

NEW DEVELOPMENTS ON RF POWER SOURCES

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Abstract

The classical generation of RF power with klystrons and tetrodes is evolving and changing to meet the demands of higher efficiency and simpler maintenance. Developments of IOT tubes for FEL, Energy Recovery Linacs and Storage Rings, together with solid state technology approaches and combination techniques for the high power generation are opening new alternatives to the classical ones.

INTRODUCTION

Accelerator design is intimately linked with the definition of the main RF parameters for beam acceleration: pulsed or CW operation, RF frequency, type of cavity and required power. In order to make the appropriate choice of RF power source, not just technical, but also financial and operation related aspects are considered, often with different results for various projects. Larger projects on the forefront of accelerator technology often include R&D programmes, partly in collaboration with industry, for new concepts of RF power generation, which are tailored to their application. Many smaller accelerator centres with user facilities, such as light sources, tend to select state of the art technologies or even purchase turn key transmitters from industry. The technologies available on the market evolve according to innovations for commercial systems such as broadcast transmitters, radars, security or medical applications and also following developments for larger scientific projects.

In the next section, examples of different technologies used in accelerators for high power RF amplification are briefly reviewed. Their power/frequency characteristics are plotted in Fig. 1 together with some typical figures from supplier data sheets [1, 2, 3]. The graph shows that several solutions are in competition for accelerators requiring CW RF power at UHF frequencies between 350 MHz and 1.3 GHz. Examples of applications of these different amplifiers in recent storage rings or SC Linac projects will be discussed in the third section.

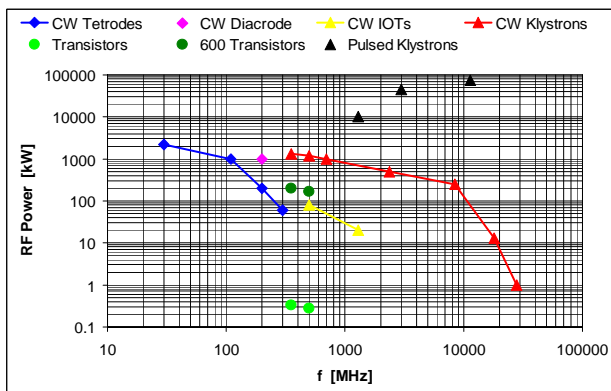


Figure 1: Typical RF sources used in accelerators.

RF POWER SOURCES FOR ACCELERATORS

Tetrodes

For accelerators operating at frequencies below 300 to 400 MHz, grid tubes are still used for high power amplifiers. At much higher frequencies, finite electron drift time limits the achievable gain. Tetrode transmitters deliver between 10 kW and 2 MW CW or average power, correspondingly more in pulsed mode. With its symmetric geometry optimized for the coupling to a $\lambda/2$ coaxial resonator, the Thales *diacode* achieves twice as much frequency-power product as a conventional tetrode [1].

Klystrons

For frequencies above 350 MHz, klystrons, which exploit the finite electron drift time, are commonly used to build very high power amplifiers for accelerators. A dc electron beam is velocity modulated with low RF drive power in a first cavity, leading to bunching after a given drift. The better the bunching, the higher the proportion of DC input power converted into RF power, which is then extracted by means of an output cavity. Intermediate idle cavities are tuned to enhance the bunching and to achieve a high efficiency. The collector then receives the electrons with their rest energy, the spent beam, and dissipates the fraction of power not converted into RF.

The catalogues of klystron manufacturers offer a large variety of klystrons for either CW or pulsed operation in a frequency range between 350 MHz and 3 GHz.

Commercial TV klystrons typically delivering 60 kW CW at 500 MHz with an efficiency of 45% have been widely used in accelerators [4].

Dedicated *superklystrons* providing a MW or more CW RF power at 352, 500, 700 MHz have been developed for large accelerators and have also later been used to build other machines such as the larger synchrotron light sources ESRF, APS and SPring-8. Not only do these klystrons have a high efficiency of typically 62 % but also a ca. 42 dB high gain and thus require less than 100 W of RF drive power. Moreover, a modulating anode allows to maintain a high efficiency at reduced output power.

Klystrons with short pulses ($<10 \mu\text{s}$) and a peak power as high as 35 to 45 MW at 3 GHz have been developed for S band electron Linacs such as SLAC and are being used for the pre-injectors of many other machines including existing light sources.

