Session 1-1
Chairman : H. Braun (CERN)

RF Systems & Components

REVIEW OF SESSION 1.1 - RF SYSTEMS & COMPONENTS

H. Braun (Chairman)
CERN

List of talks

Stefan Choroba	DESY	The TESLA RF System
Roberto Corsini	CERN	CTF3 A demonstration of the CLIC RF Power Source
Igor Syratchev	CERN	RF Pulse Compressor Systems for CTF3
Peter Pearce	CERN	Klystron-Modulators for the 3 TeV CLIC Scheme – An Overview

Stefan Choroba gave an overview of the TESLA RF system. Particular interesting is the successful high power test of the multibeam 1.3 GHz klystron and the careful analysis of the overall mains to RF power efficiency.

Roberto Corsini presented the plans for the CLIC Test Facility 3. This facility aims to demonstrate the efficient production of 30 GHz power by means of the CLIC drive beam scheme.

Igor Syratchevs showed a scheme for producing a flat compressed RF pulse with a phase programmed klystron and a single compact energy storage cavity (barrel open cavity). Although this scheme is presently foreseen for use in the CTF3 drive beam accelerator it could as well serve as a compact high power source for small linacs.

Peter Pearce gave a comprehensive overview of all the different klystrons needed in the present CLIC scheme. Compared with TESLA the relative low number of high power klystrons seems attractive, while the high number of special devices seems impractical (see table 1).

	TESLA	CLIC	
E_{CM}	0.5 TeV	3 TeV	
		drive beam accelerator	others
Number of Modulators & Klystrons	560	364	136 of 5 different types
average RF power per klystron	66 kW	500kW	10-500kW

Table 1 Klystron needs of TESLA and CLIC

THE TESLA RF SYSTEM

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Abstract
The Tesla project proposed by the TESLA collaboration is a 500 to 800GeV e+/e- linear collider with integrated free electron laser facility. The collider is based on superconducting cavity technology. ~20000 superconducting cavities operated at 1.3GHz with a gradient of 23.4MV/m or 35MV/m will be required to achieve the energy of 500GeV or 800GeV respectively. For 500GeV ~600 RF stations each generating 10MW of RF power at 1.3GHz at a pulse duration of 1.37ms and a repetition rate of 5 or 10Hz are required. This paper describes the layout of the entire RF system and gives an overview of its various subsystems and components.

1. INTRODUCTION

The TESLA project proposed by the TESLA collaboration is 33km long 500 to 800GeV e+/e- linear collider with integrated free electron laser facility. It is based on superconducting cavity technology. Details can be found in the TESLA Technical Design Report [1].

In this paper the TESLA RF system with emphasis on its high power part will be described. The RF system consists of a number of RF stations converting AC line to RF power at 1.3GHz for the superconducting cavities of the main linac and for the accelerating structures of the injectors. In the remainder of this paper the RF system layout for the 500GeV collider will be presented. The RF system layout for the 800GeV upgrade differs almost only in twice the number of RF stations.

2. REQUIREMENTS

In order to reduce the cost and to improve the reliability of the entire RF system the total number of RF stations is chosen as small as possible, only limited by the maximum output power which can be generated reliably by a single RF source. The output power of one RF station is then distributed to a number of accelerating cavities.

At a center of mass energy of 500GeV the peak RF power needed for one superconducting cavity at full gradient and maximum beam current, i.e. 23.4MV/m and 9.5mA during the pulse, is 231kW. At TESLA twelve 9-cell cavities will be installed in one 17m long cryo module. The nominal peak power needed for three modules with thirty-six cavities is 8.3MW. Taking into account a regulation reserve of 10% for phase and amplitude control and another 6% for circulator and waveguide losses 9.7MW are required. The particle beam pulse consists of 2820 micropulses with a spacing of 0.337μs resulting in a macropulse duration of 950μs. 420μs are needed to fill the cavity with RF. Hence the RF pulse length is 1.37ms. The repetition rate is 5Hz for the major part of the linac. At the low energy part of the e^--linac the stations will be running at a repetition rate of 10Hz for FEL operation.

3. BASIC RF STATION LAYOUT

Each RF station consists of subsystems required to convert AC line power to RF power and to distribute the RF power to the cavities. A modulator converts AC line power into high voltage pulse power. Its main parts are a high voltage power supply, a high voltage pulser unit and a pulse transformer. A klystron generates pulsed RF power from pulsed high voltage power and a waveguide RF distribution system distributes the RF power to the cavities and also protects the RF source from reflected power. A low level RF system controls the shape, amplitude and phase of the RF. Various auxiliary devices for the klystron and the modulator are also required. A control and interlock system controls each RF station and protects the linac and the station in case of malfunction.

In order to provide RF power for all cavities at an energy of 500GeV, 560 RF stations in the main linac are required. 12 additional stations will be installed in the main linac as spare stations. Another 12 RF stations are required for the injectors. For the 800GeV upgrade the number of stations of the main linac will be doubled to 1144. With the exception of the modulators high voltage power supply and pulser unit, the RF stations will be installed in the tunnel with a separation of 50m (25m for the 800GeV). The modulators high voltage power supplies and the pulsers will be installed in the access halls, which have a separation of about 5km. The connection between the pulser and pulse transformer will be accomplished by high voltage pulse power cables. There will be also additional cable connections for the interlock system between the halls and the tunnel. The number of modulators per hall will be typically 100.

4. THE 10MW MULTIBEAM KLYSTRON

For Tesla a new developed 10MW multibeam klystron was chosen as RF power source. Comparison of different types of klystrons constructed and built so far have shown that a low microperveance p of the klystron electron beam defined as $10^6 \times I/V^{3/2}$ (I=klystron beam current, V=klystron voltage) results in a high efficiency [2, 3]. This is due to lower space charge forces in the beam, which make the bunching easier and more effective. For a single beam klystron at very high output power the demand for high efficiency leads to low microperveance and hence to very high voltage resulting in a reduced reliability. The solution is to use many small low voltage, low microperveance beams in parallel in one vacuum vessel. This principle is utilized in the multibeam klystron. With a multibeam klystron an efficiency of 70% or more seems to be feasible whereas with a single beam 5MW klystron a maximum efficiency of just 45% can be reached.

Fig. 1 The multibeam klystron Thomson TH1801.

Figure 1 shows the multibeam klystron TH1801 produced by Thomson Tubes Electroniques [4]. In this klystron seven beams are produced by the cathode and accelerated by the klystron gun. Each beam has a microperveance of 0.5. The beams share common cavities but have independent drift tube sections. After RF extraction in the output cavity, the spent electron beams are absorbed in the collector. Two output waveguides are required to handle the RF power of 2 x 5MW in the output windows. The total height of the klystron is 2.5m. The multibeam klystron was successfully tested and one klystron is now in use at the TESLA Test Facility (TTF). It achieved an output power of 10MW with an efficiency of 65%. Table 1 summarizes the design parameters and the parameters achieved with the prototype test. More detailed information can be found in [5].

The gain of 48dB means that the drive power is below 160W, and solid state amplifiers can be used. They will be installed near to the klystrons inside the collider tunnel. The klystrons will be mounted in the horizontal position together with the modulators pulse transformer inside a container. The complete assembly will be moved with the tunnels monorail system to its location inside the tunnel and installed below the walk way.

Table 1
Design and measured parameters of the multibeam klystron

	Design	Measurement
Operation Frequency	1300MHz	1300MHz
RF Pulse Duration	1.5ms	1.5ms
Repetition Rate	10Hz	5Hz
Cathode Voltage	110kV	117kV
Beam Current	130A	131A
HV Pulse Duration	1.7ms	1.7ms
No. of Beams	7	7
Microperveance	3.5	3.27
No. of Cavities	6	6
RF Peak Power	10MW	10MW
RF Average Power	150kW	75kW
Efficiency	70% goal	65%
Gain	48dB	48.2dB
Solenoid Power	4kW	6kW

5. MODULATOR

The modulator converts AC line voltage to pulsed high voltage in the 120kV range to be applied to the klystron cathode. The pulse shape must be as rectangular as possible. The flat top ripple should not exceed ±0.5% in order to limit phase and amplitude variations of the klystron RF output. The rise and fall times of the pulse should be as short as possible in order to maximize the total efficiency. The pulse-to-pulse stability must be better than ±0.5%. In case of klystron gun sparking the energy deposited into the spark must be limited to a maximum of 20J. The modulator requirements are summarized in table 2.

Table 2
Modulator requirements

	Typical	Maximum
Klystron Gun Voltage	115kV	120kV
Klystron Gun Current	130A	140A
High Voltage Pulse Duration (70% to 70%)	<1.7ms	1.7ms
High Voltage Rise and Fall Time (0 to 99%)	<0.2ms	0.2ms
High Voltage Flat Top (99% to 99%)	1.37ms	1.5ms
Pulse Flatness during Flat Top	< ±0.5%	±0.5%
Pulse-to-Pulse Voltage fluctuation	< ±0.5%	±0.5%
Energy Deposit in Klystron in Case of Gun Spark	<20J	20J
Pulse Repetition Rate for 90% of the Modulators	5Hz	5Hz
Pulse Repetition Rate for 10% of the Modulators	10Hz	10Hz
Transformer Ratio	1:12	1:12
Filament Voltage	9V	11V
Filament Current	50A	60A

Various types of modulators meeting these requirements are conceivable. It turned out that a bouncer modulator consisting of a DC high voltage power supply, a pulser unit and a pulse transformer seems to be the most promising solution regarding cost and ease of the design and reliability [6].

Several modulators of the bouncer type were built and are in use at the Tesla Test Facility. A very detailed description of the modulator is given in [7, 8, 9, 10].

A modulator based on the SMES (Superconducting Magnetic Energy Storage) principle as a possible alternative will be tested at TTF. Here a superconducting solenoid is used instead of a capacitor bank for the intermediate energy storage [11].

The very elegant solution of the bouncer modulator is sketched in Figure 2

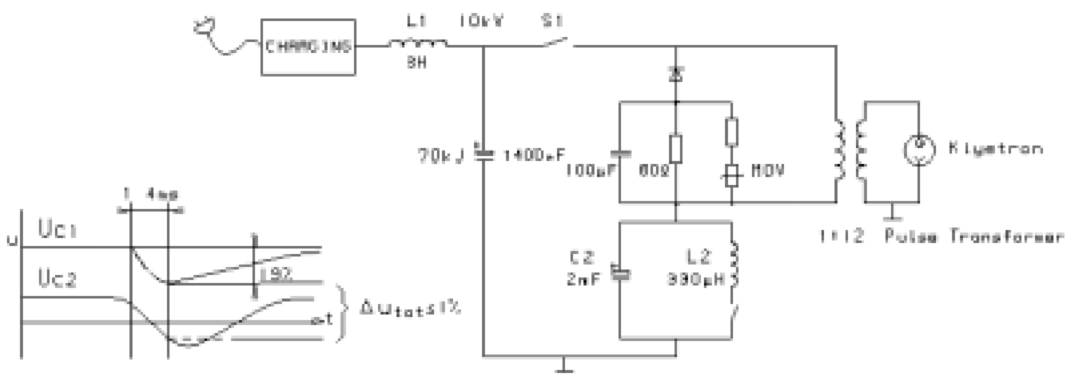

Fig. 2 Circuit diagram of the modulator (schematic).

In operation the DC power supply keeps capacitor C1 charged to the 10kV level. The output pulse is started by closing switch S1 and connecting C1 to the pulse transformer primary. Semiconductor devices like Isolated Gate Bipolar Transistors (IGBT) or Integrated Gate-Commutated Thyristors (IGCT) can be used. The pulse is terminated after 1.57ms (1.37ms flat top +0.2ms rise time) by opening S1. The nominal current switched by S1 is 1.56kA. The primary pulse of 10kV is stepped up to the klystron operating level of up to 120kV by the 1:12 pulse transformer.

During the pulse, capacitor C1 discharges by 19% of its initial voltage, putting an intolerable slope on the output pulse. To correct the slope to the 1% level without resorting to a 29mF capacitor in the C1 location, a bouncer circuit is required. This is a resonant LC circuit, which creates a single sine wave with a period of 5ms and an amplitude at the 1kV level. The bouncer is triggered slightly before the main pulse so that the linear, bipolar portion of the cycle compensates the droop during the main pulse. The size of the pulser units is 2.8m(L) x 1.6m(W) x 2.0m(H). They will be installed in the access halls, typically 100 pieces per hall.

The output pulse of the pulser unit has an amplitude of up to 10kV. Therefore it must be transformed to the 120kV level by means of a pulse transformer disturbing the rectangular pulse shape as little as possible. The rise time of the high voltage pulse is mainly determined by the pulse transformers leakage inductance, which therefore has to be as small as possible. Several transformers with leakage inductances slightly above 300µH have been built and operated at TTF. Some new transformers having even less than 200µH are now available and will be used at TTF. The voltage level of 120kV requires that the transformer will be installed in a tank filled with transformer oil. The klystron socket housing the klystron cathode will be installed in the same tank.

Although the total weight of the pulse transformer tank is 6.5t, its size of 3.2m(L) x 1.2m(W) x 1.4m(H) allows an easy installation inside the tunnel below the walk way together with the klystron. Figure 3 shows a klystron and a pulse transformer during installation in the TESLA tunnel.

