Pulse Tube Cryocoolers:

An Option for Cooling without Cryogenic Liquids

Guenter Thummes

TransMIT-Center for Adaptive Cryotechnology and Sensors
TransMIT GmbH, Giessen, Germany

at the

Institute of Applied Physics, University of Giessen

Content

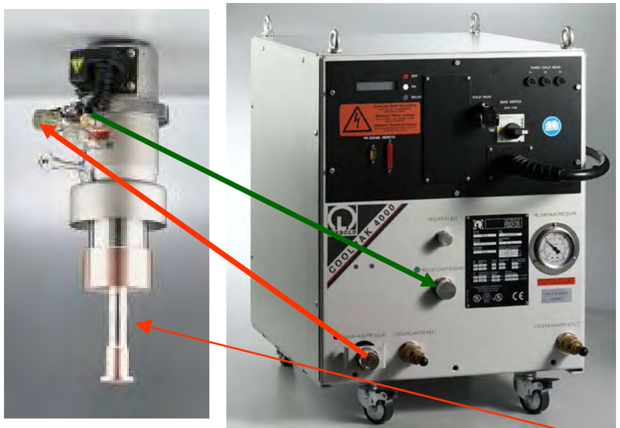
- **Short Introduction to Pulse Tube Cryocoolers (PTCs)**

  Classification, Working Principle, Advantages

- **Two-Stage 4 Kelvin PTCs and some Applications**
- **Single-Stage PTCs for T ≥ 15 K and some Applications**

Classification: Regenerative Cryocoolers

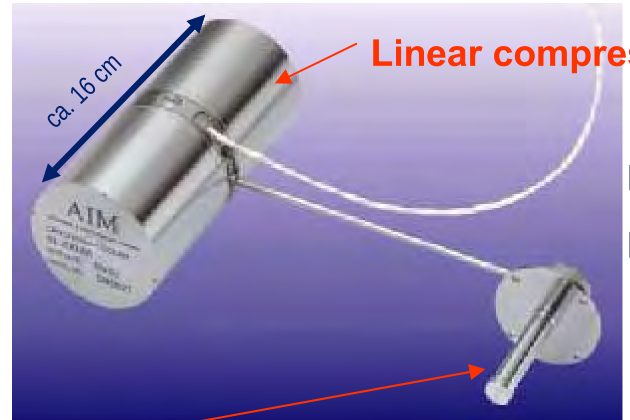
Gifford-McMahon (GM)-cooler, f = 1-2 Hz



P_{in} = 2-8 kW

M ≈ 100 kg

Mini-Stirling-cooler, f = 40–60 Hz



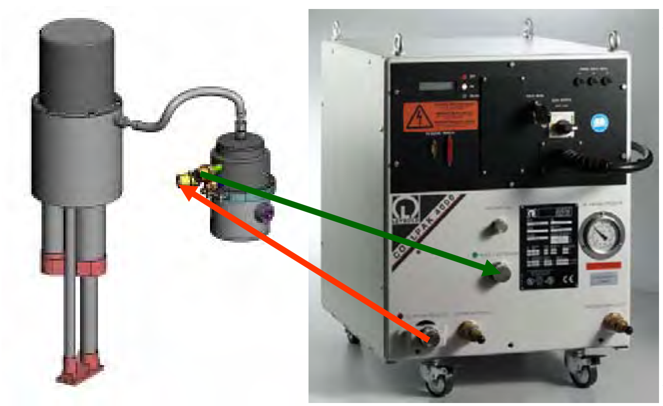
Linear compressor

P_{in} ≈ 100 W

M ≈ 4 kg

Expansion controlled by piston ("displacer") → vibrations, internal wear

"GM-type" PTC



70 cm

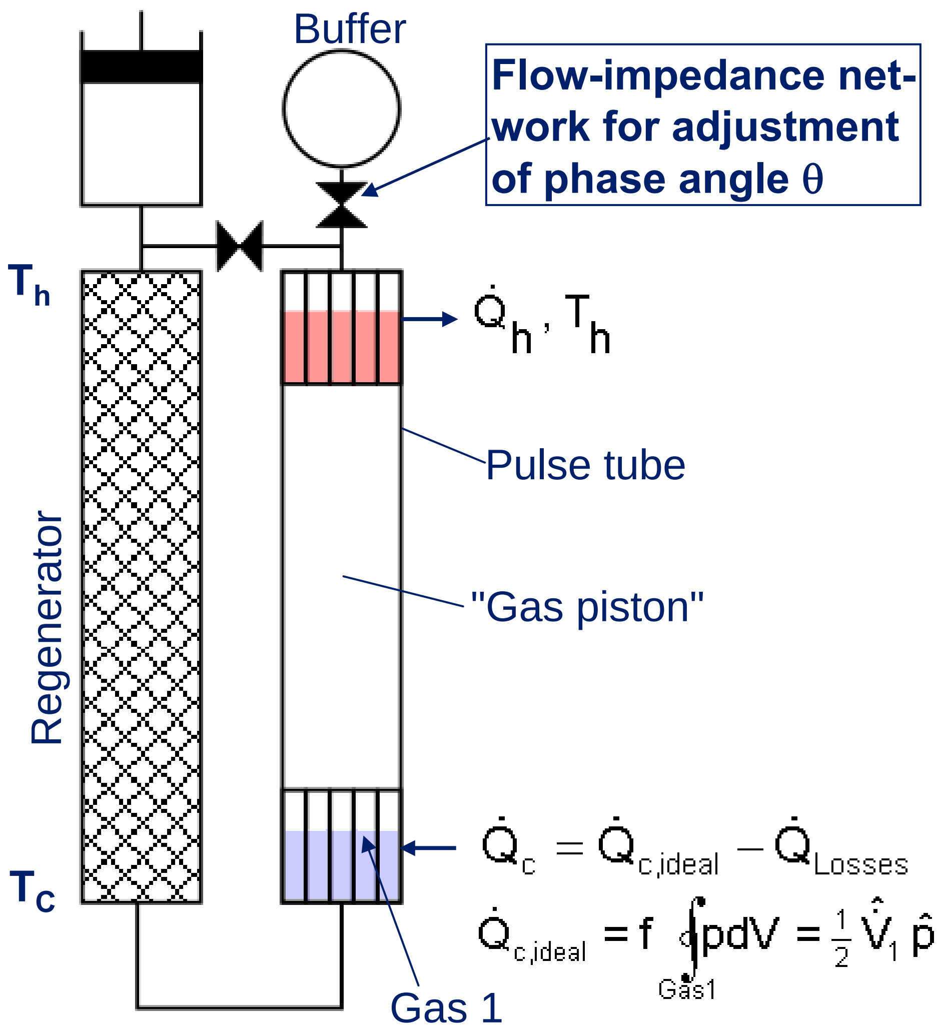
"Stirling-type" PTC

22 cm

→ No moving displacer in the PTC cold head !

Working principle of a PTC

Schematic of single-stage Stirling-type PTC



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

$$\dot{Q}_{c,ideal} = f \oint_{Gas1} p\,dV = \tfrac{1}{2} \hat{\dot{V}}_1\, \hat{p} \cos\theta$$

No moving solid displacer at cold end

→ <u>Advantages of PTCs</u>

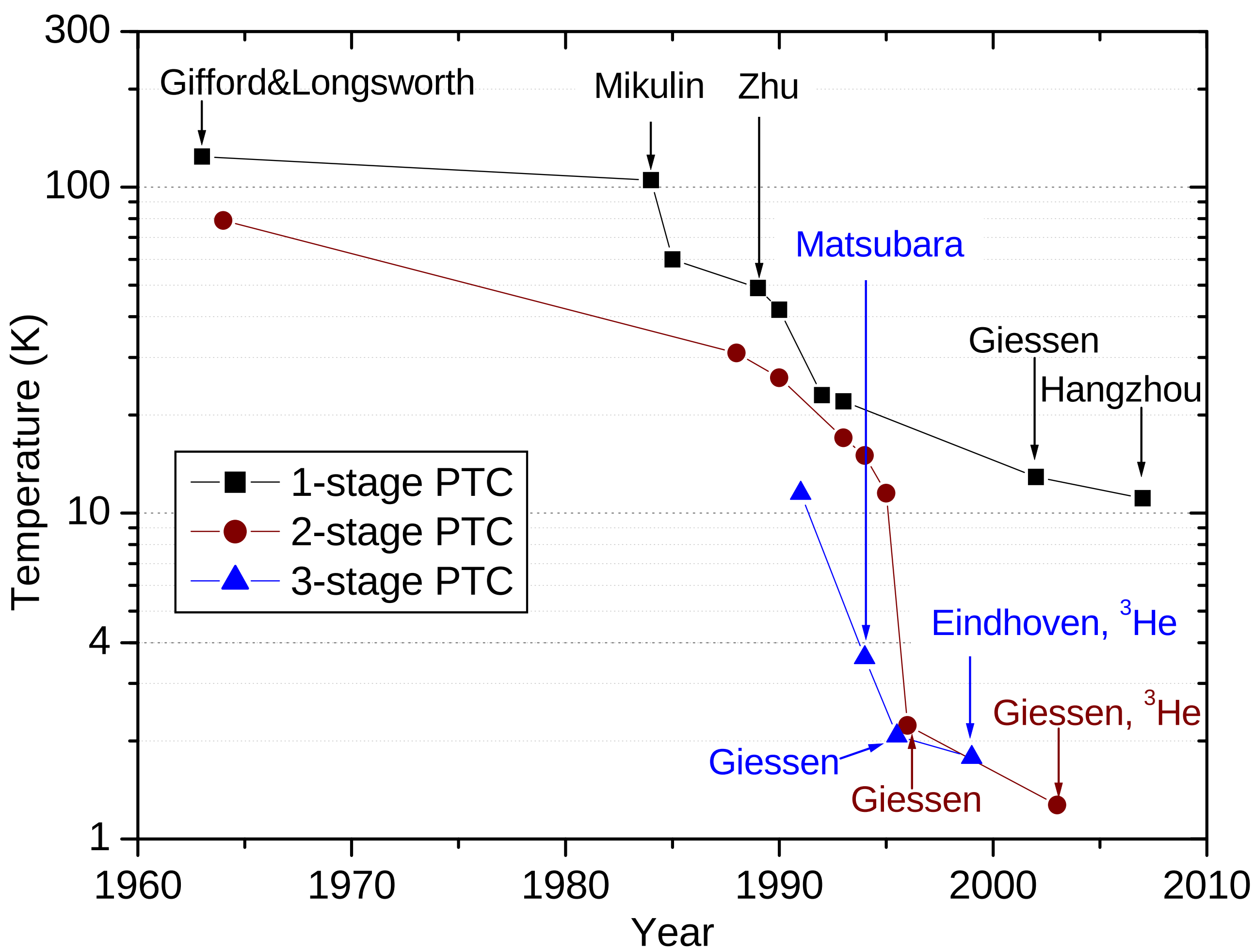
- **Higher reliability**
- **No regular maintenance of the cold head**
- **Lower vibrations and EMI from cold head**
- **No precision parts at the cold end → Can be easily adapted to the particular needs of an application**

