R&D for a Super Compact SLED System at SLAC

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1. Motivation
   • X-Band deflector applications for beam diagnostics at LCLS
   • High RF power needed for Improvement of resolution and future joint usage with LCLS-II
2. Design of Super-Compact SLED System
   • Basic principle of SLED
   • Unified 3db Coupler / Mode convertor / Polarizer
   • High Q spherical cavity
   • Coupler design
   • Assembly
3. Microwave Measurements
4. High Power Operation
5. Summary
1. Motivation

- X-Band deflector applications for beam diagnostics at LCLS
- High RF power needed for improvement of resolution and future joint usage with LCLS-II
Diagnostics Layout of the X-ray Temporal Measurement at the LCLS.
Maximum traverse deflection for one 1m section is $5.46 \sqrt{P_{\text{in}}(\text{MW})}$ MV (Pin is Peak RF Power).

Considering the transmission loss, the maximum total kick for two 1m sections was 45 MV.

- In order to reach higher temporal resolution, using the new SLED system with new 50 MW klystron would double the total kick to 95 MV.
- In the future, the SLED power can be shared with a similar diagnostics system for LCLS II without adding another RF station.
2. Design of Super Compact SLED System

- Basic SLED principle
- Unified 3db Coupler / Mode convertor / Polarizer
- High Q spherical cavity
- Coupler design
- Assembly
Forty-Year Anniversary of S-Band SLED System at SLAC

Key microwave components:
- 3db 90° Hybrid Coupler
- Two energy storage cavities

P. Wilson  G. Loew  H. Hoag  D. Farkas
Original SLED RF System
Transverse Field Distribution in Deflector for SLEDed and Non-SLED Pulses

Deflector Parameters
Structure Length $L = 1.0 \text{ m}$
Transverse $r_\perp = 41.9 \text{ M}\Omega/\text{m}$
(Constant Impedance)

Group Velocity $V_g/c = -3.165\%$
Filling Time $T_f = 106 \text{ ns}$
Attenuation Factor $\tau = 0.62 \text{ Neper}$

X-Band SLED Cavity Parameters
$Q_0 = 10^5$
$\beta = P_e/P_c = Q_0/Q_e \sim 7-8$

If the pulse is flat without SLED
$E = e^{-\tau z/L}$

Beam Direction
RF Feeding Direction
SLED Gain as Function of Coupling $\beta$ for Different Pulse Widths and $Q_0$ Values

Optimized $B \sim 7-8$ for $Q_0 \sim 90k$ Pulse. 1 $\mu$s
Geometry of the New SLED System

Sphere Cavity for Energy Storage

Integrated 3db Coupler/Mode Convertor/Polarizer
Two Rectangular Waveguide Modes Couple to two Polarized Circular Waveguide Modes

TE20→ TE11

TE10→ TE11
Movie to animate the Unified 3db Coupler/Mode Convertor/Polarizer

Superposition of Two Linear Polarized TE11 Modes with 90° quadrature

TE10 Mode input from WR90 Waveguide

Mixed TE10 and TE20 Modes

TE10 Mode output to Deflectors via WR90 Waveguide

Notice: Circular port is a matching port without reflection in this simulation
Movie to animate the Unified 3db Coupler/Mode Convertor/Polarizer

Deflectors via WR90 Waveguide
Wave potential of TE Modes

\[(F_r)_{mnp} = \hat{J}_n(u_{np} \frac{r}{a}) P_n^m(\cos \vartheta) \left\{ \begin{array}{c} \cos m\varphi \\ \sin m\varphi \end{array} \right\} \]

where \( \hat{J}_n \) is sphere Bessel Function and \( P_n^m \) are associated Legendre Polynomials \( m \leq n \)

1st interesting property:
Sphere radius \( a \) is independent of mode index \( m \), there are numerous degeneracies because \( \hat{J}_n(u_{np}) \) is independent of \( m \).

For TE mode, the \( E_\varphi = H_\theta = 0 \) at surface \( r=a \).
It means \( \hat{J}_n(u_{np})=0 \). The following table shows the lower order modes.

<table>
<thead>
<tr>
<th>( n )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<th>6</th>
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<td>4</td>
<td>17.221</td>
<td>18.689</td>
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</table>

Sphere radius can be calculated using wave propagation constant \( k \) and value of \( u_{np} \)

\[ a = \frac{u_{np}}{k} = \frac{c \times u_{np}}{k} = 0.41767u_{np} \]
Examples for TE Mode Studies

Where the Legendre Function $P_{m}^{n}$ has $m \leq n$
If we select TE$_{0np}$ mode, the degeneracy possibility is only 0 and 1
TE Modes in Sphere Cavity - II

Practically, let’s choose TE_{m14} modes. There are three possible modes:

\[ (F_r)_{014} = \frac{r}{a} J_1(14.066 \frac{r}{a}) \cos \theta \]

\[ (F_r)_{114} = \frac{r}{a} J_1(14.066 \frac{r}{a}) \sin \theta \cos \varphi \]

\[ (F_r)_{114} = \frac{r}{a} J_1(14.066 \frac{r}{a}) \sin \theta \sin \varphi \]

For perfect spherical cavity, these three modes have the same mode patterns except that they are rotated 90° in space from each other.

