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OPERATIONAL PERFORMANCE AND IMPROVEMENTS TO THE RF POWER SOURCES FOR THE COMPACT LINEAR COLLIDER TEST FACILITY (CTF3) AT CERN

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The CERN CTF3 facility is being used to test and demonstrate key technical issues for the CLIC (Compact Linear Collider) study. Pulsed RF power sources are essential elements in this test facility. Klystrons at S-band (29998.55 GHz), in conjunction with pulse compression systems, are used to power the Drive Beam Accelerator (DBA) to achieve an electron beam energy of 150 MeV. The L-Band RF system, includes broadband Travelling Wave Tubes (TWTs) for beam bunching with "phase coded" sub pulses in the injector and a narrow band high power L-Band klystron powering the transverse 1.5GHz RF deflector in the Delay Loop immediately after the DBA. This paper describes these different systems and discusses their operational performance.

Introduction

CTF3 is installed in the building previously used by the LEP pre-injector (LPI) at CERN. Where possible, to save on construction costs, equipment from the LPI has been recycled or upgraded.

S-Band klystron modulator parameters and performance

For the CTF3 nominal phase [1], ten 3 GHz high RF power sources producing 35 or 45 MW peak RF power at the output of the klystron are being used. [2, 3] The maximum pulse repetition rate for 8 of the modulators is 100 Hz while the other two most recent klystron modulators, using switched mode d.c. capacitor charging supplies rather than the resonant D'Qing charging in previous modulators, can operate at a pulse repetition rate of 10Hz. [4]. An overall summary of the S-Band klystron modulators available in CTF3 can be found in Table 1. The basic modulator circuit diagram can be seen in Figure 1.

Pulse Forming Network (PFN)

The line type modulator uses a capacitance-inductance lumped component line as its PFN, comprising of 25 cells. Each cell has a capacitance of 33nF and inductance of 700nH. The 25 cell PFN produces a "rectangular" pulse of width 7.6 µS at 70% height. The pulse width for the PFN is defined by $\tau = 2n\,(LC)^{1/2}$ seconds (n=number of cells) and the equivalent impedance $Z = (L/C)^{1/2}\ \Omega$

Parameters	37MW MDK	45 MW MDK	Units
RF Frequency	2998.5	2998.5	MHz
RF Peak Output	35	45	MW
RF Power Gain	53	54	dB
Klystron efficiency	45	44	%
RF pulse width	5.5	5.5	µs
Klystron Voltage	273	305	kV
Klystron Current	285	335	A
PFN Impedance	4.6	4.6	Ω
Pulse Transformer Ratio	1:13	1:14.85	
Pulse Voltage Ripple	±0.15	±0.15	%
Pulse to Pulse Stability	±0.1	±0.1	%
Maximum pulse repetition rate	100	100 (*)	Hz

(*) 10 Hz for switch mode charging
Table 1 Klystron modulator summary

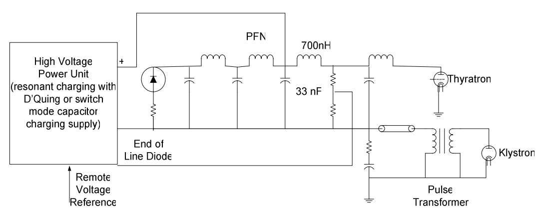

Figure1. Modulator basic circuit diagram

The adjustment of the pulse width, flat top ripple and mismatch with the klystron load is made by varying the inductance of the coil in each cell by adjusting the distance that an aluminium plunger is inserted into each coil. A typical klystron voltage waveform and the ripple on the flat top is shown in Figure 2.

Pulse transformer

The klystron presents a dynamically varying diode type load to the pulse forming network during the voltage pulse. As the applied voltage to the klystron increases the klystrons dynamic impedance decreases. The klystron resistance $R_k = V_k/I_k$ and $I_k = \rho V_k^{1.5}$ where ρ is the klystron perveance, hence the klystron resistance is written as $R_k = 1/\rho.\ (V_k)^{-1.5}$. A typical perveance value for a new klystron used in the CTF3 modulators is
$\rho = 2 \times 10^{-6}\ A.V^{-1.5}$.

