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Improved Overhead Counting in the NLC Main Linac

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Abstract: The NLC main linac contains 1,116 RF power units, of which 5% are considered ``spares" for replacement of failed power units, make-up of the energy gain during an RF breakdown, and energy feedback. A more careful accounting for the effects of beam loading indicates that the NLC can operate with less BNS overhead and a smaller mean phase offset than was originally specified, and that as a consequence the total number of spares is actually about 7.9% of the total.

Improved Overhead Accounting in the NLC Main Linacs

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1 Introduction

The NLC main linac consists of 1,116 RF power stations, each of which supplies power to 8 RF structures. Like most high-performance linacs, the NLC main linacs do not require that every RF power station be active to achieve the design energy (250 GeV per beam). Instead, each linac includes a number of spare stations: some of the spares are dedicated to energy feedback, and by default they are phased to provide no net energy gain to the beam, while other spares are triggered in such a way as to operate when the beam is not present. When an RF station which is accelerating the beam fails, a combination of rephasing the feedback stations and moving some spares from "out-of-time" to "in-time" pulsing can quickly make up the loss in energy gain from the failed station.

The issue of the total number of spares needed by the linac is a tradeoff between building more spares to ease operation and building fewer spares to save money. The nominal NLC specification is for a total of 5% spares per linac. Of the 5%, 3% are expected to be used to make up RF stations that have suffered a serious failure (klystron or modulator stops working entirely), while 2% are dedicated to feedback and short-term make-up for stations which have dropped out for a few seconds to recover from an RF breakdown. The number of spares is closely connected to the NLC's specifications for RF breakdown rates and RF component lifetimes. A larger number of spares would permit a higher breakdown rate and/or a shorter klystron/modulator lifetime.

1.1 Determining the Amount of Overhead

Each 60.17 cm RF structure is specified to produce 65.2 MV/meter on-crest accelerating gradient, for a total energy gain per station of 313.85 MeV. Since the beam enters the linac with 7.87 GeV from the pre-linac and bunch compressors, this would imply that only 772 RF units are required to reach 250 GeV at the end of the main linac. Unfortunately, a number of phenomena reduce the available gradient.

1.1.1 Fundamental-Mode Beam Loading

The beam excites the fundamental (11.424 GHz) accelerating mode of the structures when it passes through them. Since conservation of energy obviously won't permit the beam to excite the structures in an accelerating phase, it winds up exciting them in a decelerating phase. For the

NLC with its design beam current of 860 mA, the fundamental mode beam loading corresponds to 13.1 MV/m decelerating gradient in the steady-state.

1.1.2 Higher-Order Mode Beam Loading

In addition to the fundamental mode, the beam excites a large number of higher-frequency monopole modes at decelerating phase. These modes are basically single-bunch, in that by the time the second bunch arrives the HOM fields from the first bunch have decayed. The HOM loading is an additional 0.38 MV/meter of decelerating gradient.

1.1.3 Average Phase

In addition to reducing the mean energy gain of each structure, the HOM loading increases over the length of one bunch, causing the tail to experience greater loading than the head of the bunch. This can be compensated by accelerating the beam ahead of the crest, so that the loading and the differential acceleration from off-crest operation cancel one another. Off-crest acceleration reduces the total energy gain, so linacs often run with incomplete compensation of the HOM energy spread. The NLC is no exception: the energy spread at the end of the linac is a two-horned “batman” distribution with 0.25% RMS spread, 0.91% FWHM. This is about an order of magnitude larger than the minimum achievable energy spread at 250 GeV/beam, but achieving the minimum would require running even further from the crest and would result in a larger “voltage tax.”

Since the NLC main linac requires an energy spread for BNS damping which is larger than the desired 0.25% RMS (see next section), none of the linac structures are at the “mean phase” – some are phased to accelerate closer to the crest, and some further away. We can nonetheless calculate the mean phase from a given distribution of phases as follows: if the cosine-like and sine-like components of the RF are computed,

$$\begin{aligned} V_c &= \sum V_n \cos(\phi_n), \\ V_s &= \sum V_n \sin(\phi_n), \end{aligned} \tag{1}$$

then the mean phase for the linac is given by:

$$\bar{\phi} = \tan^{-1}(V_s/V_c). \tag{2}$$

The mean phase is an invariant of the linac configuration: for a given desired energy spread, all the sets of linac voltages and phases which achieve that energy spread will have the same mean phase.

