EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/PS 90-27 (LP)
June 1990

Present Performance of the LEP Pre-injector Klystron Modulators and the Impact of a Proposed Upgrade

P. PEARCE, S. HUTCHINS
CERN, Geneva, Switzerland

ABSTRACT

This paper reviews the actual working parameters of the LEP pre-injector (LPI) klystron modulators, and looks at the equipment reliability from the early commissioning stages to the present production runs for LEP.

In order to improve the positron particle production rate in the LPI, to match improvements envisaged in the LEP programme, several closely linked modifications are being studied and are discussed.

Increasing the repetition frequency of the klystron modulators is one of the possible changes that could be made, and an improvement factor in the production rate of between 1.5 to 2.0 could be obtained. An analysis has been made of the modulator system in order to pin-point areas where equipment modifications would be required, to realise the improved performance, and without degrading the present reliability.

Paper presented at the *19th Power Modulator Symposium,*

June 26 - 28th 1990, San Diego, California

Present Performance of the LEP pre – injector Klystron Modulators and the impact of a proposed upgrade.

P. PEARCE, S. HUTCHINS

CERN, Geneva, Switzerland

Abstract

This paper reviews the actual working parameters of the LEP pre – injector (LPI) klystron modulators, and looks at the equipment reliability from the early commisioning stages to the present production runs for LEP.

In order to improve the positron particle production rate in the LPI, to match improvements envisaged in the LEP programme, several closely linked modifications are being studied and are discussed.

Increasing the repetition frequency of the klystron modulators is one of the possible changes that could be made, and an improvement factor in the production rate of between 1.5 to 2.0 could be obtained. An analysis has been made of the modulator system in order to pin – point areas where equipment modifications would be required, to realise the improved performance, and without degrading the present reliability.

1. The present modulator system

1.1 Introduction

The present LEP injector linac, LIL, consists of two linear accelerators [1] in tandem. The first one, LIL – V, has a nominal energy of 200 MeV, and is followed by LIL – W having an energy of 600 MeV. This configuration is shown in Figure 10 (A). A high intensity electron gun in the LIL – V accelerator provides a beam for the standing wave buncher and the four travelling wave sections. Positrons are produced using this LIL – V beam in a converter target located just upstream of LIL – W. The electrons that are accelerated in the 12 travelling wave sections of LIL – W are also supplied by LIL – V.

The RF power for the buncher and the 16 travelling wave sections is generated by 6 klystron modulators. The four accelerating sections of LIL – V are driven by a single klystron equipped with a LEP Injector Power Saver (LIPS). This is an RF pulse compression system based on the SLED principle [2] invented at SLAC. Two other groups of four sections in the LIL – W accelerator are also fitted with LIPS.

Modulator tests began in 1983 as the result of a collaboration study between LAL Orsay, Paris, and CERN, Geneva. The machine commisioning and installation tests of the production modulators was started in the LIL klystron gallery at CERN in 1985 and the first electron beam was produced in June 1986. In October 1987 both electron and positron beams were available. Once all of the klystron modulators and LIPS had been installed in the LPI the full range of their capabilities [3] was exploited, and a programme was started to match modulator reliability and performance to the longer term aims of LEP.

1.2 Modulator description

The modulator pulse forming network (PFN), is composed of 25 individual cells with a nominal impedance of 5 ohms, and creates a pulse with a 5.5 μs flat top. A power supply recharges this PFN after each output pulse to about twice the dc power supply voltage due to the resonant influence of the charging diodes and the series charging inductance with a D'Quing winding. In the ideal case with no circuit losses, the PFN voltage is given by:

$$V_{PFN} = V_{dc}(1 - \cos\omega t)$$

where

$$\omega = \frac{1}{\sqrt{LC}}$$

The value of L, the charging inductance, seen on the primary winding being 7.44H, and the total PFN capacitance C to be charged is about 650nF. The charging time $t = \frac{\pi}{\omega}$ is then 6.4ms. The individual cell inductances are of the order of 625nH while the cell capacitance is about 25nF. The PFN capacitors are left charged at the peak voltage value because of the blocking action of the charging diodes whilst the charging power supply recovers. The action of the D'Quing system in a well adjusted modulator enables a consistent PFN voltage stability of better than 0.1%. Typical PFN voltage values used are between 30 and 36kV. The ITT thyratron discharges the PFN capacitors through the primary winding of the 1:13 step – up pulse transformer creating a negative going voltage pulse of about 260kV amplitude at the klystron cathode. The ripple on the flat top of this pulse is made to be about ± 0.5% by fine adjustment of the PFN. The referred impedance of the klystron, seen on the primary side of the pulse transformer, is slightly (10%) higher than the PFN impedance so that more than half of the stepped up PFN voltage appears across the klystron.

