Klystron-Modulators for the 3 TeV CLIC Scheme — An Overview

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1. Introduction.

The CLIC (Compact Linear Collider) design is based on the Two-Beam technology [1,2] being developed at CERN and the overall layout for a 3 TeV scheme is shown in Figure 1. The Drive Beam accelerator design will have about 200 multi-beam klystron-modulator (MBK-M) RF power sources for each Drive Beam linac. These multi-beam klystrons (MBKs) should provide up to 50 MW peak power at 937 MHz, with a 100 μs pulse width and operating at 100 Hz repetition frequency. The CLIC Drive Beam injector will also use a number of these MBK-Ms operating at slightly lower power levels. A 0.5 MW peak power, 468 MHz klystron with a bandwidth of around 150 MHz will be required for the sub-harmonic buncher in each Drive Beam injector chain as well.

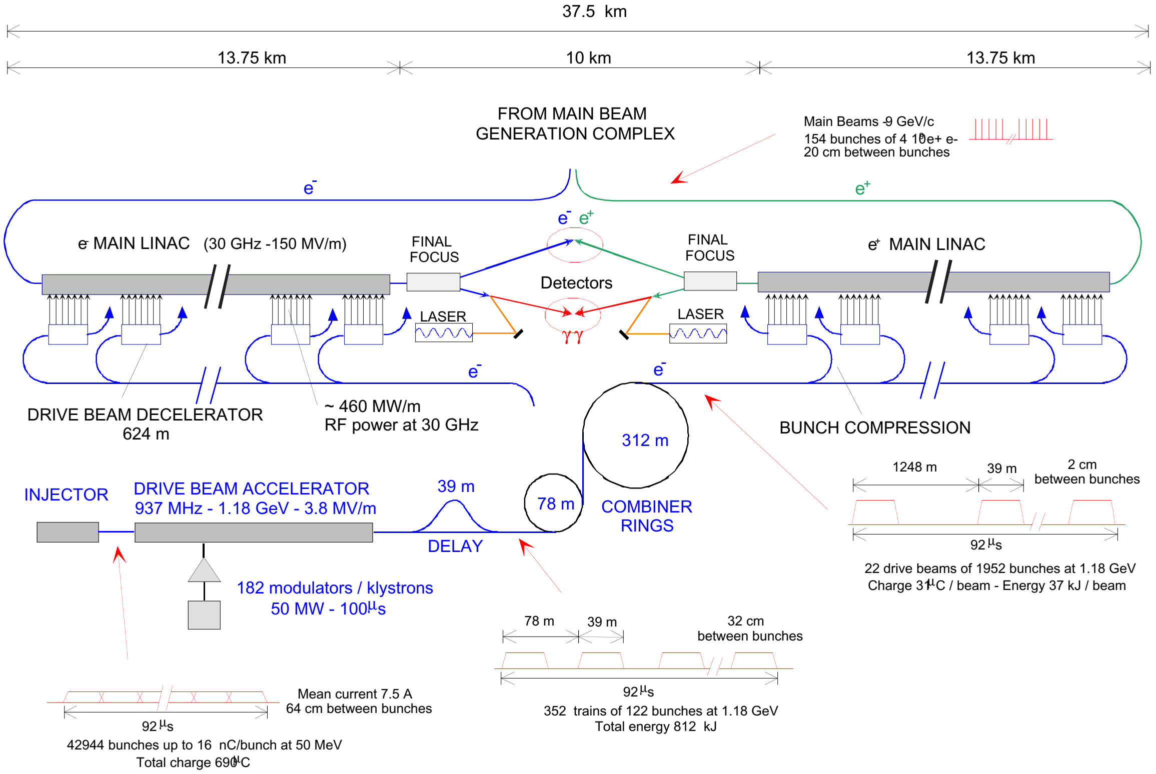

Figure 1. Layout of the CLIC scheme for 3 TeV centre of mass.

