DEVELOPMENT AND FUTURE PROSPECTS OF RF SOURCES FOR LINAC APPLICATIONS

E. Jensen, CERN, Geneva, Switzerland

Abstract

This paper gives an overview of recent results and future prospects on RF sources for linac applications, including klystrons, magnetrons and modulators.

INTRODUCTION

Linear accelerators are key elements for many future large scale particle physics facilities, both at the high energy frontier and at the intensity frontier [1, 2]. Multi-MW proton driver linacs are needed for spallation neutron sources and for muon production, amongst other applications. Superconducting linacs are the approach of choice for FEL based X-ray sources, normal- or superconducting linacs for e^+e^- colliders of the next generation, which require beam powers in the tens of MW range. Since radio-frequency electromagnetic fields are the only possible force to obtain this acceleration in vacuum, highly efficient and reliable high power RF sources with large peak and average power are a common need for these facilities for very different applications [3].

THE CHALLENGES

Power Challenge

Future accelerators for both the energy frontier and the intensity frontier require large power beams. Table 1 lists a subset of those facilities, selected as "typical" for the need in high power RF. The International Fusion Material Irradiation Facility (IFMIF, [4]) aims at two continuous 5 MW deuterium beams, the European Spallation Source (ESS, [5]) and the SPL-II study [6] both aim at the 4 to 5 MW average proton beam power range, operated with ms pulses and duty cycles of around 3 %.

The next two columns in Table 1 refer to the two complementary linear collider concepts ILC [7] and CLIC [8]; both require beam powers above 10 MW for each beam in order to achieve the required luminosity.

It should be noted that CLIC uses a two-beam scheme and the indicated technology concerns the drive beam. The RF to drive beam efficiency is 97%, and the necessary compression and creation of 12 GHz power is performed by a drive beam recombination scheme [8].

Table 1 tries to estimate the average power levels at different stages of the conversion from the AC power grid to the useful beam power, thus stressing the importance of the efficiency of these different stages and the resulting overall size of the installation. The last row of Table 1 gives the overall power conversion efficiency from the AC power grid to the beam; this may not be a fair comparison, since the total AC power includes other installations not strictly related to beam acceleration, it gives however the correct orders of magnitude and allows to identify the weakest elements in the power conversion chain.

Efficiency Challenge

The overall power conversion efficiency from the power grid to the beam must be maximized for a number of reasons: Every MW not converted into useful beam power will still have to be installed, cooled and paid for. The variation of the installed AC power with the overall efficiency can be seen from equation (1); as a consequence, with the indicated overall efficiencies in the order of 10% as indicated in Table 1, a variation in the efficiency by a single percent point will change the installed power of the facility by the entire beam power;

$$\delta(P_{AC}) = -\frac{P_{beam}}{\eta^2}\,\delta(\eta)\,. \tag{1}$$

At the same time, this variation by one percent point in the overall efficiency also results in a change of the power converted into heat (to be cooled) by the entire beam power. To see the variation of the electricity bill, we will assume an annual operation of 5,500 hours and an assumed cost of 40 \$ per MWh; the result is given in equation (2);

$$\delta(\text{annual electricity cost}) = -\frac{\frac{P_{beam}}{\text{MW}}\,220\,\text{k\$}}{\eta^2}\,\delta(\eta) \tag{2}$$

Table 1: Average Power Levels of Some Linac Driven Accelerators

	IFMIF [4]	ESS [5]	SPL II [6]	ILC @ 500 GeV [7]	CLIC @ 3 TeV [8]
Frequency	175 MHz	704 MHz	704 MHz	1300 MHz	1000 MHz
Technology	Grid tubes	klystrons	klystrons	MBK	MBK
Total AC power		38 MW	40 MW	230 MW	415 MW
modulator output	60 MW	17.8 MW	26.5 MW	135 MW	255 MW
power source output	25 MW	8.9 MW	10.7 MW	88 MW	180 MW
acc. structure input	15 MW	6.5 MW	7.8 MW	67 MW	101 MW
total beam(s) power	10 MW	5 MW	4 MW	21.6 MW	28 MW
efficiency		13.5 %	10 %	9.4 %	6.7 %

The order of magnitude of the annual electricity cost thus becomes 2.2 M$ for every MW of beam power; a variation in the efficiency by a single percent point will change the annual electricity bill by 220 k$ for every MW of beam power. With these numbers in mind, the importance of the power conversion efficiencies becomes measureable. A dedicated R&D program to maximize these efficiencies thus potentially leads to direct savings and to more acceptable installation in terms of size and environmental impact.

