CLIC main linac accelerating structure optimization.

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for CLIC Study team
Outline

• Introduction
• Optimum frequency and gradient for CLIC main linac
  • Optimization procedure
  • Optimization constraints
  • Optimization results
• Design of X-band accelerating structure for CLIC
  • Higher order mode damping
  • Analysis of X-band test results
Compact Linear Collider (CLIC) main linac

CLIC 3 TeV

Layout of CLIC for 150 MV/m, 30 GHz
Main ingredients:

- Cell design: Hybrid Damped Structure (HDS)
- Tapered structure model: 3 cells interpolation for fundamental and dipole modes
- Structure bandwidth model
- Beam Dynamics (BD) constraints
- RF constraints:
  - Pulsed surface heating
  - RF breakdown model
  - High gradient measurement results (new data at 30 GHz become available in 2006)
- Optimization cost functions:
  - Luminosity per power
  - Total cost model (become available in 2006)
Cell design

Hybrid Damped Structure (HDS)

- Excellent wakefield damping
- $E_{\text{surf}} / E_{\text{acc}}$ and $H_{\text{surf}} / E_{\text{acc}}$ are only by 7 and 9% higher than in undamped cell, respectively
- 4 metal pieces per structure
- No brazing is necessary
- Good pumping capabilities
Structure parameters are calculated using parameters of the three cells: first cell, middle cell, last cell.

Single cell parameter interpolation.
Structure bandwidth model

<table>
<thead>
<tr>
<th>a [mm]</th>
<th>v_g/c</th>
<th>δf@-3dB [GHz]</th>
<th>δf/f@-3dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0.08</td>
<td>1.8</td>
<td>0.06</td>
</tr>
<tr>
<td>1.6</td>
<td>0.051</td>
<td>1.0</td>
<td>0.033</td>
</tr>
<tr>
<td>1.2</td>
<td>0.02</td>
<td>0.38</td>
<td>0.013</td>
</tr>
<tr>
<td>0.8</td>
<td>0.005</td>
<td>0.07</td>
<td>0.002</td>
</tr>
</tbody>
</table>

δf/f = 1.48\cdot(v_g/c)^{5/4} - is the best fit

t_r = (δf)^{-1} = (f\cdot1.48\cdot(v_g/c)^{5/4})^{-1} - rise time

P

η → η'

P

\[ \tag{1} \]

\[ \tag{2} \]

\[ \tag{3} \]

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USHGCW, 24 May 2007
Beam dynamics (BD) constraints based on the simulation of the main linac, BDS and beam-beam collision at the IP:

- \( N \) - bunch population depends on \( \langle a \rangle / \lambda, \Delta a / \langle a \rangle, f \) and \( \langle E_{\text{acc}} \rangle \) because of short-range wakes
- \( N_s \) - bunch separation depends on the long-range dipole wake and is determined by the condition:
  \[
  W_{t,2} = 10 \, \text{V/pC/mm/m for } N = 4 \times 10^9
  \]

RF breakdown and pulsed surface heating (rf) constraints:

- \( \Delta T^{\text{max}}(H_{\text{surf}}^{\text{max}}, t_p) < 56 \text{K for CuZr} \)
- \( E_{\text{surf}}^{\text{max}} < 380 \text{MV/m} \)
- \( P_{\text{in}} t_p^{1/3}/C_{\text{in}} = \text{const} \)
\[ P/C \cdot t_p^{1/3} = \text{const} \]

**H60VG4S17**: \(a_1 = 5.7 \text{ mm}; P=59 \text{ MW for } \langle E_a \rangle = 65 \text{ MV/m} \)

demonstrated: \(\langle E_a \rangle = 85 \text{ MV/m @ 100ns, BDR=10^{-6}}\)

\[ \Rightarrow P/C \cdot t_p^{1/3} = 13.0 \text{ MW/mm\cdotns}^{1/3} \]

**H90VG3**: \(a_1 = 5.4 \text{ mm}; P=95 \text{ MW for } \langle E_a \rangle = 70 \text{ MV/m} \)

demonstrated: \(\langle E_a \rangle = 70 \text{ MV/m @ 100ns, BDR=10^{-6}}\)

\[ \Rightarrow P/C \cdot t_p^{1/3} = 13.0 \text{ MW/mm\cdotns}^{1/3} \]
Cu rf constraints: 30 GHz

\[ P/C \cdot t_p^{1/3} = \text{const} \]

CTF3-120°-Cu: \( a_1 = 1.75 \text{ mm}; P = 54 \text{ MW for } <E_a> = 150 \text{ MV/m} \)

demonstrated: \( <E_a> = 90.5 \text{ MV/m} @ 70\text{ ns}, \text{BDR}=10^{-3} \)

\[ => \quad P/C \cdot t_p^{1/3} = 7.3 \text{ MW/mm}\cdot\text{ns}^{1/3} \]

