

HIGH-FIELD ELECTRON LINACS

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ABSTRACT

High-field electron linacs are considered as potential candidates to provide very high energies beyond LEP. For almost twenty years little improvement has been made on linac technologies as they have been mostly kept at low and medium energies to be used as injectors for storage rings. Today, both their efficiency and their performances are being reconsidered, and for instance the pulse compression scheme developed at SLAC and introduced to upgrade the energy of that linac is a first step towards a new generation of linear accelerators. However this is not enough in terms of power consumption and more development is needed to improve both the efficiency of accelerating structures and the performances of RF power sources.

1. INTRODUCTION

After introducing briefly the needs for higher gradient electron linear accelerators by showing that simple extrapolation of present technologies would fail in trying to reach much higher energies, we shall review different ways of improving these conventional techniques and their related problems. Since high gradient means also high RF power we shall also present and discuss a new type of RF power source based on the double aim of reaching much higher peak power with short pulses and having much higher efficiencies.

The present report will not deal with totally new accelerating techniques such as laser-plasma and wake-field accelerators, since they are taken up by other lecturers.

2. EXTRAPOLATION OF PRESENT TECHNOLOGIES

There are three large electron/positron linacs operating in the world (Table 1) as injectors for storage rings (although LAL and SLAC were initially built as high-energy physics facilities).

Laboratory	Energy [GeV]	Accelerating length [m]	overall length [m]
LAL/ORSAY	2.3	230	360
KEK/TSUKUBA	2.5	320	400
SLAC/STANFORD	24	3050	3350

Table 1 Large linacs in the world

The accelerating gradient lies in the range of 8 to 14 MeV/m. Recently the SLAC linac has been upgraded to 33 GeV and soon is expected to reach 50 GeV with new klystrons followed by a pulse compression system<sup>1,2)</sup>. In the last mode of operation the accelerating gradient will

be as much as 17 MeV/m. Two bunches, electrons and positrons, will be simultaneously accelerated, then transferred in the two arms of a circular transport system in such a way that they will collide once at a given location. This will be the first linear collider (SLC) coming into operation in the world, at an energy level comparable with LEP stage 1. It will serve as a test bed for future linear colliders as well as for studying the intermediate boson  $Z_0$ .

In order to reach many hundred GeV or a few TeV in the center of mass with electrons and positrons, it appears that linacs are better suited than storage rings since circular machines would lead to enormous power being radiated in the bends; remember that in LEP, operating at 100 GeV per beam, each particle will lose 2.8 % of its energy per turn. Clearly the SLC scheme, with a single linac plus a circular transport system, will be also avoided for higher energies, and future linear colliders will consist of two linacs firing against each other.

Consider now a first step in the linac energy, by roughly one order of magnitude, using present SLAC technology for the accelerating sections. Table 2 gives the resulting constraints and three possible schemes have been considered, knowing that :

$$E_{acc} \propto [P_{input}]^{1/2}$$

$$P_{a.c.} \propto f_{rep} N_K \eta_K^{-1} P_K$$

where  $E_{acc}$  is the accelerating gradient,  $P_{input}$  the input RF power at the structure,  $f_{rep}$  the linac repetition frequency,  $N_K$ ,  $P_K$ ,  $\eta_K$  being respectively the total number of klystrons, the peak power and the efficiency of each klystron.

	SLAC (~ today)	Super SLAC (1)	Super SLAC (2)	Super SLAC (3)
E [GeV]	30	300	300	300
L [Km]	3	30	3	3
$N_K$	240	2400	240	960
$P_K$ [MW]	38	38	3800	950
$E_{acc}$ [MV/m]	10	10	100	100
$f_{rep}$ [Hz]	180	180	180	180
sections/klystron	4	4	4	1
pulse length [ $\mu$ s]	2.5	2.5	2.5	2.5
$P_{a.c.}$ [MW]	13.7	137	1370	1370

Table 2 Extrapolation of SLAC up to 300 GeV

Clearly a higher gradient keeps the linac length to a reasonable value but introduces strong constraints on the power. For instance new power sources need to be developed at the level of 1 GW peak. The state of the art in klystrons is 50 MW peak with 5  $\mu$ s RF pulse

length which can be compressed to increase the effective peak power by a factor 4. A 150 MW, 1  $\mu$ s klystron is also under development at SLAC<sup>3)</sup>.

Consider another exemple of a high gradient linear collider using the CERN site. On Fig. 1 two linacs have been drawn along a LEP diameter as if the circumference of LEP were the ultimate possible size for a new accelerator (this is not a statement). Table 3 shows the possible stages in energy that can be considered for this exemple<sup>4)</sup>. The first case uses conventional technologies such as iris loaded travelling wave structures and 50 MW, 5  $\mu$ s klystrons followed by a pulse compression system. However the power consumption

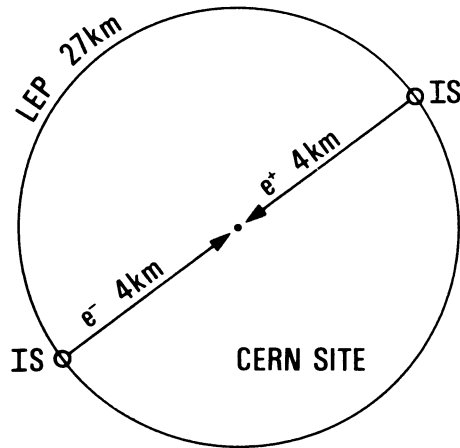


Fig. 1 LEP site with a linear collider

Gradient MV/m	Energy/beam GeV	a.c. Power/linac MW	Comments
25	100	200	conventional
125	500	1500	need for new power sources
250	1000	-	need for new power sources and new structures
1250	5000	-	new accelerating methods

Table 3 Possible stages for a linear collider along a LEP diameter

has been minimized by matching the accelerating structures to the pulse compressor (see next section), but even so it is too high to compete with the LEP storage ring at the same energy. The second case uses an accelerating gradient of 125 MeV/m which has been already reached on experimental structures. However it can only work if one uses 1GW, short pulse RF power sources which do not exist yet. In both cases a linac repetition rate of 1000 Hz has been considered.

Improvements on the power consumption may come from improvements in the efficiency of accelerating structures and also from some tricks such as for instance the use of pulse current trains that can lower the repetition rate for the same luminosity<sup>5)</sup>.

3. RF COMPRESSION SCHEME

3.1 - Present situation

Although this scheme can be considered as an already existing technique<sup>2)</sup>, it is worthwhile to recall the principles since one can expect to improve the efficiency of the system in the near future.