The Main Beams injector complex is required to deliver e^+ and e^- beams at 9 GeV via the transfer lines to the CLIC Main Beam accelerator. The present Main Beams injector complex layout [3] has a series of linacs to accelerate the e^+ and e^- beams generated by RF guns (and with a target used for the e^+ beam) working at 1.5 GHz up to an energy of 1.98 GeV before they are put into damping rings. Each of these beams then pass through a 3 GHz compressor before acceleration to the Main Beam injection energy of 9 GeV by a common 3 GHz Booster Linac. This paper describes the major parameter requirements and configurations for the range of klystrons and modulators in the Drive and Main Beam linacs.

2. Klystron-Modulators for the Drive Beam accelerating sections.

A modular RF power system is being studied for the CERN Compact Linear Collider (CLIC) scheme using pulsed high-power multi-beam klystrons (MBKs) operating at a frequency of 937 MHz. Each RF power module will provide up to 100 MW of peak power, during a 100 µs long pulse, for each accelerating structure in a fully-loaded and conventional L-band linac. An RF module [4] consists of two 50 MW MBKs, as in Figure 2, with their outputs connected via a 3 dB power combiner to a single, 3.4 m long, travelling wave accelerating structure. Each 50 MW MBK will have a separate high-power modulator.

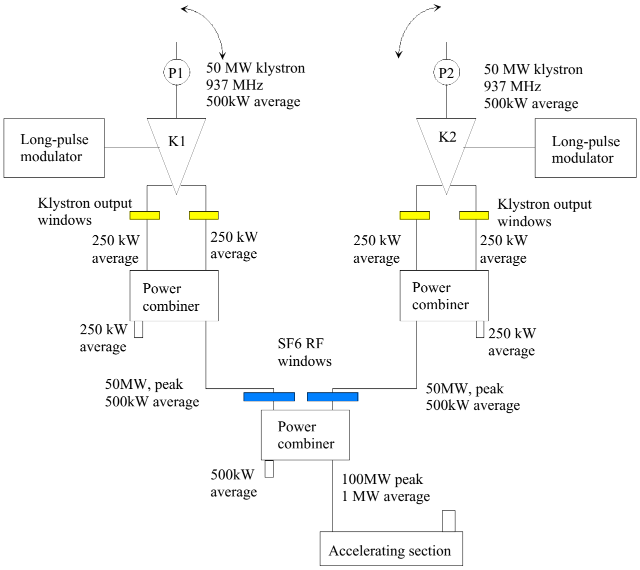

Figure 2. A CLIC Drive Beam accelerator RF Module.

A design study is being made with a klystron manufacturer to determine the feasibility of a 7 beam MBK, operating close to the desired 50 MW output power. Table 1 shows some of the calculated parameters for this tube. A first prototype klystron with 6 beams, and 25 to 40 MW output, with the design scaled up from an existing 10 MW tube, is seen as a possible solution in the medium term.

Parameter	Value	Units
RF Frequency	937.5	MHz
Repetition frequency	100	Hz
RF pulse width	100	µs
Microperveance	0.5	$I/V^{3/2}$
Number of beams	7	n_b
Jmax	6	A/cm^2
Efficiency	65 to 70	%
Gain at saturation	≥43	dB
Klystron beam voltage	212	kV
Klystron beam current	342	A
Peak RF output power	47	MW

Table 1. MBK parameters

The Drive Beam modulator baseline design being studied (Figure 3) is a conventional line-type system. The overall conversion efficiency from input AC wall-plug power to pulsed RF output power is important. A high-efficiency switched-mode unit is proposed for the high voltage charging system, and a double Rayleigh multi-cell pulse-forming network (PFN) is discharged by thyratron switches through a step-up pulse transformer into the MBK load. Different solid-state switch modulator solutions are also being considered including the replacement of the thyratron switches with IGBT or IGCT assemblies.

The parameters in Table 2 for the 100 Hz, 50 MW baseline klystron-modulator show that the overall design has a relatively high PFN charging power, and high average thyratron switch current compared to existing CERN and other standard S-band modulators.

