Some aspects of RF sources stability for a Sled operation.

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Abstract

For an efficient SLED operation the stability of the RF generator has to be taken into account. This aspect becomes even more important if the RF plants are to be pushed to their operational limits. Here follow results concerning unwanted effects induced by the RF source amplitude and phase instabilities with special attention to the RF energy redistribution inside the Sled pulse.

1. INTRODUCTION

The electromagnetic field, necessary to accelerate particle beams in a Linac section, is generally provided by a high power RF generator, usually a Klystron, that supplies the required energy as RF pulses.
For a correct operation and to avoid beam energy instabilities, the RF pulses emitted by the generator should be kept constant in amplitude and without any phase rotation inside. For this purpose, one of the key issues to be taken into account is the stability of the high voltage pulser used to drive the generator: a constant voltage, with no diversion from the stability level exceeding a few ‰ points inside the pulse, is usually required. Unfortunately in some cases, it is not possible to fulfil these conditions completely and a non perfect behaviour of the driving high voltage pulse (ripple, amplitude oscillations, rise and fall times, pulse drop, etc.) can lead to RF amplitude modulations and phase rotations from the generator. A few aspects concerning the beam energy losses, due to the above mentioned problems, will be analyzed here. The subject, treated in a pulse compression context, has been split into two different points:

-the first deals with the gradient losses expected in an accelerating section due to different amplitude modulation of the RF pulse;

-the second relates to the beam energy loss derived from the RF phase rotations.

2. GRADIENT LOSS

In a pulse compression scheme, the characteristic equations describing the electric field behaviour at the input of an accelerating section are [1]:

$$1)\ E_L = E_e - E_k\ ; \qquad 2)\ T_c \frac{dE_e}{dt} + E_e = \alpha E_k$$

Where T_c is the filling time of the Sled cavities, E_L is the field directed to the load (the accelerating section), E_e is the field emitted by the Sled cavities, E_k is the field from the generator and $\alpha = 2\beta/(1+\beta)$, with β the coupling coefficent of the Sled cavities.
The previous equations have been treated and solved [1] using an ideal square function for the E_k envelope. Here the same equations have been solved taking into account different analytical approximations for the envelope of the RF pulse. The following cases have been studied (see fig.1):

a) Lin/Lin: use of a linear function for the fall/rise time and for the pulse flat top.

b) Par/Lin: parabolic rise/fall time and linear flat top.

c) Lin/Sin: linear rise/fall time and oscillating flat top.

d) Par/Sin: parabolic rise/fall time and oscillating flat top.

For each of them, E_k can be expressed in analytical form in the following way:

a)Lin / Lin

$$[0,p] \Rightarrow E_k = E_0\left[\frac{1-m}{p}t + m\right]$$
$$[p,t_1] \Rightarrow E_k = E_0\ ;\ [t_1,t_2] \Rightarrow E_k = -E_0$$
$$[t_2,t_3] \Rightarrow E_k = E_0\left[\frac{1-m}{p}(t-t_2) - 1\right]$$
$$[t_3,\infty] \Rightarrow E_k = 0$$

b)Par / Lin

$$[0,p] \Rightarrow E_k = E_0\left[\frac{m-1}{p^2}t^2 + \frac{1-m}{p}2t + m\right]$$
$$[p,t_1] \Rightarrow E_k = E_0\ ;\ [t_1,t_2] \Rightarrow E_k = -E_0$$
$$[t_2,t_3] \Rightarrow E_k = E_0\left[\frac{1-m}{p^2}(t-t_2)^2 - 1\right]$$
$$[t_3,\infty] \Rightarrow E_k = 0$$

c)Lin / Sin

$$[0,p] \Rightarrow E_k = E_0\left[\frac{1-m}{p}t + m\right]$$
$$[p,t_1] \Rightarrow E_k = E_0 + E_m \sin\omega(t-p)$$
$$[t_1,t_2] \Rightarrow E_k = -E_0 - E_m \sin\omega(t-t_1)$$
$$[t_2,t_3] \Rightarrow E_k = E_0\left[\frac{1-m}{p}(t-t_2) - 1\right]$$
$$[t_3,\infty] \Rightarrow E_k = 0$$