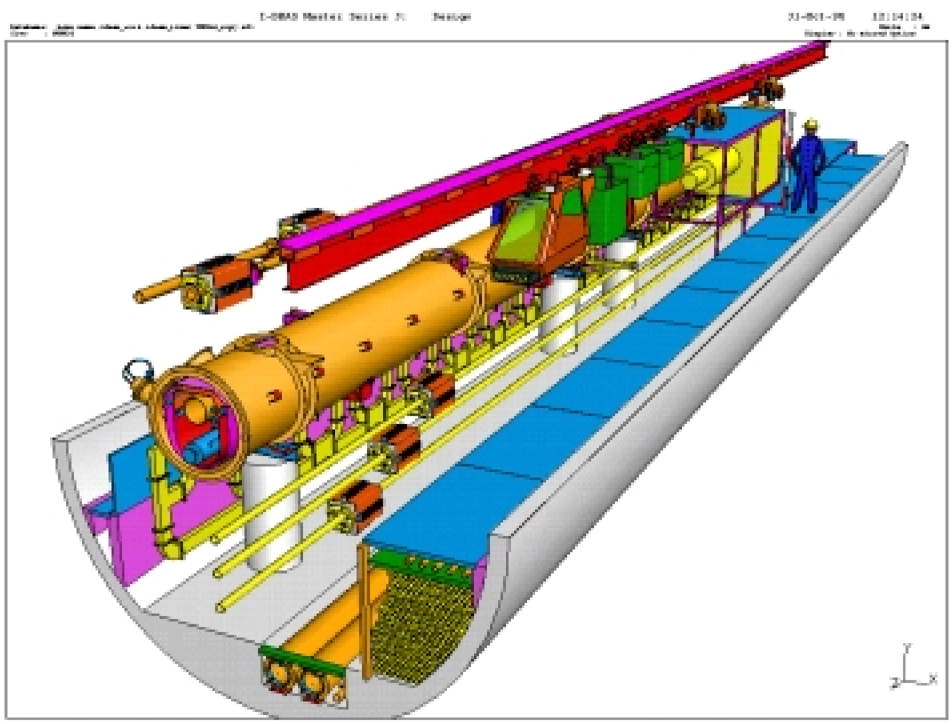

Fig. 3 Klystron and pulse transformer during installation in the TESLA tunnel

The energy transport from the modulator to the transformer will be done via pulse cables. The distance between the different service halls and the location of the pulse transformers inside the tunnel is up to 2.8km. The required cross section of the copper current lead is 300mm^2 per conductor. In order to transmit the high voltage pulse without significantly distorting the pulse shape, especially at the leading edge of the pulse, the cable impedance must be matched to the klystron impedance, and the skin effect must be minimized. Therefore four cables will be installed, each with a cross section of 75mm^2 and an outer diameter of 30mm. The cable impedance Z_0 of the four cables equals 6.45Ω. The cables are of coaxial construction to prevent electromagnetic noise, which might be generated by the cables, from spreading inside the tunnel. The inner lead is at high potential (12kV). The outer lead is at the potential of the bouncer circuit (±2kV). There is an additional shield of overall 16mm^2. As insulation material VPE will be used. Additional line matching to the pulse transformer will be done via a RC network. The power losses on the cable will be 2% on average. Simulation results and further information on the cable are given in [12].

The high voltage power supply, which charges the pulsers main capacitor, has to meet two requirements. The capacitor has to be charged to an accurate value of voltage in order to obtain the same voltage at the klystron from pulse to pulse. The low repetition frequency of 5Hz and 10Hz respectively has to be suppressed in order not to produce disturbances of the mains.

Each modulator will have a separate switch mode power supply. The input voltage will be three phase low voltage grid. The voltage output is 12kV, the nominal power of each power supply is 150kW for 5Hz and 300kW for 10Hz repetition rate respectively. The power supply is built in modules, which ensure a high reliability. As switch mode units buck converters will be used. Series resonant converters are a possible alternative.

The power supply regulation is a digital self-learning regulation of the input power, made possible by the high regulation dynamic of the switch mode supply. In addition the voltage at the capacitor bank at the firing time of the pulse will be regulated within 0.5% accuracy.

The size of a high voltage power supply is 1.2m(L) x 1.6m(W) x 2.0m(H). Further information about the power supplies can be found in [13].

In addition to the main high voltage power supply auxiliary power supplies are required for the operation of the klystron and the modulator. These are a power supply for the klystrons focusing solenoid, a power supply for the klystron filament, vacuum pump power supplies for the klystron and a core bias power supply for the pulse transformer. Since the klystron will be installed together with the pulse transformer in the collider tunnel, the auxiliary power supplies will be installed together in a rack near to the klystron below the walk way in the tunnel.

6. EFFICIENCY AND POWER REQUIREMENTS

The klystrons must deliver a RF power of 9.7MW when required. This takes into account the regulation reserve of 10% for phase and amplitude control and 6% for losses in the waveguide distribution. To allow for the regulation, the klystron must be run slightly below saturation, and the efficiency drops from the design (saturation) value of 70% by a few percent. Taking this into account, we assume a klystron efficiency of 65%; a corresponding klystron voltage of 117kV is then required. The high voltage pulse of the modulator meets this requirement during the flat top but not during the rise and fall times. The pulse rise time is of the order of 200µs, however the average rise time of the HV pulse at the klystrons will be above 200µs because of the long cables between the pulse forming units in the service buildings and the pulse transformer-klystron units in the tunnel.

Since the first 420µs of the RF pulse will only be used to fill the superconducting cavities with RF power the RF pulse can be started already during the rise time of the high voltage pulse. Although the klystron RF output power during the rise time will be lower than during the flat top it can already be used to fill the cavities. When the klystron voltage reaches 80% of the flat top voltage, ca. 100µs after the beginning of the high voltage pulse, the RF pulse can already be started. The klystron output power at this voltage is about 4MW. As a result of the changing klystron voltage the RF phase shifts by ca. 320^{o} until the flattop is reached. This phase shift can be compensated by the low level RF.

With this method the rise time efficiency of the modulator, defined as the ratio of the energy per high voltage pulse used for RF generation to the total energy per high voltage pulse, can be increased to 96%. The electronic efficiency of the modulator is 90%. We also take into account ohmic losses of 2% in the pulse cables. This results in a total modulator efficiency of 85%.

In order to generate 9.7MW in a 1.37ms long RF pulse at 5Hz repetition rate an average AC power from the wall plug of 120kW per RF station is required. In addition 14kW for the auxiliary power supplies must be added. The total average AC power required for 560 active RF stations is therefore 75MW. Table 3 summarizes the power requirements for RF generation in the main linac. For FEL operation 6.7MW AC power must be added to these numbers.

Table 3
Efficiency and power requirements of the RF system

RF peak power per RF station	9.7MW
Duty cycle	0.685%
Average RF power available per RF station	66kW
Klystron efficiency	65%
Modulator efficiency	85%
Total efficiency	55%
AC power per RF station	120kW
Auxiliary power per RF station incl. LLRF and waveguide tuner	14kW
Total wall plug power per station	134kW
Number of active stations	560
Total wall plug power	75MW

7. MODULATOR AND KLYSTRON PROTECTION AND CONTROL

For the reliable and save operation of the RF system a comprehensive interlock system is necessary. In the event of a klystron gun spark the energy deposited in the spark must be kept below 20J to avoid damage of the klystron gun. The response to a spark will be an immediate opening of the concerned IG(B)CT switch to disconnect the capacitor bank from the sparking klystron. The energy stored in the transformer leakage inductance and in the power transmission cable is dissipated in two networks, one at the cable end near the IG(B)CT consisting essentially of a reverse diode and a resistor. The second one is made up by an 80Ω resistor across the transformer primary and by a 100μF capacitor which limits the peak inverse voltage at the primary to 800V when the IG(B)CT is opened. In addition a crowbar is fired. Other important interlocks are control of cooling water flow and temperature, of the focusing solenoid current, and a vacuum interlock. Other interlock conditions result from sparks in the RF distribution system, reflected power, RF leaks, power couplers and from cryogenics.

In order to meet the different safety requirements, different interlock techniques will be used. The interlock, which inhibits RF operation during tunnel access, is accomplished by a hard-wired system. This will be made by two separate and independent systems, which switch off the klystron RF drive power and the modulators high voltage power supply.

The technical interlock, which protects the linac and the RF station in case of malfunction, will be realized with programmable logic controller (PLC) and system-on-programmable-chip (SOPC) techniques. Today these systems are industrial standard techniques. Therefore knowledge in planning, structure and programming is well known. Hardware for almost all applications is available from different manufactures.

Besides system protection and providing start up and shut down procedures for the RF stations, the control and interlock system will offer a comprehensive diagnostics of the RF systems. It will allow to measure and to diagnose actual parameters as well as to adjust set points within certain limits for each RF station and its subsystems and to react to different fault conditions in a flexible manner. Communication with the accelerators main control will be accomplished by VME bus.

The interlock system will be divided in two units, one installed in an electronic rack in the tunnel near to the klystron and another installed near to the pulser and the high voltage power supply unit in the access hall. Connection and communication between these two units are accomplished by glass fiber cables, which allows fast transfer of the interlock signals. The interlocks of each unit are summarized into categories. Only these sum interlocks will be exchanged between the units and therefore the number of fibers connecting both units is limited to ten. Each unit is connected via its own VME bus to main control.

8. RF WAVEGUIDE DISTRIBUTION SYSTEM

The 10MW multibeam klystron has two RF output windows and has to supply thirty-six 9-cell cavities, which are installed in three modules. Therefore the RF distribution is based on two symmetrical systems, each supplying eighteen cavities. For the RF distribution a linear system branching off identical amounts of power for each cavity from a single line by means of directional couplers will be used. It matches the linear tunnel geometry best and leads to lower waveguide losses than a tree-like distribution system, because long parallel waveguide lines can be avoided. Such a system is already in use for the HERA superconducting RF system and has also been successfully tested in TTF.

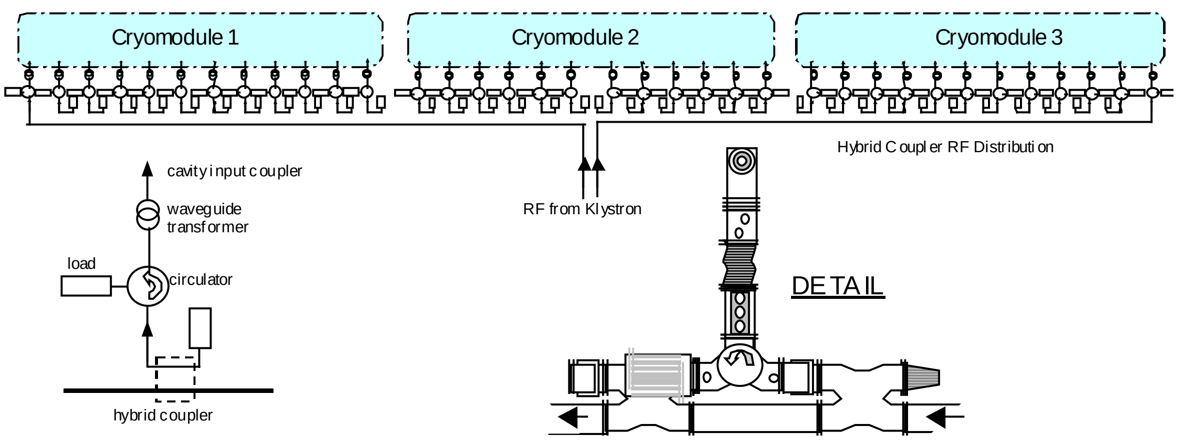

Fig. 4 RF waveguide distribution of one RF station

Circulators are indispensable. They have to protect the klystron against reflected power at the start of the RF pulse during filling time of the cavity and at the end of the pulse. In conjunction with load resistors and the power input coupler, they define the loaded cavity impedance as seen by the beam.

Only 4% of the average power generated by one klystron will be lost in the waveguides, additional 2% in the circulators. Thermal expansion will result in a RF phase shift of 6^o and 12^o for operation at full power and pulse duration at 5Hz and 10Hz respectively. This can be compensated easily by the waveguide transformers (three-stub waveguide transformer) installed between the circulators and each cavity. The waveguide transformers provide an impedance matching range from $1/3Z_W$ to $3.0Z_W$ and the possibility of $\pm 50^o$ phase adjustment. Each stub will be equipped with a motor, which will be controlled by the low level RF system.

The RF distribution system will be equipped with several interlock sensors, for instance for reflected power, sparking and RF leakage. Similar systems meeting these demands are in use at TTF. Additional information on the design criteria of the waveguide distribution system can be found in [14].

9. LOW LEVEL RF

The low level RF system controls amplitude and phase in the superconducting cavities of the linac. Fluctuations must be kept small in order to keep the energy spread below a maximum tolerable level of $5x10^{-4}$. The main source for perturbations are fluctuations of the beam current and fluctuations of the cavity resonance frequency due to mechanical vibrations and due to Lorentz force detuning. The amplitude and phase errors to be controlled are of the order of 5% and 20^o respectively as a result of the Lorentz force detuning and mechanical vibrations. These errors must be suppressed by a factor of at least 10. Long term variations (on the timescale minutes or longer) are counteracted by the use of cavity frequency tuners while fast variations are counteracted by a fast amplitude and phase modulation of the incident RF power. Since most of theses perturbations are of a repetitive nature, a fast feed forward system can be used. For non-repetitive pulse-to-pulse and intra-pulse variations a feed back system is required. The RF modulator for the incident wave is designed as an I/Q modulator to control the in-phase (I) and quadrature (Q) component of the cavity field. Each RF station has one RF modulator. Therefore only the vector sum of thirty-six cavities can be controlled. More detailed information of the LLRF system can be found in [15, 16, 17, 18, 19].

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CTF3 - A DEMONSTRATION OF THE CLIC RF POWER SOURCE

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Abstract
The CLIC (Compact Linear Collider) RF power source is based on a new scheme of electron pulse compression and bunch frequency multiplication. In such a scheme, the drive beam time structure is obtained by the combination of electron bunch trains in isochronous rings. The next CLIC Test Facility (CTF3) at CERN will be built in order to demonstrate the technical feasibility of the scheme. It will also constitute a 30 GHz RF source with CLIC's nominal peak power and pulse length, which can be used to test accelerating structures and other RF components. CTF3 will be installed in the area of the present LEP pre-injector complex and its construction and commissioning will proceed in stages over five years. In this paper we present an overview of the facility and provide a description of the different components.

1. INTRODUCTION

The CLIC design of an e^+e^- linear collider aims at a centre of mass energy in the multi-TeV range. In order to demonstrate the feasibility of such a collider, a number of key issues must be addressed and, whenever possible, experimentally proven. Some of these issues are common to any multi-TeV collider (like the generation and preservation of small-emittance beams, final focus and collimation problems and detector performance in a high beamstrahlung regime), while others are specific to the technology chosen for CLIC.