***

<u>Disadvantage of PTCs</u>

- **Orientation dependence of performance in low-frequency ("GM-type") PTCs**

"History" of 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)*

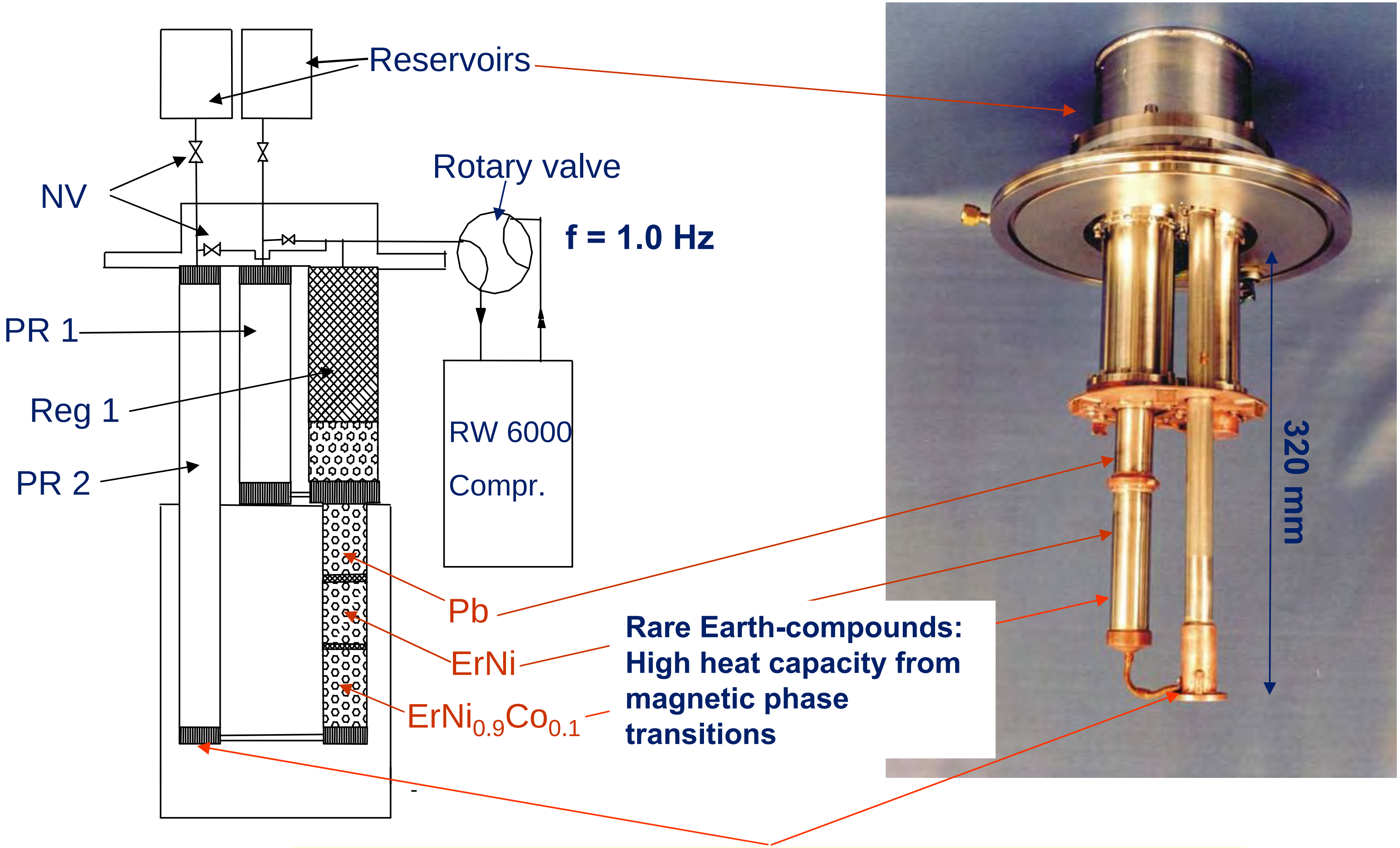
1.27 K, ^{3}He *(Giessen 2003)*

3-stage PTCs

3.6 K *(Y. Matsubara, 1993)*

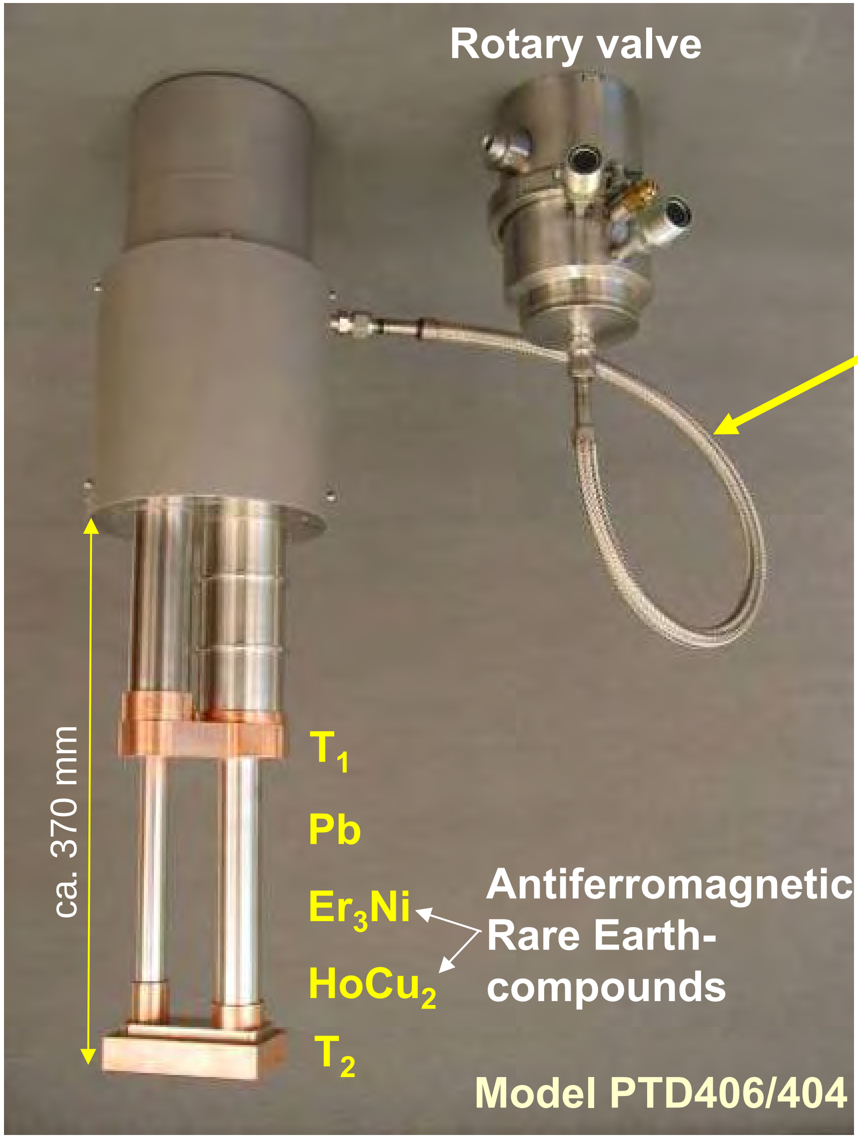
2.07 K *(Giessen 1996)*

First 2-stage 4 K PTC (Giessen 1996)



T_{min} = 2.23 K, Q_2 = 370 mW @ 4.2 K with P_{in} ≈ 6 kW

Current 2-stage 4 K PTC (Giessen)



"Split-Design"

Flexible pressure line (0.5 – 1 m)

→ Reduction of vibrations from rotary valve

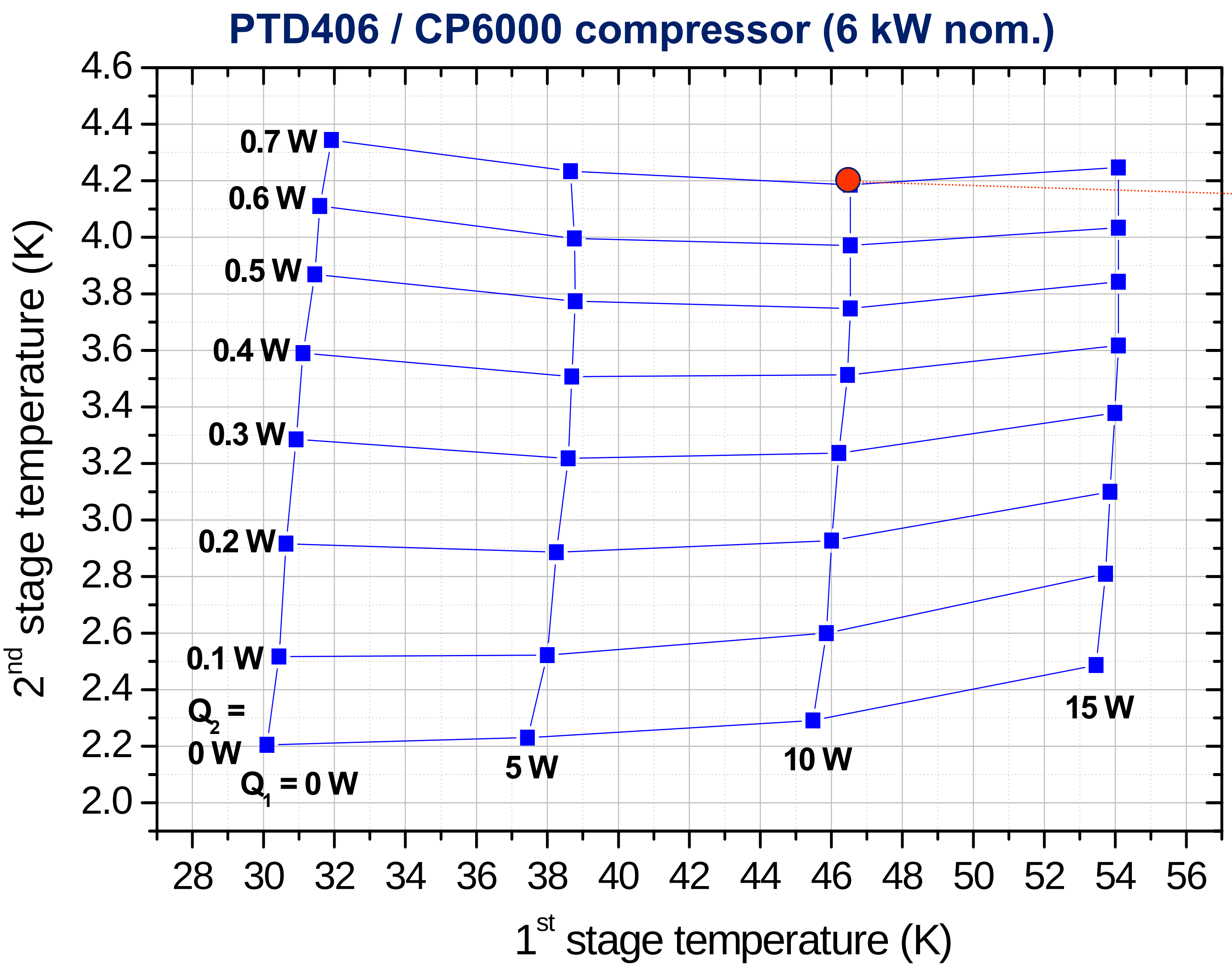
→ Makes possible the positioning of the rotary valve in low stray field (< 20 mT)

Performance data of some 4 K PTCs

Model	P_{in} (steady state)	Typical cooling power	T_{min}	Cool down to 4.2 K *)
TransMIT, PTD402S	2.0 kW	0.15 W @ 4.2 K 2 W @ 54 K	< 3.0 K	< 180 min
TransMIT, PTD404	3.6 kW	0.6 W @ 4.2 K 10 W @ 59 K	< 2.5 K	< 90 min
TransMIT, PTD406	5.8 kW	0.7 W @ 4.2 K 10 W @ 47 K	< 2.4 K	< 75 min
TransMIT, PTD411	9.5 kW	1.1 W @ 4.2 K 30 W @ 53 K	< 2.4 K	< 70 min

**) With standard copper radiation shield installed*

Cooling Load Map of PTD406



T_{min} = 2.21 K

Simultaneous cooling powers:

2nd stage:
Q_2 = 0.71 W @ 4.2 K

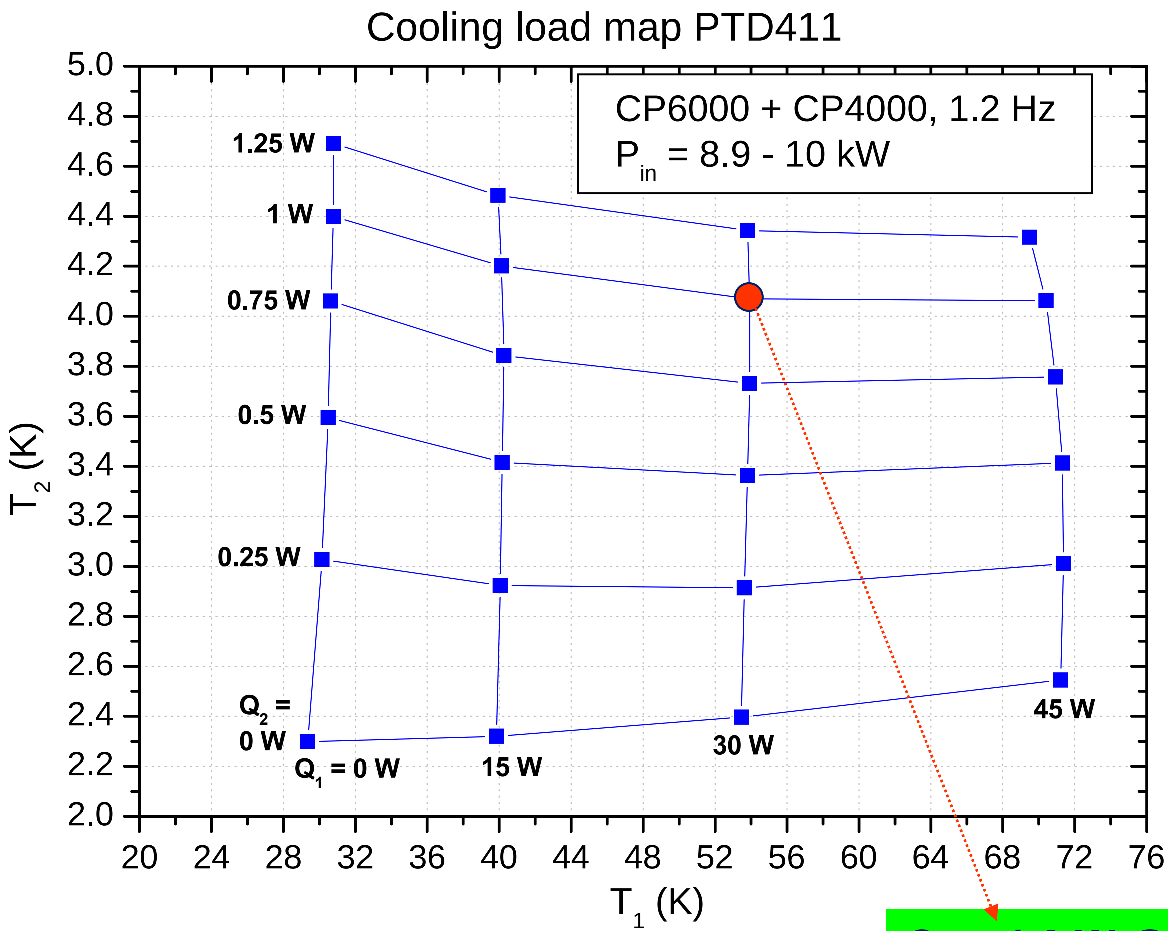
1st stage:
Q_1 = 10 W @ 46.6 K

at P_{in} = 5.5 kW

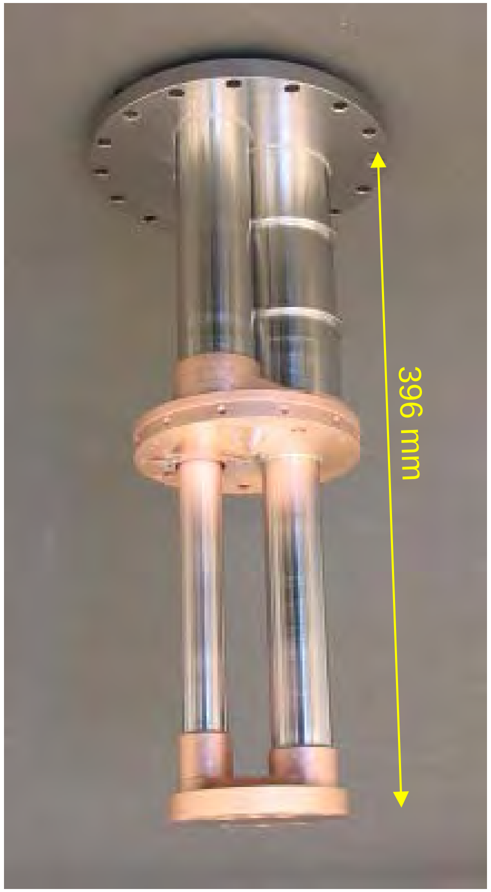
Cool down time to 4.2 K: ≈ 70 minutes

4 K PTC with increased cooling power

Giessen 2006



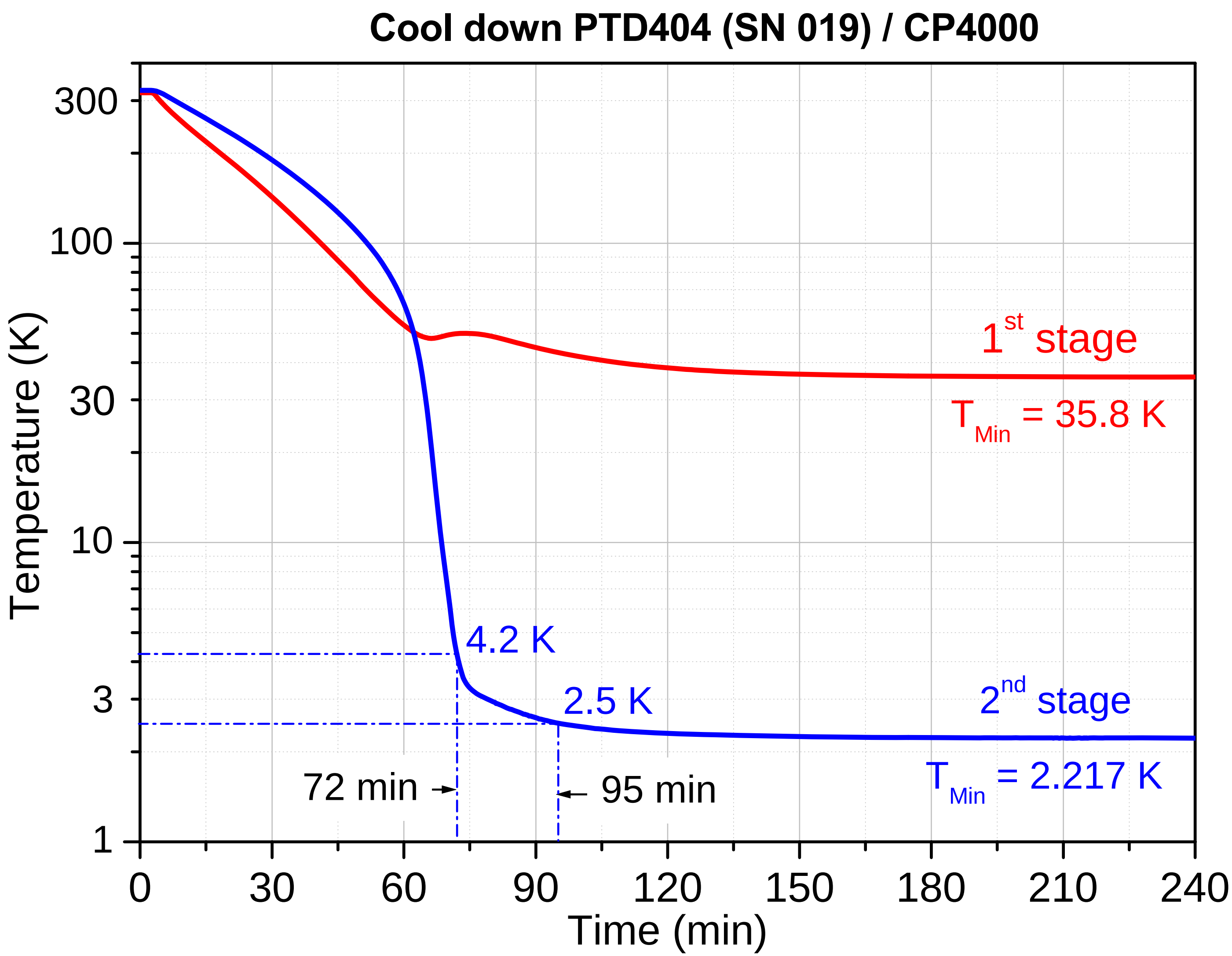
PTD411



Cool down to 4.2 K ≈ 1 h

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

Typical cool down curve (4 kW compressor)

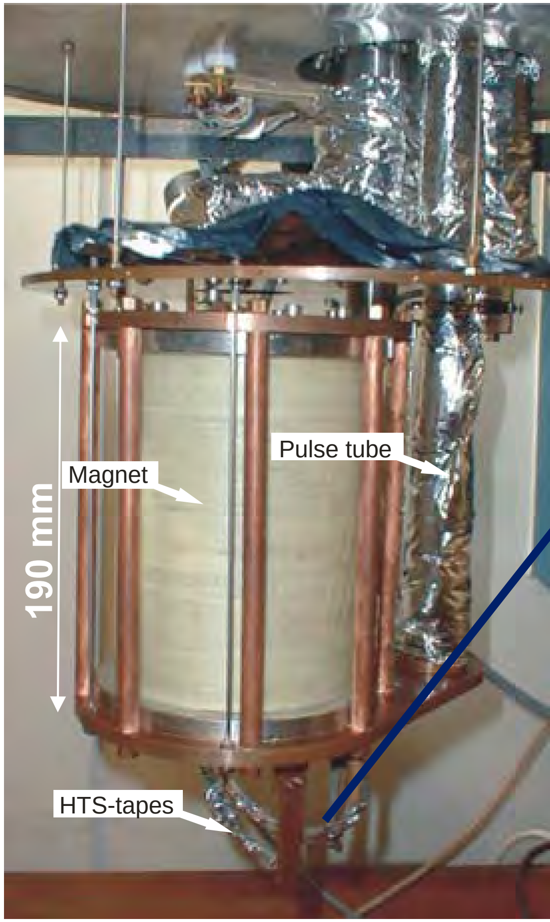


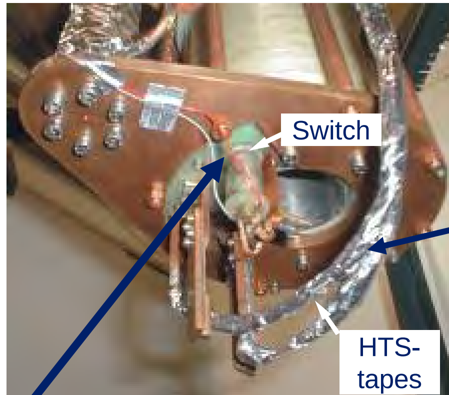
Applications of 4 K PTCs (Giessen)

- **Small scale Helium-liquefaction** (0.15 L/h, *1997)*
  (0.3 - 0.7 L/h, *2006)*
- **"Dry" 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 magnet with top-loading system *(2007)*
- **^{3}He PTC with T-min = 1.27 K and Q = 30 mW @ 2.0 K** *(2003)*
- **PTC for narrow gap magnet *(2007)***
- **"Dry" cooling of Josephson-voltage standards** *(2002-2007)*
  Co-operation with: IPHT Jena, PTB Braunschweig
- **Precooling of sub-Kelvin cooling stages**
  - 5 T NbTi-magnet for ADR *(2000)* → T_{min} = 96 mK *(with CSP, Ismaning)*
  - Miniature ^{3}He/^{4}He-dilution refrigerator with T_{min} = 50 mK
    Co-operation with: Institute of Applied Photonics e. V., Berlin (2006)

5.5 T NbTi magnet with persistent current switch

Giebeler, Best, Thummes (EUCAS 2003)





