



Recent Development Status of Compact 2K GM Cryocoolers

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Background & progress

Critical technologies

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Conclusions

Background

Background

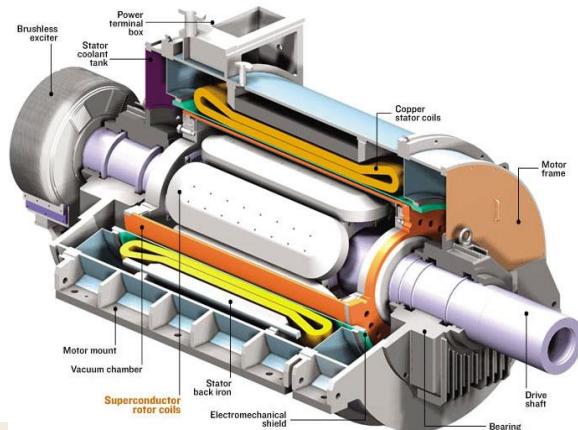
C30rD 4K cryocoolers
Contribution ID: 83



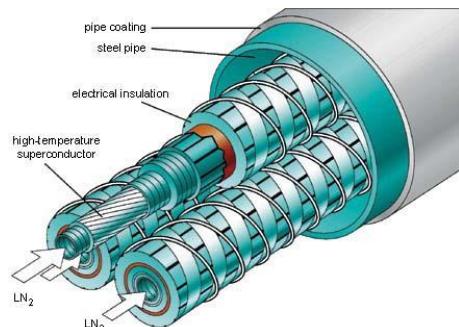
Cryogenic applications



http://en.wikipedia.org/wiki/Magnetic_resonance_imaging



<http://spectrum.ieee.org/images/jan04/images/transf2.jpg>



<http://micromagazine.fabtech.org/archive/05/03/images/0503MI81.gif>

Cryocoolers



<http://images.iop.org/objects/phw/world/13/3/8/pw-13-03-08fig4.jpg>

Background

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Rapid growth of superconducting electronic devices

Development of 2K GM cryocooler

Short supply of high reliability cryocoolers with bottom temperature under 3K

Item	Objective
1 st Temperature with 1 W	60 K
2 nd Temperature with 20 mW	2.3 K
Height reduction of expander comparing to the existing 0.1W 4K GM cryocooler	33.3%
Temperature oscillation displacement	<±20 mK

(Development target)

Commercially available smallest
4K GM cryocooler: RDK-101D

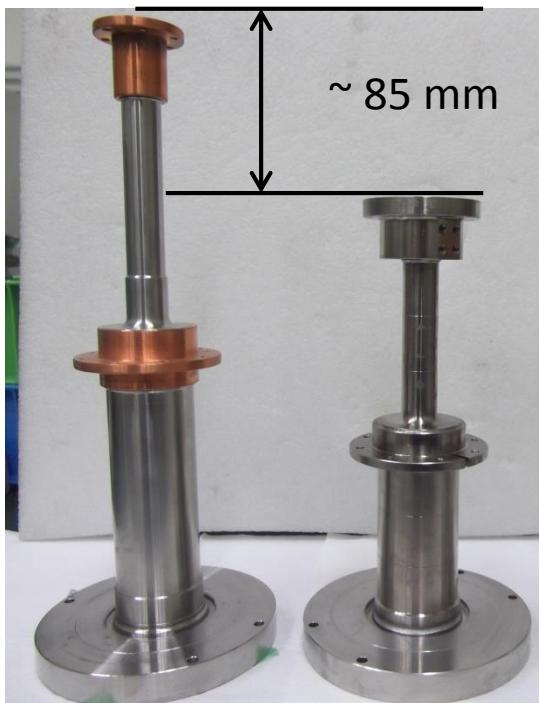


Performance specification:

Power supply	50 Hz	60Hz
2nd stage capacity @ 4.2 K	0.1 W	0.1 W
1st stage capacity @ 60 K	3.0 W	5.0 W
Cooldown time to 4.2 K	150 min	150 min
Weight		7.2 Kg
Height		442 mm
Maintenance		10,000 Hours

RDK-101D

2013 Proto



(Presented in ICEC 2014)

Expander cylinder

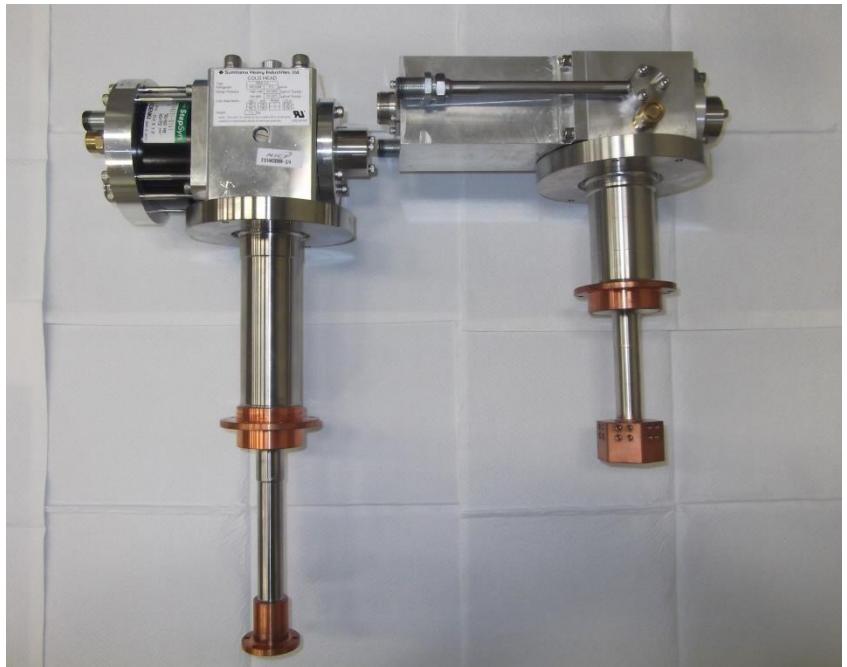


325 mm

240 mm

226 mm

Housing assembly



442 mm

299.7 mm → -32.3%

Critical technologies

Simulation analysis

C30rD 4K cryocoolers
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A 1-D simulation method
developed for 4K GM cryocooers

