Multimoded RF Systems for Future Linear Colliders

Sami G. Tantawi
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We wish to Thank all operators that took shifts 24 hours a day for several months
Outline

• Dualmode resonant delay line pulse compression system for the Next Linear Collider (NLC)
  1. Introduction
  2. Components: design and cold tests
  3. Dualmode Delay Lines: Design and Experimental results
  4. High power experimental results
RF Accelerator Structures needs a short, high power, rf pulse. For example the current NLC design requires a flat-top 396 ns rf pulse with a power level of about 95 MW/m at 11.424 GHz, and a repetition rate of 120 Hz to feed each accelerator structure.

One need to transfer the CW wall plug power to rf pulses with high power and low duty factor. Hence

1. A storage system is needed.
2. A Switch or a switching mechanism is needed to control the charging and discharging of the system.
3. A device to generate the RF power
Storage Systems:

1. **Capacitors; i.e. Modulators.**
   Switches include pulse forming networks, thyrotrons, IGBTs, and grided guns on microwave tubes.

2. **Kinetic energy of an electron beam ; i.e. two beam accelerator,**
   Switches include RF beam kickers

3. **In the accelerator structure; i.e. super conducting accelerators.**

4. **In rf transmission lines and cavities; i.e. rf pulse compression systems.**
   Switches includes rf phase manipulation between rf sources, and solid state switches.
In general most of rf systems, suggested for a linear collider, contains elements from several of the above storage system.

To compare these system one has to consider:
1- Philosophy of the design
   • Modularity: one may choose to have a unit that contains one rf source, and compact pulse compression system such as SLED-II
   • Flexibility in the operating rf frequency: one may choose Two beam systems
   •…..
2- Efficiency
3- Cost
The choice of the system is greatly affected by the available technology of the components.

If one has

1- A really inexpensive efficient rf source

2- A very efficient and inexpensive modulator system using a very fast switch (such as grided gun on the rf source)

One might use several thousands of these devices to power the main Linac of a collider

However, neither the *inexpensive* rf source nor the *very fast* modulator exist, only ideas at the moment.
The need for RF Pulse compression

1- It is usually easier to build rf sources with low power and long pulse width.
2- Rf sources are expensive, one should get as much energy from them as possible, i.e., the longest possible pulse. One should not let an expensive rf source in an idle mode most of the time.

Hence, rf pulse compression is needed to match the long pulse low power of available rf sources such as klystrons to the high power short pulse needed for the accelerator structure.
• Pulse Compression should be used with as high of a compression ratio as possible until
  a) The cost of the compression system starts to exceed that of the klystrons and modulator
  b) Or, the available pulse width of the klystrons is exhausted

• The cost of the main linac is directly proportional to the efficiency of the pulse compression system.
RF Pulse compression for RF Linacs and Colliders

- Resonance Delay Lines (SLED-II)
- Binary Pulse Compression (BPC)
- Delay Line Distribution System (DLDS)

- Two-Stage systems, any combination of two or more of the above systems
Sled-II Pulse compression system

Sled-II pulse compression system with a circulator and active switches
Two banks of power sources each has an $n_k/2$ klystrons

a) Single-moded Binary Pulse Compression

b) Binary pulse compression can have several improvements including the use of a circulator and several modes to reduce the delay line length.
Delay Lines

Accelerator Structures

Bank of \(n_k\) of klystrons

A set of hybrids that switches the combined rf to different outputs

Not all the output need to be used. The unused outputs are terminated by an rf load

a) A Unit of a Single-Moded DLDS

Multi-Moded Delay Lines. The total number of these lines is \(n_p\)

A mode launcher which takes \(n_m\) inputs and produces \(n_m\) modes into a single waveguide delay line

b) A Unit of a Multi-Moded DLDS

c) A Unit of an Active DLDS
The challenges facing most of these pulse compression system are

1- Compactness, how to produce a storage system which is relatively compact

2- Efficiency, for the resonant delay lines, efficiency could be boosted by an rf switch.

