SIEMENS

Grid-Controlled Tubes for RF-Excited CO_2 Lasers

At its tubes plant in Berlin (Berliner Röhrenwerk) Siemens has been producing an extensive range of electron tubes for more than 50 years. Grid-controlled high-μ triodes and tetrodes are especially suitable for the RF excitation of CO_2 lasers.

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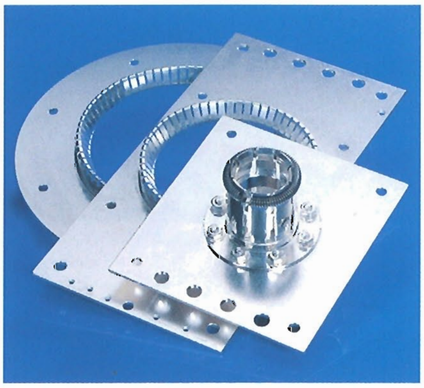

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Techniques, Applications and Trends in CO_2 Lasers

This information brochure from the Electron Tubes Division of Siemens AG is intended to offer you assistance and ideas when you are selecting circuitry concepts, tubes and RF cavity resonators for exciting CO_2 lasers.

We offer our customers not only the active component, i.e. the tube, but also, if they wish, allround consulting on how to design an RF source, right down to design blueprints and demonstrations of sample equipment.

Stimulated Emission – the Principle of the Laser

When a photon impacts with an excited atom, the latter will emit a new photon of the same frequency and the same direction and fall into a lower excited state.

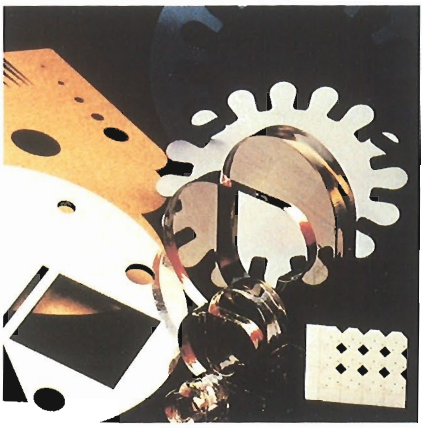
If you can invert the population of the upper state compared to the lower state, the radiation will be amplified.

When such an inverted medium is put between two mirrors that reflect the emitted light back into the medium, this light will be amplified as long as inversion can be maintained, the two mirrors acting as an optical resonator. If one of the two mirrors is semi-transparent, part of the radiation can leave the resonator.

A steady state can be achieved where the inversion is just enough for the resonator losses to be compensated by the amplification. Such a process for generating and amplifying monochromatic and directional radiation is called "light amplification by stimulated emission of radiation" or LASER.

In a CO_2 laser the gas, a mixture of He, N_2 and CO_2, has to be ionized. This ionized gas, also called plasma, is produced by a DC or RF glow discharge. So, depending on the type of discharge, you distinguish between DC or RF plasma – with their physical differences that mark the advantages and drawbacks of the CO_2 laser.

Contours cutting

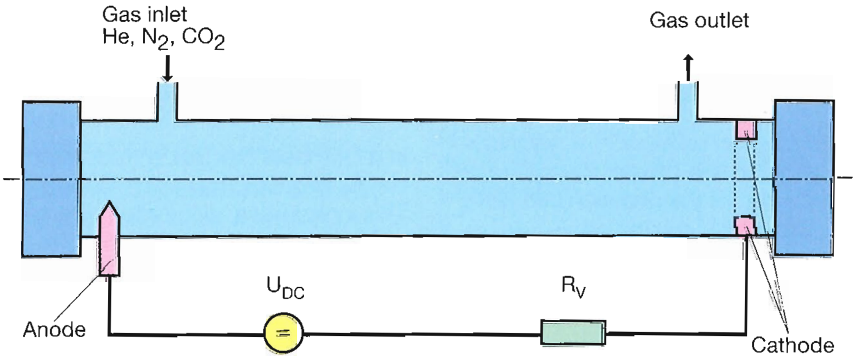


The CO_2 Laser: Applications and Trends

Since its invention in the mid-60s the CO_2 laser has captured a mass of applications, especially in the processing of materials, e.g. cutting, welding, drilling, hardening and surface treatment. In contrast to the mechanical processing of materials, laser light does not wear out. Complicated structures can be cut and worked precisely under computer control.

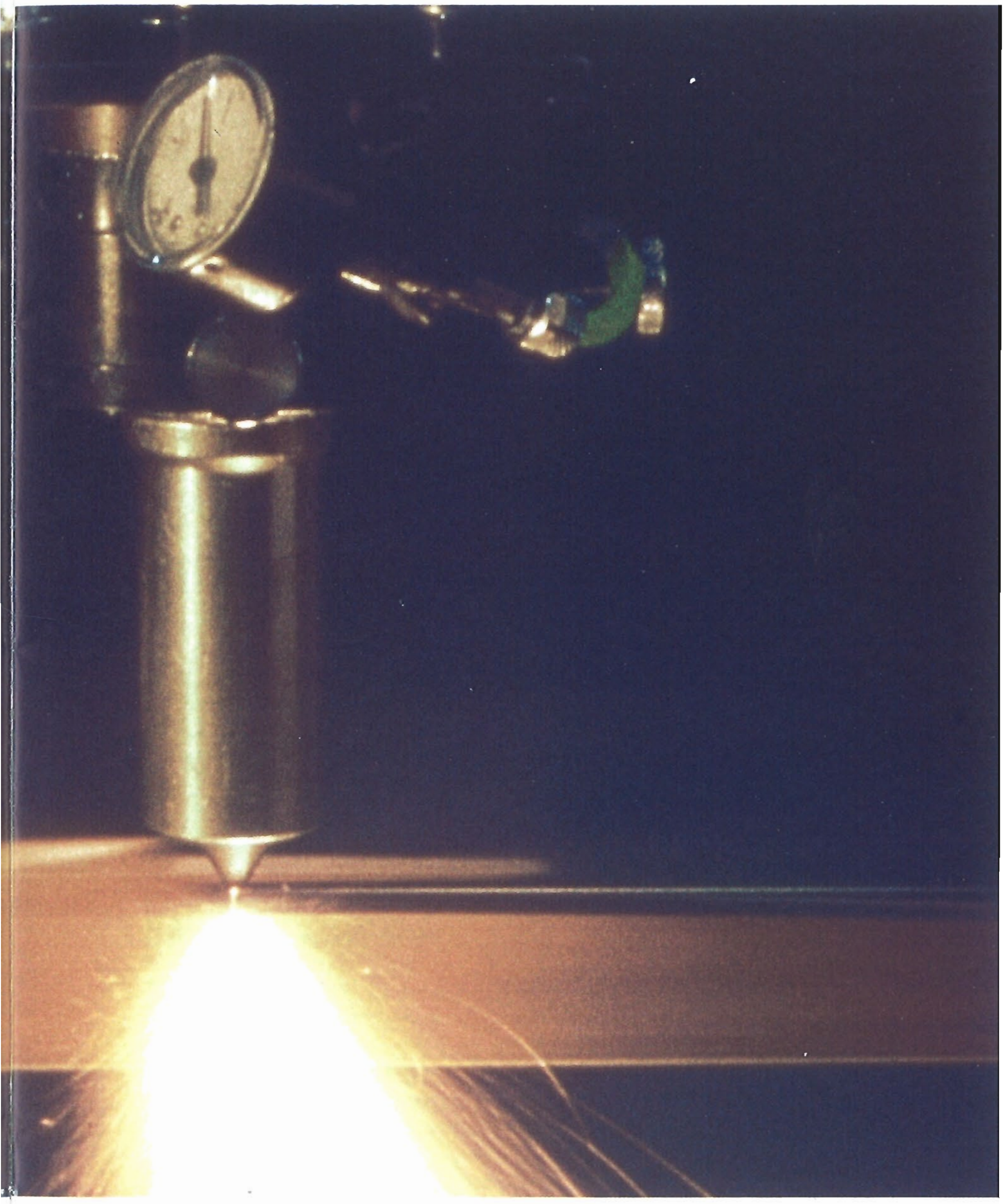
To begin with there were DC-excited lasers with axial or transversal gas flow. But today, for light output of 1.5 kW and more, the emphasis is on RF-excited lasers. Typical applications are cutting and welding. The reason for this is the superior pulsing capability of RF-excited lasers. For some years now CW power of up to 5 kW has been quite customary.

