Extended Linear Cryocooler Development Process: Accelerating Time-to-Market and Enhancing Performance

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ABSTRACT

This article reviews the development and performance of the Extended Linear (ELI) cryocooler models K589 and K591.

The focus of this article is the SPRINT development cycle, which emphasizes simulation, risk reduction, and the creation of lean prototypes.

Initial simulations used SAGE software to highlight the potential for performance improvements. It provided the groundwork for optimizing the design while keeping dimensions as close as possible to K588/K590.

In the next phase, the risk reduction phase focused on mitigating any potential design weak point by performing detailed analysis. These included magnetic flux density evaluations in both DC and AC conditions.

The development of lean prototypes has a crucial role in the final phase, allowing rapid iteration and validation of design changes.

By streamlining these processes, the SPRINT cycle significantly reduces time-to-market, enabling faster deployment of high-performance cryocoolers in various applications. Additionally, the project life cycle and system engineering principles are explored, highlighting how they contribute to optimizing development speed, product quality and performance.

The K589/K591 achieved significant improvements particularly in cooling power while maintaining efficiency. It can reach a steady state working point of 3/4W@120K@71ºC.

Those cryocoolers are well-suited for SWaP-constrained applications:

It has been optimized to deliver high cooling power with efficient use of energy. By modifying the compressor design the cooler achieves significant cooling performance while maintaining a power-efficient operation.

Project life cycle and system engineering play crucial roles in enhancing the effectiveness of a sprint development cycle, particularly in complex projects like this. The project life cycle provides a structured framework that ensures each phase of development is properly complying with the market requirements. By applying system engineering principles, potential issues can be identified and addressed early in the sprint cycle, thus minimizing risks and optimizing the final product.

Detailed performance comparisons between the K589/K591 and RICOR's other linear models are presented, highlighting key variations and their implications for efficiency and reliability.

Keywords: Linear Stirling Cryocooler, simulation, K589, K591, development cycle, SWaP, RICOR, Dual Opposed, Generic Cold Finger

1. INTRODUCTION

In the rapidly evolving landscape of cryogenic technology, RICOR stands at the forefront with its innovative cryocoolers, essential for infrared (IR) cameras in surveillance and defense applications.

The growing trend in recent years, characterized by the demand for more pixels, greater processing power, and higher resolution, has led to an increased need for enhanced cooling capabilities. At the heart of RICOR's advancements in this

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area is the K589/K591 cryocooler, a model that exemplifies the company's commitment to excellence and innovation. The K589/K591 serves as a testament to RICOR's strategic focus on reducing time to market through an agile development cycle that emphasizes simulation and iterative design.

RICOR's sprint development process within its R&D department accelerates product development by focusing on iterative cycles of simulation, design, testing, and refinement. In addition, RICOR's capabilities include state-of-the-art manufacturing and testing capabilities that enable rapid design and optimization: enabling RICOR to bring new products to market significantly faster than by the traditional methods. By utilizing established building blocks and well-known technologies, engineers can effectively transition from existing products to innovative new solutions.

The Extended Linear Cryocooler Development Process represents a transformative approach in the field of cryogenic technology, aimed at significantly accelerating time-to-market while enhancing the overall performance of cryocoolers.

By prioritizing speed and efficiency, this development process facilitates rapid prototyping and testing, enabling engineers to quickly identify and implement improvements. This not only reduces the time required to bring a product from concept to market (delivery of first prototypes 12 months from kick off) but also ensures that the final solution is optimized for performance under real-world conditions. Furthermore, the process leverages cutting-edge simulation tools and data-driven decision-making to streamline operations and minimize risks, ultimately leading to a more competitive edge in the fast-paced cryogenic market.

RICOR's methodologies, combined with in-house expertise drive advancements in cryocooler development. The company's R&D capabilities and extensive knowledge enable it to quickly bring new products to market that meet the rigorous performance standards required in surveillance and defense applications. The K589/K591 cryocooler, built on the foundational knowledge and technological advancements of its predecessors, the K588 and K590, not only enhances cooling power but also improves reliability and operational endurance in extreme conditions. By integrating lessons learned from previous models and leveraging proven technologies, RICOR ensures that its products stand up to harsh specifications and extreme conditions. This strategic approach, as detailed in this article, enables RICOR to be a worldwide market leader in technological advancements and meet the demanding needs of modern defense applications.

2. SPRINT DEVELOPMENT CYCLE

2.1 Development Process

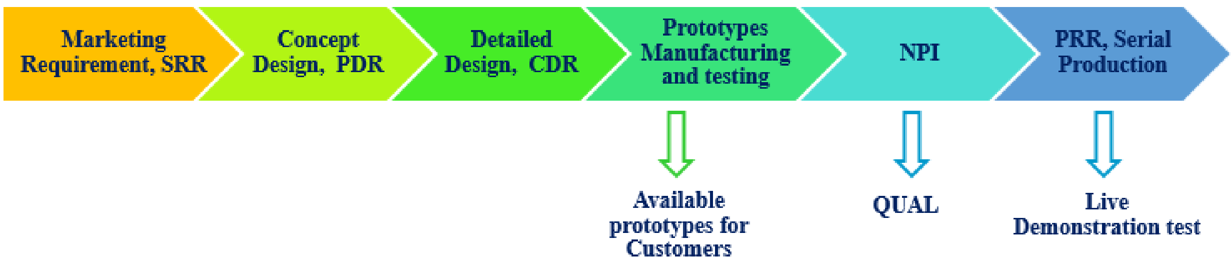

Figure 1: Development Process

RICOR's development process involves six-key stages, beginning with determining cryocooler requirements specified by the system engineer based on customer and marketing inputs. This leads to the creation of a Marketing Requirement Document (MRD) that outlines both technical and business needs. The R&D team then develops a specification and conducts a System Readiness Review (SRR) with multiple departments to ensure all requirements are understood.

Subsequent stages involve brainstorming and analyzing conceptual designs, which are reviewed during the Preliminary Design Review (PDR). After selecting a concept, detailed design proceeds, exploring multiple concepts to reduce risks. Designs undergo a Critical Design Review (CDR), after which parts are manufactured and prototypes assembled for testing. Some prototypes are assessed by potential customers.

The R&D and manufacturing teams then collaborate on preparing for production, with initial cryocoolers produced for reliability testing. The process concludes with a Production Readiness Review (PRR), finalizing readiness for serial production, followed by life testing on selected units.

The K589/K591 program's timeline was challenging, requiring delivery of first prototypes 12 months from kick off. A lean approach was used, mirroring the design of existing models K588 and K590, which expedited prototype manufacturing and testing. Risk management strategies, including a Development Failure Mode and Effect Analysis (DFMEA), were implemented early to address potential issues, ensuring the project met its goals effectively.

To meet the program's requirements, several strategies were implemented, including adopting a lean methodology. It was decided to use a design similar to the already successful K588 and K590 cryocoolers, which have over 3,000 units shipped. Production of prototypes was expedited, allowing parts to be completed and subassemblies tested just weeks after finalizing designs.

A risk management program was started at the outset to ensure milestone targets were met. This included a detailed project plan that was monitored weekly. Additionally, a technical risk management strategy using DFMEA was employed to identify potential failure modes and apply corrective actions across all components and procedures. Tests were conducted to validate these measures and ensure risks were managed efficiently.

The sprint development process was enabled by:

- Utilizing simulation tools that are well-integrated into the R&D department.

- Leverage existing knowledge

- Simulating major changes to get the trend

- Lean prototypes on existing models for go/no go decision

- Risk reduction towards PDR

3. SIMULATION TOOLS

3.1 SAGE®

Understanding the thermodynamics of the split Stirling linear cryocooler cycle requires consideration of many conjugated parameters from heat transfer, fluid flow, electromagnetics and energy flow across the system.

SAGE® software, developed by Gedeon Associates, is a one-dimensional steady-state simulation tool for modeling cryocoolers and Stirling engines. It uses a comprehensive approach of building a complete model of a cryocooler from basic components like pistons, cylinders, and heat exchangers. The analysis is based on both theoretical models and empirical correlations.

Key features of SAGE include Interactive optimization by Identifying major factors affecting performance, hierarchical structure that connect components logically from compressor to cold tip, derived parameters to show performance dependency on geometry and key characteristics.

The modeling craft needs to be performed carefully, for the conjugated nature of the equations tends to appear with slightly wrong input on every level of component. It is important to simulate the different ambient conditions, as the ambient and heat source temperature strongly affects damping factors and cooler performance.

Using this tool is helpful in checkups for upgrading an existing model to new customer demands, before diving into the tedious labor of dimension changes in drawings and cad models. The user can get an idea of what needs to be changed to achieve the proper cooling power in optimum efficiency.

