# SHI's Two-Stage 4 K GM Cryocoolers: Enriching Emerging Technologies through Leading-Edge Advancements

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## ABSTRACT

The SHI Cryogenics Group, along with its parent company Sumitomo Heavy Industries, Ltd., is a global leader in cryogenic technology. During its 60-year history it has grown to design and manufacture the broadest array of cryocoolers and related cryogenic systems worldwide, serving magnetic resonance imaging (MRI), semiconductor, flat panel display, laboratory, aerospace, and other research applications. Aligning with our goal to create a better tomorrow through innovative solutions, we enable emerging technologies through advancements in cryocooler development and provide exceptional performance and service through our global network.

With our customers facing helium supply shortages and higher costs, we developed the leading-edge RDE Two-Stage 4 K Gifford-McMahon (GM) Cryocooler Series, enabling the MRI industry to transition from helium bath designs to low cryogen designs. Specifically, we present the RDE-418D4 cryocooler, which increases cooling performance by 20% over our previous models and provides 2.0 W at 4.2 K and 50 W at 50 K with a power consumption as low as 7.5 kW at 60 Hz.

For the fast growth of quantum technologies, our RDK-101D(L) cryocooler, which has been the world's smallest two-stage 4 K GM cryocooler, continues to evolve and enables applications like desktop quantum systems, single photon detectors, and optical quantum systems. This innovative, low-vibration cryocooler features a guaranteed minimum temperature of <2.3K and provides 0.16/0.2 W at 4.2 K (50/60 Hz) with about 1 kW input power. Our pulse tube refrigerator product line is expanding rapidly to meet the growing needs of dilution refrigerators and quantum computing systems. Our newest model, RP-222B3S, provides 2.0 W at 4.2 K.

## INTRODUCTION

With roots in both Sumitomo Heavy Industries (Japan) and Air Products and Chemicals (United States), SHI Cryogenics Group has been providing solutions for cryogenic refrigeration to government, industry, and academia for well over 60 years. We reach around the globe with manufacturing in Japan, the Philippines, and the United States; research and development in Japan and the United States; and sales and service support in Germany, the United Kingdom, Japan, China, South Korea, Taiwan, and the United States.

A strong research and development program has enabled our group to provide reliable products for the ever-changing applications around us. This R&D effort has enabled our current com-

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| Cold Head Model | | RDE418D4 |
|---|---|---|
| 2nd Stage Capacity | 50 Hz | 1.8W @ 4.2K |
| | 60 Hz | 2.0W @ 4.2K |
| 1st Stage Capacity | 50 Hz | 42W @ 50K |
| | 60 Hz | 50W @ 50K |
| Minimum Temperature | | <3.5K |
| Cooldown Time (min) | 50 Hz | <60 |
| | 60 Hz | <60 |
| Weight | | 20.0 kg (44.1 lbs) |

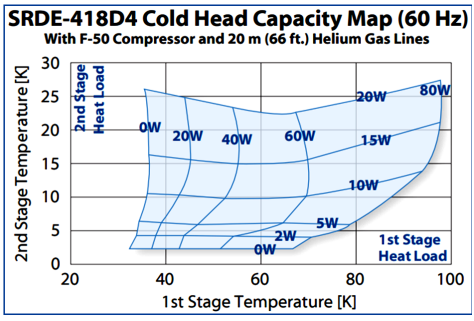


**Figure 1**. Specified and typical performance of the RDE-418D4 cold head

mercial cryogenic product line to include single- and two-stage GM cryocoolers, single- and two-stage GM-type pulse tube cryocoolers, cryopumps, cold traps, and helium compressors.

Recent improvements in our two-stage 4 K products have helped lead the way for emerging applications in magnetic resonance imaging (MRI) and quantum technologies.

## 4 K GM ADVANCEMENTS FOR LOW-CRYOGEN MRI

Clinical MRI has revolutionized medicine, but it has also become the largest single consumer of helium, representing approximately 20% of the global helium demand [1]. Each new traditional MRI system ships with 1,000 liters or more of liquid helium. A cryocooler typically prevents helium loss after a system's final installation. However, shipping, maintenance, and service events consume significant additional quantities of liquid helium, as cryocooler operation is generally unavailable during these times. To confront the increasingly tight helium supply, MRI manufacturers have begun to introduce systems with little helium content. In 2019, Philips introduced the first commercial low-cryogen MRI system, their BlueSeal product, containing only seven liters of liquid helium and is sealed against helium loss. In 2021, Siemens released their Magnetom Free.Max system containing less than one liter of liquid helium and also sealed against loss. These systems no longer have the temperature stability and heat capacity of the liquid helium bath and no longer can be cooled down with liquid helium. Therefore, they require 4 K cryocoolers with high quality and reliability, increased capacity with higher efficiency, faster cool-down, and backward compatibility. Working on these goals in advance of the need, SHI's development program allowed us to have our fourth generation RDE-412D4 and RDE-418D4 cold heads available when needed.