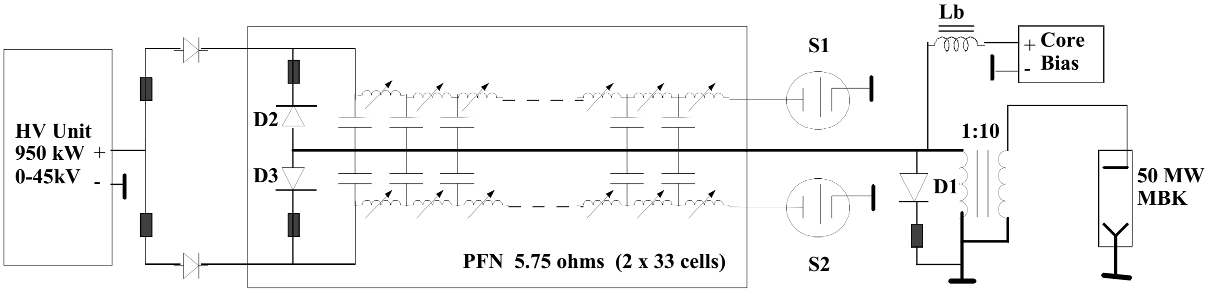

Figure 3. Conventional line-type MBK-modulator design

Parameter	Value	Units
Modulator pulse width (FWHM)	108	µs
Voltage pulse rise-time (10-90%)	12	µs
PFN voltage (max)	43	kV
Single PFN impedance	11.5	Ω
Stored energy in PFN	8.5	kJ
Single thyratron peak current	1800	A
Single thyratron average current	19.5	A
Pulse transformer ratio	1:10	-
Pulse transformer volt-seconds	22.5	Vs

Table 2. Baseline modulator parameters

3. Klystron-Modulators in the Drive Beam Injector.

In the Drive Beam injector scheme of Figure 4, a thermionic gun is followed by a sub-harmonic bunching system that provides a 10 MeV beam to the short injector linac. This linac accelerates the beam to 50 MeV before injection into the Drive-Beam linac. The two sub-harmonic bunching cavities are driven by a low-power, 0.5 MW klystron operating at a centre frequency of 468 MHz and instantaneous (1dB) bandwidth of 150 MHz, and with 100 µs output RF pulse width. The first buncher cavity B1 requires 1 MW of RF power at the drive beam frequency of 937 MHz, with a 100 µs output RF pulse width.

Although MBK tubes are presently being considered for the injector klystrons, the two sub-harmonic cavities could each be driven with single-beam klystrons (SBKs) of the above power and frequency. These SBKs would have an extended interaction output cavity to obtain the 150 MHz wide bandwidth, as is proposed for CTF3. The two SBK klystrons could also be powered from a single modulator, or alternatively a single 1 MW peak-power SBK could be used. Both these klystron types would need to be developed.

In operation, the phase of the RF power driving the SHB cavities is switched rapidly by 180^o every 130 ns, in order to produce a train of phase-coded sub pulses within the ~100 µ s output RF pulse of the wide-band klystron. This effectively shifts in time the alternate sub pulse trains to synchronise them for deflection in the x2 delay by the 468 MHz RF deflectors and provides a means of separating the sub-pulses after acceleration and keeps a constant current in the Drive Beam accelerator.

The pre-buncher cavity B1 could also be powered by a separate narrow-bandwidth, 1 MW peak, 937 MHz, SBK. For a more economic solution, this RF power could be taken from the MBK module that drives the buncher section B, and used to power the pre-buncher cavity B1 with a correcting shift in phase. The modulators for these MBK tubes would be similar to those used for the Drive Beam accelerator (Figure 2), whilst the sub-harmonic buncher klystrons would need a low-power version of this. More optimisation of the RF power requirements and the layout for this injector are needed.

