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The road to 1k – Iris Technology's continued development of high power CCEs

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Abstract. Iris Technology's upcoming high power CCE is a leap forward with an electrical power capacity reaching 1000 watts— a fivefold increase over existing Iris CCE solutions. At its core, the design will feature a flexible architecture in the input ripple filter (IRF) and augmented output capabilities, aligning with the dynamic requirements of today's burgeoning space economy and allowing the standardized application of this architecture across the Iris CCE lineup.

1. Introduction

Iris Technology is on the forefront of designing, developing and producing space-based Cryocooler Control Electronics for a variety of cryocoolers. As our customers' needs have grown and their mission requirements have become more complex, Iris Technology continues its development of a higher power CCE architecture that leverages our legacy designs. This paper will highlight the progress made in developing the 1kW CCE, ICE-G2-1000 and provide insight on the next steps in advancing this exciting, new technology.

2. ICE-G2-1000

2.1 Background

The observation of astronomical phenomena in deep space and for astrophysics-centric instruments will use space-based detectors that need to be cooled to temperatures at or below 4K. Such low temperatures require cryocoolers with more cooling power and CCEs capable of providing higher input power or multiple stages of input power to these cryocooling systems.

The intended development milestones for the ICE-G2-1000 are as follows:
Phase 1 – Confirm output drive stage scalability to 1000W output (Completed Summer 2024)
Phase 2 – Develop and demonstrate improved Input Ripple Filter (IRF) (Late 2025/Early 2026)
Phase 3 – Integrate input and output stage hardware
Phase 4 – Full prototype with control loop (temperature control and AVC) performance testing

2.2 Architecture

The ICE-G2-1000 leverages the overall ICE-G2 system architecture as proven out on the ICE-G1-30, ICE-G2-60, ICE-G2-100 and ICE-G2-200 designs. The use of Gallium Nitride (GaN)