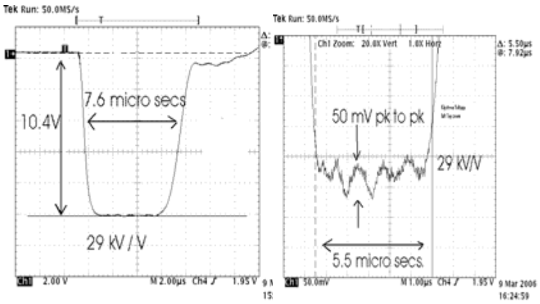

Figure2. Klystron Waveform and ripple on flat top (+/- 0.25%)

For a 45MW klystron a maximum pulsed voltage of about 305 kV is required and the choice of the step up high voltage pulse transformer is important to obtain a positive mismatch between the klystron load and PFN impedances. The choice of the pulse transformer turns ratio N is closely linked to the amount of mismatch, the transformer efficiency, and the maximum PFN voltage desired. This is optimised by defining a mismatch expression for a step up transformer with an efficiency as $V_{kly} = (V_{pfn}\ N\ \eta) / (2\text{-}m)$,η= transformer efficiency and due to reflection with the transmission line impedance the percentage voltage mismatch m, can be seen and measured on the voltage waveform at the klystron.

$m = v / V_{kly}$ as shown on the waveform from the simulation model in Figure 3

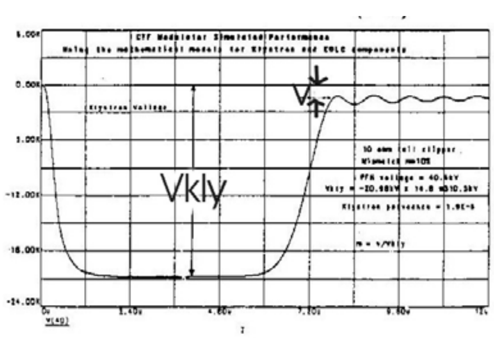

Figure 3 Klystron Voltage Simulation

Choosing a transformer ration of 1:14.8 and calculating for a positive mismatch of 5% gives a maximum operating voltage on the PFN of 41.5kV. The pulse transformer and pre-magnetisation inductor specifications are given below in Table 2

Parameter	Units	Value
Secondary pulse voltage (max)	kV	305 (280)*
Turns Ratio	N	1:14.8 (1:13)*
Secondary dist. Capacitance	pF	110
Pulse width at 70%	µs	7.6
Flat top Pulse width at 99%	µs	5.5
Pulse rise time (10-99%)	ns	700
Tx core volt-seconds	Vs	2.1 (1.68)*
Repetition Rate	Hz	100
Flat top pulse droop (max)	%	1
Pre-magnetisation current	A	17
Pre-magnetisation inductor	mH	12

* 35MW klystron specification

Table2 Pulse transformer specification

Thyratron

The thyratron switch used in the modulator is the E2V model CX1836A with a maximum peak current capability of 10kA and a maximum operating voltage of 50kV on the anode. The peak thyratron current is a function of the PFN voltage and the combined impedance of the klystron load and the impedance of the PFN.

$I_{thy} = V_{pfn} / (R'_{kly}+Z_{pfn})$, (R'_{kly} is klystron resistance referred to the primary of the pulse transformer) see Figure 4.

$I_{thy} = \rho\ [V_{pfn}\ / (2\text{-}m)]^{1.5}\ N^{2.5}$ A.

With a PFN voltage of 41.5kV and a mismatch of 5% this will give a maximum peak current in the thyratron of 5230 amps.

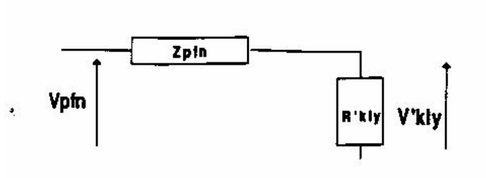

Figure 4 Equivalent output circuit

A positive mismatch allows the thyratron to recover over a long period (¬100µs) after each pulse without it being extinguished by any inverse voltage in the immediate post pulse period. To ensure a jitter free and reliable operation of the gas filled thyratron a keep-alive pulse of 500V is applied to Grid 1 and a trigger pulse of 2kV to grid 2 is applied simultaneously from a trigger amplifier. The CX1836A also has a barrettor stabiliser that maintains a constant internal pressure (a few millibars) in the hydrogen gas. The thyratron reservoir voltage therefore does not need regular adjustment (as with previous models) as the gas is consumed during operation. The barrettor ensures that the correct pressure is maintained over its lifetime (about 12-18000 hours).

