Cryogenics by use of 4 K Pulse Tube Cryocoolers

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Outline

- **Short overview: PTC development in Giessen**
- **Status of two-stage 4 Kelvin PTCs**
- **Examples of applications** ***(He-liquefaction, magnet cooling, ….)***
- **Low-temperature limit of PTCs** ***(^{3}He-PTC with T_{min} = 1.27 K)***
- **Cooler-induced vibrations and vibration decoupling**
- **(Powerful single-stage PTC)**
- **(Possible problems: --** ***Orientation dependence of performance***
  -- ***Intrinsic temperature oscillations*****)**

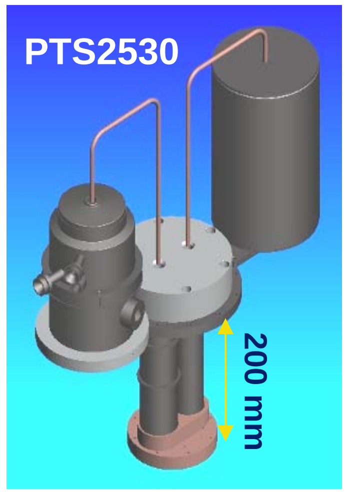
Pulse tube development in Giessen since 1993

Gifford-McMahon (GM)-type PTCs
f = 1 - 2 Hz

2-stage PTCs for LHe-temperatures

Input power: 2 – 10 kW
Cooling power:
0.2 – 1.1 W @ 4.2 K

1-stage PTCs for cooling at 25-100 K

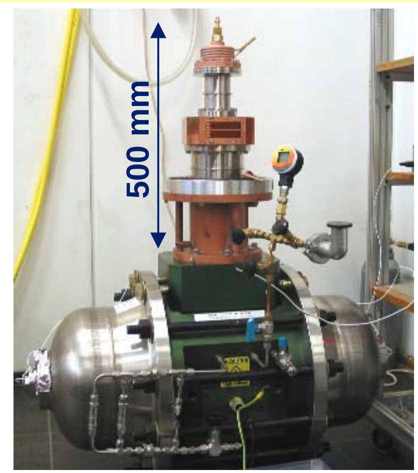


Input power: 2 – 12 kW
Cooling power:
80 W @ 50 K (6 kW)
30 W @ 80 K (2 kW)

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

With 50 - 200 W linear compressors
Cooling power: 0.2 – 8 W @ 80 K

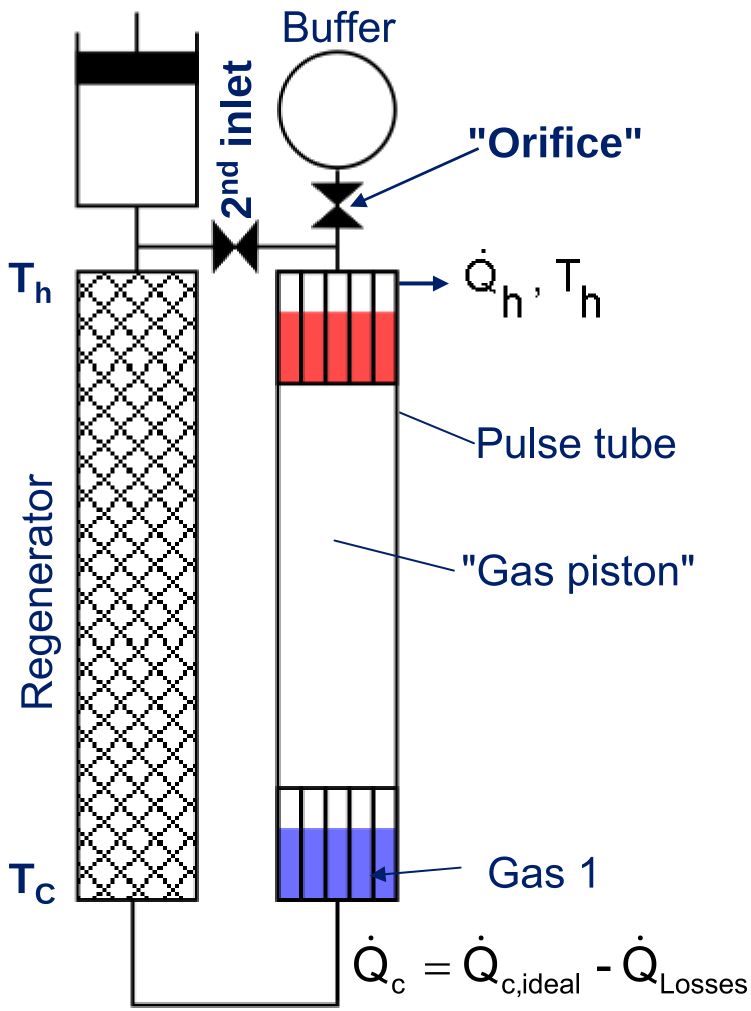
With 10 kW linear compressor
Cooling power: 350 W @ 80 K



Additionally, under development: 2-stage STPTC versions for cooling below 20K

Working principle of a PTC

Schematic of single-stage PTC



Ideal cooling power

$$\dot{Q}_{c,ideal} = f \oint_{Gas\,1} p\,dV = \frac{1}{2}\hat{\dot{V}}_1\,\hat{p}\,\cos\theta$$

for ideal gas and harmonic p(t)

Adjustment of phase angle θ by use of :

-- Orifice + Buffer volume *(Moscow 1984)*

-- 2nd inlet *(Xian 1990)*: 2nd inlet reduces "useless" mass flow through regenerator!

Net Cooling Power

$$\dot{Q}_c = \dot{Q}_{c,ideal} - \dot{Q}_{Losses}$$

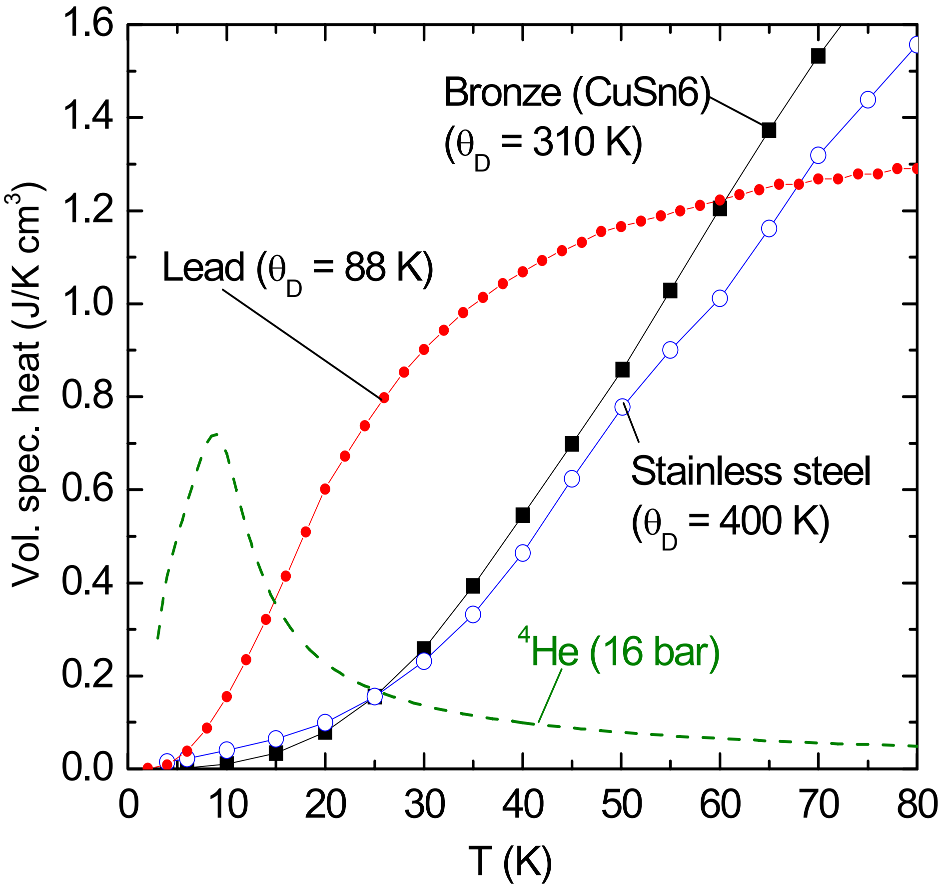
- Regenerator losses (heat capacity, heat transfer, pressure drop)
- Gas mixing in pulse tube
- Heat conductance, radiation

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

Regenerator materials

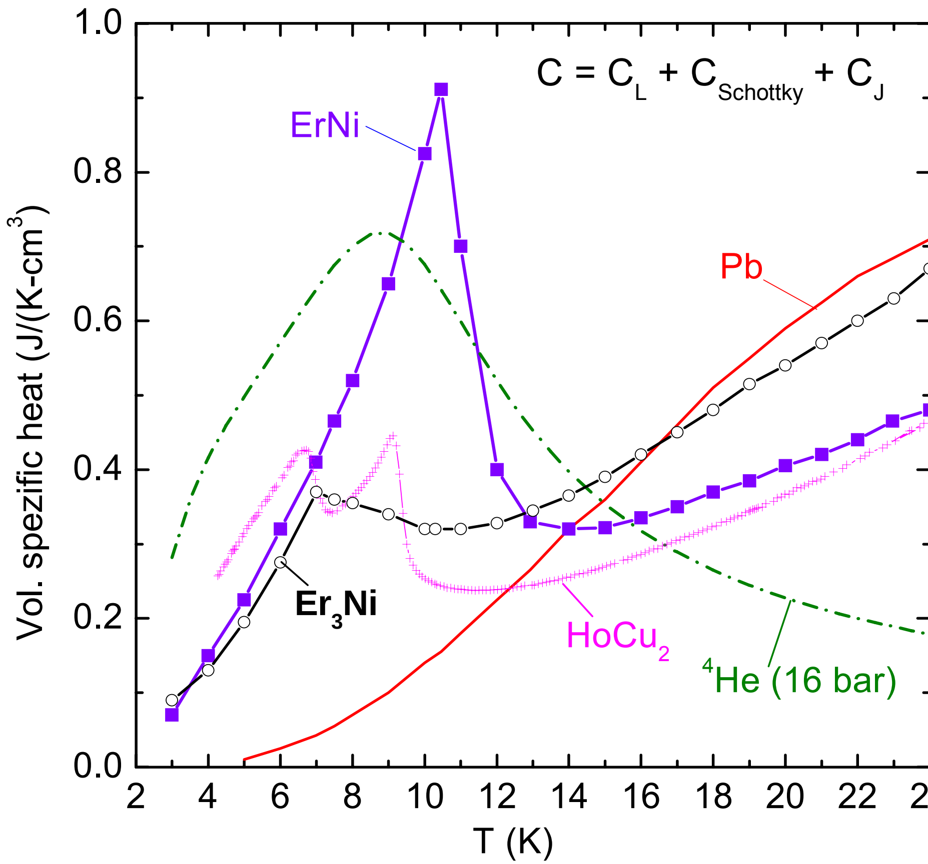
Efficient regenerator → $C_{Matrix} >> C_{Gas}$ must be valid.

Conventional regenerator materials for T_c > 15 K



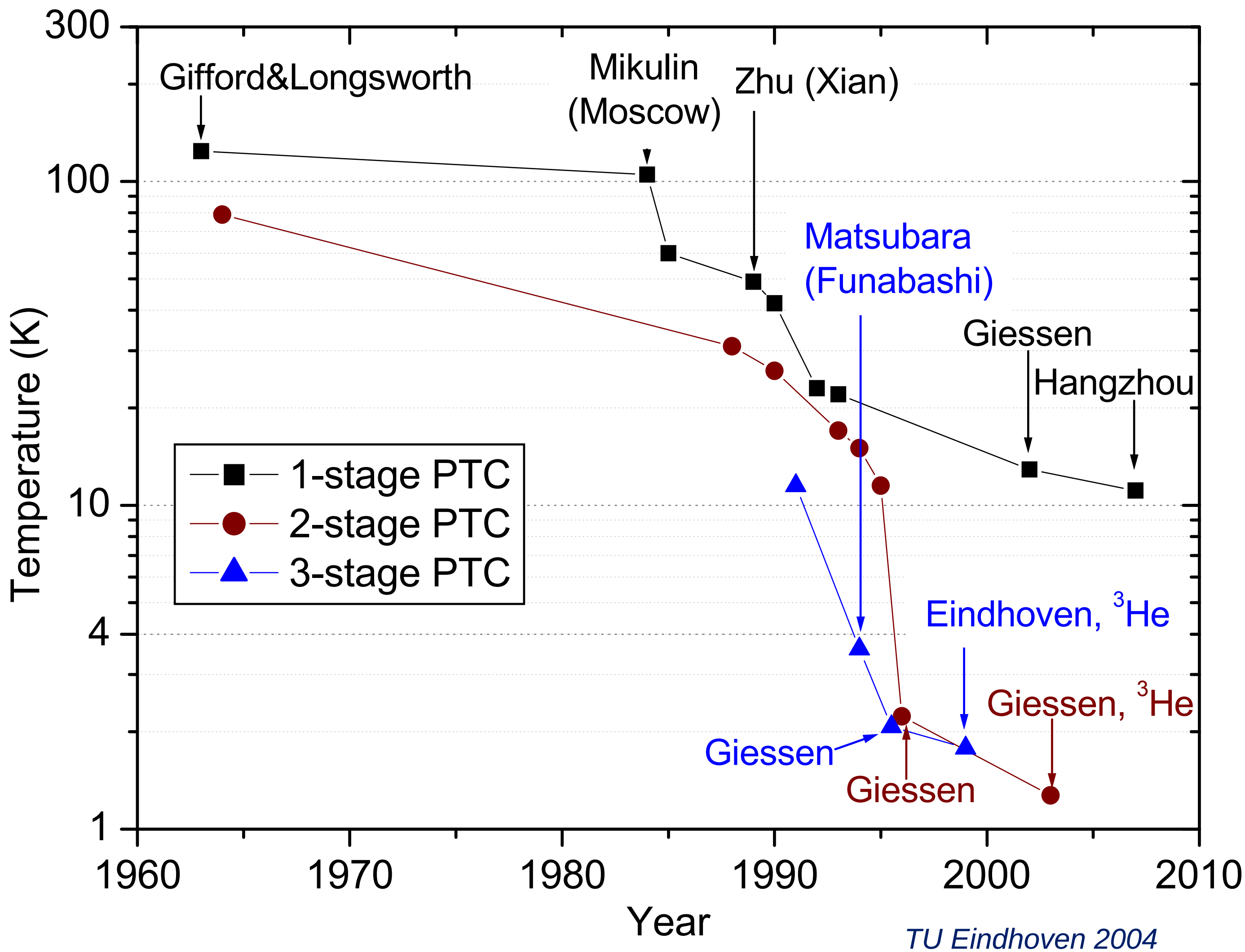
Material geometry:
-- Screens -- Spheres (lead)

Rare Earths materials for 4 K *(since 1989)*



Material geometry:
spheres or granules $\phi \approx 0.2$ mm

"History" of GM-type PTCs



TU Eindhoven 2004
U Giessen 2007

Record low-temperatures:

1-stage PTCs

12.9 K *(Giessen 2002)*

11.1 K *(Hangzhou 2007)*

2-stage PTCs

2.23 K, ^{4}He *(Giessen 1996)*

1.27 K, ^{3}He *(Giessen 2003)*

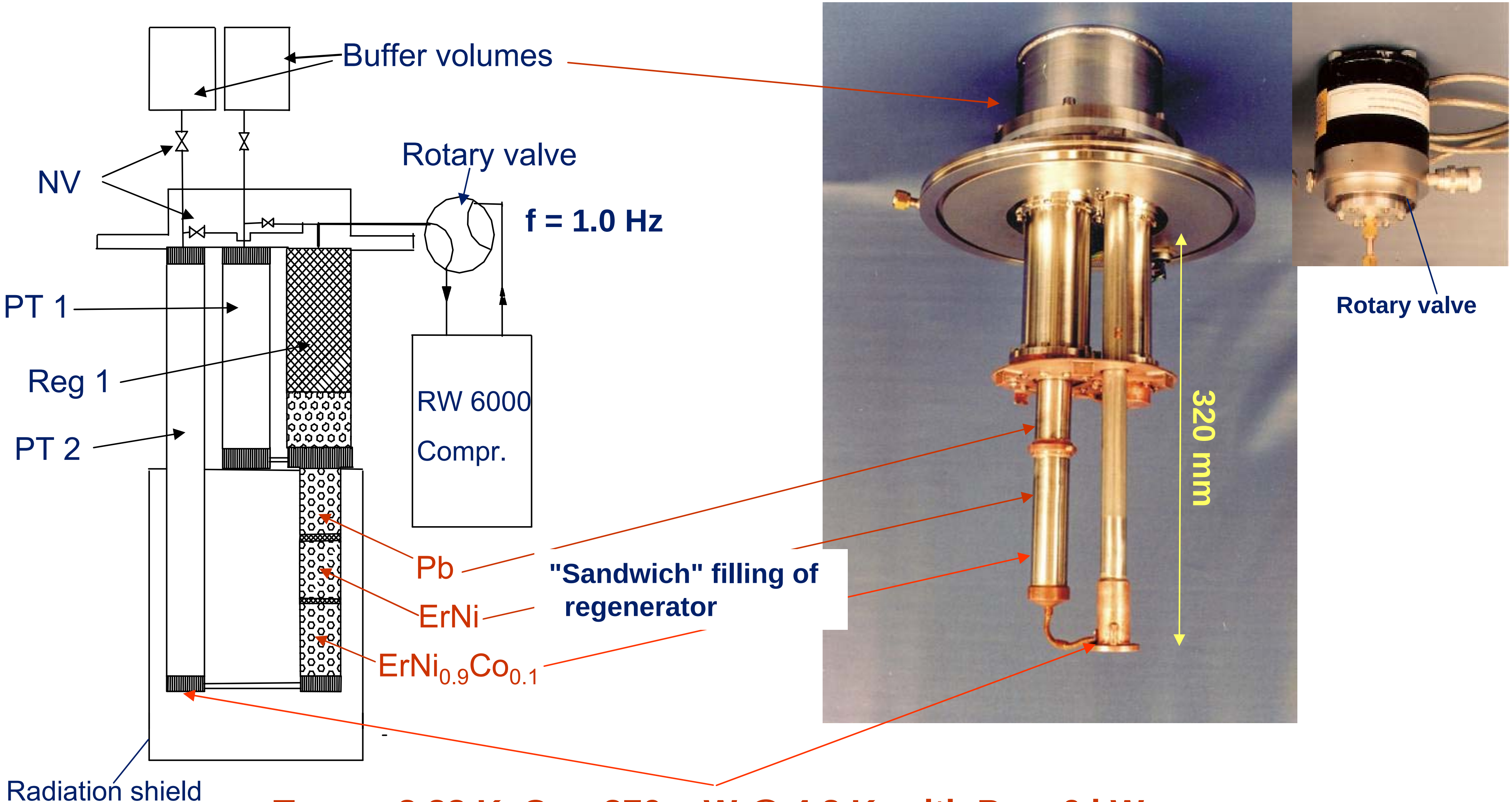
3-stage PTCs

3.6 K *(Y. Matsubara, 1993)*

2.07 K *(Giessen 1996)*

1.78 K, ^{3}He *(Eindhoven 1999)*

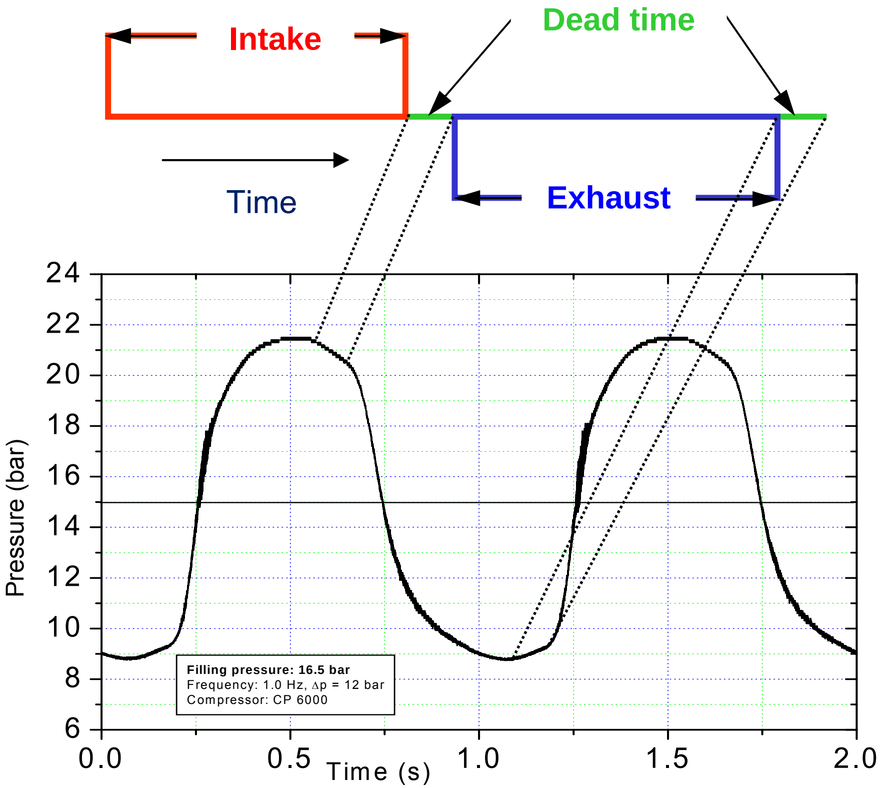
First 2-stage 4 K PTC (Giessen 1996)



$T_{2,min}$ = 2.23 K, Q_2 = 370 mW @ 4.2 K with $P_{in} \approx$ 6 kW

4 K PTC Optimization

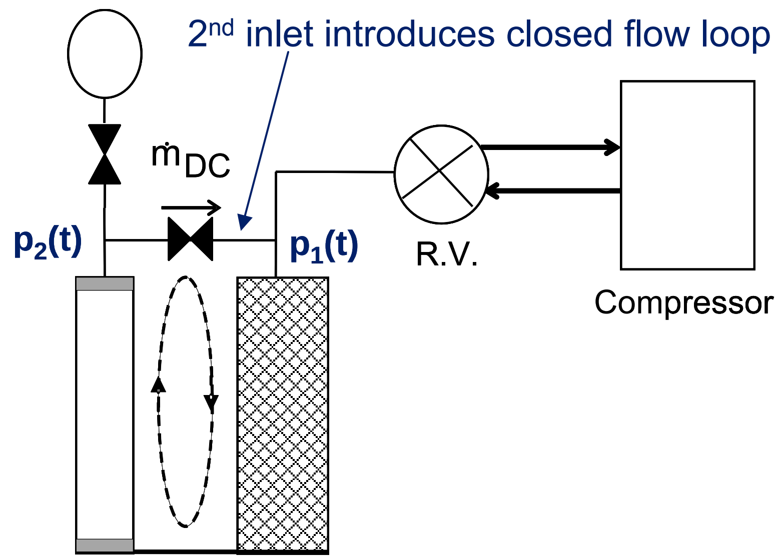
- Pressure waveform (Timing of r.v.)



T = 4 K, f = 1 Hz, Δp = 12 bar, 6 kW-compressor

-- pV-power
-- DC-flow

- Control of unidirectional flow ("DC-flow") through 2nd inlet

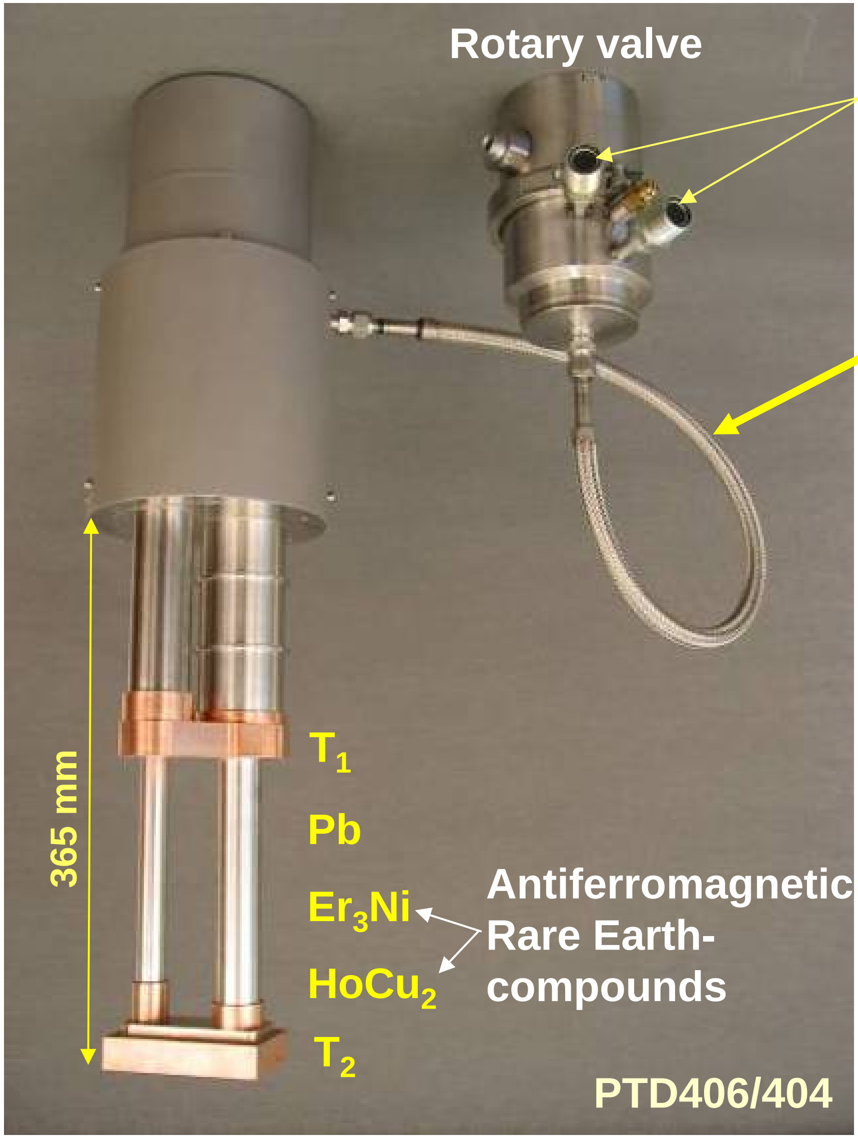


$\dot{m}_{DC} \sim \langle p_1 - p_2 \rangle$

Improper DC-flow introduces high heat load to the cold stage !

→ Use of needle valve arrangement with <u>adjustable flow symmetry</u>

Current 2-stage 4 K PTC (Giessen)



HP- and LP-Connections

"Split-Design"

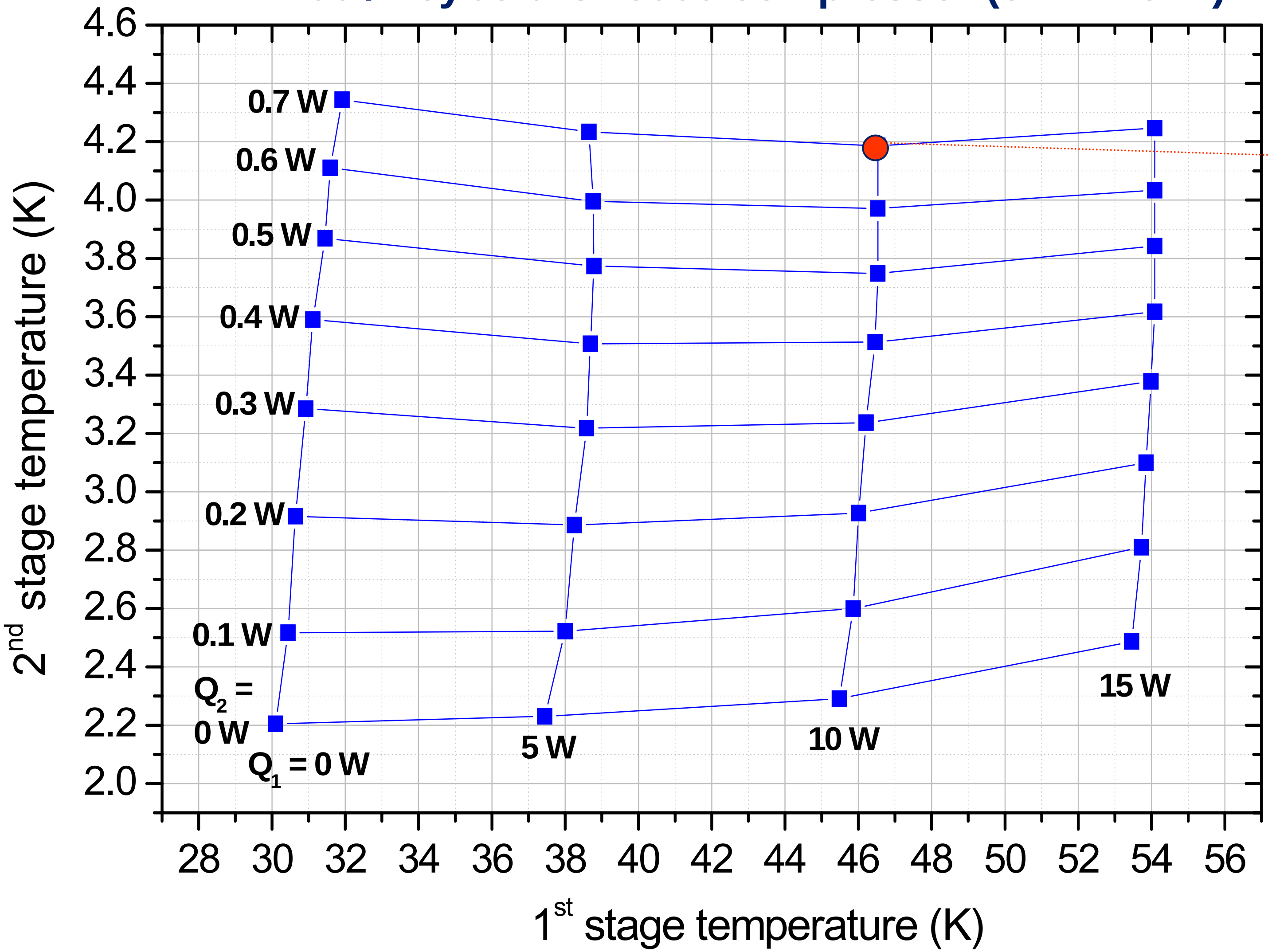
Flexible pressure line (0.5 – 1 m)

→ Reduction of vibrations from rotary valve

→ Makes possible the positioning of the rotary valve in low stray field (< 20 mT)

Cooling Load Map of PTD406

PTD406 / Leybold CP6000 compressor (6 kW nom.)