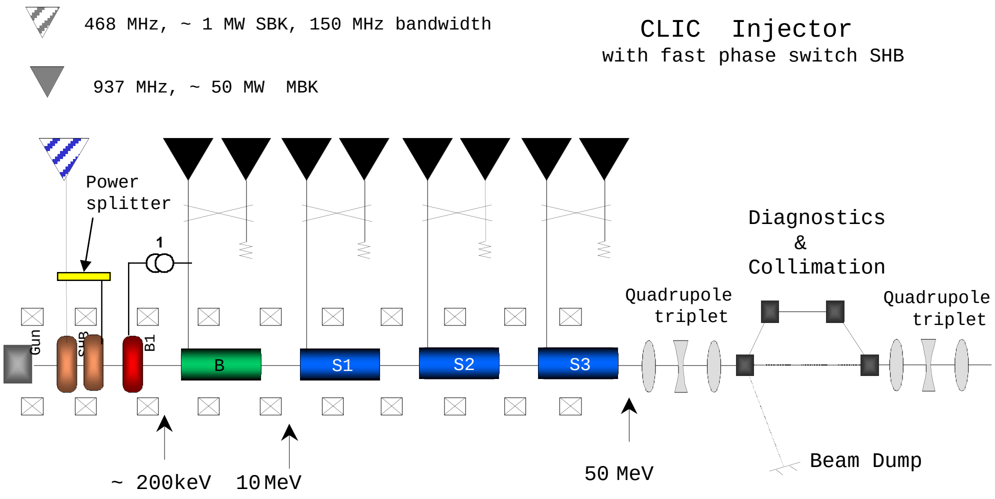

Figure 4. Alternative CLIC Drive Beam Injector layout

4. Klystron-Modulators for the RF deflectors.

The drive beam accelerator pulse-compression scheme uses a series of RF deflectors that are driven by high-power klystron-modulators. These RF deflectors are part of the scheme to create power at 30 GHz that is distributed to the transfer structures feeding the Main Beam linacs. This high peak-power generation and frequency multiplication process (Figure 1) starts with long (~100 µs) beam pulses that leave the drive beam accelerator. Figure 5 shows the positions of the RF deflector klystron-modulators within the CLIC scheme.

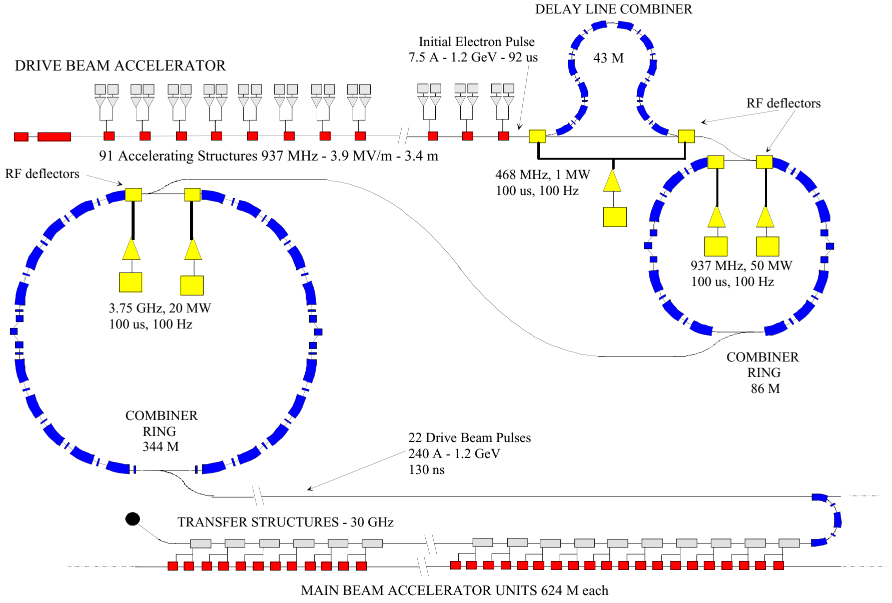

Figure 5. RF deflector klystron-modulators in CLIC

These long beam pulses pass through a x2 delay-line combiner, where odd and even sub-pulses are separated by a transverse RF deflector that operates at 468 MHz. The even bunch trains are delayed with respect to the following odd ones by 130 ns. A second RF deflector, operating at the same frequency, causes the sub pulses to be recombined, two-by-two, by bunch interleaving. The peak power of the beam and the bunch frequency are doubled. A peak RF power of about 0.5 MW at 468 MHz, with ~100 µs pulse width, is required from the klystron-modulator system at each deflector.

This same interleaving principle is used in the first combiner ring RF deflector, operating at the Drive Beam frequency of 937 MHz, where the trains are combined in a four-by-four process. Two klystron-modulators, each producing ~50 MW peak RF power at 937 MHz with ~100 µs pulse width will be needed to power these two RF deflectors. A standard single MBK-M configuration can be used here as in Figure 6 below.