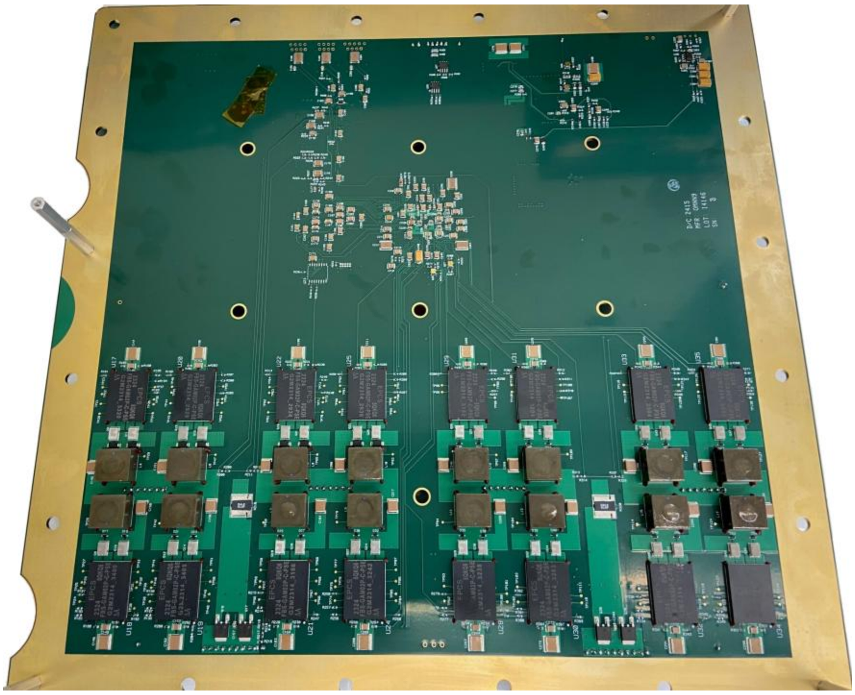

Figure 1. ICE-G2-1000 Brass Board

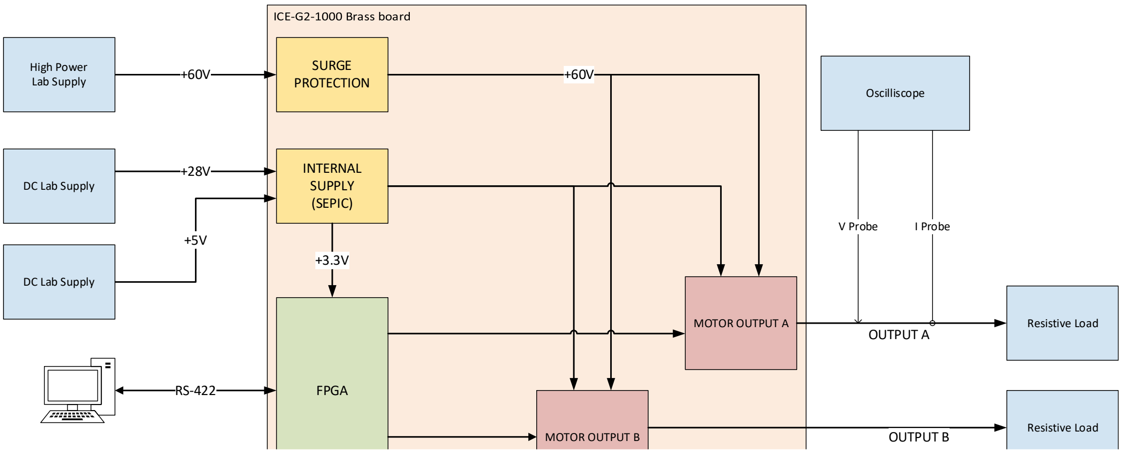

Figure 2. ICE-G2-1000 Brass Board test setup

components on the output drive stage has increased efficiency of the ICE-G product family when compared to Iris Technology previous design architectures that implemented MOSFETs on the output drive circuits[1].

2.3 ICE-G2-1000 Brass Board

As the ICE-G2 design was scaled up by a factor of five (5) from 200W to 1000W, two (2) potential issues were identified to be of most concern: (1) increased ringing due to using parallel GaN FET drive circuits to provide power and (2) thermal issues on the output stage due to increased power output. To mitigate these potential issues, the ICE-G2-1000 lab demonstration brass board decoupled the input stage boost converter and Input Ripple Filter (IRF) from the rest of the design

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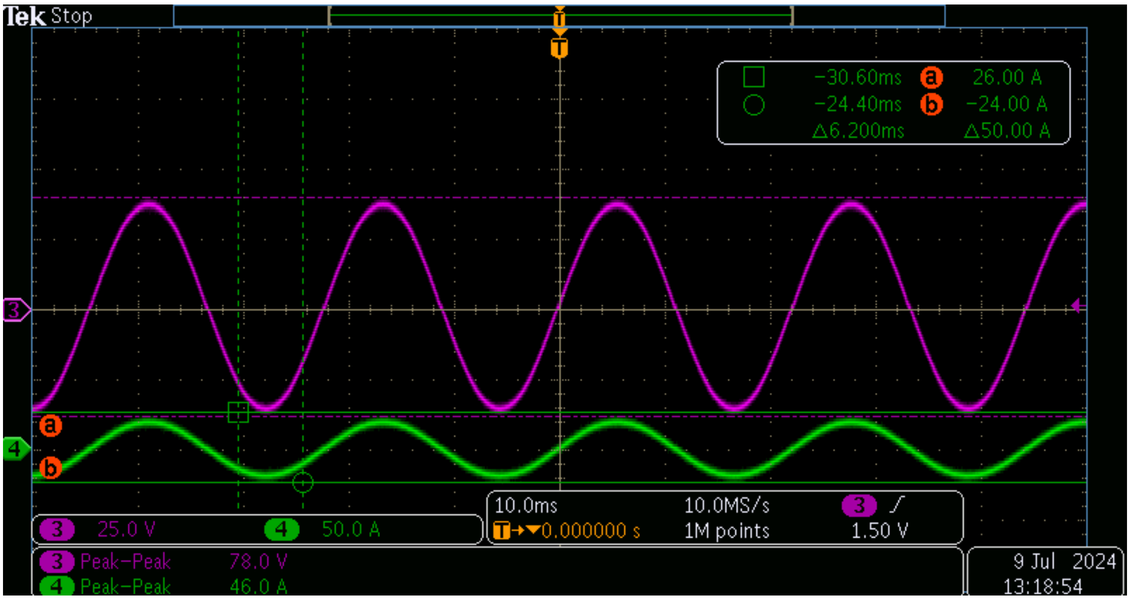

