

# STATUS AND FUTURE STRATEGY FOR ADVANCED HIGH POWER MICROWAVE SOURCES FOR ACCELERATORS

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## Abstract

Energy efficient conversion of electrical grid power into radio frequency power is becoming one of the key aspects of future accelerators. A significant part of the initial investment and running costs of these machines will be determined by the cost and efficiency of their RF systems. For large-scale accelerators, which are proposed for instance by the International Linear Collider Study or by the Future Circular Collider Study, RF efficiency will likely be a determining factor in the approval process. Efforts are already in place to stretch the efficiency of existing RF sources to higher levels. Well-known technologies such as klystrons are being reinvented with modern-day beam physics, inductive output tubes are being combined for higher power output, and modular solid state amplifiers are becoming more popular as RF sources for accelerators. This talk will give an overview of recent advances and trends in RF source developments. It will discuss future needs and the strategy towards higher efficiency devices for the benefit of the accelerator community.

## THE NEED FOR HIGHER EFFICIENCY RF SOURCES

The electrical power consumption of future accelerators will be driven to a large part by their RF systems. This is particularly true for electron colliders, circular (e.g. FCC) or linear (e.g. ILC or CLIC), which need RF systems in the order of 100 MW or above (see Table 1, [1–6]). Other examples with significant RF power consumption are high power hadron linacs (e.g. ESS) and cyclotrons (PSI) for neutron science or Accelerator Driven Systems. In the case of hadron colliders, magnet systems dominate electrical power consumption while RF systems only use a few percent. At CERN, where most accelerators are circular, only 6% of the annual consumption ( $\approx 1.1$  TWh in 2017) are caused by the RF systems.

For a 3 TeV CLIC machine, around 50% of the facility power consumption is due to the RF system. With an estimated yearly total of 2.74 TWh [4], and a European average price for non-household consumption of 0.1 €/kWh in 2017, this translates into 187 M€ of electricity costs/year for the RF system alone. Therefore every percentage point in RF efficiency has a significant impact on the running cost.

For Accelerator Driven Systems (ADS), the power to run the accelerator complex (including cooling, ventilation, cryogenics, offices, etc.) must be small (5-10%) compared to the power, which is produced in the ADS core. To achieve these values the accelerator complex must have a total efficiency between  $0.2 < \eta_{acc} < 0.4$  [7], which presents a challenge for today's accelerators. If not achieved, the idea

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Table 1: RF Power for Various Future Accelerators

Project	$P_{total}$ [MW]	$P_{RF}$ [MW]	$P_{beam}$ [MW]
PSI*	10	4	1.3
LEP2 <sup>†</sup>	120	42	19
FCC-ee <sup>†</sup>	tbd	165	100
ESS*	35	15	5
CLIC 500*	272	109	9.8
ILC 500*	164	68	9.4
CLIC 3000*	582	289	28

\* total power is for the whole facility with experiments, <sup>†</sup>without injector

of using ADS for energy production is unlikely to become economically viable [8].

## TODAY'S TECHNOLOGIES & NEW DEVELOPMENTS

In the following we will review today's state of the art of high-power RF sources (see Table 2) and point to developments, which may change their efficiencies or power reach in the near future. As pulsed and Continuous Wave (CW) operation pose different challenges to the RF sources both modes of operation will be treated.

### Modulator Efficiency

Most high-power RF sources need a High-voltage (HV) modulator, which transforms the voltage of the electrical grid to the HV and pulse pattern needed by the RF source. For CW operation in general but also for pulsed operation of gridded tubes (tetrodes, IOTs), the modulator is basically a HV power supply. Pulsed power for gridded tubes is obtained by simply pulsing the grid using the input RF signal, whereas HV pulses for the operation of non-gridded tubes (klystrons, magnetrons) have to be formed by the modulator itself. Various topologies have been developed in recent years, which are adapted to different pulse lengths and voltage needs [9]: i) Traditional pulse transformer based modulators with efficiencies between 85% and 90% and rise times in the range of a few hundred microseconds. ii) High-frequency transformer based modulators such as the resonant polyphase design employed at SNS [10], or the stacked multi-level (SML) design developed and used by the European Spallation Source (ESS) with efficiencies up to 92% and with a very short rise time in the range of 100  $\mu$ s. iii) Transformerless modulators such as the Marx generator [11], which have the potential for even higher efficiency, or direct switch designs.