The new test facility CTF3 has been proposed in order to test mainly the issues specific to CLIC, namely acceleration with high gradients (150 MV/m) in high-frequency (30 GHz) normal-conducting structures, and the use of a two-beam acceleration scheme to generate the RF power. The requested power is 240 MW per metre of linac length, with a pulse length of 140 ns. A very efficient and reliable RF source is required in a frequency region above the range of conventional sources, like klystrons. The proposed scheme is based on a high-current drive beam, with relatively low energy, running parallel to the high-energy main beam. The drive beam time structure carries a strong 30 GHz component and RF power is extracted from it periodically in Power Extraction and Transfer Structures (PETS) and transferred to the main beam.

A novel scheme has been proposed in order to generate, transport and make efficient use of the drive beam [1]. A long electron bunch train with low bunch repetition frequency is initially accelerated using cavities with low RF frequency, for which commercial sources are available. Efficiency is of utmost importance for CLIC, therefore the drive beam is accelerated in fully-loaded cavities, such that the RF power is fully converted into beam energy. The drive beam bunches are then interleaved by injection in isochronous rings with transverse RF deflectors, thereby increasing the bunch repetition frequency and shortening the bunch train. Schematically, the drive beam can be thought of as an intermediate energy-storage device, converting long RF pulses of low frequency to short RF pulses of high frequency and higher peak power. The process is analogous to "standard" RF pulse compression or delay distribution systems, with the advantage that high compression ratios can be achieved with very low losses, and RF frequency multiplication becomes possible.

The main goal of CTF3 is to demonstrate the technical feasibility of the key concepts of the new RF power generation scheme, that is the generation of high-charge, high-frequency electron bunch trains by beam combination in a ring using transverse RF deflectors and operation with a fully-loaded drive-beam accelerator. CTF3 will also be used to test the CLIC critical components and in particular will provide the 30 GHz RF power at the nominal peak power and pulse length such that all 30 GHz components for CLIC can be tested at nominal parameters.

2. CTF3 DESCRIPTION

The project is based in the PS Division of CERN with collaboration from other Divisions, as well as from INFN-Frascati, IN2P3/LAL at Orsay, and SLAC. The facility will be built in the existing LPI (LEP Pre Injector) complex and will make maximum use of equipment available following the end of LEP operation. In particular, the existing 3 GHz RF power plant from the LEP injector Linac (LIL) and most of the LPI magnets will be used.

CTF3 will be built in stages over five years. The new accelerating cavities with very strong damping of the transverse Higher Order Modes (HOMs), required in order to ensure the transverse stability of the high current drive beam, will not be available before 2003. Therefore, it is planned to perform at first a low-current test of the scheme, using the present accelerating structures from LIL (CTF3 Preliminary Phase). A new 80 keV electron gun, necessary to get the right time structure for this experiment, was designed and constructed at LAL/Orsay. The experimental programme of this phase will start in autumn 2001, with the goal to demonstrate the funneling injection scheme and bunch train compression in an isochronous lattice. Since the beam current will be limited, the 30 GHz RF power production and the study of collective effects will only be possible in later phases.

As the new hardware becomes available, it will be installed in the LPI complex. A second stage (CTF3 Initial Phase), using the new linac, will allow a test of fully-loaded acceleration and will have a limited power production capability. The final configuration of CTF3 will be reached in the third stage (CTF3 Nominal Phase). A layout of the facility in its final configuration is shown in Figure 1.

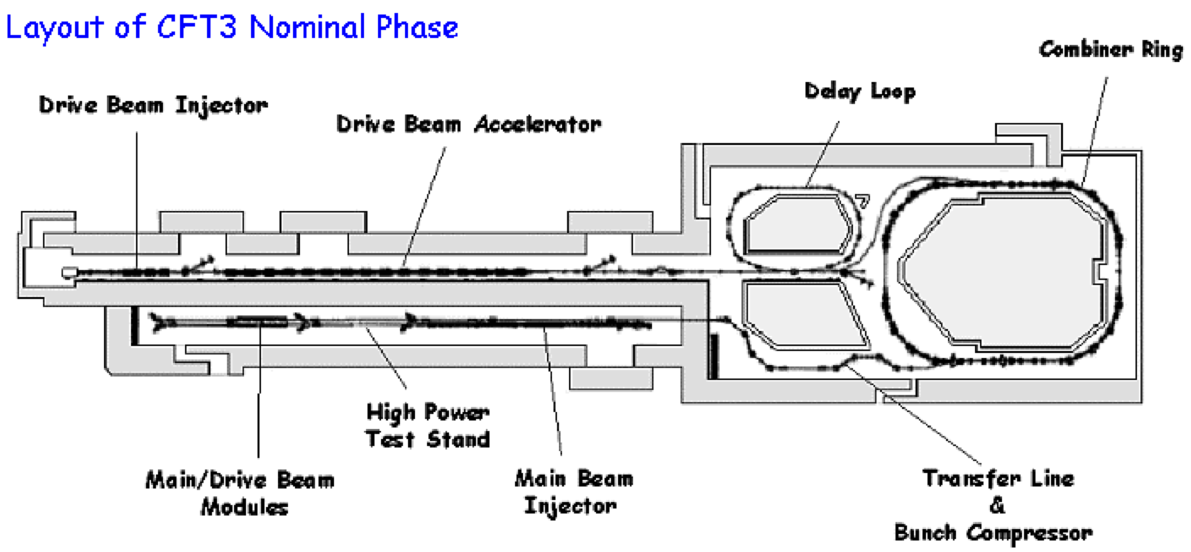

Fig. 1 Layout of the final configuration of CTF3 (nominal phase).

2.1 Drive Beam Injector

The drive beam injector [2] is to be built in collaboration with LAL/Orsay and SLAC. SLAC provides the gun triode and the beam dynamics design and LAL provides the gun electronics circuitry and the 3 GHz pre-bunchers. The 1.6 µs long drive beam pulse is generated by a 140 kV, 9 A thermionic triode gun. The time structure of the pulse is obtained in a bunching system composed of a set of 1.5 GHz sub-harmonic bunchers, a 3 GHz pre-buncher and a 3 GHz graded-β travelling-wave buncher. The phase of the sub-harmonic bunching cavities is switched rapidly by 180° every 140 ns, as needed for the phase-coding operation described in [3]. In order to obtain a fast enough phase switching time (• 4 ns), the RF power source for the sub-harmonic bunching system must have a relatively broad bandwidth (about 10 %), centered at 1.5 GHz, and a peak power level of up to 500 kW. The results of a feasibility study of a broadband klystron that satisfies these requirements are presented elsewhere at this conference [4].

The bunches thus obtained are spaced at 20 cm (two 3 GHz buckets) and have a charge of 2.3 nC per bunch, corresponding to an average current of 3.5 A. As a result of the phase switch of the sub-harmonic bunchers, the drive beam pulse is composed of 140 ns sub-pulses, which are phase-coded and can be separated by transverse RF deflectors working at 1.5 GHz.

The drive beam injector is completed by two 3 GHz fully-loaded travelling-wave structures (see Section 2.2), bringing the beam energy up to 24 MeV. Solenoidal focusing with a maximum on-axis field of 0.2 T is used all along the injector. A magnetic chicane with collimators downstream of the injector will be used to eliminate low-energy beam tails produced during the bunching process. The chicane region will also be instrumented to perform emittance and energy spectrum measurements on the drive beam.

An alternative option to the thermionic injector scheme described above, based on the use of an RF photo-injector, is also under study as a potential later upgrade for CTF3. The advantages of such a solution are smaller emittances in all of the three phase space planes, absence of low-charge parasite bunches in every second 3 GHz bucket, and easier tailoring of the 180° phase switching. A feasibility study was made by RAL/UK on the laser needed for such a scheme, with promising results [5], and experimental tests are also underway at RAL. The feasibility of photo-cathodes with the required performance in terms of average current has recently been experimentally demonstrated at CERN [6]. The injector layout is shown in Figure 2.

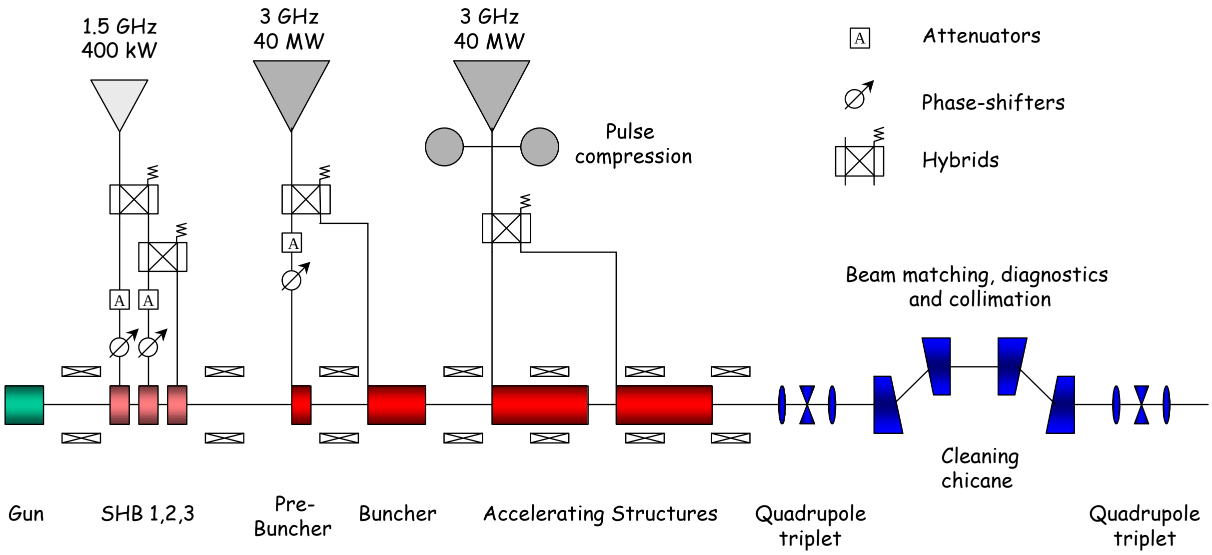

Fig. 2 Layout of the injector for the nominal phase of CTF3. The klystrons and the RF network are shown.

2.2 Drive Beam Accelerator

The drive beam is brought to its final energy (180 MeV) in the drive beam accelerator, composed of 8 modules of 4.5 m length. Each module consists of two travelling-wave accelerating structures, identical to the ones used in the injector, a beam position monitor, a quadrupole triplet and a pair of steering magnets. Beam simulations have shown that the use of triplets provides good transverse beam stability during acceleration despite the high beam current, providing that HOMs are suppressed [7].

The requirements of fully-loaded operation with a beam current of 3.5 A have lead to a $2\pi/3$ mode travelling-wave structure design with about 100 ns filling time. The structures have an active length of 1.13 m and operate at a loaded gradient (at nominal beam current) of about 8 MV/m, with an RF-to-beam efficiency of 97 %. For effective suppression of the transverse HOMs, two different structure designs have been developed. The first is derived from the 30 GHz Tapered Damped Structure (TDS) of the CLIC main beam [8], using four waveguides with wide-band SiC loads in each accelerating cell. The waveguides act as a high-pass band filter, since their cut-off frequency is above the fundamental frequency but below the HOM frequency span. The *Q*-value of the first dipole mode is thus reduced to about 18. A further reduction of the long-range wake-fields is achieved by a spread of the HOM frequencies along the structure, obtained by varying the aperture from 34 mm to 26.6 mm. A full prototype of this structure has been built and power-tested up to 40 MW (see Figure 3). The second approach (called SICA, for Slotted Iris Constant Aperture) uses four radial slots in the iris to couple the HOMs to SiC RF loads (see Figure 3). The selection of the modes coupled to the loads is not made by frequency discrimination, but through the field distribution of the modes, therefore all dipole modes are damped. The *Q*-value of the first dipole mode is reduced to about 5. Also in this case, a frequency spread of the HOMs is introduced in the structure, by nose-cones of variable geometry. The aperture can therefore be kept constant at 34 mm, so that a smaller amplitude of the short-range wake-fields is obtained. A prototype is under construction. The RF power is supplied by eight 30 MW klystrons and compressed by a factor 2 to give a peak power at each structure input of about 30 MW. The pulse compression system uses a programmed phase ramp to get an almost rectangular RF pulse. A very good amplitude and phase stability on the RF pulse flat top is required to minimize the energy spread along the drive beam pulse. Also in this case, two approaches for the RF pulse compression system are possible, based on pairs of high-*Q* resonant cavities, as in the present system used in LIL [9], or on single barrel open cavities. Both approaches are described in detail elsewhere in this conference [10].

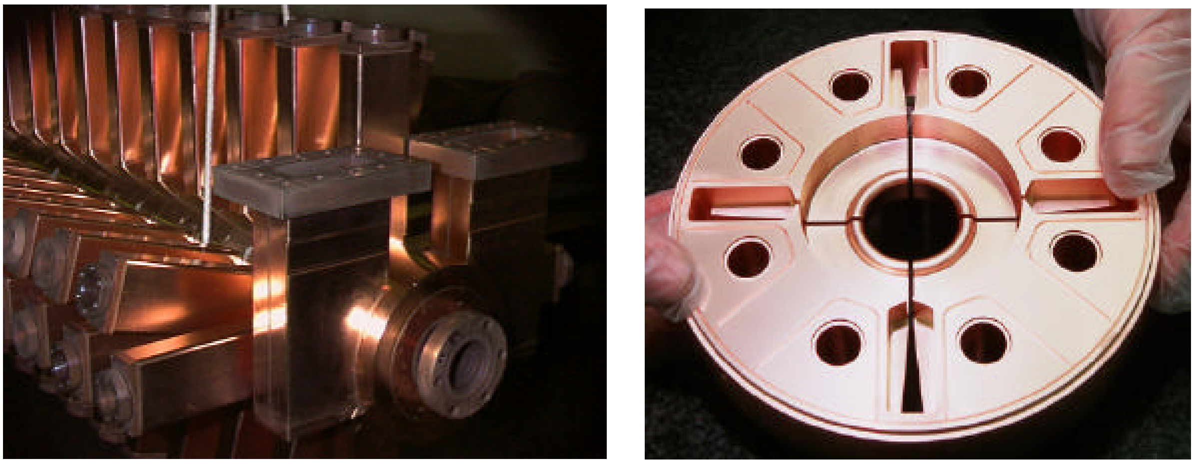

Fig. 3 Prototype of the TDS-type drive beam accelerator structure (left) and a prototype cell for the SICA drive beam accelerator structure (right). Notice the waveguide dampers sticking out of the TDS structure and the nose cones and radial slots used for damping in the SICA cell.