The pulse compression is schematically represented on Fig. 2 ; the first part of the

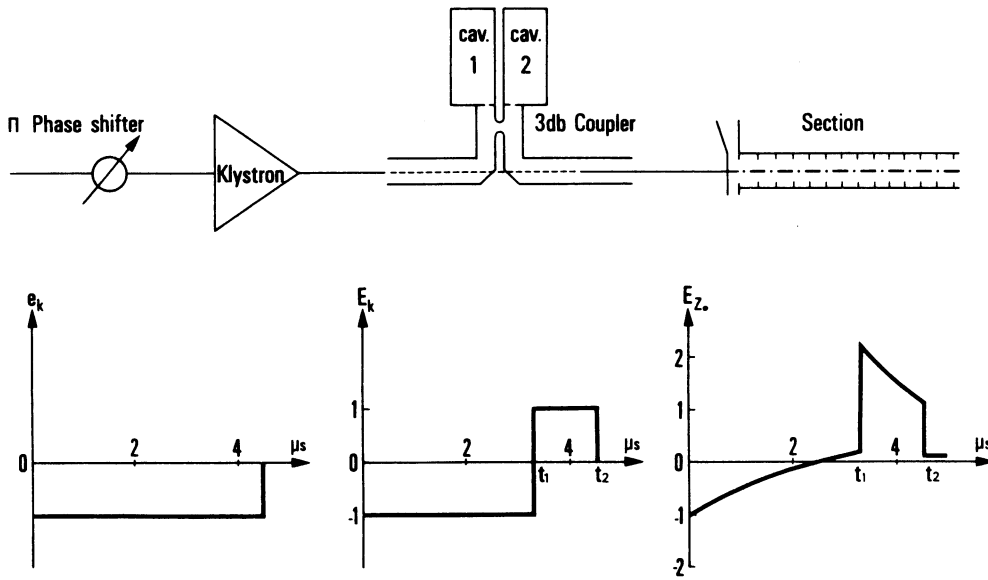


Fig. 2 Pulse compression scheme

long pulse from the klystron is stored in a couple of low loss cavities. At a given time  $t_1$  the input signal to the klystron is rapidly  $\pi$  shifted so that the energy is now reflected at the entrance of the storage cavities and directly goes to the structure. In addition the stored energy flows out of the cavities and also goes to the structure making the peak energy during the time interval  $[t_1, t_2]$  much higher than it would have been from a direct feed of the structure.

The method can be either used to increase the energy of an existing linac, or to save on the total number of power sources for a given output energy :

SLED (SLAC Energy Doubler)<sup>2)</sup>

Storage cavities are placed between the klystrons and the accelerating structures. The RF pulse length is  $5 \mu s$  and since the filling time of the structure is  $.8 \mu s$  one can adjust the switching time such that  $t_2 - t_1 = .8 \mu s$ . However the compression scheme has a poor efficiency and the maximum improvement factor on the peak power that one can expect is about 3 leading to an improvement factor  $\sqrt{3}$  on the accelerating gradient.

LIPS (LEP Injector Power Saver)<sup>6)</sup>

The scheme is used to reduce the number of klystrons by a factor 2 as shown on Fig. 3. Instead of feeding two structures from a single klystron, one can feed 4 structures with the

same total beam energy if the system is adjusted to increase the effective peak power by a factor 2. This improvement factor is lower than the previous one and can be obtained from a 3.5  $\mu\text{s}$  klystron pulse length, the filling time of the LEP injector Linac (LIL) structures being 1.2  $\mu\text{s}$ . It will be seen later that the improvement factor mainly depends on the initial klystron pulse length when all other parameters, such as for instance the filling time of the accelerating structures, have been optimized.

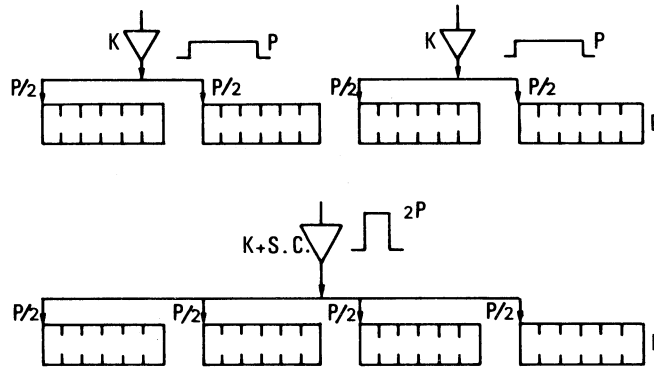


Fig. 3 The LIPS scheme

Up to here the maximum improvement factor one can reach with a conventional electron linac, by adding a compression system, is of the order of 1.7 and from there existing linacs might be able to operate with an accelerating gradient of the order of 35 MV/m, taking into account also the up-to-date klystrons and assuming that each klystron feeds a single structure. As will be seen in the next section, an additional improvement factor can be obtained by optimizing the parameters of the accelerating structures to match properly the compression system.

### 3.2 - Optimization of TW accelerating structures for SLED operation<sup>7)</sup>

The RF pulse shape due to the compression scheme, worked out by Z.D. Farkas et al.<sup>2)</sup>, is shown on Fig. 4. There are two regions of interest : region 1 which corresponds to a continuous increase of the stored energy in the cavities and region 2 which, after a  $\pi$  phase shift at the klystron input occurring at time  $t_1$ , corresponds to a relatively fast decay of the stored energy in these cavities to the benefit of the accelerating field.

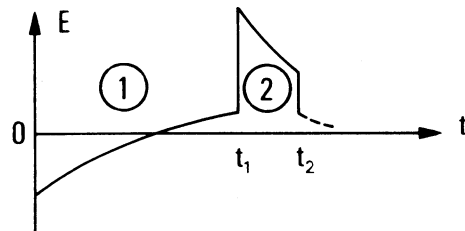


Fig. 4 Pulse shape due to compression

For a unit rectangular klystron pulse the combined field entering the accelerating section is :

$$E_1(t) = (\alpha - 1) - \alpha e^{-t/\tau_c} \quad \text{for } 0 < t < t_1$$

$$E_2(t) = \gamma e^{-\frac{t-t_1}{\tau_c}} - (\alpha - 1) \quad \text{for } t_1 < t < t_2$$

where

$\tau_c = 2Q_c/\omega(1+\beta)$  is the filling time of the storage cavities

$Q_c$  is the unloaded quality factor of the storage cavities

$\beta$  is the coupling coefficient of the storage cavities

$\alpha = 2\beta/(1+\beta)$

$$\gamma = \alpha(2 - e^{-t_1/\tau_c})$$

For a given peak power P from the klystron (rectangular pulse) the accelerating field at the input of the section would be :

$$E = E_0 \cdot E_{1,2}$$

$$E_0 = \left( P \frac{\omega r_o}{v_{go} Q} \right)^{1/2}$$

where  $r_o$ ,  $v_{go}$ ,  $Q$  are respectively the shunt impedance per unit length, the group velocity and the quality factor of the first accelerating cell.

In a constant impedance structure all the cells are identical, and hence  $r$ ,  $v_g$ ,  $Q$  will remain constant along the structure.

Due to power dissipation in the cells the amplitude of the propagating field will decrease exponentially. At a given azimuth  $z$  the field becomes :

$$E(z, t) = E_{1,2} [t - \Delta t(z)] e^{-\frac{(\omega/2v_g Q)z}{v_g}}$$

where index 1,2 refers to the two different time intervals as previously defined. Here again the expression needs to be multiplied by  $E_0$  for a given peak power P from the klystron.

$\Delta t(z)$  is the wave propagation time from the origin up to  $z$  :

$$\Delta t(z) = \int_0^z \frac{dz}{v_g(z)} = \frac{z}{v_{go}}$$

It looks interesting to use the normalized variable  $z' = \frac{z}{L}$  where L is the length of the structure. Then :

$$\Delta t = \tau_a z'$$

with

$$\tau_a = \frac{L}{v_{go}}$$

Depending whether the time  $t - \Delta t$  appears to be below or above  $t_1$ , the field  $E_1$  or  $E_2$  should be used. That tells us that a field discontinuity will appear at some location  $z'_1$  in the structure such that :

$$t - \Delta t = t_1$$

or  $t - t_1 = \tau_a z'_1$  .