Total mass: 16 kg

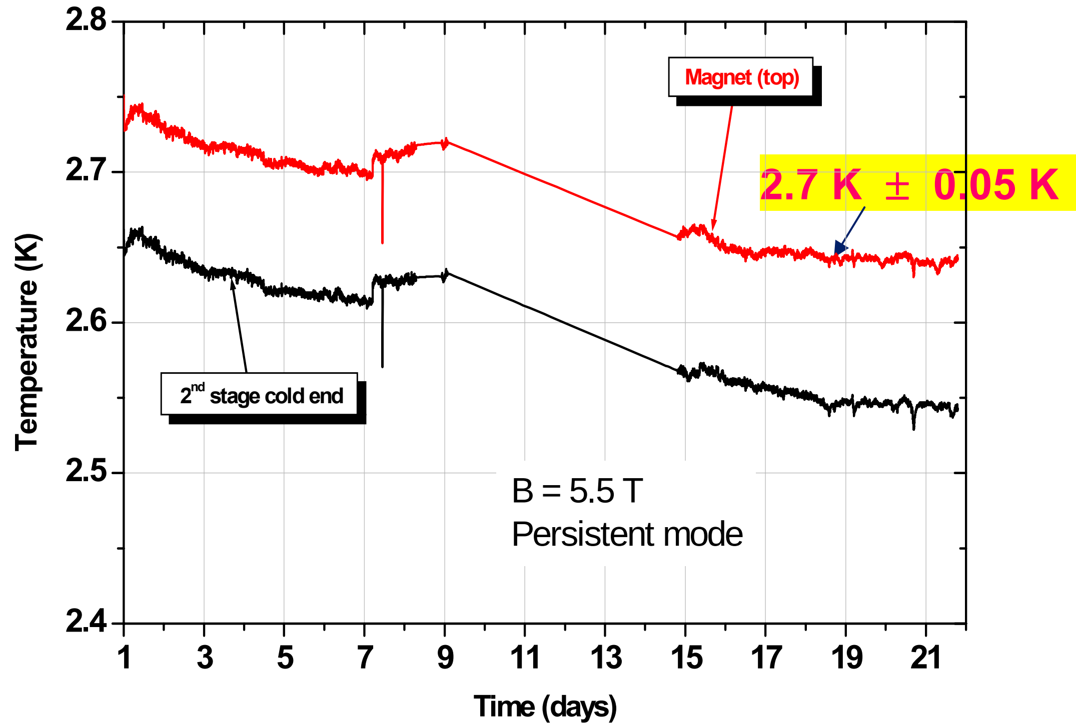
Inductance: 21 H

5.5 T @ 35 A

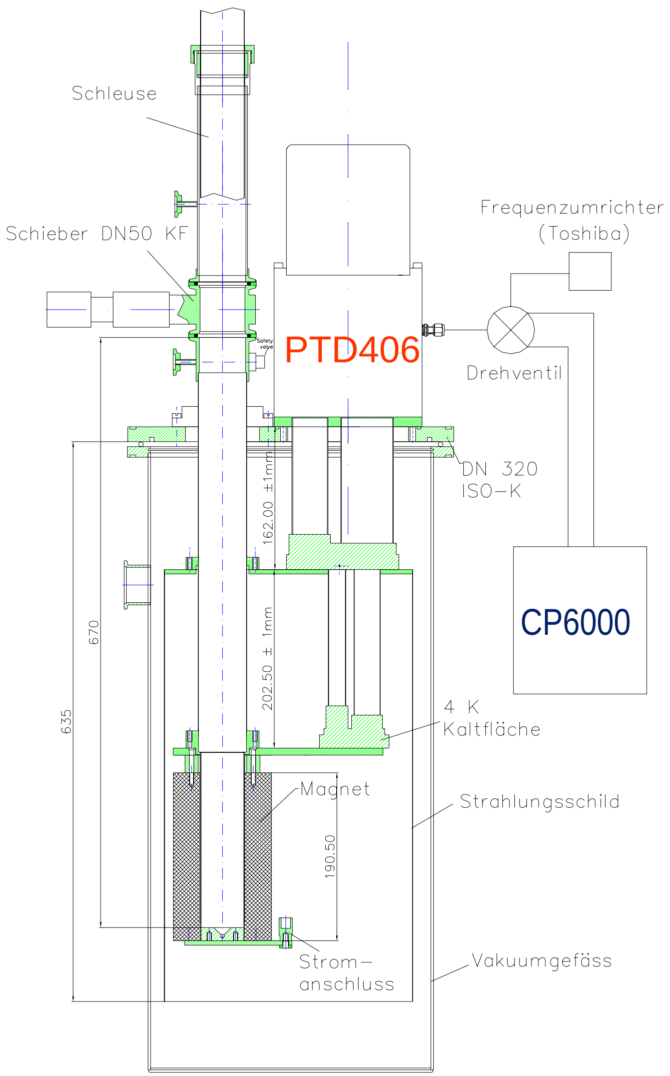
Bi2223-AgAu-current leads

Magnet cooled by PTD406, prototype

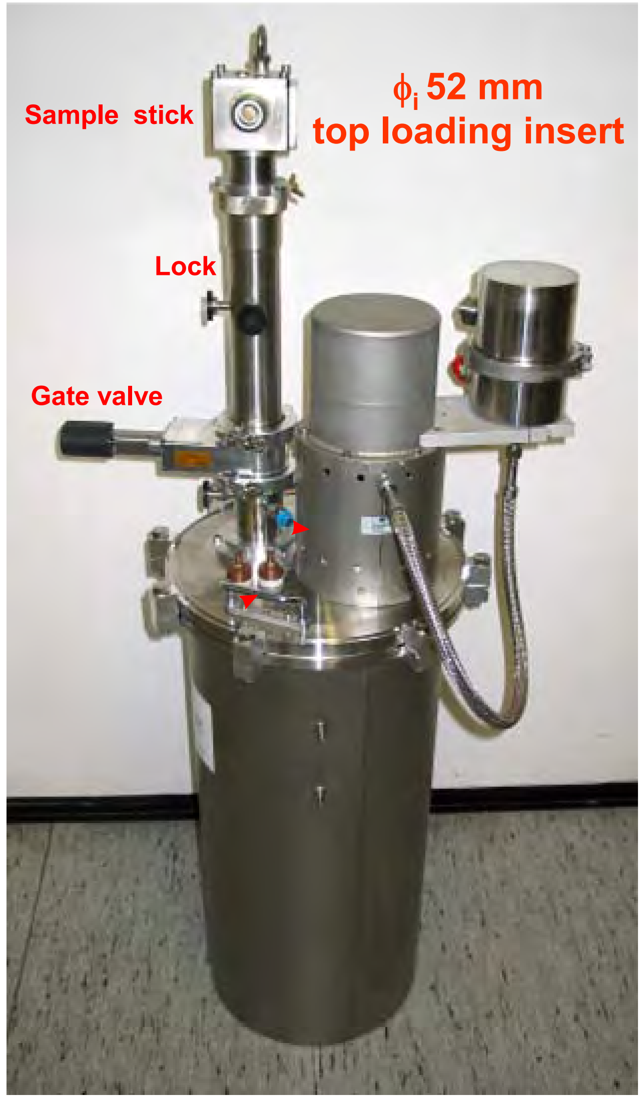
Three weeks run at 5.5 T:



“Dry” Cryostat with 5 T Magnet and Toploader



Giessen 2006-2007



User: IMS, University of Karlsruhe

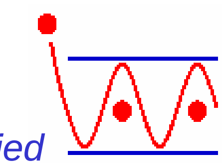
- **Cooldown time to 4 K: 7 hours (Extra mass 7.5 kg)**
- **Base temperature with sample holder inserted: 3 K**
- **Magnet sweep to 5 T: 7 min**
- **Changing of samples and cooling back to 4 K within < 2 hours**

Optional ^{3}He-sorption cooler insert:

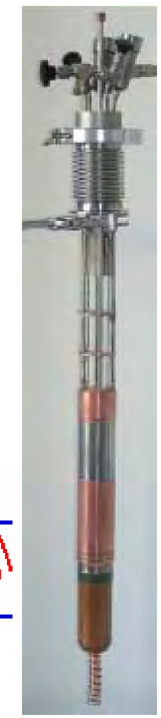
T-min = 407 mK

Hold time: 6 hours

Q ≈ 60 µW



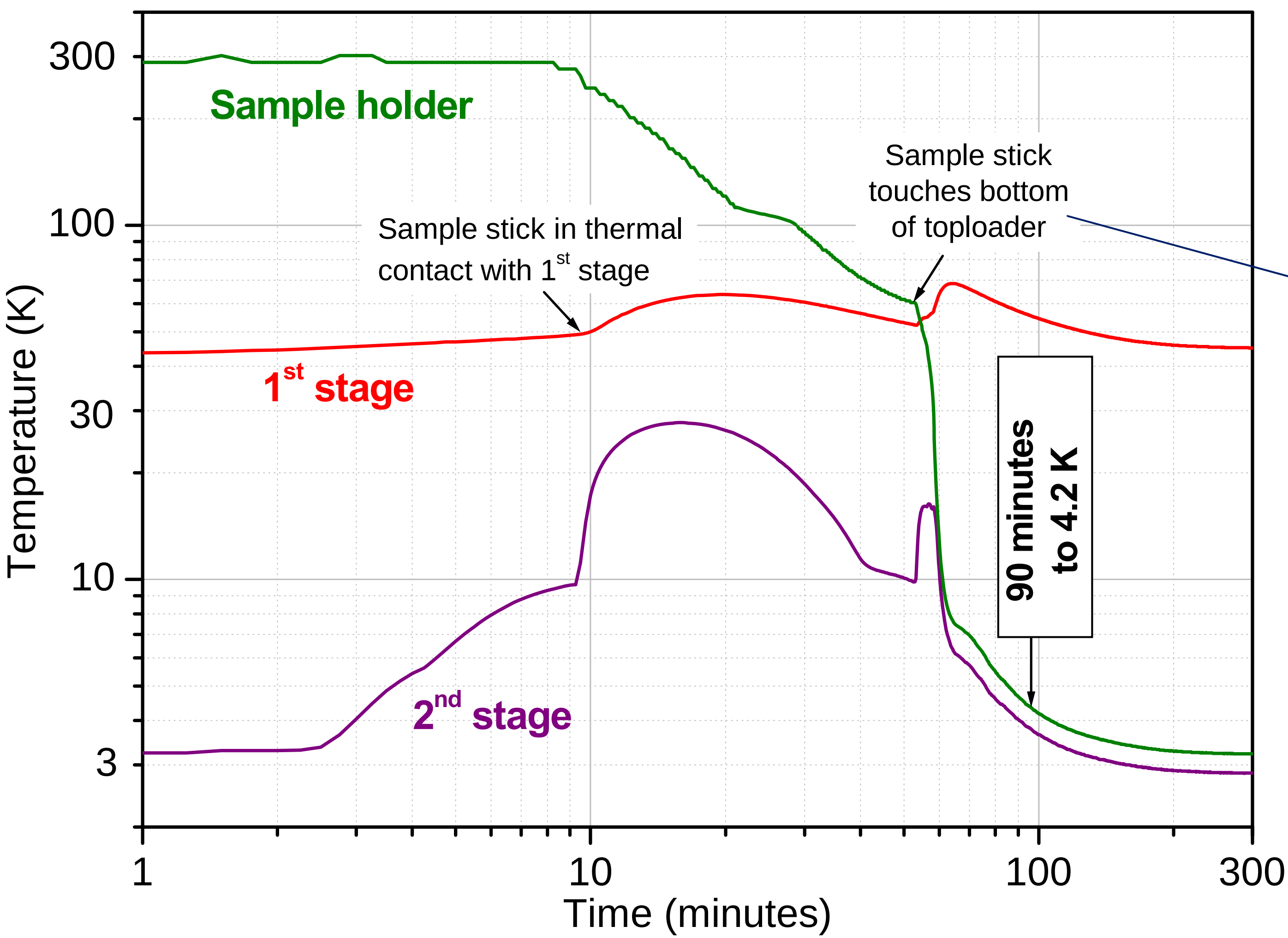
Institute f. Applied Photonics e.V. Berlin (2007)

