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OPTIMIZATION OF TW ACCELERATING STRUCTURES FOR SLED TYPE MODES OF OPERATION

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I - INTRODUCTION

The SLED method was invented at SLAC[1] in order to produce more electron (and positron) energy from the existing klystrons. It consists roughly in an RF pulse compression which increases the average peak power over a shorter pulse length, and has been successfully applied at SLAC starting from the initial 2.5 μs RF pulses (SLED 1 experiment).

Since that time higher performances were aimed at by doubling the RF pulse length (5 μs) from the klystrons and corresponding experiments are in progress right now (SLED 2 programme).

The LEP injector LINAC[2], also now is supposed to operate in the SLED-2 mode. At DESY similar developments have been undertaken too, to improve the linac performances.

However in all cases the accelerating sections were not initially optimized for such a mode of operation, and in most cases the designers ended with long accelerating sections making a more efficient use of the klystron power, with rectangular pulses, sometimes at the expense of a longer linac.

The present study deals with new approaches for designing linacs, and in particular compact linacs, considering from the beginning a pulse compression scheme, where the main feature consists of having an exponential pulse shape instead of rectangular.

Moreover a detailed comparison is made between constant impedance and constant gradient travelling wave (TW) accelerating structures. As a matter of fact the constant impedance structure when optimized looks sligthy better than the second one. In addition short structures appear to be more efficient for a given number of RF sources. Consequently linear accelerators can be made more simple and less expensive, and if one allows for higher tolerable accelerating gradients they can be made even compact.

II - ENERGY GAIN IN THE SLED MODE

II.1. Pulse shapes due to the compression scheme

This is a brief recall of what was presented in reference 1). Figure 1 indicates schematically the compression network, where two high Q cavities are coupled to the high power wave guide system, between the klystron output and the accelerating section input coupler.

The klystron pulse starts filling the storage cavities. After a while, at time t_1, the RF phase is rapidly reversed by 180° by using a fast electronic switch at the input of the klystron. Then the cavities start emptying and the corresponding output power is added to the direct klystron pulse towards the accelerating section. This results in a much higher peak power feeding the section, which however decreases exponentially until time t_2 where the klystron pulse stops. After time t_2 a small amount of power corresponding to the remaining stored energy in the cavities, still feeds the section but that part of the pulse will be ignored in what follows.

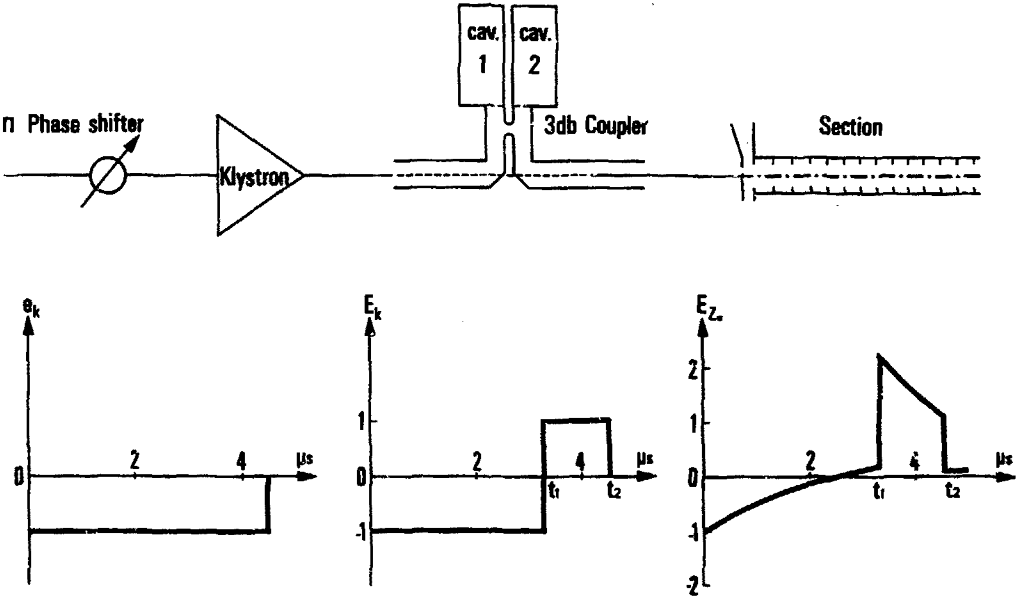

FIG. 1 - Pulse compression scheme

Let's call region 1 that part of the net load wave between 0 and t_1, and region 2 the next part between t_1 and t_2 which is the most interesting one as it corresponds to a short high peak power pulse.

For a unit rectangular RF pulse at the output of the klystron, the net load field pulse before entering the accelerating section is given by the following equations[1] :

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

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

where :

$\tau_c = \dfrac{2\, Q_c}{\omega(1+\beta)}$ is the storage cavity filling time

Q_c is the unloaded quality factor of the storage cavities

β is the coupling coefficient

$$\alpha = \frac{2\beta}{1+\beta}$$

$$\gamma = \alpha\left(2 - e^{-\frac{t_1}{\tau_c}}\right)$$

For a finite peak power P at the output of the klystron and without the storage cavities the accelerating field in the first cell of the structure would be given by :

$$E_o = \left\{ P\, \frac{\omega\, r_o}{V_{go} Q} \right\}^{1/2}$$

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.

With the compression scheme the real accelerating field is the product of E_o and the multiplication factors $E_{1,2}(t)$.

II.2. The case of constant impedance structures

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 :

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

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

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

$$\Delta t(z) = \int_o^z \frac{dz}{V_g(z)} = \frac{z}{V_{go}}$$

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 $\tau_a = \dfrac{L}{V_{go}}$

Depending wether 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 as compared to the filling time of the structure).