If  $z'_1 < 1$  the energy gain along the structure is the contribution of two field integrals :

$$V(t) = \int_0^{z'_1} E_2[t - \Delta t(z')] e^{-\frac{\omega\tau_a}{2Q} z'} dz' + \int_{z'_1}^1 E_1[t - \Delta t(z')] e^{-\frac{\omega\tau_a}{2Q} z'} dz'$$

where now  $t$  represents the time at which the particle traverses the structure (the transit time of the particle is negligible compared to the filling time of the structure).

Let us call  $V_1$  and  $V_2$  the integrals relative to  $E_1$  and  $E_2$ . One gets :

$$V = V_1 + V_2$$

$$V_1(z'_1) = -(\alpha - 1) \frac{T_1}{\tau_a} \left[ e^{-\frac{\tau_a}{T_1} z'_1} - e^{-\frac{\tau_a}{T_1} z'_1} \right] - \alpha \frac{T_2}{\tau_a} e^{-\frac{t_1}{\tau_c}} \left[ e^{\frac{\tau_a}{T_2} - \frac{\tau_a}{\tau_c} z'_1} - e^{-\frac{\tau_a}{T_1} z'_1} \right]$$

$$V_2(z'_1) = (\alpha - 1) \frac{T_1}{\tau_a} \left[ e^{-\frac{\tau_a}{T_1} z'_1} - 1 \right] + \gamma \frac{T_2}{\tau_a} \left[ e^{-\frac{\tau_a}{T_1} z'_1} - e^{-\frac{\tau_a}{\tau_c} z'_1} \right]$$

with :  $\frac{1}{T_1} = \frac{\omega}{2Q}$

$$\frac{1}{T_2} = \frac{1}{\tau_c} - \frac{\omega}{2Q} .$$

It is interesting to look at the behaviour of the function  $V(z'_1)$  in the interval  $0 < z'_1 < 1$ . It can be shown numerically that for each value of  $z'_1$  there is a value of  $\beta$  which maximizes the energy gain. This has been taken into account in the plots of Fig. 5. where it appears that the maximum energy gain corresponds to  $z'_1 = 1$ , which means that the beam should enter the structure at time  $t = t_2 = t_1 + \tau_a$  and that the width of the compressed pulse must be equal to the filling time of the structure.

The study will continue by considering only this optimum case for which :

$$V_1 = 0$$

$$V = V_2(z'_1 = 1) .$$

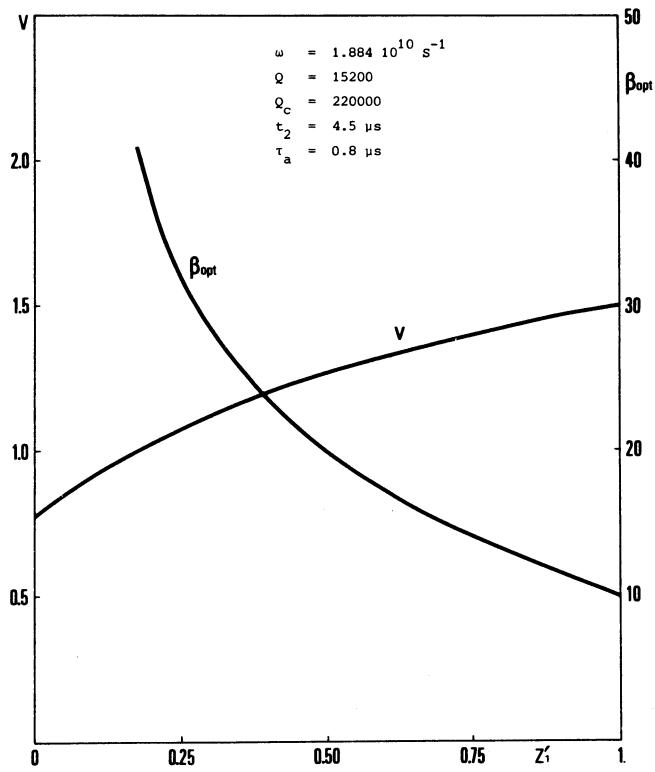


Fig. 5 Multiplication factor for a constant impedance structure as a function of the beam timing

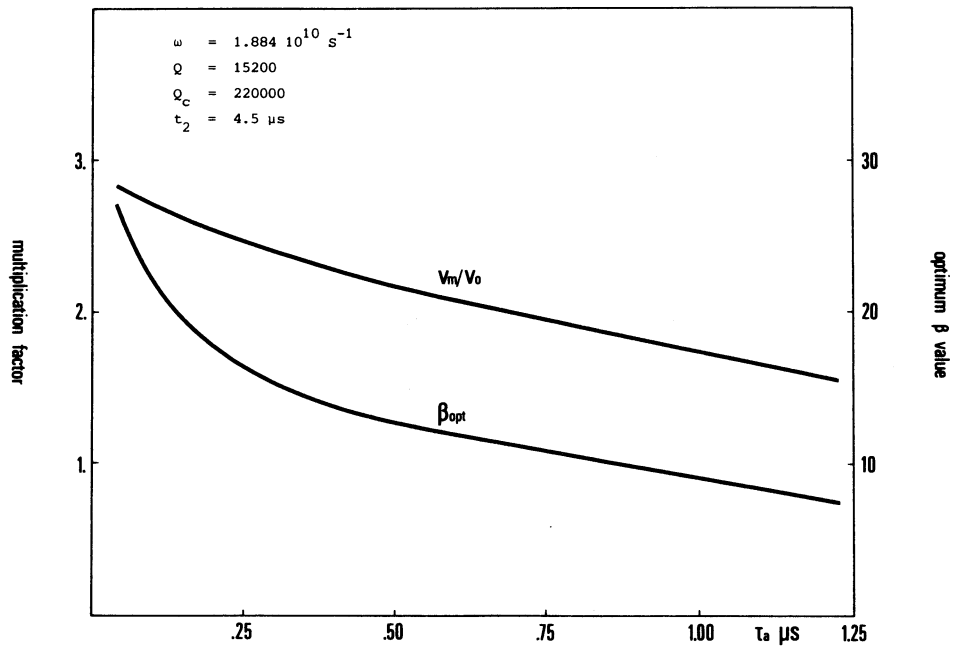


Fig. 6 Multiplication factor versus the filling time of a constant impedance structure



This leads to :

$$V_M = (\alpha - 1) \frac{T_1}{\tau_a} \left[ e^{-\frac{\tau_a}{T_1}} - 1 \right] + \gamma \frac{T_2}{\tau_a} \left[ e^{-\frac{\tau_a}{T_1}} - e^{-\frac{\tau_a}{\tau_c}} \right] .$$

However this is not the exact energy multiplication factor since for a unit pulse entering a constant impedance structure the energy gain over a unit length is :

$$V_0 = \frac{T_1}{\tau_a} \left( 1 - e^{-\frac{\tau_a}{T_1}} \right) .$$

Hence the real multiplication factor is the ratio  $V_M/V_0$ . For each value of  $\tau_a$  there is a value of  $\beta$ , hence a value of  $\tau_c$ , which maximizes this multiplication factor as seen on Fig. 6.