2.3 Delay Loop and Combiner Ring

After the linac, a first stage of electron pulse compression and bunch frequency multiplication of the drive beam is obtained, using a transverse RF deflector at 1.5 GHz and a 42 m delay loop. The phase coded sub-pulses are first separated and then recombined by the deflector after every second one has been delayed in the loop. The process is illustrated in Figure 4.

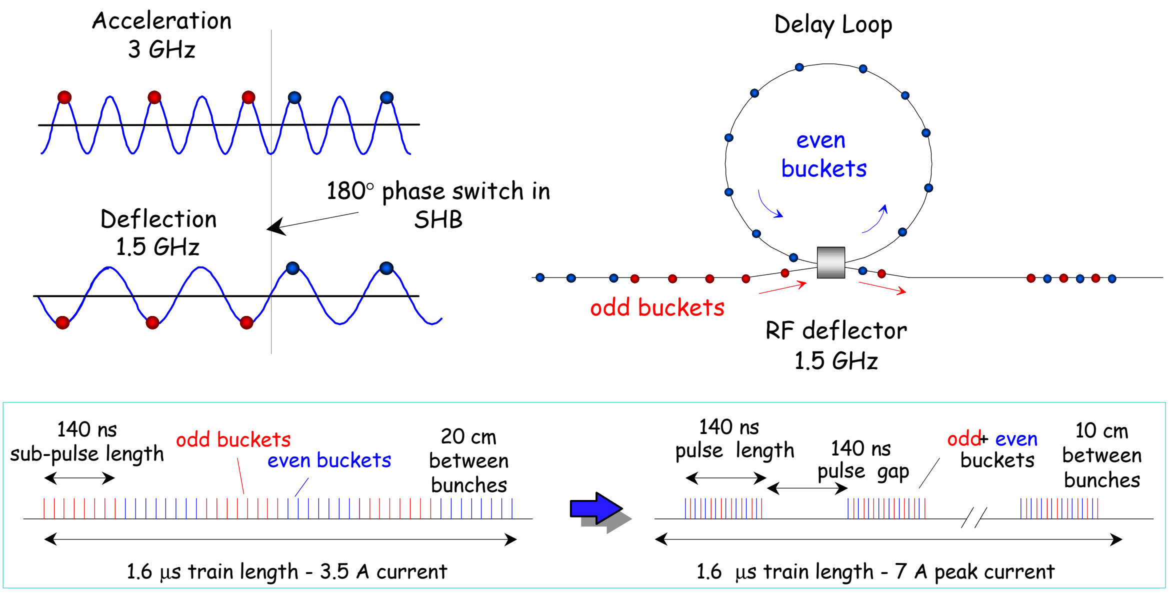

Fig. 4 Schematic description of the pulse compression and frequency multiplication process using a delay loop and a transverse RF deflector. The “odd” and “even” bunches are kicked in opposite directions by the RF deflector. When the “even” bunches come back after being delayed, they are kicked by the deflector onto the same trajectory as the “odd” ones. Note that, in reality,

the phase switch in the sub-harmonic buncher takes place over a few bunches rather than between two bunches as depicted above for illustration purposes. The time structure of the drive beam pulse before and after the delay loop is also shown.

An 84 m long combiner ring is used for a further stage of pulse compression and frequency multiplication by a factor five. After the combiner ring, the drive beam pulse is 140 ns long and has a current of 35 A. The 2.3 nC bunches are spaced at 2 cm. A schematic representation of the injection process using a pair of transverse deflectors at 3 GHz is shown in Figure 5. The delay line and the ring must both be isochronous in order to preserve the bunch length.

The design of the delay loop, the combiner ring and the related beam lines is made by INFN/Frascati [11]. Isochronous magnetic lattices, with second-order correction of the momentum compaction by sextupoles, have been developed for both the delay loop and the ring. The ring consists of four isochronous arcs, two short sections and two opposite long straight sections for injection and extraction. The ring arcs are triple-bend achromats, with negative dispersion in the central dipole. Wiggler magnets are used to adjust the circumference precisely to a (N+1/5)-multiple of the bunch spacing. Prototypes of these wigglers are under construction. A potential problem of the combination process with high bunch charge is the multi-bunch beam loading on the fundamental mode of the deflecting cavities. Studies have shown that the beam stability can be maintained by a proper choice of the deflectors and the ring parameters [12]. The short bunch length and the high bunch charge put stringent requirements on the ring impedance and make coherent synchrotron emission a serious issue. The main effects are beam energy loss and energy spread increase. In order to minimize these effects, the rms bunch length can be increased from its value of 1.3 mm in the linac to a maximum of 2.5 mm in the delay loop and ring, by a magnetic chicane placed at the end of the linac. After combination, the individual bunches are then compressed to about 0.5 mm rms in a magnetic bunch compressor. The drive beam pulse is then transported to the 30 GHz region, where is used to generate RF power.

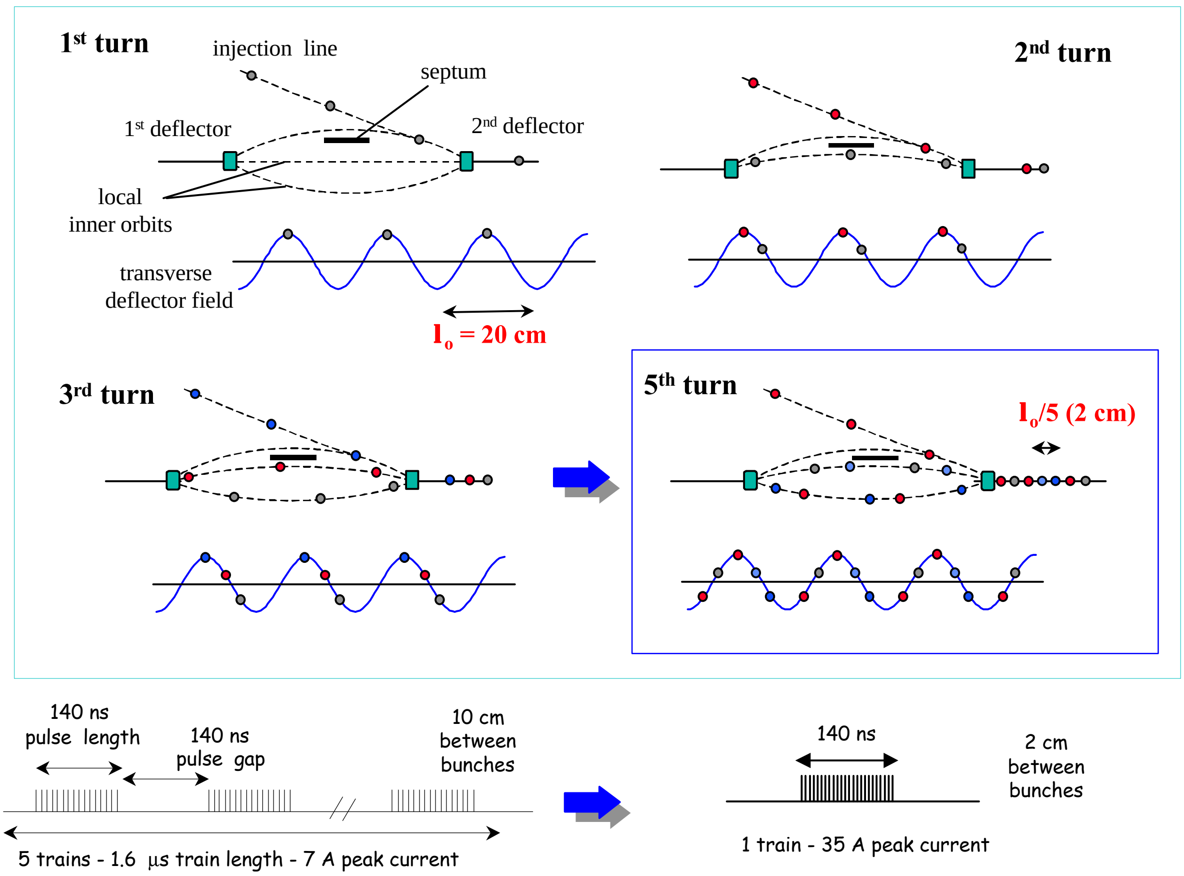

Fig. 5 Schematic description of the pulse compression and frequency multiplication by RF injection in a combiner ring. The two deflectors create a time-dependent local bump of the closed orbit in the injection region. 1) When the first train arrives, all of its bunches are deflected by the second deflector onto the equilibrium orbit. 2) After one turn the bunches of the first train arrive in the deflectors close to the zero-crossing of the RF field, and stay near the central orbit. The second train is injected into the ring. 3) The bunches of the first train are kicked on an inner trajectory, the second train bunches stay inside the septum, and the third

train is injected. The process is repeated twice more. The five trains are now combined into a single one and the initial bunch spacing is reduced by a factor five. The RF period is now full, and the train must be extracted on the other side of the ring; if not, the bunches will start hitting the septum on the next turn

2.4 Main Beam and 30 GHz Test Area

A single 30 GHz decelerating structure, optimized for maximum power production, will be used in a high-power test stand, where CLIC prototype accelerating structures and waveguide components can be tested at nominal power and beyond. Alternatively, the drive beam can be used in a string of PETS to power a representative section of the CLIC main linac and to accelerate a probe beam. The probe beam is generated in a 3 GHz RF photo-injector and pre-accelerated to 150 MeV using standard 3 Ghz accelerating structures recuperated from LIL. It can be further accelerated to about 500 MeV in the 30 GHz CLIC accelerating structures powered by the drive beam, operated at a maximum gradient of 150 MV/m. This set-up will allow to simulate realistic operating conditions for the main building blocks of the CLIC linac.

3. SUMMARY

In this paper we have described the new CLIC Test Facility (CTF3), under construction at CERN. CTF3 will be built in stages over the years 2001 - 2005. Its main goal is the demonstration of the new CLIC RF power source concept, namely the acceleration of a long-pulse, high-current electron beam (1.6 μs, 3.5 A) in a fully-loaded linac, and its compression and bunch frequency multiplication by a factor 10 using transverse RF deflectors and rings. The power source concept can be described as analogous to RF pulse compression in a delay line distribution system (DLDS) in which the energy is temporarily stored in an electron beam, with the fundamental difference that frequency multiplication and high compression ratios with low losses become possible. The resulting drive beam pulse (140 ns, 35 A) will be used to generate 30 GHz RF power, with the nominal CLIC parameters, in resonant power extraction and transfer structures. The power will be used to test CLIC 30 GHz accelerating cavities and waveguide components at full power and pulse length.

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RF Pulse Compression system for CTF3.

I.Syratchev, CERN

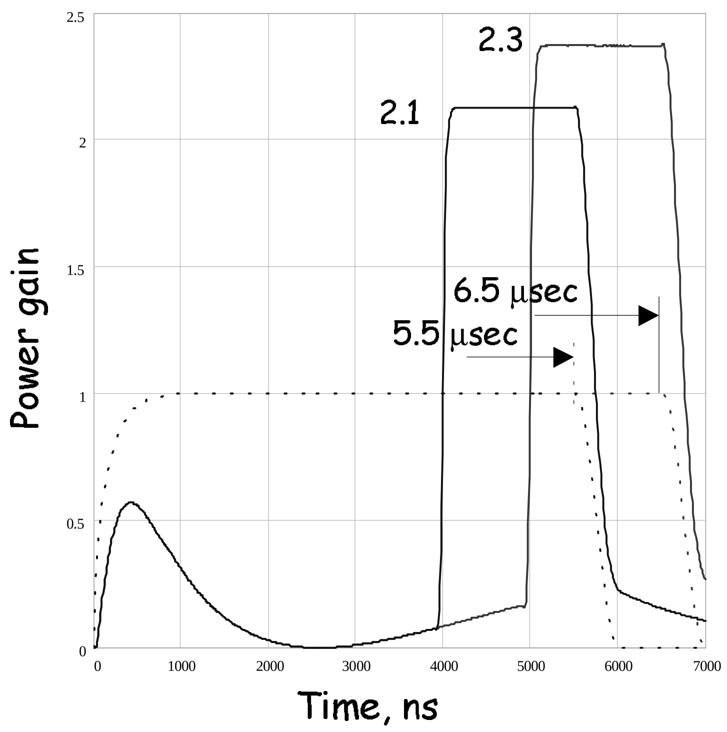
- RF Pulse Compression is the only way to increase RF power level from the number of klystrons available for CTF#3.

- RF phase/amplitude modulation is the tool to control the RF pulse shape in a system - klystron plus "SLED"-like RF pulse compressor.

RF Pulse Compression system for CTF3.

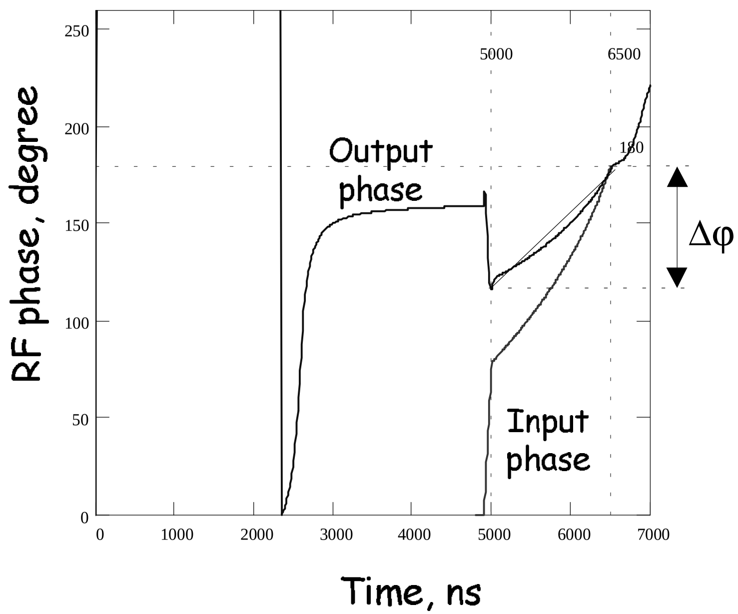
The flat pulse after the cavity based pulse compressor (LIPS), with modulation of the input RF phase (PM).

