CERN – European Organization for Nuclear Research
European Laboratory for Particle Physics

CLIC Note 435
CERN/PS 2000-014 (LP)

**A Klystron-Modulator RF Power System for the
CLIC Drive-Beam Accelerators**

A. Buenas^{*)}, P. Pearce

Abstract

An RF drive-beam power generation system is being studied for the Compact Linear Collider (CLIC) scheme at CERN, using high-power multi-beam klystrons (MBKs) operating at 937 MHz. Each RF drive module will provide up to 100 MW during a 100 μ s pulse to each accelerating structure in a fully-loaded L-band linac. An RF module consists of two klystron-modulators, each driving a 50 MW MBK, whose RF outputs are connected via 3 dB power combiners to a single 3.4 m long, travelling wave accelerating structure. The CLIC scheme will contain in total about 90 RF modules in each of the drive-beam linacs.

*Presented at the 24th International Power Modulator Symposium, Norfolk, Virginia, U.S.A.
26-30 June 2000*

^{*)} Thomson Tubes Electroniques (TTE), Paris, France

Geneva, Switzerland
21 June 2000

A Klystron-Modulator RF Power System for the CLIC Drive-Beam Accelerators

P.D Pearce

PS Division, CERN, Geneva, Switzerland.

A. Beunas

Thomson Tubes Electroniques (TTE), Paris, France.

ABSTRACT

An RF drive-beam power generation system is being studied for the Compact Linear Collider (CLIC) scheme at CERN, using high-power multi-beam klystrons (MBKs) operating at 937 MHz. Each RF drive module will provide up to 100 MW during a 100 μ s pulse to each accelerating structure in a fully-loaded L-band linac. An RF module consists of two klystron-modulators, each driving a 50 MW MBK, whose RF outputs are connected via 3 dB power combiners to a single 3.4 m long, travelling wave accelerating structure. The CLIC scheme will contain in total about 90 RF modules in each of the drive-beam linacs.

INTRODUCTION

CLIC uses the Two-Beam Accelerator (TBA) concept first proposed by A. Sessler in 1982 and adapted by W. Schnell in 1986 [1] for the design of a single bunch e^+e^- collider operating at an RF frequency of 30 GHz. The present CLIC design [2]

is a multi-bunch, high-luminosity machine, with centre-of-mass collision energies going from 0.5 to 5 TeV. A drive-beam accelerator using 937 MHz klystron-modulator RF sources accelerates an electron beam that is then used to produce RF power at 30 GHz for the main-beam accelerator. An important factor in this RF power generation scheme (Figure 1) is that by making the pulse of the klystron-modulator shorter or longer, lower or higher energies can be reached in the main-beam linacs (Table 1).

Parameters	0.5 TeV	1 TeV	3 TeV	5 TeV
Rep. Rate (Hz)	200	150	100	50
Accel.gradient (MV/m)	150	150	150	172
Total two linac length (km)	5	10	27.5	40
Number of klystrons	364	364	364	364
Klystron peak power (MW)	50	50	50	66
Klystron pulse length (μ s)	16.7	33.3	92	134
AC to beam effic. (%)	9.8	9.8	9.8	8.5

Table 1: Main beam & Drive-beam klystron-modulator parameters

Figure 1. Nominal 3 TeV drive-beam scheme

THE MULTI-BEAM KLYSTRON

CLIC requires a high conversion efficiency of AC power into klystron RF output power in order to reduce overall power consumption. A pulsed multi-beam klystron [3] is being designed for this task and is derived from the 10 MW klystron of a similar type that will be used in the TESLA [8] project. Seven low-perveance parallel beams (n_b) propagate in seven separate drift tubes, and interact in common cavities along the beam trajectory within the same vacuum envelope. The effective microperveance of the MBK is $3.5 \cdot 10^{-6} \text{ A/V}^{-3/2}$, with each single beam microperveance (μP) being $0.5 \cdot 10^{-6} \text{ A/V}^{-3/2}$. The MBK efficiency is expressed empirically as a function of the single-beam microperveance by:

$$\eta_{\text{MBK}} = (0.78 - 0.16 [\mu P])$$

This low, single-beam microperveance, with low space charge forces, enables stronger beam-bunching and so a higher electron efficiency compared to the standard mono-beam, higher microperveance tube. An efficiency of 65 to 70% is calculated for the CLIC MBK. For high efficiency, as much as possible of the kinetic energy in the bunched beams must be converted into electrical energy at the RF output. This is achieved by decelerating the electron beam in the output gap. Due to the potential drop at the collector entrance, some slow electrons are accelerated in the reverse direction, particularly from the central, seventh beam, which could give rise to oscillations and unwanted sidebands. An alternative six-beam MBK is also being investigated (Table 2) if this difficulty impacts the use of the central beam and restricts the present design.

