SWIRL* Pulse Compression Concept

1. Component configuration uses two active (and non-reciprocal) phase shifters in between two 3-db couplers. Same s-matrix as a SLED-II system with circulator and variable reflection coefficient.

2. Example given for double switching of phase shifters (at end of 1st time bin and at beginning of last time bin) with a compression ratio of 8. Compression efficiency depends strongly on round trip loss in delay-line/switch system.

3. Application to NLC parameters.

4. Propose a conventional SLED-II for 500 GeV NLC with upgrade to SWIRL for 1.0 – 1.5 TeV.

*SWItched Resonant Line
Component configuration for a SLED-2 system with circulator

Phasor conventions

\[ E = E_0 e^{j\phi} \]
\[ \phi = \omega t - k y \]

Phasor wave direction

\[ e^{j\omega t} \quad e^{-j\omega t} \quad e^{j\omega t} \]

Forward wave - 1st time bin

Extend reference planes at ports 3 + 4 by \( k\Delta y = \frac{3\pi}{2} \)
output at 3 = \(-s\)
output at 4 = \(\sqrt{1-s^2}\)

\[ \phi = \sin^{-1}s \]
Comparison with conventional SLED-II configuration with circulator

Phasor relationship at a capacitive iris

At iris $1 + \tilde{s} = \tilde{\xi}$

Conservation of energy: $\frac{s^2 + \tilde{s}^2}{1 + \tilde{s}^2} = 1$

$|s| = \sqrt{1 - \tilde{s}^2}$

Define Reference Planes

Equivalent configuration to previous page

Klystron $\rightarrow$ 1
Circulator $\rightarrow$ 2

To Accel.

To delay line $\tilde{e} = \sqrt{1 - \tilde{s}^2}$
Reverse Wave - 2nd time bin (without switching)

Forward Wave - 2nd time bin (without switching)

Note: \( \phi_B^- = \phi_B^+ = \phi \)
\[ \phi_A^- = \phi_A^+ + (\pi - 2\phi) \]
Again, same result as for equivalent configuration with circulator on p.3.
Active S wid clipping at end of 1st time bin
During time bin #1, set $\phi_A^+ = 0$, $\phi_B^+ = 0$

**Forward wave - time bin #1**

At end of time bin #1 switch $\phi_A$ and $\phi_B$ to:

$$\phi_A^+ = \phi_1, \quad \phi_A^- = \pi - \phi_1$$
$$\phi_B^+ = -\phi_1, \quad \phi_B^- = -\phi_1$$

**Reverse wave - time bin #2**

**Forward wave - time bin #2**

Port 3: $-j[\cos \phi_1 \pm \sin \phi_1]$  
Port 4: $-j[\sin \phi_1 \pm \cos \phi_1]$

If phase is flipped:

$E_3 = \cos \phi_1 + \sin \phi_1 = \sqrt{2} \left( \frac{1}{2} + \frac{1}{2} \right)$  
$E_4 = \sin \phi_1 - \cos \phi_1 = 0$

$s = \sqrt{2}/2$
SWIRL efficiency depends strongly on round trip loss in delay line and switch components.
Phase Shifter Status for Double Switching  
(Example for \( N = 8 \) in parentheses)*

| Time Bin | \( \phi_A^+ \) | \( \phi_A^- \) | \( \phi_B^+ \) | \( \phi_B^- \) | Phase
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( n = 1 )</td>
<td>0</td>
<td>Arb</td>
<td>0</td>
<td>Arb</td>
<td>0</td>
</tr>
<tr>
<td>First</td>
<td>( \phi_1 )</td>
<td>( \pi - \phi_1 )</td>
<td>(- \phi_1 )</td>
<td>(- \phi_1 )</td>
<td>( \Delta \phi_A^+ = \phi_1 (+63^\circ) )</td>
</tr>
<tr>
<td>Switching</td>
<td>(63°)</td>
<td>(117°)</td>
<td>(-63°)</td>
<td>(-63°)</td>
<td>( \Delta \phi_B^- = -\phi_1 (-63^\circ) )</td>
</tr>
<tr>
<td>( n = 2 )</td>
<td>( \phi_2 )</td>
<td>( \pi - \phi_2 )</td>
<td>(- \phi_2 )</td>
<td>(- \phi_2 )</td>
<td>( \Delta \phi_A^+ = \phi_2 - \phi_1 (-41^\circ) )</td>
</tr>
<tr>
<td>( + n = N - 1 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \Delta \phi_A^- = \phi_1 - \phi_2 (+41^\circ) )</td>
</tr>
<tr>
<td>Second</td>
<td>( \phi_2 )</td>
<td>( \pi - \phi_2 )</td>
<td>(- \phi_2 )</td>
<td>(- \phi_2 )</td>
<td>( \Delta \phi_B^+ = \phi_1 - \phi_2 (+41^\circ) )</td>
</tr>
<tr>
<td>Switching</td>
<td>(22°)</td>
<td>(158°)</td>
<td>(-22°)</td>
<td>(-22°)</td>
<td></td>
</tr>
</tbody>
</table>

