Low-Cost Cryogenic Technology for Commercial Infrared Imaging

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ABSTRACT

The recent advancement of cooled infrared imaging has resulted in a drastic increase of operational temperatures and subsequent reduction of parasitic heat inflows along with a fundamental increase of the thermodynamic performance of the associated cryogenic coolers.

The favorable combination of these factors has resulted in reduction of the power draw, faster cooldown, improved reliability and eventuated into the need for the development of a new generation of long-life, low-cost, low-size, low-weight, and low-power mechanical cryocoolers. In response to this challenge, based on existing heritage, the industry focused on gradual downscaling of existing cryogenic technologies. Because of the inherent limitations – though significantly improved – the attained reliability and cost figures still prevent the broad use of cryogenically cooled infrared imagers in a price-sensitive and highly competitive commercial market.

From the very moment of its inception in 2018, CryoTech adopted an approach of disruptive innovation, not only aiming to further improve size, weight and power indices, but first and foremost to enable essential cost reduction and higher reliability. In doing so, the CryoTech team revisited almost all the major technological cornerstones, including working agents, the concepts of regenerative heat exchanger, electromagnetic and pneumatic actuation, magnet springs, vibration control, and more.

INTRODUCTION

Technological advancements in the early 2000s have led to the development of a new generation of high operating temperature (HOT) cooled infrared (IR) detectors offering an extremely low rate of defective pixels and dark currents. This allowed them to operate at temperatures around 150K while maintaining performance indices typical of their low temperature predecessors.

The immediate benefit of raising the acceptor's temperature of the associated cryogenic cooler was a drastic reduction of parasitic (conductive and radiative) heat inflows and, therefore, the relaxing of the cooling constraints. No less important was the fundamental increase of the coefficient of performance of the thermodynamic cycle (Stirling, typically). The combination of these two factors has resulted in a favorable reduction of the power drawn by a cryogenic cooler; faster cooldown, improved reliability, etc.

In the early 2010s, it became obvious that the then commercially available cryogenic coolers (both linear and rotary) were an overkill for what is needed [1]. This understanding called for the development of a new generation of long life, cost-effective, low-Size, -Weight and -Power (SWaP) mechanical cryocoolers. In response to this challenge, based on existing heritage, the industry focused on gradual downscaling of existing cryogenic technologies. The list of the inherited features is as follows.

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Working agent. Typically, such cryocoolers operate using helium, the thermodynamic properties of which are quite close to those of an ideal gas over the entire range of temperatures and charge pressures. The favorable combination of heat conductivity and heat capacity makes helium, most probably, the best working agent for the purpose. However, because of the small size of molecules, helium is prone to fast leakage out of the sealed pressure vessels through inevitable serpentine-wise leak channels formed by nano-scaled defects. Long-term sealing of pressurized helium is, therefore, something of a black art and requires the use of special low permeable alloys, He-tight feedthroughs (in case of internal placement of driving coils) along with crushed metal seals. Another issue may be attributed to a high rate of diffusivity of water vapor (a major pollutant) into helium [2]. In this regard, it is worth recalling that specifically the loss of working agent and internal contaminations are the primary failure mechanisms limiting the life of linear cryogenic coolers [3,4].

Regenerative heat exchanger. This is the key component having a significant influence on the overall performance of the cryogenic cooler. The regenerator is typically engineered in the form of a pile of thousands of disks punched of metallic woven mesh screens stacked in the bore of a tubular displacer.

Albeit having a high wet-surface to volume ratio and excellent thermal contact, such a stacked-screen regenerator has inherently high parasitic gas-dynamic resistance and axial heat conductance. These may be primarily related to the nature of constrained zig-zagging flow of the gaseous working agent in tortuous flow channels and the presence of numerous randomly spread contact points resulting in heat conduction paths within the regenerator matrix.