Let's call V_1 and V_2 the integrals relative to E_1 and E_2. One gets :

$$V = V_1 + V_2$$

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

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

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 β which maximizes the energy gain. This has been taken into account in the plots of Figure 2 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 follow by considering only this optimum case for which :

$$V_1 = 0$$

$$V = V_2(z_1' = 1)$$

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 as for a unit pulse entering a constant impedance structure the energy gain over a unit length is :

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

Hence the real multiplication factor is the ratio V_M/V_o. For each value of τ_a there is a value of β, hence a value of τ_c, which maximizes this multiplication factor as seen on Figure 3.

II.3. The case of constant gradient structures

In a constant gradient structure all the cells are different. As the flowing power decreases due to wall losses, the group velocity is made smaller and smaller (for instance by reducing the iris diameter in

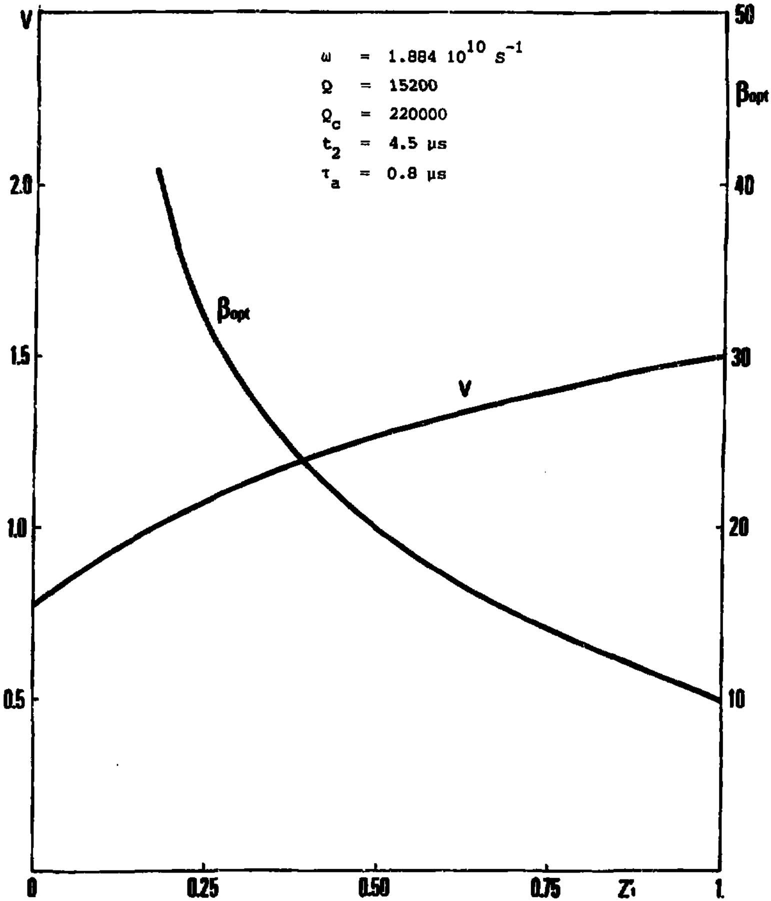

FIG. 2 - Multiplication factor for a constant impedance structure as a function of the beam timing

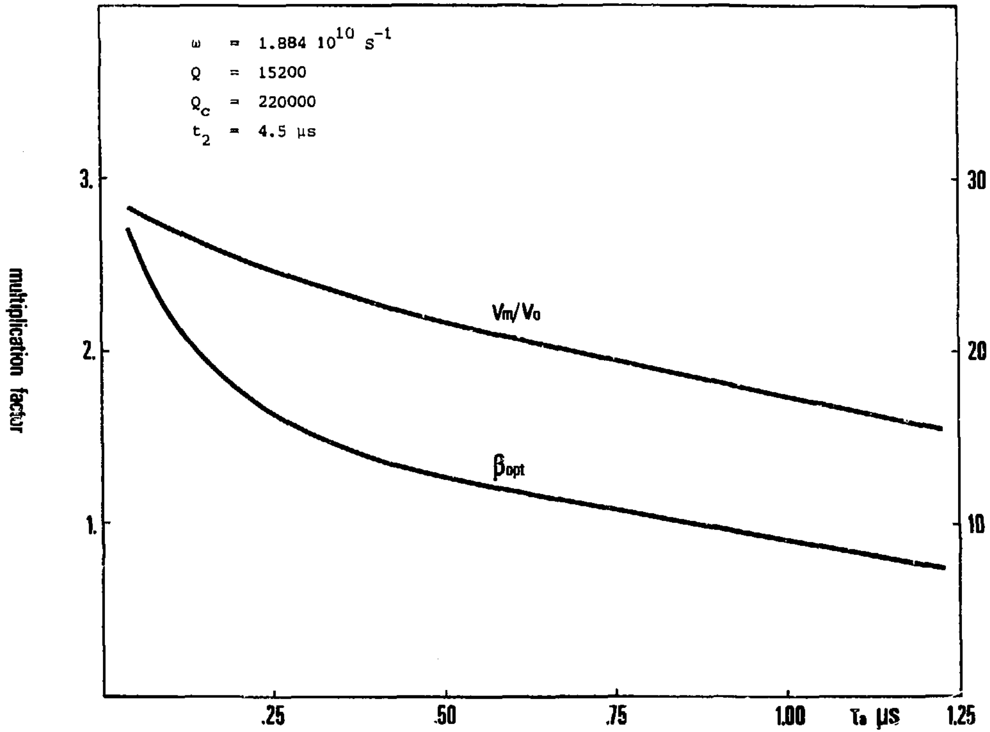

FIG. 3 - Multiplication factor versus the filling time of a constant impedance structure

an iris loaded structure) in order to keep the accelerating field constant for a rectangular input power pulse.

