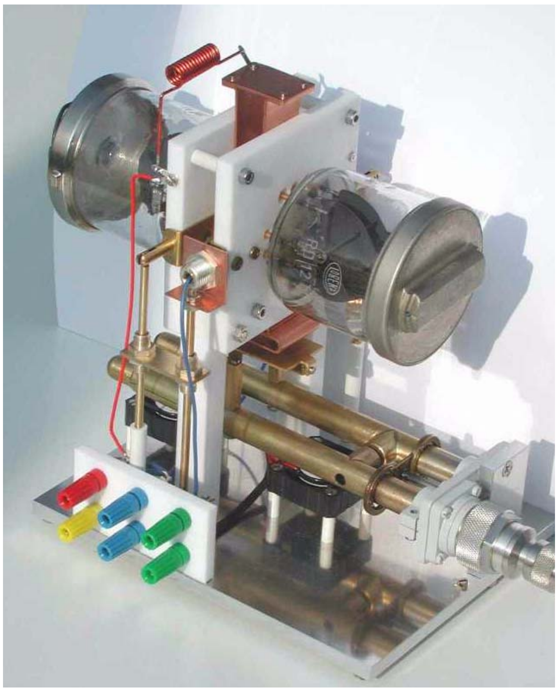
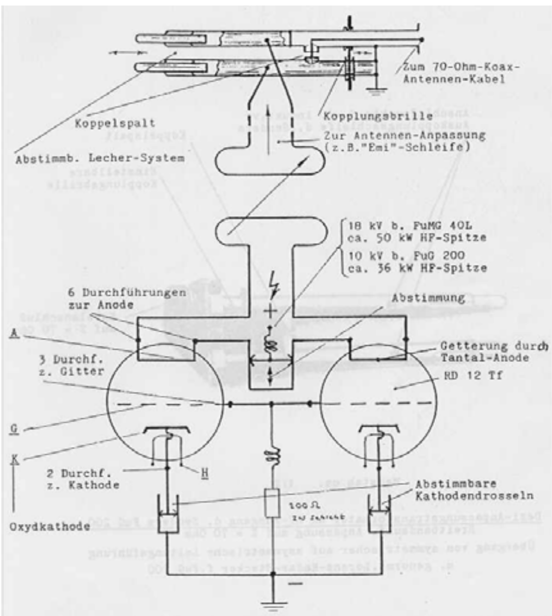
# Early German Radartransmitter Technology

The German FuG 200 transmitter was originally developed for the FuMG 41 system but later employed in the Hohentwiel radar set. This airborne radar was used for search and homing on surface ships and for navigation with land echo, and also as a blind-bombing aid in conjunction with the FuG 102 radio altimeter. It operated at the highest frequency so far used by the Germans and is also remarkable among their sets in that the transmitter generated the highest RF peak power used in German as well as Britain and American airborne radars, to enable a detection range up to 150 kilometers. The German torpedo-bombers operating over the North-Atlantic against the ship-convoys, as well as the long-range bombers that carried the radio-controlled glide bomb, were equipped with the Hohentwiel-airborne radar system.



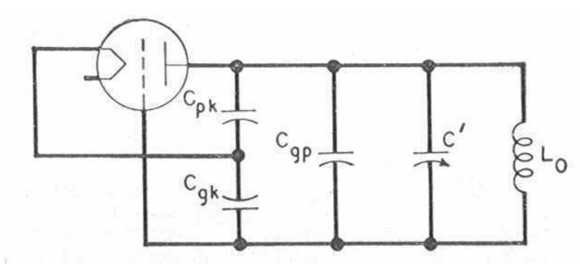
The Hohentwiel airborne radar transmitter (shown here as an open laboratory model) was developed in 1941 by the C. Lorenz company at Berlin. Its push-pull grounded-grid oscillator was tuneable between 525 - 575 MHz. Two Lorenz RD12Tf triodes with oxide-cathodes were used as oscillator tubes. The transmitter tubes were plate keyed by a thyratron modulator with 10 kV, 2 µs high voltage pulses at a pulse repetition rate of approx. 50 Hz. The photo shows the copper-plate resonant circuit with six plate connections per tube. One of the two tuneable cathode lines is visible in the foreground. The bottom of the photo shows the brass Lecher line for symmetric to asymmetric (balun) conversion of the RF-power. The transmitter generates an RF pulse power in the region of 30 kW.