One should point out that the preliminary error of the model can be quite large and show trends only, but once calibrated with a standalone prototype, it can be validated to a level of 5% error.

The validation process can be difficult if one wishes to evaluate all phase shifts and amplitude simultaneously and some parameters cannot be tested at the same time. The test bench at RICOR considers pressure across distinct parts of the cooler and displacement of the moving masses during the operation with specialized transparent covers and in-line sensors.

Validating other characteristics such as spring stiffness or flow resistance is carried out on specific rigs with the individual components.

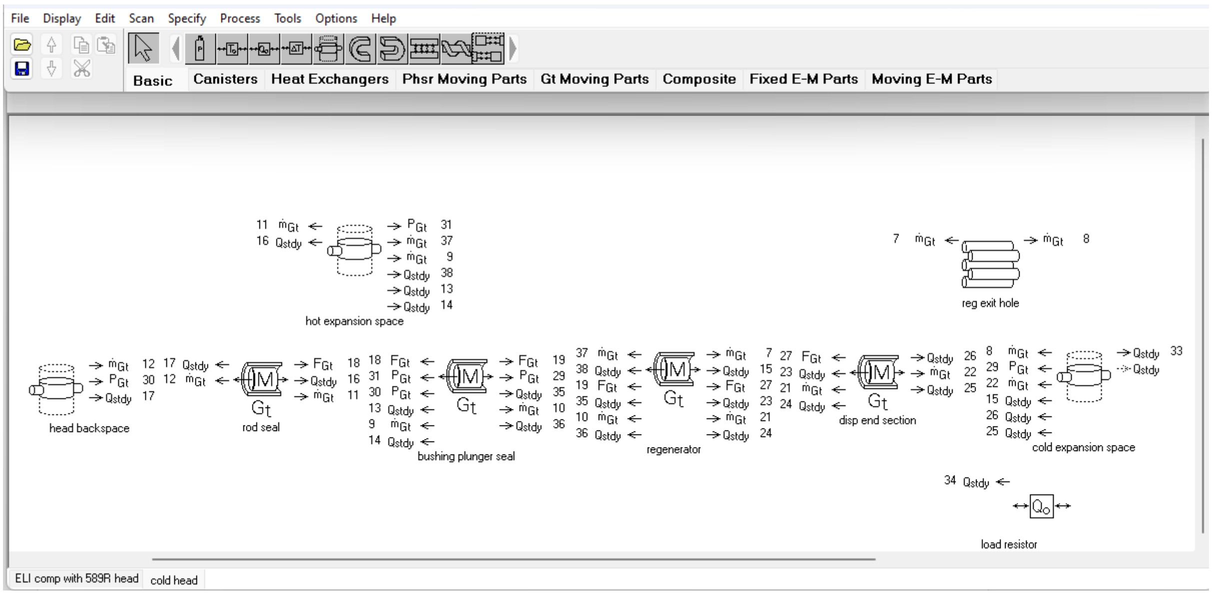

Figure 2: The second level editing window of SAGE® with a model of a cryocooler cold head.

In figure 2 the working GUI of SAGE is presented, featuring the second level of a model, representing the cold head. The root level contains the connection to the linear motor and compressor, as well as the ambient and fill pressure source. The cold head described in figure 2 consists of nine high level components, including the regenerator, and the hot and cold expansion spaces.

Each high-level component shown as a drag and drop box in the model contains sub level components such as piston and cylinder liners, moving masses and springs, seal gap modelling, porous media etc. Every subcomponent carries inside connection blocks of different forms of data transfer: heat transfer, mass flow, force, or pressure interconnections, which can be elevated to higher level components.

3.2 FEMM

Designing a linear motor to match the cryocooler demands is a demanding task, requiring knowledge of every aspect of the motor, including the electrical circuit, the magnetic circuit, and the mechanical output needed to create the pulse wave generator of the cryocooler. In order to reduce the complexity of the problem and perform a fast and lean preliminary design it is crucial to have tools to simplify the machine into a combined 2D model.

FEMM (Finite Element Method Magnetics) is a free software designed to simulate 2D electromagnetics, electrostatics, and heat transfer problems of electromagnetic components and motors. It offers fast building of motor configurations, DC current solution with high accuracy, and somewhat understanding of AC behavior and losses. It is easy to control using a Python coding interface, to map different currents and different component position/shape and its effect on the system.

FEMM is a great tool to estimate motor constat, magnetic stiffness, flux leakage, and the necessary windings and iron geometry to produce the highest force without saturation or major joule losses. It gives the designer great flexibility in trying new concepts and understanding the impact of tolerances or geometry changes.

Validating the tool was accomplished by testing motor constant and magnetic stiffness in a lab test bench against a spring-load test rig. The error level reached 0.7% on motor constant against the final design.

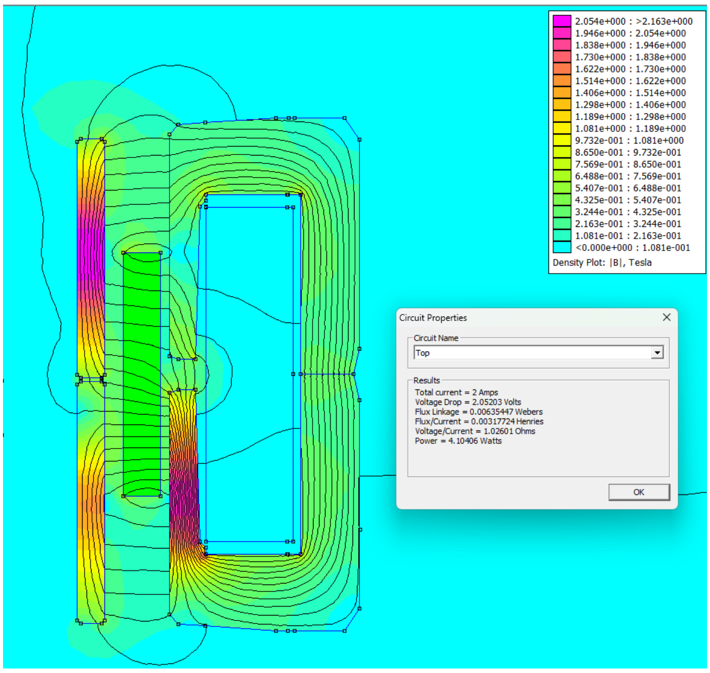

Figure 3: FEMM graphic output of flux intensity field in 2D axisymmetric DC problem.

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3.3 ANSYS mechanical workbench

Structural and thermal simulation tools have become in recent years an integral part of the engineer's toolbox. Alongside classic theoretical calculations made by hand or template standard tools, finite element software applications have facilitated the way engineers can visualize the problems they are faced with and find with much more clarity and accuracy the areas that are destined to fail in the design. One of the most trusted and used software is the ANSYS mechanical workbench, which allows among an extensive list of features the ability to simulate static problems, modal analysis, vibration endurance, and thermal management problems.

Using ANSYS, designs of flexure bearings with complicated geometry are pretested for stiffness and fatigue, pressure vessel deformations of the cryocooler's envelope are simulated and detection of sub-systems with resonance sensitivity is performed that can be treated before manufacturing the first prototype. Over the years there have been numerous validation tests in RICOR, leading to a satisfactory result, such as a fatigue test to a flexure bearing, proving the design and simulation to fulfill the lifecycle requirements.

Thermal simulation of heat evacuation from the cryocooler interface for improving efficiency or testing for system integration requirements have been performed. in addition, heat distribution in the cooler's controller was simulated and design modifications were made according to the simulation's results.

3.4 Low frequency electromagnetic field Simulation- ANSYS maxwell

A part of the ANSYS package is the electromagnetic Maxwell module, which offers static, frequency-domain and time-varying magnetic and electric fields for electric machines, transformers, wireless charging and more. It also offers specialized design interfaces for electric machines and power converters. In the development processes this software is often used to account for magnetic damping coefficient, core loss estimation and transient unexpected behavior. In the LEAN development process, it may come as a complementary tool for FEMM validation and wider exploration of the motor, but as the discussed product started its life from an existing model, the design mostly relied on earlier Maxwell simulations, focusing on other characteristics of the compressor.

3.5 Computational fluid-dynamics (CFD) capabilities

SAGE is used widely for thermodynamic, flow and heat transfer calculations performed in one-dimensional expanded computation, relying upon empirical correlations for turbulent modeling, radial heat transfer, viscous pressure gradient or shuttle losses. Sage does not compete with general purpose CFD simulation but rather encapsulates gas flow and heat transfer within several model components to form complete models of complicated systems. The study of local flow behavior and heat transfer in solid-fluid interactions is manageable with CFD software simulations.