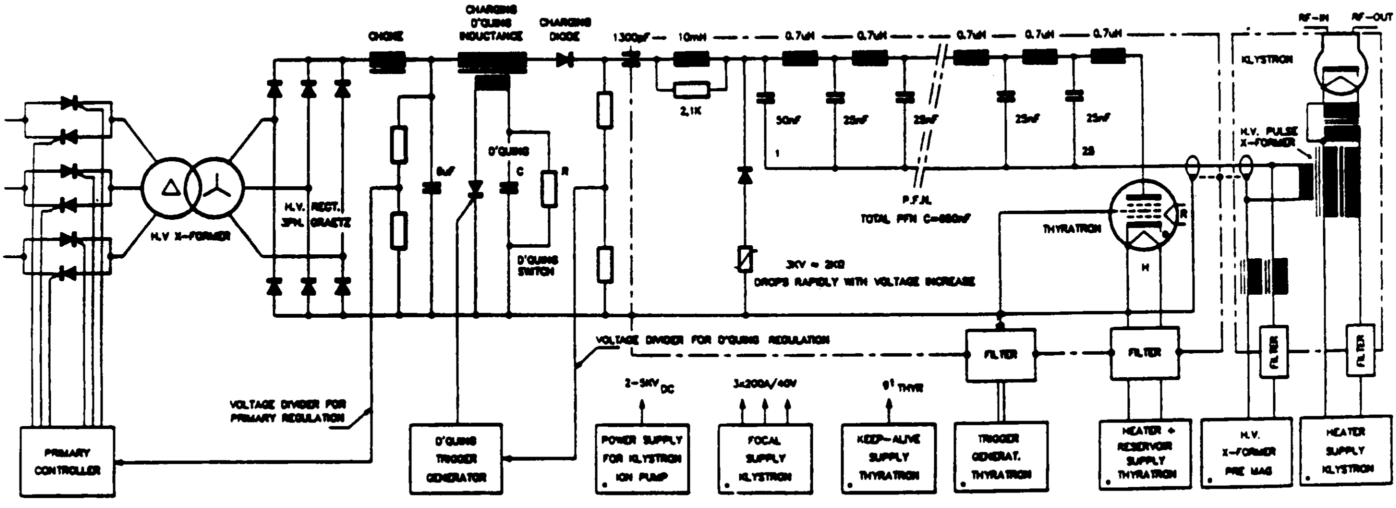

Figure 1: Simplified LIL modulator circuit diagram.

The klystron cathode voltage can be written as:

$$V_k = \frac{V_{PFN}}{2}(1+m)N$$

where N = Pulse transformer ratio

m = (R − Z)/(R + Z) the positive mismatch or reflection coefficient

And R is the referred klystron impedance and Z the impedance of the PFN.

This positive mismatch was introduced into the modulator design to improve the thyratron recovery by creating a relatively long period of low inverse voltage on the PFN. This de−ionises the thyratron prior to the re−appearance of positive voltage. The inverse voltage depends on the magnetising inductance of the pulse transformer and the total PFN capacitance. During recovery the pulse transformer is also being reset by the stabilised dc premagnetisation current of 17 amps flowing in the primary winding. The basic modulator circuit diagram is shown in Figure 1.

1.3 Operating parameters

The present set of operating parameters for the klystron modulators are shown in Table 1. The modulator system is equipped with two different klystron types; both having very similar characteristics and performance. These tubes have been made by Thomson in France, and Valvo in Germany, and are the models TH2094 and YK1600 respectively.

The Thomson klystron has a single ceramic output waveguide RF window, and a porous tungsten cathode impregnated with emissive material. The Valvo klystron has two similar RF windows and its cathode is nickel based with a thin coating of barium oxide. The data in Table 1 and the power curves of Figure 2 have been taken from a modulator that was operating up to 35MW peak power output using a Valvo klystron. The thyratron used is the KU275C from ITT.