The schematic diagram of the Hohentwiel-transmitter is shown beside. Feedback voltages for the tube cathodes are produced by voltage-dividing in the tube capacities $C_{\text{plate-cathode}}$ and $C_{\text{grid-cathode}}$. The adjustable cathode line circuits provide phase control of the feed-back. The oscillator frequency is determined by the plate-circuit inductance, the lumped plate-circuit capacitances and the internal grid-plate capacitances of the tubes. For separation from the DC high-voltage potential, inductive coupling is employed between the plate resonant circuit and the output. The RF-power is delivered via the tuneable balun transformer.

The output circuit of the Hohentwiel-transmitter with the inductive coupling loop and the tuneable balun transformer. With the adjustable stubs of the Lecher lines, at the left the output circuit is tuned to resonance with the transmitter frequency. The adjustable slide bar at the right allows matching of the output circuit to the load impedance.

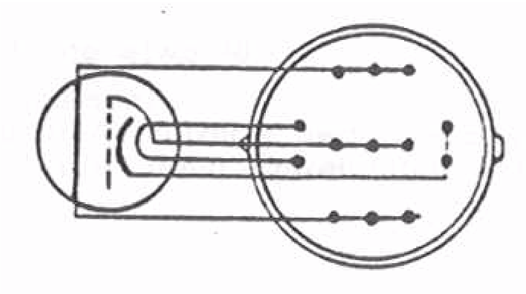
At the highest useful frequencies of triodes, the grid-return or grounded-grid circuit is of great importance for oscillators. The basic reason is the physical position of the grid between cathode and plate in a triode.




Grid-return oscillators can be made in which almost the only coupling between the frequency-determining plate circuit and the feedback to the cathode circuit is produced in the capacitive voltage divider formed by the internal tube capacities $C_{pk}$ (plate-cathode 1.35 - 1.65 pf ) and $C_{gk}$ (grid-cathode 6.3 - 7.7pf for the RD12Tf triode).

The resonant-transformation effect necessary to supply the feedback voltages to the cathode circuits is produced by this capacitive voltage divider, so that the polarity of the returned voltage is correct and that the required step-down voltage ratio is provided.


The RD12Tf transmitting-triode was developed in 1940 at the C. Lorenz tube laboratory in Berlin, for radar applications. Like its predecessor the DS320 tube, it was fitted with an oxide cathode and was laid out for operation up to 600 MHz. Its construction meets the physical requirements for airborne use. As partly visible on the photo, the tube has six plate pins and three grid pins. With forced air cooling the plate dissipation rating is 75 watts. In plate-keying operation the tube may be pulsed up to 18 kV at sea level and generate an RF output power in the region of 50 kW. For the Hohentwiel airborne transmitter a plate pulse voltage of 9 kV was applied, but it was reduced above 3000 meters flight altitude, where the low pressure caused arcing problems.



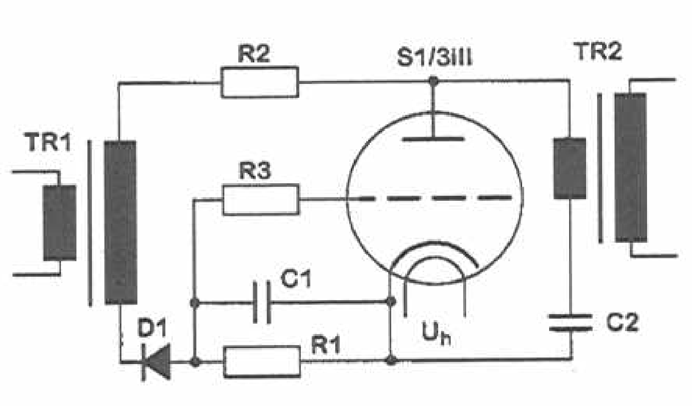
At left, the socket outline and electrical schematic of the RD12Tf tube. The construction of the tube system and the arrangement of the pins made it easy to employ symmetric Lecher line resonant circuits in push-pull oscillators.

The inherent weakness of oxide-cathodes at high plate voltages limited the standing DC plate voltage of the RD12Tf to a maximum of 1000 volts. For applications in radar systems with their typical high-power oscillators, the RD12Tf tubes cannot be operated with grid-keying and its permanent high DC plate voltage. On the other hand, plate-keying of power oscillators requires power pulse generators. Power pulse generators used in the transmitters of radar systems are most commonly referred as modulators or pulsers.
Since the function of these generators is to provide the pulse voltage to the plates of the transmitter tubes and thereby produce pulses of high-frequency energy, they have to supply high pulse powers of, depending on transmitter efficiency, twice the radiated RF-power or more.

In Germany as well as in the U.S., as a result of the initial lack of pulse generators, early radar transmitters were operated with grid-keying. The problem of development pulse generators came from the lack of fast high-current switching devices. High-vacuum electron tubes are relatively unsuitable for high-current switching because of their inherent high power-resistance.