Following our typical development process, the RDE-418D4 program was built around application experience, theoretical analysis, numerical modeling, comprehensive testing, and manufacturing process development. This program yielded over 20% improvement in 4 K capacity for the same system size, weight, and input power, Figure 1.

A close working relationship with our customers provided an early understanding of the need. Our theoretical analysis and numerical modeling identified the regenerator as an opportunity to improve our existing RDK product. We then evaluated possible configurations and changed the regenerator composition relative to its length to achieve an optimized temperature profile. This work has been more extensively reported, Xu, et al. [2]. In summary, Figure 2 shows a schematic representing our in-house numerical model and how a multi-composition regenerator can be included in the analysis. Figure 3 shows the analysis output for various regenerator compositions. Figure 4 is an example output showing P-V changes due to regenerator changes. Based on the modeling, we built successful prototypes and the eventual product.

In addition to the performance increase discussed above, we made several system operating improvements for low-cryogen MRI applications. The RDE series variable-speed capability is available for further cool down time reduction. It is based on our first-to-market and industry-changing energy-efficient SICERA® cryopump technology. This technology, featuring EtherCAT communication protocol, utilizes inverters in both cryopumps and compressors to manage cooling

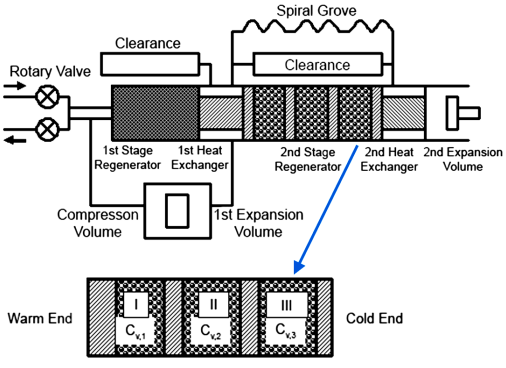


**Figure 2**. In-house numerical model schematic

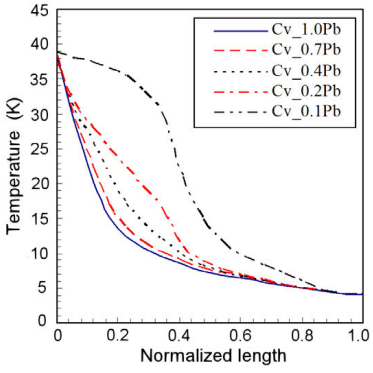


**Figure 3**. Numerical model temperature profiles for various regenerator configurations

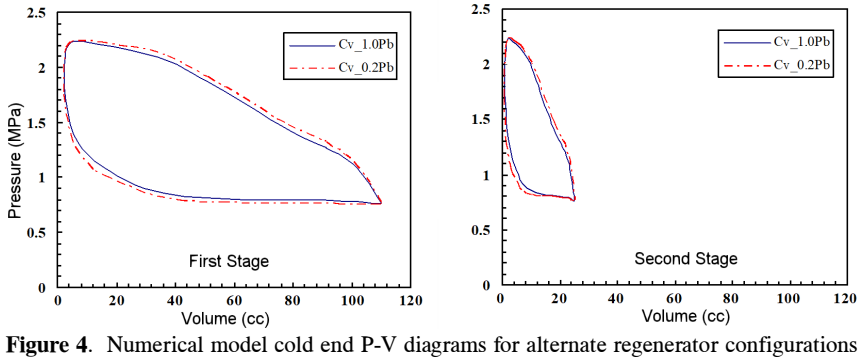


**Figure 4**. Numerical model cold end P-V diagrams for alternate regenerator configurations

loads and maximize power savings in cutting-edge semiconductor chip manufacturing processes. Other compressor improvements have increased operating up time and cryo system reliability—all-important to systems having no liquid bath to provide hold time. Specifically, increased oil separator efficiency and increased fouling resistance have decreased compressor maintenance requirements. Also, increased process monitoring, on-the-fly diagnostic algorithms, and increased customer integration via networks such as CANBUS have enabled the implementation of redundancy and allowed more efficient and remote troubleshooting and service planning.

