REDUCING ENERGY SPREAD FOR LONG BUNCH TRAIN AT SLAC

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ABSTRACT

The normal energy gain of the SLC RF system, using SLED (SLAC Energy Development) cavities, can accelerate only about 150 ns beam pulse within an energy spread of 0.5 % with 10^{11} particles per pulse. By applying two additional 180^{o} phase inversions for about 20 % of all SLC klystrons, the classical SLED pulse is flattened to achieve an energy spread of 0.5 % over 240 ns which corresponds to 680 bunches in S-band. This scheme was developed for the fixed target experiment E-154, to study the neutron spin. It was used to run at a beam energy of 48.8 GeV and a beam charge of up to 10^{11} e- per pulse. This paper describes the beam loading compensation using early beam injection scheme and new RF phase inversions which have been implemented for the SLED devices. The experimental results, obtained during fall 1995, are compared to simulations. The results surpassed the initial requested beam qualities. A similar approach might be useful for future linear colliders with long bunch trains.

1 BEAM PARAMETERS FOR E-154

The new beam has a pulse length of 120 ns which corresponds to a train of 340 bunches separated by 350 ps with a total charge of 10^{11} electrons. The repetition rate is 120 Hz and the bunch width is σ=3 ps. The 120 ns is the minimum requested. The goal is a pulse length of 200 ns or longer which corresponds to a train of 600 bunches or more. From the end of the linac the beam is transported to End Station A through a new transfer line which has a 24.5^{o} bend. The spin of the electron undergoes a precession relative to the beam direction. The calculated energy is 48.362 GeV at the target while 48.759 GeV should be reached at the end of the linac to compensate for the energy losses due to synchrotron radiation. Table 1 summarizes the parameters as requested for the E-154 experiment. The beam originates from a photo-cathode illuminated with a Ti-Sapphire laser pulse. The laser pulse length is 10 µs long and after the Pockell cells it can be adjusted according to the request. Due to the transmission efficiency in the bunching system a beam charge of $2.5*10^{11}$ e- per pulse is necessary from the photo-cathode. In order to get 48.8 GeV, the linac is used with the SLED cavities. The beam loading effects are compensated by varying the injection time and adding two 180^{o} phase inversion on 6 sub-boosters klystrons out of 30 in operation.

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2 Work supported by DOE contract DE-AC03-76SF00515.

Table 1 Beam parameters for E-154

Loaded beam energy	48.8	GeV
Polarization	≥ 80	%
Repetition rate	120	Hz
Beam pulse length	≥ 120	ns
Electrons per pulse	≤ 10^{11}	
Energy spread	ΔE/E < 0.75	%

2 SIMULATIONS

2.1 The Transient Beam Loading Compensation

The models are based on the theory described in [1]. Several programs have been written in FORTRAN and with MATLAB. Transient beam loading compensation can be applied because the beam pulse length is less than the accelerator section filling time, and therefore the beam induced voltage does not reach steady state. Different methods were proposed [2]: modulation of the RF amplitude, modulation of the RF phase or variation of the beam current amplitude. The beam arrives at an accelerator section before the beginning of the SLEDed klystron output pulse reaches the end of that section. However the energy gain margin is not very large (92 % of the unloaded energy) and the resulting energy spread is evaluated according to the beam injection timing, for a given SLED energy gain curve [3]. The main SLED and linac parameters are listed in Table 2.

Table 2 SLAC SLED cavities and linac parameters

Frequency	f	2.856	GHz
Klystron output power	P_k	65	MW
RF pulse length	t_2	3.5	µs
SLED unloaded quality factor	Q_o	100 000	
SLED external quality factor	Q_e	20 000	
Filling time of SLED cavities	T_c	1.857	µs
Quality factor for RF section	Q	13549	
Acc. section attenuation factor	τ	0.55	
Filling time of section	T_f	830	ns
Elastance [Ω s^{-1} m^{-1}]	s	76.610^{12}	
Section length	L	3	m
Nb of sections per klystron	k	4	
Number of klystrons ON Line	N_K	232	
Number of sections	N_S	240	

Figure 1 (a and b) is a plot of the amplitude and phase of the input and output fields of the SLED network. Ideal conditions, instantaneous rise/fall time and 180^0 phase change are assumed. The pulse length is 3.5 µs. The SLED network output field is the accelerator section input field.