* Reflective coefficients (depend on RT loss)

\[
S_0 = 0 \\
S_1 = 0.89 \text{ at end of time bin 1} \\
S_2 = 0.37 \text{ at end of time bin } N-1
\]

Those values optimizing voltage gain \( G_V \)

\[
G_V = S_2 + T(1-S_2)^{1/2} \left\{ \frac{N-2}{(S_1T) + (1-S_2)^{1/2} \left[ \frac{1 - (S_1T)^{N-2}}{1 - S_1T} \right]} \right\}
\]

\[
M_{\text{comp}} = \frac{G_V^2}{N} = 0.814 \text{ for } N=8, \quad T = \sqrt{0.95} \text{ (5% RT loss)}
\]

Compare \( M = 0.62 \text{ for conventional SLEO-II} \)
Realization of Circulator and Switch
(Sami Tantawi)

Circulator

Wrap around couplers

Pulsed RA source

≈ 6 mA

RF pulse width

Ferrite toroid

TE01 line

Bias pulse -- slow risetime OK.

Switch

Add fast switching pulse (few hundred amps) on top of bias pulse.
# Updated Parameters for NLC with a SWIRL Pulse Compression System

<table>
<thead>
<tr>
<th>Comp. Ratio</th>
<th>T delay (μs)</th>
<th>Pulse Energy (J)</th>
<th>Peak Power (MW)</th>
<th>Compl. Efficiency</th>
<th>Power/structure (MW)</th>
<th>Unloaded Gradient (MV/m)</th>
<th>Effective Gradient (MV/m)</th>
<th>Energy (GeV)</th>
<th>P_ac (MW)</th>
<th>Rep-Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notes</td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
<td>(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLDS 4</td>
<td>1.50</td>
<td>SM 225</td>
<td>600</td>
<td>0.85</td>
<td>170</td>
<td>73.0</td>
<td>55.4</td>
<td>1012</td>
<td>194</td>
<td>120</td>
</tr>
<tr>
<td>SWIRL 4</td>
<td>1.50</td>
<td>112</td>
<td>300</td>
<td>0.87</td>
<td>130</td>
<td>63.8</td>
<td>47.1</td>
<td>863</td>
<td>149</td>
<td>120</td>
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<tr>
<td>5</td>
<td>1.875</td>
<td>141</td>
<td>375</td>
<td>0.84</td>
<td>157</td>
<td>70.2</td>
<td>52.9</td>
<td>967</td>
<td>186</td>
<td>120</td>
</tr>
<tr>
<td>6</td>
<td>2.25</td>
<td>169</td>
<td>450</td>
<td>0.81</td>
<td>183</td>
<td>75.7</td>
<td>57.8</td>
<td>1055</td>
<td>224</td>
<td>120</td>
</tr>
<tr>
<td>8</td>
<td>3.00</td>
<td>225</td>
<td>600</td>
<td>0.77</td>
<td>230</td>
<td>84.8</td>
<td>66.1</td>
<td>1203</td>
<td>149</td>
<td>60</td>
</tr>
<tr>
<td>10</td>
<td>3.75</td>
<td>281</td>
<td>750</td>
<td>0.73</td>
<td>272</td>
<td>92.3</td>
<td>72.9</td>
<td>1325</td>
<td>186</td>
<td>60</td>
</tr>
<tr>
<td>12</td>
<td>4.50</td>
<td>338</td>
<td>900</td>
<td>0.69</td>
<td>310</td>
<td>98.6</td>
<td>78.5</td>
<td>1425</td>
<td>224</td>
<td>60</td>
</tr>
<tr>
<td>15/14</td>
<td>5.25</td>
<td>394</td>
<td>1050</td>
<td>0.66</td>
<td>344</td>
<td>103.9</td>
<td>83.3</td>
<td>1511</td>
<td>260</td>
<td>60</td>
</tr>
<tr>
<td>16</td>
<td>6.00</td>
<td>450</td>
<td>1200</td>
<td>0.63</td>
<td>376</td>
<td>108.6</td>
<td>87.6</td>
<td>1588</td>
<td>149</td>
<td>30</td>
</tr>
</tbody>
</table>

(1) Assumes 375 ns output pulse.
(2) Maximum energy per delay line (no losses); SM = single mode, MM = multi-mode.
(3) Maximum peak power seen by rf components (no losses).
(4) Assuming 5% delay line switch loss per round trip and 6% bby to accel loss.
(5) See Farkas/Wilson 8/2/99 memo for details of gradient calculation.
(6) Effective gradient: 0.903 G (final speed) = 10.5 MV/m \(\left(0.903 = 0.92 \cos 11\right)\)
(7) Energy = 17.90 Jm (9936 structures) + 20 GeV.
(8) \(P_{ac} = (U_{pulse} \times 4968 \text{ klystrons} \times \text{sep. ratio})/0.45 \times 0.45 = N_{kly}(66\%) \times N_{mod}(75\%).\)
Comparison of DLDS, SLED-II and SWIRL Pulse Compression Systems for NLC