LIPS cavity $Q_0 = 1.8 \times 10^5$, $\beta = 8$



The linear part of the phase slop will be compensated with the frequency shift:

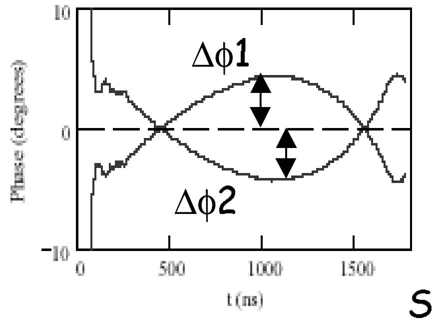
$\pm\Delta\omega T_{out} = \pm\Delta\varphi$



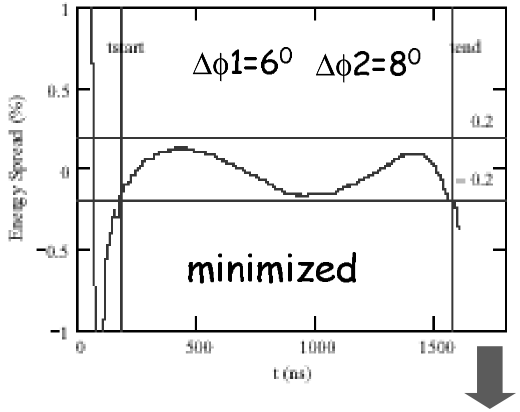
RF Pulse Compression system for CTF3.

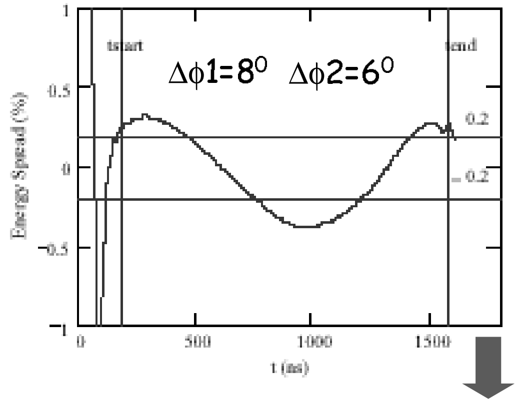
The effect of residual RF phase sage and energy spread. R. Corsini

The residual phase envelops after two RF stations

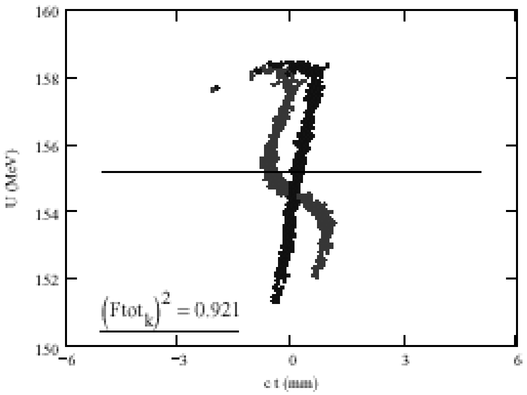


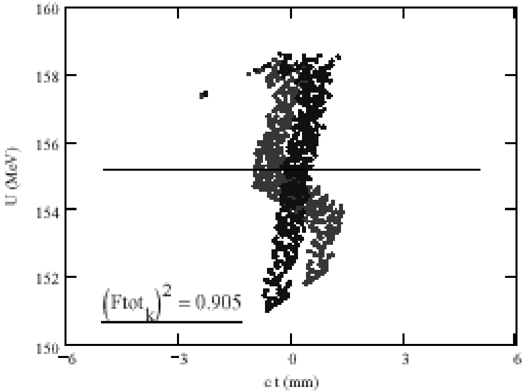
Energy spread

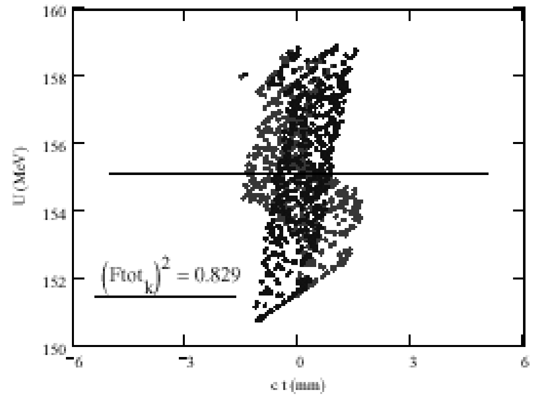




Single bunches profiles after re-combination.



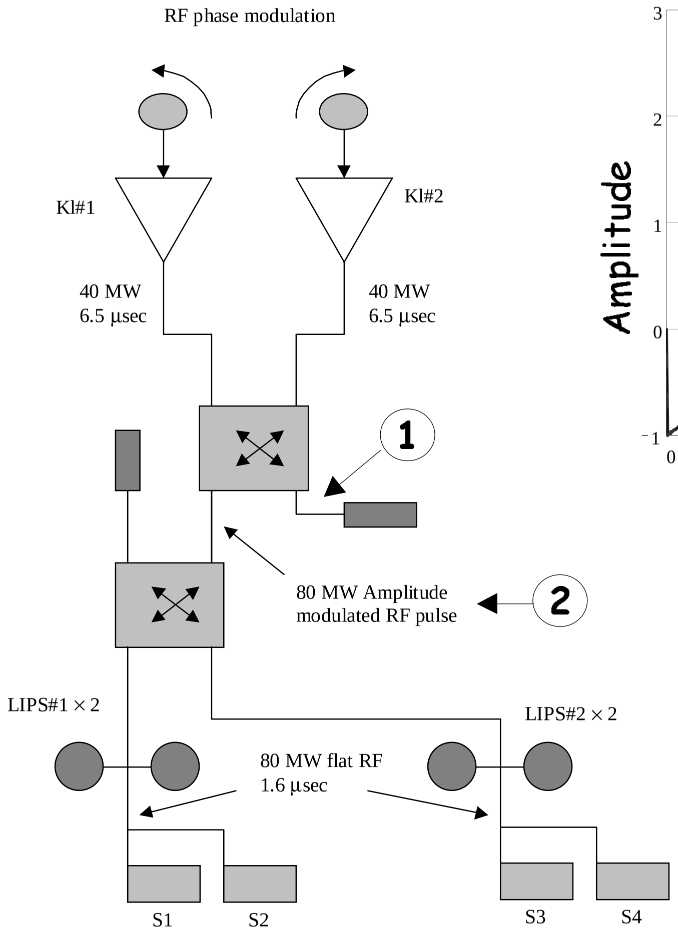


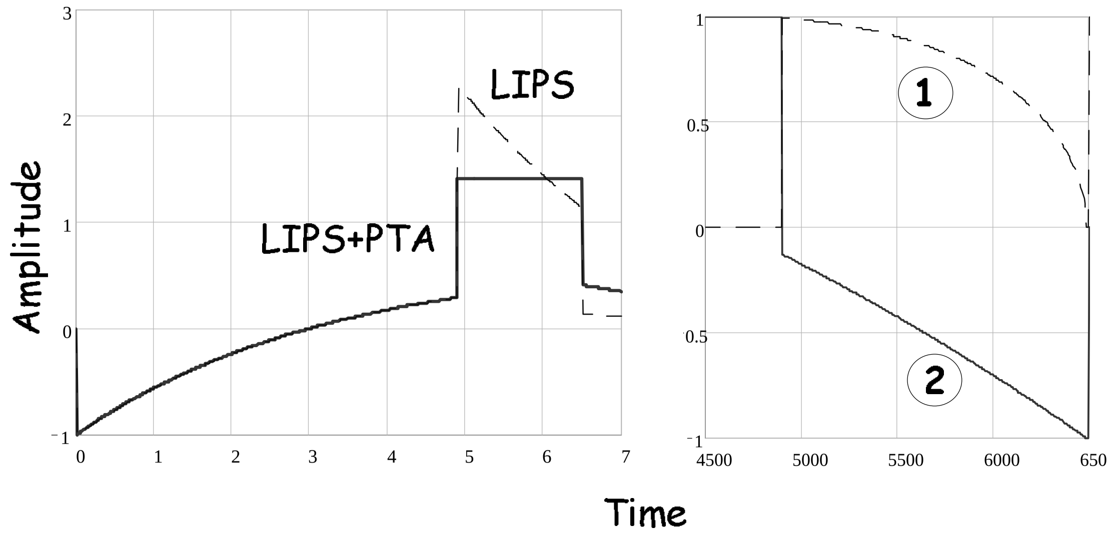


No energy spread

RF Pulse Compression system for CTF3.

The flat pulse after the cavity based pulse compressor (LIPS), with modulation of the input RF phase-to-amplitude (PTA).





Comparison between PTA and PM

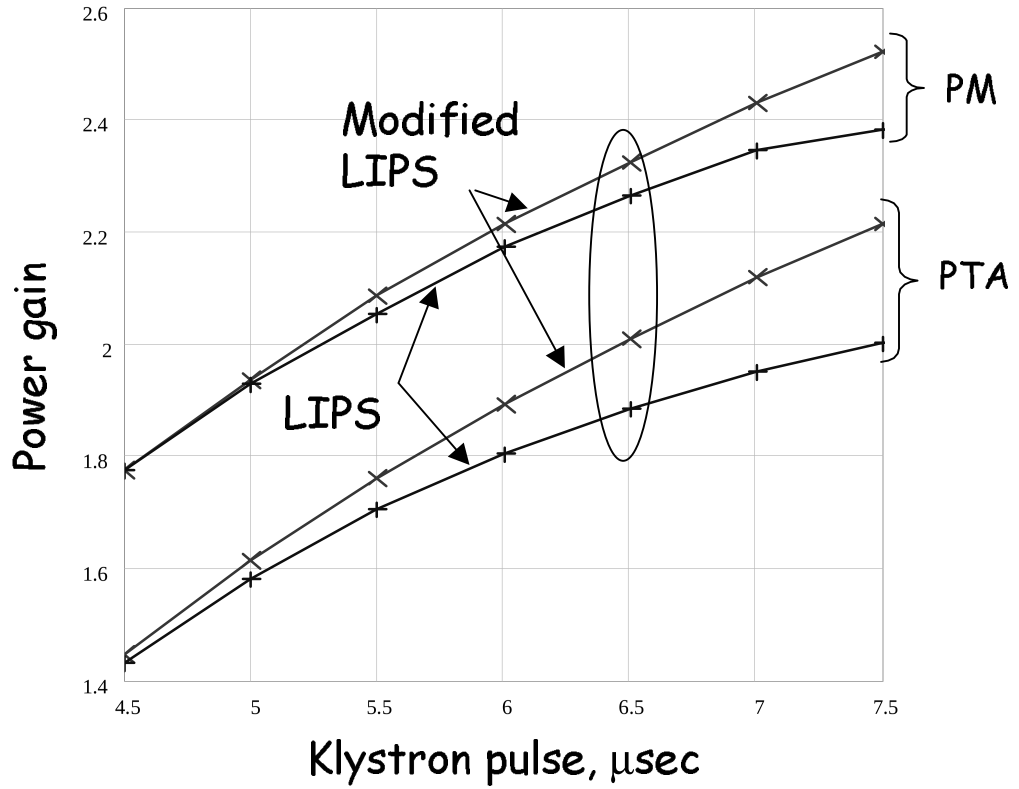
Pros:

- Output pulse flat both in RF amplitude and phase.
- Easy RF power level control.
- Better stability of operation.

Cons:

- Less efficient (~10%).
- Two klystrons needed.

Power gain.



LIPS modification is mainly the adjusting of the cavity coupling.

RF Pulse Compression system for CTF3.

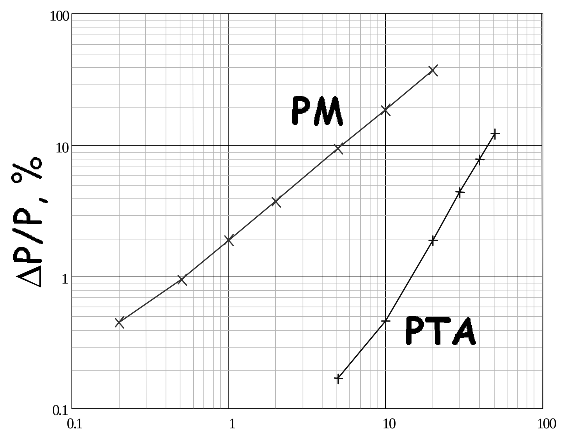
System operation stability.

Because of the energy spread, the demand on the compressed pulse flatness :

$\Delta P/P < 2\%$

The main sources of instability:

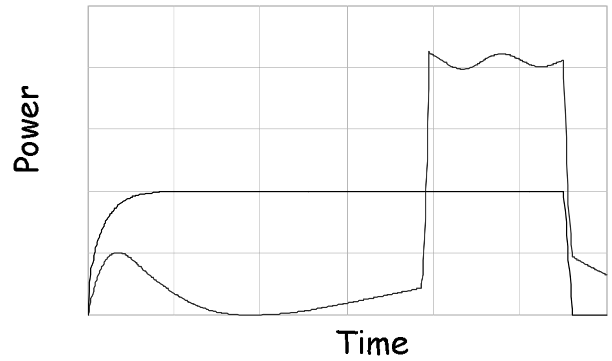
1 Klystron RF phase and amplitude jitter as result of HV supply instability.



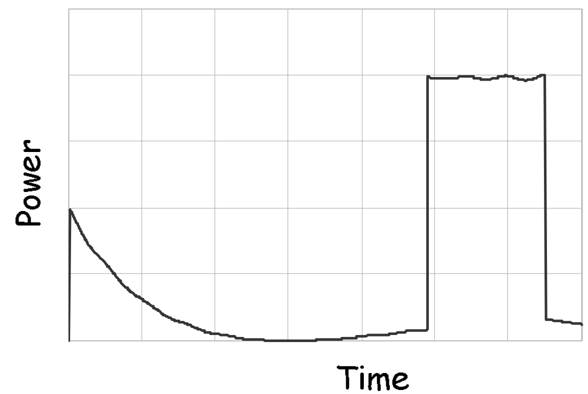
Klystron's RF phase amplitude of ripples, degree.

