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 asymetric 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 dipersion 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.

$$W(s) = 2\left|\sum_{n=1}^{N} K_n \mathrm{Exp}\left[j\frac{\omega_n s}{c}(1+\frac{j}{2Q_n})\right]\right| \qquad (2.1)$$

where for the nth 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:

$$K_n = \frac{\left|\int_L E_z \mathrm{Exp}[j\omega_n s/c]dz\right|^2}{4\frac{\omega_n a_n^2}{c} U_n L(1-\frac{v_{gn}}{c})} \qquad (2.2)$$

Here, a_n is the radius of the nth iris, L the periodic length of the cell, Ez 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_{gn} [9] and provided the synchronous phase is close to π 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

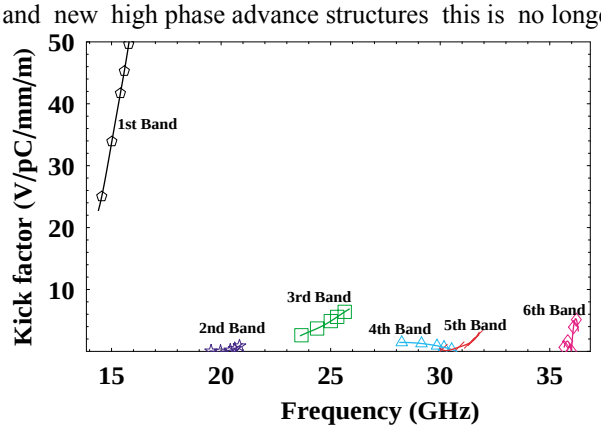


Figure 1. Kick factors in a travelling wave accelerator: DS1 (Detuned Structure). The complete set of 206 kick factors is obtained by interpolation from the calculation of kick factors for 5 cells (shown with dots). The largest kick factors are all concentrated in the first band. The third and sixth 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.

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.

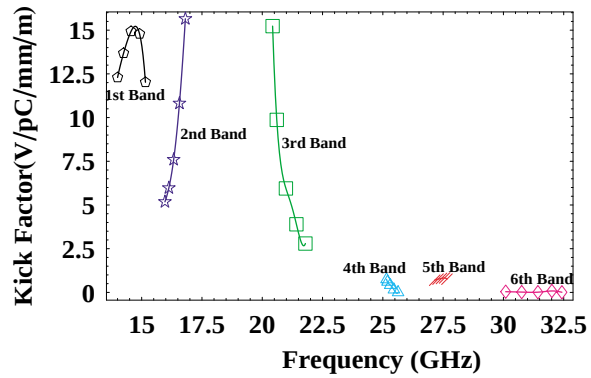


Figure 2. Kick factors in standing wave accelerator design SW1. The complete set of 120 kick factors is obtained by interpolation from the calculation of kick factors for 5 cells (shown with dots). The first three bands kicks are of similar order of magnitude and they all must be damped and detuned. 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.

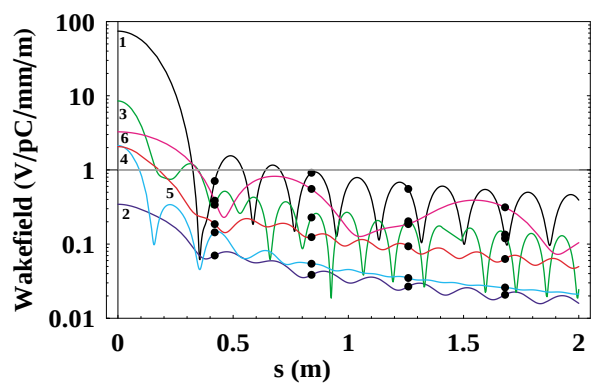


Figure 3. Individual bands, ranging from the first to the sixth of the envelope of the wakefield corresponding to the kick factors of the travelling wave structure given in Fig 1. The dots are positioned at the location of each individual bunch (spaced by 42cm). Four out of a total 191 trailing bunches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

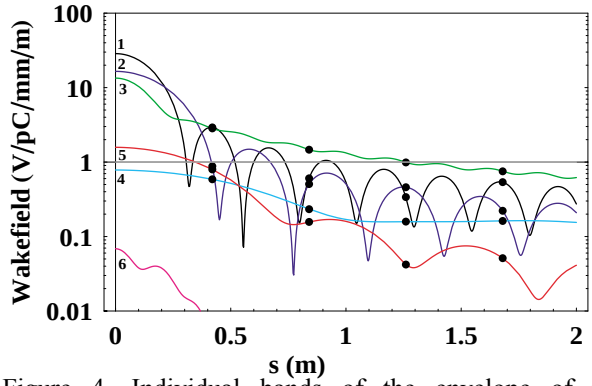


Figure 4. Individual bands of the envelope of the wakefield corresponding to the kick factors of the standing wave structure given in Fig 2.

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 *Transvrs* [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.

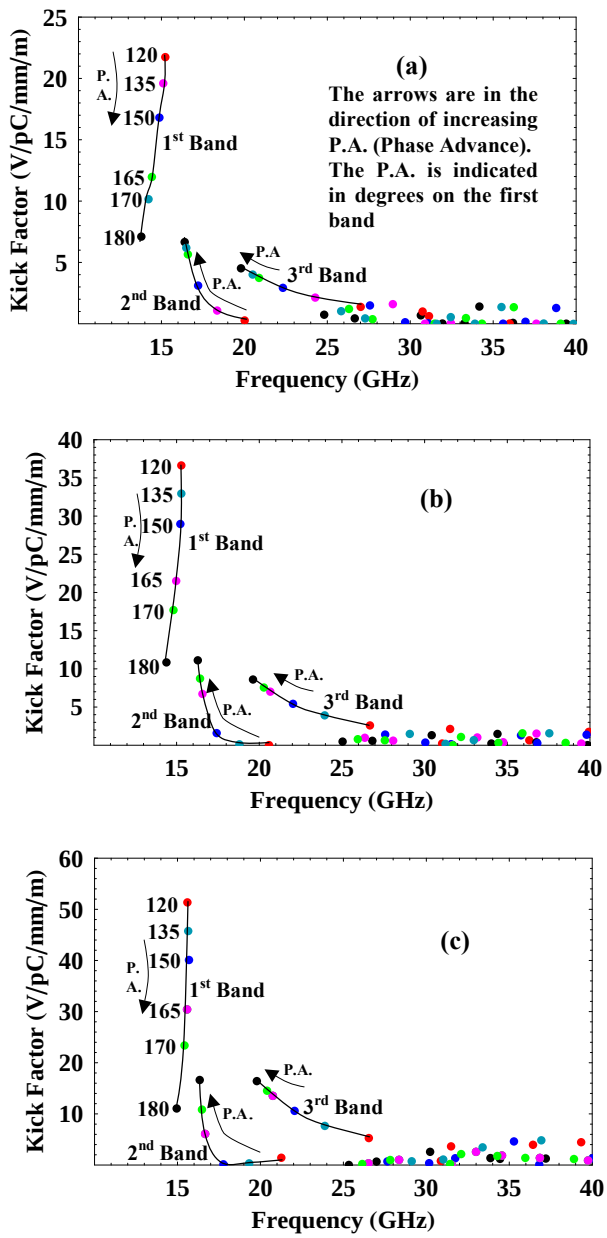
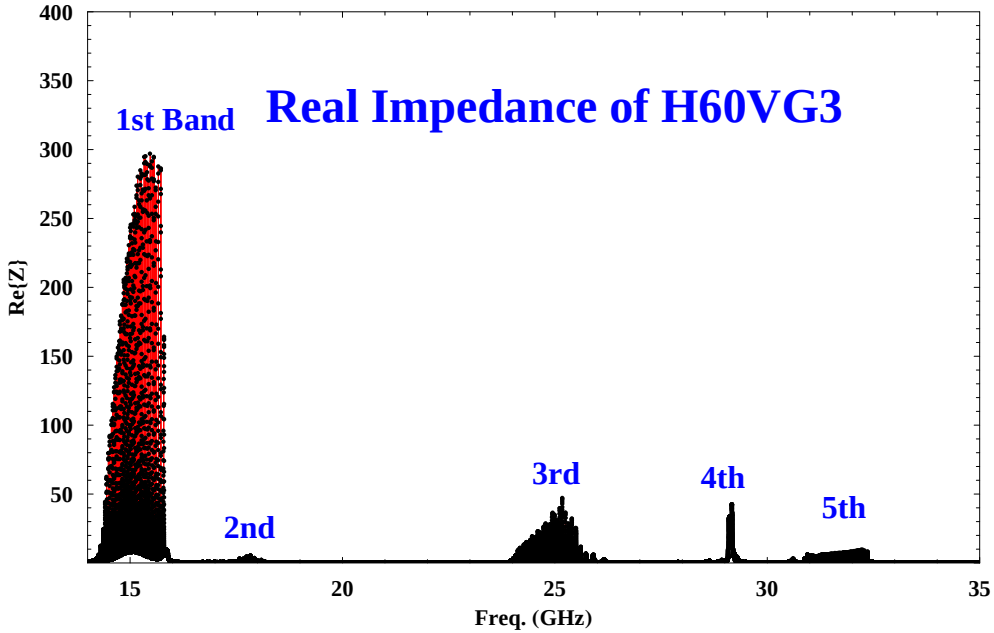
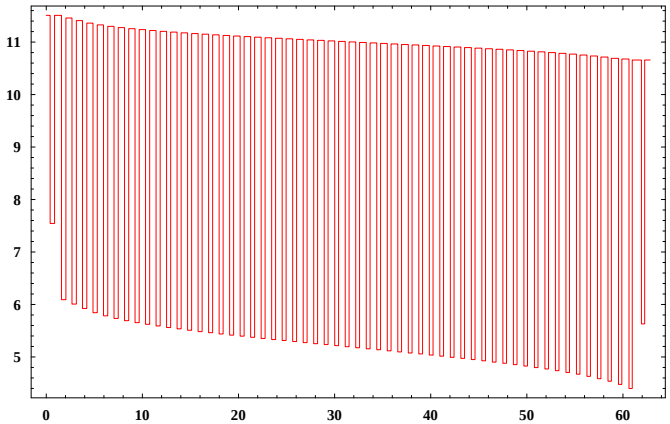


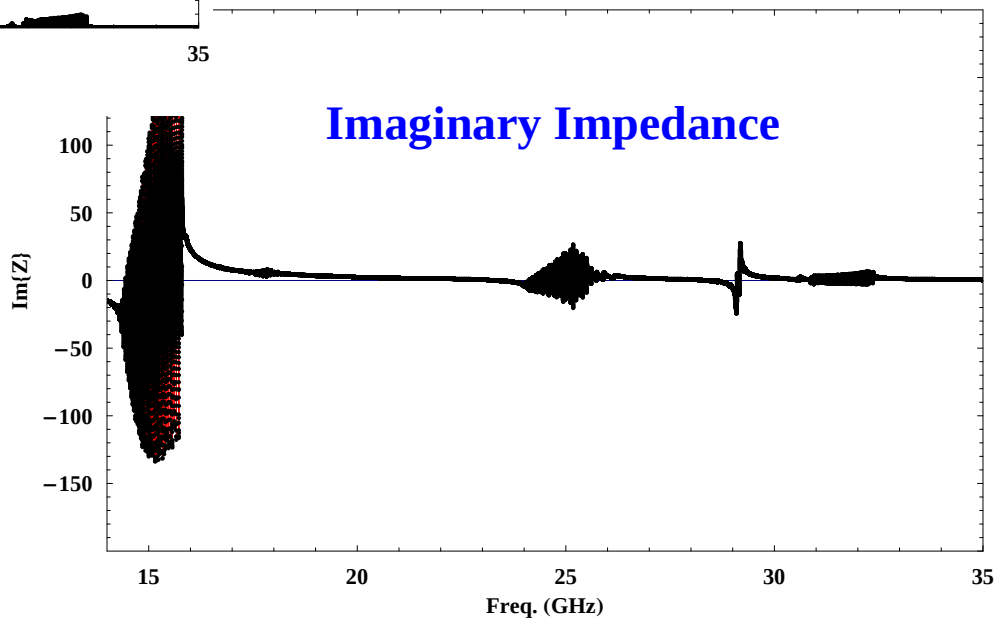
Figure 5. K_n as a function of synchronous frequency for several irises radi: (a) 6mm, (b) 5 and (c) 4.23 mm.

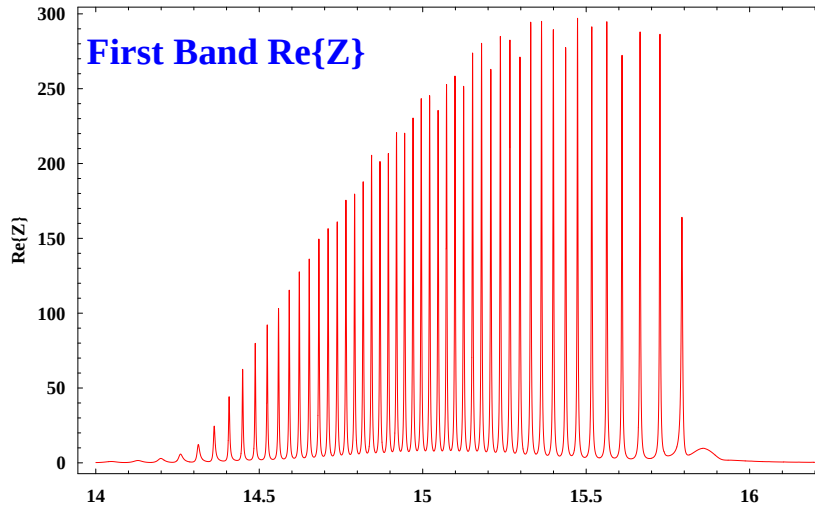
4. REFERENCES

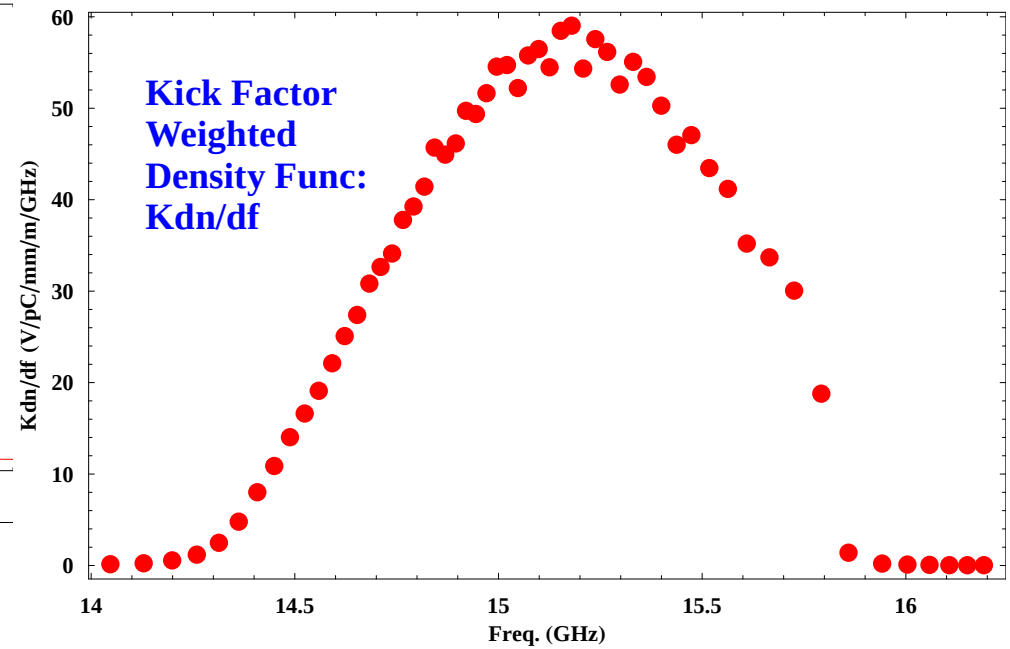
[1] R.M. Jones et al, PAC99, also SLAC-PUB-8103
[2] R.M. Jones et al, EPAC96, also SLAC-PUB-7187
[3] C. Adolphsen et al, 1997, SLAC-PUB-7519
[4] J.W. Wang et al, TH464 these proceedings
[5] T. Shintake, PAC99, also KEK-PREPRINT-99-11
[6] K.LF. Bane & R. Gluckstern, Part.Accel.42:123 -169,1993
[7] R.M. Jones et al, LINAC96, also SLAC-PUB-7287
[8] K.A. Thompson et al, Part.Accel.47:65-109,1994
[9] A. Millich and L. Thorndahl, 1999 CLIC-NOTE-366
[10] W. Bruns, PAC97, also TET-Note 97/07
[11] R.M. Jones, TH465 these proceedings
[12] B. Zotter & K. Bane, 1980, CERN ISR-TH/80-25

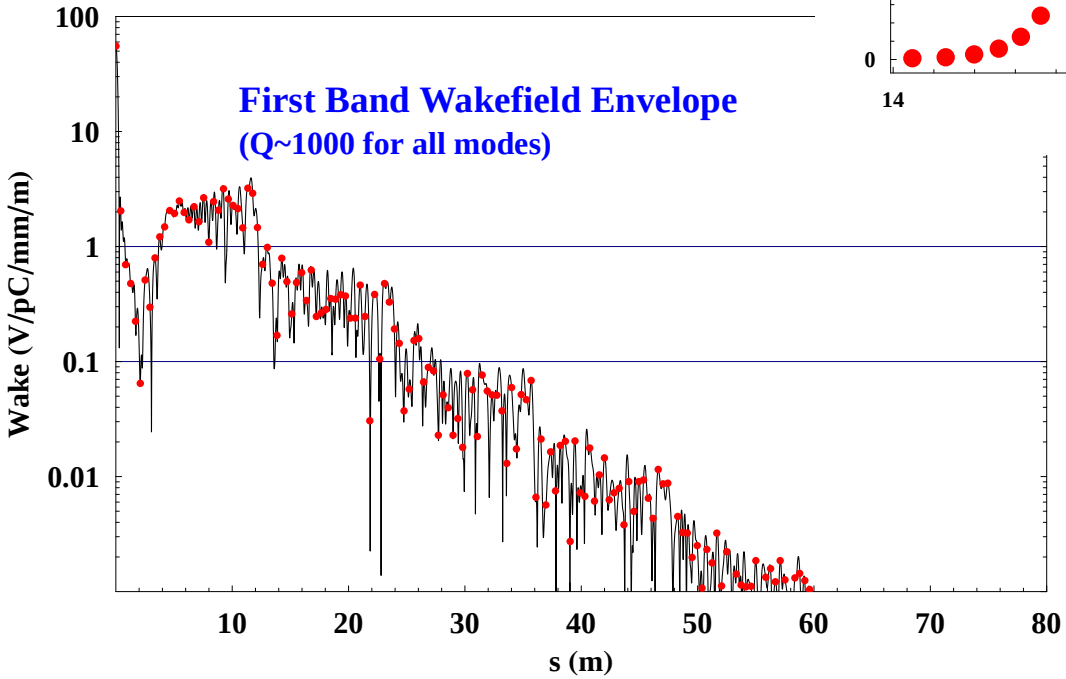

Real Impedance of H60VG3
1st Band
2nd
3rd
4th
5th
Re{Z}
400
350
300
250
200
150
100
50
15
20
25
30
35
Freq. (GHz)

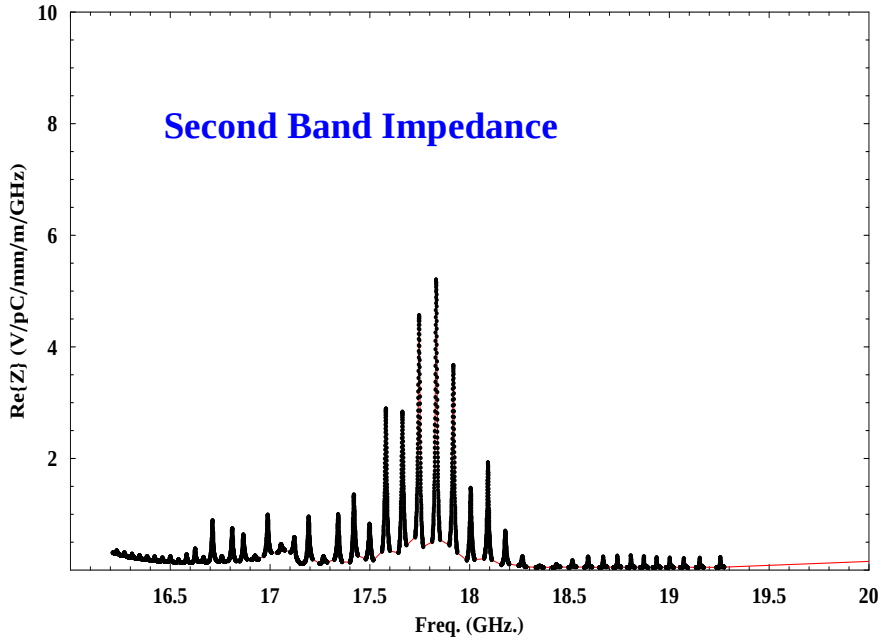

11
10
9
8
7
6
5
0
10
20
30
40
50
60

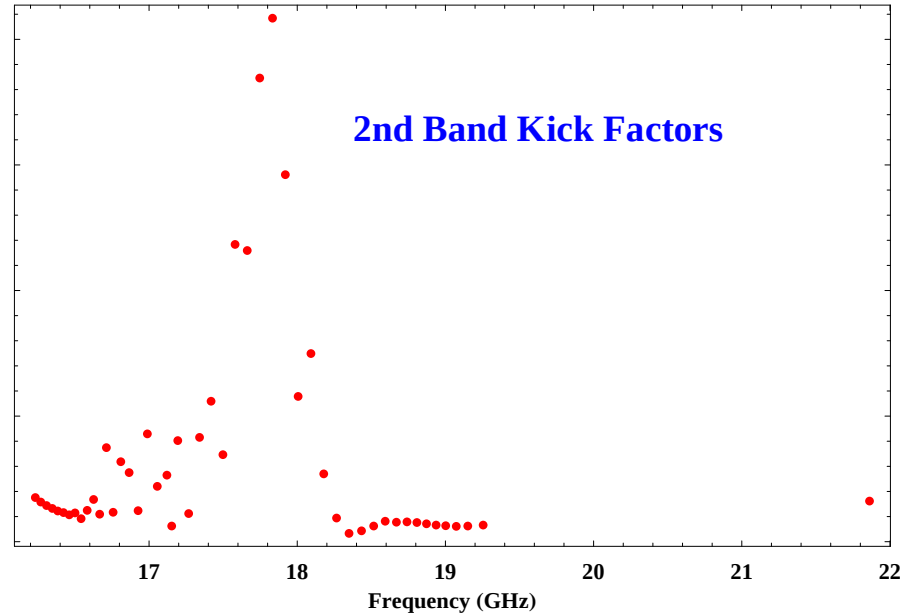

Imaginary Impedance
Im{Z}
100
50
0
−50
−100
−150
15
20
25
30
35
Freq. (GHz)

