Vacuum electronics applications at CERN

Erk Jensen

CERN, 1211 Geneva 23, Switzerland

Abstract

CERN operates a large number of vacuum electronics based RF power amplifiers covering a wide frequency range – over 300 sockets with 24 different grid tubes and klystrons are in use and require constant care to insure reliable operation of the accelerators. This is in particular true for the LHC and its injector chain, for which a program of improvement and stepwise upgrade has started. These include IOT's for the SPS and klystrons and modulators for Linac4 and SPL.

The CLIC study and the CTF3 facility are relevant to vacuum electronics in many ways: The CLIC primary RF power, to be provided at 1 GHz, requires highest possible efficiency and phase stability, MBK's are likely candidates. The CLIC RF power source and CTF3 are themselves large vacuum electronics applications, consequently there are areas of common interest and concern, including fabrication techniques, pulse compression techniques, breakdown and multipactor theory and simulation, material fatigue, numerical analysis of slow-wave structures, vacuum compatible ceramics and damping materials, just to name a few.

Vacuum electronics applications at CERN

Erk Jensen

BE-RF
CERN

1211 Geneva 23, Switzerland

Abstract: CERN operates a large number of vacuum electronics based RF power amplifiers covering a wide frequency range – over 300 sockets with 24 different grid tubes and klystrons are in use and require constant care to insure reliable operation of the accelerators. This is in particular true for the LHC and its injector chain, for which a program of improvement and stepwise upgrade has started. These include IOT's for the SPS and klystrons and modulators for Linac4 and SPL.

The CLIC study and the CTF3 facility are relevant to vacuum electronics in many ways: The CLIC primary RF power, to be provided at 1 GHz, requires highest possible efficiency and phase stability, MBK's are likely candidates. The CLIC RF power source and CTF3 are themselves large vacuum electronics applications, consequently there are areas of common interest and concern, including fabrication techniques, pulse compression techniques, breakdown and multipactor theory and simulation, material fatigue, numerical analysis of slow-wave structures, vacuum compatible ceramics and damping materials, just to name a few.

Keywords: accelerator applications; grid tubes; klystrons; multiple-beam devices; breakdown; pulse compression

Introduction

CERN, the European Particle Physics Laboratory located in Geneva, Switzerland, was founded in 1954 and has today 20 member states. It operates a number of particle accelerators for high energy physics at different energies and for different types of particles. CERN's flagship is the Large Hadron Collider LHC, which has seen first beam in 2008, and will – after a forced stop in autumn 2008 –

resume operation later this year. Since high energy, high luminosity beams require high power RF, CERN is host to major high power RF installations with a large number of commercial vacuum electronics devices and has a long standing experience with their operation. Beyond this, the research and development of particle accelerators uses similar or identical technology as vacuum electronics, and consequently much of the research and development work actively pursued at CERN has direct relevance to the vacuum electronics community.

Existing CERN RF power plants

Fig. 1 below gives an overview of the CERN accelerator Complex: the injector chain for the LHC consists for protons in Linac2, Booster, PS and SPS, whereas for Pb it consists of Linac3, LEIR, PS and SPS. Other accelerators are the antiproton decelerator AD and the isotope post-accelerator Rex in the Isolde complex. All these accelerators use high power tetrodes and triodes – their frequency range covers approximately 1 MHz to 200 MHz. CTF3 is a test facility and a huge “vacuum electronics application” in its own right. It uses pulsed high power S-band klystrons and accelerates an electron beam which is used to produce very high power (100 MW) at 30 GHz and very soon also at 12 GHz.

Many different kinds of commercial standard and custom made vacuum electronics devices, primarily tetrodes and klystrons, have been operated at CERN over many decades.

Figure 1: CERN Accelerator Complex

As a consequence, CERN has a well established expertise in the design, construction and operation of tube amplifiers and has at its disposal extensive operational statistics, significant for reliable tube life expectancy estimations. Since some of CERN's accelerators are very old (the PS will have its 50'th anniversary this year), there is a constant need of maintenance, consolidation, modernisation and upgrade of their high power RF systems. Some of the past modernisations include special methods to increase the life expectancy of these expensive devices (e.g. ramping and stabilisation of filament supply, grid modulation).

Another of our concerns is to assure continued availability of high power grid tubes from the manufacturers over many years, since the global market has significantly changed with the advent of DVB/DAB and internet TV. At the same time, we observe with interest the developments in the field high power solid-state RF electronics, but it seems likely that vacuum electronics will continue to dominate in high power RF applications at CERN.