(Xu M Y and Morie T 2012 Cryocoolers 17)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0$$

$$\nabla p = F_r = -\frac{f_r}{d_h} \frac{\rho U^2}{2} \frac{\vec{U}}{|\vec{U}|}$$

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho \vec{U} h) + h_f(T - T_s) = 0$$



Helium property calculation subroutine(NIST)
Thermal conduction of structure material

$$\rho_{He}, T_{He}, U_{He}, p_{He}, T_s$$

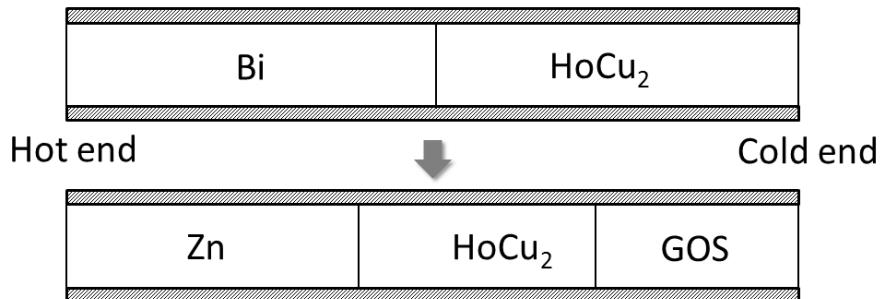
	First stage at 45 K (W)	Second stage at 4.2 K (W)
PV power	17.5	3.27
Cooling capacity after considering real gas effect	17.2	0.56
Regenerator loss	3.5	0.24
Shuttle loss	1.8	0.06
Pumping loss & thermal conduction loss	3.2	0.20
Radiation loss	1.5	0.0
Net cooling capacity	7.1	0.06

New regenerator material

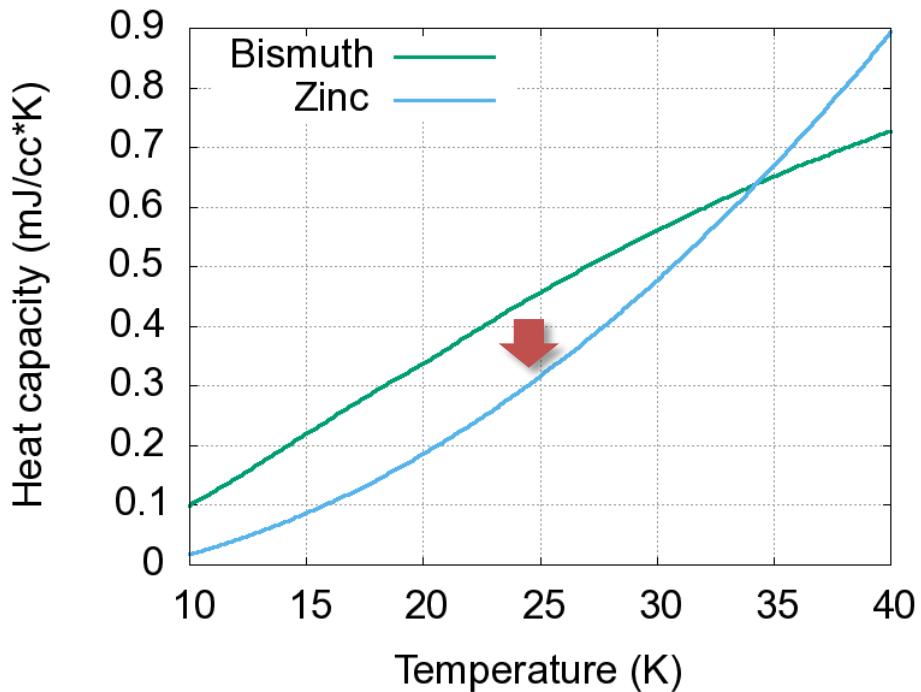
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New filling pattern inside
second stage regenerator



Heat capacity comparison of
bismuth and zinc



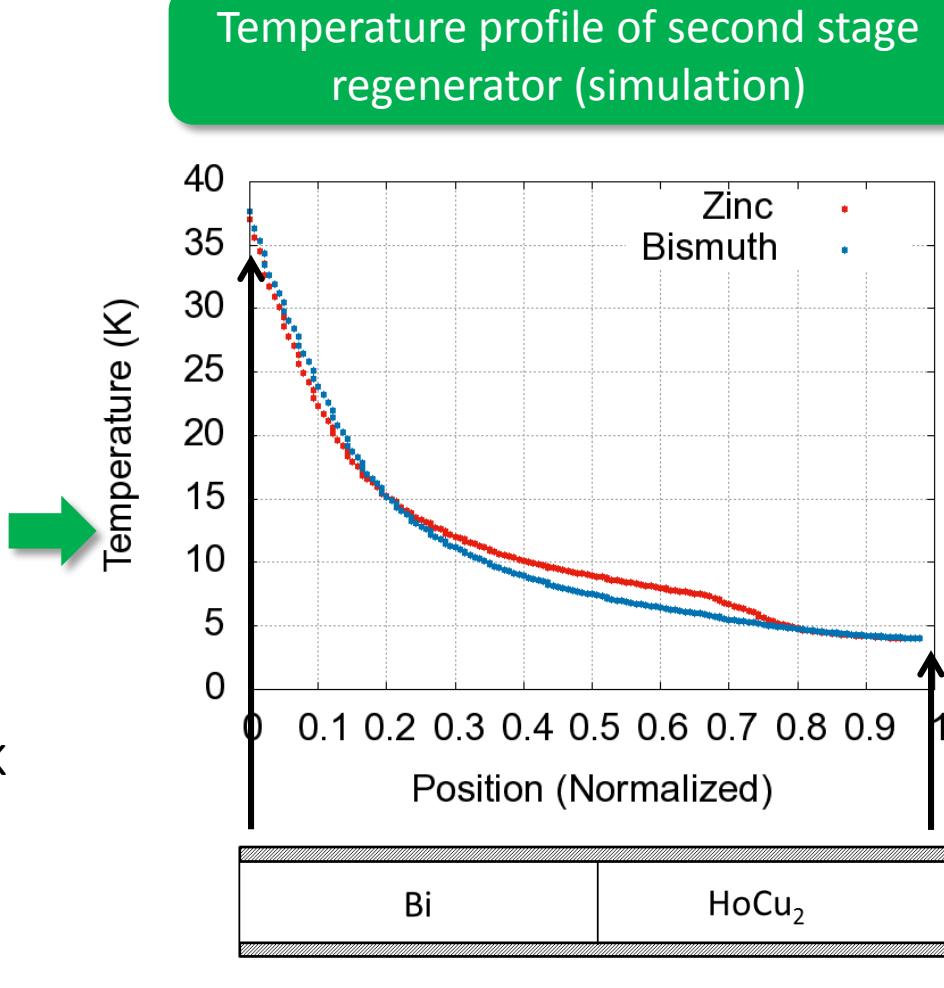
New material zinc's heat capacity is
LOWER than bismuth

