STATE OF THE ART, STATUS AND FUTURE OF RF SOURCES FOR LINACS

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Abstract

This paper tries an overview of recent developments in RF sources for linear accelerators of different scales and for various applications, spanning a frequency range from about 100 MHz to X-band, spanning duty factors from about 10^{-3} to CW, and spanning power levels from a few kW up to hundreds of MW average. Exciting recent trends include new bunching concepts for klystrons, promising a significant increase of efficiency, and better power combiners paving the way to MW-class solid-state power amplifiers.

INTRODUCTION

Since I had the opportunity to make a similar overview presentation and paper on RF source status and developments for Linacs in 2010 [1], I will focus in the following report on recent progress, trends and developments in the field while omitting what has not significantly changed since 2010. For this reason, the following status report does not try to be comprehensive. The subsequent part on future developments is of course very personal since I cannot tell the future, but am happy to share what I personally find relevant and important for the future of RF sources for linacs.

CERN LINAC 4

Linac 4 is part of the upgrade of the CERN accelerator chain to eventually reach higher luminosity in the LHC. It will replace the 38-year-old Linac2, which accelerates protons to 50 MeV, and will accelerate H− ions through an RFQ (3 MeV), a DTL (50 MeV), a CCDTL (100 MeV) and a series of pi-mode structures (PIMS) to 160 MeV. At the time of writing the whole Linac4 hardware is ready for beam commissioning to 160 MeV, a 20 mA H− beam has reached 107 MeV in July 2016. Linac4 operates at 352 MHz with an RF pulse length of initially 600 μs, later up to 1.2 ms, and a repetition rate of initially 0.83 Hz with the possibility to later operate at 2 Hz (duty cycle $5 \cdot 10^{-4}$ to $2.4 \cdot 10^{-3}$).

The Linac4 352 MHz RF source consists of eleven 1.3 MW klystrons recuperated from LEP and adapted for pulsed operation, and eight new, state-of-the-art, 2.8 MW peak power klystrons [2]. In a later stage, when the LEP klystrons will have reached their end of life, every two LEP klystrons will be replaced by one new 2.8 MW klystron. The power distribution scheme for this later scheme, in which one klystron will power two accelerating structures, is sketched in Fig. 1. It features the use of a magic-tee and existing circulators and was optimized for small sensitivity on imperfections in circulators and power loads.

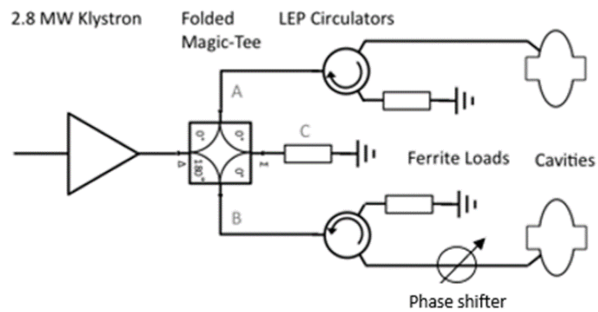

Figure 1: Powering two structures from one 2.8 MW klystrons in Linac4.

Since the LEP klystrons were not designed for pulsed operation, necessary modifications included retuning individual klystron cavities, the replacement of the HV tank, a new mod-anode voltage divider and an improved modulator that allows adjustments to cope with perveance and performance varying between individual klystrons. Figure 2 shows a recent view of the Linac4 klystron gallery.

Figure 2: View of CERN Linac4 klystron gallery.

ESS

The proton accelerator of the European Spallation features a normal-conducting front-end with RFQ and DTL similar to Linac4, operating also at 352 MHz, but with 3.5 ms RF pulses with a repetition rate of 14 Hz (duty cycle $4.9 \cdot 10^{-2}$). After the DTL (90 MeV) follow 352 MHz superconducting spoke cavities, and the main part of the linac (220 MeV to 2 GeV) consists of 704 MHz elliptical cavities, of which 36 are low-beta cavities which will be powered by 1.5 MW klystrons and 84 high-beta cavities to be powered by 1.2 MW multi-beam IOTs.