In the latest CO_2 laser developments efforts are being made to reduce the effort involved in the heat exchange of the laser gas. There has been success here in the case of stripline or waveguide lasers, where excitation frequencies of 80 to 100 MHz are called for because of the special construction.

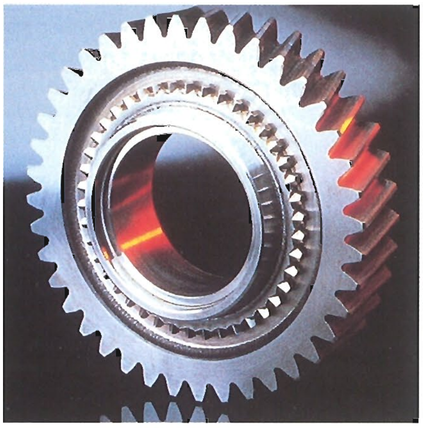


Principle of DC excitation

Fig. 1



Laser welding
in the automobile
industry



Ratchet wheel with
welded-on synchronous ring

Direct-Current-Excited CO_2 Lasers

In DC excitation the laser gas is usually converted into an electrically conductive plasma with the aid of an ignition. This burning plasma has a falling current characteristic however, and its operating voltage is far below the ignition voltage. So, to ensure stable burning, you need a series regulator, which, because of the high DC voltage, is generally designed with a tube (tetrode).

With the bigger lasers a number of discharge paths are required, each with a tetrode for series control. To make sure that the light power stays constant, there is a control to stabilize the discharge current to the required level.

The screen-grid voltage supply, heater transformer, monitoring devices and control are on high-voltage potential (U_A approx. 20 kV). So an isolating transformer is necessary for applying heater and screen-grid power. Optical fibers are used for control and monitoring because of the high-voltage insulation that is required.

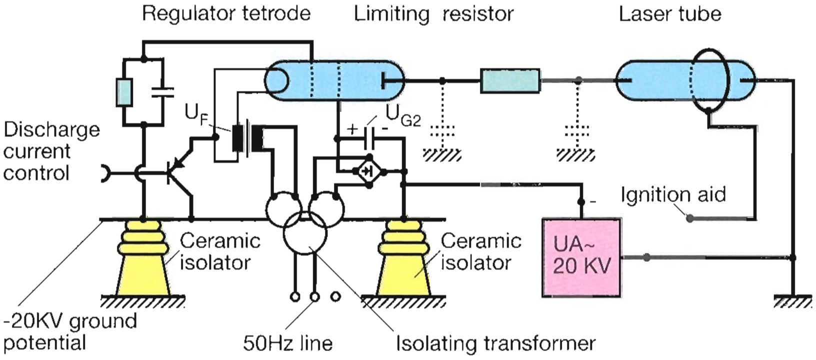


Fig. 2

Series regulator
with a tetrode

RF-Excited CO_2 Lasers

When the CO_2 laser gas is exposed to a high-frequency electric field between the poles of a plate capacitor, the RF plasma is created that is required for lasering.

For regulating the mean laser light power (you also speak of modulation), there is a very fast and elegant technical solution: you simply switch the RF power on and off with a variable pulse frequency and variable duty cycle.

The laser has to be excited with a frequency of at least 2 MHz. The reason for this is a gas layer, directly on the inside of the wall of the quartz tube, which is inactive in converting energy into laser light. Because of the high pulse frequency that is required and the short on time, a minimum operating frequency of 13.56 MHz has become established.

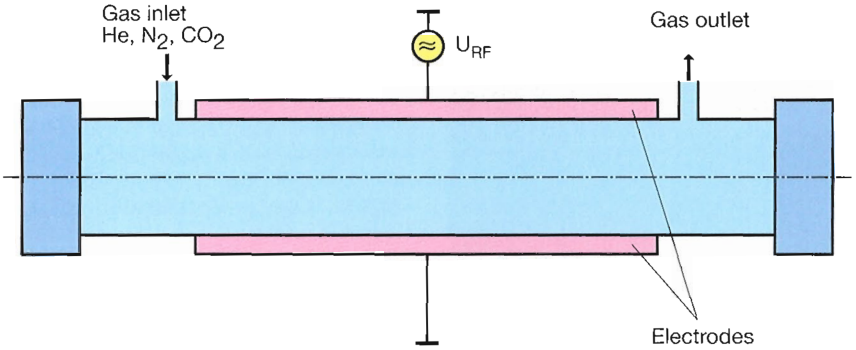


Fig. 3

Principle of RF excitation

In contrast to the cutting of a long straight seam, when you are cutting out or welding along complicated curves it is necessary to have fast control: as soon as the direction of the welded seam alters, the light energy has to be reduced. Otherwise it will not stay matched to the lower relative speed produced by the mass inertia of the moving mechanical parts.

Without the loaded Q value of the final stages being too high, pulse frequencies of approx. 50 kHz with duty cycles of 10 to 90% and more are possible with RF amplifiers and self-excited RF generators at frequencies of 13 and 27 MHz. The total power produced by the RF stage with just one tube can also be evenly distributed to a number of laser tubes. There are two concepts for this on the market.

In the first the RF source and the laser are in separate housings, connected by a flexible or rigid 50-Ω lead. In this way the individual units can be kept relatively small and light. There has to be an appropriate matching circuit to ensure that the ignited laser acts like a 50-Ω termination at the end of the cable. This guarantees optimal power transfer and the RF cable is not endangered.

In the second the RF source and the laser form a compact unit in a single housing. The cable and matching circuit can be omitted, so weight and volume are reduced.

Both kinds of RF source can be designed with RF amplifiers or self-excited generators. Either high-gain triodes in a grounded-grid circuit or tetrodes in a grounded-cathode circuit are used in stable amplifiers with frequencies of 13.56 and 27.12 MHz.

At the moment there is a clear trend towards self-excited RF generators.

The changes in frequency that occur with generators can be kept small enough – by skilful selection of the loaded Q value – to be tolerated by the overall system, i. e. tube, generator and laser. Suitable shielding measures, on both the RF generator and laser housing, make sure that regulations are maintained that refer to maximum permissible interference field strength. Generators of this kind are best fitted with high-gain triodes, but tetrodes have also been experimented with.

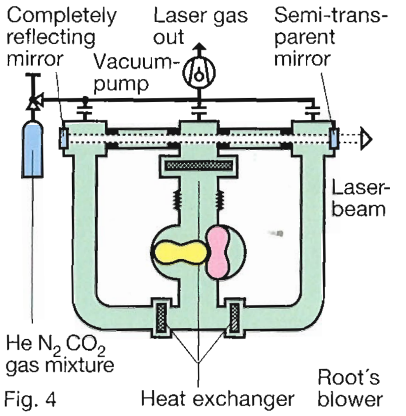


Fig. 4

Principle of the axial-flow CO_2 laser

Stripline/Waveguide Lasers

In the axial-flow and transversal-flow lasers described up to now, the electrical energy that is applied to the gas has to be expelled again in the form of heat energy, i. e. in as much as it is not converted into laser light. This is done while the gas passes through the heat exchanger, which, like the gas blower, is a determinant component of a laser.

In waveguide lasers the light is produced in a 1 to 5 mm wide gap, limited on both sides by wide, water-cooled plates. But the high energy remaining in the gas is transferred very fast and efficiently to the immediately adjacent, water-cooled plates. In this way the amount of gas that is moved – and thus the demands made of the heat exchanger and blower – can be

Comparison of DC-excited and RF-excited lasers	**RF**	**DC**
Pulsing	Fast power variation through pulse/pause ratio. Pulse repetition frequencies of up to 100 kHz are achieved.	Comparatively slow power variation because of the relatively high energy held in stray capacitances, which are a function of the equipment and cannot be avoided.
Gas impurities	There are no impurities because there is no contact between the gas and the electrodes.	The electrodes are in the laser gas, so there are gas impurities as a result of cathode wear.
Maintenance	No machine stoppages because of electrode replacement.	The cathode is used after 2000 to 4000 h and has to be replaced.
MTBF	A number of excitation paths can be fed from one generator (one tube). The resulting simple, clear circuitry reduces the risk of failure.	A separate power supply is required for each excitation path; there can be as many as eight units per laser, which increases the risk of failure.
Accident risk, shielding	On the laser tube there is only RF voltage of medium level. The electrode pairs and all parts that conduct RF voltage have to be shielded.	There can be DC voltage of up to 20 kV on the laser tube, RF shielding is unnecessary.
Power-supply costs	The power-supply costs are between 2000 and 4000 DM per kW. RF excitation is more attractively priced than DC excitation for laser light power of more than 1.5 kW.	

