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The 2.5 MW H.F. amplifier of the CERN

linear accelerator

by

E. Zaccheroni

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The 2.5 MW H.F. amplifier of the CERN linear accelerator

- Summary

The report contains a description of the grounded grid amplifier using tuned coaxial lines designed for meeting H.F. power requirements of the CERN linear accelerator. Performance curves are given for this amplifier terminated in a matched load or short circuited. Guidance is given in choosing a suitable working point to prevent damage in the cavity and in the cables due to an external mismatch.

- Introduction

One of the most important technical differences between the various linear accelerators already existing or under construction seems to be the method of generating and feeding in the H.F. power. With reference only to proton linear accelerators, there has been a tendency in the last ten years to concentrate the power in a progressively smaller number of oscillators or amplifiers. A large number of units in parallel increases the difficulty of synchronisation, which must be very accurate to keep the whole system in phase during the pulse. In the 32 MeV Berkeley machine, the accelerating cavity was fed by all the oscillators in parallel so tightly coupled that the only possible oscillation was at the natural frequency of the cavity. The simplest method of synchronisation however, seems to be to use final amplifiers fed in parallel by a common drive, which can be crystal controlled. This solution was adopted in the Minnesota and CERN linear accelerators. In both the accelerating structure is made in three sections electrically independent, each of them fed by an amplifier. The complications of electrical coupling between the various amplifiers are thus avoided. It is obvious that a reduction in the number of units involves an increase of the H.F. peak power that each unit must deliver. The technical effort in recent years has therefore been turned to the construction of more and more powerful oscillators and amplifiers. Table 1) shows the number and output power of H.F. units of various American and European linear accelerators. The evolution from the 1948 H.F.

system of the Berkeley accelerator to that of the injector for the 30 GeV Brookhaven machine is evident.

- The CERN H.F. system

Although it is not within the scope of this paper to describe the whole H.F. system proposed for the CERN linear accelerator, a brief outline will be given of the H.F. chain, which is shown schematically in Fig. I.

The three final power amplifiers, with power outputs of 1, 1.8, 1.9 MW respectively are driven by an amplifier of the same type; this in turn is driven by a chain which includes a transmitter and two amplifier units in cascade. The level of power in the different stages is indicated in the figure.

- The 2.5 MW unit

a) General considerations

The development of the project of the 2.5 MW unit was based on the following data :

frequency	202.5 MHz (1.48 m wavelength)
H.F. peak power output	> 2 MW
pulse length	200 μ sec.
repetition frequency	1 pulse/sec.,
H.F. input power	< 400 KW

As one can see, the frequency and the power suggest the choice of a "common grid" amplifier with tuned coaxial-line circuits. This type has the advantage of good separation of the input and output tuned circuits. It follows that the neutralizing system is in general very simple and often unnecessary. In our particular case neutralisation at 60 MHz was considered desirable and fitted in the prototype, but the shielding action of the grid was found to be so effective that any neutralizing system was abandoned altogether in the later versions. The tuned coaxial-line circuit arrangement

leads also to a compact design of the amplifier and limits the H.F. radiation outside the unit.

b) The valve

The 2.5 MW cavity uses the triode TH 470, which has been specially designed and constructed by "Compagnie Française Thomson-Houston" to fulfil CERN requirements. Some of the more important data of this tube are quoted below :

Cathode material	Thoriated tungsten
Heater data	(Directly heated ($V_f = 15 \text{ V.}$ $I_f = 400 \text{ A.}$
Capacitances : anode to grid	55 pF
grid to cathode	105 pF
anode to cathode	1.5 pF
Limiting values : anode voltage	40 KV
bias voltage	-1.5 KV
peak cathode current	600 A
max. anode dissipation	5 KW
max. grid dissipation	1 KW
Cooling system : for anode	water evaporation
for cathode and glass	blown air.

