LCC-0073
SLAC-PUB-9004
September 2001

Linear Collider Collaboration Tech Notes

Microwave Quadrupoles for Beam Break-up Supression In the NLC Main Linac

K.L.F. Bane and G. Stupakov

Stanford Linear Accelerator Center
Stanford, CA

Abstract: This is a preliminary study of the effect of using microwave quads (MQs) instead of rf phase shifting to induce BNS damping in the main linac of the NLC collider. We consider MQs running at X-band, and find that the total length of MQs needed for the NLC is 6% of the total length of the accelerating structures. We show through simulations that, by using MQs instead of phase shifting for BNS damping, the quad alignment tolerances can be relaxed but at the expense of shifting the tight tolerances to the MQs; this can be advantageous if the MQs can be better aligned than the quads. For the design final energy spread in the NLC of 0.3%, the quad tolerances are loosened by a factor of 2-3 when using MQs. These tolerances can be loosened by an additional factor of 1.5, but at the cost of 1.7% in energy overhead.

SLAC-PUB-9004
LCC-0073
September, 2001

MICROWAVE QUADRUPOLES FOR BEAM BREAK-UP SUPPRESSION IN THE NLC MAIN LINAC*

K.L.F. Bane and G. Stupakov
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Abstract

This is a preliminary study of the effect of using microwave quads (MQ's) instead of rf phase shifting to induce BNS damping in the main linac of the NLC collider. We consider MQ's running at X-band, and find that the total length of MQ's needed for the NLC is 6% of the total length of the accelerating structures. We show through simulations that, by using MQ's instead of phase shifting for BNS damping, the quad alignment tolerances can be relaxed but at the expense of shifting the tight tolerances to the MQ's; this can be advantageous if the MQ's can be better aligned than the quads. For the design final energy spread in the NLC of .3%, the quad tolerances are loosened by a factor of 2-3 when using MQ's. These tolerances can be loosened by an additional factor of 1.5, but at the cost of 1.7% in energy overhead.

*Work supported by Department of Energy contract DE–AC03–76SF00515.

1 Introduction

In the main linac of the Next Linear Collider (NLC) the short-range, transverse wakefields induced by the beam are extremely strong. A small amount of injection jitter, amplified by these fields, can significantly increase the projected emittance at the linac's end, in a process known as single bunch, beam break-up (BBU). To counteract this instability it will be necessary to invoke BNS damping. In the NLC it is planned to do this in the usual way, by shifting the beam's rf phase in order to induce a head-to-tail energy spread in the beam, which, in turn, results in a longitudinally correlated tune spread, which damps the instability. However, an alternative method of inducing a correlated tune spread is to add microwave quadrupoles (MQ's)—devices that focus the head of the bunch differently than the tail—to the linac. (These devices are similar, though should not be confused with, RFQ's used in focusing and accelerating protons or ions at low energies.)

Microwave quadrupoles were studied many years ago for the CLIC linear accelerator project, beginning with a paper by W. Schnell [1] (see also Refs. [2, 3]). They are non-cylindrically symmetric cavities that allow for both the acceleration and focusing of high energy electron beams, with the amount of each depending on the phase of the beam with respect to the MQ cavity wave. We, however, are primarily interested in their ability to focus differentially—to focus the head and tail of the beam differently. In this report we will study the effect of placing a dedicated MQ cavity after each quad in the linac. Potential advantages in using dedicated MQ's instead of rf phase shifting to induce BNS damping are:

- Because the energy spread in the quads is reduced, the quad alignment tolerances can be relaxed, though at the expense of tight MQ alignment tolerances. This can be advantageous if one can align the MQ's and the accelerating structures better than the quads.
- Since the acceptable final energy spread is usually significantly less than the energy spread needed for BNS damping, with phase shifting one has no BNS damping near the end of the linac, so the beam becomes especially sensitive to betatron oscillations in this region.
- One cost of phase shifting is an increase in energy overhead required, which is $\sim 3\%$ for the NLC. As we will see below, the MQ's will take up about 5% of the linac space; however, with MQ's we can have differential focusing and, at the same time, acceleration, so approximately no gradient need be lost.

The main disadvantage of using MQ's, of course, is that an extra rf system with many extra feeds (there are 500 quads in each linac) will be needed, and also extra power will be needed.

In this report we will study the applicability of dedicated MQ's to the main linac of the NLC. In addition to dedicated MQ's, we will also investigate the idea of using hybrid structures—accelerating structures that have non-cylindrically symmetric parts—which can accelerate and focus at the same time (which was one of the original CLIC ideas). With this scheme no extra power sources or feeds are needed, at the expense of further complicating the already rather involved rf cavity design, and at the expense of coupling acceleration and differential focusing. We also investigate briefly whether dedicated, cylindrically symmetric, travelling wave structures operating in a pure quadrupole ($m = 2$) mode might give us better focusing for a given amount of input power. Finally, through numerical tracking we study the effect of MQ's on single-bunch beam break-up and on alignment tolerances in the NLC linac.