Table 1

reduced. In ideal cases, where the power level is not too high, they could even be omitted.

Because of the narrow discharge space in the form of a gap of 1 to 5 mm, the total thickness of the plasma is only slight. So the inactive plasma barrier layer that is always present on the outside (quartz tube wall or water-cooled metal plate) has to be kept as small as possible. This requirement can be met with a pump frequency of approx. 100 MHz.

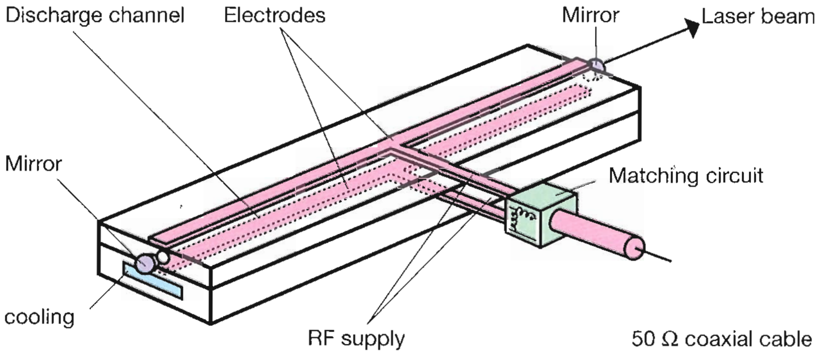


Fig. 5

Principle of an RF-excited CO_2 waveguide laser

Possible Implementations of RF Sources for Axial-Flow and Transversal-Flow CO_2 Lasers

The Tube – the Active Component

Siemens offers tetrodes and triodes suitable for equipping amplifiers and generators. Our new series of μ-100 triodes for RF laser excitation was specially devised for tough industrial environments and derives from our tried and tested range of generator tubes.

All our new μ-100 tubes – RS 3011 C, RS 3021 C, RS 3027 C, RS 3041 C and RS 3061 C – are of fully concentric metal-ceramic design. The tubes RS 3021/27/41 C have compatible bases. Their water connections are accordingly also of the same arrangement and size. This very much simplifies new designs for our customers when they move up to a different power category.

The RF power range of all models extends from approx. 8 to 100 kW continuous wave. The pulse power that can be achieved will be one and a half to four times higher if the duty factor D is 50 to 25%.

In all models fluctuations of heater voltage of at least ±5% are permissible. For the crowbar test a test wire 0.3 mm thick (RS 3061 CJ = 0.4 mm) is sufficient to protect the tubes when there is a flashover. The thickness of this test wire is a measure of energy and defines the shortcircuit current that may flow for a certain time without damaging the tube through flashover. The rugged construction of the tubes is a particular advantage when the anode power supply has to be configured with large capacitances because of long pulse times.

The anode dissipation in pulsed operation (D = 25%) can be increased to as much as four times the permissible continuous dissipation for pulse widths of max. 0.05 s. It is similar with the generously scaled grid dissipation.

A μ of approx. 100 was chosen so that large grid-cathode spacings can be used with "thick" electrode wires. This produces the necessary ruggedness, a large test-wire diameter, safety in transport and handling – as called for when personnel in industry is unskilled.

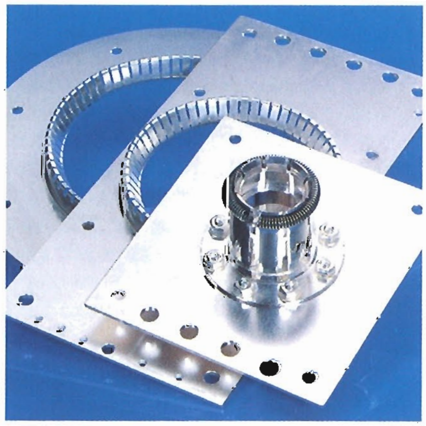
A high μ (e. g. of 200) is a hindrance to the design objectives and makes tube failures more probable. The advantage that is frequently spoken of, namely that a very high μ enables you to operate an amplifier without a bias power supply, produces the following drawbacks:

Because of manufacturing tolerances in the tube characteristics there can in some cases be an unwanted, idling anode current (1 A) that cannot be reduced for lack of a bias power supply. This means high dissipation and poor efficiency, especially in pulsed operation with a small pulse duty factor. The cooling water also becomes unnecessarily hot.

A grid-cathode shortcircuit is not noticed until high VSWR appears at the input for RF driving. Troubleshooting is more difficult because with a lower μ a fault of this kind is detected as soon as you switch on, since the fixed grid bias voltage breaks down.

In tubes with a double μ factor for example (μ = 200), the probability of unwanted self-excitation is twice as great. A lower μ produces more stable operating conditions.

In self-excited operation of a generator triodes with a lower μ prove them-



Heater, cathode and grid connector for RS 3021 C, RS 3027 C und RS 3041 C

RS 3021 CJ, RS 3027 CJ,
RS 3041 CJ

selves to be especially superior when it is a matter of high pulse power (high currents). µ-100 tubes do not require grid currents that are all that high even up to the highest anode currents and so they make good use of cathode emission.

There are uniform accessories available for use of the three mid-range models as amplifier tubes in a grounded-grid circuit. A tube socket formed of these parts is convenient, fast and secure for the end-user, electrically ideal and permits an extremely flat design, because no space is required for screws, tools or moving connections.

The RF Circuitry

Both the tube characteristics calculated from the constant-current diagram on the load line and those published in the data book presume that the AC anode and grid voltages are purely sinusoidal and, viewed from the cathode, are offset from one another in phase by 180°.

Certain circuit conditions have to be met to achieve this. The tube (current source) not only generates the fundamental current that is required for the RF power but also currents whose frequencies are an exact integral multiple (2, 3, 4...,n) of the fundamental. These harmonic currents ($I_{n\omega}$) result from a Fourier expansion of the individual RF anode-current pulses. The magnitude of the current amplitudes is given by the classes A, B, C and D and the nature of the tube characteristic. Harmonic currents are also produced in an optimally designed circuit.

The harmonic voltages ($U_{n\omega}$) generated by the harmonic currents result from the product $I_{n\omega} \cdot Z_{n\omega}$ and the type of circuit design.

Harmonic impedances ($Z_{n\omega}$) in the equipment create harmonic voltages that are superimposed on the

Amplitude relations of direct current and harmonics

		C Class $\Theta = 60°$	B Class $\Theta = 90°$
DC anode current	I_A	$0.22\ I_{AM}$	$0.32\ I_{AM}$
Amplitude of 1st harmonic*	I_1	$0.39\ I_{AM}$	$0.5\ I_{AM}$
Amplitude of 2nd harmonic	I_2	$0.28\ I_{AM}$	$0.21\ I_{AM}$
Amplitude of 3rd harmonic	I_3	$0.14\ I_{AM}$	0
Amplitude of 4th harmonic	I_4	$0.03\ I_{AM}$	$0.04\ I_{AM}$
Amplitude of 5th harmonic	I_5	$0.03\ I_{AM}$	0

*Fundamental

Table 2

desired sinusoidal voltage of the fundamental. In this way efficiency can rapidly drop to as little as 50% and power gain falls.

The linear curve with a kink is a good approximation of the actual tube characteristic (Table 2). Here I_{AM} is the peak anode current that the tube produces at its upper modulation point.

The table shows these currents for both C and B class of operation. In both cases the high value of current amplitude for the 2nd harmonic is worth noticing. For class C with $\Theta = 60°$ the current amplitude of the 2nd harmonic referred to the fundamental is:

$$I_2 = I_1 \cdot 0.28 \frac{I_{AM}}{0{,}39\, I_{AM}} = 0.72 \cdot I_1$$

For class B with $\Theta = 90°$ on the other hand it is:

$$I_2 = I_1 \cdot 0.21 \frac{I_{AM}}{0.5\, I_{AM}} = 0.42 \cdot I_1$$

It is not until after the 3rd and 4th harmonics that the amplitudes begin to reduce drastically. This means that especially low impedances are important for the current paths of the 2nd and 3rd harmonics.

In the design of a grounded-grid circuit it is consequently essential to remember that the high cathode current has to pass through the sensitive input circuit. In a grounded-cathode circuit on the other hand “only” the harmonic currents of the smaller grid current have to be thought of in the sensitive grid circuit.

