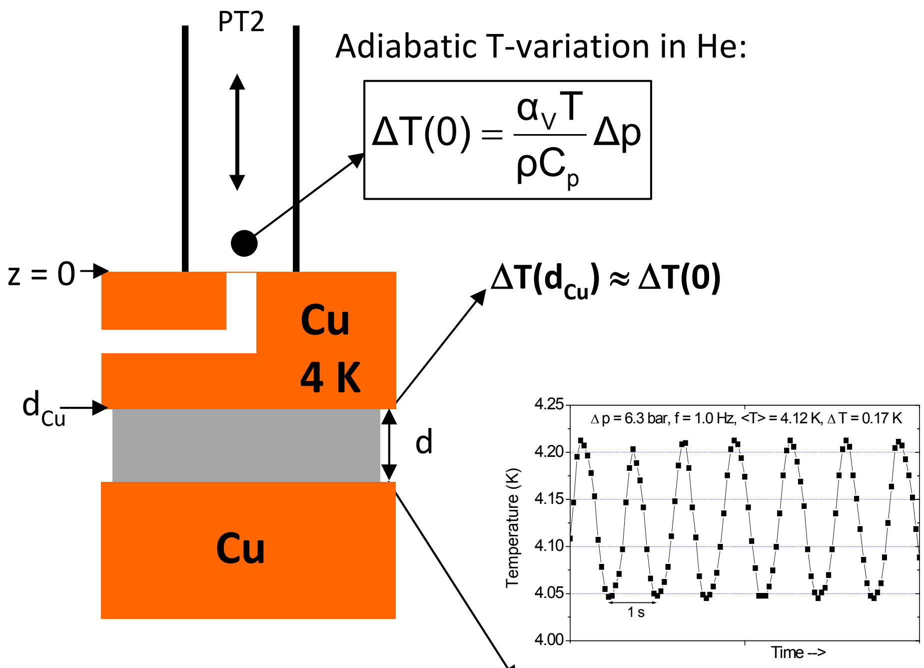

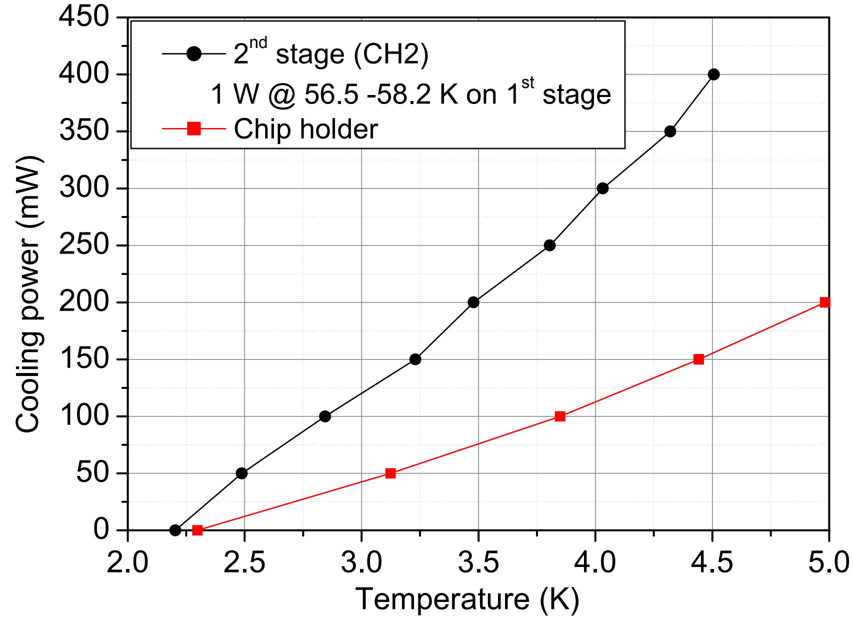

Damping of T-oscillations by sandwiching of a heat conducting plate (thickness d) with low thermal penetration depth δ_{th} (Giessen 2004):

$$\Delta T(d) \approx \Delta T(0) \exp[- d/\delta_{th}]$$

$$\delta_{th} = [a/(\pi f)]^{1/2}$$

with thermal diffusivity $a = \lambda/(\rho c_p)_{Plate}$

Material	a(4 K) [m^2/s]	λ(4 K) [W/(m·K)]	**δ_{th}(4 K,1 Hz) [mm]**
ErNi	$0.2\cdot10^{-4}$	≈ 1	**2.5**
Stainless steel (1.4301)	$0.15\cdot10^{-4}$	0.24	**2.2**
Copper (RRR = 100)	*0.735*	*660*	***480***

