R&D for a Super Compact SLED System at SLAC

Juwen W. Wang, Sami G. Tantawi, Chen Xu, Matt Franzi, Patrick Krejcik, Gordon Bowden, Shantha Condamoor, Yuantao Ding, Valery Dolgashev, John Eichner, Andrew Haase, James R. Lewandowski, Liling Xiao

SLAC National Accelerator Laboratory

May 9, 2016

IPAC2016

Busan, Korea

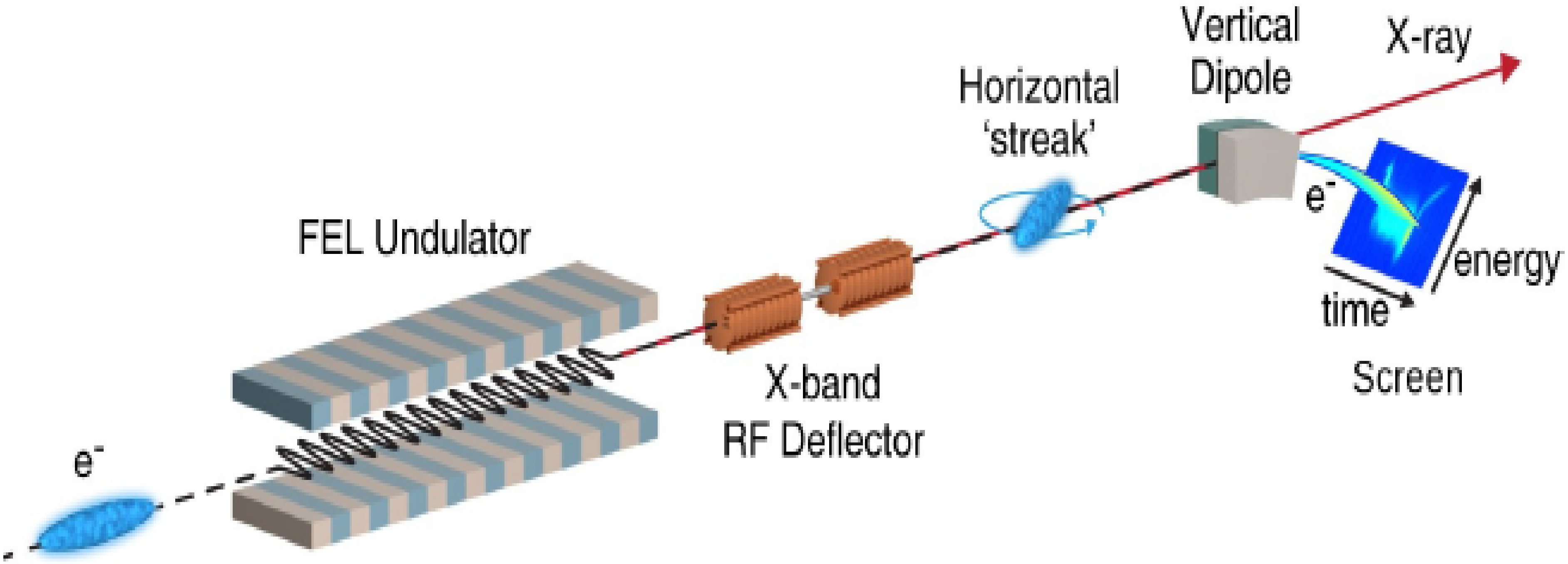
Outline

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.



Improve Beam Diagnostics Resolution and Future RF Power Sharing with LCLS-II

Maximum traverse deflection for one 1m section is $5.46\sqrt{P_{in}(MW)}$ MV (Pin is Peak RF Power).

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

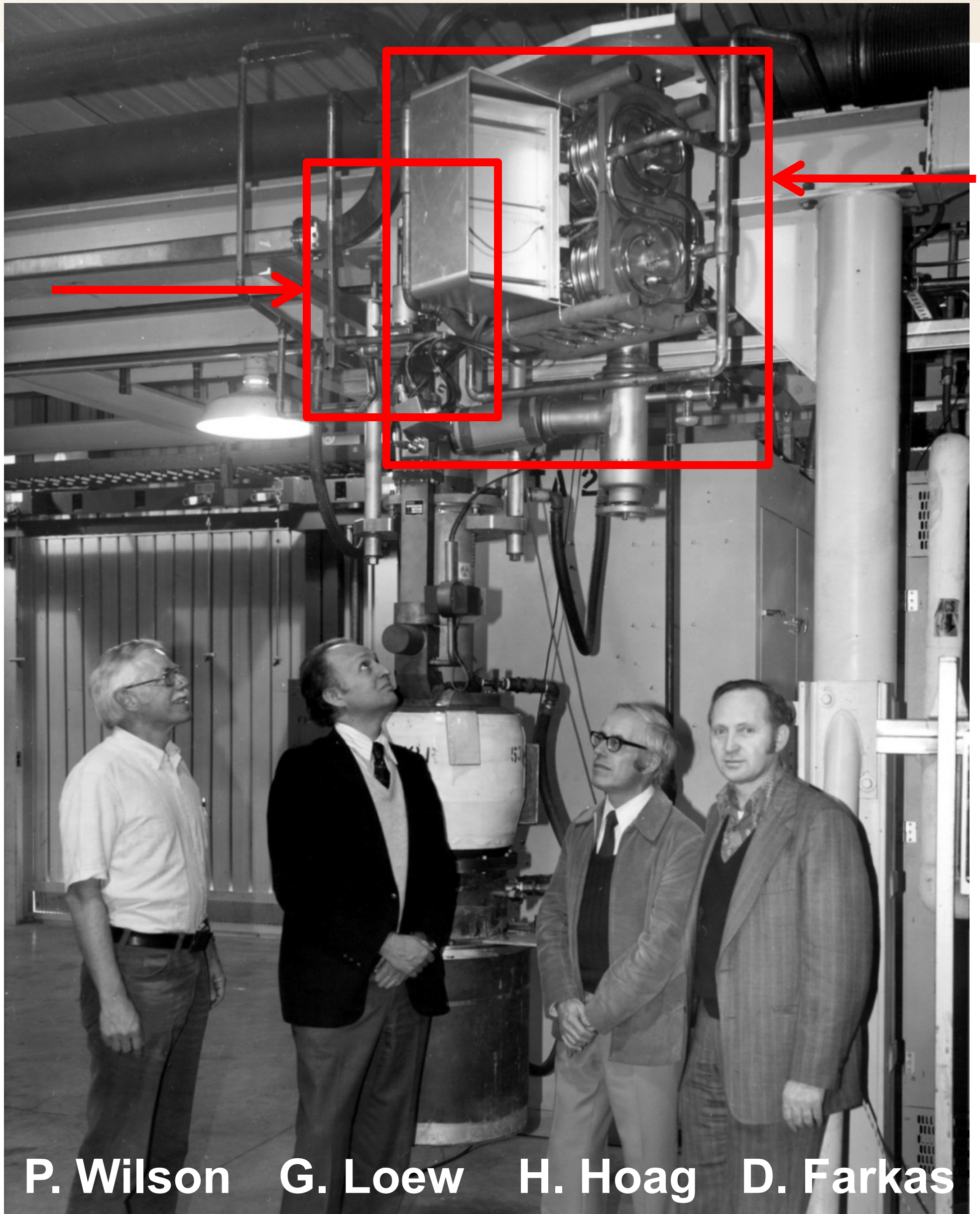
- In order to reach higher temporal resolution, Using the new SLED system with new 50 MW klystron would doule the total kick to 95 MV.
- In the future, the SLED power can be shared with a similar diagnostics system for LCLS II without adding another RF station.

2. Design of Super Compact SLED System

- Basic SLED principle
- Unified 3db Coupler / Mode convertor / Polarizer
- High Q spherical cavity
- Coupler design
- Assembly

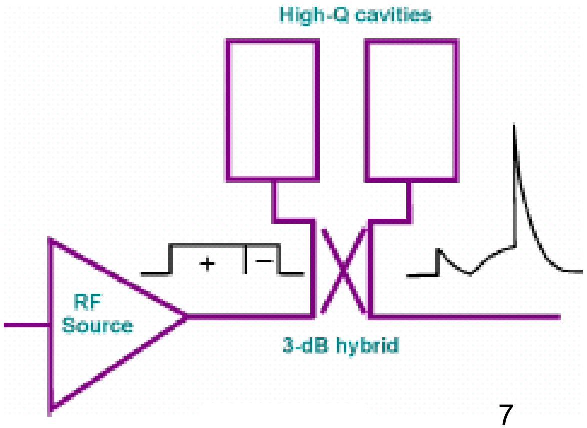
Forty -Year Anniversary of S-Band SLED System at SLAC