The required impedances and frequency stability can usually be achieved with a suitably high loaded Q, which also means small bandwidth however.

A loaded Q of 100 for $\omega = \omega_1$ produces a reactance for the fundamental of:

$$X_1 = \frac{R_A}{100}$$

i. e. 1% of the load resistance.

The admittance of the circuit for the 2nd harmonic is:

$$Y_2 = G_A + j\,(2\,\omega_1\, C - \frac{1}{2\,\omega_1\, L})$$

or

$$Y_2 = G_A + j\,\frac{3}{2}\left|X_1\right|$$

Relative to the fundamental, the reactance for the 2nd harmonic is:

$$X_2 = \frac{2}{3}\,\frac{R_A}{100} = 0.0066\, R_A$$

or 0.66 % of the load resistance.

The harmonic voltage for the 2nd harmonic resulting from the reactance, referred to the fundamental, for C class with $\Theta = 60°$ is:

$$U_2 = 0.72\,\frac{2}{3}\,\frac{R_A}{100}\, I_1 = 0.0048\, U$$

i. e. 0.48% of the voltage of the fundamental.

The same calculation for a loaded Q of 10 produces:

$$U_2 = 0.048\, U$$

i. e. 4.8% of the voltage of the fundamental.

You can see that there are soon limits to reducing the Q any further, because of the fast increase in harmonic voltages and the subsequent sacrifices in efficiency.

This applies in particular to self-excited circuits, where, in extreme cases, the harmonic voltage produced on the anode is fed back to the grid with unwanted feedback factors of 50 to 80% (values found in practice).

With an anode fundamental voltage of 12 kV and the superimposed harmonic voltage of 576 V (corresponding to 4.8% of 12 kV) there is an harmonic voltage on the grid of:

0.5 to 0.8 · 576 V = 288 V to 460 V.

These values are certainly of the level of the AC grid voltages of the fundamental projected by a designer and lead to strong distortion.

For this reason the capacitors of the described amplifiers are also mounted in the input circuit so that, viewed from the tube, they are in series with an inductance. At the 2nd harmonic a series resonance (shortcircuit) is produced and, at a low Q (for the fundamental), no harmonic voltage can be created for the 2nd harmonic.

Anode circuit with discrete components

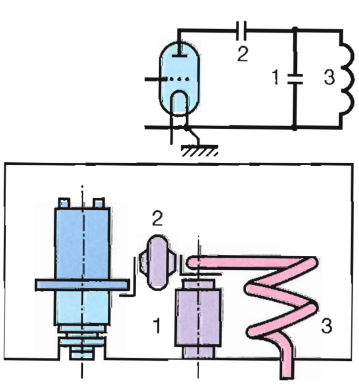


Fig. 6

Anode circuit of cavity-resonator design

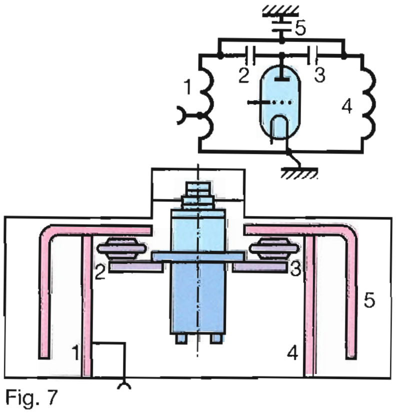


Fig. 7

Small Q figures achieved in this way produce large bandwidths and thus the possibility of increasing the pulse frequency. Furthermore, in an input circuit of low Q there is no need for a retuning device – not even after a tube is replaced.

The design of the RF anode circuits is possible with both discrete components and a cavity-resonator kind of combination consisting of tubes and metal plates. Here at least two parallel metal plates form the resonant-circuit capacitance, supported by a straight piece of tube that also acts as the inductance of the resonant circuit. Suitable discrete components are ceramic capacitors, vacuum capacitors and bent coils of copper tube.

The Amplifier as RF Source

The major advantages of amplifiers compared to self-excited generators are:

- crystal-controlled, load-independent frequency stability,
- continuous, fast power control of 0 to 100%,
- simple pulsing on the amplifier input at the smallest levels with duty factors of 10 to 90% and up to pulse frequencies of100 kHz.

Where such advantages of an RF amplifier are not necessary or only in part, a self-excited RF generator will be used.

One drawback of amplifiers compared to generators is the higher costs. These are mainly caused by the extra effort that goes into matching circuits in both the input and output circuit.

Amplifiers with Triode Final Stage

In contrast to the RF final stages of broadcast transmitters, which work into a relatively constant load, namely the antenna, an RF laser pump generates a glow discharge with a complex load that can fluctuate very considerably.

The resulting reactive component detunes the output circuit of the amplifier, which is basically stable in frequency, so that the tube of the final stage no longer works on a load line but along an elliptical curve. This means increased anode and grid dissipation with uncertainty about whether rated power will be achieved. Power reserves in the tube are then especially important.

The detuning described above can also lead to self-excitation at unwanted frequencies however. To avoid this, the stable grounded-grid circuit is preferred in triodes. Then self-excitation is only possible by way of the very small anode-cathode capacitor – quite unlike the ten to 100 times greater anode-grid capacitor of a common triode in grounded-cathode circuit.

The advantages of this circuit come at the cost of a much higher requirement for driving power however, because the AC voltage has to drive not only the grid current (grounded cathode) but also the higher cathode current (grounded grid).

To keep the necessary driving power as low as possible, the power stages are operated in class B. Then only relatively low AC drive voltages are required and anode efficiency does not drop too much compared to class C.

Triode in grounded-grid circuit exemplified by RS 3027 CJ

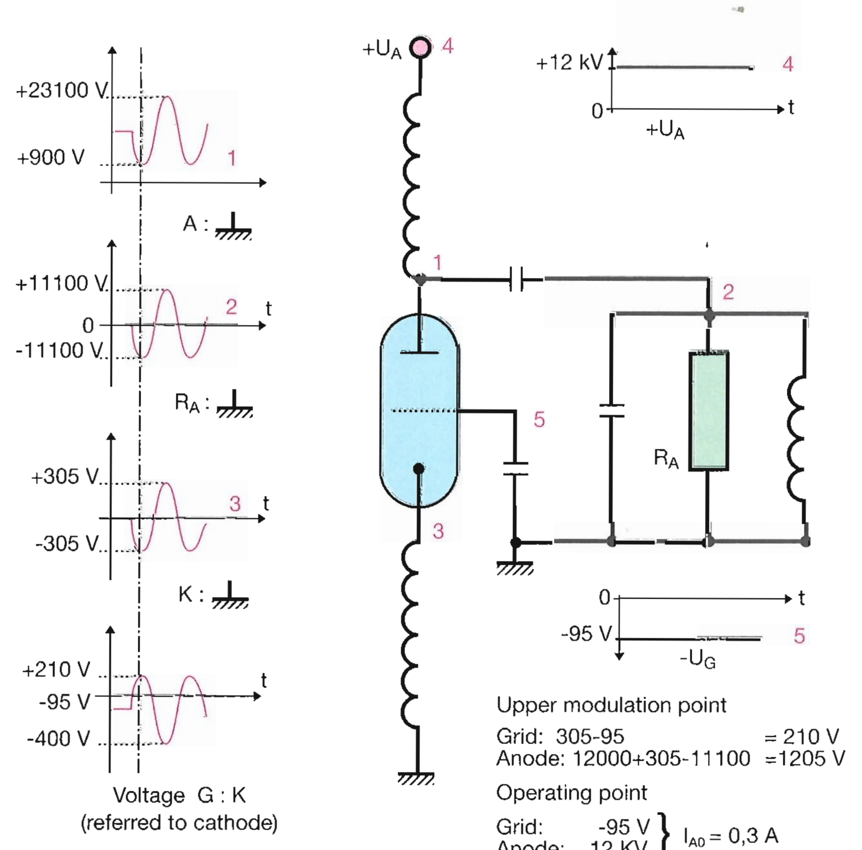


Fig. 8

The most suitable tube for minimum driving power is one that requires a low AC drive voltage and a low control-grid current. For continuous wave the limit of the tube is usually set by the maximum permissible grid and/or anode dissipation.

For RF pulse power with maximum pulse width of 0.05 s, the grid and anode dissipation of our μ-100 triodes may amount to as much as four times the permissible continuous power during the pulse. This is assuming that the duty factor does not go above 25%, i. e. averaged by time that the permissible continuous dissipation is not exceeded.