Figure 3. ICE-G2-1000 voltage and current waveforms for 897W output drive

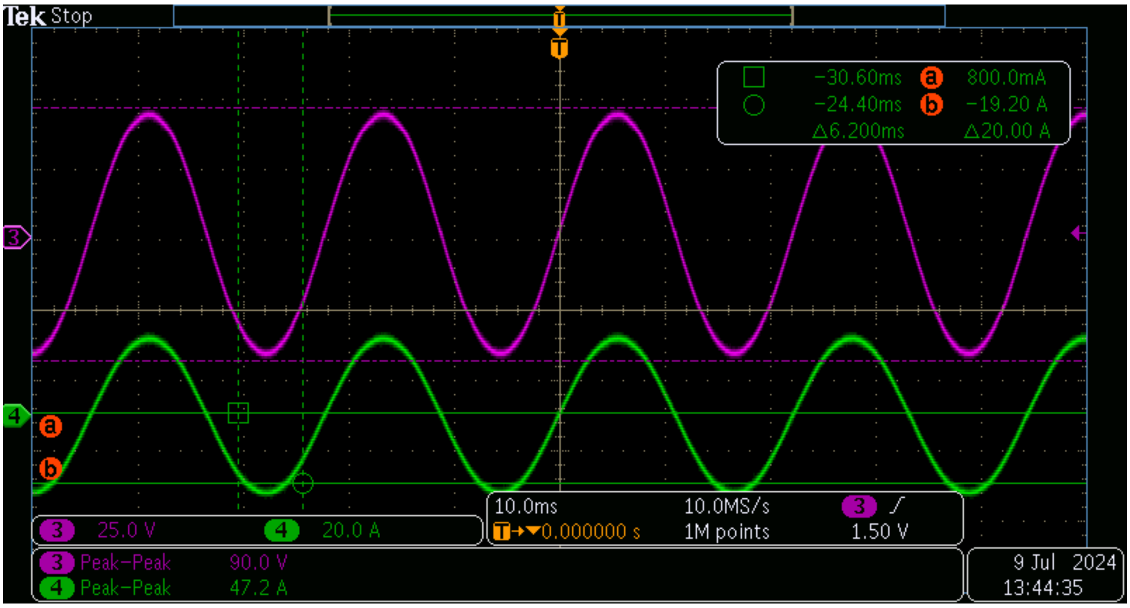

Figure 4. ICE-G2-1000 voltage and current waveforms for 1062W output drive

architecture. There are four (4) output drive stage circuits on ICE-G2-1000 brass board. Initial measurements of the output power for a single output drive circuit found it was capable of driving 330W. The ICE-G2-1000 brass board dimensions are 225 in^2 (1.45E+03 cm^2) in order to isolate the heat and electrical noise generated by the output drive stage (See Figure 1).

2.3.1 ICE-G2-1000 Brass Board Lab Demonstration

The ICE-G2-1000 Brass Board was fabricated and assembled in May 2024. Electrical bring-up and preliminary lab demonstration was performed over the summer of 2024 (See Figure 2) at Iris Technology lab facilities in Irvine, California. A Pacific Power Source 3150AFX 180kW supply was used to provide the +60Vdc output drive power rail typically provided by the Boost/IRF circuit. Two (2) TDK Lambda 60-14 DC power supplies provided +28Vdc (typical input power) and +5Vdc

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(used to generate +3.3Vdc to FPGA by the ICE-G2 internal voltage regulator). A lab computer with USB-to-RS422 interface and Iris ICE Control Console GUI were used for command, control and telemetry between the test operator and the ICE-G2-1000 FPGA. Various high power resistive loads were connected to approximate a 1.6-2Ω load on the motor drive outputs. A Tektronix oscilliscope with differential voltage probes and current probes were used for voltage and current measurements.