New regenerator material

C30rD 4K cryocoolers
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Item	Value
High pressure (MPa)	2.28 MPa
Low pressure (MPa)	0.89 MPa
Frequency (Hz)	1.0
First stage regenerator material	Bronze screens
Second stage regenerator material	Bi / Zn sphere + HoCu ₂ sphere

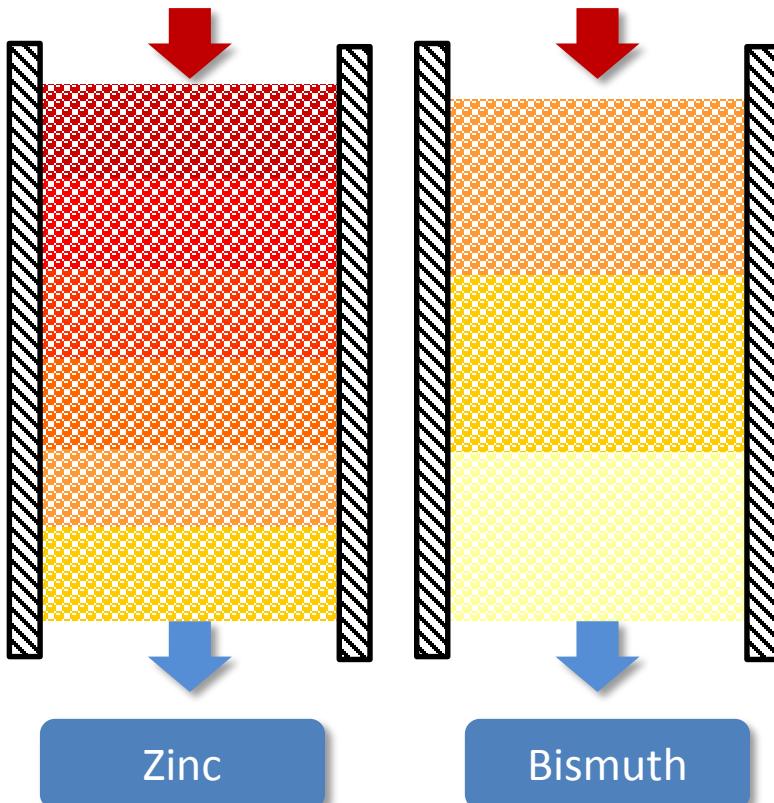


New regenerator material

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Heat transfer behavior
on the hot end



(A simulation analysis on the phenomenon)

Item	Bismuth case	Zinc case
First stage cooling power (W)	66.40	74.02 (+11.5%)
Second stage cooling power (W)	1.38	1.52 (+10.1%)
Average Helium flow rate (g/s)	4.887	5.013 (+2.6%)
First stage expansion PV(W)	94.0	100.5 (+6.9%)
Second stage expansion PV (W)	20.109	21.6 (+7.4%)

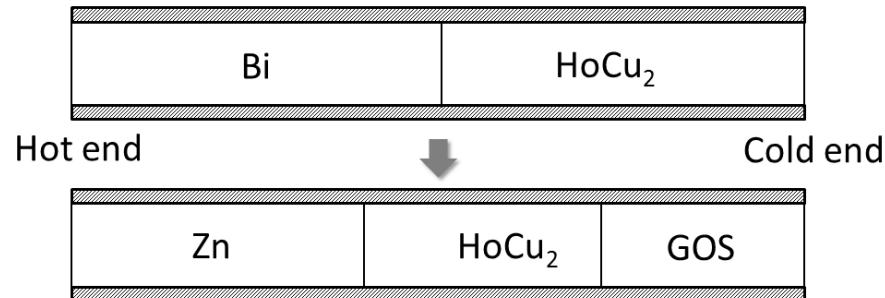
(Xu M Y and Morie T 2012 Cryocoolers, Proc. of the 17th Int. Cryocooler Conf. vol 17 pp 253-9)