In reality, they can be slightly distinguished in frequencies due to the perturbation from the different coupling in the coupler port. The TE_{014} mode is higher in frequency and could hardly be excited by the feeding orientation.

2\textsuperscript{nd} interesting properties:

Q\textsubscript{0} only depends on sphere radius, and is independent on the mode type.

Quality Factor for TE Modes \[ Q = \frac{a}{\delta} \]

\( \delta \) is the skin depth (for Copper 0.61\,\mu m)

Examples:
For TE_{014} mode a=5.8749 cm \( Q = 0.963 \times 10^5 \) \( \text{SLED Gain larger than 2.} \)
Coupling between Sphere Cavity and Circular Waveguide

Nearest mode is TE014 mode is weekly under coupled to the circular waveguide

One of the two TE114 mode, they are strongly over coupled to the circular waveguide
Mode Animation of the SLED System

TE10 Mode input from WR90 Waveguide
TE10 Mode output to Deflectors via WR90 Waveguide

Sphere Cavity for Energy Storage

Integrated 3db Coupler/Mode Convertor/Polarizer
Fat Coupling Iris between Spherical Cavity and Circular Waveguide for Low Pulse Heating

Earlier paper design with thinner iris with pulse heating of 84°C (1μs, 120 pps).

Real design with fat iris with pulse heating of 42°C (1μs, 120 pps).
Assembly of the 3db Coupler/ Mode Convertor/Polarizer
X-Band SLED System

Mechanical Design

Fabricated Assembly
3. Microwave Measurements

- Performance of Unified 3db Coupler / Mode Convertor / Polarizer
- Performance of SLED System
Transmission Measurement for Two Back-to-Back Polarizers, Coefficient Better Than 99%

More than 100 MHz broad pass band to insure stable operation

Port 1 of Polarizer 1 to Port 2 of Polarizer 1:
-0.5 dB

Port 2 of Polarizer 1 to Port 1 of Polarizer 1:
-0.45 dB
Reflection Measurement for Two Back-to-Back Polarizers, Negligible Reflection to Power Source

Reflection from Port 1 of Polarizer 1
-51.4 dB

Reflection from Port 2 of Polarizer 1
-49.0 dB
Isolation Measurement for Two Back-to Back Polarizers, Good Isolation of Power Source / Load

Port 1 of Polarizer 1 to Port 2 of Polarizer 2

-30.8 dB

Port 2 of Polarizer 1 to Port 1 of Polarizer 2

-30.9 dB
Proof

Reflection from Port 1 of Polarizer 1

-51.4 dB
Microwave Measurement Setup for the SLED System
Final SLED Frequency to Be Tuned to Exactly 11424 MHz for Vacuum, @ 20.0 C°

Theoretical Design Simulation Showing Both SLED Working Modes and Next Mode.

Measured SLED Working Modes: 
$Q_0$ 94000 and $\beta$ 7.8

Next Mode: 
7 MHz higher, far undercoupled
Perfect consistency Between Design Simulation and Microwave Measurement

Smith Chart for Theoretical Design Simulation Showing Both SLED Working Modes and Next Mode.

Smith Chart for Measured SLED Working Modes:
Q0 94000 and $\beta$ 7.8
Next Mode:
7 MHz higher, far undercoupled

There is a phase rotation due to the NWA cable length.
4. High Power Operation
Installation at Building 921 of the LCLS
High Power Operation of SLED System

Theoretical Calculation

\[
\int_{0}^{1.5} P(t) \, dt = 3.925 \\
\frac{1.335}{0.165} = 7.578
\]

High power Test

RF pulse width 1.5 μs, flip phase in last 165 ns
Average klystron output power 31.2 MW
SLEDed average power 132 MW
Peak SLEDed power 206.6 MW

Brown is klystron output, white is SLED output, blue and green are reflected signals with different scale.
Excellent High Power Operation achieved with New SLED System

- As predicted, Output RF power increased by factor of four with new X-Band SLED system.
- Maximum transverse kick increased from 45 MV to 85 MV at present power level.
- Full klystron power was not reached because of a power line transformer. With a new transformer replaced, we expect to increase the klystron power to reach 50 MW and maximum kick to reach 95 MV (10% more).
- The system has been running very stably without breakdown, sign of pulse heating, outgassing and no contact radiation observed around the SLED cavity.
5. Summary

Broad applications in the future

• Customers for the X-Band SLED system are coming.
• Other frequency applications for C- and S- Band are in the consideration.
• Possibilities for flat top pulse compression systems are under studies
• Brand new compact high power devices including variable attenuators, variable phase shifters and many other useful applications can be developed.