1.1.4 BNS Damping

In order to achieve stable linac operation, it is necessary to operate with a large head-tail energy spread within each bunch for most of the linac length, and then to remove the energy spread at the end. The resulting reduction in wakefield emittance growth is usually referred to as BNS damping [1]. This requires additional phase offsets in addition to the mean phase, and therefore constitutes an additional “voltage tax.” In the case of the NLC, this is usually specified as a fractional overhead which is dedicated to BNS damping: philosophically, accelerator physicists can tweak the phasing any way they like so long as the required increase in the number of RF stations does not exceed the specified fractional overhead.

1.1.5 Spare RF Units

Finally, some number of spare units are required for making up the total energy in the presence of RF breakdowns (which will shut individual stations off for a few seconds at a time) and more serious failures of the klystrons or modulators (which will shut stations down until repair/replacement has been completed). In the NLC main linac these two types of failure are separately accounted.

1.2 Putting it All Together

Given all of the features described above, one can write down an expression for mean effective gradient of the NLC main linac as follows [2]:

$$\bar{G} = G_u \cos(\bar{\phi})(1 - f_{\mathrm{BNS}} - f_{\mathrm{S1}} - f_{\mathrm{S2}}) - G_{L,\mathrm{FUN}} - G_{L,\mathrm{HOM}}, \tag{3}$$

where G_u is the unloaded on-crest gradient, $\bar{\phi}$ is the aforementioned mean phase, f_{BNS} is the fractional BNS damping overhead, f_{S1} is the fractional overhead for hard failures, f_{S2} is the fractional overhead for soft failures and feedback, $G_{L,\mathrm{FUN}}$ is the loading from the fundamental mode, and $G_{L,\mathrm{HOM}}$ is the loading from the higher-order modes. In the case of the NLC main linac, $G_u = 65.2$ MV/m, $G_{L,\mathrm{FUN}} = 13.1$ MV/m, $G_{L,\mathrm{HOM}} = 0.38$ MV/m, $\bar{\phi} = -12°$, $f_{\mathrm{BNS}} = 3\%$, $f_{\mathrm{S1}} = 3\%$, and $f_{\mathrm{S2}} = 2\%$. The resulting mean effective gradient is 45.2 MV/m. For 1,116 stations with 8 structures of 60.17 cm each and an injection energy of 7.87 GeV, one arrives at a final energy of 250.6 GeV. This indicates that 1,116 stations per main linac will give the 500 GeV CM NLC exactly the complement of spares and overhead specified.

2 Mean Phase for the NLC

The gradients specified in the previous section are determined by the electrical circuit design of the NLC X-band structures and by the desired unloaded gradient of 65.2 MeV/m (which in turn comes from optimization of the linac capital costs and the acceptable RF structure breakdown rate). The fractional overhead for BNS damping comes from the linac design and optimization of different steering and alignment tolerances, and the overheads for soft and hard failures are specified based on what is needed to achieve a certain linac availability.

The mean phase is determined by the desired end-linac energy spread of 0.25% RMS. The RF system calculator in the program LIAR [3] indicates that the NLC2003 main linac design requires a mean phase of $-12°$ to achieve this end-linac energy spread.

It is important to remember that LIAR's energy gain calculator is basically single-bunch. LIAR calculates the energy gain and correlated energy spread per structure as:

$$\begin{aligned} V &= L_{\mathrm{struc}} G \cos(\phi) - V_{\mathrm{SB}}, \\ \frac{dV}{dz} &= -L_{\mathrm{struc}} k G \sin(\phi) - V'_{\mathrm{SB}}, \end{aligned} \tag{4}$$

where G is the structure's loaded gradient, V_{SB} is the single-bunch average loading, V'_{SB} is the slope of the single-bunch loading, and $k = 2\pi/\lambda$ is the RF wave number. Note that LIAR uses the loaded gradient G for both the mean voltage and the energy spread calculation. This is not correct since the beam loading voltage contributes to the mean voltage but not to the energy spread – the loading voltage is always 180° out of phase with the beam, hence its slope over the beam length is proportional to $\sin(180°) = 0$. A more correct calculation for one structure is:

$$\begin{aligned} V &= L_{\mathrm{struc}} G_U \cos(\phi) - L G_{L,\mathrm{FUN}} - L G_{\mathrm{HOM}}, \\ \frac{dV}{dz} &= -L_{\mathrm{struc}} k G_U \sin(\phi) - V'_{\mathrm{SB}}. \end{aligned} \tag{5}$$

LIAR tunes its value of G to achieve the correct total voltage, which means that it underestimates the voltage slope which depends on G_U and not on G.