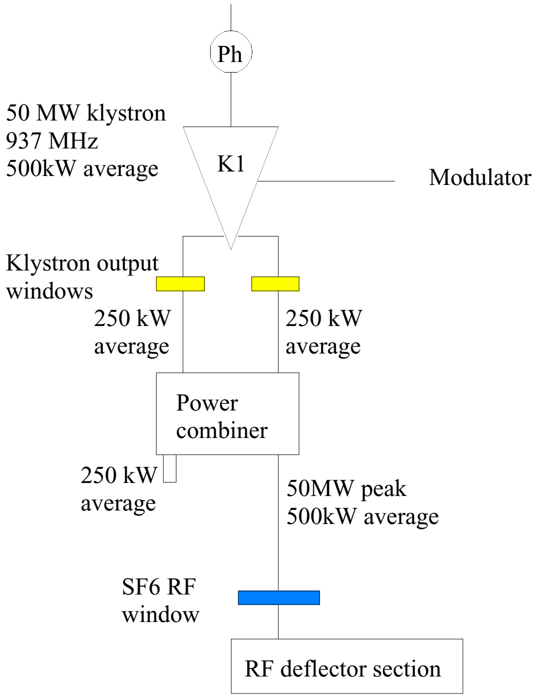

Figure 6. RF deflector klystron-modulator for first combiner ring

The second combiner ring RF deflector system operates in a similar manner, but at a frequency that is four times the Drive Beam frequency, or 3.75 GHz. Each deflector requires ~20 MW peak power and ~100 µs pulse width. This manipulation also combines the trains in a four-by-four process. A lower-power modulator with a 3.75 GHz klystron, similar to the configuration of Figure 6, can be used here.

The action of all of these RF deflectors is to create a time-dependent local deformation of the equilibrium orbit in each ring. The overall process gives a multiplication factor of 2x4x4 (32) times the Drive Beam frequency, producing a powerful multi-bunched 30 GHz electron Drive Beam that is distributed via the transfer structures to power the Main Beam linacs.

5. Klystron-Modulators for the Main-Beam Injector.

The general layout [5] of the Main Beam injection scheme is shown in Figure 7. The scheme has two production systems, one for electrons and another for positrons. The two beams are alternately selected and accelerated by a common Injector linac before being directed towards the e^+ or e^- damping rings. A 7 GeV Booster linac raises the main-beam injection energy to 9 GeV.