T_{min} = 2.21 K

Simultaneous cooling powers:

2^{nd} stage:
Q_2 = 0.71 W @ 4.2 K

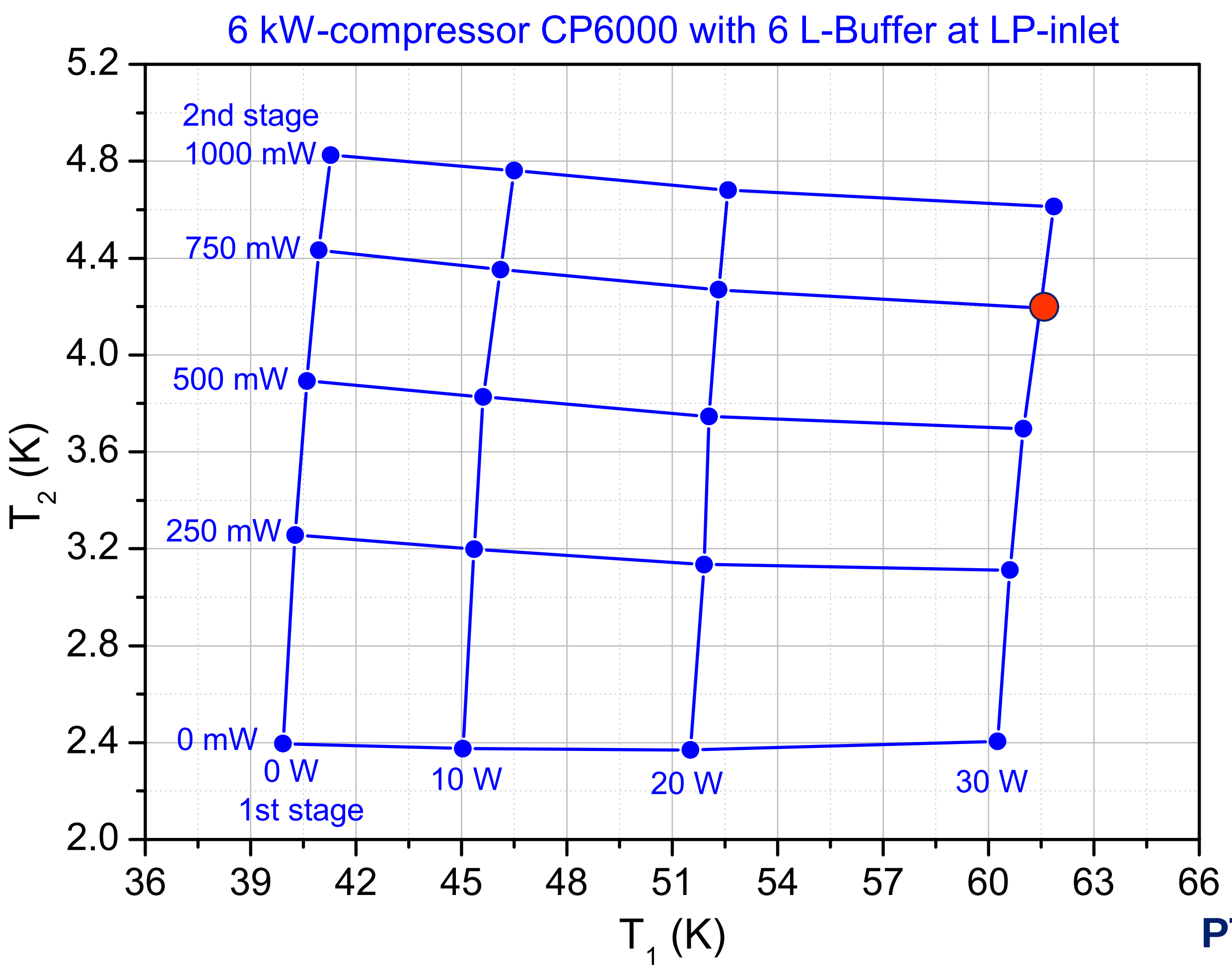
1^{st} stage:
Q_1 = 10 W @ 46.6 K

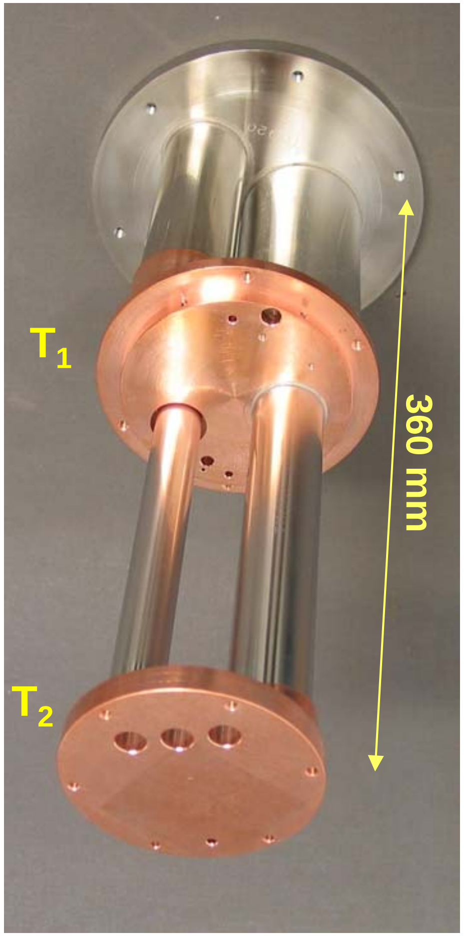
at P_{in} = 5.6 kW

Cool down time to 4.2 K: ≈ 65 minutes

Cooling Load Map of PTD406c

Giessen 2007





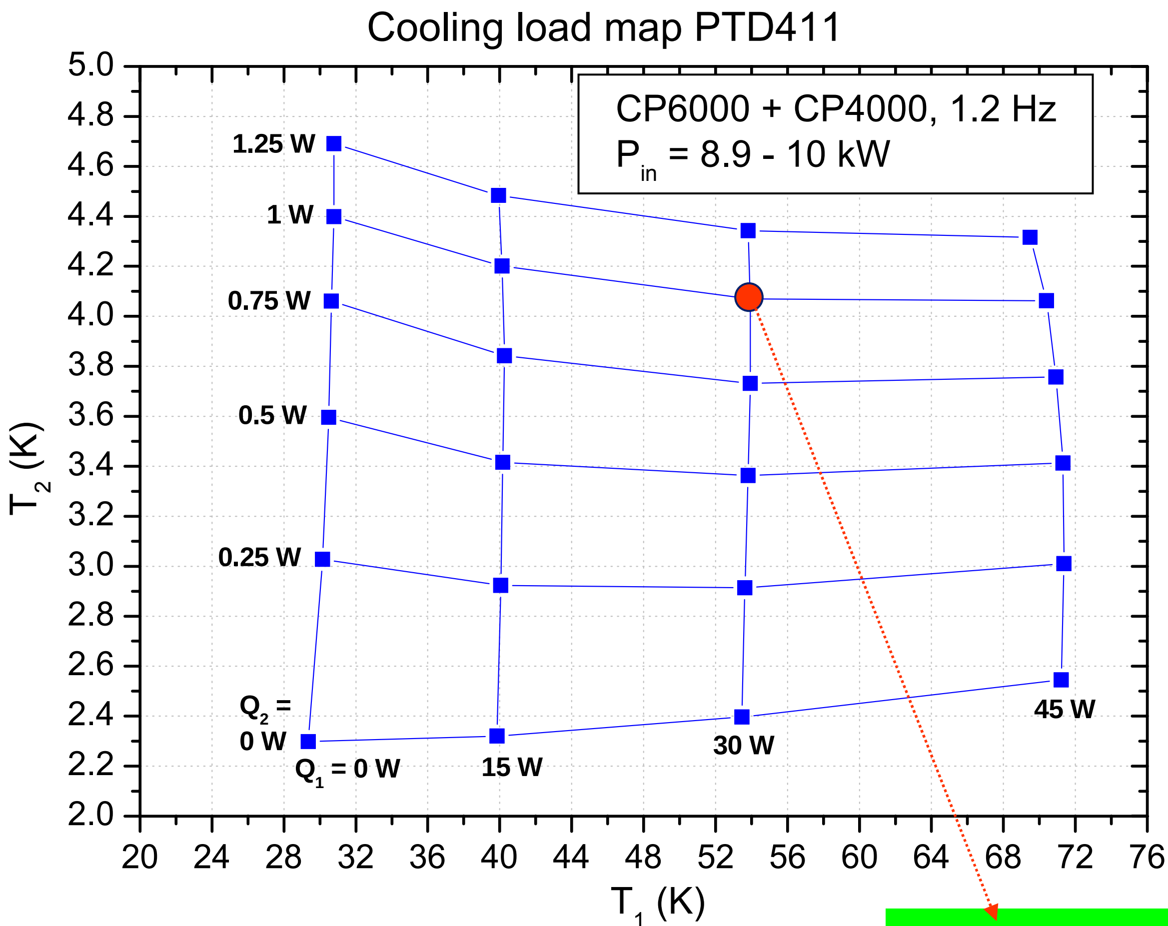
PTD406c: concentric cold platforms

Phase shifters optimized for high cooling power at 1st stage → increased cooling power at 1st stage

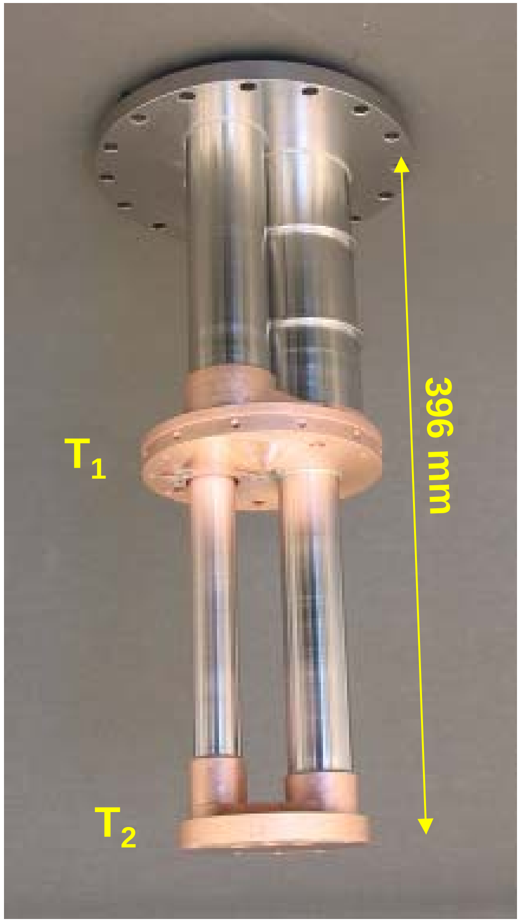
30 W @ 61.5 K and 750 mW @ 4.2 K with P_{in} = 6.0 kW

4 K PTC with 10 kW compressor (PTD 411)

Giessen 2006



PTD411: increased tube diameters

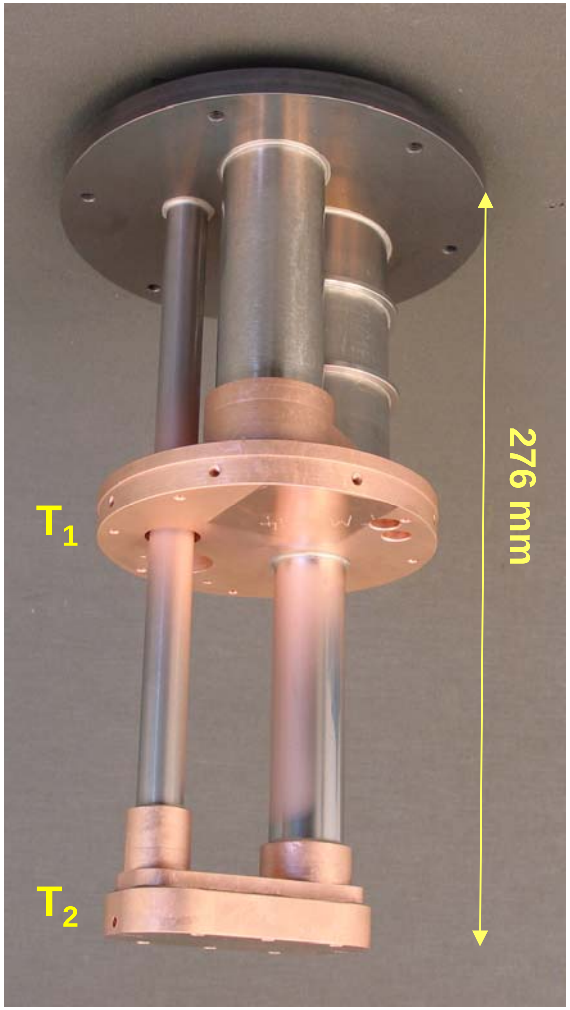


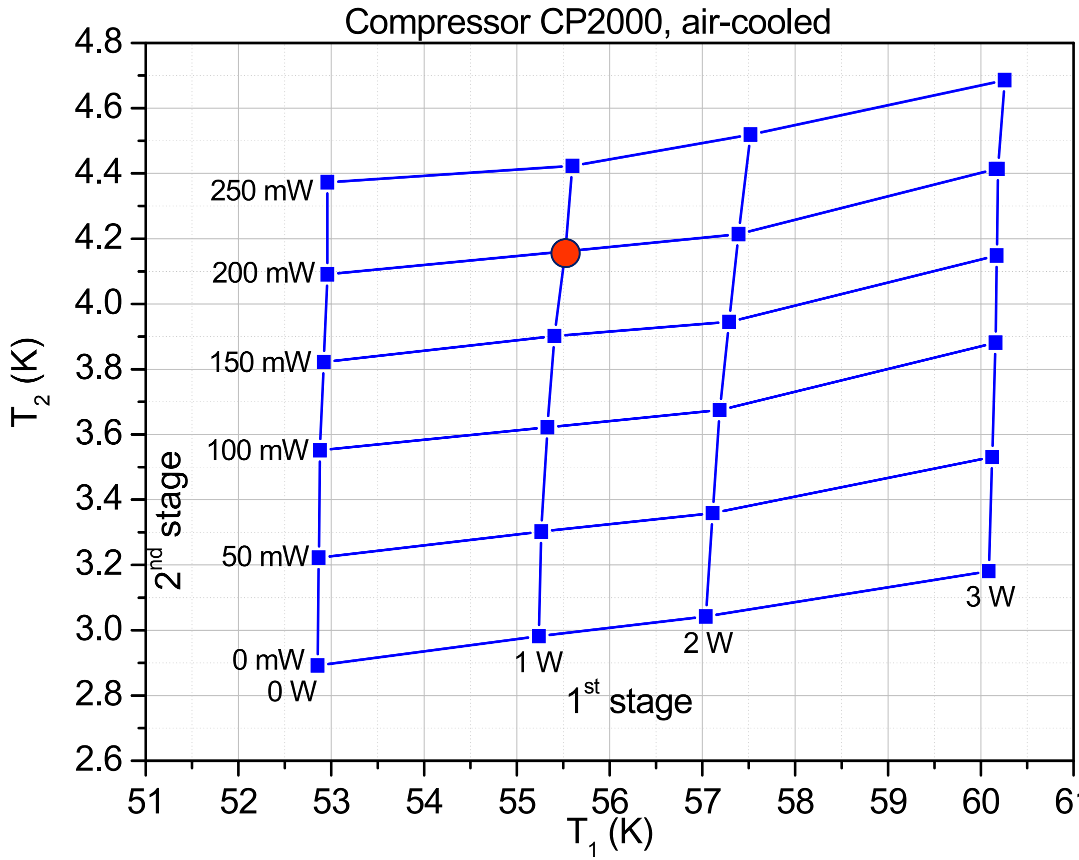
Q_2 = 1.0 W @ 4.07 K and Q_1 = 30 W @ 53 K with P_{in} = 9.5 kW

Cool down to 4.2 K ≈ 1 h

"Small" 4 K PTC with 2 kW compressor (2008)

PTD 4200





Cold head volume ≈
0.6 × cold head volume of PTD406

Simultaneous cooling powers:

200 mW @ 4.16 K and 1.0 W @ 55.6 K
with 2 kW electric input (air-cooled compressor)

(PTD4200 with 4 kW compressor → next table)

