Fabrication and Tolerance Issues and their Influence on Multi-Bunch BBU and Emittance Dilution in the Construction of X-Band RDDS Linacs for the NLC

R. M. Jones, R. H. Miller, T. O. Raubenheimer, and G. V. Stupakov

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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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Abstract
The main linacs of the Next Linear Collider (NLC) will contain several thousand X-band RDDS (Rounded Damped Detuned Structures). The transverse wakefield in the structures is reduced by detuning the modal frequencies such that they destructively interfere and by four damping manifolds per structure which provide weak damping. Errors in the fabrication of the individual cells and in the alignment of the cells will reduce the cancellation of the modes. Here, we calculate the tolerances on random errors in the synchronous frequencies of the cells and the cell-to-cell alignment.

2. MACHINING ERRORS AND EMITTANCE DILUTION
Small dimensional errors, generated when fabricating the irises and cavities of an accelerator structure, give rise to errors in the synchronous frequencies [1]. Presently, it is possible to machine the cells to an accuracy of better than 1 µm [2,3], however, when fabricating several thousand such structures, looser tolerances may reduce the fabrication costs.

The linacs consist of roughly 5000, nominally identical, structures, each of which contains 206 slightly different cells. The nomenclature that we adopt is an error type which is repeated in every cell of a structure but differs in every structure is referred to as: a systematic-random error. Whereas, an error that is repeated in every structure, but varies from cell-to-cell, we refer to as a random-systematic error. We also consider random-random and systematic-systematic (potentially the most damaging) error types making a total of 4 error types. The random errors we consider have an RMS deviation of 3MHz about the mean dipole frequency of the cells. In fabricating RDDS1, the RMS error in the synchronous frequency prior to bonding the cells was 0.5MHz [2,3] and thus simulation of larger errors is pursued with a goal of understanding how much the cell-to-cell fabrication tolerances can be relaxed.

Cell-to-cell frequency errors within an individual structure reduce the effect of the detuning cause a larger wakefield. Although BBU is a complicated effect, an indicator for the onset of BBU is provided by the
wakefield at a particular bunch which is formed by summing all wakefields left behind by earlier bunches which is denoted as the “sum wakefield” [4]. BBU will likely arise when the RMS of the sum wake is the order of 1 V/πpC/mm/m or larger. When not in the BBU regime, the sum wakefield also provides an accurate method of calculating the multi-bunch emittance dilution and will be used in the following section.

An example of the sum wakefield for a structure with 3MHz RMS errors in the cell synchronous frequencies is plotted in Fig. 2 versus a change in the bunch spacing. Changing the bunch spacing is equivalent to changing all the synchronous frequencies systematically. The wakefield with the random errors is an order of magnitude larger than in a perfect structure and if these cell errors are reproduced in every structure it would be expected to cause significant BBU.

This is confirmed by particle tracking simulations using the code LIAR [5] in which the all structures are assumed to be perfectly aligned and the beam is initially offset by 1µm. When all structures have identical random errors (this is the case of random-systematic errors) and Ss is of the order of unity, the beam clearly undergoes BBU as illustrated in Fig. 3 and the emittance grows by roughly 250%. This is supported by looking at the phase space at the end of the linac corresponding to this random-systematic error is plotted in Fig. 4(b).

The results of relaxing the tolerance are documented in [6] and it is found that even for the very relaxed case of a 5MHz error in the synchronous frequencies BBU does not occur and little emittance growth arises provided this cell-to-cell error is not repeatable over all structures.

Figure 3. Emittance growth due to 3MHz RMS errors that are (a) reproduced in every structure and (b) random from structure-to-structure.

Figure 4. Phase Space (3MHz RMS error). The phase space to the left (a) is for a linac composed of 4720 structures assumed to have identical random errors in each structure. The phase space to the right (b) has been computed from a linac composed of structures with a different random error in the synchronous frequency (non-identical structures).