Table 1: Present LIL Modulator Parameters

Accelerator Data:		
e+ production rate	4.8	10^{10} e^+/sec
Total No. LIL-V sections	4	
Electron beam hitting target	3.0	10^{11}
Electron beam energy	220	MeV
Klystron Data.		
Klystron frequency	2998.5	MHz.
Klystron voltage	275	kV
Klystron current	288	A
Microperveance	2.0	
- Peak output power	35.0	MW
- Peak input power	130	W
- Power gain	54	dB
- RF pulse width	4.5	μs
Modulator Data.		
Repetition rate	100	Hz
Thyratron anode voltage	42.0	kV
Thyratron anode current	3925	A
Pulse transformer ratio	1:13	
Voltage pulse width	6.5	μs
Nominal PFN impedance	5.0	ohms
Total PFN capacitance	0.625	μF
Peak charging current	7.7	A
PFN charging time	6.45	ms
Charging inductance	7.44	H

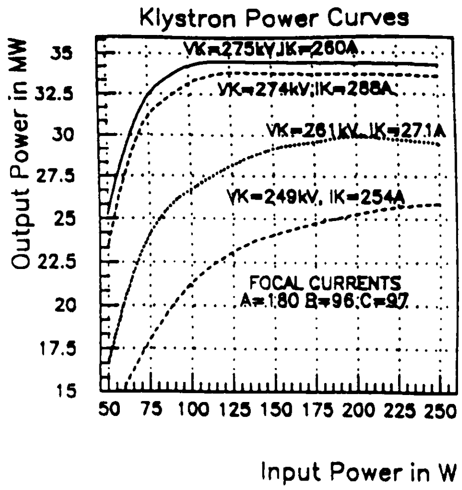

Figure 2: Power curves of a Klystron

2. Component reliability

2.1 High voltage components

The major high voltage components such as the 1:13 step−up pulse transformer, the isolating inductors in the premagnetisation circuit, the klystron heater transformer, and capacitive voltage divider are mounted in an oil filled tank. The klystron is seated on the cover plate with its heater connections inside the oil tank. This forms a modular and easily transportable unit improving the maintainability of the system. A triaxal 2 metre long cable connects the modulator cubicle (Faraday cage) to a high voltage socket on the tank unit, enabling easy disconnection for the removal of a klystron tank. These components have given almost trouble free operation since their installation. Some internal cooling and condensation problems which degraded the Diala B insulating oil and affected the calibration of the open high voltage capacitive dividers in the klystron tanks has been overcome. The klystron tank assembly with the transport frame is shown in Figure 3.

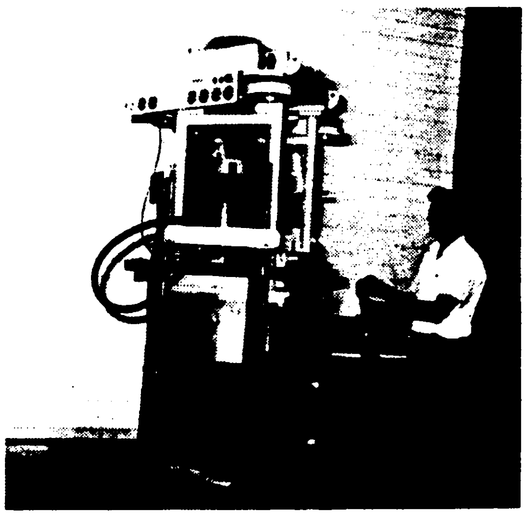

Figure 3: Klystron tank assembly and transport frame

Some problems were experienced during the early running period with the End of Line Circuit (EOLC) diodes and their grading capacitors as well as with the High Voltage Filter (HVF) connecting the charging circuit to the PFN.

The EOLC component operates in series with a parallel combination of a 5 ohm power resistor and an assembly of Varistors, and is connected to the PFN at a point furthest from the thyratron switch. The total assembly provides a low impedance load to reverse polarity in the case of a klystron fault, and so protects against large inverse voltages and currents on the PFN and in the thyratron. Internally the EOLC component consists of a series arrangement of diodes in parallel with grading capacitors and resistors. The original design has been modified to use stacks of high power rectifier diodes with high quality grading capacitors and resistors, built up into a low inductance assembly and packaged in an insulated oil container. A low inductance component is essential to prevent voltage spikes which can prematurely cut off the thyratron switch and so affect the recovery of the modulator circuit. The new EOLC diode assembly is shown in Figure 4.