Table 2: Parameter Reach of Different RF Amplifiers

	Tetrodes	IOTs/MB-IOTs*	Klystrons	Solid state	Magnetrons
Gain [db]	15	20	40-45	n.a.	25
$P_{pulsed}$ [MW]	4	0.13/1.3*	0.3 - 15	0 - 0.15	0.1
$P_{CW}$ [MW]	1.5	0.1/0.15 *	1.2	0 - 0.15	0.1
Input voltage [kV]	10 - 25	< 50	90 - 450 (60*)	n.a.	20
$T_{pulse}$ [ms]	any	any	< 4	any	any
$T_{rise/fall}$ [ns]	ns	ns	300	10 - 60	10
$\eta_{DCtoRF}^{\dagger}$ [%]	70	70	55 (>70*)	45 - 55	70*
Frequency [MHz]	30-400	<1300	300 - 15000	0 - 1300	400 - 1300
Active development	no	MB-IOT	yes	yes	little

\* under development,  $\dagger$  at working point

In summary today's modulators are already operating with very high efficiency (85 - 92%), almost independent of their output power (kW - MW), voltage (1 - 100 kV), and pulse length. For short pulses (< 500  $\mu$ s), the modulator rise time becomes an important factor in the system efficiency and this is where further developments such as the SML design can still make a significant difference.

### Klystrons

The principle of klystrons was published in 1935 by O. Heil in Germany and then developed in 1937 by Russel and Varian at Stanford University. Electrons are extracted from a heated cathode via a high DC voltage and are then velocity-modulated with the input RF signal. After a certain distance the velocity modulation is transformed into a density modulation. The bunched electron beam then excites the fundamental resonance of the output cavity from which the RF power is extracted. Typical performance values are listed in Table 2.

**Pros and Cons** Advantages of klystrons are: i) simple, mostly solid state input amplifiers due to large gain, ii) high output power in the MW range, iii) long lifetime up to 40 kh. Their disadvantages are: i) HV needs with typically > 100 kV, which translates into oil tanks for break down protection and expensive HV modulators, ii) gain curve saturates at full output power, which means that most klystrons are operated below full output power and below maximum efficiency to maintain a power margin for the LLRF system.

**Developments** In order to reduce the efficiency loss by operation below saturation, FNAL, DESY and others are developing klystron linearization algorithms, aiming for operation closer to saturation.

With the advance of modern beam dynamics tools [12], new methods to increase the energy conversion efficiency have been developed, such as the core-oscillation method (COM), [13], the Bunching, Alignment and Collecting (BAC) method [14], and the CERN-developed Core Stabilisation Method (CSM) [15]. These methods are being

evaluated by the High-Efficiency International Klystron Activity (HEIKA), which was initiated at CERN in 2014 [16]. A proof-of-principle experiment with the BAC method has already been made by retrofitting an existing multibeam S-band tube (VDBT, Moscow, 40 beams). This boosted the output power by almost 50% and increased its efficiency from 42% to 66% [17].

### Gridded tubes: Tetrodes, Diacrodos®, IOTs

The principle of gridded tubes such as triodes, tetrodes, diacrodos®, and inductive output tubes (IOTs) goes back to vacuum diodes (without grid), which were patented in 1904 by J.A. Fleming. They are built since around 100 years and are used in many of today's accelerators with frequencies up to 400 MHz and power values into the MW range. Electrons are released from a cathode and accelerated towards the anode. In triodes a control grid modulates the flow of electrons and thereby the anode current. With a resistive load in the anode circuit, the varying current results in a varying voltage. Tetrodes use an additional screen grid to decouple the control grid from the anode, which increases the gain and reduces the tendency to self-oscillate, especially with inductive loads.