Examples of Recent Klystron Developments

For the 1.3 GHz TESLA and the DESY X-FEL projects, CPI, Thales and Toshiba have developed pulsed Multi Beam klystrons, which provide high power (10 MW) at a reasonable beam voltage. The main advantage

is that keeping the perveance per beam low allows to achieve a high efficiency of 65 %, when compared to the 45 % for a classical klystron [5, 6, 7].

In the frame of the NLC and JLC projects, the development of X band Periodic Permanent Magnet – PPM - klystrons delivering 75 MW pulses at 11.424 GHz was undertaken [8, 9]. At NLC, for instance, PPM klystrons would have allowed to save as much as 80 MW of electrical power for focusing coils and a lot of space and auxiliary equipment. The PPM scheme was also considered for C and S band klystrons [8].

In the CLIC concept, instead of being drawn from a dc beam as in a conventional klystron, power is transferred by means of a PETS structure from a high intensity low energy drive beam of an S band Linac to the 30 GHz accelerating structure of the low intensity high energy beam [10]. This constitutes an extremely dedicated HF generator development. Note that in this project, the dc power is still converted into RF by means of S band klystrons.

IOTs

Inductive Output Tubes or IOTs are conceptually between the tetrode and the klystron. As in the tetrode, the beam is density modulated by means of a grid located close to the cathode. As in a klystron, the already bunched beam is then accelerated towards a short drift tube functioning as an anode and directly reaches the gap of the output cavity before being absorbed in the collector. IOTs are inserted into external output cavities, which makes a replacement very easy and fast. The already high efficiency may be further improved by means of a multistage depressed collector, which is much more effective than for a klystron, thanks to the more uniform energy distribution in the spent beam of an IOT [2].

A typical UHF TV IOT delivers up to 60 kW through an external output cavity tuned to the desired frequency, which can be selected from 460 to 860 MHz [3]. Such IOTs have replaced klystron transmitters in many TV stations. IOTs for accelerators have been optimized to deliver up to 80 kW at these frequencies [1, 2]. With an operation near class B, an efficiency as high as 70 % can be achieved, however, only a modest gain of 20 to 22 dB requires nearly 1 kW of input drive power.

For several upcoming X-FEL projects operating CW superconducting Linacs or ERLs, 1.3 GHz / 16 to 20 kW IOTs have been developed [1, 2, 3, 10]. As for other grid tubes, finite electron drift time imposes an upper frequency, which for IOTs is between 1.5 and 2 GHz.

IOTs have recently been selected for several accelerator projects. At UHF frequencies, IOTs now represent an efficient, easy to handle and compact alternative to klystrons. However, several IOTs need to be combined to achieve comparable power levels.

Transistor Amplifiers

Since its invention, the transistor has replaced vacuum tubes in many applications. As will be shown in detail in the next section, transistors have recently been used to

build high power RF amplifiers for 352 and 500 MHz cavities [12, 13]. Hundreds of amplifier modules with typically 300 W unit power are combined to deliver up to 200 kW. For that range of frequencies, solid state amplifiers therefore constitute a third way to power accelerating cavities.

UHF TRANSMITTERS FOR RECENT STORAGE RINGS AND SC LINACS

In order to identify some concrete pro and con arguments, the different approaches to the building of UHF transmitters will be addressed for some selected examples of recent machines.

Operation of High Power Klystron Transmitters at the ESRF

When the first 3rd generation 6 GeV light source was built at the ESRF at the end of the 80's, there was no realistic alternative to klystrons for feeding of the order of 1 MW of RF power to the storage ring. The same choices were made at APS, SPring-8 and many other storage rings. ESRF and APS took advantage of the 1.1 to 1.3 MW / 352 MHz klystrons that had been developed for LEP and can now look back at more than 10 years experience of operation of these tubes. Klystrons from different manufacturers (Thales, Philips, EEV) were installed. For the ESRF, the LEP RF system, including the five-cell copper cavities and the high voltage power supply (HVPS) served as reference design.

Presently, in standard 200 mA operation at the ESRF, two klystrons provide respectively 1/3 and 2/3 of 1 MW of beam power and 300 kW dissipated in six cavities. The high beam loading also imposes the covering of a large dynamic range, which is achieved by means of the klystron's modulating anode to save electricity. The three existing storage ring transmitters have sufficient power reserve for a possible doubling of the stored current at the ESRF.

