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A Digital Calorimeter

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Abstract

The paper describes a calorimeter which is used to determine the particle flux of an accelerator. It incorporates as its principal feature a Peltier module which is operated in a constant current pulse mode. Via a feedback arrangement, the Peltier module thermally compensates the heat generated by the particle beam by supplying discrete "cooling quanta." The number of "quanta" generated per unit time is measured with a frequency counter and is proportional to the beam power. The calorimeter can be calibrated via internal resistors which dissipate a precisely known amount of power in the target.

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1. Introduction

One of the most important parameters of an accelerator is the number of particles per second it can deliver. Usually this quantity is measured with a Faraday cup or an ionization chamber. Faraday cups have the advantage of high sensitivity; however, they have to operate in a "good" vacuum, require careful suppression of secondary electrons, and an exact knowledge of the charge distribution of the beam. Ionization chambers are able to measure very small beam currents; however, they saturate very quickly and require careful calibration.

To overcome some of these limitations, we have developed an instrument that uses the heat generated by the beam to measure its intensity. Calorimeter measurements are usually done in the following way: the beam strikes a suitable water-cooled target, and the flow of the water, as well as its inlet and outlet temperatures, is measured. The flow rate multiplied by the temperature difference and the specific heat of the water then gives the power generated in the target. This method can be very cumbersome and inaccurate. The employment of Peltier elements, however, affords an entirely different way of power measurements.

2. The Peltier Effect

It was found in 1834 by Jean C. A. Peltier that the passage of an electric current through the junction of two dissimilar conductors produces a heating or cooling effect, depending on the direction of the current. This is now called the Peltier effect, and is closely related to two other effects, named after Seebeck and Thomson. To make a practical "Peltier element" for cooling purposes, three different metals have to be combined, one being an "ordinary" conductor, and the other two p and n semiconductors. Several of these couples are put thermally in parallel and electrically in series to form a thermoelectric cooling module. Since the Seebeck, Peltier, and Thomson effects are reversible, heating can be obtained from a cooling module by simply reversing the current. Figure 1 shows the cooling capacity Q_C of a commercially available module as a function of the current (Ref. 1).

A simple way of using a thermoelectric module to measure beam power would be to let the beam strike a target and compensate for the generated heat with the Peltier module so that its temperature is kept constant. By using a feedback arrangement which supplies a suitable DC current to the module, the electric power delivered to the Peltier element would then be a measure for the beam power. A brief look at the theory of Peltier junctions, however, shows that this would lead to an extremely nonlinear device.

The heat flow Q_c at the cold side of a thermoelectric junction is given by

$$Q_c = \alpha_c T_c I - \frac{1}{2}\bar{\tau} I \Delta T - \frac{1}{2} I^2 \bar{R} - \bar{K} \Delta T. \quad (1)$$

Here α_c is the net Seebeck coefficient of a thermoelectric couple at the temperature T_c, I is the current, $\bar{\tau}$ is the average Thomson coefficient of a couple, $\bar{R}$ is the average resistance, and $\bar{k}$ is the average thermal conductance. Since the goal in the present application is to keep the temperature of the target constant, one can arbitrarily choose to keep it at the temperature of the hot (water-cooled) side of the junction so that $\Delta T = 0$. Then (1) simplifies to

$$Q_c = \alpha_c T_c I - \frac{1}{2} I^2 R. \quad (2)$$

In Fig. 1, the cooling power Q_c is plotted versus the electrical current I, and as can be seen from this figure and eq. (2), $Q_c(I)$ goes through a maximum.

Differentiating eq. 2 with respect to I gives

$$\frac{\partial Q_c}{\partial I} = \alpha_c T_c - IR \quad (3)$$

Setting $\frac{\partial Q_c}{\partial I} = 0$, the maximum cooling occurs at

$$I_{max} = \frac{\alpha_c T_c}{R}.* \quad (4)$$

It is important for the following to note that at I_{max} the cooling power is quite insensitive to fluctuations of the input current. From the foregoing, it is also obvious that it would be complicated to build a linear beam power meter using simple analog techniques.