A similar treatment for the case of a constant gradient structure would show that the efficiency of this type of structure is either the same, at low filling time, or slightly less, at high filling time, than the efficiency of a constant impedance structure. Hence we shall proceed with constant impedance structures in what follows.

It has been seen that for a given structure length there was an ensemble of optimum values for  $\beta$ ,  $\tau_c$  and  $\tau_a$  which realize the correct matching between the SLED pulse and the accelerating structure. It is interesting to look in more detail at the performances of these structures versus different parameters, like the parameter setting of the storage cavities ( $Q_c$ ,  $\beta$ ), the length and the aperture of the accelerating structures, the width of the direct peak power pulses from the klystrons.

For a constant impedance structure, fed by a klystron peak power pulse  $P$ ,  $t_2$ , through a couple of storage cavities with a  $\pi$  phase shift at time  $t_1 = t_2 - \tau_a$ , the energy gain is :

$$V = \left( P \frac{R\omega}{Q} \tau_a \right)^{1/2} \left\{ \frac{\gamma}{\tau_a} \left( \frac{1}{\tau_c} - \frac{\omega}{2Q} \right)^{-1} \left( e^{-\frac{\omega \tau_a}{2Q}} - e^{-\frac{\tau_a}{\tau_c}} \right) + (\alpha - 1) \frac{2Q}{\omega \tau_a} \left( e^{-\frac{\omega \tau_a}{2Q}} - 1 \right) \right\}$$

where  $R = rL$  is the total shunt impedance of the structure, and  $\tau_a = L/v_g$  its filling time.

The fact that for a given length there is an optimum value for  $\tau_a$  means that there is an optimum value for  $v_g$ , hence for the iris aperture  $2a$  of the structure. To illustrate this point let us consider the cell characteristics of the LEP injector linacs (LIL)<sup>8)</sup> which operate at 3 GHz in the  $2\pi/3$  mode :

$$\begin{aligned} Q &= 15200 \\ r &= 86 - 3.6 (2a)^2 \\ v_g/c &= (2a)^{3.23}/891 \end{aligned}$$

where  $2a$ , the iris diameter, is expressed in cm while the shunt impedance  $r$  is in  $M\Omega/m$ .

Figure 7 shows the evolution of the RF performances versus the iris diameter, for different structure lengths. As the length decreases the iris diameter also decreases in order to get the maximum gain corresponding to the right matching value for  $\tau_a$ . In all cases  $\beta$  and  $\tau_c$  have been optimized.

The maximum energy gains obtained for each structure length are plotted on Fig. 8 as well as the corresponding values of  $\tau_a$  and  $\tau_c$  which clearly remain constant.

A systematic study of the energy gain as a function of the other parameters, like  $t_2$ ,  $Q_c$  and  $Q$  ( $\frac{r}{Q} = \text{cte}$ ) leads to the following conclusions :

- neither  $Q$  nor  $Q_c$  have influence on the optimum value of  $\tau_a$ . Both give a little effect on the optimum energy gain. The optimum value of  $\tau_c$  changes with  $Q_c$
- the optimum value of  $\tau_a$  changes with the width  $t_2$  of the direct klystron wave. For long pulses one can hold a longer filling time, but that means a smaller aperture for a fixed structure length. An important increase of the energy gain follows an increase of  $t_2$
- one of the most important features, considering the results plotted on Fig. 8, is that the total energy gain from one klystron source will be higher if the power is shared between smaller structures, for the same total length. This fact is illustrated on Fig. 9, assuming no power losses in the RF networks, and knowing that the energy gain follows the square root of the input power. Of course smaller structures, when optimized, will have smaller apertures and the interesting result is that the minimum structure length will directly depend on the beam aperture requirement. For instance a minimum aperture of 1.8 cm would lead to a design length of 1.8 m for LIL type cells, according to Fig. 10.

In order to design an optimum linac structure under SLED operation, it is useful to draw design curves having the main design parameters,  $P_{\text{klystron}}$ ,  $Q$ ,  $Q_c$  and  $t_2$ . Such a design example is shown on Fig. 11. If one introduces a design constraint such as  $(2a)_{\text{min}} = 2.0 \text{ cm}$  one gets directly the remaining design parameters which in the present case are :

$$\begin{aligned} \tau_c &= 2.12 \mu\text{s} \\ L &= 2.5 \text{ m} \quad \tau_a = .8 \mu\text{s} \\ \beta &= 8 \quad t_1 = 4.2 \mu \end{aligned}$$

If a single structure is fed by one klystron the average accelerating gradient becomes 52 MeV/m. A smaller value for  $(2a)$  would lead to a higher gradient, for instance  $2a = 1.65 \text{ cm}$  gives 75 MV/m and the corresponding structure length is 1.3 meters.

Finally with short constant impedance structures optimized to match the SLED conditions, and commercially available klystrons one can get close to 100 MeV/m in a short term future.

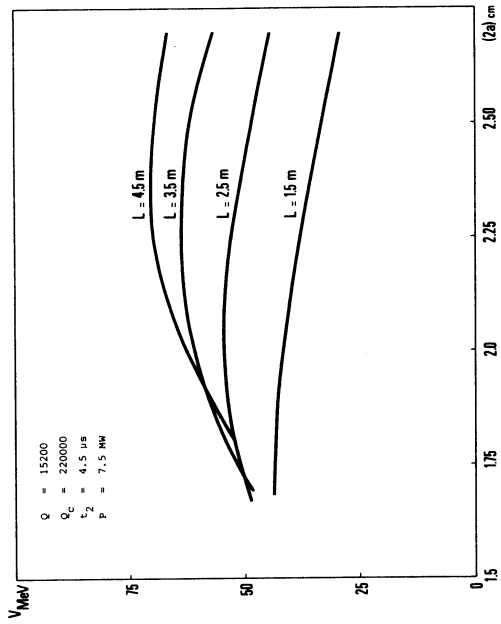


Fig. 7 Energy gain of a constant impedance structure versus the iris diameter and the structure length

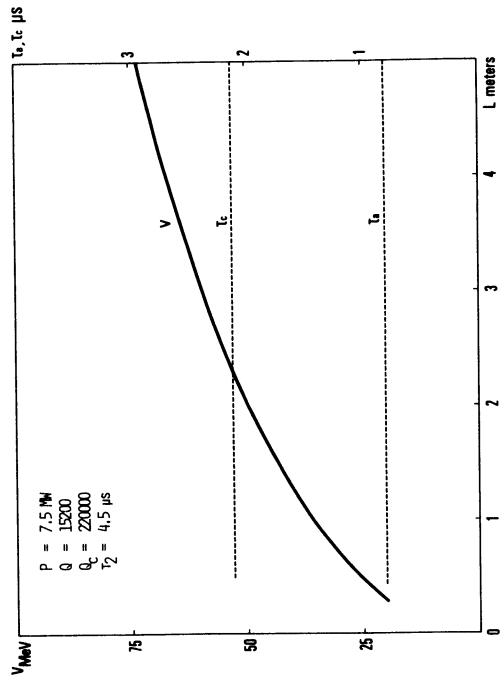


Fig. 8 Maximum energy gain as a function of the structure length

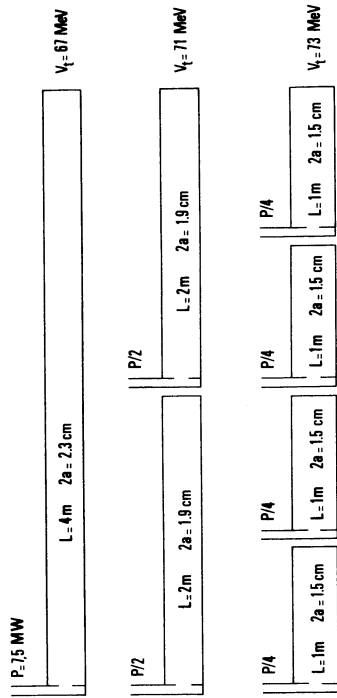


Fig. 9 Total energy gain from a single klystron as a function of the number of structures, for a given total length