The peak output power of the MBK is given by:

$$P_o = \eta_{\text{MBK}} [\mu P] n_b [V_k]^{5/2}$$

so that, with a given output power and electron efficiency, the pulse voltage reduces with an increasing number of internal beams. The gun and beam focusing complexity, however, increases. With 7 beams, a multi-beam klystron's voltage is reduced by around 45% when compared to a mono-beam klystron at the same peak power and same efficiency, enabling higher reliability and a more easily maintained modulator. The low voltage also significantly reduces breakdown occurrences at the gun due to a low $E_{\text{max}} \cdot V_k$ product (electric field x klystron voltage) with long pulses, and reduces any X-ray emission.

The voltage pulse width versus this $E_{\text{max}} \cdot V_k$ product has been shown [9] to follow the function:

$$E_{\text{max}} \cdot V_k < 100/\tau^{0.34} \text{ in (kV)}^2/\text{mm}$$

The CLIC MBK $E_{\text{max}} \cdot V_k$ product is $2291 \text{ (kV)}^2/\text{mm}$ with a $100 \mu\text{s}$ pulse. From Table 2, using the design voltage $V_k = 212 \text{ kV}$, the field gradient in the gun region must not exceed 10.8 kV/mm . A first calculation gave a field of 9 kV/mm with a beam voltage of $V_k = 208 \text{ kV}$ at this pulse width.

Cathode loading is an important gun design parameter, particularly with regard to the expected operational lifetime of the tube. Each of the 7 beams are emitted from M-type dispenser cathodes with a loading of 6 A/cm^2 . This gives a projected lifetime of around 30,000 hours.

Parameter	Units	Value
Frequency	MHz	937.5
RF pulse width	μs	100
Microperveance	$\text{A/V}^{3/2}$	0.5
Number of beams	n_b	7 (6)
Beam area convergence		5.4:1
Beam interaction length	mm	~2800
Jmax	A/cm^2	6
Efficiency	%	65 to 70
Bandwidth (-1 dB)	MHz	4 (min)
Saturated gain	dB	≥ 47
Focusing field	Gauss	975
Beam voltage	kV	212 (211)
Collector dissipation		Full beam
Beam current	A	342 (293)
Peak RF output power	MW	47 (40)

Table 2. MBK design parameters
The combined variation of cathode loading and perveance parameters in Figure 2 shows how they affect the peak output power of the MBK.

Figure 2. Cathode parameters and Peak Power

The simulated performance of the 7-beam MBK at two operating power levels is given in Figure 3 and the corresponding bandwidth is shown in Figure 4.

Figure 3. MBK power transfer curves

Figure 4. MBK bandwidth response

Due to the high RF power requirements, and to limit field distortion in the output cavity gap, the MBK will have two reduced height WR975 waveguides from this cavity connecting to two ceramic disk (Al_2O_3) output RF windows.

THE LONG-PULSE MODULATOR

The duty-cycle pulse power requirements and high RF peak power to be used in the drive-beam accelerator [4] underline the need for a high average power modulator design. A conventional line-type modulator is being studied for use with a 50 MW MBK. The basic features of this baseline design are shown in Figure 5. A double Rayleigh multi-cell pulse-forming network (PFN) is charged from a high efficiency high-voltage switched-mode unit. Two thyatron switches discharge the PFN via a 1:10 ratio step-up pulse transformer, into the MBK load. The pulse transformer has a dc core reset current applied via an isolating inductor through the primary winding. The parameters of this baseline design are given in Table 3. Present commercially available high power thyatrons have average current limits of around 25 A, so that two are used, one with each PFN. A clamping diode is

used on the transformer primary to protect against excessive inverse voltages at the MBK cathode.