If the Q and the shunt impedance remain constant the group velocity should vary linearly along the structure :

$$V_g(z) = V_{go} \left(1 - g \frac{z}{L}\right)$$

where L is the length of the structure and where the coefficient g can be expressed in term of the attenuation factor X :

$$g = 1 - e^{-2X}$$

$$X = \frac{1}{2} \, Ln \left[1 + \frac{\omega L}{Q \, V_{gL}}\right]$$

$$V_{gL} = V_g (z = L)$$

or in term of the filling time τ_a of the structure :

$$\tau_a = \int_0^L \frac{dz}{V_g(z)} = 2X \, \frac{Q}{\omega}$$

$$g = 1 - e^{-\frac{\omega \tau_a}{Q}}$$

When such a structure is fed with a SLED pulse the effective accelerating gradient is no more a constant. It can be determined analytically and integrated along the structure following the same procedure as in section II.2. This treatment has already been done elsewhere[1] but for the convenience of the reader we shall reproduce it here briefly. Defining again the variable $z' = z/L$, the propagation time is now :

$$\Delta t(z') = \tau_a \, [Ln(1 - gz')/Ln(1 - g)]$$

and the field discontinuity will appear at the location z'_1 such that :

$$z_1' = \frac{1}{g}\left[1 - (1-g)^{\frac{t-t_1}{\tau_a}}\right]$$

The energy gain, for $t_1 < t < t_2$, is the contribution of two integrals respectively on E_1 and E_2 with the right boundaries :

$$V = V_1 + V_2$$

where :

$$V_1 = (\alpha-1)(1-z_1') - \alpha\, e^{-\frac{t}{\tau_c}} \left[(1-gz_1')^{1+\nu} - (1-g)^{1+\nu}\right]\left[g(1+\nu)\right]^{-1}$$

$$V_2 = -(\alpha-1)z_1' + \gamma\, e^{-\frac{t-t_1}{\tau_c}} \left[1 - (1-gz_1')^{1+\nu}\right]\left[g(1+\nu)\right]^{-1}$$

with : $\nu = \frac{\tau_a}{\tau_c}\,[\,\mathrm{Ln}\,(1-g)]^{-1}$

The energy gain $V(z_1')$ is plotted on Figure 4, as well as the optimum values of β, as functions of z_1'. Here again it is clear that the maximum energy gain is obtained for $z_1' = 1$ corresponding to $t = t_2 = t_1 + \tau_a$:

$$V_M = \gamma\, e^{-\frac{\tau_a}{\tau_c}} \left[1 - (1-g)^{1+\nu}\right]\left[g(1+\nu)\right]^{-1} - (\alpha-1)$$

In the present case V_M represents the energy multiplication factor as for a constant gradient fed by a unit rectangular pulse, $E = 1$, the energy gain is unity after one filling time :

$$V_o = \int_o^1 E\, dz' = 1$$

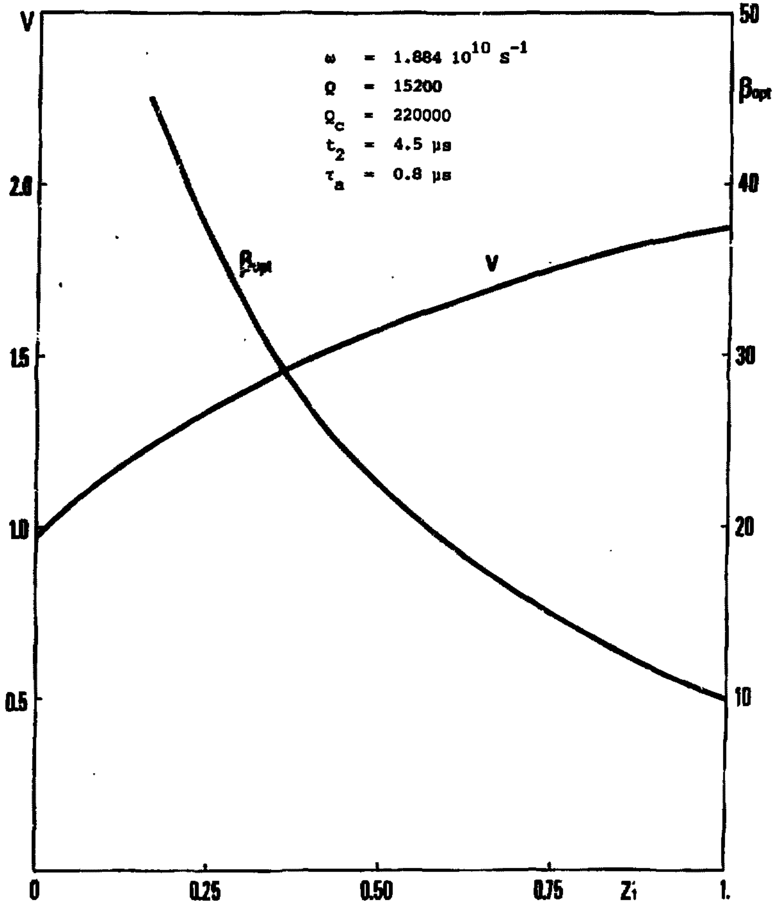

FIG. 4 - Multiplication factor for a constant gradient structure as a function of the beam timing