Amplifiers with Tetrode Final Stage

If amplifier final stages are fitted with suitable tetrodes, they can be operated at frequencies of 27 MHz in a grounded-cathode circuit and only require relatively little driving power. So the expense of powerful RF driver stages can be saved – although at the cost of more elaborate technology for the screen-grid power supply and RF screen-grid bypass capacitor, besides the comparatively high price of the tetrode.

Seeing as the driving power of a tetrode worked in grounded-cathode circuit is basically low, it can even be operated in class C with good efficiency – and without the required driver power becoming too high. In the case of triodes operated in grounded-grid circuit however, much higher driving power is called for if you move from class B to class C.

For tetrode final stages there is our proven RS 2012 CJ with CW power of 10 kW and pulse power of 30 kW, as well as the RS 2058 CJ with 50 kW of CW power and 200 kW pulse power.

Tube type		**RS 2012 CJ**		**RS 2058 CJ**	
Maximum ratings					
Frequency	MHz	30		30	
Anode voltage	kV	9.5		15	
Screen-grid voltage	kV	1.1		1.5	
Control-grid voltage	V	-250		-350	
Cathode current	A	6		35	
Peak cathode current	A	35		100	
Anode dissipation	kW	18		90	
Screen-grid dissipation	W	200		1100	
Control-grid dissipation	W	70		150	
Operating data		CW	Pulse (D = 25%)	CW	Pulse (D = 25%)
Frequency	MHz	27	27	27	27
Output power[1]	kW	11	33 (8.25)	55	210 (52.5)
Anode voltage	kV	6	8.2	11	13.3
Screen-grid voltage	V	700	1000	1000	1200
Control-grid voltage	V	-220	-220	-220	-260
Peak RF control-grid voltage	V	270	315	230	460
Anode current	A	2.3	5.1 (1.3)	7	22 (5.5)
Screen-grid current	A	0.16	0.5 (0.13)	0.2	1.7 (0.43)
Control-grid current	A	0.22	0.64 (0.16)	0.05	2.1 (0.53)
Anode input power	kW	13.8	42 (10.5)	77	293 (73)
Driver power	W	60	192	15	910
Anode dissipation	kW	2.8	9 (2.3)	22	83 (21)
Screen-grid dissipation	W	130	500 (125)	200	2050(510)
Efficiency	%	80	78.5	71	72
Anode load resistance	Ω	1300	740	910	345

Table 3

[1] Circuit losses are not included

Schematic of self-excited generator

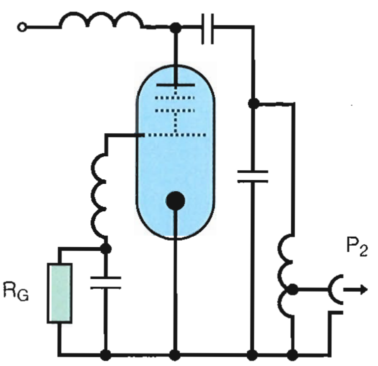


Fig. 9

Generator with Q = 10

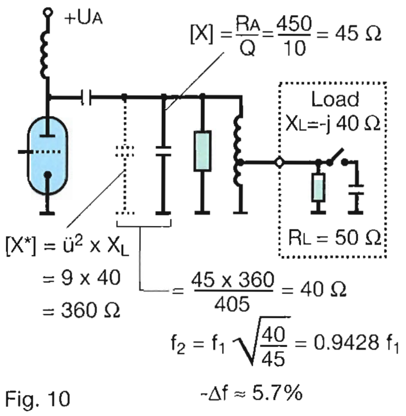


Fig. 10

Generator with Q = 100

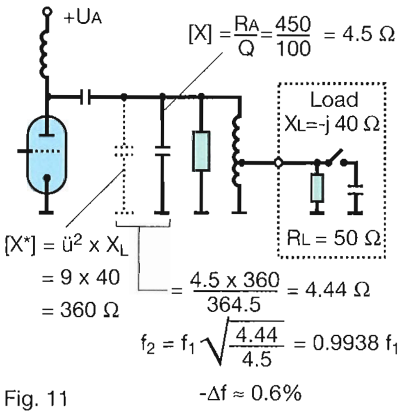


Fig. 11

The Self-Excited Generator as RF Source

The major advantage of a generator compared to an amplifier is the omission of the driving power. If the right choice of tube is made and the circuitry properly scaled, it is possible to achieve RF duty factors of 10 to 90% through grid keying at 13 and 27 MHz and up to pulse frequencies of 50 kHz, similar to the case with amplifiers. At lower pulse frequencies the duty factor ranges from 0 to 100%.

Just like with an amplifier, a self-excited generator permits fast and continuous power control between about 20 and 100% at a constant load resistance. In the region of very low power the solution with an amplifier is still superior.

When a self-excited generator works into a complex load, the transformed reactive component of the latter detunes the frequency-determining resonant circuit. So the generator tube always operates into a purely ohmic load resistance. Depending on the magnitude of the transformed load resistance (R_L), the grid or anode dissipation increases however, according to whether the anode load resistance (R_A) is large or small and as a function of the frequency response of the selected feedback circuit.

For a given reactive component (X_L) of the load, the frequency stability of a generator with a high loaded Q is greater than in the case of a lower Q. This can be seen from the examples in Fig. 10 and 11, where the same load is supplied with the necessary RF power once by a generator of low Q (10) and in the other case by one of high Q (100). The transformed reactive component of the load $X^* = 360\ \Omega$ produces a frequency reduction of 5.7% and 0.6% respectively, referred to the original frequency f_1.

Generator with μ-100 Triode

In the operation of a generator the RF output power will usually alter both with the voltage fluctuation of the 50/60-Hz supply network and with changing load resistance R_L.

In cases where fast control rates are necessary, the relatively slow thyristor controller of the high-voltage rectifier will soon prove to be ineffective. Its control tasks can be handled faster and less expensively by a controlled grid resistance. The required setting range of the grid resistance is obtained with a controlled series transistor through which the DC grid current flows.

With their relatively low DC grid-voltage requirement, a prerequisite for the use of voltage-sensitive and power-sensitive semiconductors, our μ-100 tubes are highly suitable for such applications.

If the grid resistance of an RS 3027 C tube that is self-excited at $U_A = 12$ kV is increased from 200 to 2000 Ω for example, its output power will drop from 30 to 3 kW, and the grid bias voltage shifts from approx. –300 to –150 V.

The grid resistance of approx. 200 Ω, which is especially low under full load (30 kW), is the requisite at the grid end for fast pulsing. The low biasing requirement of our μ-100 triodes is also a considerable advantage in grid-keying circuits fitted with semiconductors. Fig. 12 shows the characteristic of the tube power, the grid and anode current and the grid bias as a function of the grid resistance for a μ-20 and a μ-100 triode. The four load lines in Fig. 13 illustrate this kind of power control for a μ-100 triode.

Tubes with a substantially higher μ, e.g. 150 to 200, offer no extra advantages, because the grid-current requirement rises more than proportionally, the bias that is needed reduces to an insignificant degree, but the tendency to jump frequency increases.