Cost/complexity Challenge

Some future accelerator facilities are expensive; for the e^+e^- colliders e.g., they easily hit or surpass the 10 B$ mark. For this reason, cost drivers must be identified and addressed; in many cases the RF sources are important cost drivers. The direction for RF power source development must consequently clearly search for lower cost of the devices without compromising the above mentioned challenge for larger efficiency.

For the example of pulsed L-band klystrons, we have made some simplified conceptual estimations in order to indicate a possible trend of such a cost optimizing development, the result is given in Figure 1.

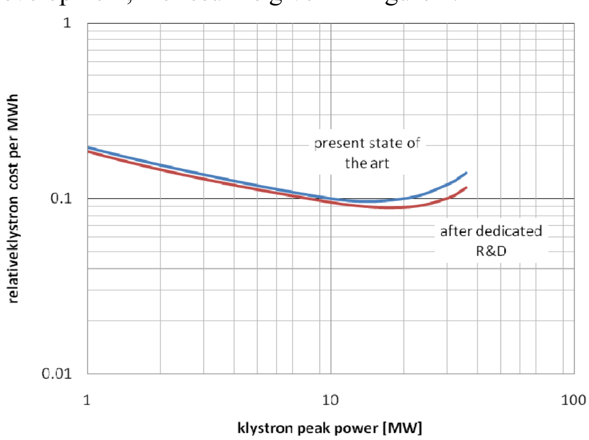

Figure 1: Relative klystron cost per MWh for the example of pulsed L-band klystrons versus the peak power in MW.

This simplified model is based on the experience with existing klystrons and their cost, an assumption on their lifetime to be expected and the readiness of the technology for higher peak power devices. Even without confirmed numbers one can clearly conclude that there is an optimum peak power per unit, which under present assumptions is in the range of 10 to 20 MW. For larger peak powers the cost increases due to the increased complexity of such devices and their decreased MTBF and increased MTTR, which would make them less attractive; this is certainly also a potential weakness of the 50 MW multi-beam klystron using whispering gallery modes, which we proposed in 2005 [9].

It seems important however in this context to address the cost of the overall RF system, including power supply/modulator, the pulse transformer (if needed), the active device, the subsequent RF power distribution and the pulse compression system (if needed) as well as the effective acceleration in the cavity itself. Only the overall system optimisation assures that one would not optimize one element of the chain at the expense of others. The efficiency optimisation of a klystron may for example result in the need for increased anode voltage, which could on the other hand significantly increase the cost for the modulator and pulse transformer, which may not be needed at all. Also the complexity and cost of the power distribution system and/or the necessity of a RF pulse compression system will be influenced by the choice and performance of the modulator and the power source [10].

STATE OF THE ART

The approximate average power levels obtained with present day active elements of different technologies are summarized in Figure 2. For highest power application, the frequency range below 300 MHz continues to be the realm of grid tubes, whereas the frequency range above is dominated by klystrons. A special grid tube is the diacrode® [11], which extends the reach of grid tubes to 1 MW CW at 200 MHz. The most successful derivate of the klystron is the multi-beam klystron (MBK).

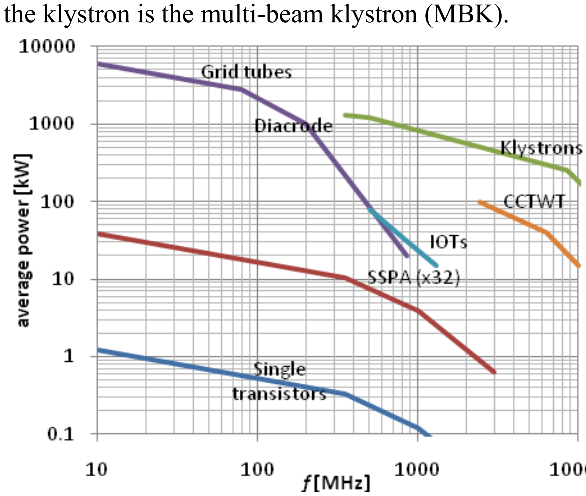

Figure 2: Typical average power levels obtained with different technologies (commercially available).

