

# YH 1045, a 12-kW High-Power Traveling-Wave Tube for Multi-Carrier Operation in Satellite Communications Ground Stations

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In the new satellite communications systems, it is intended to introduce multiple-access satellites in order to economically utilize the relatively expensive installations involved. Since the high-power amplifier will have to transmit several carriers, each with up to 120 speech channels, and in limited cases more, and possibly an additional television carrier, the output power tube must meet some particularly stringent requirements. It must exhibit virtually uniform transmission characteristics over the frequency band 5.925 to 6.425 GHz for constant operating voltages, good linearity, low intermodulation products [1, 2], and low crosstalk ratio between the individual carriers, i.e. low AM/PM conversion [1, 2, 5, 6]. These requirements are met by the Siemens traveling-wave tube YH 1045 developed from its forerunner types YH 1040 and YH 1041 [2, 3]. This tube is a wideband device meeting the additional requirements of multi-carrier operation.

## Design of the traveling-wave tube YH 1045

The YH 1045 is a metal-ceramic tube consisting of several subassemblies as shown by the longitudinal cross section in Fig. 1.

## Beam formation and guidance

Unlike the traveling-wave tubes YH 1040 and YH 1041, both of which are focused by periodic permanent magnet structures [3], a solenoid (Fig. 2, right) producing a dc field has been employed for the YH 1045. This has to provide a constant magnetic field along the tube axis, including the section, which, because of the output waveguide, could not be covered by the coil itself.

Fig. 3a shows the variation of magnetic field along the tube axis from one coil without iron weighting. The flanks become considerably steeper when the winding is shielded (Fig. 3b), and a partial short-circuit with an iron cylinder levels off the cusp of the curve (Fig. 3c). Finally, one end plate is moved away (Fig. 3d) to make room for the output waveguide. The cooling has considerable influence on the design of the solenoid. Individual disk-shaped coils stacked up on a core form the complete solenoid, between which copper plates with water pipes brazed to their circumference are located (see Fig. 2). The solenoid is magnetically shielded, and produces a 1200 G axial field with a 20% gradient at the collector end of the tube.

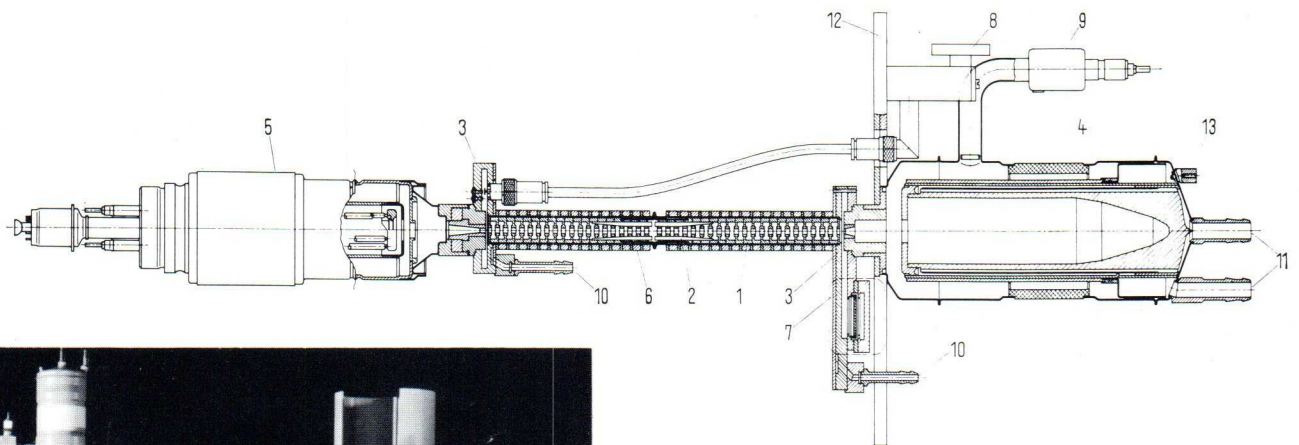


Fig. 1 Longitudinal cross section through the traveling-wave tube YH 1045

- |                      |   |
|----------------------|---|
| 1 Delay line         | 9 Ion pump  |
| 2 Absorber           | 10 Water pipe connections for both sections of the line |
| 3 Coupling waveguide | 11 Water pipe connections for the collector             |
| 4 Collector          | 12 Collector end pole plate                             |
| 5 Electron gun       | 13 Collector terminal                                   |
| 6 Field straightener |   |
| 7 Output waveguide   |   |
| 8 Input waveguide    |   |