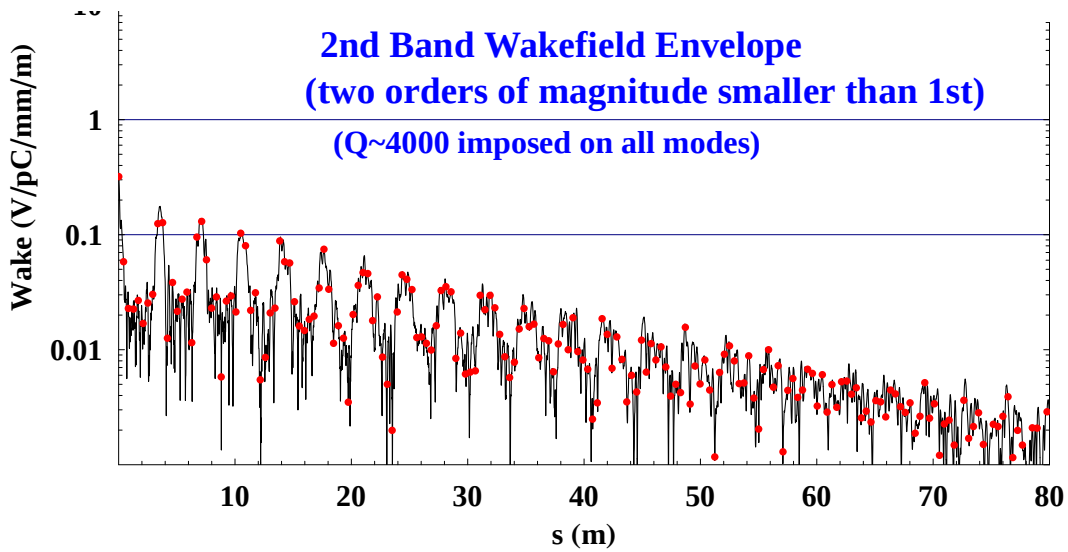

First Band Re{Z}
Re{Z}
300
250
200
150
100
50
0
14
14.5
15
15.5
16

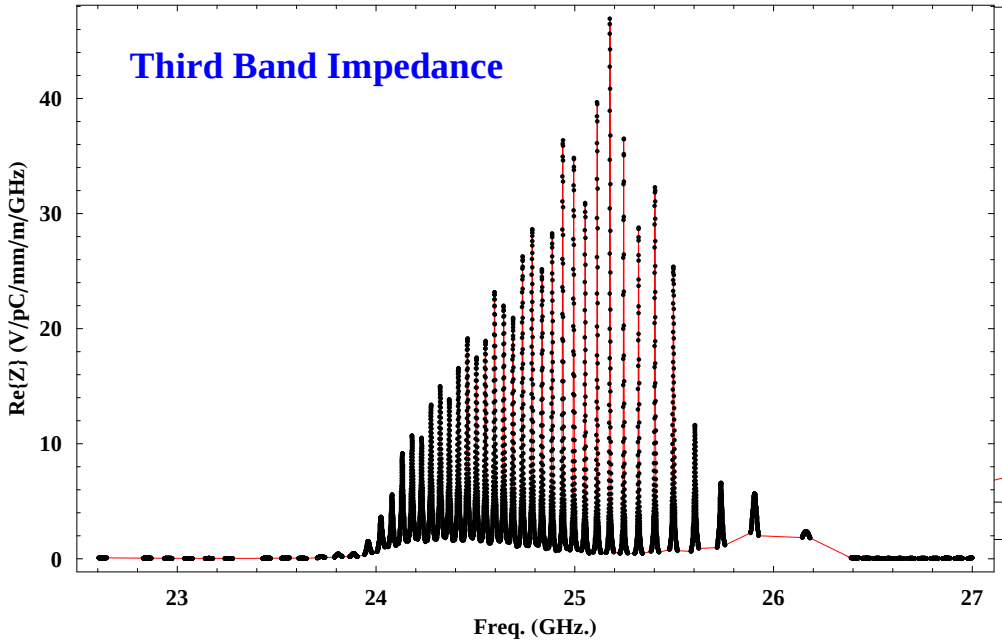

Kick Factor
Weighted
Density Func:
Kdn/df
Kdn/df (V/pC/mm/m/GHz)
60
50
40
30
20
10
0
14
14.5
15
15.5
16
Freq. (GHz)

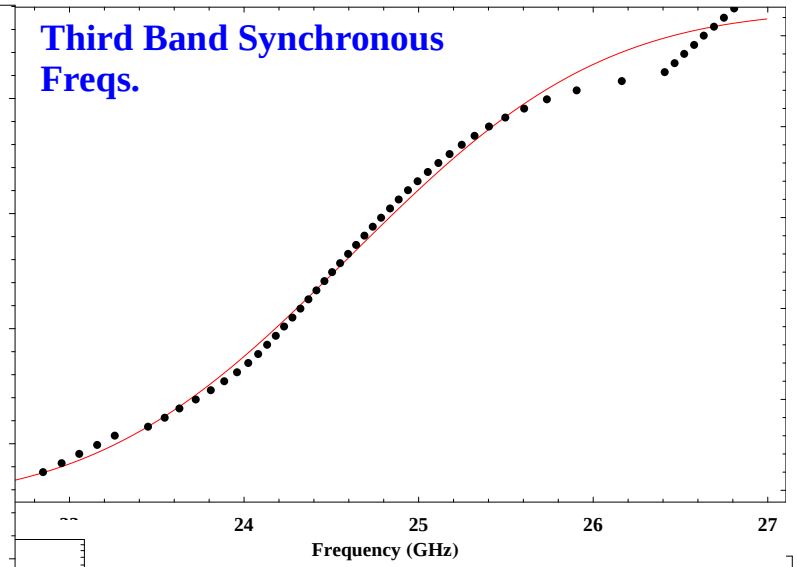

First Band Wakefield Envelope
(Q~1000 for all modes)
Wake (V/pC/mm/m)
100
10
1
0.1
0.01
10
20
30
40
50
60
70
80
s (m)

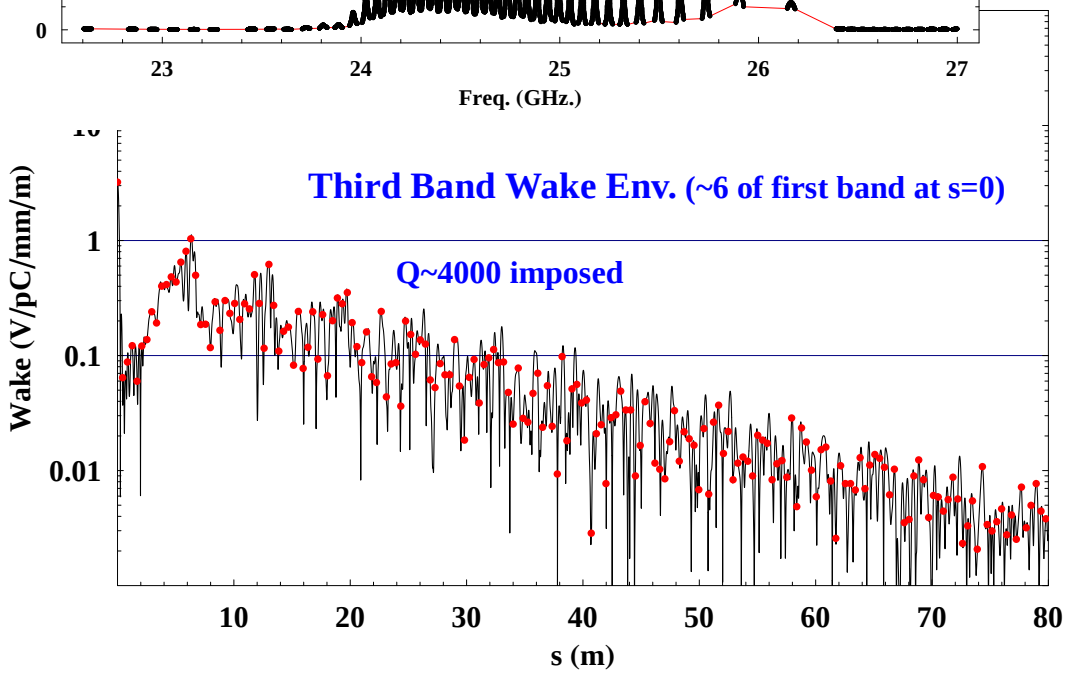

Second Band Impedance
Re{Z} (V/pC/mm/m/GHz)
10
8
6
4
2
16.5
17
17.5
18
18.5
19
19.5
20
Freq. (GHz.)

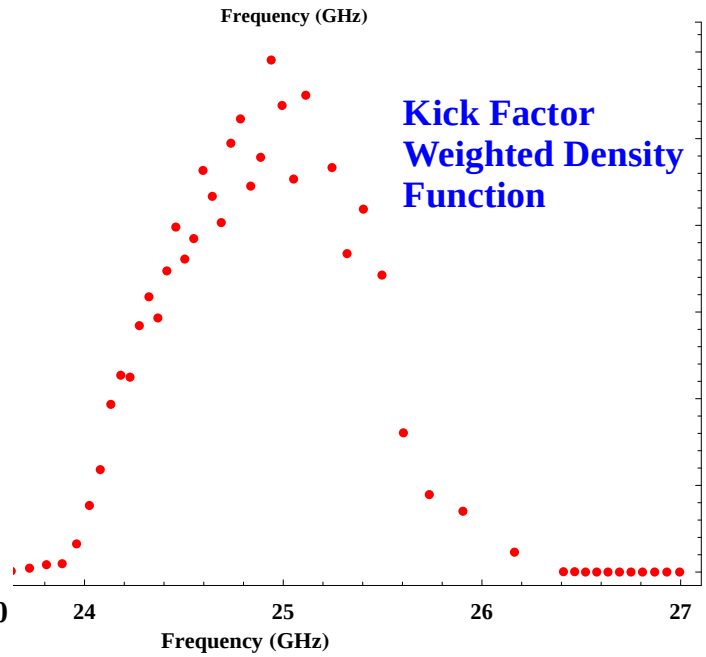

2nd Band Kick Factors
17
18
19
20
21
22
Frequency (GHz)

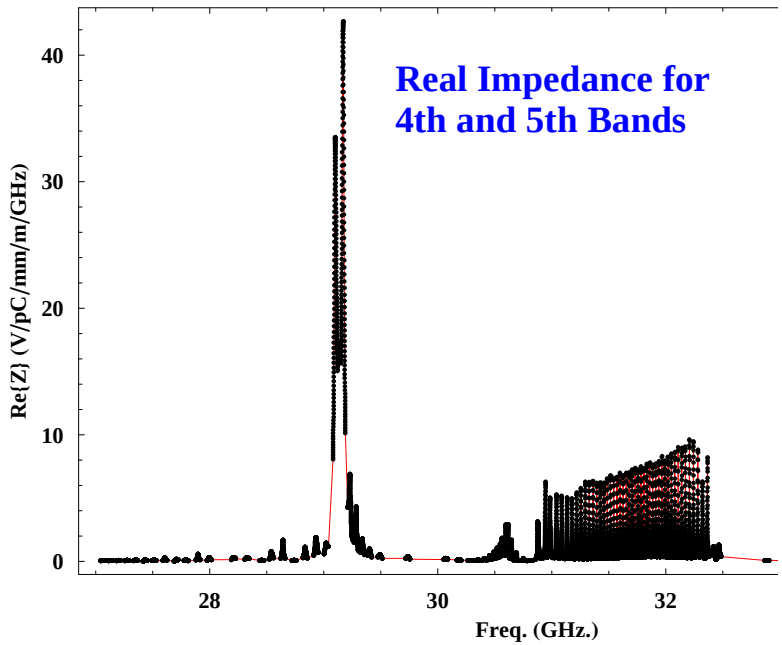

2nd Band Wakefield Envelope
(two orders of magnitude smaller than 1st)
(Q~4000 imposed on all modes)
Wake (V/pC/mm/m)
1
0.1
0.01
10
20
30
40
50
60
70
80
s (m)

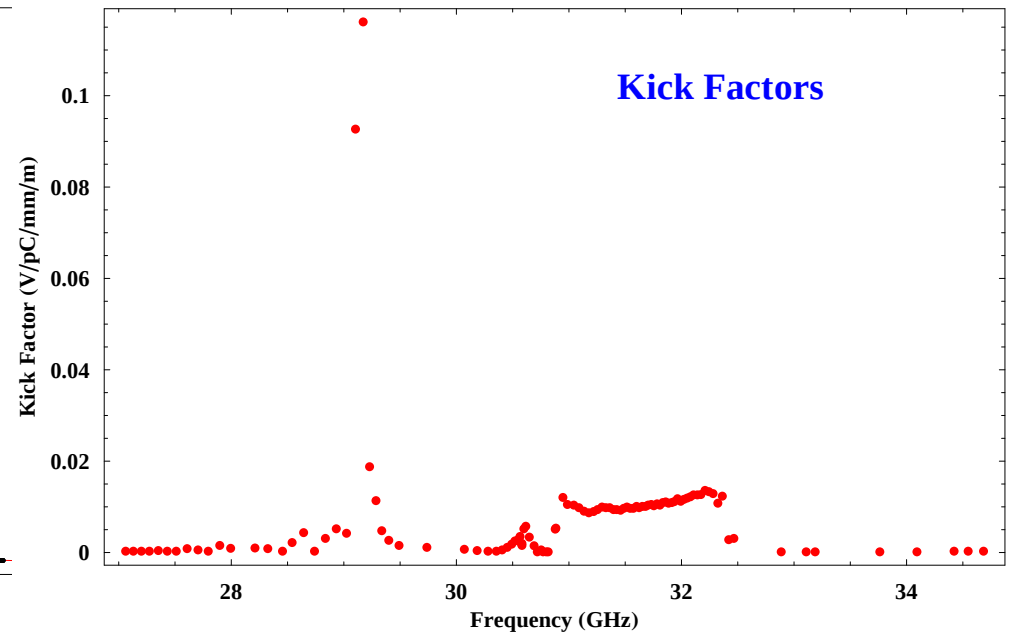

Third Band Impedance
Re{Z} (V/pC/mm/m/GHz)
0
10
20
30
40
23
24
25
26
27
Freq. (GHz.)

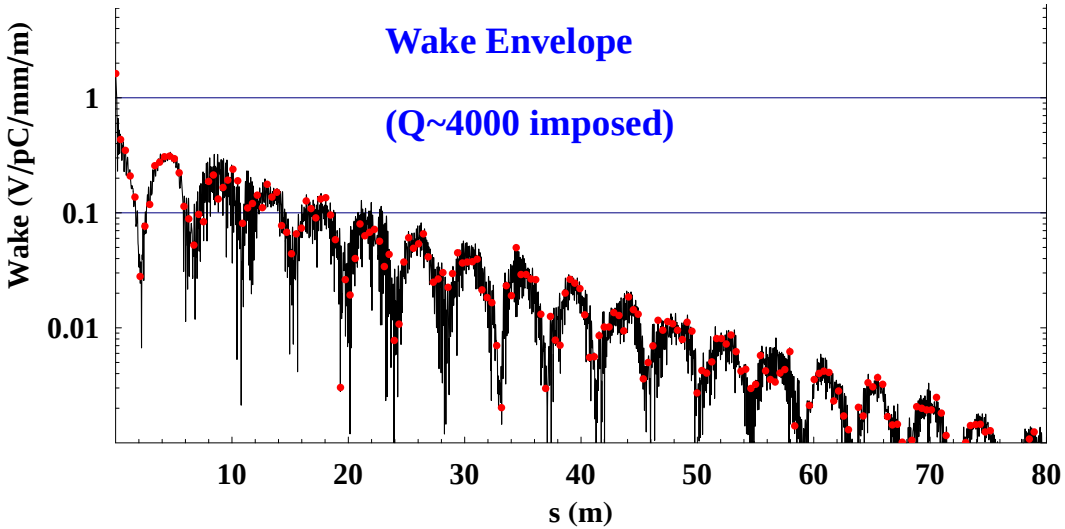

Third Band Synchronous Freqs.
24
25
26
27
Frequency (GHz)


Third Band Wake Env. (~6 of first band at s=0)
Q~4000 imposed
Wake (V/pC/mm/m)
1
0.1
0.01
10
20
30
40
50
60
70
80
s (m)

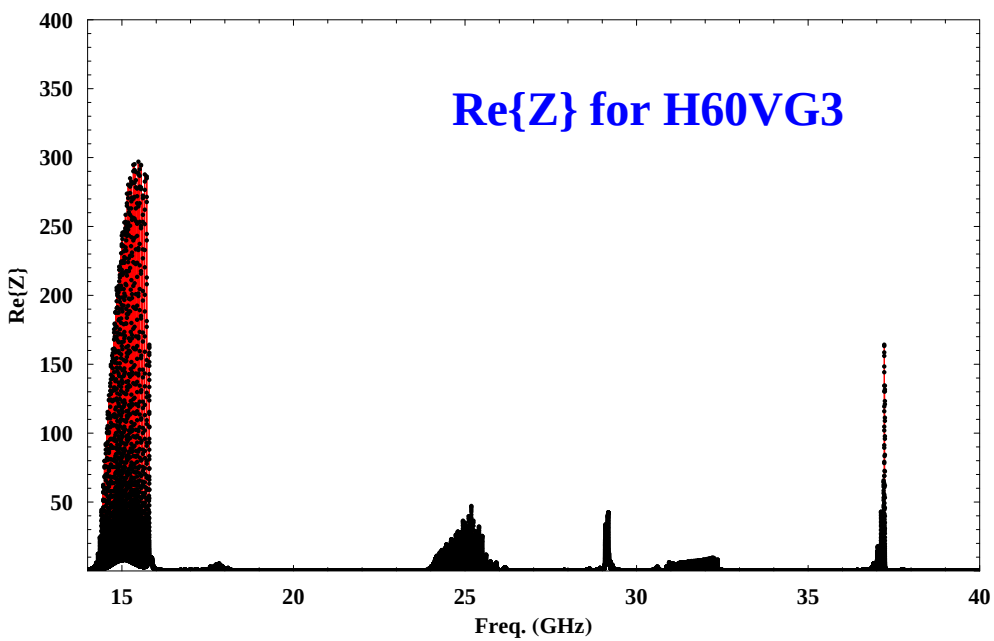

Kick Factor Weighted Density Function
24
25
26
27
Frequency (GHz)

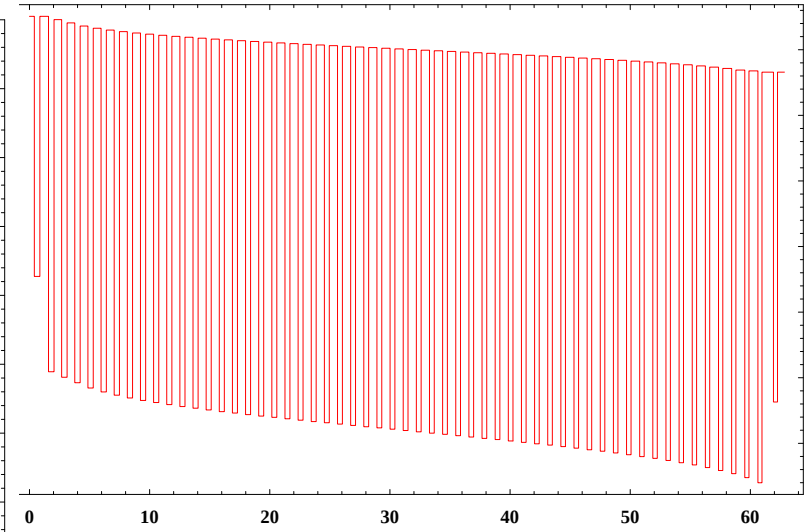


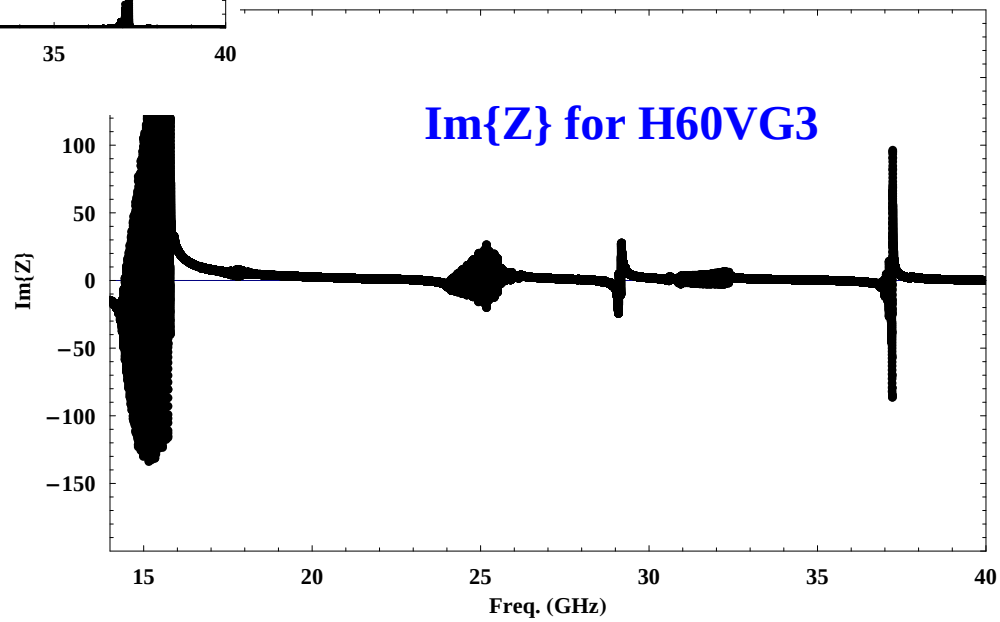


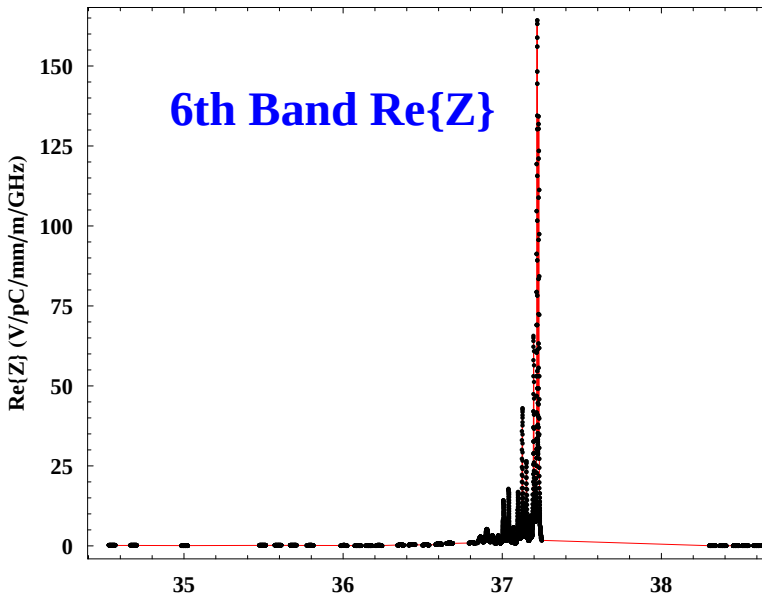


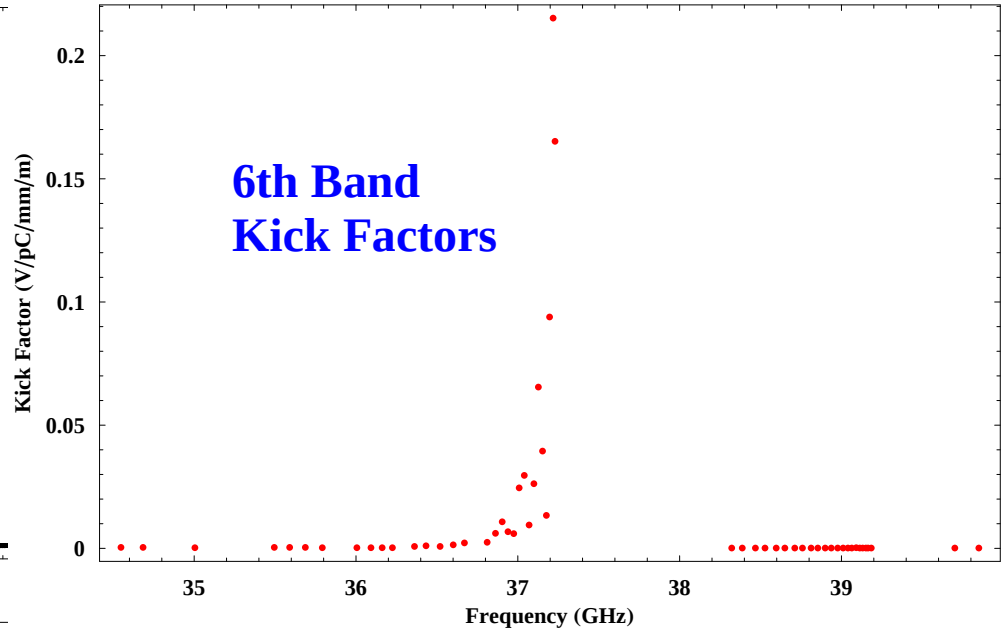
Wake of 3rd band at s=0 is ~6% that of the 1st band.
Combined wake of the 4th and 5 th bands is ~3% of the 1st band

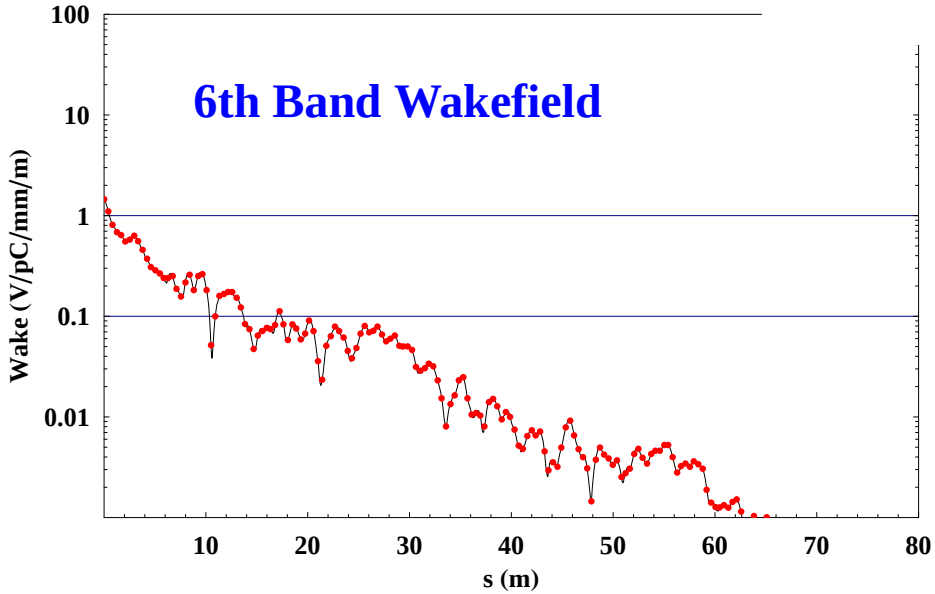

Re{Z} for H60VG3
Re{Z}
400
350
300
250
200
150
100
50
15
20
25
30
35
40
Freq. (GHz)