GRID TUBES

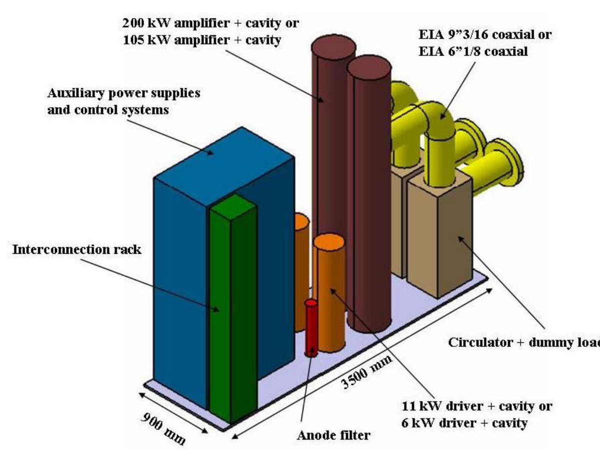

Figure 3: IFMIF Removable power module [12].

Linacs operated in the frequency range of 200 MHz, e.g. as planned for IFMIF, will continue to be based on grid tubes. This technology has not significantly changed over the decades; aspects of reliability, safety, serviceability and modularity of the systems are however more rigorously employed in modern designs. Figure 3 illustrates this on the example of the IFMIF CW 175 MHz RF power module, 42 of which will be required in total [12].

A major upgrade of the pulsed 200 MHz RF system for the Los Alamos Neutron Science Center (LANSCE) employs diacrode® amplifiers with up to 3.2 MW peak power [13]. The system has been installed and is presently under test. It represents well the present state of the art for VHF. Figure 4 shows the final power amplifier main components (left) and assembly (right).

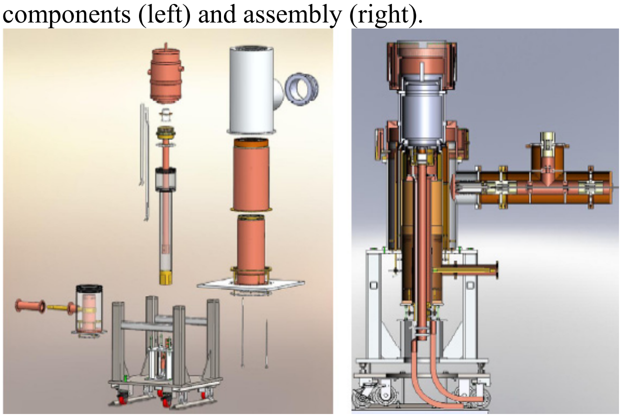

Figure 4: New LANSCE diacrode® based, 3.2 MW power amplifier [13].

SOLID STATE RF POWER SOURCES

Solid state RF power sources have made significant progress during the past decades; they will however not fully replace vacuum electronic devices in the foreseeable future. The present state of the art for solid state power sources is probably best illustrated by the Soleil 350 MHz RF system, which consists of 180 kW CW amplifiers and reaches an overall efficiency of about 50 % [14]. Since the commissioning of the first Soleil amplifier in 2006, based on 300 W modules, LDMOS technology has progressed (one speaks of the 6th and 7th generation) – today the module power has approximately doubled [15].

An interesting new idea was presented earlier this year at IPAC10 in Kyoto; for the direct RF cavity drive concept [16], a large number of solid state drivers are mounted on the outer periphery of an accelerating cavity and coupled to it in such a way that the cavity itself serves as power combiner (ref. Figure 5). Silicon-carbide vertical junction FETs (SiC vJFET) are proposed as active elements, they promise high power (> 1 kW) and high efficiency.

A potential issue of solid-state elements in the vicinity of the beam to be accelerated is of course their radiation hardness. Tests are in preparation to validate this interesting new proposal and we hope that this concept will hold up to its high expectations.

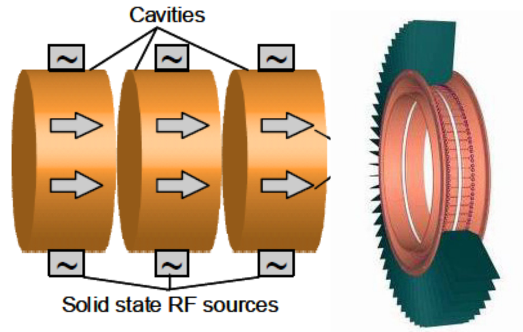

Figure 5: Left: Concept of a direct RF cavity drive [16], right: arrangement of the SS RF modules on the periphery of a cavity.

