

OPERATION OF THE LEP CW KLYSTRONS IN PULSED MODE

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Abstract

For possible future accelerator projects, as, e. g., the Super-Conducting Proton Linac, SPL, at CERN, it would be desirable to reuse as much of the LEP/RF equipment as possible. In the SPL, as in other proposed proton linacs, pulsed operation is required with RF pulse-lengths varying between 1 and 3 ms and a pulse repetition rate of 50 Hz. The LEP klystrons are equipped with a modulation anode by means of which their beam current and hence the output power can be controlled. In LEP the klystron output power had to be varied very slowly when the energy was ramped. In order to keep a high efficiency also in pulsed mode the rise- and fall-time of the beam pulse in the klystron should be considerably less than 100 μ s. This goal was achieved by modifying the tetrode modulator, the HV line between modulator and klystron, and the filter network of the HV power supply.

SPICE simulations were performed to evaluate the optimum values of capacitors and inductors in the HV filtering network of the LEP 100kV, 40A power converter when a specified DC pulse shape is required and up to eight klystrons are to be powered by one HV supply. These simulations are presented, together with the experimental results obtained on a modified LEP klystron/power converter assembly.

INTRODUCTION

For reasons of economy, the power converters for the LEP klystrons have been designed such that two klystrons could be operated by one high voltage (HV) unit. The rated output of this power converter is 100kV and 40A. In order to generate 1.3MW of RF power from a LEP 2 klystron, an operating voltage of 100kV and a beam current of 20A was required.

Each LEP klystron is equipped with a modulation anode (MA). By means of the MA voltage, the klystron beam current and hence its output power can be varied.

In LEP operation, the klystron output power was only varied during beam energy ramping. The ramping from injection to top energy lasted a few minutes during which the klystron power had to be increased from about 50kW to 1MW.

In pulsed operation the requirements for the modulation anode circuitry, with respect to the LEP operation mode, change dramatically in that its time constant must be lowered by about a factor of one hundred.

HV 100kV/40A power supply

One HV supply module was designed to power 2 klystrons in parallel, which means output voltage up to 100kV and output current up to 40A.

The power supply consists of four modules:

1. 18kV/1kV step-down extended-delta transformers. There are two transformers used, of which the first one shifts the phase between primary and secondary by +30 degrees, and the second one by -30 degrees. By this phase shift, 3 input phases are converted into 6 phases at the 1kV output side.
2. Two 3-phase thyristor bridges which are working in parallel. The control of the power converter output voltage is done in this module.
3. Two 1kV/50kV step-up transformers.
4. Rectifier and filtering choke. Both step-up transformers are connected in series to obtain output voltage from zero to 100kV DC. There is a 5H filtering choke installed in same the oil tank as the diode rectifier bridge.

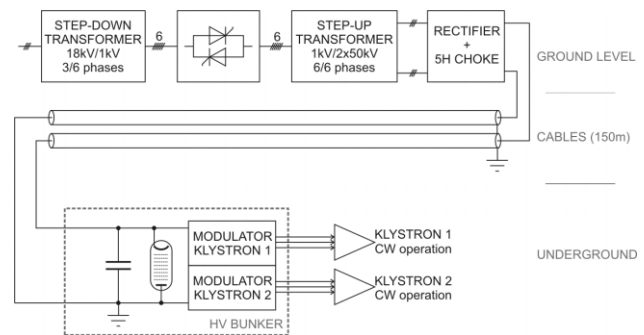


Figure 1: LEP HV system configuration

Each of these modules with the exception of the thyristor bridges is housed in a separate oil-tank.

Two-way rectification of each phase results in a 12 pole system with a 600Hz ripple, which lowers the requirements for output filtering choke and capacitor.

The power converters have been installed at the surface, and connected to HV interface bunkers by up to 600m long HV cables. The fire-proof HV bunkers, which were located next to the respective klystrons, housed the modulators, the 2 μ F decoupling capacitor, thyatron crowbar and HV commutator switch (see figure 1).

Modulation anode power supply

The LEP klystrons have been equipped with a modulation anode. By varying its voltage the klystron beam current, and hence its output power can be controlled while keeping RF drive level and operating voltage constant.

In LEP an adjustable resistive voltage divider was used (see figure 2). The variable resistor consisted of a TH5186 tetrode. Since only slow changes of MA voltage were needed in LEP, the tetrode was used in triode mode requiring less electronics. Less equipment in oil and at high-voltage potential gives higher reliability.