Another disadvantage of such a concept is the inherently high axial anisotropy of the regenerator matrix which may be primarily attributed to the manufacturing technique. In a highly porous regenerator, the screens are prone to the axial migration under high acceleration forces eventuating into a local compacting of screens and the build-up of void volumes. Specifically, displacers from the same batch may be quite disparate in terms of attainable performance.

Also, the raw material (stainless steel wire mesh, typically) is quite expensive, the waste rate is high, the entire manufacturing procedure is quite laborious and requires special equipment and skills. Further, from simulations, high temperature and high-frequency cryocoolers are operating best with regenerative heat exchangers having a porosity in excess of 85% and wire diameter smaller than 10μm. Unfortunately, the finest commercially available stainless steel screens (e.g. #635) have a minimum wire diameter of 20μm; technological constraints do not allow reaching porosities higher than 70%.

Pneumatic actuation. Traditionally, a differential piston actuates the spring-assisted pneumatic resonant displacer of a split Stirling cryocooler, which is disposed coaxially and slidably inside a tightly matched differential cylinder. Such an arrangement forms two collinear "close clearance" seals bounding the so-called warm chamber, which is in direct pneumatic communication with the compression chamber of an associated piston compressor. Such a set must be individually matched by the machining of hard and wear-resistant materials like hardened tool steel or ceramics to micrometer accuracy. Such an arrangement is expensive, adds mechanical complexity and bulk to the rear side of the cold head along with the weight to the moving assembly.

Cold fingers. The concept of differential pneumatic actuation, as explained above, requires precise alignment and concentricity of the bores of the cold finger tube and base, which is used for nesting the above-mentioned differential cylinder. Specifically, typical 30um concentricity is usually achieved by machining the entire cold finger of a single piece of low heat conductive material, such as titanium alloy Ti 6Al-4V ELI. Since titanium alloys cannot be welded/brazed directly to other metals, there is a need for at least two hybrid rings for brazing the cold finger plug (Invar, typically) and the shroud of the evacuated dewar (Kovar, typically). Such hybrid rings are usually made by explosion welding and, therefore, are extremely expensive. The combination of these two factors explains high incurred costs.

It is worth noting that titanium alloys feature a relatively low module of elasticity (96 GPa). Thus, the constraints imposed on the dynamic response of IR focal plane array (FPA) under adverse environmental conditions prevent thinning the cold finger tube below a typical 100um limit. In some extreme events, there is even a need for adding low heat-conductive front supports; this may result in added costs, mechanical complexity and additional parasitic conductive heat inflow. Further, high-temperature brazing of titanium alloys may lead to unfavorable thermal strains, phase transitions, embrittlement, and micro-cracking ensuing into the leak of the working agent and loss of vacuum.

Cold head springs. For the best cooling performance, the pneumatic displacer has to be axially centered and driven close to resonance. These objectives are usually achieved by providing a mechanical spring supporting the warm side of a displacer from the stationary base of the cold finger, whereupon the spring rate should be chosen with respect to the mass of the moving assembly and driving frequency. It is worth noting that such mechanical springs are prone to fatigue-caused failures. Further, their anchoring to the moveable displacer and static housing adds mechanical complexity, void volume, and bulk to the warm side of the cold head. Also, such springs exert essential side forces ensuing into parasitic friction, wear and extra power draw.

Electromagnetic actuator. The piston compressor is usually driven by a "moving magnet" actuator, the stator of which is comprised of a back iron assembly enveloping a driving coil and the mover of which is comprised of a ferromagnetic armature and permanent magnets attached to the compressor piston, which is arranged slidably inside the tightly matched cylinder.

Sintered material of permanent magnets usually contains numerous hidden air pockets; a release of the trapped gases and water vapor from which eventuates into rust and contamination of the cryocooler interior. Also, such magnets are quite brittle; thus, they are prone to disintegration under peaky accelerations. Finally, moving magnets add weight to the moving assembly; this results in additional vibration export. Moving magnets are also a source of powerful low-frequency electromagnetic interference, which is quite difficult to attenuate.