For this purpose, we use the leading free, open-source software OpenFOAM,[7] for solving the flow field variables and to directly model the details of the hydrodynamic behavior of the cryocooler components. As part of the OpenFOAM tools, daFOAM, which is an efficient discrete adjoint method, is being used for shape optimization purposes (including finite volumes and finite element). It supports design optimizations for a wide range of disciplines such as heat transfer, structures and hydrodynamics. Since CFD simulations are computationally intensive, time consuming and require significant computational resources, it is definitely unsuitable for design or optimization purposes. Therefore, the preferred approach is to perform the upper-level design and optimization of the overall cryocooler system using SAGE, while performing detailed flow analysis and separate effects studies using CFD approach as required.

OpenFOAM is produced by OpenCFD Ltd. It contains over 80 solver applications to simulate specific engineering problems. The code is developed in C++, and it has been released as an open-source since 2004. Being open-source and used in many active companies today, OpenFOAM is the main fluid dynamic solver in RICOR, with pre/post processing utilities. In addition, OpenFOAM handles pressures of fluid flow among other variables and therefore is capable of modeling acoustics. One benefit is that it supports mesh motion, allowing to accurately build the pressure pulse by piston/displacer movement. Computational mesh models are generated by three different tools: the mesh generation utility, blockmesh, supplied with OpenFOAM; Gmsh-opensource 3D finite element mesh generator; ANSYS meshing commercial software.

3.6 Cool-Down Time (CDT) assessment

Miniature cryocoolers manufacturers face challenges in CDT estimation due to its complex, multi-physics nature (heat transfer, fluid dynamics, electromagnetics, mechanics). While explicit numerical simulations are computationally expensive, unstable, and restricted by time step limitations, RICOR engineers[2] have developed a Python framework bridging explicit and steady-state approaches for CDT calculation, utilizing a semi-analytic method based on steady-state databases.

A control volume-based approach is employed, modeling the cryocooler's compressor, displacer, and cold tip as distinct thermodynamic systems. Energy balance equations consider heat transfer, enthalpy, and work input to the model. A system of non-linear ordinary differential equations (ODEs) is solved using SciPy's solve_ivp, an adaptive Runge-Kutta solver.

Steady-state energy flows are obtained from SAGE model that was validated beforehand, if possible, under varying operating conditions.

The cool-down time performance can be explored at various target and temperature conditions, alongside the effects of an external load, material properties or thermal capacitance on the overall cryocooler cooldown time performance.

The better the information on the detector component and structure, the better accuracy is achieved.

4. LEVERAGE EXISTING KNOWLEDGE

In recent years, the market trend has shifted from focusing on low SWAP (Size, Weight, and Power) to favoring coolers with higher energy density that offer significant cooling capacity within compact dimensions. The state-of-the-art K588/K590 models introduced by RICOR were initially developed as SWAP coolers for HOT (High Operating Temperatures) detectors, with a standard working point of 150K at 180mW and 23°C.

To meet the new market demands of maintaining the size and weight of the K588/K590 SWAP cooler models while increasing the heat load capacity for HD and HFM detector applications, a lean development approach was employed.

During K588 development, extra margin was incorporated in the cold head's displacement amplitude to ensure low power input and a long lifespan, acknowledging the cold head's potential to dissipate larger heat loads with suitable modifications.

The primary objective was to enhance performance without surpassing ICD limits. Two strategies were proposed: increasing the acoustic power from the compressor to drive the cold head and optimizing the cold head's features for efficiency under higher heat loads. As the performance of the cold head and compressor are interdependent, both strategies were pursued simultaneously, referencing the K588 model.

Previously, the K588 was simulated in SAGE and MAXWELL to a satisfactory validation level, and these results were foundational for developing the new K589/K591 model. Additionally, engineering margins were examined to assess design flexibility and determine necessary adjustments to key features like flexure bearings and stroke limits.

5. SIMULATING MAJOR CHANGES TO GET THE TREND

Relying on the existing SAGE model for revalidation and rebuilding it to meet the latest tests' result of the model, the compressor output was examined in two directions, both aiming to increase acoustic power.

The first direction was compromising the diameter of the compressor and enlarging the piston diameter. A mapping of performance vs. piston diameter was calculated to find the minimum size increase and the maximum power output possible, while trying to keep the electro-magnetic components roughly the same size and performance.

The second attempt was to increase the length of the compressor for the enlargement of compressor stroke, which in turn will increase the pressure pulse needed to drive the displacer and the thermodynamic process in the cold head.

Simply put, isolating the compressor pressure amplitude output as a key parameter while keeping the cold head the same to maximize its stroke potential will allow higher heat load to be rejected from the detector. as a result of increasing cooling power, Coefficient of Performance (COP) might be affected, as the input acoustic power increases and modifications to the cold head are needed to match it with the compressor.

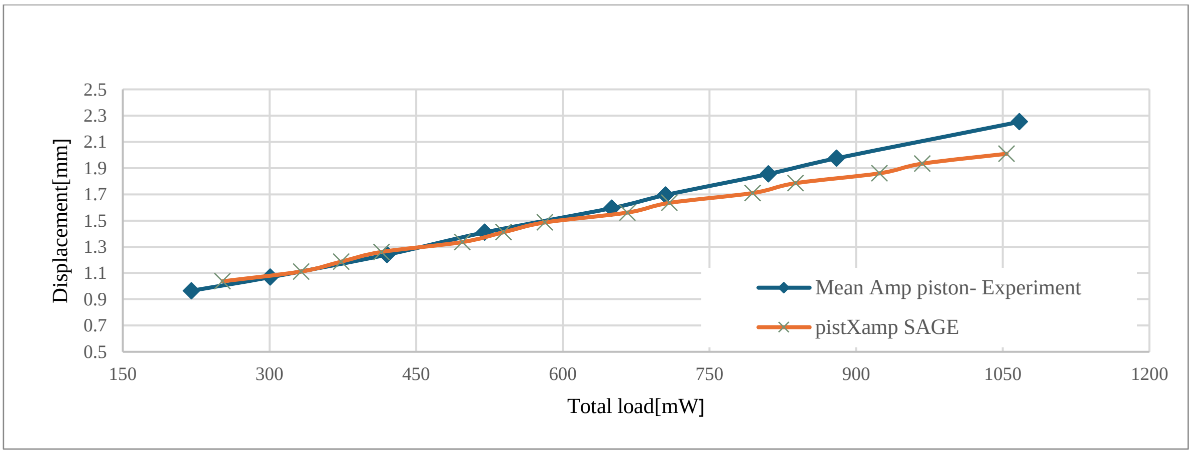


Figure 4: Piston amplitude vs. Total load SAGE Validation

Figure 4 presents the SAGE simulation result and the prototype validation of piston stroke enhancing cooling power by extending the piston displacement range thus increasing acoustic power to the cold head. There is a good correlation between the simulation and the results in most parts, but as the cooling power increases, it is getting harder to maintain the same level of certainty as the regenerator properties vary due to major changes in flow and heat transfer. The original SAGE model was much less accurate and was rebuilt to a high level of confidence.

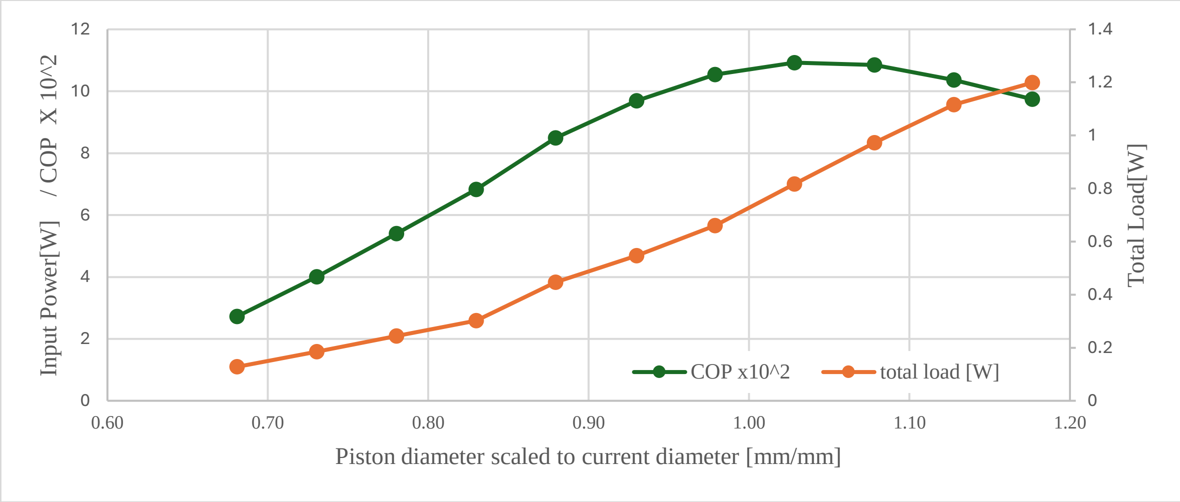


Figure 5: SAGE simulation- Piston diameter effect on performance and cooling capacity.