3db Coupler

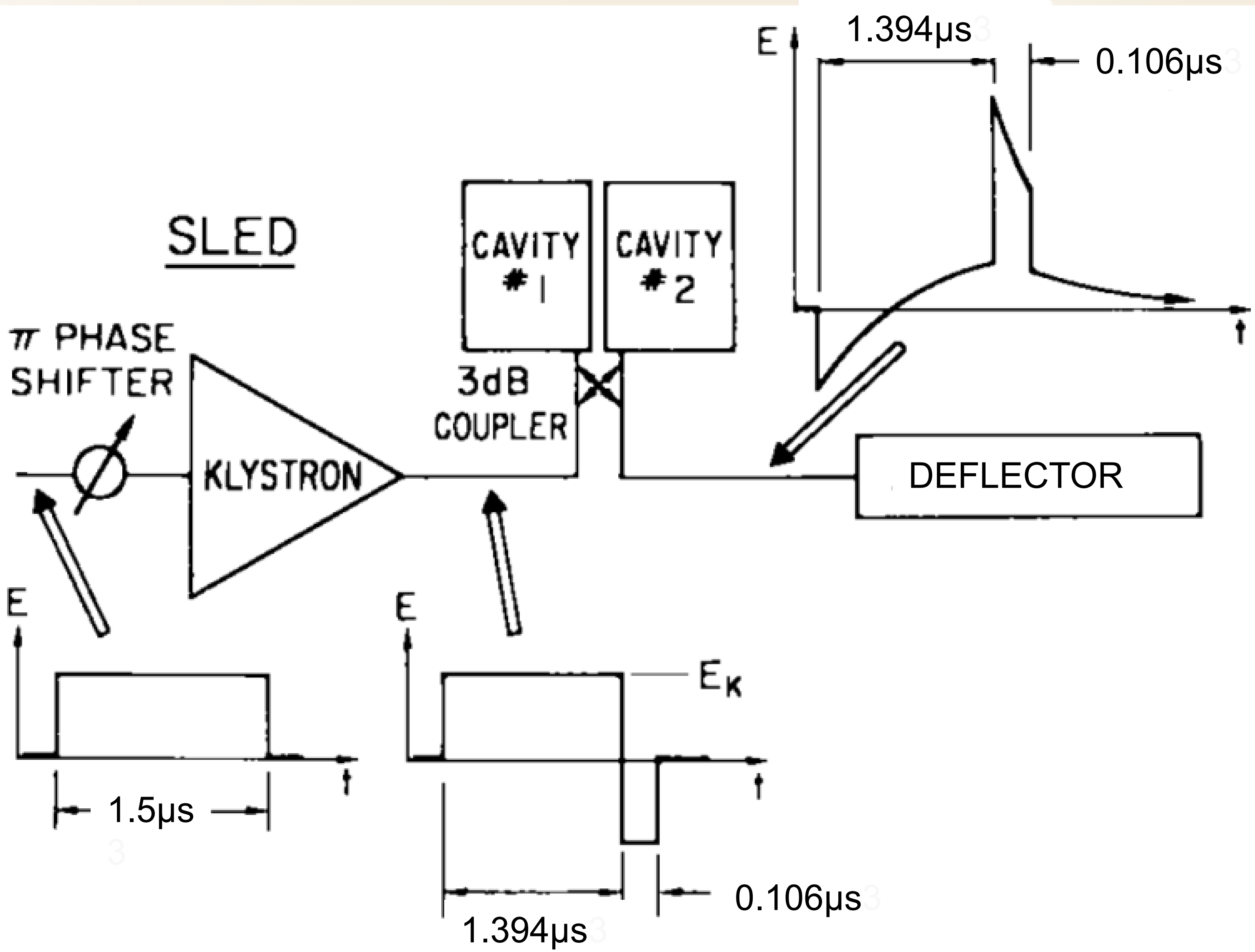


Two SLED Cavities

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



Original SLED RF System



Transverse Field Distribution in Deflector for SLEDed and Non-SLED Pulses

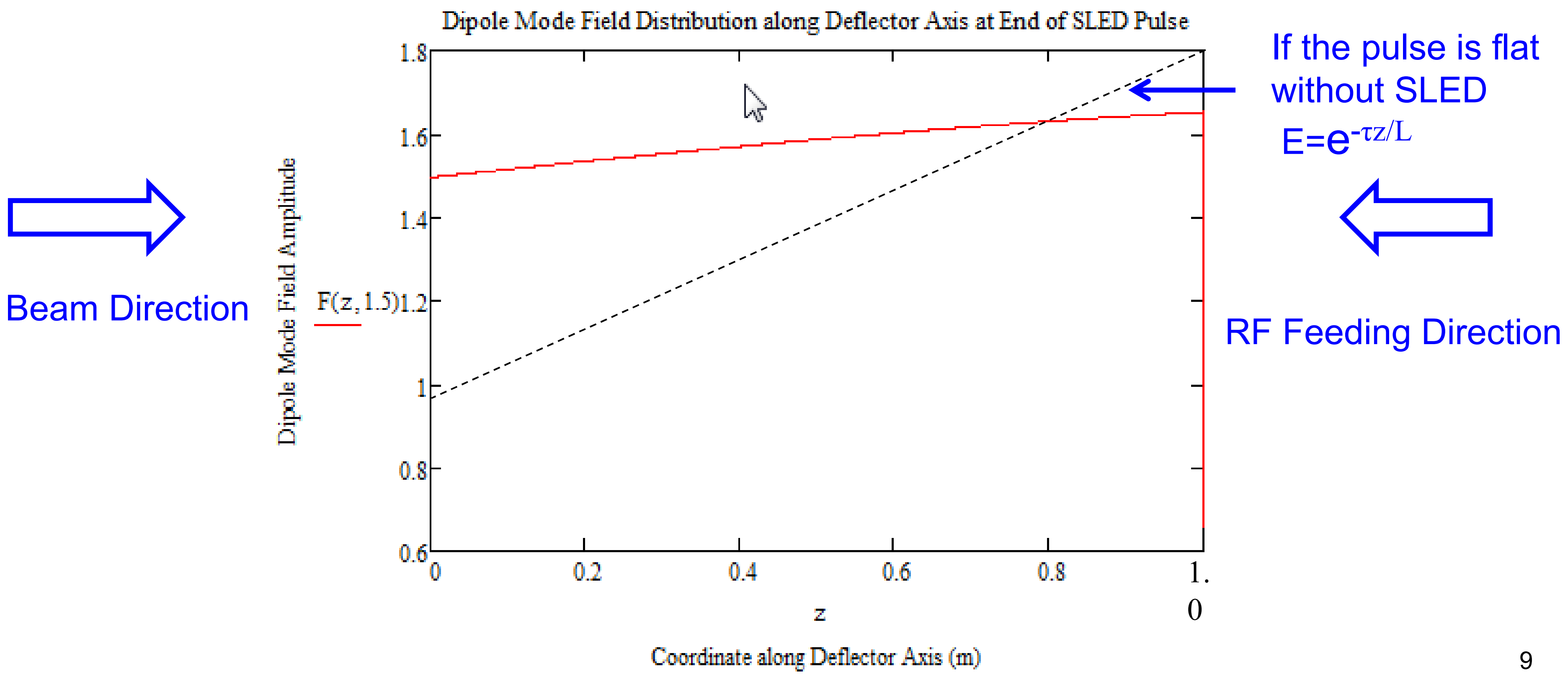
Deflector Parameters

Structure Length L=1.0 m
Transverse $r_\perp$= 41.9 MΩ/m
(Constant Impedance)

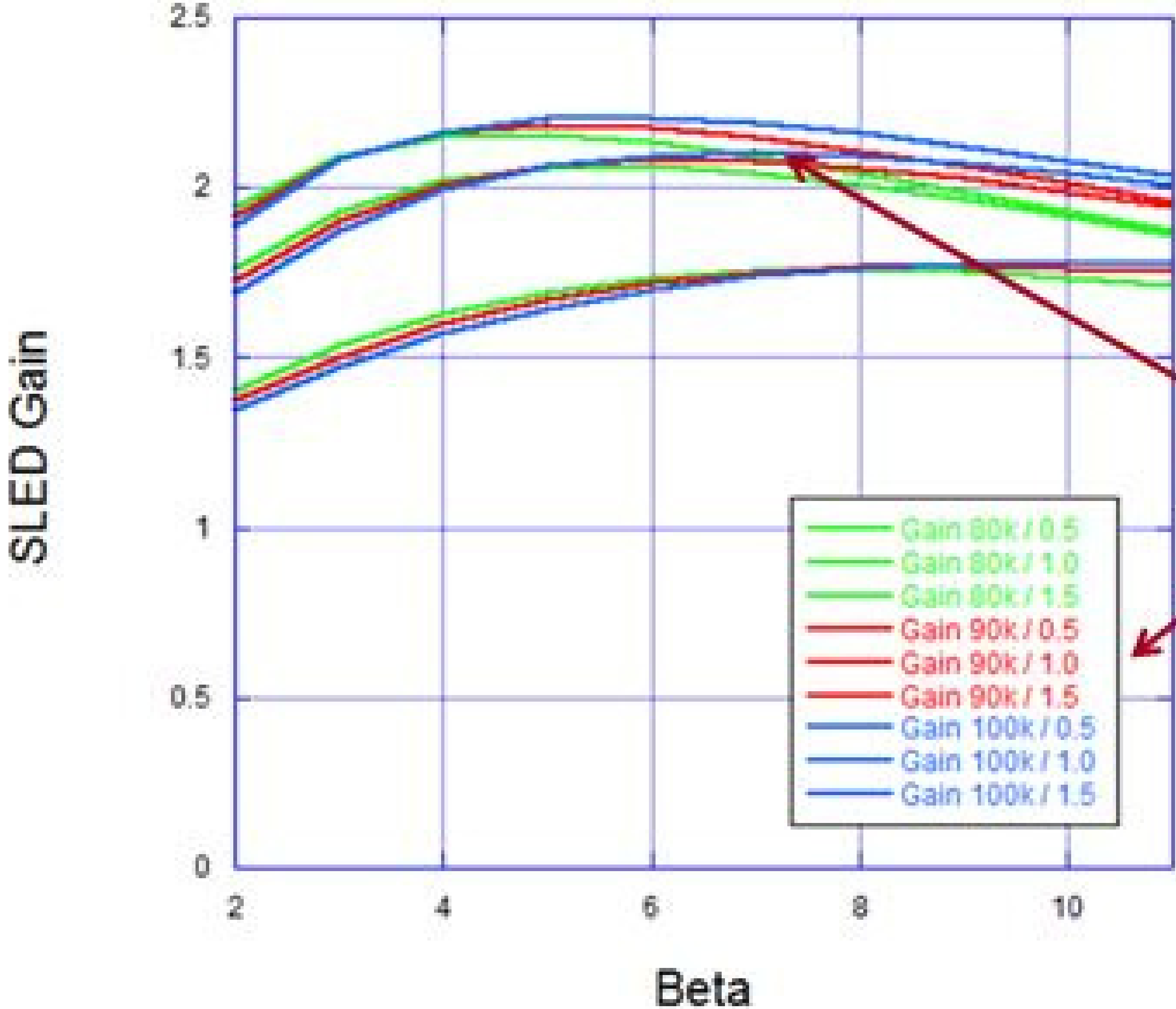
Group Velocity Vg/c=- 3.165 %
Filling Time T_f=106 ns
Attenuation Factor τ=0.62 Neper

X-Band SLED Cavity Parameters

$Q_o = 10^5$
$\beta = P_e/P_c = Q_0/Q_e \sim 7\text{-}8$



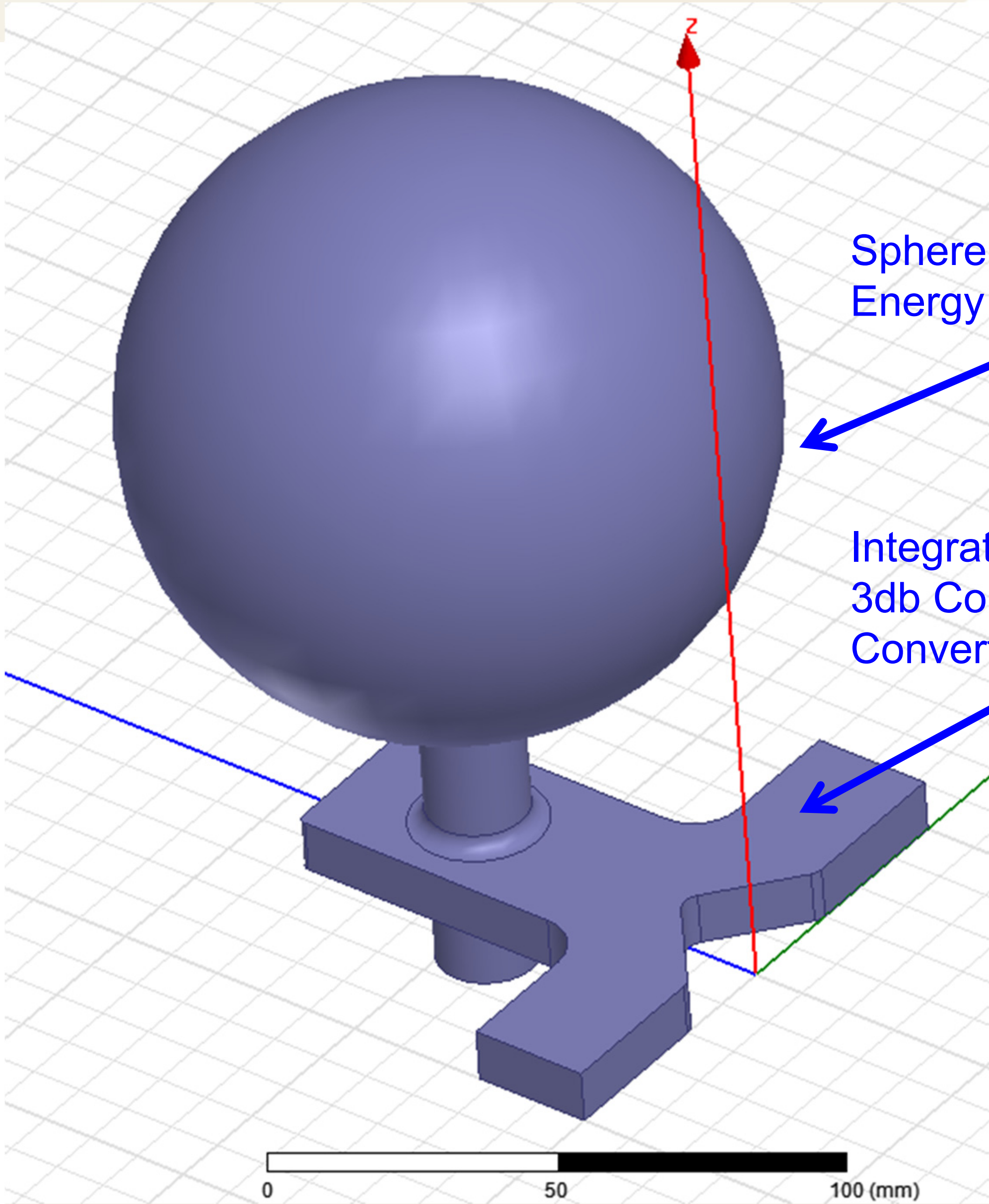
SLED Gain as Function of Coupling β for Different Pulse Widths and Q_0 Values