d)Par / Sin

$$[0,p] \Rightarrow E_k = E_0\left[\frac{m-1}{p^2}t^2 + \frac{1-m}{p}2t + m\right]$$
$$[p,t_1] \Rightarrow E_k = E_0 + E_m \sin\omega(t-p)$$
$$[t_1,t_2] \Rightarrow E_k = -E_0 - E_m \sin\omega(t-t_1)$$
$$[t_2,t_3] \Rightarrow E_k = E_0\left[\frac{1-m}{p^2}(t-t_2)^2 - 1\right]$$
$$[t_3,\infty] \Rightarrow E_k = 0$$

Where p is the rise/fall time, m is the normalized value of E(t=0), E_m is the amplitude of the sinusoidal oscillation for the cases c-d, t_1 and t_3 are respectively the phase reversal time and the end of the pulse, and $t_2=t_3-p$.
For brevity sake, only the solution to the first case (Lin/Lin) is reported:

$$[0,p] \Rightarrow E_L = E_0\left[\alpha\left[e^{-\frac{t}{T_c}}-1\right]\left[\frac{1-m}{p}T_c - m\right]+\frac{1-m}{p}(\alpha-1)t - m\right]$$

$$[p,t_1] \Rightarrow E_L = E_0\left[\alpha-1+\left[E_e(p)-\alpha\right]e^{-\frac{t-p}{T_c}}\right]$$

$$[t_1,t_2] \Rightarrow E_L = E_0\left[1-\alpha+\left[E_e(t_1)+\alpha\right]e^{-\frac{t-t_1}{T_c}}\right]$$

$$[t_2,t_3] \Rightarrow E_L = E_0\left[\alpha\left[e^{-\frac{t-t_2}{T_c}}-1\right]\left[\frac{1-m}{p}T_c+1\right]+\right.$$

$$\left.+1+\frac{1-m}{p}(\alpha-1)\,(t-t_2)+E_e(t_2)e^{-\frac{t-t_2}{T_c}}\right]$$

$$[t_3,\infty] \Rightarrow E_L = E_e(t_3)e^{-\frac{t-t_3}{T_c}}$$

For a constant impedance structure, it is possible to evaluate the maximum achievable energy gain integrating the previous equations, that provide the electric field directed to the load, between t_1 and $t_1 + T_a$, where Ta is the section filling time, assuming that $T_a \le t_3 - t_1$:

$$M = \left[E_e(t_1)+\alpha\right]\left[1-e^{-\frac{t_2-t_1}{T_c}}\right]\frac{T_c}{T_a}+1-\alpha-$$

$$T_c\alpha\frac{1-m}{p}\left[1-\frac{t_2-t_1}{T_a}\right]+\frac{T_c}{T_a}\left[1-e^{-\frac{t_1+T_a-t_2}{T_c}}\right]$$

$$\left[\alpha\left(\frac{1-m}{p}T_c+1\right)+E_e(t_2)\right]+(\alpha-1)\frac{1-m}{2p}\frac{\left[t_1+T_a-t_2\right]^2}{T_a}$$

In all the suggested cases a-b-c-d, numerical simulations have been made to evaluate the expected gradient variations related to the ideal case solved in [1]. A constant impedance accelerating section, working at 2.997 GHz fed with a 4.5 µsec RF pulse has been taken and Q_0=190000 and β=9 have been chosen for the Sled cavities
Setting m=0.8 , p=200 nsec , T_a = 780 nsec, $E_m = 0.05\,E_0$. and a ripple of 3.0 MHz, the calculated gradient losses for the four different cases are:

	Lin/Lin	Par/Lin	Lin/Sin	Par/Sin
ΔM/M	1.17%	0.98%	1.26%	1.06%

In Fig.2 the field distribution to the load (b), compared with the ideal case(a) and the gradient variations(c,d) for m=0.7, p=300 nsec and T_a=780 nsec are shown in the Lin/Lin case.