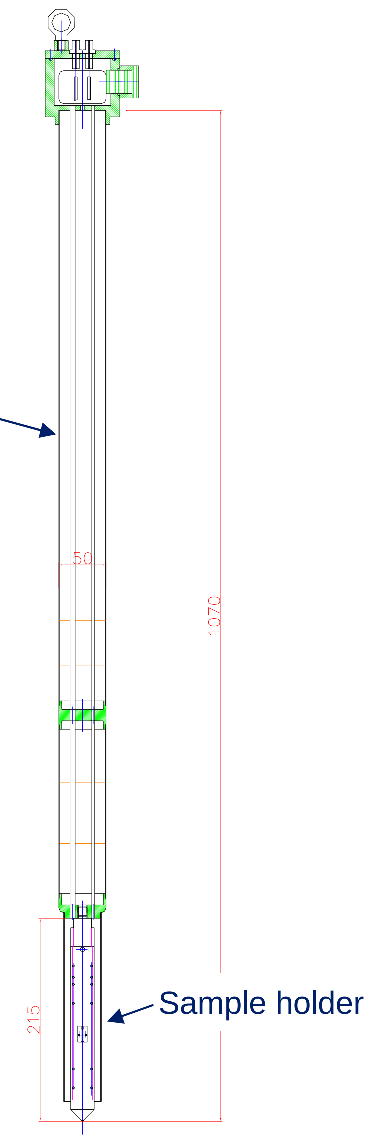


JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Cool-Down of 3 K Sample Stick in Toploader

TransMIT Gesellschaft für Technologietransfer mbH





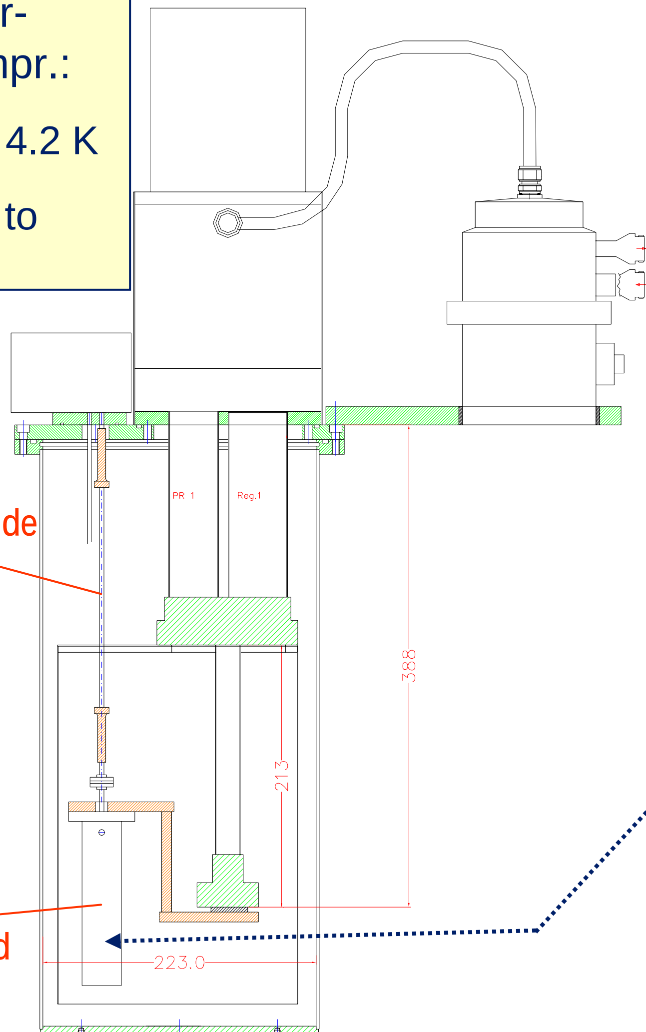
"Small" 4 K PTC (PTD 402S)

Low-noise cooling of 1 V and 10 V Josephson voltage-standards

Application: Primary voltage standards in industry and metrological institutes

PTD402S with air-cooled 2 kW compr.:

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

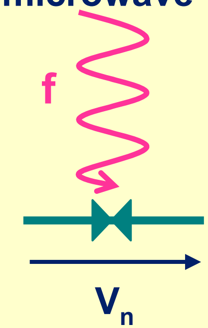


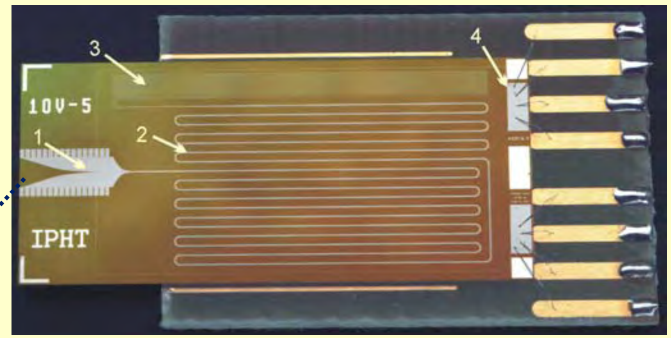
Dielectric waveguide (75 GHz)

Josephson chip in Cryoperm shield cooled to 3.8 K

Synchronisation of Josephson oscillations by an external microwave

$$V_n = n \cdot \Phi_0 \cdot f$$
$$\Phi_0 = h/2e$$
$$= 2{,}0678\ldots \ \mu V/GHz$$





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

Partners:

JENA IPHT

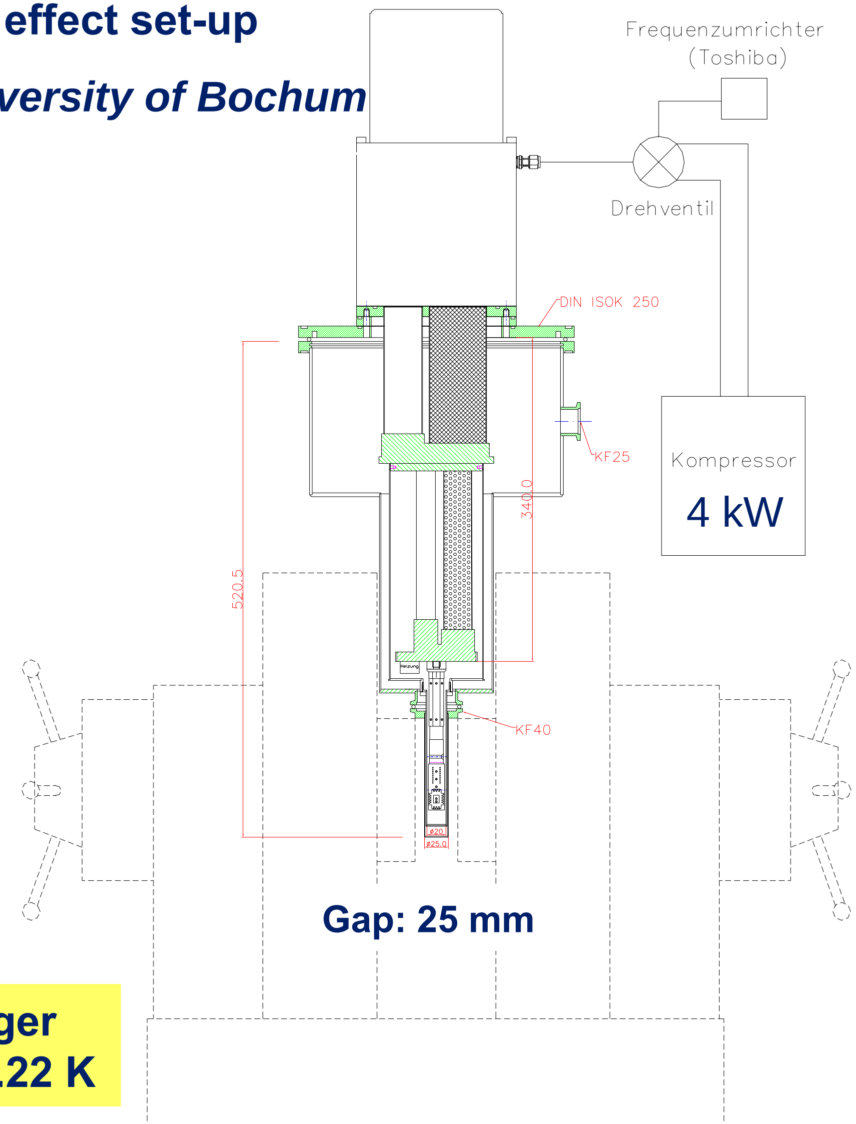
PTB

BMBF

PTC for Narrow-Gap Magnet

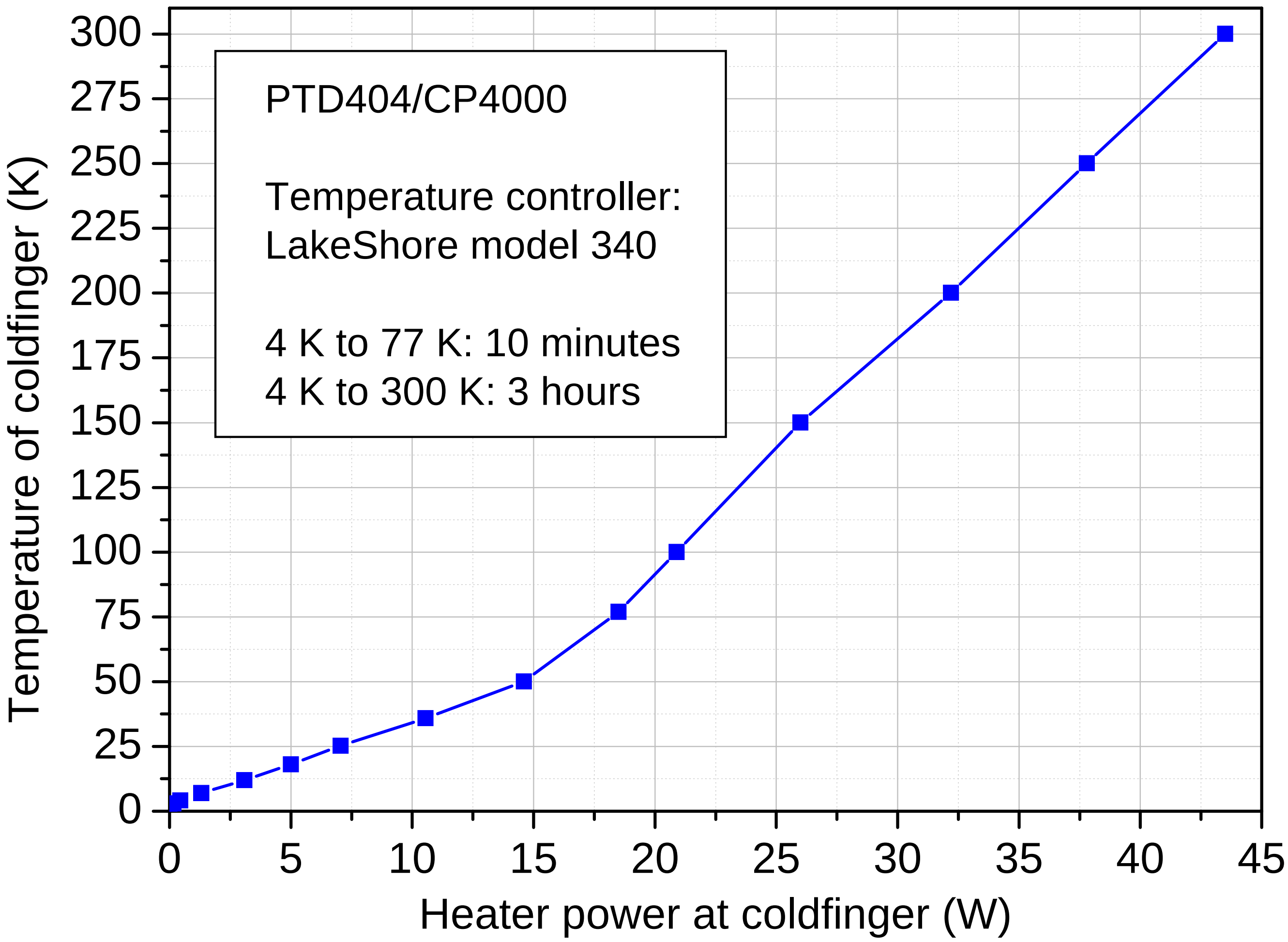
Hall effect set-up

User: University of Bochum



Coldfinger
T_{min} = 2.22 K

Operation at High Load (PTD404)



