

High power large bore CO₂ laser small signal gain coefficient and saturation intensity measurements

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Received 15 April 2002, in final form 9 December 2002

Published 9 January 2003

Online at stacks.iop.org/JOptA/5/96

Abstract

Two methods of measuring the gain medium parameters of a laser are presented (Hodgson N and Weber H 1997 *Optical Resonators—Fundamentals, Advanced Concepts and Applications* (Berlin: Springer) pp 583–91). The first method used measured only the output power of the CO₂ laser (10.6 μm is the wavelength used) using three separate output couplers, each having different couplings. Once the three different output powers were measured, the results were used in the Rigrod equation to solve for two separate Rigrod equations knowing all the variables except for two unknowns; the small signal gain coefficient and the saturation intensity. The second method was a single-pass measurement where a very low power CO₂ laser was injected into the high power CO₂ laser in question. Power readings were made before and after the injection to determine the gain. Both methods agree with each other well, within 5%, for the small signal gain calculation, which provides confidence that the calculation for saturation intensity in the first method is correct as well.

Keywords: Laser, resonator, gain, small signal gain, saturation intensity measurement, CO₂

(Some figures in this article are in colour only in the electronic version)

1. Introduction

An unstable resonator design for a large bore high power CO₂ laser system has been requisitioned. The current resonator is a stable configuration, which produces a multi-mode (thousands of modes generated) quasi-flat ('top hat') output beam. The back mirror of this stable resonator is flat, while the front coupler is nearly flat or has a radius of curvature (ROC) of 35 m. The unstable optical resonator design entails first characterizing the current system. The characterization involves determining the system's small signal gain coefficient and the saturation intensity, which are two critical parameters in determining the performance of a laser (power extraction, coupling, etc). An experimental route was chosen to determine these parameters for two reasons: (i) an experimental approach was a more trusted approach as opposed to calculating the values; (ii) the laser hardening materials evaluation laboratory (LHMEL), located at WPAFB, has ambitions to convert the CO₂ axial flow laser system into a CO axial flow system for various reasons. It is extremely difficult to obtain these laser gain parameters in a CO gain medium. Therefore, it is beneficial to have the ability to obtain these parameters experimentally for the possible design of a CO laser resonator.

For these reasons, these two studies were performed to measure the small signal gain coefficient, γ_o , and the saturation intensity, I_s . In the first study, γ_o and I_s of the CO₂ gas laser system at the LHMEL facility were measured simply by running the laser at a given output power and keeping all variables constant except one, the coupling. This study utilizes equation (1), which is known as the Rigrod equation [1]. In the second study, only the small signal gain coefficient is measured, but is compared to the small signal gain coefficients measured in the first study.

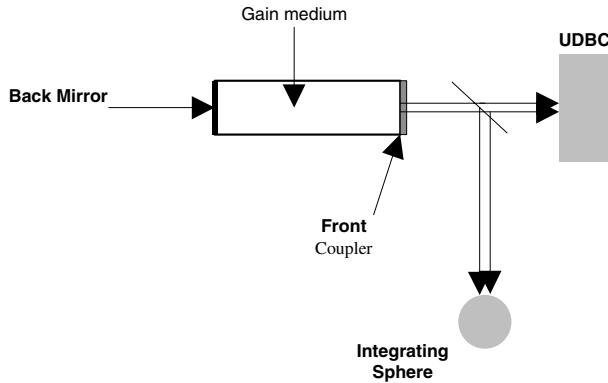


Figure 1. Setup for the small signal gain coefficient and saturation intensity measurements. The laser system is a CO₂ large bore axial flow system. It consists of a 3.5 m long, 20 cm diameter cavity. The anodes are at the ends of the cavity, which is where the gas mix enters. The gas mix exits at the cathode, which is at the centre of the resonator/cavity. The gas medium is a CO₂:He:N₂ common mix. The UDBC is a ballistic calorimeter designed by the University of Dayton. The ~25 cm diameter integrating sphere is used to integrate the energy over the duration of the exposure (~a few seconds).

