OPTIMIZATION OF TW ACCELERATING SECTIONS FOR SLED TYPE MODES OF OPERATION

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Summary and introduction

The SLED[1] scheme proposed at SLAC has been used on existing Linacs, which were not initially optimized for this purpose.

Here we show that the design of RF structures changes significantly when the pulse compression is included since the beginning. As a matter of fact, due to the peculiar shape of the compressed high peak power pulses, it appears more efficient to use short constant impedance structures instead of long constant gradient structures for the same number of klystrons and roughly the same total accelerator length[2].

The minimum length of an optimized structure then only depends on the required beam aperture. Moreover it happens that these structures are suitable to look for higher gradients and more compact linacs by just multiplying the number of RF sources, keeping in mind however, that the permissible gradient will still depend on the breakdown limits.

Energy gain in the SLED mode

The compression scheme is obtained by filling a couple of high Q storage cavities with a long klystron power pulse. At a certain time t_1 the RF phase is quickly reversed at the klystron input and the storage cavities start emptying. The combination of the direct klystron power pulse and the energy coming out of the storage cavities leads to a shorter, higher peak power pulse feeding the accelerating structure. If t_2 corresponds to the end of the klystron pulse, only a small amount of energy from the cavities will still be available after that time, but will be neglected in the following. Figure 1 gives the shape of the field entering the

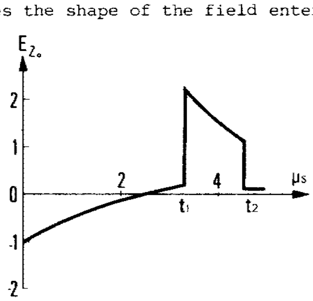

Fig. 1. Field shape in the SLED mode

accelerating section, after being compressed and for a unit direct klystron pulse. Let's call region 1 the region below t_1 and region 2 the one which lies between t_1 and t_2.

The field variation corresponding to a unit rectangular klystron pulse is described by the expressions[1] :

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

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

in which the different parameters have the following definition :

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

Q_c is the unloaded quality factor of the storage cavities

β is the coupling coefficient

$\alpha = \frac{2\beta}{1+\beta}$ and $\gamma = \alpha(2 - e^{-\frac{t_1}{\tau_c}})$

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 :

$$E_o = [P\,\omega\, r_o / V_{go}\, Q\,]^{1/2}$$

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 $E_{1,2}(t)$.

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 :

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

where $\Delta t(z) = z/V_{go}$ is the time it takes to the wave to propagate up to z. The filling time of the structure is given by $\tau_a = L/V_{go}$.

If the particle goes through the accelerating section at time t ($t \leq t_2$) it will see a field discontinuity at the azimuth z_1 such that $t - t_1 = \tau_a \frac{z_1}{L} = \tau_a\, z_1'$. Then the energy gain is the contribution of two integrals :

$$V(t) = \int_o^{z_1'} E_2[t - \Delta t(z')]\,e^{-\frac{\omega\tau_a}{2Q}z'}\,dz' + \int_{z_1'}^{1} E_1[t - \Delta t(z')]\,e^{-\frac{\omega\tau_a}{2Q}z'}\,dz'$$

It can be shown that there is an optimum value of β which gives a maximum value of V(t) for a given value of z_1', and that this maximum value has an optimum for $z_1' = 1$ or in other words when $t = t_2 = t_1 + \tau_a$. In that case $V_1 = 0$ and the maximum of V_2 is :

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

with : $1/T_1 = \omega/2Q$ and $1/T_2 = 1/\tau_c - \omega/2Q$

For a constant impedance structure the energy gain from a direct unit rectangular klystron pulse would be :

$$V_o = \frac{T_1}{\tau_a}\left[1 - e^{-\frac{\tau_a}{T_1}}\right]$$

Hence the true energy multiplication factor is $m = V_M/V_o$.

The case of a constant gradient structure under SLED pulses has already been developed elsewhere[2], neglecting however the variation of the shunt impedance r along the structure. Here again the energy gain is the contribution of two integrals corresponding to the emitted fields of regions 1 and 2, and the maximum energy gain is obtained for an optimum β value and for $z_1' = 1$ ($t = t_2 = t_1 + \tau_a$) :

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

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

In the present case $V_o = \int_o^1 E dz' = 1$, so V_M corresponds to the true energy multiplication factor.