Useable T-range:

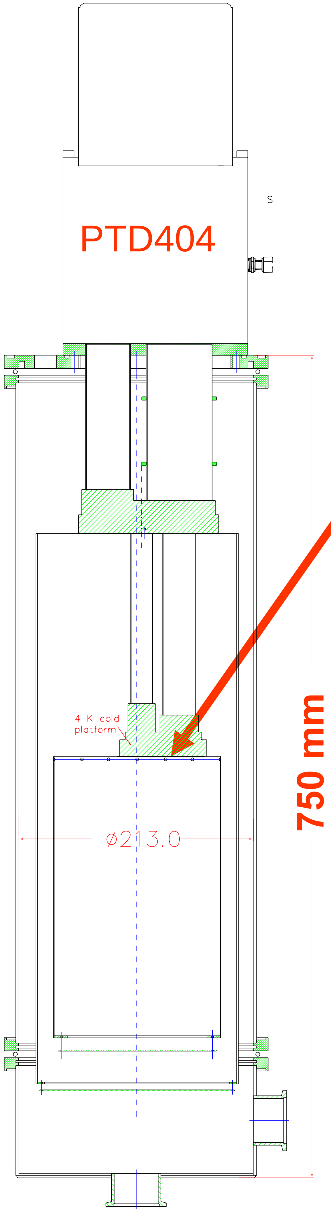
2.22 K to 380 K.

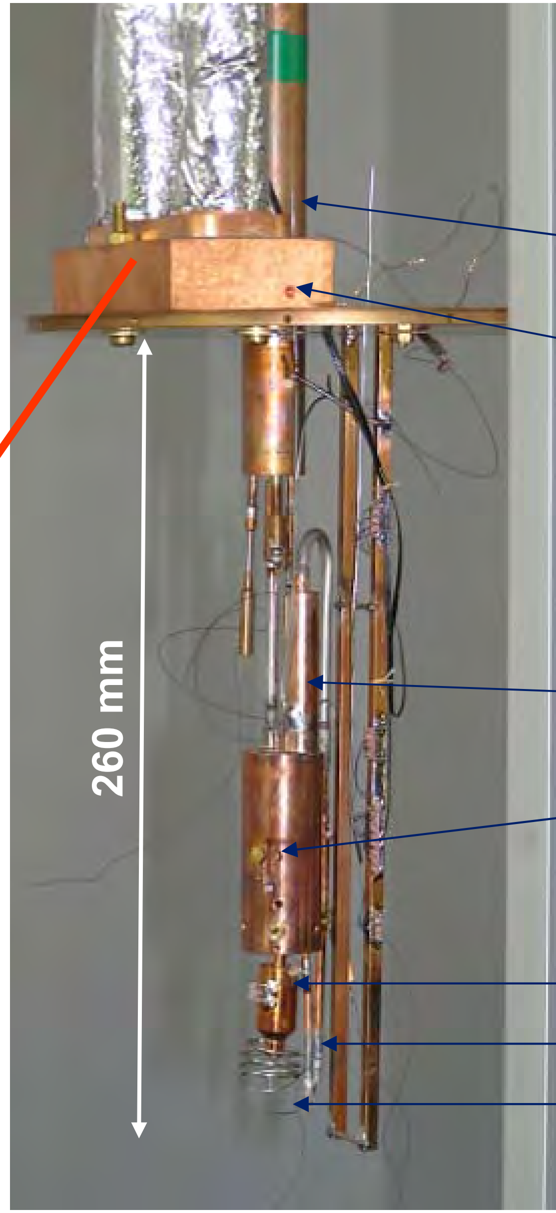
Could be extended to higher T.

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

TransMIT Gesellschaft für Technologietransfer mbH

Autonomous Mini Dilution Refrigerator with 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)

Condenser 0.4 K

^{3}He-evaporator

Mixing chamber: 50 mK

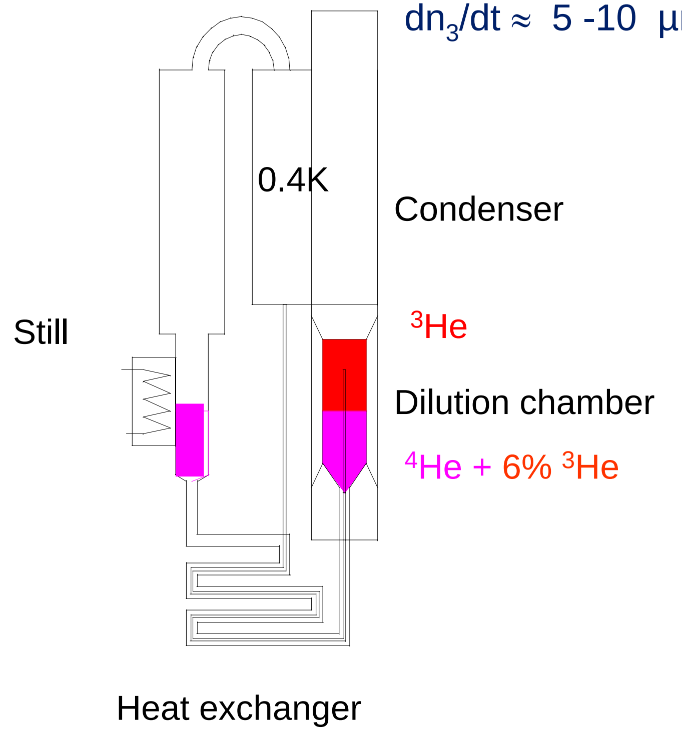
Still 0.7 K

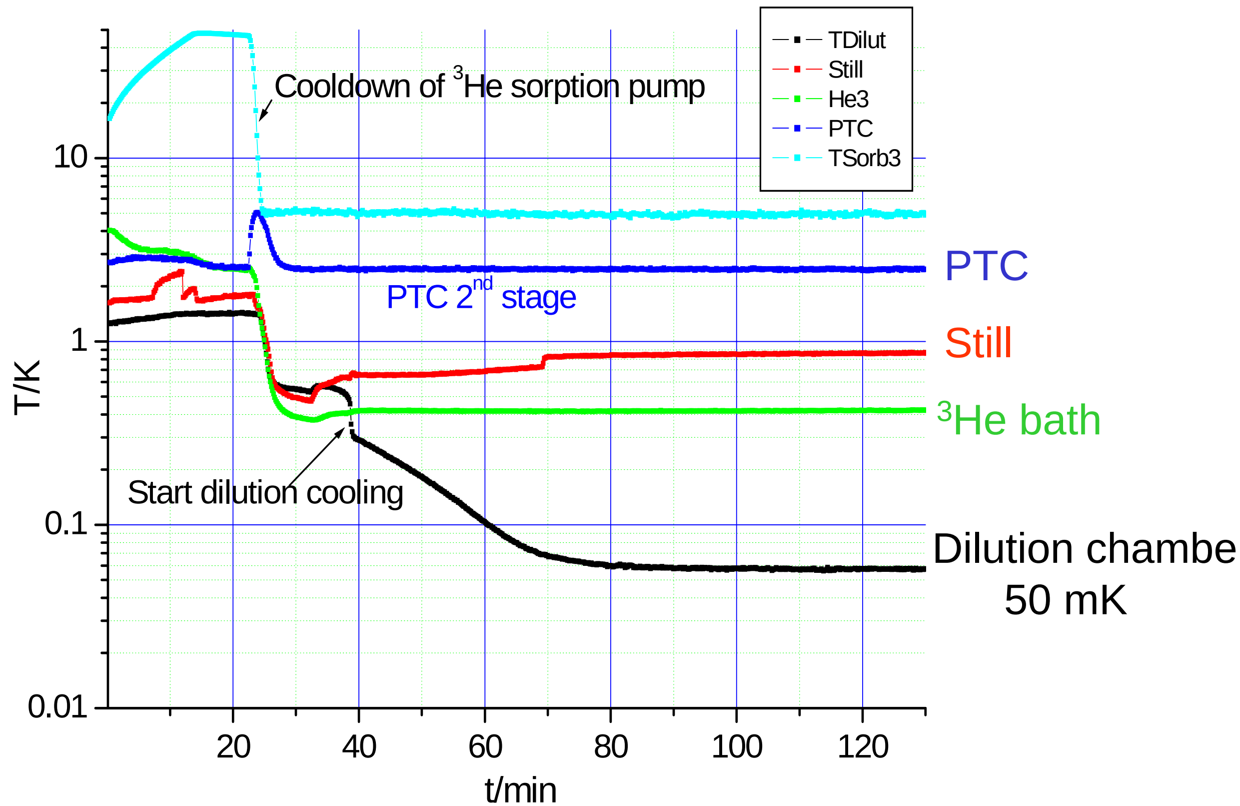
Continuous HX

Mini Dilution Refrigerator with PTC (2)

Institut of Applied Photonics e.V. Berlin

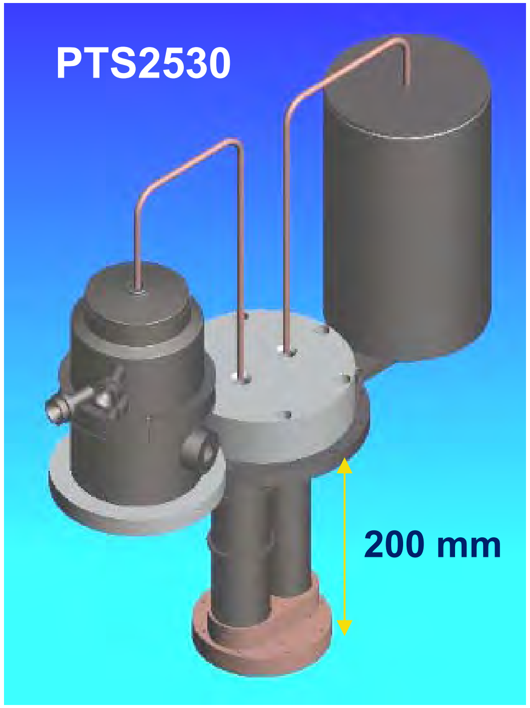
$dn_3/dt \approx$ 5 -10 µmol/s





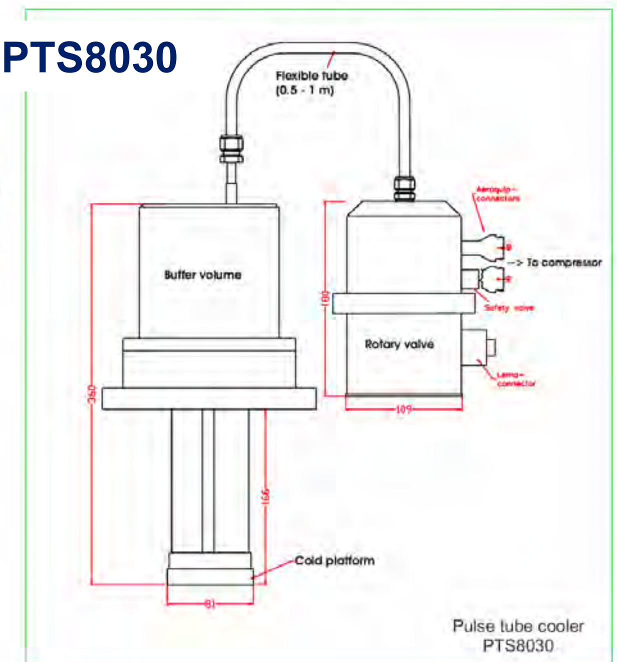
Single-stage GM-type PTCs

PTC model	Compressor input power (nominal)	Cooling power	T_{min}
PTS2530, prototype	6 kW	30 W @ 26 K 60 W @ 45 K	< 16 K
PTS8030	2 kW (air-cooled)	20 W @ 60 K 30 W @ 80 K	< 35 K