Driving coil. Driving coils are usually engineered by winding enameled magnet wire upon a tubular coil form. Since such actuators are usually intended for use with low voltage and high current drivers, large-diameter wire is typically used for manufacturing. This results in mechanical complexity and low copper fill factor (below 60%, typically).

Dual-piston compressor. In a dual-piston concept of the compressor, the vibration export is cancelled "in source" by two oppositely driven should-be identical sub-compressors sharing common compression space and driving current. Obvious penalties are added mechanical complexity, bulk, and cost. Additionally, the reliability, thermodynamic and electromagnetic performance of dual-piston compressors are typically lower than those of single-piston competitors. Assembly of such compressors also involves the time and money-consuming procedures of matching the sub-compressor assemblies that need to be identical in terms of weight of the moving assemblies, piston/cylinder gaps, electromagnetic actuators, etc.

To summarize, the existing low SWAP cryocoolers are no more than downscaled replicas of their low-temperature predecessors. No wonder such a way of low-risk sustaining innovation has not led to highly expected substantial cost reduction and development of additional markets.

From the very moment of its inception in 2018, CryoTech adopted an approach of disruptive innovation, not only aiming to further improve SWaP indices, but first and foremost to enable essential cost reduction and higher reliability. Our primary goal is to reduce the price of the cryogenic cooler to a three-digit figure in a quantity of 1,000 units annually and increase MTTF from typical 30,000 hours to at least 45,000 hours [5].

These objectives would be achieved by disruptively simplifying cryocooler topology. The list of simplifications/novelties includes helium-free, less leaking, and less pollutable gaseous working agent suitable for high temperature applications; low-cost parallel wire, synthetic microfiber regenerative heat exchanger; "moving iron" actuation of piston compressor (patent pending); pneumatic rodless displacer with magnet spring (patent pending); low-cost edgewise bobbinless coils and single-piston compressor with an optional tuned dynamic counterbalancer.

FEASIBILITY AND ENDURANCE TESTING OF V 3.0 CRYOGENIC COOLER

Figure 1 pictures the split Stirling cryocooler (V 3.0) integrated with a simulation dewar (courtesy of SCD), relying on a monolithic titanium cold finger featuring an active length of 21mm and a wall thickness of 150μm. The heat load (200mW at 150 K and 23°C) of this simulation dewar was evaluated numerically using proprietary software and further substantiated using multi-slope warm-up calorimetry [6]. Such a high heat load may be attributed to the short active length, the extended wall thickness of the experimental cold finger tube and the absence of the cold shield. In this design, the weight of the cryocooler is 140 gr, including the cold finger.

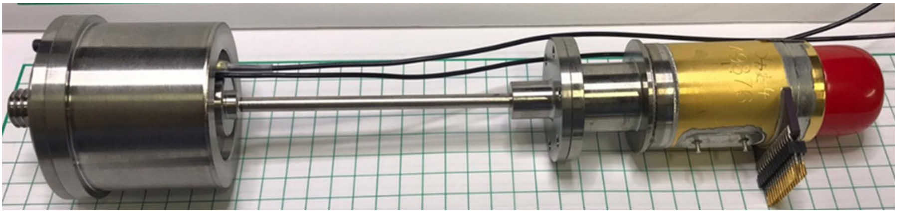

Figure 1. Split Stirling cryocooler v 3.0 integrated with simulation dewar.

The rodless type of pneumatic actuator relies entirely on the drag force resulting from the gas-dynamic interaction of the flow of the working agent and highly uniform microfiber regenerator filling the central bore of the out-of-phase reciprocating displacer supported from the cold finger base by the magnet spring (patent pending).

Major outcomes of the feasibility study were disclosed in [7]. In particular, the cooldown process from 300 K to 150 K, is only 113 seconds. In a temperature control mode at 150 K with no added heat load the power consumption is quite low: 1.4 W AC. The high power factor of 0.99 indicated good acoustic matching of compressor and expander. It was very instructive to learn that this cryocooler can work over a wide range of temperatures starting from 125 K. In particular, in a temperature control mode at 125 K, the power consumption is quite low too, namely 2.5 W AC.