Inductive Output Tubes (IOTs) were invented in 1938 by A.V. Haeff. They can be understood as a mixture of a klystron and a triode and are sometimes called klystrode. A control grid very close to the cathode regulates the electron current, which means that IOTs use current modulation (as in triodes) instead of velocity modulation (as in klystrons) to create a bunched electron beam. The bunched beam is accelerated with a DC voltage and then passes an output cavity just as in a klystron. From there the RF power can be extracted via inductively coupled coaxial transmission lines.

**Pros and Cons** Tetrodes and diacrodos® provide output power into the MW range but are limited to frequencies of  $\approx$  400 MHz. Their limited gain of  $\approx$  15 db means that high-power tetrode amplifiers need 2-3 stages of amplification, which drives up the cost and results in complicated amplifier systems. Even though tetrodes are used in many accelerators,

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the overall market is relatively small, which means: i) that many tubes are no longer produced, and ii) there are very few companies, which are capable and willing to build tetrode-based RF amplifiers. Nevertheless, once commissioned, tetrode and diacode® RF amplifiers are extremely reliable and can work for many decades if maintained adequately.

IOTs have less gain than klystrons but higher gain than tetrodes (see Table 2), which puts their input power needs within reach of commercially available solid state amplifiers. As they do not need a long drift space like klystrons, IOTs are quite compact and therefore cost efficient. IOTs and indeed all gridded tubes are limited in their frequency reach by the distance of the control grid from the cathode. The RF period has to be smaller than the time of flight from cathode to this grid. Therefore the frequency of IOTs is limited to around 1.3 GHz. The maximum power of single beam IOTs is limited to around 100 kW. As they are used for broadcasting of digital signals, there is a commercially viable market, which means that long-term availability seems relatively secure.

**Developments** Several years ago Thales developed the diacode®, an improved version of the tetrode, which can either double the power at a given frequency, or double the frequency at a given output power [18, 19]. It is successfully used since 2015 at the LANSCE accelerator in Los Alamos but has not gained widespread use.

In order to make use of the advantages of IOTs for MW-class RF amplifiers, Thales, CPI, and L3 developed two prototype 704 MHz multi-beam IOT's (MB-IOT) for ESS with an output power > 1 MW. Both tubes were tested at CERN and results are reported at this conference [20].

### Magnetrons

An early form of the magnetron was invented in 1910 by H. Gerdien, followed in 1920 by A. Hull's invention of the split-anode magnetron, and then perfected in 1936 by Aleksereff and Malearoff in Russia, who built a 3 GHz device delivering 300 W of power.

Magnetrons are so-called free running oscillators. Electrons are released by heating the cathode (see Fig. 1) and are then accelerated by a voltage difference towards the anode. A magnetic field perpendicular to the anode/cathode plane makes the electrons rotate around the cathode thereby exciting a pi-mode in the anode cavities. The pi-mode modulates the electron current into bunches, which then further excite the cavity fields. A current starts to flow as soon as the electrons start hitting the anode and RF power can be extracted from one of the cavities.

**Pros and Cons** Advantages of magnetrons are: i) high DC/RF efficiency of up to  $\approx 85\%$ , and ii) low price. Their disadvantages are: i) difficult phase/amplitude, which needs further R&D to make them usable for multi-cavity accelerators, and ii) operation below the working point may decrease the efficiency considerably.

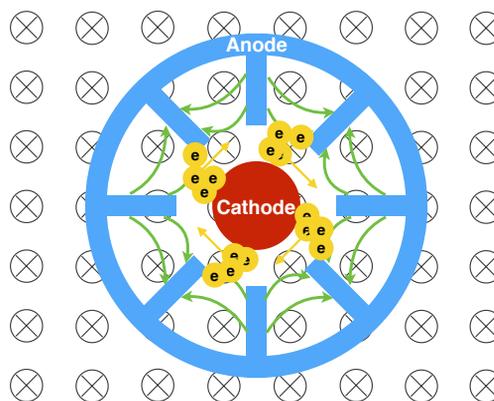


Figure 1: Electron movement in a magnetron.