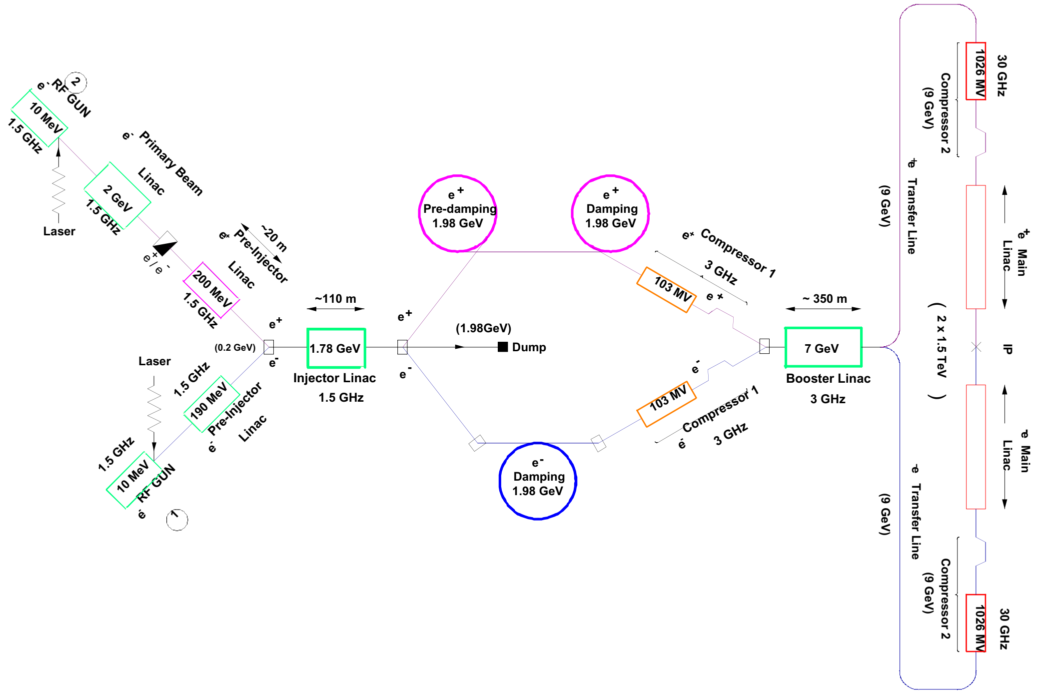

Figure 7. Main Beam Injector layout

5.1 Electron production.

For electron production, the laser system and the photo-cathode RF electron gun will produce a low-charge bunched beam of about 1 nC/bunch at an energy of 10 MeV at the gun exit. The RF gun operates at 1.5 GHz and requires ~10 MW peak output power from a klystron-modulator as shown schematically in Figure 8, and pulsed at 100 Hz with a ~4.5 µs pulse width. The use of a second RF photo-injector for the e^- beam is also envisaged. This could be used as a polarized e^- source, or as a spare RF gun.

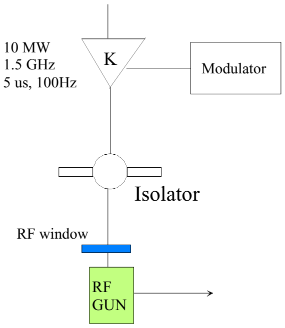

Figure 8. RF gun klystron-modulator

The 10 MeV beam from the gun is fed into the Pre-Injector Linac, also operating at 1.5 GHz. This provides an energy gain of ~190 MeV, ie. an energy of 200 MeV at the exit of the linac. The loaded gradient of each 5 m accelerating section is about 24 MV/m. The RF power for the 100 Hz Pre-Injector linac can be provided by a minimum of two klystrons, each operating at ~75 MW peak output power, and with a 4.5 μs pulse width. The klystron pulse of 4.5 μs is applied to a pulse compressor (SLED-type) creating an output pulse of ~120 ns width and of twice the peak input power. A possible configuration for this klystron-modulator is shown in Figure 9.

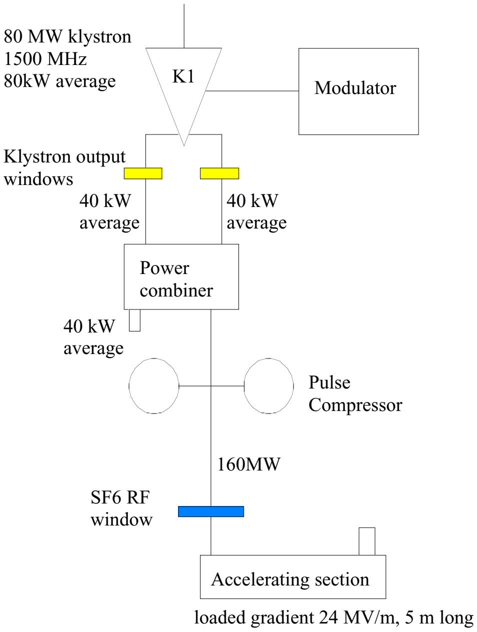

Figure 9. Pre-Injector Linac 80 MW L-band klystron-modulator

5.2 Positron production.

The present scenario for positron production is shown in Figure 7. A photo-cathode RF gun and klystron-modulator (Figure 8) produces a 10 MeV bunched beam with a frequency of 1.5 GHz and operating at 100 Hz. This is injected into the Primary Beam e^- Linac working at the same frequency and repetition rate. The electron beam is accelerated to an energy of 2 GeV. The Primary Beam e^- Linac has up to 24 of the 5 m long accelerating cavities. These cavities operate with a loaded gradient of 17 MV/m. Positrons are created in an electromagnetic shower by directing the 2 GeV electron beam onto a target of high-Z material. The output pulse of each klystron is compressed using the klystron-modulator layout of Figure 9, as in the Pre-Injector Linac.