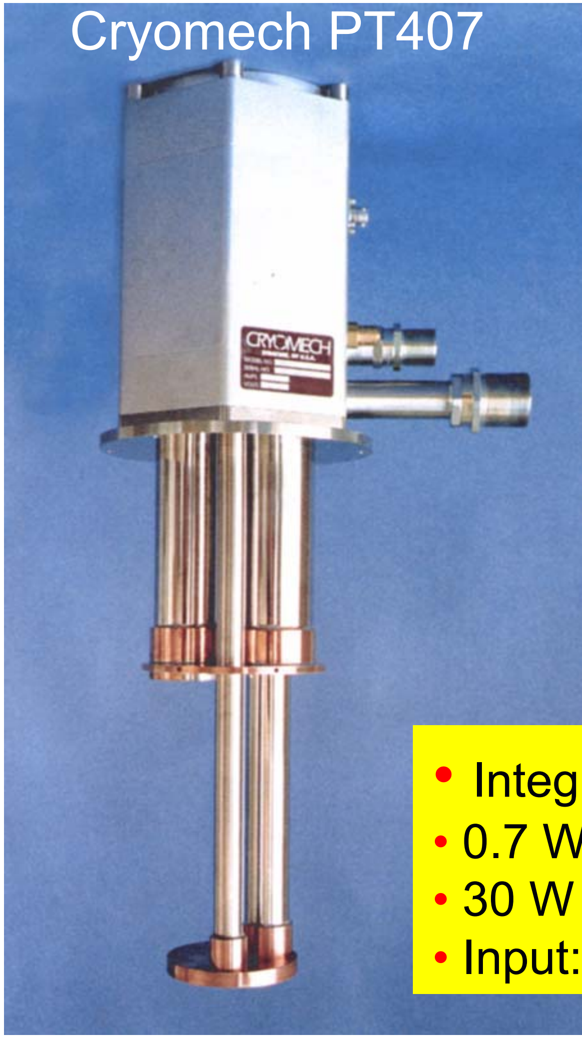
Performance data of TransMIT 4 K PTCs

Model	P_{in} (steady state)	Typical cooling power	T_{min}	Cool down to 4.2 K *)
PTD4200	2.0 kW	0.21 W @ 4.2 K 1 W @ 56 K	< 3.0 K	< 120 min
PTD4200-4kW	3.8 kW	0.45 W @ 4.2 K 10 W @ 53 K	< 2.6 K	< 75 min
PTD404	3.8 kW	0.6 W @ 4.2 K 10 W @ 53 K	< 2.5 K	< 75 min
PTD406	5.7 kW	0.7 W @ 4.2 K 10 W @ 49 K	< 2.4 K	< 65 min
PTD406c**)	6.0 kW	0.75 W @ 4.2 K 20 W @ 52 K	< 2.5 K	< 65 min
PTD411	10 kW	1.1 W @ 4.2 K 30 W @ 53 K	< 2.4 K	< 65 min

*****) Prototype with 6 L-Buffer volume at LP-side of compressor***

****) With standard copper radiation shield installed***

Some other commercial 4 K PTCs

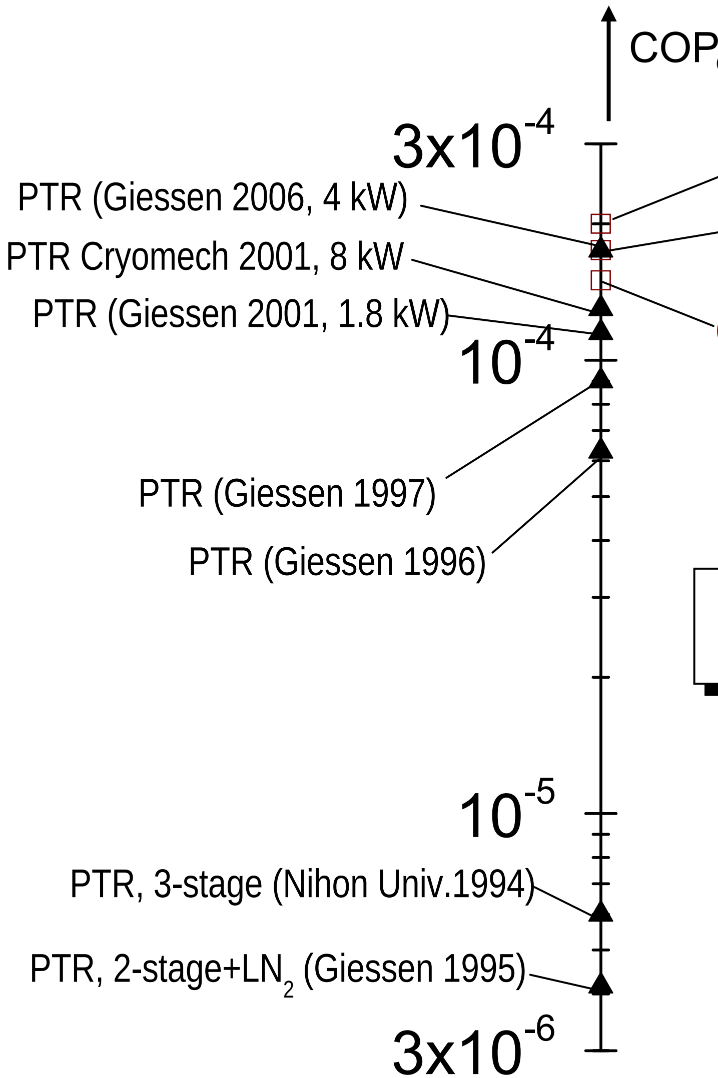


- Integral-Design
- 0.7 W @ 4.2 K
- 30 W @ 55 K
- Input: ≈ 7 kW

- Split-Design
- 0.5 W @ 4.2 K
- 20 W @ 45 K
- Input: ≈ 7.5 kW

Coefficient Of Performance of 4 K GM- and PT-Coolers

$$COP_{Carnot} = \frac{4.2\,K}{295\,K - 4.2\,K} = 1.4 \times 10^{-2}\ !$$



COEFFICIENT OF PERFORMANCE @ 4.2 K

$$COP = \frac{\text{Cooling power}}{\text{El. input power}}$$

- **Increase of COP @ 4.2 K by a factor of 45 within 12 years for the PTC**
- **Nowadays: COP(PTC) ~ COP(GM) @ 4.2 K**

Some Applications of 4 K PTCs (Giessen)

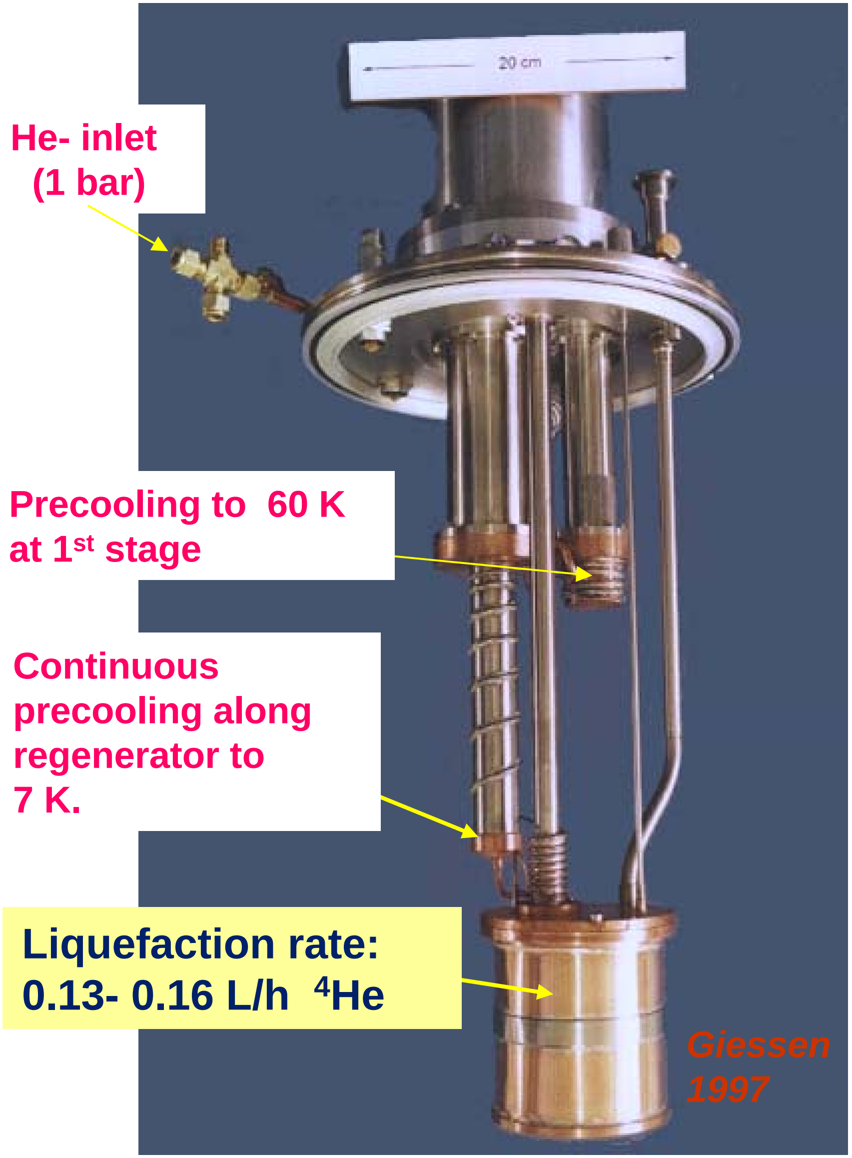
- **Small scale Helium-liquefaction** *(0.15 L/h, 1997)*
  (0.3 - 0.7 L/h, 2005)

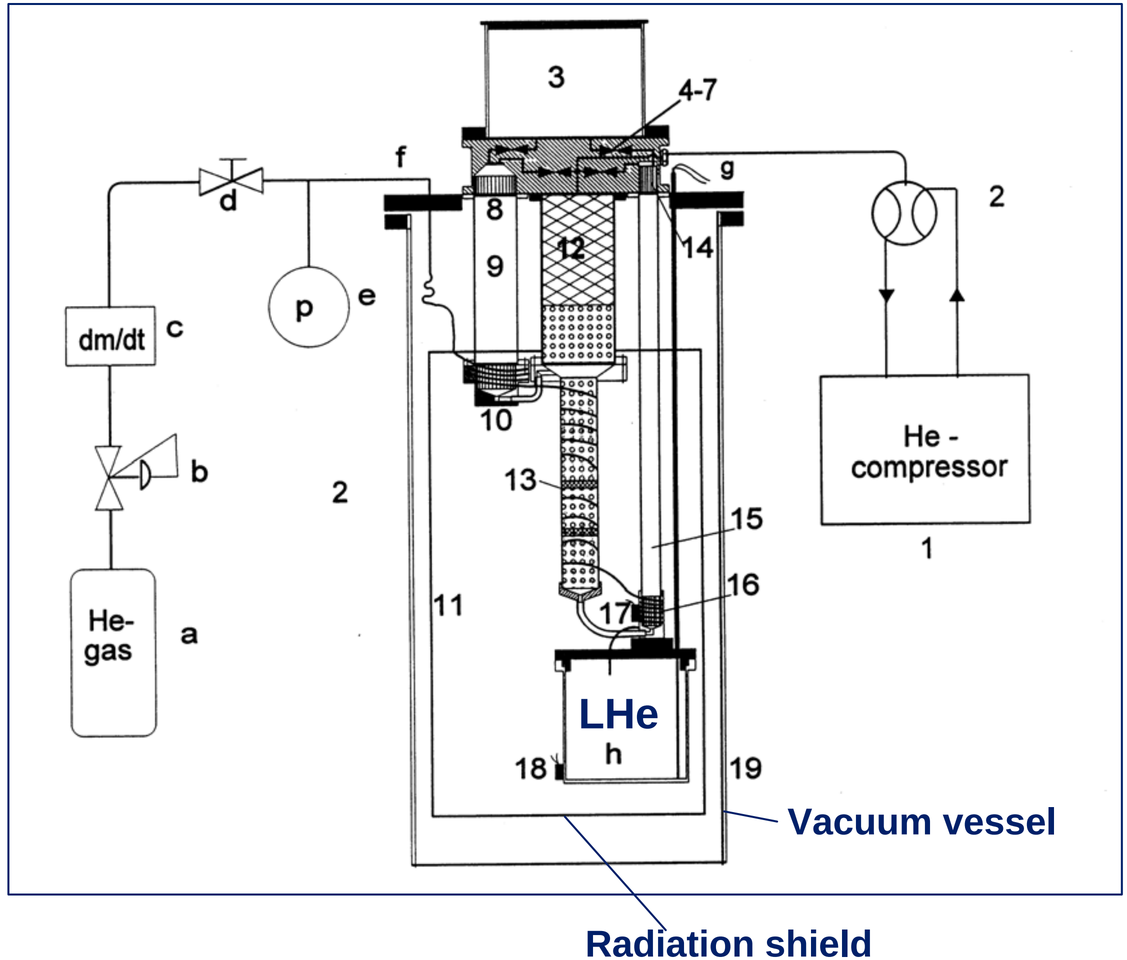
- **"Dry" superconducting magnet cooling**
  - 3 T (120 A) Nb_3Sn-magnet → *First PT-cooled SC-magnet (1998)*
  - 5.5 T NbTi-magnet with persistent mode switch *(2002)*
  - 5 T NbTi-magnet with top-loading system *(2007)*

- **"Dry" cooling of Josephson voltage standards** *(since 2002)*
  Co-operation with: IPHT Jena, PTB Braunschweig

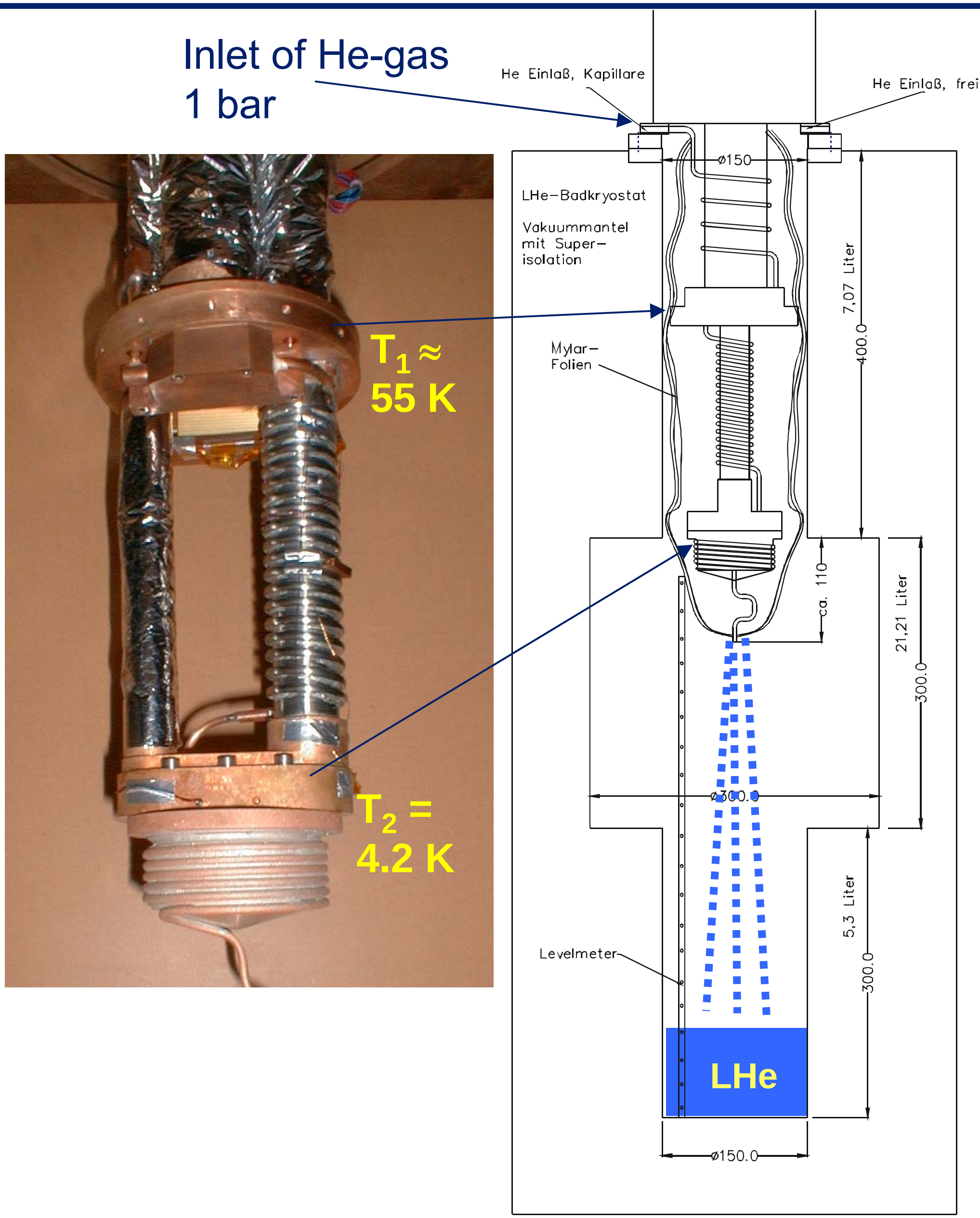
- **"Dry" precooling of sub-Kelvin cooling stages**
  - ADR with 5 T NbTi-magnet *(2000)* → T_{min} = 96 mK *(with CSP, Ismaning)*
  - Miniature $^3He/^4He$-dilution refrigerator with T_{min} = 50 mK
    Co-operation with: Institute of Applied Photonics e. V., Berlin (2006)