Early gas-filled switch tubes like mercury thyratrons lacked the fast switching capability, required for pulse applications. In the U.S. as well as Germany, experiments were made with fixed and rotary spark-gaps as switching devices, but their reliability were rather unsatisfactory.

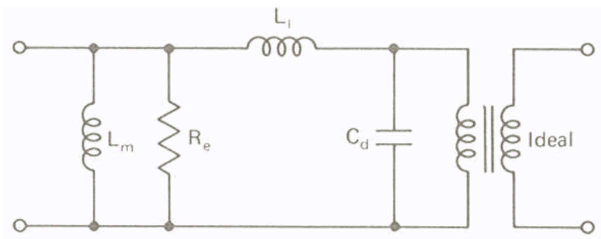
In 1941 the AEG Tube Laboratory at Berlin developed two small helium-filled thyratrons for pulse generator applications, the S1/3 and the S1/6 tubes. When the Lorenz company started the Hohentwiel program in 1941, it was realized that a new sophisticated switching device was necessary to build the compact airborne modulator, required for the powerful transmitter. On request of the Lorenz company Dr. Ahrens of the AEG tube works at Clausthal-Zellerfelde improved the S1/3 thyratron. With a large-area barium-strontium-oxide cathode carrying a current density of 40 amps/mm$^2$, the S1/3iII type was created, as shown in the photo. This tube, operated at 1000 volts, was able to switch a plate current of more than 400 amps at a pulse length of 2-3 microseconds. It could operate with a pulse repetition rate up to 500 Hz. Operated with these parameters, the tube had an expected lifetime of 1000 hours. With the S1/3iII thyratron the peak power requirements for the 100 kW Hohentwiel modulator could be met.




A simplified functional diagram of the thyratron modulator appears on the left. At the end of the charge cycle the capacitor C2 stores an electrical energy of 0.7 joules at 800 volts.

As explained in the following functional description, the Hohentwiel modulator, in opposition to the common keying devices of the early WWII epoch, was of almost “genius” simplicity.

An AC voltage of 500 Hz is used to supply the modulator circuit. Rectified by diode D1, the unfiltered half-wave voltage charges the energy-storage capacitor C2 through resistors R1 and R2. The time constant of R1 and R2, together with C2 is approximately 20 ms – to reach the final charge, 10 cycles are required. As long the thyratron does not conduct, diode D1 prevents the discharge of C2. Before the thyratron can fire and get conducting, the voltage at C2, as well as the voltage at the grid of the thyratron, have to reach a certain trip level. The thyratron fires, if the voltage at C2 at the end of the charge cycle has reached approx. 800 volts and if the grid voltage gets more positive than –10 volts. The initial high charging current of C2 causes a high voltage drop at R1 and charges capacitor C1 to a relatively high negative voltage, which is applied to the grid of the thyratron. The time constant of R-C circuit R1 - C1 is calculated such that the decreasing charging current of C2 does not compensate for its discharge. Therefore the negative voltage at the grid of the thyratron decreases slowly over the 500 Hz cycles. At the tenth have-wave cycle, the thyratron fires. This causes an instant discharge of the energy-storage capacitor C2 into the primary winding of the pulse transformer TR2 and induces a short but high voltage pulse in the secondary winding. TR2 has a turn ratio of 1:24; it provides voltage and impedance transformation between the modulator and the transmitter. The modulator circuit is dividing-down the 500 Hz half-wave cycles into the repetition rate of 50 Hz for keying the transmitter tubes with 10 kV, 2 µs pulses.

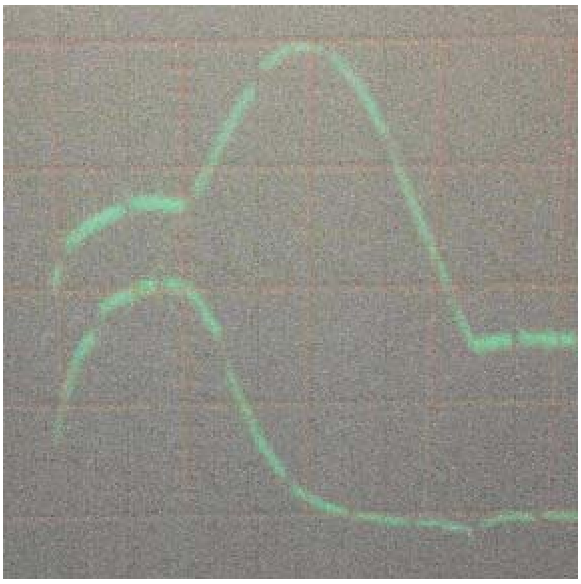



The pulse transformer TR2 is the most critical component of the Hohentwiel modulator. Its development was a trade-off between conflicting requirements. The figure shows the simplified equivalent circuit for a pulse transformer.

