Wakefield Suppression & Beam-Based Structure Alignment for the NLC

September 27th, 1999
Outline

- Fundamentals of the Dipole Wakefield and the method of Damping and Detuning the Transverse Wakes
- Modeling the DDS (Damped Detuned Structures): Circuit Theory and the Spectral Function Technique
- 1st Experimental Measurement of Wakefield vs. Theory and Continuing Advanced DDS Development
- Enhanced Shunt Impedance Structures: RDDS
- Investigation of Emittance Dilution, Cumulative BBU, Fundamental Mode Coupler Loading and Tolerances
- New Distributions: Rapid Decay of Wakefields
- Manifold Radiation and Remote Determination of Structure Alignment: Theory and ASSET Experiment on the SLC
Motivation for DDS

- The DDS (Damped Detuned Structure) alleviates the problem of *transverse wakes*.

- Transverse wakes for high freq. multi-bunch linac structures degrade the beam quality:
  1. Increases beam emittance
  2. Gives rise to a transverse instability:
     BBU (Beam Break Up)

- The *short range wake* is reduced by *detuning the cell freqs.*
Manifolds are Multi-Functional

- Long range wake is reduced by coupling out into 4 collinear manifolds.

- The radiation coupled out provides information regarding the alignment of the cells.

- Additionally the manifolds provide pumping
Fundamental Features of (R)DDS

- In our multi-bunch design we envisage the acceleration of 95 bunches with $1.1 \times 10^{10}$ particles per bunch, spaced from their neighbours by 84 cm, with the option to accelerate 190 bunches, spaced at 42 cm and $0.9 \times 10^{10}$ (higher luminosity).

- It is required to suppress interbunch transverse wakes and the modes which constitute the wake are forced to decohere by detuning the dipole freq. such that all major cell dimensions follow an Erf profile.

- Wake reappears after 10m or so. Moderate damping (Q-1000) provided by 4 manifolds attenuate the wake further.
Manifold Features of (R)DDS

- The manifold is single mode: $TE_{10}$, and cut off to the accelerating mode (little impact on the shunt impedance of the fundamental mode)
- Each manifold is tapered to maintain good coupling
- RDDS has circular manifolds (good pumping).
- Four cells either end are not coupled to the manifold
- Detuned structure modes are localised standing waves with a spectrum of phase velocities.
- Both beam coupling and manifold coupling as functions of frequency are localised around particular cells.
Circuit Model for DDS:
The manifold, modelled by transmission line sections periodically shunted with L-C circuits, couples to the accelerator via TE modes. The beam couples to the structure via TM modes.

Roger M. Jones, C. Adolphsen, N. M. Kroß, R.H. Miller, J. Wang, G. Stupakov & T. Raubenheimer (1999)
**Coupling Between Manifold-Cell**

\[ V_n = -j(I_n/C_n + i_n \kappa_n / \sqrt{C_n c_n})/\omega \]
\[ v_n = -j(i_n/c_n + I_n \kappa_n / \sqrt{C_n c_n})/\omega \]

**Network Eqns In Matrix Form**

RA = Ga

(\(H-1/f^2\))a + H_2 \hat{a} = GA = GR^{-1}G

(\(\hat{H}-1/f^2\))\hat{a} + H_1 \hat{a} = B/f^2

**Matrix Elements**

\[ R_{nn} = -2 \cos \phi_n, \quad R_{n\pm 1} = 1 \]

\[ \cos \phi_n = \cos \phi_{0n} - \alpha_n (\pi L / c)^2 F_n^2 / (F_n^2 - f^2) \sin \phi_{0n} \]

\[ \phi_{0n} = (2 \pi L / c) \sqrt{f^2 - F_{0n}^2} \]

\[ H_{nn} = 1/f_n^2 + \Gamma_n^2 / \alpha_n / (F_n^2 - f^2) \]

\[ H_{n\pm 1} = \eta_{n\pm 1/2} / (2f_n \hat{f}_{n\pm 1}) \]

\[ H_{m, n\pm 1} = \pm \eta_{m, n\pm 1/2} / (2f_n \hat{f}_{m, n\pm 1}) \]

\[ \hat{H}_{mn} = 1/f_m^2, \quad \hat{H}_{m, n\pm 1} = -\hat{\eta}_{n\pm 1/2} / (2f_n \hat{f}_{m, n\pm 1}) \]

\[ G_{nn} = \Gamma_n (\pi L / c) F_n^2 / (F_n^2 - f^2) \sin \phi_{0n} \]
Wakefield of the Damped Detuned Structure vs the Detuned Structure

Wake Function (V/pC/mm/m)

DT

DDS

s (m)