This cryocooler was let to run endurance tests, including multiple ON/OFFs and temperature-regulated operation mode switching between 125 K and 150 K. Up to now, the elapsed time is in excess of 12,500 hours; the test is in progress. Typical power consumption is 1.7 W at150 K and 23 C, thus indicating only minor deterioration in performance.

FEASIBILITY TESTING OF V 3.5 CRYOGENIC COOLER

Based on the above feasibility study and upon finalizing the concept of rodless pneumatic actuation requiring no differential piston, the shapes of the magnet spring and the displacer tube, the cold head was redesigned with the primary objective of maximizing the active length of the cold finger subjected to a 40mm constraint imposed upon the overall length of the cold head.

Another, no less important objective was the transition to a more cost-effective technique of making cold fingers. Specifically, in the concept of a plungerless expander, the entire moving assembly may be positioned inside the cold finger tube. This eliminates the need for the above mentioned accurate alignment of cold finger tube and cold finger base and facilitates the concept of the composite cold finger. In particular, such a cold finger may be composed of a commercially available seamless tube extruded of L605 alloy, stainless steel base and Invar cold plug; all three parts may be joined by direct, low temperature, laser welding with no need for hybrid rings and harmful high-temperature brazing [8].

Additional benefits may be attributed to the higher manufacturing accuracy of extruded L605 alloy tubes. Specifically, in the plungerless expanders, the pneumatic separation of the cold and warm chambers relies entirely on the close clearance seals provided by the tightly matching the outer diameter of the displacer to the inner diameter of the cold finger tube. The ±5μm accuracy of internal diameter typical of tubes extruded of L605 alloy is adequate for this purpose. It prevents the need for the individual matching of displacers as would be needed in the case of using machined titanium cold fingers, where the typical manufacturing accuracy is ±25μm.

Further, the typical surface roughness of the cold finger tube interior extruded of L605 alloy is N2 (compared to N7 typical of cold finger tube machined of a titanium alloy). This is extremely important for eliminating parasitic friction and wear of plungerless displacers, reducing power consumption, and improving operational stability and overall reliability.

Figure 2 shows the simulation dewar (courtesy of AIRS), relying on such a cold finger. Prior to integration with the cryocooler, we evaluated self-heat load of the simulation dewar at 150K using the method of multi-slope warm-up calorimetry [6]. The relatively high self-heat load 260mW@150K@23C may be explained by the absence of the cold shield and the large area of the near black surface of the substrate accepting radiation from the near black dewar shroud.

Figure 2. Simulation dewar

Figure 3. Cryocooler v3.5 integrated with simulation dewar

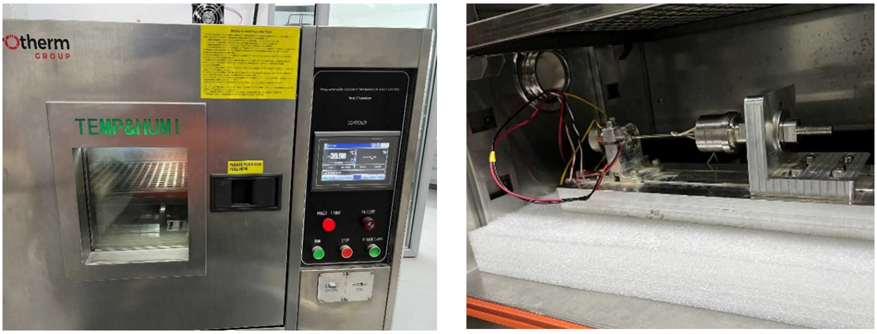

Figure 4. Testing in climate chamber

Figure 3 portrays the prototype (v 3.5) integrated with the above-mentioned simulation dewar. The outcomes of preliminary optimization and testing are detailed in [8]. Further optimization and testing at temperature extremes ranging from -40C to +70°C were performed in the climate chamber, as shown in Figure 4. Because of the relatively high heat load of the simulation dewar, the cryocooler has been pre-optimized with respect to minimum power draw in the temperature control mode 150 K with no added heat load at the typical reject temperature +23°C.