In figure 5 the SAGE simulation results present the effect of piston diameter on cooling power while holding the piston displacement constant. The optimum efficiency of the machine can be seen at piston diameter resembling the current one of the K588 compressor. Increasing the piston diameter further will result in an increase of cooling power but a slight decrease of efficiency (an issue that may be dealt with in cold head improvements). The original SAGE model was much less accurate and was rebuilt to a high level of confidence.

Evaluating the results, it was found that both directions can increase the input power exerted from the compressor by a factor of 1.5-2 without compromising on the bounding dimensions restrictions of the system presented by RICOR system, application and marketing teams. The increase in stroke needed to supply higher acoustic power was 80%, while the maximal stroke only increased by 40%. On the other hand, the increase in piston diameter was calculated to be only 13% larger, but the effects on the driving circuit are such that it needs a much higher power density in the electric motor, roughly the same size.

The SAGE results then evolved to physical demands, to be fulfilled in the CAD model design of the new compressor. Though the SAGE model was validated in the past for the K588 working point, it is still not enough to completely follow the model to a product development stage without actual proof.

6. LEAN PROTOTYPING ON EXISTING MODELS FOR GO/NO GO DECISION

To ratify the basis assumption that by increasing the acoustic power to the head will increase the heat load rejection from the cold finger, using the full stroke potential, a K590[2] cold head was connected to a K527[3] compressor. This compressor has a single piston with a diameter twice the size of the K588/K590 compressor, and a large stroke, among other differences such as working frequency, fill pressure and compression volumes.

The experiment shown in Figure 6 was carried out to increase the level of confidence in the design direction using available means in the lab. The aim of the test was to ensure that the cold head stroke potential fulfilment will indeed increase cooling capacity. The test bench included a PCB pressure sensor, a laser vibrometer to measure the cold head stroke through a glass window, an induced force accelerometer test bench, power supply and measurements of the input and output parameters from the compressor and the cold head.

The experiment included measurement of the stroke and pressure pulse. Adjusting the fill pressure and frequency and carefully tuning the current, the mixed cooler was able to reach 850mW total heat load rejected from the cold finger at

[2] K590 cold head was developed in parallel to the generic cold finger model K588 for the same performance spec, using the same compressor, for a custom shorter cold finger.
[3] A larger RICOR model consists of single piston linear compressor and a cold head that fits 8 mm diameter cold finger.

120K. The stroke was maximized to the limit with a higher-pressure amplitude and mass flow than the K588 compressor can deliver. Acoustic mismatch prevented high efficiency, as it was only a proof of feasibility.

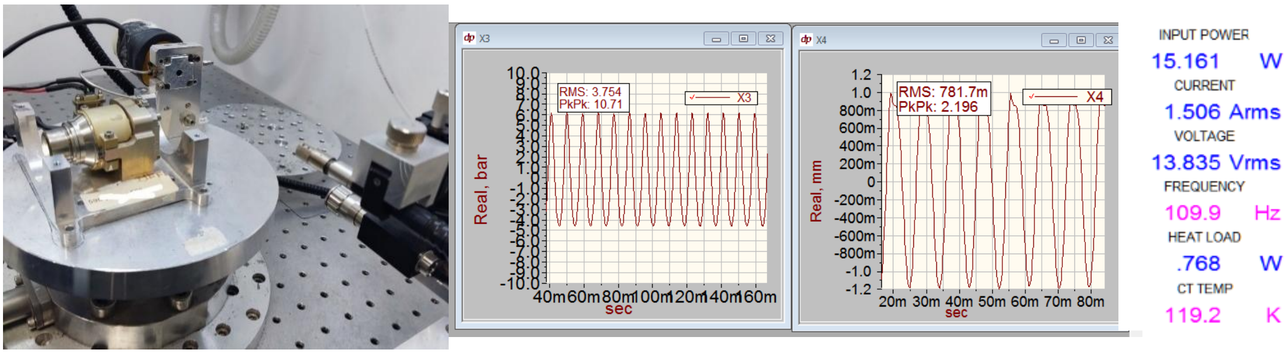


Figure 6:Test bench of the K527-K590 hybrid cryocooler. testing the cold head maximal capacity with full stroke of the cold head and unmatched compressor parameters.

A first shot FEMM model was constructed to enhance piston mover assembly stability at an extended stroke, while maintaining and increasing the electromagnetic performance and moving piece stiffness. The design considers the effects of diverging magnetic stiffness that can resist harmonic motion. Simulation was also performed for different soft magnetic materials and the magnetic impact that may occur on the piston-cylinder pair.

Quick production of necessary adaptations to the existing K588 compressor in RICOR machining department was made to prove the concepts presented by SAGE simulation.

Using fast and rough adjustments to the K588 compressor, disregarding for a moment the lifespan and endurance requirements, two early stage enhanced compressor models were created. The cylinder was honed to the new size and the piston enlarged, while reducing structure strength but keeping the K588 linear motor parts identical. The second model was using an elongated version of the covers and adjusted motor building blocks to allow the compressor stroke amplitude to stay steady in larger strokes without hitting the compressor walls.

The new prototype was not helium tight but was held in a test rig used to check compressors before welding in the lab, which hold helium long enough to perform tests comfortably and at a high certainty level.

K588 manufacturing line cold heads were used to test the prototypes in a series of tests that will be used to determine the feasibility of the concept.

An AC test run in a controlled environment (an oven) was performed, along with induced forces test at the room temperature test. Pressure and displacement sensors were attached in a customized pressure envelope and gas transfer line.

The parameters gathered were the following: Input power, heat load added, cold head temperature, cold head amplitude, induced forces, pressure amplitude at the compressor exit and at the backspace. Skin and ambient temperature values were also measured. These were sufficient to determine whether the change is viable to move forward in the design.

With both methods, the results showed the promising outcome that the prototype was able to evacuate 1000mW of heat load and maintain 120K at the cold end at 23C ambient temperature and at least 800mW at 78C ambient.

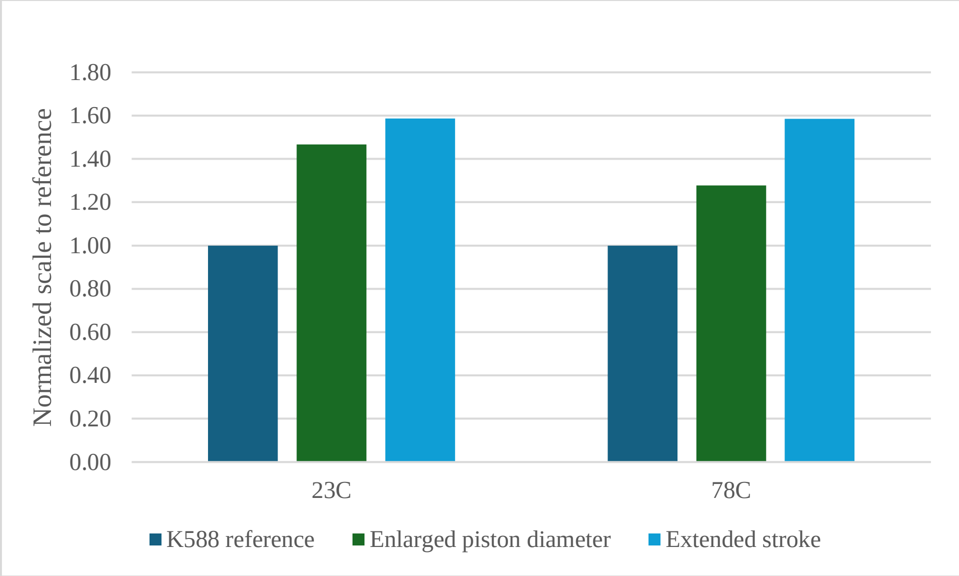


Figure 7: Normalized cooling capacity at 120K.

Featured in figure 7 are the test results of early proof of concept for increasing compression acoustic power on means of extended stroke or enlarged piston diameter. The results indicate an extension of the cooling capacity beyond the limits of the K588 model by more than 40%. Extended stroke configuration shows better cooling capacity since there is no need for adaptation of the cold head for increased volumetric flow at low piston amplitudes. Furthermore, the extension of the motor components allows more flux to flow without reaching saturation in the iron.