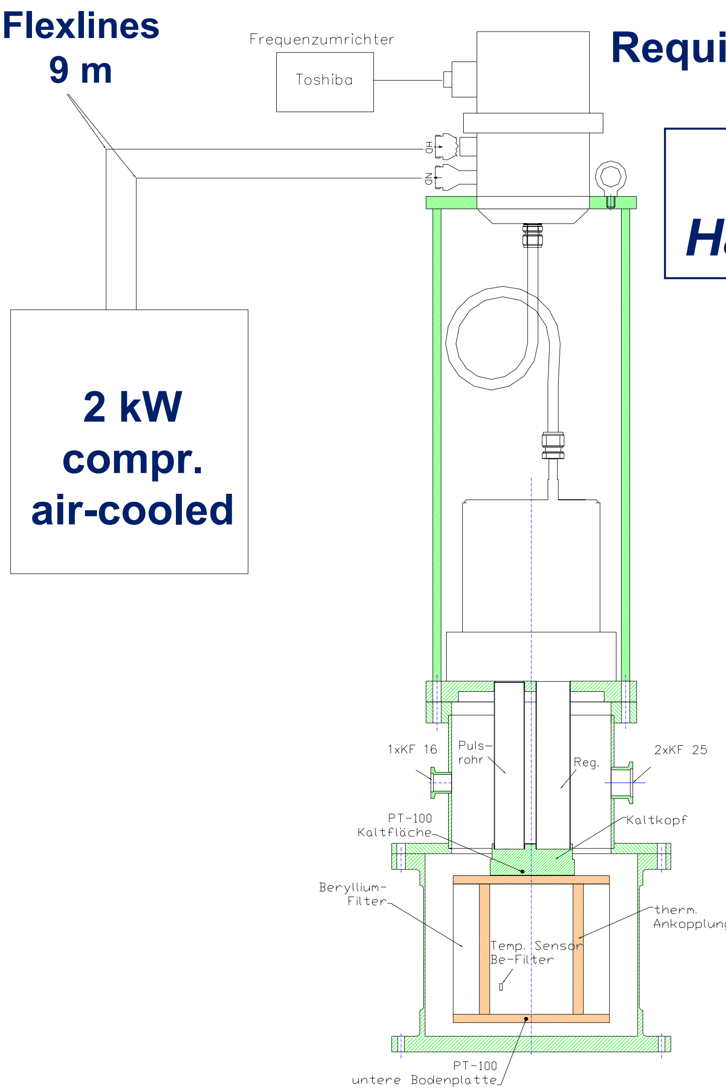
Application: Cooling of a 0.4 MW HTS-motor at Siemens AG (2002)

PTS8030



Pulse Tube Cooling of a Beryllium-Filter (1)

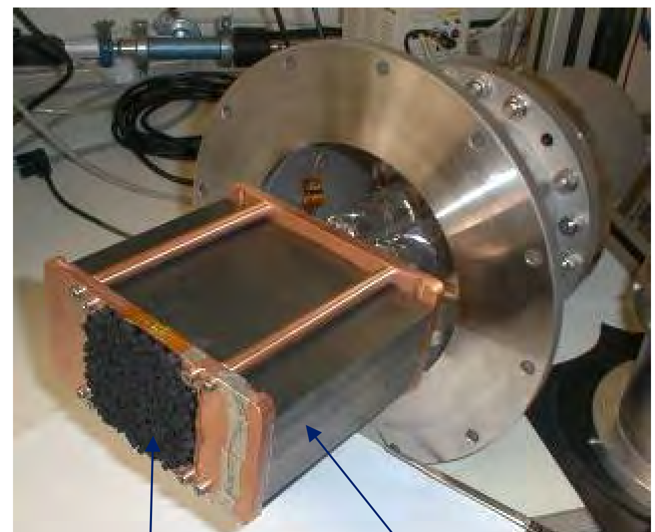
PTS8030



Requirement: B < 20 mT at rotary valve

User:
Hahn-Meitner-Institute Berlin

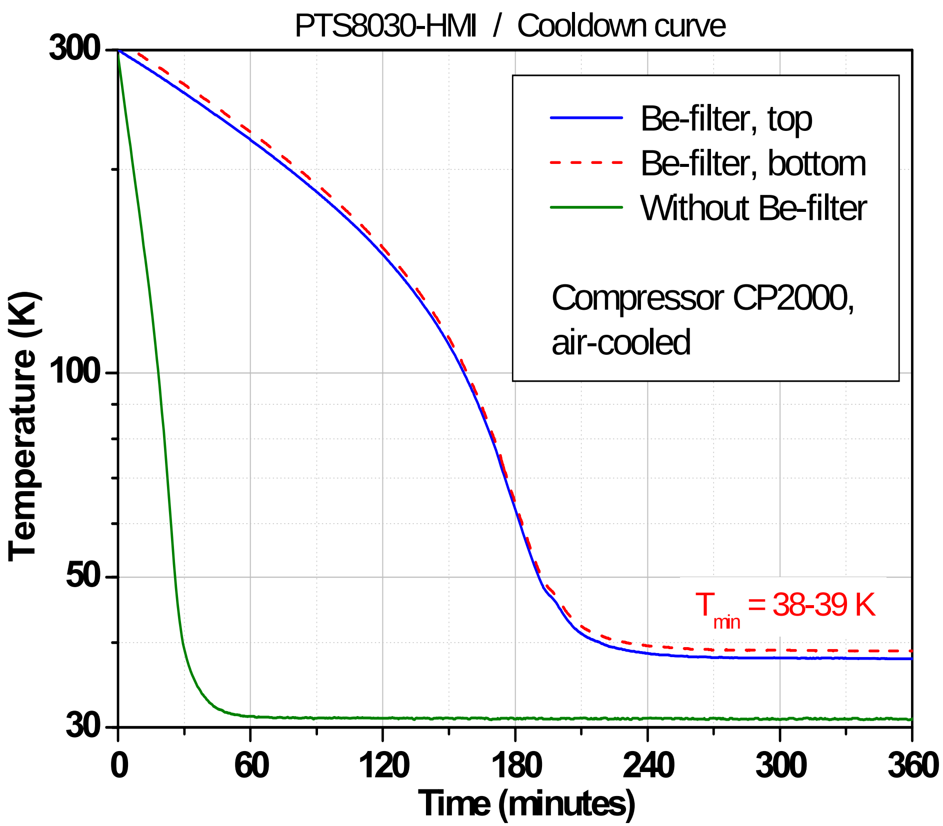
Total mass to be cooled: 2.9 kg

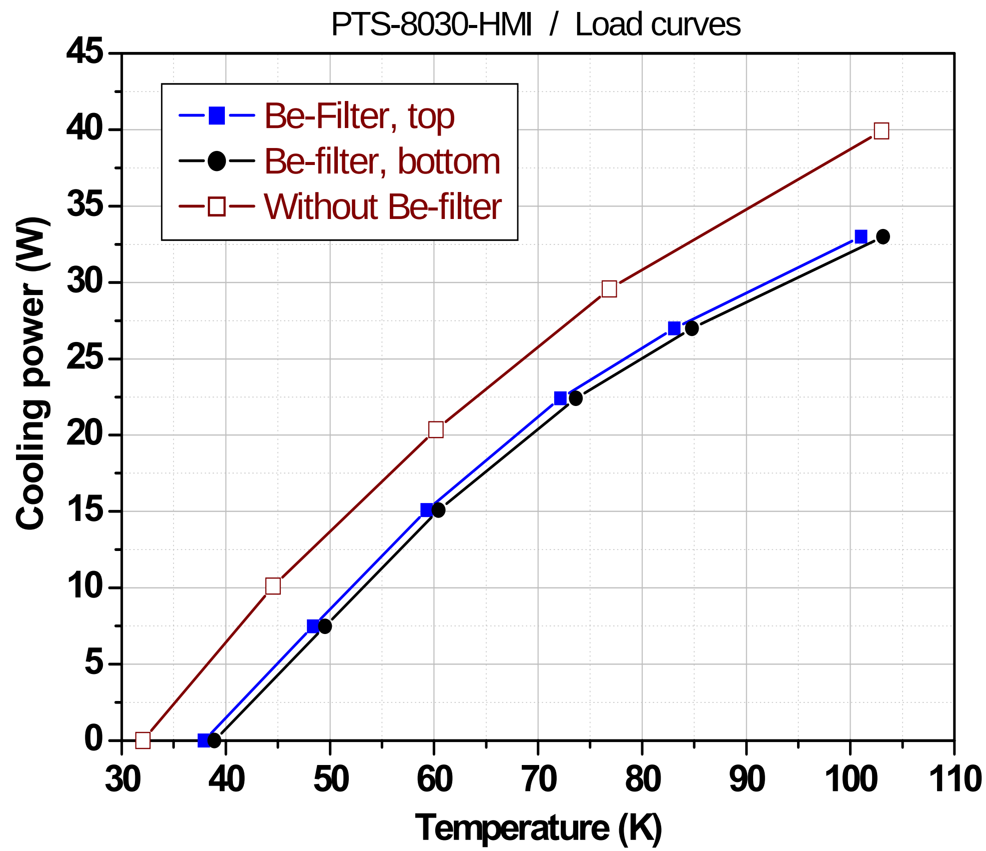


Beryllium-block

Charcoal pump

Pulse Tube Cooling of a Beryllium-Filter (2)





Cooldown to 80 K: 170 min (22 min without Be-filter)

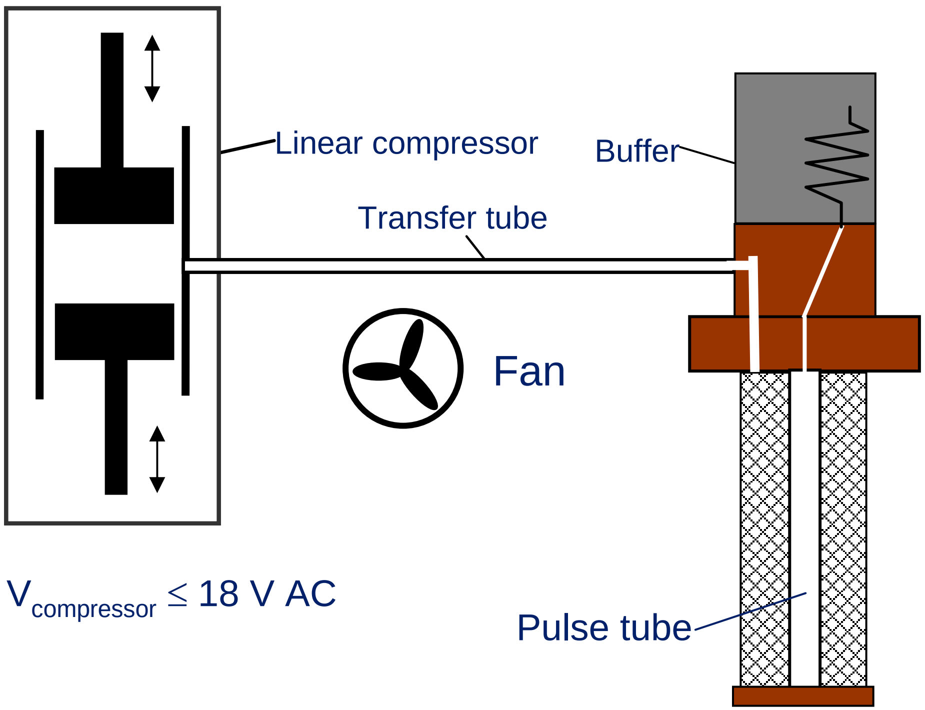
T-stability (no controller): ± 0.2 K within 5 days

→ Load from heat radiation on Be-filter: ≈ 7 W

(no superinsulation)

