Wakefield Optimization in H60VG3 Linacs

1. Higher band wakes in H60VG3

2. Effect on wake of removal of upstream (I/P) HOM coupler in H60VG3

3. H60VG3S17 optimized design

4. Latest H60VG4 with asymmetric dipole distribution
Higher Band Wakefield Analysis for H60VG3

* 55 cell structure, ~60cm in length, 150 deg phase adv/per cell

* Use the geometry as found from the energy dispersion beam loading calc.

* Take all a, b, t (thickness is detuned) and run mode matching code on complete structure => mode impedance.

* Fit all the resonance in the impedance to lorentzians => synchronous freq and the area under each resonance gives the kick factor.

* Obtain wake up to 35GHz.

How important are the higher band wakes?
~6% of the total wake is in the 3rd band.
where for the \( n \)th mode, \( K_n \) is the transverse kick factor, \( \omega_n/2\pi \) is the synchronous frequency and \( Q_n \) is the quality factor of the mode. A modal expansion similar to eq. (2.1) is also found in \([8]\). The kick factor is evaluated as:

\[
K_n = \frac{\int E_z \exp[j \omega_n s/c] dz}{\frac{4 \omega_n^2 a_n^2}{c} U_n L (1 - v_m^2/c^2)}
\]  

(2.2)

Here, \( a_n \) is the radius of the \( n \)th iris, \( L \) the periodic length of the cell, \( E_z \) is the on-axis electric field and \( U_n \) is the energy stored per cell in a mode. The kick factor also depends on the group velocity \( v_g \) \([9]\) and provided the synchronous phase is close to \( \pi \) then the group velocity dependence will be a negligible correction and it can be ignored. For all DDS structures is has indeed been found to be a small correction. However, for the SW and new high phase advance structures this is no longer the case. We calculated the kick factors and wakefields for a representative TW detuned structure known as DS1 and for a 8 SW structures each of which consists of 15 cells and they are both detuned with a 10% bandwidth. The 8 different SW structures effectively make up a 120 cells structure. We require 8 structures as the detuning provided by 15 cells in one structure alone is insufficient.

The results of these calculations, performed with HFSS and GdfidL \([10]\), are shown in Figs 1 and 2 respectively. For the standing wave structure the kick factors are no longer linearly dependent on the synchronous frequency and they are not concentrated in only the first band. The wakefield that results from each of these bands for the travelling wave detuned structure and the standing wave structure is shown in Fig 3 and 4 respectively. In this calculation we have not included the effects of the finite group velocity of the dipole mode.

![Figure 1](image1.png)

Figure 1. Kick factors in a travelling wave accelerator: DS1 (Detuned Structure). The complete set of 206 kick factors is obtained by interpolation from the calculation of kick factors for 5 cells (shown with dots). The largest kick factors are all concentrated in the first band. The third and sixth bands, although they are almost an order of magnitude smaller than the first, also affect the beam dynamics in the linac. All of these three bands must be detuned.

![Figure 2](image2.png)

Figure 2. Kick factors in standing wave accelerator design SW1. The complete set of 120 kick factors is obtained by interpolation from the calculation of kick factors for 5 cells (shown with dots). The first three bands kicks are of similar order of magnitude and they all must be damped and detuned. The 4th and 5th bands are an order of magnitude smaller than the first three but they also must considered in a full analysis of the beam dynamics as they also contribute to BBU instability.

![Figure 3](image3.png)

Figure 3. Individual bands, ranging from the first to the sixth of the envelope of the wakefield corresponding to the kick factors of the travelling wave structure given in Fig 1. The dots are positioned at the location of each individual bunch (spaced by 42cm). Four out of a total 191 trailing bunches are shown.

Beam dynamics studies \([11]\) indicate that the wakefield must be below unity in order that the BBU instability not be an issue. The wake at the position of the bunches is shown in Fig 3 for the travelling wave structure and it is clear that the wake remains below unity at these locations and thus BBU is unlikely to be a problem. The 3rd and 6th bands have significant kick factors compared to the first band and these modes were detuned by enforcing and
Erf variation to the iris thickness of all cells. The wakefield for the SW structure shown in Fig 4 reveals that the first three bands are all equally important and consequently they all must be carefully damped. The wake at the position of the first trailing bunch is below unity for all bands apart from the third band. The third band requires additional detuning in order to accelerate the rate of decay of the wake.

Figure 4. Individual bands of the envelope of the wakefield corresponding to the kick factors of the standing wave structure given in Fig 2.

