Preliminary Results on Long Range Wakefield Study in Cold LC

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• TESLA main linac layout
• Dipole wakefields
• RMS of sum wake
• Bunch dynamics simulations
• Random detuning and interleaving
• Dipole modes in TTF cavities
Introduction

• Study various options for minimal long range wakefield effects in TESLA
  - cavity detuning
    • random detuning
    • interleaving: purposely detuning sets of cavities
  - tolerance on misalignment of cavities

• Tolerances
  - systematic errors in frequency
  - beam dynamics simulations
  - study of RMS and standard deviation of sum wakefield
**TESLA Linac**

- **Based on TESLA500 design**
  - 12 1m-long cavities (9 cells/cavity) per cryo-module
  - ~10,000 cavities per linac
  - cavity misalignment 500 μm
  - phase advance per FODO cell: 60 deg
  - 1\(^{\text{st}}\) section: 4 modules / FODO
  - 2\(^{\text{nd}}\) section: 6 modules / FODO

- **Accelerating mode**
  - gradient: **25 MV/m**
  - \(f_0 = 1.3\) GHz,
  - \(Q = 3.e6\), \(k_{\text{loss}} = 2.\) V/pC

- **Bunch train**
  - 2820 bunches, but use only 5-600 (steady state reached)
  - 3.2 nC, 337 ns spacing
  - injection energy 5 GeV
HOMs in TTF Modules

- Consider 14 dipole modes from 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} dipole passbands, with highest impedance (as measured at TTF1)
Dipole Wakefield

Wake [V/pC/mm/m] vs. Time [us]

- Wake
- Wake envelope
- Wake seen by bunches

Sum wake (for different bunch spacing)

- Best case
- Worst case

$tvar_{i_1} = 0\%$
$tvar_{i_2} = -0.013\%$

dir$_{i_1} = "dtScan_noRmsDetun\C1-F0.0001-t0"

dir$_{i_2} = "dtScan_noRmsDetun\C1-F0.0001-t-13600"
RMS and Standard Deviation of Sum Wake

• For NLC
  ➢ relatively standard tools to measure WF effects

  ➢ 1. the wakefield at the first trailing bunch
  ➢ 2. RMS of sum wake → indicator whether BBU will occur
  ➢ 3. StDev of sum wake → indicator of alignment tolerances
Example for one NLC Structure
Beam Dynamics Simulations with MAFIA-L

- Assumptions
  - No beam loading
  - No detuning
  - No short range wakes
  - No misalignment of cavities
  - 4 µm injection offset (σ ~ 18µm)
• Compare tracking with
  ➢ 510 bunches (then normalize emittance to full train)
  ➢ 2820 bunches

• Simulation
  ➢ no cavity misalignment
  ➢ 4 µm injection offset

• ⇒ it is sufficient to track 5-600 bunches down the long linac then normalize to full train
Emittance Scan

- Simulate systematic error in cavity detuning by varying bunch spacing
  - $t_b = t_{b0} (1 + \delta t)$
  - no misalignment of cavities
  - 4 µm injection offset
RMS of Sum Wake

- no misalignment of cavities
- 4 μm injection offset

![Graph showing the RMS of sum wake and emittance growth.](image)
Cavity Misalignment

- Misalign cavities: 500 µm rms
- Inject bunch train on axis

- Even for design bunch spacing: $\Delta \varepsilon \sim 25\%$
- But detuning of cavities has positive effect
Emittance Growth

\( dt = 0 \)

**no cav. misal.**

\[
\text{dir}(i_{0}) = \text{"dirScan_noRmsDetun/C1-F0.0001-t0"}
\]

**max emittance growth**

**no cav. misal.**

\[
\text{dir}(i_{0}) = \text{"dirScan_noRmsDetun/C1-F0.0001-t-13600"}
\]

**with cav. misal.**

\[
\text{dir}(i_{0}) = \text{"dirScan_noRmsDetun/C1-F0.0001-t0"}
\]

**with cav. misal.**

\[
\text{dir}(i_{0}) = \text{"dirScan_noRmsDetun/C1-F0.0001-t-13600"}
\]
Wake Field and Sum Wake

\textbf{dt = 0}

\begin{align*}
\text{Wake} &\quad [V/m] \\
\text{Wake envelope} &\quad [V/m] \\
\text{Wake seen by bunches} &\quad [V/m]
\end{align*}

\begin{align*}
\text{RMS id} &= 0.04 \cdot \frac{V}{\text{pC/mm}} \\
\text{StDev id} &= 4.176 \cdot 10^{-3} \cdot \frac{V}{\text{pC/mm}}
\end{align*}

\text{Sum wake}

\begin{align*}
\text{tvar}_{i0} &= 0\% \\
\text{emall}_{i0} &= 0.307123 \times 0\% \\
\text{RMS}_{\text{dir}} &= 0.472 \cdot \frac{V}{\text{pC/mm}} \\
\text{StDev}_{\text{dir}} &= 0.072 \cdot \frac{V}{\text{pC/mm}}
\end{align*}

\begin{align*}
\text{tvar}_{i1} &= -0.0136\% \\
\text{emall}_{i1} &= 7.630935 \times 0.0\% \\
\text{tvar}_{i2} &= 0.0136\% \\
\text{emall}_{i2} &= 0.0\%
\end{align*}

\begin{align*}
\text{max emit growth}
\end{align*}
Detuning

- **Random detuning**
  - from fabrication tolerances
  - TDR: 0.1%

- **Interleaving**
  - n-fold interleaving =
    - ncl = 1 .. 15
  - df\(_{\text{shift}}\) = maximum detuning range
    - df\(_{\text{shift}}\) = 0.1 .. 1%
    - In first 3 TTF modules
      - 0.5 .. 0.6% for 1\(^{\text{st}}\) band
      - 0.05 .. 0.2% for 2\(^{\text{nd}}\) band
  - all modes shift with same percentage df (i=0..n-1)

\[
f_{i,m} = f_{0,m} \cdot \left(1 + i \frac{df_{\text{shift}}}{n-1}\right)
\]
Emittance with Detuning and Interleaving