New regenerator material

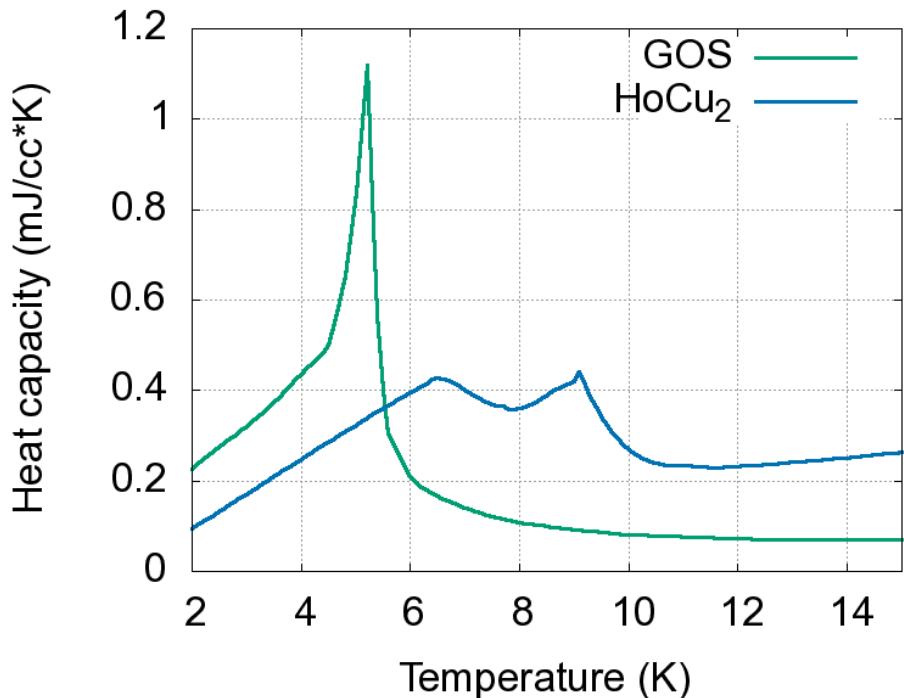
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New filling pattern



Heat capacity comparison of HoCu₂ and GOS



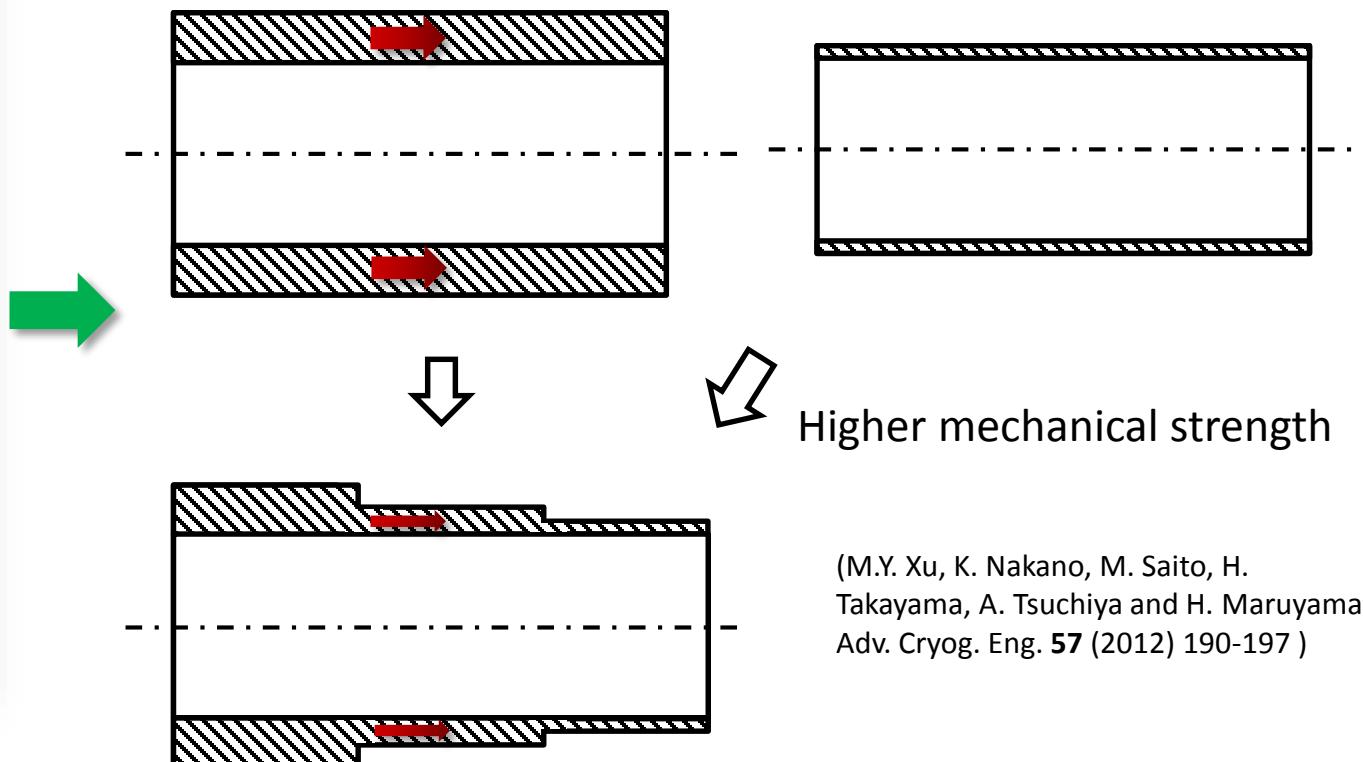
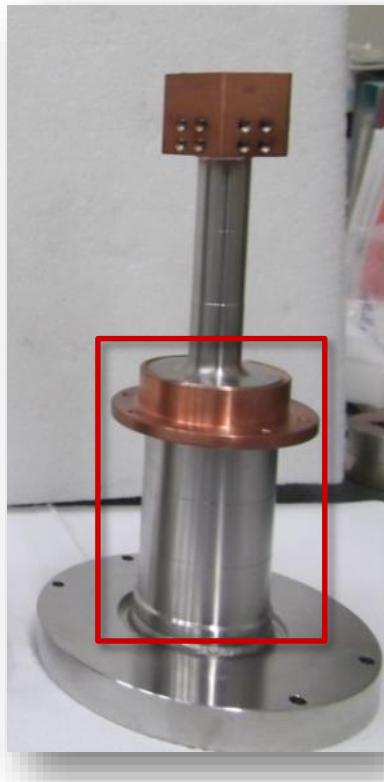
(T. Numazawa, et al.: "A new ceramic magnetic regenerator material for 4K cryocoolers", Cryocooler **12** (2003) 473-481)

