# Calorimetric system for recording plasma blowoff and scattered light distributions from laser plasmas

D. M. Villeneuve

*National Research Council of Canada, Division of Physics, Ottawa, K1A 0R6, Canada and University of Waterloo, Waterloo, Ontario*

M. C. Richardson

*National Research Council of Canada, Division of Physics, Ottawa, K1A 0R6, Canada*

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A complete system is described for the measurement of the distribution of energy emanating from laser-produced plasmas in the form of (1) plasma blowoff (ions, electrons, neutral particles, and x rays), and (2) scattered laser light. The detectors consist of small modules containing two differential calorimeters in one package, one for each form of energy. Modular autozeroing amplifiers enable the slowly varying signals to be measured by computer with the aid of CAMAC analog to digital converters. The computer is also capable of absolutely calibrating the units *in situ*. The programs used to record and display the data, and to calculate the fraction of laser energy absorbed, are described.

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## INTRODUCTION

An important question associated with all laser interaction investigations, especially those of laser-fusion interest, is centered on accounting for the eventual partition of the incident laser energy. Apart from the importance of simply a knowledge of the effective absorption or coupling efficiency, the form and parametric dependence of the angular distributions of the plasma blowoff and the scattered laser light can be a signature of specific interaction or hydrodynamic effects. Thus, in recent years, considerable effort has been expended to devise accurate recording systems to accomplish these aims.

There are two basic approaches to the measurement of the scattered laser radiation and the kinetic energy of particulate matter from laser-produced plasmas. The first utilizes devices which fully integrate all the emission, either photonic or particulate, from the plasma. Examples of systems which record the integrated scattered laser radiation are, the $4\pi$ integrating radiation box calorimeter,[1] the $2\pi$ and $4\pi$ integrating ellipsoidal mirror–pyroelectric detector combinations,[2–4] and the Ulbricht sphere.[5] In addition the total energy deposited into particulate matter has been recorded using integrating plastic[6] and glass[7] spheres, and in early Russian work, by the measurement of the blast wave velocity induced in a background gas surrounding the plasma.[8] With the exception of the latter technique, in which the presence of the background gas may alter the laser-plasma interaction process itself, all these approaches, whilst providing the greatest accuracy (~3% in the case of the box calorimeter[9]) suffer the strong disadvantage of inhibiting nearly, if not all other forms of plasma diagnosis. Moreover, they provide no information on the form of the plasma blowoff or scattered laser light distribution.

The second basic approach to the measurement of scattered laser energy or emitted plasma energy, utilizes an array of calibrated detectors which sample the total distribution. Total energy accounting them may be accomplished through integration, and in addition, by suitable disposition of detectors, the angular form of the distribution can be deduced. Although intrinsically less accurate than $4\pi$ integration methods of predicting total energy partition, this approach facilitates the deployment of other diagnostics, and hence can be utilized as an on-line diagnostic. Moreover, both time-dependent and time-integrated detectors can be used, with or without various filtering elements, providing detailed characterization of the interaction processes. Whereas calibrated photodiodes can be used for measuring the scattered laser radiation in 1 $\mu$m experiments, similarly sensitive detectors, deployable en masse, are not practical for $CO_2$ laser experiments. For measurements of the ion flux, and total absorption, charge collectors have often been used. However, due to uncertainties of charge state, and secondary electron emission characteristics of the electrodes within the collectors,[10] this approach is no longer widely used. Moreover, all time resolving signal detectors suffer the potential effects of electrical interference associated with the laser system or with the production of the plasma itself.

Calorimetric devices[1,11] and pyroelectric detectors[12] do not suffer many of these constraints. Calorimeters, depending upon bulk absorption by a massive absorber, rather than the measurement of charge, yield an unequivocable measure of the energy incident on the detector. In addition, their long time response makes them insensitive to electrical noise associated with laser and target emission. They may easily be configured in differential form, and as will be described here, can

