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H.F. POWER METER FOR OPERATION

AT 2.5 MW PULSED POWER

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HP. POWER METER FOR OPERATION AT 2.5 MW PULSED POWER

- Summary

A description is given of an oil-cooled dummy load specially constructed to measure the output power of the 2.5 MW pulse amplifier of the CERN linear accelerator. The equipment can be used both as a dummy load and as a calorimetric power meter. Arrangements have been made to use it also as an attenuator of more than 30 db.

- Introduction

The construction and the operation of the 2.5 MW pulsed power amplifier (ref. 2 and 3) of the CERN linear accelerator raise the problem of dissipation and measurement of the output power.

The characteristics of the power pulse are as follows:

- maximum pulsed power 2.5 MW
- pulse length 200 µsec.
- radic-frequency 202.6 MHz
- repetition frequency 1 pulse/sec.

A dummy load is needed which can withstand the high voltage corresponding to a 2.5 MW pulse and dissipate a mean power of the order of 500 W. It will be used both for the final installation and laboratory work. For installation a simple load is required. It will be connected to the power divider inserted between the drive stage and the final amplifier of the H.F. chain (fig. 1).
The regulation is done by dividing the output power of the drive stage between the dummy load and the input to the final stage in any required ratio. If necessary, the power can be diverted completely into the dummy load. The distribution of power can be measured by power flow monitors (ref. 5), and no absolute power meter is required. For laboratory work, however, it is desirable to have a power meter of reasonable accuracy for checking amplifier performance and calibrating the power flow monitors. The oil-cooling proposed for the dummy load suggested the idea of using the equipment also for calorimetric power measurement.

Coaxial resistor dummy load

A "lossy line" consisting of a cylindrical resistor in a suitable outer conductor (fig. 2) has been used as reflection-free termination of the 50 Ohm output line of the amplifier. The high peak power level raises surface breakdown problems on the inner conductor and fixes a minimum length for the resistor. The resistor used in the carbon coated Siemens Karbowid 50 ohm 100 watt type. It stands easily the voltage corresponding to the 2.5 MW peak power if immersed in oil; when tested with water some breakdown was experienced. The heat during the 200 usec. pulse is carried away from the carbon layer by the ceramic former, so that the rise in temperature of the carbon at the end of the pulse is less than 150°C.

Oil cooling does not help appreciably during the pulse but it increases considerably the mean dissipation of the resistor.

The fixed frequency of operation makes it possible to choose between different shapes of outer conductor. The simplest form would be a cylindrical sleeve of any reasonable diameter connected at one end to the resistor. It is easy in fact at any given frequency to compensate the reactive part of the load impedance and to transform the resistive part into the wanted value. However,
It is shown in the Appendix that the input impedance of such a dummy load is equal to the resistance of the inner resistor and is independent of its length. The distribution of current along the resistor is uniform and no reflection will occur inside the dummy load. In principle, no coaxial transformer is needed. In practice, there may be some mismatch on the line; it will, however, be so small that the increase in voltage is negligible, and a very simple matching transformer can be used.

As illustrated in fig. 3 the outer conductor is connected to the extremity of the inner resistor by means of a brass cap. An insulating rod running along the axis fixes the inner conductor of the tapered line at the other end of the resistor. The impedance compensation is provided by adjusting the diameter of the inner conductor in the line that precedes the taper. The whole structure is contained in a box filled with paraffin oil (dielectric constant \( \varepsilon = 2.17 \)), holes being provided in the outer shell to allow free circulation of the oil.

The maximum temperature reached during operation is about 50°C. The dielectric constant does not appreciably change over this range of temperature.

- Dummy load for power meter

  The apparatus described above can work, in principle, as a calorimeter for measuring the power dissipated in the dummy load, if some precautions are taken to avoid heat leakage. The measurement, however, would be very inconvenient, because the heat capacity of the volume of oil is large and so the temperature rise would be very slow. In order to avoid this difficulty, the oil is confined by a plexiglass cylinder to a 2 mm annular space around the resistor (fig. 4). Sufficient cooling is obtained by circulating the oil at constant flow, and the power is calculated by measuring the difference in temperature.

- Calculating power
The dummy load is surrounded by an external jacket in which the oil flows from the bottom to the top around water cooling pipes. It goes then to the first thermometer and descends through annular space between the plexiglass tube and the resistor. Heat exchange between the resistor and the outer conductor is thus practically eliminated. The residual heat conduction along the end cap has been made very small by covering it with insulating varnish. The same has been done at the other end of the resistor along all the surface of the tapered line, which is in contact with the oil.

A further reduction in heat exchange has been obtained by adjustment of the oil flow so as to give a temperature difference of only a few degrees.

With $\Delta T = 1$ or $2^\circ C$ the error in reading the thermometers becomes appreciable; a compromise has been reached by allowing a rise of the order of 5 degrees for 2.5 MW power. Arrangements have also been made to stir up the oil before it reaches the second thermometer so as to have a stream of uniform temperature. Air bubbles must be carefully avoided, because they can affect the measurements. The closed circuit of oil and the submerged pump produce a stream completely free of bubbles. Nevertheless valve points are provided to eliminate bubbles which may occur during filling.

- Calibration of power meter

To calibrate the meter, 50 Hz power is applied to the resistor through an a.c. wattmeter and the power level adjusted by means of a Variac auto-transformer (fig. 6).