3- Most of these systems could have a more compact topology if one have, a nonreciprocal RF device (circulator), or a switch.
Compactness

• A waveguide near cutoff, hence, a low group velocity. One can use a higher order mode to reduce the losses. A bad idea, dispersion will destroy the pulse shape at a group velocity less than 4.

• Loaded waveguide (slow wave structure). A bad idea because of dispersion and losses.

• Multimoded Waveguide, the only good idea with no draw backs. We are using highly overmoded waveguide systems no mater what, using an extra mode, or two, or four, .. Is a bonus.
Single Moded DLDS
Multi-Moded DLDS (number of modes=3)
Active DLDS
Multi-Moded BPC (A high power circulator and 3 modes)
Multi-Moded SLED II (A high power circulator and 3 modes)
Active SLED II (One time Switching [7])

\( n_k = 8 \)

Relative Cost
Compression Ratio

- Single-Moded DLDS (\( n_k =4 \), number of modes =3)
- Multi-Moded DLDS (\( n_k =4 \))
Electric Field breakdown strength in a 16% Group velocity copper waveguide at 11.424 GHz
Pulsed Heating of Copper Surface Vs. Surface H Field for Different Pulse Durations
Dual mode waveguide carrying 200 MW

Compressed output > 600 MW 400 ns.

Single mode waveguide input to the pulse compression system; 100 MW/Line for 1.6 µs

Output Load Tree

Dualmode Resonant Delay lines ~30m

RF Input to the 4 50 MW klystrons

NLC experimental rf pulse compression system
The Head of the pulse compression system

- **TE_{01}/TE_{11}** to loads
- **TE01** to delay Lines
- **TE_{01}/TE_{11}**
- **TE_{10}/TE_{20}**
- **Super Hybrid**
- **Pumpout**
- **Dualmode directional coupler**
- **Dualmode Combiner**
- **Two fundamental mode inputs**
Dual-Mode Combiner

@ 600 MW  \(|E_s|_{\text{max}} = \sim 45.7 \text{ MV/m}\)
\(|H_s|_{\text{max}} = \sim 218 \text{ kA/m}\)

TE\(_{10}\)

@ 600 MW  \(|E_s|_{\text{max}} = \sim 31.5 \text{ MV/m}\)
\(|H_s|_{\text{max}} = \sim 73.9 \text{ kA/m}\)

TE\(_{20}\)
Dual-Mode Combiner/Splitter

@ 600 MW  $|E_{\text{max}}^s| = \sim 45.7 \text{ MV/m}$

$|H_{\text{max}}^s| = \sim 218 \text{ kA/m}$

@ 600 MW  $|E_{\text{max}}^s| = \sim 31.5 \text{ MV/m}$

$|H_{\text{max}}^s| = \sim 73.9 \text{ kA/m}$
Width taper to match our standard overmoded waveguide.
Simulated electric fields (HFSS) of the multi-moded circular to rectangular taper

Dual-Moded Rectangular ↔ Circular Converter/Tapers

Taper Geometry (Operating Frequency=11.424 GHz)
Dualmode
Rectangular-to-Circular
Taper
Instrumental components for cold testing of multimode components:

1. $\text{TE}_{11}$ Mode launcher
2. $\text{TE}_{01}$ Mode launcher
3. Width taper
4. Height taper
5. Small waveguide sections with different lengths at all waveguide cross sections

We followed a strict methodology of designing these instruments. They had to be simulated with at least three different codes and have a performance that is much better than any component that we have. Of course we can only do that because there is no restrictions on field levels.
Cold Test Components/Calibration Standards

Width Taper, Height Tapers and Jog Mode Converter

TE$_{01}$ Mode Converter, TE$_{11}$ Mode Converter, and Size Taper

Multimoded Matched Load
Measured $S_{12}$ between the Rectangular TE$_{02}$ mode and the circular TE$_{01}$ mode. These measurements include the response of mode transducers necessary to launch the modes at both ends of the taper.
Measured $S_{12}$ between the rectangular $\text{TE}_{01}$ mode and the circular $\text{TE}_{11}$ mode. These measurements include the response of mode transducers necessary to launch the modes at both ends of the taper.
Cold Test Setup for the Splitter and Circular-to-Rectangular Taper
Cold Test Results of:
Splitter-Circular to rectangular taper-Wraparound mode converter-instrumental height taper-instrumental width taper. Total losses at 11.424 GHz = 1.3%
Jog Converter and Mode Mixer