Since ESS targets a total average beam power of 5 MW, energy efficiency has clearly been a main concern, and ESS have taken the opportunity offered by their schedule (target: 2023) to invest in R&D of multi-beam IOTs with industry [3]. Inductive Output Tubes (IOTs) feature a grid control like tetrodes and output cavities like klystrons.

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IOTs offer two potential advantages as compared to klystrons: 1) different from IOTs, klystrons reach maximum efficiency (η) in saturation, from which one has to back off in operation to allow amplitude control, 2) klystrons draw a significant bias current with the HV on but the RF off, while IOTs draw no quiescent current. Goal of this R&D is to develop an industrial device that combines these advantages with an appropriate power level, since commercial IOTs operate at power levels below 100 kW. In September 2014, ESS have placed two major R&D contracts with industry for this development, one with a consortium of Thales and CPI, the second with L3 Communications. Figure 3 shows the concept of these two devices.

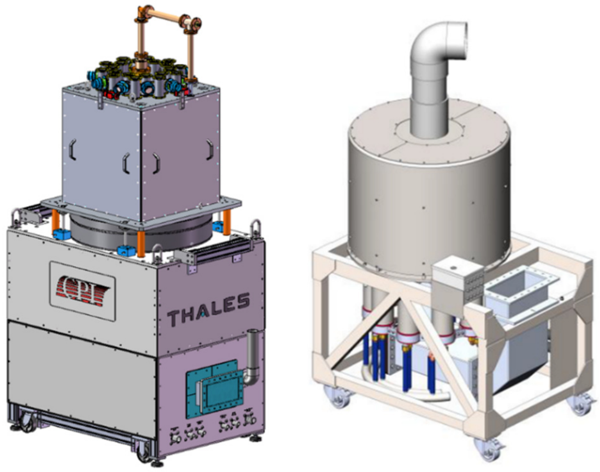

Figure 3: Concepts of the 704 MHz multi-beam IOTs by the Thales/CPI consortium (left) and by L3 (right) for ESS.

Recent progress is encouraging; as example, Fig. 4 shows recent results of the L3 device. An output power of 1.2 MW was reached with an efficiency of above 60% in the power range of 650 kW to 1.2 MW, the best efficiency reached is 68%.

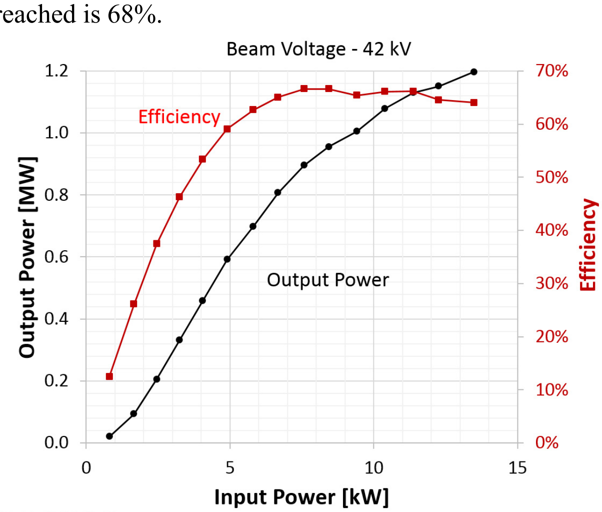

Figure 4: preliminary results of output power (black, left scale) and efficiency (red, right scale) of the L3 prototype 10-beam IOT L6200.

SNS

The Spallation Neutron Source in Oak Ridge is driven by a pulsed, superconducting 1 GeV proton linac. Fully commissioned in 2006, 1 ms, 60 Hz (duty cycle $6 \cdot 10^{-2}$), it has reached its target beam power of 1.4 MW in 2013. The normal conducting front end of SNS operates at 402.5 MHz and 805 MHz and brings the beam up to 185 MeV, where a superconducting 805 MHz linac takes over with 33 medium-beta cavities in 11 cryomodules followed by 48 high-beta cavities in 12 cryomodules.

Figure 5: SNS klystron gallery, klystrons CPI VKP-8291B.