New cylinder wall structure

C30rD 4K cryocoolers
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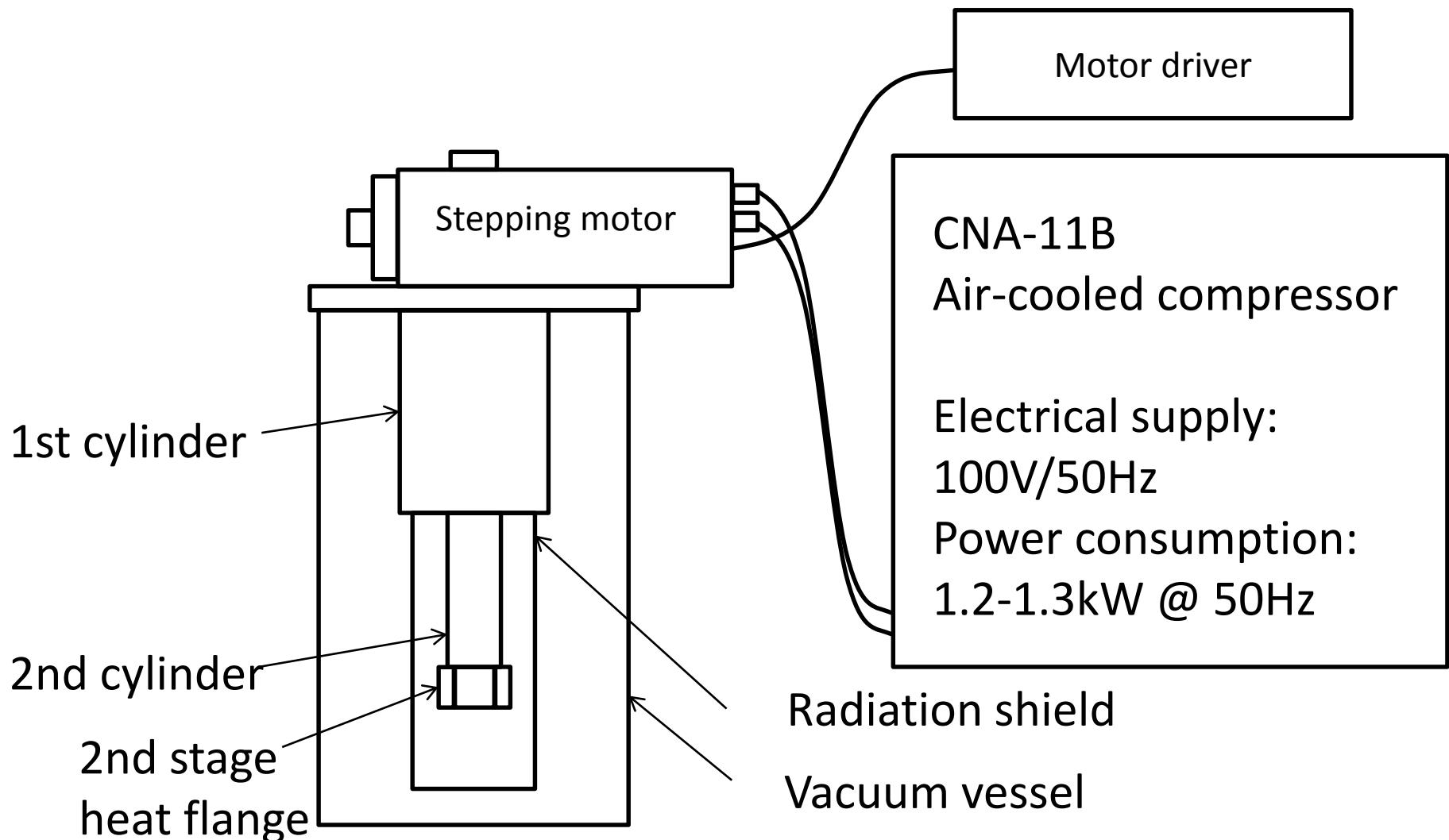
A new step-wise cylinder wall structure
for reducing thermal conduction