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4 K PTCs for IR-Astronomy

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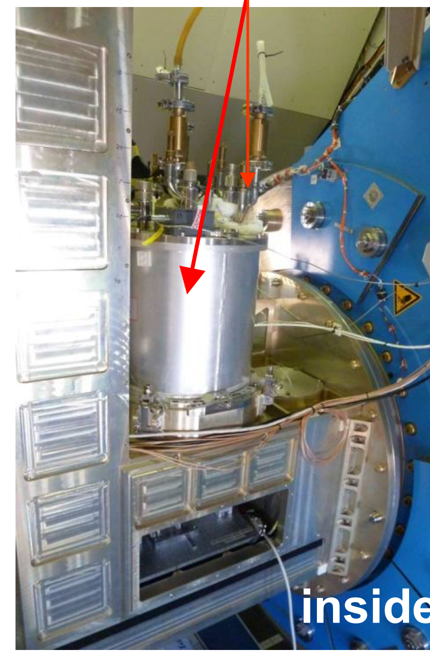
SOFIA project (USA, Germany)

Far-IR spectrometer (MPI for Radio Astronomy, Bonn, Germany)

Vacuum vessels for cryocoolers



Requirements for cooling the detector (1.25-1.5 THz) and electronics:

- **No large LHe-bath → Cryocooler needed**
- **Refrigeration temperature ≈ 4 – 4.5 K**
- **Cooling power ≈ 0.5 – 0.7 W !**
- **Compressor must be air-cooled !**

- **Temperature variations < 20 mK without loss of cooling power !!**

→ 4 K PTC with small LHe pot as damping unit

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4 K PTC with LHe-pot Damping Unit

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He gas inlet
from outer He-cylinder