3. GENERAL PROPERTIES REGARDING BAND PARTITIONING OF KICK FACTORS

In order to assess the behaviour of band partitioning as a function of synchronous frequency we used the Fortran code *Transvers* [12] driven with by a Mathematica input to the data set to calculate the kick factors and synchronous frequencies. The results of this calculation are shown in Fig 5 for a/λ given by 0.229 (a), 0.19 (b) and 0.161 (c), in which the kick factors are calculated for structures with a phase advance ranging from 120 to 180 degrees. The general trend for the first three bands is quite clear, namely, rather independently of the iris dimension, the second and third dipole bands are enhanced at the expense of the first band as the phase advance per cell increases from the initial value of 2π/3. The effect of finite group velocity on the kick factor has been left to a later publication as until recently the code was unable to incorporate this effect. However, inclusion of the finite group velocity does not modify our general conclusions on the partitioning of modes.

In conclusion, the present NLC design limits a/λ ~0.18 and thus the first three bands of the SW structure will be required to be damped and detuned. For the 5π/6 structure only the first dipole bands must be damped and the cell frequencies detuned together with the third band which will be required to be detuned and moderately damped or not damped at all. Further studies are in progress on assessing the damping requirements of the 3rd dipole band in the 5π/6 structure.

Figure 5. K_n as a function of synchronous frequency for several irises radii: (a) 6mm, (b) 5 and (c) 4.23 mm.

4. REFERENCES

[10] W. Bruns, PAC97, also TET-Note 97/07
First Band $\text{Re}\{Z\}$

First Band Wakefield Envelope
(Q~1000 for all modes)

Kick Factor
Weighted Density Func:
$\text{Kdn/df}$

Roger M. Jones, (ISG-10, SLAC, June 18, 2003)
3 (of 6). March 6, 2003 1:31 pm, T:\RMJ\Common Work + Home Files\FrameMaker\HDS_3_03.fm
Second Band Impedance

2nd Band Kick Factors

2nd Band Wakefield Envelope
(two orders of magnitude smaller than 1st)
(Q~4000 imposed on all modes)

---

Roger M. Jones, (Structures Meeting, SLAC, March 6, 2003)
Wake Envelope

(Q~4000 imposed)

Real Impedance for 4th and 5th Bands

Kick Factors

Wake of 3rd band at s=0 is ~6% that of the 1st band.
Combined wake of the 4th and 5th bands is ~3% of the 1st band.
Roger M. Jones, (Structures Meeting, SLAC, March 27, 2003)
6th Band $\text{Re}\{Z\}$

6th Band Kick Factors

6th Band Wakefield

Wake of 6th band at $s=0$ is $\sim 3\%$ of first
combined Wake of 4th and 5th band at $s=0$ is $\sim 3\%$
Wake of 3rd band at $s=0$ is $\sim 6\%$ of first
First Band $\text{Re}\{Z\}$ for 3-Fold Interleaving (Shift Iris Radius)

Roger M. Jones, (Structures Meeting, SLAC, March 27, 2003)
First Band Interleaved Wakefield
(achieved by shifting iris aperture by +/- 15 microns)

Interleaved Kick Factors from 3 structures.

First Band Wakefield from 3-fold interleaving of structures

Roger M. Jones, (Structures Meeting, SLAC, March 27, 2003)
10 (of 11), March 27, 2003 9:23 am, T:RMJ|Common Work + Home Files\FrameMaker\HDS_3_03.fm
Third Band Interleaved Impedance

~50MHz

~>50MHz
Re\{Z\} For Three-Fold Interleaved H60VG3A18
Shift iris radius by +/-15micons and thickness by +/-40.

First Band Three-Fold Interleaved Wakefield.

Roger M. Jones, (Structures Meeting, SLAC, March 27, 2003)
Single Structure Kick Factors

Kick Factor Weighted Density Function: $2Kdn/df$

Roger M. Jones, (Structures Meeting, SLAC, March 27, 2003)
Three-Fold Interleaved Re\{Z\}. Shift the radius of all cells by +/- 15 microns and the thickness by +/-40 microns

THIRD DIPOLE BAND: H60VG3A18

~60MHz

~50MHz
This is obtained from an *optimized* spectral function calc for the first band - n.b. the optimized parameters have not been used in the mode matching calculation due to time considerations.