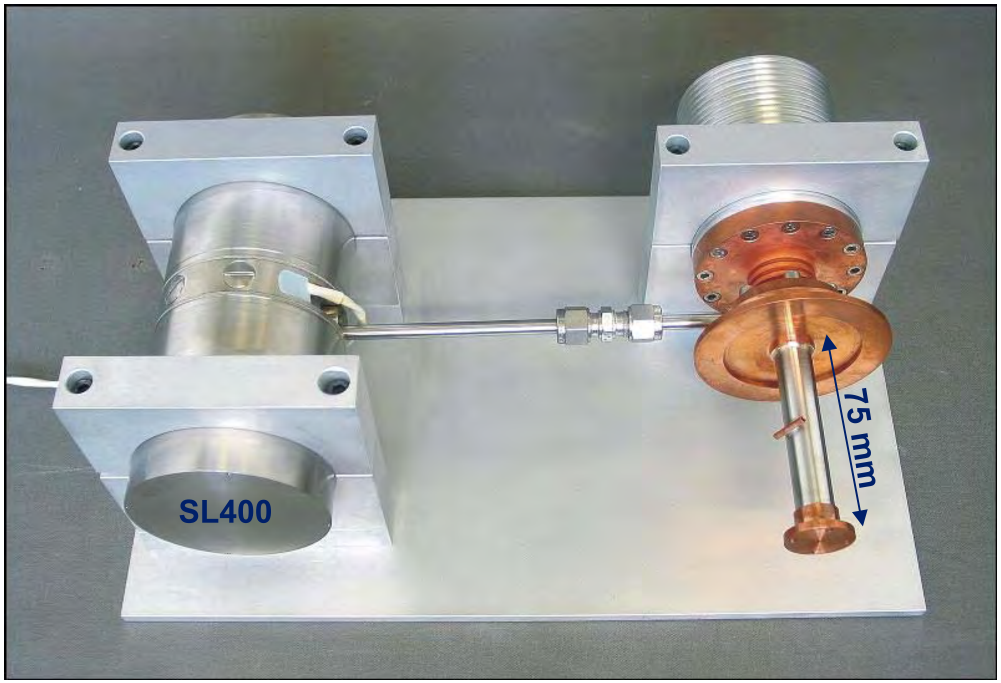
Small Stirling-type Coaxial PTCs (1)

- **Coaxial design of pulse tube cold head → compact coldfinger**
- **Long-life, oil-free linear compressor (AIM GmbH, SL400), input power ≤ 100 W**
- **Performance nearly independent of orientation, due to "high"-frequency (40-50 Hz)**
- **Warm end: air- or water-cooled**

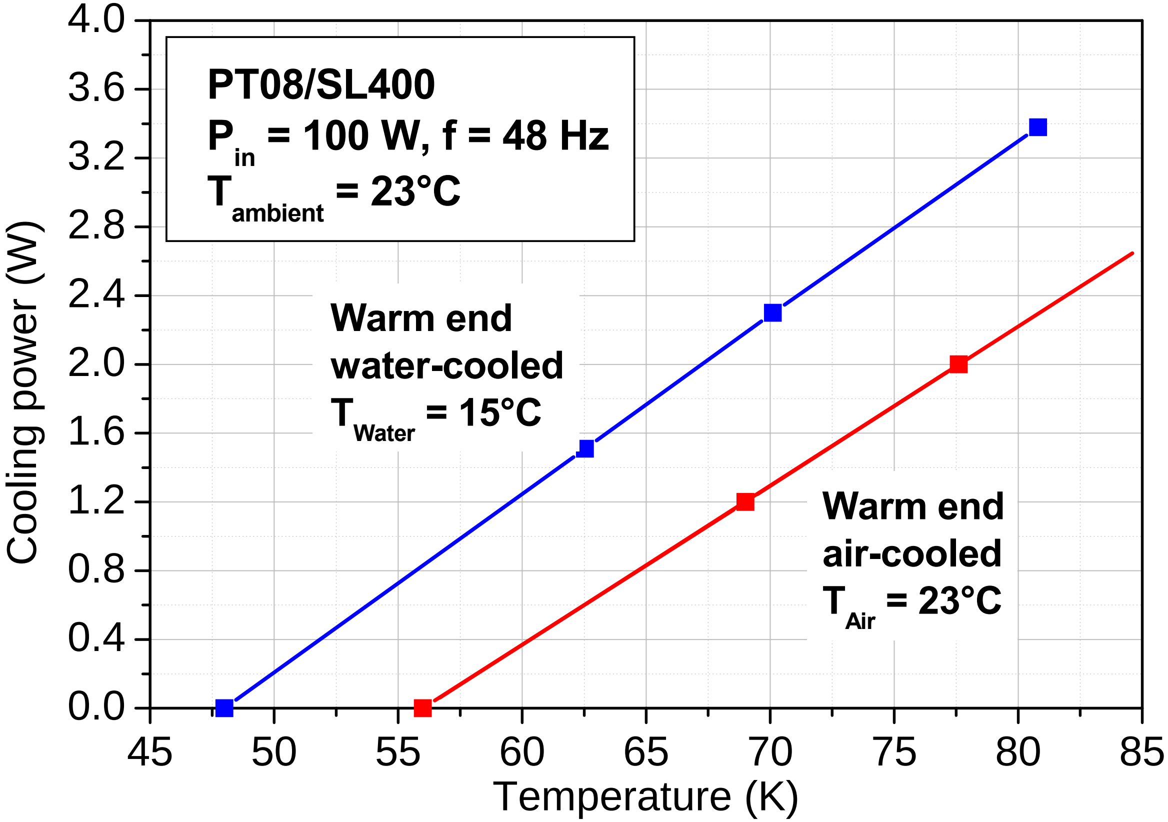


$V_{compressor} \leq 18$ V AC

Model PT08, air-cooled



Small Stirling-type Coaxial PTCs (2)



Water-cooled laboratory model

PT08, air-cooled

Cooling power @ 80 K (P_{in} = 100 W, horizontal coldfinger):

2.2 W with air-cooling at $T_{ambient}$ = 23°C

3.2 W with water-cooling at T_{Water} = 15°C

Application sample: Cooling of gas adsorption cells at HMI Berlin

Small Stirling-type Coaxial PTCs (3)

Cooling of gas adsorption cells at BENSC HMI Berlin

Courtesy of Michael Meißner (HMI)

Thank you for listening !

More information on PTCs needed ?

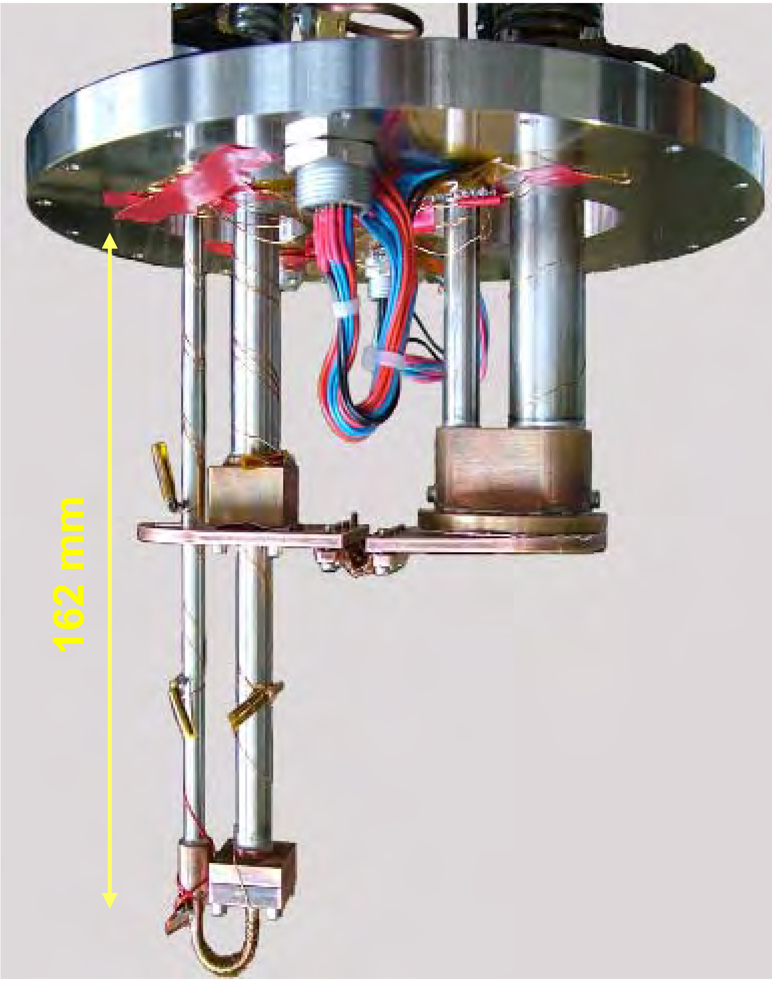
Please visit us at our poster !

Present scientific/technical staff at the TransMIT-Center :

Dr. Kai Allweins, Marc Dietrich, Birgit Gobereit, Yusuf Kücükkaplan, Dr. Daming Sun

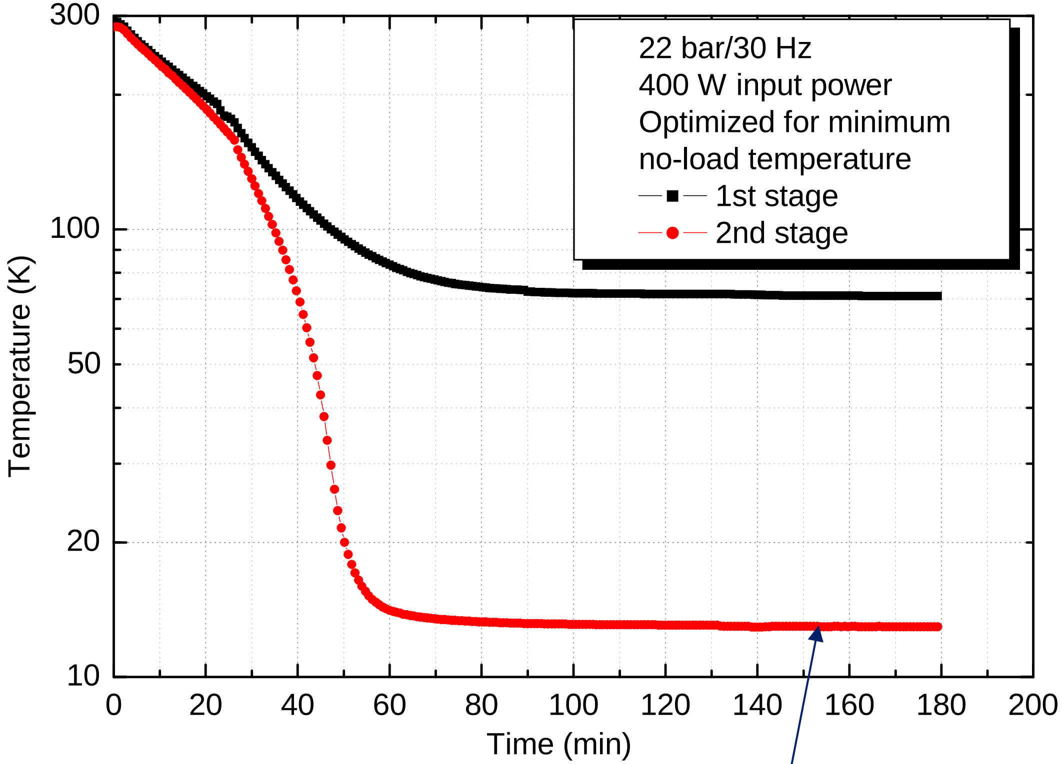
2-stage STPTC with conduction-coupled stages

Giessen 2004



Driven by 2 x Polar compressor with 2 x 200 W input power ; 22 bar/30 Hz

Cool-down curves



$T_{2,min}$ = 12.96 K
Q_2 = 58 mW @ 15 K

Cooling to 4 K with high-frequency STPTC needs more than two stages!