Upon completion of electrical bring up, the brass board was configured to use two (2) of the four drive circuits in parallel for each drive output channel. For these demonstrations the Iris ICE Control Console GUI was used to command the brassboard to output four (4) drive power levels between 800W and 1000W. See Figure 3 and Figure 4 for the voltage and current waveforms captured for output drive levels of 897W and 1062W, respectively.

The following calculations were performed to determine output power from the scope traces:

897W Output:

$$V_{out} = 78V_{p-p} = 27.577V_{rms};\ I_{out} = 46A_{p-p} = 16.263A_{rms}$$

$$P_{1-channel} = I_{out} \times V_{out} = 27.577V_{rms} \times 16.263A_{rms} = 448.5W$$

$$P_{total} = 2 \times P_{1-channel} = 897W$$

1062W Output:

$$V_{out} = 90V_{p-p} = 31.82V_{rms};\ I_{out} = 47.2A_{p-p} = 16.68A_{rms}$$

$$P_{1-channel} = I_{out} \times V_{out} = 31.82V_{rms} \times 16.68A_{rms} = 531W$$

$$P_{total} = 2 \times P_{1-channel} = 1062W$$

These drive waveforms were captured in quick succession with the heat dissipated by the resistive loads causing an increase of resistance from 1.69 Ω to 1.9Ω. The goal of confirming the scalability of the ICE-G2 output drive stage to output ≥ 1000W was deemed a success and the next phases of development for the ICE-G2-1000 were assessed.

3. ICE-G2-100 and 200 Legacy and Application to ICE-G2-1000

Having achieved the initial goal of providing > 1000W output power on the output stage brass board, assessment of which functional elements of the ICE-G2 architecture was performed to determine scaling considerations and/or improvement for integration with the output stage. Additional testing was performed with the ICE-G2-100 and past test data for the ICE-G2-200 was reviewed to provide the necessary technical context with which to measure the development of the ICE-G2-1000 design.

3.1 ICE-G2-100 and 200 Input Stage

Tests were performed to measure the power factor of the boost voltage circuit with output drive voltage disabled (Standby Mode). While the ICE-G2 is in Standby Mode, the boost converter circuit

Table 1. ICE-G2-100 and ICE-G2-200 Boost Converter Power Factor Data

Model	V_{boost} (Vdc)	V_{in} (Vdc)	P_{in} (W)	Power Factor (PF)
ICE-G2-100	42	24	3.025	0.9038
		28	3.05	0.9343
		32	3.215	0.9303
ICE-G2-200	56	24	3.104	0.9083
		28	3.308	0.9108
		32	3.663	0.9194