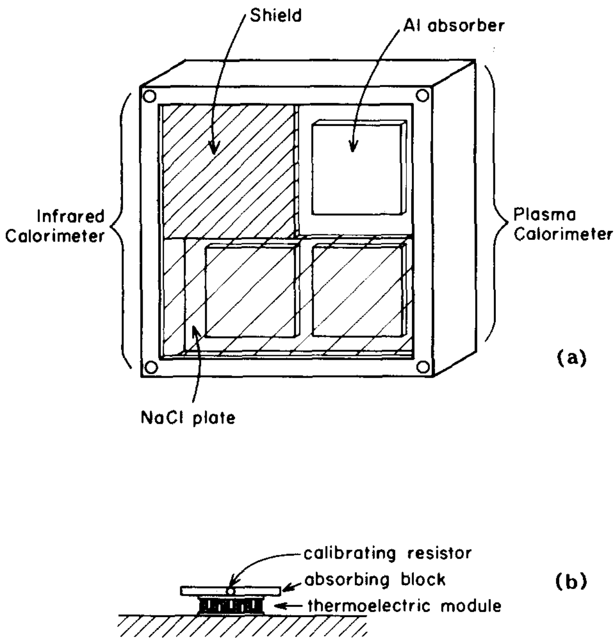


FIG. 1. (a) View of the combined calorimeter module. The left half is the infrared calorimeter and the right half is the plasma calorimeter. The aluminum absorbers for the infrared half are coated with $Al_2O_3$; those for the plasma half are polished. (b) Detail of the attachment of the absorbers to the thermoelectric modules.

be devised to include regular *in situ* calibration of their sensitivity.

This paper describes the design of a calorimetric module, which differentially measures both plasma blowoff energy and scattered laser light, suitable for $CO_2$ laser-plasma studies. It was developed from concepts originally devised by S. R. Gunn[13] for similar instrumentation utilized in 1-$\mu$m laser-fusion experiments. In order to determine the shape of the plasma blowoff and scattered laser light distributions from targets irradiated with intense nanosecond $CO_2$ laser pulses, a large number of these detector modules were deployed in a three-dimensional array about the target. The signal handling and data retrieval system devised for on-line recording is described. In addition, some discussion is included on the subsequent reduction and display of the data.

## II. CALORIMETER DESIGN

Details of the combined plasma and radiation calorimeter module are shown in Fig. 1(a). It basically comprises two separate differential calorimeters with filter combinations selected to measure (a) the total energy in particulate matter and x rays, and (b) total photonic energy in the visible and IR region, principally the 10.6 $\mu$m laser radiation.

The body of the unit, which acts as a heat sink, is made of aluminum and has outside dimensions, $64 \times 64 \times 19$ mm. Its exposed surfaces are anodized to reduce scattering of infrared radiation. Inside each module are four separate 19-mm-square 2.1-mm-thick absorbing blocks mounted on Peltier effect thermoelectric cooler modules[14] as shown in Fig. 1(b). The thermoelectric coolers are used in the reverse sense of their normal mode of operation, converting the temperature difference to a voltage. These units, which measure $13 \times 13 \times 5.3$ mm, are comprised of 17 pair of thermoelements connected electrically in series, and thermally in parallel, sandwiched between ceramic insulators. Their response is approximately 6 mV/K, and they have an impedance of less than 1 $\Omega$. These thermoelectric modules are fastened between the absorbers and the calorimeter base by silver-filled epoxy glue[15] cured at 80 °C.

The two aluminum absorbers used in the infrared calorimeter are coated with $Al_2O_3$, which has excellent absorption characteristics for 10.6-$\mu$m radiation.[16,17] One absorber is covered by a 3-mm-thick NaCl window which absorbs all particle emission from the plasma and all but a negligible fraction of its x-ray emission, while the second is totally obscured from view by a thick metal shield. The difference signal between these two elements then yields a signal proportional to the infrared radiation.

The two absorbers which comprise the plasma calorimeter are also made of aluminum and have optically polished external surfaces. Aluminum has been found to have low energy losses due to sputtering, secondary electron emission, secondary fluorescence and backscattering.[1,18] One absorber is covered by a NaCl window, thus permitting it to receive only the scattered infrared radiation, while the other is exposed to all emission, particulate and electromagnetic, emanating from the plasma. Compensation for the 8% Fresnel reflection losses at the NaCl window is made by reducing the mass of the covered absorber by a corresponding fraction. In addition only a small fraction of the infrared radiation is absorbed in either absorber since the polished aluminum surface acts as a good reflector for 10.6 $\mu$m radiation. The signals from the two thermoelectric units are then subtracted to give a signal proportional to the flux of ions, electrons, and x rays. The degree to which the infrared signal is rejected may be determined by placing a NaCl plate in front of the entire detector, thus inhibiting all incident flux except infrared radiation. In practice it was found that in the worst case, response of the plasma calorimeter to infrared radiation was ~5% of the infrared signal.

