CERN 59-15
Proton Synchrotron Division
7th April, 1959.

POWER FLOW MONITORS FOR THE LINAC H.F. SYSTEM

by

E. Zaccheroni

GENEVE
Contents

I - Summary
II - Introduction
III - Choice of the monitoring system
IV - Basic theory of the reflectometer
V - Construction
VI - Calibration
VII - Accuracy
VIII - Presentation of information
IX - Acknowledgements.
POWER FLOW MONITORS FOR THE LINAC H.F. SYSTEM

by

E. Zaccheroni

I Summary

A general outline of the LINAC power flow monitor programme is given. The design of reflectometers for the different stages of the H.F. chain is described and brief details are given of their practical construction. Calibration methods are discussed and curves for the different types of reflectometers are reported.

II Introduction

The H.F. system supplying the LINAC accelerating structure consists of a transmitter which drives two amplifier stages in cascade (ref. 1). A 400 kW pulsed power level is obtained; this feeds a 2,5 MW amplifier (ref. 2 and 3) that, in turn, drives three final amplifiers in parallel, one for each accelerating cavity. Power dividers (ref. 4) are provided between the drive stage and the final amplifiers to divert a desired amount of power into dummy loads. The power which is being transferred through the transmission lines connecting the different stages is monitored by means of directional couplers (reflectometers). The suggested position of such monitoring devices in the H.F. chain is shown in fig. 1. The level of power in the different stages and the corresponding peak voltages are indicated in the same figure. The frequency of operation is 202.5 MHz, and the R.F. pulses are of 200 μsec. duration. The nominal repetition rate is approximately 1 p.p.s.

III Choice of monitoring system

The more important considerations involved in the choice of the monitoring
system are:

1) The power to be monitored is that in the pulses, no average measurement is necessary. The power level varies in the different stages between 1 kW and 2.5 MW.

2) No great accuracy of the power detector calibration is needed, the relative change in power flow being a more useful parameter than the absolute value of the power.

3) No particular bandwith problems arise in the detector design, because the chain works at a fixed frequency.

4) The monitoring device must be very simple and take a negligible amount of power. In other words, it must not affect the performance of the line in which it is mounted.

5) Good directivity is required, in order to monitor separately the forward and the reflected power. Good sensitivity and stability are also important.

All these conditions are satisfied when a directional coupler is used. A simple loop fixed at one point of the line will not suffice as an indicator of power, because the measured value depends on the relative position of the loop and the standing wave, and a shift of this will cause errors in the indication. This inaccuracy becomes greater as the standing wave ratio deteriorates. The "reflectometer", on the contrary, is sensitive only to the wave travelling in one direction and therefore does not depend on the position of the standing wave. So, with a pair of reflectometers, the forward and reflected components of the standing wave can be separately measured, making it possible to calculate the reflection coefficient and the power transfer.

The constructional complexity and the stability of the reflectometer are comparable with that of a simple measuring loop. The adjustment of
directivity is easy enough in this particular case where a reflected power of the order of a few percent of the forward power is still considered negligible.

IV Basic theory of the reflectometer (ref. 7 and 8)

Let us consider a loop parallel to the inner conductor of a coaxial line and coupled through the wall into the field inside. One arm of the loop is terminated in a resistance $R$, whereas the other end is connected to a detector (fig. 2). The loop constitutes both a magnetic loop and a capacitive probe and responds to both current and voltage. Since all dimensions are chosen to be much smaller than the wavelength, the distributed parameters can be replaced by lumped ones as indicated in fig. 3. The magnetic coupling can be represented by a primary inductance, $L_1$, a secondary inductance $L_2$ and a mutual inductance $M$ (fig. 4). The capacity coupling is represented by the capacitor $C$. The impedance $Z_L$ of the loaded line appears in parallel between the inner and the outer conductor, that is between the inner and the ground. The load of the reflectometer is represented by an impedance $Z_m$.