2 Microwave Quad Properties

For the simple model of a pillbox cavity with a narrow slot through which the beam travels, Schnell derived a relation between the focusing strength and the accelerating gradient. Consider a bunch of electrons moving at speed of light c through a microwave quad cavity. If the voltage gain is given by

$$E_z(z) = \hat{E}_z \cos(k_{\mathrm{rf}} z + \phi) \quad , \tag{1}$$

with z the longitudinal position within the bunch ($z < 0$ is to the front), $\hat{E}_z$ the peak voltage gradient, k_{rf} the rf wave number of the fundamental mode, and ϕ the phase of the rf wave, then the focusing strength can be written as [1]

$$G(z) = \eta \frac{k_{\mathrm{rf}} \hat{E}_z}{2c} \sin(k_{\mathrm{rf}} z + \phi) \quad . \tag{2}$$

If the slot is oriented horizontally, then a positive sign for G indicates vertical focusing. We include the efficiency factor η in Eq. 2 to allow for real structures, which will have reduced focusing compared to the idealized model. It appears that for realistic structures, such as cylindrically symmetric cavities with elliptical irises, or elliptical cavities with circular irises, an efficiency factor of 0.8 can be achieved [3].

If we run the MQ at phase $\phi = 0$ we have maximum differential focusing, with the head of the beam defocused and the tail focused. To change the sign of the differential focusing, we can either change the phase to $\phi = \pi$ or rotate the cavity by 90° about its axis. Note, however, that at $\phi = 0$ the beam will, in addition, gain energy from the MQ, whereas at $\phi = \pi$ it will lose energy. For typically short bunches $G(z) \approx G'(0)z$, where

$$G'(0) = \eta \frac{k_{\mathrm{rf}}^2 \hat{E}_z}{2c} \cos\phi \quad . \tag{3}$$

2.1 Microwave Quads for BNS Damping

The main linac lattice of the NLC is approximately a FODO lattice, with the average beta function $\bar{\beta}$, the focal length of the quads f_q, and the spacing between quads (the half-cell length) L all scaling roughly as $\mathcal{E}^{1/2}$, with $\mathcal{E}$ the beam energy. We consider placing an MQ cavity next to each quad in the linac. We want to separate the functions of focusing (in the quads) and differential focusing (in the MQ's). Therefore, we will run the MQ's at phase $\phi = 0$, where we have no focusing (for the beam center), maximum differential focusing, and maximum acceleration in the MQ. In the focusing plane of the quad, we want the MQ to contribute stronger focusing to tail particles; *i.e.* next to a y-focusing quad the wide direction of the cavity or irises should be aligned horizontally, and next to an x-focusing quad it should be aligned vertically. Note that, with MQ's, we can run all accelerating structures at phase ϕ_0, the phase that minimizes the energy spread in the beam, and therefore, don't need energy overhead for phase shifting.

We can characterize the MQ strength by the ratio of the MQ focusing at $z = \sigma_z$ behind bunch center to the focusing of the adjacent quad:

$$\alpha \equiv \frac{f_{mq}^{-1}(\sigma_z)}{f_q^{-1}} \quad , \tag{4}$$

where $f_{mq}^{-1}(z)$ is inverse focal length due to rf quads, and f_q^{-1} is inverse focal length due to normal quads. The inverse focal length at σ_z due to the MQ's is

$$f_{mq}^{-1}(\sigma_z) = ceG'(0)\sigma_z L_{mq}/\mathcal{E} \quad , \tag{5}$$

with L_{mq} the length of the MQ. The required value of α is given by the amount of BNS damping needed. Note, however, that to counteract the instability the α needed is not given by a precise value; rather any value in a certain range will do. We can estimate an appropriate value from a two-particle approximation for the energy spread needed for autophasing in a FODO lattice [4]

$$\alpha_{auto} = \frac{eNW_x(2\sigma_z)L^2}{12\mathcal{E}} \left(1 + \frac{3}{2}\cot^2\frac{\mu}{2}\right) \quad , \tag{6}$$

with N the bunch population, W_x the dipole wake, and μ the lattice phase advance per cell. From simulations for the NLC presented below, we find that a value of α that is half this value will also do, which turns out to be on the order of 1%.

The required length of the MQ's to the cell half-length

$$\begin{aligned} \frac{L_{mq}}{L} &= \frac{\alpha\mathcal{E} f_q^{-1}}{ceG'(0)\sigma_z L} \\ &= \frac{8\alpha\mathcal{E}}{ceG'(0)\sigma_z\bar{\beta}^2} \left(\frac{\sin(\mu/2)}{\sin^2\mu}\right) \quad , \end{aligned} \tag{7}$$

with $\bar{\beta}$ the average of the maximum and minimum beta functions. Note that for the NLC lattice the ratio is approximately independent of energy. The power requirements for an MQ structure are

$$P = \frac{\hat{E}_z^2 L_{mq}}{R_s(1 - e^{-2\tau})} \quad , \tag{8}$$

with R_s the shunt impedance per length and τ the filling time parameter for the structure. Note that the shunt impedance for the MQ may be less than for the analogous cylindrically symmetric structure. For example, calculations in Ref. [3], where elliptical cavities replace cylindrical ones and $\eta = 0.8$ is achieved, R_s is reduced by 25%.

2.2 Microwave Quads in the NLC Linac

For the NLC we consider MQ cavities operated at X-band, with properties similar to those of the linac accelerating structures, though, as we shall see, the MQ's will be shorter. Possibly their cavities will be elliptical in shape and their irises will be round (as suggested in Ref. [3]). They may need extra damping to avoid multi-bunch beam break-up. (The short-range wakefields of the MQ's, however, though more complicated than usual, should not significantly affect the beam emittance.)