The resulting signals are of microvolt amplitude rising to a maximum within 2 s and decaying exponentially for several minutes. As described in the following section, the peak value is determined by extrapolating the decay to the zero time, and measuring the peak step height.

Calibration of each calorimeter is provided by the insertion of a small ⅛-W resistor into a hole in each absorber. Calibration of any differential pair of absorbers can then be made by discharging a known electrical energy through the calibration resistor of one of the absorbers, thus yielding an absolute calibration in volts per Joule. This method of calibration has the advantage that it may be easily performed remotely, on a large number of calorimetric modules positioned inside the

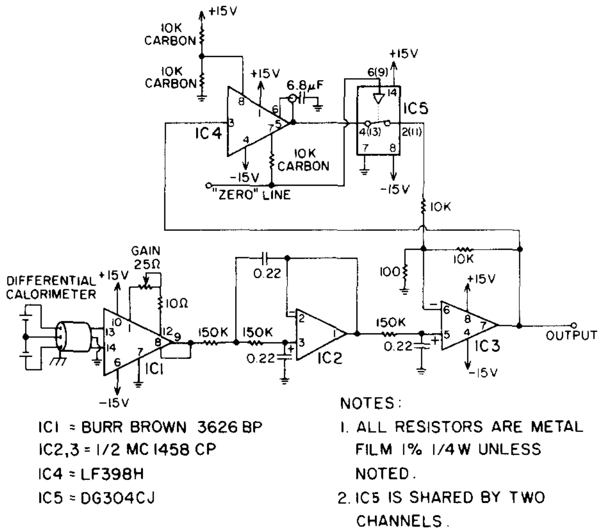


FIG. 2. Schematic diagram of the amplifiers used for each calorimeter channel.

evacuated target chamber. It was found in practice that, for a single absorber pair, the calibration had a standard deviation of 2%, its absolute value remaining constant to within 3% over several months of regular operation.

## III. SIGNAL AMPLIFICATION

The electrical signals produced by the calorimeters are typically of microvolt level, and consequently require significant amplification before being recorded. Amplifiers used for this purpose must possess low noise level, good common mode rejection, and a differential input to match the opposing thermoelectric module source. Simple operational amplifiers cannot meet these requirements, and hence commercial hybrid instrumentation amplifiers were used.

Figure 2 shows a schematic diagram of the amplifier. The balanced differential signal is passed to IC1, a Burr–Brown 3626-BP instrumentation amplifier with a gain of 1000. This device is available in three grades (A, B, and C), noise level being the significant factor. For the present application, the B-type was found to be satisfactory. The signal then goes through IC2, a low pass filter having a 2-Hz cutoff to reduce noise. Amplifier IC3, provides an additional gain of 100 and also subtracts the offset voltage from IC5.

Devices IC4 and IC5 form the auto-zeroing part of the circuit. This is not necessary if the recording device is to be a chart recorder with good zero-offsetting range, but is necessary if the output is to go to an analog to digital converter (ADC), since very small dc offsets at the input can cause the output to swing off scale. These dc offsets can be relatively large, especially for the infrared calorimeters which are exposed to strong background light. IC4 is a sample-and-hold amplifier which holds this offset voltage for several minutes with negligible droop. When the "zero" line is pulled low, IC4 captures the offset level, and when the "zero" line is high, the offset is passed through switch IC5 to be subtracted at the output stage.

Two such amplifiers are required for each calorimeter module. Eight amplifiers may be mounted in a NIM module, including the circuitry required to automatically calibrate the calorimeters with four different energy levels. The "zero" input is common to all amplifiers.

The sensitivity of these calorimeters is approximately 100 $\mu J/cm^2$, which is determined chiefly by noise in the instrumentation amplifier. The sensitivity may be increased by making the absorbers less massive, however this approach makes difficult the insertion of calibration resistors.

## IV. DATA COLLECTION

Figure 3 shows the layout of the entire calorimeter system. Each combined calorimeter module in the vacuum chamber is connected to its two amplifiers by a six-conductor shielded cable, the shield being common to the target chamber. Great attention was paid to elec-