Further information will be found in "Revue Technique CFTH" (ref. I).

c) The coaxial-line circuits

The simplified equivalent circuit of the common grid amplifier is shown in Fig. 2. The coaxial-line anode-grid and grid-cathode circuits can be tuned independently by means of movable plungers. The grid-cathode line is contained within the anode-grid line to minimize the height of the structure (Fig. 3). Both lines operate in the $3/4 \lambda$ mode. The anode D.C. blocking capacitor C is also of the coaxial type. It has to withstand at least 50 KV pulse voltage and at the same time present a very low reactance at 200 MHz. An attempt to use a "lumped" type capacitor composed of aluminium disks insulated by mica led to a bulky structure that was rather transparent

to H.F. radiation and left high voltages dangerously exposed. The solution adopted is the quarter wavelength coaxial line shown in Fig. 4. The diameter of the inner cylinder has been chosen as small as possible to permit a reasonable overall diameter for the unit without hindering quick removal of the valve. The outer diameter has been so chosen that the distance b-b' can withstand both H.F. and D.C. voltage. During the tests some trouble was experienced with breakdown in the upper part of the cavity, inside the pyrex tube and between the pyrex tube and the lid. It was found that the level of the cooling water in the anode jacket was rather critical. A change of ± 1 cm from the optimum level is equivalent to a change of at least 7 cm in the length of the pyrex tube for the same safety factor. The valve is held by three ceramic supports at 120° . The shape of these supports has been studied to avoid breakdown along the surface. It is desirable that the weakest part of the cavity should always be between two points in air. Then a random internal breakdown due, for example, to an external impedance mismatch does no permanent damage. The anode voltage is supplied through a half-wavelength stub that acts as a H.F. blocking system.

d) The power output coupling system

The arrangement for coupling the amplifier to a load consists of three untuned loops located symmetrically near the face of the anode-grid tuning plunger. This solution has been preferred to a single loop for the following reasons :

- 1) The symmetry of the electric and magnetic fields is less distorted by three loops than by one.
- 2) A power of 0.8 MW can be carried by commercially available coaxial cables; this would not be the case for 2.4 MW.

The complete system from the loops to a dummy load is shown in Fig. 4. Rigid air-spaced coaxial lines are fixed to the tuning plunger. Each inner conductor ends with a loop whose shape is a compromise between consideration of coupling area and voltage gradient between the loop and the cavity wall. The self-inductance of the loop has been kept low by using wide brass strip.

The active area of the loop can be varied by changing the length of the inner conductor directly from the outside.

Three 50 ohm coaxial cables join the air-spaced coaxial lines to a junction box acting as a quarter-wave transformer from 16.7 ohms to 50 ohms.

The 50 ohm side of the transformer can be connected either to the input of the accelerating cavity or to a 50 ohm dummy load.

- Cavity performance and measurements

The tests that have been made on the cavity can be divided into 3 principal groups :

- a) Test without H.F. signal
- b) H.F. power tests with matched dummy load
- c) H.F. power tests with short circuit at the end of the output line.

The test assembly is shown in schematic form in Fig. 5.

The anode voltage pulse is supplied by a pulse-forming network and can be varied from a few kilovolts up to 50 KV by changing the charge voltage of the line.

The value of the pulse voltage is read through a 1000/1 voltage divider.

The input H.F. power is supplied by a driver and can reach 400 KW. Its value is read through a reflectometer (ref. 5) at the output of the drive unit. Another reflectometer measures the output power. The anode and cathode currents are measured across a $.02 \Omega$ non inductive coaxial resistor. The bias voltage can be varied by a 10Ω potentiometer between cathode and ground.

The dummy load provided for the tests of group b) consists of a 50Ω carbon film resistor within an exponential outer conductor. This dummy load is oil cooled and a system is provided for the calorimetric measurement of the power (ref. 3).

The tests of group c) are carried out by terminating the line with a movable short-circuit plunger mounted in half-wavelength line.

a) Test without H.F. signal

The valve and the coaxial-lines stand easily 40 KV anode voltage. Some breakdown was experienced at 65 KV in the stub holding the anode voltage cable. Higher anode voltage may cause breakdown inside the tube.

b) H.F. power tests with matched dummy load

- b1) A set of tests was carried out to find the optimum size of the output loops. The cavity was tuned and the anode voltage fixed at 40 KV. The area of the loops was decreased by steps and the drive power varied between 150 and 330 KW. The relation between loop size, drive power and output power is given in Fig. 6. The loop area is expressed in percentage of the optimum value (in our particular case 12.43 cm²). Every position of n corresponds to a variation of 8.5 n o/o. The dotted line limits a region of probable breakdown inside the cavity due to undercoupling. A study of Fig. 6 shows that a good compromise between safety and efficiency can be reached by choice of the point A (it corresponds in our case to ~ 13 cm²).