For NLC linac parameters we take: initial energy $\mathcal{E}_0 = 8$ GeV, final energy $\mathcal{E}_f = 250$ GeV, and active length (total structure length) $(L_a)_{tot} = 5100$ m. In the NLC the cell half-lengths L do not vary continuously along the linac. The lattice can be described as a sequence of 3 different constant-period FODO lattice pieces that are matched at the ends. The half-cell lengths L, are roughly 6.5 m, 13.0 m, 19.5 m, which are meant to accommodate a number of accelerating structures plus 20%. At present the structure length L_a is not fixed. Let us suppose here, however, that $L_a = 1.8$ m, so that there are 3, 6, and 9 structures between quads. In Fig. 1 we plot the average of the maximum and minimum beta function in each cell,$\bar{\beta}_y$, and the phase advance per cell μ_y. The dashed curves give $\bar{\beta}_y = \bar{\beta}_{y0}\sqrt{\mathcal{E}/\mathcal{E}_0}$ with $\bar{\beta}_{y0} = 7.5$ m, and the average phase advance per cell $\langle\mu_y\rangle = 85.9°$. We see that the approximation $\bar{\beta}_y \sim \mathcal{E}$ with $\mu_y \sim$ (constant) is reasonably good.

Beam parameters are $N = .75 \times 10^{10}$ and $\sigma_z = 110$ μm. For the final beam spectrum to fit in a 0.8% energy window (a requirement) means that the average accelerating structure phase $\phi_0 = -10.9°$. For the MQ's we take: $\eta = 0.8$, $k_{\rm rf} = 240$ m^{-1} (X-band), $\hat{E}_z = 50$ MV/m, and $\phi = 0$; then $G'(0)\sigma_z = 0.4$ T/m. The wake $W_x(2\sigma_z) \approx 20$ V/pc/mm/m[4]; therefore, the autophasing condition, Eq. 6, yields $\alpha = 2\%$. Simulations (given below), however, show that $\alpha = 1\%$ suffices. For $\alpha = 1\%$ we plot, in Fig. 2, the length L_{mq} as given by Eq. 7. Note that for the simplified model $\beta \sim E^{1/2}$ and $\mu_y =$ (const), the ratio $L_{mq}/L = 0.06$ (the dashes in the figure) which, over the linac, gives the same average as the more detailed calculation.

The basic unit of the linac, the lattice cell, comes in 3 versions. In a similar manner, for simplicity we propose building 3 versions of MQ's (with two orientations each), differentiated by their lengths, with each version fed by a fixed input power. If there are, *e.g.* 3, 6, and 9 accelerating structures between quads with each accelerating structure consists of 103 cells, we can satisfy $L_{mq}/L = 0.06$ by building 3 types of MQ's that are similar to the accelerating structures, but have lengths of only 45, 90, and 135 cells. The power required per MQ, supposing $R_s = 60$ MΩ/m (25% less than in the main X-band structures[5]) and $\tau = 0.5$,

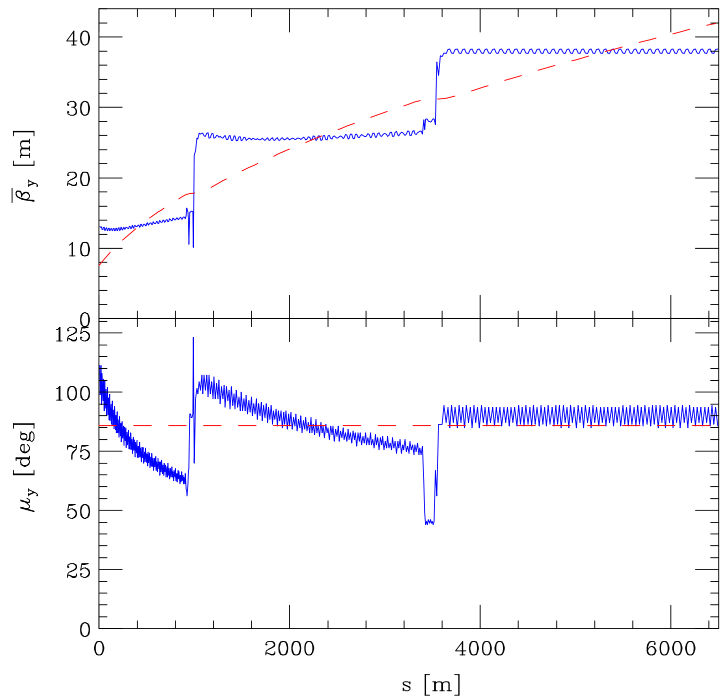

Figure 1: Average beta function $\bar{\beta}_y$ and phase advance per cell μ_y for the main NLC linac. Also given is the best fit to $\beta_{y0}\sqrt{\mathcal{E}/\mathcal{E}_0}$, with $\beta_{y0} = 7.5$ m, and the average phase advance per cell $\langle\mu_y\rangle = 85.9°$ (the dashes).

is 25, 50, 75 MW, respectively.

Finally, one concern with using MQ's is that, since the focusing depends on longitudinal position, from the Panofsky-Wenzel theorem it follows that the acceleration gradient must depend on transverse position. The relative voltage gradient error due to this effect, for offset y, is given by

$$\frac{\Delta\hat{E}_z}{\hat{E}_z} = \frac{ycG'(0)\sigma_z L_{mq}}{\hat{E}_z L} \quad . \tag{9}$$

For a 1 mm offset, the voltage gradient error becomes $\Delta\hat{E}_z/\hat{E}_z = 1.5\times10^{-4}$, which is small compared to the 1% bandwidth in the final focus of the NLC. Another concern might be the sensitivity of the focusing to phase error. If $\alpha = 1\%$ for the NLC, this implies that a 1° phase error in the MQ changes the focusing at bunch center by 6.6×10^{-3}.