In principle, one calibration would suffice to determine once and for all the function $W = f(\Delta T)$ at constant flow (fig. 7). Nevertheless a substitution method is preferred because it allows the performance of the equipment to be checked continuously. The 50 Hz power is applied to the
bution, so errors due to heat exchange are avoided. Application of 50 Hz power to the resistor at the same time as H.F. power has been made possible by replacing the direct short circuit of the end piece by a capacitor of negligible reactance, (fig. 6). The capacitor consists of a 0.1 mm polyester film covering the silvered terminal of the cylindrical resistor and clamped under a copper strip fixed to the outer conductor. The 50 Hz circuit is completed through the loop of the H.F. supply.

Accuracy of the measurement depends only on the accuracy of reading a fixed temperature rise from the two thermometers and the mean power on the a.c. wattmeter. Facilities are provided for connecting an external voltmeter and ammeter if higher precision is required. An accurate measurement by the substitution method takes about 40 minutes. A faster method using the dummy load as an attenuator has been developed, as described below.

- Dummy load as attenuator

A fixed proportion of the power dissipated in the load can be measured directly by low-power equipment. As the frequency is fixed, the frequency sensitivity of the divider is not important, so that a single probe situated inside the resistor can be used. The coupling can be varied by adjusting the depth of insertion of the probe. The coupling must be loose enough not to affect the impedance matching of the dummy load. A 60 ohm coaxial line carries the attenuated power to a thermal wattmeter, the position of the probe being chosen to give a power ratio of 2000/I (-33 db). Five minutes is sufficient for a good measurement.

- Conclusion
b) by substitution of 50 Hz power for the H.F. power to be measured. The difference in reading of an a.c. wattmeter with and without the H.F. gives the amount of H.F. power.

c) by reading on a low-power thermal wattmeter when the attenuation is known.

The most accurate of the three methods is b). It forms the basis of the calibration for methods a) and c).

On the contrary the most practical is method c) which allows a fairly accurate measurement in quite a short time. Once the mean power is measured, the pulse power can be calculated if the pulse length \( \tau \) and repetition time \( \tau' \) are known,

\[
W_{\text{pulse}} = \frac{\tau'}{\tau} W_m
\]

If the pulse is rectangular there will be no uncertainty in measuring its length on the oscilloscope, but if the rise and fall times are not negligible the effective length is calculated from the expression

\[
\tau = \frac{\int v^2(t) \, dt}{\int v^2(t) \, dt}
\]

where \( V \) is the amplitude of the flat top.

The amplitude stability can be monitored with the accuracy of 0.5 o/n by a "gated pulse voltmeter" (ref. 7) connected to a power flow monitor.

The overall accuracy of the apparatus can be kept better than 3 o/n over the range from 100 kW to 2.5 MW by suitable choice of oil flow and attenuation.

I would like to thank Mr. Dind for his help in the design and construction.
Appendix

Let us consider a coaxial line with a resistive inner conductor whose length is not negligible compared with the wavelength (fig. 2). We can write the well-known transmission line equations:

\[ \frac{dV}{dx} = (r + j\omega l) I \]

where \(r, l, g, c\) are the line constants and \(I = I(x, t)\) \(V = V(x, t)\) are the current and the voltage at a point \(x\) from the end of the line.

Let \(Z\) be the characteristic impedance at the point \(x\). From \(Z = \frac{V}{I}\) it follows:

\[ \frac{dZ}{dx} = \frac{1}{I} \frac{dI}{dx} - \frac{V}{I^2} \frac{dI}{dx} = (r + j\omega l) - (g + jwc) Z^2 \]

In this case we can assume \(g = 0\). It follows that

\[ \frac{dZ}{dx} = r + j\omega (1 - c Z^2) \]

If we choose \(cZ^2 = 1\), that is \(Z = \sqrt{\frac{1}{c}}\) the above equation becomes:

\[ \frac{dZ}{dx} = r \quad Z = rx + k \]

If the line is short circuited at the end
equal the resistance of the length $x$ of the inner conductor.

But, as specified above $Z = \frac{1}{\sqrt{c}}$, so that the dimensions of the line in any point must be those of a non-dissipative line of impedance $Z$.

It follows then, from the familiar

$$Z = \frac{60}{\sqrt{c}} \ln \frac{b}{a}$$

and equation (5)

that

$$b = a e^{\frac{r x \sqrt{c}}{60}}$$

The inner diameter $a$ being constant, $b$ must vary exponentially.

At the point $x = l_o$, where $l_o$ is the length of the inner conductor,

$$Z = r l_o = R$$

The resistance $R$ can be chosen to be equal to the characteristic impedance of the feeding line so that the dummy load can match the line directly.

Although in this case it is not important, it is worth noting that, if $c z^2 = 1$, the dummy load impedance is independent of frequency.
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T: transmitter (crystal controlled)
S: pre-amplifiers
T.H.: drive and final amplifiers
P.D.: power dividers
D.L.: dummy loads

Fig. 1
Calibration curve of the power meter

*Fig. 7*

broken line: check of calibration curve three months later
General view of coaxial resistor dummy load.
Coaxial resistor and tapered outer conductor.
Front view of power meter with gated pulse voltmeter, thermal wattmeter and a.c. meters.
Rear view of power meter, showing the H. F. input, power flow monitor and constant flow pump.