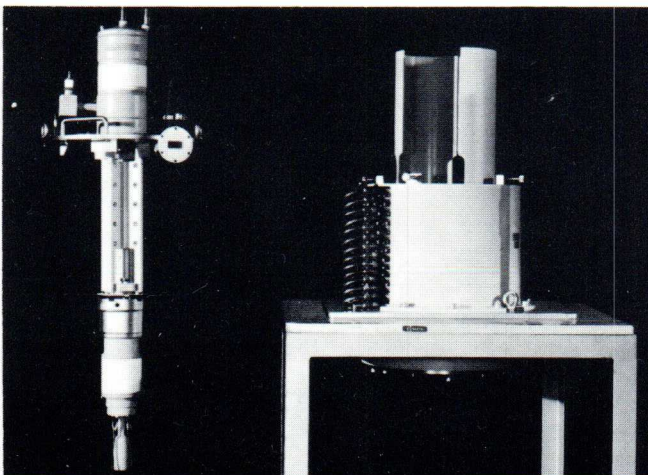


Fig. 2 Traveling-wave tube YH 1045 (left) and associated solenoid MS 1045 (right)



The electron gun incorporates a flat metal dispenser cathode 16 mm in diameter and providing a current of 3 A at 18 kV beam voltage. A reversing field (see Fig. 4) compresses the beam to a diameter of 2.5 mm. This type of field has the advantage over a steadily rising field of ensuring that both converging and diverging electron streams can be matched to the main field. In order that the electron streams arrive compressed and parallel in the main field, the path of the electrons must be bent both inwards and outwards at least once. A magnetic prefocusing field of about 500 G produces the inward bending near the second anode, with a reduction causing the outward bending. In the practical version, the prefocusing field is generated by two coils connected such that the resultant field opposes the main field. One prefocusing coil is connected into the main coil circuit, the other is supplied from a separate source. A magnetic plate between the main and prefocusing coils defines the position of the transition through zero field strength.

The prefocusing field is optimized the first time the tube is fired up: No further correction is required for subsequent switch-on, and the turn-on time is then only a function of the power supply unit.

Because of inevitable asymmetries, the mechanical and magnetic axes will not coincide from the very outset. As Fig. 2, right, shows, four positioning screws are provided for centering the tube, and these are adjusted to give minimum delay line current when the tube is first fired up. Furthermore, undesired transverse magnetic forces can occur, which would deflect the beam and hence damage the delay line. These radial field components are considerably reduced (from 7 to 1 or 2 G) by a field straightener on the tube. This field straightener consists of soft iron rings spaced evenly along the tube axis. The rings form a "Faraday cage" and shield so effectively that in the position of maximum possible tilt to which the tube can be adjusted (about  $0.75^\circ$ , corresponding to a transverse field of about 7.5 G), the delay line current is

only 25% higher than when the tube is optimally positioned. The water-cooled collector is made of vacuum copper. A water flow rate of about 60 liters/min is required to dissipate the heat developed at the maximum beam power of 70 kW. The specific loading is about  $0.1 \text{ kW/cm}^2$ , requiring an outlet back pressure of at least 2 atmospheres. In order to increase overall efficiency, the collector has also been designed for depressed operation. On full RF power (6 kW), the collector voltage may be as much as 7 kV below the delay line voltage. The electrons thus reach the collector with a velocity lower by the 7 kV, thereby reducing the collector dissipation; the efficiency increases from 12 to 20%.

#### Slow wave structure (delay line)

The slow wave structure is of the same design as that used in the YH 1041. The individual resonator, or cell, made from vacuum-cast copper, is cold stamped and the top slot milled in subsequently. The cells are stacked up on a gauge and brazed together with silver solder to form a vacuum-tight subassembly [3]. The slot inductance has been chosen such that the gain at 6 GHz is wideband. The upper cutoff frequency of the line is 12.5 GHz. Any higher modes of the delay line are so high that the tube cannot oscillate when the line voltage is applied. Amplification is obtained by interaction of the beam with the first forward space harmonic [4]. The line length is such that the minimum gain over the band 5.9 to 6.4 GHz is 30 dB.