Optimized
B ~ 7-8
for Q_0~90k
Pulse.1 μs

Geometry of the New SLED System

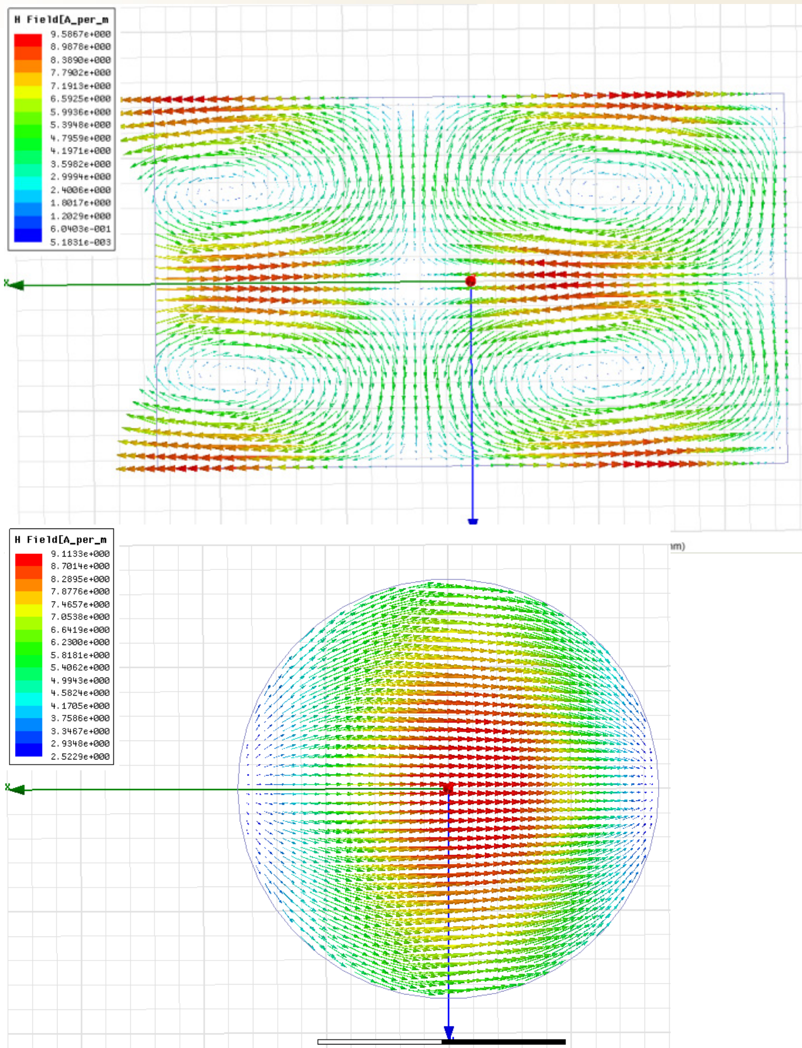
SLAC



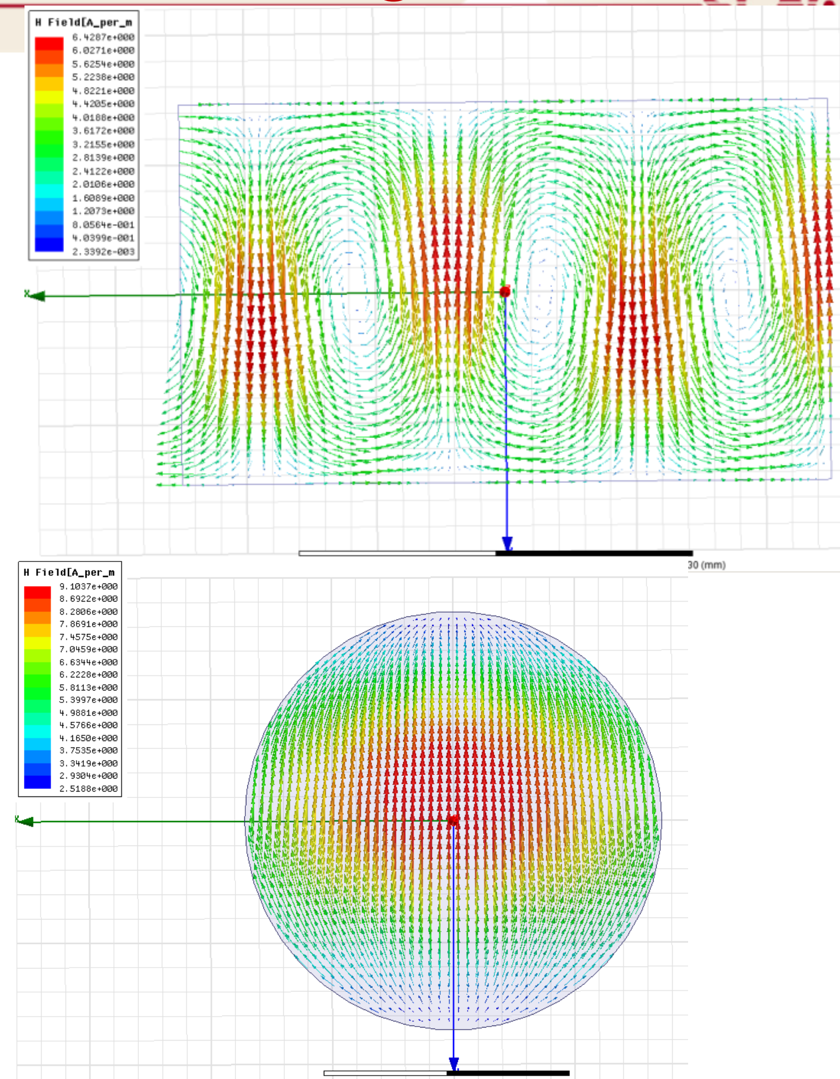
Sphere Cavity for Energy Storage

Integrated
3db Coupler/Mode Convertor/Polarizer

Two Rectangular Waveguide Modes Couple to two Polarized Circular Waveguide Modes

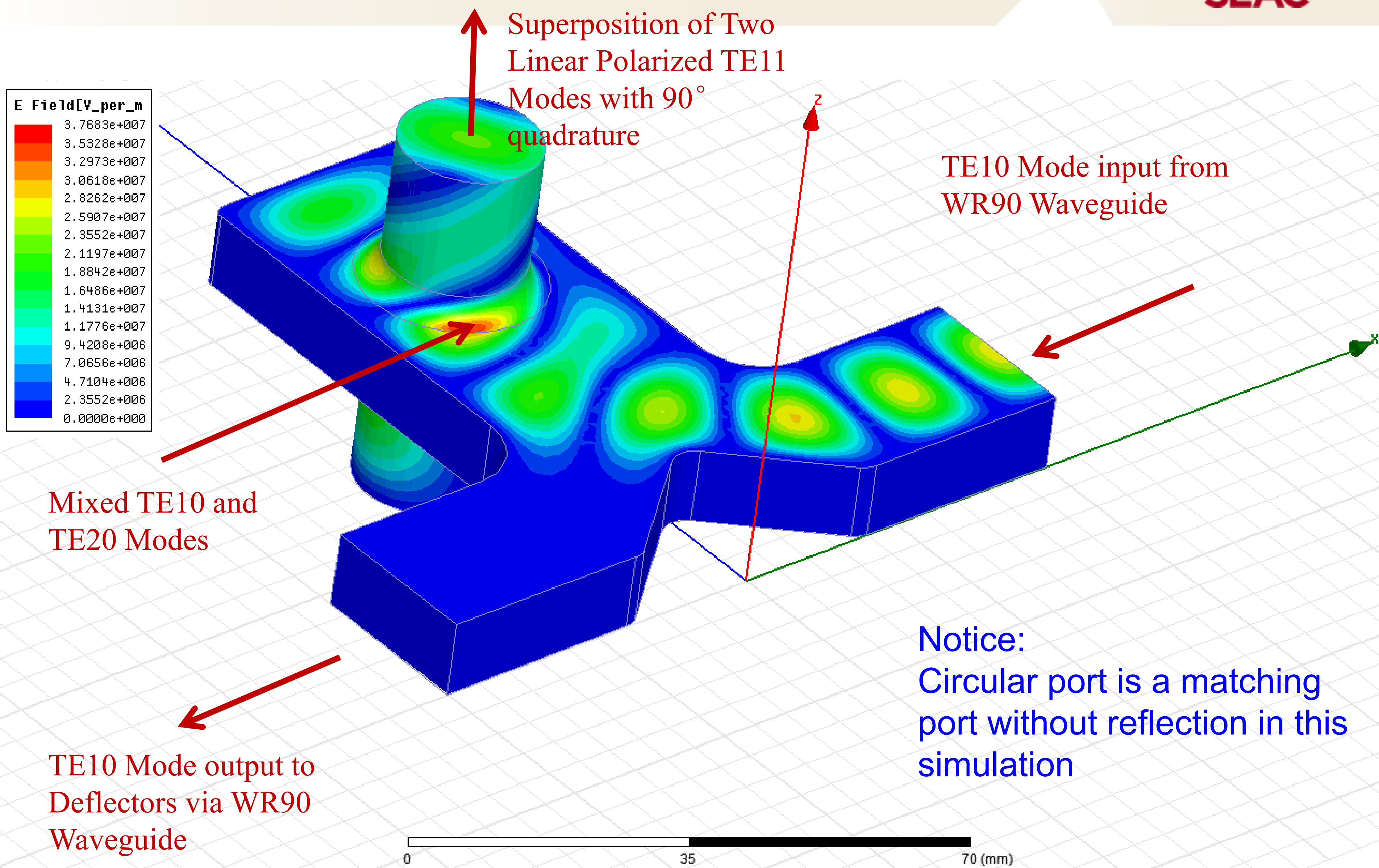


TE20-> TE11

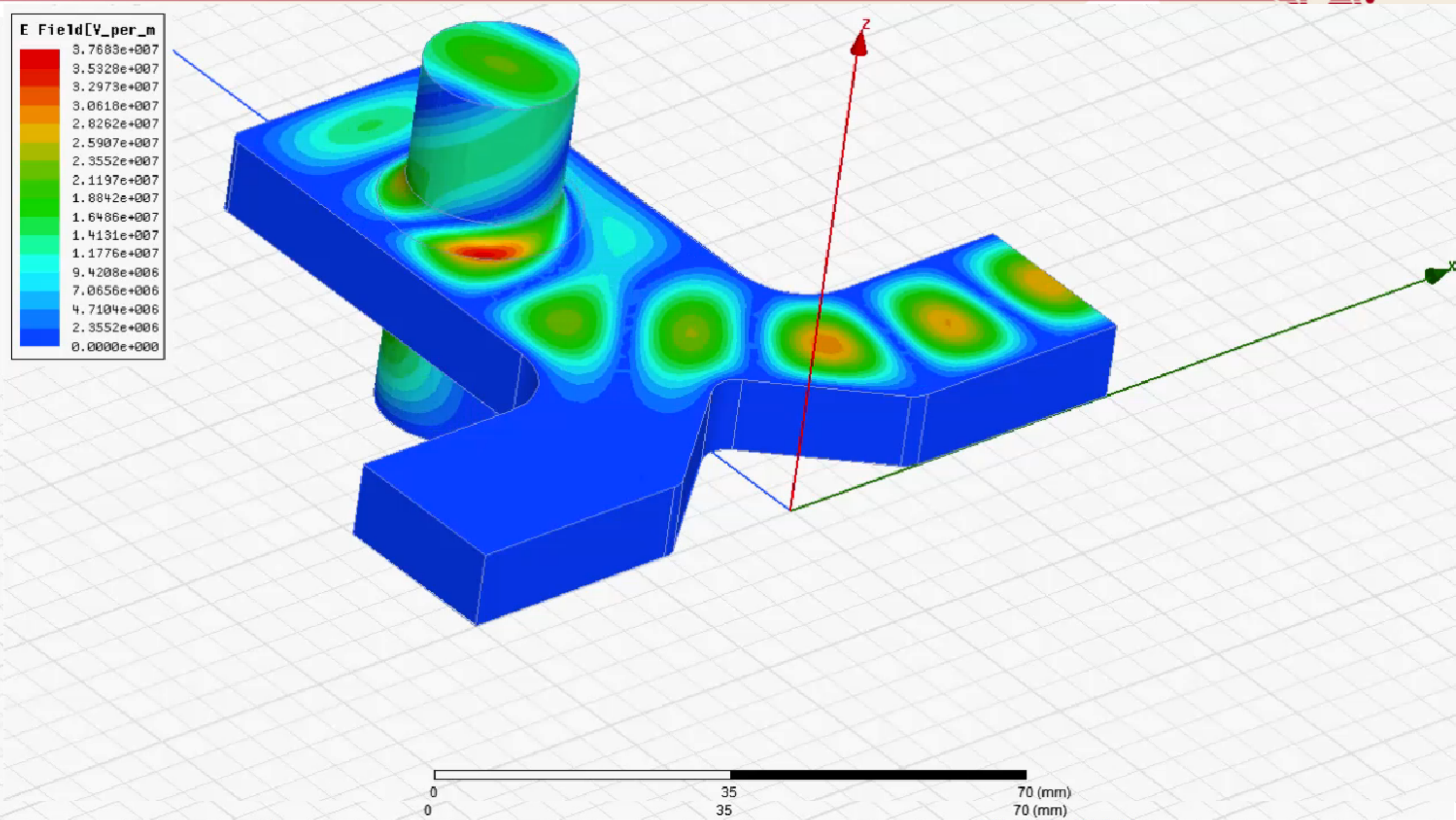


TE10-> TE11

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



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



Deflectors via WR90
Waveguide

TE Modes in Sphere Cavity - I

Wave potential of TE Modes

$$(F_r)_{mnp} = \hat{J}_n(u_{np}\frac{r}{a})\,P^m{}_n(\cos\vartheta)\begin{Bmatrix}\cos m\varphi\\ \sin m\varphi\end{Bmatrix}$$

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.