SNS has proposed the Proton Power Upgrade project [4], aiming at increasing the beam power to 2 MW and the beam energy to 1.3 GeV, adding 28 high-beta cavities and power stations and retrofitting the DTL klystrons to cope with slightly increased beam loading. The project awaits approval in 2017 and aims at completion in 2023. Figure 5 shows a view in the present SNS klystron gallery

LANSCE

The Los Alamos Neutron Science Center features an 800 MeV proton/H− linac with up to 1 MW beam power capability. It started operation as early as 1972 as LAMPF, the Los Alamos Meson Physics Facility, and is based on a normal-conducting linac. A 201 MHz drift-tube linac brings the beam to 100 MeV, it is powered by four 3.4 MW, diacrode based transmitters. The following 805 MHz side-coupled linac (SCL) is powered by 44 1.25 MW klystrons. RF pulses are 825 µs long, the repetition rate is 120 Hz (resulting in a duty factor close to 10%). Successive pulses can be directed to as many as 5 different users with a switch yard.

Diacrodes

The original 201 MHz system started operation in 1972 and was originally based Burle triodes 7835, which became unavailable around 2006 and thus made operation at 120 Hz repetition rate virtually impossible. A completely new RF system was designed in 2009 to 2011, built and delivered with Continental Electronics during the last years (see Fig. 6). Three systems have been built and are now fully operational [5]. Diacrodes are double-sided tetrodes and have first been introduced by Thomson Tubes Électroniques, the predecessor of Thales, in 1996 [6] and they can be considered an evolution of the Burle 7835 double-sided triode. To our knowledge, the new LANSCE 201 MHz system is now the largest operational facility based on diacrodes, and with operational experience exceeding 9000 h with 6 tubes, relevant statistical data on their long-term performance start to emerge [7]. The first two TH628 were installed in 2014 and still show no sign of fatigue after ≈12000 filament hours; not a single diacrode failure has been experienced. Exchanging a tube now takes about 2 hours, while for the pressurized Burle system this intervention took almost one day. The new system also allowed to replace the old, transformer/rectifier based anode supply, which was complex and inefficient, and to reduce the cooling water installation by roughly a factor 2.

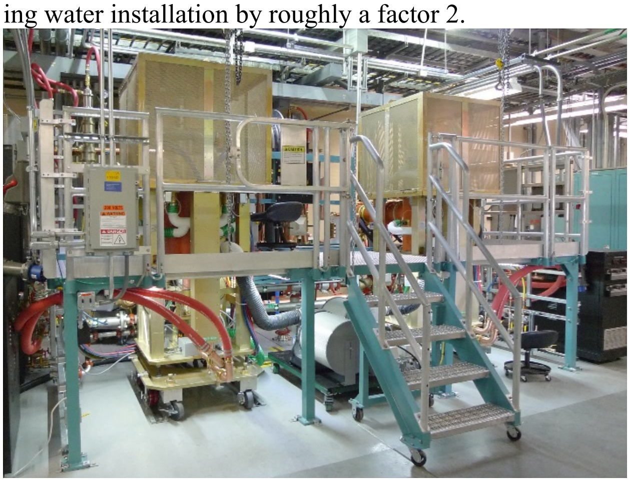

Figure 6: LANSCE 201 MHz, 3.4 MW RF power source with two Thales TH628L diacrodes.

The power of two diacrodes is combined with a coaxial 3-dB hybrid shown in Fig. 7.

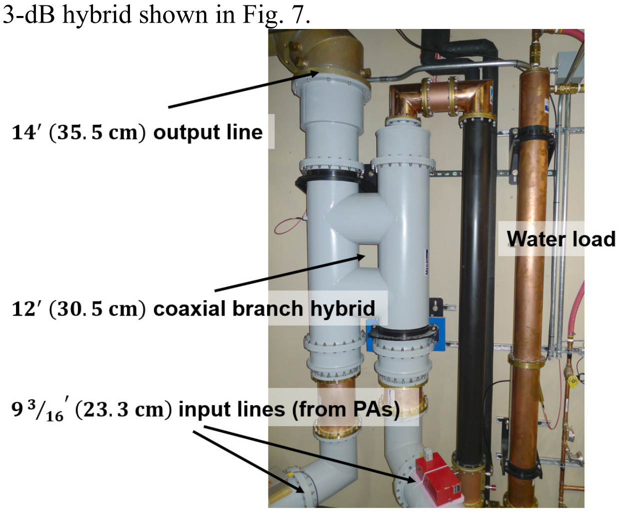

Figure 7: Coaxial 201 MHz power combiner.