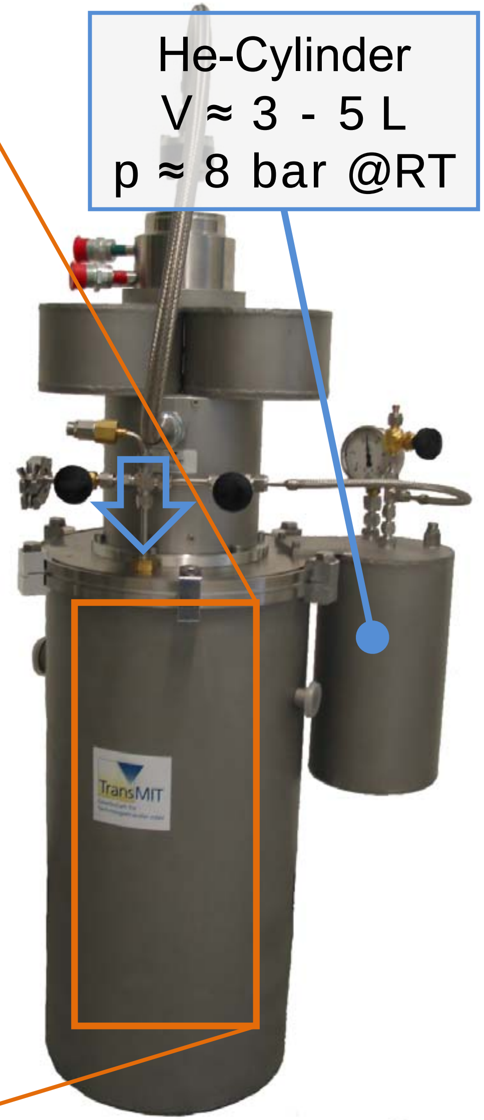
Precooling of
gaseous He at 1st stage

Gradual cooling-down of
He gas in capillary
along regenerator 2

Cold flange 2nd stage

Fast liquefaction of
precooled He at
2nd stage into
Helium pot

Mounting Platform
for Experiment



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Function of the LHe-pot

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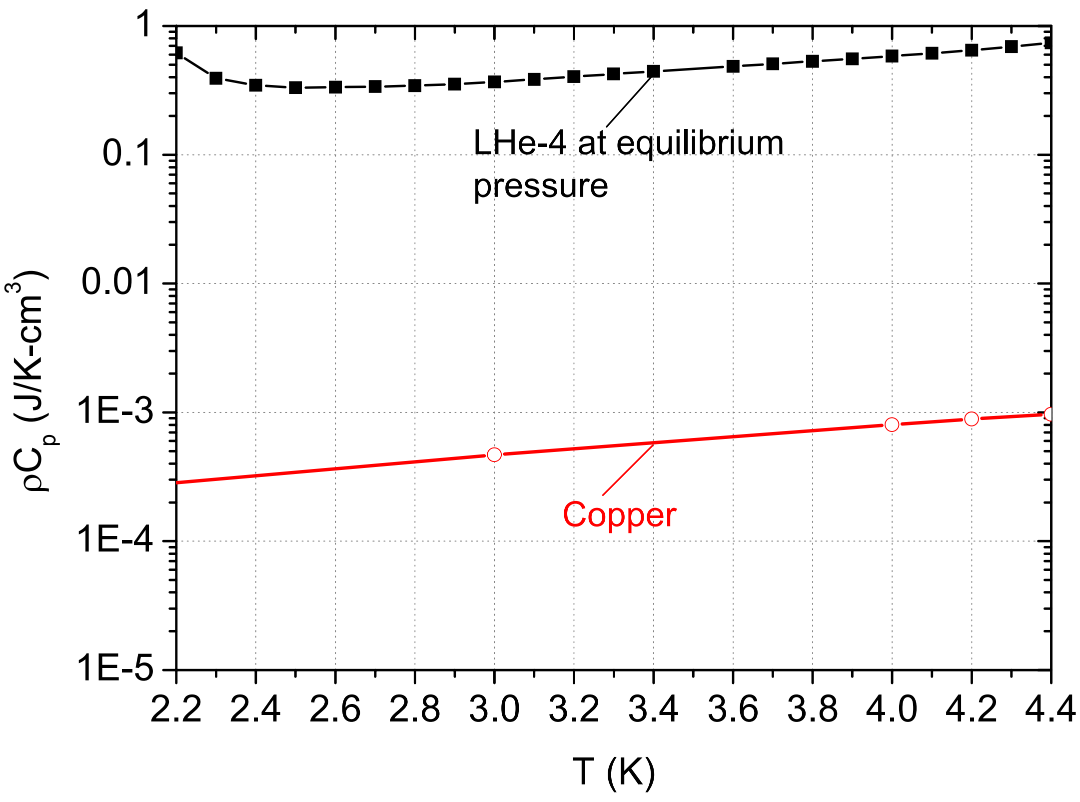
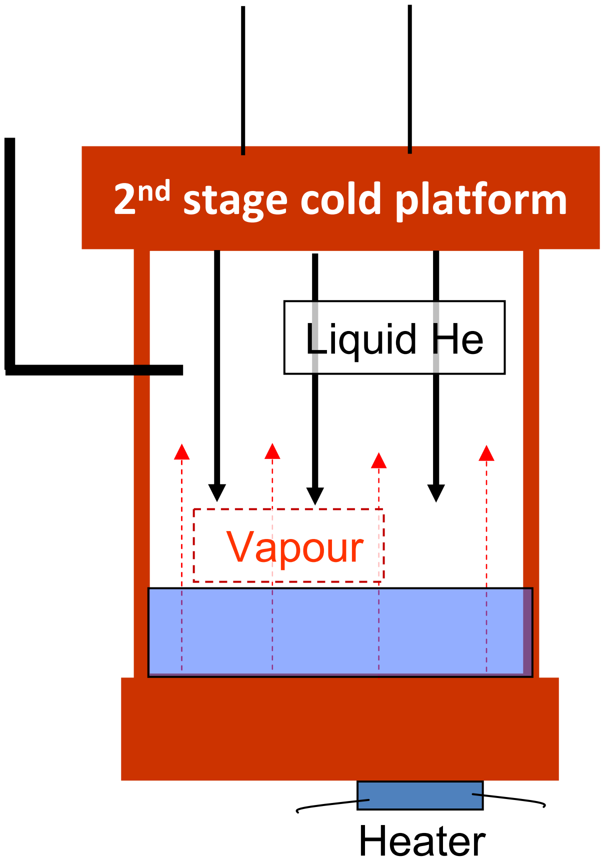
Damping of T-oscillations by the high volumetric heat capacity of LHe