Maximum ratings for CW operation[1]		**RS 3011 C**		**RS 3021 C**		**RS 3027 C**		**RS 3041 C**		**RS 3061 CJ**		
Frequency	f	50	150	40	120	40	120	40	110	30		MHz
DC anode voltage	U_A	7.2	5	14	10	14	10	15	10	15		
kVDC grid voltage	U_G	−500	−500	−800	−800	−800	−800	−800	−800	−800		V
DC cathode current	I_K	3	3	5	5	6	6	12	12	20		A
Peak cathode current	I_{km}	12	12	25	25	30	30	48	48	80		A
DC grid current	I_G	1	0.85	1.7	1.3	2.3	1.7	3.3	3	4.2		A
No-load DC grid current	$I_{G\ leer}$	1.25	1.1	2.1	1.7	2.8	2.2	4.2	3	5.3		A
Anode dissipation, RS 30●● CL	P_A	5	5	10	10	15	15	25	25	–		kW
Anode dissipation, RS 30●● CJ	P_A	5	5	20	20	25	25	35	35	50		kW
Grid dissipation	P_G	350	280	500	330	1000	600	1200	700	2200		W
Grid resistance for blocked tube	$R_{G\ block}$	15	15	15	15	12	12	10	10	4		kΩ
Operating data		**CW**	**Pulse**[3]	**CW**	**Pulse**[4]	**CW**	**Pulse**[4]	**CW**	**Pulse**[4]	**CW**	**Pulse**[4]	
Frequency	f	50	100	120	80	120	80	70	70	30	30	MHz
Output power	$P_{2\ OSZ}$	8	13	20	66	32	104	65	140	110	220	kW[2]
DC anode voltage	U_A	6.5	6.5	10	11	10	11.5	11	12	12	13.5	kV
DC grid voltage	U_G	−280	−250	−290	−400	−280	−200	−300	−400	−350	−300	V
Peak RF grid voltage	U_{gm}	570	660	500	875	590	840	635	970	855	1100	V
Feedback factor	K	9-7	11-2	5-4	9	6-6	8.2	6.3	8.8	7.8	9	%
DC anode current	I_A	1.6	2.7	2.5	8	4.15	12.9	7.6	15.4	12	22.6	A
DC grid current	I_G	0.78	1.4	0.9	3.15	1.5	4.9	2.8	6.2	3.7	7.2	A
Grid resistance	R_G	360	180	325	127	185	41	107	64	95	42	Ω
Anode input power	P_{BA}	10.4	18	25	88	41.5	148	84	184	144	305	kW
Driver power	P_1	0.41	0.84	0.42	2.5	0.83	3.7	1.65	5.5	2.9	7	kW[2]
Anode dissipation	P_A	2.1	4	4.4	20	8.7	40	17	39	31	78	kW
Grid dissipation	P_G	190	480	160	1300	400	2700	790	3000	1600	5000	W
Oscillator efficiency	η_{OSZ}	76.5	73	80	75	77	70	77.5	76	76.3	72	%
Anode load resistance	$R_{A\ OSZ}$	2.2	1.3	2.1	0.72	1.27	0.5	0.77	0.43	0.54	0.34	kΩ

Table 4

[1] Maximum ratings can be expanded on enquiry for pulsed operation

[2] Circuit losses are not included

[3] Max duty = 50 %

[4] Max duty = 25 %

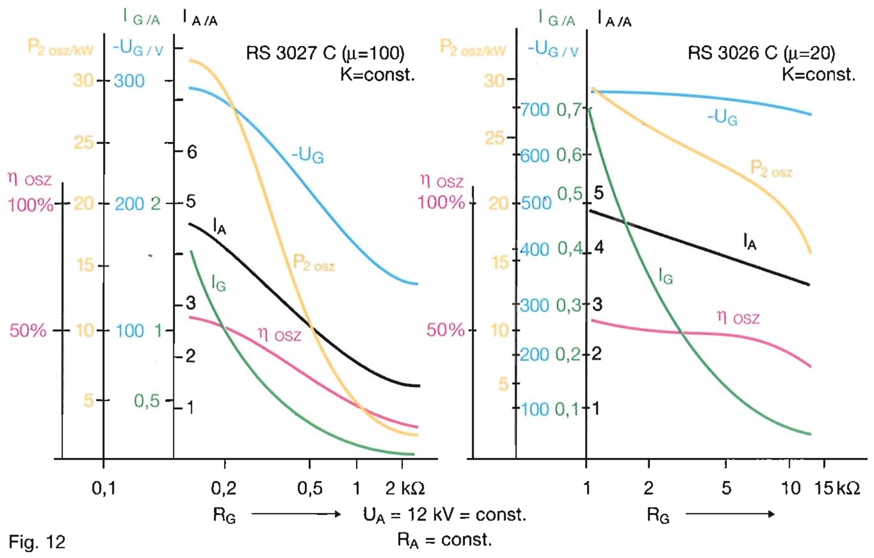


Fig. 12

Control of generator power simply by altering the grid resistance for different tube μ figures

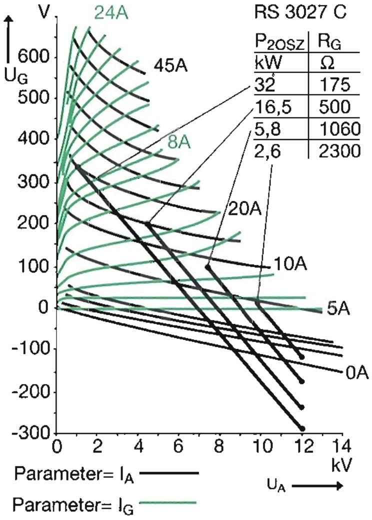


Fig. 13

Load lines when controlling generator power by altering the grid resistance

Generator with Tetrode

In general self-oscillating generators can also be constructed with tetrodes. The main advantage of a tetrode as opposed to a triode is that the power can be generated with lower driving voltages, in other words with higher amplification. This effect is obtained by using a second grid called a screen grid.

Tetrodes have a particularly important role to play in amplification technology, where it is important to minimize the driving power.

However, in oscillator technology, where high driving power is already available, this fact is insignificant; indeed, the sensitive input circuit of the tetrodes causes uncontrolled oscillation at undesirable frequencies.

In tetrodes the electrical field at the cathode produced by the control-grid voltage is only slightly reduced by the opposing effect of the AC anode voltage. This is due to the screening effect of the second grid.

In order to compensate for the reduced influence of the DC anode voltage on the acceleration of the electric field, the screen grid is supplied with positive DC voltage.

Controlling Power with Screen-Grid Voltage

If one observes the constant current diagram of tetrodes at different screen-grid voltages, one will notice that for the same driving voltage the pulse anode current increases as the screen-grid voltage grows.

Thus, with the help of variations in the screen-grid voltage, it is possible to influence the anode current of the tetrode.

If the anode load resistance (R_A) remains constant, as is normally the case, and one reduces the anode current by decreasing the screen-grid voltage, then the RF anode voltage, the feedback peak RF grid voltage at the control grid and thus the output power are reduced.

Since constant DC anode voltage (U_A) and decreasing peak RF anode voltage (U_{am}) cause the residual anode voltage U_R to increase, the efficiency of the oscillators decreases, just like a triode oscillator in which the grid resistor has been increased:

$U_A = U_{am} + U_R$

In short, the fast and continuous power regulation of the output power using the screen grid of a tetrode has no particular advantage over a grid-resistance-regulated triode.

On the contrary, extra costs are incurred through the necessity of using a screen blocking capacitor, an additional screen-grid power supply equipped with interlock, a more complex tube socket and last but not least, a more expensive tube.

If one wishes to use a tetrode without screen-grid power supply in an oscillator circuit, which means the screen-grid voltage is zero or negative, then a more powerful tube must be used in order to reach the required anode current.

The principle of power regulation can be demonstrated taking the RS 2058 CJ tetrode as an example where, simply by changing the screen-grid voltage from 700 V to 1100 V, the output power can be increased from 53 kW to 124 kW.

Fig. 14 and 15 show the position of the load line in the constant-current diagram at screen-grid voltages of 700 V and 1100 V from which the operation characteristics can be determined by graphical integration.

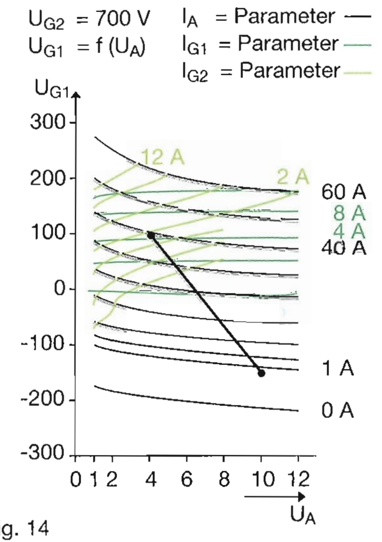


Fig. 14

Load line for RS 2058 CJ
$P_{2\,osz}$ = 53 kW at:
U_A = 10 kV, U_{G2} = 700 V,
U_{gm} = 240 V, R_{G1} = 204 Ω,
R_A = 326 Ω, K = 4.1 %