2. Method 1: output coupling variation—measurement of γ_o and I_s

In the first study, three different output couplers were used to vary the output coupler's reflectivity, r_2 or t_2 ($t_2 = 1 - r_2$), where t_2 is known as the coupling. Using three different output couplers produced three different measured output power values, P_1 , P_2 and P_3 . Thus, three different output intensities, I_{out1} , I_{out2} and I_{out3} were calculated from these output powers using $I = P/\text{area}$. By using two of the three output intensities, the corresponding reflectivities (r_2) and output couplings (t_2), the Rigrod equation, (1), was used to solve for γ_o and I_s :

$$\frac{I_{out}}{I_s} = \frac{t_b t_2 [\gamma_o l_g - \frac{1}{2} \ln(\frac{1}{t_a^2 t_b^2 r_1 r_2})]}{\left(1 - \sqrt{t_a^2 t_b^2 r_1 r_2}\right)\left(1 + \sqrt{\frac{r_2 t_b^2}{r_1 t_a^2}}\right)}. \quad (1)$$

The setup for the first study is shown in figure 1. In equation (1) above, the output power is dependent on various parameters, such as the output coupling, t_2 , and the length, l_g , of the gain medium. The length of the gain medium is 210 cm, while the length of the cavity, L , is 355 cm. Also, t_b and t_a are internal transmittances of the gain medium; for the CO₂ medium they are equal to one. The reflectivities for the back and front mirrors are denoted r_1 and r_2 , respectively, and I_{out} is the output intensity.

In figure 1, the back mirror has a ROC of 35 m and a reflectance $r_1 = 99.5\%$. The three front couplers (x , y and z) are flat ZnSe windows. These windows, or couplers, each have their specific surface reflectance given by $r_x = 75\%/\text{AR}$, $r_y = 17\%/\text{AR}$, $r_z = 60\%/\text{AR}$. That is, one side of each is reflective with the other side anti-reflection (AR) coated. The 17% reflectance is the Fresnel reflectance of a ZnSe surface at 10.6 μm. The Fresnel equation for normal incidence for this coupler is given by [2]

$$r_y = \left(\frac{1-n}{1+n}\right)^2. \quad (2)$$

The index of refraction, n , of ZnSe is 2.40 at 10.6 μm [3], which gives $r_y = 0.17$ or 17%.

The beam splitter in figure 1 is a ZnSe 2%/AR optic. It splits the 10.6 μm beam between the University of Dayton's ballistic calorimeter (UDBC) and the integrating sphere. The integrating sphere is a hollow sphere which has the interior coated with a substance (infragold, NIR–FIR) that is nearly a perfect diffuse reflector. Light that enters the sphere is reflected from the wall and distributed uniformly around the interior. A thermopile detector is placed at a hole in the sphere wall, which samples the reflected light. A baffle is located inside to prevent the detector from having a direct view of the input beam [4]. The thermopile is a thermoelectric, voltage-generating device and, therefore, requires no bias voltage or current for operation. The UDBC is used to calibrate the integrating sphere. The UDBC consists of a number of thermocouples that convert the heat of the laser beam into a voltage that is plotted on graph paper using an x – y plotter. Each grid square on the graph paper is equal to 1 cm. A curve is produced on the x – y plotter from the UDBC and the number of grid squares is counted under the curve. A calibration of the UDBC given by the National Institute of Standards and Technology (NIST) gives a value of 709.36 J cm⁻¹/grid² [5]. Every year the NIST calibrates the UDBC. The amount of energy in joules is calculated from

$$E = (709.36 \text{ J cm}^{-1}) \times (\text{number of centimetre grid squares}). \quad (3)$$

Equation (3) is within $\pm 0.1 \text{ J cm}^{-2}$, which is typically a much lesser error than the human error of measuring the number of grid squares on the x – y plotter. It is safe to say that one can easily be within 0.1 cm (or a tenth of one grid square) accurately. For all the measurements, in both methods, the computer records the resulting calibrated thermopile voltage, laser operation time, discharge voltage and current levels (40 kV and 1.75 A) and cavity pressure (49–52 T). The CO₂, N₂ and the He fraction for the gain medium are a 1:5:30 mixture. The laser has two sections, A and B, where the discharge current in each section is recorded ($I_A + I_B$).