Perhaps the most important purpose of the pulse transformer is the transformation of the stored energy in capacitor C2 into a pulse matched to the impedance level of the transmitter RF oscillator. Another important requirement for the pulse transformer is to generate a suitable pulse shape to modulate the transmitter.

Parameters like the leakage inductance $L_l$ and the stray capacity Cd of the primary und secondary windings, as well as unsuitable magnetic core material, can seriously degrade the transformer function. The leakage inductance can be reduced by subdividing the winding configurations.

Measurements on the original Hohentwiel modulator have shown that, during the discharge, much of the 0.7 joules energy stored in capacitor C2 is lost in the pulse transformer. The reason is the limited saturation flux density and the high eddy-current loss in the unsuitable magnetic core material available at the time of manufacture.



Upper Trace: Primary current of the pulse transformer during the discharge of 0.7 joules stored in capacitor C2.

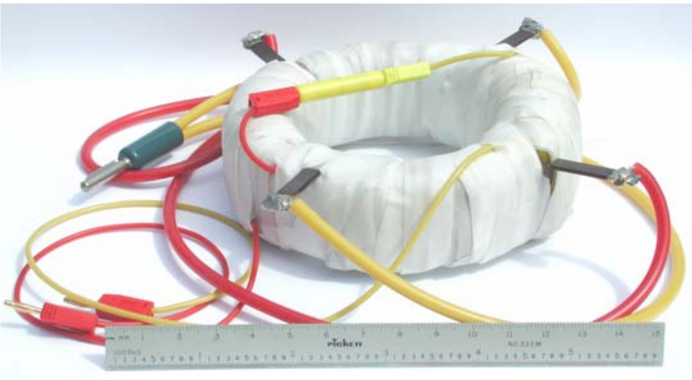
Vertikal deflection: 200 amps/division

Lower Trace: Secondary current of the pulse transformer supplied into the 1000 ohms load, during the discharge of 0.7 joules stored in capacitor C2.

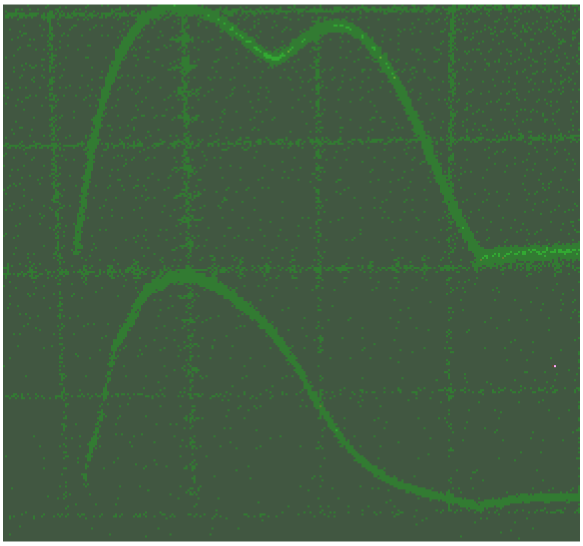
Vertikal deflection: 5 amps/division

Horizontal deflection: 2 µs/division

The pulse shapes in the oscilloscope traces show that at the beginning of the discharge the current in the transformer secondary winding follows the increase of the primary current. When the magnetic flux density has reached saturation the secondary current decreases into the pulse trailing edge, but the primary current starts increasing again to a peak of approximately 500 amps before it decreases into the trailing edge.
However this second sharp rise of the primary current cannot increase the magnetic flux density and therefore causes a loss of the remaining energy stored in capacitor C2; the energy is converted to heat and dissipated in the transformer.



An experiment with the new pulse transformer in the photo, built with a modern tape-wound toroidal core of high saturation flux density and low eddy current loss, has confirmed that the power requirements of the modulator can be met with a reduced stored electric energy of only 0.32 joules. For the reduction of the leakage inductance a subdivided winding configuration is employed.



Upper Trace: Primary current of the new pulse transformer during the discharge of 0.32 joules electric energy.

Vertikal deflection: 100 amps/division

Lower Trace: Secondary current of the pulse transformer supplied into the 1000 ohms load, during the discharge of 0.32 joules electric energy, stored in capacitor C2.