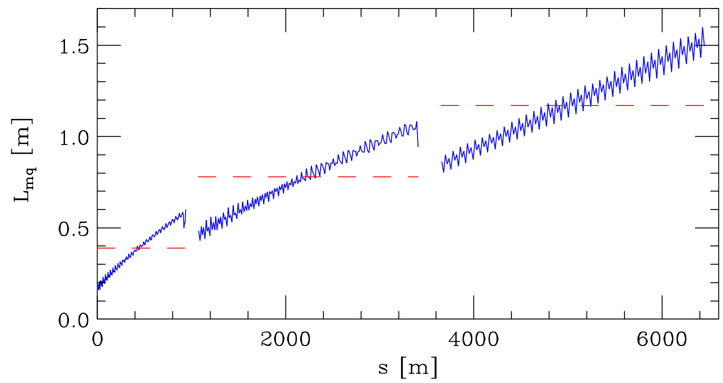

Figure 2: The required L_{mq} for the NLC linac, assuming $\hat{E}_z = 50$ MV/m and $\alpha = 1\%$. The dashes give $L_{mq}/L = 0.06$.

3 Other Microwave Quad Configurations

3.1 Hybrid Accelerating Structures

Another MQ configuration, one that was originally envisioned for the CLIC linear collider, is to incorporate non-cylindrically symmetric parts (such as elliptical cavity bodies or elliptical irises) into some of the linac accelerating structures. The advantage over dedicated MQ's is, of course, that an extra rf system is not needed. One disadvantage is that it complicates the design of some accelerating structures. Another is that, now, differential focusing is coupled to acceleration. This should normally not be a severe limitation since BNS damping is not sensitive to the exact value of the beam's tune spread; however, one cannot, for example, turn off all differential focusing without, at the same time, losing a significant amount of acceleration.

Suppose we build two types of accelerating structures, one with asymmetric cavities or irises and therefore also an MQ function (an "hybrid cavity"), and one cylindrically symmetric, and therefore, without an MQ function (a "normal cavity"). One hybrid cavity is placed right after each quad, and the rest are normal cavities (for a sketch, see Fig. 3b). Again we propose using 3 types of MQ's (and each type again needs 2 orientations). The hybrid cavities are phased at $\phi = 0$ for acceleration and differential focusing, and no focusing at the center of the beam. The other cavities are phased to ϕ_0, which locally minimizes the beam energy spread. In Fig. 4 we sketch the idea for three structures in the first part of the linac. We assume that each structure is powered for the same peak gradient. Each arrow is a phasor of the same length, representing the accelerating gradient of one structure. In the sequence labelled "No BNS" all three phasors are aligned at the required average phase ϕ_0. In the sequence labelled "With BNS" the hybrid structure is set to $\phi = 0$, and the two normal accelerating structures adjust their phase so that again the average phase is ϕ_0. The cost of the phase shifting is some energy overhead.

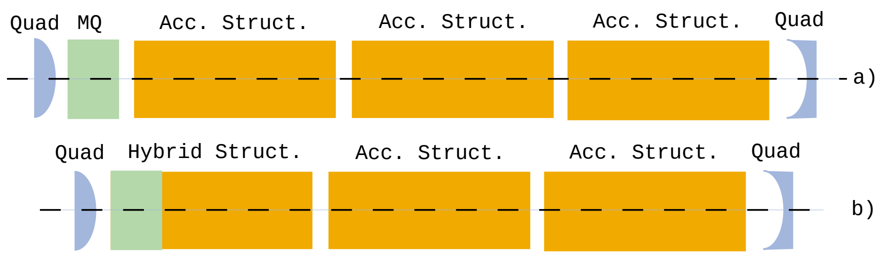

Figure 3: Sketch of 1/2 cell when: dedicated MQ structures are used (a), and hybrid structures are used (b). For this illustration we assume that there are locally 3 accelerating structures per half-cell.

Since ϕ_0 is small, the (relative) extra gradient needed locally is given by $\frac{1}{2}\phi_0^2/(n_i - 1)$, where n_i is the number of structures between quads (= 3, 6, or 9). Since the lengths of the different linac regions come approximately in the ratio 1:2:3, the total energy overhead for the NLC, when taking $\phi_0 = -10.9°$, will be 0.4%, which is small compared to the $\sim 3\%$ needed when, without MQ's, phase shifting alone is used to induce BNS damping.

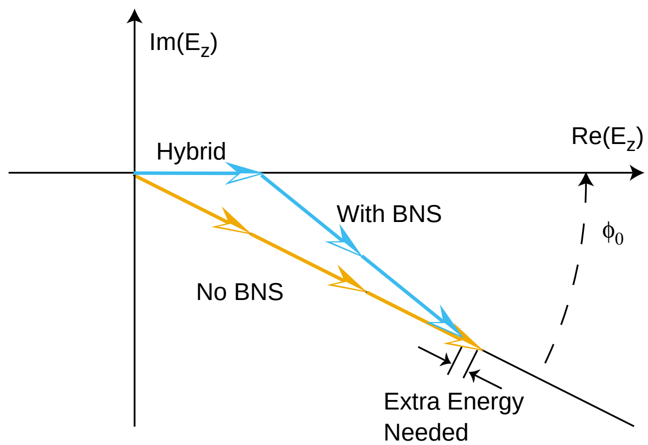

Figure 4: Phasor diagram sketching the difference in rf phasing when MQ focusing is obtained from accelerating structures, as compared to when no BNS damping is invoked ($\phi = \phi_0$ everywhere). This sketch represents the situation between adjacent quads in the first part of the linac (with three structures between quads), with each arrow representing the contribution of one structure.