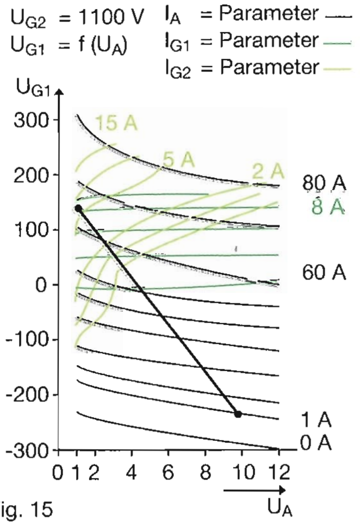
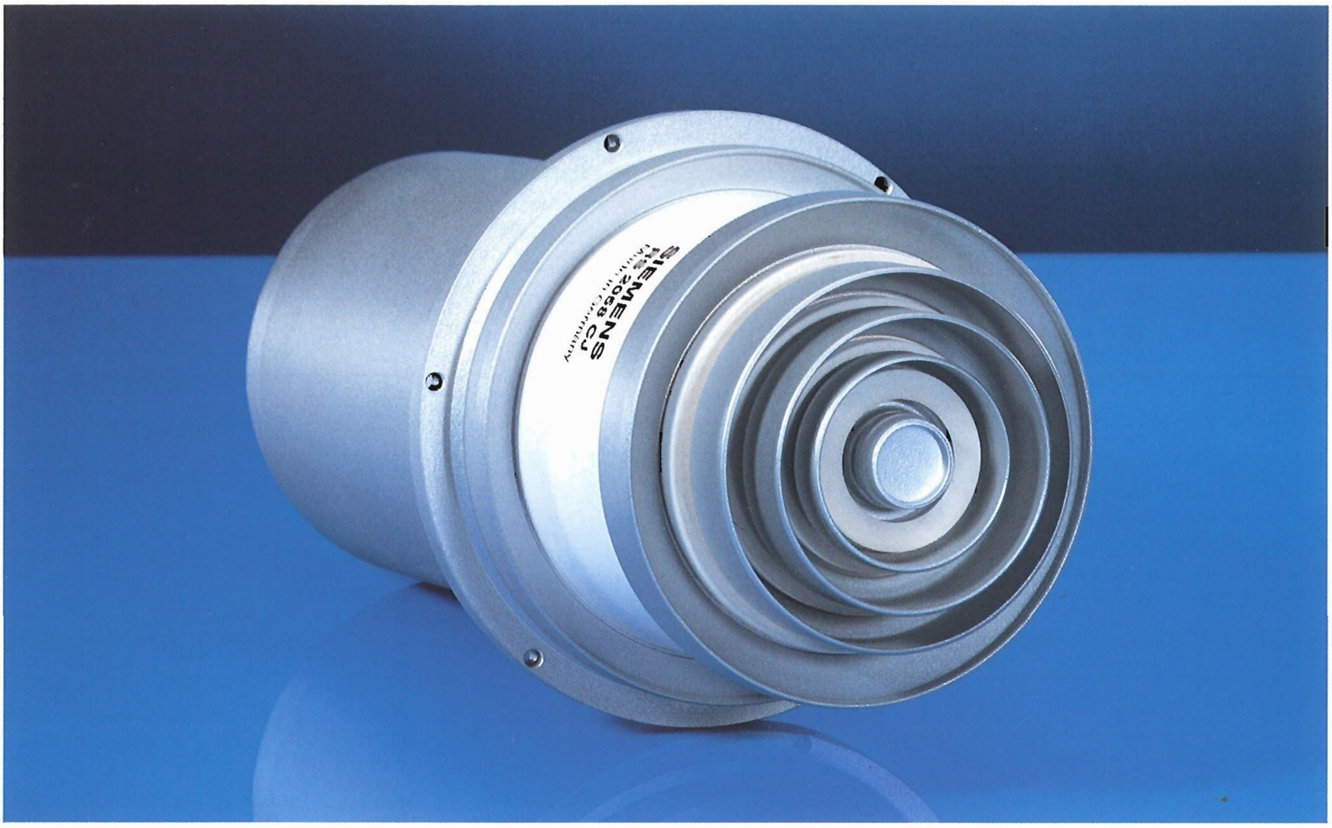


Fig. 15

Load line for RS 2058 CJ
$P_{2\,osz}$ = 124 kW at:
U_A = 10 kV, U_{G2} = 1100 V,
U_{gm} = 370 V, R_{G1} = 204 Ω,
R_A = 326 Ω, K = 4.1 %



Operating data for RS 2058 CJ from Fig. 14 and 15

Operating data (Oscillator)		RS 2058 CJ		
Frequency	f	30	30	MHz
Output power[1]	$P_{2\,\mathrm{OSZ}}$	53	124	kW
Anode voltage	U_A	10	10	kV
Screen-grid voltage	U_{G2}	700	1100	V
Control-grid voltage	U_{G1}	−150	−230	V
Control-grid voltage (peak)	U_{gm}	240	370	V
Anode current	I_A	11	16.8	A
Screen-grid current	I_{G2}	147	983	mA
Control-grid current	I_{G1}	0.74	1.11	A
Control-grid resistance	R_{G1}	204	204	Ω
Anode input power	P_{BA}	110	168	kW
Driver power	P_1	164	390	W
Anode dissipation	P_A	56	44	kW
Control-grid dissipation	P_{G1}	55	130	W
Screen-grid dissipation	P_{G2}	103	1080	W
Anode load resistance	R_A	326	326	Ω
Efficiency	η_{osz}	48.5	74	%
Feedback factor	K	4.1	4.1	%

Table 5

[1] Circuit losses are not included

RS 2058 CJ

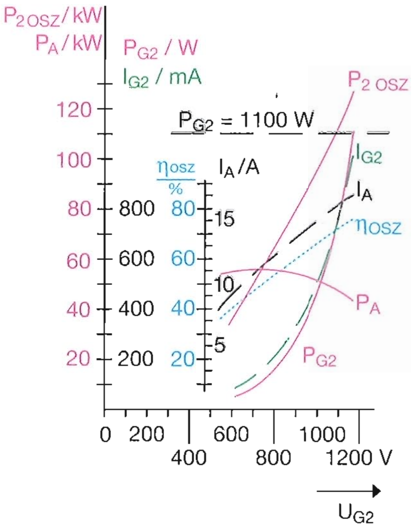


Fig. 16

Oscillator power $P_{2\,\mathrm{OSZ}}$, operating data as function of screen-grid voltage

Possible Implementations of RF Sources for Stripline/Waveguide Lasers

Single-ended infeed

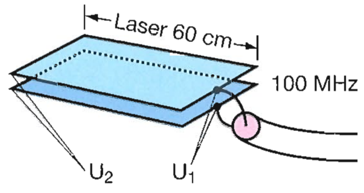


Fig. 17

Central infeed

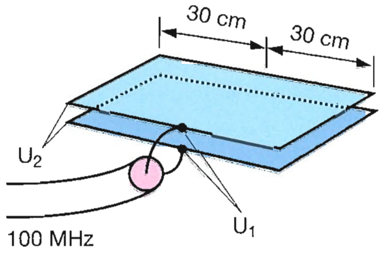


Fig. 18

Central infeed,
voltage characteristic
with ends open-circuit

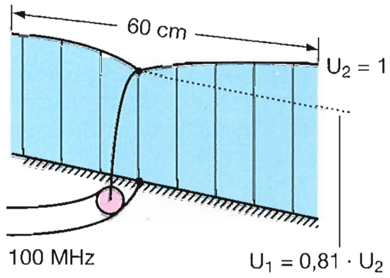


Fig. 19

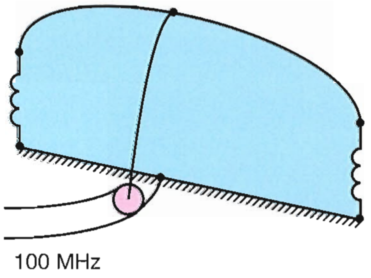


Fig. 20

Central infeed,
voltage characteristic
with compensating
coils at ends

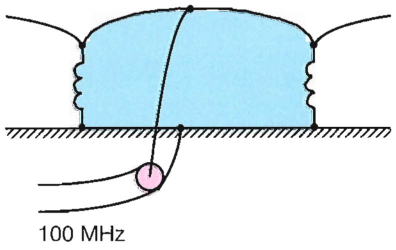


Fig. 21

Central infeed,
voltage characteristic
with optimally configured
compensating coils

RF Sources for Stripline/Waveguide Lasers

As already mentioned, you need frequencies of around 100 MHz to excite stripline lasers. The lengths of these lasers are 0.5 to 1 m and the free-space wavelength is 300 cm, so you have to investigate the voltage distribution along the length of the laser.

This was performed in the laboratory by simulating a stripline laser from RF aspects and measuring the lengthwise voltage distribution with RF voltmeters.