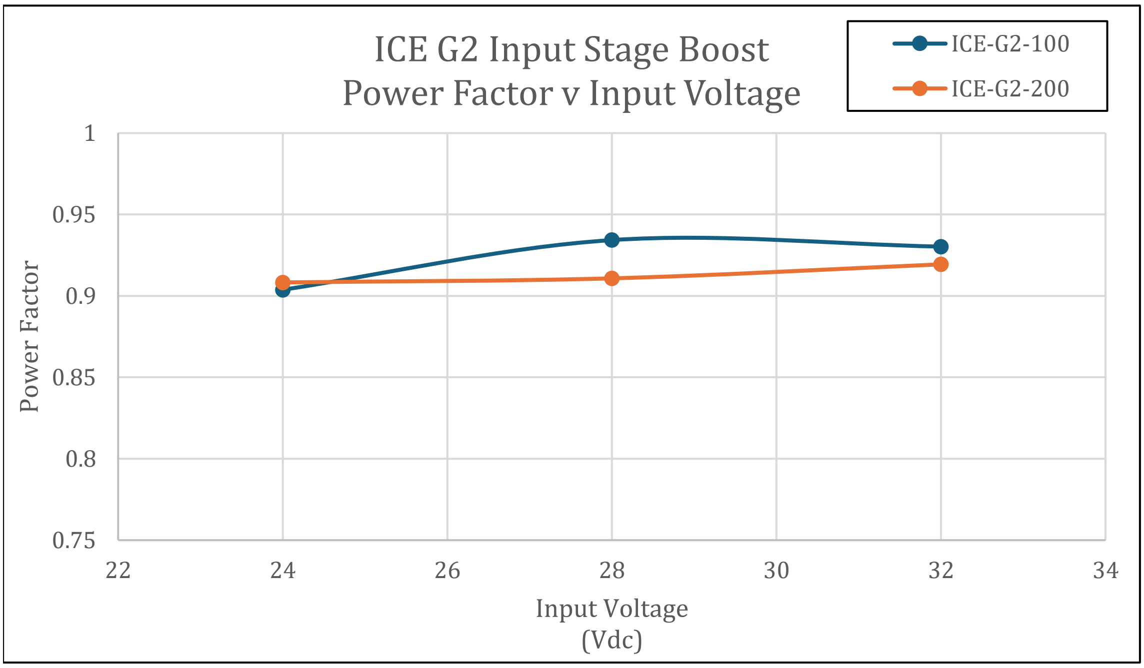

Figure 5. ICE-G2-100 and ICE-G2-200 Boost Converter Power Factor Plot

converts the supplied input voltage (typically +24 to +32Vdc) to +42Vdc (ICE-G2-100) or +56Vdc (ICE-G2-200). Since the outputs of the ICE-G2 were disabled for this test, power factor was used to determine how the boost converter circuit behaved with different input voltages. Power factor (PF) is the ratio of Real Power and Apparent Power. PF and power efficiency are not equivalent. However, PF is a good preliminary indicator of how efficiently the system will use power. In other words, optimizing PF (> 0.9) will lead to a more efficient system but a lower PF (< 0.9) may make optimization of the overall system power efficiency difficult. The ICE-G2-100 showed power factors between 0.9038 and 0.9343, over the input voltage range of +24 to +32Vdc. While the ICE-G2-200 had power factors between 0.9083 and 0.9194 for the same input voltage range. See Table 1 and Figure 5. At lower input voltages, the boost converter will increase the switching duty cycle to generate the boost converter output (V_{boost}) to the intended level. As the input voltage increases, the boost converter duty cycle decreases, dissipates less power, and the power factor of the converter increases. Assuming a target V_{boost} of +60Vdc, the ICE-G2-1000 boost converter design