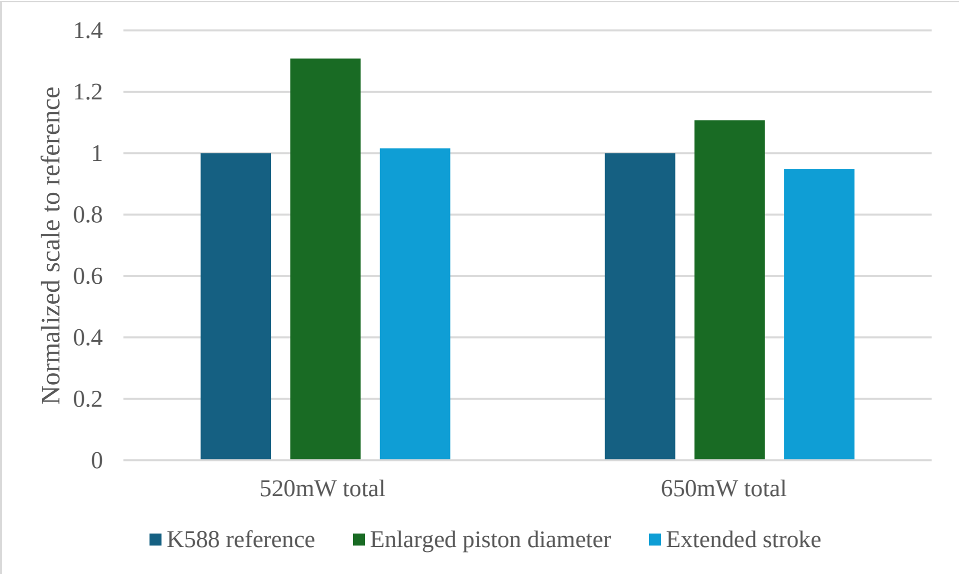


Figure 8: Normalized AC power input at 78C@120K.

In figure 8 are the input power test results of the same prototypes. The results show that keeping the piston diameter similar to the K588 model prevents excess power losses due to magnetic saturation and cold head flow resistance that may arise with enlarging the piston diameter. It seems that changing piston diameter may require more changes in the cooler than desired in a sprint development process.

It was noticed that with the enlarged piston diameter, the compressor magnetic components have reached saturation for the increase of electrical input power was not as correlative to the compressor pressure output and performance. This result was coherent with the FEMM simulation performed to assess the impact of keeping the compressor diameter as small as possible and "shaving off" of the inner parts thickness. The increase in compressor diameter was less desired and it was favorable to keep it as similar as possible.

In light of the performance proof of concept and taking into consideration the geometry limitations, it was decided to move forward with piston stroke extension over piston diameter.

Figure 9: The new compressor design vs. the K588/K590 compressor. A minimal change in outer dimension to provide over 25% increase in cooling capacity.

7. RISK REDUCTION TOWARDS PDR

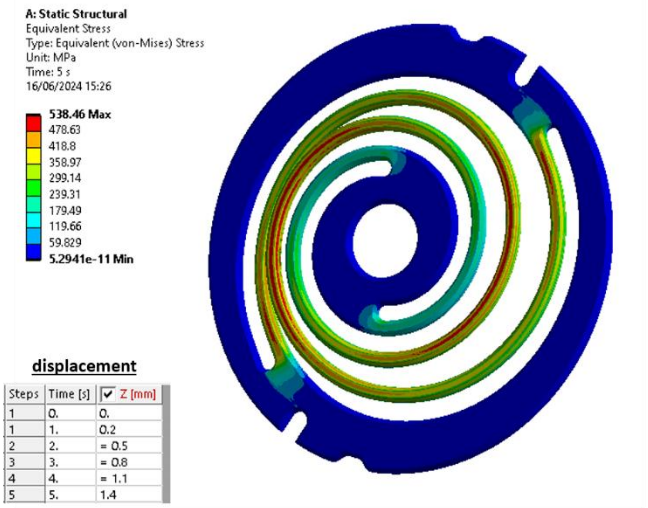
In the proof of concept, the components used were not applicable to a deliverable product. The next phase towards the goal was reducing risks involving harsh new environmental conditions and the evidently higher loads applied on the compressor and cold head components.

A basic list of components that may be impaired by higher ambient temperatures and higher forces, currents and heat loads was assembled in a DFMEA process. Each component was then categorized as a risk reduction process of either simulation or test.

The winding coil and electric components were subjected to high AC currents at extreme ambient temperatures and thermal cycles to assess which failure mode was the most dominant, and what part needed to be redesigned. It was found that within the project requirements the components were well below the critical limit for the design.

Flexure bearing simulation analysis was reperformed for large deflections using ANSYS mechanical, and alternative materials were suggested to increase the margin on fatigue failure. A fatigue S-N curve is currently being constructed for the flexural element of the cold head where higher amplitudes were already checked and are consistent with the simulation.

The stress field analysis shown in Figure 10 considers the displacement of the bearing and the applied force to which the spring axial stiffness correlates. Axial stiffness is important to the dynamic behavior of the moving components, while the radial stiffness is less dominant in a friction-based design. Static failure mode is simulated and validated to find the safety factors. Soderberg criteria are used to refine a base line assumption of a third of the yield strength as the fatigue limit of the design.



displacement

Steps	Time [s]	Z [mm]
1	0.	0.
1	1.	0.2
2	2.	= 0.5
3	3.	= 0.8
4	4.	= 1.1
5	5.	1.4

Sandvik chromflex $\sigma_y = 1300MPa$

	Mode	Frequency [Hz]
1	1.	1073.5
2	2.	1279.5
3	3.	1332.2
4	4.	1630.7
5	5.	1631.4
6	6.	2597.6

	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	1.	7.1322e-012	76.762	16.192
2	2.	1.7967e-011	192.04	40.502
3	3.	2.8731e-011	307.44	64.869
4	4.	4.0861e-011	422.92	89.328
5	5.	5.2941e-011	538.46	113.9

302 SST $\sigma_y = 1100\ MPa$

	Mode	Frequency [Hz]
1	1.	1040.9
2	2.	1240.6
3	3.	1291.7
4	4.	1595.4
5	5.	1596.1
6	6.	2531.

	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	1.	3.4516e-012	74.616	15.773
2	2.	8.5858e-012	186.67	39.452
3	3.	1.4704e-011	298.83	63.185
4	4.	2.2404e-011	411.06	87.002
5	5.	2.8545e-011	523.33	110.93

Figure 10: Flexure bearing stress analysis in static displacement conditions.

Modal analysis was also performed to mitigate risks of resonance in working frequency harmonies. The results showed the design had a larger safety factor with the new material suggested for the design. The risk of failure in the working conditions required is very low, and below the fatigue limit calculated. A test to evaluate S-N diagram for the design in the K588 material is being performed and currently the results are reassuring.

Verification of the FEMM simulations was carried out by testing for the motor constant and magnetic stiffness, as shown in Figure 11, resulting in very similar outcome as the simulation, thus maintaining a high level of confidence in the design.

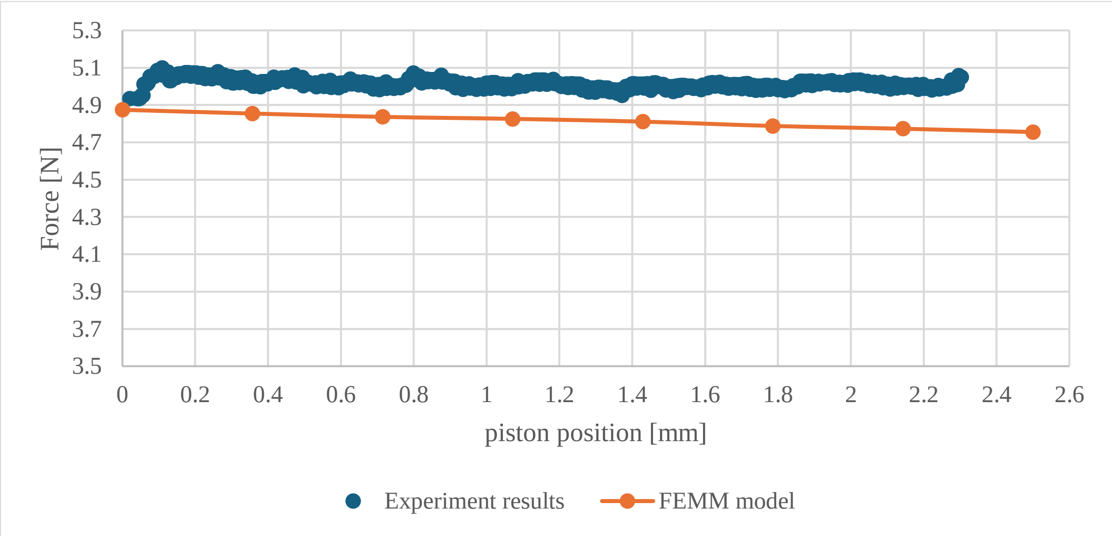


Figure 11: Motor constant validation by experiment vs. FEMM 2D model.