The mesh equations written in Laplace transformation are:

$$u = (Z_L + pL_1) I_1 - Z_L I_2 + pMI_3$$

$$0 = Z_L I_1 + (Z_L + R + \frac{1}{pC}) I_2 - R I_3$$

$$0 = pMI_1 - RI_2 + (R + Z_m + pL_2) I_3$$

where $p = j\omega$

Imposing the condition that $I_3 = 0$ when the line is matched ($Z_L = Z_0$) and $M$ has the proper sign, the following equation is obtained:
\[ Z_R - pM \left( Z_o + R + \frac{1}{pC} \right) = 0 \] \hspace{1cm} (2)

By equating real and imaginary parts, it follows that:

\[ Z_o = \frac{M}{C} \]

(3)

and

\[ pM (Z_o + R) = 0 \]

The first condition can be fulfilled by the right choice of elements and is generally done empirically. The second one cannot be theoretically satisfied, since \( M, Z_o \) and \( R \) are always finite, but in practice \( Z_o + R \) can be made negligible compared with \( \frac{1}{pC} \), making \( pM \) small also helps in approaching this second condition. These requirements mean that the reflectometer must not load the line capacitively or inductively. With this in mind, the current through the capacitor can be considered negligible compared with the current through \( Z_L \). The small value of \( pM \) allows one also to neglect the influence of the loop on the primary current; as a result of this simplification, the current in \( L_1 \) and \( Z_L \) is the current \( I \) of the line and the voltage through \( Z_L \) is \( V = Z_L I \), that is the normal voltage of the line.

A new equivalent circuit can be shown (fig. 5) and, at open circuit \( (Z_m = \infty) \), the following expression for the output voltage can be written:

\[ e = \frac{1}{p} M I + p R CV = pK \left( V + \frac{Z_o}{p} I \right) = pK V \left( 1 + \frac{1}{p} \right) \] \hspace{1cm} (4)

where \( K = \frac{M}{Z_o} = RC \) and \( \rho = \frac{Z_L}{Z_o} \)

But the voltage \( V \) of a standing wave is:

\[ V = V_f + V_r \]
where \( V_f \) and \( V_r \) are respectively the voltage of the forward and reflected wave.

We can also write:

\[
V = V_f (1 + \Gamma)
\]

\[
V = V_r (1 + \frac{1}{\Gamma})
\]

(5)

where \( \Gamma \) is the reflection coefficient, defined as \( \Gamma = \frac{V_r}{V_f} \).

From (4) and (5) and the relation \( \rho = \frac{1 + \Gamma}{1 - \Gamma} \)

\[
e_+ = 2 Kp V_f
\]

\[
e_- = 2 Kp V_r
\]

(6)

for \( + M \) and \( - M \) respectively, corresponding to the two positions obtained by rotating the loop 180°.

If \( Z_m \) is finite, it follows from Thevenin's theorem that:

\[
v = \frac{Z_m}{Z_i + Z_m} e
\]

(7)

where \( Z_i \) is the impedance that is measured between the terminals \( AB \), when the voltage source is short-circuited.

\[
Z_i = (R, \frac{1}{pC}) + \frac{\omega M^2}{Z_L} + pL_2
\]

(8)

\( Z_i \) does not depend on the sign of \( M \). Considering that from the second condition of (3) \( (R, \frac{1}{pC}) = R \) and that at working frequency \( \frac{\omega M^2}{Z_L} \) and \( pL_2 \) are negligible compared with \( R \), it follows that:

\[
Z_i = R
\]
Putting \[ m = \frac{Z_m}{R + Z_m} \]

from (6) and (7) the following expressions are obtained:

\[ v_+ = \frac{Z_m K_p V_f}{R} \]
\[ v_- = \frac{Z_m K_p V_r}{R} \]

(9)

The proportionality of \( v_+ \) with \( V_f \) and \( v_- \) with \( V_r \) is evident.

V Construction

Two types of reflectometers are provided for the LINAC H.F. chain. They differ from one another in the size of the air-spaced coaxial lines that form the body and in the amount of coupling. The type "H" used for higher power fits the 76.5/33 mm 50 ohm standard line, whereas the type "S" is mounted on the 58/25 mm line provided for low power transfer. The both types, however, consist of a coaxial line body and of two detector heads, one opposite the other (fig. 6). No further description is needed for the body; the only details that are worth mentioning are the beryllium copper spring contacts of the inner conductor and the supports assuring the coaxiality of the line.

In the "S" type the inner conductor is centred by two cross supports made of polystyrene (Trolitul) whereas for the "H" type dielectric disks are used.

The detector heads are mounted as a brass cylinder of 40 mm in diameter divided in two parts by a transversal frame separating the high frequency and low frequency parts of the detector. Both the upper and the lower ends of each head are closed by brass disks. The coupling loop is supported by a pair of feed-through insulators in the lower brass disk. The capacitive coupling is obtained by a small brass plate soldered in the central part of the loop (1).

(1) No attempt has been made to compute the values of magnetic and electric coupling, since these may easily be adjusted experimentally.
One end of the loop terminates in a 100 ohm resistor (fig. 7) whilst
the other feeds a germanium rectifier type OA86, the output of which passes
through the internal frame of the cylinder.

The low frequency circuit is composed of a decoupling 47 pF capacitor
and a variable voltage divider. The d.c. output is taken off by means
of a coaxial cable. For adjustment, the heads must rotate in their sockets.
A four position click-stop mechanism permits the loop to be located parallel
or perpendicular to the inner conductor.

VI  Calibration

a) Zero setting.

The electric and magnetic coupling of the reflectometer must be balanced
to obtain "zero" response when the head is in the "reflected" position and the
load is matched. A dummy load with V.S.W.R. 0.97 has been used and the ba-
lancing has been carried out by keeping fixed the dimensions of the loop and
by reducing the probe to a suitable dimension for satisfactory compensation.
This adjustment has been made by the cut and try method. Good balancing can
be checked in several ways :

1) The reflectometer must not be sensitive to the standing wave (see curves
   fig. 8).
2) The "reflected" pulse must be zero if the line is matched.
3) The "reflected" pulse must be equal to the "forward" one if the
   line is short-circuited.
4) The amplitude of the output pulse of the reflectometer when the
detector head is oriented in the "forward" position and the load
is matched, must be twice the amplitude one can read when it is
turned by 90°.

The practical application of method 1) is not simple. In order to
check the sensitivity of the detector head to the standing wave, a relative
shift of the loop end of the standing pattern is needed. A sliding short-
circuit at the end of the line affects the output of the H.F. generator and, consequently, in the "forward" pulse, changes every time the short-circuit piston is moved. It is possible to restore it at the previous value by adjusting the generator, but this method is long and inaccurate.

An alternative would be to change the position of the detector head along the line, keeping fixed the standing wave pattern. But the displacement of the detector head from one reflectometer body to another requires good mechanical tolerances of all the components. The displacement of the whole reflectometer unit is also subject to similar tolerance problems.

Method 2) is not very accurate. In fact, near zero, the square law of the "reflected" pulse leads to a calculated ratio of forward and reflected power better than it actually is.

Method 3) is the best one and is independent of the value of the "forward" power.

Method 4) can be used as a check of good parallelism between the inner conductor of the line and the coupling loop. In fact, if the head rotates by 90°, the loop becomes perpendicular to the inner conductor. The magnetic coupling will then be zero, whereas the electric coupling remains practically unchanged. But, for the previous balance, magnetic and electric couplings are equal in magnitude and they add together in the forward position. When the loop is perpendicular to the inner conductor, the pulse must obviously be half that of the "forward" pulse. This is not true when the loop, in the "forward" position, is not parallel to the inner conductor.

All the above methods have been used.

Our principal aim has been that of keeping the accuracy to satisfactory values.

Better accuracy than that obtained would involve waste of time and effort.
b) **Power calibration.**

Once the balancing is obtained, a calibration of the "forward" pulse voltage in terms of H.F. power has been done by measuring the actual power dissipated in the dummy load (fig. 9). A calorimetric method was used; a detailed description of the measuring apparatus is given in another report (see ref. 5).

The amplitude of the "forward" pulse depends on the amount of total magnetic and electric field that is coupled. A first limitation in increasing the amplitude is that the reflectometer must not disturb the field distribution. This was assumed in the calculation above. At the same time, it is desirable that the amplitude of the "reflected" pulse should be large enough to avoid square-law detection. Of course, if we want to detect a very small reflection, we cannot avoid square-law detection. From low power measurement done on the detector circuit, we can state that linearity is still reasonable at 0.5 V.

**VII Accuracy**

The accuracy obtained in measuring the H.F. power by means of a reflectometer is limited by various sources of error, some inherent in the reflectometer itself, some due to the methods of reading the output pulse of the reflectometer and to its calibration.