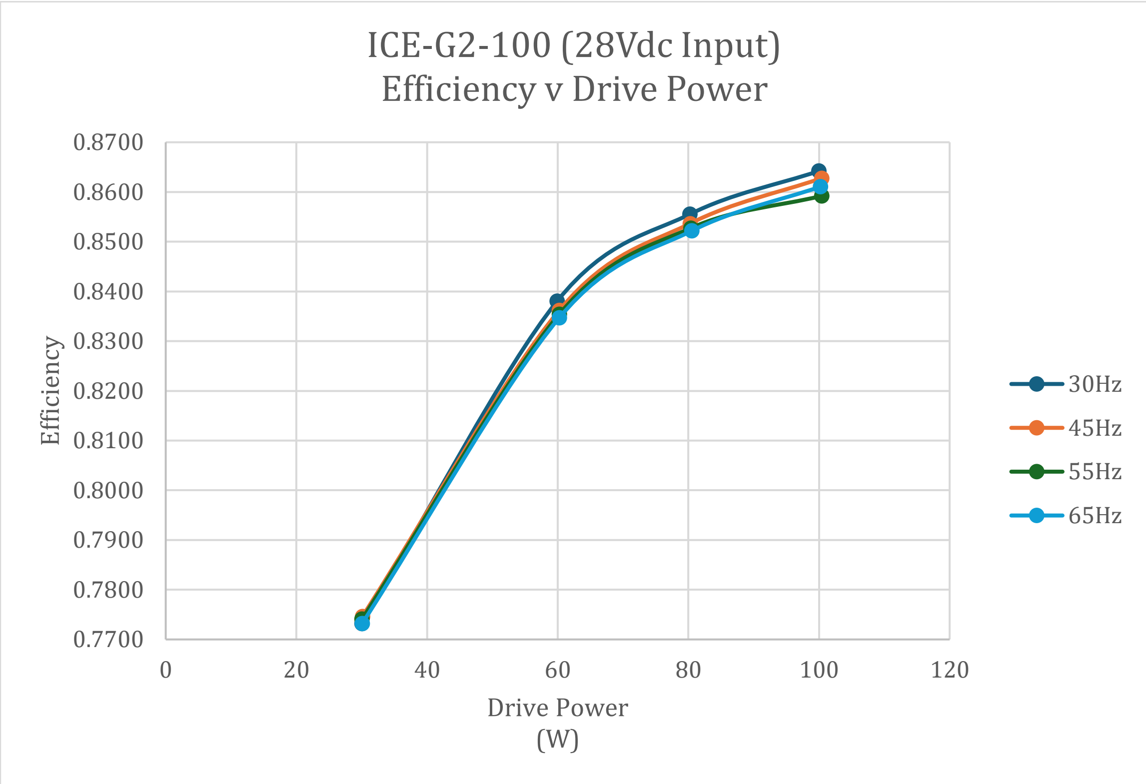

Figure 6. ICE-G2-100 Efficiency v Output Drive Power at 28Vdc Input

will be optimized for a PF = 0.90 to 0.95 to align with the boost converter designs on ICE-G2-100 and ICE-G2-200.

3.2 ICE-G2-100 and ICE-G2-200 Efficiency

In addition to testing the current designs for boost converter power factor, tests were performed on the ICE-G2-100 to measure efficiency. For these tests, the input voltage to the ICE-G2-100 was set to +24Vdc, +28Vdc and +32Vdc. For each of these input power settings, the output drive frequency was set to 30, 45, 55 and 65Hz. And at each frequency, the output power was set to 30, 60, 80 and 100W. For each case, the input power and output power were measured. Efficiency was calculated from these measurements.

The resulting data shows that the efficiency of the ICE-G2-100 increases as output drive power increases (See Figure 6). This may be due to a decrease in voltage drop across the high side switching element in the output stage circuit as the output drive voltage increases. However, as this voltage drop decreases, conduction losses, thermal losses and losses associated wth the output LC filter elements become more predominant. We can also see that efficiency improves slightly at lower output drive frequencies for the ICE-G2-100.

ICE-G2-200 efficiency data taken during the development of that design architecture confirms that as output drive power increases, efficiency increases until other losses are the predominant factors on efficiency of the ICE-G2 architecture (See Figure 7).

Additionally, we see the same behavior as noted during the power factor measurements that efficiency increases as input voltage to the ICE-G2-100 increases (See Table 2).