3. The Principle of the Digital Calorimeter

A property of Peltier junctions that has not been considered so far is their thermal response. The thermal time constant θ of a cooling module is mainly a function of the heat load, the temperature differential, and the heat

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*For the module considered in this report, I_{max} is approximately 9 A.

capacity of the target to be cooled. In the application considered here, θ is approximately 2 minutes. This large thermal time constant makes it possible to apply electrical power to a module in short periodic pulses--as long as their frequency f satisfies the condition $f \gg 1/\theta$. In a practical case, f = 0.1 Hz can be considered a safe lower limit.

In principle, any amplitude can be chosen for the current pulse, but it is most advantageous to select the value corresponding to the maximum of $Q_c(I)$ in Fig. 1. This will minimize the influence of amplitude fluctuation of the pulse current generator on the cooling power, as was mentioned before, and it will allow the maximum cooling power to be generated whenever the duty factor of the pulses approaches 100 percent. If the energy per pulse is chosen to be equal to a "round number" of watt-seconds or calories of heat flow into the target, then the repetition frequency f can be made to be a direct measure of the beam power in watts or calories per second. For example, assuming that a thermoelectric module will produce 20 watts of cooling power, at 10 A DC current, a 10-A pulse of 50 μs will then correspond to a cooling "quantum" of $20 \times 50 \times 10^{-6} = 10^{-3}$ Ws. Consequently, 10-A pulses of 50 μs length applied to the module at a frequency of 1 Hz will correspond to a cooling power of 1 mW; therefore, the pulse frequency measured in kilohertz becomes a direct measure of the cooling or beam power in watts. All that is necessary to make this into a linear beam power meter is to design a suitable feedback system.

4. The Feedback System

Figure 2 shows schematically the electrical and mechanical parts of the calorimeter; on the left the power measuring module that intercepts the beam, and on the right the associated electronic modules. The Peltier element is "sandwiched" between the target and a water-cooled backing. The target as well as the backing plate contain thermistors* which form part of a Wheatstone bridge. Without beam and without current through the Peltier module, the target assumes the temperature of the backing plate ($\Delta T = 0$), and the bridge circuit is adjusted for zero output. Energetic particles impinging on the target cause an increase of its temperature which is detected by the front

*It is conceivable that the properties of the thermistors could change reversibly and/or irreversibly under very high radiation levels (neutron and/or gamma). In this case, it would be preferable to use thermocouples. This, however, would not in any way alter the operating principle of the instrument.

thermistor and imbalances the bridge. The error voltage is amplified and converted into a frequency via a voltage-to-frequency converter (VFC). The VFC triggers a constant-current constant-width pulse generator which feeds power into the Peltier element, which in turn reduces the temperature of the target (i.e. the thermistor) until it is again equal to the temperature of the backing plate ($\Delta T = 0$). The frequency of the pulse generator is measured with a frequency meter, and is proportional to the power supplied by the Peltier element. A measure of the beam power integral (i.e., total number of beam particles) can be obtained simply by connecting the frequency output to a digital counter. The width of the pulses is chosen such that there is a simple conversion between frequency and beam power. In our prototype model, 1 kHz corresponds to 1 watt, which requires a pulse width of approximately 45 μs at about 10 A. The gain-frequency characteristic of the feedback loop was optimized with an analog computer, and it was found that, in order to obtain a short response time while maintaining stability, a differentiating stage had to be inserted between the error amplifier and the VFC. This feedback arrangement has a property that might, at first, not be obvious. At zero input power, the output frequency of the current pulse generator is zero, and the feedback loop is open. This requires a design that is unconditionally stable over a wide, dynamic range.

An overtemperature detector pulls the target automatically out of the beam as soon as the beam intensity exceeds the cooling capacity of the Peltier module, which is, at present, 20 watts.

5. Calibration

To provide a beam-independent calibration, four small resistors are embedded in the target in addition to the thermistor. They can be connected to a stable power supply, and will generate a precisely known amount of power. The pulse width of the constant-current pulse generator is adjusted to make the power measured in watts correspond directly to the frequency in kilohertz.