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
<th>R</th>
<th>$T_k$ (μsec)</th>
<th>Delay Line Modes/Dia.</th>
<th>Peak Power (MW)</th>
<th>Pulse Energy (J)</th>
<th>Comp. Efficiency</th>
<th>$P_t$ (MW)</th>
<th>$G_0$ (MV/m)</th>
<th>E (GEV/TEV)</th>
<th>$N_k/L_A$</th>
<th>Relative Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLDS</td>
<td></td>
<td>4</td>
<td>1.5</td>
<td>1 M/4.75</td>
<td>600</td>
<td>225</td>
<td>0.85</td>
<td>170</td>
<td>73.0</td>
<td>515/1.01</td>
<td>0.97/0.97</td>
<td>1.01/1.01</td>
</tr>
<tr>
<td>(8/98)</td>
<td></td>
<td>8</td>
<td>3.0</td>
<td>2 M/7.125</td>
<td>600</td>
<td>450</td>
<td>0.83</td>
<td>166</td>
<td>72.1</td>
<td>490/0.96</td>
<td>0.51/1.02</td>
<td>1.02/1.02</td>
</tr>
<tr>
<td>SLED-II</td>
<td></td>
<td>8</td>
<td>3.0</td>
<td>1 M/4.75</td>
<td>600</td>
<td>225</td>
<td>0.57</td>
<td>171</td>
<td>73.2</td>
<td>520/1.02</td>
<td>0.72/0.97</td>
<td>1.02/1.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>4.5</td>
<td>2 M/4.75</td>
<td>900</td>
<td>338</td>
<td>0.43</td>
<td>194</td>
<td>78.0</td>
<td>555/1.09</td>
<td>0.67/0.90</td>
<td>1.09/1.09</td>
</tr>
<tr>
<td>SLED-II</td>
<td></td>
<td>16</td>
<td>6.0</td>
<td>1 M/7.125</td>
<td>900</td>
<td>338</td>
<td>0.69</td>
<td>310</td>
<td>98.6</td>
<td>720/1.43</td>
<td>0.52/0.69</td>
<td>1.43/1.69</td>
</tr>
</tbody>
</table>

Notes:
1. Compression ratio = klystron pulse length $T_k/375$ ns.
2. 1 M = TE$_{01}$ mode only; 2 M = TE$_{02}$, and one polarization of TE$_{02}$, in delay line.
3. Peak power $\hat{P}$ in delay lines or in any rf component, ignoring losses; klystron power = 75 MW.
4. Pulse energy = maximum peak power in (3) times longest pulse length in a delay line or t-f component.
5. Compression efficiency $\eta_{comp}$ assumes a 3% loss from klystron to compression system input, and 3% loss from delay line tap-offs or SLED output to accelerator structure inputs.
6. $P_s = \text{input power at each accelerator structure}; \ P_s = \hat{P} \eta_{comp} / n_s$, where $n_s$ is the number of structures per output spigot. $n_s$ = 3 for DLDS systems; $n_s$ = 2 for SLED-II/SWIRL systems.
7. $G_0^2 = \text{unloaded gradient} = (\hat{P}/170)^{1/2} \times 73.0$ MV/m.
8. Effective gradient is $G_s$ (MV/m) = 0.903 $G_0$ $-0.5$ at 0.95 x 10$^6$ particles/bunch. Energy is $E = 8.95$ km (4968 structures) x $G_s$ + 20 GeV. Energy following slash is for 17.90 km machine.
9. $N_k$ = no. of klystrons normalized to 1656; $L_A$ = active length for 500 GeV where 1.O = 8.95 km.
### Table I
Comparison of Delay Line Lengths

<table>
<thead>
<tr>
<th>System</th>
<th>Max. No. of Modes in Delay Line</th>
<th>Delay Line Length* per 6 Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. DLDS 4</td>
<td>1</td>
<td>1.5 T</td>
</tr>
<tr>
<td>2. DLDS 4</td>
<td>2</td>
<td>1 T</td>
</tr>
<tr>
<td>3. DLDS 4</td>
<td>3</td>
<td>0.75 T</td>
</tr>
<tr>
<td>4. DLDS 8</td>
<td>2</td>
<td>2 T</td>
</tr>
<tr>
<td>5. DLDS 8</td>
<td>3</td>
<td>1.5 T</td>
</tr>
<tr>
<td>6. SLED-II</td>
<td>1</td>
<td>3 T</td>
</tr>
<tr>
<td>7. SLED-II</td>
<td>2</td>
<td>1.5 T</td>
</tr>
<tr>
<td>8. SWIRL</td>
<td>1</td>
<td>1.5 T</td>
</tr>
</tbody>
</table>

*T = output pulse length = 375 ns ≈ 110 m of delay line.
6 structures = 10.8 m of active length
Delay line length/structure length ≈ 10 x where number in column is xT.