5.3 Common linacs.

The common 1.5 GHz Injector Linac uses sections at a loaded gradient of 17 MV/m as in the Primary Beam linac above. The Injector Linac is approximately 110 m long and accelerates the beam by about 1.78 GeV. It will also have up to 24 of the 5 m long sections and 24 L-band klystron-modulators, and will accelerate both electron and positron beams to a final energy of 1.98 GeV before they are switched into the damping rings. The klystron-modulator modules used in this linac can also be those shown in Figure 9.

The common Booster Linac operates at the S-band frequency of 3 GHz and accelerates by ~7 GeV. This linac has a loaded gradient of 21 MV/m and will be approximately 350 m long in order to boost both electron and positron beams up to an energy of 9 GeV. These beams are transported via transfer lines and the 30 GHz compressors before injection into the Main Beam accelerator.

The Booster Linac will have about 112 sections, each 3 m long, and each requiring about 63 MW of RF drive power to obtain an energy incease of 7 GeV with the 1A bunched beam. The klystron-modulators provide a 9 µs RF pulse to the input of each SLED-type pulse compressor, so that two consecutive pulse compressions can take place within this ~10 µs drive pulse width. The first pulse is for the e^+ acceleration and the second for e^- acceleration using the compressed peak power 102 ns, 126 MW pulses in Figure 10.

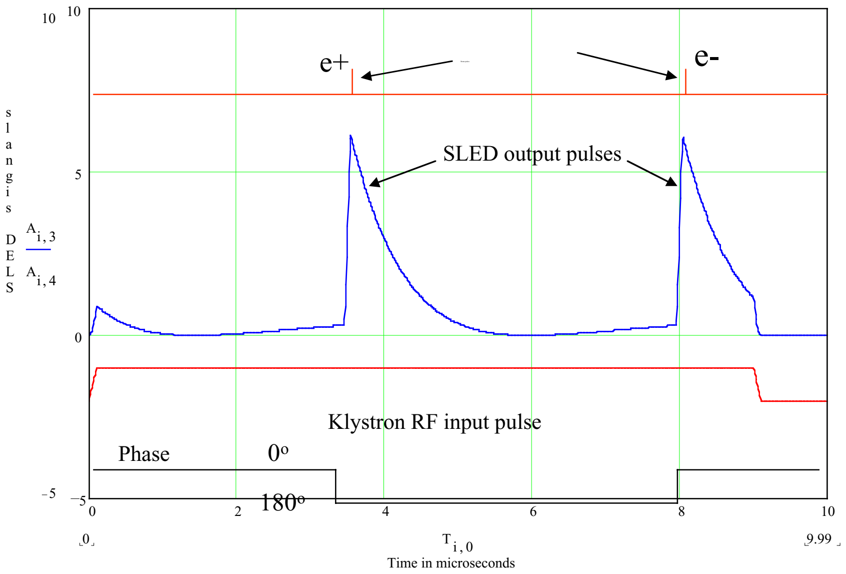

Figure 10. Double RF pulse generation with SLED

The simplest klystron-modulator RF module configuration to obtain reliable operation and have a minimum of components in the high-power output could be the one of Figure 11. Here there are 56 RF modules, and each module drives two accelerating sections using a 63 MW (70 MW) klystron, a pulse compressor with a gain of two and a single 3 dB power splitter. Other configurations are also a possibility, such as driving four sections from two parallel-operated klystrons but this requires installing a few more power splitters and there could be a loss of flexibility in operation.