6. Error Compensation

The cooling power Q_c of a given thermoelectric module is a function of the current I, the temperature of the hot side T_h, and the temperature difference DT between the hot and cold sides. The variation in cooling power ΔQ_c as a function of changes in these three parameters is then, to first order,

$$\Delta Q_c = \left(\frac{\partial Q_c}{\partial DT}\right) \Delta DT + \left(\frac{\partial Q_c}{\partial T_h}\right) \Delta T_h + \left(\frac{\partial Q_c}{\partial I}\right) \Delta I. \tag{5}$$

As outlined before, the operating point of the module is chosen so that $(\partial Q_c/\partial I) = 0$; and, in addition, I is kept constant by the constant-current generator so that $\Delta I = 0$, and the last term in eq. (5) vanishes. The remaining change of the cooling power is due to slight changes in DT with varying heat load Q_c and changes in the temperature of the hot side T_h which cannot be kept exactly constant because of the finite thermal impedance of the cooling circuit. Fortunately, however, $(\partial Q_c/\partial DT)$ is in general negative, and (Q_c/ T_h) is positive. Through proper design of the thermal impedances, both effects can therefore be made to cancel each other so that

$$\left[\frac{\partial Q_c}{\partial DT}\right]_0^{P_{max}} \Delta DT + \left[\frac{\partial Q_c}{\partial T_h}\right]_0^{P_{max}} \Delta T_h = 0 \tag{6}$$

For the following calculations, we will refer to Fig. 3, and introduce the following conventions.

$$\frac{\partial Q_c}{\partial DT} \equiv \alpha; \quad \frac{\partial Q_c}{\partial T_h} \equiv \beta; \quad \frac{\alpha}{\beta} \equiv -\gamma; \quad \varepsilon_1 \equiv \frac{d_1}{D_1}; \quad \text{and } \varepsilon_2 \equiv \frac{d_2}{D_2} . \tag{7}$$

ε_1, ε_2 = normalized distances between the thermistors and the Peltier module.

- ΔT_{13} = temperature drop across the target;
- T_2 = temperature of the first thermistor;
- ΔT_{34} = DT = temperature drop across the Peltier module;
- T_5 = temperature of the second thermistor;
- ΔT_{46} = temperature drop across the cooling block;
- T_6 = temperature of the cooling water.

With the following definitions:

- Q_1 = beam power;
- D_1 = thickness of the target;
- σ_1 = thermal conductivity of the target;
- F_1 = area of the target;

the temperature drop across the target can be written as

$$\Delta T_{13} = \frac{Q_1}{\sigma_1} \frac{D_1}{F_1}. \qquad (8)$$

A similar expression holds for the temperature drop across the cooling block

$$\Delta T_{46} = \frac{Q_2}{\sigma_2} \frac{D_2}{F_2}. \qquad (9)$$

The feedback mechanism keeps both thermistors at the same temperature so that

$$T_2 = T_5.$$

Assuming a linear temperature drop across the target and the cooling block, we obtain

$$T_3 = T_2 - \varepsilon_1 \Delta T_{13}, \text{ and}$$
$$T_5 = T_6 + (1 - \varepsilon_2)\Delta T_{46};$$

also,

$$T_4 = T_6 + \Delta T_{46}.$$

Combining the last four equations, we obtain

$$\Delta T_{34} = T_4 - T_3 = \varepsilon_2 \Delta T_{46} + \varepsilon_1 \Delta T_{13}. \qquad (10)$$

With $DT \equiv \Delta T_{34}$ and $\Delta T_h = \Delta T_{46}$, combining (6) and the definitions (7), gives

$$\Delta T_{46} = \gamma \Delta T_{34}.$$

Using (10) to eliminate ΔT_{34} results in

$$\Delta T_{46} = \gamma(\varepsilon_2 \Delta T_{46} + \varepsilon_1 \Delta T_{13}).$$

This leads to a final equation for the compensation

$$\boxed{\Delta T_{46} = \frac{\gamma \varepsilon_1}{1 - \gamma \varepsilon_2} \Delta T_{13}.} \qquad (11)$$

It is shown in the Appendix that this condition can easily be fulfilled through proper choice of the geometrical and thermal parameters of the target and cooling block. Figure 4 shows the deviations from linearity in the relation $P = \eta f$ where P is the simulated beam power and f is the frequency. The mean value of η is: 1.000±0.001 W/Hz over a range of 80 mW to 21 W.