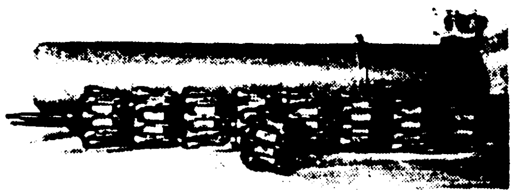

Figure 4: End of Line diode assembly

The original High Voltage Filter capacitors were made with large diameter tubes of polypropylene as the dielectric. Due to voltage breakdown problems these have been replaced with commercially made, low inductance capacitors. Also modified are the power damping resistors in the filter, which together with the capacitor protects the charging diodes and choke from being damaged by the fast rising thyratron wave propagating in the PFN. The original flame-sprayed aluminium end contacts of these tubular resistors have been replaced with metal caps machined from brass that reduce the current density in the contact region. More efficient air cooling methods are being tried [4] to reduce the overall operating temperature in preparation for higher repetition rate working. The components used in the new HVF assembly are shown in Figure 5.

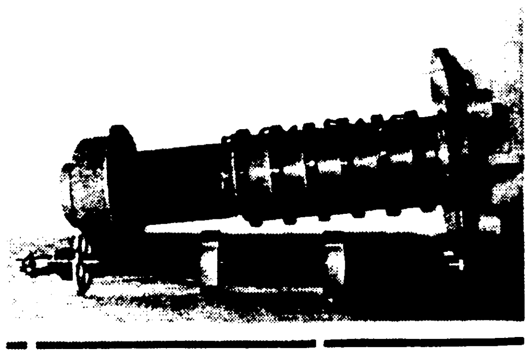

Figure 5: High voltage filter components

2.2 Thyratrons and Klystrons

The present six modulator stations are fitted with the same type of thyratron, and although these tubes have been moved around the modulators for various reasons, they all have accumulated approximately the same number of running hours. As with the SLAC experience, the good performance and long lifetime of LIL thyratrons is attributed to the regular adjustment of the reservoir voltages. The present useful lifetime for these tubes looks to be in excess of 16000 hours at the 100Hz rate with 35kV, 3400 Amps and a voltage pulse width of 6.5μs. The air cooled thyratron unit is shown in Figure 6.

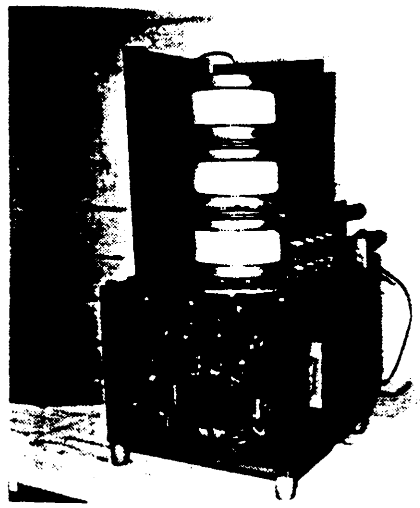

Figure 6: Air cooled thyratron unit

The Klystron tubes were all installed around the same time, with each now having accumulated about 14000 high voltage hours and 16000 heater hours. The peak output power from each klystron has varied over this operating period from 13 to 35MW, according to the required accelerator conditions. At present, individual klystron outputs are adjusted to give between 13.5 and 24MW, depending on their position in the linear accelerator and the number of sections being driven. The performance of each klystron has been regularly monitored, with checks being made on the power output and gain, using the nominal operational settings.