Third band is calculated via mode matching. The iris thickness and diameter have been modified “by hand” to optimize the effect of interleaving.
**Emittance and Phase Space Incl. First Band Wake**

Normalised Horizontal & Vertical Beam Emittance For NLC
Inset is the % Emittance growth
Initial Emittance: {0.000165, 3., 0.02}
Final Emittance: {12.9, 3., 0.0209}

**Emittance and Phase Space Incl. First and Third Band Dipole Wakes** (thickness+radius interleaving)

Normalised Horizontal & Vertical Beam Emittance For NLC
Inset is the % Emittance growth
Initial Emittance: {0.000165, 3., 0.02}
Final Emittance: {12.9, 3., 0.021}
Higher Dipole Bands in H60VG3

*If the first band is optimized and the upper dipole bands are ignored does BBU occur?
Yes!

* If the thickness and the radi are changed in adjacent structures to interleave the dipole frequencies of higher bands then no BBU occurs. A Q~4000 has been assumed for the upper dipole bands. The first dipole band is manifold damped with a Q~1000.

* In addition to the first band, the sixth band is the main band that requires damping. The sixth band is an order of magnitude smaller than the first band (comparing the total kick)
One Structure: All Bands
(Wt(0) ~ 63)

One Structure: First Band Only

All Bands Apart From First
(Wt(0) ~ 5.4)

All Bands Apart From First and Sixth
(Wt(0) ~ 4.1)
The beam is initially offset by 1 micron and is then subject to identical wakes. The wakes are those of the optimized three-fold interleaved first band and the non-optimized non-interleaved higher bands (as far as the sixth band).
Without optimized interleaving of the higher bands then the higher bands make a significant contribution to the overall wakefield.

**Single Structure Wake:**
First Band Only (Optimized Dist. calculated via spectral function)
The beam is initially offset by 1 micron and is subject to the combined wakefield of the optimized interleaved first band and the non-optimized higher bands. Clearly interleaving of the higher bands is also necessary - this was demonstrated to be successful in the previous week’s meeting.
H60VG3S17

* Effect of Removal of I/P (Upstream) HOM Coupler
14.5 15 15.5 16

Frequency (GHz.)

Spec. (V/pC/mm/mGHz)

Wake (V/pC/mm/m)

HOM Coupler Influenced Wake

Perfectly Matched Coupler Wake
Removal of I/P Coupler
O/P Coupler reflection coefficient given below.

RMS of Sum Wake

Envelope of Wake

Roger M. Jones, (Structures Meeting, SLAC, April 17, 2003)
At the nominal bunch spacing
(no errors)
At the nearest position in the bunch spacing which gives a peak Sum Wake (~+7.9 MHz)

Normalised Horizontal & Vertical Beam Emittance For NLC
Inset is the % Emittance growth
Initial Emittance: \( \{0.000165, 3., 0.02\} \)
Final Emittance: \( \{12.9, 3., 0.0237\} \)
Shift center frequency down by 7.9 MHz to achieve minimum in RMS of Sum Wake

Roger M. Jones, (Structures Meeting, SLAC, April 17, 2003)

Normalised Horizontal & Vertical Beam Emittance For NLC
Inset is the % Emittance growth
Initial Emittance: \(\{0.000165, 3., 0.02\}\)
Final Emittance: \(\{12.9, 3., 0.0207\}\)
* Two-fold interleaving will not give rise to BBU or significant emittance dilution if we shift the central freq down by ~7.9 MHz (to lie on the minimum of the sum wakefield)

* Now that the latest NLC design is for 8 structures per girder (Tor, DOE review 4-03) 4-fold interleave the structures.
Power Radiated to HOM Couplers:

Two conditions are indicated:
1. I/P and O/P Couplers have the same reflection coefficients.
2. The I/P coupler is completely removed

HOM Reflection Coefficients (Z. Li)
H60VG3S17

* Baseline NLC design 8 structures per girder
  => 4-fold interleaving of structures

* Spectral code => Optimized 4-fold interleaved bandwidth 9.88%
  Effect on wake of perfectly matched vs. real HOM
  * Wake meets R1/R2 requirements
  => no BBU & no appreciable emittance dilution from long range wake!