Parameter	Units	Value
Modulator pulse width (FWHM)	μs	108
Voltage pulse rise time (10-90%)	μs	12
PFN voltage (max)	kV	43
Single PFN impedance	ohms	11.5
PFN cell capacitance	nF	155
Stored energy in PFN	kJ	8.5
Klystron to PFN mismatch (max)	%	6
Single thyatron peak current	A	1800
Single thyatron average current	A	19.5
Pulse transformer ratio		1:10
Pulse transformer volt-seconds	Vs	22.5

Table 3. Baseline modulator parameters

End-of-line diodes with energy dumping resistors on each PFN protect against inverse voltages caused by any MBK gun short-circuit faults. The step-up pulse transformer is in an oil tank, connecting directly to the horizontally mounted MBK. Preliminary calculations using nominal Stangenes transformer parameters give a pulse rise time of about 12 μs (10-90%), and a dc bias of 12 A will be needed to prevent core saturation. Using a double, multi-cell PFN enables pulse droop to be compensated by tapering the PFN impedance. This also enables the flat top ripple to be kept within drive-beam system requirements.

Other modulator configurations being studied using solid-state switching systems are based on IGBT devices. In one system the PFN and thyatron switches were replaced by a high voltage storage capacitor working at 22 kV with an IGBT array switching the stored energy directly into the pulse transformer. Minimizing the stored energy in the capacitor to about 120 kJ resulted in a klystron voltage droop of $\sim 3\%$ over the 100 μs pulse. This droop can be compensated with a TESLA [5] style bouncer circuit.

A second solid-state modulator being considered uses a split core pulse transformer [6] to create the high-voltage klystron pulse. This is similar to the fractional wound pulse transformer design [7] being investigated for the NLC project at SLAC, having a 3 μs voltage pulse width. An advantage of these types of circuit is the low (1 to 2 kV) voltage on the transformer primary windings, so that no series-connected solid-state switches are used. However, creating a flat-topped ($\pm 0.1\%$) 100 μs long pulse with this circuit topology is seen as being much more challenging.

Figure 5. Basic long-pulse modulator circuit

THE RF DRIVE POWER NETWORK

The RF power outputs of two MBKs are connected as in Figure 6. This scheme is one possible arrangement to obtain the 100 MW peak drive power for an accelerating structure. The two-MBK drive connection scheme also permits a fine adjustment of the summed output amplitude, via fast differential phase changes during the long pulse, allowing electronic correction of the RF pulse flatness over this period. High-power SF₆-to-vacuum RF windows separate the accelerator vacuum from the klystron-modulator system. The waveguide lengths in the system between MBKs, combiners and the accelerating sections need to be minimized to reduce power losses. Water cooling of these components will be necessary in order to keep good phase stability and reasonable operating (30-40°C) temperatures.

large extent will determine the overall system efficiency. The AC-to-RF power efficiency of one CLIC klystron-modulator is estimated as 52% when operating with a klystron of 65% efficiency. The estimated total AC line power for the 364 klystron-modulators to provide RF power for the drive-beam linacs is shown in Figure 7.

Figure 7. AC line power for klystron-modulators

Figure 6. The 50 MW MBK RF network module

KLYSTRON-MODULATOR EFFICIENCY

A key operational consideration for any collider design is the efficiency with which AC line power is converted to RF power for accelerating particle beams. The klystron-modulators are an important part of the CLIC drive-beam scheme, and to a

SUMMARY

The CLIC drive-beam klystron-modulators are high average power systems that need to be reliable, power efficient and cost-effective. A detailed design for a multi-beam klystron and different modulator configurations are being studied.

REFERENCES

- [1] W. Schnell, "A two stage RF linear collider using a superconducting drive linac" CERN-LEP-RF/86-06
- [2] J.P Delahaye, I. Wilson et al. "CLIC a Multi-TeV e^+e^- Linear Collider", CERN/PS 99-062 (LP).
- [3] R.M Philips SLAC (editor), "High Energy Density Microwaves", P107, AIP Conf. Proc. 474, 1999. ISBN 1 - 56396-767-0.
- [4] H.H Braun et al. "The CLIC RF Power Source, A Novel Scheme for Two-Beam Acceleration of Electron-Positron Colliders", CERN 99-06
- [5] H. Pfeffer et al. "A long pulse modulator for reduced size and cost" 4th EPAC conference, London, 1994.
- [6] W. Crewson. Crewson Engineering Inc, Private communication.
- [7] R. Cassel, et al. "The capacitor charging power supply for a Next-Generation Linear Collider". International Power Modulator Symposium, June 1998.
- [8] R. Brinkman et al. "Conceptual Design of a 500 GeV e^+e^- Linear Collider with Integrated X-ray Laser Facility". DESY 1997-048.
- [9] R. Latham (editor). "High Voltage Vacuum Insulation", Chapter 11. Academic Press, 1995, ISBN 0-1243175-2.