For the RDE-418D4, as with our new designs generally, we completed extensive product validation testing to ensure performance, reliability, and manufacturability. We have testing labs in both Japan and the United States to support our entire product line. As an example of validation testing, results of the effect of magnetic field on second stage temperature are presented here, Morie, et al. [3]. Figure 5 gives test chamber field profile, and Figure 6 shows the effect of field strength on second stage temperature with different regenerators.

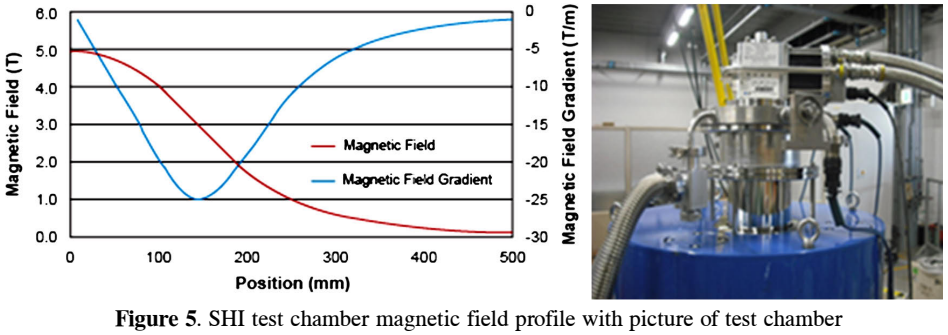


**Figure 5**. SHI test chamber magnetic field profile with picture of test chamber

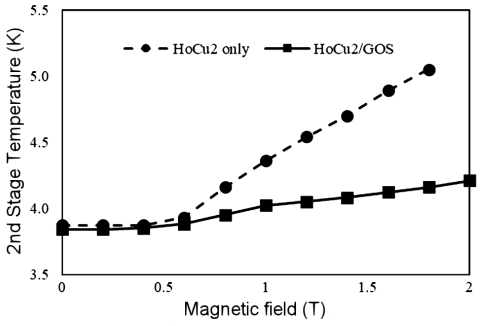


**Figure 6.** 2nd stage temperature variation with axial field strength and type of regenerator

**Table 1**. RDK-101D Specified Performance

| RDK-101D 4K Cryocooler | 50 Hz | 60 Hz |
|---|---|---|
| 2nd Stage Performance | 0.16 W @ 4.2 K | 0.20 W @ 4.2 K |
| 1st Stage Performance | 3.0 W @ 45 K | 5.0 W @ 45 K |
| Weight | 7.2 kg | |
| Dimensions | 442 x 130 x 226 mm | |

## 4 K GM ADVANCEMENTS FOR QUANTUM APPLICATIONS

SHI 4 K advancements meet the needs of quantum applications in various ways. Several emerging technologies rely on the small footprint and low input power of our RDK-101 GM cold head. We offer the RDK-101D with standard performance, Table 1, and the more recent RDK-101DL, with a guaranteed minimum temperature below 2.3 K.

One application, desktop quantum computing, especially benefits from the RDK-101D's minimal size and power. The company Equal1 is exploring a concept, Figure 7, based on their Disruptive Quantum on Silicon technology that incorporates an RDK-101D cold head with a CNA-11 air-cooled compressor. In addition to small size, this cryocooler system's ready availability and reliability eliminated refrigeration setbacks and enabled Equal1's fast development pace. Montana Instruments CryoCore® platform, Figure 8, is another example of a system enabled by the small size of the RDK-101 series cold head. This system, capable of sample temperatures from 4.9 K to 350 K,

