SCALING LAWS AND OPTIMIZATION OF ELECTRON LINEAR INDUCTION ACCELERATORS

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Significant progress has been made in the last years in the development of high current high energy electron Linear Induction Accelerators (LIA). The paper deals with scaling laws of such accelerators. We deal in particular with scaling of the size of such accelerators and its relation to the choice of the core magnetic material. It is shown that for pulse length of more than 50 ns the application of Metglass as the core magnetic material may enable increased effective accelerating gradients to be achieved. Efficiency considerations are also presented. The efficiency is strongly influenced by pulse shape quality requirements. A new scheme of pulse shape compensation by application of opposite polarity modules in the LIA is proposed. Such a scheme may enable improved pulse quality with a high efficiency LIA design. Problems of beam propagation and stability are not addressed in this paper.

1. Introduction

Linear Induction Accelerators (LIA) for electrons play an increasingly significant role as accelerators for high current, high quality electron beams in the energy range of 10 MEV or more. This type of accelerator is the only existing machine that can produce electrons in this energy range with currents of 1 to 10 kA and with a high enough brightness which is critical for many applications. The LIA concept still has two significant drawbacks that limit its use for more applications - its size and its limited efficiency. Since the size of the accelerator plays a critical role in its price and in the price of the real estate that has to be devoted to the accelerator, any significant reduction in the accelerator size may make this accelerator a more attractive candidate for many commercial and scientific applications. The efficiency considerations play an especially important role in high rep rated LIA's.

A typical LIA module design is shown schematically in Figure 1. It is assumed that the module is fed by a generator that supplies a square pulse to the module. The basic equivalent circuit of the induction module is shown in Figure 2. It is assumed that the module is fed by a pulse forming Blumlein line that has a characteristic impedance Z_0 (ohms), is charged to a voltage $2V_0$ and has an electrical length $\Delta t/2$. The details of the pulse power system will not be dealt with in this paper, it is only assumed that the Blumlein is discharged into the module by closing an ideal switch which is also shown in Figure 2. Figure 2 also shows a resistance Rb which represents the beam resistance in parallel with any compensating resistors that might be connected in parallel with the module.

For the ideal circuit shown in Figure 2, the accelerating voltage of the module is:

$$V(t)=2V_0\,\frac{Rb}{Rb+Z}\,e^{-t/\tau} \qquad (1)$$

where τ =L/Zeff is the decay time constant of the circuit. L is the inductance of the module and Zeff is the effective impedance of the line in parallel with Rb. The voltage droop Δt Zeff/L can be kept small by keeping L large or by keeping the impedance-Zeff low enough. The standard way of limiting the droop of LIA modules is by insertion of a high permeability core in the module, which is also shown in Figure 1.

A second limiting factor in the core material is its saturation magnetic field. If we denote by B_s(T) the saturation induction of the core material we require:

$$V\ \Delta t \leq 2B_sA \qquad (2)$$

where it is assumed that the core was polarized to $-B_s$ before the pulse is applied V is the voltage on the load.

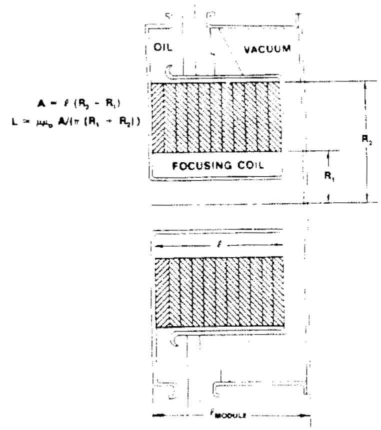

Figure 1 - Schematic of a LIA module

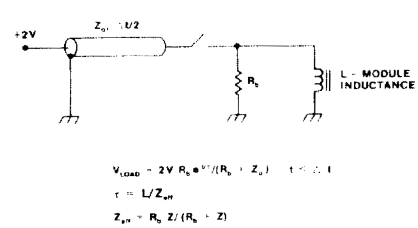

Figure 2 - Equivalent circuit of a module electrical driver

2. Length Scaling Relationship

For a given magnetic material the geometry of the module is governed by the magnetic properties of the core material. The core has to have a large enough area to satisfy the saturation requirement and it has to have a high enough inductance to assure a low enough droop during the pulse.

Most of the work that has been done on LIA development by LLNL used Ferrite as the core material in the induction modules. Ferrite is a very convenient choice of the magnetic material due to its very high intrinsic resistivity. This resistivity ensures a skin depth of the order of many tens of cm for 50 ns pulse length, which in

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turn assures relative permeability of the order of 10^3 for such pulses. A significant limitation of Ferrite is its relatively low saturation field. Typical values for Ferrite materials are $2B_s=0.7T$. Using eq (4) we find that for a typical LIA design with a 200 kV voltage module and a 50 ns pulse length the required area is $A>150\ cm^2$.