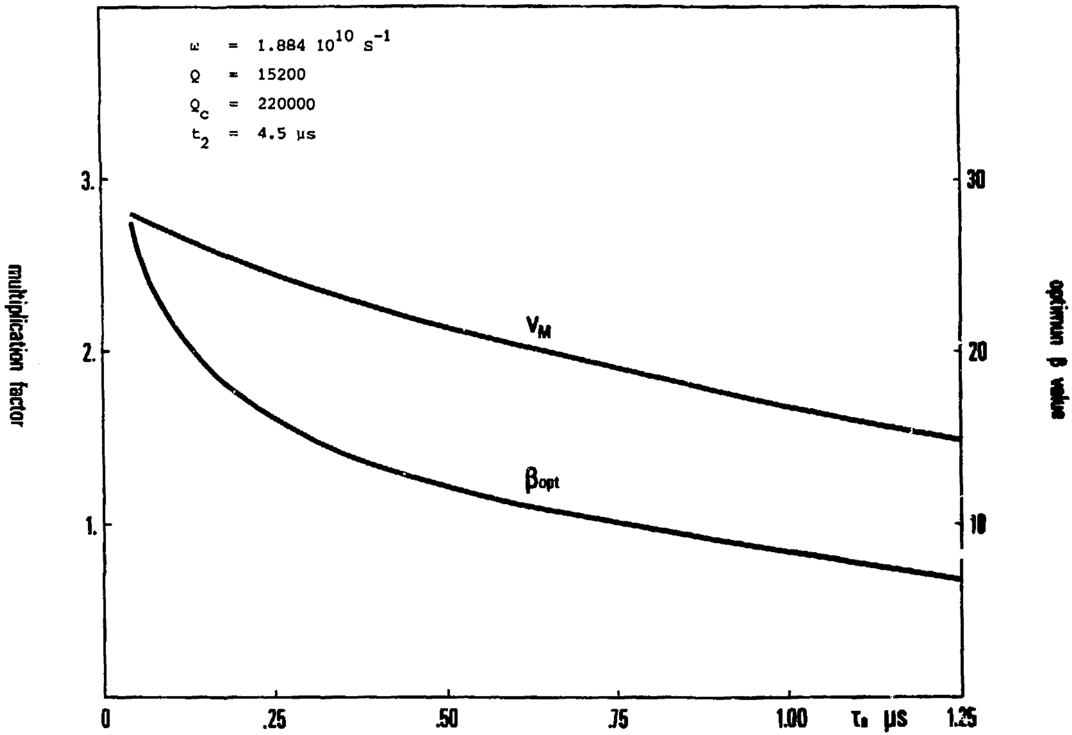

FIG. 5 - Multiplication factor versus the filling time of a constant gradient structure

The energy multiplication factor V_M is plotted on Figure 5 as a function of the filling time τ_a, for optimum β values.

II.4. Rough comparison between both structures

The qualitative behaviour of a constant gradient structure under SLED pulses is very similar to that of a constant impedance structure although the tendency has been reversed. As a matter of fact for a constant gradient structure fed with a SLED pulse the effective accelerating field as seen by the particle will increase with z due to the fact that at the output of the structure the particle will see the highest field emitted at time t_1 which has no effective attenuation. On the reverse for a constant impedance structure the attenuation of the structure is more or less compensated by the increase of the emitted field with z. This behaviour is shown on Figure 6.

Quantitatively, the multiplication factor is slightly better for a constant impedance structure, although this is not very impressive. However to clarify this it is necessary to compare the exact energy gain of each structure, having the same filling time, and the same input power, and considering that the shunt impedance of the cells varies with the inner geometry, hence with the group velocity, while the Q is roughly constant. To illustrate this point let's consider the cell characteristics of the LEP injector linacs (LIL)[3] which operate at 3 GH_z in the $2\pi/3$ mode :

$$Q = 15200$$

$$r = 86 - 3.6\,(2a)^2$$

$$v_g/c = (2a)^{3.23}/891$$

where 2a, the iris diameter, is expressed in cm while the shunt impedance r is in MΩ/m.

For a 4.5 metres long structure and input direct peak power of 7.5 MW, Figure 7 gives the energy gain of the two types of structures as a function of τ_a, which can be varied by changing the iris diameter