Figure 2: Part of the SPS power plant

When all CERN accelerators operate, around 300 sockets of are heated with tubes of 24 different types. The vacuum electronics devices in the CERN high power RF installations include:

- Linac2 and 3: 11 triodes, 12 tetrodes 200 MHz
- LEIR, REX and AD: 2 triodes, 16 tetrodes
- PSB: 16 tetrodes 1 ... 16 MHz
- PS: 64 tetrodes 2.7 ... 200 MHz
- SPS: 108 tetrodes 200 MHz, 8 klystrons 800 MHz
- LHC: 48 tetrodes, 16 klystrons 400 MHz, 300 kW CW
- CTF3: 13 klystrons 1.5 and 3 GHz, 4 TWTs

Figure 3: Part of the LHC power plant (16 klystrons 400 MHz, 300 kW CW)

As examples of these installations, Fig.2 shows a small part of the SPS 200 MHz RF power plant, which was installed in 1980, Fig. 3 shows part of the LHC power plant.

Vacuum electronics required for LHC upgrades

The left part of Fig. 4 summarizes the accelerators of the present LHC injector chain, indicating their first year of service and energy reach. On the right, possible phases of a stepwise upgrade of the LHC luminosity and eventually its energy are given. The first of these phases, the Linac4 project [1], has started construction in 2008; the SPL design is approved and the PS2 initial study has started. Many of the upgrades of LHC and its injectors are implemented in wide international collaborations.

Figure 4: The accelerators of the LHC injector chain possible phases of their upgrade.

Smaller upgrades that are required to assure operation or our ageing complex (internally known as “consolidation program”) are progressing in parallel. The upgrades include

- The modernization of the very old SPS 800 MHz power plant from klystrons (Valvo YK1198) to IOT's. The needs are now well defined; the project is in the preparation of the call for tender.
- The upgrade of the SPS 200 MHz system (Fig. 2) to more powerful diacode® technology.
- The operation of some former LEP 352 MHz, 1.3 MW CW klystrons in pulsed mode is planned for Linac4. This is challenging for the power converters and klystron modulators. The call for tender for additional, higher power (2.6 MW), pulsed klystrons is in preparation,
- The SPL will operate at 704 MHz, where new klystrons and modulators will be required. Industry has been contacted for the development of these tubes.

The CLIC study and its relevance to Vacuum Electronics Applications

It is recognized [2] that, to complement the LHC results and to push the energy and luminosity frontier further,

research and development of a linear collider is necessary. In this context, the CLIC (Compact Linear Collider) international collaboration hosted at CERN [3] is focussing on a possible two beam accelerator scheme aiming at the highest practical accelerating gradient with normal-conducting structures. CLIC has a nominal centre-of-mass energy of 3 TeV and a design luminosity of $6 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$.

The CLIC RF power source: The two-beam accelerator scheme is a huge vacuum electronics application in its own right: Instead of many individual power sources, the drive beam complex itself, sketched in Fig. 5, constitutes the CLIC power source. Rather than through RF waveguides, the necessary power is transported in the drive beam, and with special decelerating structures (power extraction and transfer structures, PETS for short) the needed RF power is extracted and transferred to the nearby accelerating structures.

Figure 5: One CLIC drive beam complex (of two), simplified

Another essential element of the concept is the pulse compression scheme: as opposed to RF pulse compression, the beam pulse compression not only multiplies the power, but simultaneously the frequency; it also is conceptually loss-free. It works with rings and RF deflectors. For CLIC, the compression factor is 24.

Effective compression by another factor 24 is obtained using 24 return lines which distribute sequences of the drive beam pulse-train to different sectors of the main linac, and these return lines can be arranged in such a way that the compressed power is available where it is needed just when the main beam pulse arrives.

Klystrons for the drive beam accelerator: The drive beam itself is accelerated at 1 GHz with 150 μs RF pulses. The 2x326 40-MW-klystrons (or a larger number of smaller devices) are not readily available; their design must be optimized for efficiency, e.g. with an MBK [4], and require challenging R&D. An initial study with Thales and Lancaster University is ongoing.

Since any phase error will equally be multiplied by the beam pulse compressor, the requirements for low phase

jitter are unprecedented. This makes also the klystron modulator design challenging.

Operating the travelling wave drive beam accelerating structures in the so-called “fully beam loaded” condition, the efficiency of RF power transfer to the drive beam can be made as high as 97 %.

The main facility of this study is the CLIC Test Facility, CTF3, at CERN. It has already demonstrated very successfully the fully beam loaded operation and the beam pulse compression by factors up to 10. CTF3 uses the S-band high power installation from LEP times, with 11 klystrons running up to 45 MW, 5 μs.

RF pulse compression: In addition to the beam pulse compression described above, RF pulse compression with flat output pulses is routinely used with the barrel open cavity (BOC) when operating CTF3 [5]. Fig. 6 a shows the concept of the BOC cavity, where an Ω-shaped waveguide couples through many holes to a whispering gallery mode in a barrel-shaped cavity; Fig. 6 b shows the flat output pulse of the pulse compressor (right), obtained with phase modulation at the klystron input, as compared to the standard “LIPS/SLED” output (left), obtained with 180° phase flip.