7. Applications

The principal application of the described instrument is to measure the power generated by an accelerator beam and deduce from it the particle flux. The beam power N (in watts) can be calculated using the expression: $N = IE/q$;

where I is the beam current in μA, E is the particle energy in MeV, and q is the charge of the accelerated particles. The number of particles per second (pps) is then easily found from the expression

$$pps = \frac{N_{(watts)}}{E_{(MeV)}} \times 6.24 \times 10^{12}.$$

Several components have been added to the calorimeter to increase its versatility. The silver target is electrically insulated from the Peltier element and can be used as a Faraday cup. Two permanent magnets establish a magnetic field of approximately 1 kG parallel to its surface. This field, together with an electric shield that can be biased negatively with respect to the target, effectively prevents the escape of secondary electrons and allows a reliable beam current reading. Measuring the beam current and the beam power, and knowing the average charge state of the particles, their energy can be calculated: $E = Nq/I$.

8. Appendix

In the prototype digital calorimeter, the cooling power compensation has been achieved in the following way.

The temperature coefficients of the thermoelectric module at $T_6 \approx 15°C$ and $T_4 \approx 0°$ are:

$$\alpha = -.30 \text{ W/°C}$$

$$\beta = +.090 \text{ W/°C};$$

consequently, $\gamma = 3.3$,

and, from eq. (11), $$\Delta T_{46} = \frac{3.3\ \varepsilon_1}{1 - 3.3\ \varepsilon_2}\ \Delta T_{13}. \quad (12)$$

Solutions to the compensating problem are obviously restricted to $\varepsilon_2 < 0.3$. Equation (12) allows several different combinations of the design parameters for the target and the cooling block. The target material should have a low heat capacity, however, and good heat conductivity. This can be achieved with a thin silver disk.

For 20 watt beam power, we have

Q_1 = 20 watts;

σ_1 = 4.19 W/cm/°C (silver);

$F_1 = 5\ cm^2$ (one inch diameter target)*;

and $D_1 = 0.5$ cm.

For mechanical reasons, $\epsilon_1 = 0.5$ was chosen. It then follows from eq. (8) that

$$\Delta T_{13} = .48^\circ C$$

and from eq. (12):

$$\Delta T_{46} = \frac{0.80}{1 - 3.3\epsilon_2} . \qquad (13)$$

For the cooling block, <u>brass</u> was chosen as a material of moderately <u>low</u> thermal conductivity. The other parameters are:

$Q_2 = 55$ W (corresponding to $Q_1 = 20$ W) (Ref. 1);

$F_2 = 10\ cm^2$;

$\sigma_2 = 1.1$ W/cm/°C (brass);

$D_2 = 0.85$ cm;

we then obtain, from eq. (9)

$$\Delta T_{46} = 4.25^\circ C$$

and with eq. (12)

$$\epsilon_2 = 1 - \frac{0.80}{\Delta T_{46}}\ 3.3 = .25.$$

Since $\epsilon_2 \equiv \frac{d_2}{D_2}$ and $D_2 = .85$ cm, it follows that $d_2 = .21$ cm.

At this point, all parameters are specified, and eq. (11) is satisfied.

*It is assumed that the beam heats the whole target uniformly.

Figure Captions

Figure 1: Electrical input power P(I) and cooling power $Q_c(I)$ of the Peltier module used in the prototype digital calorimeter (CAMBION Model No. 801-3958-01, Ref. 1).

Figure 2: Schematic diagram of the digital calorimeter showing the mechanical components on the left and the electronic modules on the right.

Figure 3: Temperature relationships inside the beam power measuring module (see text for explanations).

Figure 4: Check of the frequency-to-power conversion factor η for several power values. The average value $\eta = 1.000 \pm 0.001$ is indicated by the dashed line.