0
10
20
30
40
50
60

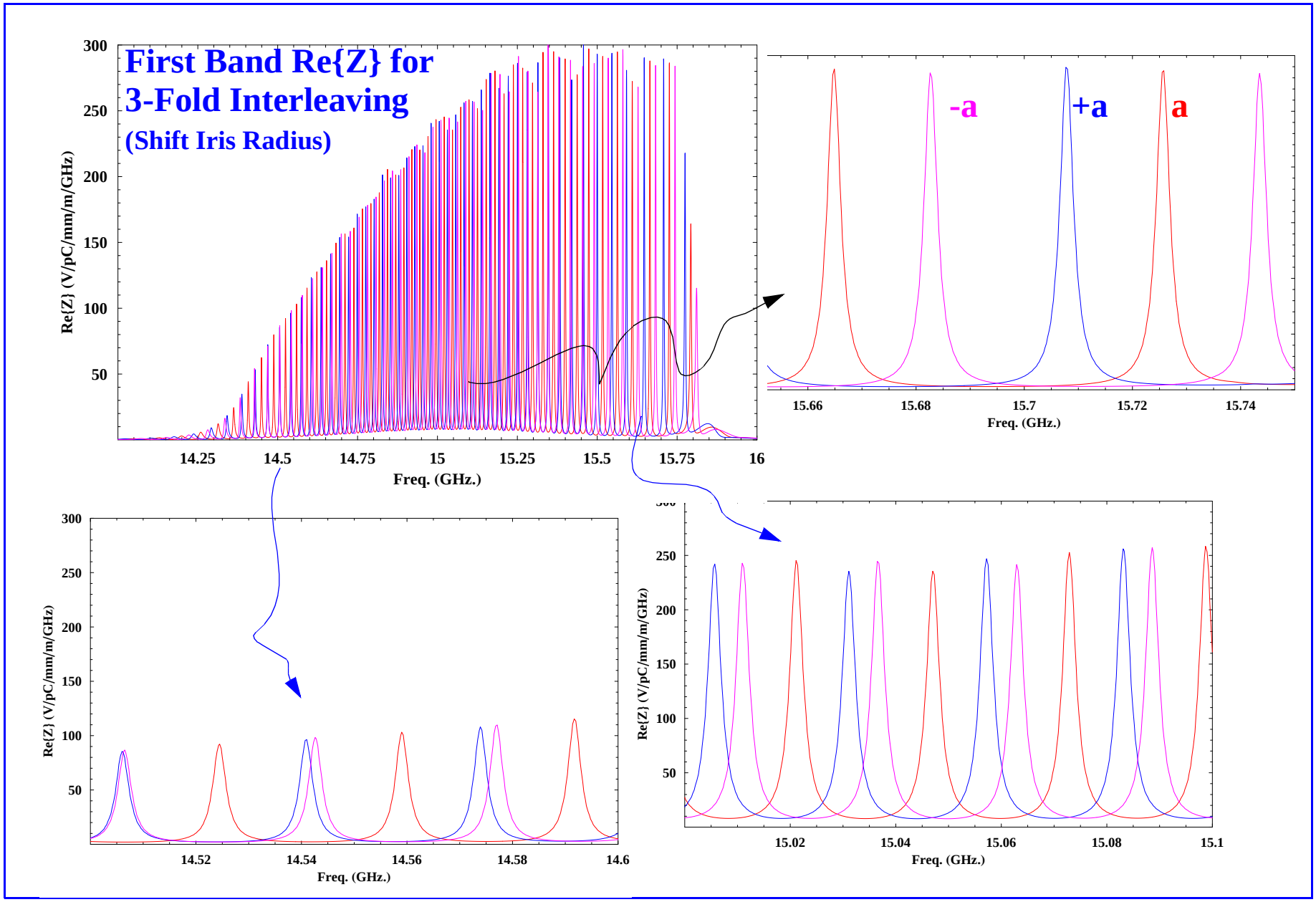

Im{Z} for H60VG3
Im{Z}
100
50
0
−50
−100
−150
15
20
25
30
35
40
Freq. (GHz)





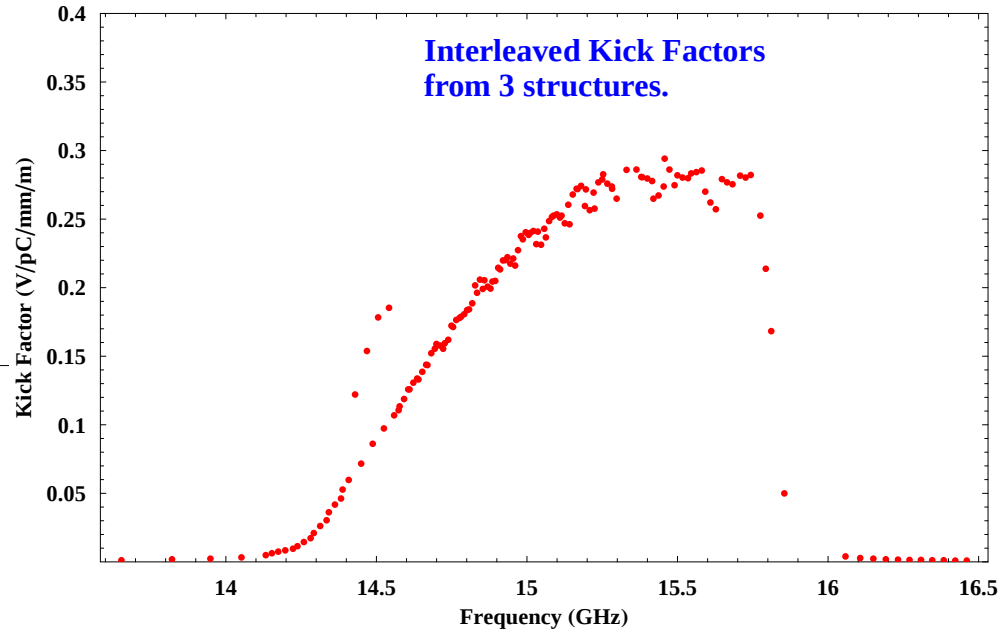


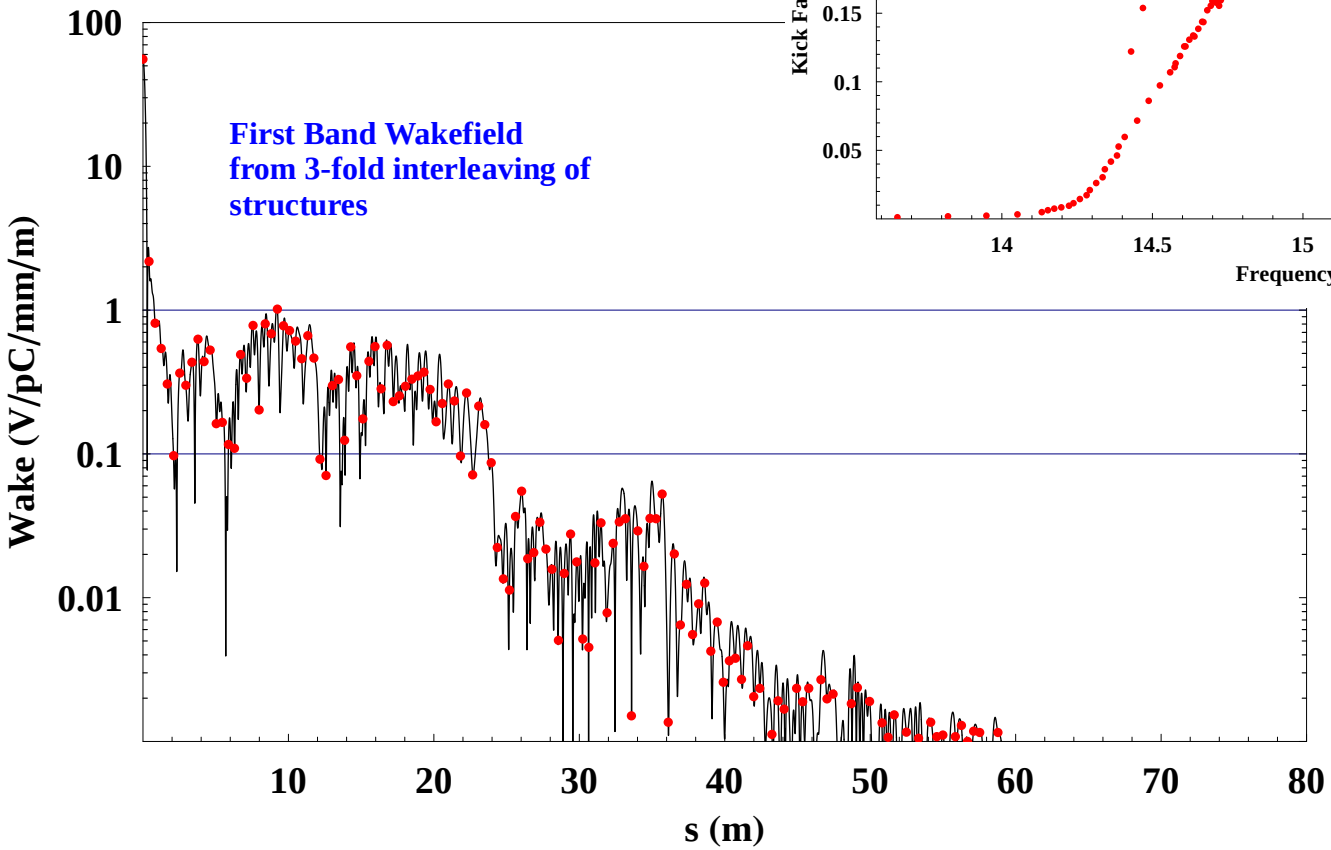
Wake of 6th band at s=0 is ~3% of first
combined Wake of 4th and 5th band at s=0 is ~3%
Wake of 3rd band at s=0 is ~6% of first


First Band Re{Z} for
3-Fold Interleaving
(Shift Iris Radius)
Re{Z} (V/pC/mm/m/GHz)
Freq. (GHz.)
-a
+a
a

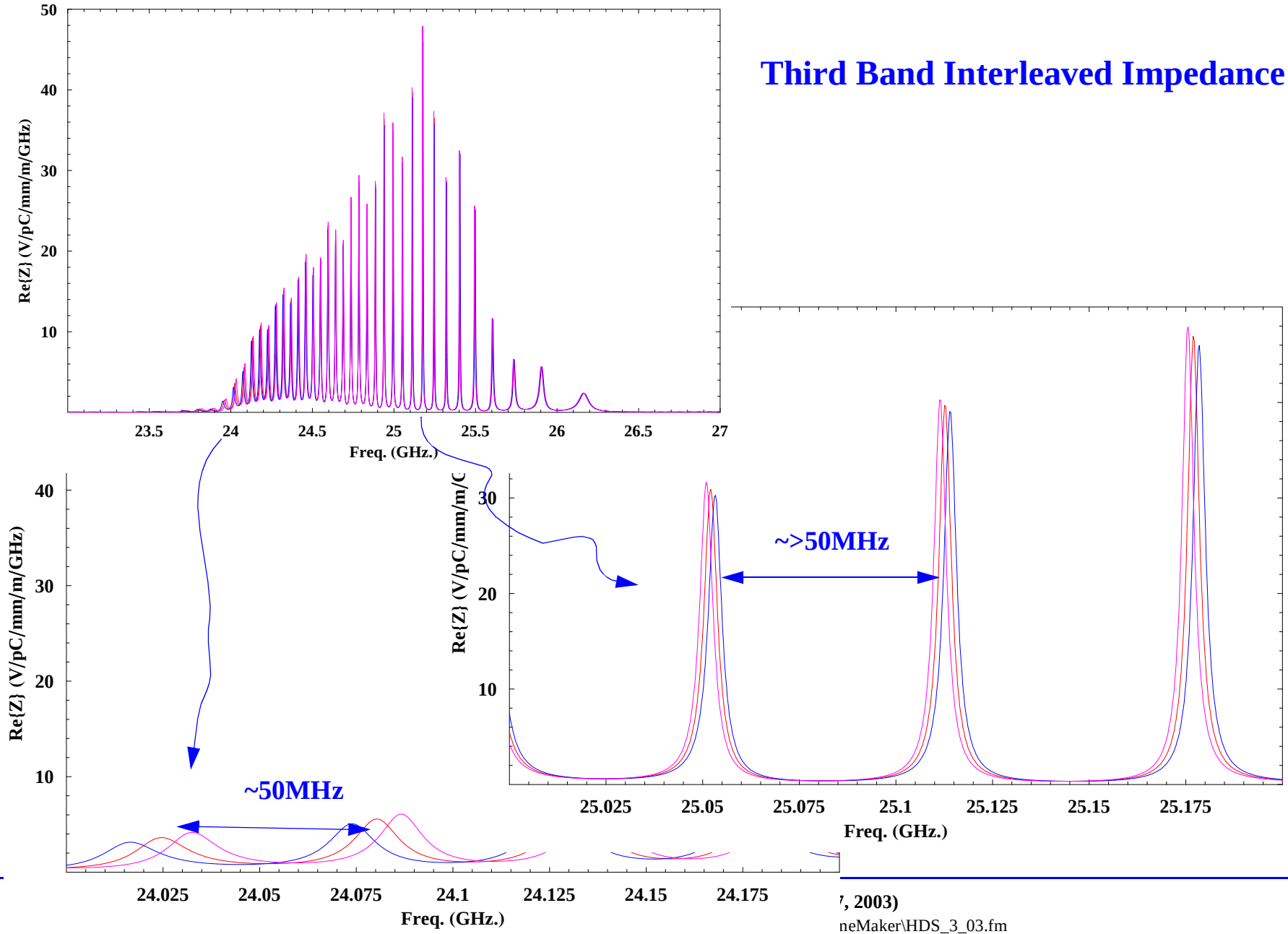
First Band Interleaved Wakefield

(achieved by shifting iris aperture by +/- 15 microns)