KLYSTRONS

The efficiency of a klystron is maximised when the bunch length in the output cavity is minimized. Space charge forces however limit how much bunches can be shortened – the higher the beam current, the larger the debunching forces will become. To limit the effect of space charge forces, the perveance K of the beam should be small, but according to

$$I_{beam} = K \cdot V_a^{3/2} \tag{3}$$

this would also reduce the beam current (and power) if the anode voltage V_a is to be kept. This is the basic consideration which led to the invention multi-beam klystrons (MBKs), where by way of combining many small so-called beamlets in a single device, the total current can be multiplied, whereas the perveance of the single beamlets governs the space charge effects.

Figure 6: Thales 1.3 GHz, 10 MW MBK “TH1802”.

The present state of the art for L-band power sources probably best illustrated by the 10 MW, 1.5 ms, 10 Hz, 1.3 GHz, 65 % efficiency, 49 dB gain, 115 kV MBK’s for X-FEL/ILC, developed and built independently by CPI, Thales and Toshiba [17]. Two of these tubes are shown in Figures 6 and 7. Based on the technology developed for this device, an increase in efficiency seems possible by a few percent by a) either increasing the number of beamlets, b) increasing the anode voltage or a combination of a) and b). A larger number of beamlets will make the device even more complex; the larger voltage will increase complexity and cost of the modulator/pulse transformer.

Figure 7: CPI 1.3 GHz, 10 MW MBK “VKL 8301B”.

IOTS

Inductive Output Tubes (IOT’s) are – compared to conventional grid tubes and klystrons – relatively modern vacuum tubes. They combine the grid control of a tetrode with the output cavity of a klystron. Their typical range of operation is 500 to 800 MHz, with CW output powers of up to 100 kW. They build shorter and run at lower anode voltages than klystrons (typically 35 kV) and reach easily efficiencies in the order of 70%. Their disadvantage is the smaller gain (about 23 dB). An attractive feature of IOT’s is that they could run without modulator – like grid tubes they could be switched off with a negative grid bias.

Another distinct advantage of the IOT is illustrated in Figure 8: While a klystron reaches its maximum efficiency only in saturation, the IOT still has a positive differential gain when operated at its maximum efficiency. Positive differential gain is necessary to allow feedback loops to control the output signal.

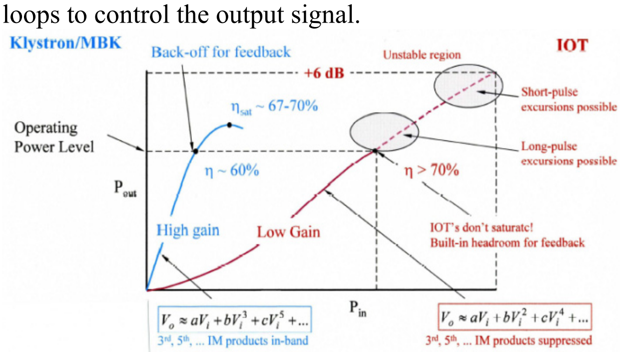

Figure 8: Different characteristics of a klystron (blue) and an IOT (red).

An interesting development that combines the appealing features of the IOT (high efficiency and no saturation) with larger power is ongoing at CPI: The higher order mode (HOM) IOT, a prototype of which has been built and successfully tested up to 920 kW peak power at 700 MHz with an efficiency of 62% [18], promises to be an interesting alternative to multi-beam klystrons that certainly deserves follow-up. It is depicted in Figure 9.