RMJ, NMK & RHMI
```
#VOLUME

COORDINATES/M
FULL RANGE / WINDOW
< [ .0000, .0217271]
[ .0000, .0217271]
[ .0000, .0217271]
[ .0000, .0217271]
[ .0000, .0087478]
[ .0000, .0087478]

SYMBOL: CYLINDER_7
TIME: 0.00000E+00

MATERIALS:
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3D PLOT OF THE MATERIAL DISTRIBUTION IN THE MESH
Manifold Loaded Q

![Graph showing quality factor versus frequency. The graph has two lines: one labeled "Perturbation Solution" and another labeled "Exact" Iterative Solution. The x-axis represents frequency (GHz) and the y-axis represents quality factor. The graph shows oscillations in quality factor with frequency.](image-url)


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Frequency Detuning Induced By Manifold Coupling

![Graph showing frequency shift vs. mode frequency with perturbation and exact iterative solutions.]

Envelope of Wakefield for DDS 1: Calculation (incl. VSWR of HOM Couplers and Decoupled Cells) vs. ASSET Experimental Results
Fig 1: Shown uppermost is twice the kick factor weighted density function \(2\frac{df}{df}\) for the DT (damped deflected) structure. The succeeding curves are of the spectral function for \(a = 1\), \(a = 2\) and \(a = 3\). The significant improvement in the matching to the HOM loads for DDS 2 reduces the amplitude of the oscillations of the spectral function. DDS 3 uses similar HOM couplers and loads as DDS 2 but the cells have been redistributed using a recently developed mapping function method. The integral is dashed.

Fig 2: Shown uppermost is the wake function for the DT structure. The succeeding curves are of the wake function for DDS 1 (HOM couplers included and ASSET data points), DDS 2 and DDS 3. The dots in DDS 2 and DDS 3 indicate the position of the 82 bunches placed 2.8 m apart. The long range wake for DDS 1 is improved over the DT structure by an order of magnitude or more, the medium and long range wake for DDS 2 by a factor.
Rounded Damped-Detuned X-band Accelerator Structures (RDDS)

- Need to damp or decohere long-range dipole modes to prevent the Beam Break-Up instability
- Each X-band structure has 206 cells, each with a different dipole mode frequency
- Manifolds provide signal for beam-based alignment
- Latest structure design: RDDS has cells with +12% shunt impedance
The disks are made of OFHC copper. The design value of its outer diameter is 61.000mm and thickness 8.74377 mm (as defined at 20 deg C.

The central portions of the disks are concaved in a way to form resonant cavities when neighboring disks are bonded in the final assembly
Figure 2: Uppermost is the spectral function for all cells coupled (where the dots indicate the smoothed undamped spectral function). The subsequent curves are computed for 1 cell decoupled, followed by three, and four cells (lowermost) decoupled from both the upstream and downstream end of the RDDS.

Figure 3: Uppermost is shown a comparison of the RDDS versus the RDT (Rounded Detuned, see main text) wake function for all cells coupled. The subsequent curves are computed for 1 cell decoupled, three, and finally 4 cells (lowermost) decoupled from both the upstream and downstream end of the RDDS.
Figure 1: The spectral function and its integral for RDDS 1 for an initial design. The uppermost is the spectral function for a structure with perfectly matched HOM (Higher Order Mode) couplers and all cells coupled. The second is for series of three interleaved structures in which the synchronous frequency of each structure differs from its neighbor by 3.8 MHz. The third curve is for the case of three interleaved structures with six cells decoupled and a HOM load with a VSWR of 1.05. The fourth is for the most up-to-date design, RDDS 1 with circular contours.

Figure 2: The wake function and its integral for RDDS 1. All wakes are the counterparts of the spectral functions given in fig. 1. The dots are located at the bunch locations. One V/pC/mm/m is indicated as beam emittance considerations dictate that the transverse wake function, at the bunch locations, may not be larger than this value. The lowermost curve is for RDDS1 with circular features to the irises and cavities. The load has is assumed to have a VSWR = 1.
RDDS1 HOM Ref Co: Four Cells Decoupled, 11.2% BW, 4.75 Sigma

Envelope of Wake for RD51 Incl. Coupler Loading:
Four Cells Decoupled, 11.2% and 4.75 Sigma
Figure 1: The above shows the result of tracking through 10 km of accelerator a beam with an initial bunch offset of 1 μm or approximately one quarter of σ₀ (= 3.9 μm) in the vertical plane and 1 μm in the horizontal plane (σ₀ = 35.9 μm). Uppermost is shown the normalised vertical and horizontal emittance in units of μrad.m (and inset is indicated the emittance growth as a percentage of the initial emittance at injection to the X-band linacs, for both the single bunch and the multi-bunch cases). In phase space we normalise, Y, the vertical displacement, with respect to \( (\beta_y \varepsilon_y)^{1/2} \) and \( Y^* \) with respect to \( (\varepsilon_y / \beta_y)^{1/2} \).