Klystrons

The LANSCE 805 MHz klystrons are specified for 1.25 MW, 120 Hz, 1 ms, 44% efficiency and 50 dB gain. A total of around 100 klystrons had originally (during the 1970's) been purchased from two vendors. From 2006, when the number of the valid spare klystrons became critical, careful analysis of the original klystron performance and longevity allowed preparing a new order of 45 klystrons with identical specifications, which was released in 2009. The last klystron of this series was delivered in 2014, bringing the number of spares to a reasonable 34 today [8].

CLIC

One cannot treat RF sources without mentioning the **C**ompact **LI**near **C**ollider (CLIC) study. The baseline CLIC concept is a two-beam scheme using drive beam and main beam [9]. The high-current, 2.38 GeV drive beam is accelerated at 1 GHz with very high efficiency; its sole purpose is to generate the extremely high peak power RF at 12 GHz to accelerate the main beams to nominally $\sqrt{s} =$ 3 TeV, so the drive beam itself, its acceleration and deceleration constitute in fact the CLIC RF power source. To keep the overall energy efficiency competitive in spite of the seeming complication, the main ingredients of this scheme are: 1) very high efficiency, long-pulse (150 µs, 50 Hz) power sources at 1 GHz, 2) fully loaded acceleration of the drive beam, 3) drive beam manipulation to create short (240 ns), intense bursts of bunches, 4) deceleration and full extraction of drive beam energy at 12 GHz, 5) low loss power transfer from drive beam to main beam and 6) efficient main beam acceleration. The dedicated facility CTF3 was conceived, built and operated to demonstrate all of the above. Fully loaded acceleration with RF-to-beam efficiency of 96% was successfully demonstrated in 2006 [10], drive beam bunch recombination with multiplication of the drive beam current (and bunch repetition frequency) by a factor 4 in 2013 [11]. The efficient low-loss power transfer was demonstrated recently with two power-extraction structures (PETS) in the drive beam and 4 accelerating structures for the test beam [12]. CTF3 will thus have successfully demonstrated the CLIC feasibility issues it was conceived for, and 2016 will be its last year of operation.

L-Band Klystrons

Even with the high efficiency two-beam scheme described above, the overall CLIC energy efficiency strongly depends on the efficiency of the primary RF source, the 1 GHz long-pulse klystrons.

Industry was asked to extrapolate from present-day technology towards higher efficiency, and initial results are encouraging [13]. The specifications for this tube were: 1 GHz, 20 MW peak, 150 µs, 50 Hz, efficiency >70%. Thales has proposed a 10-beam MBK with a calculated efficiency of 77%, Toshiba a 6-beam device with calculated 75%. The Toshiba prototype was built and tested at full power with 25 Hz repetition rate, Fig. 8 shows the device during factory acceptance tests. A total peak power of 21 MW with the correct pulse length could be obtained and a remarkable efficiency of 71.5% was measured at full power.

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Figure 8: Prototype Toshiba 1 GHz MBK at Factory Acceptance Test (2016) [13].

X-Band

The CLIC two-beam scheme has been proven to be very effective for a 3-TeV Linear Collider. Responding to the request by Physics and in view of a staged design however, the CLIC Study group is now also looking into a collider operating at $\sqrt{s} \approx 380\,\mathrm{GeV}$, for which the two-beam scheme could be an unnecessary complication [14]. To investigate the validity of a klystron-based CLIC, but also since X-band RF structures must be tested and conditioned, and finally since X-band technology is interesting for other applications (e.g. medical, FEL …), CERN has invested in 3 dedicated, stand-alone X-band RF test facilities called the Xboxes. The most recently accomplished of these facilities, Xbox-3, described in detail in [15] and shown in Fig. 9, is based on four 6 MW, 400 Hz repetition rate klystrons, which are driven with smart phase coding such that 4 test slots can be used simultaneously at 100 Hz.