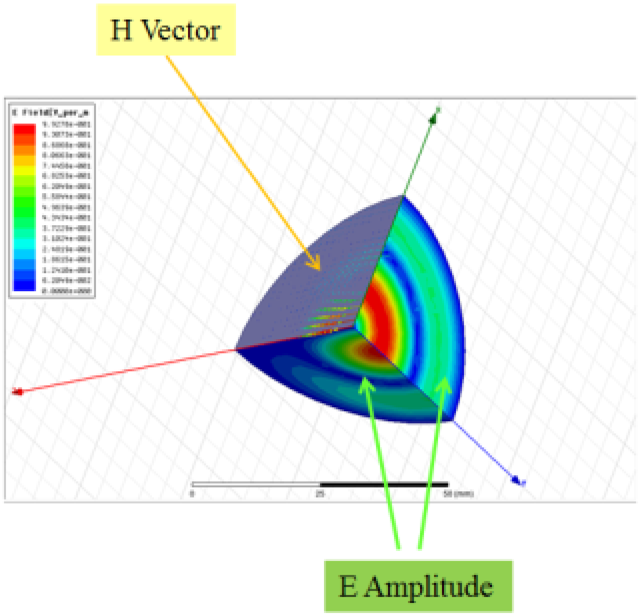
For TE mode, the $E_\varphi = H_\theta = 0$ at surface r=a.
It means $\hat{J}_n(u_{np})=0$. The following table shows the lower order modes.

p \ n	1	2	3	4	5	6	7	8
1	4.493	5.763	6.988	8.183	9.356	10.513	11.657	12.791
2	7.725	9.095	10.417	11.705	12.967	14.207	15.431	16.641
3	10.904	12.323	13.698	15.040	16.355	17.648	18.923	20.182
4	14.066	15.515	16.924	18.301	19.653	20.983	22.295	
5	17.221	18.689	20.122	21.525	22.905			
6	20.371	21.854						

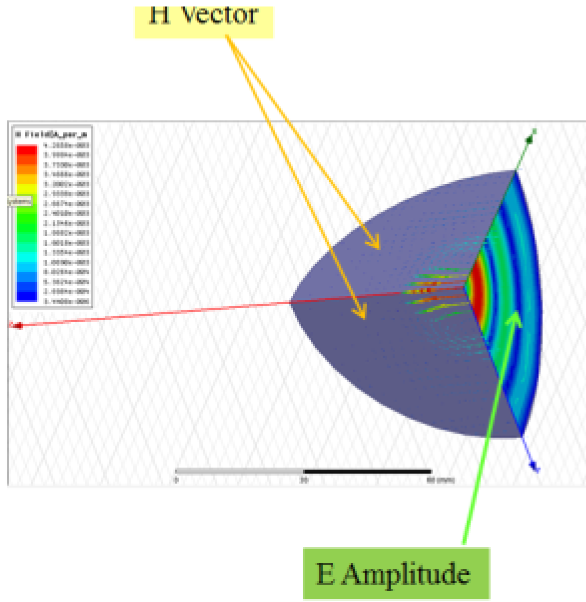
Sphere radius can be calculated using wave propagation constant k and value of u_{np}

$$a = \frac{u_{np}}{k} = \frac{c \times u_{np}}{k} = 0.41767 u_{np}$$

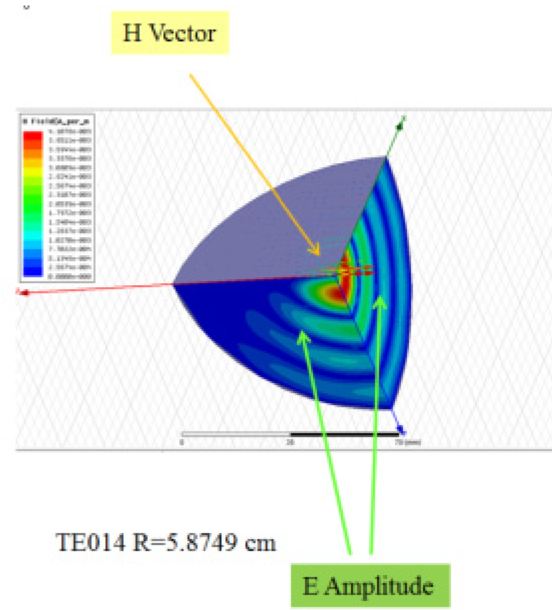
Examples for TE Mode Studies



TE012 R=3.2265 cm



TE013 R=4.5543 cm



TE014 R=5.8749 cm

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 TEm14 modes. There are three possible modes:

$$(F_r)_{014} = \hat{J}_1(14.066\frac{r}{a})\ Cos\vartheta$$

$$(F_r)_{114} = \hat{J}_1(14.066\frac{r}{a})\ Sin\vartheta Cos\varphi$$

$$(F_r)_{114} = \hat{J}_1(14.066\frac{r}{a})\ Sin\vartheta Sin\varphi$$

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.

2nd interesting properties:

Q_0 only depends on sphere radius, and is independent on the mode type.

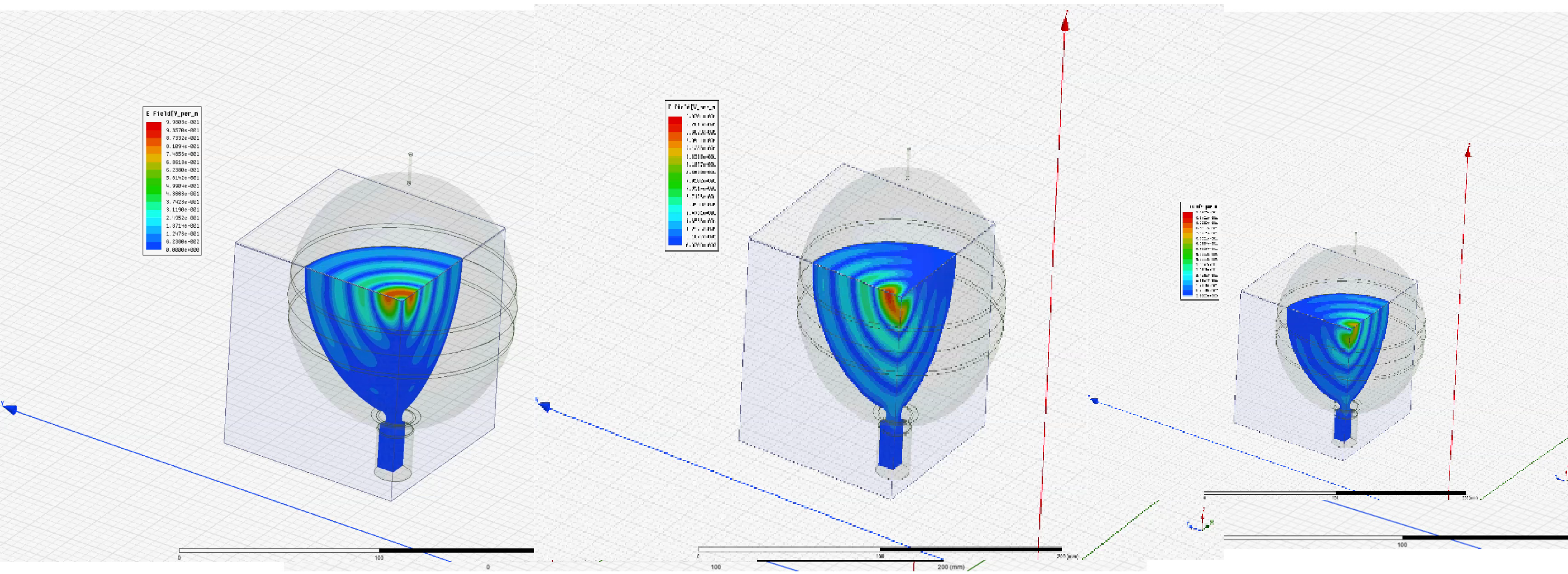
Quality Factor for TE Modes $Q = \frac{a}{\delta}$ δ is the skin depth (for Copper 0.61μm)

Examples:

For TE_{014} mode a=5.8749 cm Q = 0.963x10^5 SLED Gain larger than 2.

Coupling between Sphere Cavity and Circular Waveguide

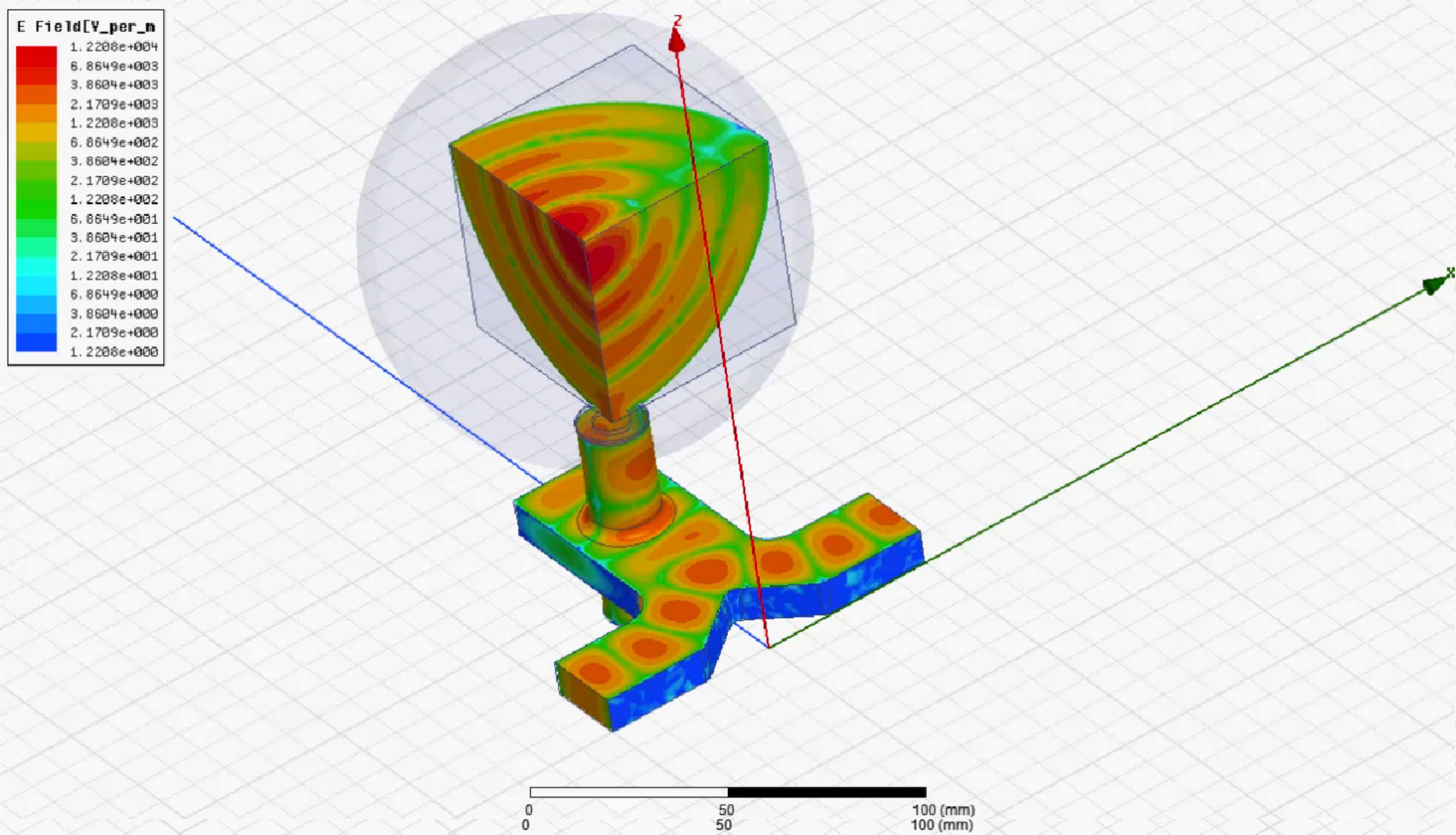
SLAC



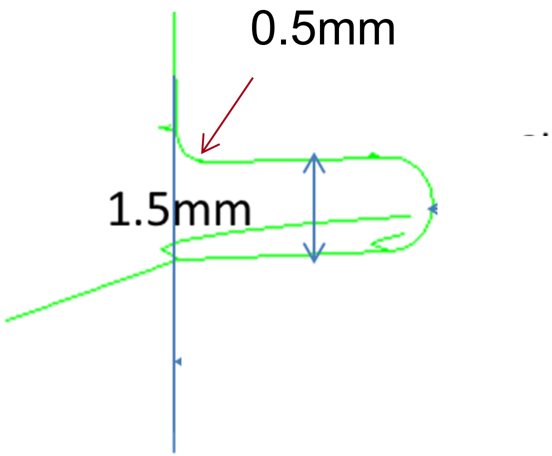
Nearest mode is TE014 mode is weekly under coupled to the circular waveguide