Vertikal deflection: 5 amps/division

Horizontal deflection: 2 µs/division

The pulse shapes on the oscilloscope traces show, that the secondary transformer current follows the increase of the primary current up to the saturation level at approx. 200 amps, then the secondary current decreases into the pulse trailing edge. The primary current begins to decrease too, but then it rises again until the extra energy of the storage capacitor is gone. With the new core material the secondary current of 10 amps could be reached with 200 amps primary current. There is still some extra energy stored in the capacitor C2. The capacity of C2 could be reduced further without degradation the modulator performance.

An experimental laboratory setup for the function of the Hohentwiel modulator, with the new pulse transformer. The two green wide-band pulse transformers are used for measurement of the primary and secondary pulse currents. The unit at the bottom with the brass bar is a 1000 ohms noninductive dummy load, simulating the transmitter load. The peak voltage of the high voltage pulse is measured with a Sensitive Research electrostatic crest voltage meter.

**Project: Transmitter RF Peak-Power Measurement**

Studies of reports written by the CIOS and BIOS teams about their investigations in German industrial and government laboratories at the end of WWII as well as documentation of the U.S. National Bureau of Standards, have shown that procedures for accurate RF peak power measurements at UHF or microwave frequencies did not exist, in either in Germany or in the U.S., at the time of WWII.
So RF peak pulse power measurements on early UHF radars were rather difficult ventures.

Surprisingly, however, the government laboratories and industrial companies, as well as the military agencies, specified this parameter with tight tolerances, although neither standard methods nor accurate test equipments were available in those days. The original technical specifications for the equipments found their way into the post-war literature, probably without further verification in most cases.
The presumption is therefore obvious, that many of the specified RF peak powers were rather unreliable and probably optimistic.

Various methods for RF peak-power measurements at UHF and microwave frequencies have been developed and standardized over the past fifty years.
In general, the aim has been to develop instruments which indicate the measured quantity directly. Indirect methods such as calculation of the pulse power from the average power are limited in accuracy, because they are strongly influenced by changes in the duty cycle caused by pulse shape fluctuations, etc. It seems therefore worthwhile and interesting to measure the RF peak pulse power of the Hohentwiel radar transmitter with present-day instrumentation, as long as several independent sets of transmitting tubes are available in good conditions.


For the RF peak power measurements the Hohentwiel-transmitter was operated through a Narda directional coupler into a dummy load. The power was measured with a Boonton Electronics peak-power sensor model 56318, at the directional coupler and indicated on the Boonton Electronics model 4530A peak-power meter. The pulse shape could be observed either on the display of the 4530A or with the HP8472A detector.


The Boonton Electronics 4530A Peak Power Meter in combination with the 57318 Peak Power Sensor, allows peak power measurements between +20 to -39 dBm with an accuracy of ± 0.06 dB (2.1%).

For the RF-peak power measurements five pairs of Rd12Tf triodes and two S1/3iII thyratrons were available.

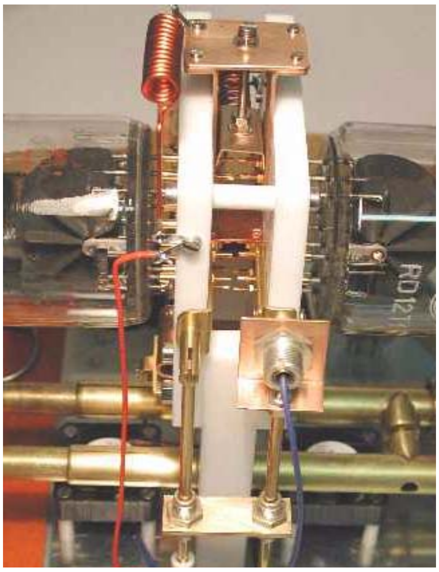
### S1/3iII thyratrons

Comparative measurements were made between the two S1/3iII thyratrons, but the measurements did not indicate striking differences.

Both thyratrons were operated with plate voltages of 800 volts and plate peak currents up to 500 amps. Although the result of a comparison between only two samples, is not very impressive, it seems that the thyratron of the Hohentwiel modulator is not a critical component. Earlier experiences with hydrogen thyratrons have moved me to the conclusion that thyratrons either work fine or are broken!

**RD12Tf triodes**

Comparative measurements of the RF peak powers were made with the five pairs of RD12Tf. Average RF power measurements and their conversion to peak powers is problematic because of the reduced accuracy of the result. The inherent low duty cycle of the Hohentwiel system, of approximately 0.000125 and the Gaussian distribution of the RF pulse shape make the conversions inaccurate. The average RF power is in the region of only three to four watts.



The power measurements were done at 525 MHz with a plate pulse voltage of approximately 9 kV.