Experiment setup and result

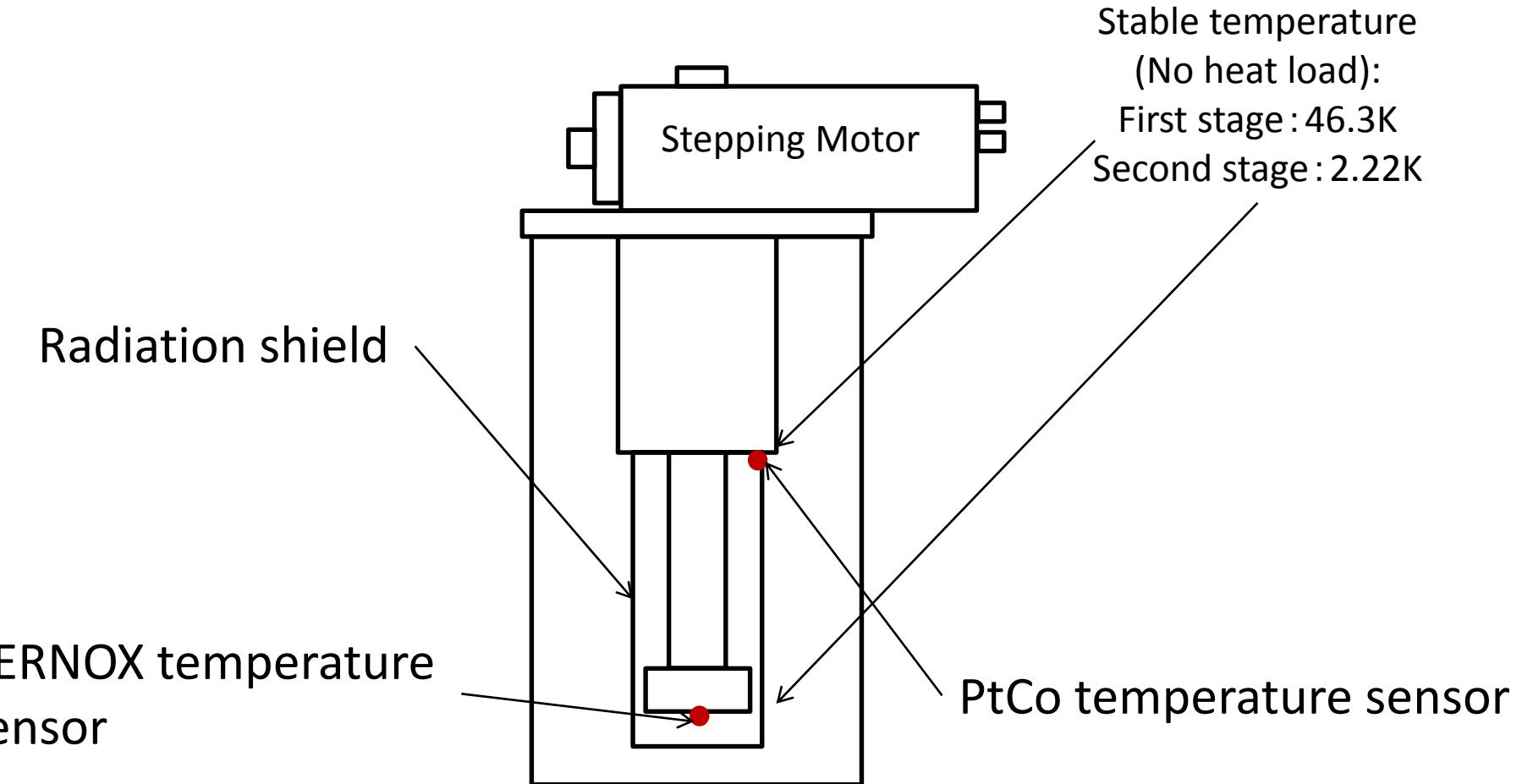
Experiment setup

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Temperature measurement

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Conclusions

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1. A new, compact 2K GM cryocooler has been developed and the cooling capacity of prototype unit was tested in this study.
2. Cylinder shortened: 99 mm; housing assembly shortened: over 43 mm;
Total length: 442 mm → 299.7 mm
3. The prototype unit showed sufficient cooling capability
No-load condition: 46.3 K / 2.22 K
4. Future work:
 - New stepping motor (smaller housing assembly)
 - Further confirmation on cooling capacity

Acknowledgement

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- The research results have been achieved by “Development of a Compact Superconducting Single Photon Detector System for Photon-Quantum Information and Communication”, the National Institute of Information and Communications Technology (NICT), JAPAN

Thank you!

亜鉛による性能改善の効果

Performance Improvement

- Performance improvement with a new regenerator material

Regenerator Material	1 st Stage Temperature(K)	2 nd Stage Temperature(K)
Bismuth	45.7	2.46
New material	42.2	2.41

- Performance improvement with a HoCu₂/GOS hybrid regenerator

Magnetic Regenerator Material	1 st Stage Temperature(K)	2 nd Stage Temperature(K)
HoCu ₂ only	50.7	2.32
HoCu ₂ /GOS hybrid	46.5	2.22

- Performance of the new 2K GM cooler

Item	Object	Measured Results
1 st stage temperature with 1 W	60 K	44.4 K
2 nd stage temperature with 20 mW	2.3 K	2.23 K
No-load 2 nd stage temperature	2.2 K	2.09 K
Expander height	67 % of RDK-101D	81 % of RDK-101D
2 nd temperature oscillation displacement	± 20 mK	± 20 mK

使用温度範囲

	低温側リミット	高温側リミット
Cernox™	0.10K ³	325K
Cernox™ HT	0.10K ³	420K

³ 型番に依存する(例: CX-1030の場合0.3K)

反応速度1.5ms @ 4.2K

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校正後の確度⁴

	センサーの確度 ⁵ (ティピカル)	長期安定性 ⁶
1.4K	± 5mK	± 25mk
4.2K	± 5mK	± 25mk
10K	± 6mK	± 25mk
20K	± 9mK	± 25mk
30K	± 10mK	± 25mk
50K	± 13mK	± 25mk
77K	± 16mK	± 25mk
300K	± 40mK	± 153mk
400K	± 65mK	—

到達温度を考える時、
0.01Kまで信頼性があるとは言えない

⁴ ベアチップの校正ができるのはリード線を取り付けた後です。リード線が不要な場合は除去してください。再びリード線をボンディングするスペースはあります。

⁵ $[(\text{校正の不確かさ})^2 + (\text{再現性})^2]^{0.5}$

⁶ 長期安定性の値は200回のサーマルショックの結果です(305K~77K)

温度応答データ(ティピカル)

温度(K)	CX-1010		CX-1030		CX-1050		CX-1070		CX-1080	
	抵抗 8 (Ω)	dR/dT (Ω /K)	抵抗 (Ω)	dR/dT (Ω /K)	抵抗 (Ω)	dR/dT (Ω /K)	抵抗 8 (Ω)	dR/dT (Ω /K)	抵抗 (Ω)	dR/dT (Ω /K)
4.2	277.32	-32.209	574.2	-97.344	3507.2	-1120.8	5979.4	-2225.3	—	—
10	187.11	-8.063	331.67	-19.042	1313.5	-128.58	1927.2	-214.11	—	—
20	138.79	-3.057	225.19	-6.258	692.81	-30.871	938.93	-46.553	6157.5	-480.08
30	115.38	-1.819	179.12	-3.453	482.88	-14.573	629.9	-20.613	3319.7	-165.61
77.35	70.837	-0.51	101.16	-0.82	205.67	-2.412	248.66	-3.15	836.52	-15.398
300	30.392	-0.065	41.42	-0.088	59.467	-0.173	66.441	-0.201	129.39	-0.545
400 (HT)	—	—	34.779	-0.05	46.782	-0.093	51.815	-0.106	91.463	-0.261
420 (HT)	—	—	33.839	-0.045	45.03	-0.089	49.819	-0.094	86.55	-0.231