3. TOLERANCES IMPOSED ON STRUCTURE ALIGNMENT

Next, assuming that BBU is not an issue, let us consider the effect of misalignments of the cells and the structures on the multi-bunch beam emittance. In order to estimate the growth of the projected emittance Δε of a train of bunches caused by misaligned structure cells we use the following formula for the expectation value of Δε [5]

\[
\langle \Delta \varepsilon \rangle = \bar{r}_e N^2 \beta_0 L N_s \langle \Delta S^2 \rangle \frac{1 - \left( \frac{\gamma_0}{\gamma} \right)^1/2}{\gamma_0 \beta_0} \quad (3.1)
\]

where \(r_e\) is the classical electron radius, \(N\) is the number of particles in the bunch, \(\bar{\beta}_0\) is the average value of the
beta function at the beginning of the linac, $N_s$ is the number of structures in the linac, $L_s$ is the length of the structure, $\gamma_0$ and $\gamma_f$ are the initial and final relativistic factors of the beam, and $S_k$ is the sum wake. The quantity $S_k$ is defined as a sum of the transverse wakes $w_i$ generated by all bunches preceding the bunch number $k$, $S_k = \sum_{i=1}^{k} w_i$ and $\Delta S_k$ is the the difference between $S_k$ and the average value $\langle S \rangle$, with $\langle S \rangle = N_c \sum_{i=1}^{N_b} S_i$, where $N_b$ is the number of bunches. Also, $S_k = \langle S^2 \rangle^{1/2}$. Eq. (3.1) is derived assuming a lattice with the beta function smoothly increasing along the linac as $\beta \propto E^{1/2}$.

For small misalignments, $w_i$ is a linear function of cell offsets, $w_i = \sum_{i=1}^{N_c} W_{i,x}$ which can be found from the solution of Maxwell’s equations for the structure. The matrix $W$ for the NLC structure RDDS1 with 206 cells is based on the method described in [7]. It has a dimension of $N_b \times 206$. In our calculation we used $N_b = 95$ for bunch spacing 2.8 ns.

In order to verify Eq. (3.1), we tracked a multi-bunch beam through the complete linac (approx 11 km) using the computer code LIAR [4] for RDDS1 with the following linac parameters: beam final energy - $E_f = 500$ GeV, number of structures in the linac - $N_s = 4720$, and number of particles in the bunch - $N = 1.1 \times 10^{10}$. The multi-bunch emittance growth which arises with structures rigidly misaligned is shown in Fig. 5. It is evident that structures randomly misaligned with an RMS value of 40 $\mu$m gives rise to an overall emittance growth of 10% which grows linearly along the linac as predicted by Eq. (3.1).

The result of many simulations in which each structure is divided up into groups of cells and each individual group is moved randomly transverse to the axis of the linac is illustrated in Fig. 6. It is seen that the analytical formula based on the sum wakefield (line) generally agrees well with the LIAR simulation (points). It should be noted that the single bunch emittance growth due to rigid structure misalignments imposes a much more severe tolerance than that due to the multi-bunch emittance growth [8] however the multi-bunch effects sets that tolerances on the alignment of the individual cells and short pieces of the structure. The tolerance for the cell alignment is about 6 $\mu$m in this piecewise model. Alternately, assuming a random walk model for the cell-to-cell alignment [9], each cell must be aligned with respect to its neighbour with an RMS of 2–3 $\mu$m.

**4. CONCLUSIONS**

We have discussed four distributions of frequency errors. BBU will arise in the NLC from cell frequency errors of many MHz which are repeated in every structure. However, in practise it is expected that fabrication errors will occur randomly from cell-to-cell and from structure-to-structure and hence BBU is unlikely to occur. Furthermore, to meet a prescribed multi-bunch emittance growth of 10%, the cells in the present RRDS structure design structure must be aligned to better than 6 $\mu$m and the average alignment of the structure must be better than 40 $\mu$m. Of course, the average alignment tolerance is dominated by single bunch averaging and must be closer to 10 $\mu$m[8].

**5. REFERENCES**