CTF3-120°-Cu: \( a_1 = 1.75 \text{ mm}; P = 54 \text{ MW for } <E_a> = 150 \text{ MV/m} \)

scaled: \( <E_a> = 63 \text{ MV/m} @ 70\text{ ns}, \text{BDR}=10^{-6} \)

\[ => \quad P/C \cdot t_p^{1/3} = 3.6 \text{ MW/mm}\cdot\text{ns}^{1/3} \]

HDS60-Cu:

demonstrated: \( (P/C)_{HDS} = \frac{3}{4} (P/C)_O \)
\( P/C \cdot t_p^{1/3} \cdot f^q = \text{const} \) connects two frequency with one parameter

- Experimental results for circular structures scaled to BDR=10^{-6}

\[ 13.0 \cdot 11.4^q = 3.6 \cdot 30^q \]

N.B. For two structures with scaled geometry that would mean:
\[ E_a \cdot t_p^{1/6} = \text{const} \]
Experimental data at X-band and 30 GHz

- **Cu 70 ns 30 GHz**
- **HDS60 rev 70 ns**
- **HDX11 70 ns**
- **HDX11 150 ns**
- **Cu NLC 70 ns 11 GHz**
- **CLIC GOAL**

Scaled structures
Luminosity per linac input power:

\[
\frac{L}{P_l} = \frac{L_{b\times} N_b f_{rep}}{eE_c N N_b f_{rep}} = \frac{1}{eE_c} \cdot \frac{L_{b\times}}{N} \eta
\]

Collision energy is constant

Figure of Merit (FoM = \eta L_{b\times}/N) in [a.u.] = [1e34/bx/m2\cdot%/1e9]
Total cost = Investment cost + Electricity cost for 10 years

\[ C_t = C_i + C_e \]

\[ C_i = \text{Excel}\{f_r; E_p; t_p; E_a; L_s; f; \Delta \varphi\} \]

- Repetition frequency;
- Pulse energy;
- Pulse length;
- Accelerating gradient;
- Structure length (couplers included);
- Operating frequency;
- rf phase advance per cell

\[ C_e = (0.008+0.6/\text{FoM}) \]
All structure parameters are variable:

\[ \langle E_{\text{acc}} \rangle = 90 - 150 \text{ MV/m}, \]
\[ f = 10 - 30 \text{ GHz}, \]
\[ \Delta \varphi = 50^\circ - 130^\circ, \]
\[ \langle a \rangle / \lambda = 0.09 - 0.21, \]
\[ \Delta a / \langle a \rangle = 0.01 - 0.6, \]
\[ d_1 / \lambda = 0.025 - 0.1, \quad d_2 > d_1 \]
\[ N_{\text{cells}} = 15 - 300. \]
Optimizing $L/P$ and $C_t$

$max\{L/P\}$ \quad $L_1/N^*\eta$ [a.u.]

$min\{C_t\}$ \quad $L_1/N^*\eta$ [a.u.]

$\langle E_{acc}\rangle$ [MV/m] vs. $f$ [GHz]

Total Cost [a.u.]

$\langle E_{acc}\rangle$ [MV/m] vs. $f$ [GHz]

Total Cost [a.u.]
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Why X-band? A simplistic explanation:

Crossing gives the optimum frequency

Determined by RF constraints
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Different damping

Pulsed surface heating temperature rise:

\[ \Delta T_{\text{max}} \sim E_a^2 \left( \frac{H_{\text{surf}, \text{max}}}{E_a} \right)^2 \cdot f^{1/2} \cdot t_p^{1/2} \]

Reducing gradient from 150 to 100 MV/m gives factor 1.5 margin in surface fields which can be used in cell redesign. For example, it allows to increase \( H_{\text{surf}, \text{max}} / E_a \) by 1.5
Different damping

HDS

Waveguide Damped Structure (WDS)

$d_{wi} = 1.6 \text{mm}$

$H_{surf}^{\text{max}}/E_a = 2.8 \text{ mA/V}$

$d_{wi} = 3.5 \text{mm}$

$H_{surf}^{\text{max}}/E_a = 4.2 \text{ mA/V}$
Thanks to C. Adolphsen and S. Doebert for providing the data.

\[ \langle \frac{P}{C^* t_p^{1/3}} \rangle = 15.2 \text{ Wu} \]

\[ [\text{Wu}] = \left[ \frac{\text{MW}}{\text{mm} \cdot \text{ns}^{1/3}} \right] \]
$\eta$: $t_p = t_b + t_f + t_r$

$\Delta T \sim (t_p^T)^{1/2}$: $t_p^T = [(t_b + t_f + t_r)^{1/2} - 0.5(t_f + t_r)^{1/2}]^2$

$P/C^* (t_p^P)^{1/3}$: $t_p^P = \text{time when } P_{in}/P_{in,\text{load}} > 0.9$
Rect-pulse => NLC-pulse
65 MV/m => 67.5 MV/m