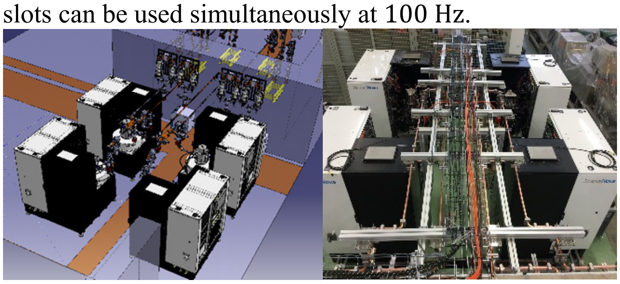

Figure 9: Xbox-3: 3D integration concept (left) and photo of the actual implementation.

A GLIMPSE TO THE FUTURE

Very High Efficiency Klystrons

More than 70 years after its invention in 1939 [16], the klystron is mature and well understood, its technology is well mastered and the klystron's possible performance limits were believed to be known. A combination of remarkable inventions surfacing in 2014 however seem to surpass those known limitations and may potentially lead to a klystron with efficiency beyond what was believed possible. These inventions can be summarized as 1) the concept of "congregated bunches", 2) the concept of "bunch cores oscillations" and 3) the "BAC method" (bunch – align – collect).

Details on those new ideas can be found in [17]. Explained qualitatively and in a simplified way, the concept of bunch core oscillations leads to a slower but more effective bunching; instead of trying to create very short bunches at any rate, oscillations of the forming bunches in longitudinal phase space are explicitly welcome and supported, allowing space charge to drive apart the forming bunches again and again, since during this periodic process outliers, which in conventional klystrons would be accelerated in the output cavity and thus decrease efficiency, have the time to slowly unite with the forming bunch. Also the common belief that very short bunches are prerequisite to highest efficiency had to be refined: as long as particles in the head or the tail of the bunch see the correct output field to best decelerate them, they will still contribute to increasing efficiency. This latter thought leads to the need to introduce an energy distribution (chirp) over the bunch, which is included in the new approach. Consequently, the well-established empirical dependence of maximum efficiency on perveance seems to be equally violated by the new method as illustrated in Fig. 10.

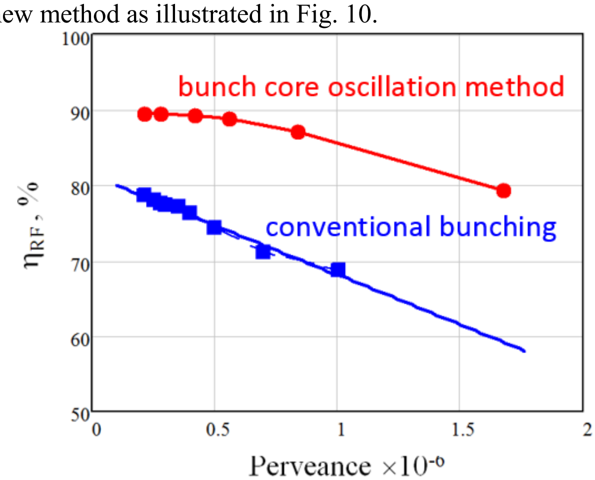

Figure 10: Comparing the potential reach in electronic efficiency vs. perveance of conventional klystrons (blue) to the novel bunch core oscillation method (red) [17].

A collaboration of klystron experts around the world has formed to investigate both theoretically and experimentally these intriguing new ideas, it is referred to the HEIKA collaboration ("High Efficiency International Klystron Activity"), which is equally embedded in the EuCARD^2 Network Activity "EnEfficient" [18].

As a first experimental verification of these novel ideas, the Russian Company VDBT has retrofitted an existing S-band MBK that had operated with an efficiency of 42% with new cavities following the novel ideas described above. In first tests both at VDBT and at CERN earlier this year, an electronic efficiency in excess of 60% could be measured. Figure 11 shows the klystron during initial testing at CERN.

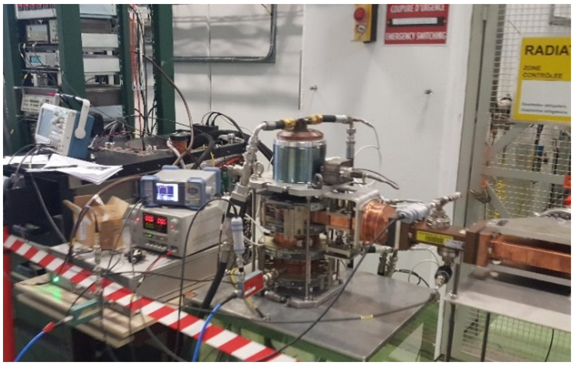

Figure 11: The prototype VDBT 40-beam, 7-MW S-band klystron in its test set-up at CERN.