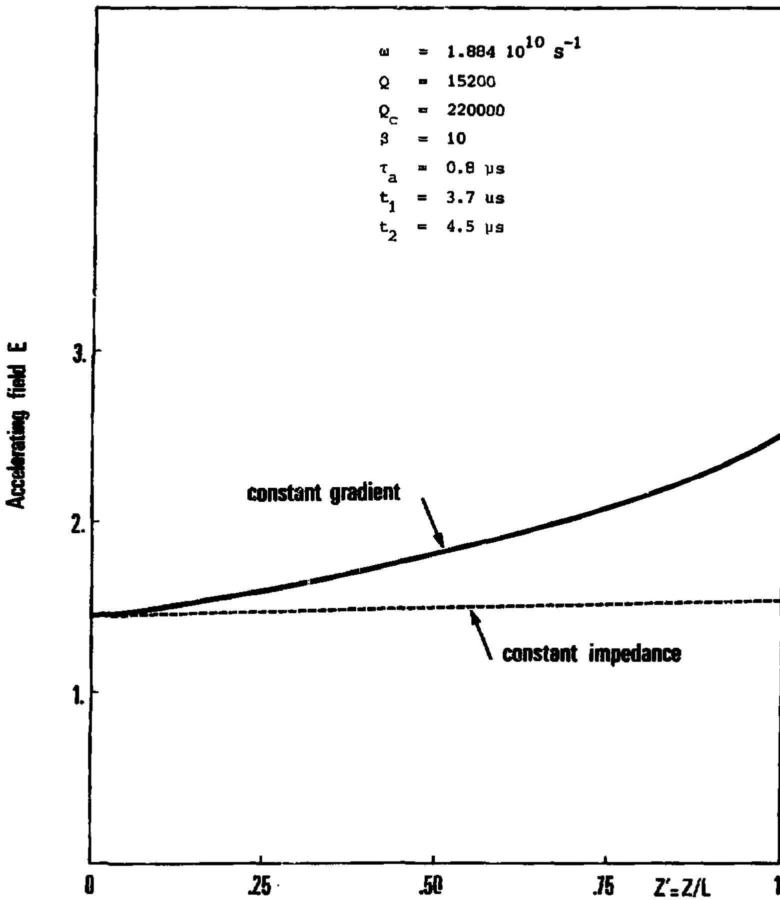

FIG. 6 - Effective accelerating field along the structure in the SLED mode

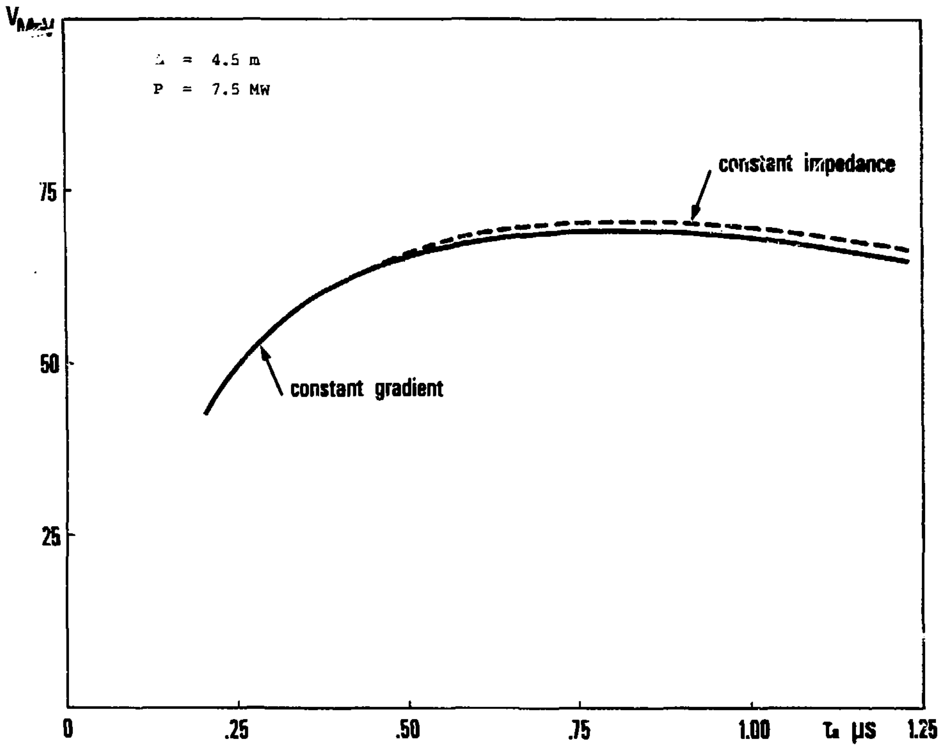

FIG. 7 - Energy gain as a function of the filling time of the structures

of the cells. It can be seen that the constant impedance structure is slightly more efficient (about 1.7 %). In both cases there is an optimum value of τ_a which means that when τ_a is too high the compression scheme becomes worse, and when τ_a is too low the efficiency of the structure to convert RF power into accelerating field becomes poor. For the present case $(\tau_a)_{opt} \simeq .8\ \mu s$, $(\tau_c)_{opt} = 2.12\ \mu s$ (with $Q_c = 220000$, $\beta = 10$, $t_2 = 4.5\ \mu s$) and the corresponding iris diameters

$$\text{constant gradient} \quad \begin{cases} (2a)_o = 2.74\ \text{cm} \\ (2a)_L = 2.00\ \text{cm} \end{cases}$$

$$\text{constant impedance} \quad 2a = 2.40\ \text{cm}$$

Table 1 gives a more complete comparison of both structures for different values of the structure length.

III - OPTIMUM STRUCTURE LENGTH AND SLED PARAMETERS SETTING

In what follows we shall concentrate only on constant impedance structures, knowing from the previous section that they are slightly more efficient and considering that they will be much easier to build.

It has been seen that for a given structure length there was an ensemble of optimum values for β, τ_c and τ_a which realize the correct matching between the SLED pulse and the accelerating structure. It is interesting to look in more details at the performances of these structures versus different parameters, like the parameter setting of the storage cavities (Q_c, β), 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 π phase shift at time $t_1 = t_2 - \tau_a$, the energy gain is :

Constant gradient

$L_{[m]}$	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
$(2a)_o$ [cm]	1.80	1.99	2.16	2.30	2.44	2.56	2.68	2.74	2.85
$(2a)_L$ [cm]	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.0	2.1
$\beta_{opt.}$	10	10	10	10	10	10	10	10	10
τ_a [µs]	.8	.8	.8	.8	.8	.8	.8	.8	.8
τ_c [µs]	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
$V_{[MeV]}$	35.7	43.1	49.0	54.0	58.3	62.4	65.9	69.0	72.0

Constant impedance

$L_{[m]}$	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
2a [cm]	1.5	1.7	1.9	2.0	2.1	2.2	2.3	2.4	2.4
$\beta_{opt.}$	10	10	10	10	10	10	10	10	10
τ_a [µs]	.8	.8	.8	.8	.8	.8	.8	.8	.8
τ_c [µs]	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
$V_{[MeV]}$	36.1	43.6	49.6	54.8	59.3	63.3	67.0	70.2	73.2

Table 1 : Comparison between optimized constant gradient and constant impedance structures