The optimum charge pressure and driving frequency were found to be 1MPa and 80Hz respectively. Under these conditions, the cryocooler delivered heat lift 260mW at 150 K and 23°C at a power consumption as low as 1.6 W AC.

Figure 5 shows the load curves – dependency of the power consumption on the added heat load at different reject temperatures (a), dependency of the power consumption on the regulated cold temperature at different reject temperatures (b) and dependencies of the power consumption on the reject temperature

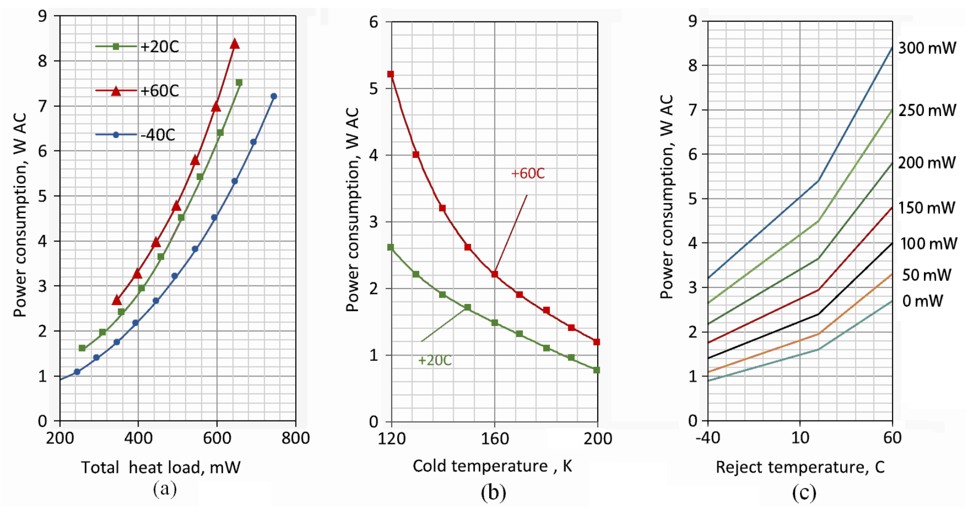

Figure 5. Load curves. dewar heat load 260 mW at 150 K and 23°C

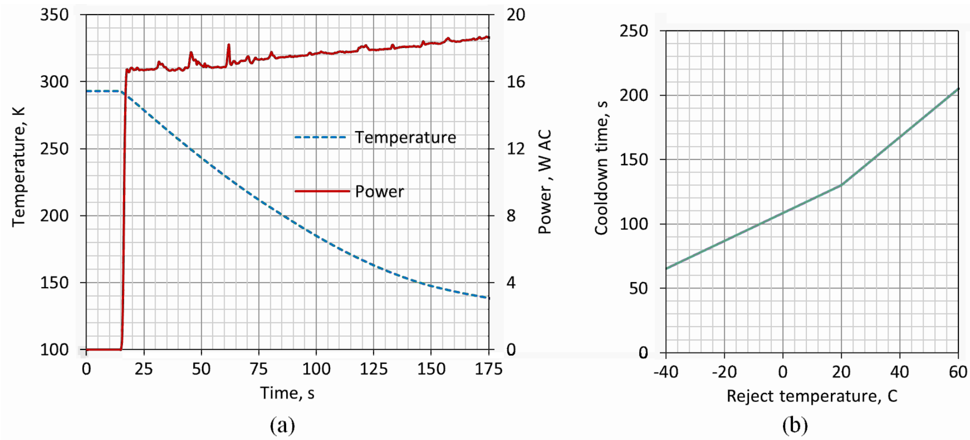

Figure 6. Cooldown at +20°C: (a) and cooldown times at different reject temperatures; (b) dewar heat load 260 mW at 150 K and 23°C