3.PHASE SHIFT AND ENERGY LOSS

To evaluate the beam energy variation due to the generator phase rotation, the following approximate relation has been used:

$$\Delta\vartheta = \frac{2\pi L}{T}\left(\frac{1}{v_1}-\frac{1}{v_0}\right)$$

where $\Delta\vartheta$ represents the phase rotation induced by a step variation, V_1-V_0, of the generator driving voltage, L is the generator drift length, T is the RF period and v_1, v_0 are the beam velocities related to V_1, V_0 (reference voltage).
For a generator working at 3 GHz, with 300 kV reference voltage and for $(V_1-V_0)/V_0 = 1\%$, the evaluated phase variation is about 6 degrees, that is in a good agreement with the measured one.
Since in an accelerating section, the beam energy gain can be expressed as [2]:

$$E = \sqrt{P_0}\cos\theta_0$$

where θ_0 is the RF phase angle that maximizes the beam energy gain and P_0 is the rf power of the pulse, it is possible to obtain the normalized energy loss due to a source phase rotation $\Delta\vartheta$ and a power variation P_0-P_1 as:

$$\frac{\Delta E}{E} = 1-\sqrt{\frac{P_1}{P_0}}\frac{\cos(\theta_0+\Delta\vartheta)}{\cos\theta_0}$$

Nevertheless, in a more general case, it should be necessary to consider that the generator driving voltage is time depending in the interval (t_0, t_1) and constant in the remaining part of the pulse, between (t_1, t_2). Consequently, $v_1=v_1(t)$ in (t_0,t_1) and:

$$\Delta\vartheta(t) = \frac{2\pi L}{T}\left(\frac{1}{v_1(t)}-\frac{1}{v_0}\right)$$

Therefore, the normalized energy loss becomes:

$$\frac{\Delta E}{E} = 1-\sqrt{\frac{P_1}{P_0}}\left(1-\frac{t_1}{t_2}\left(1-\frac{\int_0^{t_1}\cos(\theta_0+\Delta\vartheta(t))}{t_1}\right)\right)$$

Taking the previous parameters for the accelerating section and the Sled cavities, for Lin/Lin case, with m=0.9, p=200nsec, numerical simulations show a $\frac{\Delta E}{E} \cong 3\div4\%$.

4.CONCLUSIONS

The effects of the amplitude and phase instabilities of an RF generator on the maximum achievable beam energy from an accelerating section have been investigated. The analysis, carried out in a Sled context, shows that an energy loss between 3÷4% or greater could be expected as a consequence of an incorrect operation of the RF source. Consequently special attention has to be devoted to the behaviour of the high voltage pulse driver of the RF generator to keep any modulation at the minimum.