3.2 Quadrupole (m=2) Mode in Cylindrically Symmetric Travelling Wave Structure

A third idea that we consider is using dedicated, cylindrically symmetric, travelling wave structures operating in a quadrupole ($m = 2$) mode to be our MQ's. The main question we want to answer here is, For a given amount of input power, can one gain in differential focusing over the dedicated, non-cylindrically symmetric type of MQ structures described in Section 2 above? Note that one practical difficulty of using such an idea is that strong, lower frequency monopole and dipole modes will need to be strongly damped so as not to affect the beam.

For a cylindrically symmetric structure operating in a quadrupole mode, the focusing is related to the peak gradient $\hat{E}_z$ at $r = a$, with a the iris radius, by

$$G(z) = \frac{2\hat{E}_z(r=a)}{ck_{\rm rf}a^2}\sin(k_{\rm rf}z + \phi) \quad . \tag{10}$$

For a given input power and assuming a given rf wave number $k_{\rm rf}$, structure length L_{mq}, and filling parameter τ, the ratio of the focusing for such a structure to that of a normal MQ is given by

$$g_{qm} = \frac{4}{\eta k_{\rm rf}^2 a^2}\sqrt{\frac{(R_s(r=a))_{qm}}{R_s}} \quad , \tag{11}$$

with $(R_s)_{qm}$, R_s, respectively, the shunt impedance of the quadrupole mode structure and that of a normal MQ structure. [For a quadrupole mode we define the shunt impedance $R_s(r) = |V(r)|^2/(ck_{\rm rf}U)$, where $|V(r)|$ is the maximum voltage gain for a test particle offset to radius r, and U is the energy per length stored in the mode.] Note that for X-band, with $a = 5$ mm and $\eta = 0.8$, $4/(\eta k_{\rm rf}^2 a^2) = 3.5$.

As an example, consider now a simple disk-loaded structure, for which two cells are sketched in Fig. 5. (If the cavities are rounded, like in the NLC accelerating structure, the shunt impedance can be increased by $\sim 10\%$.) The dimensions are iris radius a, cavity radius b, gap length g, and period p. We use MAFIA[6] to find the frequencies, R_s/Q, and Q of this structure. For the comparison structure we calculate for the same geometry; then we assume that R_s will be reduced by 25% when the cavities become elliptical rather than cylindrically symmetric, and that we can achieve $\eta = 0.8$. The comparison structure operates at 11.4 GHz in a $2\pi/3$ mode; the parameters are: $a = 4.94$ mm, $b = 11.2$ mm, $g = 6.89$ mm, $p = 8.75$ mm, the reduced $R_s/Q = 8.0$ kΩ/m, $Q = 6720$; therefore $R_s = 55$ MΩ/m (note that for the rounded, optimized NLC accelerating structure $R_s \sim 90$ MΩ/m).

Consider now a cylindrically symmetric, travelling wave structure operating at 11.4 GHz in the lowest quadrupole ($m = 2$) mode with phase advance $2\pi/3$. The parameter b needs to be increased to ~ 21 mm. Our results for the quantity g_{qm} as function of a is given in Fig. 6. We note that near $a = 5$ mm there is only a weak dependence on a. If we choose $a = 5$ mm, for example, $g_{qm} = 1.3$, $R_s(r = a) = 7.1$ MΩ/m, and $Q = 8400$. It appears that a g_{qm} much greater than 1 cannot be achieved.

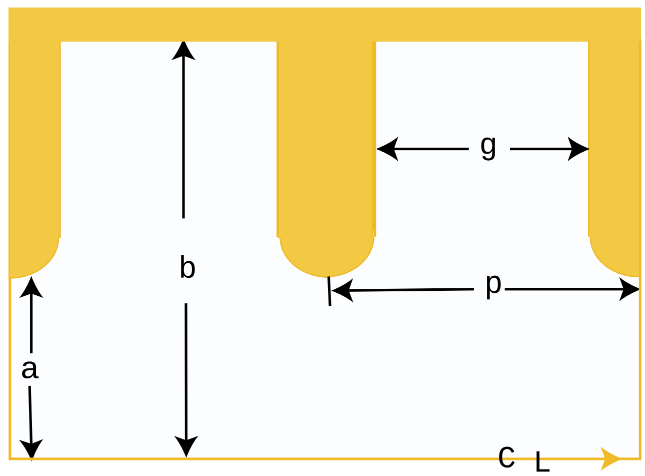

Figure 5: Two cells of the model structure used for calculations.

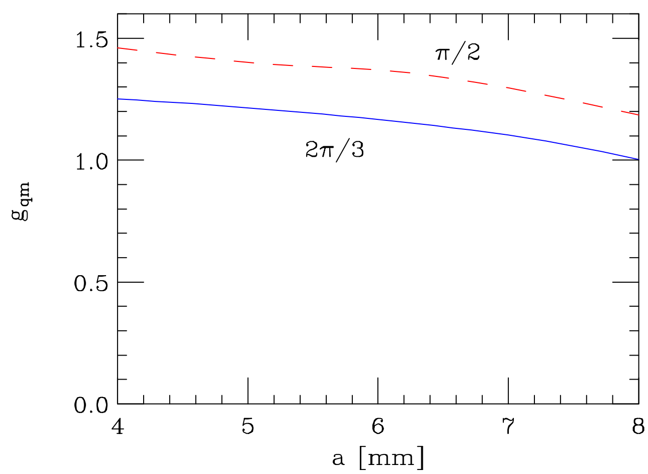

Figure 6: Cylindrically symmetric, disk-loaded structure operated in a quadrupole ($m = 2$) mode: the relative (compared to the normal MQ structure) strength factor g_{qm} *vs.* iris radius a. For the normal MQ structure we take $\eta = 0.8$ and R_s to be 25% less than that of the cylindrically symmetric model.

