TRANSIENT BEAM LOADING COMPENSATION IN LOW-ENERGY PULSED LINEAR ELECTRON ACCELERATORS

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Abstract

In pulsed traveling-wave high-intensity electron linacs large beam energy spreads are caused by the transient beam loading phenomenon. This energy spread is not only critical in high-energy accelerators, as the next generation of linear colliders, but it causes also problems in modern low-energy high-intensity linacs. Different compensation schemes were proposed recently for SLED driven structures in the framework of the Next Linear Collider project, but these schemes are too complicated for the compact low-energy linacs, that are widely used in scientific research, radiotherapy and industry. We propose a new method of transient beam loading compensation. This method is based on a step variation of the RF pulse amplitude during the filling time. A theoretical model is developed and a detailed study of beam loading compensation for different linac section types is performed, showing that very good energy spectra can be obtained, over a wide range of intensities and energies. The beam loading compensation scheme proposed here has been demonstrated to work very well in the 15 MeV Ghent University linear electron accelerator facility.

1 INTRODUCTION

Compact pulsed low-energy electron linacs are extensively used in medicine and industry. Recently, they also experience a growing importance as novel radiation sources in several fields of basic research. The common feature to these machines is that they use only one high power RF generator, feeding one or maximum two accelerator sections. For industrial and research purposes, the actual trend is towards high intensities. RF electron linacs have reached recently at 10 MeV beam power levels between 50 and 200 kW [1]. There are also some biomedical applications requiring high intensities [2,3]. These high-intensity linacs are characterised by heavy beam loading, with RF conversion efficiencies up to 80 %.

The behaviour of an electron beam in a linac is influenced by beam loading, particularly during the transient phase lasting one structure filling time after starting electron injection. Transient beam loading will have an important degradation effect on the energy spectrum. In most industrial applications a narrow energy spectrum is not always a critical requirement. A number of applications of intense electron beams, however, do require a fine energy spectrum to optimise and certify the lateral and depth dose distributions in the specimen (within ± 1 %) [4]. A second consequence of transient beam loading in industrial irradiators is the contamination of the beam by fill-time electrons with an energy substantially higher than the nominal value. At a nominal steady-state energy of 10 MeV, the energy of the fill-time electrons can be well above photo-neutron thresholds, where neutron yields increase rapidly with energy, causing activation hazards, an effect especially dramatic in food and drug irradiation [5].

We will describe a new approach to reduce substantially, the transient energy spectrum degradation in individual sections of an electron linac, particularly applicable to low-energy linacs. In the following the theoretical background and the implementation of the method will be given, together with a discussion of the practical realisation at the Ghent University 15 MeV 20 kW linear electron accelerator facility, demonstrating the efficacy of this method.

2 THE COMPENSATION METHOD

Several authors have investigated different mechanisms for the (partial) compensation of the transient energy variation. A method already proposed in 1963 [6], consists of the anticipated injection of the electron pulse, already during the RF filling time (ΔT technique). As will be illustrated further, the best energy spread that can be obtained in a single structure system is not better than 10 %. By 'staggered triggering' (variable timing of RF source turn-on with respect to the beam) in accelerators with different RF power supplies, the energy spread can be further reduced. In a recent publication [7] a method is proposed where the RF waveform is ramped during the filling time (ΔS technique). Li et al. [8] proposed a beam loading compensation method (ΔF technique) for SLED driven accelerator structures, based on earlier work of Wang [9]. Here, some of the consecutive accelerator sections are detuned at F ± ΔF frequencies. These methods, combined with the ΔT technique, lead to intrinsic energy spreads below 0.2%. But they are too complicated (ΔS technique) or not applicable (ΔF technique) to machines with a single RF source.

We therefore elaborated a new method particularly suited to compact electron linacs, powered by one RF source. The basic idea is to produce an RF field profile so that the field reduction due to beam loading is compensated by an appropriate step of the RF power pulse amplitude (we will call it the ΔA technique). The ΔS technique in which the RF power level is ramped during a certain time [7] can be incorporated as a single extension in our theoretical analysis. Because a combination of both techniques is also possible we treat them simultaneously.