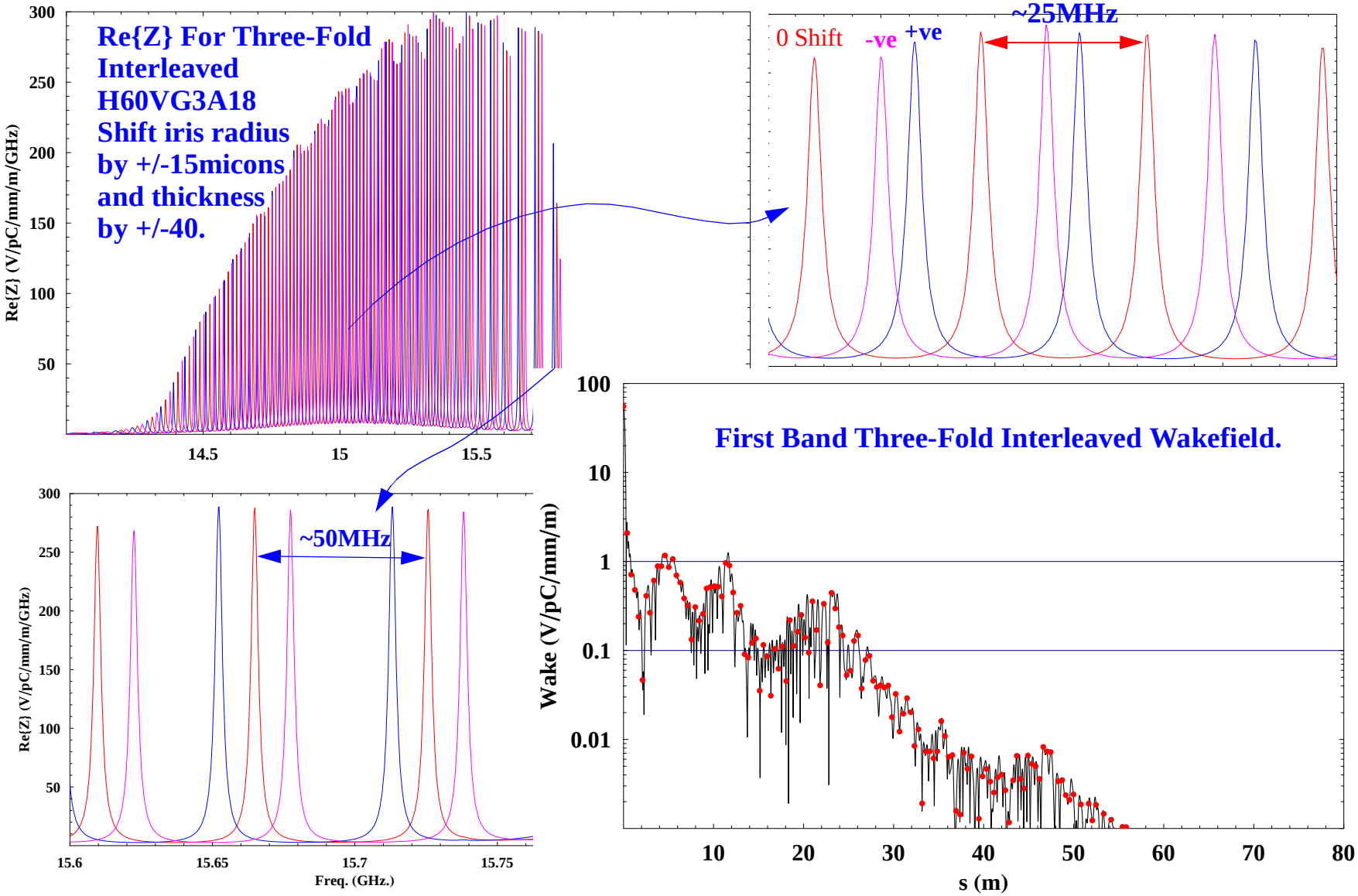


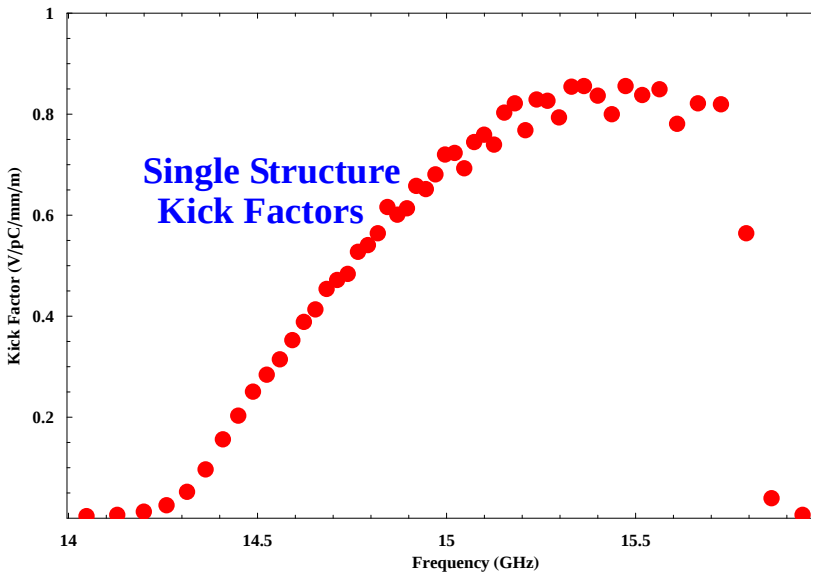


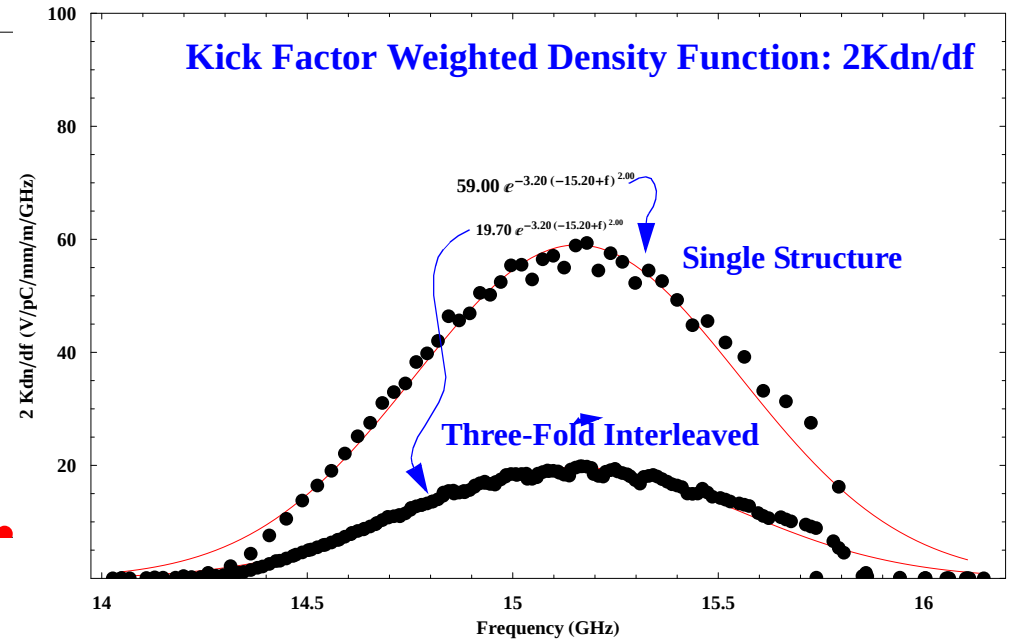
Third Band Interleaved Impedance

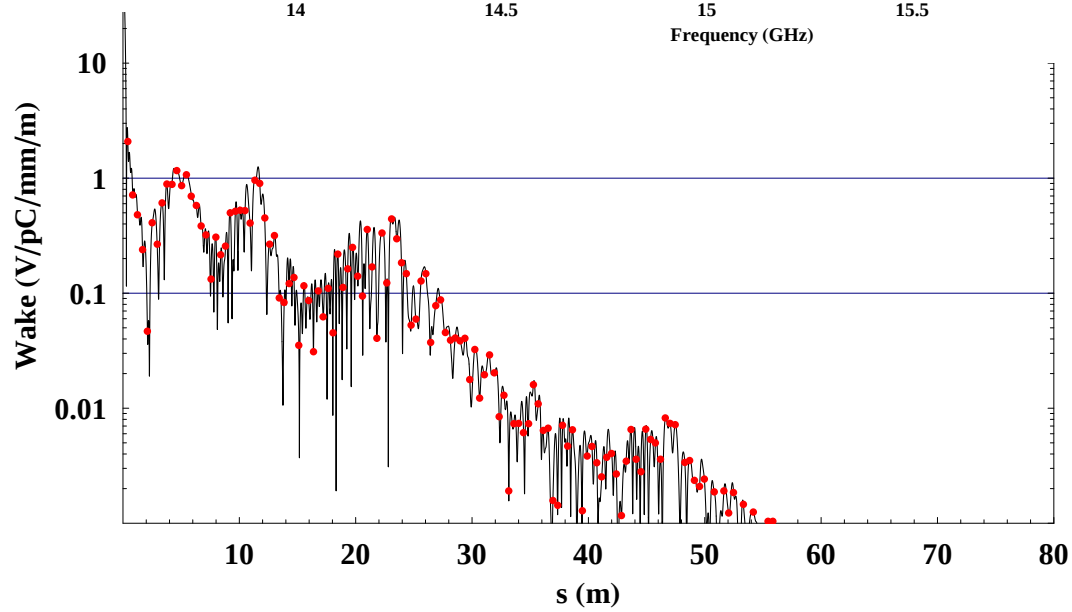


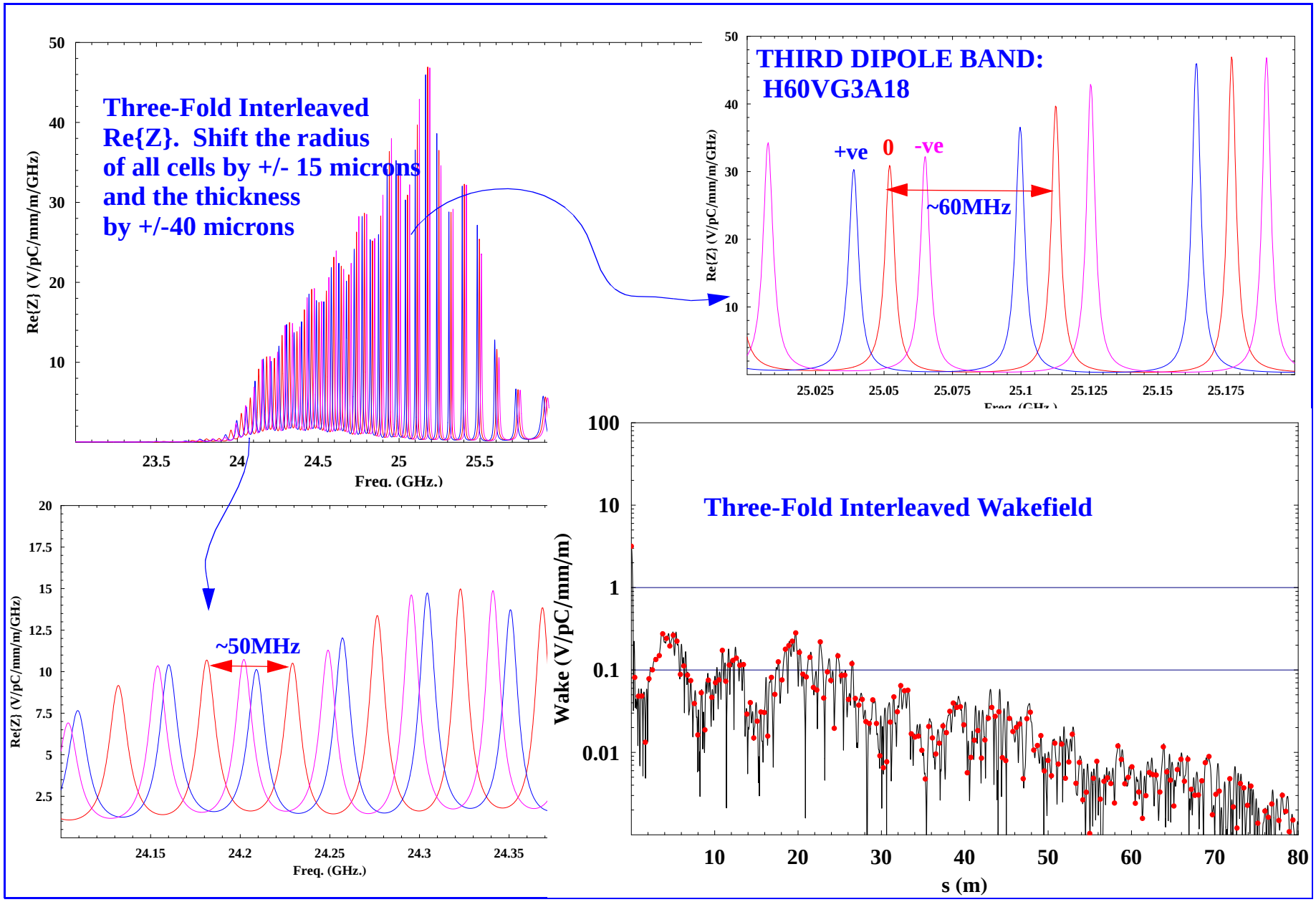
FIRST DIPOLE BAND: H60VG3A18

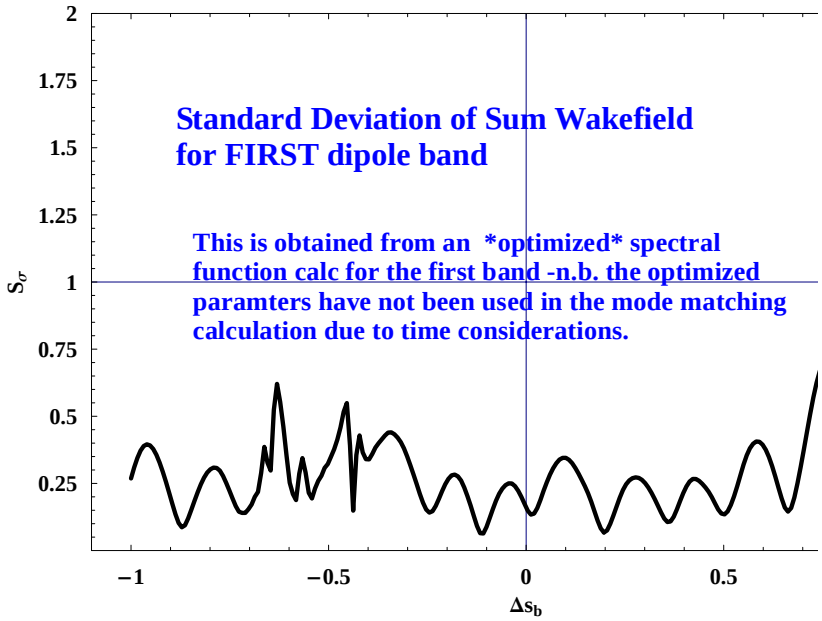


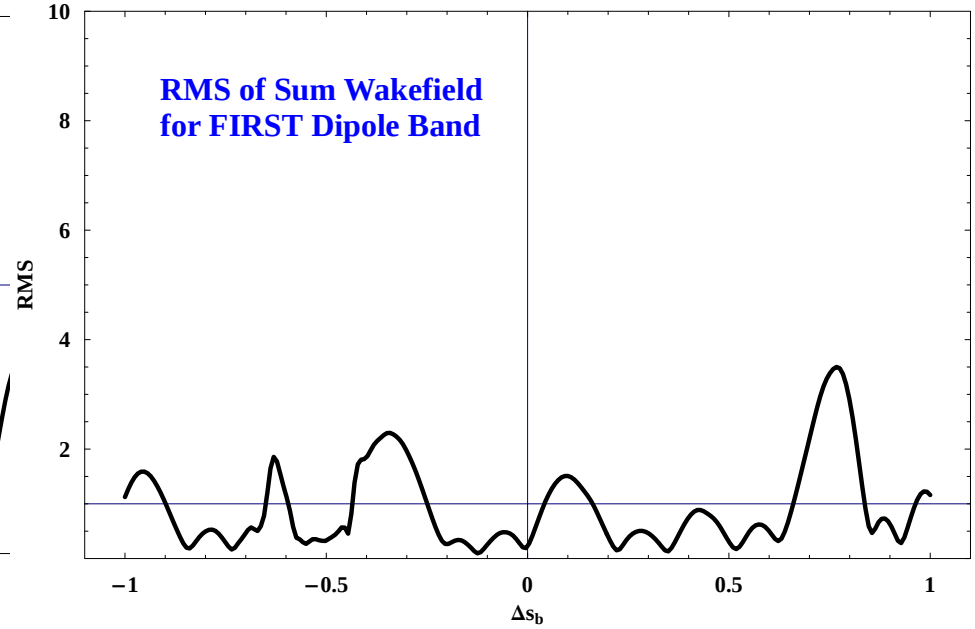

Single Structure
Kick Factors
Kick Factor (V/pC/mm/m)
Frequency (GHz)
1
0.8
0.6
0.4
0.2
14
14.5
15
15.5

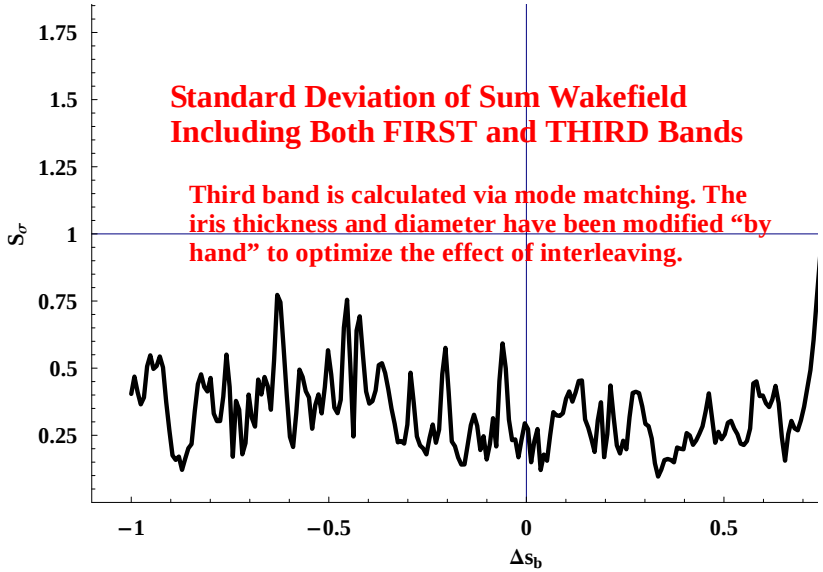

Kick Factor Weighted Density Function: 2Kdn/df
59.00 e^−3.20 (−15.20+f)^2.00
19.70 e^−3.20 (−15.20+f)^2.00
Single Structure
Three-Fold Interleaved
2 Kdn/df (V/pC/mm/m/GHz)
Frequency (GHz)
100
80
60
40
20
14
14.5
15
15.5
16

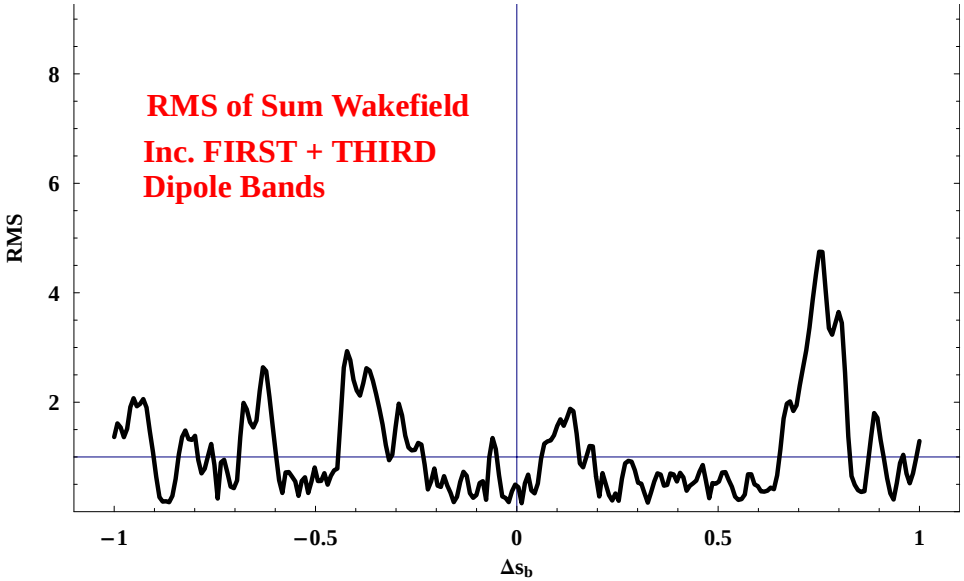

Wake (V/pC/mm/m)
s (m)
10
1
0.1
0.01
10
20
30
40
50
60
70
80


Three-Fold Interleaved Re{Z}. Shift the radius of all cells by +/- 15 microns and the thickness by +/-40 microns
Re{Z} (V/pC/mm/m/GHz)
Freq. (GHz.)
THIRD DIPOLE BAND: H60VG3A18
+ve
0
-ve
~60MHz
~50MHz
Three-Fold Interleaved Wakefield
Wake (V/pC/mm/m)
s (m)


Standard Deviation of Sum Wakefield
for FIRST dipole band
This is obtained from an *optimized* spectral function calc for the first band -n.b. the optimized paramters have not been used in the mode matching calculation due to time considerations.
S_σ
Δs_b


RMS of Sum Wakefield
for FIRST Dipole Band
RMS
Δs_b

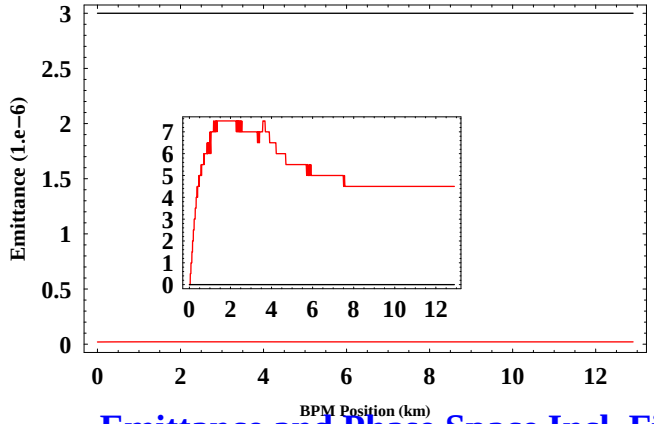

Standard Deviation of Sum Wakefield
Including Both FIRST and THIRD Bands
Third band is calculated via mode matching. The iris thickness and diameter have been modified "by hand" to optimize the effect of interleaving.
S_σ
Δs_b

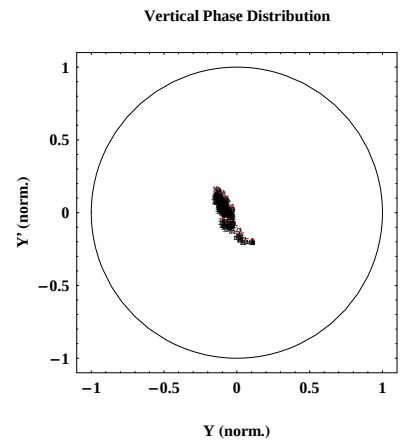

RMS of Sum Wakefield
Inc. FIRST + THIRD
Dipole Bands
RMS
Δs_b

Phase ()

Emittance and Phase Space Incl. First Band Wake

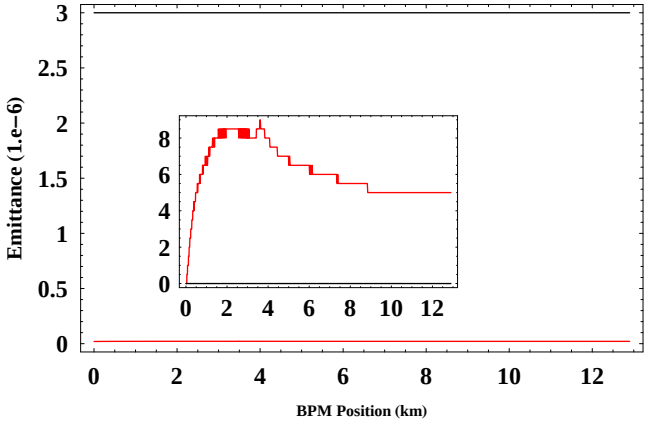
Normalised Horizontal & Vertical Beam Emittance For NLC
Inset is the % Emittance growth
Initial Emittance: {0.000165, 3., 0.02}
Final Emittance: {12.9, 3., 0.0209}

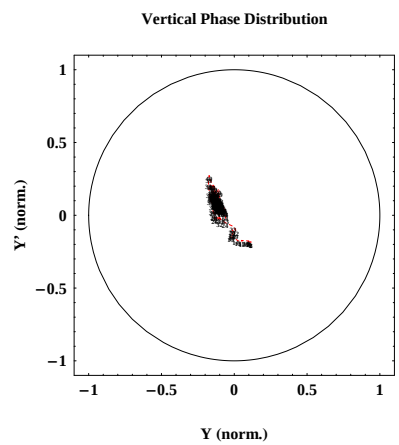




Emittance and Phase Space Incl. First and Third Band Dipole Wakes (thickness+radius interleaving)

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}





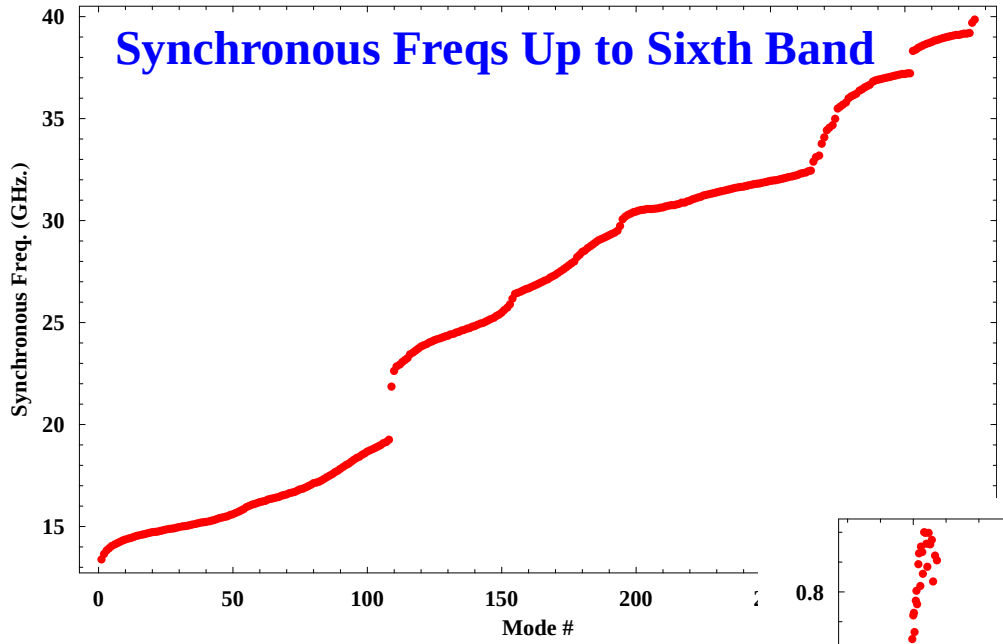
Higher Dipole Bands in H60VG3

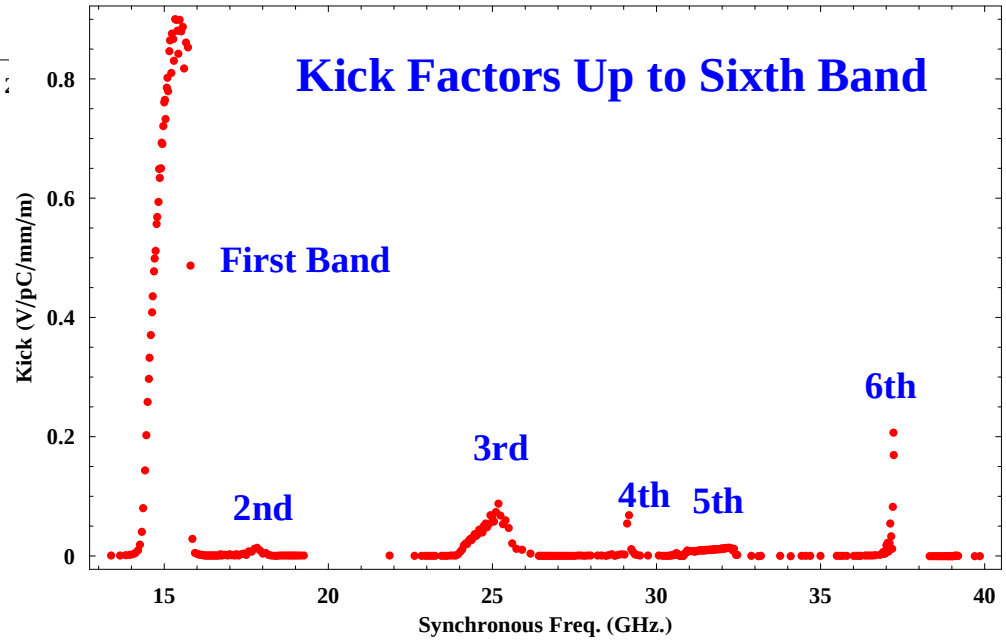
***If the first band is optimized and the upper dipole bands are ignored does BBU occur?**
Yes!

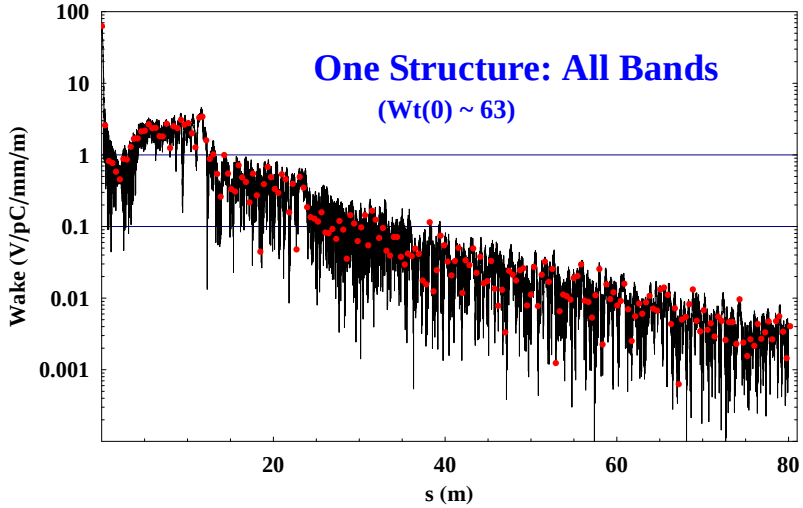
*** If the thickness' and the radi are changed in adjacent structures to interleave the dipole frequencies of higher bands then no BBU occurs. A Q~4000 has been assumed for the upper dipole bands.**
The first dipole band is manifold damped with a Q~1000.

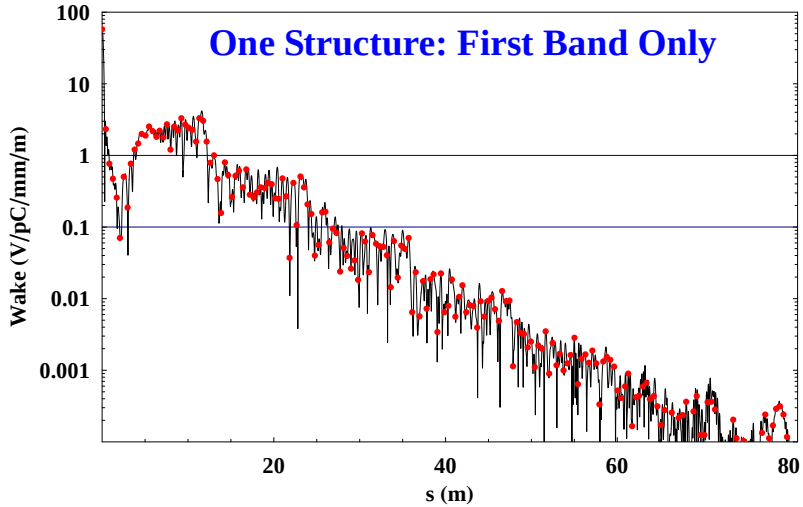
*** In addition to the first band, the sixth band is the main band that requires damping.**
The sixth band is an order of magnitude smaller than the first band (comparing the total kick)

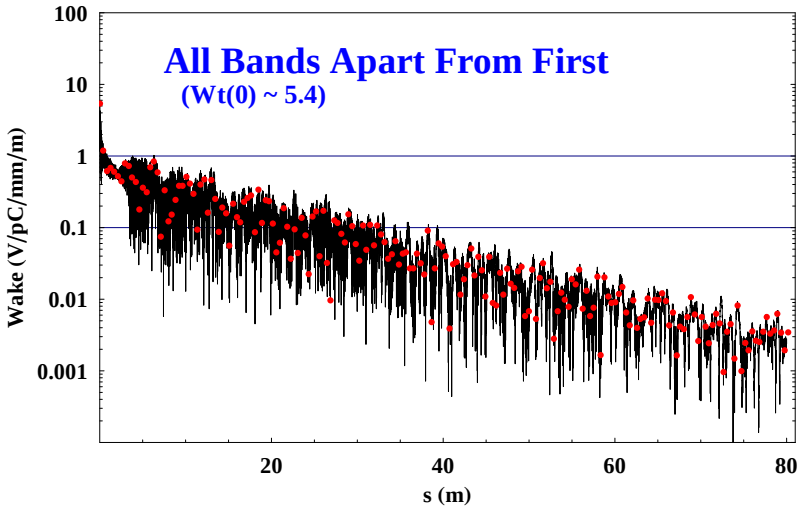
Single-Structure (part of the three interleaved structures) Kicks Factors and Synchronous Freqs Up to Sixth Band