For each tube pair the transmitter frequency had to be adjusted on the plate resonant circuit. (See the plate tuning slide bar in the photo.

The cathode lines in the photograph as well as the Lecher line and the adjustable slide bar of the transmitter output circuit were tuned for a maximum power at 525 MHz.

The RD12 Tf tube systems have a label with the serial number brand on the small internal sheet-metal connection between the two cathode pins. The results of power measurements below are referenced to these tube serial numbers.

The following RF peak powers and plate peak currents were measured:

| Tube Serial Numbers | Peak power (kW) | Peak plate current (amps) | RF Pulse width (µs at -3dB) | DC to RF Efficiency |
|---|---|---|---|---|
| Ser. Nr. 0336 / Ser. Nr. 8540 | 32.4 | 9.5 | 2.8 | 38% |
| Ser. Nr. A672 / Ser. Nr. G983 | 28.3 | 9.2 | 2.6 | 34% |
| Ser. Nr. T686 / Ser. Nr. A409 | 30.4 | 9.8 | 2.6 | 34% |
| Ser. Nr. V230 / Ser. Nr. 18064 | 31.5 | 9.4 | 2.8 | 37% |
| Ser. Nr. T736 / Ser. Nr. G512 | 27.8 | 9.1 | 2.5 | 33% |

The equivalent dynamic resistance of the Hohentwiel transmitter was approximately 1000 ohms.

## Conclusion

The measurements confirm that the RF peak power of the Hohentwiel transmitter was in the region of 30 kW. This project has cleaned out some doubt about the correctness of the specified RF peak power referenced in numerous documents and publications.

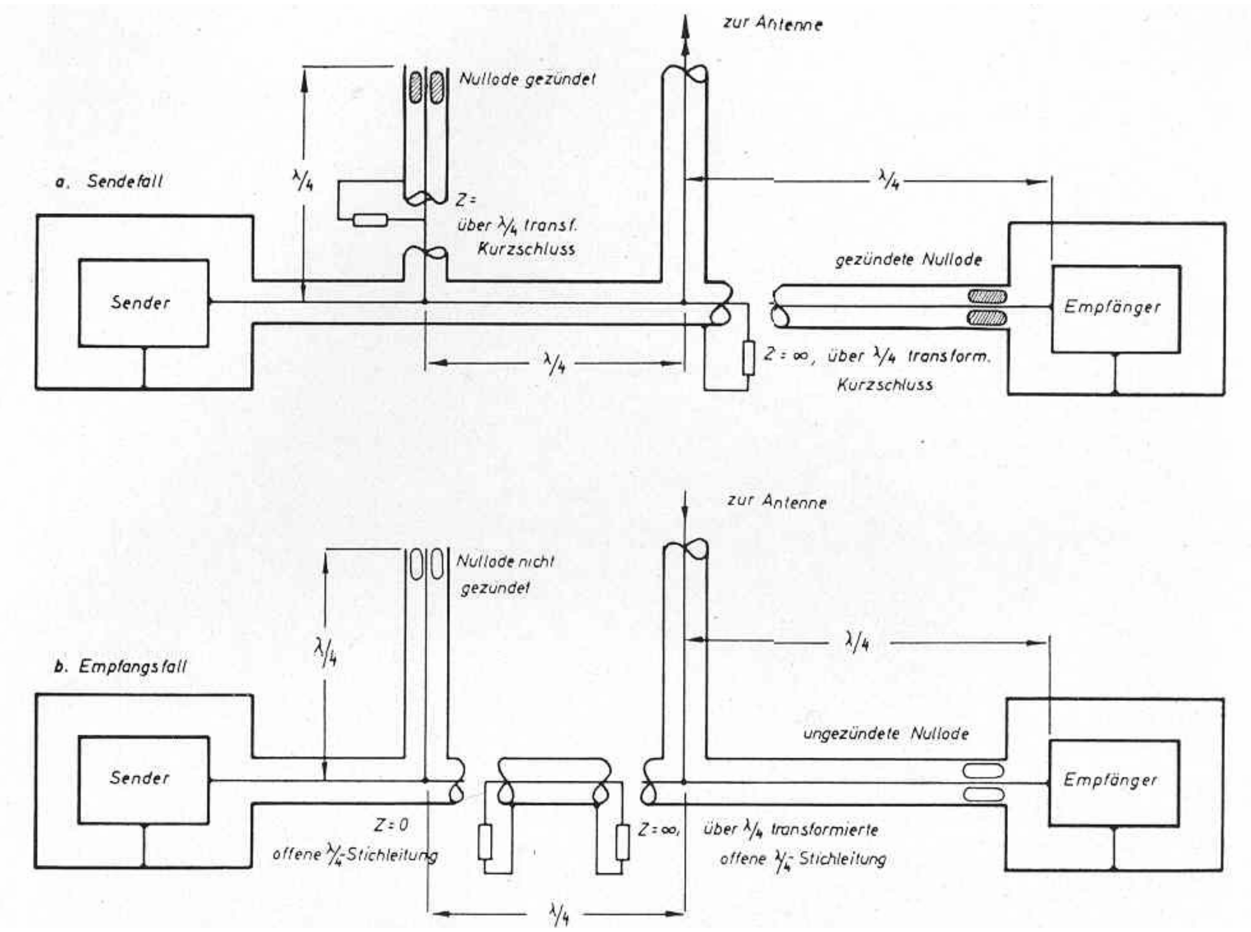
## Hohentwiel-Equipment with common transmit / receive antenna