Figure 2: The simulation is similar to that of Fig. 4 except that all of the structures have one cell decoupled and the HOM couplers have realistic terminations, i.e. frequency dependent reflection coefficients corresponding to the transition between circular and rectangular manifold have been included. In both cases, the short range (transverse and longitudinal) wake has been included in the simulations, together with the long range transverse wakefield. BNS damping of the short range wakefield has been included in the simulations by including a variation in the phase of the R.F. over the linac.
Tolerance allowable for 10% Emittance Dilution: Tracking Code Results vs Analytical Model
Thrice convolved II(x) Function (=II*II*II*II)

Envelope of Wake for RDDS.
All Cells Coupled Thrice Convolved II (Sinc^4), 9.524% BW

Figure 5.21: Electric field pattern (from cell 21 to 28) of a monopole mode at 11.422 GHz.

good at large distances. At short distances, the cavity-diffraction model predicts a sharper rise than the periodic-optical model does, which is due to the slower decay ($\omega^{-1/2}$) of the diffraction model at high frequencies than that of the optical resonator model ($\omega^{-3/2}$).

The longitudinal wakefield per unit length for a Gaussian bunch with bunch length $\sigma_z = 100 \, \mu m$ using formula 5.4 is shown in Fig. 5.22(b). The loss parameter of the NLC accelerating structure is found to be 1149.2 V/pC.

Figure 5.22: For NLC: (a) Longitudinal wakefield (Green’s function). (b) Longitudinal wakefield per unit length for a Gaussian bunch with bunch length $\sigma_z = 100 \, \mu m$.
Manifold Radiation and Structure Alignment

September 27th, 1999
Outline

- Method employed to model complete DDS: circuit theory
- Calculation of power spectrum of radiation radiated from manifold: comparison with experiment
- Relation of power spectrum to cell location: Linear relation between cell location and minimised power at a given freq.
- Mode location and frequency mapping of cell misalignments
Power Transfer To Manifold

\[
\begin{align*}
\text{Manifold MRI} & \quad \text{MRI manifold} \\
\sin \theta & = \frac{\text{coupled B}}{3T} \\
\cos \theta & = \frac{\text{coupled A}}{3T} \\
\sin \phi & = \frac{\text{coupled A}}{3T} \\
\cos \phi & = \frac{\text{coupled B}}{3T}
\end{align*}
\]
Power flow in manifold

\[ P = \frac{4 \Phi^2 D \delta x \delta T}{8 \pi} \frac{E \sin\phi \Delta A}{(1+R)^2} \] \text{ (W/GHz)}

\( Q \): Beam charge \((1.5\text{nc})\)

\( L \): Structure length \((1.8\text{m})\)

\( \delta x \): Transverse offset \((1.3\text{mm})\)

\( \Delta T \): Pulse repetition rate

\( \Delta A \): manifold amplitude

\( E \): Frequency component

\( 1.25 \rightarrow 31.25 \) \text{ (W/GHz)}

(Including ~50W losses in manifold)
**FIGURE 2.** Computed and measured downstream power spectra compared for a uniformly displaced beam. Relative amplitudes (comparable absolute values are not known) are adjusted to facilitate comparison.

**FIGURE 3.** Computed and measured downstream power spectra for a uniformly displaced beam compared over a limited frequency band. A 1 MHz spectrum analyzer bandwidth setting facilitates comparison of the oscillatory structure.
Mechanical Alignment Data Measured Prior To ASSET Exp.
Coupled & Uncoupled Synchronous Frequency vs Cell Number
Frequency-to-Cell Mapping Function for the Structure Straightness of DDS 3 (ASSET '98)

Roger M. Jones, C. Adolphsen, N. M. Kroll, R.H. Miller, J. Wang, G. Stupakov & T. Raubenheimer(1-99)
CMM Data Set #2 and ASSET Power Minimisation Position Data Remapped From Freq. To Cell Number
A CMM (Coordinate Measuring Machine) Scan of DDS 3 vs. Power Minimisation Data of using Frequency-to-Cell Mapping for the Structure Straightness of DDS 3 (ASSET ‘98)

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Summary

- Circuit Model/Spectral Function Method provides a useful design tool
- RDDS Rapidly Damps the Transverse Wakefield
- Good agreement achieved between Exp. and Spectral Function Theory for DDS1.
- First RDDS will be measured in ASSET in the SLC in Feb/March 2000
- BBU and Emittance Dilution results from one or more modes that drive the instability.
- Decoupling Cells Degrades the Damping of the RDDS
- Loading the final cell with a Q of approx 30 substantially improves the Spectral Function, as does a recent Redistributed Non-Gaussian Design
- Manifold Radiation provides a convenient Beam Position Monitor and details as to Structure Alignment.
- Coupled Synchronous Frequencies provide direct info. regarding Structure Misalignment.