Reference

1. The CAMBION Thermoelectric Handbook, Cambridge Thermionic Corporation (1972) p. 48.

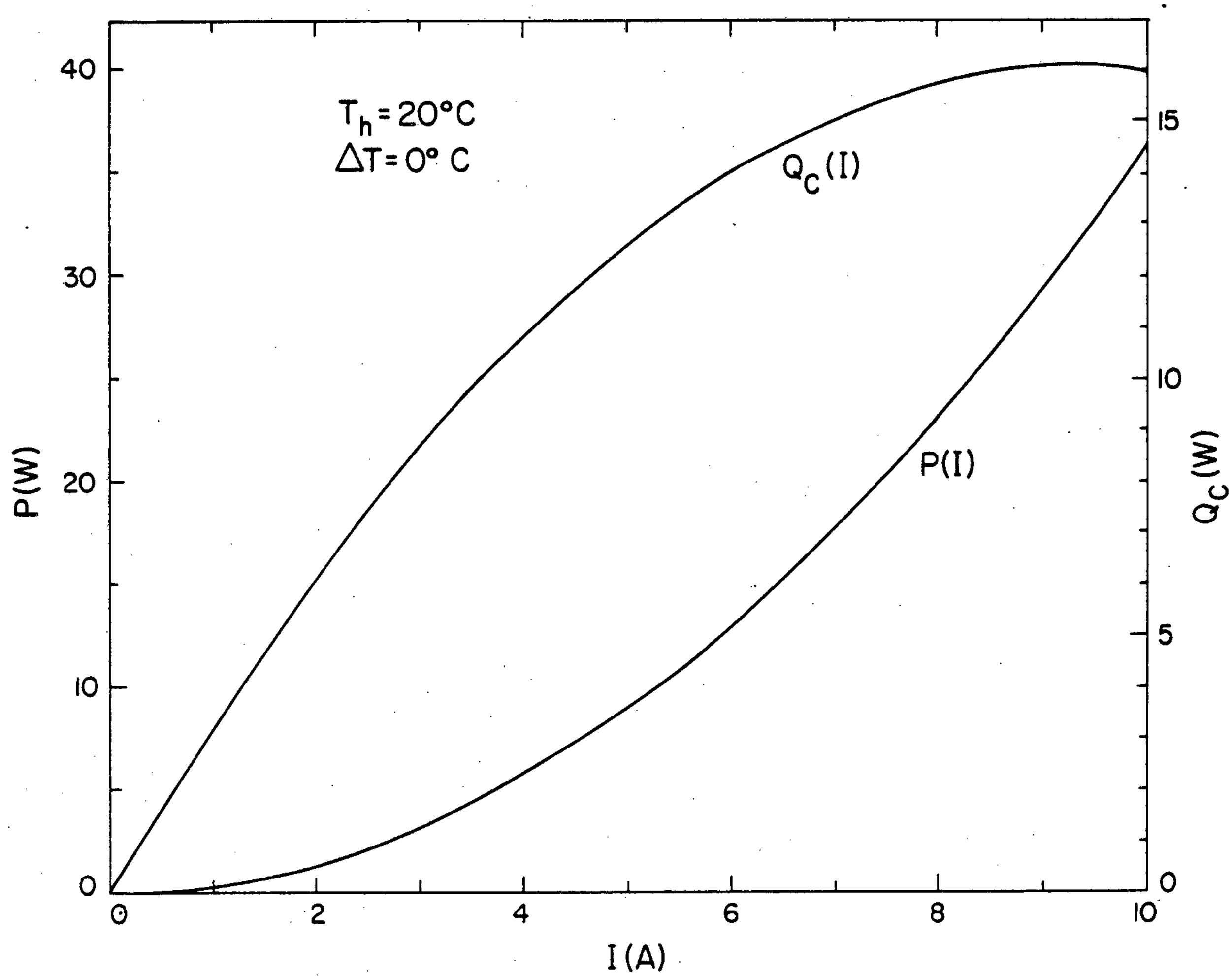

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Fig.1