- b2) With the loops fixed in this position, the anode voltage at 40 KV and the cavity accurately tuned we have reached a power level of 2.5 MW ± 5 o/o. Some breakdown occurred in the pyrex tube (see Fig. 3) and between the walls of the anode-grid tuning coaxial line. We could get rid of the breakdown in the pyrex tube by lengthening it, but this hardly seemed worth while since at slightly higher power, breakdowns across the cavity become rather frequent. Several breakdowns have been experienced also when slightly mismatching the dummy load impedance. Measurements have been carried out of the output power as a function of anode voltage and drive power. The relationship is given in Fig. 7.

c) H.F. power tests with short circuit at the end of the output line.

- c1) The short circuit problem

The tests carried out on the amplifier when connected to a matched load do not give a sufficient idea of its performance if connected to the accelerating cavity. In the condition of working as a final amplifier there are two possibilities of short circuit. The first, that we can define as normal because it appears at the beginning of each pulse, is due to the

difference between the build-up time of the field in the accelerating cavity and the rise time of the power of the amplifier.

The second is random and may be caused by a flash-over inside the accelerator or by a refusal of the field to build up. Both the short circuits produce a standing wave in the output line and consequently points of increased voltage. There is however a difference between the two types of short circuit: in the first case the antinode is fixed, in the second one it can change according to the position where power reflection occurs. The voltage at the antinodes may damage the lines if they are not designed to withstand safely twice the normal voltage, but, as will be seen later, a solution of this kind is rather complicated. A better solution is to arrange the various parameters so that the amplifier reacts to the short circuit condition by an automatic reduction in output power. The result will then be that the line is subjected to twice the voltage for only a very short time, the voltage falling for the rest of the pulse.

- c2) Forward (or reflected) power as a function of the short circuit position

The influence of the short circuit position on the forward output power will now be studied. The cavity is put in the test condition of Fig. 7 but the matched load has been replaced by a sliding short circuit. In order to be as near as possible to the final operating conditions the charging voltage of the modulator was kept constant rather than the anode voltage itself. The forward output power was read by means of a reflectometer for different positions of the sliding short circuit plunger and for different values of drive power.

The results are plotted in Fig. 8. The curves show how in a particular position ($\lambda = 60$) it is practically impossible to prevent a breakdown inside the amplifier cavity even with very low drive power. At a distance of a quarter wavelength ($\lambda = 23$) however it is possible to increase the drive power without causing breakdown. There is the alternative of changing the position of the anode-grid tuning piston keeping fixed the short circuit plunger. To investigate this, a measuring loop has been mounted on the anode-grid piston. The modulator charging voltage and the drive power were again fixed. These parameters will probably be different in the final installation; so the curves

of Fig. 9 will only have qualitative significance. They show that it is possible to find a resonance of the anode cavity and output lines system for different combinations of the positions of the piston and of the plunger. The dotted curve shows how the variation of the voltage of the forward (= reflected) power in the output line follows the resonance. It also shows, as was expected, that a displacement of a few millimeters of the anode-grid tuning piston would correspond to a displacement of several centimetres in the short circuit plunger. It follows that in the case of a fixed short circuit it will be useful to choose the length of the output line and the position of the anode-grid tuning piston so as to be as far as possible from resonance.

- c3) The reaction of the amplifier to a sudden short circuit

The power output available into a matched load must, however, still be taken into account in making any changes to the position of the anode piston. When the output power requirement is very high, anode piston setting is very critical and no range of adjustment is available for influencing other parameters. It follows then that the length of the output line is the only available variable.

In Fig. 10 are plotted curves of various drive power levels and various modulator charging voltages when the cavity feeds either a matched dummy load or a short circuit in position $\mathcal{K} = 23$. The curves a, b, c correspond to increasing values of the charging voltage. On the x axis is shown the output power into a matched load and on the y axis the forward (= reflected) power when the output is short-circuited. It appears that it is advantageous to work with high anode voltage (curve c). A power level of 1.89 MW into a matched load ($\hat{v} = 13,7$ KV) corresponds in the three curves a, b, c to 0.88, 0.8, 0.7 MW (18.7 KV, 17.9 KV, 16.7 KV at the antinodes). It will be seen that these maximum values will considerably simplify the design of the output lines. The case of an erratic short circuit still remains to be considered. It may happen that this coincides with the position $\mathcal{K} = 60$. The voltage at the antinodes increases (with 1.89 MW it will be 27.4 KV). But the antinodes in this case occur in a position in which the anode cavity is completely off tune : it therefore seems useful to put a spark gap at the antinode point. The position of this safety spark gap must be fixed according to the position of the anode-

grid piston. It seems possible to put a protective circuit also on the input side of the cavity. In fact it was seen during the tests that near resonance of anode cavity a large reflection occurred at the input. This suggests putting a spark gap at an antinode of the input line or arranging an electronic device to react when the reflected wave increases.