The experiment was performed on a spring stiffness test bench. The mover was pushed by the rig piston in one direction, while measuring the force on the loadcell while applying steady DC current of 1[A] to the coil. The same setup was used for magnetic stiffness while current was set to 0[A]. The results were reaffirmed by measuring several times on both pushing and releasing the loading piston and were repeated on the other symmetrical direction by reversing the current and the direction of loading on the motor. The test was performed in open air environment.

Innovative improvements to the compressor design were also considered and risk management was applied to new components, including interference fit and preload calculations for mounting inner part in the compressor assembly.

8. EXPLORING EFFICIENCY ENHANCING VECTORS

8.1 Cold head improvements

While increasing acoustic power to the cold head leads to higher cooling capacity, the cooler efficiency does not correlate to this trend. Better adjustment of the cold head for increased gas flow and reducing hydraulic resistance may improve efficiency. Also, improvements in heat transfer are essential to reduce parasitic losses. Compromises should be made when performing such an adaptation without expanding system boundaries.

Using the SAGE model to enhance the performance of the cold head while bounding the design considerations for existing tooling and easy assembly, a new cold head design was constructed. The three main concerns were objectives for the design: heat transfer to the system boundaries; heat transfer and flow optimization in the regenerator, and reliability of sealing mechanisms. The harmonic Dynamics of the moving parts were also modified considering the suggested changes.

Furthermore, the new cold head dynamics resulted in higher induced forces in the cold head due to mass increase and stroke extended (to fulfill the potential cooling power from the cold head). Frequency was then optimized to reduce the induced forces as frequency affects them largely.

Combined flow and heat transfer models were used in CFD analysis to manage the heat transferred from the gas in the "hot" side to the surrounding material which in turn delivers the heat to the system evacuation lane.

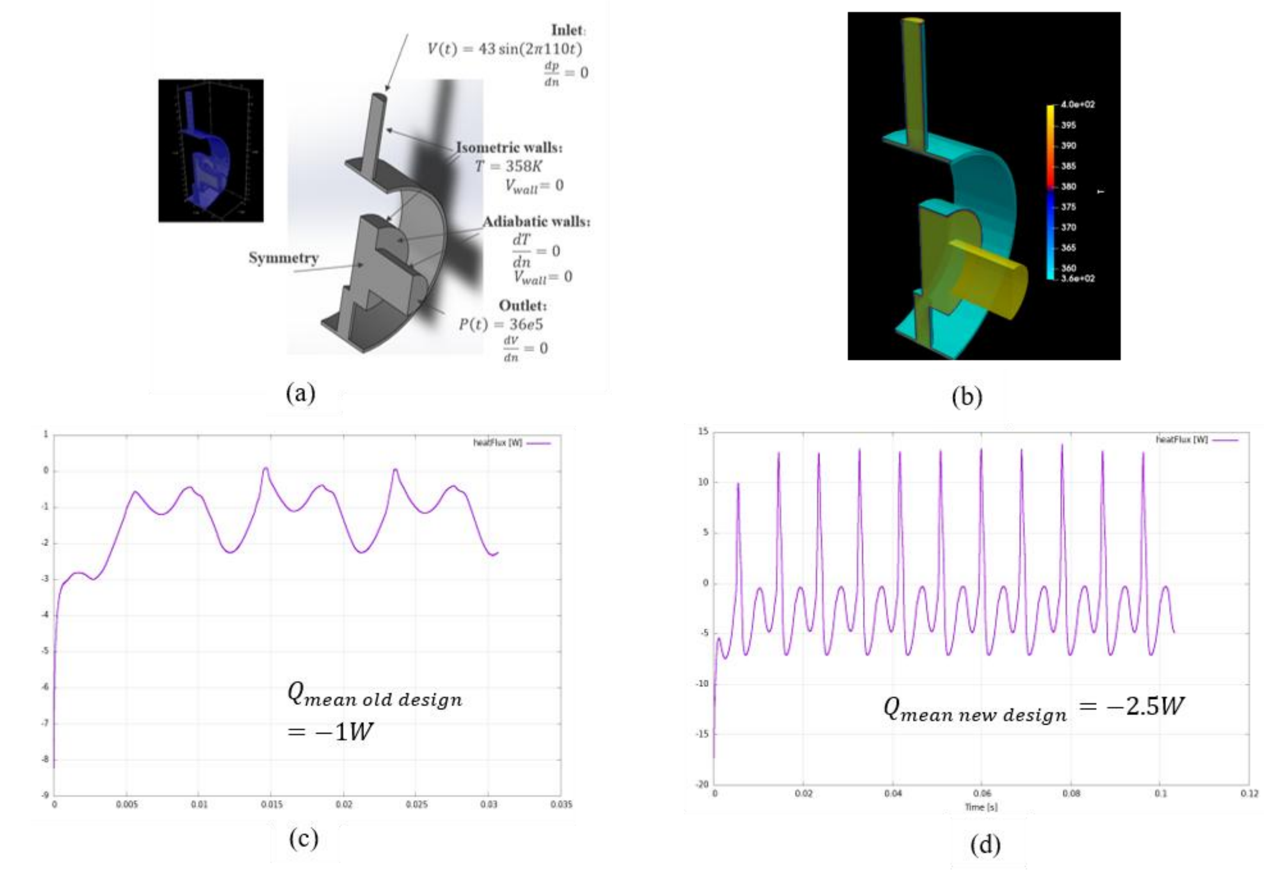


Figure 12: CFD analysis for transient heat transfer from the gas to the solid interface in the cold head ambient rejector.

Increasing wetted surface area and time in the heat exchanger volume by diverging the flow through a longer, wider pathway will increase the heat exchanged by a factor of 2.5 according to the results, as demonstrated in figure 12. This may cause better efficiency and better heat management by the encapsulating system; 12(a) features some of the simulation conditions over the new model; 12(b) shows simulation starting point temperature distribution; 12(c) old design heat transfer through the wetted area over time; 12(d) new design heat transfer through the wetted area over time.

Regenerator parameters were changed to increase heat transfer efficiency to the matrix while reducing friction losses in the flow. This required the adjustment of the pneumatic drive of the plunger to move the gas across the regenerator.

Changes in the regenerator allowed lower pressure pulse to be built and reduced stress to the sealing mechanisms, which were reinforced to achieve higher reliability.

The modifications adapted to the cold head design resulted in increased efficiency as expected. The COP of the K588 in the original 150K@180mW working point ranged from 0.11-0.14 depending on the ambient temperature. The new compressor design enabled the cooler to supersede **120**K@**750**mW at even higher ambient temperatures, but at the expense of the COP that dropped to 0.04-0.06. The new cold head design and frequency modification regained the efficiency lost and restored the COP to 0.07-0.10.

8.2 Controller

The K589/K91 coolers are designed to be driven by a new compact controller providing high efficiency, low weight, compact mechanical structure, and a uniform enclosure/electrical interface. The controller design is based on a single PCB structure, enclosed in a uniform case and providing an electrical interface based on uniform connectors in place of the traditional wire soldering method. Table 1 shows the main specification parameters of the controller; Figure 13 illustrates the external view and the outline of the controller.

Table 1: Main characteristics of the controller

Parameter	**Arbel – EP controller**
Controller type	Digital
Efficiency	>80% (Calculated, @ >200Mw)
Input voltage	10VDC – 14VDC
Control logic	PID (PID parameters per user definition)
Temperature stability	±0.1K
Temperature drift	±0.2K
Dimensions [mm]	45X33X16
Weight [gr]	35gr
Communication protocol	RS422
Protection	Reverse-polarity protection without extra heat dissipation
Set points	Control of four set points per user definition
Temperature control	Digital temperature control with flexible zoom point

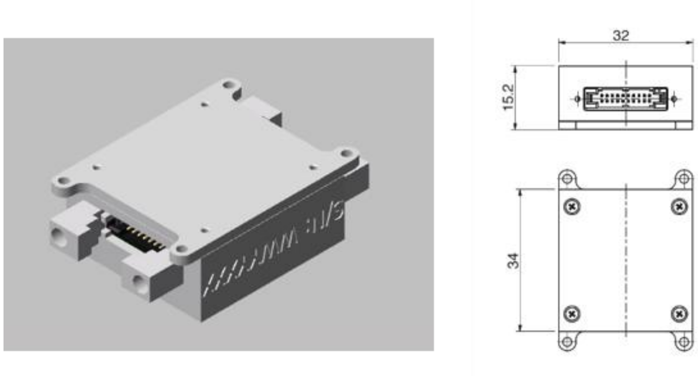


Figure 13: Controller dimensions [mm]

This controller is derived from the "ARBEL" K588/K590 model. During the design phase, we utilized the "ARBEL" controller to validate certain performance aspects of the cooler, which helped us reduce risks throughout the design process. Both the "ARBEL-EP" and "ARBEL" controllers share the same mechanical interface, allowing the use of the "ARBEL" controller with the K589/K591 models for lower operating points.