($P = 7.5$ MW $t_2 = 4.5$ µs $Q = 15200$ $Q_c = 220000$)

t_2 µs	4.5	4.5	4.5	5.5	3.5	2.5	4.5	4.5	4.5
Q	15200	15200	15200	15200	15200	15200	14200	13200	12200
Q_c	220000	150000	100000	220000	220000	220000	220000	220000	220000
$2a$ cm	2.4	2.4	2.4	2.3	2.5	2.6	2.4	2.4	2.4
β_{opt}	10	7	5	9	13	16	10	10	10
τ_a µs	.79	.79	.79	.91	.69	.61	.79	.79	.79
τ_c µs	2.12	1.99	1.77	2.34	1.67	1.37	2.12	2.12	2.12
V_{MeV}	70.2	68.7	66.5	74.2	64.9	57.4	69.0	67.7	66.1

Table 2 : Energy gain versus SLED parameters setting (L = 4.5 m)

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

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 τ_a means that there is an optimum value for V_g, hence for the iris aperture 2a of the structure. For the previous example of LIL cells Figure 8 shows the evolution of the RF performances versus the iris diameter, for different structure length. As the length decreases the iris diameter also decreases in order to keep the right matching value for τ_a. In all cases β and τ_c have been optimized.

The maximum energy gains obtained for each structure length ar plotted on Figure 9 as well as the corresponding values of τ_a and τ_c which clearly remain constant.

Table 2 gives the energy gain as a function of the other parameters, like t_2, Q_c and Q ($\frac{r}{Q} = cte$). The following conclusions can be drawn :

- neither Q nor Q_c have influence on the optimum value of τ_a. Both give a little effect on the optimum energy gain. The optimum value of τ_c changes with Q_c

- the optimum value of τ_a changes with the width t_2 of the direct klystron wave. For long pulses one can hold 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 feature, considering the results plotted on Figure 9 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 Figure 10, assuming no power losses in the RF networks, and knowing that the

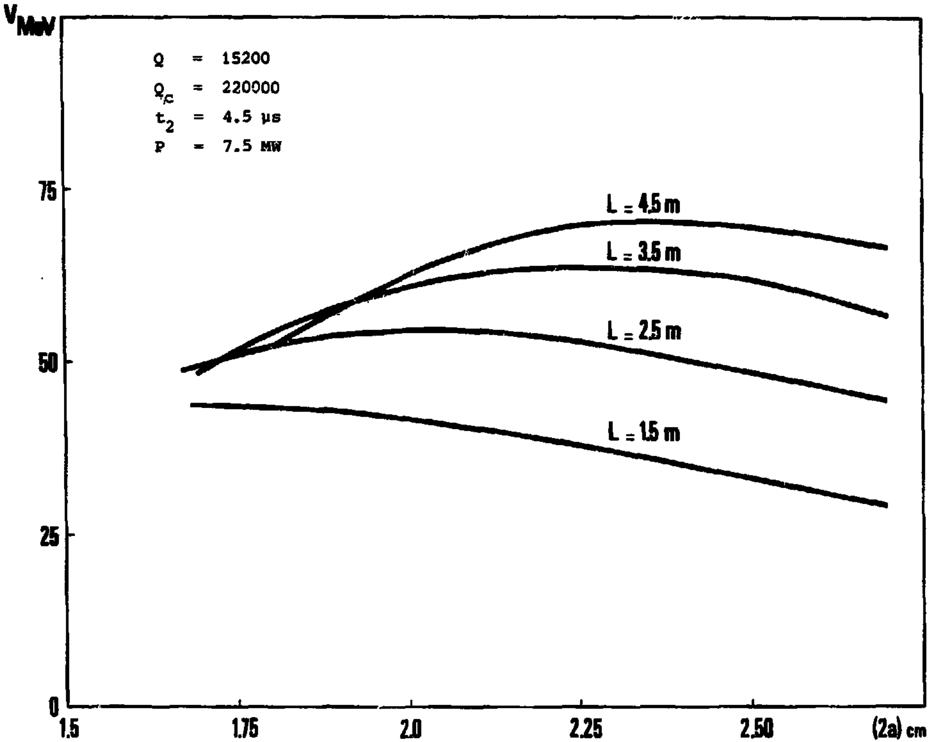

FIG. 8 - Energy gain of a constant impedance structure versus the iris diameter and the structure length