#### Absorbers

To prevent feedback from the output to the input of the tube, the input and output sections of the line are provided with integral wedges of attenuating material [3]. Four absorbers are used per line section; the attenuation of one metal-ceramic absorber is about 30 dB. The absorbers must be extremely closely matched to the line, and the power reflected may not exceed 0.05%.

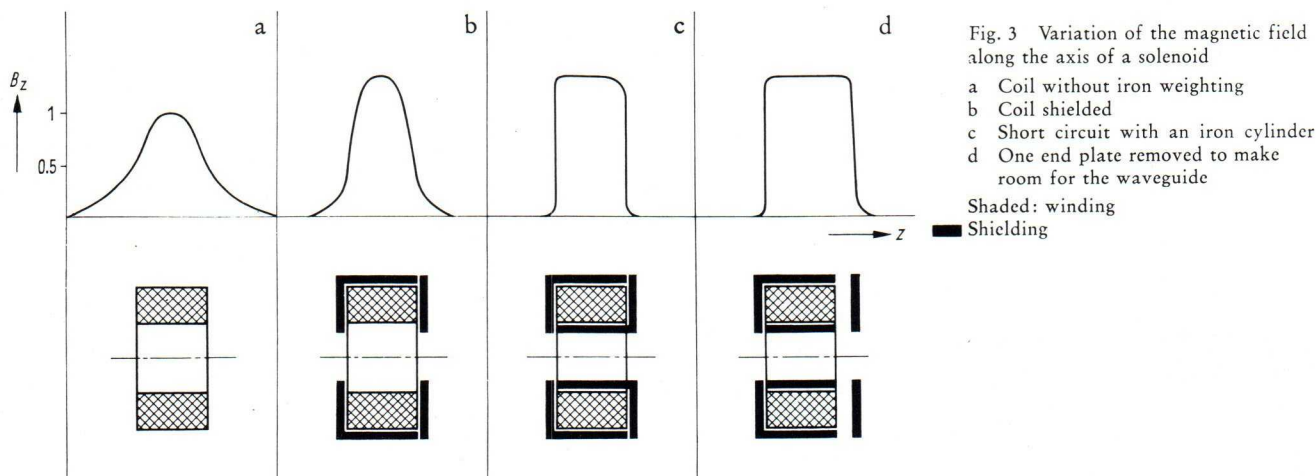


Fig. 3 Variation of the magnetic field along the axis of a solenoid

- a Coil without iron weighting
- b Coil shielded
- c Short circuit with an iron cylinder
- d One end plate removed to make room for the waveguide

Shaded: winding  
 ■ Shielding

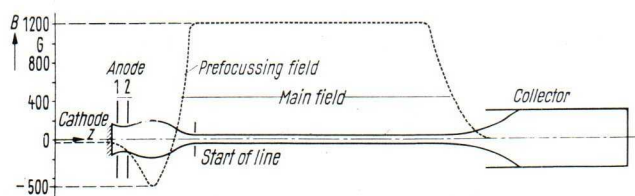


Fig. 4 Variation of the magnetic field strength  $B$  between the electron gun (left) and collector (right) of the traveling-wave tube YH 1045  
 Dotted line:  $B = f(z)$



## RF input and output

Special attention has been given to "shading" the dielectric window as much as possible from the electron beam. For this purpose rectangular waveguides normal to the tube axis are brazed to the line. A ceramic window is brazed into the output waveguide parallel to its wider side, and the RF energy is coupled through this window into a second rectangular waveguide. In the interests of field-replaceability, the input section is provided with a coaxial window to keep the cross sectional dimension of the tube small enough to permit insertion by the gun end into the solenoid.

## High-frequency properties of the traveling-wave tube YH 1045

### Bandwidth

In order that the tube can operate with several carriers simultaneously (each carrier usually containing 120 telephone channels), the operating voltages must remain constant, and the gain may not vary by more than  $\pm 3$  dB over the complete frequency band. The curve a in Fig. 5 shows the gain variation with frequency at a constant input power of 0.5 W.