8 セルノックスセンサーには標準温度カーブが規定されておらず、また、非常に幅広い値を取り得るので、本表にはティピカルな抵抗値を掲載しています。

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一方、2K付近では感度(d R/ dT)が高いので、分解能を考えると、1mKまで分解能的には全然問題ない

User's Guide Model 44C Cryogenic Temperature Controller

Cryo-con Model 44C

Specifications, Features and Functions

NTC Resistor Sensors

Configuration: Constant-Voltage AC resistance bridge with excitations of 100mV, 10mV, 1.0mV, 300µV, 100µV, 30µV or 10µV RMS.
Fixed or auto-ranged.

Excitation Current: 10mA to <300pA, Continuously-variable.
Minimum sensor power dissipation limited to 0.5 Pico-Watt.
Four ranges of 10KΩ, 1.0KΩ, 100Ω and 10Ω.

Excitation Frequency: 1.63Hz bipolar square wave.

Accuracy (% reading + % range)
Reading >4Ω and < 30KΩ : ±(0.05% + 0.05%).
Reading >0.04Ω and < 3.0MΩ : ±(0.15% + 0.15%).

Drift: >10Ω, 15ppm/°C. <10Ω, 25ppm/°C

DC Offset Current: <200pA by active cancellation.

Resolution: Shown below are typical RMS resistance noise values measured at 50% of full-scale on a room-temperature resistor with a 3-Second analog time-constant.

Resistance Range: 0.5Ω to 2.0MΩ.
Minimum resistance is Range / 4
Maximum resistance is Vbias / 300pA with a maximum of 2.0MΩ

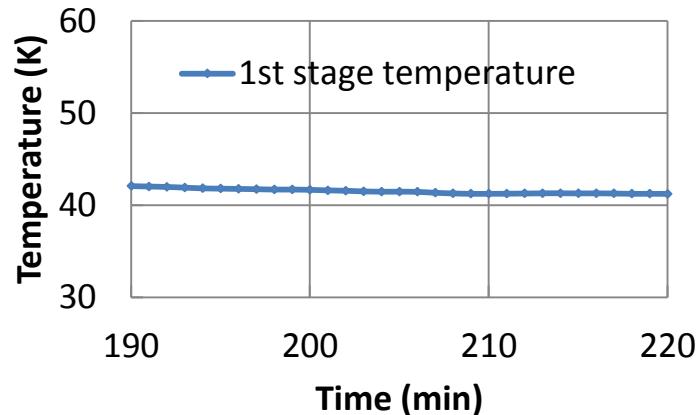
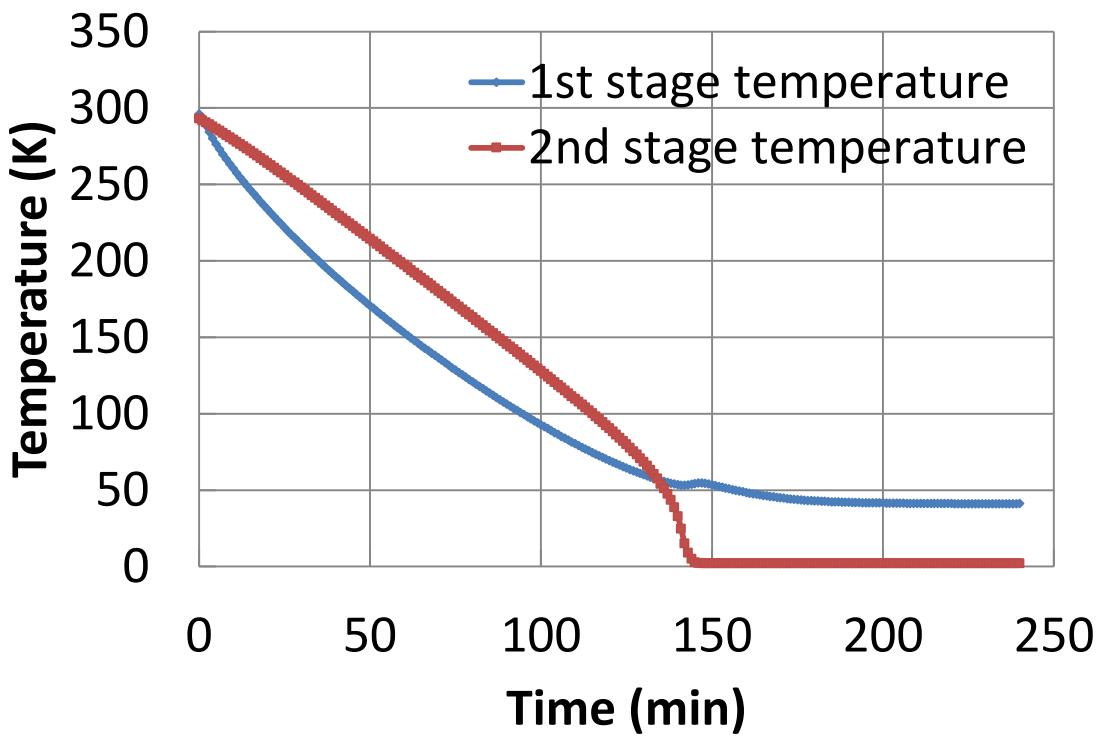
Range	100mV	10mV	1.0mV	300µV	100µV	30µV	10µV
20Ω	10mA 2.6µΩ	1.0mA 255µΩ	100µA 2.6mΩ	30µA 85mΩ	10µA 260mΩ	3µA 8.6Ω	1.0µA 25Ω
200Ω	1.0mA 26µΩ	100µA 2.6mΩ	10µA 26mΩ	3µA 855mΩ	1.0µA 2.5Ω	300nA 86Ω	1.0µA 250Ω
2KΩ	100µA 260µΩ	10µA 26mΩ	1.0µA 260mΩ	300nA 8.6Ω	1.0µA 25Ω	30nA 830Ω	1.0µA 2.5KΩ
20KΩ	10µA 2.6mΩ	1.0µA 250mΩ	1.0µA 2.5Ω	30nA 83Ω	1.0µA 250Ω	3nA 8.3KΩ	(Excitation Resolution)