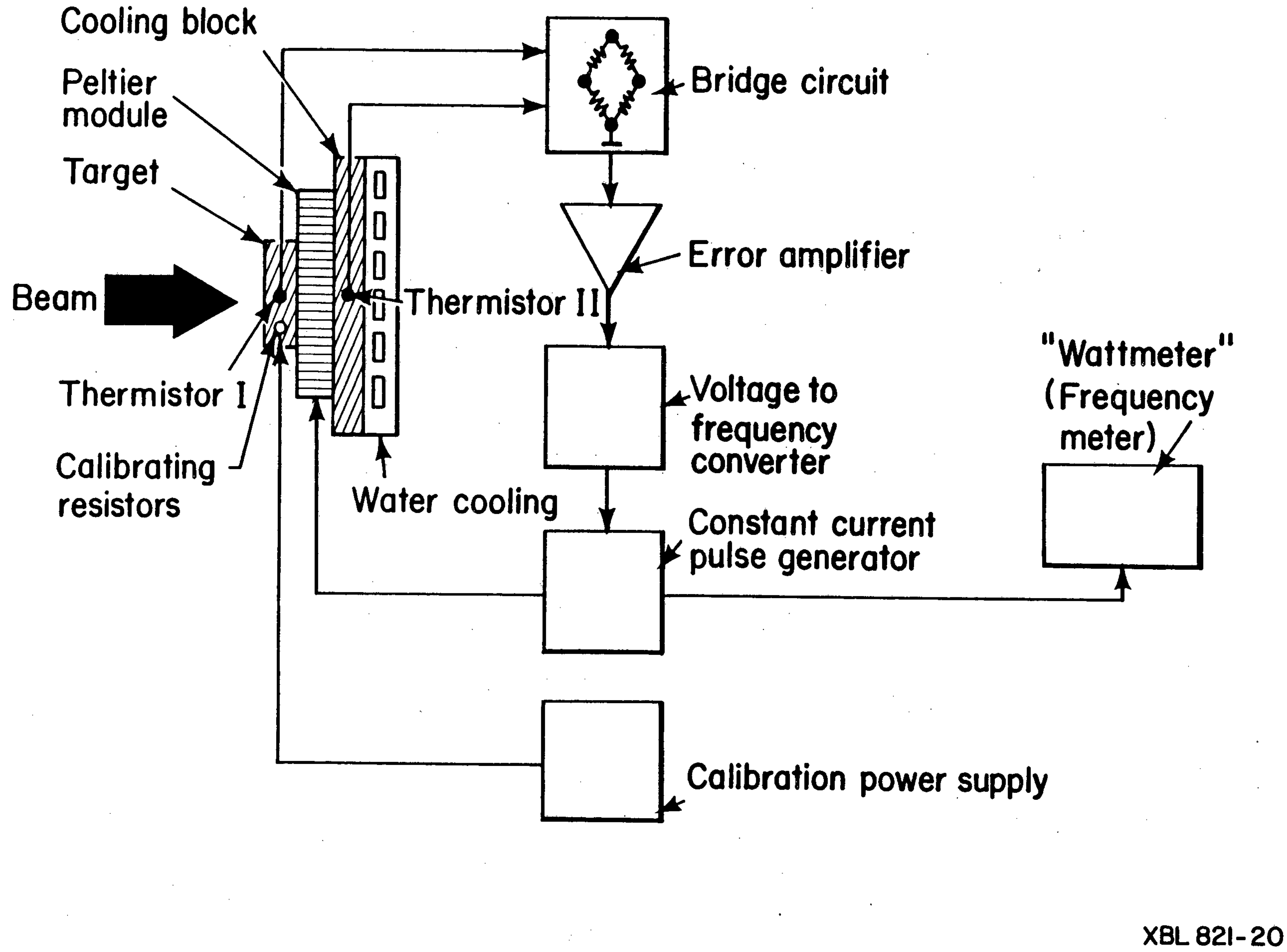
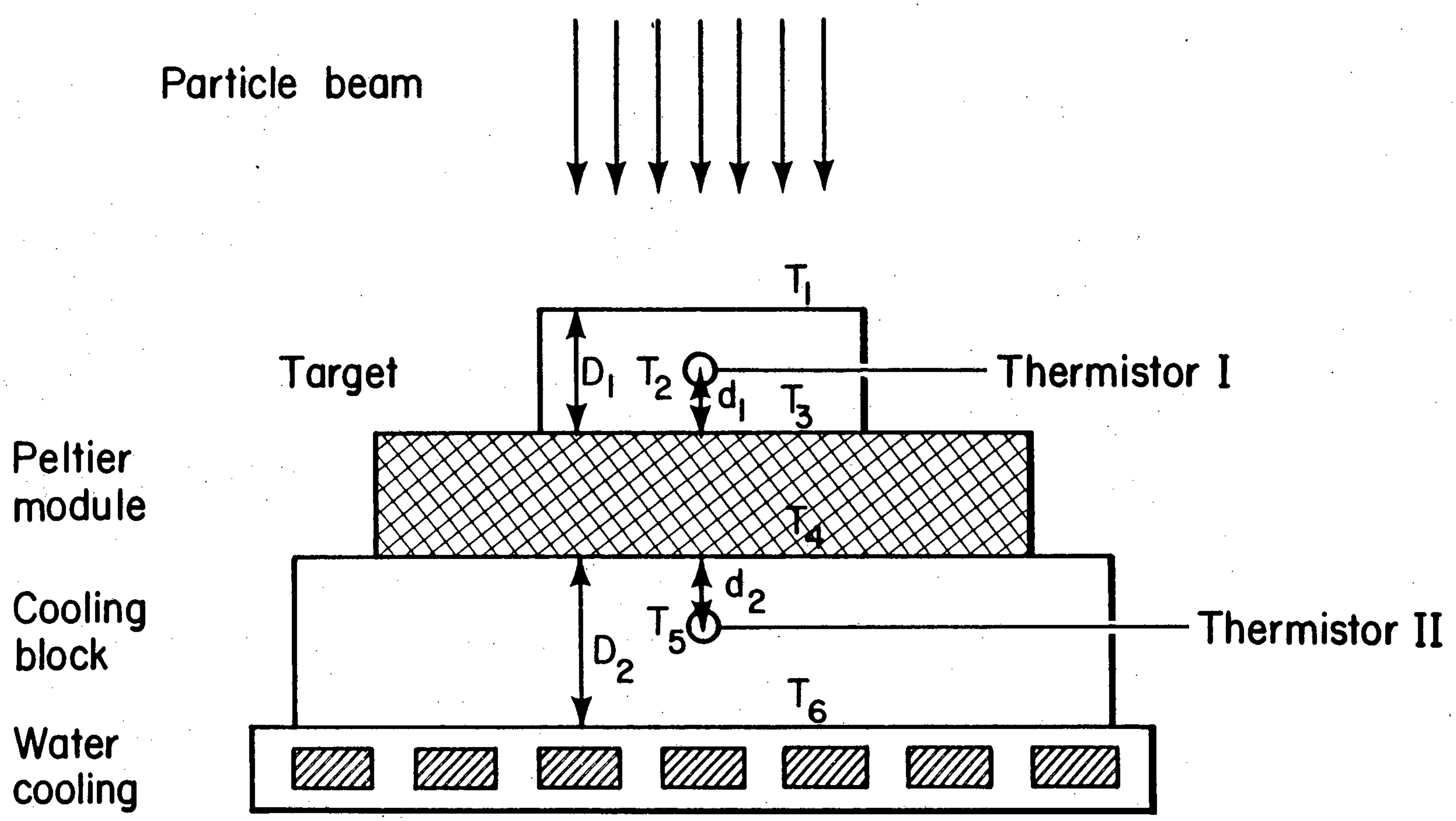