After the laser was aligned with the 75% coupler, a calibration run of the laser was taken. The x – y plotter produced 12.6 cm grid² under the UDBC curve, which, when multiplied by 709.36 J (cm⁻¹/grid²) gives a calibration factor of 8938 J of energy produced by the laser. The plot of the signal from the integrating sphere is shown in figure 2. As shown in figure 2, lasing occurred between 4.8 and 11 s for an interval of 6.2 s and an average integrating sphere voltage of 1.1 V. The laser energy of 8938 J divided by the time interval gives an average power for the 75% coupler of 1442 W. The calibration factor for the 75% coupler, C_{75} , can be found by

$$C = \frac{\text{Laser power (W)}}{\text{Integrating sphere signal (V)}}, \quad (4)$$

$$C_{75} = \frac{1442}{1.081} \text{ W V}^{-1}, \quad C_{75} = 1333 \text{ W V}^{-1}.$$

By the same process the calibration factors were found for the 17%/AR and 60%/AR couplers. The results are given in table 1.

The 17 and 60% calibration factors differ from the 75% calibration factor because the 75% coupler data are taken later after the system has been completely realigned. These

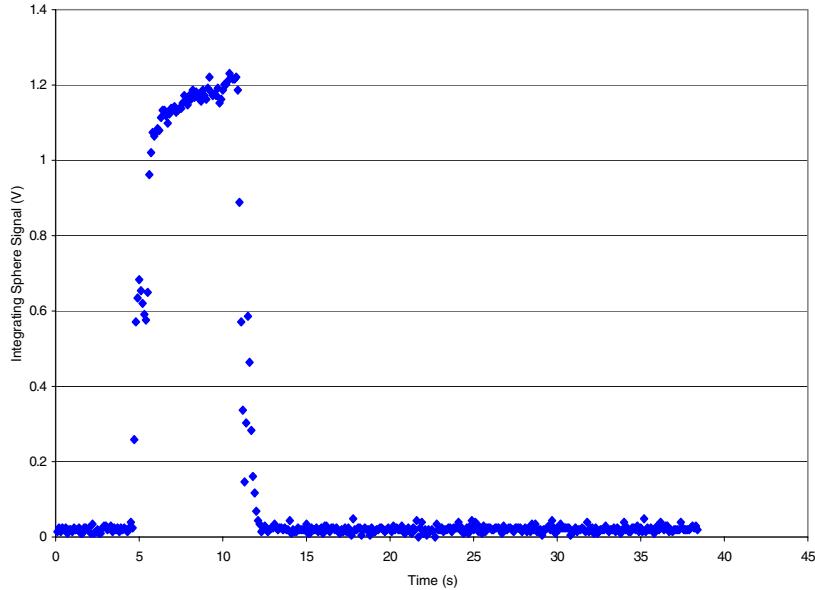


Figure 2. Integrating sphere signal with the 75% coupler for 8938 J laser output.

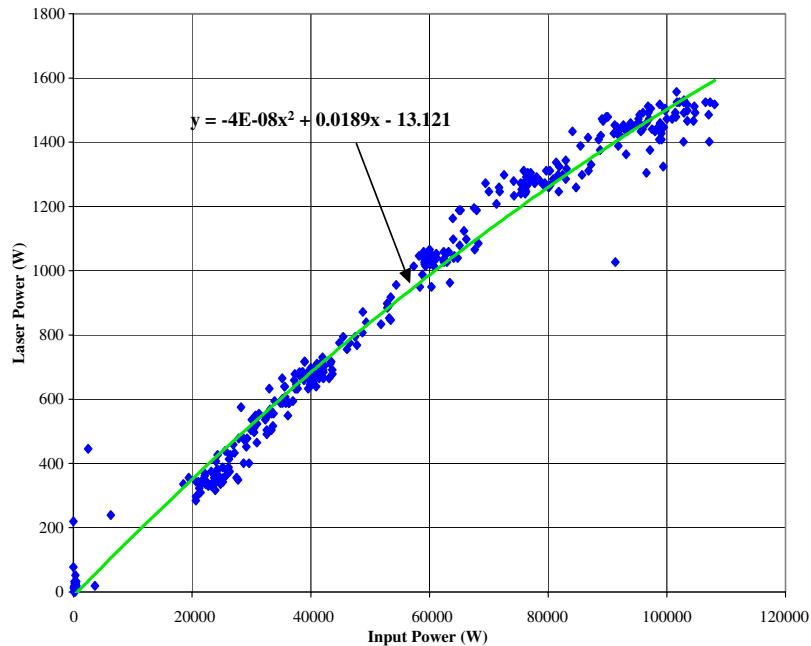


Figure 3. Laser power characteristics using the 75% coupler.