**Developments** Up to now magnetrons are only used in accelerators that use a single RF source, such as electron machines for X-ray production. The combination of several magnetrons with a precise phase and amplitude control has been demonstrated with proof-of-principle experiments [21, 22] but has so far not been employed in multi-cavity accelerators. In the US a consortium of CCR, CPI, and FNAL is actively developing a magnetron based RF system for accelerators using 1.3 GHz magnetrons capable of 100 kW peak power and a 10% duty cycle [23].

### Solid State

Solid state, transistor-based RF amplifiers promise cost-efficient RF power generation and the advantages of modular systems, which may allow hot-swapping of faulty units during operation. Most of today's systems operate below 100 kW at frequencies below 1.3 GHz with DC to RF efficiencies below 55%.

**Pros and Cons** Single amplification units are limited to around 1 kW. As there is no significant commercial market for higher power transistors it is unlikely that this value will be increased significantly in the near future. This means one needs to combine a large number of single units for high-power RF amplifiers. Traditionally this power combination is done in pairs of 2 and since each combination carries a certain loss it is relatively inefficient to go beyond some 10s of kilowatts. In most accelerator scenarios, the RF amplifiers have to withstand significant amounts of reflected power and if the amplifier itself cannot withstand these reflections, circulators are used to deviate power into water-cooled RF loads. For solid state amplifiers, the addition of circulators for all single units and/or for the combined output often makes the whole system too expensive.

**Developments** The key to making cost-efficient solid state amplifiers for power values > 100 kW lies in the effective combination of the single units. A promising solution is the use of combiner cavities, which can combine the output power of all single units in one stage. However, matching hundreds of input antennas and minimising the reflected

power due to manufacturing tolerances of the electronics or due to failed units is far from trivial.

## CONCLUSIONS ON PARAMETER REACH AND OVERALL RF SYSTEM EFFICIENCY

The power and frequency reach of the various RF sources is summarized in Fig. 2. The chart is limited to frequencies < 1.3 GHz and the MW range because higher values can basically only be covered by klystrons and with very short pulses. In the range between 10s of kW to 100 kW solid state has to compete with tetrodes in the low-frequency range and with IOTs in the higher frequency range and in both cases the efficiency of solid state amplifiers is lower than the competition. In some cases, however, the modularity of solid state systems may outweigh this disadvantage and there the combining cavities are most likely the way towards higher power units. The development of multi-beam IOTs, which may rival klystron-based systems is encouraging but it may still take some engineering effort to make them as reliable and cost-efficient as their counterparts. The development of high-efficiency klystrons and klystron linearisation algorithms is highly promising and will make klystrons not only more efficient but smaller with increased average output power, and it will lower the HV needs thereby reducing the needs for HV protection and making the modulators cheaper.

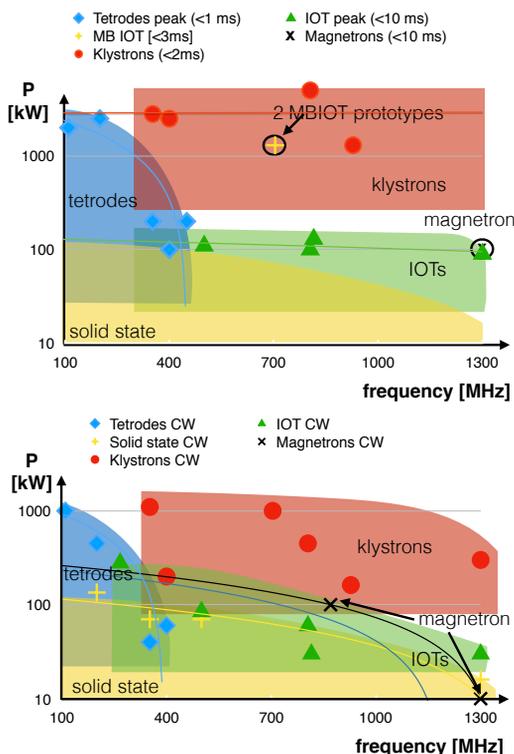


Figure 2: Power/frequency chart of RF sources for pulsed (upper chart) and CW (lower chart) operation up to 1.3 GHz