For this value of A and a typical core average radius of 0.2 m, and a relative permeability of 500 we calculate a module inductance of $L=7.5\ \mu H$. The resulting droop of such a core is relatively very low. For Zeff=10 ohm and a 50 ns pulse width the droop is 3.5%. Thus, the limiting value that fixes the core dimensions for a Ferrite core is the saturation of the magnetic induction.

The development in the last years of amorphous magnetic materials-Metglass(R) by the Allied Corporation may open up new possibilities of designing LIA's with reduced size and increased accelerating gradients. Metglass magnetic materials have very high static permeabilities and high saturation fields in the range of $2B_s=3T$ which is about 4 times higher than that of Ferrite. Nonetheless, high permeability at short pulses can be achieved only by using very thin layers of material that are wound to form a toroidal core.

Measurements[7] of pulsed permeability of 2605CO and 2605SC, 22 μm Metglass ribbons indicate a pulsed permeability of the order of 600 for $dB/dt=10T/\mu s$. The corresponding saturation fields are 2.9T for 2605SC and 3.3T for 2605SC.

Another set of measurements[8] is summarized in Figure 3. Here the permeability of 1 mil 2605SC cores is plotted as a function of pulse width. As can be seen from Figure 3, the relative permeability dependence on pulse width can be approximated by:

$$\mu = 1.3 \times 10^6 \sqrt{\Delta t} \tag{3}$$

Combining eq (1) and (3) we find that for a specific permitted pulse droop η the maximum pulse width that can be accelerated on a given module is:

$$\sqrt{\Delta t} < \frac{1.3 \times 10^6\ \mu_o l (R_1 - R2)\ \delta\eta}{(R_1+R_2) Zeff} \tag{4}$$

where l is the core length. A finite filling factor $-\eta<1$ is incorporated in eq (4). The saturation limitation can be written in a similar manner:

$$\Delta t < \frac{B(R_2 - R_1)\ l}{V} \tag{5}$$

Figure 4 is a plot of the two limits set by eq 4 and 5 on the pulse length that can be achieved as a function of the module length. Figure 4 shows that for short pulse length $\Delta t<40$ ns the accelerating gradients that can be achieved with Ferrite is better than that of 2605SC. For $\Delta t \sim 100$ ns the accelerating gradient that can be achieved with 2605SC is almost twice as large as the Ferrite value. For $\Delta t<150$ ns and even for 400 kV/module the droop requirement (10%) is dominant for 2605SC. For the case of low rep rate LIA's the droop requirement can be met more easily by decreasing PFL impedance which effects the efficiency of the LIA. This will result in an even larger accelerating gradient for a Metglass core LIA. The saturation requirement limits the size of the accelerator only for $\Delta t>250$ ns. This means that for Δt 100-200 ns a Metglass based LIA will actually operate far from its saturation limit.

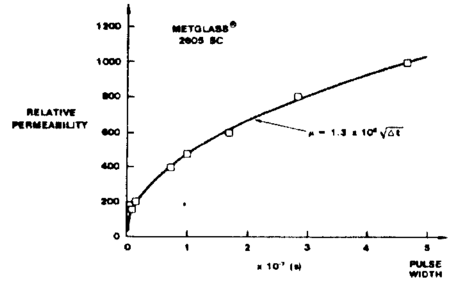

Figure 3 - Pulsed permeability of Metglass 2605SC as a function of pulse width. Sandia measurements (Ref. 8).

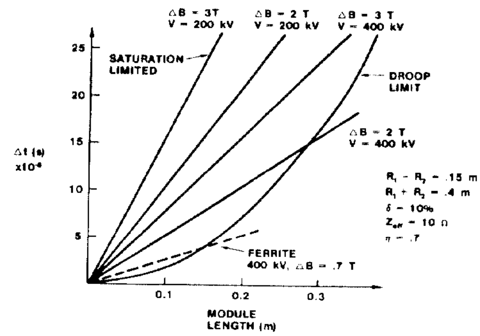

Figure 4 - Maximum pulse width as a function of core length. A droop of 10% is assumed.

3. Efficiency Considerations

Optimizing the efficiency of an LIA is of prime importance for high rep rate operation of these accelerators. For a beam current Ib and neglecting the droop influence on the idealized efficiency, the efficiency - ε of the module shown in Figure 2 is:

$$\varepsilon = \frac{2RbIbZ}{(Rb+Z)V} = \frac{2ZeffIb}{V} \tag{6}$$

If the beam current -Ib could be chosen as a free parameter then the efficiency of the module would approach unity for Ib=2V/Z or for impedance matching between the load and the PFL. In reality the beam current is limited because of beam handling and beam quality problem in long LIA's. Another approach could be to increase Zeff by increasing the PFL impedance. This is very limited, however, because of the increased droop that will result. Eq. (6) shows that for a given value of Ib that can be propagated in the accelerator, the module voltage should be as low as possible to optimize the accelerator efficiency.