4 Simulations of Injection Jitter

For our simulations we used a version of the computer program LIAR [7] modified to include microwave quadrupoles. The MQ's are simulated as having zero length. The beam is sliced longitudinally and the MQ's kick each slice transversally according to Eq. 2. Note the we ignore the wakefields of the MQ structures themselves. Since they represent a small part of all structures in the linac, their wakefields are relatively small compared to that of the accelerating structures.

For simulations we used nominal parameters of the NLC linac: initial energy $\mathcal{E}_0 = 8$ GeV, final energy $\mathcal{E}_f = 250$ GeV, number of particles in the bunch $N = 7.5 \times 10^9$, rms bunch length $\sigma_z = 110$ μm, normalized vertical beam emittance $\epsilon = 2 \times 10^{-8}$ m. The MQ's were positioned in the lattice after each magnetic quadrupole, and their focusing strength was set to the fraction α of the adjacent quad (see Eq. 4).

In order to check the stabilizing properties of the MQ's in the absence of beam energy spread, the longitudinal wakefield in the code was turned off, and the beam was accelerated on the rf crest. This resulted in an rms beam energy spread of $< 5 \times 10^{-4}$. The beam was launched with an initial vertical offset of 2 μm (the initial rms beam size $\sigma_y = 1.7$ μm). The emittance growth of the beam, for several values of α, is shown in Fig. 7. Note that without MQ's the emittance grows to $\epsilon_y = 2 \times 10^{-7}$ m, which is about ten times the initial value.

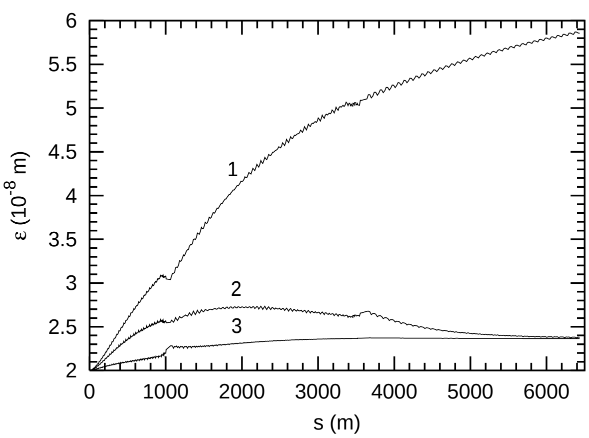

Figure 7: Beam emittance growth for several values of α: *1* – $\alpha = 0.005$, *2* – $\alpha = 0.01$ and *3* – $\alpha = 0.02$.

As is seen from Fig. 7, the value of α of about 1% is sufficient for suppression of the BBU instability to the level where the emittance increase is about 20% of its initial value.

In Fig. 8 we show, for comparison, results when phase shifting, instead of using MQ's, is used to invoke BNS damping. Shown are the energy spread and emittance growth profiles along the linac. We see that the emittance growth in this case is comparable to the case of MQ's with $\alpha \approx 1\%$. Note that the energy overhead needed for phase shifting is about 3%.

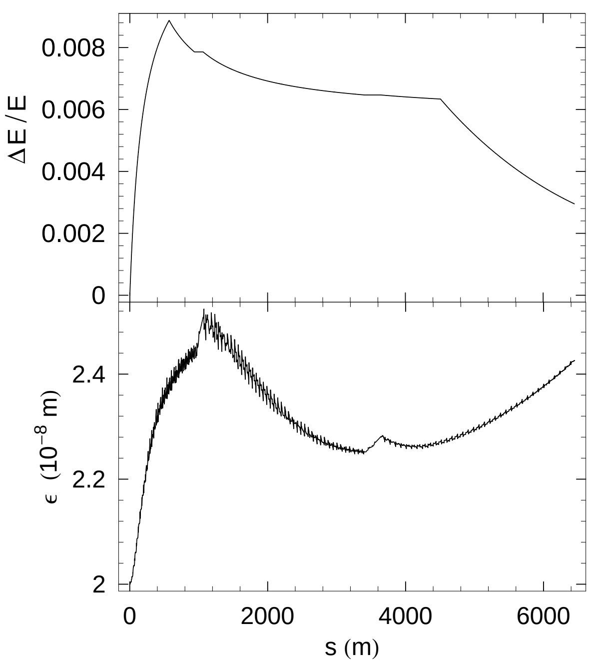

Figure 8: Correlated energy spread for BNS damping (top) and vertical emittance growth in the beam for an initial offset of 2 μm (bottom).