KLYSTRON

Three types of klystron are used in the modulators. Thales TH2132 (45MW peak power) , Thales TH2100C (37MW peak power, possible to condition to 45MW), Figure 5, and a Valvo YK1600 (35MW peak power). To achieve the peak power with a 5.5 µs RF pulse at 50 Hz repetition rate a voltage pulse of 7.6 µs is required from the modulator. [13] The peak voltage and current used are 305 kV and 335 A.

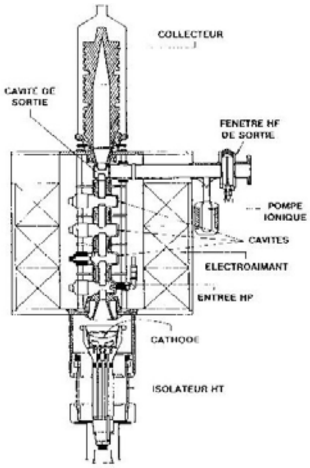

Figure 5 A TH2100C klystron (cut through view)

The heater cathode of the klystron provides the electron beam in the tube and works in the space-charged limited regime where the current is given by the Child Langmuir law. The perveance is then $\rho = I/V^{1.5}$ typically this is about 2 x 10^{-6} $A/V^{1.5}$ for the maximum power output. The peak input power to the klystron from the pulsed high voltage modulator unit is about 100 MW for a klystron efficiency of 45%. The focussing field is provided my three electromagnetic solenoids positioned around the klystron. The electron beam current density in the klystron is 540 A/cm^2 compared to 6 A/cm^2 at the cathode and a temperature monitoring interlock on the klystron body is necessary to ensure that the beam does not touch and damage the internal cavity walls of the klystron. The klystron has an overall gain of 54dB and a RF power source of 300 W is used to drive the input cavity.

The pulse to pulse voltage stability and the ripple on the flat top of the voltage pulse are important for the klystron The phase stability has been calculated and measured as $\Delta\theta$ = 1.8 degrees per kV variation when operating at full power [12]

The pulse to pulse accuracy of the capacitor charging supplies is ± 0.1% giving about 0.56 degrees variation at 305kV. The periodic ripples created by the PFN's 25 lumped impedance cells also contribute to the overall beam energy fluctuation and phase stability. The typical measured voltage ripple is about ± 0.25% or 1.4 degrees of phase jitter.

The klystron amplifier tubes lifetime depends on several parameters, including careful running in and conditioning, adequate protection against reflected power at the window, excessive inverse cathode voltage, correct focusing of the beam and cooling of its critical components. We achieve typical lifetimes of 24000 hours with the main reasons for klystron failure being either cathode failure, arcing in the klystron gun, or arcing on the klystron output windows.

Drive Beam Accelerator (DBA) High Power Components

The basic layout of klystron modulators for CTF3 is shown in Figure 6. Eight of the 3 GHz power sources provide the RF power for the Drive Beam Accelerator (DBA) producing an electron beam energy of 150 MeV with a beam current of 3.5 A at the end of the linac. The waveguide system from the output of the klystrons, where possible uses the old LIL networks via pulse compressors to the new accelerating structures, two structures being powered from each pulse compressor through a 3dB splitter. The copper waveguide type WR325 with LIL type flanges is used either under vacuum or under pressurised SF6 gas.

One S-Band klystron modulator is used to provide RF power at the injector. The power from the klystron modulator MKS02 is split to provide power to the pre buncher and buncher, no pulse compression is necessary.

Another S-Band system without pulse compression is used to provide RF Power to the two transverse RF deflectors in the combiner ring.

A high power L band klystron provides RF power to the transverse deflector operating at 1.5 GHz that injects the phase coded bunches produced by the Sub Harmonic Bunching (SHB) system into the Delay Loop. The RF power for the SHB is produced by 3 broadband Travelling Wave Tubes (TWT) also operating at 1.5GHz.

Drive Beam Accelerating Structure

The DBA consists of 16 travelling wave accelerating structures, each of 32 cells and a total length of 1.3 m, operated in the $2\pi/3$ mode at an accelerating gradient of 7 MV/m. The structures are designed to operate at almost 100 % beam loading. This increases the efficiency of the machine as most of the RF power travelling down the structure is converted to beam energy with very little being dissipated in the output loads. Four iris slots per cell, couple dipole wakes to integrated SiC loads to provide strong dipole wake damping.

The nominal parameters are:
Number of DBA cells/structure: 32 cells + 2 coupler cells
RF power at input of structure: 30 MW
RF pulse width into structure: 1.6 µs

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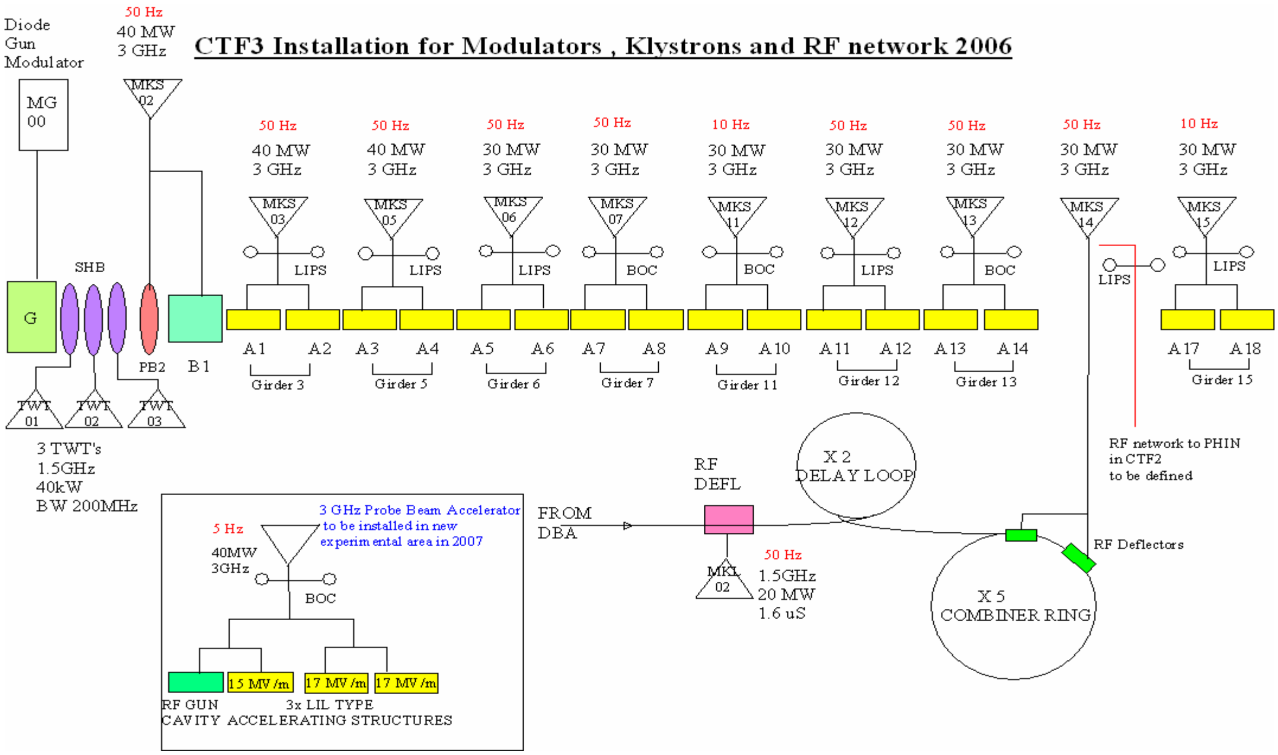

Figure 6 Installation for modulators, klystrons and RF network

Beam current: 3.5 A
Beam loading coefficient[1]: 98%
RF to beam efficiency: 93%
The accelerating structures known as SICA [5] (Slotted Iris – Constant Aperture) are designed to be scalable to operate at the CLIC frequency of 937 MHz.

Pulse Compression

To achieve the constant 30 MW peak RF power over a 1.6 µs pulse width at each accelerating structure the RF output power from the klystrons is compressed by cavity based pulse compressors. [1, 3, 6]
Some of the two-cavity LIPS pulse compressors from LPI are used and mobile tuners correct any frequency errors in the cavities.
In order to reduce the costs for the manufacture of the additional pulse compressors required, a new single-cavity Barrel Open Cavity (BOC) [7] pulse compressor was developed at CERN. These cavities have to be manufactured to very high precision to achieve the required frequency, as they do not have mobile tuners. Small errors in frequency can be corrected by adjusting the water temperature of the water-cooling system.
Initial operation showed that the response time of the temperature control system to a step change in peak power from the pulse compression system was very slow and to achieve a stable and useful RF output it took approximately one hour for the system to become stable.

[1] defined as the ratio of power transferred to the beam to the power available for the beam

A new temperature control system has now been installed where refrigerated water is heated to the required temperature for a given power setting. The temperature setting for each pulse compressor can be individually set remotely for any given power and the response time is now a manageable 2 minutes with a temperature precision of ± 0.1 deg C [14]
In LPI a short (900 ns) compressed pulse with a gain of 5 in peak power and an exponential decay was achieved by applying a 180° phase shift after 3.5 µs in the 4.5 µs RF pulse at the input to the klystron. To achieve the 1.6 µs rectangular pulse after compression that is required for CTF3 a phase modulation program is applied to the input of the driver amplifier before the klystron, and the RF pulse length has been increased to 5.5 µs. A typical RF pulse from the klystron and the resultant compressed pulse at the output of the pulse compressor, after phase programming has been applied, can be seen in Figure 7.
To compensate for the phase error along the flat top from one klystron pulse the mirror image of the phase programming is applied to the following klystron. This phase program will be used in a feed forward loop to control the amplitude stability during operation.
As expected, measurements have shown that the gain in peak RF power after pulse compression is 1.9 for LIPS and 1.95 for BOC. A power amplitude variation of ±1% and a phase sag of the compressed pulse of 6° was achieved.

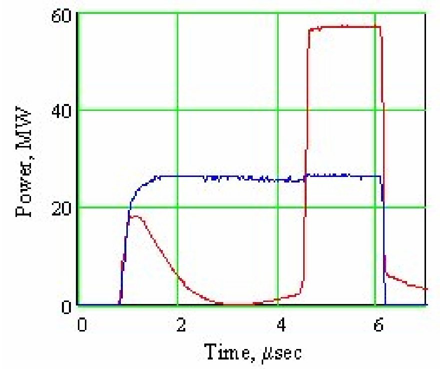

Figure 7 Klystron output pulse and resultant compressed pulse out of pulse compressor when phase programming has been applied

L-Band (1.5GHz) for the Delay Loop

For bunch interleaving with the Delay Loop, a bunching system at the injector is needed to give the required time structure of the pulse [1]. Each of the three Sub Harmonic Bunchers is powered by a Travelling Wave Tube [8] producing a peak RF power of 40kW.

High bandwidth TWTs were chosen as the RF power source for these cavities to allow RF phase to be switched rapidly (within 3 to 4 ns) by 180° every 140 ns. This allows the production of a train of "phase coded" sub pulses that is required in the injector Figure 8. Initial test results using the first bunching cavity can be seen in Figure 9.

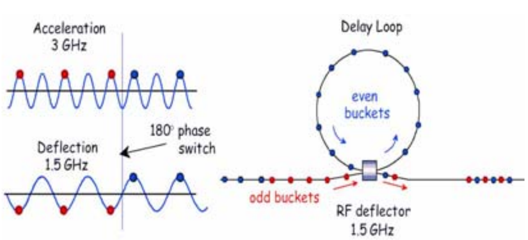

Figure 8 Phase coding of RF bunches

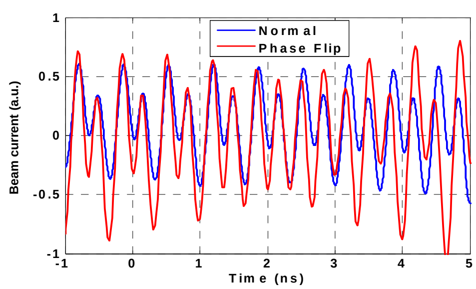

Figure 9 1.5 GHz time structure before and after 180 deg phase flip

The delay loop has two identical standing wave transverse RF deflectors each requiring a peak power of 10 MW. A new 1.5 GHz klystron [9] has been bought to produce this power. The klystron was chosen to have the same micro perveance as the S-Band klystrons so that it could be easily adapted to the existing S-Band modulators. A circulator was not necessary as a 4 port hybrid was used to split the RF power from the klystron to the cavities and a high power load on the 4th port is used to absorb any reflections from the cavities. The waveguides are WR 650 made from aluminium and are operated under SF6 at a pressure of 2 bar.

The wide band TWT's and the RF deflector klystron work together in the bunch interleaving scheme that increases the beam frequency to 3 GHz before injection into the combiner ring.

The performance of the TWT and klystron are summarised in tables 3 and 4 respectively.

Parameter	Value	Unit
RF Frequency	1.5	GHz
Bandwidth (-1dB)	>150	MHz
RF peak output	40	kW
Gain	35	dB
Cathode Voltage (V_c)	-20	kV
Beam Current	9	A
Collector Voltage	0.8 V_c	
RF pulse width	3	µs
Duty cycle	0.0015(*)	
RF Drive Power	15	W

Table 3 TWT parameters

Parameter	Value	Unit
RF Frequency	1.5	GHz
Bandwidth (-1dB)	>8	MHz
Peak output power	22	MW
RF pulse width	5.5	µs
Maximum Repetition frequency	100	Hz
Electronic efficiency	40	%
Beam Voltage	270	kV
Microperveance	1.9 to 2.1	$\mu A/V^{3/2}$
Gain	49	dB
Peak RF Drive Power	200	W

Table 4 L Band klystron parameters

Combiner Ring RF Deflectors

The transverse, travelling wave 3 GHz RF deflectors [10, 11] in the combiner ring, enable the interleaving of the bunches to increase the beam repetition frequency from 3 to 15 GHz by successive injections with the RF deflectors placing each newly injected bunch behind the already circulating ones. The peak RF power required from the klystron to power the two RF deflectors is 20 MW, no pulse compression is necessary. A high power phasor and attenuator is installed in the RF network towards one of the deflectors to enable the relative power and phase between the two deflectors to be adjusted

30 GHz Power Testing of RF Structures [15]

In 2007 a new experimental area will be added to CTF3 to enable a 35 A, 150 MeV bunched electron beam to drive scaled CLIC PETS (Power Extraction and Transfer Structures) to produce 30GHz power for the development of high gradient accelerating structures.

In order to allow a program for the development of CLIC equipment before this date a special generating station using the first third of the DBA has been built, giving a 70 MeV electron beam up to 5 A, with 3 GHz bunch spacing and 1mm bunch length. This has allowed initial testing of 30 GHz RF structures to a power of 100MW, 70ns pulse with and an accelerating gradient of 150MV/m . A special "dog-leg" transmission line was built in the DBA to allow easy switching between the 30 GHz RF power production and the rest of the CTF3 facility. When the 30 GHz power production is being used it is not possible to operate the rest of the CTF3 complex. For this reason the klystron used to provide the RF power to the Combiner Ring RF deflectors has been configured to allow future testing of a future Photo-Injector RF cavity in parallel with 30Ghz testing.

Further Requirements for CTF3

For the CLIC Experimental area (CLEX) one more S-Band klystron modulator system will be required to provide the power for the probe beam. A collaboration between CERN and CEA Saclay in Paris is now studying and designing the system so that it will be ready in 2007.

Conclusions

The high power hardware is successfully installed and the commissioning up to the end of the Delay Loop is in progress. The combiner ring will be completed in 2006 and is scheduled to be commissioned by the end of the year. The high power RF sources will be required to be available for up to 6000 hours per year up until 2010 and a rigorous maintenance and reliable operation program will be necessary to obtain these goals

Acknowledgements

Many thanks to all members of CERN, and our external collaborators, working on the CTF3 project who helped with the installation and commissioning of the system.

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