One of the two TE114 mode, they are strongly over coupled to the circular waveguide

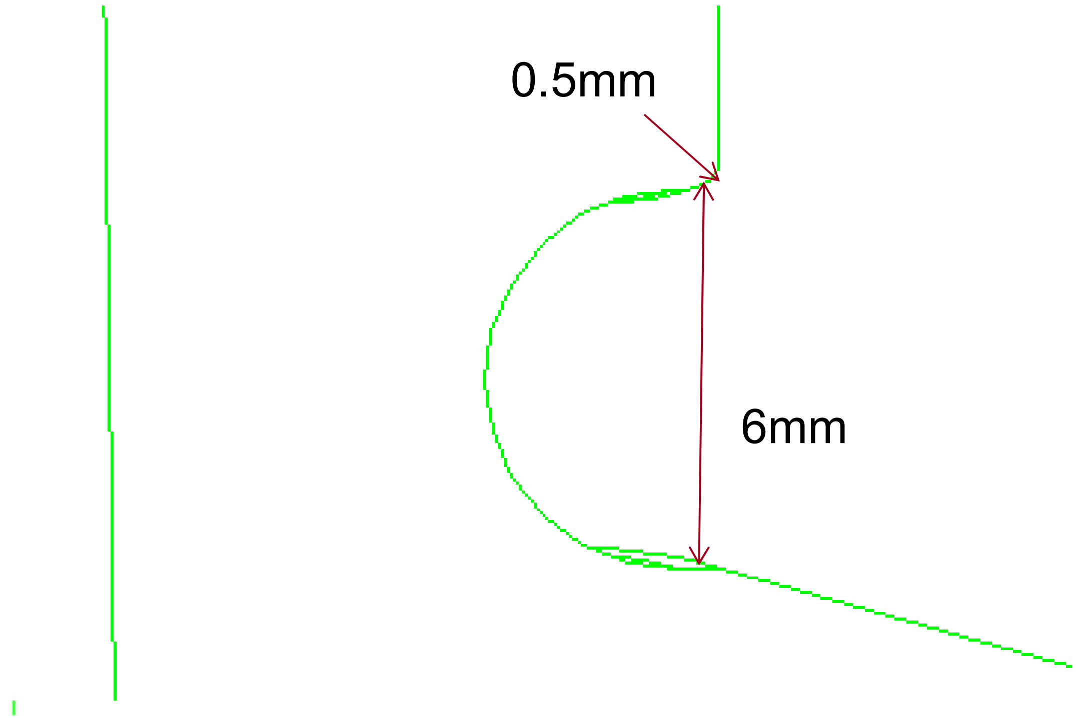
Mode Animation of the SLED System



Fat Coupling Iris between Spherical Cavity and Circular Waveguide for Low Pulse Heating

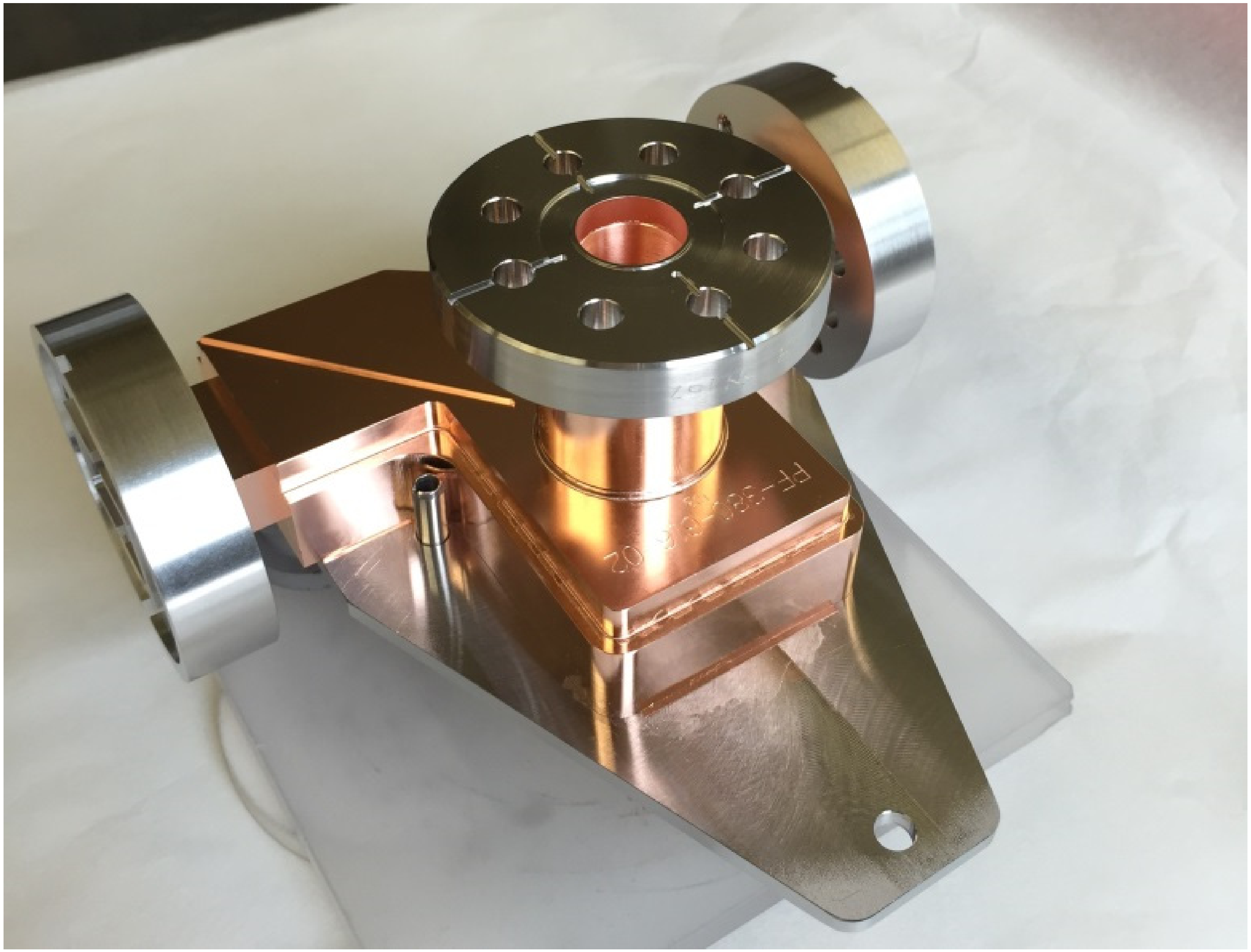


Earlier paper design with thinner iris with pulse heating of 84°C (1μs, 120 pps).

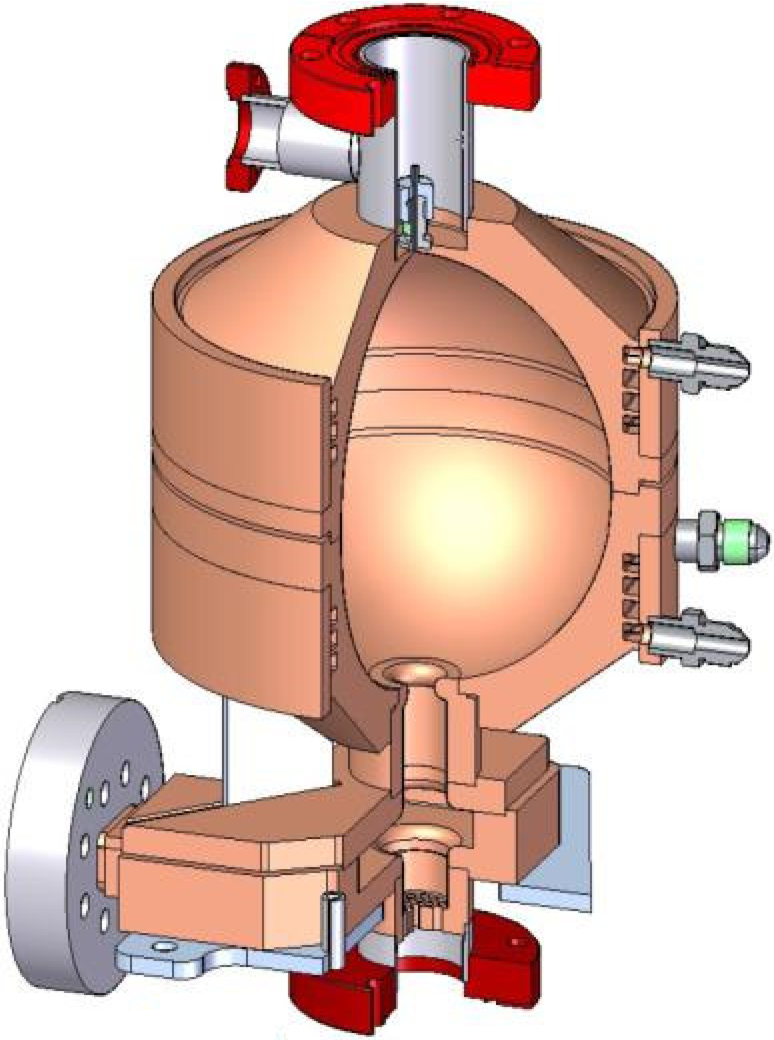


Real design with fat iris with pulse heating of 42°C (1μs, 120 pps).

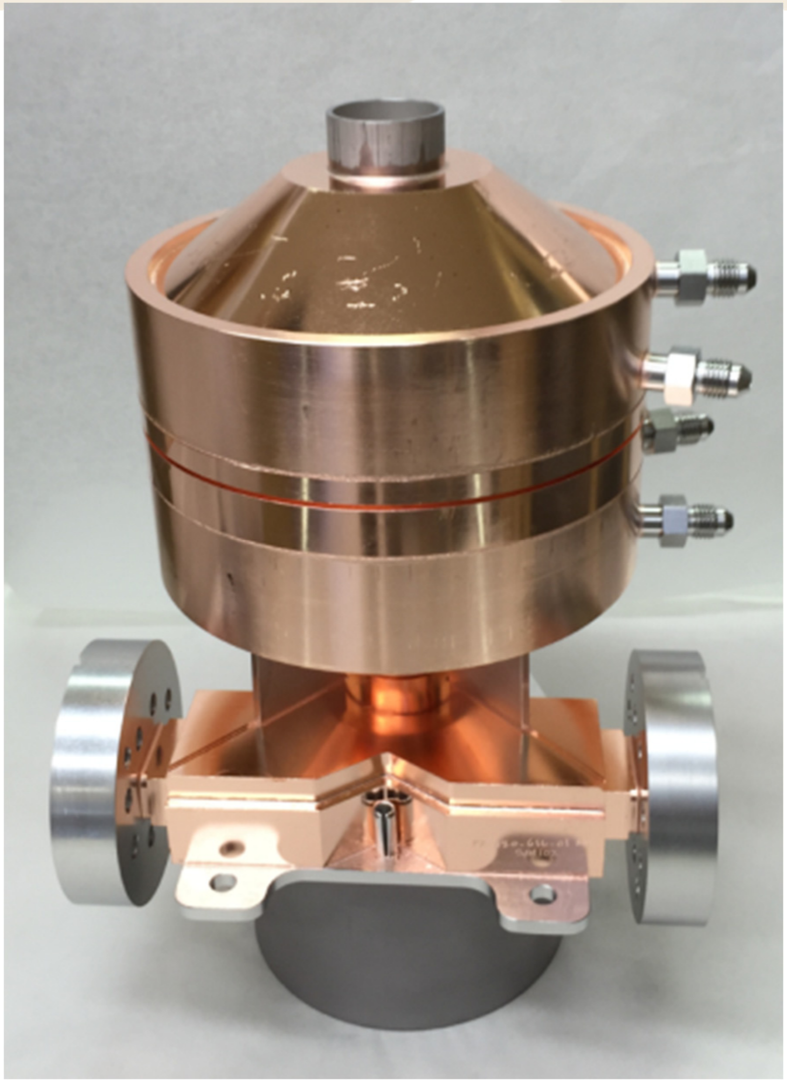
Assembly of the 3db Coupler/ Mode Convertor/Polarizer