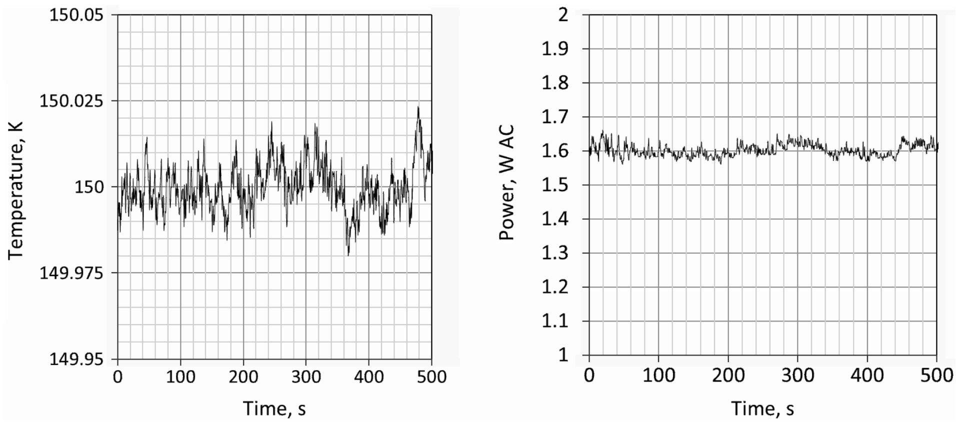

Figure 7. Cryocooler stability in the temperature stabilization mode 150 K.

at different added heat load (c). It is worth noting that by varying charge pressure and driving frequency the cryocooler may be optimized for different working conditions.

Figure 6a shows the time dependency of the temperature and power draw during an "open loop" cooldown phase at the reject temperature of +20°C; the maximum power consumption was trimmed to be below 18 W AC. From Figure 6a, the cooldown time is 130 s. Figure 6b shows the dependence of the cooldown time on the reject temperature.

Figure 7 shows stability of the cryocooler in a temperature stabilization mode. In particular, the temperature deviation from the set point is better than ±0.05 K; averaged power consumption is 1.6W AC.

Figure 8 portrays the response of cryocooler to a sudden application of an added heat load of 50 mW.

RELIABILITY IMPROVEMENT

Low ownership cost means not only low buying price but also extended life span. Major cryocooler vendors already announced MTTF of their linear cryocoolers to be 30,000 hours.

The above explained technological novelties allow CryoTech for aiming at furthering reliability of linear technology; the ultimate design goal is set, therefore, to be basic MTTF [9] in excess of 45,000 hours.

The primary failure mode – loss of the working agent [3,4] – is addressed by (i) replacing helium by an alternative, less leaking, working agent having larger molecules, and (ii) external placement of the driving coil requiring no potentially leaking feedthrough.

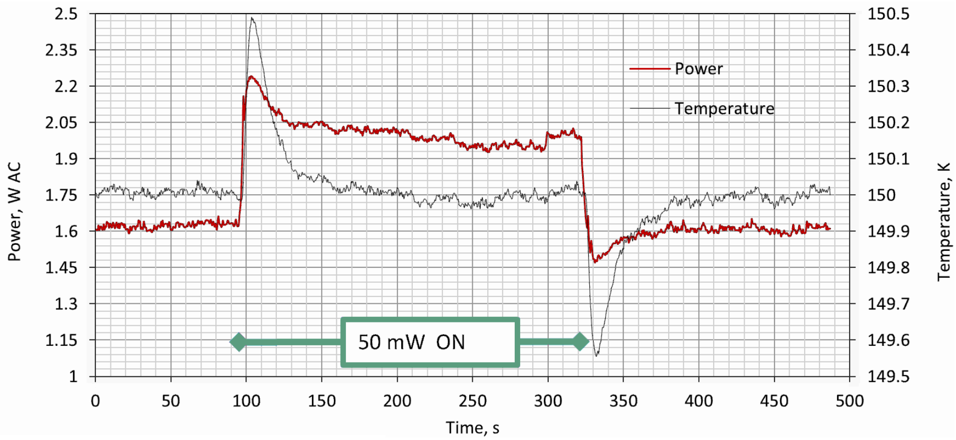

Figure 8. Cryocooler response to application of added heat load 50mW.