The present indications are that the average lifetime of the two types of klystrons will probably not exceed 15000 heater hours. This is based on klystrons having similar cathode structures used in other accelerators, and our own observations with these klystrons. The most useful indication of the actual condition of a klystron and its cathode is by its perveance. This value is usually expressed in terms of microperveance, or $\mu Perveance = I(V)^{-\frac{3}{2}}$. From the voltage and current measurements, the calculated klystron perveance data has been used, together with peak power and tube vacuum pressure to estimate the average lifetime and establish a replacement policy [5]. It has been proposed [6] that the klystron cathode end of life could be defined as when the perveance has dropped to 90% of the factory tested value. This level also corresponds to the drop in perveance defined as the

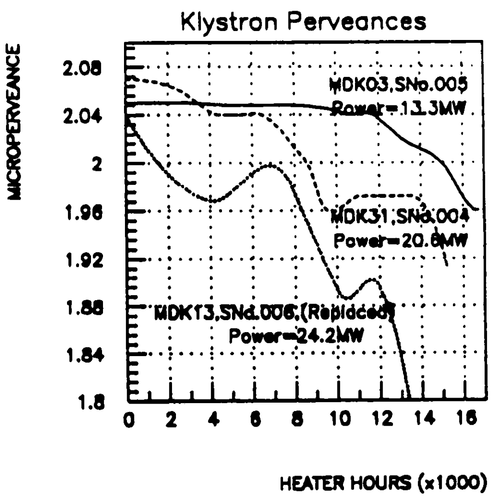

Figure 7: Klystron perveance changes with time

contractual end of life of the LIL klystrons. Figure 7 shows the progression of some of the measured perveance values from a group of three LPI modulators. One klystron in this group which has passed this 90% point suffered also from a large drop in gain and was replaced. It is being evaluated in a test modulator where these deficiences can be more readily accepted and compensated for. The experience so far shows that there is a fairly rapid reduction in perveance during the latter stages of a klystrons life and is most probably the time when the cathode emissive material has been largely depleted. During the early stages in the life of the cathode, the evaporation speed of this material has been shown [7] to follow approximately a law of $(t)^{-\frac{1}{2}}$, but the measured perveance, as shown in Figure 7, actually reduces more slowly.

Since each of the LPI klystrons are running with different output powers for a major part of the time, the effects of peak output power on the perveance ageing rate, using the limited sample of six klystrons, has been calculated.

The perveance ageing rate K is defined as:

$$K = \frac{\Delta \mu Perveance}{\Delta t}$$

An approximate fit from the available data is given in Figure 8.

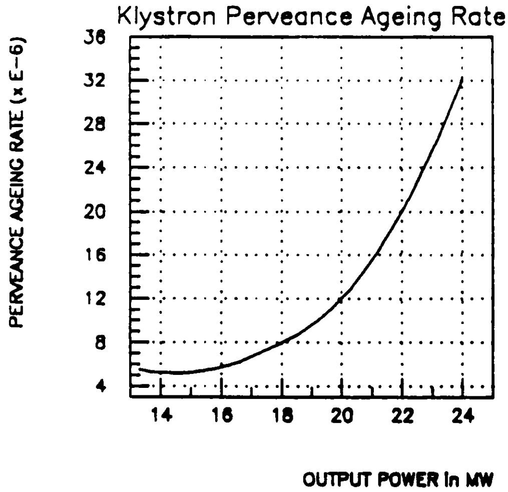

Figure 8: Klystron perveance ageing with power

3. Operational features

3.1 Computer control

The hard-wired safety and control system of each modulator, directly linked to its own front-end microprocessor, enables the status of the major elements to be displayed locally or at a remote operator console. These local microprocessors are linked via a computer network so that the status of any modulator can be controlled remotely as well. Having all the relevant data for a modulator on one screen eases the maintenance task, with photographs being regularly taken and used as part of the logbook data. One of these modulator data screens is shown in Figure 9. As well as including the safety features of Faraday cage doors, earthing rods and temperatures in the interlock chain, all currents and voltages are closely monitored and are part of the control loop. The Faraday cage together with other extensive electrical noise filtering are essential requirements for stable control by the computer network.

3.2 Stability

During the early running period, and particularly in hot weather when the klystron gallery temperature has exceeded 30 deg C, an important variation in the PFN charging voltage, as a function of ambient temperature was recorded. Using higher stability components in the control circuits of the D'Quing power supplies has reduced greatly these effects, and the voltage stability is now inside the 0.1% tolerance

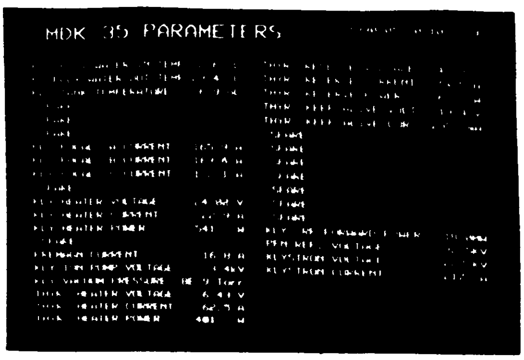

Figure 9: Klystron Modulator screen data

band.