- The "plumbing" problem

The connection between the output loops of the amplifier and the load is made by air-spaced coaxial lines and solid dielectric cables. A system of only rigid lines would not have enough mechanical flexibility to follow the movement of the anode-grid tuning piston, so cables are provided to connect the rigid lines at the output of the amplifier to the rigid line at the input of the load. The three output lines ($\emptyset$ 58/25), if considered without any support holding the inner conductor, have a power handling capacity of four times the maximum power required when calculated on the basis of breakdown at 30 KV/cm. The presence of dielectric cross supports decreases the breakdown voltage so much that the safety factor at full power is completely lost. Plexiglas rods flash over with tracking at low power (0.6 MW). Polystyrene is better (0.8 MW) but not sufficient. An attempt has been made to hold the inner conductor directly by the loop itself. This involves using strong loops fixed at the tuning piston. The top of the loop can slide along the inner conductor to change the effective area. Concentricity is assured by the cable connector screwed on the opposite end of the line. The other teflon or polystyrene supports along the lines have been suppressed by simple mechanical arrangements. Particular care has been taken in avoiding sharp metal corners and in designing the spring connectors and the joints.

- The cables problem

The only weak point that still remains is the connection between the air-spaced coaxial lines. The cable used is RG17/U (15.4 KV peak); it will not safely withstand a short circuit at 2.4 MW power level, but arrangement can be made as described above to reduce the antinode voltage under these conditions. This cable is however the biggest readily available and cannot

easily be replaced. The connection between the rigid line and the cable is made by means of moulded connectors of special design (ref. 4) that are being developed. A provisional connector for laboratory use has been filled with "relcompound" filler. Its electrical performance is good if air voids are carefully eliminated but it has tendency to crack and retain dust.

- Conclusion

As seen above the amplifier can reach the 2.5 MW level only if some precautions are taken. In particular the cooling water level, the cleanliness of the cable connectors and the impedance match have to be carefully controlled. For safety in the case of a short circuit the amplifier parameters and the line length have to be chosen as indicated in the report, after final installation of the cavity.

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T A B L E I

LIST OF PROTON LINEAR ACCELERATORS

	Energy	Total HF peak power	Type of final unities	Number of final unities	HF peak power per unit	Type of tube	Repetition rate	Pulse length	Frequency	Notes
	MeV	MW		No	MW		cps	μsec	MHz	
Berkeley	32	2.2	oscillator	26	0.09	GL-434 triode (4)	15	600	200	year 1948
				9	0.25	3W 10000 A3 (EIMAC)				year 1950
Berkeley	10	0.5	oscillator	3	0.17	3W 10000 A5 (EIMAC)	1/6	500	200	Bevatron injector
University of Minnesota	68	6.4	resonator	3	0.7; 2.3; 5.4;		60	300	200	
Brookhaven National Laboratory	50	~ 5	klystron ²	1	5	(EIMAC)	5	200	200	30 GeV machine injector
CERN	50	~ 5	grounded grid amplifier	3	0.8; 1.8; 1.9;	TH 470 (CPTH)	1	200	200	25 GeV proton synchrotron injector
Harwell AERE Lab.	50	~ 5	grounded grid amplifier	3	0.83; 1.71; 1.86;		50	400	200	

² Under consideration.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

CAVITY N° 3

Fig. 7

Fig. 8

V measuring
loop

CAVITY № 3

loop position A
grid tuning 00138
bias resistor 6Ω
modulator setting fixed
output line { as in fig. 4
drive power + reflect (20cm)
fixed (<40W)
dotted line shows
direct (or reflected) power
along the output line

26 (anode tuning)
position

27

28

29

30

22

24

25

s.c. plunger position

Fig. 9

CAVITY N°3

Fig. 10

The triode TH 470 being lowered into the cavity.

View of the cavity partially opened showing the cooling system and the anode voltage stub.

Top view of the cavity without the TH 470 triode.

Top view of the cavity with the TH 470 triode in position.

Anode-grid tuning piston and the output loops.

General view of the cavity.

The junction box, the reflectometer and the dummy load.