9. PROJECT LIFE CYCLE AND SYSTEM ENGINEERING

To meet the time constraints for delivering a customer-ready prototype, while simultaneously fostering innovation and technical enhancements in assembly ease and robustness, a risk management strategy was adopted. RICOR R&D team developed a low-risk pathway known as the Minimum Viable Product (MVP), which incorporates only the most essential modifications to the original K588 model to enhance its cooling capacity. Following this, four additional variations were designed, each featuring incremental design enhancements that presented new challenges and required more extensive risk mitigation efforts. These variations were tested to ensure they could be compared directly with the MVP.

More than ten units of the MVP configurations were assembled and delivered to customers. Meanwhile, the four alternative configurations were instrumental in evaluating improvements in several key performance metrics, including COP, cooling capacity, dynamic stability, life span and adaptability to diverse environmental conditions. Furthermore, potential risks were proactively addressed by subjecting the units to extreme testing scenarios that exceeded the established operating limits to quickly identify potential failures.

As the development process moved forward, preparations were made for cryocooler testing—either at RICOR's facilities or at customer locations—it became crucial to develop technical interface documents. Among the critical components of these documents are the heat dissipation requirements, which are essential for ensuring the cryocooler's effective operation at both the system level and during research and development evaluations. The K589/K591 unit, recognized for its compact design and significant cooling capacity, presents unique challenges due to its high-power density. This factor necessitates meticulous consideration in both system design and testing methodologies. The heat dissipation interface document provides comprehensive details regarding heat rejection surfaces and established skin temperature limits. Additionally, other vital interface documents that cover mechanical and electrical specifications were established.

Performance at various operating points remains a central focus, particularly as customers often desire early insights into the product's capabilities. This need for early predictions is pivotal when preparing for large-scale production. However, accurately assessing performance during the early development phase poses a challenge, as only a limited number of cryocoolers have been tested. Since the K589/K591 model is derived from the K590 and K588 models, which are already in extensive serial production, statistic data from the existing K588 and K590 models is utilized to estimate the performance of the K589, based on tests conducted on ten K589 units assembled and tested in the R&D lab.

The first MVP prototypes were successfully delivered from the R&D department to customers by the end of 2023, marking less than a year from the project kickoff in March 2023 and the Go/No-Go decision. We are currently engaged in the New Product Introduction (NPI) process, with engineering models being manufactured on the production line. The qualification phase is slated to begin in the second quarter of 2025, with preparations for the production line expected to conclude by the fourth quarter of 2025, positioning us for serial production.

The final K589 configuration is the baseline for the K591 model.

The same compressor and controller are used for both models with two different cold fingers.

Figure 14: Marketing map of the compressor and cold head configurations.

10. K589 PERFORMANCE

10.1 Prototype performance

The first R&D prototypes were assembled and tested. The accumulated tests results and data analysis are presented here in brief. All tests were performed with a 12V DC input voltage and at cooler working frequency of 100Hz. Figure 15 presents the cryocooler "load-line" while the cooler is at 78°C ambient, the cold-tip reaches 120K and under growing power load. It is important to mention that the maximum allowed skin temperature on the cooler is 88°C, for all working points.

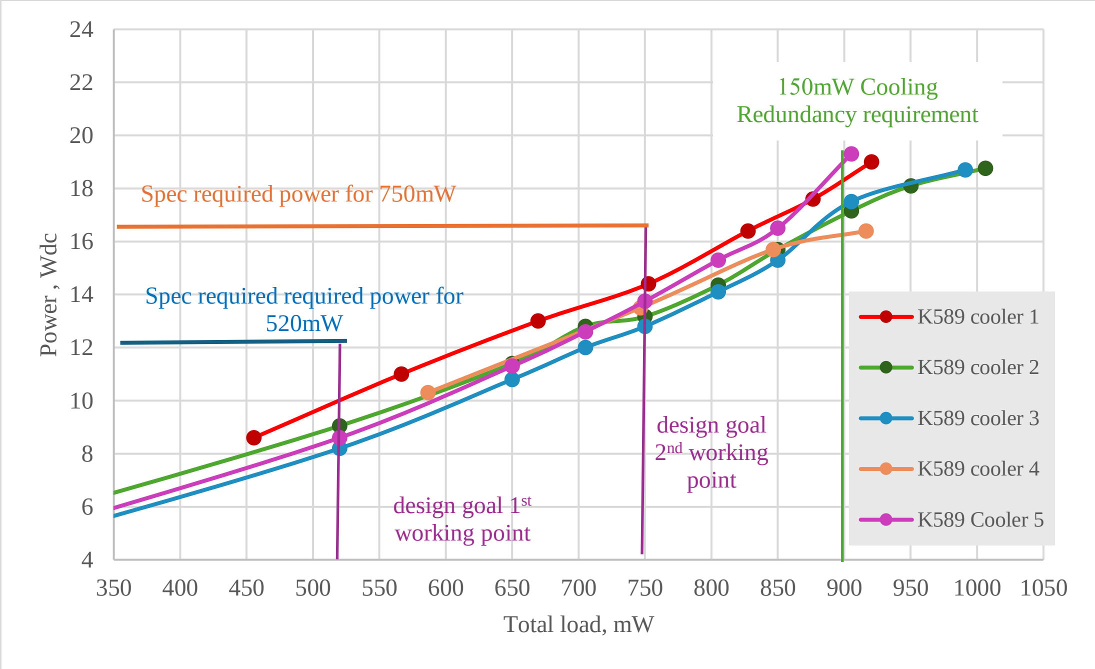


Figure 15: Prototype load line @120K@78°C ambient. The working points are marked to demonstrate the coolers' performance. The data are drawn from the controller input power measurements.

Induced forces created by the cooler are presented Figure 16. The chart shows the cold heat and compressor stand-alone forces in a 90 degrees setup configuration to eliminate constructive or destructive interferences.

From

, it can be seen that as expected, the cold head induced force is growing with the cooler load while the compressor induced force does not follow this trend as much. The compressor induced force behavior is also expected since this is a linear dual piston cryocooler.

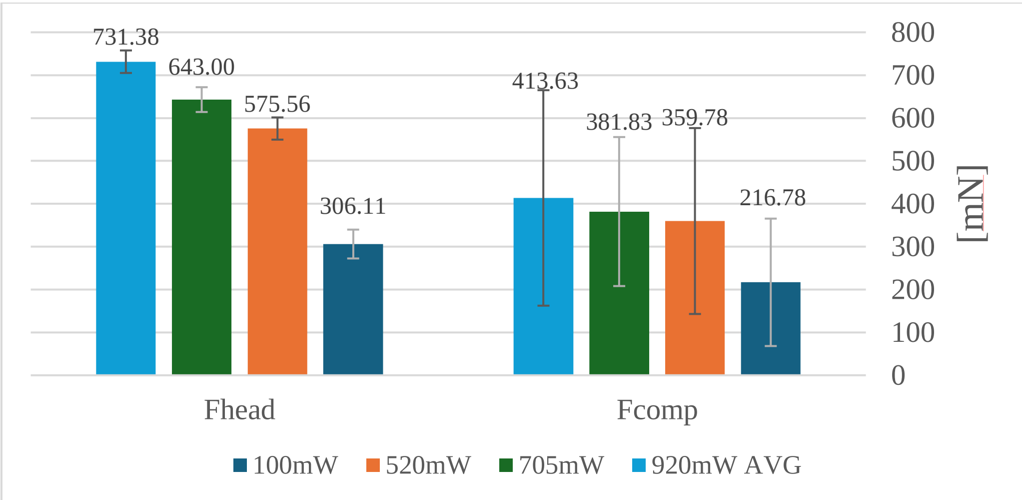


Figure 16: Averaged induced forces measured on 8 prototypes in four different working points. The chart shows the cold heat and compressor stand-alone forces in a 90 degrees setup configuration to eliminate constructive or destructive interferences.

From the typical induced force for a "side-by-side" configuration of the compressor and the cold head presented in 420mW.

, the working frequency harmonies are visible. Such data is important in order to determine if there are any natural modes of the system structure that may be excited. The cooler interface frame is very important to control the harmony excitation of forces in higher frequencies. Constructive or destructive interferences may occur in a side-by-side configuration, so the distribution inside the spec bounds is wider.