Figure 6: a) conceptual view of the BOC pulse compression cavity, b) normal (left) and flat output pulse (right)

CLIC technology R&D: In order to keep the overall length of a future linear collider, the CLIC study explores which maximum gradient is possible. To operate a linear collider with 72000 accelerating structures, where a single breakdown may result in the loss of this beam pulse for luminosity, breakdown rates per linac length must be kept

well below 10^{-6} m^{-1} . For the accelerating structure referred to as T18 (designed, fabricated and tested in collaboration between KEK, SNAL and CERN), the design accelerating gradient of 100 MV/m was recently demonstrated [6]. Fig. 7 shows the measured breakdown rates and how they decrease with conditioning (at 60 Hz, 1200 h corresponds to $2.6 \cdot 10^8$ pulses).

Figure 7: Measured breakdown rates of the T18 accelerating structure after 250, 500, 900 and 1200 h of conditioning

This structure does however not yet have all features required for CLIC: the essential damping of higher order modes (HOM's) was still missing, but a number of full featured structures are presently in fabrication.

Advanced materials: HOM damping is implemented in practically all CERN accelerating structures. Similar to the techniques applied in high power klystrons and gyrotrons, the damping material must be compatible with the ultra-high vacuum and the joining techniques, so typically ceramics like SiC or AlN based composites are used. SiC, the material that has been successfully used at CERN in the past, is however often used (and specified) for its mechanical properties only, and most manufacturers cannot control the reproducibility of its RF related characteristics. We seem to share this concern and are addressing it jointly with our colleagues at KEK, CEBAF and Thales.

The successful design of CLIC and in particular the T18 structure was a result of both a development of improved model of the breakdown physics and extensive numerical field simulations, jointly applied in a complex, multi-parameter optimisation procedure and backed-up by experimental data. It was found that, in addition to field emission, the most important limiting quantity can be expressed in terms of the complex Poynting vector near the structure surface [7] and correctly describes the dependence on frequency and group velocity. A third limiting factor comes from the pulsed surface heating due to surface currents induced by the magnetic field. This pulsed surface heating and the local heating that occurs during breakdown has lead to an extensive R&D program on possible alternatives to annealed Cu as conducting material [8].

Other R&D work at CERN relevant for vacuum electronics applications:

- Under the auspices of the ISTC program, IAP Nizhny Novgorod has developed a 30 GHz high-power gyro-klystron (now finished).
- The SNAL klystron department is building for CERN and in collaboration with PSI, Elettra and LNF, high power X-band klystrons for a stand-alone power source at 12 GHz, scaling from their existing XL-4 klystron.
- CERN continually develops high power microwave components in L-, S- and X- and Ka-band, including e.g. hybrids, adjustable splitters and phase shifters, pumping manifolds, RF compatible vacuum sector valves, high power loads, RF vacuum windows and flanges.
- The “electron cloud” effect can be a serious intensity limitation for the LHC and its injector chain. This effect is very similar to multipactor, and the methods for its mitigation/suppression are common (surface coatings to reduce SEY, grooves, DC polarisation...). Collaboration with ESA on this subject is being set up.
- A study of high power RF recovery schemes to increase overall efficiencies has been started recently – initial ideas involve vacuum electronics devices.

Acknowledgements

For this paper I have taken the liberty to fall back on the material produced by colleagues both at CERN and at collaborating labs, and I am pleased to acknowledge here their original work and thank them – without it this overview would not have been possible.

References:

1. <http://linac4.web.cern.ch/linac4/>
2. http://council-strategygroup.web.cern.ch/council-strategygroup/Strategy_Statement.pdf
3. <http://clic-study.web.cern.ch/CLIC-Study/>
4. E. Jensen, I. Syratchev: “CLIC 50 MW L-Band Multi-Beam Klystron”. Kalamata, Greece, 2005, *AIP Conf. Proc.* 807 (2006) pp.90-99
5. R. Bossart et al.: “High-power Microwave Pulse Compression of Klystrons by Phase-Modulation of High-Q Storage Cavities”, 2004, <http://cdsweb.cern.ch/record/741401>
6. S. Döbert et al.: “High Power test of a low group velocity X-band Accelerator Structure”, 2008, <http://cdsweb.cern.ch/record/1141224>
7. A. Grudiev, S. Calatroni and W. Wuensch: “A new local field quantity describing the high gradient limit of accelerating structures”, to be published.
8. G. Arnau-Izquierdo et al.: “Material Selection and Characterization for High Gradient RF Applications”, PAC07, Albuquerque, <http://cdsweb.cern.ch/record/1059256>