### Intermodulation

When an amplifier with a nonlinear transfer characteristic is driven by several signals simultaneously, each of a different frequency, the output spectrum consists not only of the original input signals or carriers, but also of so-called intermodulation products. The number of carriers and the required maximum level of the intermodulation products below the carriers determine the necessary saturation power, and hence the size of the tube [1, 2]. The curve b in Fig. 5 illustrates the variation of the third-order distortion factor  $d_3$  with frequency using the "two-tone" test with two carriers each of 500 W or 1 kW total average output power. If the total power is doubled ( $2 \times 1000$  W), the curve shifts by 6 dB, for example from 30 to 24 dB.

### AM/PM conversion, nonlinear crosstalk

When two or more frequency-modulated signals are simultaneously amplified by one traveling-wave tube, the channels of different carriers belonging to the same baseband influence each other because of the frequency-dependent gain variation of the tube coupled with the additional AM/PM conversion [1, 2]. A measure for the resultant crosstalk modulation is the so-called "intelligible crosstalk modulation factor"

$$D_k = 20 \log \left( \frac{\pi}{90} F_B \Delta G k_p \right)$$

where  $F_B$  is the bandwidth of the baseband in megahertz (between 2 and 5 MHz),  $\Delta G$ , the gain variation in decibels per megahertz (as obtained from the curve a in Fig. 5) and  $k_p$ , the AM-to-PM conversion, i.e. the change in phase difference between the input and output voltage for a change in amplitude of the input voltage, expressed in degrees per decibel.

The curve c in Fig. 5 shows the AM/PM conversion over the frequency band 5.9 to 6.4 GHz for an output power of 5 kW. For two 500 W carriers the intelligible crosstalk modulation factor for a 5 MHz baseband is  $\leq 45$  dB.

### Variation of the group delay in a transmission channel

In order to keep the group delay distortions as low as possible, the dispersion characteristic [4] of the space harmonic used for amplification has been made virtually independent

of frequency. In this way the phase and group delays are almost constant over the frequency band of interest, which is an important prerequisite for multi-carrier operation.

## Characteristics of the traveling-wave tube YH 1045

The most important characteristics of the YH 1045 are tabulated below. The Table also contains guiding values for the power supply when the tube is connected up as shown in Fig. 6.

The tube can also be operated without depressed collector, in which case the two separate power supplies for the delay line and collector can be replaced by a single supply capable of a maximum current of 3.5 A. The single supply unit must, however, meet the stability and hum requirements recommended in the Table for the delay line power supply.

The delay line and collector power supplies can also be connected in series, then the voltage  $E_{dl}$  must be variable from 0 to 7 kV at 120 mA when the collector voltage  $E_b$  is constant at 13.5 kV. The control network must withstand 20 kV. It is advisable to derive the grid No. 2 voltage  $E_{c2}$  from a potential divider ( $R_1$  in Fig. 6) with a total resistance of about 500 k $\Omega$ .

The relay S in the delay line circuit must cut out the delay line voltage within 15 ms with excessive delay line (body) current (without RF 40 mA, with RF depending on the level of the output power and the depression 90 mA).

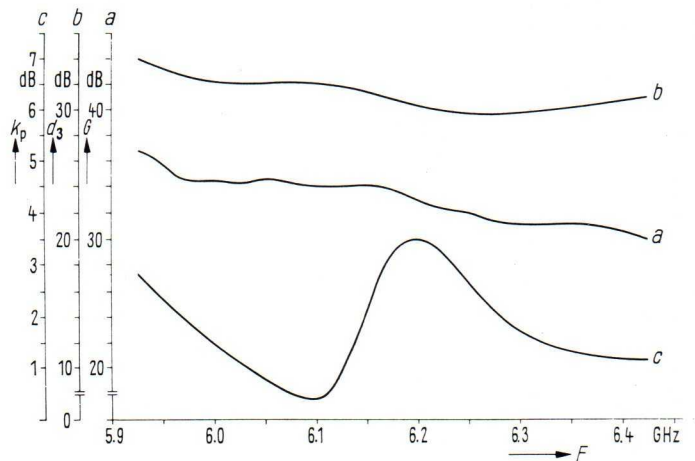


Fig. 5 Variation of the gain  $G$  with frequency for an input power of  $P_i = 0.5$  W (curve a), variation of the third-order distortion factor  $d_3$  with frequency (curve b) and variation of the AM/PM conversion  $k_p$  with frequency (curve c)