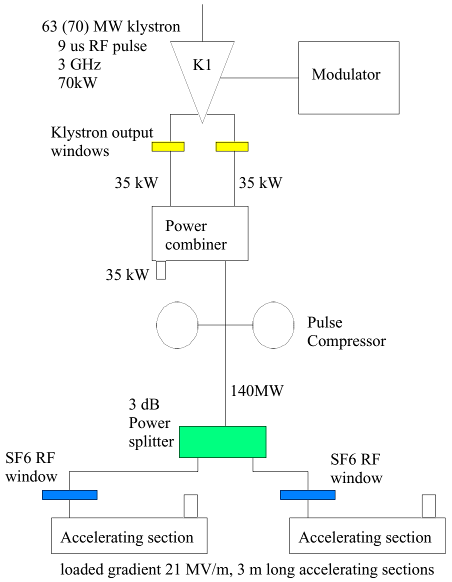

Figure 11. Booster Linac Klystron-Modulator RF module

5.4 RF power for the Electron/Positron Guns.

The 10 MeV RF guns for e^- and e^+ production have been shown with their own 1.5 GHz klystron-modulator system (Figure 8). In order to reduce the number of klystron-modulator installations it is possible to extract RF power from the first high-power klystron-modulator in the appropriate production chain. Since the maximum amount of peak power required is less than 10 MW, this could be done as shown in Figure 12, using a power splitter, attenuator and phase-shifting arrangement. This would also reduce the number of types of klystrons that need to be developed for CLIC.

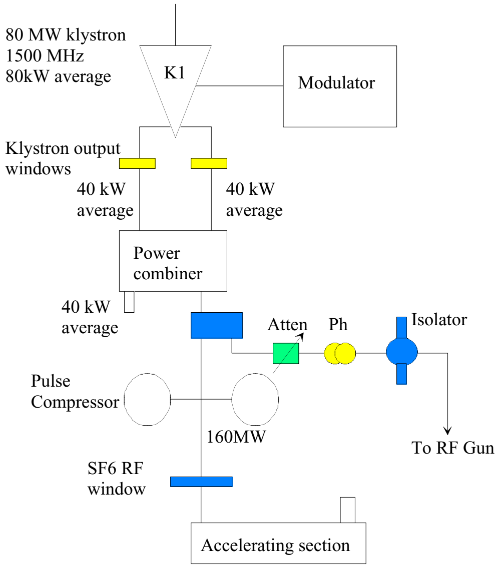

Figure 12. Alternative source of RF power for injector guns

6 Summary.

A high-energy, high-luminosity e^+e^- Compact Linear Collider (CLIC) is being studied at CERN as a possible new high-energy physics facility for the post-LHC era. The CLIC design is such that energy upgrades from the lower energy of 0.5 GeV through the optimised 3 TeV design, to 5 TeV can be made in stages without any major modifications. The klystron-modulator designs need to take this into account. In particular, the Drive Beam klystron-modulators will require their pulse width to be lengthened as the centre-of-mass energy is increased but the actual hardware is exactly the same.

MDK RF System	Number MDKs	Klystron Type	Pulse width µs	Frequency MHz	Peak Power MW	Average Power kW
Drive-Beam Accelerator	364	MBK	100	937	50	500
Drive-Beam Injector	16	MBK	100	937	50	500
Drive-Beam Injector	2	SBK, WB	100	468	1	10
RF Deflectors	4	SBK	100	3750	20	20
RF Deflectors	4	MBK	100	937	50	500
RF Deflectors	2	SBK	100	468	1	10
e^- Gun and Pre-Inj. Linac	2	SBK/MBK	5	1500	80	40
e^+ Gun and Inj. Linacs	26	SBK/MBK	5	1500	80	40
Common Inj. Linac	24	SBK/MBK	5	1500	80	80
Common Booster Linac	56	SBK/MBK	10	3000	80	80

Table 3. Klystron-Modulator types required for the CLIC 3 TeV scheme

As a consequence the entire Drive Beam generation system has to be installed in the first stage of CLIC. A list of the present number of klystron-modulators and the basic operating requirements of the klystrons for the 3 TeV CLIC scheme are shown in Table 3. At the present time only the multi-beam 937 MHz, 50 MW klystron and its modulator are being studied.

7. References.

1. CLIC Study Team. A 3 TeV e^+e^- Linear Collider Based on CLIC Technology CERN 2000-008, 2000

2. CLIC Study team. The CLIC RF Power Source- A Novel Scheme of Two Beam Acceleration for Electron-Positron Linear Colliders. CERN 99-06, 1999

3. L. Rinolfi. A CLIC injector complex for the main beams CLIC Note 354, 2000

4. P. Pearce, A klystron-modulator RF power system for the CLIC drive-beam accelerators , 24th International Power Modulator Symposium, Norfolk, Virginia, June 2000.

5. CLIC Note 359, 2000