For the case of Metglass and assuming the same pulse width dependence of the permeability, eq (4) can be combined with eq (6) to give a dependence between the efficiency of the module and the pulse width. The results of such a simple scaling are shown in Figure 5 for a few typical values of beam effective impedance and a few droop values. As can be seen in Figure 5, typical efficiencies of 12% can be achieved for 5% droop values and beam loading of 200 ohm for Δt=50 nsec.

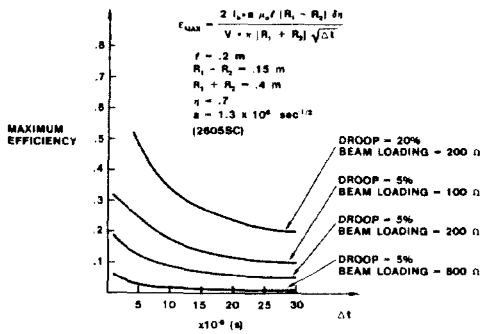

Figure 5 - Electrical efficiency as a function of pulse width. It is assumed that the permeability depends on pulse length according to Figure 3.

One way of overcoming this situation is by shaping the pulse at the input to the module to compensate for the voltage droop, this may not be very simple for these power levels. Another way is by adding compensating modules to the LIA. Such modules operating at an opposite polarity relative to most of the modules in the accelerator can compensate easily and efficiently for the voltage droop. Thus, the LIA can operate at an increased droop value and increased efficiency without sacrificing the flat top quality of the driving voltage. One simple way of accomplishing such a compensating pulse is by driving the module from a relative high impedance PFL to get a significant droop in the opposite polarity. If for example, we use one compensation cell after each N cells we get total effective voltage at the end of the pulse:

$$V(\Delta t) = NV_0 e^{-t/\tau} - V_0 e^{-t/\tau_1} \qquad (7)$$

If we require no droop at the end of the pulse, we have to meet the requirement.

$$V(o) = V(\Delta t)$$

or

$$NVe^{-\Delta t/\tau} - Ve^{-\Delta t/\tau_1} = (N-1)V \qquad (8)$$

For example, if we choose a case $\Delta t/\tau = 0.2$ (20% droop) and choose N=5 we find that equation (10) is solved for $t/\tau_1 = 2.37$. Thus, the PFL feeding the compensating module can be built with an LIA that is $2.37/0.2 \backsim 12$ times larger than that of the standard cell. Figure 6 shows an idealized pulse shape that is achieved with no compensation and also shows the compensated pulse shape. The effective droop of the system is reduced from 22% to 5.5%. The compensating cell can be made much shorter since it requires a much lower inductance. It can also be fed by a higher impedance PFL so its influence on the LIA length and its energy consumption can be negligible. By allowing a factor of 4 increase in the droop value, the LIA can be made significantly more efficient and significantly shorter.

This method of compensation may be used in order to compensate for other pulse shape distortions as well. The method can be used only for relativistic particles which is no basic limitation in the case of electron LIA's. The effect of such compensation on beam stability and propagation still has to be studied.

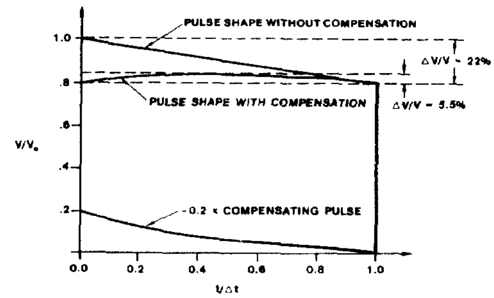

Figure 6 - Compensation of pulse top distortion by a reversed polarity module. The pulse shapes are calculated for an N=5 case. Pulse distortion is reduced from 22% to 5.5%.

References

[1] R.E. Hester, et al, IEEE Trans. Nuc. Sci. NS-26, No. 3, (June 1979).

[2] L.L. Reginato, et al , IEEE Trans. Nuc. Sci. NS-28, 2758, (June 1981).

[3] D.L. Birx, et al, LLNL Report UCRL-90554 (June 1984).

[4] D.L. Birx, and M.W. Smith, LLNL Report UCRL-91936 (March 1985).

[5] G.J. Caparaso, et al in Beams 83, 5th International Conference on High Power Particle Beams, San Francicso, CA (1983).

[6] D. Rogers, et al in 16th IEEE Pulse Power Modulator Symposium, Arlington, VA, (June 1984).

[7] C.H. Smith, L. Barberi, IEEE International Pulsed Power Conference, Crystal City, VA, (June 1985), and also private communication with C.H. Smith.

[8] J.P. Vandevender - Private communication