A modified version of the Hohentwiel equipment with a common rotatable transmit/receive antenna array came in use later in WWII for the U-boats of the German Navy. For the separation of the transmit and receive path a T/R switch device was necessary, the so-called "Simultan-Gerät". The T/R switch device must switch the antenna between transmitter and receiver rapidly and provide receiver protection during transmission.

The figures below show the function of the T/R switch device:

a. for the transmit case

b. for the receive case



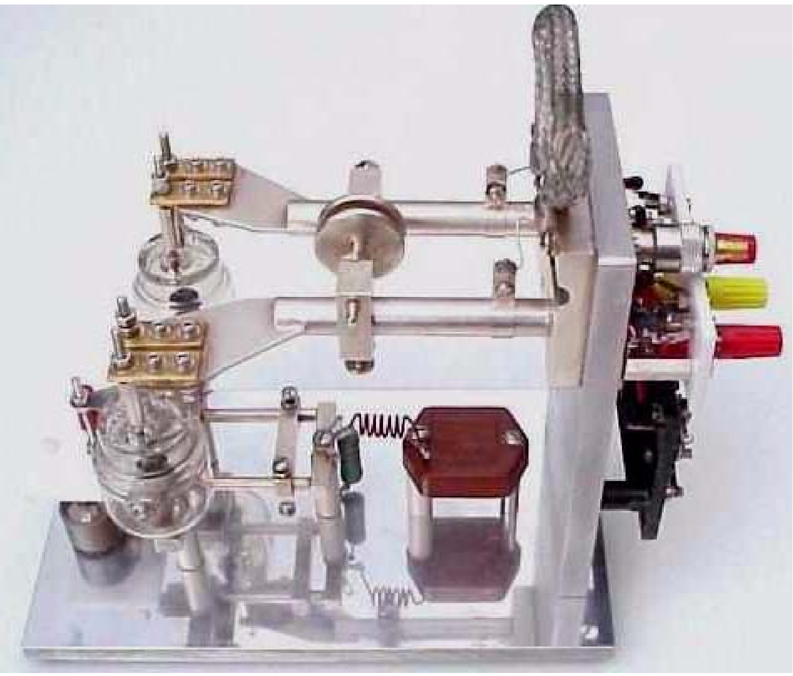

Gas-discharge tubes (German designation Nulloden) were utilized for the T/R switch device. The strong electric fields rapidly ionize the gas, thereby presenting a very low impedance to the transmitted signal during the transmitted pulse.

During reception, the T/R tubes passes the low-level receive signal with little insertion loss.

The figure on the left shows a photo of the Telefunken LG 71 TR-tube utilized in the Hohentwiel-Simultangerät as switch device (in Germany was the tube designated as a so called Nullode)

## AN/APS-18 transmitter for the American ASB airborne radar set

It is remarkable that the RF peak power of the Hohentwiel transmitter was far beyond those of the AN/APS-18 airborne radar transmitters developed in the same period for the American ASB airborne radar set.



American AN/APS-18 airborne radar transmitter (original line circuits)

Developed 1941 at the Naval Research Laboratory, Washington DC

Frequency 515 MHz
RF Pulsewidth 2 µs
PRF 400 Hz
RF Peak Power 5 kW

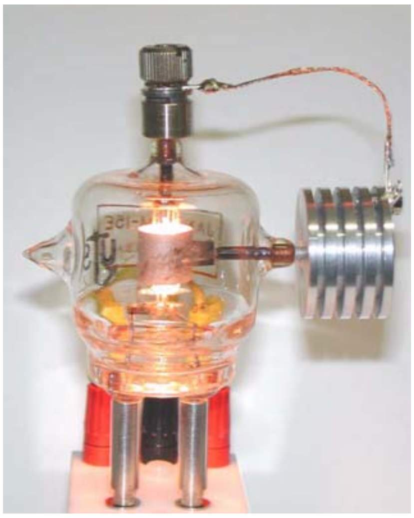
Self-quenched keyed by a large R-C time constant in the grid circuit (see mica capacitor and grid resistor)