Suppose that the no-load energy of an accelerator section with length L is given by E_0L. The ΔA technique consists of the injection of an RF power pulse with an accelerating field amplitude E_1 at $t = t_1$, followed by the injection of a second pulse E_2 at $t = t_2$, leading to a stepped-field profile. Because beam loading is only a problem at the leading edge, the pulses can be assumed to be infinitely long. In the ΔS technique a ramped pulse with a slope S is injected at $t = t_3$. The length of the ramp is ΔT_s so that $t_4 = t_3 + \Delta T_s$. The electron beam with a peak amplitude I_0 is injected at time $t = t_b$.

Starting from the well-known power-diffusion equation and using Laplace transformations the time-dependent accelerating voltage V(t) over a constant gradient section can be calculated. The detailed calculations are described elsewhere [10,11]. We limit ourselves here to the results for the more common constant gradient structure. $U(t-\delta)$ is the unit step function which has the value zero for $t < \delta$ and value 1 for $t > \delta$. For a section with RF frequency ω, quality factor Q, shunt impedance R_0, filling time σ_f and attenuation constant τ, V(t) is given by:

$$\begin{aligned} V(t) = {} & f_1(E_1,t_1)U(t-t_1) - f_1(E_1,t_1+\sigma_f)e^{-2\tau}U(t-t_1-\sigma_f) \\ & + f_1(E_2,t_2)U(t-t_2) - f_1(E_2,t_2+\sigma_f)e^{-2\tau}U(t-t_2-\sigma_f) \\ & + f_2(S,t_3)U(t-t_3) - f_2(S,t_3+\sigma_f)e^{-2\tau}U(t-t_3-\sigma_f) \\ & + f_2(S,t_4)U(t-t_4) - f_2(S,t_4+\sigma_f)e^{-2\tau}U(t-t_4-\sigma_f) \\ & + f_3(I_0,t_b)U(t-t_b) - f_4(I_0,t_b+\sigma_f)U(t-t_b-\sigma_f) \end{aligned}$$

with

$$f_1(E,T) = \frac{EL}{1-e^{-2\tau}}\left[1 - e^{-2\tau\frac{t-T}{\sigma_f}}\right]$$

$$f_2(S,T) = \frac{SL}{1-e^{-2\tau}}\left[(t-T) - \frac{\sigma_f}{2\tau}e^{-2\tau\frac{t-T}{\sigma_f}}\right]$$

$$f_3(I_0,T) = \frac{\omega R_0 L I_0}{2Q(1-e^{-2\tau})}\left[e^{-2\tau}(t-T) - \frac{\sigma_f}{2\tau}(1-e^{-2\tau\frac{t-T}{\sigma_f}})\right]$$

$$f_4(I_0,T) = \frac{\omega R_0 L I_0 e^{-2\tau}}{2Q(1-e^{-2\tau})}\left[(t-T) - \frac{\sigma_f}{2\tau}(1-e^{-2\tau\frac{t-T}{\sigma_f}})\right]$$

The parameters E_1, E_2, S, and the different times can now be used to control the energy dispersion minimisation process.

3 TRANSIENT BEAM LOADING COMPENSATION

With the general expression for the accelerating voltage variation induced by transient beam loading it is possible now to investigate the new ΔA compensation scheme more in detail and to compare it with the theoretical performance of the ΔS technique proposed recently. As can be seen from the equation above we can generate, for a given constant gradient section, unloaded energy E_0 and peak beam amplitude I_0, different solutions corresponding to different combinations of field magnitudes (E_1 and E_2), slope S and time shifts. By changing some of these parameters the time-dependent energy gain can be modified to minimise the beam loading induced energy spread.

To illustrate the method, a solution for the time-dependent energy gain in a typical S-band (SLAC type) linac structure (σ_f = 0.83 µs, τ = 0.57, L = 3 m, RF frequency = 2856 MHz) is calculated for a high electron peak current of 500 mA. The nominal energy is 30.2 MeV. Figure 1 gives a plot of the relative energy gain in the transient region, for four different cases: no beam loading compensation and the best possible energy variation compensation obtained with the ΔT technique, the ΔA technique and the ΔS technique.

If no compensation is applied, the energy gain of the fill-time electrons will change, due to beam loading, from 50 MeV down to 30.2 MeV, corresponding to an energy variation of 65.5 % of the nominal energy. As can be deduced from figure 1, the best energy spectrum compensation obtainable with the ΔT technique is a concentration within 11.4 %. With the techniques proposed here, the transient beam loading induced energy spread is compressed within 2.7 % (ΔA method) and 0.3 % (ΔS method).