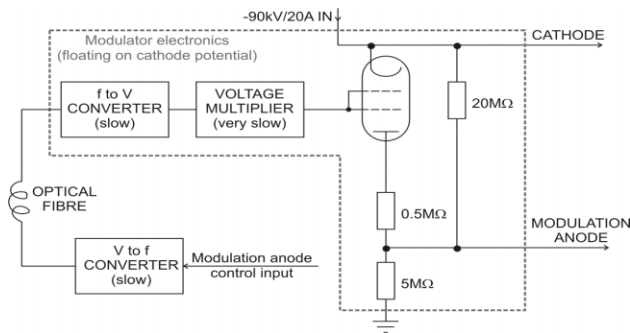


Figure 2: LEP klystron modulator circuitry

The resistors forming the MA voltage divider have had relatively high values to keep the thermal power dissipation in the oil tank as low as possible.

The HV cable connecting the modulator tetrode with the klystron modulation anode was 25m long, representing a total capacity of 5nF. Together with the tetrode anode resistor of 5MΩ, this capacity fixes the time constant of the modulation anode system to 25ms.

Because the tetrode is at cathode potential, all control signals must be galvanically insulated. For this reason an optical fibre was employed. A signal, the frequency of which was proportional to a control signal, was sent via the optical fibre to the electronics of the tetrode grid.

For pulsed operation with millisecond pulses, the time constants of the system must be reduced significantly. This requires a complete redesign of the tetrode modulator circuitry.

PULSE OPERATION OF LEP CW SYSTEM

In order to operate the LEP/RF CW system in pulsed mode the following items must be modified or rebuilt:

- The modulator
- The interconnection between modulator and klystron
- The HV power supply filtering network

For economy, it is envisaged to re-use as many LEP RF components as possible.

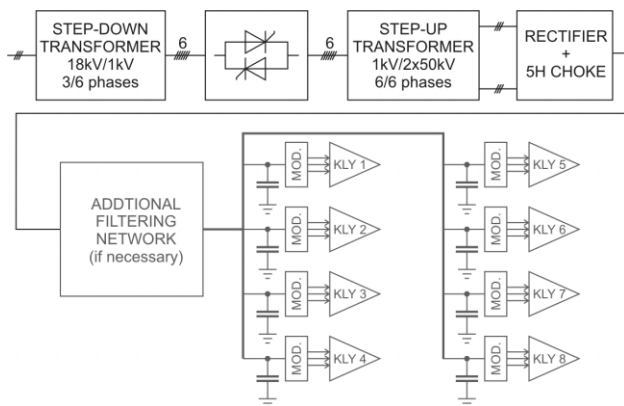


Figure 3: HV system for pulsed operation of the klystrons

Modulator modifications

As discussed earlier, the modulator electronics and the cable connection to the klystron determine the speed of the whole circuit.

First, the tetrode electronics was redesigned. To increase its current capability, the short circuit between screen and control grid was removed enabling operation of the tube in tetrode mode. An additional stabilized power supply for the biasing of the screen grid had to be installed.

The voltage multiplier for the control grid was replaced by a stabilized power supply with a fast linear voltage regulator. With these modifications, 70kV pulses with rise and fall times of 100μs at the modulator output could be generated.

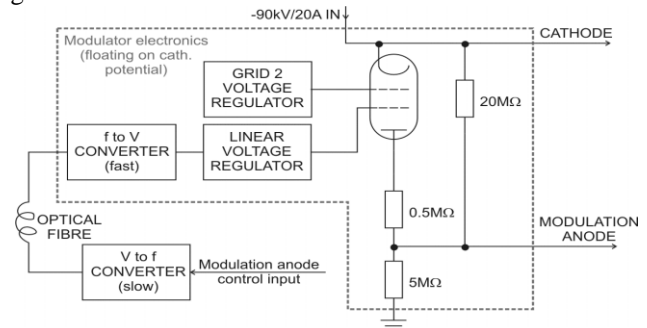


Figure 4: Modified modulator circuitry

The anode resistor has been lowered by a factor of more than three to its final value of 1.5MΩ. The lower limit for the anode resistor value is determined by the maximum acceptable power losses in the modulator tank. At $R_A=1.5M\Omega$ and $U_{CATH}=90kV$ more than 5.5kW are dissipated which must be extracted by a oil-to-water heat exchanger.

HV interconnection cable between modulator and klystron

The capacity of the HV cable used in LEP is 200pF per meter, and the input capacity of the modulation anode is 130pF. These capacities are the main limitations for short rise and fall times of the modulation anode pulses. The only possibility to reduce the capacity of the link between modulator and klystron was to make the HV cable as short as possible and remove its shielding.

By shortening the cable to 3 meters, and removing the shielding, a rise time of 600μs and a fall time of 100μs were achieved.

It would be desirable to integrate the tetrode with the HV resistors in the oil tank attached to the klystron gun. However, this would require a bigger oil tank.

High voltage feeding system modifications

The filtering network of the LEP 100kV/40A power converter consisted of a 5H choke and a 2μF capacitor. In order to operate klystrons in pulsed mode with a power supply designed for continuous mode a special filtering network must be installed. This network must isolate as far as possible the varying load from the power supply.