*Design based on 60cm, 55 cells, 150 fundamental phase advance per cell
Four-Fold Interleaved, Perfectly Matched HOM Coupler (S11=0)

Roger M. Jones, (ISG-10, SLAC, June 18, 2003)
Min $|S_{11}|$ of 0.0147 at 15.11 (GHz)
Mean $|S_{11}|$ = 0.123648

Min $|S_{11}|$ of 0.0127 at 15.27 (GHz)
Mean $|S_{11}|$ = 0.0928747

Roger M. Jones, (ISG-10, SLAC, June 18, 2003)
Four-Fold Interleaved, HOM Coupler S11 for H60VG3S17

BW\%_\sigma = 9.883, 4.643
Four-fold interleaving

Envelope of Wakefield

RMS of Sum Wakefield

The increased reflection leads to a slightly larger sum wakefield. Overall there is little impact on the wakefield.

Roger M. Jones, (ISG-10, SLAC, June 18, 2003)
Four-Fold Interleaved, Perfectly Matched HOM Coupler (S11=0)

BW, Sigma = 11.75, 5.45 (2.145)

Roger M. Jones, (ISG-10, SLAC, June 18, 2003)
Four-Fold Interleaved, HOM Coupler S11 for H60VG3S17

BW, Sigma = 11.75, 5.45 (2.145)

Roger M. Jones, (ISG-10, SLAC, June 18, 2003)
Increased Dipole Bandwidth: H60VG4S17

* Baseline NLC design 8 structures per girder => 4-fold interleaving of structures

* Increase dipole bandwidth (9.4% -> ~11%) to reduce surface field ($R_{sh}$ fundamental mode reduced for first cells) with little change to power input (Z. Li) => Quite markedly asymmetric dipole kick factor weighted density distribution ($K_{dn/df}$)

* Is the wakefield adversely affected?
  Yes!
  Significant shoulder in the wakefield felt by the first few bunches means that the RMS sum wakefield is too large to be acceptable (BBU is likely to occur).

* However, rather small changes to the sigma width width fixes this.
Simulation Based on:

* Design based on 60cm, 55 cells, 150 fundamental phase advance per cell

* To-date we have Omega3 freq-phase points from 3 cells with no manifold-cell coupling

=> Supplement this simulation with the manifold coupling parameters from the previous H60VG3S17 design with manifold coupling included
Brillouin Diagram for Tapered H60VG3 Structure CELL # 1

Cell 1

Brillouin Diagram for H60VG3 Structure CELL # 27

Cell 27

Brillouin Diagram for SLAC H60VG3 Structure CELL # 55

Cell 55

Single H60VG4 Tapered Structure
(BW, Sigma = 11%, 4Sigma)

Roger M. Jones, (ISG-10, SLAC, June 18, 2003)

11 (of 19)
Single H60VG4 Tapered Structure (BW, Sigma = 11%, 4Sigma)

Kick and Kick Factor Weighted Density Func.

Figures showing Kick and Kick Factor Weighted Density Func., 2nd Dipole Band Mode Vg, and 1st Band Dipole Vg for different cell numbers.

Roger M. Jones, (ISG-10, SLAC, June 18, 2003)
Resulting wakefield is the convolution of the FT of $K_{dn/d\phi}$ with a sinc ($=\sin(\pi x)/\pi x$) function.

Wakefield via Inverse Fourier Transform of Uncoupled Kick Factor Weighted Density Function
Single H60VG3 Tapered Structure Wakefield
(BW,Sigma = 11\%, 4\Sigma)
Four-Fold Interleaved H60VG4 Tapered Structure Spectral Function
(BW, Sigma = 11%, 4Sigma)

Roger M. Jones, (ISG-10, SLAC, June 18, 2003)
Four-Fold Interleaved H60VG3 Tapered Structure Wakefield
(BW, Sigma = 11%, 4Sigma)
**OPTIMIZED Four-Fold Interleaved H60VG3 Tapered Structure Wakefield**

(BW, Sigma = 11.009%, 4.065Sigma)
Some Thoughts on H60VG4

* The large asymmetry in the uncoupled kick factor weighted distribution function gives rise to a significant shoulder in the wakefield.

* For a small change in the bunch spacing (which will arise due systematic errors in fabrication) the RMS of the four-fold interleaved sum wakefield is ~ 4. This is dangerous! BBU is likely to occur.

* A small change in the bandwidth of the distribution puts the first bunch on a minimum of the envelope function. This is quite stable to changes in the bunch spacing.

* This is a 2-D model of the accelerator with manifold-cell coupling taken from the previous (untapered) H60VG3. A full 3-D simulation (Zenghai) to input the manifold parameters to the circuit model is of course required to confirm how the shoulder is removed by optimized interleaving.