NLC High-Power RF
Component Development

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ISG8
SLAC
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8-Pack Phase I Dual Mode SLED-II

4 XL4’s
150-200MW

Klystrons

Height taper
Dual-mode combiner

TE01 or TE11
Circ-rect taper
E-plane bend

Dual-mode directional coupler

Reflective
TE01 → TE02
Mode converter /
tuning plunger

TE01
TE02
TE02
TE01

Iris

Cross potent

H-plane bend

Load trees

Possible add-on

Dual-mode splitter

Mode mixer

Mode-preserving taper

Mode-preserving taper
(TE02 cutoff at small end)

4 XL4’s

All major components will be high-power tested in Phase I of the 8-Pack Project.
Isometric Engineering Graphic
Cross Potent Subassembly

- rect.↔circ. converters
- jog converters
- width tapers
- dual-mode combiner
- height tapers
- pump-out screen
Breakdown Threshold Measurements for Copper Waveguide

Max. surface electric field [MV/m]

- circles - high magnetic field waveguide
- boxes - low magnetic field waveguide

Time [ns]

Electric Field (MV/m)

0 20 40 60 80 100

Pulse Width [ns]

0 200 400 600 800 1000 1200 1400

V.A. Dolgashev, S.G. Tantawi, SLAC
Pulsed Heating
Redesigned Magic H Hybrid

All corners radiused to 1/16”.

@ 150 MW,
0.800” height:
|E_s max| = ~30.5 MV/m
|H_s max| = ~113 kA/m

0.400” to 0.800” Height Taper
@ 150 MW,
|E_s max| = ~35.2 MV/m
|S_{11}| = -47 dB
Alternative Design Attempt

@ 600 MW,
0.800” height:

$|E_{\text{max}}| = \approx 43.6 \text{ MV/m}$

$|H_{\text{max}}| = \approx 131 \text{ kA/m}$
Height Tapers (0.400”→1.435”)

rounded stepped height taper

@ 75 MW  $|E_{\text{max}}^s| = \sim 48.4 \text{ MV/m}$
$|H_{\text{max}}^s| = \sim 58.9 \text{ kA/m}$

septum height taper

@ 75 MW  $|E_{\text{max}}^s| = \sim 32.8 \text{ MV/m}$
$|H_{\text{max}}^s| = \sim 57.5 \text{ kA/m}$
Height Tapers (cont.)

<table>
<thead>
<tr>
<th></th>
<th>(P 1 M 1)</th>
<th>(P 2 M 1)</th>
<th>(P 2 M 2)</th>
<th>(P 2 M 3)</th>
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<td>(P 1 M 1)</td>
<td>0.0093</td>
<td>0.9998</td>
<td>0.0048</td>
<td>0.0157</td>
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<td>0.5662</td>
<td>0.824</td>
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</table>

@ 75 MW  \[|E_{\text{max}}^s| = \sim 25.0 \text{ MV/m}\]
\[|H_{\text{max}}^s| = \sim 54.8 \text{ kA/m}\]

blended arc height taper
Dual-Mode Combiner/Splitter

@ 600 MW  \(|E_s^{\text{max}}| = \sim 49.3 \text{ MV/m}\)

\(|H_s^{\text{max}}| = \sim 277 \text{ kA/m?}\)

(unrounded point)

@ 600 MW  \(|E_s^{\text{max}}| = \sim 45.5 \text{ MV/m}\)

\(|H_s^{\text{max}}| = \sim 113 \text{ kA/m}\)
Jog Converter and Bend Converter

@ 600 MW  $|E_s| \max = \sim 37.5 \text{ MV/m}$

$|H_s| \max = \sim 82.4 \text{ kA/m}$

@ 600 MW  $|E_s| \max = \sim 37.8 \text{ MV/m}$

$|H_s| \max = \sim 83.8 \text{ kA/m}$
Mode Mixer

@ 600 MW

$|E_{\text{max}}^s| = \sim 37.2 \text{ MV/m}$

$|H_{\text{max}}^s| = \sim 83.0 \text{ kA/m}$

needs refinement.
Cross Potent Superhybrid as a Dual-Mode Launcher

@ 600 MW
\[ |E^s_{\text{max}}| = \sim 42.9 \text{ MV/m} \]
\[ |H^s_{\text{max}}| = \sim 190 \text{ kA/m} \]