calibration constants are then used to calculate the output power knowing the output voltage given by a detector that is in the beam train. The detector is a low power detector (or an integrating sphere), which samples only a very small percentage of the beam that has been split off with a BS. The UDBC takes the remaining $\sim 99\%$ (or more) of the beam and, as mentioned, converts that beam into heat and thus into a voltage that is plotted on the $x-y$ plotter. Finally, by using these calibration factors, the P_{out} can be determined for each coupler and plotted versus input power. The input power, P_{in} , is manually, yet accurately, stepped up at a constant rate. This provides a nearly linear plot (actually a polynomial)—see figure 3.

A plot of output power versus loaded input power can then be made as shown in figure 3 for the 75% coupler, where

$$\text{Input power} = (\text{Power supply voltage})(I_A + I_B). \quad (5)$$

In figure 3, we started the high power CO₂ laser at 10 kW, or 2.5 A, and slowly stepped down to 0.0 A to achieve the distribution shown. The plot follows a second-order polynomial. The equation, which fits the data in figure 3, is given by

$$P_{out} = k_o + k_1 P_{in} + k_2 P_{in}^2. \quad (6)$$

In this equation, P_{in} is equal to the loaded input power and P_{out} is equal to the output power.

By a similar process, the data for the 17%/AR and 60%/AR couplers were collected and analysed. Table 2 displays the

Table 1. Calibration factors for the three output couplers.

C_{17}	1153 W V ⁻¹
C_{60}	1159 W V ⁻¹
C_{75}	1333 W V ⁻¹

Table 2. Polynomial coefficients for each coupler.

P_{out} (%)	k_2	k_1	k_0
17	$-9 e^{-8}$	0.0269	-976.34
60	$-1 e^{-7}$	0.0329	-757.38
75	$-4 e^{-8}$	0.0189	-13.21

Table 3. Output powers and intensities for each coupler at 70 kW input.

Coupler (%)	P_{out} (W)	I_{out} (W cm ⁻²)
17	465.7	65.9
60	1,056	149.3
75	1,114	157.6

Table 4. Values for γ_o and I_s , obtained from coupler data.

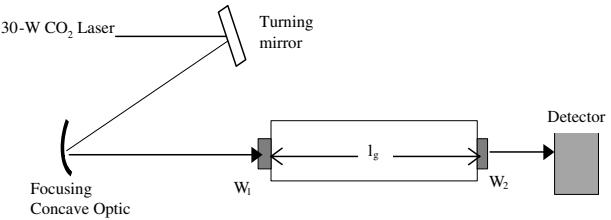
Coupler pair (%)	γ_o (cm ⁻¹)	I_s (W cm ⁻²)
75 and 17	0.0067	131
60 and 17	0.0066	137

coefficients of equation (6) for each coupler. The polynomial fits were used to calculate the output power, from which, by using the area of the beam, the output intensity could be determined. All three couplers had the same diameters of 3.0 cm (1.18 in). Thus, the area of the beam out is 7.07 cm².

In order to compute γ_o and I_s , the value of the input power into the system was 70 kW (40 kV × 1.75 A) for each coupler. This value was chosen because it corresponds to 1.75 A. In the second study, described in the next section, 1.75 A was also the operating current along with 49–52 Torr and the same gas mixture. Substituting 70 kW into the three polynomial equations for the three couplers gives the values in table 3 and the corresponding intensities. The intensities in table 3 were used with equation (1) to solve for γ_o and I_s , which was carried out by using the pair of values I_{out75} and I_{out17} in equation (1), thereby providing two equations and two unknowns. The same was done with I_{out60} and I_{out17} . However, it was *not* done for I_{out75} and I_{out60} because the values for this pair were too close to give meaningful results. Now, from the Rigrod equation, (1), the mathematical computer program, MathCad, was used to solve for the two unknowns, γ_o and I_s . The results are given in table 4 for each coupler.