TE_{10}  

1.442"

orthogonal 50/50 mixes

TE_{20}

 orthogon al

50/50 mixes

<table>
<thead>
<tr>
<th>(P 1 M 1)</th>
<th>(P 1 M 2)</th>
<th>(P 2 M 1)</th>
<th>(P 2 M 2)</th>
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<tbody>
<tr>
<td>(P 1 M 1)</td>
<td>0.0018</td>
<td>0.0048</td>
<td>0.707</td>
</tr>
<tr>
<td>(P 1 M 2)</td>
<td>0.0048</td>
<td>0.0087</td>
<td>0.7072</td>
</tr>
<tr>
<td>(P 2 M 1)</td>
<td>0.707</td>
<td>0.7072</td>
<td>0.0019</td>
</tr>
<tr>
<td>(P 2 M 2)</td>
<td>0.7072</td>
<td>0.707</td>
<td>0.0048</td>
</tr>
</tbody>
</table>
## Magic H Hybrid

### Dimensions and Parameters

<table>
<thead>
<tr>
<th>(P 1 M 1)</th>
<th>(P 2 M 1)</th>
<th>(P 3 M 1)</th>
<th>(P 4 M 1)</th>
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<tbody>
<tr>
<td>0.0028</td>
<td>0.7071</td>
<td>0.0028</td>
<td>0.7071</td>
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<td>0.7071</td>
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</table>

- **Height at 600 MW**: 1.435”
- **Electrical Field Maximum**: $|E_{\text{max}}| = 45.6 \text{ MV/m}$
- **Magnetic Field Maximum**: $|H_{\text{max}}| = 168 \text{ kA/m}$

![Graph showing frequency response](image)

C. Nantista ‘02
To the pulse compressor

@ 516 MW,

$|E_{\text{max}}^s| = \sim 45.8 \text{ MV/m}$

$|H_{\text{max}}^s| = \sim 156 \text{ kA/m}$

To/From Pulse Compressors

Planer 3-dB Hybrid

Combiner/Splitter

Jog-Converter
Jog mode mixer
Combiner/Splitter
Planer 3-dB Hybrid
Planer Super-Hybrid
Port
Port 1
Port 2
Port 3
Port 4
Circular to Rectangular Tapers
Jog-mode converter
Planer 3-dB Hybrid
Mitered Bends
Combiner/Splitter
Planer Super-Hybrid
Jog mode mixer
Circular TE$_{11}$ mode transmission and reflection between port 1 and port 4 ($S_{41}$) for different conditions at port 2 and port 3.
Reflection measurements ($S_{11}$) for the circular $\text{TE}_{01}$ mode from port 1 while shorting both port 2 and port 3 and matching port 4.
Circular $\text{TE}_{01}$ mode transmission between port 1 and port 4 ($S_{41}$) while shorting both port 2 and port 3.
Bend Converter Design

@ 600 MW

\[ \left| E_s^{\text{max}} \right| = \sim 37.8 \text{ MV/m} \]

\[ \left| H_s^{\text{max}} \right| = \sim 83.8 \text{ kA/m} \]
Dual-mode Splitter: For either incident mode the power is evenly divided between the two output ports, which launch the TE\textsubscript{01}. 
Load Tree: The input power, carried by the $\text{TE}_{01}$ mode, is split 4 ways to be absorbed at the loads
Four Way Splitter Design

|S₁₁| < -57 dB @ 11.424 GHz

WC160

WR90
Power Divider

Port 1
Port 2
Port 3
Port 4

Frequency (GHz)

dB
High Power Load Design
Rectangular waveguide for coupling the TE\(_{01}\) mode

Circular Waveguide

Ridge waveguide for coupling the TE\(_{11}\) mode

- The waveguide sizes are chosen to match wavelengths between the circular waveguide modes and side waveguide fundamental mode
- The coupling hole pattern represents a Hamming window