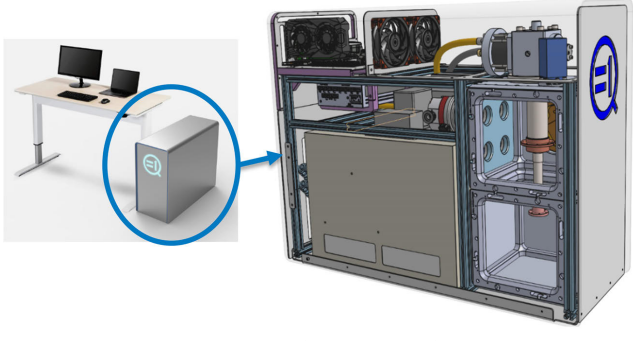

**Figure 7**. Equal1's desktop quantum computing concept with RDK-101D and CNA-11 compressor

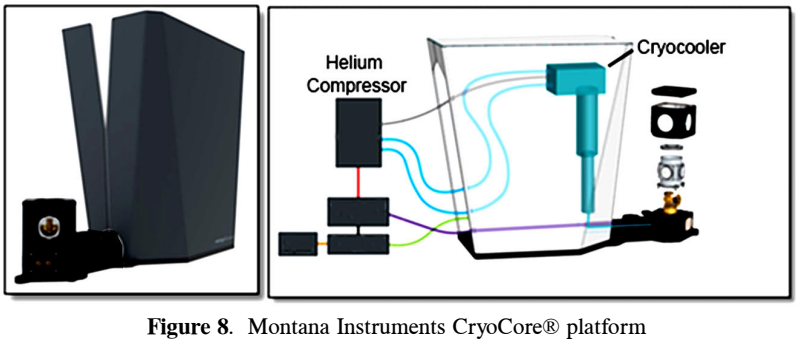


**Figure 8**. Montana Instruments CryoCore® platform

**Figure 9.** Photon Spot systems using the RDK-101D cryocooler

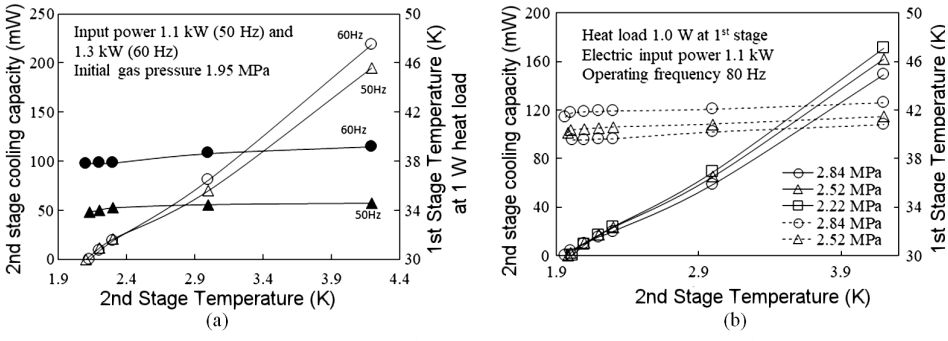


**Figure 10.** RDK-101D performance with (a) CNA-11 compressor and (b) linear compressor

mounts on optic benches in a user-friendly, compact manner and allows the user to pay minimal attention to the cryocooler. In yet a third example, Photon Spot, a maker of cryogenic systems and superconducting photon detectors, also relies on the small size of the RDK-101D for their smaller systems, Figure 9. They benefit from cold head temperatures reliably below 3 K. For some configurations, they use a sorption refrigerator in conjunction with an SHI cryocooler to reach 0.8 K.

We have also tested the RDK-101D with a linear compressor prototype. This work, previously reported in more detail, Hiratsuka [4], has demonstrated the ability to extend the low-temperature capability using the same input power, Figure 10. It is a further example of the breadth of our development programs and shows a potential way to achieve the low temperatures used in quantum systems.

Until recently, the RDK-101 series cold heads were the smallest commercially available, but our new RDC-02 GM cold head now holds that distinction. Figure 11 shows the 20% smaller size of the RDC-02 compared to the RDK-101D. Our previously reported work on this cold head, Xu,

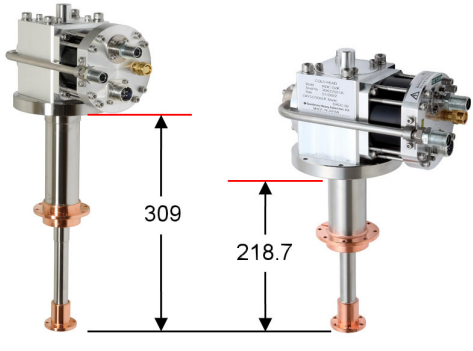


**Figure 11**. CNA-11 cold head (left) and RDC-02 cold head (right) with cold end lengths

**Table 2**. RDC-02 specified performance

| RDC-02 Cold Head Specification | 50 Hz | 60 Hz |
|---|---|---|
| 2nd stage performance | 20 mW @ 2.3 K | 20 mW @ 2.3 K |
| 1st stage performance | 1.0 W @ 60 K | 3.0 W @ 60 K |
| Base temperature | ≤ 2.2 K | |
| Weight | 7.0 kg | |
| Dimensions | 351.7 x 130 x 226 mm | |