It is worth while to discuss here separately the different points:

a) **Calibration of the forward and reflected power.**

The calibration is done by reading the output detected pulse on an oscilloscope or on a gated pulse voltmeter and measuring the mean power on a power meter. The accuracy of the mean power measurement is of the order of 3 c/o.

b) **Measurement of the variation of the power level.**

The overall accuracy depends on the stability of the detector head and on the accuracy of the meter used to measure the detected pulse.
If a "gated pulse voltmeter" is used, a change in amplitude of 25 mW can be read for a pulse between 2.5 and 25 V.

c) **Sensitivity to the standing wave.**

After balancing the sensitivity of the reflectometer to the standing wave is practically negligible (fig. 8).

d) **Change of the detection head.**

Every pair of heads forms a unit with a reflectometer body. Heads cannot be replaced separately, the complete reflectometer being treated as a unit. The interchange of the detector heads would have been possible only if closer tolerances in geometrical dimensions and electrical circuit had been introduced.

**NB.** The two opposite heads are normally fixed, one in the forward and one in the reflected position, in order to monitor remotely both forward and reflected waves.

**VIII Presentation of information.**

A double-beam cathode-ray tube unit is being constructed which will display simultaneously forward and reflected signals. A 400 microsecond sweep will be used on a tube with type "N" afterglow screen. A high final anode voltage on the tube ensures sufficient afterglow for interpretation of the information appearing once per second.

A panel of three such tubes at the Linac control position will show the signals in the feeds to the three tanks. Switching to a jumper cable will allow observation of signals from reflectometers in other parts of the system. A gated pulse voltmeter (ref. 6) is available when meter indication is required.
Acknowledgements

The equipment described in this report and in the two previous ones ("The 2.5 MW amplifier of the CERN Linear Accelerator" CERN 58.22 and "HF power meter for operation at 2.5 MW pulsed power" CERN 58.27) was either developed in the RF section of the Linac group of CERN-PS or in collaboration with French Thomson Houston in Paris.

Particular mention should be made of Dr. Geiger from CERN and Mr. Afanassieff from F.T.H. who originated the developments and I would also like to thank Dr. Hereward, Leader of the Linac group in CERN, for his suggestions during the work, Mr. Block and Mr. Marti for carrying out most of the measurements on the reflectometer and all the staff both from CERN and FTH who have been closely associated with the work.

E. Zaccheroni.

750 copies.
EZ/ac.
REFERENCES

1. U. Kracht  "The Linac R.F. power system below 400 KW"  

2. I. Afanassieff  "Générateur à impulsions de 2 MW crête"  
   Revue Technique C.P.T.H.  

3. E. Zaccheroni  "The 2.5 MW H.F. amplifier of the CERN  
   Linear Accelerator"  

4. P. Bramham  "A coaxial line variable power divider and  
   phase-shifter for high power"  

5. E. Zaccheroni  "R.F. power meter for operation at 2.5 MW  
   pulsed power"  

6. M. Geiger and  E. Zaccheroni  "A gated pulse voltmeter"  
   CERN-PS - LINAC/RF - March 1957.
Fig. 7
Sensitivity to Standing wave pattern

These curves are obtained by decreasing the capacitive surface of the probe. The loop dimensions remain same in each case.

<table>
<thead>
<tr>
<th>Surface of capacitive probe:</th>
<th>curve no:</th>
</tr>
</thead>
<tbody>
<tr>
<td>in mm.</td>
<td></td>
</tr>
<tr>
<td>7.1 x 9.45</td>
<td>1</td>
</tr>
<tr>
<td>7.1 x 8.85</td>
<td>2</td>
</tr>
<tr>
<td>7.1 x 8.3</td>
<td>3</td>
</tr>
<tr>
<td>7.1 x 7.8</td>
<td>4</td>
</tr>
<tr>
<td>7.1 x 7.35</td>
<td>5</td>
</tr>
<tr>
<td>7.1 x 7</td>
<td>6</td>
</tr>
</tbody>
</table>

Voltage in the forward direction 12V.

4 different readings are taken along the line at λ/8 intervals.
Courbe d'étalonnage réflectomètre "H."

Calibration curve of the "H." reflectometer
Courbe d'étalonnage réflectomètre "S".

Calibration curve of the "S" reflectometer.

Fig. 9b
Reflectometer with the two measuring heads.

Reflectometer showing coaxial line with inner conductor support and the two measuring heads.
Measuring head of a reflectometer showing the coupling loop and the various components of the circuit.