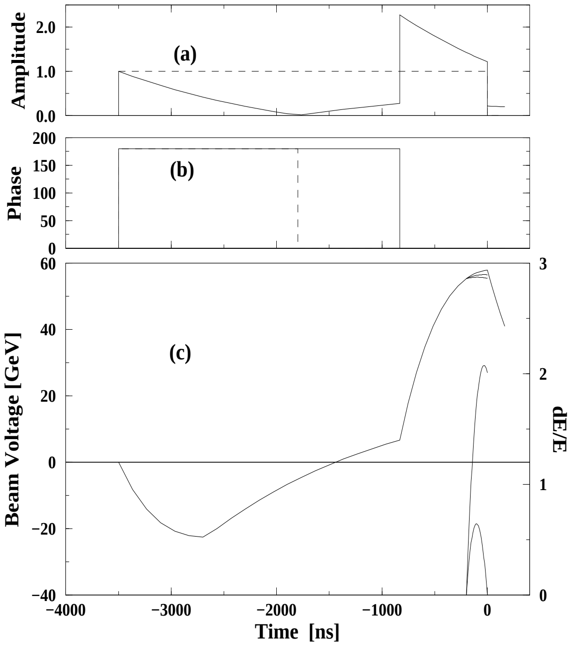

Figure: 1 SLED input (dashed) and output (solid)
a) Amplitude b) Phase c) Beam voltage,
loaded voltage; and energy spread (lower curves).

The steady state voltage, at the end of the linac, is given by:

$$V_s = N_K \sqrt{\eta\, s\, T_f\, P\, L_k},$$

where L_k is the section length feed by one klystron, η is the section efficiency. For a constant gradient section, like the SLAC linac :

$$\eta = \frac{1-e^{-2\tau}}{2\tau}.$$

The other parameters are listed in the Table 2.
For the SLAC linac, one has: L_k = 4 x 3m = 12 m, η = 0.6065. With 89% of efficiency between the klystron output and the section input, P = 58 MW. This will provide a total energy of 38 GeV. With the energy gain multiplication factor G_{max} = 1.6 , one obtains an unloaded energy gain of V_{un} = 60 GeV.
This is the theoretical value. However the maximum measured unloaded energy is 55 GeV. This value is consistent with the theoretical one because not all klystron are connected to 4 sections as assumed in the simulations. Figure 1 (c) plots the unloaded beam voltage, during 3.5 µs, under these conditions.

2.1.1 Beam Induced Voltage

For a constant gradient section, the beam induced voltage is given by [2]:

$$V_b = k\ N_S\ \frac{n\,q}{t_b}\ \frac{s\,L\,T_f}{4\tau}\left[\frac{1-e^{-2\tau t'} - 2\,\tau\, t'\, e^{-2\tau}}{1-e^{-2\tau}}\right]$$

with $t' = t / T_f$ and t_b the beam pulse length. q is the charge of the electron.
For $n = 10^{11}$ e$^-$, t_b = 200 ns (E-154 conditions), the maximum induced voltage at t = 200 ns is V_b = 1.44 GV. The loaded voltage is V_{un} - V_b.

2.1.2 Energy Spread

The energy spread within the pulse is calculated. Also plotted in Figure 1 (c) are the loaded beam voltage and the energy spread during a 200 ns beam pulse for a current of 80 mA (nominal for 10^{11} particles) and for 141 mA which minimizes the energy spread. For the nominal current, the pulse length was varied and the energy spread calculated. Figure 2 plots the maximum energy spread as a function of the beam pulse length.

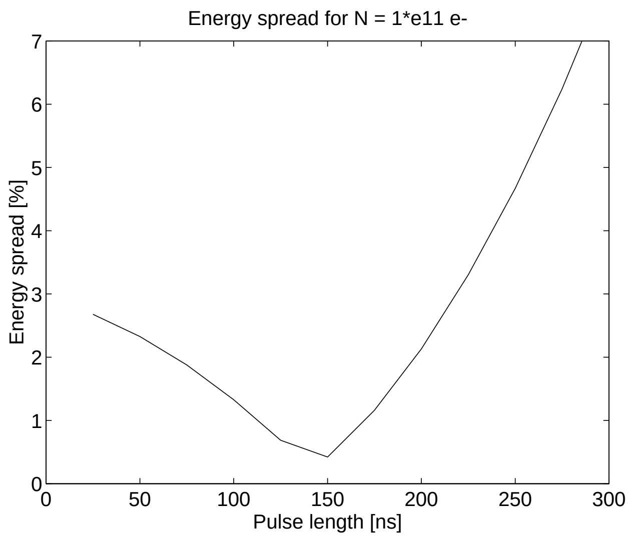

Figure: 2 Maximum energy spread versus t_b for 10^{11} e$^-$

For a pulse of 200 ns and a beam charge of 10^{11} e$^-$, the maximum energy spread is 2 %. This value is greater than the value required by the experiment. In order to achieve a smaller energy spread with a long pulse (200 ns), new RF phase inversions were implemented.