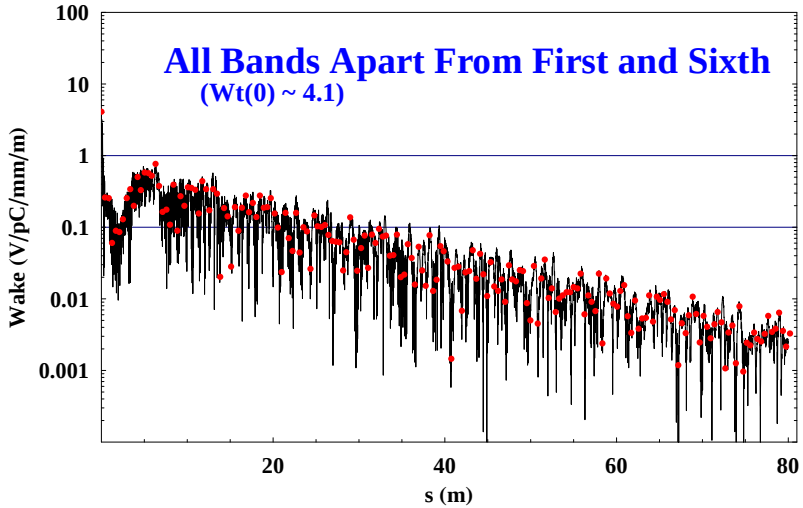




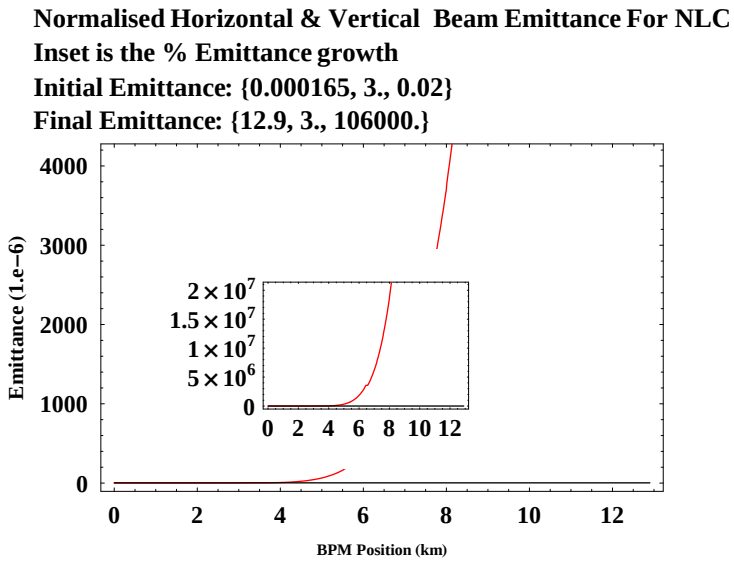

One Structure: All Bands
(Wt(0) ~ 63)
Wake (V/pC/mm/m)
100
10
1
0.1
0.01
0.001
20
40
60
80
s (m)

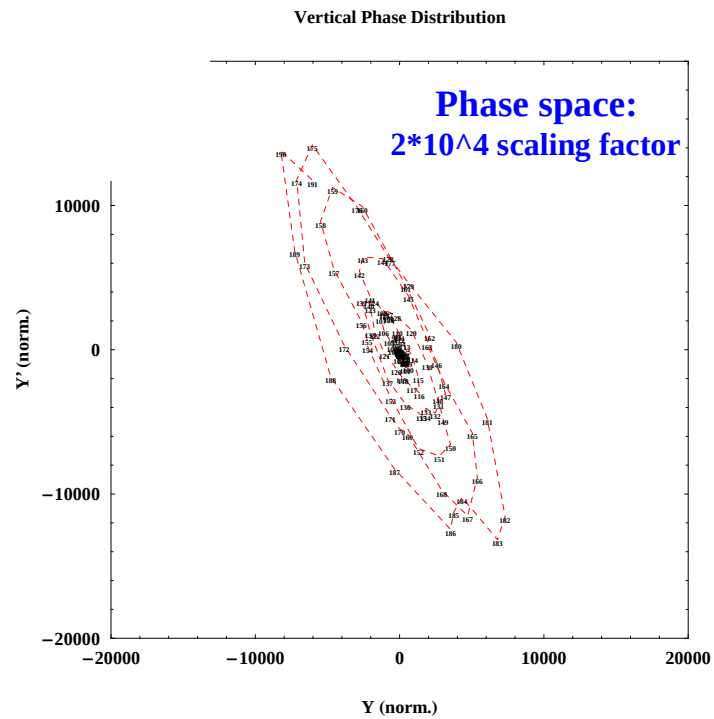

One Structure: First Band Only
Wake (V/pC/mm/m)
100
10
1
0.1
0.01
0.001
20
40
60
80
s (m)


All Bands Apart From First
(Wt(0) ~ 5.4)
Wake (V/pC/mm/m)
100
10
1
0.1
0.01
0.001
20
40
60
80
s (m)

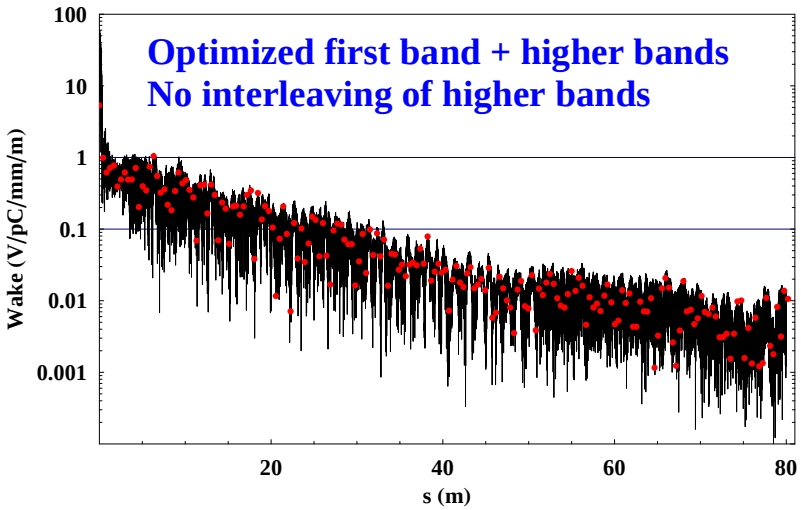

All Bands Apart From First and Sixth
(Wt(0) ~ 4.1)
Wake (V/pC/mm/m)
100
10
1
0.1
0.01
0.001
20
40
60
80
s (m)

Beam Dynamics: Single-Structure incl. All Band Dipole Wakes

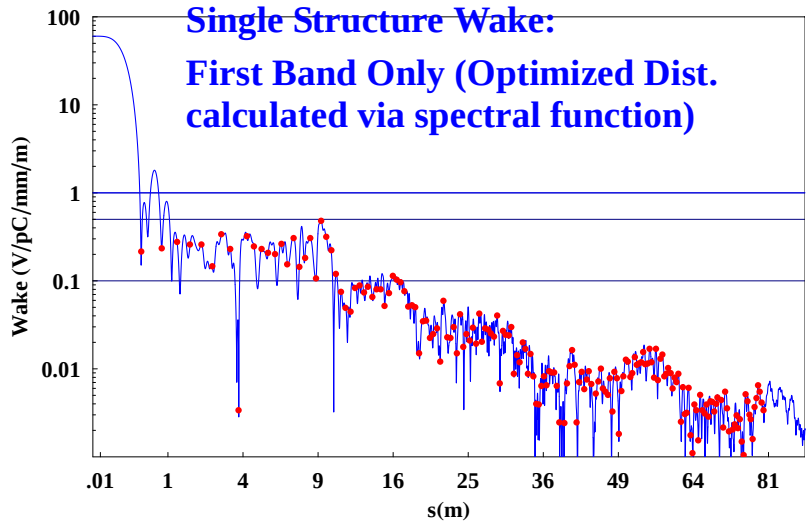




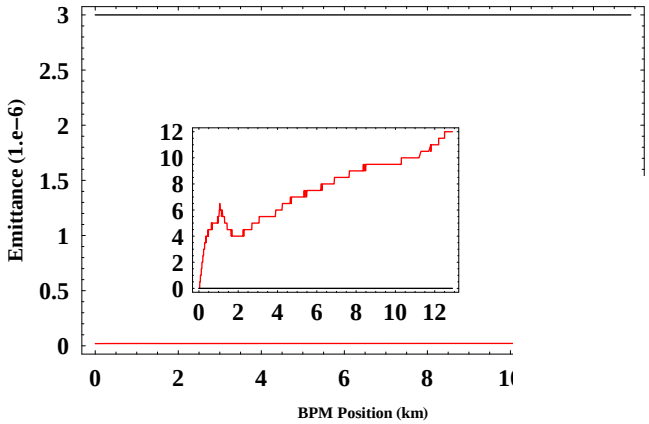
The beam is initially offset by 1 micron and is then subject to identical wakes. The wakes are those of the optimized three fold interleaved first band and the non-optimized non-interleaved higher bands (as far as the sixth band)



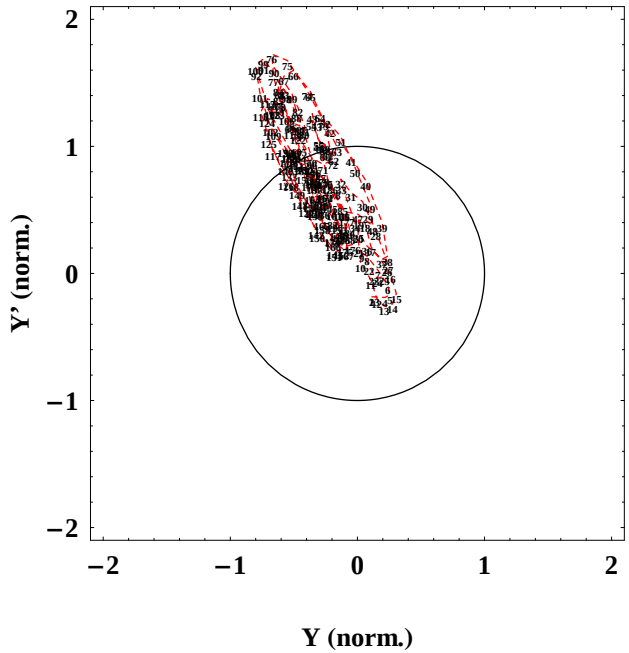
Without optimized interleaving of the higher bands then the higher bands make a significant contribution to the overall wakefield



Normalised Horizontal & Vertical Beam Emittance For NLC
Inset is the % Emittance growth
Initial Emittance: {0.000165, 3., 0.02}
Final Emittance: {12.9, 3., 0.0224}



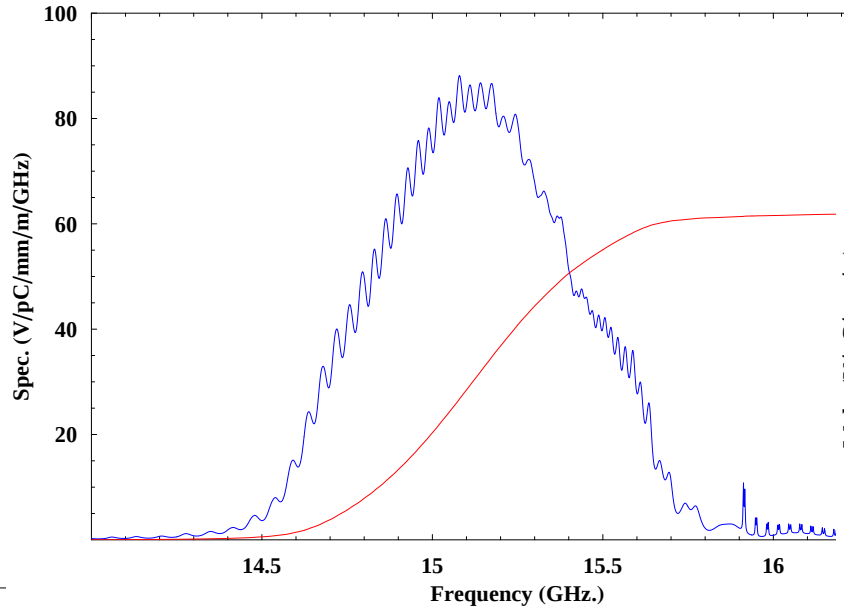
Vertical Phase Distribution

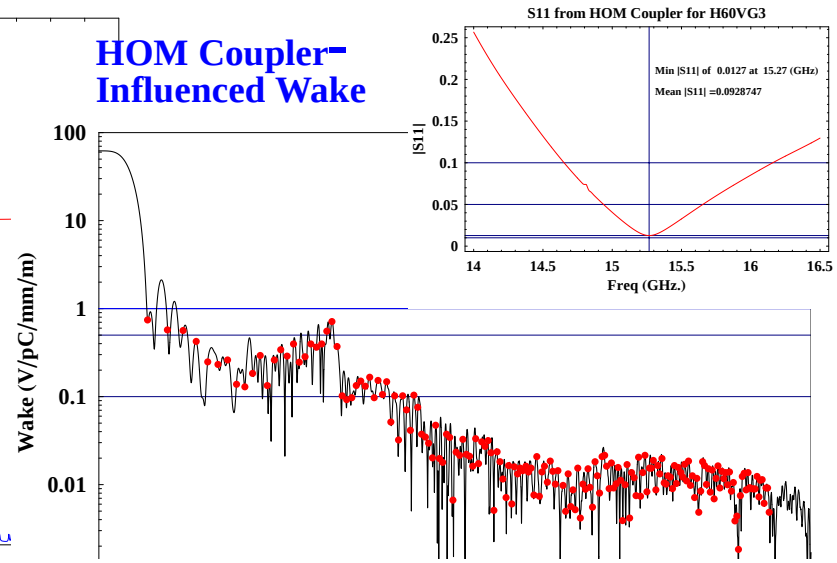


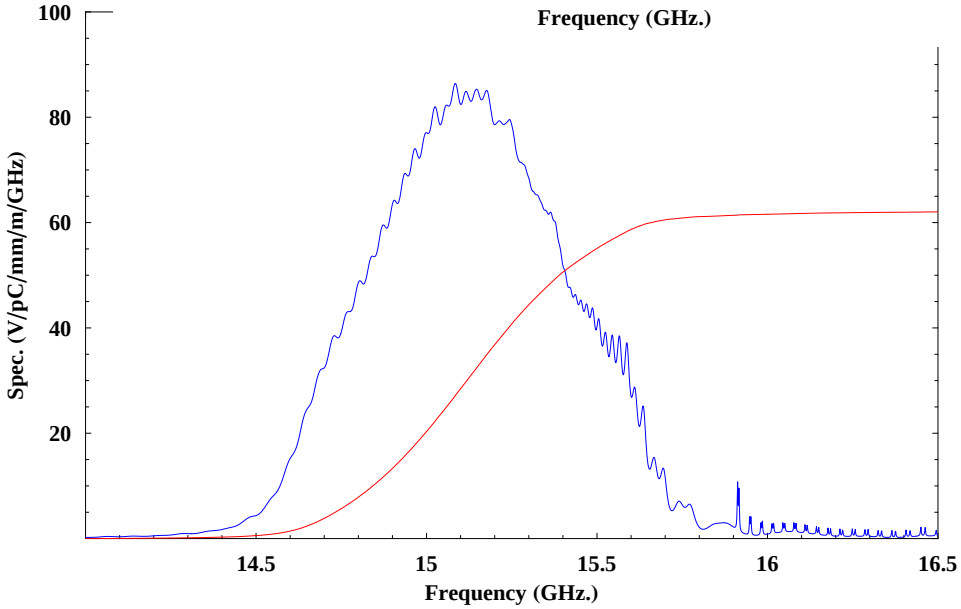
The beam is initially offset by 1 micron and is subject to the combined wakefield of the optimized interleaved first band and the non-optimized higher bands. Clearly interleaving of thew higher bands is also necessary -this was demonstrated to be successful in the previous week's meeting.

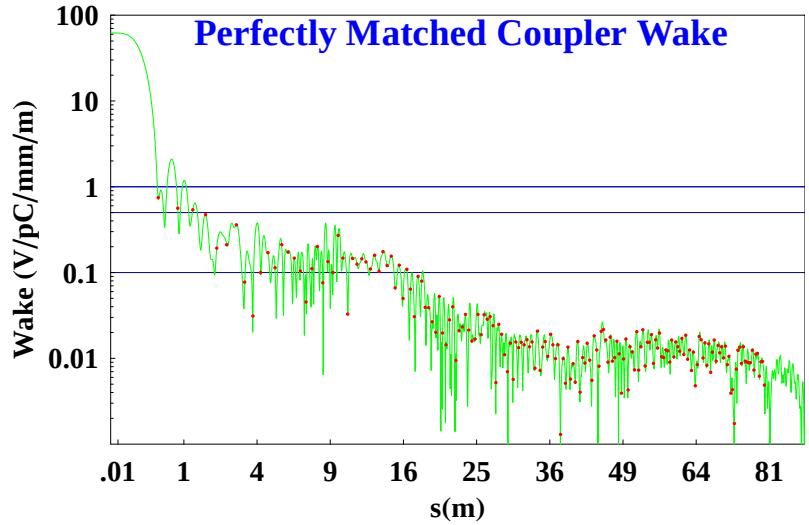
H60VG3S17

* Effect of Removal of I/P (Upstream)HOM Coupler


Spec. (V/pC/mm/m/GHz)
100
80
60
40
20
14.5
15
15.5
16
Frequency (GHz.)

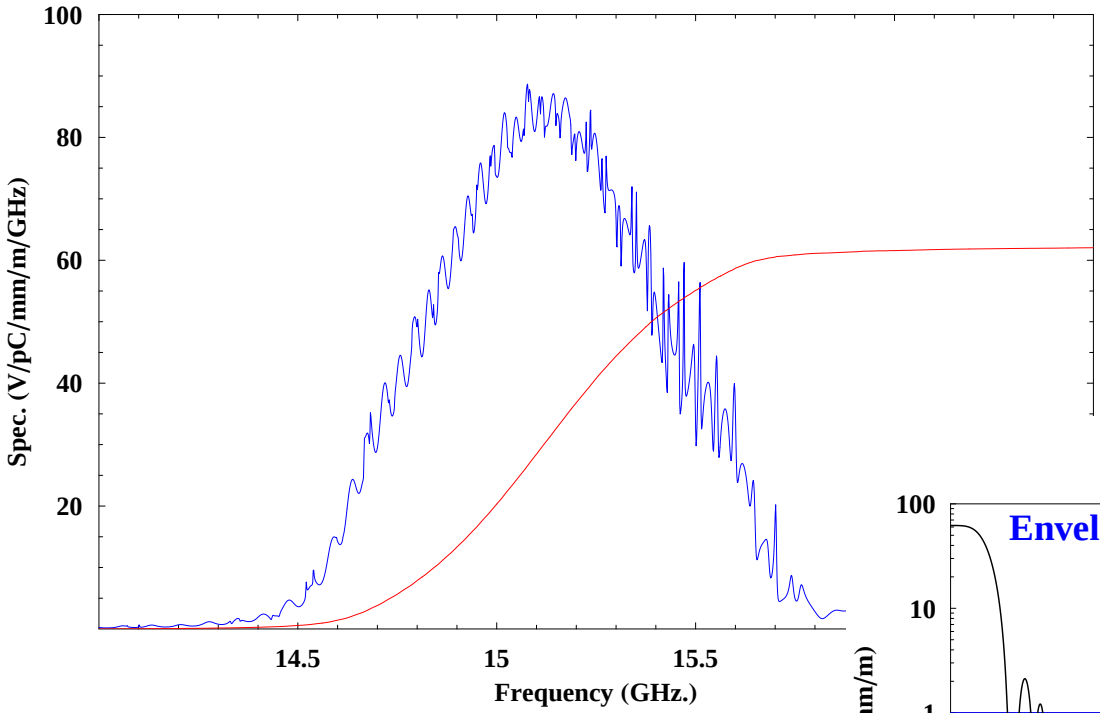

HOM Coupler-
Influenced Wake
S11 from HOM Coupler for H60VG3
Min |S11| of 0.0127 at 15.27 (GHz)
Mean |S11| =0.0928747
|S11|
0.25
0.2
0.15
0.1
0.05
0
14
14.5
15
15.5
16
16.5
Freq (GHz.)
Wake (V/pC/mm/m)
100
10
1
0.1
0.01

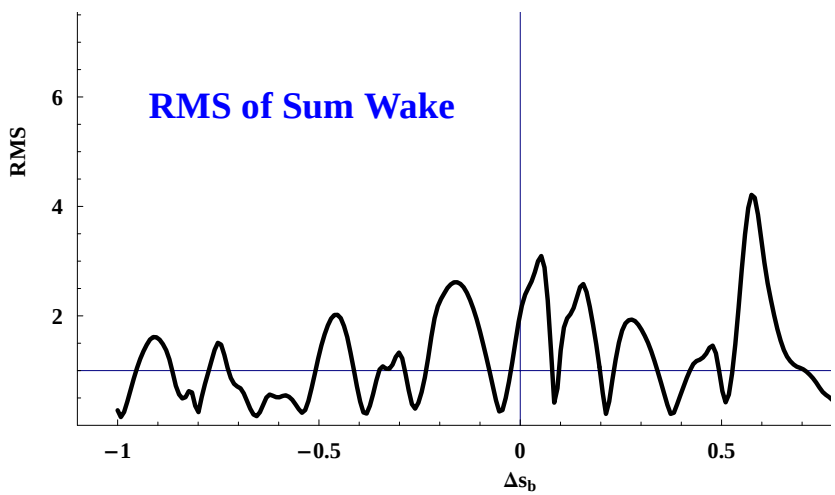

Spec. (V/pC/mm/m/GHz)
100
80
60
40
20
14.5
15
15.5
16
16.5
Frequency (GHz.)

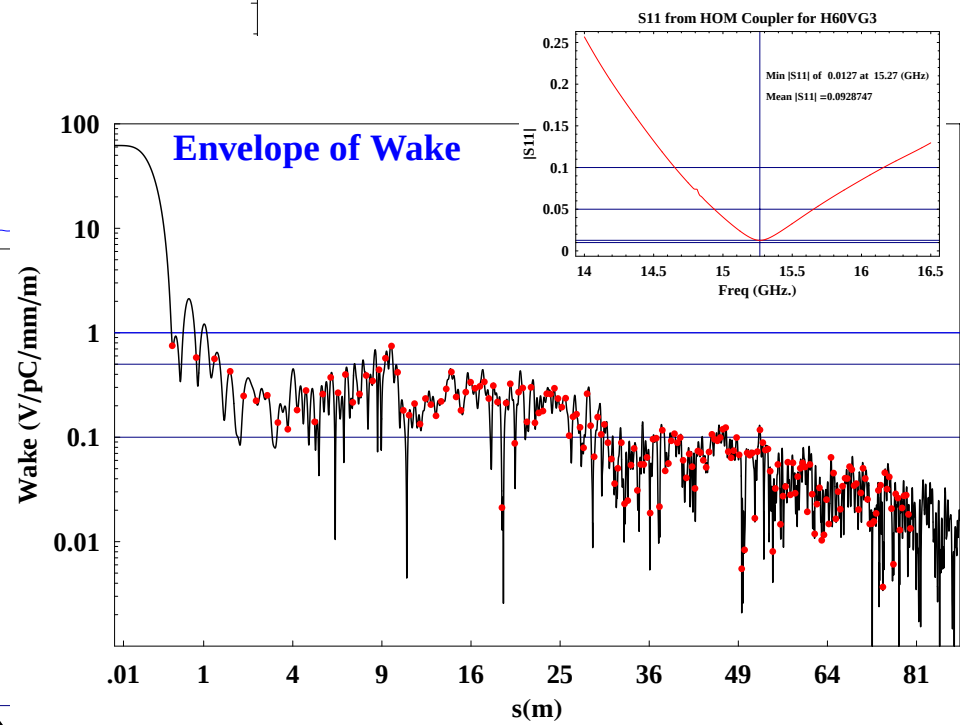

Perfectly Matched Coupler Wake
Wake (V/pC/mm/m)
100
10
1
0.1
0.01
.01
1
4
9
16
25
36
49
64
81
s(m)

Removal of I/P Coupler

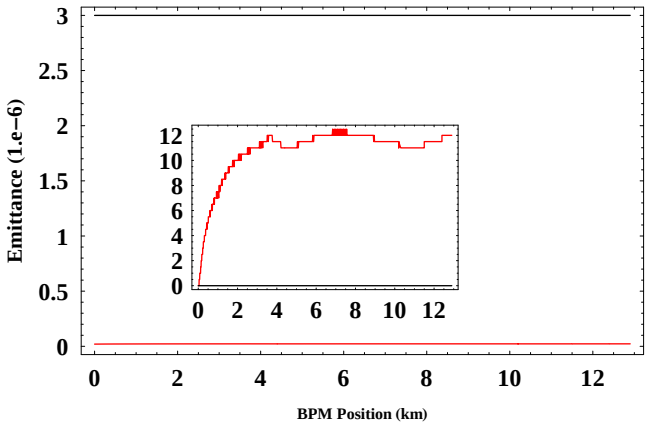
O/P Coupler reflection coefficient given below.