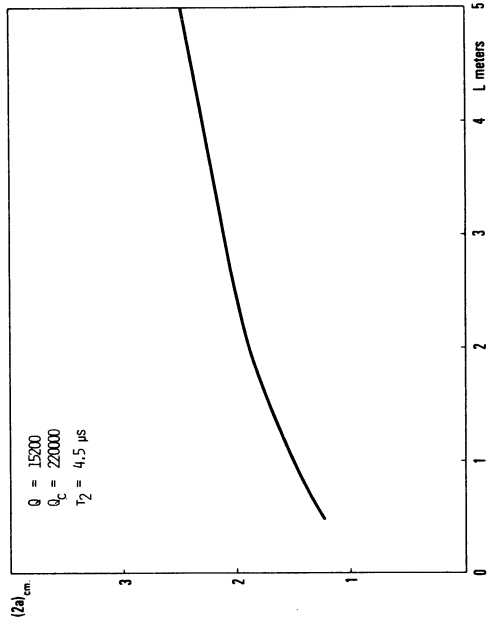


Fig. 10 Optimum aperture of an iris loaded structure versus the structure length

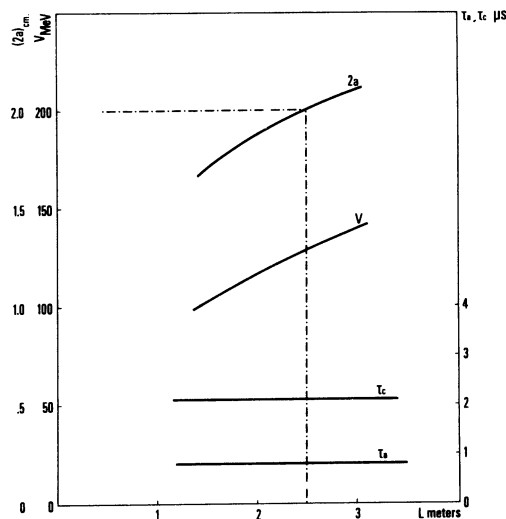


Fig. 11 Design example :  $P = 40 \text{ MW}$ ,  $Q = 15200$ ,  
 $Q_c = 180000$ ,  $t_2 = 5 \mu\text{s}$

#### 4. ULTIMATE ACCELERATING GRADIENTS IN CONVENTIONAL STRUCTURES

A question can be raised now : can we reach in practice the gradient previously mentioned and can we go even further ?

The answer to the first part of the question is mainly related to breakdown limits in warm structures and will be treated in this section. If no limitation occurs one way to go further consists of improving both the efficiency of accelerating structures and the peak power of RF sources (their efficiency too) and this will be treated in the next two sections.

##### 4.1 - The Kilpatrick criterion

Breakdown phenomena may occur at high field level on the walls of accelerating structures and they are not very well understood at microwave frequencies. The study done by Kilpatrick<sup>9)</sup> is one of the few investigations of breakdown phenomena and was in the past very often referred to by accelerator designers. He empirically derived a relationship between frequency and maximum electric field :

$$f = 1.643 E_{\text{max}}^2 \exp(- 8.5/E_{\text{max}})$$

where  $f$  is the RF frequency in  $\text{MH}_z$  and  $E_{\text{max}}$  is the maximum electric field in  $\text{MV/m}$ . At  $f = 3000 \text{ MH}_z$  this relation predicts  $E_{\text{max}} = 46.8 \text{ MV/m}$ .

The corresponding maximum accelerating field now depends on the type of structure. For instance disk loaded waveguides have a ratio  $E_{\text{wall}}/E_{\text{acc}}$  of the order of 2, hence the maximum expected gradient would be 23  $\text{MV/m}$ . This could be one reason why accelerating gradients have been kept below this value for a long time, but certainly another good reason was that the klystron peak power was still low and long accelerating structures were making a better use of this power in terms of maximum beam energy per klystron (no SLED). The overall linac length was not a big worry at that time.

Accelerating structures with higher shunt impedances would lead to lower maximum accelerating gradients since, as a matter of fact, the ratio  $E_{\text{max}}/E_{\text{acc}}$  increases when the shunt impedance increases.

Since recently the need for higher gradients became more and more obvious and new checks of the Kilpatrick criterion became of real concern at a few places. As a result it is now believed that the Kilpatrick criterion is pessimistic, at least under pulsed RF conditions.

#### 4.2 - The experiment at VARIAN<sup>10)</sup>

The experimental set up is shown on Fig. 12, where a single nose cone cell is fed by a magnetron (2.6 MW, 4.4  $\mu$ s).

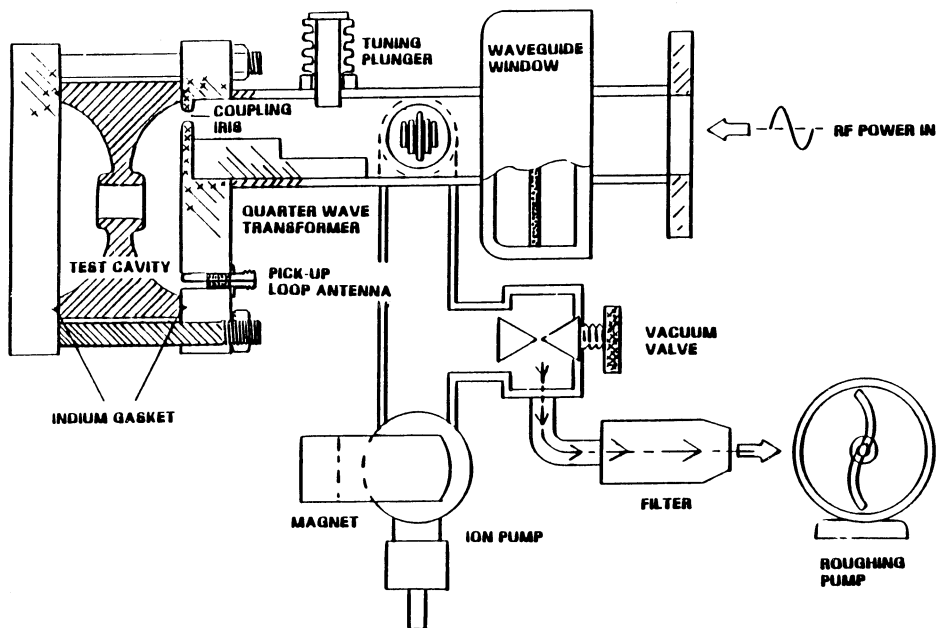


Fig. 12 A cross-sectional view of the cavity test system

In this experiment the repetition rate could be varied between 70 and 300 pps while the output peak power could be varied from 0.2 to 2.6 MW.