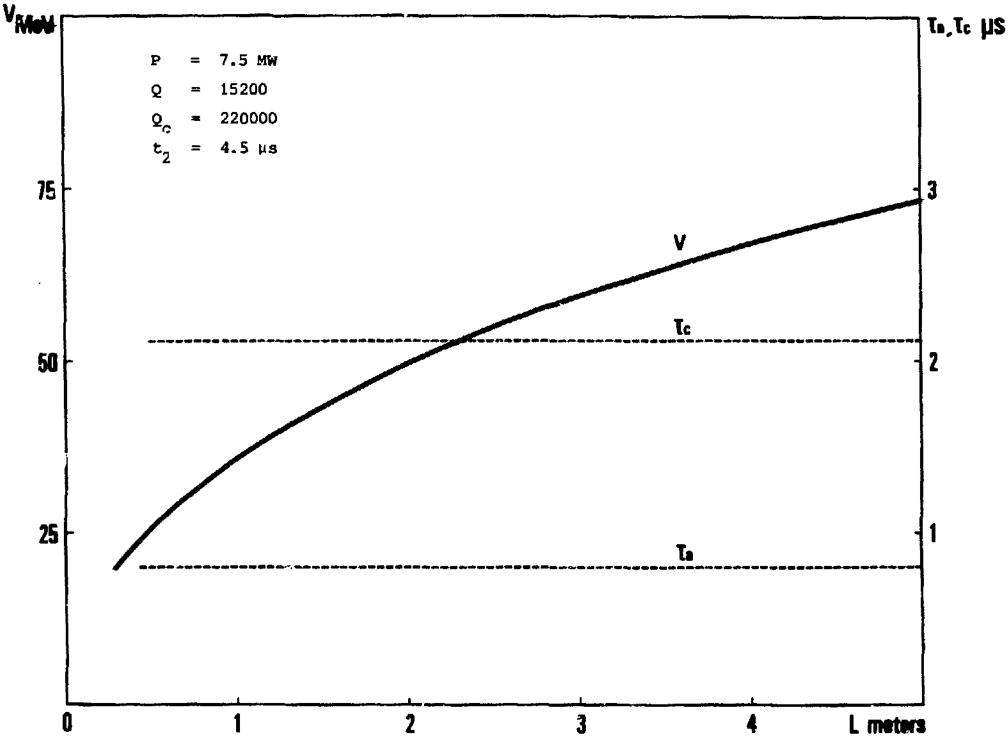

FIG. 9 - Maximum energy gain as a function of the structure length

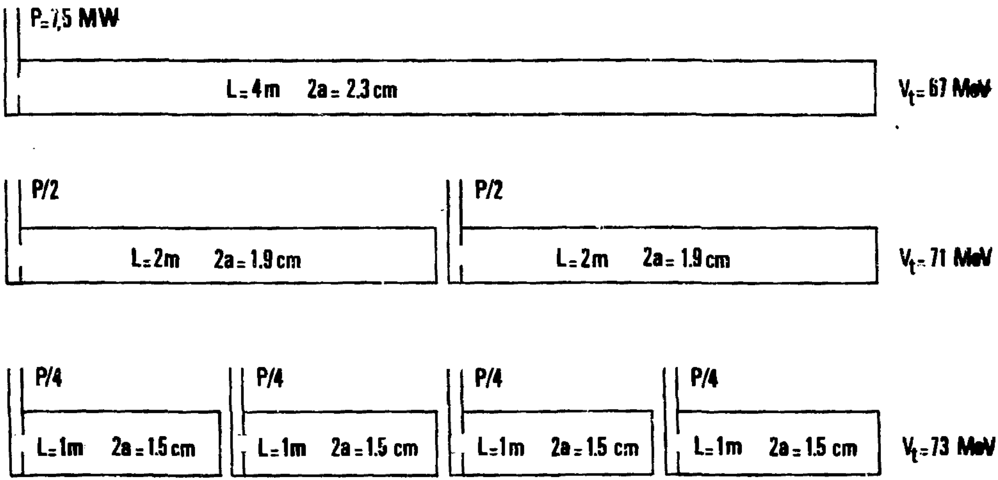

FIG. 10 - Total energy gain from a single klystron as a function of the number of structures, for a given total length

energy gain follows tne square root of the input power. Of course smaller structures, when optimized, will have smaller aperture 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 Figure 11.

IV - APPROACHES FOR COMPACT LINAC DESIGN

This section is an application of the previous results, where as an example we propose to design a 250 MeV linac, by introducing the following constraints :

$$(2a)_{min} = 2.0 \text{ cm}$$

$$\omega = 2\pi f = 1.884.10^{10} \text{ S}^{-1}$$

$$Q = 15200$$

$$Q_c = 180.000$$

$$t_2 = 5 \ \mu s$$

$$P_{klystron} = 40 \text{ MW}$$

The corresponding design curves are plotted on Figure 12. The design parameters which answer to the problem are :

$$L = 2.5 \text{ m}$$

$$\beta = 8$$

$$\tau_c = 2.12 \ \mu s$$

$$\tau_a = .8 \ \mu s$$

$$t_1 = 4.2 \ \mu s$$

Depending on the number of structures which are fed by a single klystron we obtain the following energy gains/klystron and effective

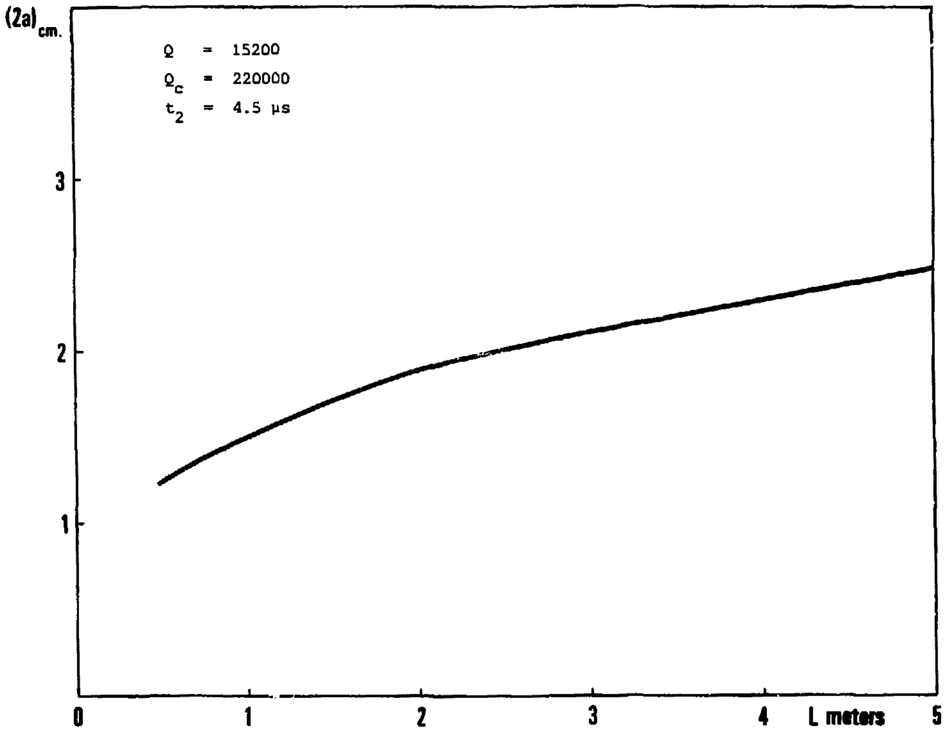

FIG. 11 - Optimum aperture of an iris loaded structure versus the structure length