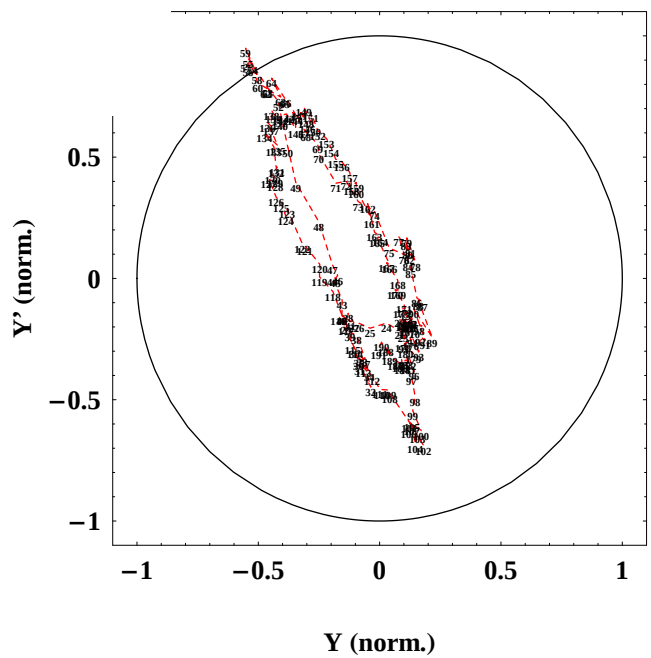


Normalised Horizontal & Vertical Beam Emittance For NLC
Inset is the % Emittance growth
Initial Emittance: {0.000165, 3., 0.02}
Final Emittance: {12.9, 3., 0.0224}

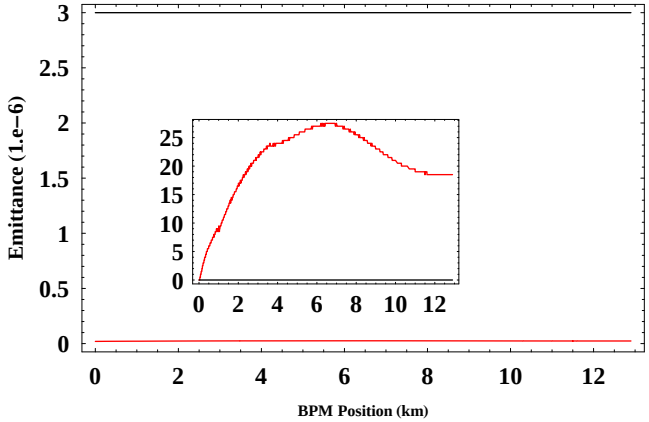


At the nominal bunch spacing (no errors)

Vertical Phase Distribution

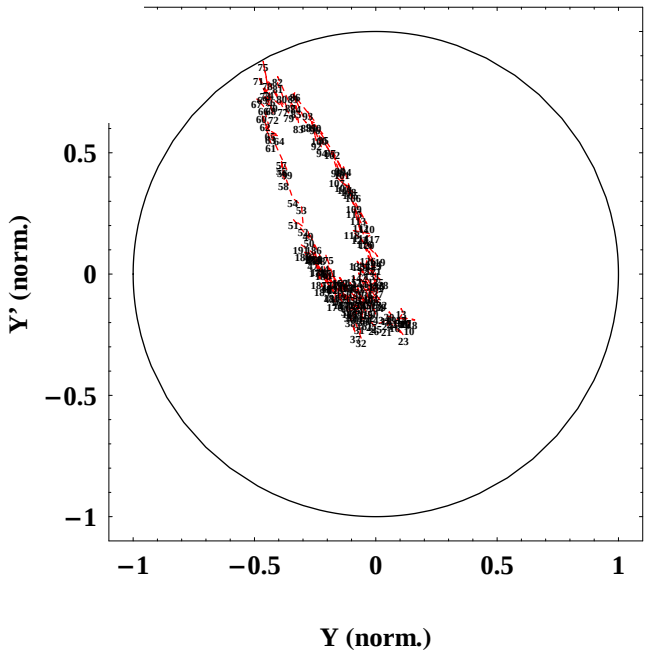


Normalised Horizontal & Vertical Beam Emittance For NLC
Inset is the % Emittance growth
Initial Emittance: {0.000165, 3., 0.02}
Final Emittance: {12.9, 3., 0.0237}

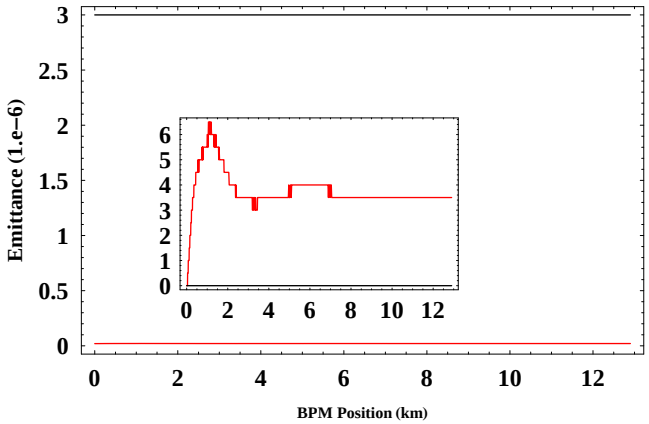


At the nearest position in the bunch spacing which gives a peak Sum Wake (~+7.9 MHz)

Vertical Phase Distribution

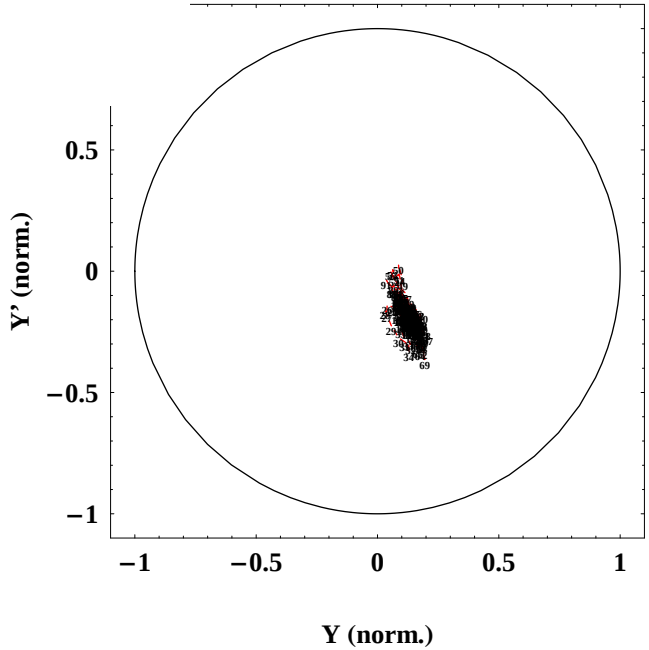


Normalised Horizontal & Vertical Beam Emittance For NLC
Inset is the % Emittance growth
Initial Emittance: {0.000165, 3., 0.02}
Final Emittance: {12.9, 3., 0.0207}



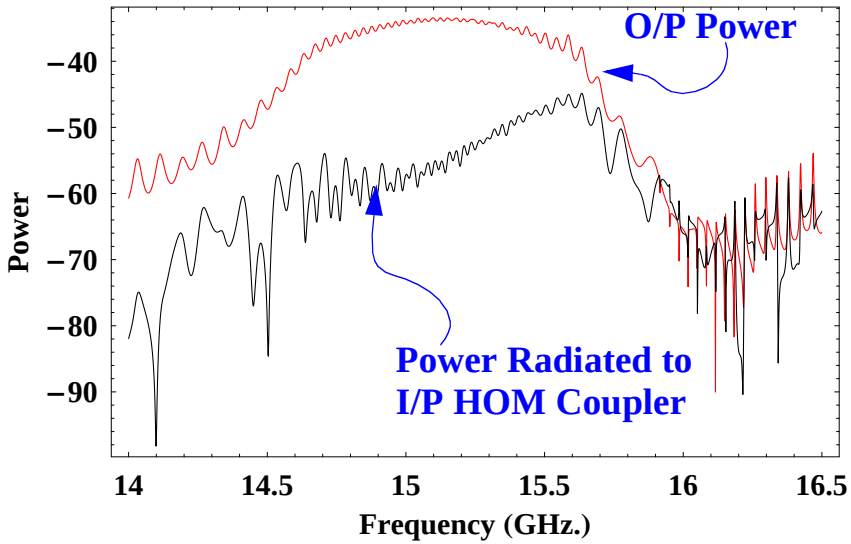
Shift center frequency down by 7.9 MHz to achieve minimum in RMS of Sum Wake

Vertical Phase Distribution



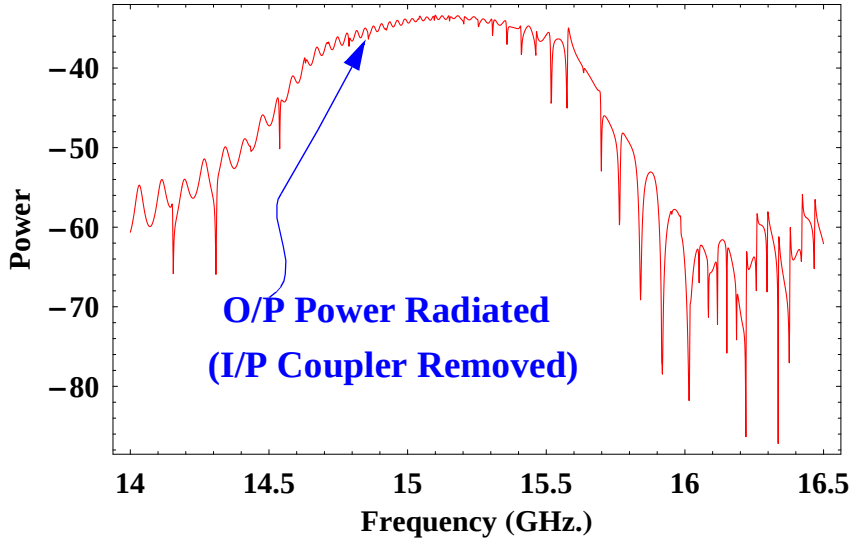
*** Two-fold interleaving will not give rise to BBU or signicant emittance dilution if we shift the central freq down by ~7.9 MHz (to lie on the minimum of the sum wakefield)**

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

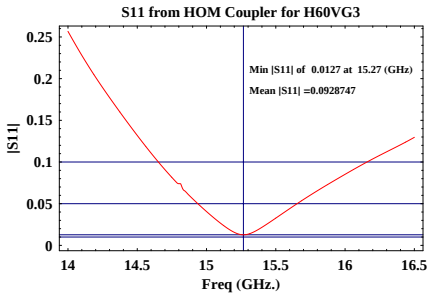


Power Radiated to HOM Couplers:

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)



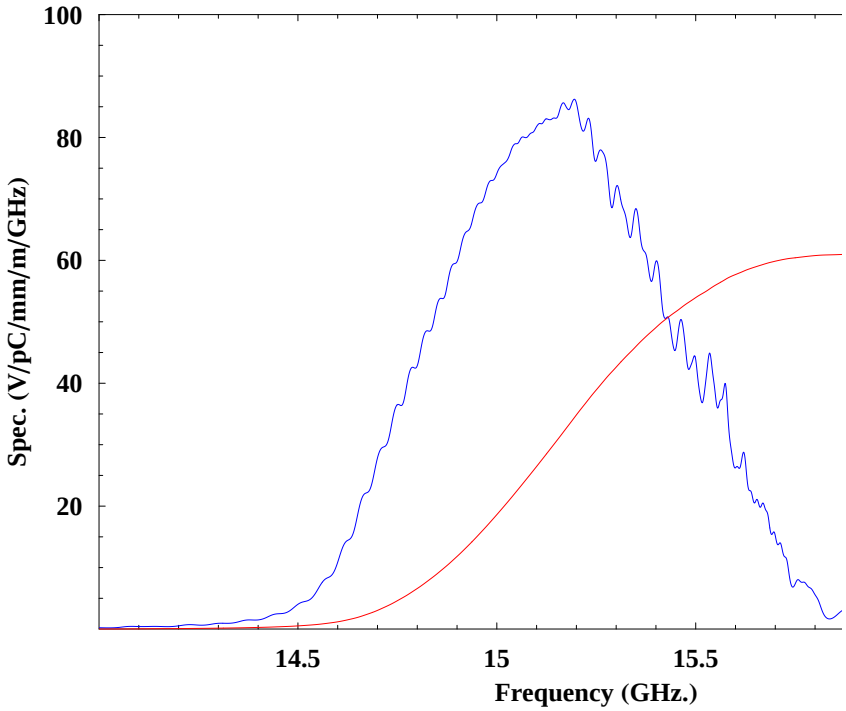
H60VG3S17

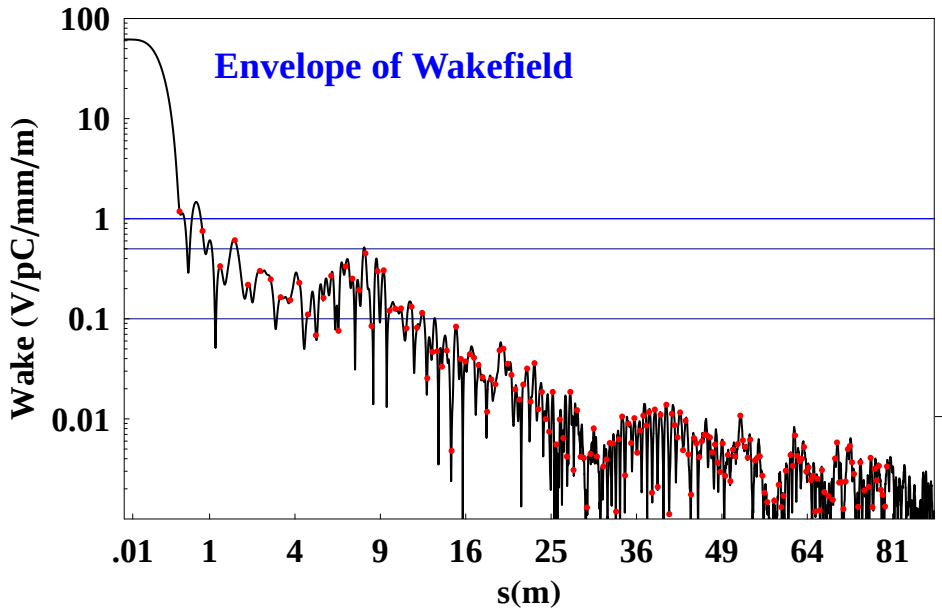
*** Baseline NLC design 8 structures per girder**
=> 4-fold interleaving of structures

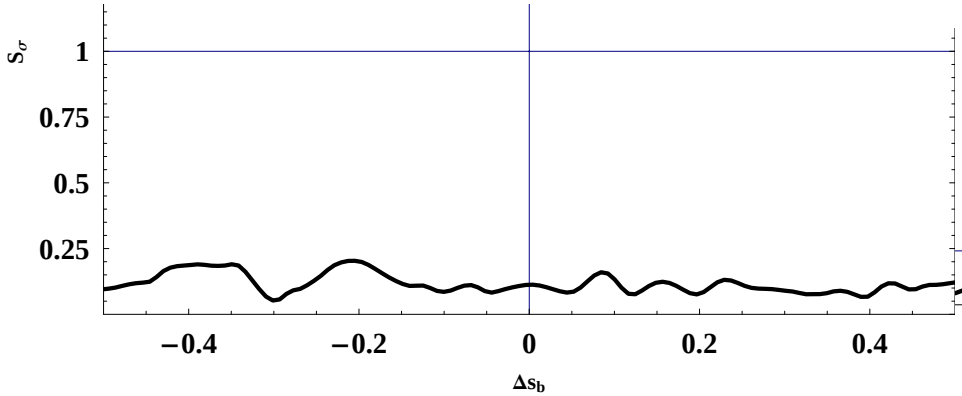
*** Spectral code => Optimized 4-fold interleaved bandwidth 9.88%**
Effect on wake of perfectly matched vs. real HOM
*** Wake meets R1/R2 requirements**
=> no BBU & no appreciable emittance dilution from long range wake!

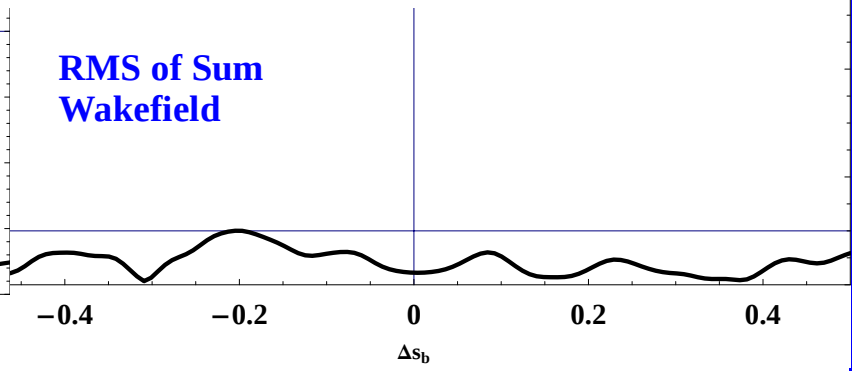
***Design based on 60cm, 55 cells, 150 fundamental phase advance per cell**

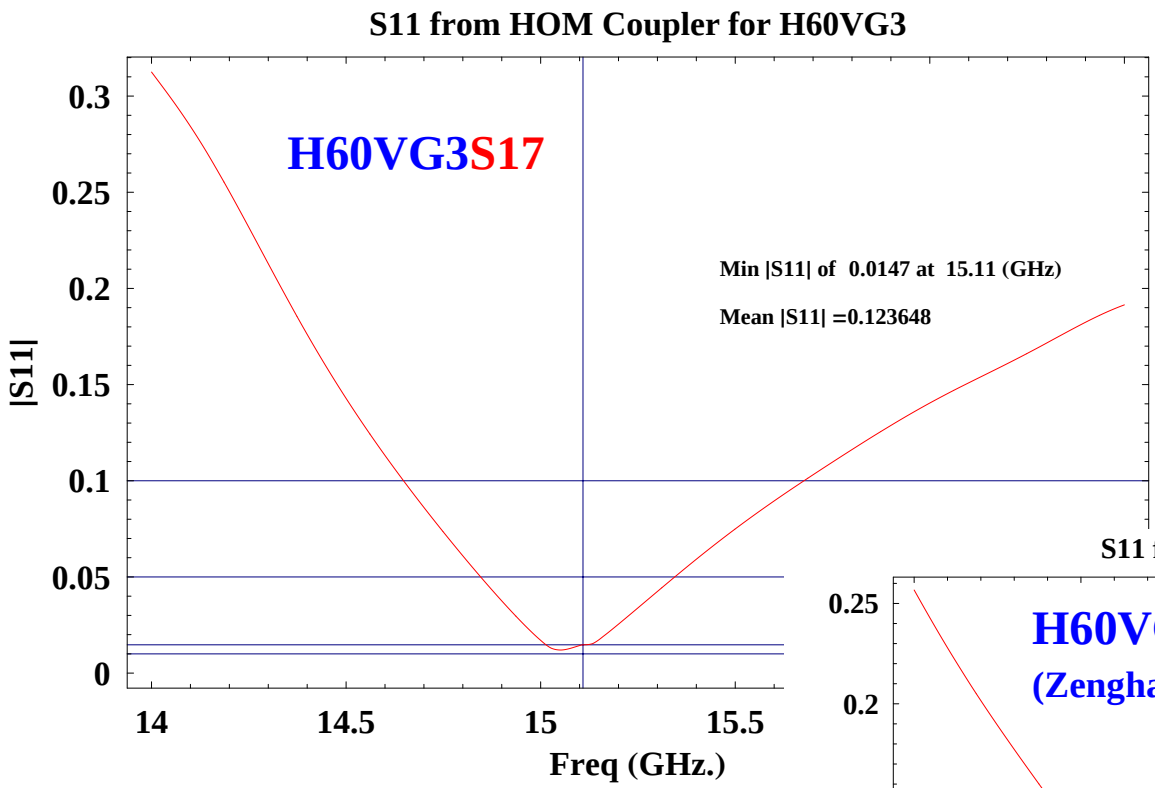
Four-Fold Interleaved, Perfectly Matched HOM Coupler (S11=0)

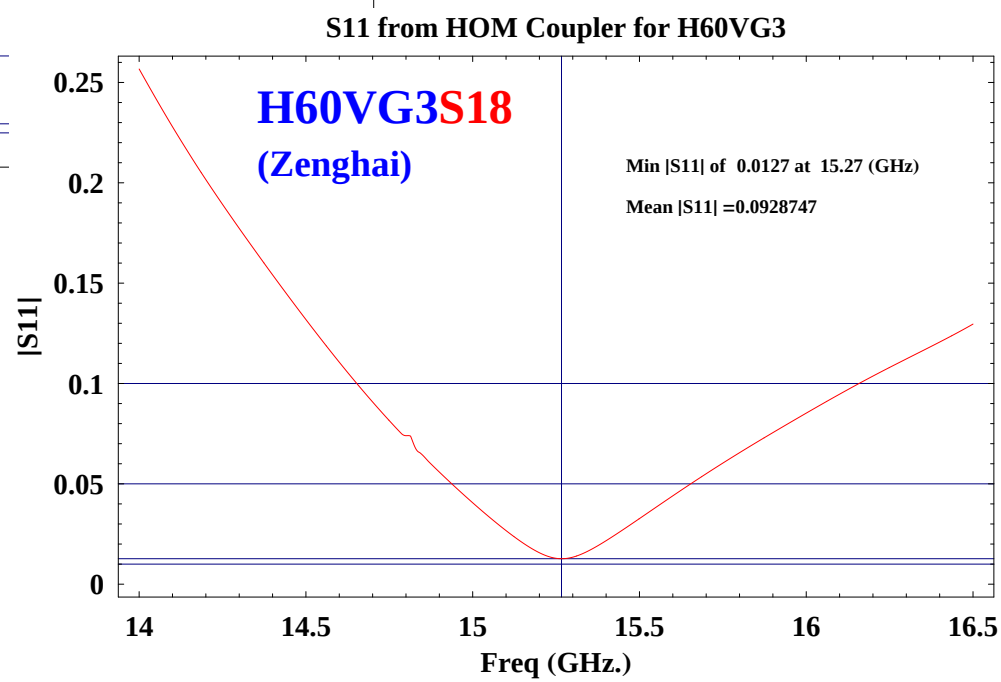




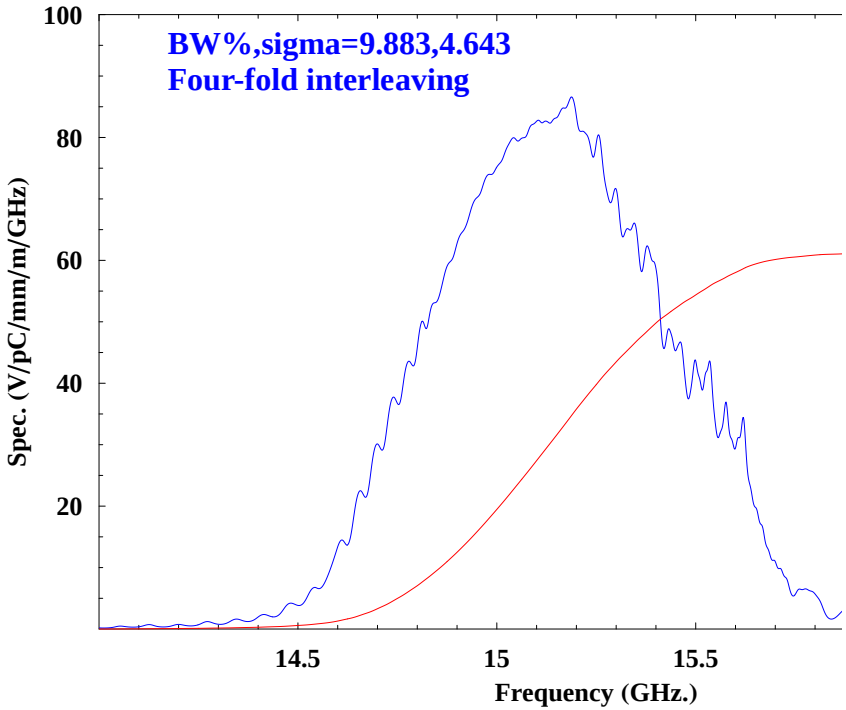


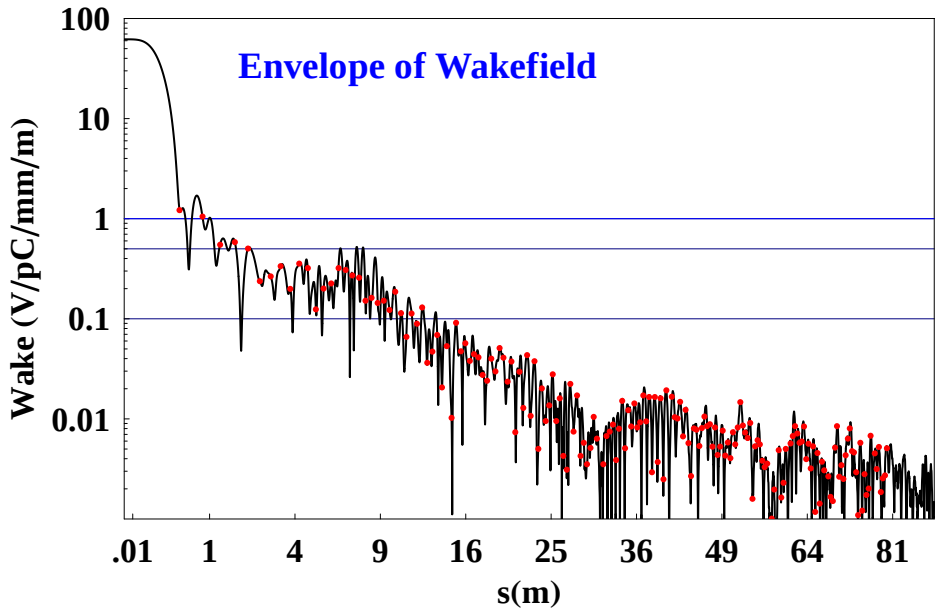


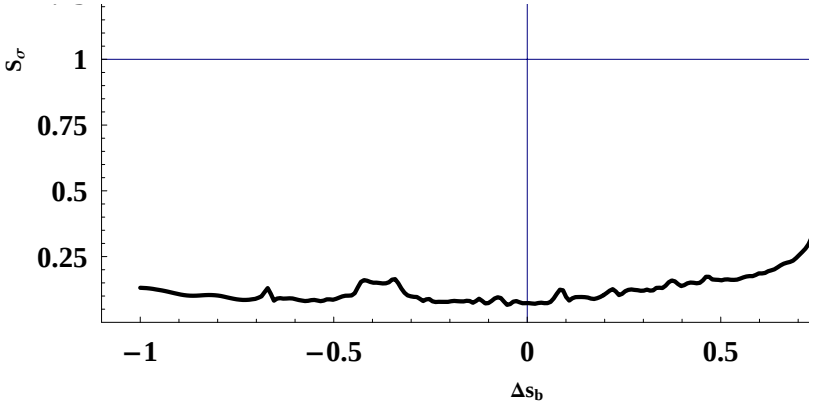

S11 from HOM Coupler for H60VG3
H60VG3S17
Min |S11| of 0.0147 at 15.11 (GHz)
Mean |S11| =0.123648
|S11|
0.3
0.25
0.2
0.15
0.1
0.05
0
14
14.5
15
15.5
Freq (GHz.)