For peak electron beam intensities of 300 mA and 100mA at a nominal energy of 30 MeV, the values of the energy spreads due to transient beam loading are, in the

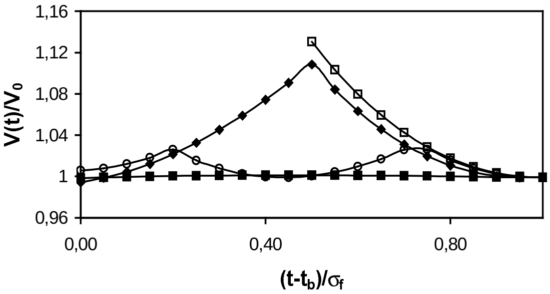

Figure 1: Relative time-dependent accelerating voltage with beam loading in SLAC structure: (a) no compensation (□), ΔT- (♦), ΔA- (O) and ΔS-compensation (■).

same structure, respectively 39.4 % and 13.2% (no compensation), 11.2 % and 7.7 % (ΔT technique), 2.4 % and 0.9 % (ΔA method), and better than 0.2 % in both cases for the ΔS compensation method. Similar calculations were performed for other accelerator structures, leading to comparable results, always indicating a clear improvement by applying the ΔA method and especially the ΔS method, which allows an almost perfect transient beam loading compensation. For example, in our 6 m long 3 GHz sections, in use for high duty factor applications with low accelerating gradients of 2 MeV/m, the non-compensated beam loading energy decrement of 53 % at 50 mA, can be reduced to a value of 1.6 % (ΔA method) and to 0.25 % (ΔS technique).

4 IMPLEMENTATION AND RESULTS

Compared to the ΔA method the compensation performance of the ΔS technique is always superior. However the practical implementation of the ΔS method is much more complicated. A voltage variation on the klystron induces a phase variation of the RF wave. Sophisticated schemes are developed to produce phase-shift-free RF amplitude variation [7]. Optimisation of transient beam loading compensation using our theoretical model reveals that in the ΔA method the optimum beam injection time is always situated after the voltage step. So, the electron bunches never experience the klystron-induced phase variation. Because the simpler ΔA method already improves the transient beam loading compensation to a level acceptable for modern compact low-energy machines, it seems to be the method of choice for this class of accelerators.

The Ghent University is equipped with a 15 MeV 20 kW linear electron accelerator facility. This is an accelerator with two constant gradients sections powered with one common klystron. The major part of the applications require a great machine flexibility, with electron beams fully adjustable in energy (between 3 and 15 MeV) and intensity (covering a range over 16 orders of magnitude), while maintaining a high beam quality (low emittance and narrow energy spectrum) even under high beam loading conditions [12]. Electron beams with average power densities up to 150 kW/cm^2, are produced at a rate of 5000 pulses/s. The klystron pulses are generated and controlled by a hard-tube modulator.

We developed a control system to produce an RF pulse shape with a stepped field amplitude during the leading edge (ΔA technique), by pulse shaping of the hard tube driver pulse. Timing and amplitude ratio for best transient beam loading compensation can be optimised to maximise directly the slope of the leading edge of the energy-analysed electron beam time profile. As an example, figure 2 shows the measured energy-analysed electron beam pulse on target (10 MeV, 60 mA peak, 2000 Hz), with and without transient beam loading compensation, after an energy-analysing slit system allowing the passage of an energy bin of ± 0.5 %.

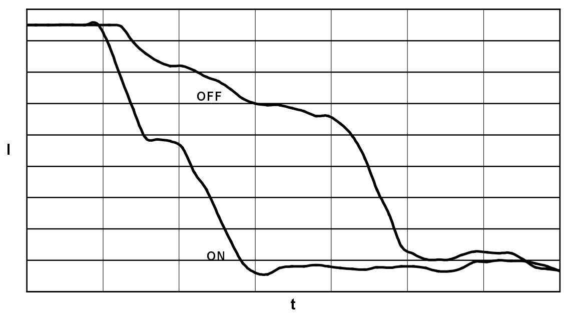

Figure 2: Leading edge of the measured time-dependent energy-analysed beam intensity with (ON) and without (OFF) transient beam loading compensation (time scale = 0.2 µs/div.)

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