When commissioning a new klystron or simply installing a spare tube, delicate tuning is required. The difficulties directly linked with the complexity of klystrons can be summarized as follows:

- The harmonic 2 of the RF couples to the waveguide section down to the circulator input, which constitutes a kind of over-moded resonator at 704 MHz. Sometimes nearly 1 kW is extracted from the harmonic dampers. Fine tuning of the klystron/circulator distance is then essential to avoid resonances and minimize the harmonic power.
- Multipactor in the input cavity can lead to unstable behaviour and impair the operation of the ring. Most of the time, a careful adjustment of the working point solves the problem, but in some cases, it is difficult to guarantee stability over a large dynamic range.
- Breakdowns in the gun between anode and body are another source of trips. There are several possible causes: backward propagating ions, reflected electrons and/or x-rays, resulting in a charging up of the gap

ceramics. Fine tuning of the focusing and of the RF working point as well as conditioning generally help.

- Other breakdowns linked to the HV and high RF fields, especially in the output coupler of the last cavity, occur on new klystrons but disappear with operating time.
- After early experiences with pollution of the ceramics by barium from the cathode, leading to excessive anode currents and breakdowns, the heating of each tube is re-optimized once a year for the actual working point. A low heating mode when no beam is drawn from the cathode also contributes to an increased tube lifetime.
- Sometimes, the resonance frequencies of the individual klystron cavities need to be retuned.

For some klystrons it is tedious, at times even impossible, to overcome these difficulties for a large range of working points. But once stable conditions are established, a tube can generally run thousands of hours without generating any trip or instability.

At the ESRF, with 5500 hours/year of beam scheduled for the users, a total MTBF above 40 hours and an availability of at least 98 % are standard. The RF system, including transmitters, waveguides and cavities, is typically responsible for 25% to 30% of the machine trips:

- The number of RF trips due to klystron failures is slightly below the number of klystron auxiliary equipment failures. This is an argument in favour of a small number of high power transmitters rather than many low power units, as a larger number of auxiliaries would most likely increase the overall trip rate.
- Even with the nominal uneven share in power between two transmitters delivering 900 kW and 450 kW, respectively, both contribute equally to the number of RF trips, which therefore suggests that the trips are not strongly dependent on the output power level.

Due to the long drift space, the output phase of the ESRF klystrons changes by 7° for a 1% variation of the beam voltage. Due to the ripples of the conventional HVPS, sidebands show up at multiples of 300 Hz with a peak of up to -50 dBc at 600 Hz. A phase regulation loop reduces the sidebands by 20 dB down to -70 dBc. Unfortunately, these sidebands couple strongly to the beam with its coherent synchrotron frequency evolving from 2 kHz at 0 mA to 1.2 kHz at 200 mA of stored beam. Today, one would probably implement a modern crowbarless switched mode power supply with less ripple, operating typically in the 20 kHz range, i.e. far above the synchrotron frequency.

From the three initial suppliers only Thales still offers 352 MHz super klystrons. In particular since the shut down of LEP there are only a few customers left and this uncomfortable situation raises the question of the possible obsolescence of these very specific tubes.

The recent current upgrade of PEP II highlighted an intrinsic problem with klystrons typically operated close to saturation: a serious reduction in signal gain of the RF feedback that is needed to stabilize the cavity voltage at high beam loading. This could be overcome by means of a sophisticated digital klystron linearizer [14].

IOT Transmitter for DIAMOND

DIAMOND is the first storage ring in the world powered by IOTs. Each transmitter combines the power from four 80 kW TH793 IOTs to feed as much as 300 kW into each of the initial two and ultimately three 500 MHz superconducting cavities [15, 16]. Thales supplies the complete transmitters including the tubes, their common HVPS and the switchless waveguide power combining systems sketched in Fig. 2. The first combination is performed with classical 3 dB hybrids and the second with two magic-T combiners connected through two phase shifters S1 and S2. While each hybrid only transmits 100 % of the input power when both connected IOTs are powered at the proper phase, the second stage can transmit 100 % of any possible input combination by adjusting the phase shifters accordingly [15]. When one IOT is switched off, half of the power from its "twin" is lost in the rejection load. Thus, this scheme still allows to produce 188 kW if one IOT is in fault, thereby sustaining a degraded operation of the ring.

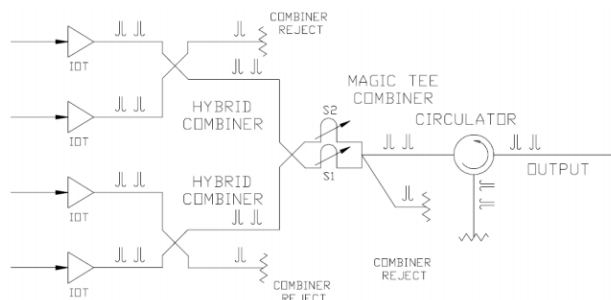


Figure 2: Combiner for 4 IOTs for Diamond.