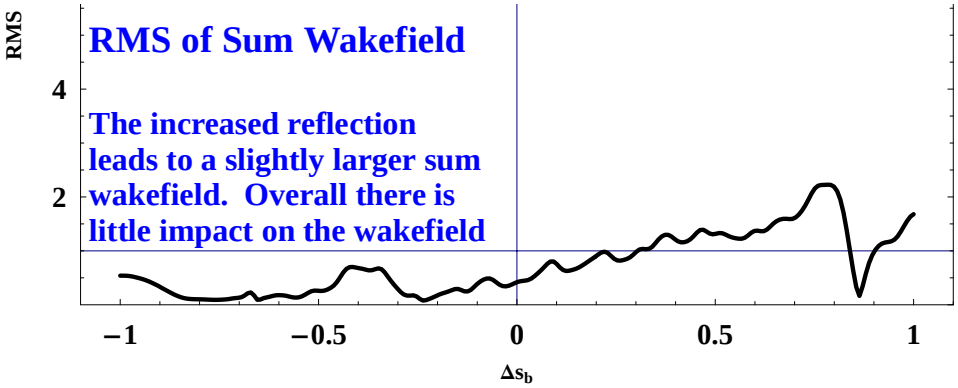

S11 from HOM Coupler for H60VG3
H60VG3S18
(Zenghai)
Min |S11| of 0.0127 at 15.27 (GHz)
Mean |S11| =0.0928747
|S11|
0.25
0.2
0.15
0.1
0.05
0
14
14.5
15
15.5
16
16.5
Freq (GHz.)

Four-Fold Interleaved, HOM Coupler S11 for H60VG3S17

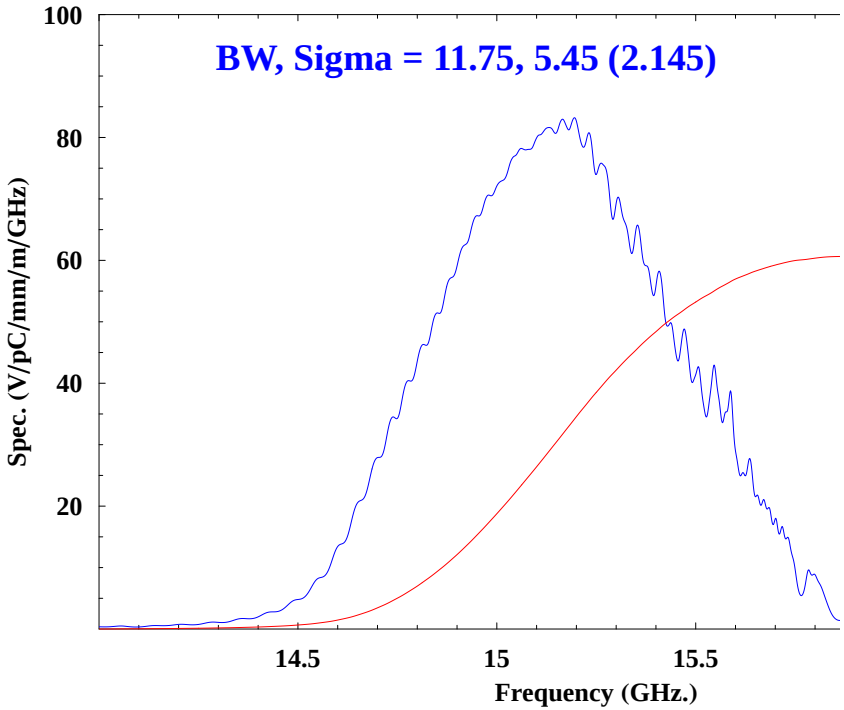


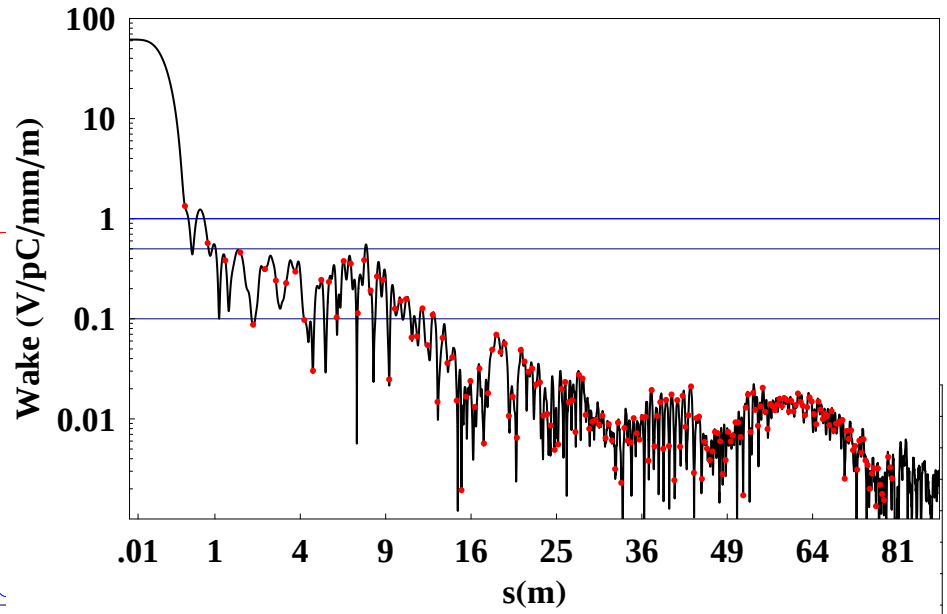


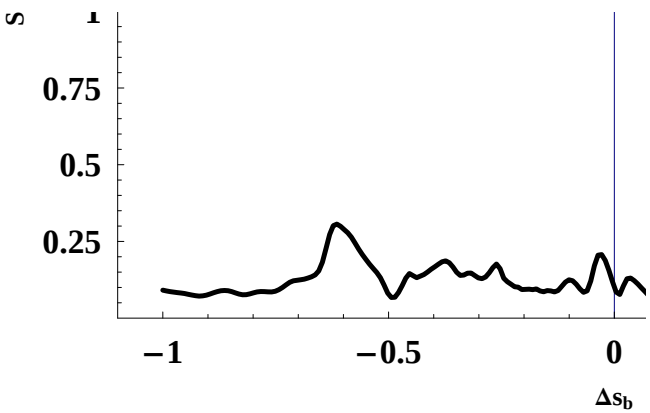


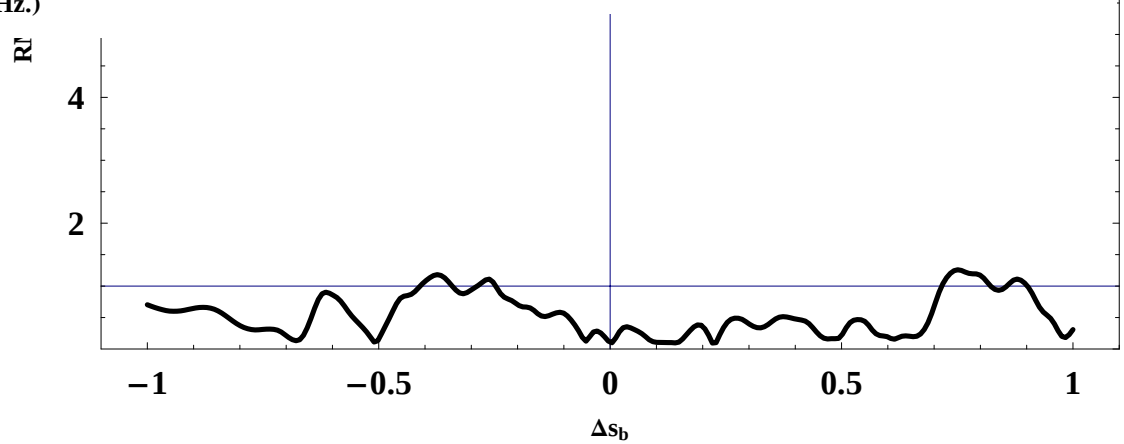


Four-Fold Interleaved, Perfectly Matched HOM Coupler (S11=0)

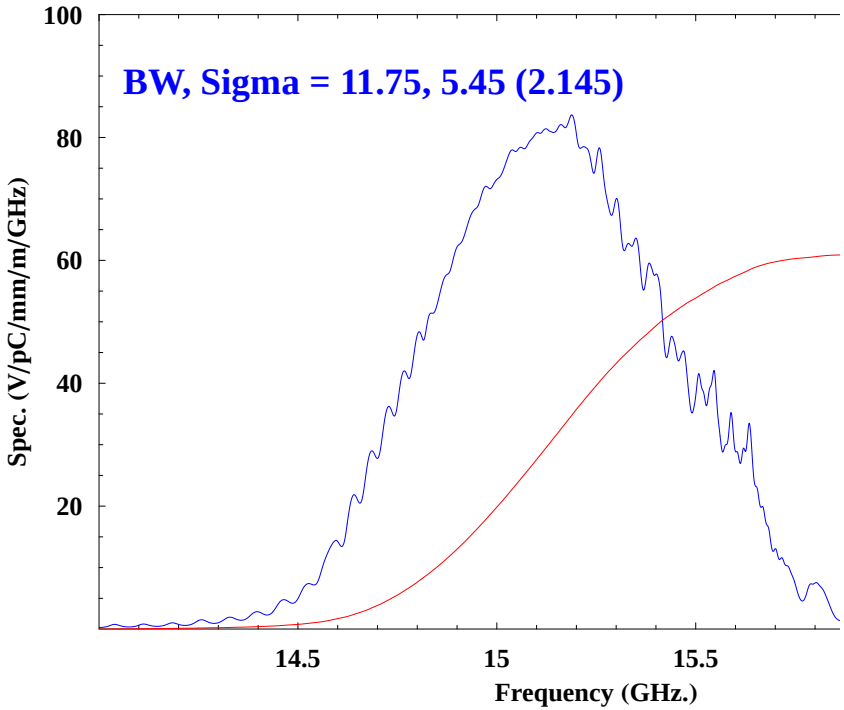


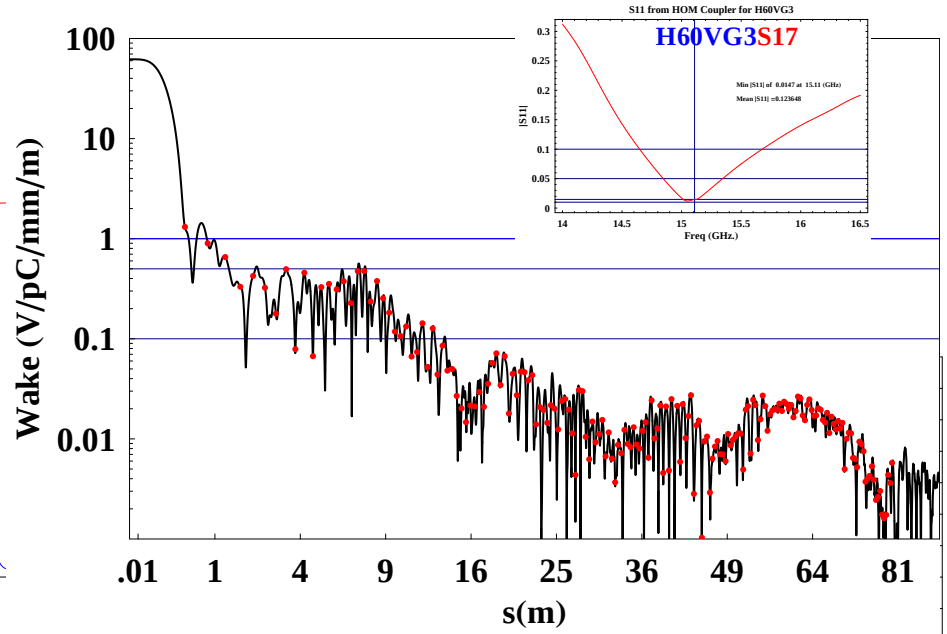


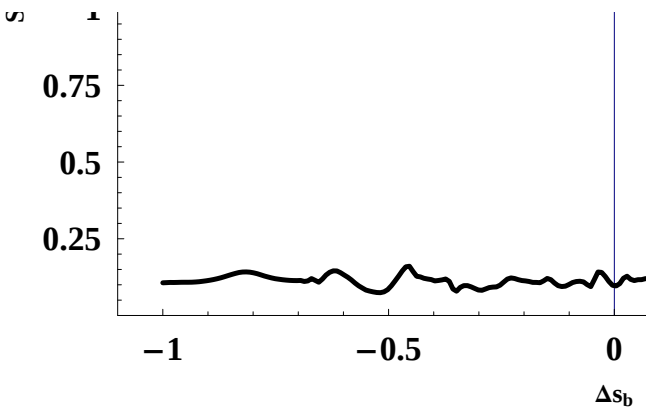


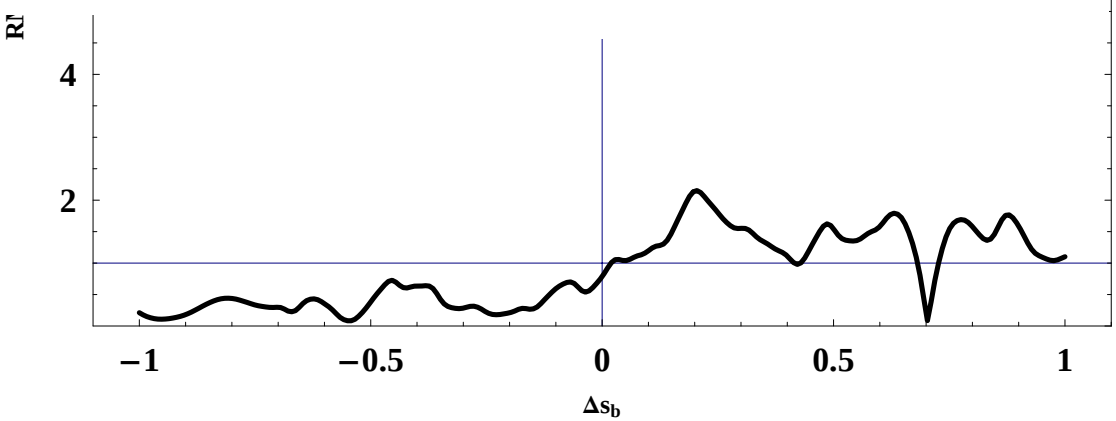


Four-Fold Interleaved, HOM Coupler S11 for H60VG3S17









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 (Rsh fundamental mode reduced for first cells) with little change to power input (Z. Li)**
=> Quite markedly asymmetric dipole kick factor weighted density distribution (Kdn/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).

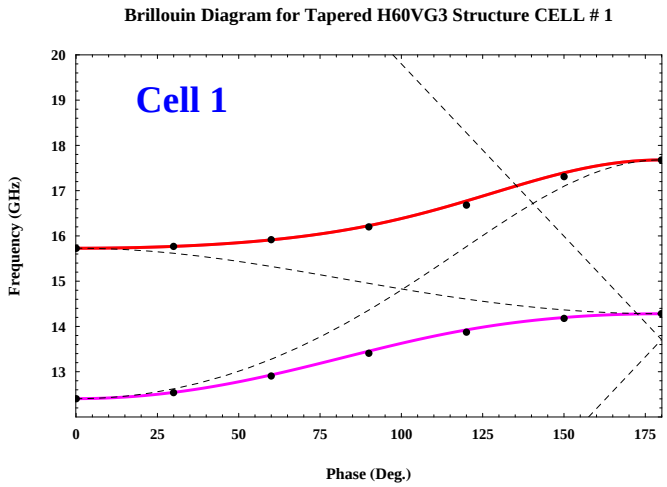
***However, rather small changes to the sigma width width fixes this.**

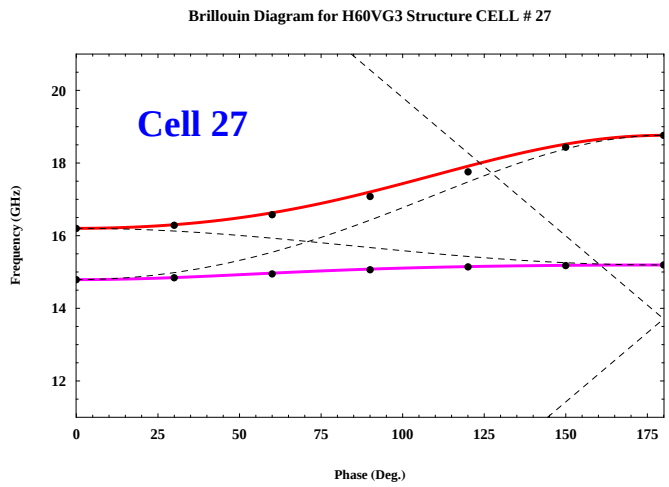
Simulation Based on:

***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**

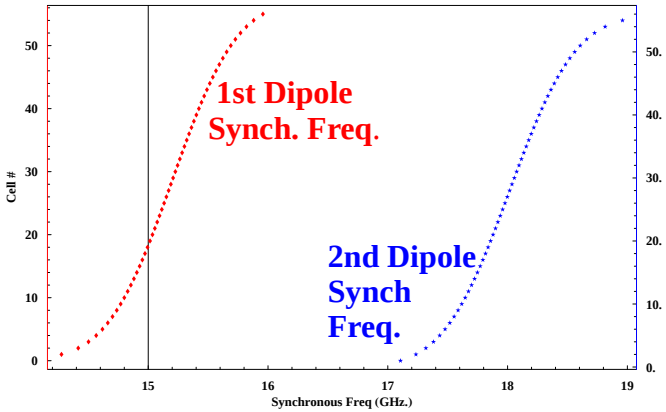
=> Supplement this simulation with the manifold coupling parameters from the previous H60VG3S17 design with manifold coupling included

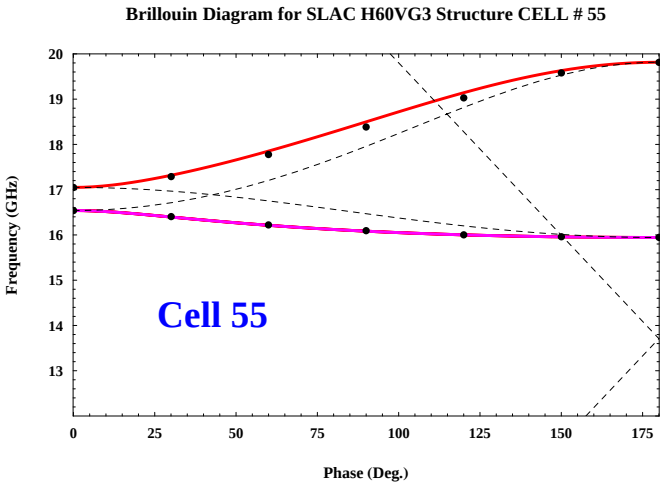




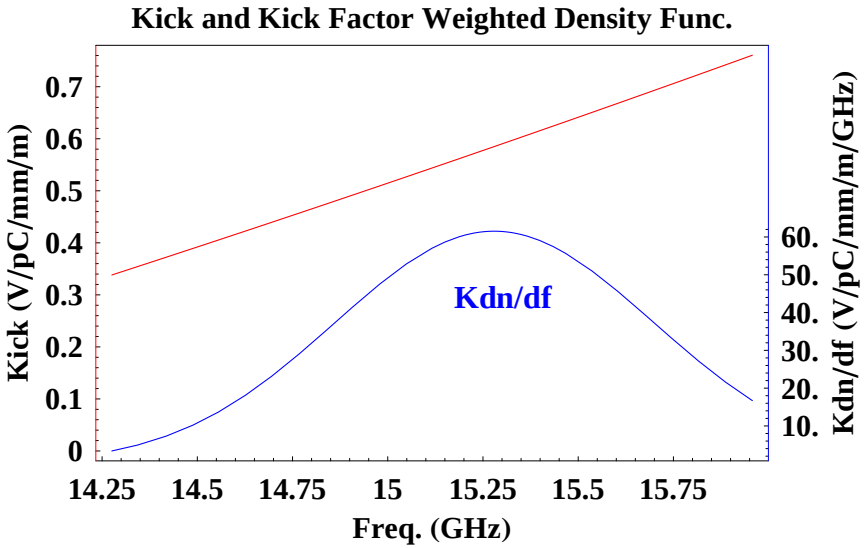
Single H60VG4 Tapered Structure

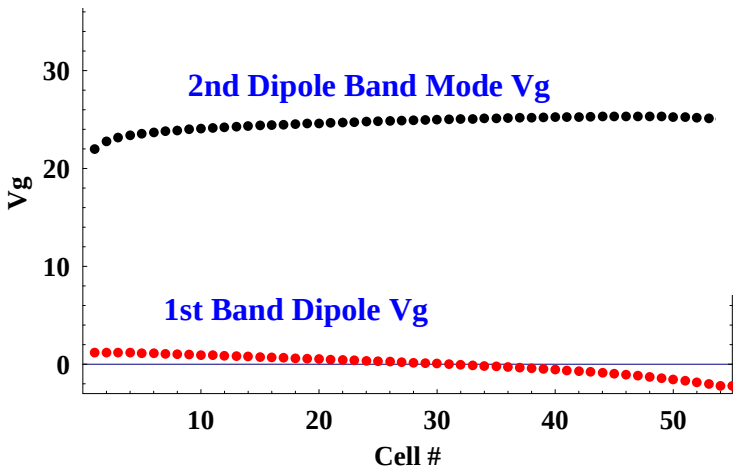
(BW,Sigma = 11%, 4Sigma)