The examples of the compressed RF pulse distortion due to the klystron RF phase ripples.

a) RF Phase modulation. Klystron RF phase ripples 3^0 peak-to-peak.



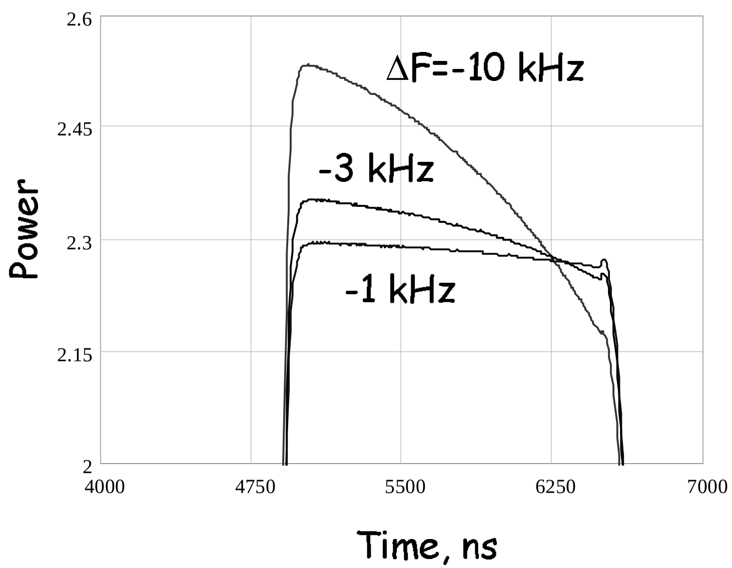
b) RF Phase-to-amplitude modulation. Klystron RF phase ripples 10^0 peak-to-peak.

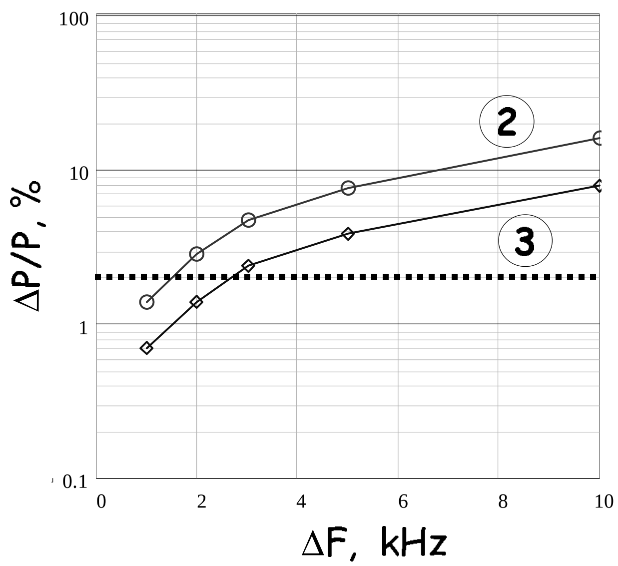


System operation stability.

(2) The frequency deviation of the storage cavity, mainly because of the temperature variation.

(3) The identity of the LIPS cavities resonant frequencies.



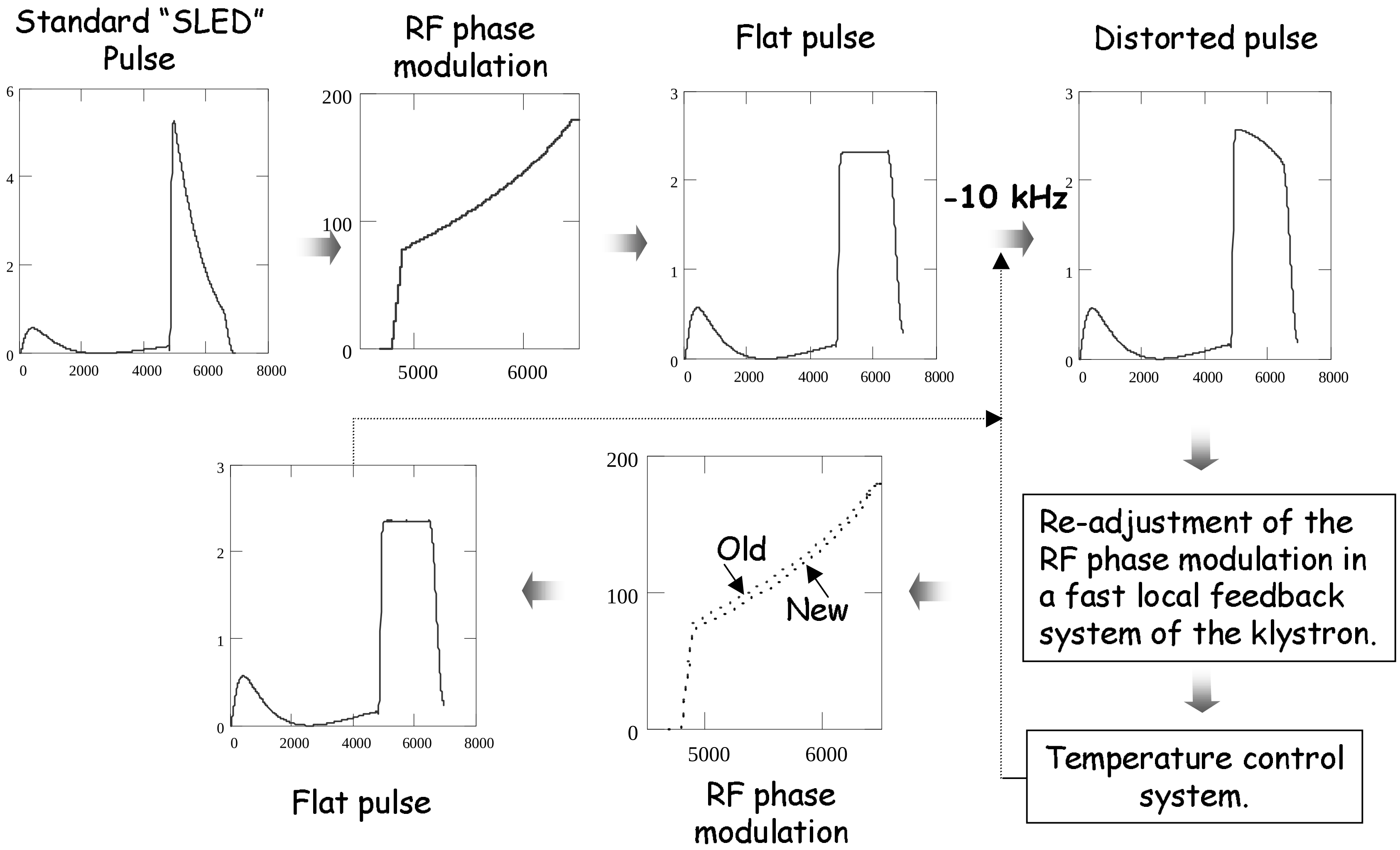


To keep the flatness of the compressed pulse within specified $\Delta P/P$, the temperature stabilization of the cavity must be < $\pm 0.04\ ^{0}C$.

RF Pulse Compression system for CTF3.

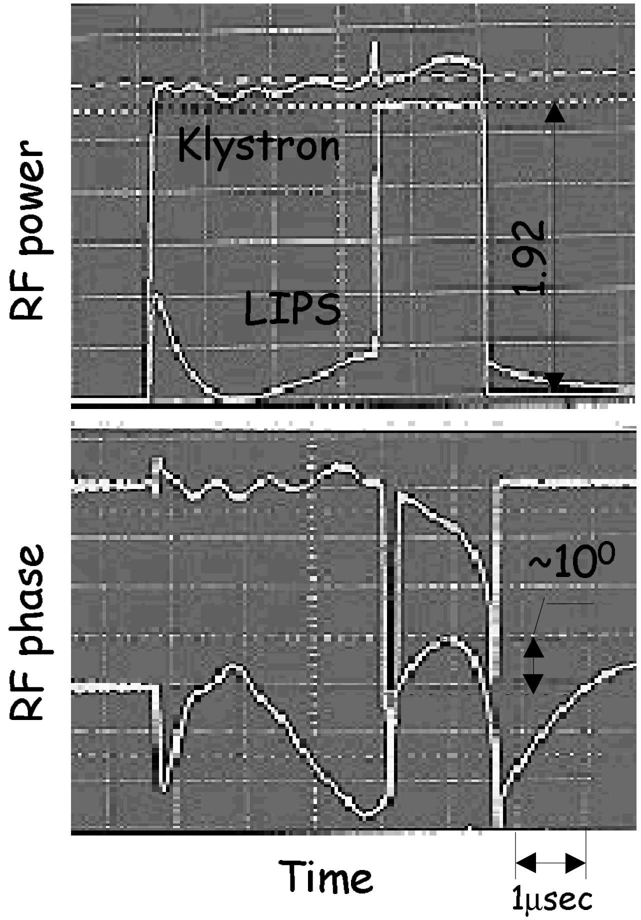
System operation stability.

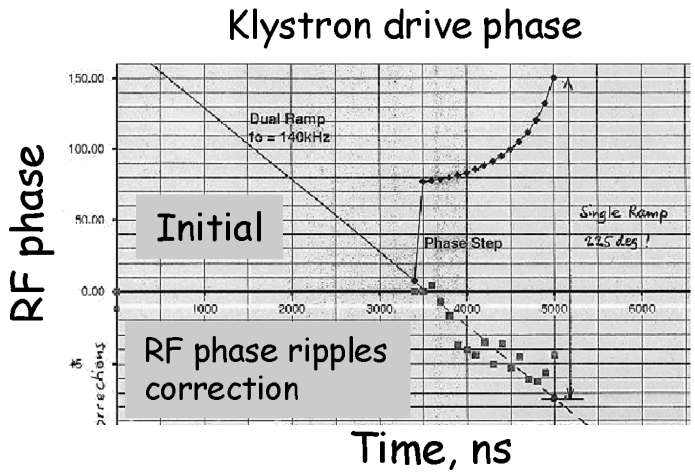
Algorithm of the fast correction of the cavity frequency shift.

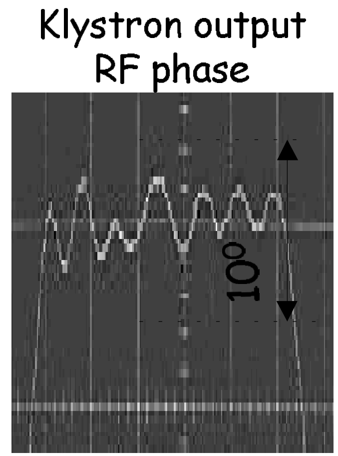


RF Pulse Compression system for CTF3.

Experiments with high RF power level. R. Bossart, December 2000.







Parameters:

Q unloaded	1.6×10^5
Coupling	8.0
Tin	5 μsec
Tout	1.4 μsec
P out/in	34.7/18 MW
P gain/teor.	1.92/2.04
ΔP/P	< 1%

Barrel Open Cavity pulse compressor.
3 GHz version.

WHY?

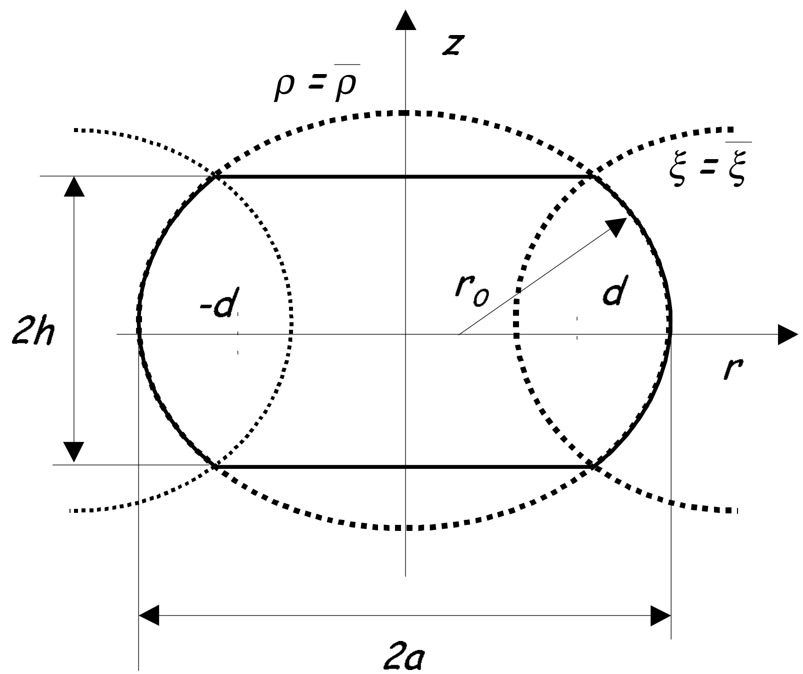
1. We need at least four more RF pulse compressors.

2. The BOC has one cavity, operating in a travelling wave regime - solves the problem of the cavity's pair identity.

3. Easy to manufacture than LIPS. We can do it in CERN.

4. *The test prototype is preparing for the high RF power test.*

The Barrel-cavity theory.