X-Band SLED System



Mechanical Design



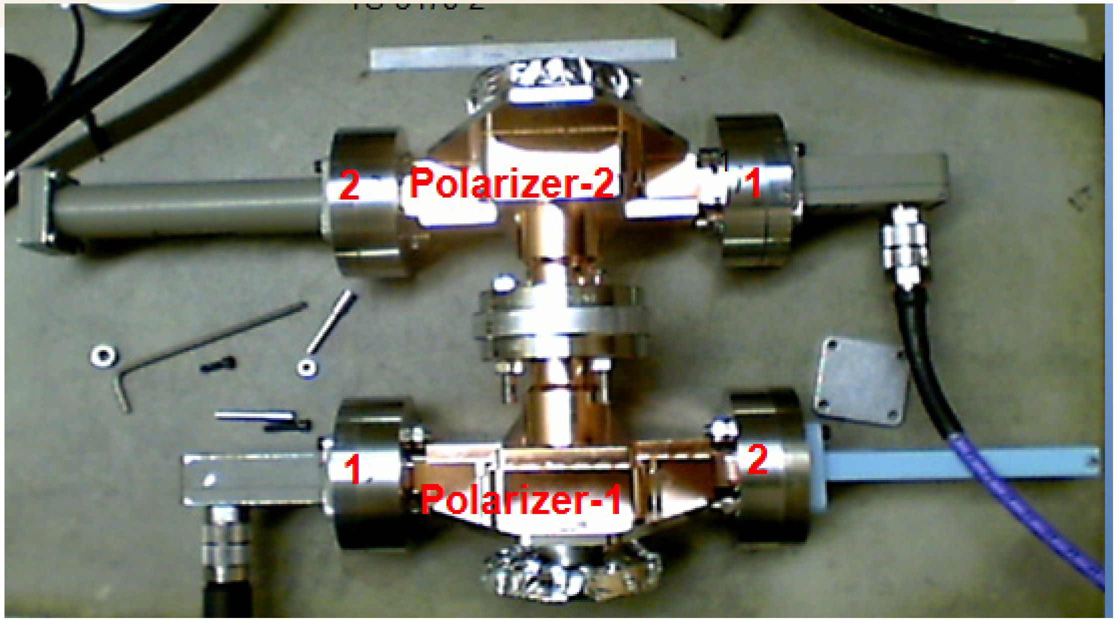
Fabricated Assembly

3. Microwave Measurements

- Performance of Unified 3db Coupler / Mode Convertor / Polarizer
- Performance of SLED System

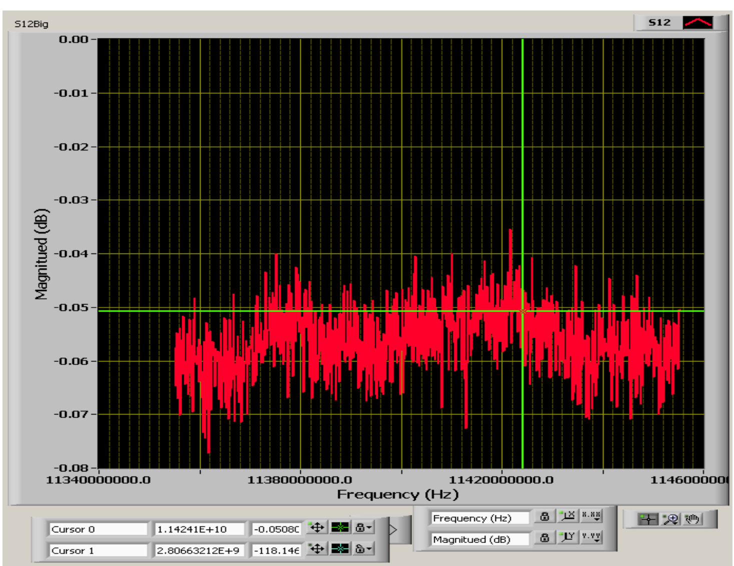
Transmission Measurement for Two Back-to Back Polarizers, Coefficient Better Than 99%

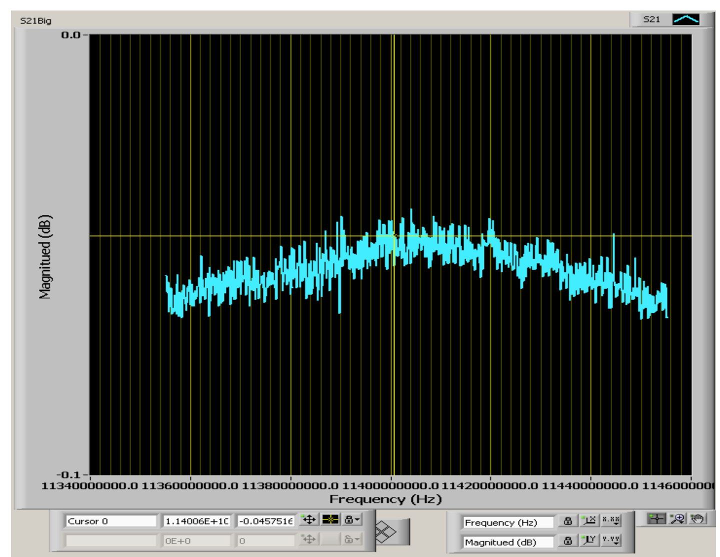
More than 100 MHz broad pass band to insure stable operation



Port 1 of Polarizer 1 to Port 2 of Polarizer 1

-0.5 dB

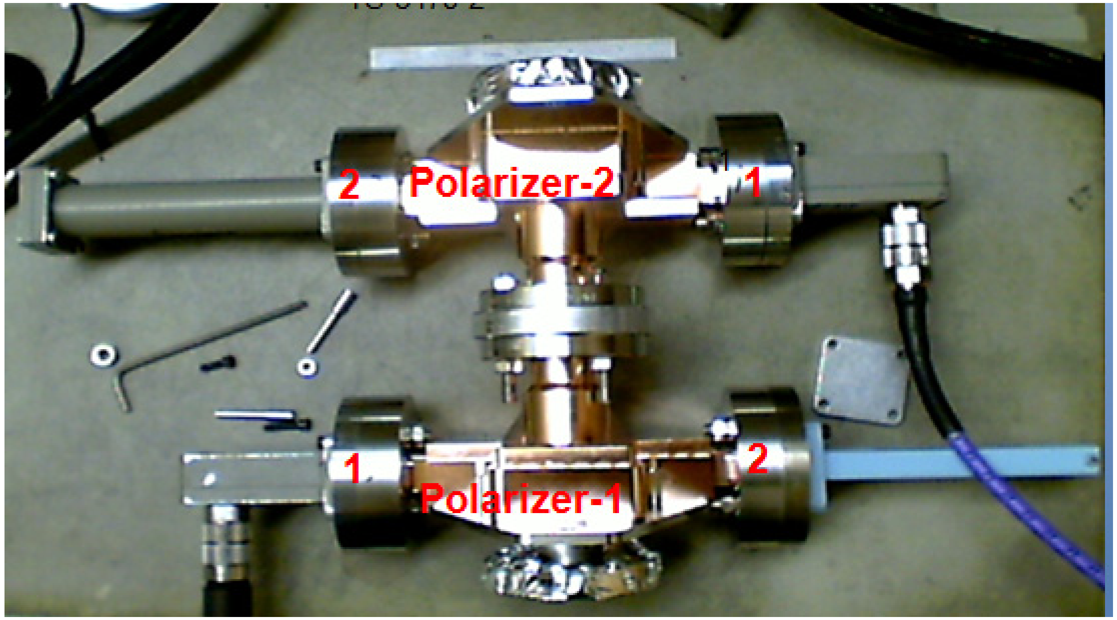




Port 2 of Polarizer 1 to Port 1 of Polarizer 1

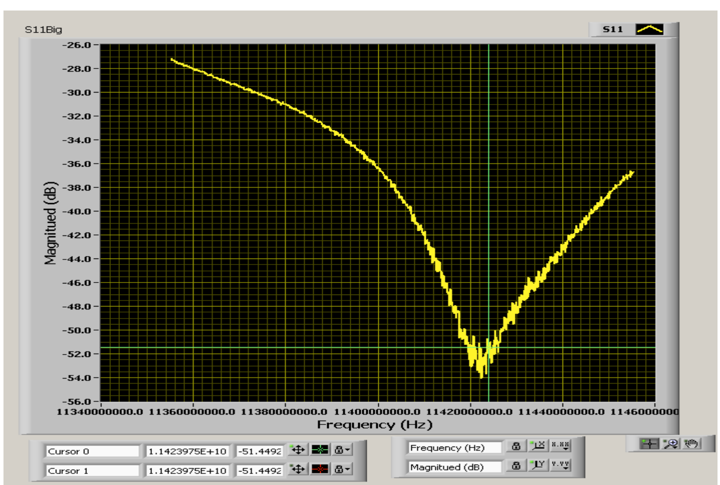
-0.45 dB

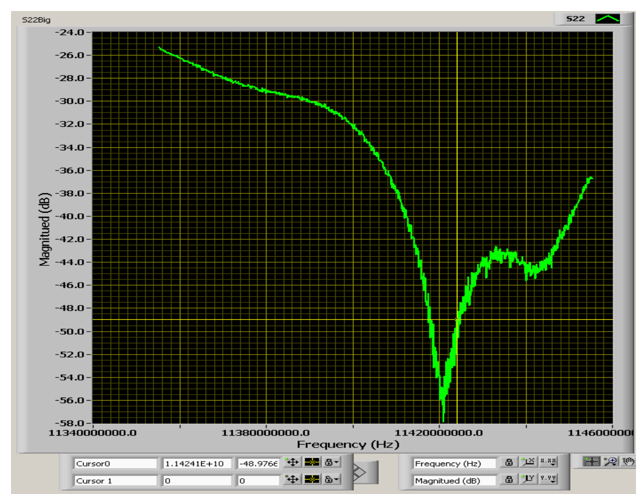
Reflection Measurement for Two Back-to Back Polarizers, Negligible Reflection to Power Source