Solid State Power Amplifiers (SSPA)

The general trend away from vacuum electronic devices towards solid state has become apparent during recent years. After pioneering work at Soleil and ESRF, CERN has now placed a contracts with Thales Communications and Security and Gerac for two 2 MW transmitters to upgrade the SPS 200 MHz systems, which will be based on SSPA technology. The above are however all synchrotrons, which from the RF point of view is correlated with the fact that here the beam energy can be increased turn by turn, whereas in linacs this happens in a single passage. This leads to either CW operation of at least peak powers not significantly above the average powers, while very small duty cycles with the corresponding very high peak powers are not in reach of present-day SSPA technology. The first linacs clearly would be those operated in CW, like LCLS-II or ERLs.

LCLS-II is based on a superconducting 1.3 GHz linac operated in CW. While the cavity technology was initially developed for ILC (pulsed with duty cycle $1.6 \cdot 10^{-2}$) and is has become a de-facto world-wide standard, the LCLS-II RF sources will be based on SSPA technology. The linac will need 284 SSPA's of 3.8 kW CW at 1.3 GHz and 16 of 2 kW at 3.9 GHz [19]. Prototypes of these amplifiers were built by R&K in Japan, shipped initially to FNAL and JLAB for testing, see Fig. 12. With the RF power not being the main issue of these systems anymore, the design is optimized for availability and reliability.

Figure 12: The first 1.3 GHz CW SSPAs for LCLS-II fabricated by R&K.

Trying a longer-term vision for the development of SSPA's and trying to answer the question whether or not they will be able to replace pulsed klystrons, I would like to share a thought E. Montesinos formulated earlier this year [20]: he argued that, considering the trends for wireless networks with more and more cells to reach larger and larger coverage, but staying with relatively small cells, considering limitations of individual portable devices in necessary RF power and battery life, it seems that larger power levels for single chips are not attractive for this sector of the market. Considering also that even with the most ambitious projects of future accelerators in mind, RF for accelerators will at best cover 0.1% of the market for RF power transistors, it seems to be good strategy to find solutions based on RF chips not much larger what is available today. This immediately shifts the focus from the individual chips to most effective power combiners with many inputs. As a recent example for this development, a SPS 2 MW transmitter will be based on sixteen 144 kW amplifiers, each of which combines the power of 160 LDMOS transistors. It is clear that special care is taken to address the situation in which either a single amplifier or even a single transistor fails. Figure 13 below shows work on a prototype 144:1 power combiner.

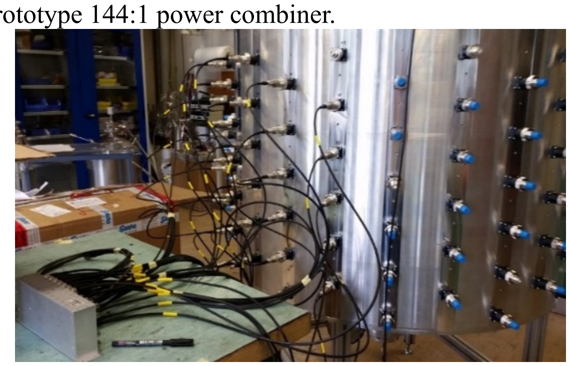

Figure 13: Prototype of a 144:1 cavity combiner during test set-up at CERN.

SUMMARY AND OUTLOOK

RF sources for linacs have seen remarkable progress during the last 6 years: CERN's Linac4 is ready for beam, ESS has started and is progressing well with exciting R&D on MB-IOTs. LANSCE has modernized their RF systems to be ready for the next decade and has successfully deployed diacrodes. The CLIC test facility CTF3 has successfully demonstrated critical CLIC feasibility issues in its last year of operation, CLIC X-band technology has become mature.

Concerning developments paving the way into the future, we see a remarkable and promising innovation of the good old klystron, promising a significant increase in electronic efficiency. LCLS-II is pioneering the user of solid-state power amplifiers, which have already demonstrated their strength in synchrotrons.

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