Cooling block
Peltier module
Target
Beam
Thermistor I
Calibrating resistors
Thermistor II
Water cooling
Bridge circuit
Error amplifier
Voltage to frequency converter
Constant current pulse generator
"Wattmeter" (Frequency meter)
Calibration power supply
XBL 821-20

Fig. 2



XBL 821-19

Fig.3

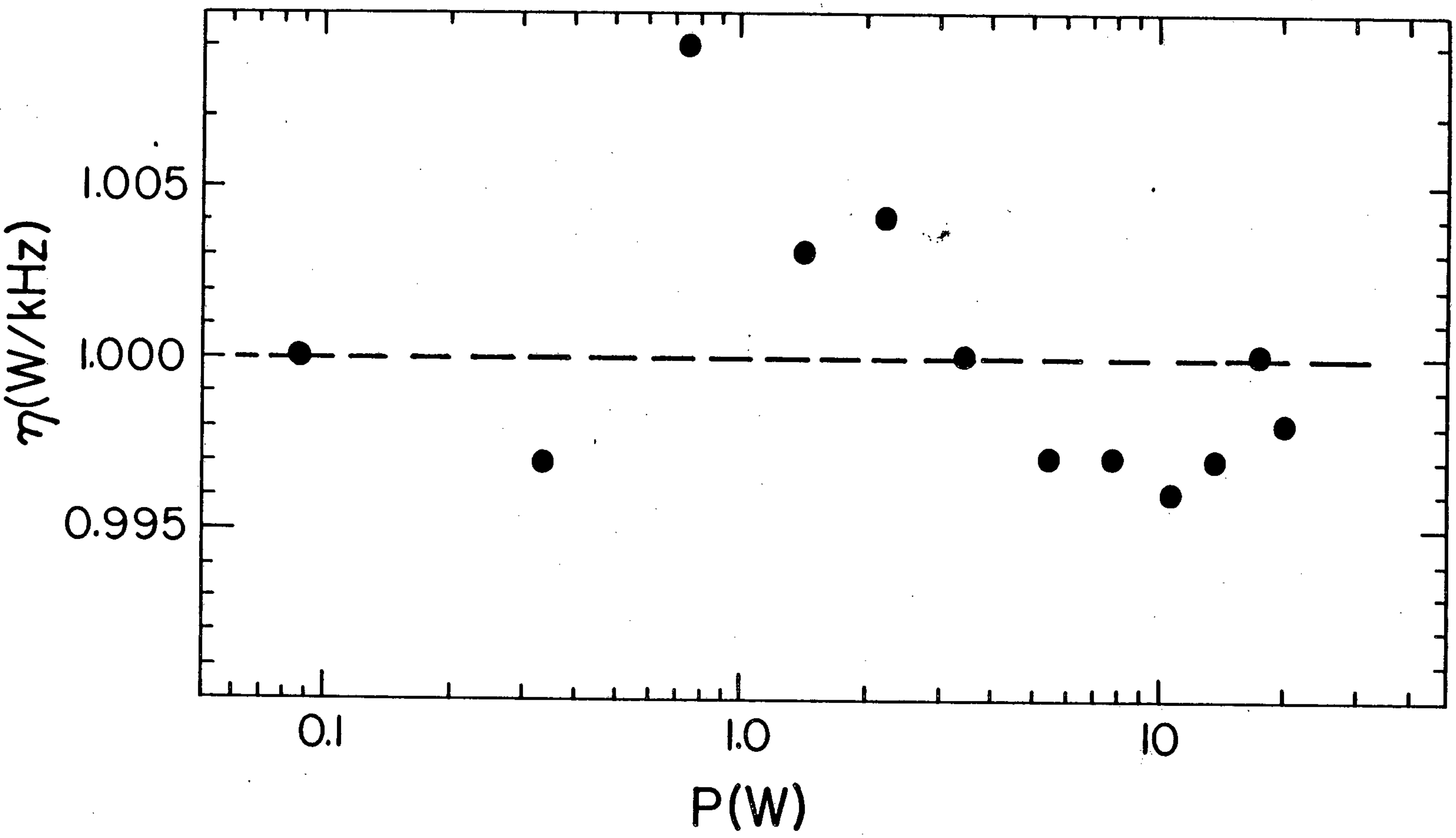


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Fig.4

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