- Design bunch spacing

<table>
<thead>
<tr>
<th>Misalig. (500 (\mu)m rms)</th>
<th>Rand detun.</th>
<th>Interl. (max)</th>
<th>Emit. growth [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>- (#)</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>x</td>
<td>-</td>
<td>5 / 1%</td>
<td>24</td>
</tr>
<tr>
<td>- (#)</td>
<td>-</td>
<td>5 / 1%</td>
<td>0.006</td>
</tr>
<tr>
<td>x</td>
<td>10 / 1%</td>
<td></td>
<td>4.7</td>
</tr>
<tr>
<td>x</td>
<td>0.1%</td>
<td>-</td>
<td>3.7</td>
</tr>
<tr>
<td>X(1)</td>
<td>0.01%</td>
<td>-</td>
<td>2.7</td>
</tr>
<tr>
<td>X(2)</td>
<td>0.01%</td>
<td>2 / 0.1%</td>
<td>3.7</td>
</tr>
<tr>
<td>X(3)</td>
<td>0.01%</td>
<td>5 / 0.1%</td>
<td>4.3</td>
</tr>
<tr>
<td>X(4)</td>
<td>0.01%</td>
<td>10 / 0.1%</td>
<td>3.3</td>
</tr>
<tr>
<td>X(5)</td>
<td>0.01%</td>
<td>15 / 0.1%</td>
<td>3.3</td>
</tr>
</tbody>
</table>

# - injection offset 4 \(\mu\)m

X – 500 \(\mu\)m random misalignments (no injection offset)
Geometrical Spread in TTF1 Cavities

- 24 cavities
- St. dev. of cavity length: 6.3 mm → 0.6%
- St. dev. of frequency of first monopole mode 16 MHz → 0.7%
Frequency Errors in TTF1 Cavities

The graph shows the frequency errors in TTF1 cavities as a function of frequency. The y-axis represents the standard deviation in percentage, while the x-axis represents the frequency in MHz. Different modes (TE111, TM110, TM011) are indicated on the graph with distinct markers. The TTF1 cavity is marked by a specific pattern.
Correlation between Frequency and Length Errors (TTF1)

Correlation between Frequency and Length Errors (TTF1)

-30 -20 -10 0 10 20 30

Error in cavity length [mm]

-30 -20 -10 0 10 20 30

Error in frequency [MHz]

TE111 max st dev (0.60%)
TE111 min st dev (0.25%)
TM110 max st dev (0.60%)
TM110 min st dev (0.05%)
TM011 max st dev (0.69%)
TM011 min st dev (0.58%)
Correlation between Frequency and Length Errors (TTF1)

-2.5  -2   -1.5  -1   -0.5  0    0.5  1    1.5
-10 -5  0    5   10  15

Error in cavity length [mm]

Error in frequency [MHz]

TE111 max st dev (0.60%)
TE111 min st dev (0.25%)
TM110 max st dev (0.60%)
TM110 min st dev (0.05%)
TM011 max st dev (0.69%)
TM011 min st dev (0.58%)
Length of TTF Cavities

• Cavity length:
  - average: +4.16 mm
  - st. dev.: 5.74 mm (0.45%)
# Length of TTF Cavities by Series

<table>
<thead>
<tr>
<th>Series</th>
<th># cav</th>
<th>Ave [mm]</th>
<th>Ave_diff [mm]</th>
<th>Stdev [mm]</th>
<th>Stdev [%]</th>
<th>fabricated between</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>14</td>
<td>1282.72</td>
<td>6.52</td>
<td>4.82</td>
<td>0.38</td>
<td>07-Mar-95 - 19-Jan-04</td>
</tr>
<tr>
<td>D</td>
<td>12</td>
<td>1279.37</td>
<td>3.17</td>
<td>3.93</td>
<td>0.31</td>
<td>24-Aug-95 - 19-Sep-03</td>
</tr>
<tr>
<td>S</td>
<td>15</td>
<td>1276.32</td>
<td>0.12</td>
<td>5.61</td>
<td>0.44</td>
<td>30-Jul-96 - 22-Apr-02</td>
</tr>
<tr>
<td>AS</td>
<td>5</td>
<td>1268.48</td>
<td>-7.72</td>
<td>1.01</td>
<td>0.08</td>
<td>24-Apr-97 - 14-Dec-01</td>
</tr>
<tr>
<td>A</td>
<td>6</td>
<td>1279.07</td>
<td>2.87</td>
<td>5.95</td>
<td>0.46</td>
<td>19-Mar-98 - 01-Jul-03</td>
</tr>
<tr>
<td>AC</td>
<td>27</td>
<td>1284.38</td>
<td>8.18</td>
<td>2.32</td>
<td>0.18</td>
<td>06-Jul-00 - 05-Mar-04</td>
</tr>
<tr>
<td>Z</td>
<td>6</td>
<td>1281.91</td>
<td>5.71</td>
<td>1.87</td>
<td>0.15</td>
<td>07-Aug-00 - 19-Mar-03</td>
</tr>
</tbody>
</table>
Outlook

• Study various options:
  - interleaving:
    • 2-fold up to 10-fold
    • various frequency range
  - random detuning
    • various detuning range

• For each case study tolerances on fabrication

• Use information from newest TTF cavities