The type of cavity which is used has a high shunt impedance, as much as 130  $M\Omega/m$ , at 3  $GH_z$ , and the corresponding  $E_{\text{wall}}/E_{\text{acc}}$  ratio is of the order of 8. The observed breakdown limit corresponded to an accelerating field of 30 MV/m and a maximum field of 240 MV/m on the inner surface of the cell. With different geometries corresponding to different  $E_{\text{wall}}/E_{\text{acc}}$  ratios the maximum field was roughly the same.

It was also observed that above a certain level of wall polishing there was no effect on the breakdown limit. The limit also was found to be independent of the repetition frequency in the range previously mentioned.

From this experiment one can conclude that the maximum surface electric field can be at least as high as five times the limit predicted by Kilpatrick. Extrapolating this result to disk loaded cavities one can expect at least accelerating gradients close to 120 MV/m.

#### 4.3 - Experiments at SLAC<sup>11,12)</sup>

The first high gradient test at SLAC was done on the normal SLAC accelerating structures. In order to increase the gradient two klystrons operating in the SLED mode were combined, so that each of the four sections normally fed by one klystron could receive an input peak power as high as 87 MW (Fig. 13).

The corresponding SLED field in the sections was then up to 32 MV/m on the axis and 65 MV/m on the walls. At this level no breakdown occurred in the sections.

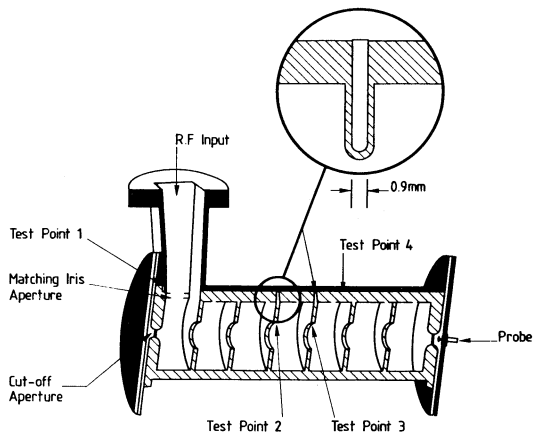


Fig. 14 Resonant structure used for the second experiment. Test points indicate locations of thermocouples

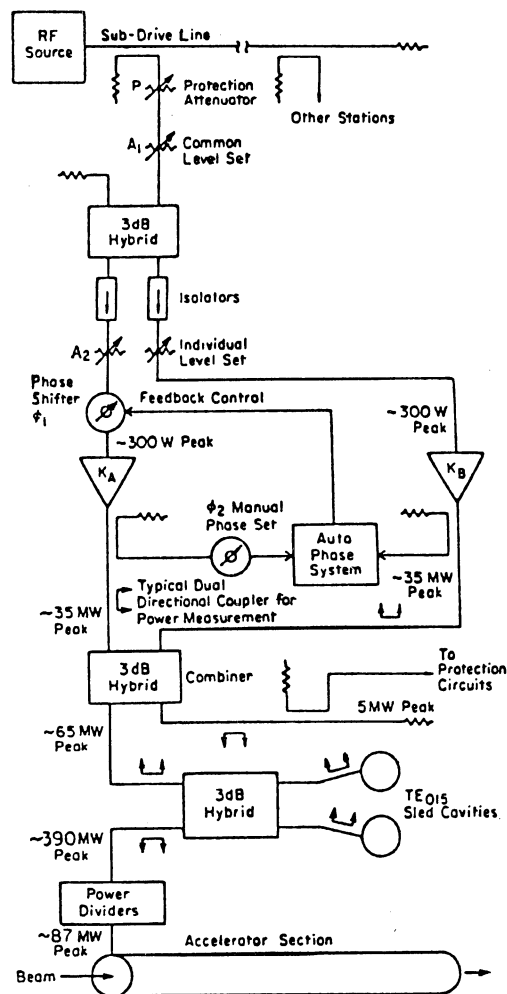


Fig. 13 The first experimental configuration

In order to increase the gradient a second experiment was set up in which a short disk-loaded structure was designed to operate in the  $2\pi/3$  S.W. mode (Fig. 14).

The cavity fed by 30 MW RF peak power did not show breakdown problems after a short processing. The maximum equivalent travelling wave accelerating and surface fields in these conditions were respectively 133 MV/m and 259 MV/m.

However it should be noticed that in this experiment considerable X-ray radiation was detected around the section corresponding to a strong field emission.

#### 5. A SURVEY OF ACCELERATING STRUCTURES

Previous experiments tell us that accelerating gradients of the order of 100 MV/m can be achieved with conventional disk loaded structures, but this will need very high peak

power and correspondingly high average power to fit the luminosity requirements in a linear collider.

Efforts have already been made to improve the efficiency of accelerating structures and at least four types of accelerating structures, either operating in L-band or in S-band, have been developed for the acceleration of electrons (Fig. 15). One can make the following remarks :

- the disk loaded structure is very well known since it has been used for a long time in linac design. It has a relatively low shunt impedance but a very good ratio  $E_{\max}/E_{\text{acc}}$ .