For both structures the multiplication factor and the optimum β value increase when τ_a decreases. It can be shown that for a given filling time τ_a the multiplication factor is larger for a constant impedance structure than for a constant gradient structure. However to appreciate properly this behaviour it is necessary to take into account the variation of the shunt impedance along the constant gradient structure. Let's consider for example the RF characteristics of the LIL (LEP Injector Linacs)[3] cells :

$$f = 3\ \mathrm{GH_z} \quad ; \quad r = 86 - 3.6\ (2a)^2$$

$$Q = 15200 \quad ; \quad V_g/c = (2a)^{3.23}/891$$

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

Now, for a 4.5 meters long structure, a direct klystron power pulse [7.5 MW, 4.5 µs] and Q_c = 220000, Figure 2 gives the energy gain of the two types of structures as a function of τ_a. It is seen that the constant impedance case is slightly more efficient and that in both cases there is an optimum value of τ_a which can be explained as follows : if τ_a is too large the compression scheme is worse and if τ_a is too small the efficiency of the structure to convert power into accelerating field becomes poor. The same kind of behaviour would happen for any structure length.

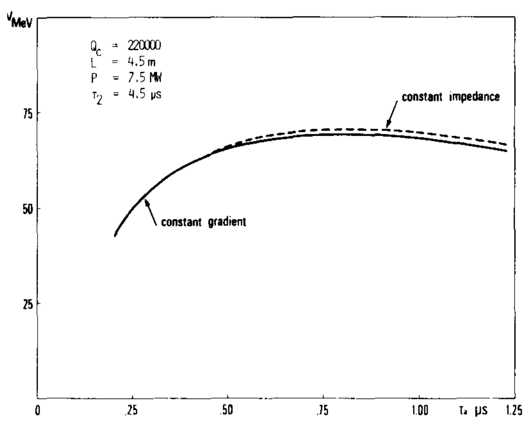

Fig. 2. Energy gain versus the filling time

On the top of that it is interesting to note that in the case of a constant gradient structure, fed by a SLED pulse, the effective accelerating field, as seen by the particle, increases along the structure, while for a constant impedance structure the effective field is roughly constant.

Optimum structure length and SLED parameter setting

In the following we shall consider only constant impedance structures, knowing that they are slightly more efficient and easier to build.

It has been shown earlier that for a given structure length there is an ensemble of optimum values, β, τ_c, τ_a which fulfil the right matching between the SLED pulse and the structure. Given the length, the optimum of τ_a means that there is an optimum value for the group velocity V_g hence for the iris diameter 2a (in the case of a disk-loaded structure). Figure 3 gives the variation of $(2a)_{opt}$ versus the structure length while Figure 4 gives the corresponding maximum energy gain. From these results it appears that the total energy gain from a single klystron source will be higher if the power is shared between smaller structures, for the same total length. This fact is illustrated on Figure 5. The optimized shorter structure will have a smaller iris diameter so that finally the minimum structure length, when designing a linac, only depends on the beam aperture requirement.

We have already noticed that for fixed values of Q, Q_c and t_2 the optimum τ_a remained constant. A complementary study shows that neither Q nor Q_c have influence on τ_a (the optimum τ_c however varies with Q_c). But a change in the klystron pulse width t_2 will change τ_a and it is a fact that for longer pulses one can hold a longer structure filling time, hence a smaller aperture for a given length. Moreover a drastic increase in the energy gain will follow an increase of t_2 although this is partly counteract by the previous statement.