Dual-moded Directional Coupler
End taper for $\text{TE}_{11}$ coupler
End taper for the $\text{TE}_{01}$ coupler
Directional Coupler Cold Test
Coupling between the $\text{TE}_{01}$ mode and the $\text{TE}_{11}$ coupler arm

Since the coupling coefficient for the desired mode is -47 dB, isolation between coupler arm and the unwanted mode is better than -45 dB.
Measured directivity for the TE_{01} Arm
Pumpout design: the set of holes are designed to cancel any coupling or self-coupling for the $\text{TE}_{01}$ and the $\text{TE}_{11}$
Vacuum Pumpout Cold Test

**WC159 Vacuum Pumpout Transmission**

**WC159 Vacuum Pumpout Match**

Amplitude of $S_{11}$ vs. Frequency (GHz)

Amplitude of $S_{21}$ vs. Frequency (GHz)
Dual Moded Delay line occupy only half the length of a single moded delay line
Dual-Moded Delay Line

Dual-moding the delay lines cuts their required length approximately in half.

\[ L = \frac{T v_{g1} v_{g2}}{2 v_{g1} + v_{g2}} \]

- input taper
- 17.08 cm delay line
- ~29 m long
- end taper
- mode converter / tuning short

Diagram:
- TE_{01}
- TE_{02}
- TE_{02}
- TE_{01}
Reflective TE\(_{01}/\)TE\(_{02}\) Mode Converter

R = 4.1275 cm

Vacuum feed-through plunger

\[
S = \begin{pmatrix}
\frac{e^{i\phi} - \cos \theta}{2} & -\frac{e^{i\phi} - \cos \theta}{\sqrt{2}} \\
-\frac{e^{i\phi} - \cos \theta}{2} & \frac{e^{i\phi} - \cos \theta}{\sqrt{2}}
\end{pmatrix}
\]

\[
= \begin{pmatrix}
\frac{2 \sin \theta}{\sqrt{2}} & \frac{\sqrt{2}}{\sin \theta} \\
\frac{\sqrt{2}}{\sin \theta} & \cos \theta
\end{pmatrix}
\]

\[
S = \begin{pmatrix}
(P 1 \ M 1) & 0.0102 & 0.9999 \\
(P 1 \ M 2) & 0.9999 & 0.0102
\end{pmatrix}
\]

\[
S_{\text{Freq}} = \begin{pmatrix}
11.2 & 11.3 & 11.4 & 11.5 & 11.6
\end{pmatrix}
\]

\[
\begin{pmatrix}
-40.0 & -30.0 & -20.0 & 0.0
\end{pmatrix}
\]

Frequency (GHz)
Field Pattern within the device. Peak field at 300 MW (one device per transmission line) is 26.6 MV/m. This field is in the middle of the small guide.
End mode converter simulations

End taper and mode converter

<table>
<thead>
<tr>
<th></th>
<th>$\text{TE}_{01}$</th>
<th>$\text{TE}_{02}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(P\ 1\ M\ 1)$</td>
<td>0.0147</td>
<td>0.9999</td>
</tr>
<tr>
<td>$(P\ 1\ M\ 2)$</td>
<td>0.9999</td>
<td>0.0147</td>
</tr>
</tbody>
</table>
End Taper (before the $\text{TE}_01$-$\text{TE}_02$ Mode converter)
Input taper design
Input Taper for a Dual-Moded System

![Image of input taper for a dual-moded system with two plots showing transmitted and reflected signals in dB versus frequency in GHz. The graph includes two curves: one for TE01 transmitted (red) and one for TE02 reflection (blue).]
Measured Delay through 75 feet of WC475 waveguide terminated with a flat plate. The round trip delay time is 154 ns

Measured delay through 75 feet of WC475 waveguide terminated with a TE01-TE02 Mode converter. The round trip delay time is 320 ns
Multimoded Taper Cold Test
Measured frequency response and constructed time response of the dual-modded taper assembly.
Measured Response of the dual-mode SLED-II Pulse compression system at a compression ratio of 4. Delay line length is ~35 feet. Output pulse width is 150 ns.
Delay Line Cold Tests
Delay Line Cold Tests

Small mid-time-bin steps seen (mode impurity).
Spurious reflection after first round trip (irises removed)

Amplitude oscillation due to interference with slight wrap-around mode launcher mismatch (~-48 dB).