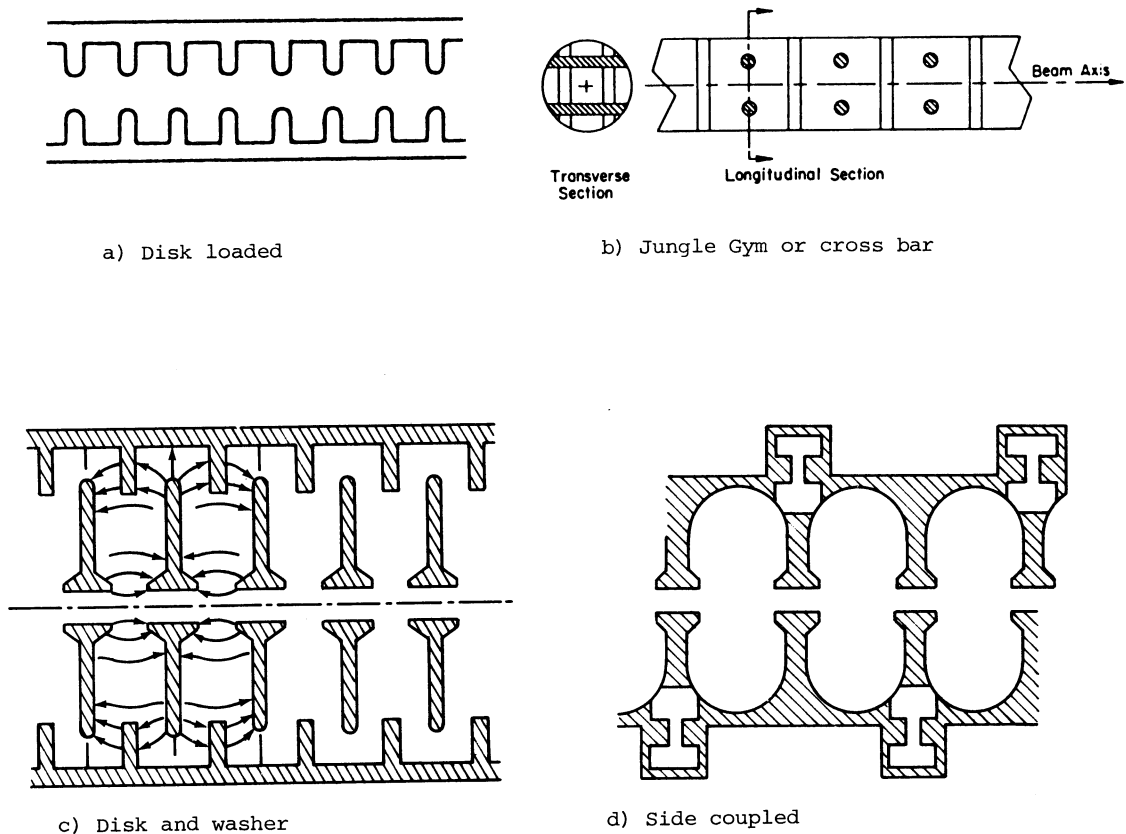


Fig. 15 Different types of accelerating structures

- The jungle gym structure has been first developed at low frequency. Since it has no revolution symmetry it is hard to study this structure with computer codes, and hence it needs more prototype work. However it is expected to get from this structure an improved shunt impedance with a high group velocity.

- The disk and washer structure is an open structure, as the previous one, which makes the wall losses smaller and correspondingly leads to a higher shunt impedance. It has also a higher  $Q$  but not a higher  $r/Q$ .

- The side coupled structure has a very high shunt impedance but a very bad ratio  $E_{\max}/E_{\text{acc}}$ .

The last two structures are quite complicated to build, and up to now they have been mostly considered in the S.W. mode according to their high shunt impedance.

From the power consumption point of view it is well recognized that for a given type of structure, operation in the S.W. mode is less efficient (although not obvious when considering small linear accelerators) than operation in the T.W. mode if correct matching of the source is made in both cases<sup>13)</sup>. Hence it is still preferable to consider T.W. structures for very high energy linacs and in that case the parameters of real importance are  $r/Q$ ,  $E_{\max}/E_{\text{acc}}$  and  $v_g/c$ . For these reasons it is believed that the jungle gym structure may become a good possibility but still needs more development. In the meantime the old disk loaded structure will remain a good candidate.

Another advantage of the T.W. accelerating structure comes from the fact that it can be used in the SLED mode. Moreover, if the group velocity is high the klystron pulse can be made very short and correspondingly the peak power can be increased which is the right direction to follow in the non SLED case.

Table 4 compares the performances of several structures in the T.W. mode, at different frequencies<sup>14)</sup>. The disk and washer is also shown for comparison.

	$r$ (M $\Omega$ /m)	$Q$	$v_g/c$	$L$ (m)	$\tau_a$ ( $\mu$ s)
<u>2856 MHz</u>					
Disk-Loaded (a = 1.16 cm)	56	13,300	.012	3	.83
Disk-Loaded (a = 1.50 cm)	46	13,000	.035	6	.57
Disk and Washer	76	32,000	--	--	--
Jungle Gym ( $\pi/2$ )	51	9,000	.20	6	.10
Jungle Gym ( $\pi/3$ )	60	9,000	.10	6	.20
<u>4040 MHz</u>					
Jungle Gym ( $\pi/2$ )	61	7,500	.20	6	.10
Jungle Gym ( $\pi/3$ )	71	7,500	.10	6	.20
<u>5712 MHz</u>					
Jungle Gym ( $\pi/2$ )	72	6,500	.20	6	.10
Jungle Gym ( $\pi/3$ )	85	6,500	.10	6	.20

Table 4 comparison of structure for a collider

It is still worthwhile developing short disk loaded structures in the frame of improved power sources.

#### 6. RF POWER SOURCE : THE LASERTRON

Up to now pulsed klystrons have been used to provide high RF peak power to electron accelerating structures. Peak powers up to 50 MW within 5  $\mu$ s pulse length have already been achieved but the efficiency of these devices is still below 50 %. A higher peak power klystron, about 150 MW, at a shorter pulse length, about 1  $\mu$ s, is under development at SLAC<sup>3)</sup>,



and it seems very difficult to go much higher. As a matter of fact high beam power either requires a higher beam current which would create strong space charge effects, or a higher accelerating voltage which would reduce the bunching efficiency, hence the amount of power contained in the fundamental and the extraction efficiency.

To overcome these difficulties, although not proven to be fundamental limitations, a new microwave RF power tube has been recently proposed<sup>15,16)</sup> in which a photocathode, illuminated by a modulated laser, emits short, dense current pulses which, after being accelerated, traverse an output cavity where the RF beam modulation is extracted (Fig. 16).

Here, a high accelerating voltage is necessary to compensate for the space charge forces which otherwise would distort the emitted short bunches and reduce the extraction efficiency. Since in principle the laser can provide a train of such bunches with a given repetition rate, the accelerating voltage can be d.c.

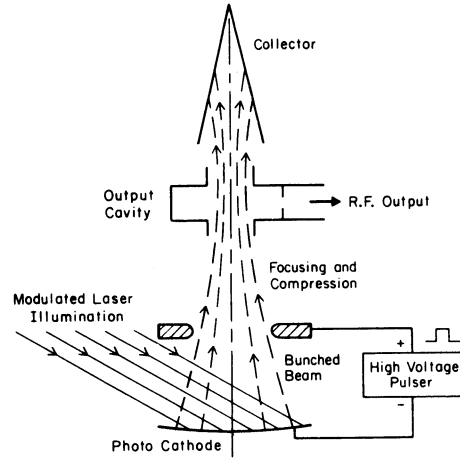


Fig. 16 Schematic of a photocathode microwave power source

Considering the fast pulsed photo-emission it is believed that the maximum charge which can be extracted per pulse from the photocathode is equal to the superficial charge<sup>17)</sup>:

$$Q = \epsilon_0 E_{\perp} S = \frac{\epsilon_0 S}{d} V = CV$$

where  $E_{\perp}$  is the accelerating field at the photocathode,  $S$  the useful area of the photocathode,  $d$  the distance between the cathode and the anode,  $C$  the gun capacitance and  $V$  the accelerating voltage.

This maximum charge is twice the space charge limit, showing that the limitation of such a tube is very different from that of a klystron. As a matter of fact, if  $f_{RF}$  is the repetition frequency of the laser pulses, the average current per laser burst is:

$$I_o = f_{RF} CV$$

and the beam power:

$$P_b = f_{RF} CV^2$$

while in a klystron the maximum current is related to the voltage through a parameter  $k$  called perveance:

$$k = I_o / V^{3/2}$$

$$P_b = k V^{5/2}$$

A 2-D simulation of the lasertron has been already performed<sup>18)</sup> which, for a given accelerating voltage, shows an increase of the energy spread and an increase of the bunch length above a certain average beam current, or beam power (Fig. 17).