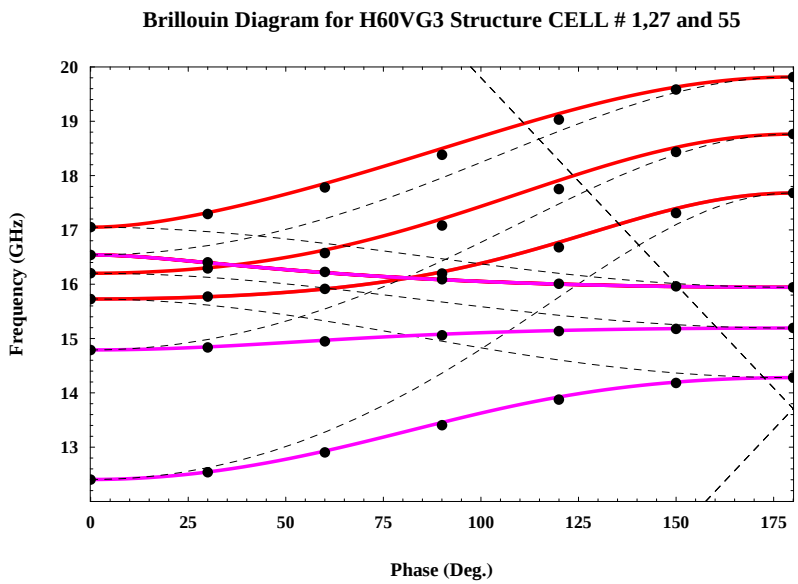




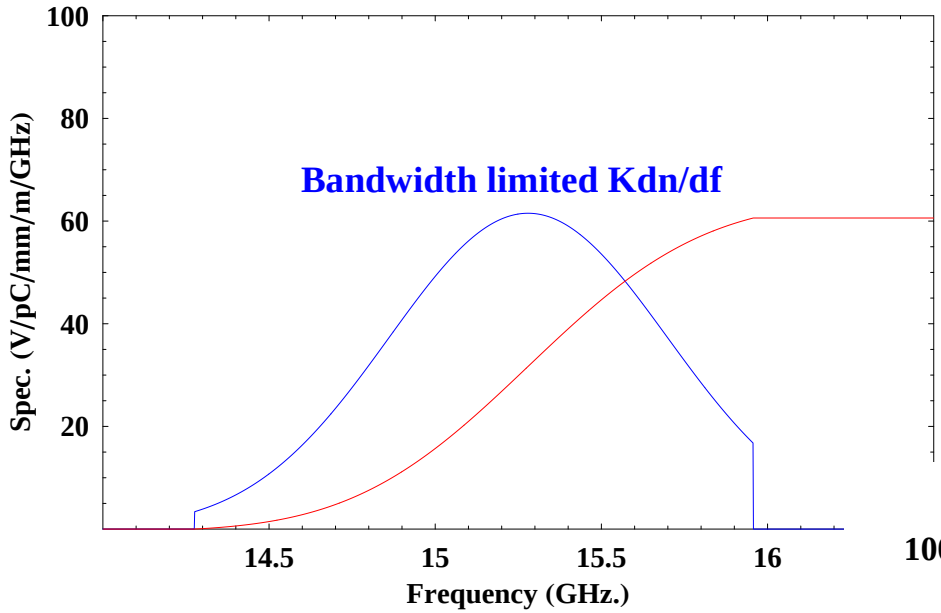
Single H60VG4 Tapered Structure (BW,Sigma = 11%, 4Sigma)



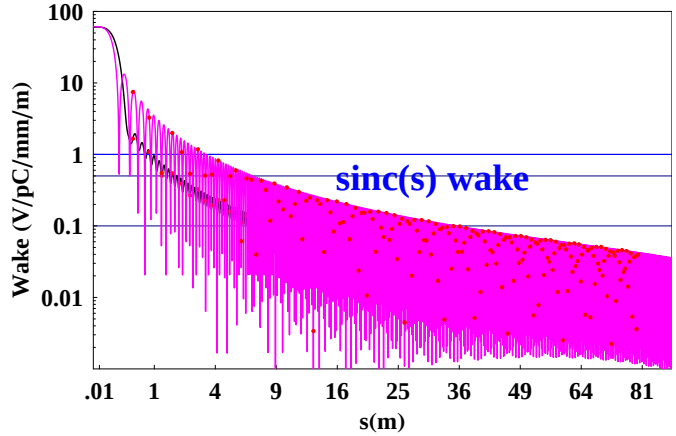


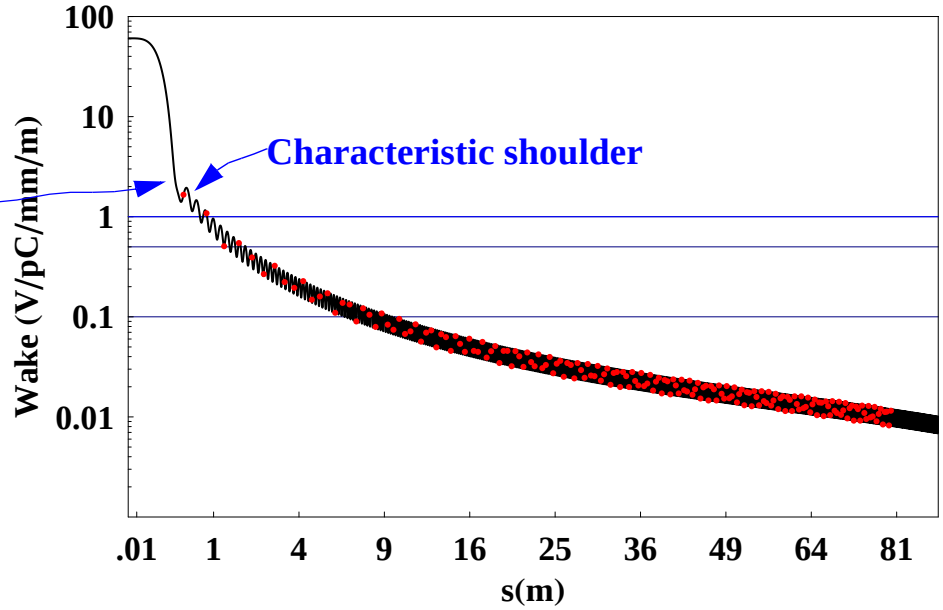


Wakefield via Inverse Fourier Transform of Uncoupled Kick Factor Weighted Density Function

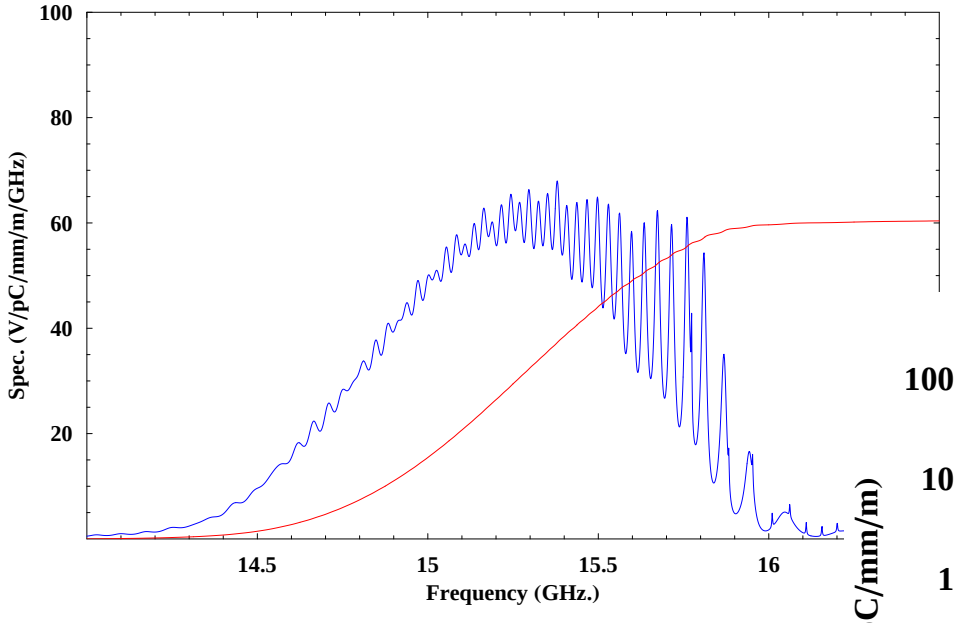


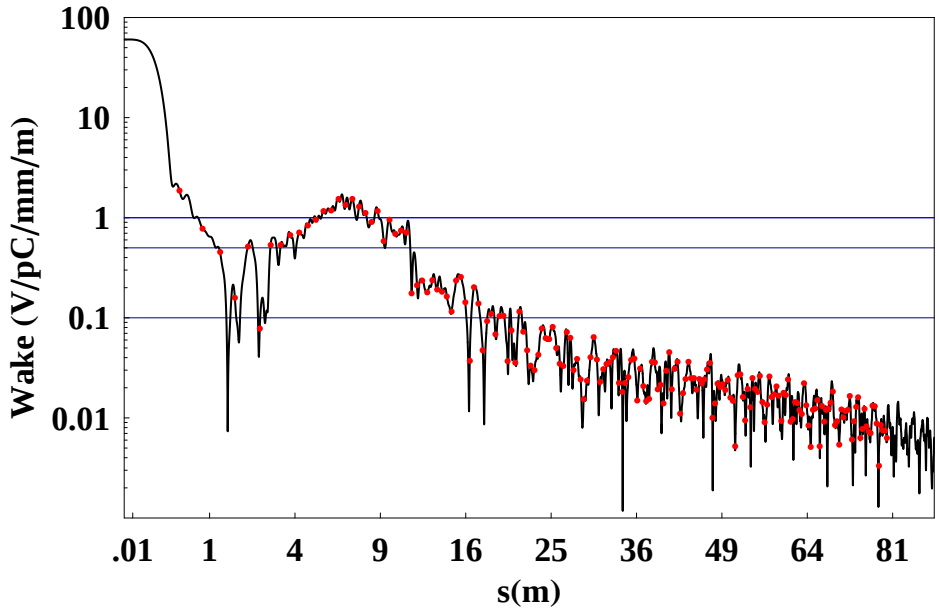
Resulting wakefield is the convolution of the FT of Kdn/df with a sinc (=sin(πx)/(πx)) function.

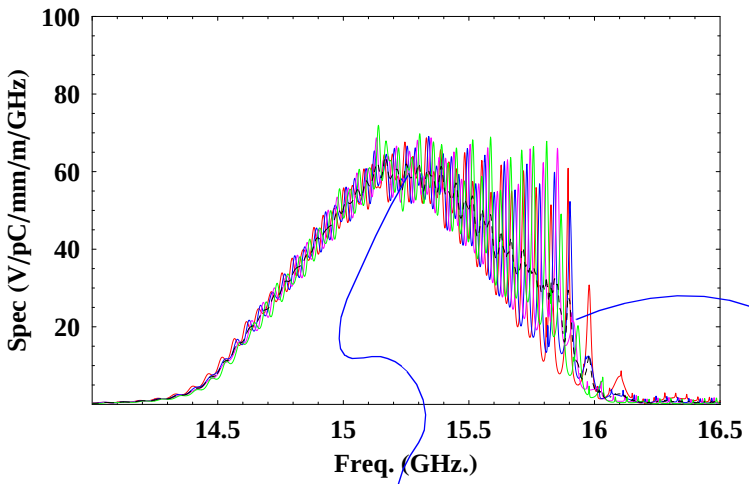


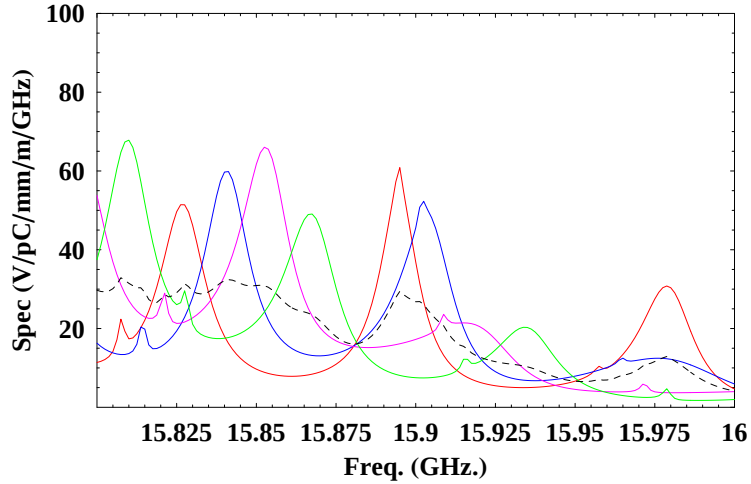


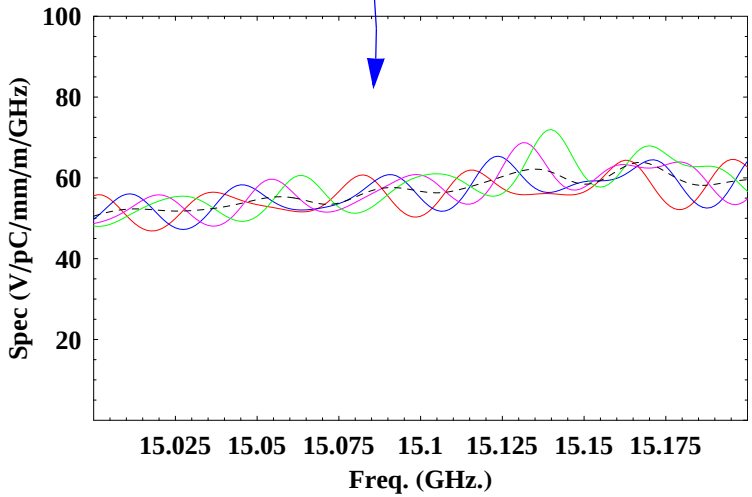
Single H60VG3 Tapered Structure Wakefield (BW,Sigma = 11%, 4Sigma)





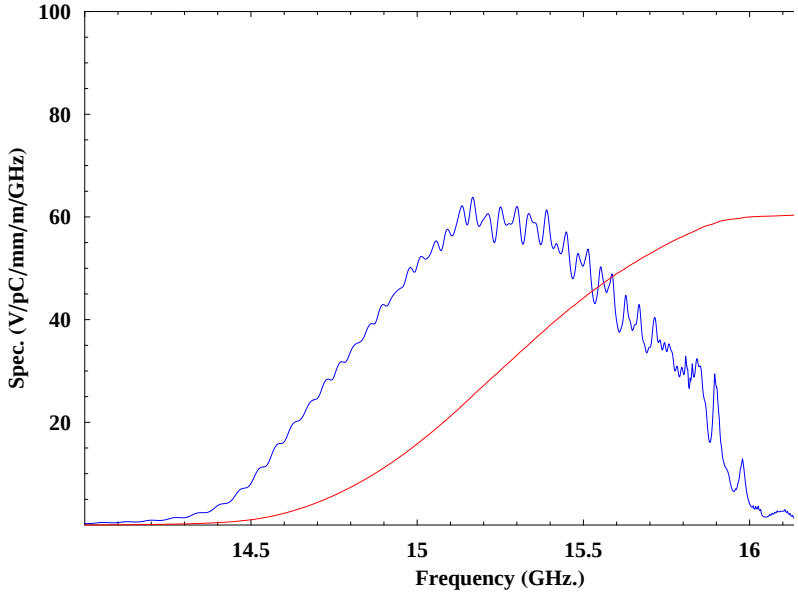


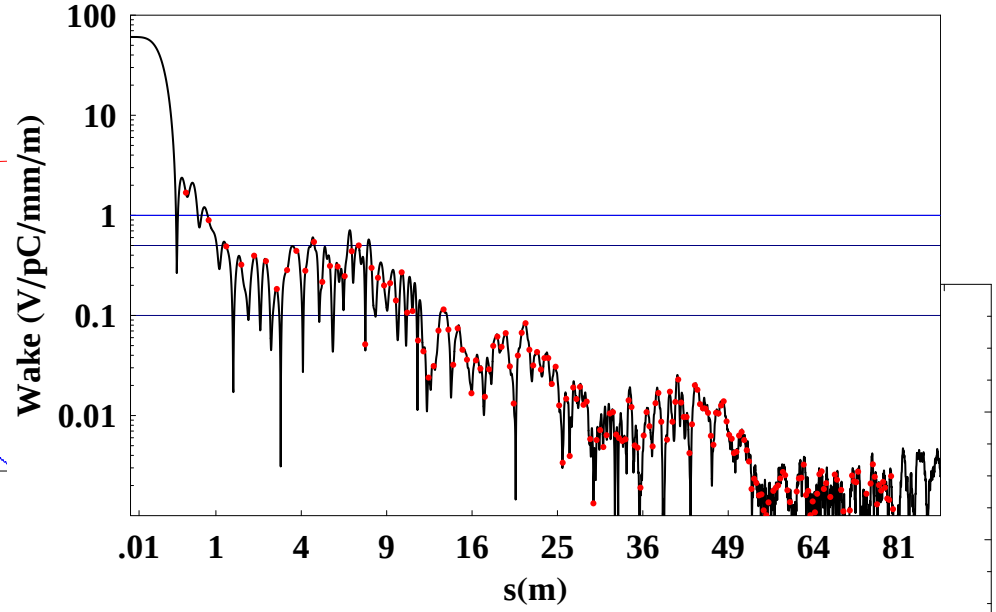


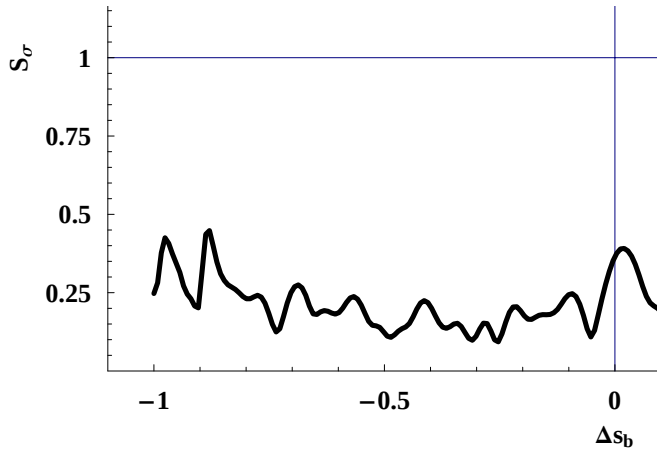


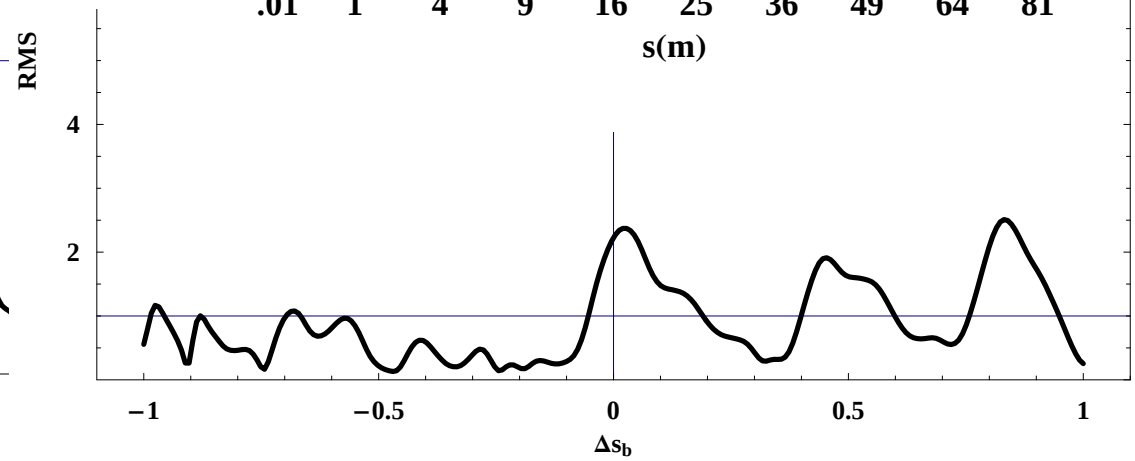
Four-Fold Interleaved H60VG4 Tapered Structure Spectral Function (BW,Sigma = 11%, 4Sigma)

Four-Fold Interleaved H60VG3 Tapered Structure Wakefield (BW,Sigma = 11%, 4Sigma)

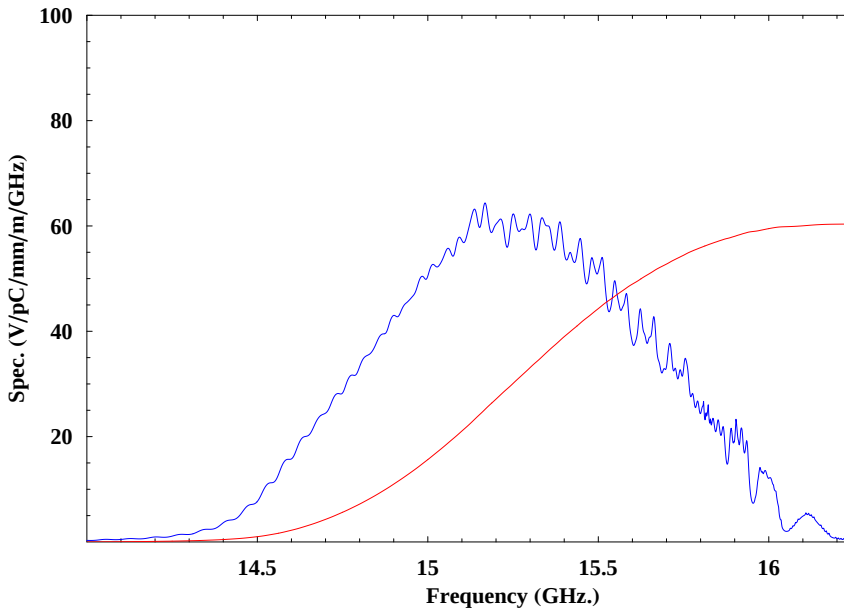


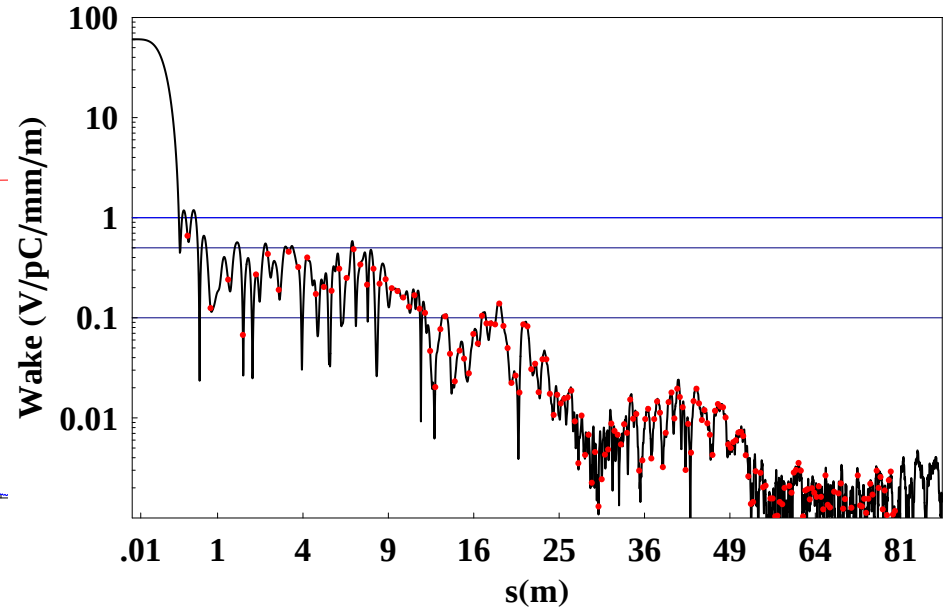


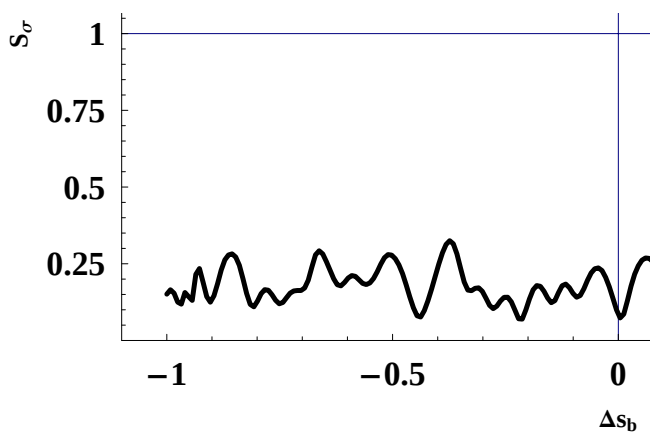


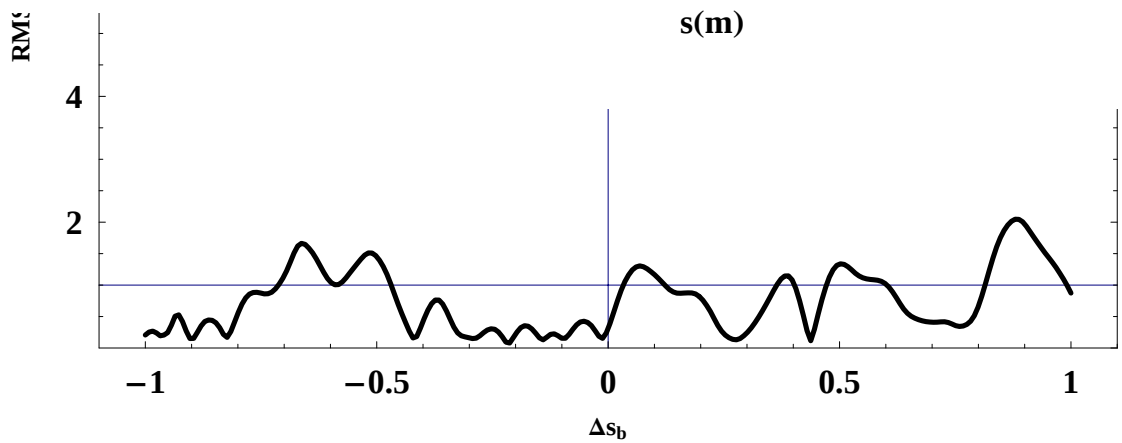


OPTIMIZED Four-Fold Interleaved H60VG3 Tapered Structure Wakefield (BW,Sigma = 11.009%, 4.065Sigma)









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.