3. Method 2: single-pass measurements of γ_o

In this study, the small signal gain coefficient, γ_o , was directly determined by introducing a low power input from an Advanced Kinetics (AK) laser beam (30 W maximum output power) into the laser *high* gain medium being measured. The input beam was running at approximately 0.5 W or slightly less. From this, the amplified output was measured after only one pass through the medium. This amplified signal is known

**Figure 4.** Setup for the single-pass G_o measurement. W_1 and W_2 are the windows in contact with the laser medium.

as the single-pass, small signal power gain, G_o , given by [1]

$$G_o = \frac{\text{Power out}}{\text{Power in}} = \frac{P_{out}}{P_{in}}, \quad (7)$$

and is related to γ_o by

$$G_o = \exp(\gamma_o I_g). \quad (8)$$

Using the measured value of G_o , from equation (7), γ_o can be solved

$$\gamma_o = \frac{1}{I_g} (\ln G_o), \quad (9)$$

where $I_g = 210$ cm. The setup to measure G_o is shown in figure 4. In figure 4, the AK laser system was adjustable, which allowed the laser system to be set to minimal output power (~0.5–1 W). The beam diverges as it passes through the 355 cm laser cavity; therefore, a concave mirror with a ROC of 35 m was used to reduce the divergence of the laser beam. With this arrangement, a burn pattern (see next paragraph) was taken of the laser beam at the input to the cavity and at the detector, giving an input beam diameter of 1.0 cm and a beam diameter at the detector of 1.5 cm. Since the detector diameter is about 5 cm, the detector power head collected the entire laser beam. The AK laser power supply was adjusted to produce a minimum output at the detector of 0.4 V (an optical power of ~0.5–1 W). This small output was important to ensure that the LHMEL IR gain medium was not being saturated while G_o was measured.

The burn pattern was on very sensitive IR coated transparency sheets. This IR sensitive material has the ability to display much of the real beam structure at short exposures (~0.5 s). From this IR sensitive material (or paper, as we refer to it), the beam could be measured within a human error of ~10%. The IR sensitive material used was also compared with an IR imaging system/camera, which has shown the same beam structure and beam size (within ~10%) as the paper. The IR sensitive paper is typically used for these types of measurements for its ease and speed (setup time) of use.

The windows, W_1 and W_2 , were 3.8 cm thick ZnSe flats with one side having 1.0% reflectance and the other side 0.2% reflectance. The 0.2% reflectance surfaces faced towards the incoming AK laser beam. The windows were witness samples and were wedged, so W_1 was tilted counterclockwise and W_2 was tilted clockwise (about the z axis) to prevent any lasing inside the cavity. Only one detector was needed because the AK laser was continuously running throughout the entire experiment, that is, before and during the excitation of the LHMEL IR laser medium. The plot in figure 5 illustrates a typical measurement run.

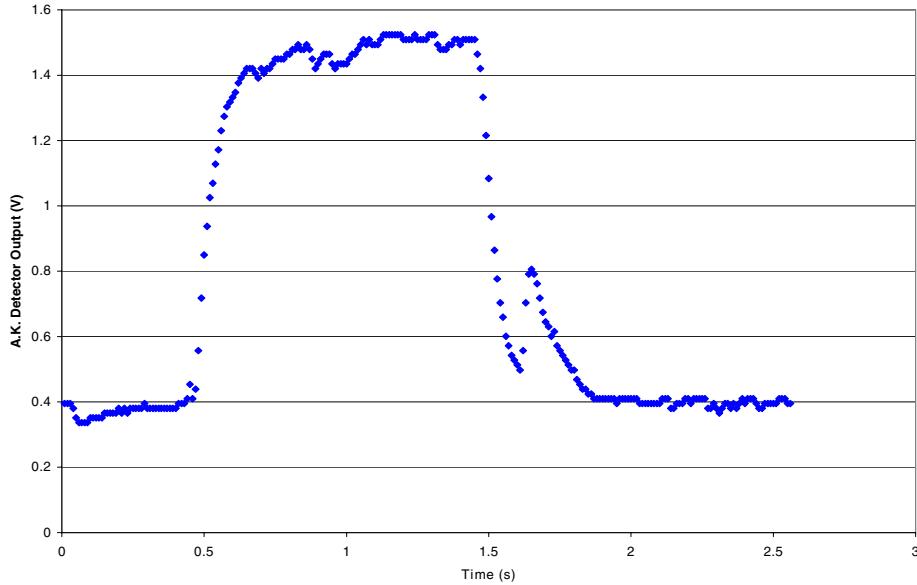


Figure 5. Detector output versus time for single-pass, γ_o measurements.