**Table 3.** Customer RDC-02 temperature data

| RDC-02K Prototype at 50 Hz (on-site) | Averaged temperature (2nd stage) | Averaged temperature (1st stage) |
|---|---|---|
| Test 1 | 1.963 K | 30.91K |
| Test 2 | 1.895 K | 30.81K |
| Test 3 | 1.987 K | N/A |
| Test 4 | 1.934 K | N/A |

**Table 4.** Customer RDC-02 vibration data

| Vibration reduction | X-axis | Y-axis | Z-axis |
|---|---|---|---|
| RDC-02K 60 Hz | <1 um | ~1 um | ~12 um |
| Reduction compared to RDK-101D 60 Hz | 81% | 63% | 9% |
| RDC-02K 70 Hz | <1 um | ~1 um | ~11 um |
| Reduction compared to RDK-101D 70 Hz | 83% | 69% | 11% |

et al.[5], covered results for the R&D prototypes. Through further refinement, we reduced the length to the current 218.7 mm. Table 2 shows the specified performance of this cutting-edge product.

Testing of this cold head at S2 Corporation has demonstrated very good second stage temperature below our guaranteed minimum of 2.2 K, Table 3, and 9 to 11% z-axis vibration reduction compared to the RDK-101D, Table 4. S2 Corporation's low vibration cryogen-free cryostats feature rapid sample change and turn-around time. They benefit from the RDC-02's robustness for variable speed operation, which permits a 38% reduction in cool down time, Figure 12.

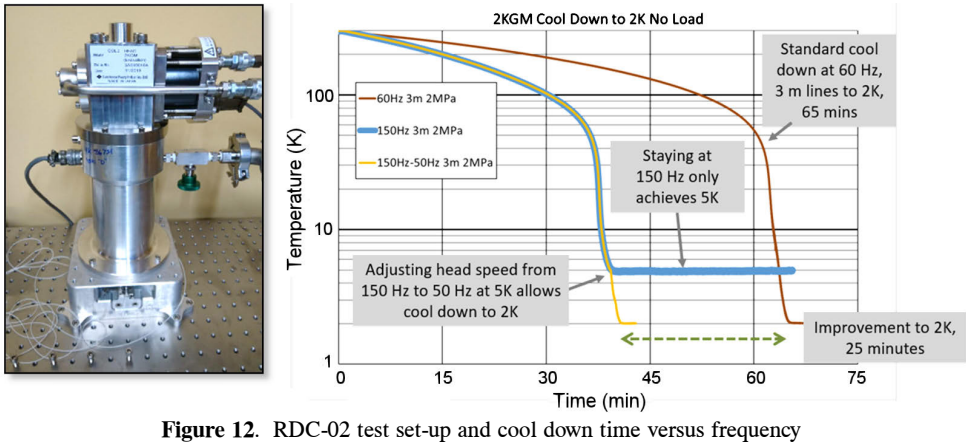


**Figure 12**. RDC-02 test set-up and cool down time versus frequency


**Figure 13**. ColdEdge Technologies Stinger® system with SHI cold head

**Figure 14**. ColdEdge Technologies ULV system with SHI cold head

For high cooling capacity quantum applications, both our GM cryocooler and GM-type pulse tube advancements support emerging technologies such as larger dilution refrigerators for quantum computing. Our new RP-222B3S pulse tube provides 2.0 W/4.2 K and 60 W/50 K cooling and low vibration when operating at either 50 or 60 Hz. Compared to our RP-182B2S pulse tube, it has a simplified layout, equivalent or lower vibration, and greater than 20% efficiency improvement. As for our larger 4K GM cryocoolers, these are also used in vibration-sensitive applications through products such as ColdEdge Technologies' Stinger® and Ultra-Low Vibration (ULV) systems. Their Stinger® system, through a separate circulation loop, provides 4 K cooling at points remote from the GM cryocooler, Figure 13. Their ULV system, Figure 14, provides 4.2 K cooling with nanometer scale displacement.

## CONCLUSION

Emerging technologies need reliable, available commercial products to move them past basic research and into the real world. Through a strong research and development program, extensive customer interaction, and proven ability to manufacture and service commercial products, SHI continues to advance 4 K GM technology to meet this need.

## ACKNOWLEDGMENT

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