Table 8: NTC Resistor Sensor Resolution vs. Bias Voltage

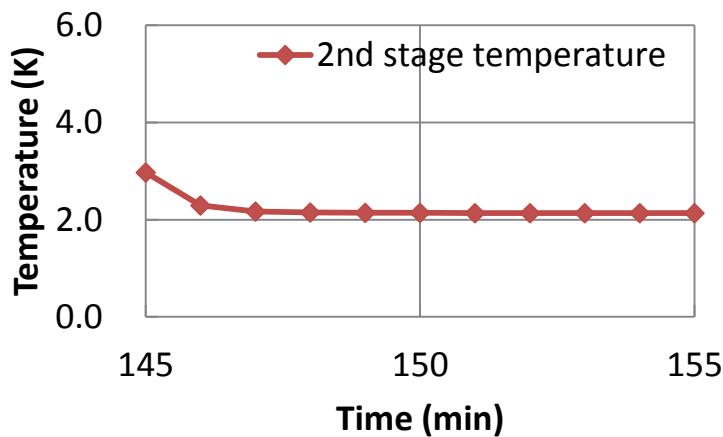
$$\text{Noise} = 0.26 \text{ Ohm} * 1\text{K} / 1100 \text{ Ohm} \\ = 0.236 \text{ mK}$$

→振動測定する時1mKの分解能はできる

クールダウン曲線- No SI

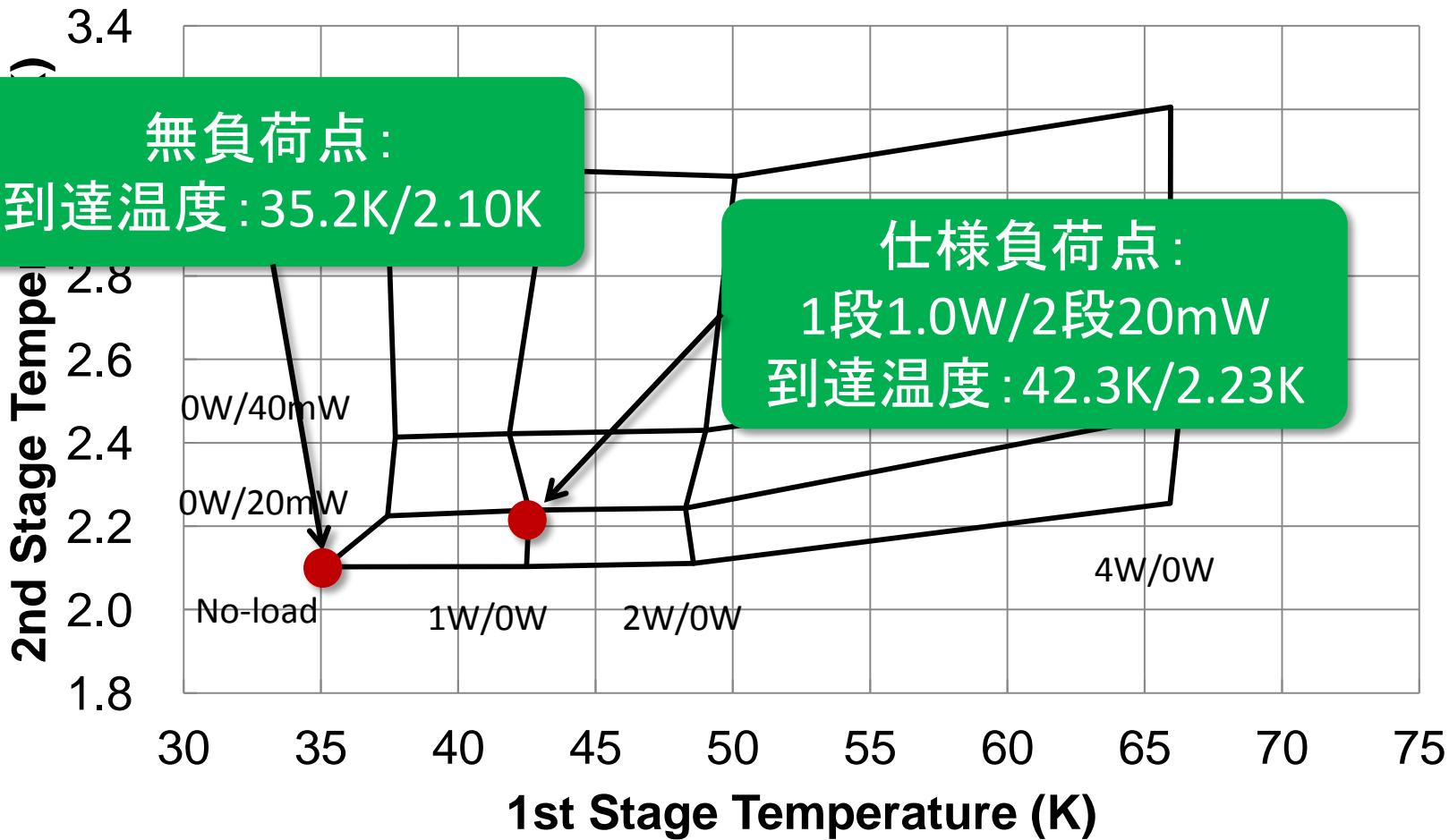


1段無負荷到達温度 : 42.3K



2段無負荷到達温度 : 2.10K

冷凍ロードマップ



ラムダ点付近の挙動について:

