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Abstract

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A 50Hz LOW-POWER SOLID-STATE KLYSTRON-MODULATOR

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ABSTRACT
A solid-state klystron-modulator has been designed for use with the drive-beam injector of the new Compact Linear Collider (CLIC) test facility (CTF3) at CERN. The modulator uses an Integrated Gate Commutated Thyristor device (IGCT) as the on-off switch, operating at about 5.5kV in a simple step-up pulse transformer circuit. A compensated capacitor discharge network enables an excellent pulse shape with very small voltage droop during the maximum required 5µs pulse width. The paper discusses the simulation results and compares these to the measured waveforms made on a prototype modulator.

DRIVE BEAM INJECTOR

The CTF3 (1) facility will test many vital components and demonstrate the feasibility of RF frequency multiplication techniques proposed for CLIC, a next generation linear particle accelerator. To obtain the required CTF3 bunch time structure, the beam pulse produced by a thermionic triode gun is bunched by the drive beam injector system shown in Figure 1.

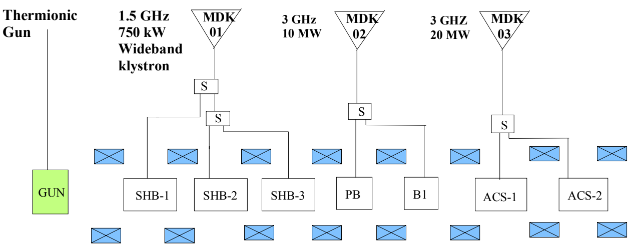

FIGURE 1 CTF3 drive beam injector layout

The phase of the sub-harmonic bunching cavities are switched rapidly (in about 10 ns) through 180° every 140 ns using the 750 kW peak power, wideband klystron and modulator. It is very important to minimize the RF phase shift at the klystron output due to any voltage variation across the modulators high-voltage pulse width. Any phase changes produced by this effect would add progressively to the programmed switched phase changes at 140 ns intervals and reduce the overall bunching efficiency. A wideband klystron (2) (3) has been designed that enables the phase switching to create a train of "phase-coded" 140 ns wide sub pulses, within the required RF pulse width. This phase switching shifts alternate sub-pulses in time so as to synchronize them with the RF deflection and interleaving processes that will finally produce RF power at a frequency of 30 GHz. The stability and reproducibility of the RF pulses from the klystron is therefore very dependent on the modulators' voltage flat top performance.

KLYSTRON-MODULATOR

The parameters for the wideband klystron and solid-state modulator (4) are shown in Table 1.

Parameters	Value	Units
Klystron frequency	1.5	GHz
Bandwidth (-1 dB)	≥ 150	MHz
Repetition frequency (max)	50	Hz
Peak RF output power	750	kW
RF pulse width	≤ 2.5	µs
Klystron voltage (max)	70	kV
Klystron current	37	A
Klystron efficiency	29	%
Perveance	$2.\ 10^{-6}$	$A/V^{1.5}$
Focusing field	650	G
Large signal gain	40	dB
Modulator capacitor voltage	5.4	kV
Peak IGCT pulse current	520	A
Step-up pulse transformer ratio	1:13	-
Pulse voltage rise time (10-90%)	1.5	µs
Pulse voltage fall time (90-10%)	3	µs
Flat top voltage deviation	< ±0.1	%

TABLE 1 Klystron-Modulator parameters

The electrical circuit of the modulator is shown in Figure 2. Practical aims and constraints were to design a circuit using available in-house components wherever possible, and to reduce the size of the modulator compared to the existing 3 GHz main linac klystron-modulators. During operation, when the solid-state switch is triggered ON, the positive terminals of the two storage capacitors (Cprim1) are pulled to the ground potential, allowing the opposite terminals to swing the pulse transformer primary winding negative. This produces a negative going voltage pulse on the secondary winding that is applied to the cathode of the grounded anode klystron. The pulse duration is determined by the width of the optically coupled trigger pulse given to the solid-state IGCT ON/OFF switch. The single cell PFN connected to the storage capacitors helps to match this network to the klystron load in terms of the voltage rise time. A diode and resistor circuit (D2, R2) placed across this network clamps the IGCT anode voltage (at turn-off) to the voltage level on the storage capacitor, helping to prevent over-voltages.

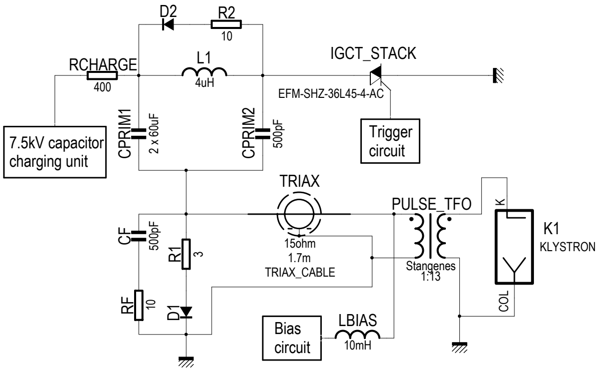

FIGURE 2 Basic electrical circuit of modulator

Figure 3 shows the construction of the prototype solid-state modulator.

FIGURE 3 The prototype modulator construction

The second diode and resistor circuit (D1, R1) placed across the pulse transformer primary to ground limits positive voltage excursions at the klystron cathode. Because the modulator pulse is connected to the klystron load via a pulse transformer using a standard, low (15 Ω) characteristic impedance triaxial transmission cable, there is an impedance mismatch that will cause some oscillations during the pulse rise time. An integrating CR network (C_F, R_F) at the modulator end of the transmission cable is used to damp out any perturbations.

IGCT SWITCH

The Integrated Gate-Commutated Thyristor (IGCT) switch used is a reverse blocking type (5) with low switching and on-state losses, and has fast turn-on and turn-off times. It is very suitable for series connection and has a simple optical fibre control interface with status feedback. Four IGCT modules in series are used for this application as in Figure 4. The basic switch parameters are given in Table 2 and the IGCT switch assembly is shown in Figure 5.

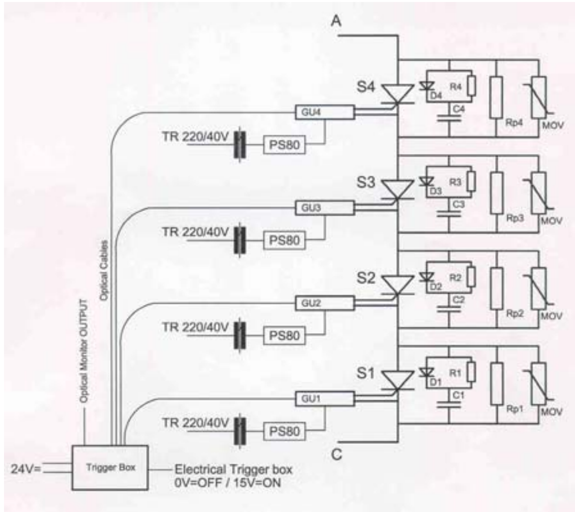

FIGURE 4 IGCT assembly electrical circuit

Parameter	Value	Units
Blocking		
Forward peak off-state voltage	4500	V
Reverse peak off-state voltage	4500	V
On-state		
On-state Voltage across device	<7.75	V
Max. on-state current	4000	A
Max. current rate-of-rise	1000	A/µs
Turn on trigger energy	<1.5	J
Turn on delay	<3	µs
Off-state		
Max. controlled turn-off current	4000	A
Max. rate of turn-off current	600	A/µs
Turn off trigger energy	19.5	J
Turn off delay	<6	µs

TABLE 2 IGCT switch module parameters

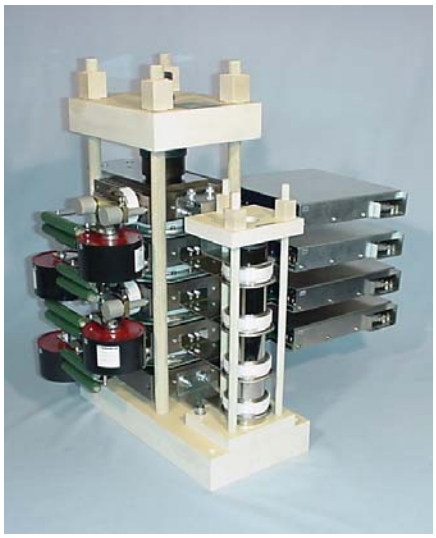

FIGURE 5 IGCT switch assembly

The IGCT technology combines the advantages of GTO thyristors and IGBT's (Insulated Gate Bipolar

Transistor), but unlike an IGBT at turn-off the IGCT gate is reversed biased to absorb the maximum anode current. This hard turn-off gate current is provided by integrated, optically coupled, on-chip drivers, which are encapsulated in the low inductance housing. This hard turn-off mode of operation reduces the carrier storage time in the gate region to about 1 μs, so enabling easier series connection of devices without prior parameter selection. For improved reliability and to avoid false triggering due to cosmic radiation the device operating voltage is generally derated by about 30%.

SIMULATIONS

The solid-state modulator parameters were initially calculated using a simple MathCad model. This model was then transformed into a more general PSpice simulation file for further development. A study of the predicted performance and behavior under normal operation and under fault conditions was made before the actual prototype modulator was built.

The IGCT assembly circuit was modeled by using one closing and one opening switch connected in series for each switch module. The non-linear Metal Oxide Varistor (MOV) protection resistors are modeled using a table of values that correspond to the voltage/current characteristics of the MOV type used.

All component parameters on the secondary winding circuit have been referred to the primary side of the step-up (1:13) pulse transformer. The first PSpice simulations were made with the non-linear klystron impedance being replaced by a resistor to give comparison data for the initial tests on the prototype modulator. Figure 6 shows the simulation model with the klystron load modeled as a voltage controlled current source. The simulated voltage waveforms on both the klystron and the resistive loads predict a very flat top modulator pulse with about ±0.1% voltage droop shown in Figure 7. The value of the cell inductor L1 had to be varied in the model and in the actual modulator circuit in order to optimize the rise times for both the resistor and klystron load conditions. The snubber resistors values (R1 to R4 in Figure 4) were also modified to optimize the fall time of the voltage waveform. These resistors are effectively in parallel with the core loss resistance and affect the L/R time constant, during the recovery of the pulse transformer, due to the stored energy in the magnetizing inductance, after the IGCT assembly has switched off.

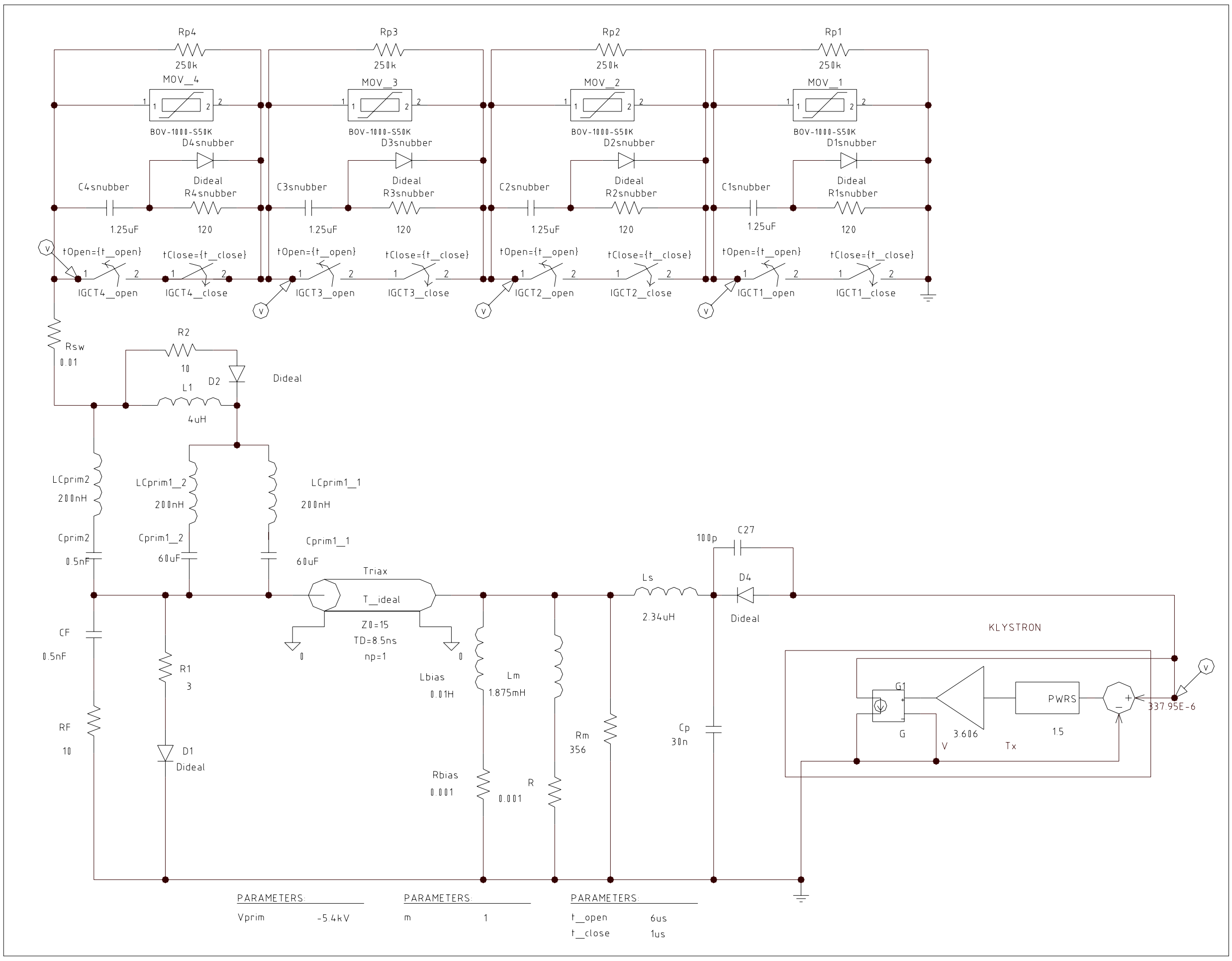

FIGURE 6 Simulation circuit with klystron model

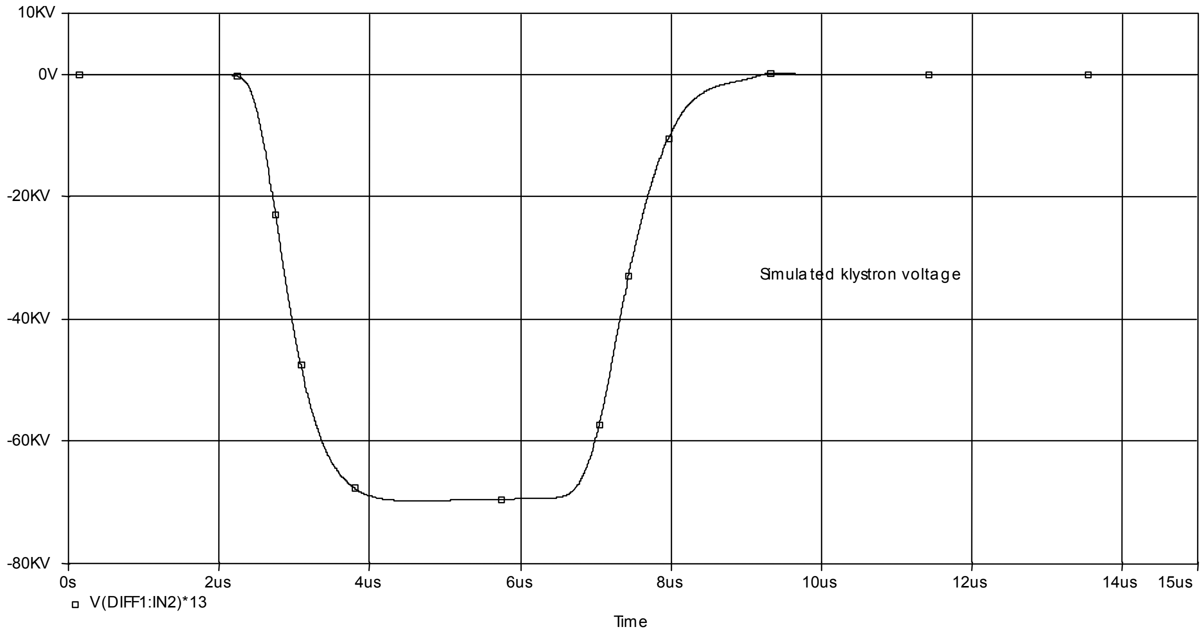

FIGURE 7 Simulated klystron voltage

TEST MEASUREMENTS

A first series of tests was made using a high power resistor in place of the klystron load. This assembly with the resistors and pulse transformer is shown in Figure 8. The load assembly shown is operated in an oil-filled klystron tank. The load voltage is monitored with a capacitive divider and the load current with a fast current transformer.

FIGURE 8 Load resistors and pulse transformer

A typical voltage waveform across the resistive load (R ~2000 Ω) is shown in Figure 9 together with the IGCT trigger pulse. A small voltage bump can appear at the end of the flat top region that is linked to the IGCT switch-off gate current. In Figure 10 this bump vanishes when the IGCT current being switched is comparable to the gate turn-off current, and best flat top performance is got at higher IGCT anode currents.

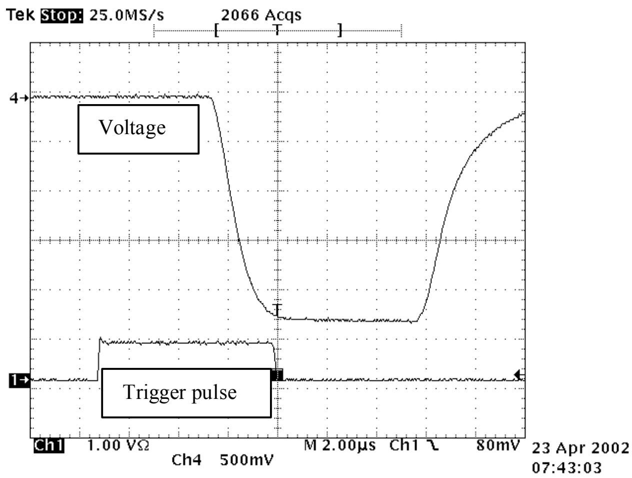

FIGURE 9 Measured voltage pulse on load resistor

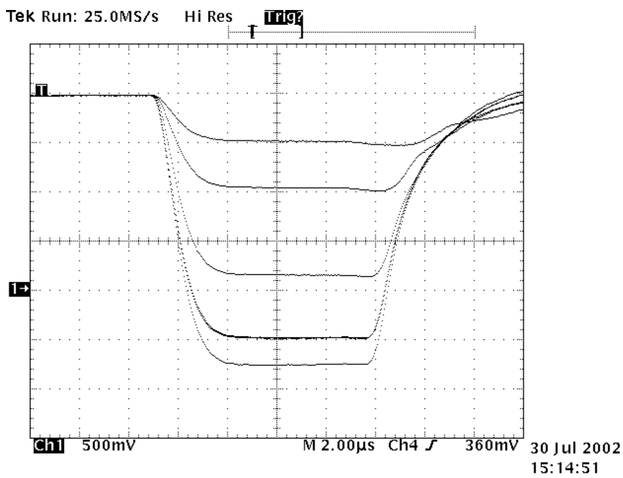

FIGURE 10 Voltage pulse at 1, 2, 4, 5.4 & 6kV

The effect of using different values of snubber resistors in the IGCT assembly on the voltage pulse fall-time is shown in Figure 11.

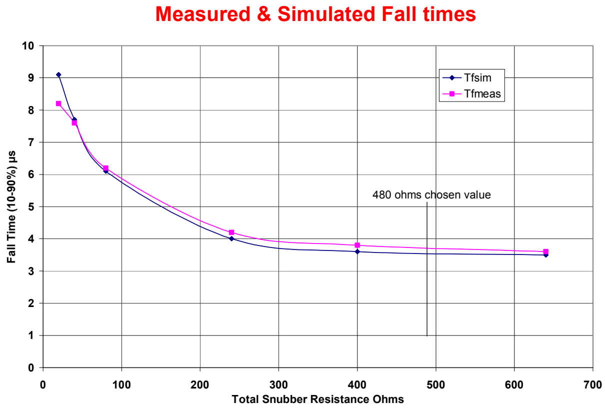

FIGURE 11 Snubber resistance and fall-time

Tests have started with a klystron load at voltages up to 80 kV on the secondary winding and a pulse width of 6 µs at half-height. The pulse waveform in Figure 12 shows that the flat top droop is within specification at the required beam voltage of 70kV (5.4 kV primary voltage) and operating at the 50 Hz rate.

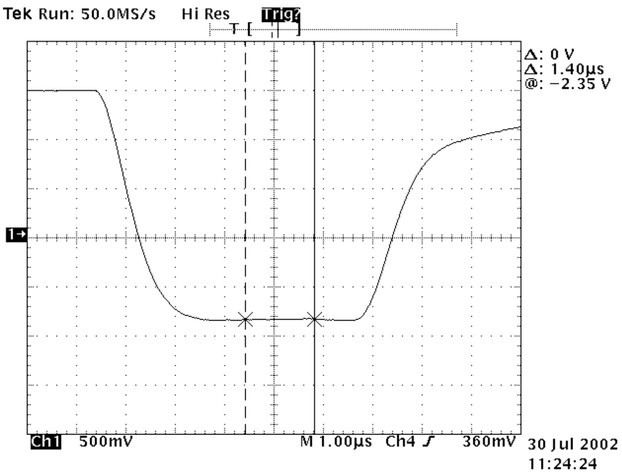

FIGURE 12 Measured voltage pulse on klystron load

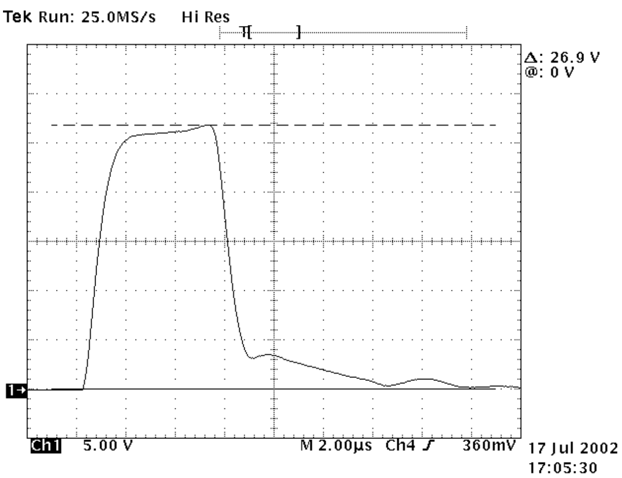

FIGURE 13 IGCT cathode current at 5.4kV primary

Figure 13 shows the IGCT current increasing linearly over the pulse width to compensate the transformer impedance decrease with frequency. The pulse width was increased until the onset of transformer saturation appeared, highlighting this effect as in Figure 14.

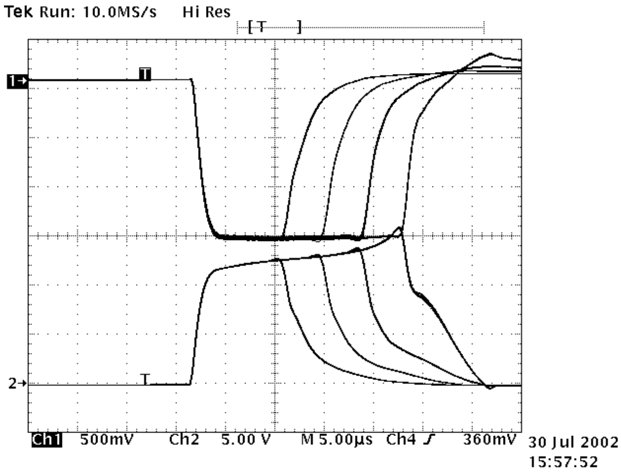

FIGURE 14 Load voltage and IGCT cathode current

The load voltage rise-time jitter due to the IGCT has been measured with primary voltages up to 6 kV and found to be about 100 ns as shown in Figure 15. The jitter on the fall time is of the same order. The delay between the trigger pulse and the ON/OFF action of the IGCT is about 4 µs and 6 µs respectively as in Figure 9. Both pulse jitter and delay time can probably be improved by the IGCT switch manufacturer.

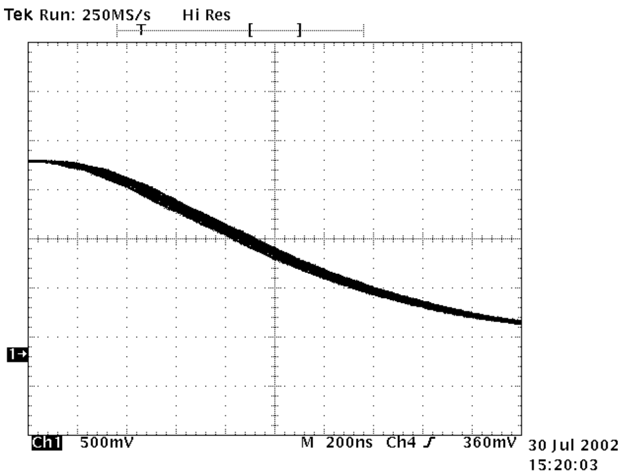

FIGURE 15 Load voltage rise time jitter

PROTECTION SYSTEM

All high-power semi-conductor switches need some form of protection against fault current and over-voltage conditions. The voltage distribution across the four IGCT switch modules in Figure 5 is equalized by resistors for the DC conditions, and by R, C and diode networks for AC and pulsed operation. Furthermore, MOVs are used to reduce the amplitude of fast voltage transients. The MOV action is very useful in case of a

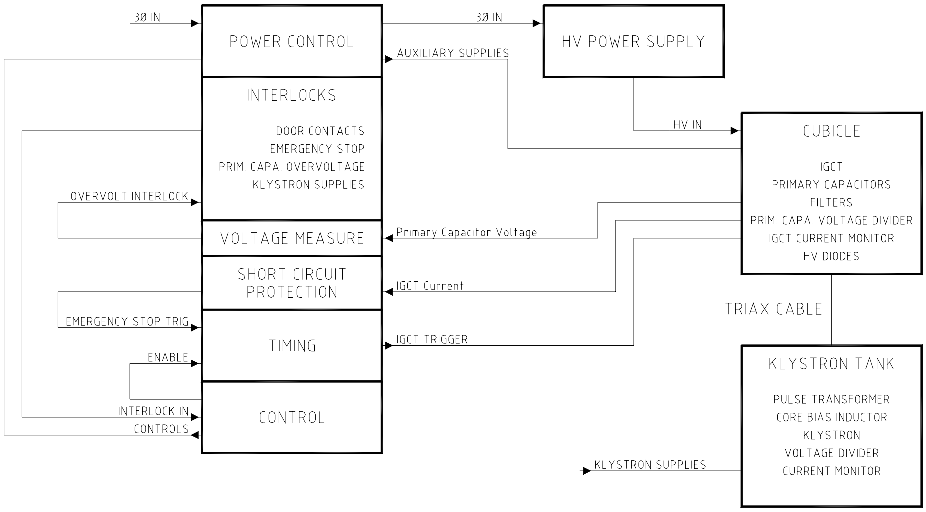

FIGURE 16 Block diagram of the modulator

short circuit load, which may occur due to klystron gun breakdown or pulse transformer saturation. The IGCT current is monitored by a fast current transformer and compared to a reference level that has been determined for normal modulator operating conditions. If the level is exceeded during the pulse the interlock system will stop the IGCT trigger within 150ns to switch off the IGCT current.
The storage capacitor voltage is also monitored and compared to the maximum allowable IGCT voltage. If the reference level is exceeded at any time the high voltage charging unit is also switched off. The block diagram of the modulator featuring the interlock and protection scheme is shown in Figure 16.

SUMMARY OF RESULTS
The test results so far indicate that the pulse performance with a load resistor and a standard 35 MW S-band klystron can be achieved. A comparison with the simulated waveforms shows that the flat top droop of ± 0.1% can be obtained. The modulator has been pulsed with repetition frequencies of 50 Hz and 100 Hz at the required klystron operating voltage of 70 kV. To have a clean pulse shape with a good flat top at these microsecond pulse widths the IGCT assembly seems best operated at the higher anode voltages. During this initial development phase the over voltage and current protection system has proved very useful.

FUTURE DEVELOPMENT
Further testing and development is required to finalize the design of the compact modulator with a klystron load. A new Programmable Logic Control and protection system is being designed for the operation of the modulator with the accelerator controls. The IGCT switch assembly has proven easy to operate and integrate into the modulator circuit. Using the possibility of increasing the primary voltage to 8kV would enable a klystron beam voltage of about 105 kV to be obtained. A six or seven stage IGCT assembly with lower trigger delay and jitter has been proposed for a similar modulator design with an output voltage pulse of about 200 kV. The repetition frequency would be increased to at least 200 Hz for this application.

ACKNOWLEDGEMENTS
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