Enhanced heat transfer due to two- phase flow of He in the pot



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4 K PTC with LHe-pot: Damping Results

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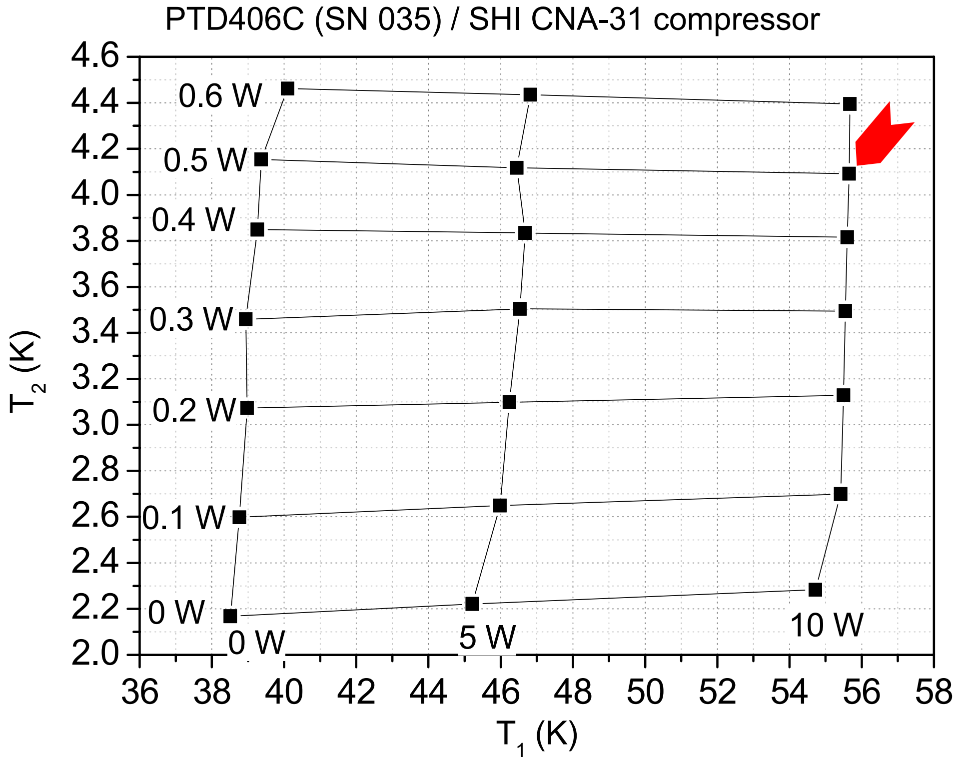