Reflection from Port 1 of Polarizer 1

-51.4 dB

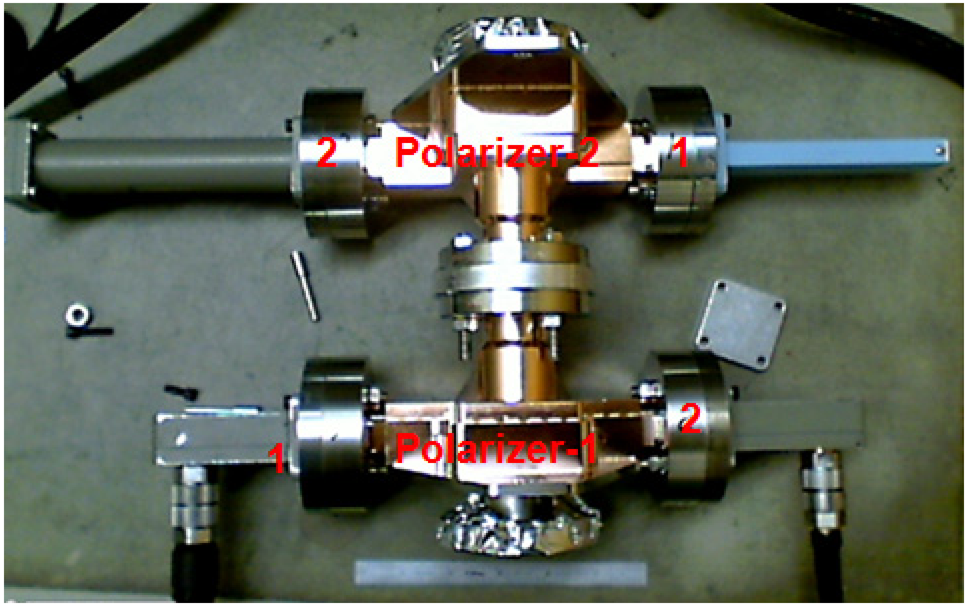




Reflection from Port 2 of Polarizer 1

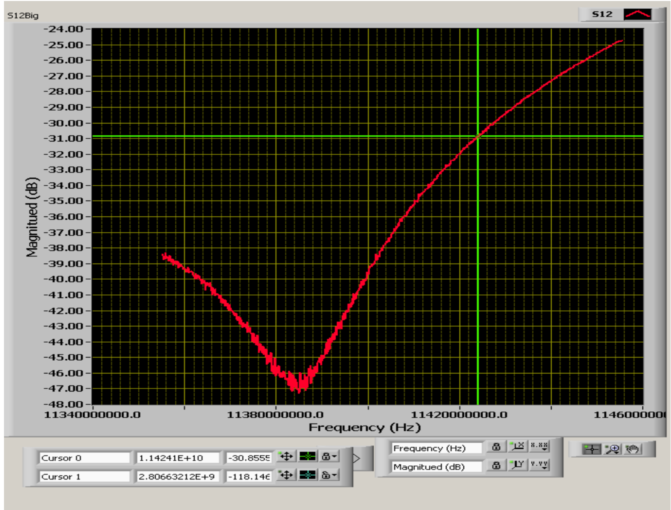
-49.0 dB

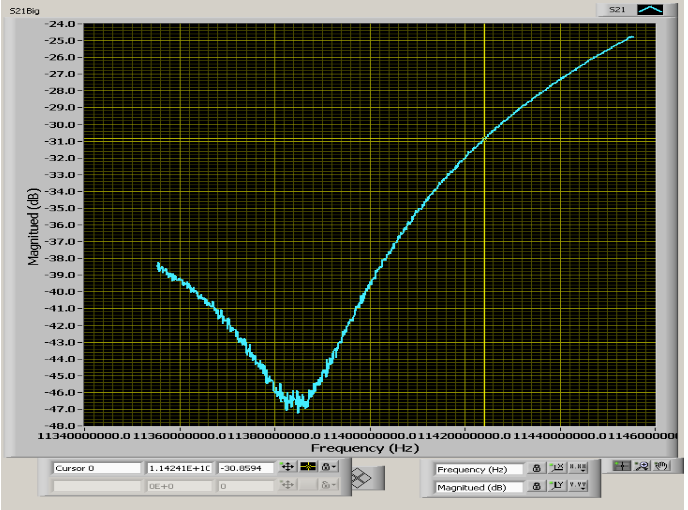
Isolation Measurement for Two Back-to Back Polarizers, Good Isolation of Power Source / Load