Operation of the 300 kW IOT transmitter at nominal power has been demonstrated but some initial problems have also been experienced with e.g. arcing on the IOT and inside the output cavity [16, 17]. On 30th May, DIAMOND accumulated their first 2 mA in the storage ring and latest news on the RF status will be given at this conference [18].

Being much shorter than klystrons, the phase sensitivity to HV ripples is about 10 times smaller for IOTs, corresponding to 20 dB less phase noise. This is confirmed at DIAMOND where highest sidebands still below -70 dBc have been measured at 50 kHz from the carrier. However, part of the measured reduction and the higher sideband frequency are to be attributed to the use of a Thales PSM (Pulse Step Modulator) type switched power supply [16].

Given that DIAMOND has just started commissioning the storage ring, they have not yet gained any operation experience with IOTs on accelerators. Some time should also be allowed for teething problems of the combined IOT solution before being able to compare it with a single klystron transmitter in terms of reliability, availability, and operation follow up.

IOT Transmitter with Cavity Combiner for ALBA

At ALBA, 150 kW will be fed to each of the six 500 MHz single-cell copper cavities from the combined power of two 80 kW IOTs [19]. A first transmitter is being delivered by Thales, who also propose a cavity combiner instead of a waveguide combiner for this application. In parallel, using Microwave Studio, the ALBA team has designed an improved cavity combiner as shown in Fig. 3. It is perfectly matched when symmetrically powered with IOTs on both lateral input ports, but it can also provide matched operation with a single IOT. To achieve this, when one of the IOTs fails, its output cavity is first detuned in order to reflect the power coming from the combiner. Then, the operational IOT is matched by means of a tuning plunger in the output waveguide [20].

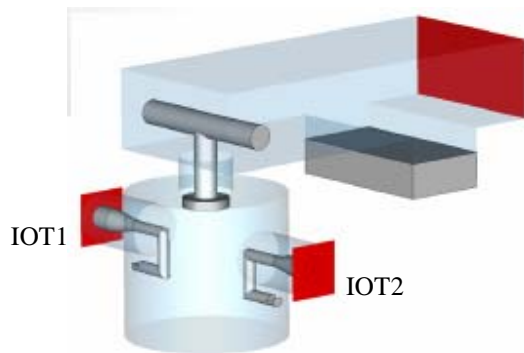


Figure 3: Cavity combiner CaCo for two IOTs for ALBA.

In this application the combining technique is nicely exploited to provide redundancy. The total number of IOTs will be the same as for DIAMOND, but the unit power is closer to the requirements for copper cavities than for SC cavities and leads to a less complex combination of two instead of four IOTs.

IOT Transmitter for ELETTRA

ELETTRA is the typical example of a user facility that decided to use commercial 60 kW klystron based TV transmitters to power their 500 MHz cavities. The systems have been working well for 12 years and are the cause of only a small part of user downtime. Klystrons have generally been replaced after loss of emission.

A major upgrade of the ELETTRA storage ring in current and energy has now started. It requires an upgrade of the RF transmitters to 150 kW output power per unit [21, 22]. The existing 60 kW klystron transmitters will be replaced one by one with pairs of independent 80 kW IOT transmitters, the outputs of which are combined by means of a switchless combiner. The complete systems, from the 13 dBm input of the pre-amplifier to the 150 kW of the combiner, are delivered by a TV transmitter supplier, with TH793 IOTs from Thales. Again, the combiner is designed such that one transmitter can be stopped for maintenance while its “twin” continues to deliver its total power to the cavities. An efficiency higher than 65 % has been specified.

Each IOT will be powered from a crowbarless switched mode power supply with an adjustable switching frequency between 16 and 21 kHz, that allows shifting the resulting RF sidebands off possible spurious resonances.

ELETTRA’s choice was strongly motivated by the offer of IOT amplifiers on the TV transmitter market.