First small-scale He-liquefier with PTC (Giessen 1997)





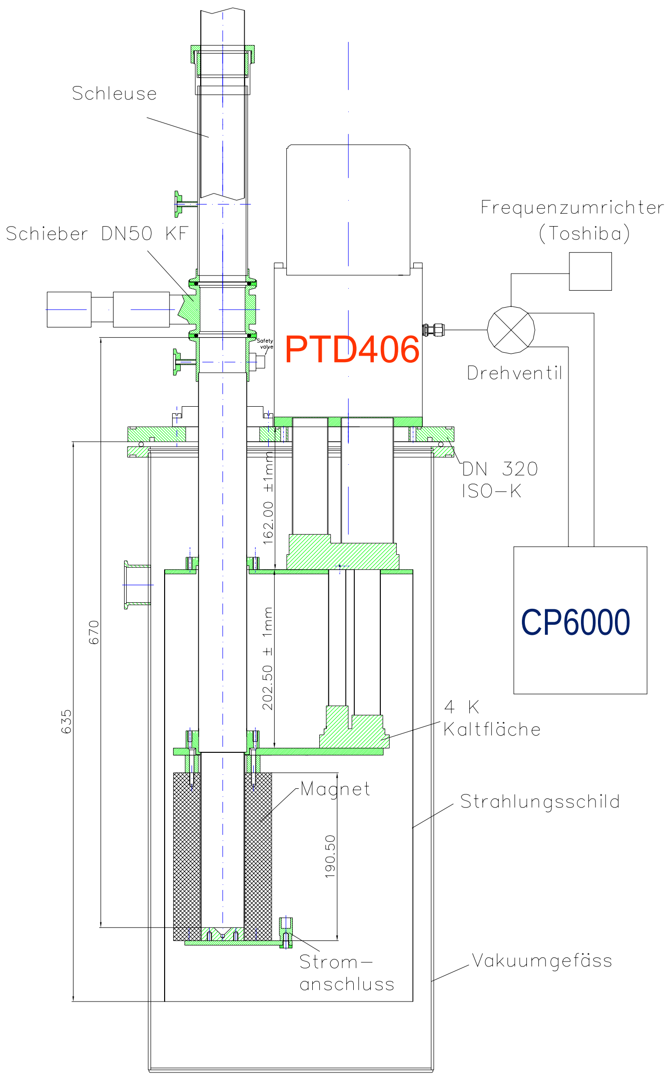
Current He-liquefier with PTC (Giessen 2005)



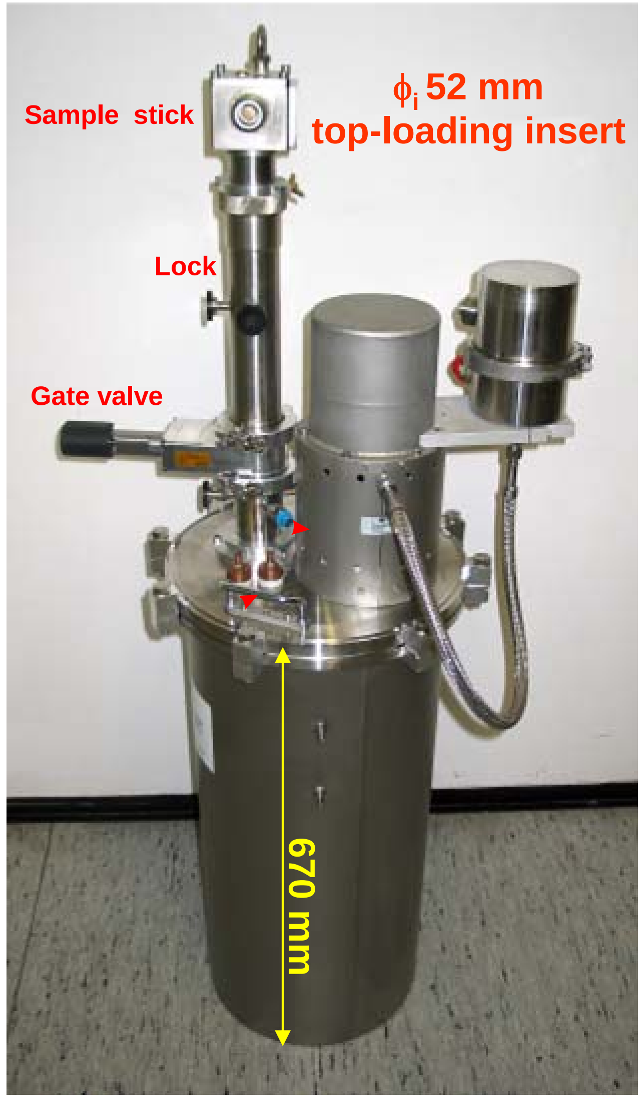
- **Operation of cold head in He-gas !**
- **6 kW compressor (Leybold CP6000)**
- **Helium inlet through capillary:**
  → liquefaction rate: 0.50 L/h
- **Free inlet of helium gas:**
  → liquefaction rate: 0.46 L/h

  → Rather efficient precooling already by contact of the gas with the cold head parts
- **Disadvantage of capillary: Risk of plugging by the freezing of gas impurities !**

“Dry” Cryostat with 5 T Magnet and Top-loader



Giessen 2006-2007



User: IMS, University of Karlsruhe

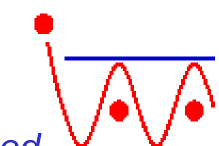
- **Cooldown time to 4 K: 7 hours (Extra mass ≈ 8 kg)**
- **Base temperature with sample holder inserted: 3 K**
- **Magnet sweep to 5 T: 7 min**
- **Changing of samples and cooling back to 4 K within < 2 hours**

Optional ^{3}He-sorption cooler insert:

T-min = 407 mK

Hold time: 6 hours

Q ≈ 60 µW



Institute f. Applied Photonics e.V. Berlin (2007)

Low-noise cooling Josephson voltage standards

1 V and 10 V Josephson voltage standards

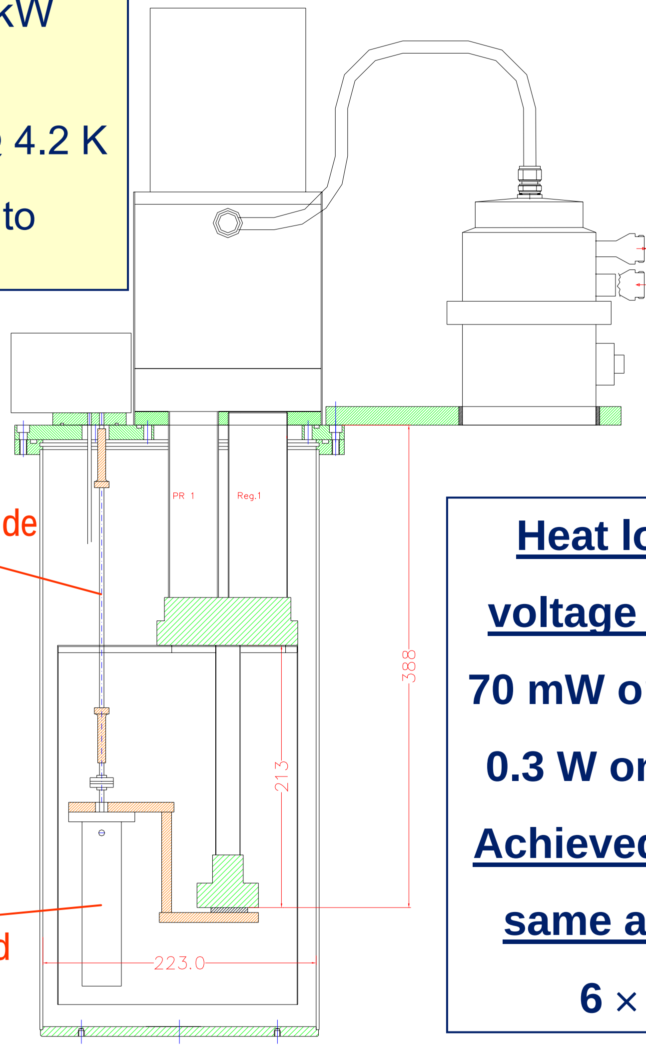
Application: Primary voltage standards in industry and metrological institutes

JENA IPHT

PTB

PTD402s with 2 kW compressor

- Q_2 = 150 mW @ 4.2 K
- Cool down time to 4.2 K: 160 min



Dielectric waveguide (70 GHz)

Josephson chip in Cryoperm shield cooled to 3.8 K

Heat load from voltage standard:

70 mW on 2^{nd} stage

0.3 W on 1^{st} stage

Achieved accuracy same as in LHe:

6×10^{-10}

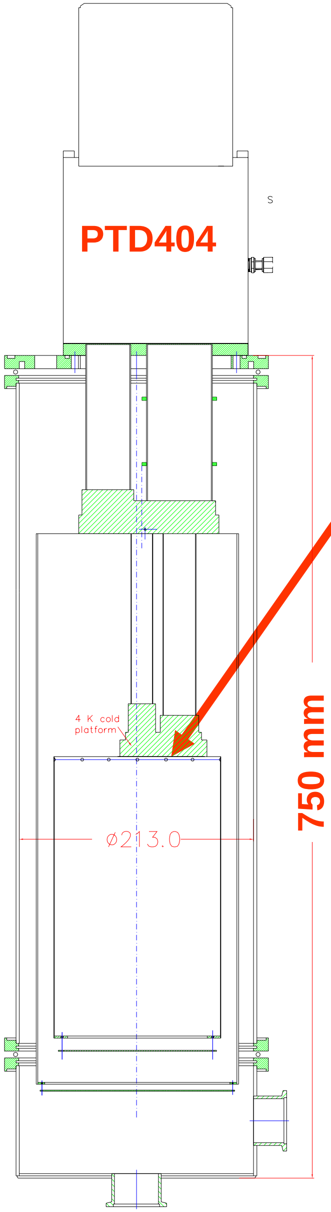
Electrical insulator for reduction of noise from r.v.

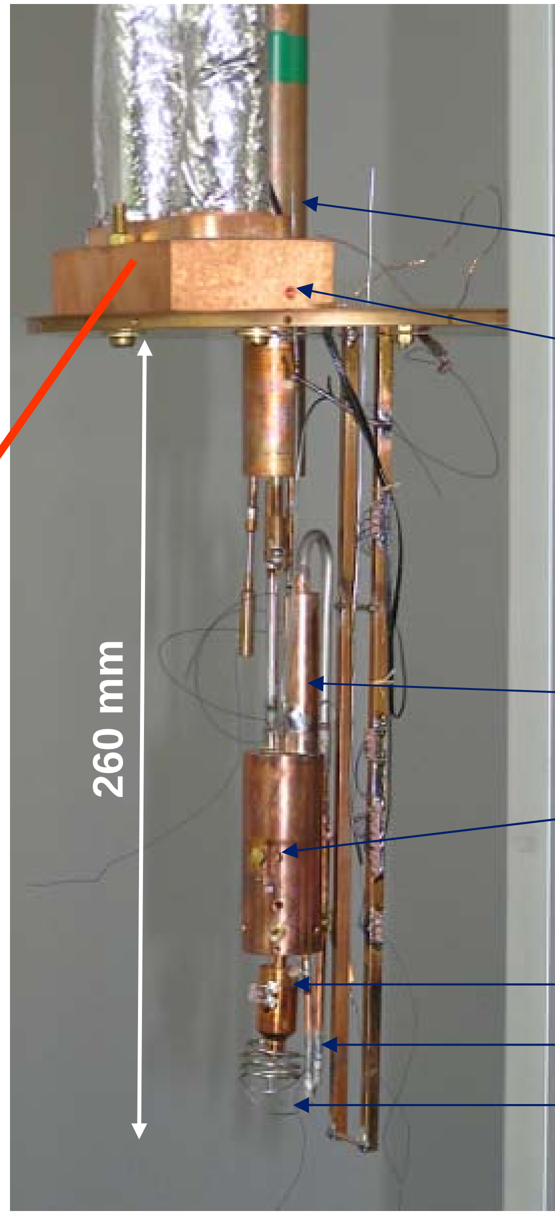
New system with PTD4200 / CP2000A

Q_2 = 200 mW @ 4.2 K

(Giessen 2009)

Autonomous Mini Dilution Refrigerator with 4 K PTC





Institute of Applied Photonics e.V.
Berlin (2005)

^{3}He-sorption pump

$T_{2,PTC}$ = 2.46 K (PTD404 with 4 kW compressor)

Precooling of the ^{3}He-^{4}He-stage only by PTC (2.46 K) and one ^{3}He-sorption stage (0.4 K)

^{3}He condenser of DR: 0.4 K

^{3}He-evaporator of ^{3}He sorption stage

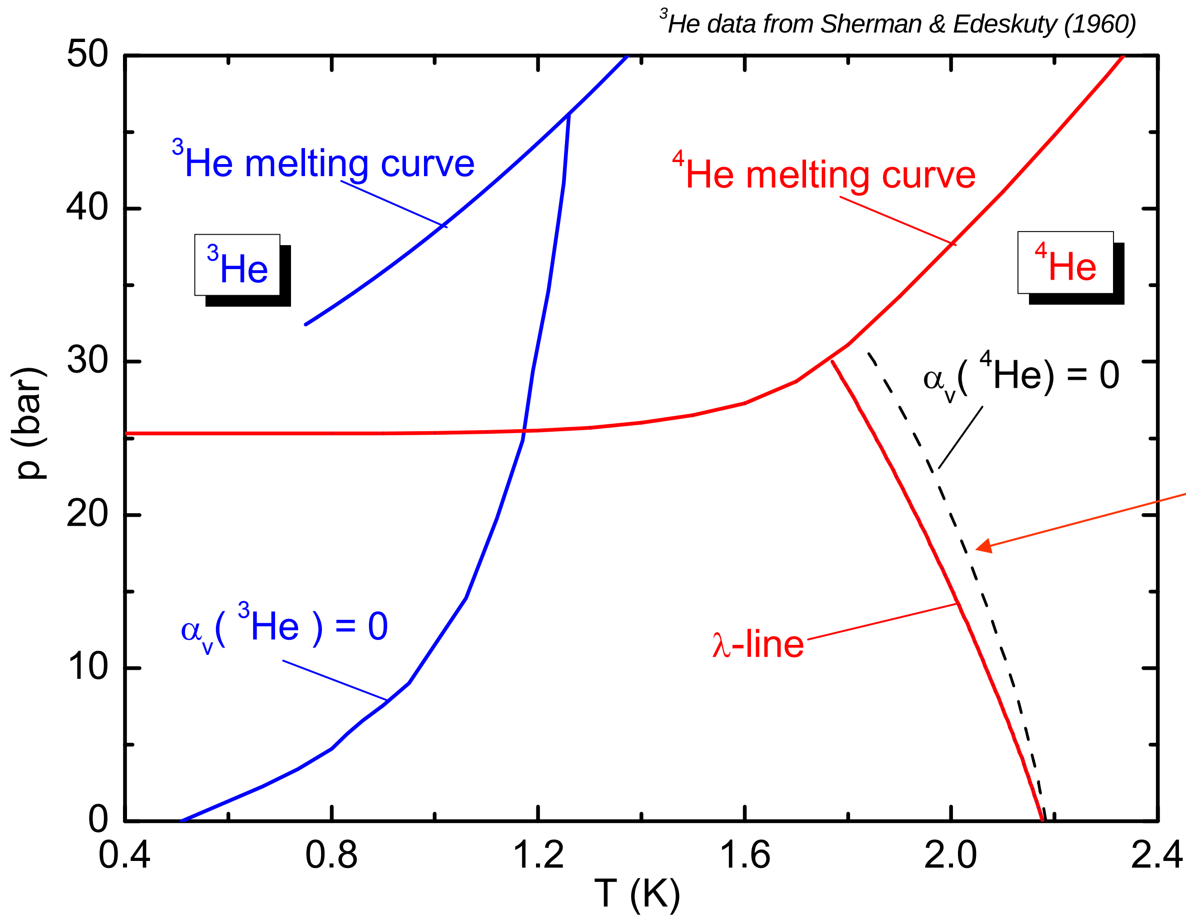
Mixing chamber: 50 mK

Still 0.7 K

Continuous HX

Low-temperature limit of PTCs ?