5 Misalignment Tolerances for Quadrupoles and MQ's

To evaluate tolerances for the misalignment of quadrupoles and MQ's we performed a set of simulations in which the beam travels through the lattice with misaligned elements. At the same time, an on-the-fly steering of the beam orbit was applied. In the steering algorithm the position of the beam was measured and the quads, MQ's, and accelerating structures were moved to the beam orbit. Ideally, this algorithm perfectly aligns the lattice to the orbit and eliminates both chromatic and wakefield-generated emittance growth. In reality, due to the finite resolution of the BPM's, steering errors result in residual emittance growth of the beam. The goal of these simulations was to find the sensitivity of the emittance growth on quad and MQ alignment errors. In this study we ignored the tolerances for accelerating structure alignment, assuming that they can be perfectly aligned to the orbit. This eliminates the effect of the transverse wakefields of the structures.

As a baseline for comparison, we first simulated emittance growth for the case when energy spread, rather than MQs, is used for BNS damping (for the energy spread profile of Fig. 8). The resulting emittance growth for bpm errors of 3 μm, averaged over 100 seeds, is shown in Fig. 9.

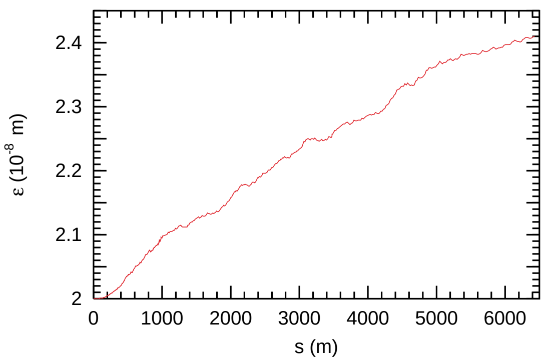

Figure 9: Beam emittance growth due to bpm errors without MQ's with the energy spread profile of Fig. 8 generated by RF phasing. The rms bpm errors are 3 μm with averaging over 100 seeds.

In a second set of alignment tolerance simulations MQ's were used instead of phase shifting. The energy spread, now corresponding to a constant accelerating phase of -10.9 degrees, is shown in Fig. 10. One can see that the energy spread is about 2–3 times smaller than for the BNS case shown in Fig. 8. The emittance growth for same 3 μm bpm errors averaged over 100 seeds, and the emittance growth for MQ misalignment errors of 3 μm are shown in Fig. 11. Comparing with Fig. 9 we note that the tolerances for MQ misalignment are slightly looser than the original tolerances on the quads.

Let us, however, assume that the MQ's can be aligned much more precisely than the normal quads. Then we see from Fig. 11 that the emittance growth is about 4 times smaller than in the case of using energy spread for BNS. This implies that the quad tolerances are two times looser with MQ's. The limiting factor in relaxing the quadrupole tolerances is the residual energy spread in the linac — making it smaller than the one shown in Fig. 10 would further suppress the chromatic emittance growth due to the misalignment of magnetic quads. According to Ref. [8], the normalized emittance growth $\Delta\epsilon$ due to the bpm errors e_k in a FODO lattice with slowly varying parameters, after 1-to-1 steering, is

$$\Delta\epsilon = 4\sum_k \delta_k^2 \frac{\gamma_k \langle e_k^2\rangle}{l_k} \tan\frac{\mu_k}{2} \quad , \tag{12}$$

where δ_k is the rms relative energy spread, γ_k is the relativistic gamma factor, l_k is the FODO cell length, μ_k is the phase advance per cell, at the location of the kth quadrupole, and the summation goes over all quadrupoles in the lattice. We see from Eq. (12) that the emittance growth scales as the square of the energy spread, indicating looser tolerances for smaller energy spread.

If we move further off crest, to $\phi_0 = -15°$, we can reduce the final rms energy

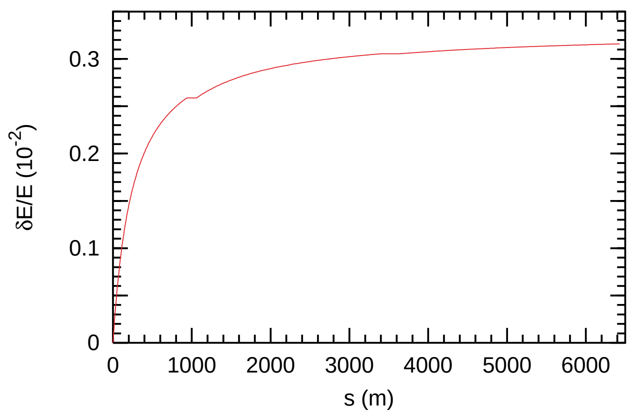

Figure 10: Energy spread in the beam for RF phase of -10.9 degrees.

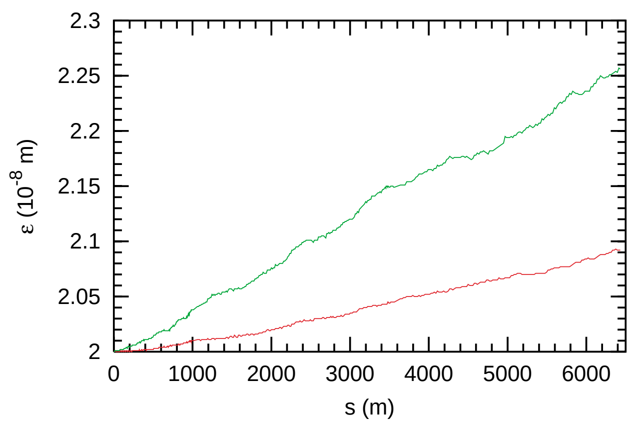

Figure 11: Case using MQ's: emittance growth for 3 μm quadrupole alignment errors (red, bottom line) and 3 μm MQ alignment errors (green, top line).

spread to .2%, which will increase our quad alignment tolerance by $\sim 50\%$. However, this will require an extra energy overhead of $\cos 10.9°/\cos 15° - 1 = 1.7\%$. One can reduce the energy spread even further, if one is able to properly shape the bunch distribution. For the NLC parameters, the bunch shape that gives zero correlated energy spread is shown in Fig. 12 (for the method of calculation, see Ref. [9]). With such a bunch shape, the quad tolerances are very loose and given by the (small) uncorrelated energy spread in the beam. It is not clear, however, whether even an approximation to such a bunch shape can be generated for the NLC linac.