The small thyratron trigger amplifiers which are used to trigger the main thyratron have been a source of timing stability problems. The anode delay time varying from unit to unit with age, has prompted the development of a replacement semiconducter amplifier. Cooling water temperature variations on the waveguide network and LIPS pulse compressors cause RF reflected power to be detected at the klystron which will stop a modulator via its interlock system. From recent tests the stability of the water temperature for the LIPS devices appears to be more critical than for the accelerating sections, contrary to the initial supposition.

4. Upgrading the system

4.1 Peak power requirements

From the possible schemes for an improved LPI e+ production rate [8], it is shown that the modulators will require some important modifications. The options to be considered in an upgrade are:

- Raise the output power from each modulator
- Increase the number of modulators
- Equip all modulators with LIPS pulse compressors
- Operate at a higher repetition rate

The typical performance power curves of a modulator equipped with a new klystron operating at the present 100 Hz rate has been given in Figure 2. The experience so far obtained shows that as the pe ıt-put power has been increased, by raising the klystron voltage, t ılt rate of some high voltage components also increased. The maximum output power that can be produced at repetition rates greater than 100 Hz with the present klystrons and the same RF pulse width will also be a limitation. From the modulator viewpoint, the positron production rate $\dot{N}_+$ can be seen as a function of the linac repetition frequency (Hz), the energy of the primary electron beam (GeV) and therefore the peak klystron power delivered to an accelerating section.

The present configuration with the five klystron modulators used for beam acceleration is shown in Figure 10 (A). The sixth klystron modulator used for driving the bunching cavity, just after the gun, is not shown in the diagram. A possible modulator configuration in an upgraded linac is shown in Figure 10 (B), where each klystron tube is driving a LIPS pulse compressor with two LIL accelerating sections. The likely positron accumulation rate, with all improvements including those to the modulators [9], is given in Figure 11. This shows the expected positron production rate as a function of peak klystron power output per modulator, and repetition frequency.
The positron accumulation rate has been defined as:

$$\dot{N}_+ = \eta_e \eta_p E^- N^- f$$

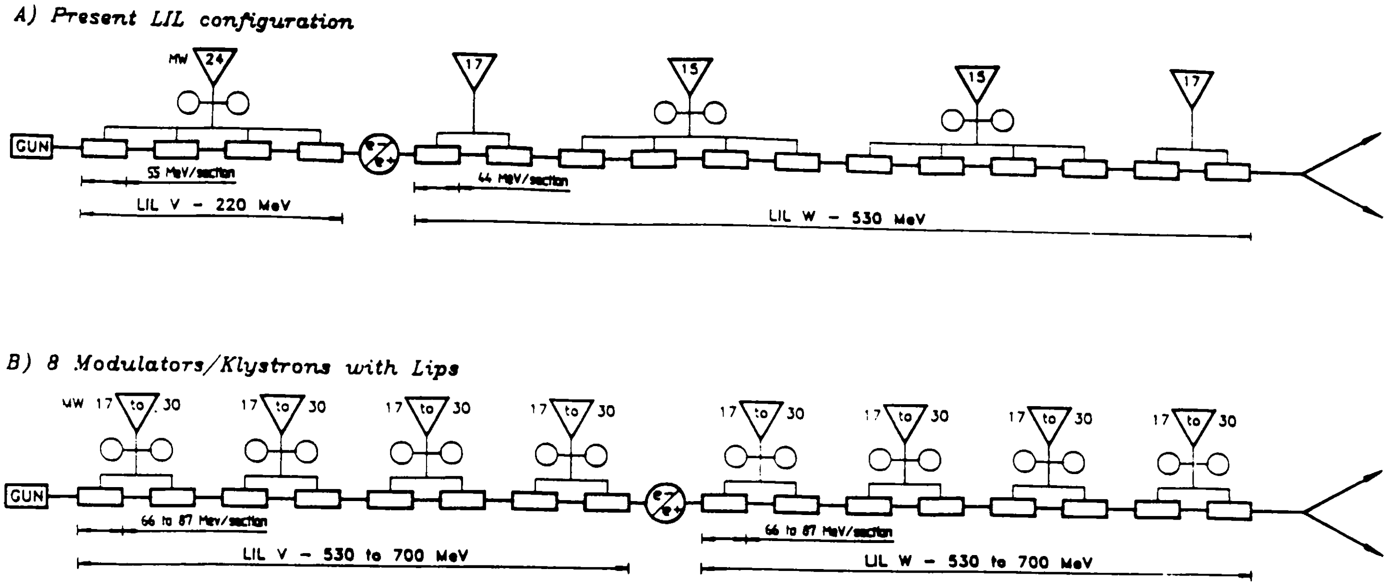

Figure 10: LIL Modulator configurations

where:

η_e = the Electron Positron accumulation efficiency (%)

η_p = target conversion efficiency (e^+/e^- per GeV)

N^- = number of primary beam particles

E^- = energy of the primary beam (GeV)

f = linac repetition frequency (Hz)

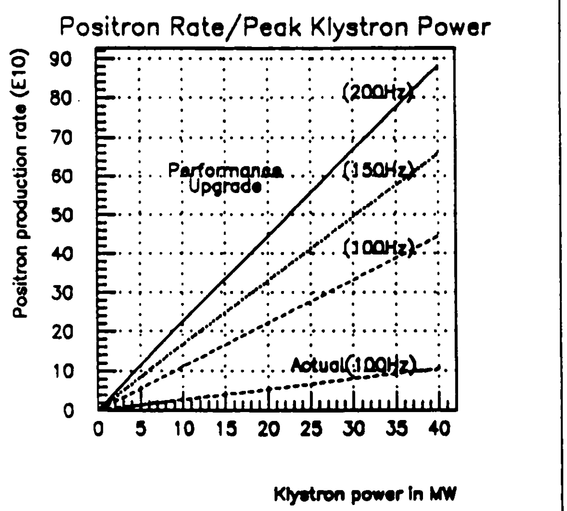

Figure 11

In principle, all these machine parameters may be improved upon, but only frequency and peak output power directly concern the modulator performance contribution.

4.2 Component changes

In order to obtain a 1.5 to 2.0 improvement factor in the positron production rate with the modulators, some major components need to be modified or changed. The klystron peak power output at frequencies above 100 Hz has to be de-rated, mainly because of average power limitations at the output RF window(s). The present double windowed klystron is capable of producing 30MW peak power at 150 Hz with an RF pulse width of 4.5μs, whilst the single windowed klystron can produce 25MW under the same conditions. Both tube types have yet to be tested with the LIL modulators in this operating mode. Other factors such as focal current optimisation and conditioning of the tubes at the higher repetition rate need also to be taken into account.

The thyratron performance at the increased repetition rate appears to be adequate, although we can probably expect a reduction in the tube lifetime and faster depletion of the gas reservoir, with more frequent tracking adjustments of the reservoir voltage. At present this adjustment is made about every 500 hours of operation. Table 2 shows the expected thyratron performance at the highest operating frequency that was considered.

Table 2: Thyratron Performance

Parameter	Tube max spec.	100Hz	200Hz
I peak (A)	5000	4300	4300
V peak (kV)	50	43	43
I av. (A)	8.0	2.7	5.4
I rms (A)	200	108	152
VA.pps(10E9)	400	18.5	37.0

The present PFN capacitors will have to be replaced if a change in the operating frequency is made. These units are an impregnated mixed dielectric type inside a polypropylene case. The increase in the average current at the higher frequency will increase the body temperature close to its maximum of 70 deg C, which would severely reduce the expected lifetime from its present value of about 10^{10} pulses.

The high voltage step-up (1:13) pulse transformer, similar to the original SLAC design, is adequately dimensioned to allow operation at 200 Hz. The peak pulse voltage and current is limited to 260kV and 260A with a pulse width of 6.5μs (70% level). At the higher repetition rate, with 17 amps of dc core bias and the klystron heater current flowing through the secondary windings, the transformer losses will increase to about 1200 watts. The high voltage tank cooling system will need some attention to handle this change.