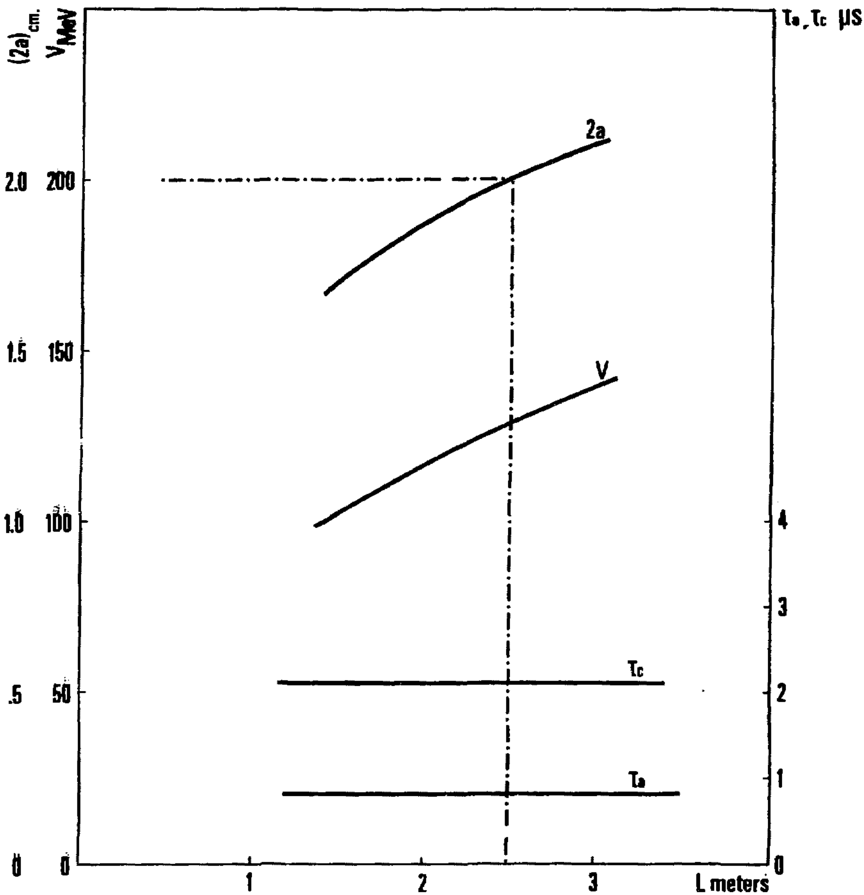

FIG. 12 - Design exemple : P = 40 MW, Q = 15200, Q_c = 180000, t_2 = 5 μs

accelerating gradients (Table 3).

Number of structures/klystron	Total energy gain [MeV]/ klystron	Effective accelerating gradient : MV/m	Linac length [m] for V ≥ 250 MeV	Minimum number of klystrons
1	129	51.6	5	2
2	182	36.5	10	2
3	223	29.8	15	2
4	258	25.8	10	1

Table 3 : Linac performances versus the number of structures per klystron

Clearly if we want to keep the gradient at a reasonable level, a single klystron feeding 4 accelerating structures would be fine. If doubling the gradient is acceptable then one can consider having twice as many klystrons for half the total linac length. That would be the approach for a compact linac. However the breakdown limit, whatever it is, is not represented by the effective accelerating field, but rather by the maximum instantaneous field which happens at the input of the structure at time t_1 and which is given by :

$$E_{MAX} = E_o(\gamma - \alpha + 1)$$

In the present worse case (first line of table 3) this leads to :

$$E_{MAX} = 85 \text{ MV/m}$$

This maximum field will be somewhat lower for an optimized constant gradient structure. However such a structure would be longer in order to satisfy the aperture requirement (this can be seen on Table 1 though the parameter setting is different there).

It is believed, from laboratory experiments, that gradients up to 100 MV/m can be achieved[4,5], but it remains to prove that they can also be achieved in the presence of a beam.

With the present state of the art in peak power klystrons and assuming permissible gradients up to 100 MV/m, the choice between the number of klystrons and the linac length, at least for low and medium energy linacs, will be rather determined by cost and site considerations.

It may be also worthwile considering the possibility of moving sligtly away from the optimum structure length to reach a certain fixed linac energy, but in case of an energy reduction it is certainly better to reduce the klystron peak power.

V - CONCLUSIONS

It has been shown that the optimum structure length only depends on the beam aperture requirement, when fed by a SLED type pulse, and that it will be shorter for a constant impedance structure than for a constant gradient structure. The minimum length for a structure leads to the best efficiency even if that means feeding many more structures with a single klystron.

The short constant impedance structures are suitable for higher gradients and more compact linacs, and this is obtained by adding more power sources. In addition they are easier and cheeper to build. It has been shown also that with present existing klystrons (commercially available) it is hardly possible to push the effective accelerating voltage well above 50 MV/m, at least keeping the aperture of conventionnal iris loaded structures at a reasonable level. One possible improvement would consist in an increase of the klystron pulse width, but this is partly counteract by an increase of the optimum filling time. In other words the simple feeling that the compressed pulse can be made very narrow to increase the instantaneous peak power is not completely relevant.

The aim at very high gradients, using TW accelerating structures, will need developping new types of accelerating structures and power sources, but it may also need developping new compression schemes. At present time, mostly the U.S. Laboratories are doing serious efforts in these directions, limited to improvements or extensions of conventionnal technics of linear acceleration.

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