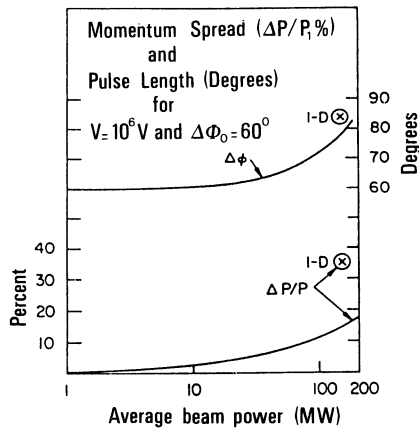


Fig. 17 Pulse length and momentum spread versus beam power

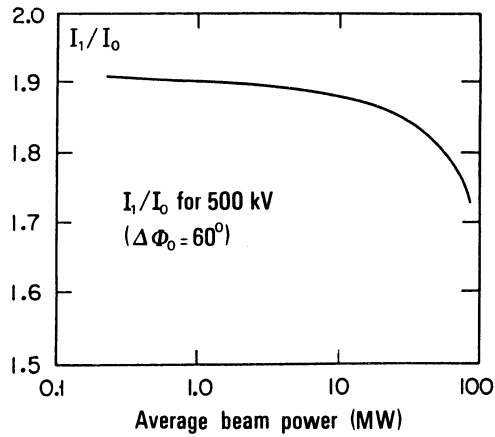


Fig. 18 Amplitude of the fundamental versus beam power

A corresponding decrease of the ratio  $I_1/I_0$ , where  $I_1$  is the amplitude of the first harmonic of the current modulation, is shown on Fig. 18, leading to a decrease of the efficiency and to a saturation of the extracted RF power. This is shown on Fig. 19 for the case of the prototype under consideration at SLAC<sup>19)</sup>. Improvement of the saturation level would follow an increase of the accelerating voltage.

The main parameters of the SLAC prototype<sup>20)</sup> are given in Table 5. The power level is comparable to the peak power of the best klystron, and this is a first step to check the lasertron principle before envisaging much higher peak power.

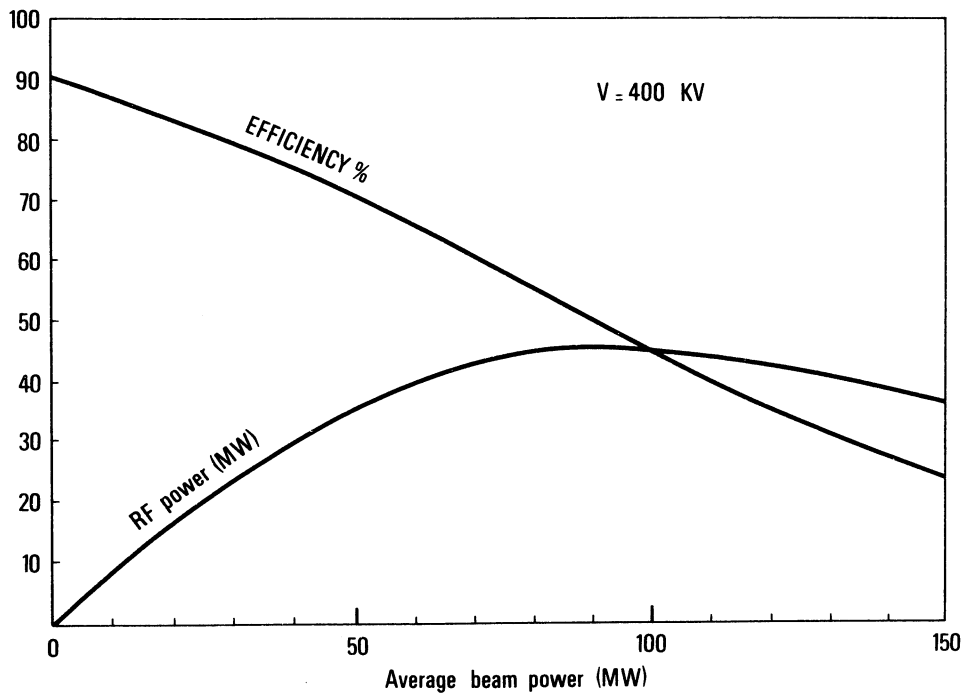


Fig. 19 Efficiency and RF power versus beam power

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Peak RF Output Power	35 MW
Beam Power	50 MW
Efficiency	70 %
Voltage	400 kV dc
Peak Pulse Current	735 A
Cathode Diameter	3 cm
Average Pulse Current ( $\approx$ Peak/6)	126 A
Optical Pulse Length	60 ps FWHM
Optical Pulse Separation	350 ps
for a 2856 MHz Rate	
Microwave Pulse Length or	1 $\mu$ s
Optical Pulse Train (Comb) Length	
Average Power (Power Supply Limited)	< 4 kW
Peak Electric Field in Gun Region	< 15 MV/m
Electric Field on Planar Cathode	10 MV/m
Maximum Magnetic Focusing Field	0.2 T

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Table 5 parameters of the SLAC prototype lasertron

Prototypes are also under consideration in Japan and in France.

Among the difficulties encountered in designing a lasertron it is worthwhile mentioning the high current photocathode. Remembering the poor efficiency of lasers, the photocathode must have a very good quantum efficiency. Unfortunately it happens that efficient cathodes, like AsGa for instance, show poor lifetime. On the contrary, metallic cathodes are robust but with a poor quantum efficiency.

Modulated lasers at S-band or C-band frequencies, with long pulse trains and high repetition rate have to be developed also, with optical frequencies either in the visible (green) or in the VUV.

Figure 20 taken from reference 20) gives a good idea of the lasertron geometry as well as the technologies involved.

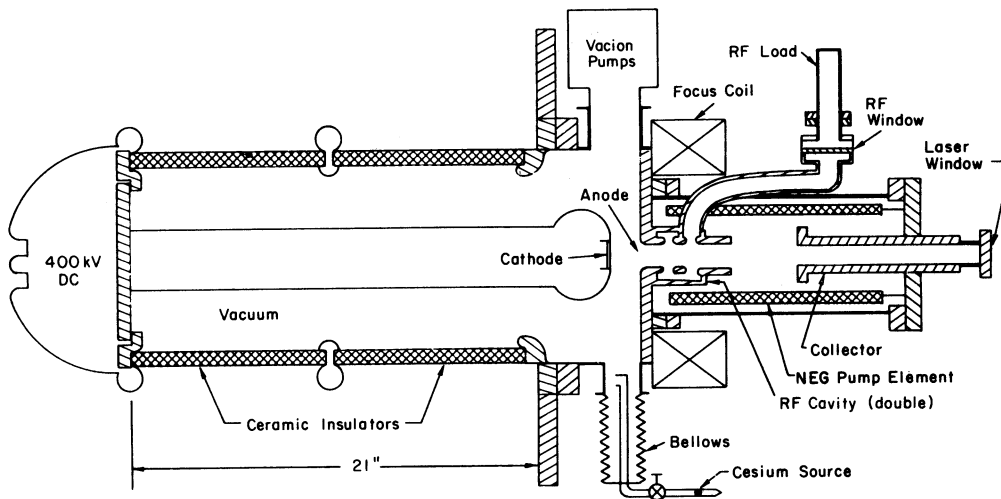


Fig. 20 Geometry of the SLAC prototype lasertron

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