@ 600 MW
\[ |E^s_{\text{max}}| = \sim 38.4 \text{ MV/m} \]
\[ |H^s_{\text{max}}| = \sim 104 \text{ kA/m} \]
8-Pack Phase I Cross Potent

short (vacuum screen) @ 150 MW

$|E_{\text{max}}^s| = \sim 29.8 \text{ MV/m}$

$|H_{\text{max}}^s| = \sim 190 \text{ kA/m}$

@ 150 MW SLEDed to 600MW

$|E_{\text{max}}^s| = \sim 48.5 \text{ MV/m}$

$|H_{\text{max}}^s| = \sim 256 \text{ kA/m}$

(depending on phase of reflected wave)

This configuration allows SLEDed (TE$_{01}^\circ$) and unSLEDed (TE$_{11}^\circ$) operation and (with an additional mode mixer and SLED-II iris removed) BPC operation.

will improve with mode mixer refinement.
Width Taper (0.900”→1.442”)

@ 600 MW  \( |E_{\text{max}}| = \sim 36.8 \text{ MV/m} \)
\( |H_{\text{max}}| = \sim 106 \text{ kA/m} \)

\[
\begin{array}{ccc}
(P 1 M 1) & (P 2 M 1) & (P 2 M 2) \\
(P 1 M 1) & 0.0001 & 1 \quad 8.586e-006 \\
(P 2 M 1) & 1 & 0.0001 \quad 8.587e-006
\end{array}
\]

@ 600 MW  \( |E_{\text{max}}| = \sim 37.1 \text{ MV/m} \)
\( |H_{\text{max}}| = \sim 116 \text{ kA/m} \)

\[
\begin{array}{ccc}
(P 1 M 1) & (P 2 M 1) \\
(P 1 M 1) & 0.0050 & 1 \\
(P 2 M 1) & 1 & 0.0060
\end{array}
\]
H-Plane Bend and E-Plane Bend

@ 600 MW
$|E_{s\text{ max}}| = \sim 36.7 \text{ MV/m}$
$|H_{s\text{ max}}| = \sim 81.3 \text{ kA/m}$

@ 300 MW
$|E_{s\text{ max}}| = \sim 46.3 \text{ MV/m}$
$|H_{s\text{ max}}| = \sim 135 \text{ kA/m}$

R=1.413”

R=1.510”

dual-mode combiner/splitters
Dual-Mode Rectangular-to-Circular Taper

Simulated electric fields (HFSS) of the multi-moded circular to rectangular taper

@ 600 MW $|E_{\text{max}}| = \sim 37$ MV/m

Taper Geometry
Prototype Component Testing

Wraparound mode converter, circular to rectangular taper, jog mode converter, height tapers,
An Assembly to test new components and concepts: height tapers, jog mode converter, circular to rectangular tapers

Frequency response of the assembly ($S_{12}$)  Transmitted pulse through the assembly
Reflection after an approximately 30 ns transmission line

height taper, jog converter, circular-to-rectangular taper

30 ns shorted transmission line

Reflection after an approximately 30 ns transmission line
Dual Mode Circular Waveguide Directional Coupler

Rectangular waveguide for coupling the $\text{TE}_{01}$ mode

Circular Waveguide

Ridge waveguide for coupling the $\text{TE}_{11}$ 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 Mode Directional Coupler
Coupled Waveguide Matching

End taper for TE\textsubscript{11} coupler

End taper for the TE\textsubscript{01} coupler
Directional Coupler Response

$\text{TE}_{01}$ directional coupler response (relative)

Coupler Length = 50.6 cm  
Number of coupling holes = 44

Points represent: $\text{TE}_{11}$, $\text{TE}_{21}$, $\text{TE}_{01}$, $\text{TE}_{31}$

$\text{TE}_{11}$ directional coupler response (relative)

Coupler Length = 38.3 cm  
Number of coupling holes = 51

Points represent: $\text{TE}_{11}$, $\text{TE}_{21}$, $\text{TE}_{01}$, $\text{TE}_{31}$
Reflective TE\textsubscript{01}/TE\textsubscript{02} Mode Converter

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

\text{Frequency (GHz)}: \begin{array}{c}
11.2 \\
11.3 \\
11.4 \\
11.5 \\
11.6
\end{array}

\begin{array}{c}
\text{dB} \\
-40.0 \\
-30.0 \\
-20.0 \\
-10.0 \\
0.0
\end{array}

\text{Figure:}
- \text{Reflective TE}_{01}/\text{TE}_{02} \text{ Mode Converter Diagram}
- \text{Frequency Response Plot}
- \text{S Matrix Representation}
Demonstration of Multimoded Reflective Delay Line

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 TE<sub>01</sub>-TE<sub>02</sub> Mode converter. The round trip delay time is 320 ns.