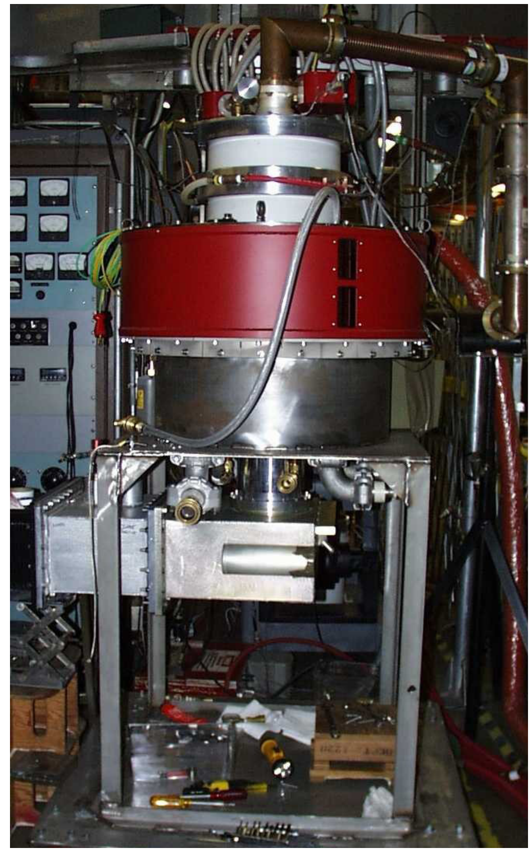

Figure 9: CPI HOM-IOT “VHP-8330” in its test stand.

The prototype tube performance was limited by a weakness of the annular cathode/grid configuration; it was suggested to use a large number of standard IOT guns instead.

MAGNETRONS

Magnetrons as used in large quantities in microwave ovens are relatively inexpensive devices with very high intrinsic efficiency. State of the art magnetrons reach some MW in pulsed and some tens of kW in continuous operation. They are oscillators, so their phase is not easily controlled. Single magnetrons are nevertheless commonly used in small accelerators. Their use in large accelerators however requires locking the phase of a number of magnetrons to sufficient precision – this has been the main challenge for their application as accelerator RF sources.

A group of Jefferson Lab and Lancaster University collaborators [19] have recently demonstrated successful phase stabilisation of a simple cooker magnetron – not known for its low noise – to a remarkable level of 0.8° r.m.s. with very moderate locking power. This constitutes an important step forward.

If validated with larger power levels the magnetron thus could become an interesting contender in the race for the optimum low cost, high efficiency power source. It remains to be seen whether the oscillation onset time is short enough not to lose a considerable fraction of the created RF pulse energy, thereby potentially reducing again the efficiency for short-pulse operation.

MODULATORS

The role of a modulator is to store energy that can be charged slowly and will be discharged rapidly. Energy is typically stored in capacitors or transmission lines, and the rapid switching is typically performed with semiconductor switches (IGBT's). The most frequently used topology is the bouncer type modulator, in which pulse shape during discharge is optimized using a simple tuned LC circuit. A more modern and potentially more efficient and cost-effective topology is the multi-cell Marx modulator, a prototype of which has been developed, built and recently successfully tested at SLAC. The basic idea of the Marx type modulator is that many different cells can be charged in parallel, while they are discharged in series thus adding their voltages. The SLAC Marx prototype P1 delivers 120 kV, 1.6 ms, 140 A with a repetition rate of 5 Hz and does not require a pulse transformer. P1 has now successfully been feeding a 10 MW klystron. Figure 10 shows the L-band test stand [20] at SLAC.

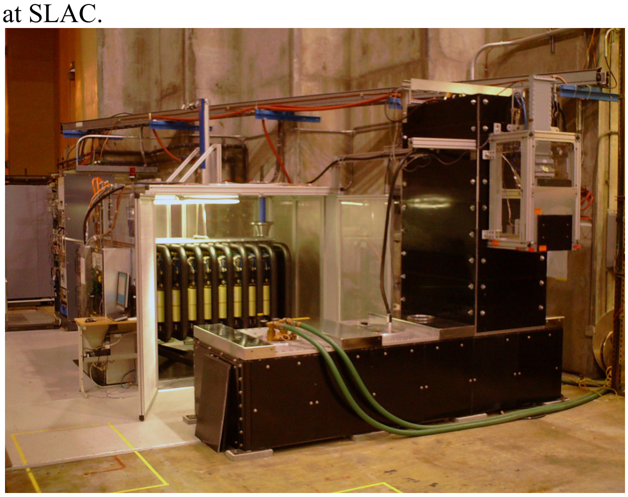

Figure 10: L-band test stand at SLAC. In the foreground the klystron in its shielding, behind it the 16 cell Marx prototype P1 [20].

CONCLUSION

Many future accelerator projects are based on linacs with multi-MW beam power (proton drivers and e^+e^- colliders). They all require cost-effective high-power, high efficiency RF power sources, which are not readily available. For this reason we advocate a strengthened dedicated R&D on high efficiency RF power sources, which should go beyond the extrapolation of existing devices. The overall system efficiency must be optimised, including modulators, the active devices, RF distribution and efficient acceleration. Present contenders include – amongst other, less conventional ones – solid state sources, klystrons, IOT's and magnetrons.

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