To correctly calculate the mean phase, recall that the point of setting the mean phase is to force dV/dz to a certain acceptable value, therefore to get the slope from the RF to cancel the slope from the single-bunch wakes to a desired level. Since LIAR indicates that the acceptable cancellation occurs when the mean phase is -12° and the gradient G is 50.6 MeV/m, the correct mean phase is given by $G_U \sin(\bar{\phi}) = G \sin(-12^\circ)$, therefore $\bar{\phi} = \sin^- 1(G\sin(-12^\circ)/G_U)$, or -9.3°. The previously specified mean phase of -12° is therefore seen as somewhat more conservative than necessary.

3 BNS Overhead

The present NLC main linac uses an RF phase configuration of +10° from 7.87 GeV to 30 GeV, followed by -3° from 30 GeV to 170 GeV, followed by -30° from 170 GeV to 250 GeV, assuming a gradient of 50.6 MV/meter in the powered RF stations. The BNS overhead is the difference between the number of RF stations needed in this configuration and the number needed if all stations are run at the average phase.

Since the key parameter for BNS damping is the voltage slope at the center of the bunch, once again the single-bunch calculation overestimates the phase offset required. Since the voltage slope comes from the unloaded gradient, the actual phases required are 7.75° from 7.87 GeV to 30 GeV, -2.33° from 30 GeV to 170 GeV, and -22.8° from 170 GeV to 250 GeV.

The number of RF stations needed to achieve an energy gain V at a phase ϕ is given by

$$N = \frac{V}{4.8138 \text{ m}(G_U \cos(\phi) - G_{L,\text{FUN}} - G_{L,\text{HOM}})}. \tag{6}$$

Given the gradient parameters and BNS phases listed above, the number of stations requires is 89.9 in the first BNS region, 562.9 in the second, and 356.4 in the third, for a total of 1009.2 stations. At the mean phase of -9.3°, only 988.9 are needed. Rounding to 1009 and 989, we find that the actual BNS overhead is 2.0% rather than 3%.

4 Putting it All Together

Let us now revisit Equation 3, with a mean phase of -9.3° and a BNS overhead of 2.0%. If we preserve the desired 5% overhead for hard and soft RF station faults, we find a mean gradient of 46.4 MeV/meter, yielding a final energy of 257.1 GeV rather than 250.6 GeV. This means that there is actually an additional overhead of about 2.9% compared to the amount estimated when the calculation is performed with overlarge mean phase and BNS overhead values.

5 Multibunch Loading Compensation

The phases and gradients reported here are for the case of steady-state beam loading, which is the state after one fill-time worth of beam has passed through a given structure. In the NLC the beam loading transient in the first fill-time worth of beam is compensated by initially filling the structure to an unloaded gradient equal to the steady-state loaded gradient, and then gradually allowing the unloaded gradient to rise to the full value of 65.2 MeV/meter.

In the case of off-crest running, we want both the cosine-like and the sine-like voltages seen by the first bunch to be equal to the steady-state values. This implies that both the unloaded gradient and the phase required for the first bunch are different from what is needed in steady-state. The first bunch sees an unloaded gradient G_1, a total loading $G_{\rm SB}$ of 1.14 MV/meter (corresponding to the HOM loading plus the single-bunch component of the fundamental mode loading), and a phase ϕ_1. In order to make both the sine-like and cosine-like components of the applied voltage equal to the steady-state, we require:

$$\begin{aligned} G_U \cos(\phi) - G_{L,\rm FUN} - G_{L,\rm HOM} &= G_1 \cos(\phi_1) - G_{\rm SB}, \\ G_U \sin(\phi) &= G_1 \sin(\phi_1). \end{aligned} \tag{7}$$

Considering all of this, gradient and phase for bunch 1 should be 52.8 MV/m and 9.58° in BNS region 1, 52.8 MV/m and -2.87° in BNS region 2, and 53.9 MV/m and -28.0° in BNS region 3.

6 Conclusion

The NLC main linac is usually quoted to require a mean phase of -12° and 3% RF overhead for BNS damping, leaving a total of 5% overhead in the present NLC design for spare RF stations and energy feedback. This calculation is an overestimate because it does not take account of the fact that beam loading reduces the mean acceleration of each structure but does not reduce the slope induced by off-crest running (essentially, it loads the cosine-like but not the sine-like component of the structure field). When this fact is properly accounted for the actual mean phase is -9.3°, only 2% overhead is required for BNS damping, and the present linac configuration has almost 8% total spares rather than 5%. This asymmetry in the loading also has minor implications for the beam-loading compensation method used in the NLC main linac.

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References

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[2] C. Adolphsen, private communication.

[3] R. Assmann *et al*, "LIAR, A Computer Program for the Modeling and Simulation of High Performance Linacs" (1997).