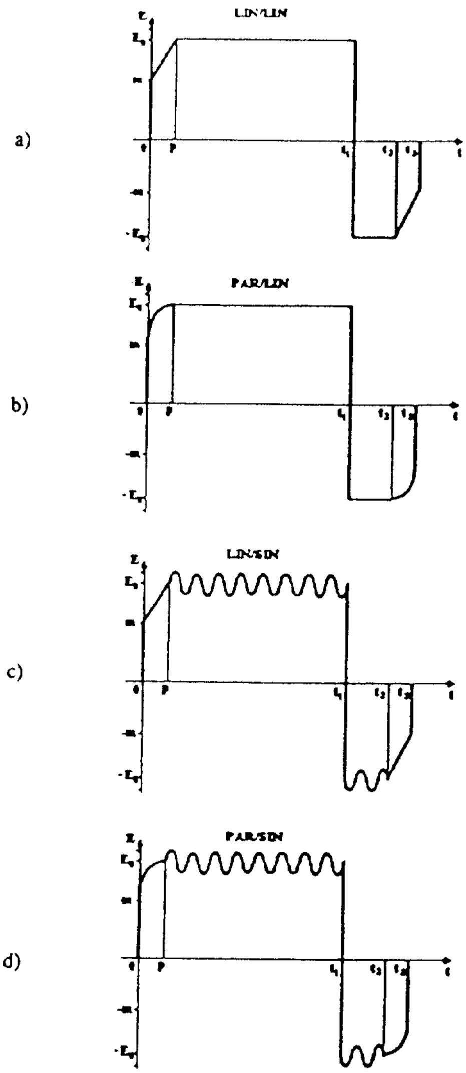

FIG.1 The field envelope for the four approximations choosen : a) Lin/Lin, b) Par/Lin, c) Lin/Sin, d) Par/Sin,

5. ACKNOWLEDGMENTS

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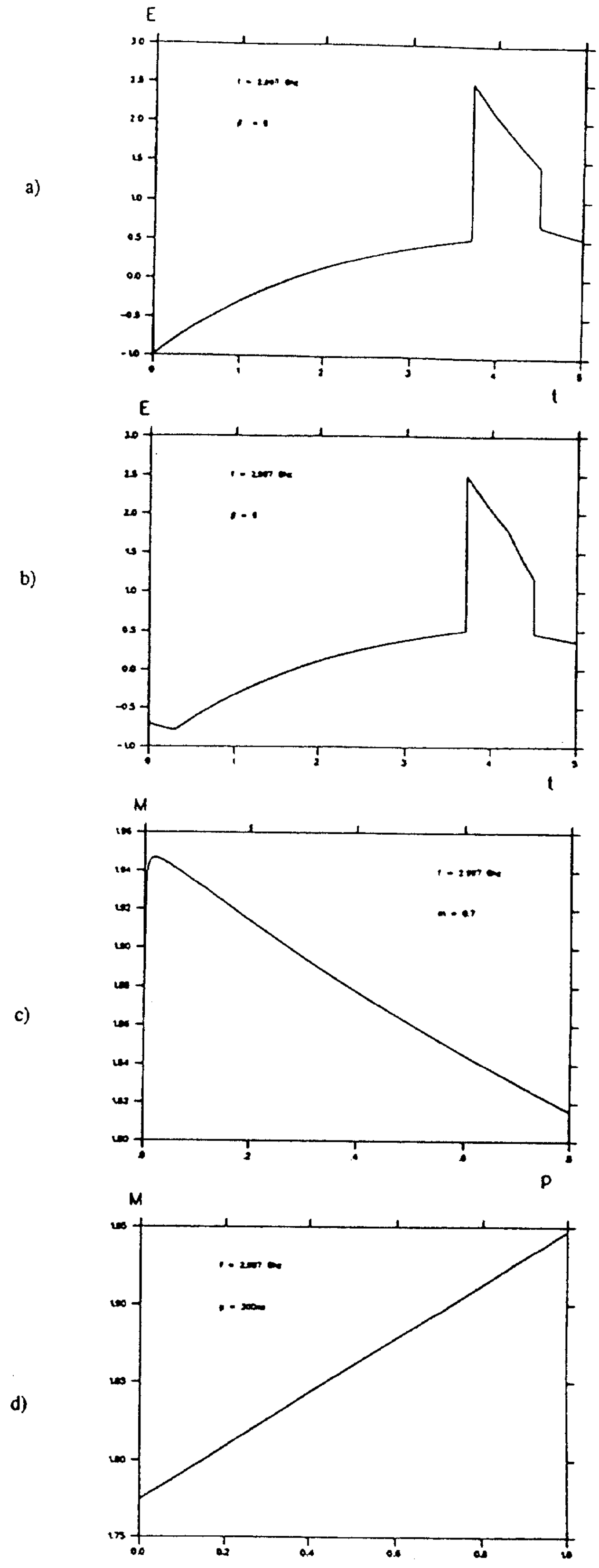

FIG.2 The envelope of the field directed to the load in the ideal (a) and Lin/Lin (b) case, and the maximum gradient variation depending on p (c) and m (d).