Assuming: $E_a \cdot t_p^{1/6} = \text{const}$
400ns => 320ns

NLC: $t_f = 100 \text{ ns}; t_b = 300 \text{ ns}$

Thanks to
S. Doebert
**WDS120 optimum versus $\langle a \rangle/\lambda$**

**18 Wu**

Maximum FoM

$L_s = 23 \text{ cm}$

Optimum

$\langle a \rangle/\lambda = 0.12$
Parameters versus structure length

Parameters for \( \langle a \rangle / \lambda \) = 0.11 (solid line) and 0.12 (dashed line)

- \( \eta \)
- \( \eta L/N \)
- \( C_i / C_{i-1} \min \)
- \( P_{in} / 2 \)
- \( t_p / 10 \)

Maximum FoM

Minimum Cost

18 Wu

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## Parameters of CLIC acc. structure

<table>
<thead>
<tr>
<th>Structure name</th>
<th>CLIC nominal</th>
<th>CLIC_vg1 test</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF phase advance per cell: $\Delta \phi$ [$^\circ$]</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Average iris radius/wavelength: $&lt;a&gt;/\lambda$</td>
<td>0.12</td>
<td>0.128</td>
</tr>
<tr>
<td>Input/Output iris radii: $a_{1,2}$ [mm]</td>
<td>3.87, 2.13</td>
<td>3.87, 2.53</td>
</tr>
<tr>
<td>Input/Output iris thickness: $d_{1,2}$ [mm]</td>
<td>2.66, 0.83</td>
<td>2.66, 1.25</td>
</tr>
<tr>
<td>Group velocity: $v_g^{(1,2)}/c$ [%]</td>
<td>2.39, 0.65</td>
<td>2.4, 0.95</td>
</tr>
<tr>
<td>N. of reg. cells, str. length: $N_c, l$ [mm]</td>
<td>24, 229</td>
<td>18, 179</td>
</tr>
<tr>
<td>Bunch separation: $N_s$ [rf cycles]</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Number of bunches in a train: $N_b$</td>
<td>265</td>
<td>261</td>
</tr>
<tr>
<td>Pulse length, rise time: $\tau_p, \tau_r$ [ns]</td>
<td>244, 30</td>
<td>208, 19</td>
</tr>
<tr>
<td>Input power: $P_{in}$ [MW]</td>
<td>76</td>
<td>81</td>
</tr>
<tr>
<td>Max. surface field: $E_{surf}^{max}$ [MV/m]</td>
<td>323</td>
<td>304</td>
</tr>
<tr>
<td>Max. temperature rise: $\Delta T^{max}$ [K]</td>
<td>57</td>
<td>54</td>
</tr>
<tr>
<td>Efficiency: $\eta$ [%]</td>
<td>31.0</td>
<td>31.1</td>
</tr>
<tr>
<td>Luminosity per bunch X-ing: $L_{bx}$ [m$^2$]</td>
<td>$2.6\times10^{34}$</td>
<td>$3.0\times10^{34}$</td>
</tr>
<tr>
<td>Bunch population: $N$</td>
<td>$5.8\times10^9$</td>
<td>$7.0\times10^9$</td>
</tr>
<tr>
<td>Figure of merit: $\eta L_{bx}/N$ [a.u.]</td>
<td>13.7</td>
<td>13.4</td>
</tr>
</tbody>
</table>
Parameters of CLIC acc. structure

18 Wu

Test structure

Parameters of unloaded (dashed) and loaded (solid) structure

\[ P_{\text{load}} = 75.7 \text{ MW}, \quad P_{\text{out}} = 12.1 \text{ MW} \]

Eff = 31.0%,

\[ t_r = 30.3 \text{ ns}, \quad t_f = 59.8 \text{ ns}, \quad t_p = 244.1 \text{ ns} \]

\[ t_{\text{in}} = 172.1 \text{ ns} \]

\[ P_{\text{in}}, P_{\text{load}} \]

\[ E_{\text{surf}} \text{ (green)}, E_{\text{acc}} \text{ (red)} \]

\[ \Delta T \text{ (blue)} \]

\[ t \text{ [ns]} \]

\[ P \text{ [MW]} \]

\[ \text{iris number} \]
• In 2006, optimization of CLIC frequency and gradient has been done, based on the cost model and taking into account new experimental data at 30 GHz and some of the NLCTA measurement results at X-band
• This (together with some other considerations) resulted in major change of CLIC parameters (from 150MV/m@30GHz to 100MV/m@12GHz)
• RF design of X-band CLIC accelerating structure has been done, based on the waveguide damping and taking into account most of NLCTA measurement results
• X-band test structure has been designed in order to test most of the assumptions made in rf design of CLIC accelerating structure
• New CLIC parameters list
• High power testing
  • CLIC\_vg1 test structure
  • Non-damped version of CLIC\_vg1 test structure
  • Comparison of the same rf design but made in brazed disks
    and in quadrants
  • Testing of pulse shape dependence of the structure gradient
• New (or old) concepts and ideas in rf design of
  accelerating structures. Application to CLIC.
  • Different damping
  • Power feeding and distribution schemes
• RF breakdown modeling

See more at http://clic-study.web.cern.ch/CLIC-Study/