For that reason, most of the pulse energy must be stored in capacitors located close to the klystron. These capacitors provide the peak current required for the pulsing of up to eight 1.3MW klystrons, and are charged by the rated current of the power supply (40A) during the idle period.

The filtering choke together with the capacitor form an L-C network, which tends to oscillate when operated in pulsed mode. These oscillations could cause voltage overshoots, which are dangerous for the klystrons. Special care must be taken in designing an appropriate filtering network.

SPICE simulations were used to find the voltage drop and circuit current during the pulse as a function of capacity installed per klystron. Results are shown in table 1 and pictures 5,6 and 7 (conditions for simulations – $U_{CATH}=90kV$, 6 klystrons, 20% duty cycle, 50Hz repetition rate).

Table1: SPICE simulated currents and voltages

Capacity per klystron	Cathode voltage		Klystron current	
	U_{avg} (kV)	Ripple (kV)	I_{avg} (A)	Ripple (A)
2 μ F	90	29.2	25.8	15.9
2.6 μ F	90	21.2	26.2	11.2
3.3 μ F	90	16.8	26.4	8.6
4 μ F	90.1	13.7	26.5	6.9

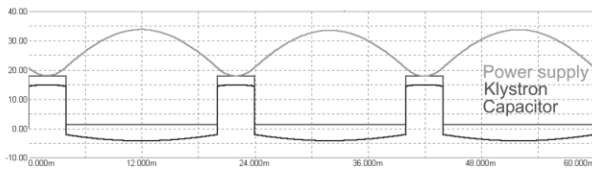


Figure 5: Circuit currents

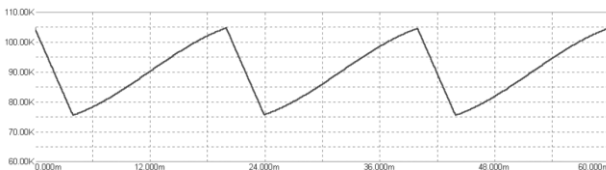


Figure 6: Klystron cathode voltage

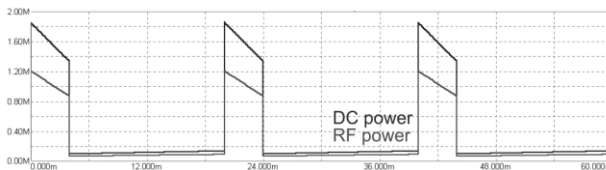


Figure 7: Klystron DC and RF power

MEASURED RESULTS

Measurements were done in view of a possible application in SPL, i.e. at a pulse repetition rate of 50Hz and pulse width of 5ms up to a peak power level of 850kW. No warming up of the oil-insulated capacitors could be observed. The output RF pulse followed the pulse supplied to the modulation anode of the klystron (see figures 8-11).

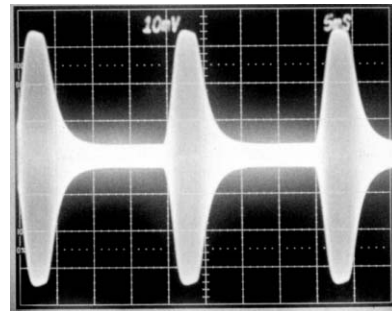


Figure 8: Shape of the RF pulses using LEP modulator

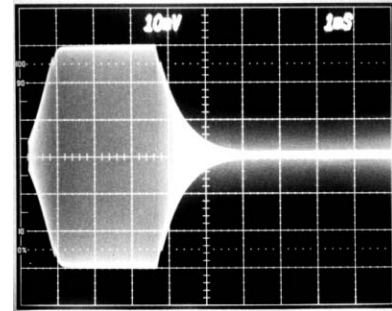


Figure 9: Detail of the pulse generated by the LEP modulator

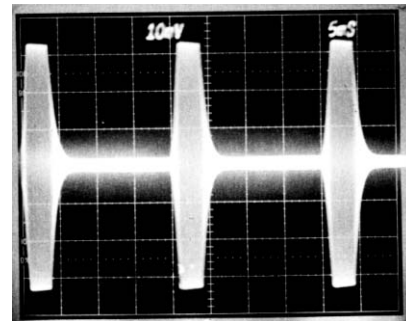


Figure 10: Shape of the RF pulses using modified modulator

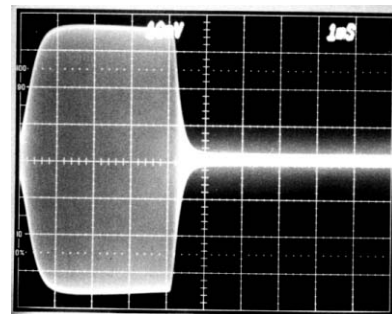


Figure 11: Rise and fall times of the RF pulse provided by the modified modulator

ACKNOWLEDGEMENTS

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