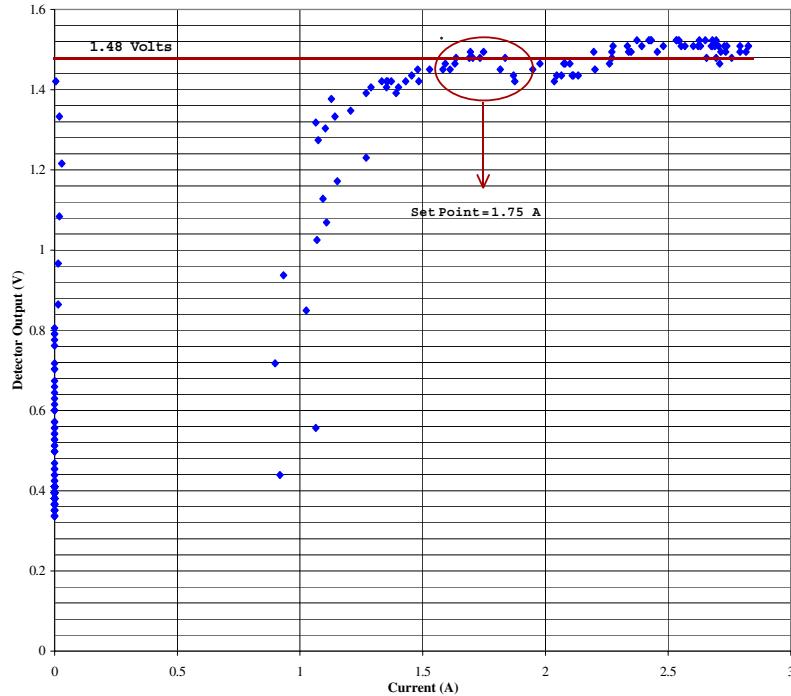


Figure 6. Detector output versus current for the signal-pass γ_o measurement.

The analysis of the data in figure 5 gives an average signal over 0.0–0.5 and 1.9–2.55 s of 0.385 V, which corresponds to P_{in} . Likewise, the average detector output during 0.5–1.5 s when the plasma laser medium had gain was 1.48 V, which corresponds to P_{out} . The data in figure 5 from 1.5–1.9 s were not considered. These data represent a flash (electrical short) that occurs in the plasma when the system is turned off. The small signal power gain, calculated from equation (7), is

$$G_o = 3.85.$$

The resulting small signal gain coefficient becomes

$$\begin{aligned} \gamma_o &= \frac{\ln(3.85)}{210 \text{ cm}} \\ &= 0.0064 \text{ cm}^{-1}. \end{aligned}$$

This procedure was repeated three times. The results of γ_o are summarized in table 5. The values using the Rigrod equation and the single-pass γ_o measurements are summarized in table 6. The same plasma current was used for both the Rigrod equation and the single-pass measurements. This current was determined from plots of detector output versus current. This is illustrated in figure 6 for the single-pass γ_o coefficient measurement.

Table 5. γ_o from the single-pass gain measurements.

Run	γ_o (cm ⁻¹)
1	0.0064
2	0.0063
3	0.0064
Mean	0.0064

Table 6. Small signal gain coefficients from both experiments.

	γ_o (cm ⁻¹)
75% and 17% coupler	0.0067
60% and 17% coupler	0.0066
Single-pass	0.0064
Mean γ_o	0.0066

As shown in figure 6, each study had the same current level of 1.75 A. The cavity pressures were in the range of 49–52 Torr. The gas mixtures were plotted against time and were essentially constant.

4. Conclusion

Summarizing the results of the two studies, we found the small signal gain coefficient to range between 0.0064 and

0.0067 cm⁻¹, while the saturation intensity ranged from 130 to 136 W cm⁻² for the specified conditions. Table 6 gives the results and an average of 0.0066 cm⁻¹ for the small signal gain coefficient, and table 4 provides the data for the saturation intensity for the first experiment—an average of 133 W cm⁻². Using the averages of both γ_o and I_s , the output power was calculated theoretically to be 13 kW and the experimental measured value, for the laser's optimal operating conditions, is typically \sim 12 kW, which is within 10%, according to the instruments (UDBC, etc) calibrated by NIST.

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