TE01 mode contamination
bottom line: ~-34 dB
top line: ~-26 dB
The wavelengths for these phase oscillations are 14.2 mm and 16.1 mm, respectively.

Measurements show a phase cycle over ~ 16 mm, indicating mode contamination predominantly from the delay lines and tapers.

Slight amplitude oscillations reveal a very small fixed mismatch in wrap-around mode launcher.

Non-periodic amplitude change can be attributed to longer range beating between a small cup error contamination and that from the lines/tapers (60.3 mm).
Problem Fixed by:

• Permutations of tapers

• Adjusting iris distance

• Choosing good resonant position for tuning plunger (3 within range of motion).
System test (1)
Before Closing (gap on top line~1.5 mm)
Signal Amplitudes at the Launcher

Time (ns)
Measurements Through The TE01 Arm of the Directional Coupler

![Graph showing measurements through the TE01 arm of the directional coupler. The x-axis represents time (ns) ranging from -1000 to 1000, and the y-axis represents power gain ranging from 0 to 3.2. The graph shows a series of peaks and valleys indicating the power gain over time.]
Power Seen at the TE11 Arm

Power

Time (ns)
Comparison between the signal seen at the TE11 Arm with the signal at the TE01 Arm

$10^3 \times \text{Measured Power at the TE11 Arm}$

$\text{Measured Power at the TE01 Arm}$

Time (ns) vs. Power graph showing the comparison between the two signals.
System test (2)
System Cold Tests

before removing the spacer

resonance between combiner and SLED head

spacer in

spacer removed
16 steps 2 klystrons
High Power Experiments
8-Pack Phase 1
After pulse breakdown
(Loads)
Upper Delay Line end pump
Upper Delay Line Input Pump
Zero Power
421 MW 360 ns
NLC experimental rf pulse compression system

Dualmode Resonant Delay lines ~30m

Output Load Tree

Compressed output > 600 MW 400 ns.

Dual mode waveguide carrying 200 MW

Single mode waveguide input to the pulse compression system; 100 MW/Line for 1.6 µs

RF Input to the 4 50 MW klystrons
System Modifications

- Replaced a pumpout
- Replaced the whole line of WR90
- Cooled down the WR90 with fans
- *Hard wired* the klystrons driver together
Dualmode Resonant Delay lines ~30m

RF Input to the 4 50 MW klystrons

Single mode waveguide input to the pulse compression system; 100 MW/Line for 1.6 µs

Compressed output > 600 MW 400 ns.

Dual mode waveguide carrying 200 MW

Output Load Tree

NLC experimental rf pulse compression system

RF Input to the 4 50 MW klystrons
436 MW 360 ns
Dualmoded SLED-II Performance
December 4, 2003 11 am
TE$_{01}$ - Input TE$_{01}$ - Output
Dualmoded SLED-II Performance
December 6, 2003 1:00 am
TE_{01} - Input TE_{01} - Output

Power (MW)

Time (µs)
Dualmoded SLED-II Processing
$TE_{01}$ - Input $TE_{01}$ - Output

![Graph showing Dualmoded SLED-II Processing](image_url)

- **Input**
- **Output**

- **Power (MW)** axis
- **Time ($\mu$s)** axis

Values:
- Power (MW) range: 0 to 600
- Time ($\mu$s) range: 0 to 2
Error = 100 \times \frac{\text{Detector Measurement} - \text{Calorimetric Measurement}}{\text{Detector Measurement}}
Low-Level RF Architecture

PLL to 11.424 GHz

Bi-phase Modulator

IQ-Modulator

Timing Switch

Voltage-controlled Switch

AFG 1

AFG 1

Computer

Data Acquisition

From High Power rf measurements

Klystron 1

Klystron 2

Klystron 3

Klystron 4

119 MHz

TWT1

TWT2

From High Power rf measurements
Multimoded SLED-II output with feedback

Input

Output

Power (MW)

Time (µs)

Sami Tantawi (1/27/2004)
Full Run One Minute Power Data

30 Hz

Two 26 hrs. gaps w/ no trips.