The secondary failure mode – contamination of the cryocooler interior [3,4] – is addressed by hot drying the regenerator material, cleaning and baking of internal parts and subassemblies, using the alternative working agent absorbing substantially smaller amount of water vapor, using a "moving iron" actuator featuring external to pressure vessel actuator stator containing driving coil and static permanent magnets.

Further major failure mode – fatigue fracture of mechanical springs in the compressor and expander is addressed by making use of failure-free magnet springs. Further improvement is expected due to a specific topology of the parallel wire microfiber regenerative heat exchanger preventing its channels from being clogged by condensing contaminants.

Additionally, using static permanent magnets outside the pressure vessel prevents failures related to the fracturing of their sintered brittle material under peaky acceleration forces. Also, friction and wear of rubbing clearance seals in the compressor is reduced by geometrical optimization aimed at minimizing side forces.

CryoTech completed development and deployment of a life test station allowing for simultaneous driving and monitoring of eight cryocoolers working in the temperature regulation mode under supervision of the demo controllers, see [8]. Test was initiated in Nov 2021 and is still in progress.

WHAT NEXT? TECHNOLOGIES UNDER DEVELOPMENT

CryoTech is developing a more compact single piston compressor (patent pending) featuring a moving iron actuator. In this novel concept, the inherently porous sintered permanent magnets are static and embedded into the actuator stator, which is placed entirely external to the pressure vessel. This completely eliminates the major failure modes related to the contamination of the cryocooler interior due to eventual outgassing from hidden pockets in the highly porous sintered magnets, adhesives, corrosion and disintegration under peaky accelerations. Further, the use of static magnets reduces the level of low frequency electromagnetic interference. Substantially reduced weight of the moving assembly results in the lowering of the required driving force and vibration export.

Figure 9 shows a 3D CAD model and dimensional drawing; the axially oppositely magnetized permanent magnet rings are colored red and blue. The overall weight of such a compressor is 110 gr. Figure 10 shows such a compressor integrated with the simulation dewar based on the generic cold finger (courtesy of LYNRED); this cryocooler is currently under evaluation.

For applications where the use of optional tuned dynamic counterbalancer is impossible, CryoTtech is extending its portfolio by developing a dual-piston compressor, the overall length and diameter of which are 52mm and 28.4mm, respectively; the weight is 170 gr. Such a compressor features a 380mm^2 integrated mounting pedestal intended for mechanical and thermal interfacing to the host system (e.g. enclosure of infrared imager), see Figure 11.

Figure 12 shows a 3D CAD model and dimensional drawing of the inline integral derivative of the above mentioned split cryocooler. The overall length is 73mm and outer diameter is 28.4mm. This topology offers better use of volume, lower weight (100 gr excluding cold finger), higher robustness because of the

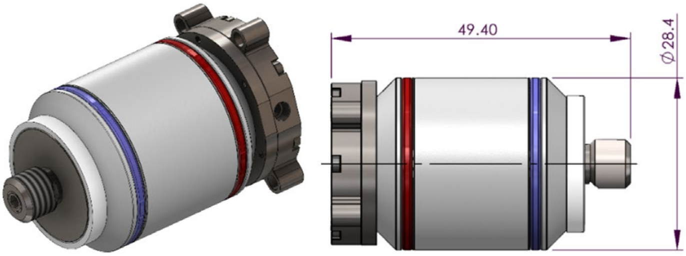

Figure 9. Moving iron compressor (under development)