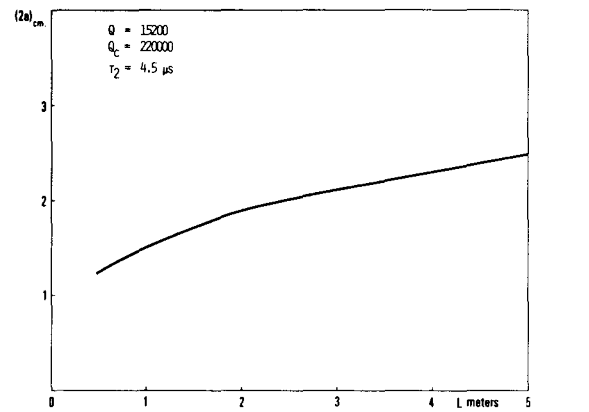

Fig. 3. Optimum iris diameter versus the structure length

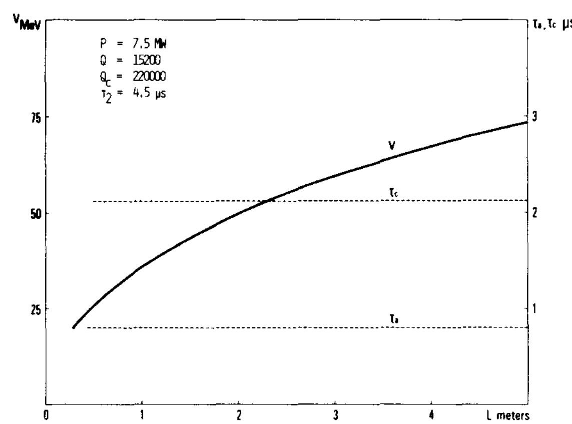

Fig. 4. Maximum energy gain versus the structure length

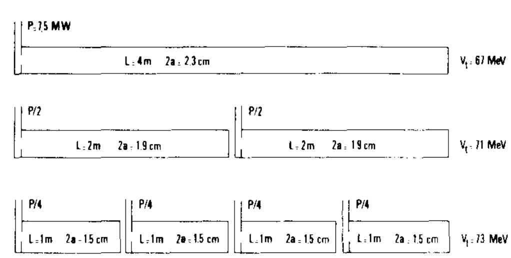

Fig. 5. Total energy gain from a single klystron as a function of the number of structures for a given total length

Approach 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:

$(2a)_{min} = 2.0$ cm $\qquad Q = 15200$

$\omega = 2\pi f = 1.884.10^{10}\ s^{-1} \qquad Q_c = 180.000$

$P_{klystron} = 40$ MW $\qquad t_2 = 5\ \mu s$

The corresponding design curves are plotted on Figure 6. The design parameters which answer to the problem are :

$L = 2.5$ m $\qquad \tau_c = 2.12\ \mu s \qquad t_1 = 4.2\ \mu s$

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

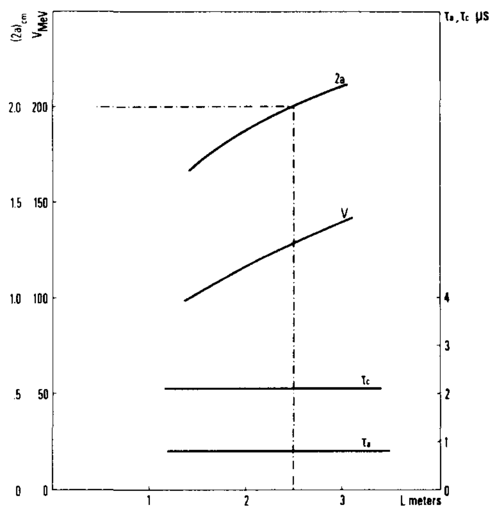

Fig. 6. Design example : $P = 40$ MW, $Q = 15200$, $Q_c = 180.000$ $t_2 = 5\ \mu s$

Depending on the number of structures N which are fed by a single klystron we obtain the following energy gains/klystron V_k and effective accelerating gradients G as well as the minimum linac length L for $V \geq 250$ MeV (Table 1).

N	V_k [MeV]	G [MV/m]	L [m]	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 1 : 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 1) 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.

It is believed, from laboratory experiments[4,5], that gradients up to 100 MV/m can be achieved 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.

Conclusion

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 cheaper 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 disk-loaded structures at a reasonable level.

The aim at very high gradients, using TW accelerating structures, will need developing new types of accelerating structures and power sources, but it may also need developing new compression schemes.

References

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