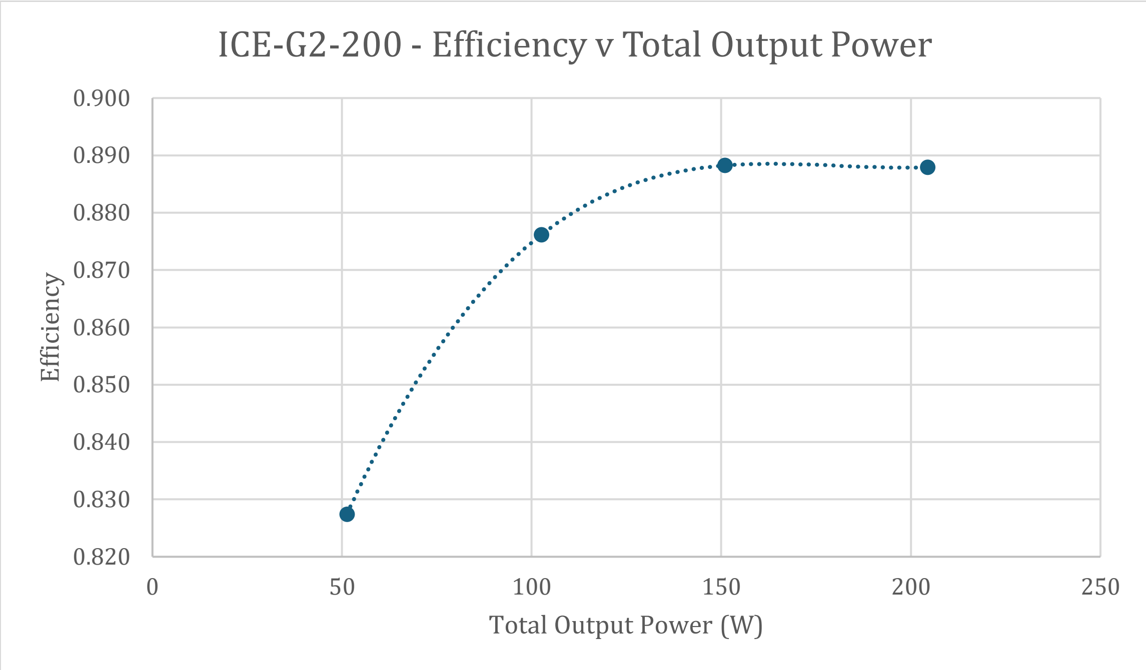

Figure 7. ICE-G2-200 Efficiency v Output Drive Power at 28Vdc Input

Table 2. ICE-G2-100 Efficiency v Input Voltage at Output Drive of 100W over Various Frequencies

ICE-G2-100, 100W Output Efficiency v Input Power				
Vin (Vdc)	**Efficiency**			
	30Hz	**45Hz**	**55Hz**	**65Hz**
24	0.857	0.854	0.853	0.853
28	0.864	0.863	0.859	0.861
32	0.872	0.869	0.868	0.868

How the ICE-G2 architecture's efficiency is affected by input voltage, output drive and frequency will be taken into consideration as potential performance measures when scaling and improving the input stage circuits for the scaled up output power of the ICE-G2-1000. This includes boost converter Power Factor > 0.9 and Overall Power Efficiency of > 0.85 (or 85%) when integrated with the output stage.

3.3 Boost/IRF Considerations

With the successful demonstration of the ICE-G2-1000 output stage, focus turns to scaling the Boost/IRF input stage. It was determined that the current ICE-G2-100 (V_{boost}= +42Vdc) and ICE-G2-200 (V_{boost}= +56Vdc) boost converter power factor decreases as boost voltage increases. The targeted boost voltage for the ICE-G2-1000 is approximately +60Vdc. The following improvements to the boost converter will be considered: (1) minimizing losses due to higher boost voltage, (2) increasing input current storage by scaling the input inductor, and (3) increasing the output energy storage. Appropriate thought will be placed on the potential design trade-offs (weight and size) when scaling this circuit.

The increase of boost voltage and output power also presents potential problems due to increased input ripple current as the boost storage continually charges and discharges. As the input ripple current increases, efficiency will decrease and EMI/EMC becomes more of a concern. The Input Ripple Filter (IRF) is currently undergoing proof-of-concept development to mitigate these concerns when scaling the output power of the ICE-G2 architecture.

4. Conclusion

We have presented the successful lab demonstration of the ICE-G2-1000 output stage brass board. Lab demonstration data shows that the output stage is capable of providing > 1kW output power. The IRF circuit is in development with the hope of lab demonstrations by end of 2025 or early 2026. After this, the next anticipated milestones in the on-going develop of the ICE-G2-1000 design include the integration of the input and output stages and full prototyping with control loop performance.

Iris Technology looks forward to carrying on the effort to develop the next generation of high powered CCEs. We hope our contributions will help in the realization of the advances in cryocooler systems to meet the challenges and opportunities in space-based sensing and scientific discovery.

Acknowledgments
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References

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