~357 hrs. @ 30 Hz w/ ~ 156 trips

~357 hrs. @ 30 Hz w/ ~ 156 trips

~455.7 hrs. on total w/ ~272 trips*

~98.75 hrs. @ 60 Hz w/ ~ 116 trips

*“trips” here includes accidental and deliberate human induced interruption of operation.
SLED Breakdown Event
Unclear event
Klystron Breakdown event
Dualmode Resonant Delay lines ~30m

RF Input to the 4 50 MW klystrons

Single mode waveguide input to the pulse compression system; 100 MW/Line for 1.6 µs

Compressed output > 600 MW 400 ns.

Dual mode waveguide carrying 200 MW

NLC experimental rf pulse compression system

Output Load Tree

Dualmode Resonant Delay lines ~30m

RF Input to the 4 50 MW klystrons
Analysis Corrected for SLED Mistuning and Human Interference

SLED Out Power (MW)

Klystron Tear (137)

WG and Tuning (76)

SLED-II
0.03 / hr at 30 Hz
(< 0.08 / hr required)

Hours of High Power Operation
Diode Trip Analysis (Since 2/11)

Out of 211 trips in 365.65 hrs (30Hz equivalent)

- 29 - SLED or Combiner
- 1 - Klystron 5
- 15 - Klystrons 5&6
- 18 - Klystron 6
- 72 - Klystron 7
- 28 - Klystrons 7&8
- 38 - Klystron 8
- 1 – Loads
- 7 - ?

+ dig. Vac. faults
Power Distribution

6 dB directional coupler

4.8 dB directional coupler

3 dB directional coupler

hybrids

structures
Mode Stripper

TE\textsubscript{01} power (to NLCTA)

TE\textsubscript{11} power (to load tree)
3 dB Directional Coupler Cold Test
<table>
<thead>
<tr>
<th>Vg/c</th>
<th>100ns Delay Length (cm)</th>
<th>Losses/100ns (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.119911</td>
<td>359.484</td>
<td>2.78738</td>
</tr>
</tbody>
</table>

\[D_g = 6.725''\]

\[T = 0.1''\]

\[D_i = 3''\]

\[P = 8.500''\]
<table>
<thead>
<tr>
<th>Vg/c</th>
<th>100ns Delay Length (cm)</th>
<th>Losses/100ns (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13649</td>
<td>409.156</td>
<td>2.35132</td>
</tr>
</tbody>
</table>

\[ D_g = 6.725'' \]
\[ T = 0.1'' \]
\[ D_i = 3'' \]
\[ P = 11.5035'' \]
The cell is not matched enough. We can match two cell or structure of several cells by placing the cells at right distance from each to other. But to get more smooth passband is better to match each cell by iris.

Geometry of cell with matching irises.
Total length of SLED-II can be not more then 5m
Wrap-Around Mode Converter for Tap-off, and extraction, tested to 470 MW
Conclusion:

- We have introduced a fully dual mode rf system.
- We have shown design and experimental data for over moded components that propagates two modes at the same time. These components perform all possible functions found in single moded rf systems.
- At the operating frequency of 11.424 GHz, the peak electric field is ~49 MV/m (400 ns) and the peak magnetic field is ~0.17 MA/m (400 ns). This was demonstrated to be low enough for a reliable high power operation of the system.
Conclusion:

• We have introduce a fully dual mode rf system

• We have shown design and experimental data for over moded components that propagates two modes at the same time. These component perform all possible function found in single moded rf systems

• At the operating frequency of 11.424 GHz, the peak electric field is ~49 MV/m (400 ns) and the peak Magnetic field is ~0.17 MA/m (400 ns). This should be low enough for a reliable high power operation of the system (remain to be seen)

• We have invented several new measurement techniques and instrumental components needed for characterizing dual moded rf systems.