## CERN NEEDS & DEVELOPMENTS

At CERN around 80 high-power RF systems (> 100 kW) are in operation, half of which based on tetrodes, followed by klystrons and some first solid state units, which are presently being tested for the 200 MHz SPS RF system upgrade. An overview of all systems is given in Table 3.

**Tetrodes & klystrons** When Linac2 is replaced by Linac4 in 2021 most high power systems will be based on klystrons, making these the most important R&D target for CERN. Within the HEIKA network efforts are made to develop a 400 MHz high-efficiency klystron based on the CSM method for the LHC [24] and the FCC study. The goal is to keep the existing LHC modulators and power supplies, and to increase the available output power by having an improved efficiency. Developments for 800 MHz have also started in the FCC frame. A similar development may also become interesting for the 352 MHz klystrons of Linac4 in order to limit the cost of replacing existing units.

In a quest for high peak power CERN established three 12 GHz klystron-based test stands to condition and characterise high-gradient accelerating structures. In the X-band test facilities 1 and 2 (Xbox-1 & 2) [25] single 50 MW klystron/modulator units provide 1.5  $\mu$ s pulses of 50 MW with a 50 Hz repetition rate. A pulse compressor [26] transforms these into 250 ns long pulses with 140 MW peak power. In Xbox-3 [27] a novel approach was developed, combining two times two 6 MW 5  $\mu$ s klystrons, capable of running at 400 Hz repetition rate. After pulse compression and power combination each pair provides 2 test places with 45 MW in 250 ns pulses with a 200 Hz repetition rate [28].

To maintain the availability of tetrodes, CERN has made agreements with industry to receive limited manufacturing licences in case certain tube types go out of production.

**IOTs** CERN has built a test stand stand for MW-class IOTs, which has been used to successfully test two MB-IOTs, which have been procured by ESS and built by CPI/Thales and L3. Whether MB-IOTs can compete with the new high-efficiency klystrons will depend on the final cost of the series units.

**Solid state** CERN is presently working very closely with Thales on the realisation of 200 MHz solid state amplifier towers based on combiner cavities. Each of the 32 towers shall be capable of > 100 kW, which will then be combined to a total power of  $2 \times 1.4$  MW for the SPS travelling wave accelerating cavities [29, 30]. In Linac3 there are plans to replace two pulsed 100 MHz tetrode amplifiers, delivering 300-400 kW each, with solid state units.

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Table 3: Overview of High-Power (> 100 kW) RF Systems at CERN

	Type	P [MW]	f [MHz]	T <sub>pulse</sub> [μs]	Rep. rate [Hz]	N <sub>systems</sub>	N <sub>tubes/units</sub>
Linac2	Tetrode	0.07 - 2.7	202	350-1000	1	11	18
Linac3	Tetrode	0.3 - 0.7	101/202	350-1000	1-10	4	8
Linac4	Klystron	1.2 - 2.8	352	1000	1	14	14
REX	Tetrode	0.1	101/202	1000	1-100	6	6
RFQD	Tetrode	1.7	202	150	1	1	2
PS	Tetrode	0.1	2.6-9.5	< 200 ms	0.8	2	6
PS	Tetrode	0.4	40/80	300	0.8	5	15
SPS	Tetrode	1	202	10 - 5 s	43 kHz/0.1	4	88
SPS (LIU)	SSA	1 - 1.4	202	10 - 5 s	43 kHz/0.1	6	32
SPS	IOT	0.24	808	10 - 5 s	43 kHz/0.1	2	16
LHC	Klystron	0.30	400	CW	CW	16	16
XBOX1,2	Klystron	50	12000	1.5	50	2	2
XBOX3	Klystron	6	12000	5	400	1	4

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