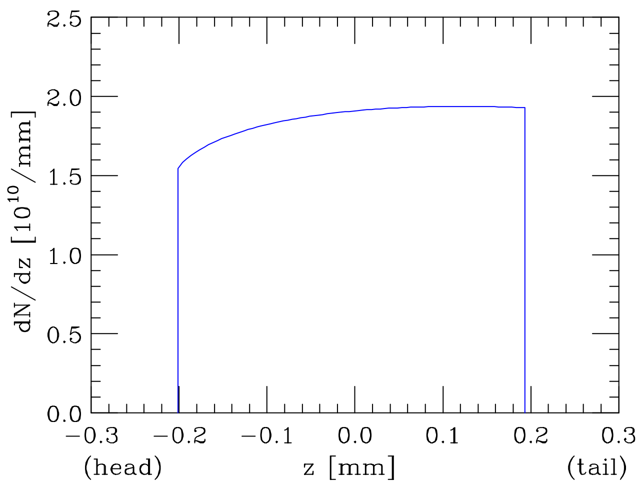

Figure 12: Bunch shape that results in zero correlated energy spread in the NLC linac, when $N = .75 \times 10^{10}$ and the rms bunch length $z_{rms} = 110$ μm. The average phase $\phi_0 = -15.2°$.

6 Conclusion

We have presented a preliminary study of how the inclusion of microwave quads (MQ's) would impact tolerances in the main linac of the NLC. We studied 2 different possible configurations of MQ's: (i) as dedicated, independently powered cavities following each normal quad in the linac, and (ii) as part of hybrid structures (both MQ and accelerator structure) that follow each quad. The advantages of the former are that the main rf cavities, which are already quite complicated, are not affected; the advantage of the latter is that an extra rf system is not required. We also studied, for the case of dedicated MQ's, whether cylindrically symmetric, travelling wave structures operating in a quad ($m = 2$) mode might not result in higher shunt impedance, and found that there is not much gain; the extra complication in not operating in the fundamental (lowest) mode would probably make one decide against this option.

For the NLC we studied the use of dedicated MQ's, operating at X-band, that look very much like the normal accelerating structures, except with broken symmetry, *e.g.* with elliptical cavities. We found that the total length of MQ's needed is about 6% of the total length of the accelerating structures. However, since at zero rf phase the MQ's give maximum acceleration along with maximum differential focusing, the linac does not need to be made 6% longer to reach the required final energy. We envision MQ's built in 3 lengths (with each version coming in 2 orientations). We estimate that the required input power will be 25, 50, or 75 MW, respectively, for the 3 different MQ versions.

One result of using MQ's instead of phase shifting to induce BNS damping is that the quad alignment tolerances can be relaxed but at the expense of shifting the tight tolerances to the MQ's. We have presented LIAR simulations that verify this effect. This behavior is an advantage if the MQ's can be aligned better than the quads. The tolerances on the quads depend linearly on the beam energy spread. For the design final energy spread of .3%, phase shifting for BNS damping induces 2–3 times larger average (over the linac) energy spread than with MQ's; therefore, the quad tolerances are loosened by a factor 2–3. Our simulations confirmed this result. The tolerance can be loosened by an additional factor 1.5 if the beam average phase is moved more off-crest, but at the cost of 1.7% energy overhead.

This has been a first look at MQ's for the NLC main linac. If one is serious about this option, of course, more detailed calculations will be needed.

7 Acknowledgements

The authors thank T. Raubenheimer for suggesting this subject and explaining how MQ's, in principle, can help with alignment tolerances, and Z. Li for helpful discussions on rf properties of structures.

References

[1] W. Schnell, "Microwave Quadrupoles for Linear Colliders," CERN/CLIC-Note 34, March 1987.

[2] I. Wilson and H. Henke, "Transverse Focusing Strength of CLIC Slotted Iris Accelerating Structures," CERN/CLIC Note 62, 1988.

[3] W. Schnell and I. Wilson, "Microwave Quadrupole Structures for the CERN Linear Collider," *Proc. of 1991 Part. Accel. Conf.*, San Francisco, 1991, p. 3237.

[4] NLC ZDR Design Report, SLAC Report 474, 589 (1996).

[5] Z. Li, private communication.

[6] MAFIA User's Guide, CST GmbH, Darmstadt, Germany.

[7] R. Assmann, *et al*, "LIAR: a computer program for the modeling and simulation of high performance linacs," SLAC-AP-103, SLAC, April 1997.

[8] G. V. Stupakov, "Quadrupole misalignments and steering in long linacs," SLAC-PUB-8694, SLAC, Nov. 2000.

[9] G.A. Loew, J.W. Wang, "Minimizing the Energy Spread within a Single Bunch by Shaping its Charge Distribution," *Proc. of 1985 Part. Accel. Conf.*, Vancouver, 1985, p. 3228.