SOLEIL 325 MHz 190 kW Solid State Amplifier

The absence of commercially available vacuum tubes at 352 MHz in the 180 to 400 kW power range led the SOLEIL project team to develop 190 kW solid state amplifiers for the storage ring, on the basis of their 35 kW booster amplifier design [12]. Each of the current two, and later four SC cavities, is fed with one such 190 kW amplifier. The individual 12 dB gain 315 W power modules are built with LDMOS FET (LR301), which were specifically developed and optimized for this project in collaboration with the supplier POLYFET. The efficiency is about 50 %. The transistor of each module is protected by a circulator with a 500 W load. This circulator also ensures unconditional stable conditions. No further isolator is required at higher power levels. The RF modules are installed together with their individual DC/DC converter power supply boards on a water cooled support. Various specific RF combiners and splitters were developed for the different power levels giving the arrangement of four combined 50 kW towers seen in Fig. 4.

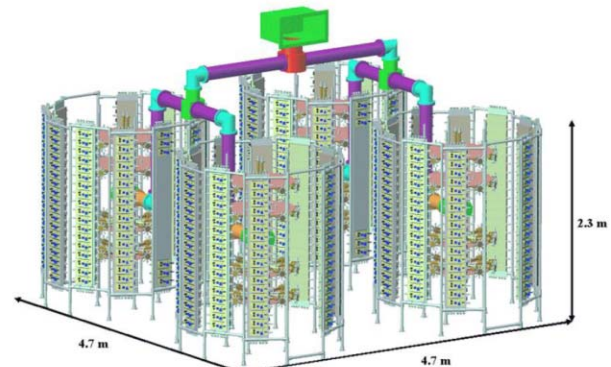


Figure 4: 190 kW SOLEIL solid state amplifier, combining the power from 682 modules.

The following features are claimed [23]:

- Extreme modularity, simple elementary devices.
- High redundancy: no interruption if some modules fail, operation sustained with fewer modules.
- Easy intervention with an additional 42 installed modules in standby.
- No need for HV, no high power circulator.
- Simple start-up procedures, operation and maintenance.
- High reliability expected from booster experience.

During a 1000 hours run test with a 50 kW tower, only 5 transistors were damaged. In April 2006, 180 kW were delivered by the first complete amplifier. With the recent successful storage of beam at SOLEIL, most of the expectations will soon be checked.

Based on the SOLEIL design, a 60 kW 500 MHz solid state amplifier is currently also being developed for the SLS booster, with a slightly lower power of 250 W per module. It shows extremely low sideband levels, and harmonic 2 is 44 dB below the fundamental. Much lower costs are expected than for an equivalent klystron transmitter. Tests of new transistors providing 300 W up to 1 GHz are also foreseen [13].

1.3 GHz IOT for CW SC Linac FELs

A number of new CW Linac or ERL based X-FEL projects, such as the BESSY X-FEL, the 4GLS ERL or the MIT X-FEL, are based on the 1.3 GHz SC TESLA cavities. They have created a market for which manufacturers Thales, CPI and E2V have designed and are now proposing 16 to 20 kW IOTs. There is no equivalent klystron available, and, for example, the study made for the MIT project indeed highlights the superiority of IOTs for this application: higher efficiency, less sensitivity to HV ripples in terms of amplitude and phase noise, no collector over-heating after loss of RF drive, and expected lower costs [11].

CONCLUSION

This non exhaustive review of recent accelerator projects indicates a clear trend towards compact and modular RF transmitters for frequencies up to 1.3 GHz.

As for recent TV transmitters, IOTs with their high efficiency of 65 to 70 % are selected for an increasing number of accelerator applications. Up to 300 kW per transmitter are obtained at 500 MHz by combining the power from 80 kW IOTs. Combiners are designed to sustain operation at reduced power when one IOT fails. The modularity and easy manipulation constitutes an attractive feature of IOTs for modern user facilities which must achieve a high up time with only limited manpower. The intrinsically lower phase noise, the high efficiency and expected lower costs constitute the major advantages of IOTs for the 1.3 GHz CW Linac and ERL applications.

With the SOLEIL project, transistor amplifiers have entered the field of high RF power generation and this could become the next trend for accelerator applications. A total of nearly 1 MW of RF power will be available at SOLEIL from the combination of thousands of 315 W modules. This innovative approach could open the door to a highly industrialised mass production of RF power modules. Once all teething problems are resolved, the operation and maintenance of such modular solid state amplifier systems could indeed become very easy, even for small crews. With well established replacement procedures and a good procurement strategy, the overall reliability and availability could possibly approach 100%.

For accelerator applications requiring RF power sources at the MW or multi-MW level (or hundreds of kW at 1.3 GHz), there is still a need for classical klystron transmitters. It remains to be seen what their replacement with the combined power of tens of IOTs would signify in terms of complexity, reliability and costs. Finally, there is

currently no real alternative to high power klystrons at frequencies above 1.3 GHz.

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