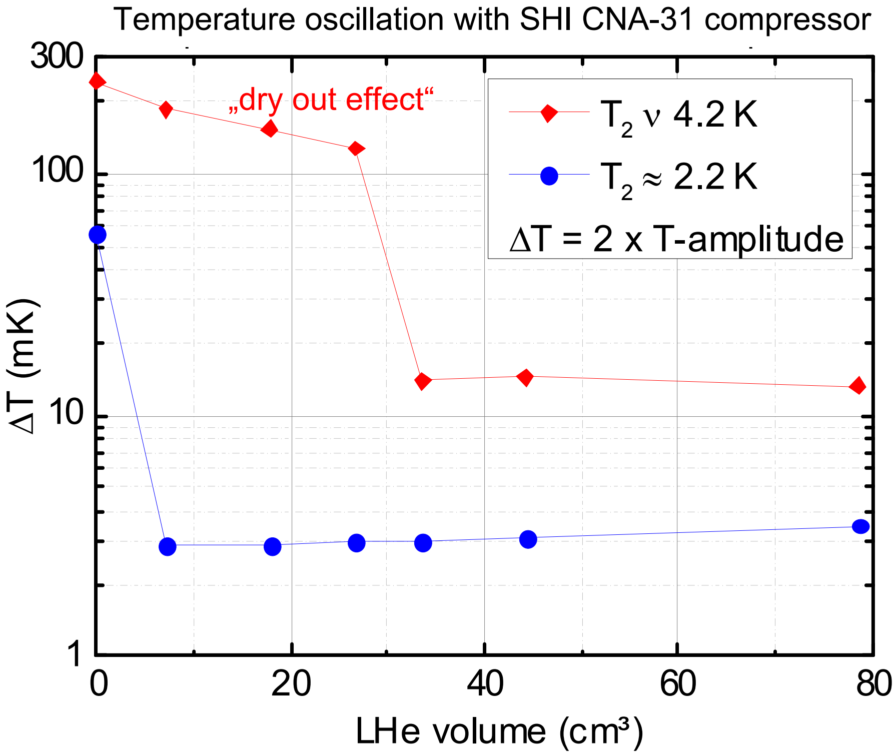

Cooling power with air-cooled SHI CNA-31 compressor:

0.5 W @ 4.10 K at bottom of LHe-pot with 10 W @ 55.6 K and 3.5 kW el. input !

Base temperature (no load): 2.17 K

- **ΔT (4.2 K) ≈ 14 mK for $V_{LHe} \geq 35$ cm³**
- **Sufficient damping without loss of cooling power at 4.2 K !**

Up to now:
four units with LHe-pot built and sold...

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Measured Temperature Oscillation

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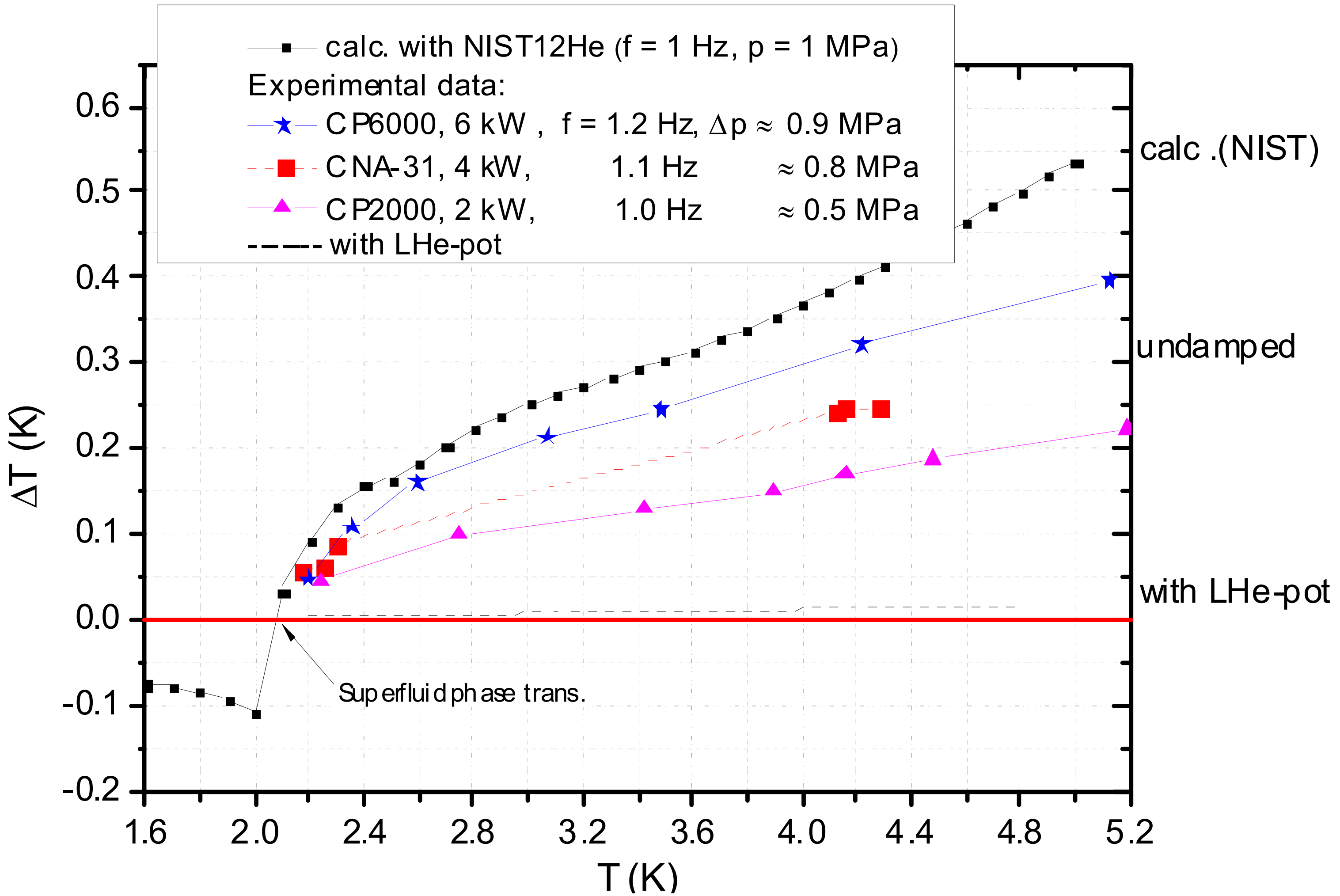