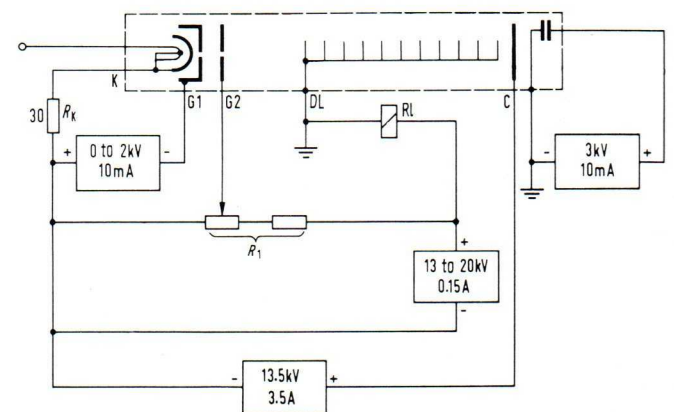


Fig. 6 Recommended power supply for the traveling-wave tube YH 1045



## Characteristics of the traveling-wave tube YH 1045 and power supply data

	Power supply	Recom. stability and hum	Modulation sensitivity
<b>Heater (ac/dc)</b>			
$E_f$	5 V	4 to 6 V	$\pm 1\%$
$I_f$	13 A	12 to 16 A limited to 30 A	—
Standby	$0.85 E_f$	—	—
<b>Grid No. 1</b>			
$E_{c1}$	300 V	100 to 400 V	$\pm 0.1\%$
$E_{c1 \text{ max}}$ (switch-on value)	2 kV	2.5 kV	$\pm 5\%$
$I_{c1}$	50 $\mu$ A	10 mA	$\pm 0.1\%$
<b>Grid No. 2</b>			
$E_{c2}$	9.5 kV	7 to 12 kV	$\pm 0.1\%$
$I_{c2}$	50 $\mu$ A	—	—
<b>Delay line</b>			
$E_{d1}$	18.5 kV	13 to 20 kV	$\pm 0.1\%$
$I_{d1}$	20 mA (without RF)	150 mA (at 5 kW)	—
$I_{d1 \text{ max}}$ (at switch-on)	70 mA	—	—
<b>Collector</b>			
$E_b$	13.5 to 18.5 kV or 13.5 kV fixed	11 to 20 kV or 13.5 kV fixed	$\pm 5\%$
$I_b$	3 A	3.5 A	—
<b>Solenoid</b>			
Main coil (Sol1)			
$E_{sol1}$	280 V	380 V	$\pm 1\%$
$I_{sol1}$	11 A	6 to 12 A	—
Prefocusing coil (Sol2)			
$E_{sol2}$	4 V	12 V	$\pm 1\%$
$I_{sol2}$	3.5 A	0.5 to 8 A	—
<b>Ion pump</b>			
$E_p$	3 kV	3.3 kV	$\pm 5\%$
$I_p$	<1 $\mu$ A	10 mA	—

## Running up the traveling-wave tube YH 1045

After inserting into the solenoid MS 1045, the tube supply leads are connected up according to the color code, and the tube centered optically with the aid of the four centering screws. Once the cooling system has been turned on the grid No. 1 voltage is applied at its switch-on value of  $E_{c1} = -2$  kV, and the heater voltage brought up slowly to its nominal value. The collector voltage  $E_b = 13.5$  kV can also be applied at this time since it has no influence on the gun. When the ion pump current at full heater voltage has fallen to 2  $\mu$ A or less, the heater voltage is reduced by 15% ( $0.85 E_f$ ); this cathode temperature corresponds to the full 3-A operation since the cathode current drawn cools the cathode. The grid No. 2 potential divider ratio should be set to about 1:2, i.e.  $E_{c2} \leq 1/2 E_{d1}$ . The solenoid coil currents are now set to the values given on the card accompanying the tube. The 13-kV delay line voltage can now be applied immediately or brought up slowly from zero. It is now recommended that the tube position be optimized by adjusting the four centering screws for minimum delay line current. Next the delay line voltage is brought up to nominal and at 16 to 18 kV the grid No. 1 voltage reduced to its normal operating value. The delay line current is again minimized by adjusting the current  $I_{sol2}$ . Once the tube has been fired up for the first time, the full operating voltages can be applied, with the heater voltage switched to its full value when the high voltage is applied, and the grid No. 1 voltage reduced from  $-2$  kV to its normal operating value when the delay line voltage reaches about 17 kV. Both of these switching processes can be carried out automatically using simple relay circuits.

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