The American AN/APS-18 transmitters used two or four Eimac 15E triodes with thoriated tungsten filaments for the self-quenched keyed push-pull or ring oscillators. Self-quenched keyed transmitters do not need an extra pulse modulator and with thoriated tungsten filament tubes it is possible to supply their oscillators with a permanent high DC plate voltage.

The 15E UHF triode was developed in 1940 at the Eitel-McCullough company San Bruno CA for pulse oscillator applications. The 15E has a direct heated thoriated tungsten filament. The plate dissipation of the tube is 20 watts and it can be operated up to a maximum plate voltage of 12.5 kV. The 15E tubes were used by the U.S. Navy in various grounded-plate oscillators at frequencies between 400 and 600 MHz. These early pulse type oscillators were typically self-quenched keyed employing large R-C time constants in the grid circuits.

Tubes with oxide coated cathodes like the RD12Tf have an inherent higher pulsed emission density ($mA/cm^2$) than tubes with thoriated tungsten filaments.
So transmitters equipped with oxide cathode tubes were able to generate a higher RF peak power with the same plate voltage, but on the other hand they had to be keyed on the plate and required power pulse modulators.

Comparative measurements of the cathode emissions were done with a number of 15E's and RD12Tf's triodes.



The 15E's with the thoriated tungsten filament were operated with 5.5 volts. The 15E's showed pulsed filament emissions in the region of 4 amperes at 6 kV. For the measurements the tubes were operated with a plate - grid connection as diode. The photo shows a 15E, with a plate heat dissipating connector, occasionally the filament emission measurement.
The RD12TF's with the oxide cathodes were operated at the highest filament voltage of 14.4 volts, allowed, so far for pulse operation. They showed cathode emissions in the region of 10 amperes at 6 kV.

In retrospect it may be pointed out that the development of oxide cathode transmitting tube as the RD12Tf for its application in the early Hohentwiel radar transmitter as well as the development of the Helium thyratron for the modulator was far advanced in 1941. Some time later for the development of microwave radar magnetrons the application of oxide cathodes was a prerequisite to meet the requirements and thyratron modulators came in common use.

**Acknowledgment**

This project could not have been undertaken without the support of Ed Willi, Günther Hütter, Günther Riedl, Dieter Beikirch and Arthur Bauer. The author wish to thank these gentlemen for providing some authentic key components, documentations and much advice.

**References**

Müller G. Funkmessgeräte Entwicklung bei C. Lorenz AG, 1935 – 1945, Firmeninternes Archivheft der SEL, 2. Erweiterte Fassung, Dezember 1981

RLM Werkschrift 4108, Bordfunkmessgerät FuG 200, G. Kdos. August 1943

RLM Vorschrift Nr. 75/790, Prüffibel für Bordfunkmessgerät FuG 200, Oktober 1944

RLM Luftfahrtsröhren Ringbuch, Daten und Richtlinien über die Verwendung von Luftfahrtsröhren, Januar 1945

Dr. Steimel K. Bericht über den Zustand der Röhrentechnik in Deutschland zum Abschluss des Krieges, August 1945

U.S. Air Material Command Dayton OH, Summary Report No. F-SU-1109-ND, The High Frequency War - A survey of German Electronic War, 10th May 1946

CIOS Final Report 1746, German development of modulator valves for radar applications

CIOS report XXX-36, Physikalisch-Technische Reichsanstalt, June 1945

CIOS Report XXVII-46, Design of Radar Test Equipment at Siemens-Halske Munich

BIOS Report 1228, HF Instruments & Measuring Techniques

Achievement in Radio, Radio Science, Technology, Standards and Measurements at the National Bureau of Standards, US Department of Commerce, October 1986

Megla Gerhard, Dezimeterwellentechnik, Kapitel Messgeräte und Messmethoden bei Dezimeterwellen, Fachbuchverlag Leipzig, 1952

Radio Measurements, Proceedings of the IEEE, Volume 55, June 1967

Hewlett Packard, Microwave Measurement Handbook, Chapter RF Peak Power Measurement, Procedures and Equipments

Boonton Electronics Company, Application Note AN-50, Measuring the Peak Power

U.S. Naval Research Laboratory, ASB Radar Alignment Procedure, November 1942