Phase diagrams and $\alpha_v = 0$ - line for ^4He und ^3He



α_v = Volume expansion coefficient

Dynamic T-oscillation in He-gas (adiabatic):

$$\Delta T = \alpha_v \langle T \rangle / (\rho c_p) \, \Delta p$$

$$\Delta T \rightarrow 0 \text{ for } \alpha_v \rightarrow 0$$

Cooling power → 0 for ΔT → 0

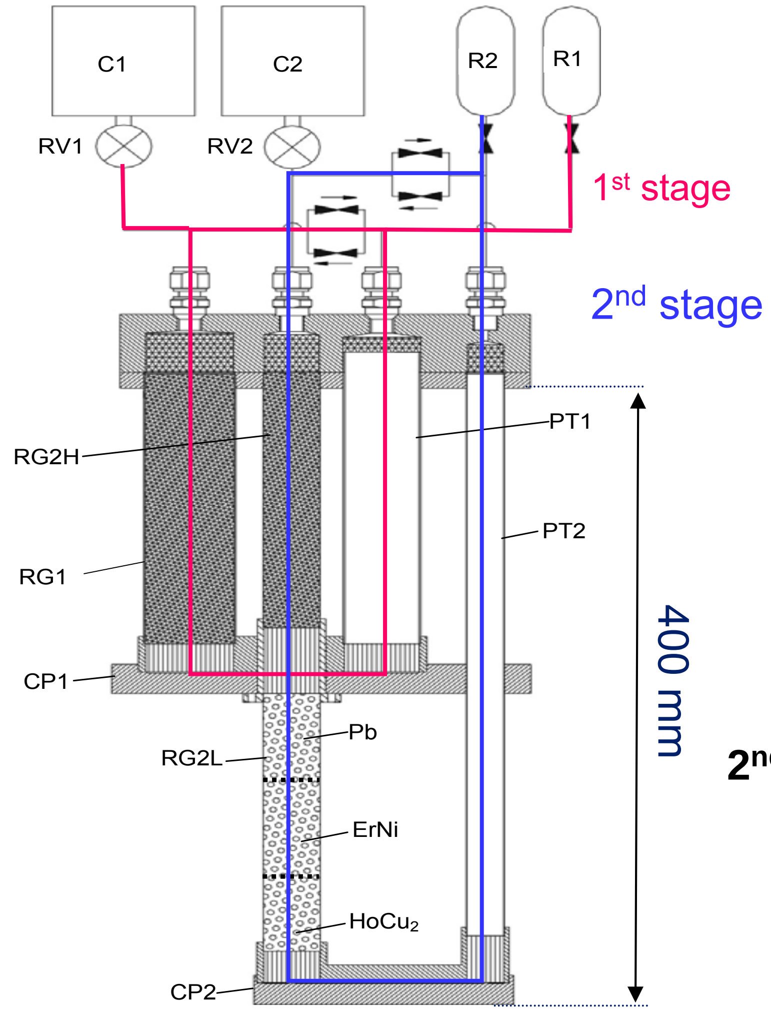
Conclusions:

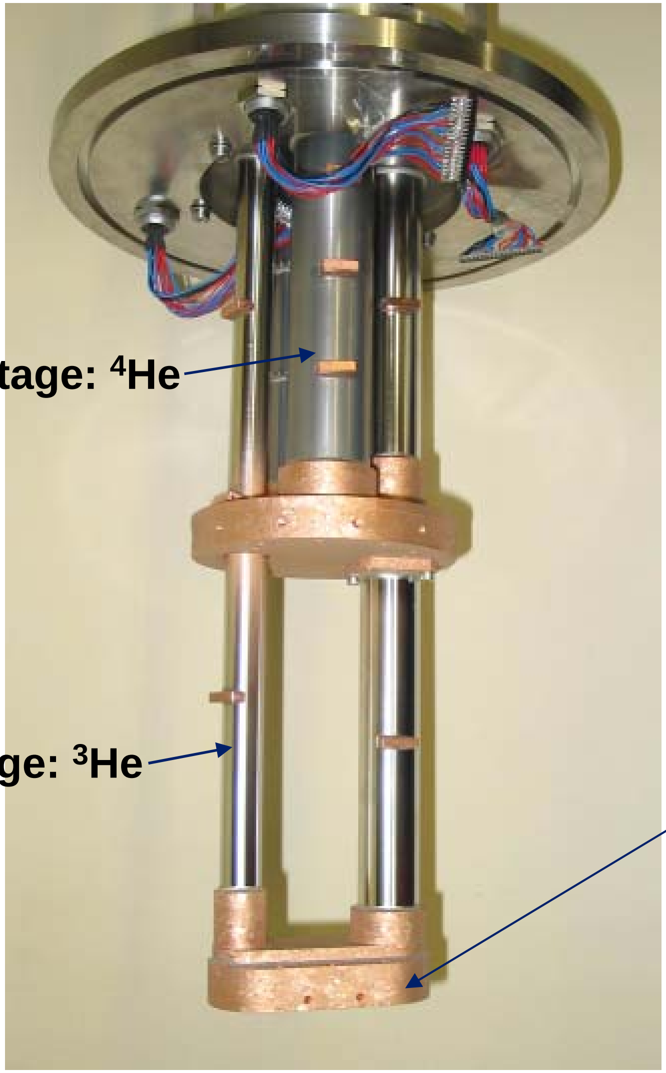
- **λ-line cannot be reached with ^4He, since $\alpha_v = 0$ for $T > T_\lambda$!**
- **With ^3He, temperatures well below 2 K could be achieved.**

Problem: Regenerator efficiency below 2 K

PTC with ^{3}He-stage

Lab model: 2-stage PTC with separate gas circuits *(Giessen 2003)*





Record low temperature:

T_{min} = 1.27 K

Cooling power:

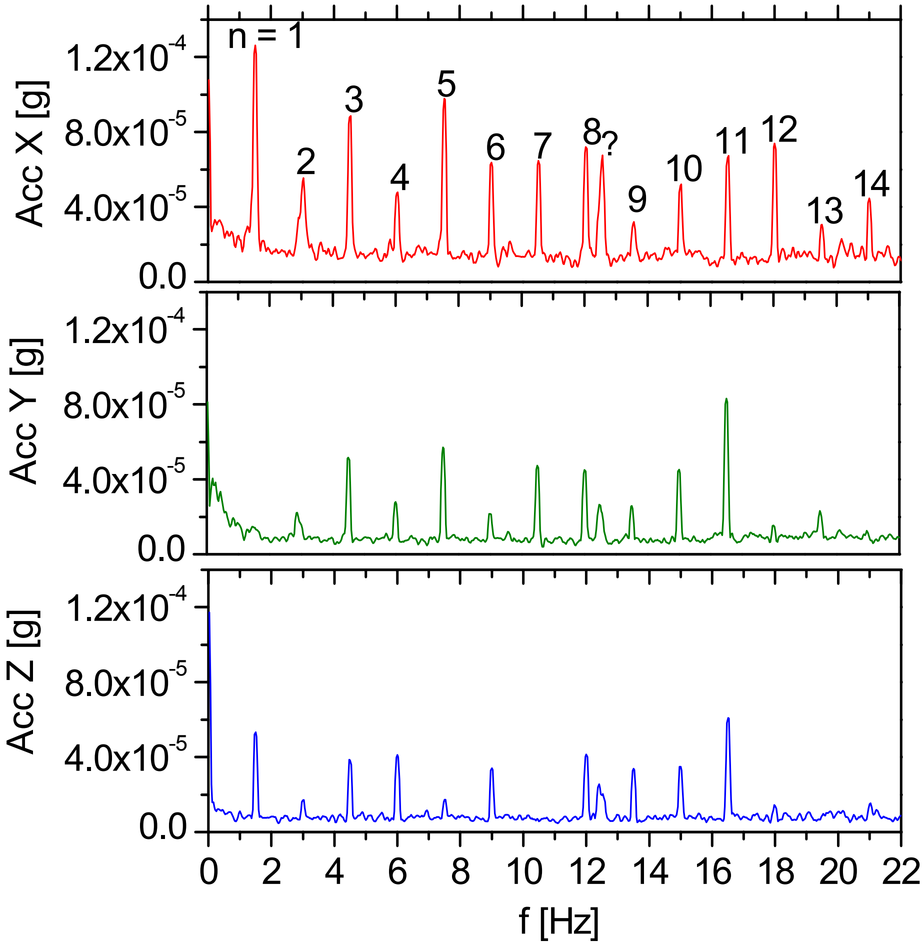
30 mW @ 2.0 K

$P_{in,2}$ = 1.2 kW

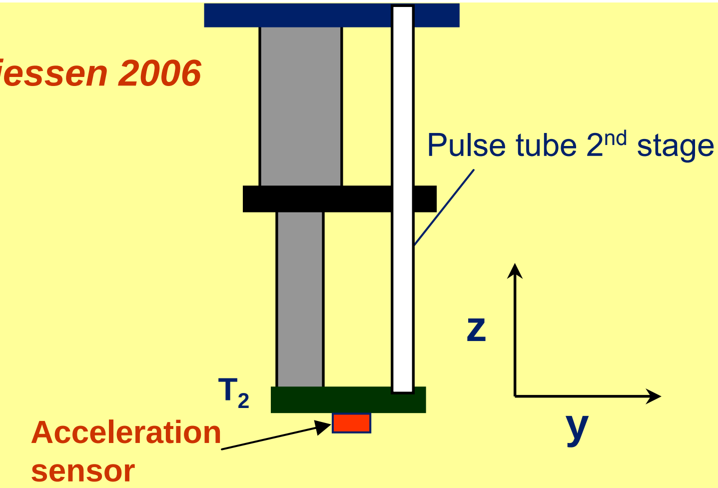
1st stage: 6 kW-compressor
2nd stage: 2 kW-compressor

Vibrations of 4 K PTCs: PTD406 (6 kW)

Acceleration-spectra of PTD406, f = 1.5 Hz, 6 kW-compressor, Δp = 13 bar, $T_2 \approx 0$ °C



Giessen 2006



PTC-induced acceleration (PTD406):

x: a_{rms} = 1.2×10^{-4} g (n = 1)
y: a_{rms} = 0.14×10^{-4} g (n = 1)
z: a_{rms} = 0.61×10^{-4} g (n = 1)

Compare: $a_{GM\text{-}cooler} \approx 10^{-2}$ *g*

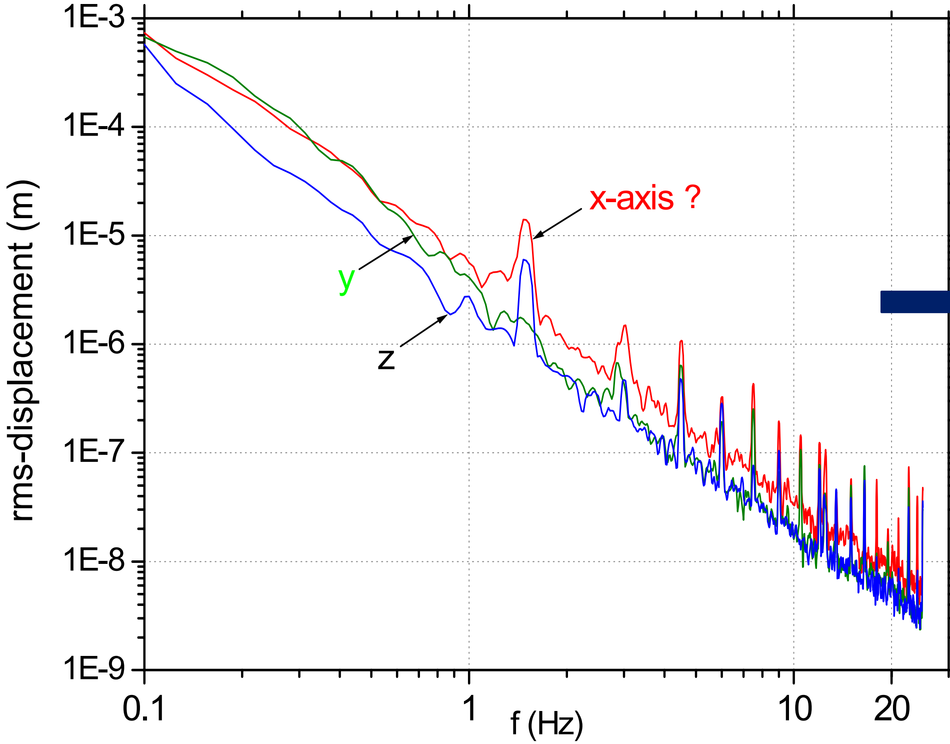
<u>Origin:</u> Elastic deformation of the stainless steel tubes due to pressure oscillation

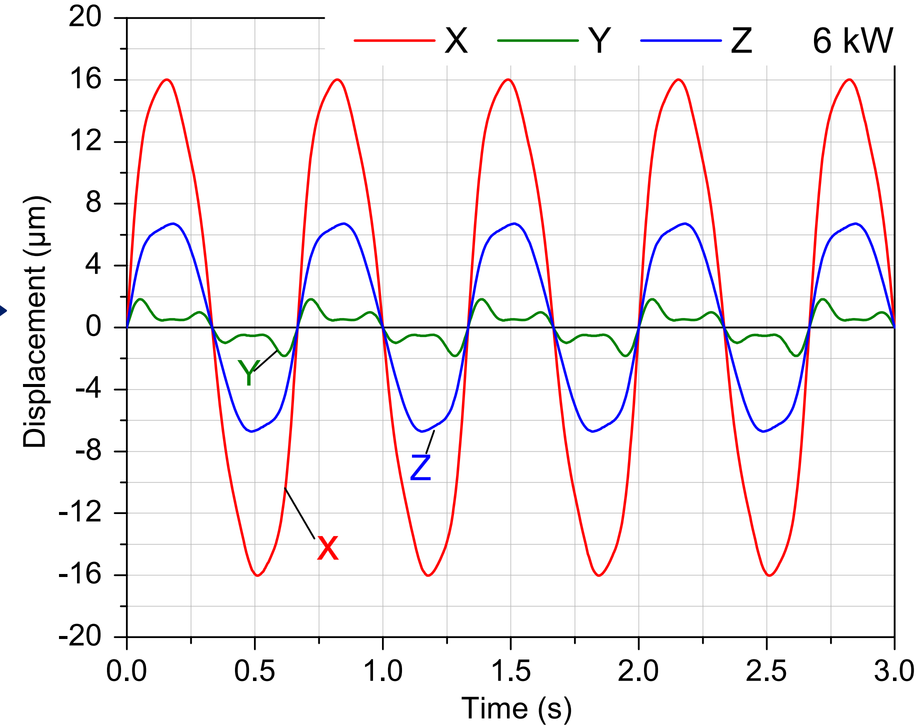
$$\Delta L/L \sim E^{-1} (r/s) \Delta p$$

r = tube radius s = wall thickness

Displacement from residual vibrations (6 kW)

Diplacement-spectra of PTD406, f = 1.5 Hz, 6 kW-compressor, Δp = 13 bar, $T_2 \approx 0$ °C





<u>Further reduction of vibrations:</u>

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

(all measures at the cost of available cooling power !)