The charging/D'quing power supply in each modulator was designed for 100Hz operation. Increasing the operating frequency requires that many of the power components need to be replaced if the voltage pulse width is maintained at 6.5μs, which would be the case. Most of these changes will require attendant modifications to the control and stabilisation circuits of the charging/D'Quing systems.

The expected positron production, and the operating parameters of each klystron modulator, with all improvements to the LIL accelerator being made is given in Table 3.

Table 3: Required LIL Modulator Parameters

Accelerator Data:		
e+ production rate	45	10^{10} e⁺/sec
Total No. LIL-V sections	8	
electron beam hitting target	4.6	10^{11}
electron beam energy	660	MeV
Klystron Data:		
Total No. main klystrons	8	
HF Peak output power	30	MW
HF pulse width	4.5	µs
Modulator Data:		
Repetition rate	150	Hz
Thyratron anode voltage	36	kV
Thyratron anode current	3400	A
Pulse transformer ratio	1:13	
Voltage pulse width	6.5	µs
PFN impedance	5.0	ohms
Total PFN capacitance	0.625	µF
Peak charging current	10.0	A
PFN charging time	4.3	ms
Charging inductance	3.3	H

5. Summary

During the last two years the LIL and the klystron modulators have become much more a production facility. Over 5000 hours of electron and positron beam time is now available for LEP and other users yearly. A large effort has been made to reduce the downtime due to modulator faults, and this is an ongoing commitment. Components with marginal performance characteristics such as the high voltage filters and the end of line diode assemblies have been redesigned for improved reliability. It was seen during the 1989 physics period that the fault rate was nearly proportional to the output power level of the klystrons, although this was not a limiting factor for the accelerator operation. The ageing trends of both the klystrons and thyratrons are being closely monitored and a tube replacement policy is being pursued to ensure adequate availability. In particular, the klystron lifetimes of both tube types in use are being compared with results obtained in other accelerator laboratories, and the methods used to prolong their useful life.

There are several possible scenarios for an eventual modulator upgrade. Each of them will enable a higher level of performance in the production of positrons. The scenario described in Figure 10 (B) is the one which will permit the greatest gain in the production rate, and requires the maximum amount of modification to the accelerator. However, before this is done, feasibility tests at 100 Hz will have to be made to observe the high accelerating field performance of two LIL sections powered by one klystron/LIPS assembly at 30 MW. With the present modulators it is not safely possible to increase, on a production basis, the repetition rate above 100 Hz, and the new frequency chosen should be a multiple of the basic mains 50 Hz to avoid internal synchronisation and stability problems. A frequency of 150 Hz is most appropriate for the final scenario. Output power tests, in collaboration with the klystron manufacturers, will have to be made in order to ensure reliable operation for this different mode. A modified high voltage charging/D'quing power supply and other system components will require life testing before large scale changes are made. The upgrading of the modulators will be part of an overall improvement programme for the LIL machine which requires that the equipment changes for improved performance do not degrade the present high reliability.

Acknowledgements

The authors wish to acknowledge the excellent technical work done by I. Kamber, J.P Perrine and J.C Thomi during the design and commissioning of the modulator system.

References

1. J.H.B Madsen *LEP Injector Linacs. CERN PS/LP Note 89-56*
2. Z.D Farkas et al. *SLED: A method of doubling SLAC's Energy. IX Conference on High Energy Accelerators. 1974*
3. J.P Perrine *Utilisation des Klystrons 35MW et des Thyratrons KU275C. CERN PS/LPI Note 87-32*
4. S.C Hutchins *Cooling for the LIL modulators HV Filters. CERN PS/LP Note 90-20*
5. P.D Pearce *Klystron replacement planning. CERN PS/LP Note 90-27*
6. M.A Allen et al. *Reliability and lifetime predictions of S Klystrons SLAC PUB - 4863*
7. G. Noel *Cathodes pour tubes hyperfréquences de grande puissance. Laboratoires d'Electronique et de physique Appliquée, Paris.*
8. J.P Delahaye, K. Hübner *Proposal for an Improved Positron Accumulation Rate in LPI. CERN PS/LP Note 89-32*
9. P.D Pearce *Upgrading the LIL modulators. CERN PS/LP Note 90-05*

---

0 No Bud-