Cavity profile

$$z = \sqrt{a r_0 \left\{1 - \left(\frac{r}{a}\right)^2\right\}}$$

The eigen-frequency of the Barrel cavity with E_{mnq} oscillation is the solution of the next equation:

$$ka = \nu_{mn} + \frac{(q - 1/2)\alpha}{\sin\theta}$$

ν_{mn} is a root of the Bessel function that for the big *m* can be approximated as:

$$\nu^{o}_{mn} = m - \mu t^{0}_{n} \qquad (n = 1, 2, \ldots),$$

$$-t^{0}_{n} = [(n - 0.25)1.5\pi]^{2/3}, \qquad \mu = \left(\frac{m}{2}\right)^{1/3}.$$

The optimal radius r_0, when the external caustic has the smallest height comes from: $r_0 = 2a \sin^2\theta$ where α and θ are derived from:

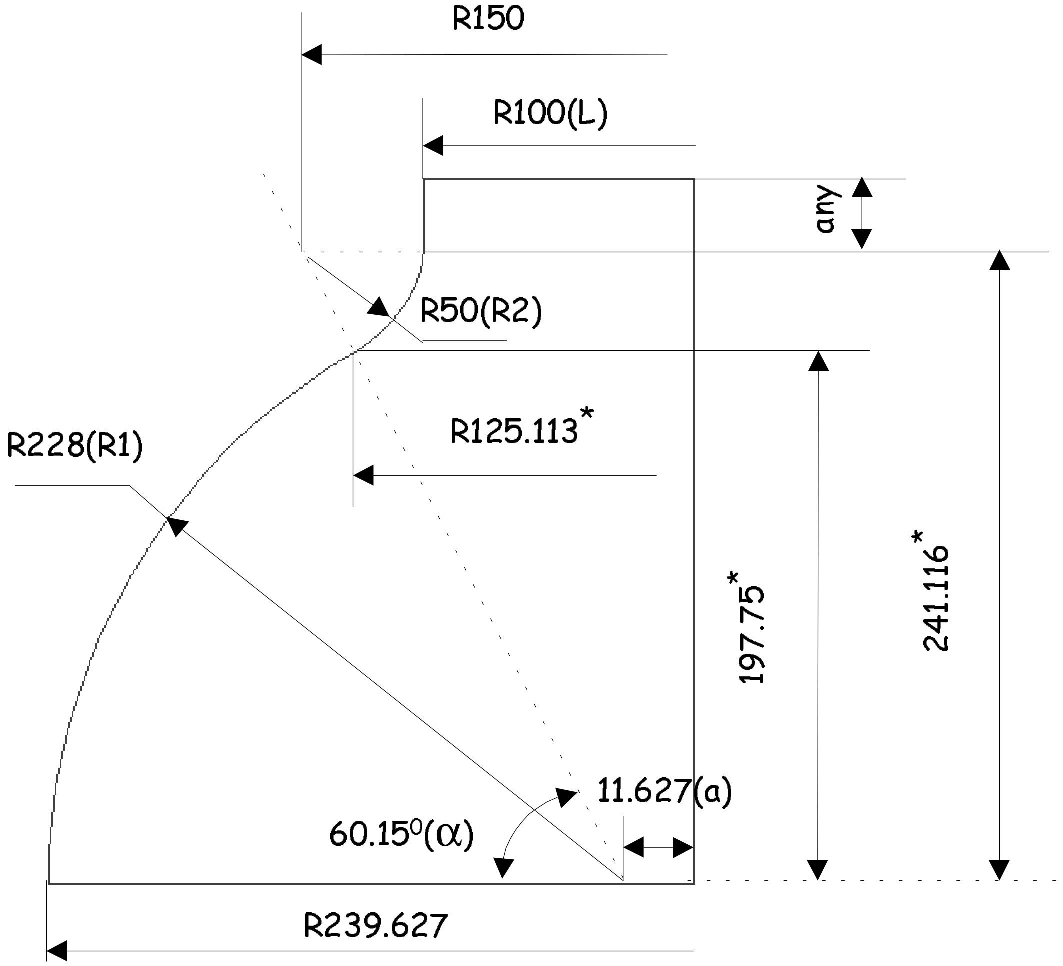
$$\sin\alpha = \sqrt{\frac{a}{r_0}} \sin\theta \qquad \cos\theta = \frac{m}{\nu_{mn}}$$

Finally the height of the external caustic and Q-factor of the cavity are:

$$z_{q-1} = 2\sqrt{(q - 1/2)\frac{a \sin\theta}{k \sin 2\alpha}}$$

$$Q_E = \frac{a}{\sigma_s}$$

The shape of the 3.0 GHz Barrel-cavity.

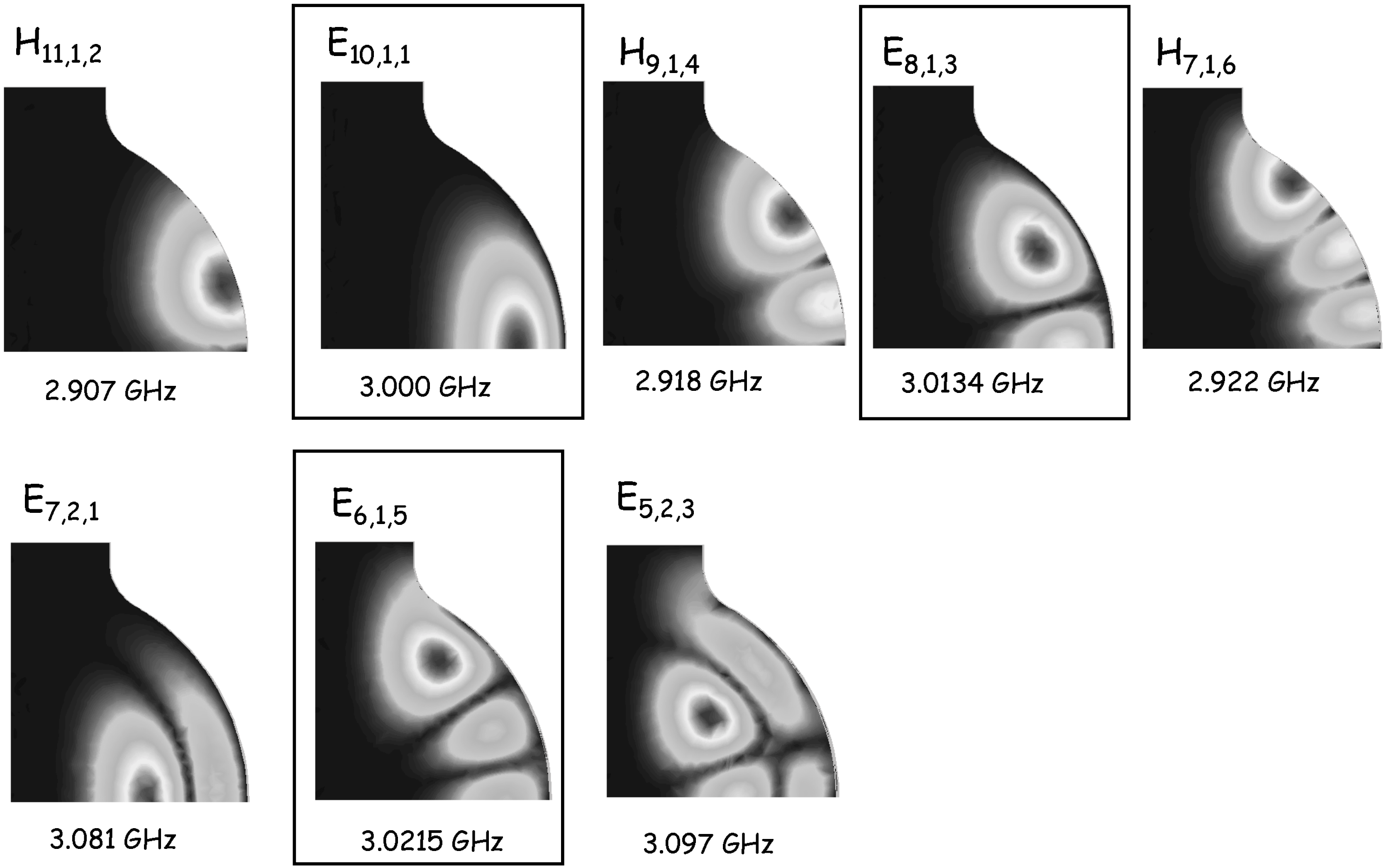


$Q=1.9780*10^5$

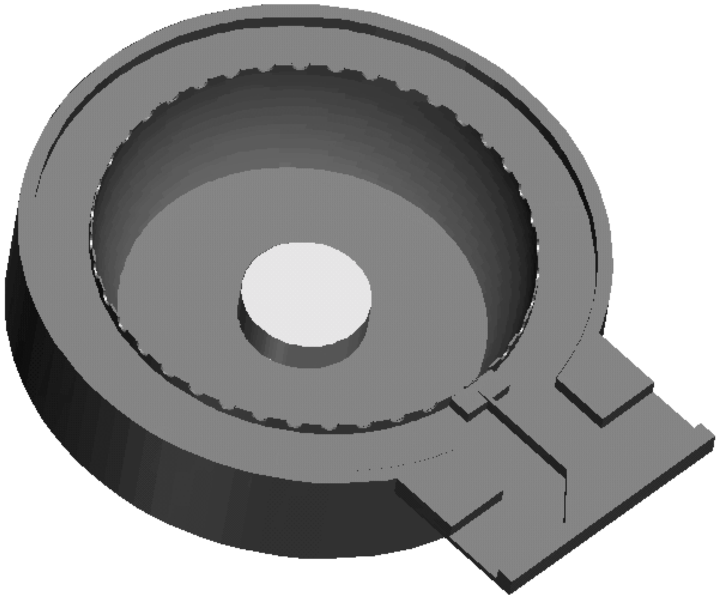
F=2.99855 GHz

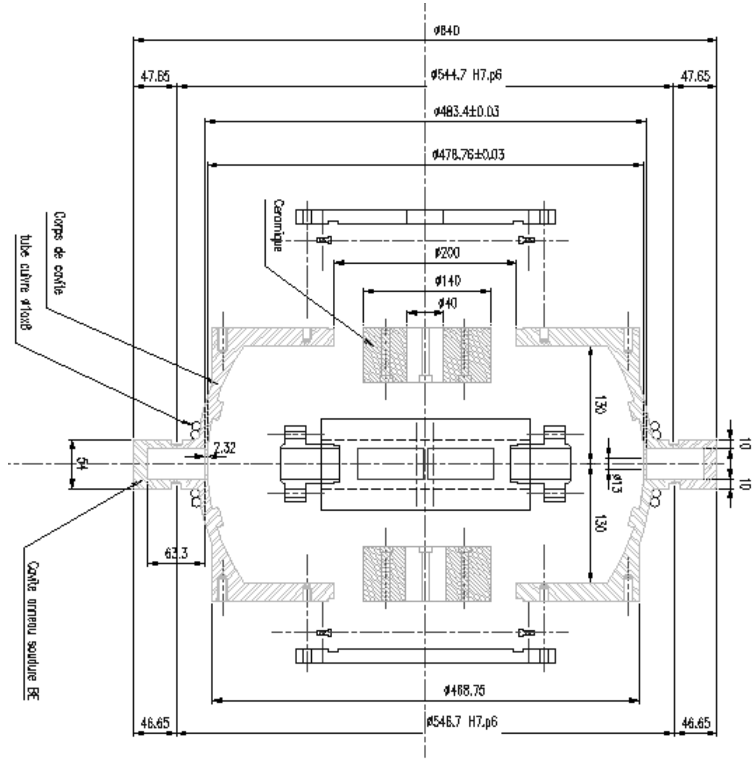
CLIC

The modes of the 3.0 GHz Barrel-cavity.



General view and technical sketch of the 3.0 GHz BOC RF pulse compressor.





Discussion...

Questions ?...

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

P. Pearce, CERN, Geneva, Switzerland

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.

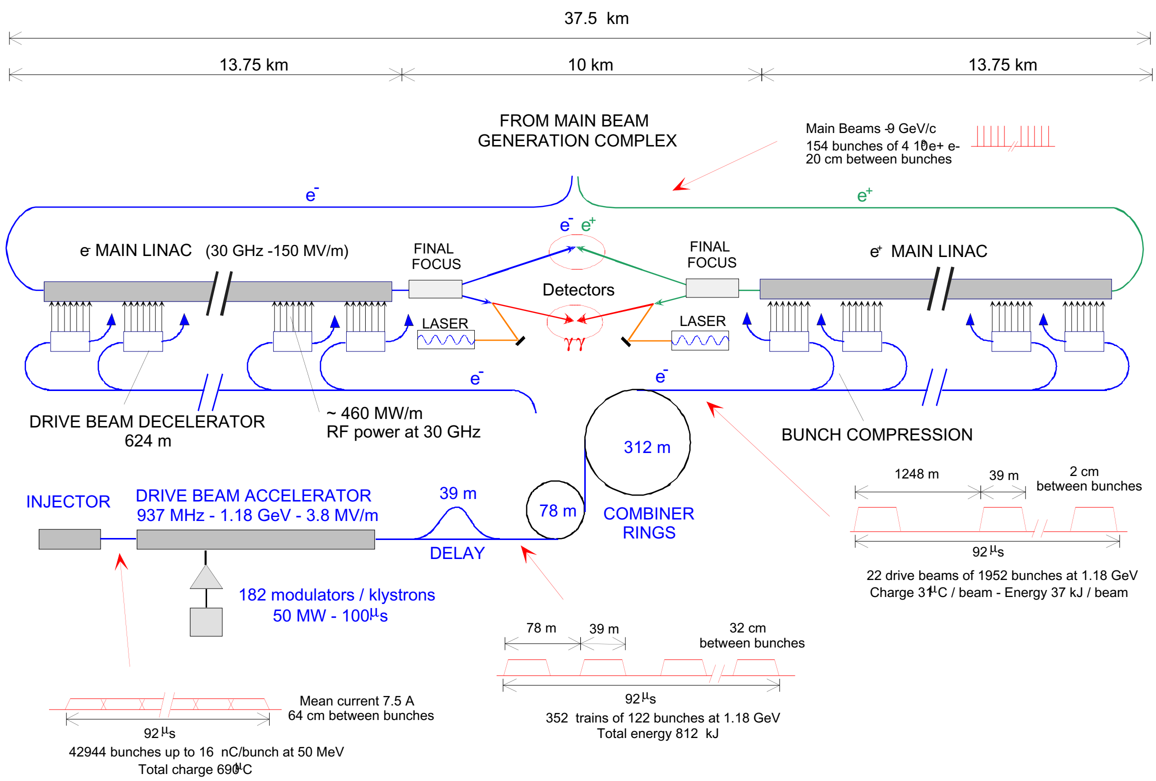


Figure 1. Layout of the CLIC scheme for 3 TeV centre of mass.

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.