6 kW compressor:

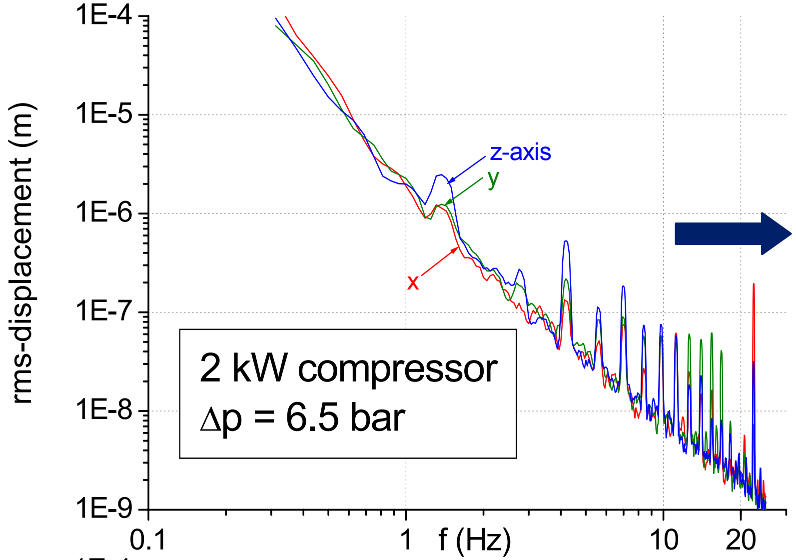
x : ± 16 µm (background ?)

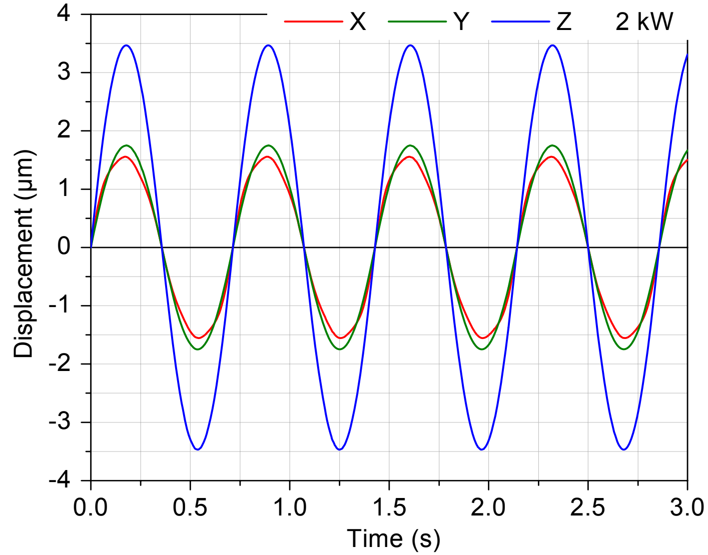
y : ± 1.8 µm

Z : ± 6.7 µm

Displacement-spectra of PTD4200 (2 kW and 4 kW)

PTD4200, f = 1.44 Hz, $T_2 \approx 0$ °C



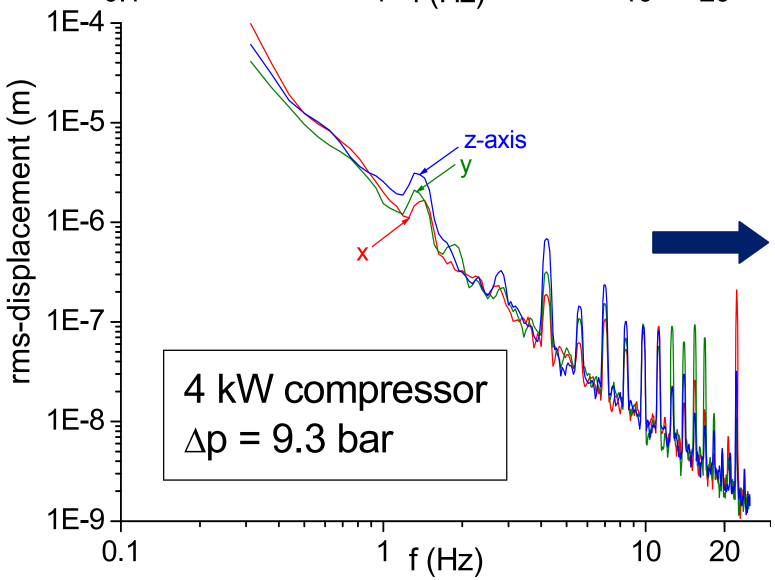


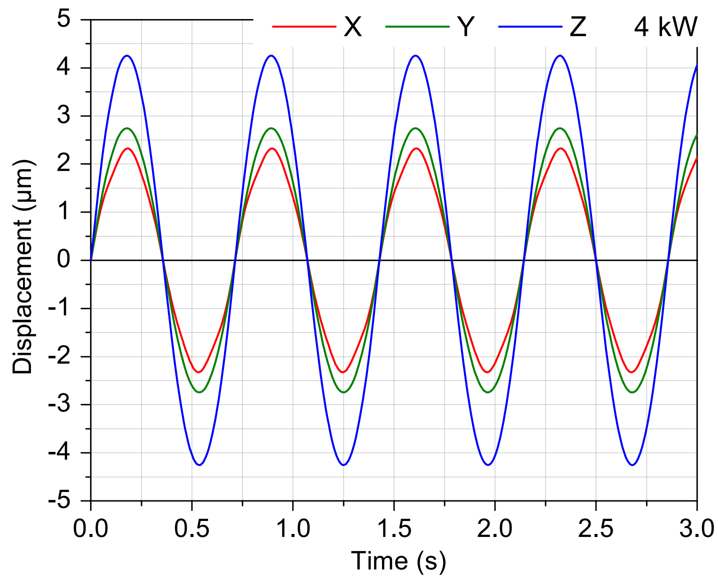
2 kW compressor:

x : ± 1.6 µm

y : ± 1.8 µm

z: ± 3.4 µm





4 kW compressor:

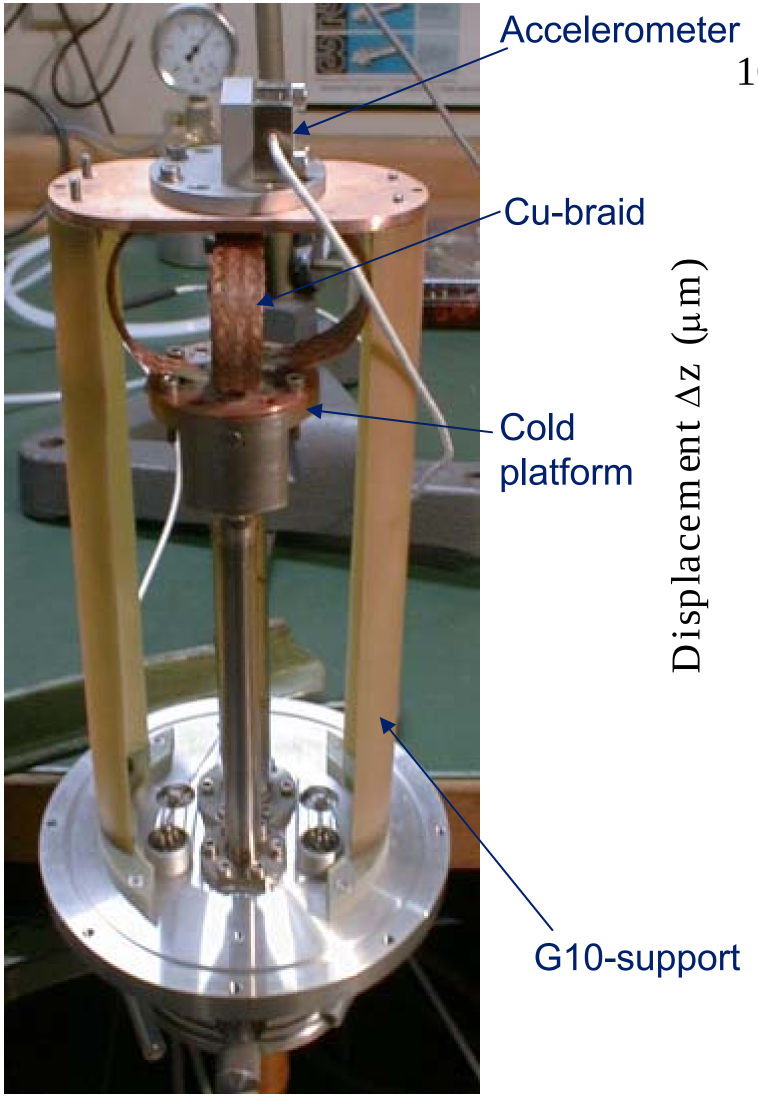
x : ± 2.3 µm

y : ± 2.7 µm

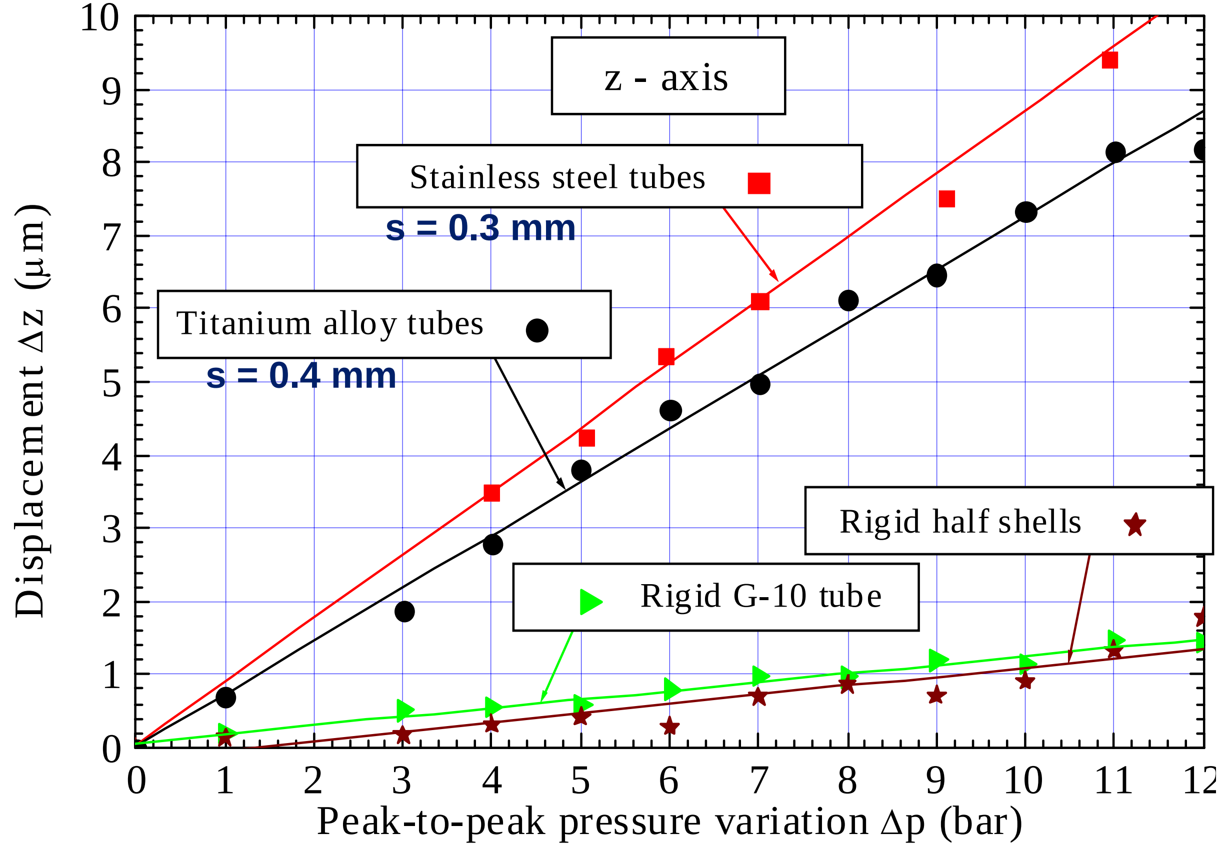
z: ± 4.4 µm

Damping of vibrations: small 1-stage PTC

Giessen 1999



1-stage PTC for HTS-SQUID cooling: 2 kW compressor, f = 4.6 Hz



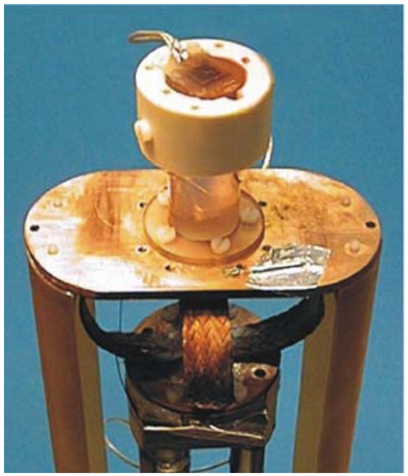
Titanium tubes: Δz = 5 µm at cold platform

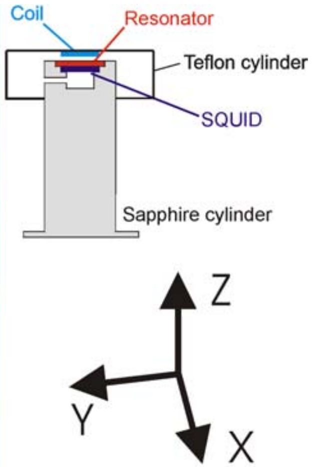
→ Δz < 1 µm with vibration reduction

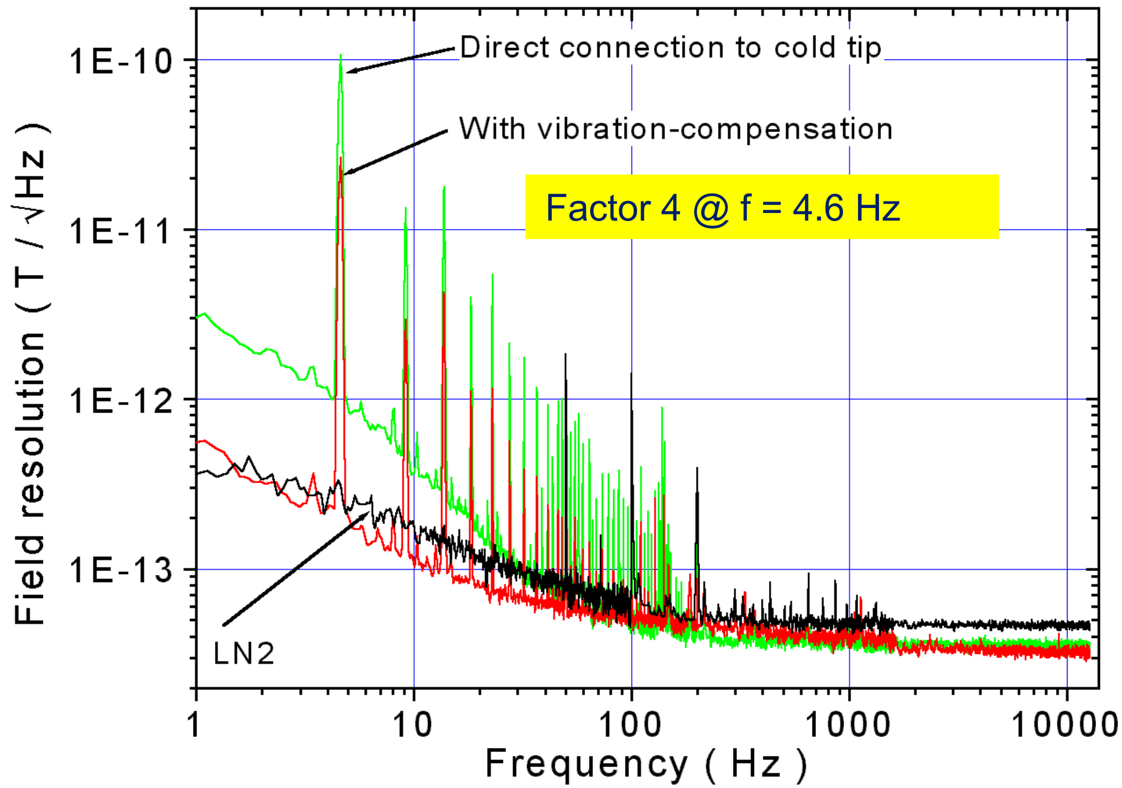
at typical operating condition of Δp = 7 bar