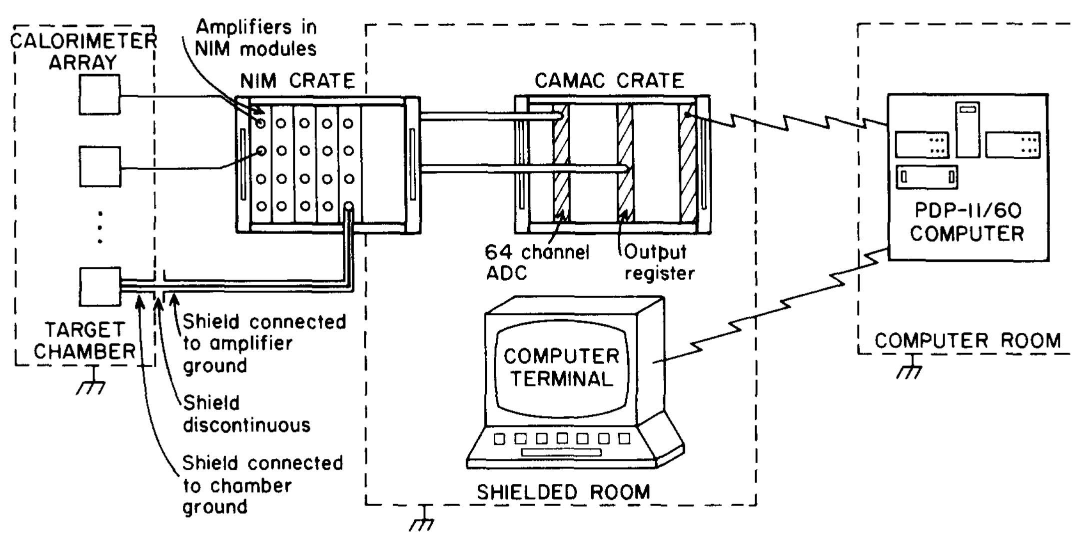


FIG. 3. Layout of the entire calorimeter measurement system. The jagged lines represent fiber optic links.

trical ground continuity. The plasma produced by intense $CO_2$ radiation generates copious fluxes of high energy electrons, which create strong field gradients when they impinge on the walls of the vacuum chamber. It is then necessary to inhibit the propagation of this noise to areas of sensitive detection, and to shield signal lines, and in some cases detectors, within the vacuum tank from these noise sources. The amplifiers in their NIM modules are mounted flush with the surface of a shielded room, facing outward, and the electrical grounds of the calorimeters are kept separate from the target chamber ground.

The outputs from the amplifiers (40 at this time) are read by an analog to digital converter in a CAMAC crate inside the shielded room, and the control lines to the amplifiers (zero and calibrate commands, and calibration levels) are controlled by a CAMAC output register. This CAMAC crate is connected over a fiber optic serial highway to a BI-RA MBD-11 programmable branch driver which is interfaced[19] to a PDP-11/60 computer with the RSX-11M operating system.

The software related to the real-time experiment is divided up into a number of autonomous tasks, each responsible for a particular diagnostic, which communicate through a common block. The task responsible for the calorimeters is started 5 s before the laser fires, and at that time zeroes the amplifiers and samples the voltages to establish the baseline for each calorimeter. When the laser fires, each calorimeter is sampled once a second for 50 s in order to establish a 50-point description of its waveform. A straight line approximation is then fitted to the exponential decay of each calorimeter signal and extrapolated back to the time at which the laser fired. The voltage step measured at that point is then converted to an energy density by accessing the calorimeter calibration file, and then to J/sr by means of the calorimeter position file. These results are normalized to the incident laser energy which is obtained from another task. The absorbed energy fraction is then calculated and the interim results are displayed on the computer terminal in the experimental area. All the results are written into the shot file, along with any waveforms which did not meet a goodness-of-fit criterion. These waveforms may be displayed later and the values corrected as required. In addition, the entire shot file may be accessed for detailed review and analysis. A typical analysis program would average the calorimeter readings of a number of shots, compute the absorption and the energy partition between the front and back of the target, and calculate error bars for the results.

Absorption is calculated by multiplying each calorimeter's signal by a weighting factor, which is proportional to the relative area of a sphere that the calorimeter represents. These representative areas, and the detector positions, are carefully chosen so that the emission distributions are well sampled and so that those detectors with large representative areas are placed where the distribution is smoothest. This method has been found to yield fast and accurate absorption figures.

This automated detector system is currently being used in investigations of $CO_2$ laser target interactions of interest in laser fusion. It has already provided valuable data on the energy partition and plasma blowoff distributions from single-sided irradiation of microdisk targets.[20] In producing detailed information on the plasma blowoff and scattered laser light distributions, it provides a valuable on-line diagnostic to these investigations. It facilitates the incorporation of a large number of detectors, thereby providing much greater ease and accuracy than could be achieved by non-computerized systems.

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