Looking at the unignited laser: if a 60-cm-long "laser" (RF stripline) is fed single-ended for example, then, as in the theory of the unloaded RF line, a voltage maximum forms at the open end at U_2 and:

$$U_1 = U_2 \cos\left(360\,\frac{60}{300}\right)$$

$$U_1 = 0.31 \cdot U_2$$

So it is better to make the RF infeed not single-ended but central. Then a voltage maximum is created at each open end (at U_2), but this time:

$$U_1 = U_2 \cos\left(360\,\frac{30}{300}\right)$$

$$U_1 = 0.81 \cdot U_2$$

You obtain a more even distribution than with single-ended infeed.

If $\frac{U_1}{U_2} = 0.81$ also applied for the voltage distribution on an ignited laser, the power at the two ends of the line would be $\left(\frac{1}{0.81}\right) 2 = 1.5$ times higher than at the RF infeed point in the middle of the laser, leading to a highly inhomogeneous RF plasma. Problems of this kind are encountered in plastic welding at 27 MHz with seam lengths of more than 2 m, where compensating coils are used to remedy the situation (Fig. 20). A further improvement is produced if appropriately scaled inductances are arranged as shown in Fig. 21.

In an ignited laser with its linear expansion, the electric power is not seen by a single resistance at the end of the line but by a large number of resistances distributed along the line. This is where the graphic illustration fails, because the laser can no longer be regarded as an unloaded, lossfree RF line with a cosinusoidal voltage distribution.

The dependence of the RF voltage on length was investigated and calculated at 100 MHz between two metal plates whose spacing a and characteristic impedance Z were varied. 16 uniformly distributed, low-inductance resistors of 20 or 80 Ω simulated the "ignited" laser, the result being 1.25 or 5 Ω.

Central infeed,
voltage characteristics
for different R/Z
relationships

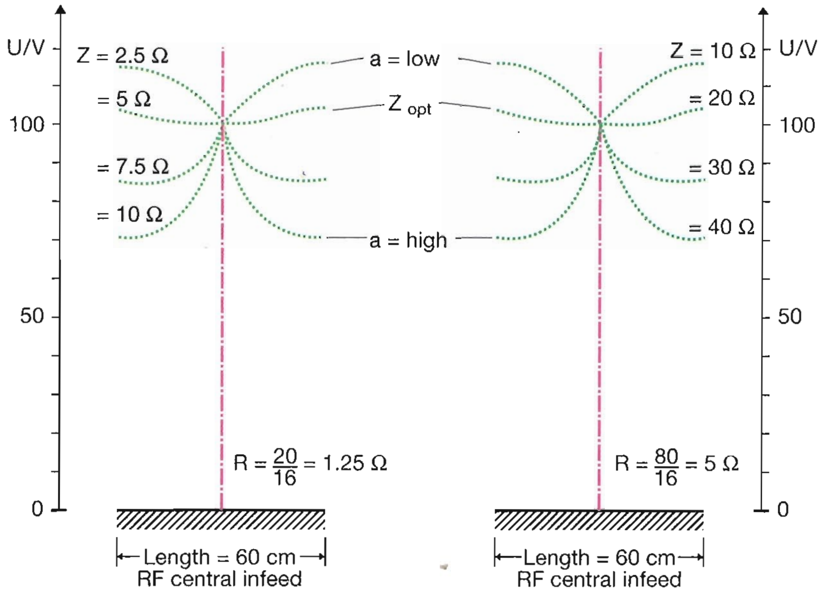


Fig. 22

It is possible to see that, for a certain combination of characteristic impedance of the stripline and resulting total resistance, a very constant voltage can be forced along the laser. The RF power produced in the volume unit is virtually constant and independent of the location of the volume along the line. If the characteristic impedance becomes greater than the optimal characteristic impedance Z_{opt} (in the example 5 or 20 Ω), the voltage will drop towards the end of the line, due to the strong attenuation along the line. If the characteristic impedance becomes smaller than Z_{opt} (Q factor increases), the voltage will increase towards the end of the line, like in an undamped line.

Triode Oscillator
up to 8 kW and 80 to 100 MHz

A compact, self-excited generator was developed for CW power up to 8 kW in the frequency range 80 to 100 MHz. With only slight modification, both the air-cooled and water-cooled versions of our μ-100 triode RS 3011 C can be operated in it.

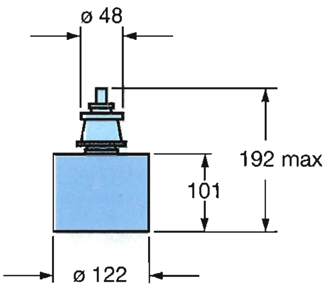
The simplicity of the construction is worthy of attention, with the possibility of simple change of frequency, of fine tuning in operation and of routing the cooling water – to the anode and back again – without RF voltages having any influence on the cooling-water pipe. The variable feedback, based on the principle of a TPTG (tuned-plate tuned-grid) oscillator circuit, consists of a workable sheet-metal loop. The power of the generator can also be varied, of course, by altering the grid resistance.

Triode Oscillator
up to 35 kW and 100 MHz

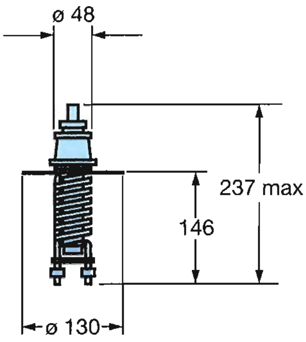
For CW power from 15 to 35 kW and for a frequency of approx. 100 MHz there is another newly developed, self-excited generator available, designed for incorporation in 19-inch racks. Because of the base compatibility of our three tubes RS 3021/27/41 CJ, all three of them can be operated in this generator with very little modification. So, if increased power is required, more powerful tubes are needed but only slight alterations on the RF side.

This concept means that our customers can progress to a different power class quickly, securely and inexpensively. A lab model is on hand for demonstrations.

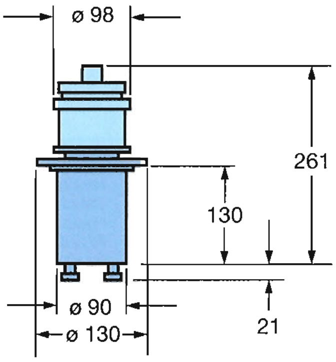
Dimensioned Drawings of High-μ Triodes and Tetrodes



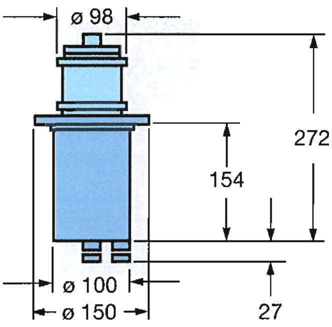
RS 3011 CL



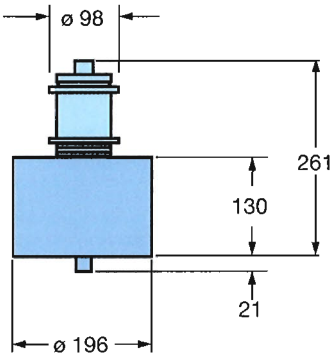
RS 3011 CJ



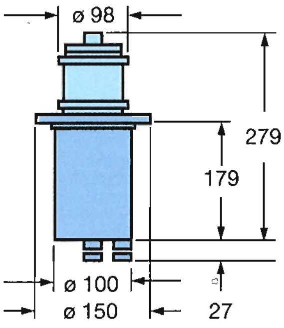
RS 3021 CJ



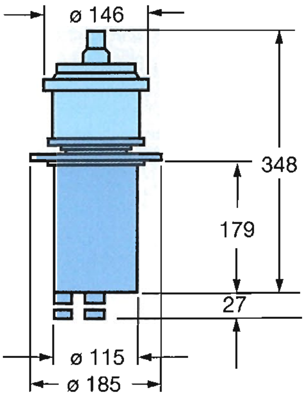
RS 3027 CJ



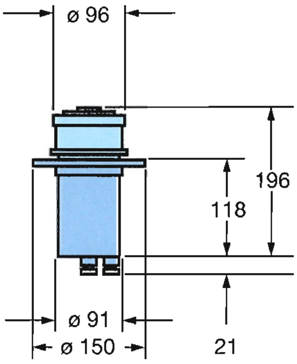
RS 3041 CL



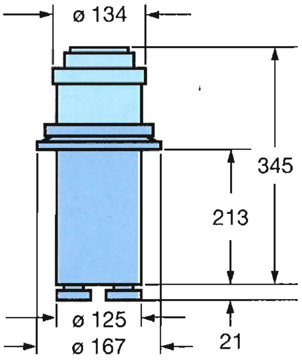
RS 3041 CJ



RS 3061 CJ



RS 2012 CJ



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