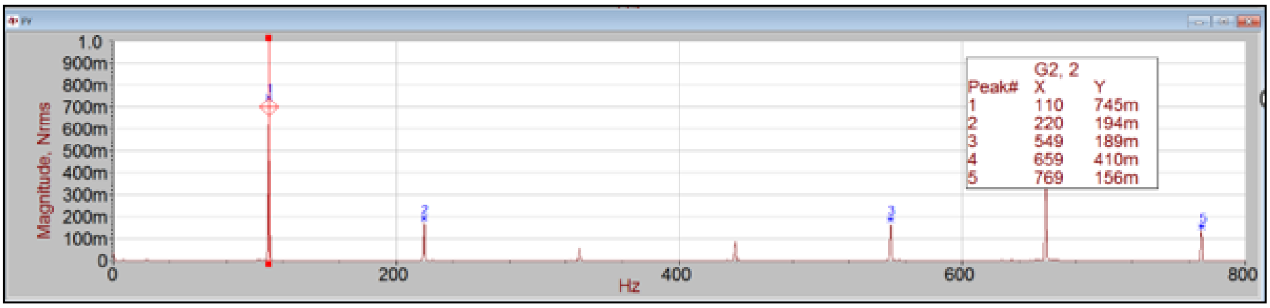


Figure 17: Typical Induced Forces - Side-By-Side Configuration @23°C@120K@420mW.

The cryocoolers tested met the acoustic noise requirements for less than 20 meters during close loop operation, as shown in Figure 18.

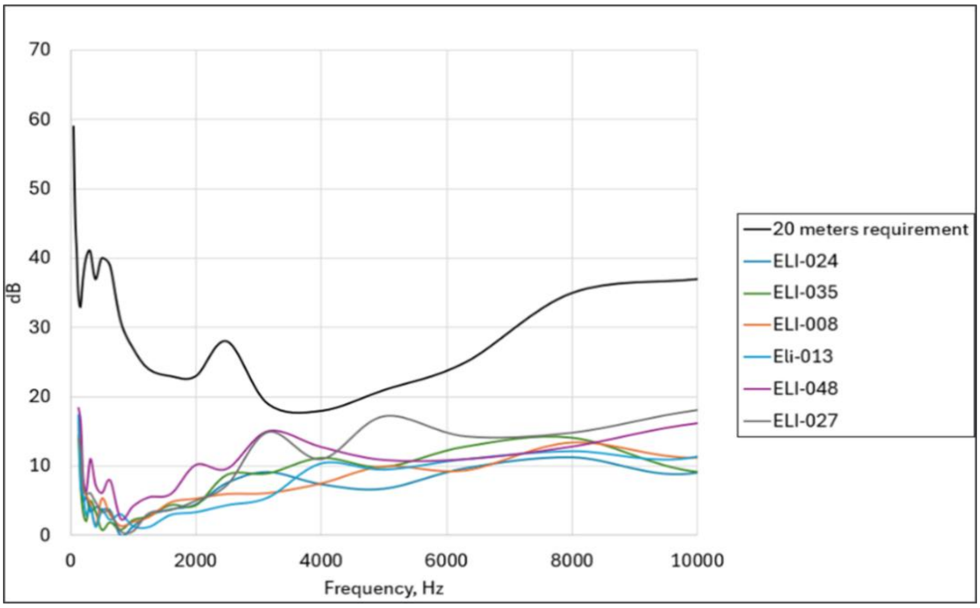


Figure 18: Acoustic noise test: Acoustic noise measured in an anechoic room, hanging on a flexible mount.

10.2 Cool-down time estimation

Cooler cool-down time is measured from the time in which the cooler is turned on until the time the CHT reaches the stabilized temperature with a tolerance of ±0.5K or ±0.1K (depending on the requirement).

Figure 19 demonstrates a validation process of the cooldown time estimation tool against CDD results of the K590 as a basis for elevating confidence level in the CDT assessment of the miniature linear family of cryocoolers, that share the fundamental design building blocks.

At the moment, the cool-down time estimation of the K589 and K591 with our CDT assessment tool is being validated with empirical tests from our customers' CDD assemblies, as our simulation dewars have a different thermal mass that directly affects the CDT.

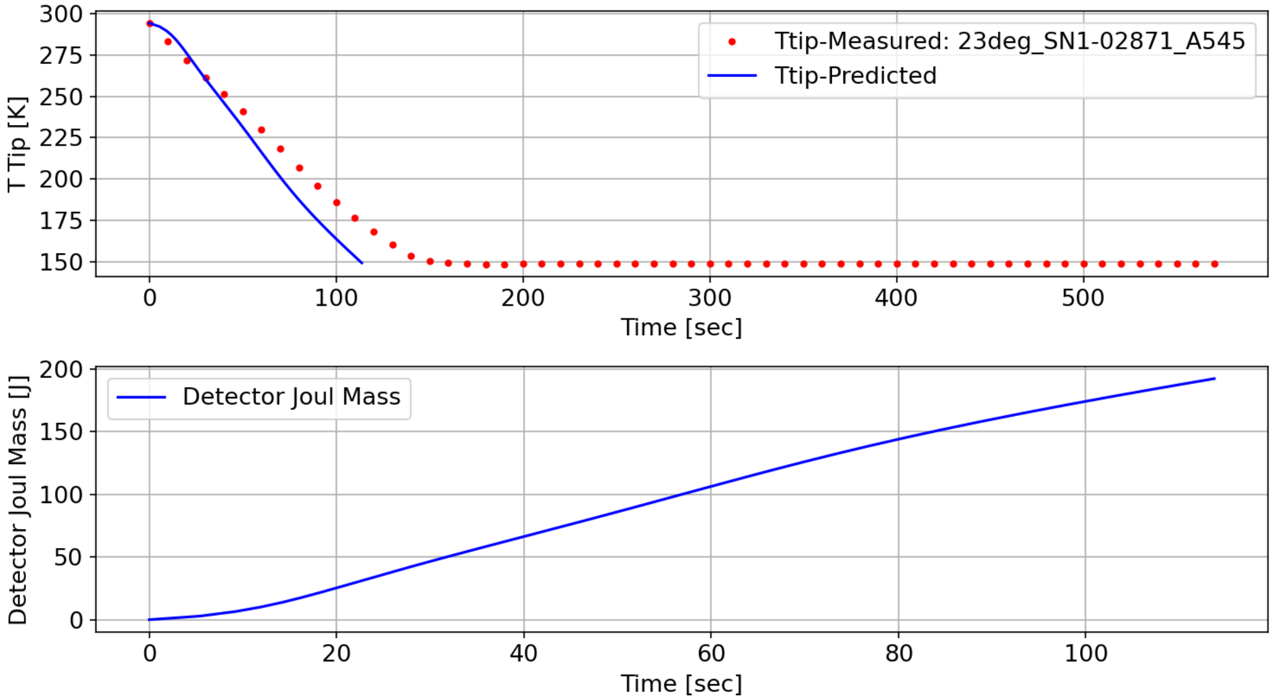


Figure 19: cool-down time tool validation process with the K590 cryocooler CDD data at 23ºC. Error value achieved is less than 30% of the experimental values.

11. SUMMARY

This article details RICOR's development of the K589/K591 linear cryocoolers, emphasizing their innovative Extended Linear (ELI) development process. This process prioritizes speed and efficiency through iterative simulation (using SAGE and FEMM software), design, testing, and refinement cycles, significantly reducing time-to-market (12 months from project kickoff). The K589/K591 models are built upon previous designs (K588/K590), improving cooling power while maintaining efficiency to meet the growing market demand for higher pixel counts, greater processing power, and higher resolution in infrared cameras used in surveillance and defense applications. A lean prototyping approach, utilizing existing models, and risk mitigation strategies (DFMEA) were crucial for meeting tight deadlines, enabling RICOR to quickly provide customers with prototypes to advance their own development while simultaneously progressing to NPI and serial production. Detailed performance comparisons, including induced force analysis and acoustic noise testing, are provided. The article concludes by highlighting the successful completion of the R&D phase and the transition towards serial production, positioning RICOR as a worldwide market leader in cryogenic coolers.

The K589/K591 models will complete qualification testing and conclude the new product introduction (NPI) process this year.

- Based on the success of the K588/K590 and K589/K591, RICOR has embarked on its next challenge: developing a cooler with extensive cooling capacity.

- Leveraging our expertise in design, simulation, system engineering, and market analysis, this new cooler will utilize a single compressor adaptable to three different operating points using existing Dewars.
- RICOR's parallel development of advanced testing and support equipment ensures a streamlined and efficient development process.
- The effort will be invested in utilizing a single compressor to achieve three working points, leveraging the versatility of three existing Dewars.

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