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Summary

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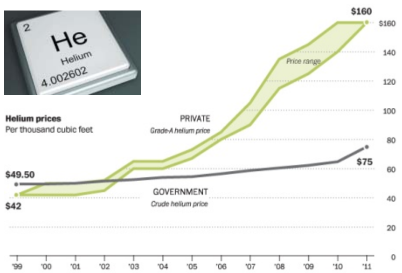
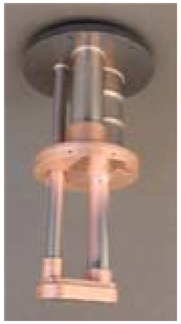
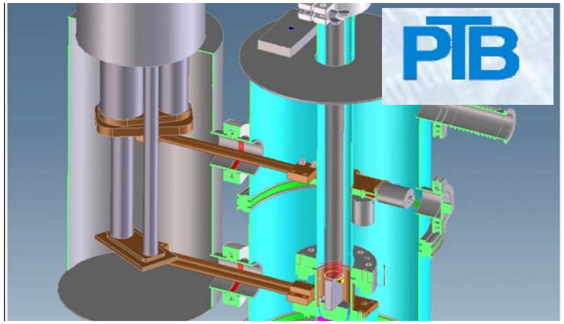
- **Growing demand of 4 K PTCs**
  because of growing ^4He price
  and expected ^4He shortage

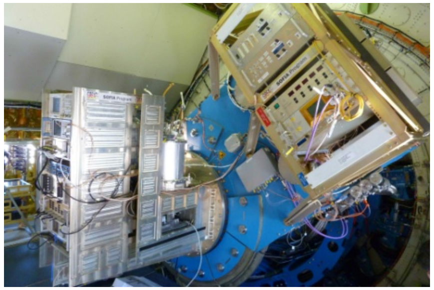


- **Customized TransMIT 4 K PTCs**
  for low-vibration applications
  - „compact“ tube layout (PTD4200)
  - mechanical decoupling from the experiment (e.g. PTB/ESA Laser interferometer)





- **Methods for damping the temperature oscillation of PTCs**
  - metallic alloy plate (Josephson sc voltage standards)
  - LHe- pot (THz-detectors in astronomy)



courtesy of Dr. Christophe Risacher, MPIfR Bonn

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