2.2 New RF phase inversions

To reduce the energy spread even further, the particles with the higher energy in the middle of the beam pulse (compare Fig. 1 c) should receive less energy. This is done by inverting the klystron rf during that time. After about 400ns the SLED output is reduced nearly to zero and the energy is stored in the SLED cavity, so the output is even higher after the third inversion. Figure 3 shows a zoom of Fig.1 (a). A realistic rise time of σ = 30 ns for the klystron is the reason for the slow rise and fall times compared to Fig. 1. The rf switches were implemented at the low voltage level which drive the original 180^{o} rf-switch, by adding a inverted signal (which should be of the order of the beam pulse length) to the original long pulse.

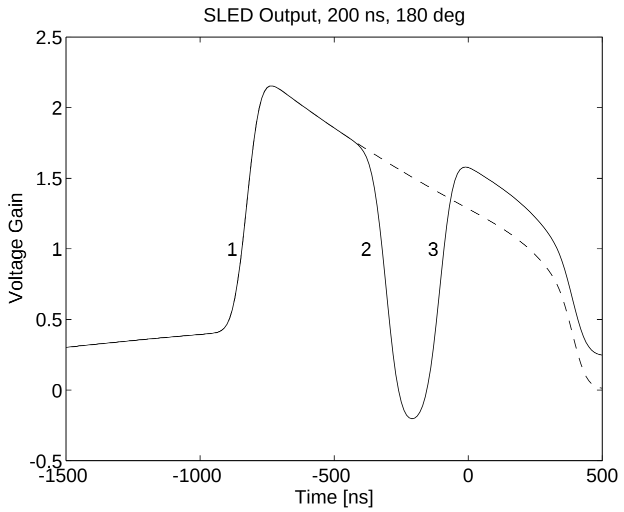

Figure: 3 RF amplitudes with 1 and 3 phase inversions
(- - -) Simulated case with normal single inversion
(—) Simulated case with 3 phase inversion.

3 EXPERIMENTAL RESULTS

The experimental (o) and the expected (dashed) energy gain curves, plotted in Fig. 4 are in good agreement, except at the end. This is due to the dispersion through the accelerator section which was not taken into account in the simulations.

The experimental energy scale is adjusted as if all spare energy would be used. This was assumed in the simulations. The solid curve shows the beam loaded simulation, but no data are available for this case. Although 6 sectors are equipped with the new rf phase inversions, the lowest energy spread can be achieved with 4 sectors of the SLAC linac. The experimental energy loss due to the inversion (star) is in good agreement with the simulation. For a pulse of 240 ns and 10^{11} particles, the measured energy spread was σ = 0.12 % (core) with a tail down to –0.36 % (10% particles)in the first 40 ns, coming probably from the loading in the S-band buncher.

Different beam charges were requested and used by the experiment E-154. Each time with this new rf phase inversions, the energy spread was always below 0.5 % and the experiment was able to record very clear and useful data.

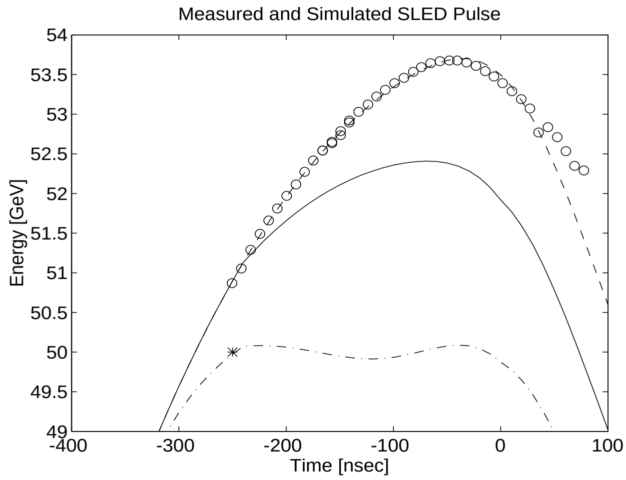

Figure: 4 Beam energy gains simulated and measured
(- - -) Simulated unloaded energy gain
(ooo) Measured unloaded energy gain
(—) Simulated loaded energy gain with early injection
(. _ .) Loaded energy gain with 3 rf inversions

4 CONCLUSION

The basic demand was a long beam pulse of >120 ns with an energy spread of less than 0.75%. By combining the transient beam loading compensation together with two specific RF phase inversions during the pulse, the experimental results surpassed the initial requested beam qualities. Such scheme could be studied and may be applied for the future linear colliders where bunch trains vary between 10 and 800. However the beam charge per bunch is one or two magnitudes larger and this issue remains to be studied.

5 ACKNOWLEDGMENTS

We would like to thank J. Sheppard for his continuous support of this work, K. Jobe for the program developments, R. Akre for a fruitful rf discussion and R. Pitthan for the original proposal to implement a longer beam pulse for E-154.

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