S. Tantawi
Dual Mode Input Stepped Taper

- Dual Mode Input Stepped Taper
- Frequency [GHz]
- R [in]
- Z [in]
- dB
- TE01 Transmitted
- TE02 Reflection

Graphs showing the transmission and reflection characteristics for TE01 and TE02 modes as a function of frequency and position.
Dual Mode End Stepped Taper

End Taper (before the $TE_{01}$-$TE_{02}$ Mode converter)
Delay Line Losses

Ohmic attenuation constants versus copper waveguide diameter for $TE_{01}$ and $TE_{12}$

Average delay line ohmic loss efficiency factor for dual-modeled $TE_{01}/TE_{12}$ DLDS systems with compression ratios of four and eight and for single moded DLDS versus delay line diameter.
Generalized Telegraphist’s Equations

Mode coupling due to small perturbations of the circular waveguide wall can be analyzed by Fourier decomposing the deformation in $\phi$ and then integrating a set of coupled first-order differential equations along $z$. (see e.g. J.L. Doane, “Polarization converters for circular waveguide modes,” Int. J. Electronics, 1986, vol. 61, no. 6, pp. 1109-1133.)

$$r(\phi, z) = a + \delta(\phi, z)$$

$$\delta(\phi, z) = a_0^c(z) + \sum_{l=1}^{\infty} \left[ a_l^c(z) \cos l\phi + a_l^s(z) \sin l\phi \right]$$

ordinary polarization:

$$\frac{d}{dz} A_n^c(z) = \sum_n \left[ K_{mnc}^{oo} a_{p-q}^c(z) + C_{mnc}^{oo} a_{p+q}^c(z) \right] A_n^c(z)$$

$$+ \left[ K_{mnc}^{ox} a_{p-q}^s(z) + C_{mnc}^{ox} a_{p+q}^s(z) \right] A_n^s(z) \right] e^{i\delta_{mn} z}$$

cross polarization:

$$\frac{d}{dz} A_n^s(z) = \sum_n \left[ K_{mnc}^{xo} a_{p-q}^s(z) + C_{mnc}^{xo} a_{p+q}^s(z) \right] A_n^s(z)$$

$$+ \left[ K_{mnc}^{xs} a_{p-q}^c(z) + C_{mnc}^{xs} a_{p+q}^c(z) \right] A_n^c(z) \right] e^{i\delta_{mn} z}$$

except that $a_0^c(z)$ is replaced by $a_0^s(z)$ for diameter variation coupling ($a_0^s \equiv 0$), and $a_i^{c,s}(z)$ are replaced by $a_i^{c,s**}(z)$ for curvature coupling.

p and q are the azimuthal indices of modes m and n.
Mode Conversion Sensitivity

Effect of a Constant .005" a2 Distortion on TE01 in WC354, WC475 and WC672 (r,c,g)

- **Green** – 6.725”
- **Blue** – 4.75”
- **Red** – 3.54”
Dual-Moded DLDS Heads

8×4

8×8
\( \times 4 \) and \( \times 8 \) MDLDS

Normalized Delay Line Length

DLDS4: 1
MDLDS4: 2/3
MDLDS8: 4/3
### Dual-Moded x4 DLDS:

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<th>Feed gaps /x-section</th>
<th>Max. pipes</th>
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### Dual-Moded x8 DLDS:

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<td>20</td>
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8-Pack Phase II MDLDS Schematic

- TE11/TE12 converter
- 400ns delay line
- Solid state modulator
- Klystrons
- Cross potentials
- Extractor
- Dual moded turn-around
- Converter
- Accelerator structures
- Beam direction

C. Nantista