Damping of vibrations: small 1-stage PTC

Giessen 1999





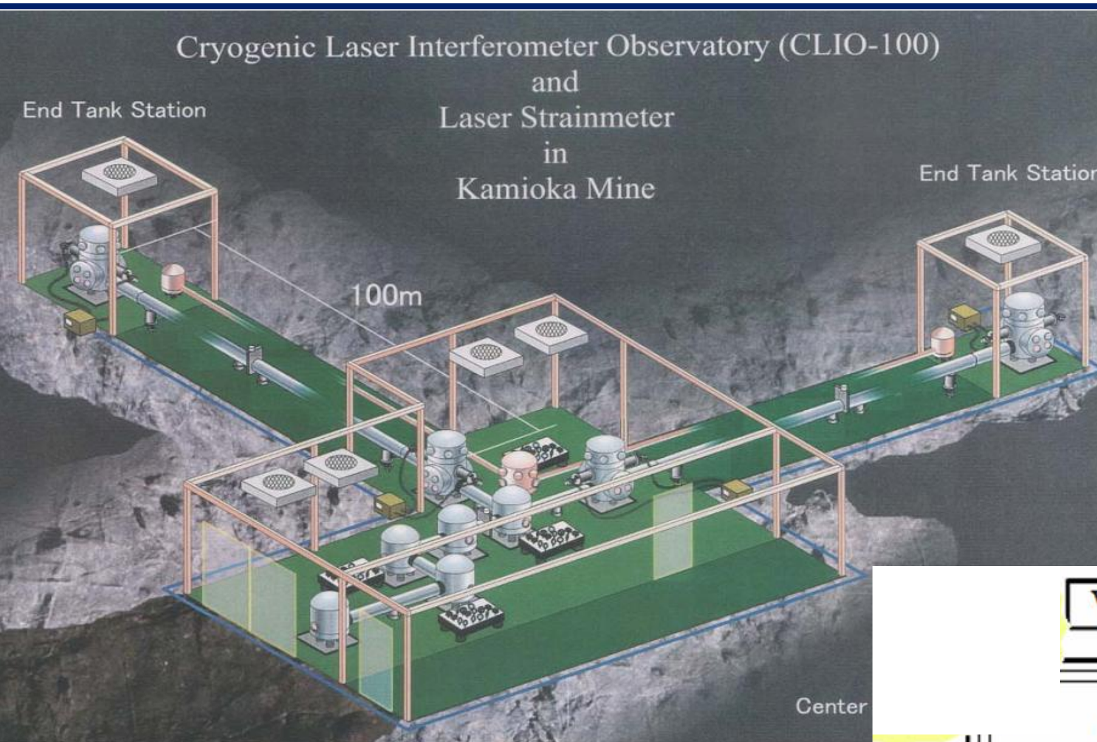


YBCO-rf-SQUID (FZ Jülich)

LN2 (77 K): 45 fT/√Hz above 100 Hz

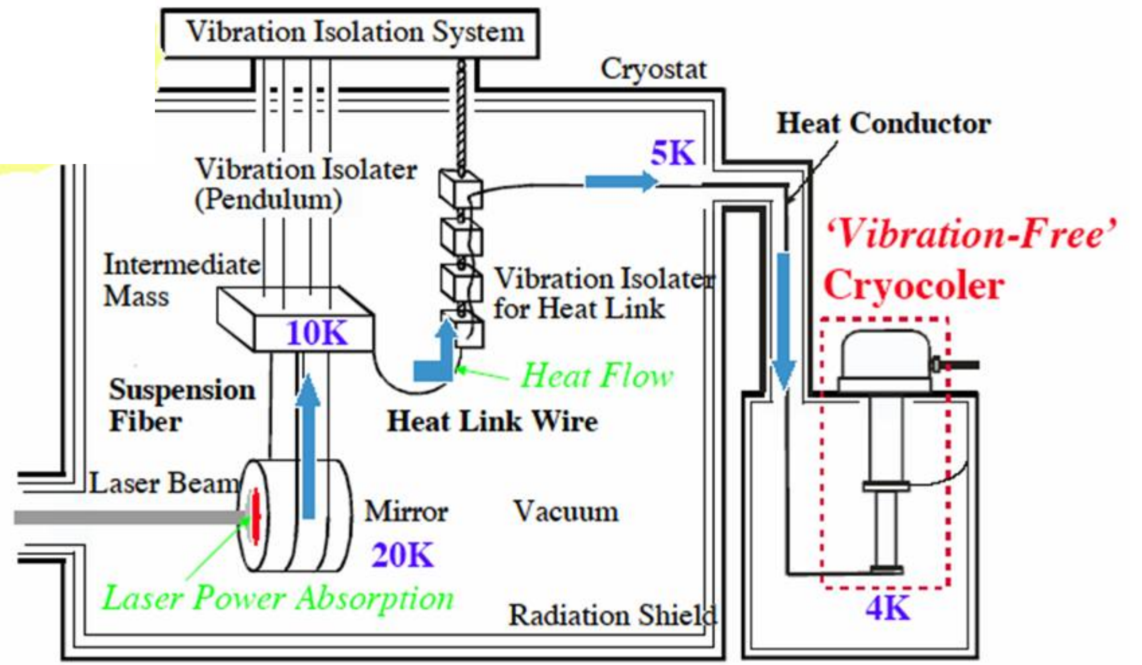
PTC (70 K): white noise 35 fT/√Hz

Advanced vibration isolation for 4 K PTCs (CLIO-100)



Specification for the CLIO cryocooler system

	4 K cryocooler unit		80 K cryocooler unit
Number of cryocoolers	4 units		6 units
Basic cryocooler	Two stages pulse tube cryocooler		Single stage pulse tube cryocooler
Compressor power consumption	7 kW		7 kW
Power frequency	60 Hz		60 Hz
Cold stages	2nd stage	1st stage	80 K stage
Objects to be cooled	Mirror and inner shield	Outer shield	Laser-beam duct shield
Cooling performance requirement	0.5 W at 5 K	20 W at 50 K	50 W at 80 K
Vibration amplitude requirement	<±1 μm	<±1 μm	<±1 μm



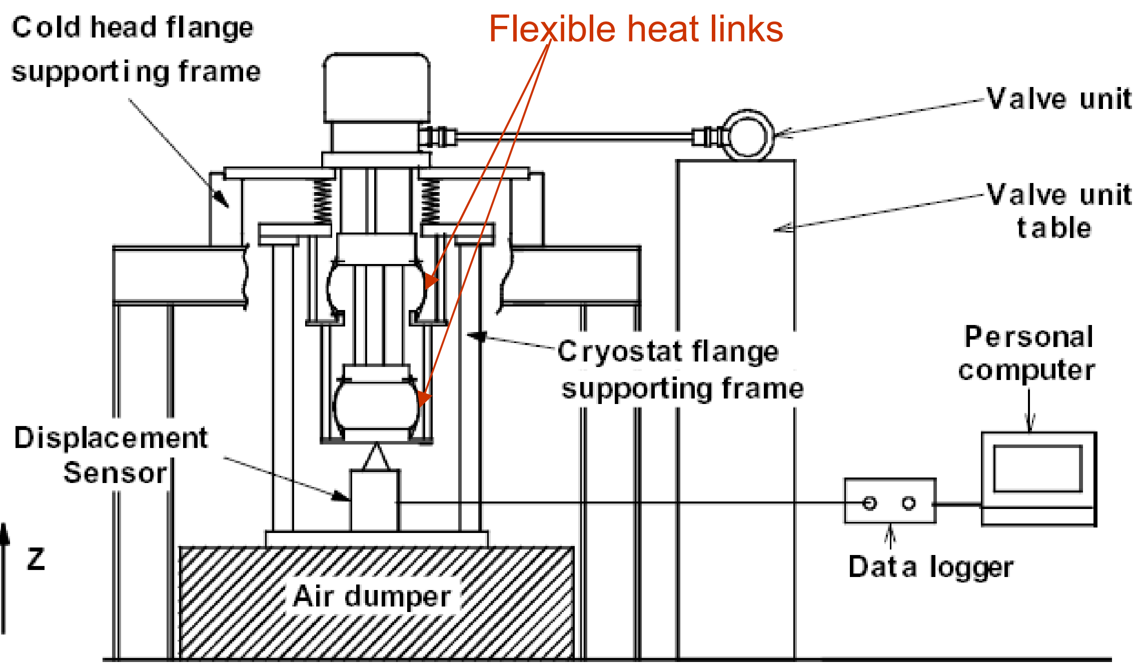
"Vibration-free" 4 K PTC for CLIO, T. Tomaru et al., Cryocoolers 13 (2004), p. 695

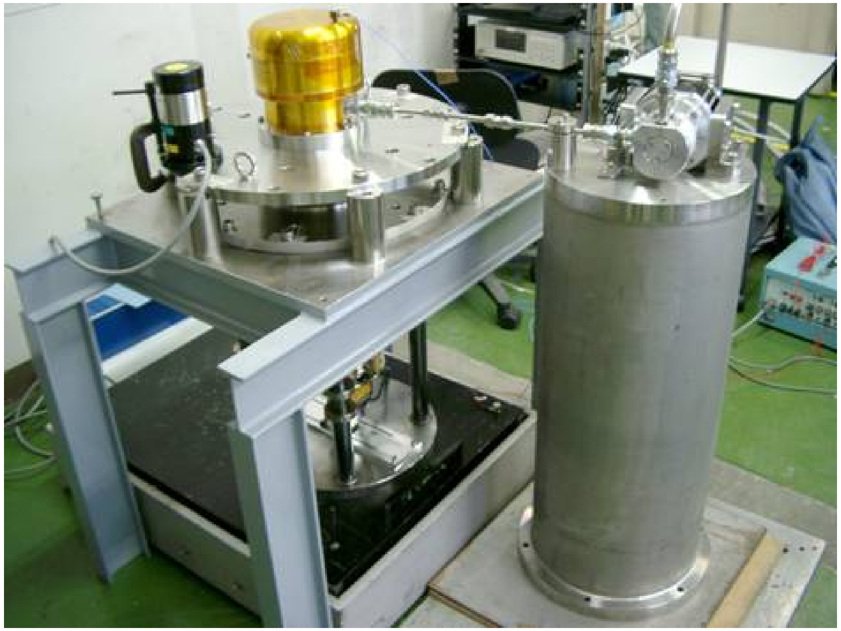
Y. Matsubara, WEH-Workshop "Applied Cryoelectrics" (2006)

Y. Ikushima et al. , Cryogenics <u>48</u> (2008) p. 406

Vibration reduction of Sumitomo 4 K PTC

Y. Ikushima et al. , Cryogenics 48 (2008) p. 406
R. Li et al., Cryocoolers 13 (2004), p. 695





4 K PTC: Sumitomo SRP-052A (7 kW compressor)

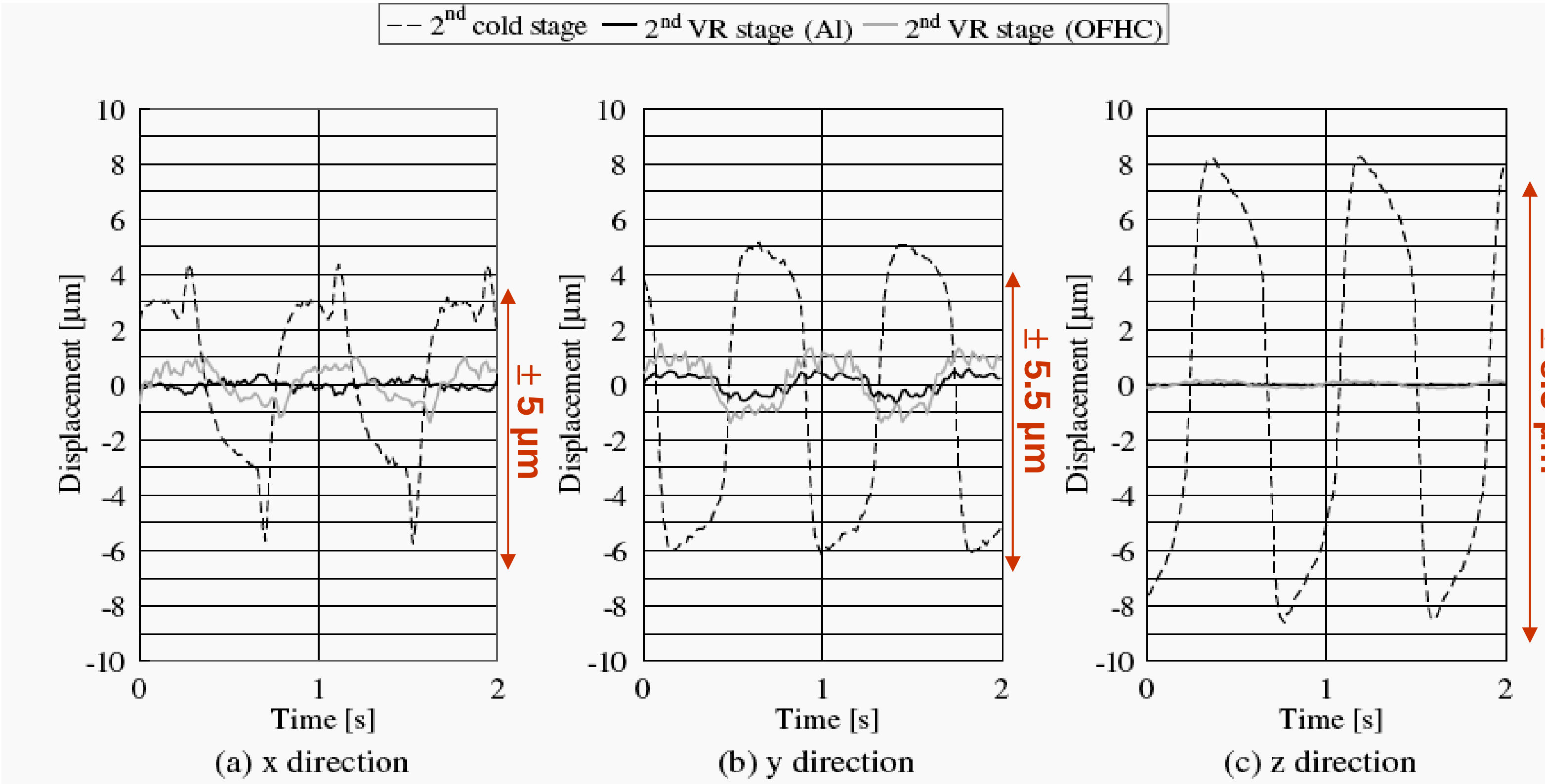
0.5 W @ 4.2 K and 20 W @ 42 K

with 40 cm line from rotary valve to cold head

*Remark: A PTC system with **active vibration compensation** was built and tested by the **group of Fulvio Ricci (Rome)***

Vibration of Sumitomo 4 K PTC

R. Li et al., Cryocoolers 13 (2004), p. 695 and Y. Ikushima et al. , Cryogenics 48 (2008) p. 406



Displacements of 2nd stage with vibration isolation:

Flexible heat links	x	y	z
OFHC-Cu	±1.2 μm	±1.5 μm	±0.2 μm
High-purity Al	±0.2 μm	±0.1 μm	±0.02 μm

Requirement of amplitude < 1 μm for CLIO fulfilled

Summary

- Nowadays, 4 K PTCs have proven to be reliable cryocoolers with low intrinsic vibration level.
- Cooling powers range from 200 mW to more than 1 W @ 4.2 K
- By use of special set-ups for vibration isolation the residual vibration amplitudes can be reduced to a "tolerable" level of < 1 µm, as shown for example by the Cryogenics Group of CLIO-100.

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