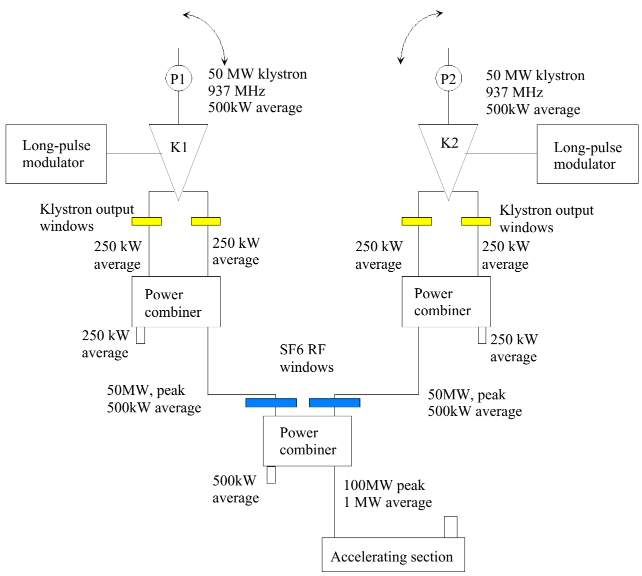


Figure 2. A CLIC Drive Beam accelerator RF Module.

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.

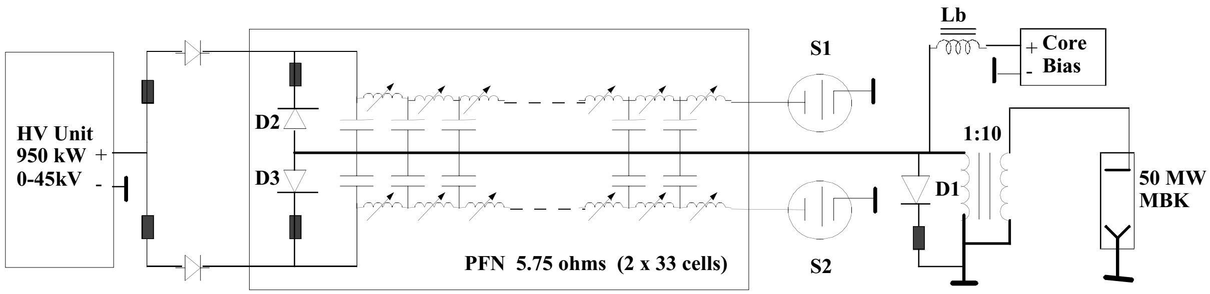


Figure 3. Conventional line-type MBK-modulator design

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.

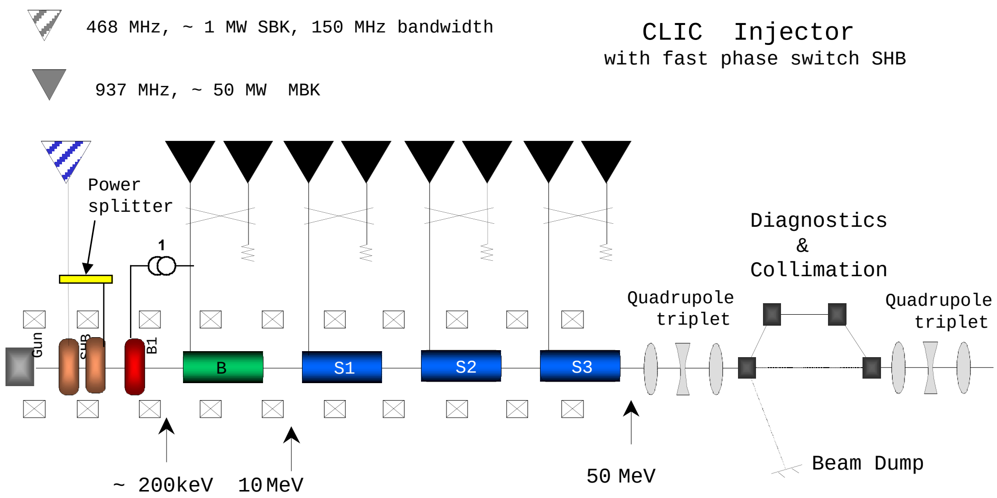


Figure 4. Alternative CLIC Drive Beam Injector layout

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.

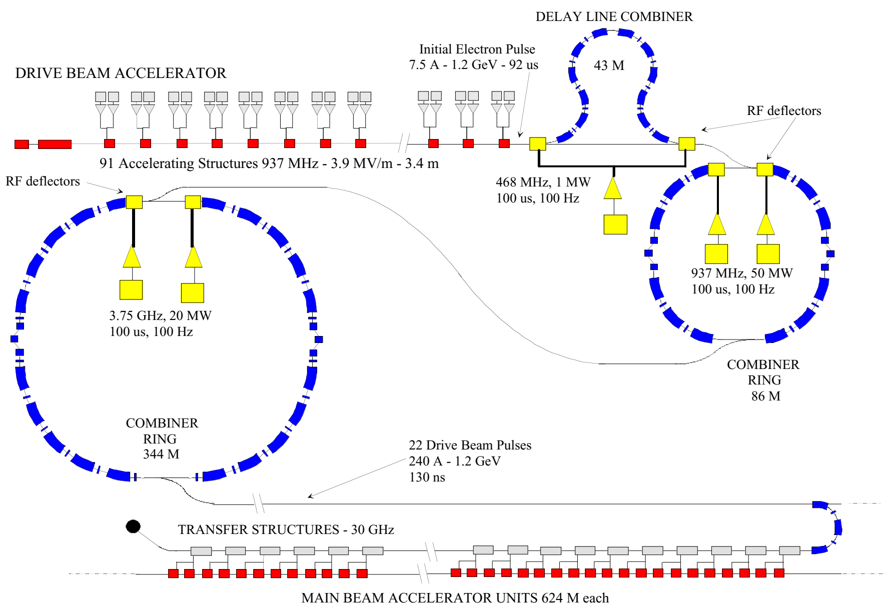


Figure 5. RF deflector klystron-modulators in CLIC

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.

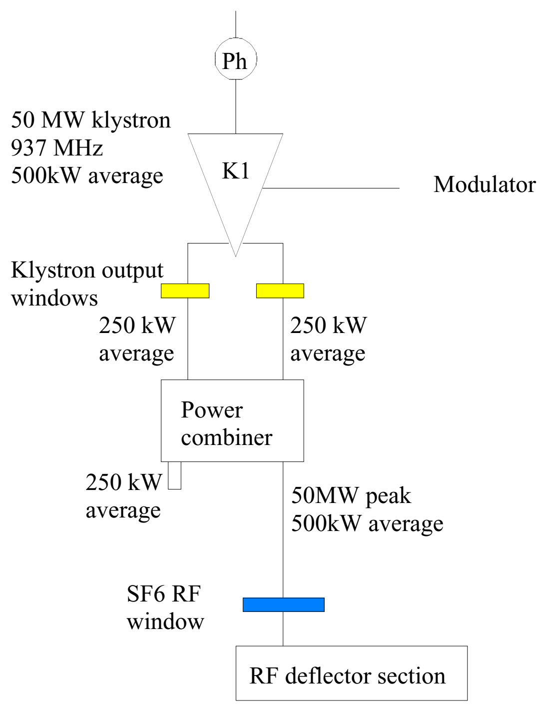


Figure 6. RF deflector klystron-modulator for first combiner ring

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.

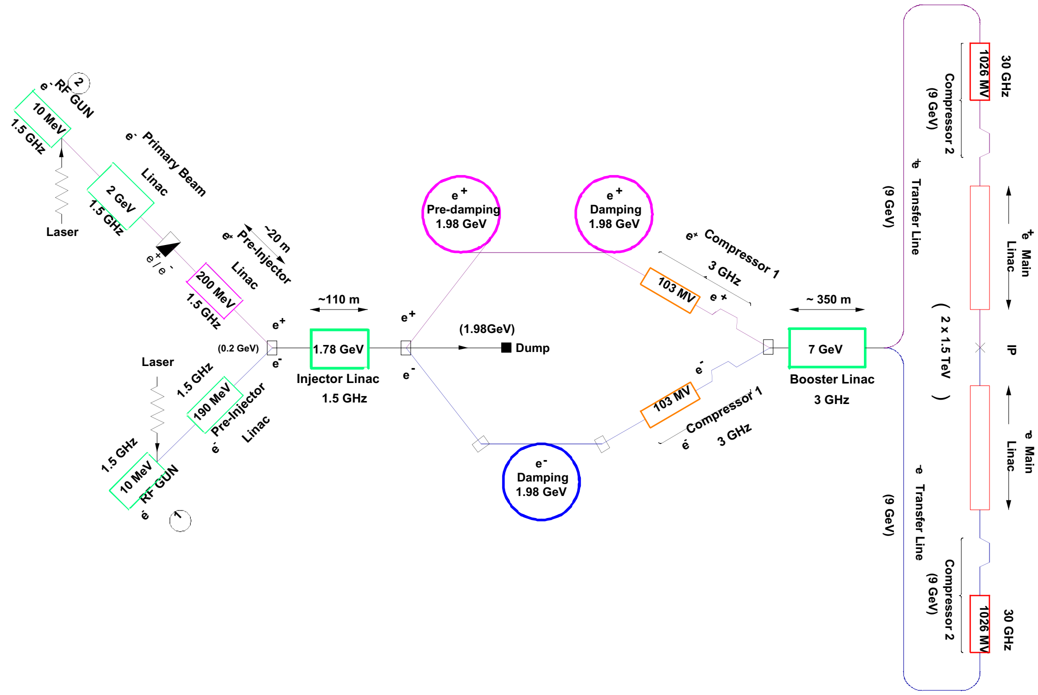


Figure 7. Main Beam Injector layout

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.

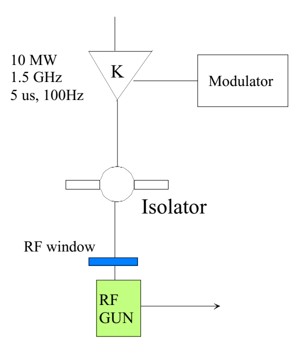


Figure 8. RF gun klystron-modulator

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.

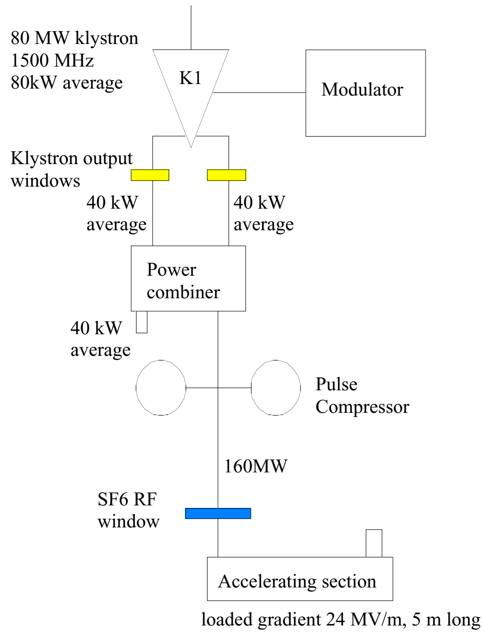


Figure 9. Pre-Injector Linac 80 MW L-band klystron-modulator

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.

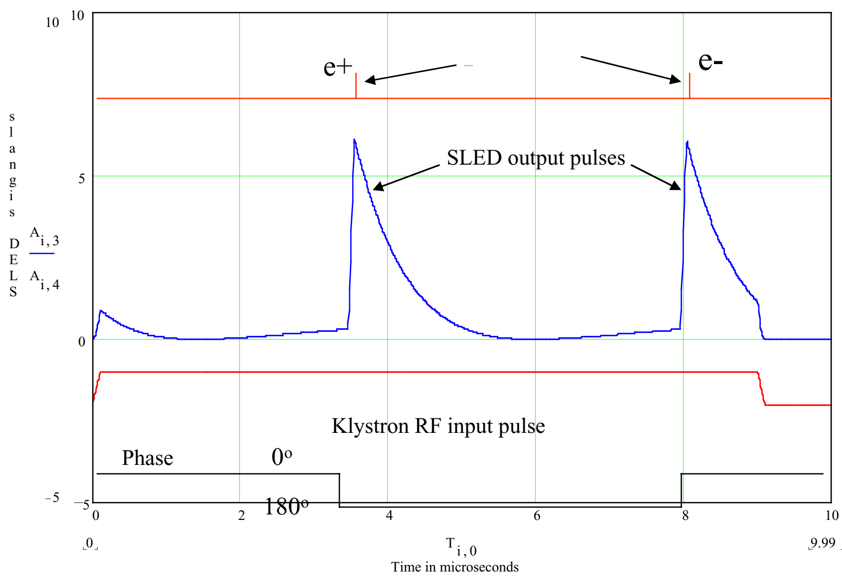


Figure 10. Double RF pulse generation with SLED

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.

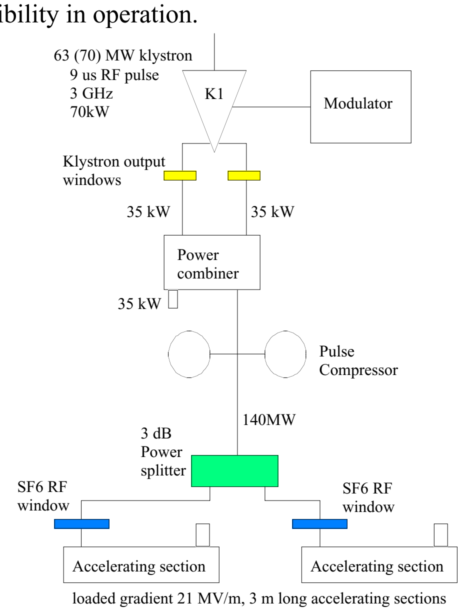


Figure 11. Booster Linac Klystron-Modulator RF module

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.

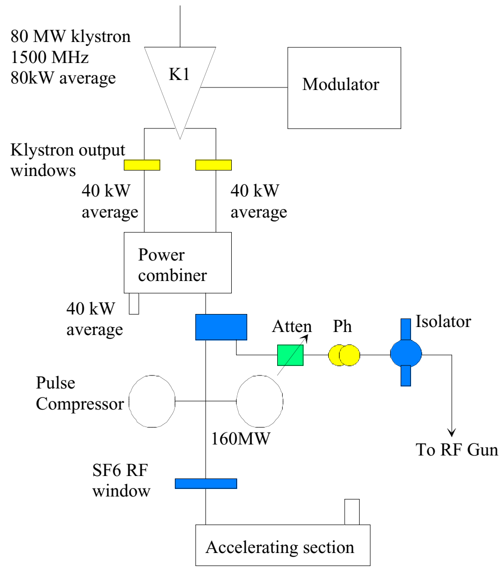


Figure 12. Alternative source of RF power for injector guns

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.

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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