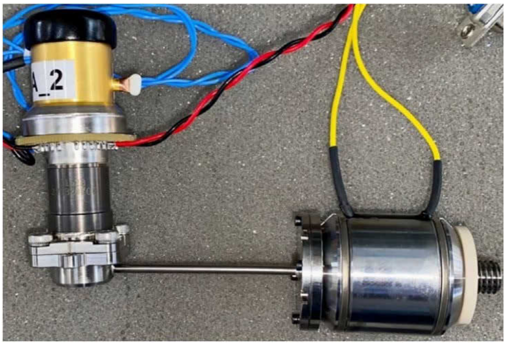

Figure 10. Split Stirling cryocooler with moving iron compressor

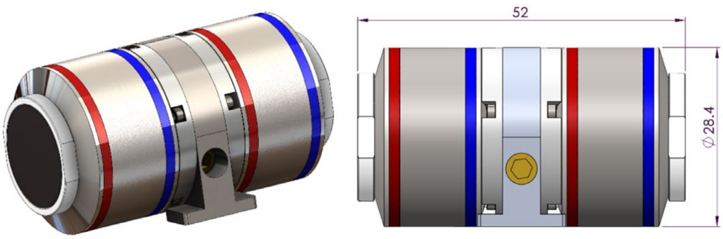

Figure 11. Dual piston compressor

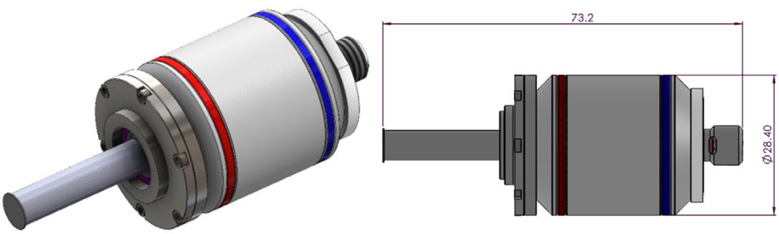

Figure 12. Inline integral linear cryocooler

absence of the transfer line, lower power consumption, zero vibrational moment, etc. It is worth noting that such an integral derivative allows development of frameless IR modules.

Figure 13 shows a 3D CAD model and dimensional drawing of the dual-piston T-type integral linear cryocooler. The overall length is 58mm and outer diameter is 28.4mm. This topology offers better use of volume, low weight (170 gr excluding cold finger), robustness because of the absence of the transfer line, options for frameless imager, lower power consumption, zero vibrational moment, etc.

It is worth noting that the length in the optical direction is 40mm while the active length of the cold finger is 28mm; more than half of the cold finger is concealed inside the bore of the compressor housing. It

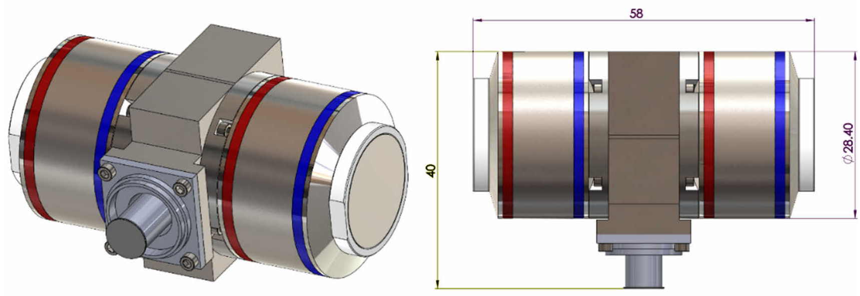

Figure 13. Dual-piston integral linear cryocooler (T-type)

is worth noting that the special squared shape of the compressor housing allows for convenient mechanical/thermal/optical interfacing to the host structure and mounting of the proximity electronic boards.

ACKNOWLEDGMENTS

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CONCLUSIONS

CryoTech presented the full-scale feasibility study on novel technologies paving way to a new generation of affordable cryogenic coolers for commercial IR imaging.

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