Port 1 of Polarizer 1 to Port 2 of Polarizer 2

-30.8 dB

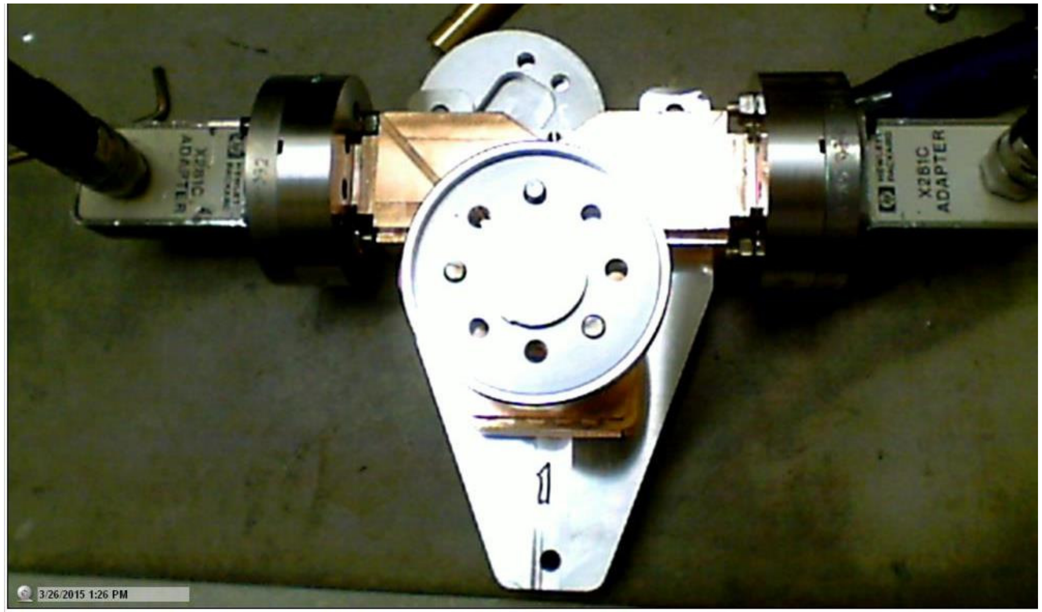


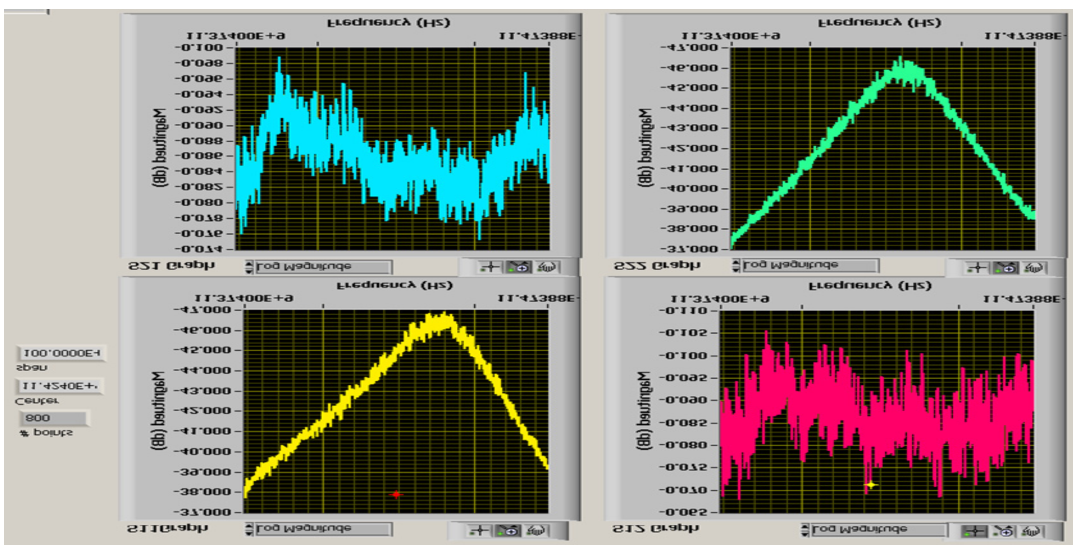


Port 2 of Polarizer 1 to Port 1 of Polarizer 2

-30.9 dB

Proof

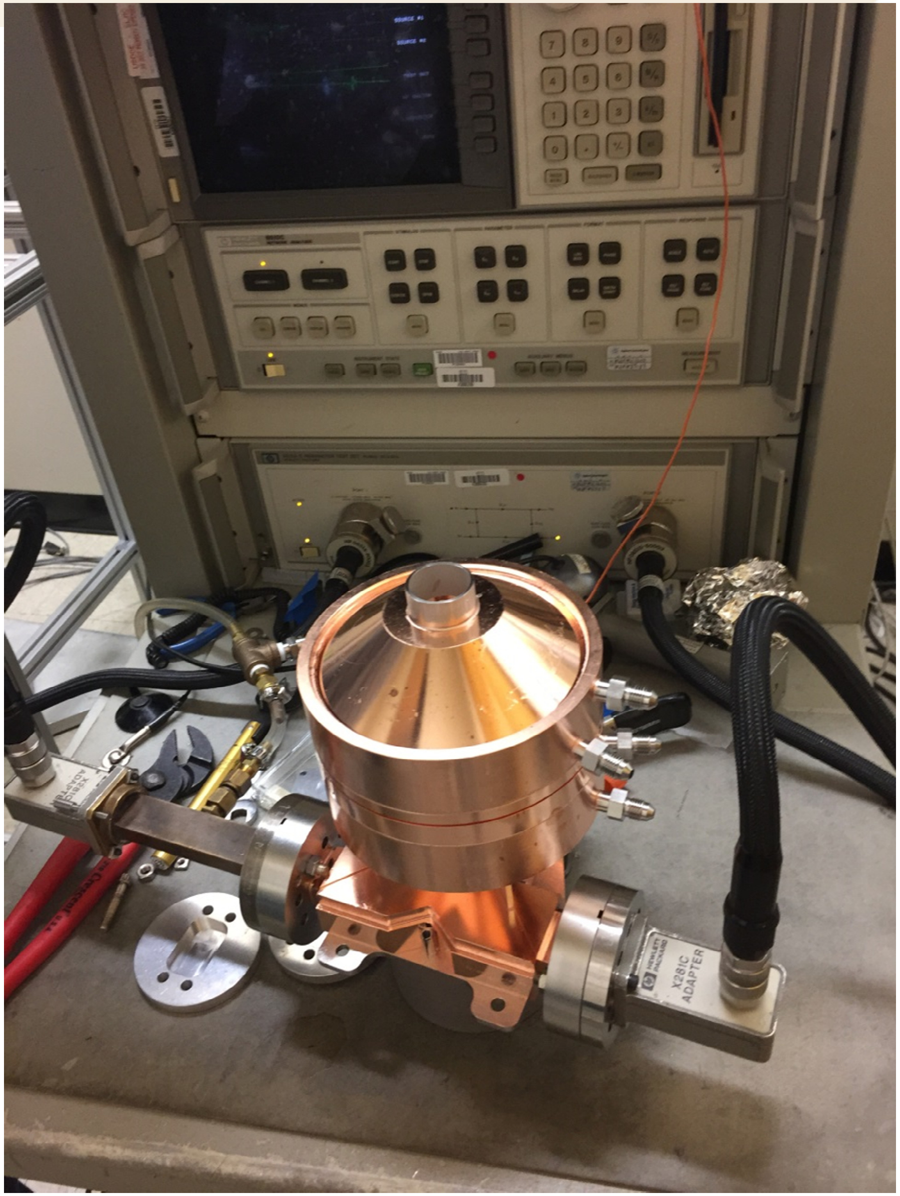




Reflection from Port 1 of Polarizer 1

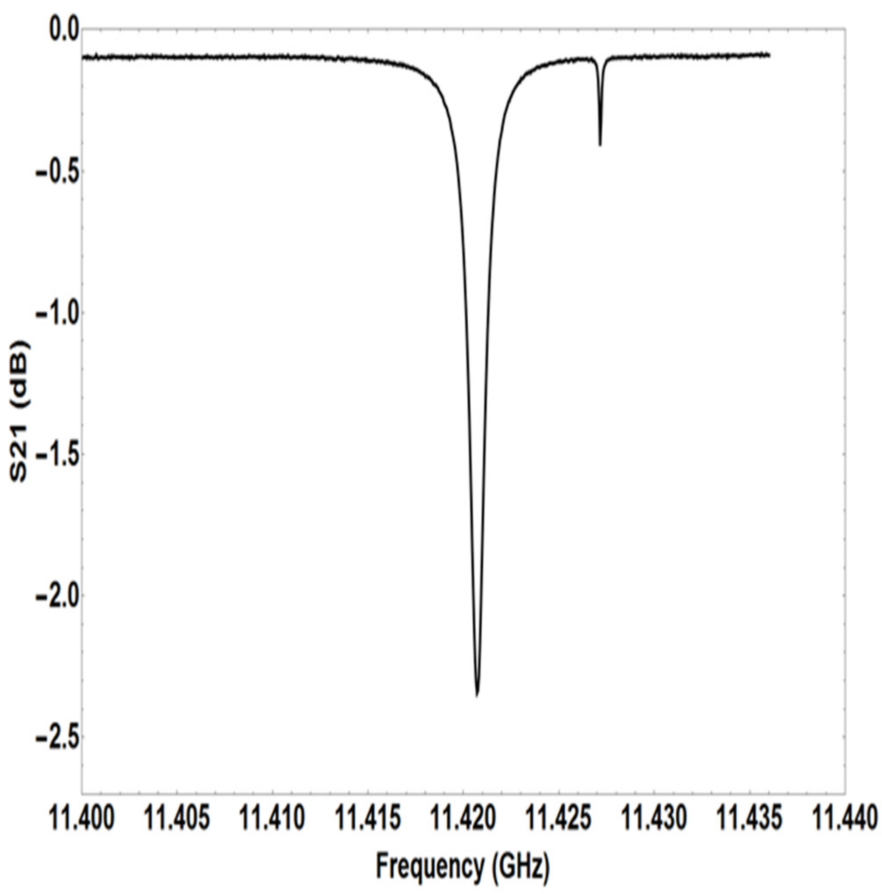
-51.4 dB

Microwave Measurement Setup for the SLED System

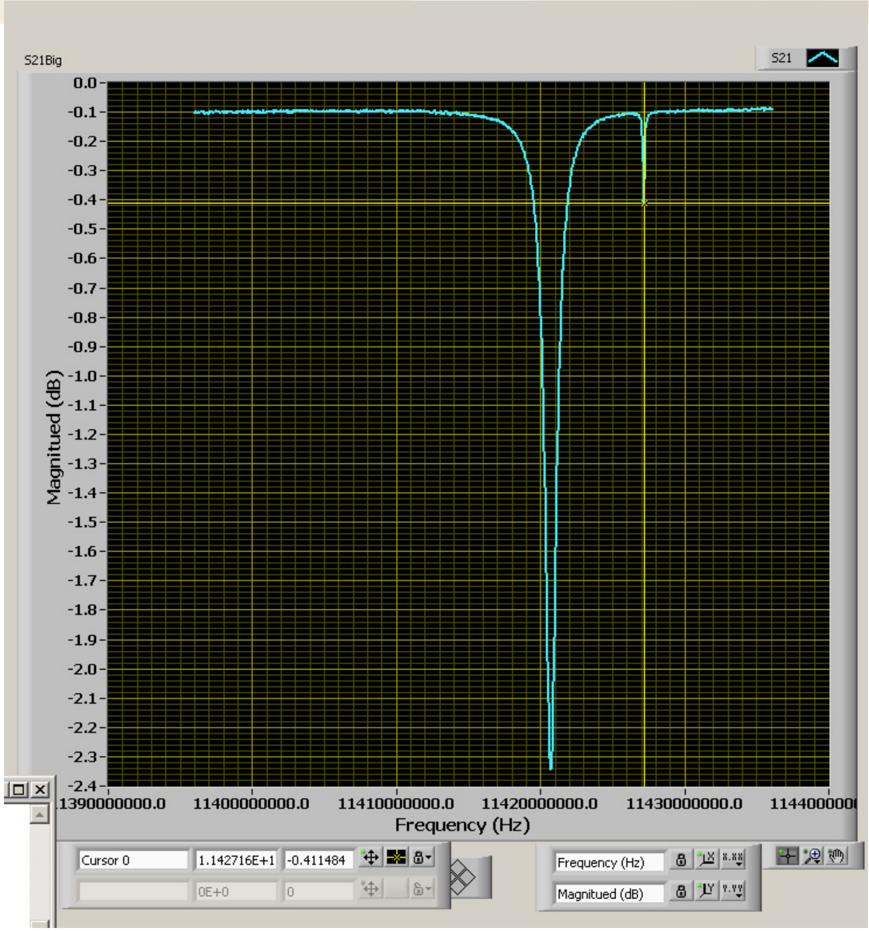


Final SLED Frequency to Be Tuned to Exactly 11424 MHz for Vacuum, @ 20.0 C°

SLAC

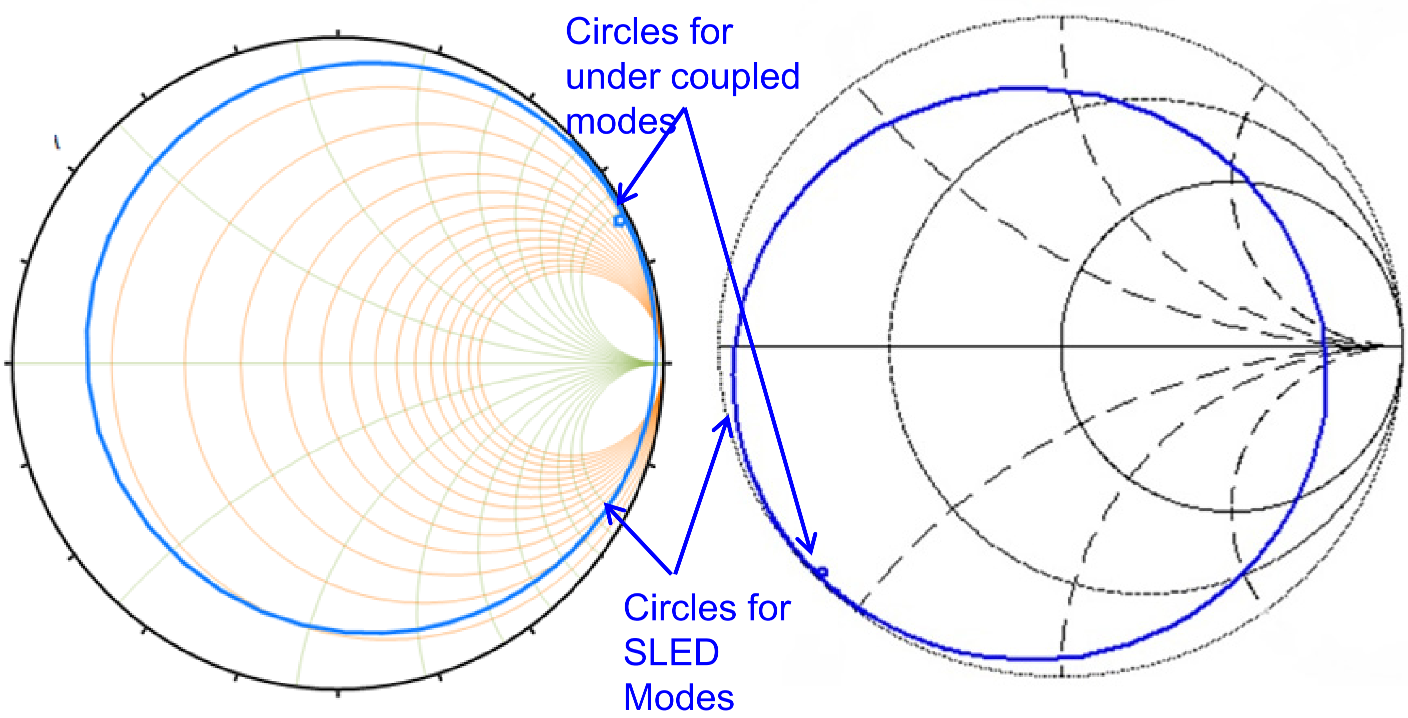


Theoretical Design Simulation Showing Both SLED Working Modes and Next Mode.



Measured SLED Working Modes:
Q_0 94000 and β 7.8
Next Mode:
7 MHz higher, far undercoupled

Perfect consistency Between Design Simulation and Microwave Measurement



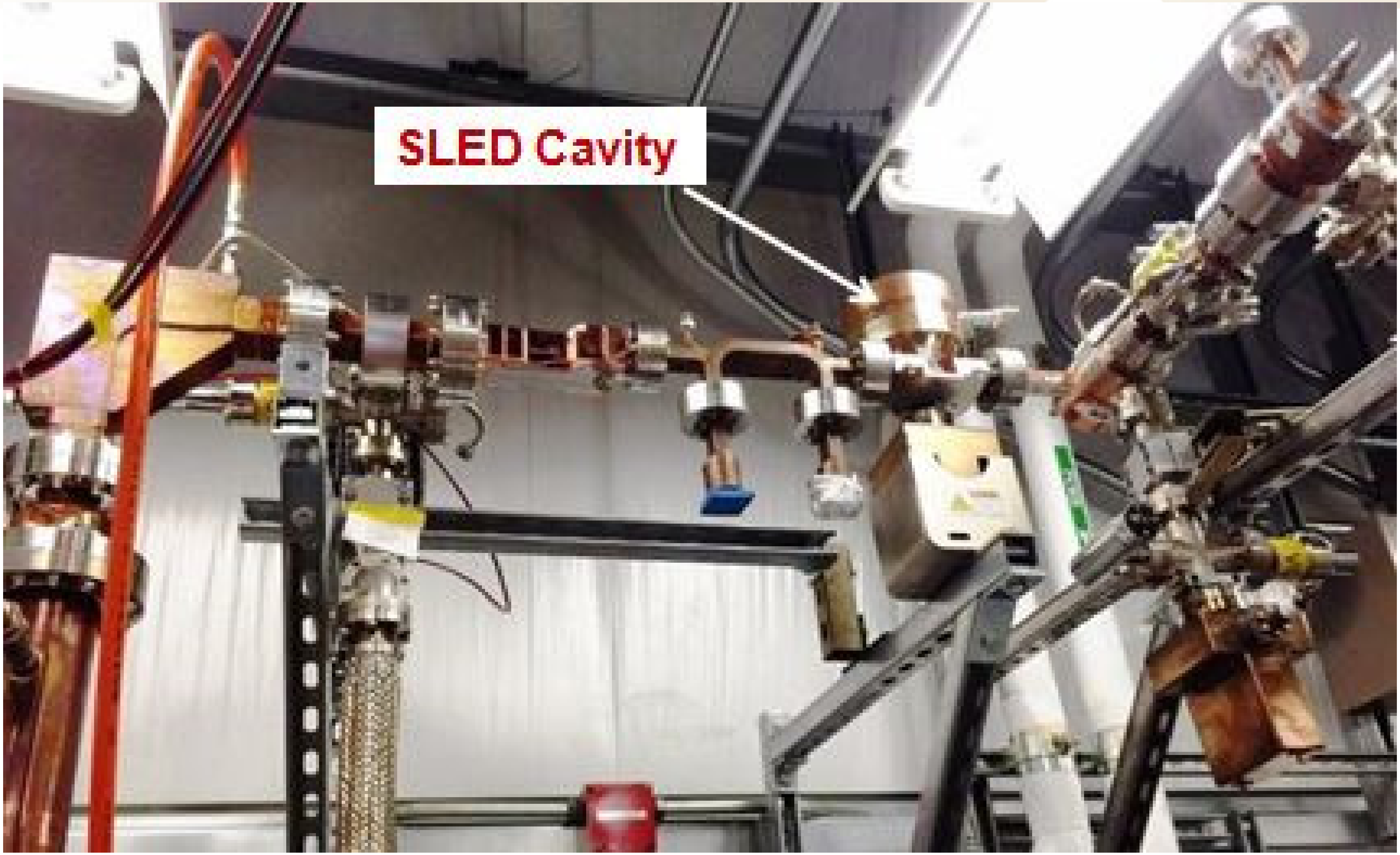
There is a phase rotation due to the NWA cable length

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

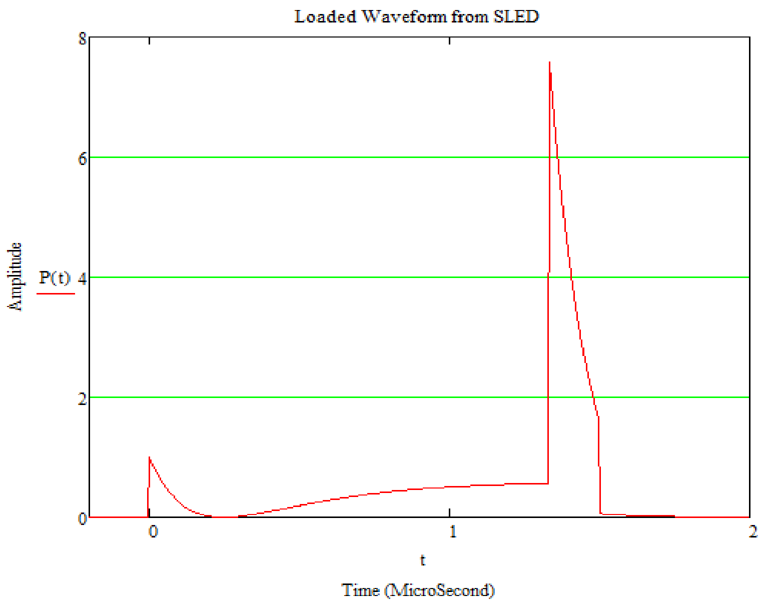
Smith Chart for Measured SLED Working Modes:
Q0 94000 and β 7.8
Next Mode:
7 MHz higher, far undercoupled

4. High Power Operation

Installation at Building 921 of the LCLS



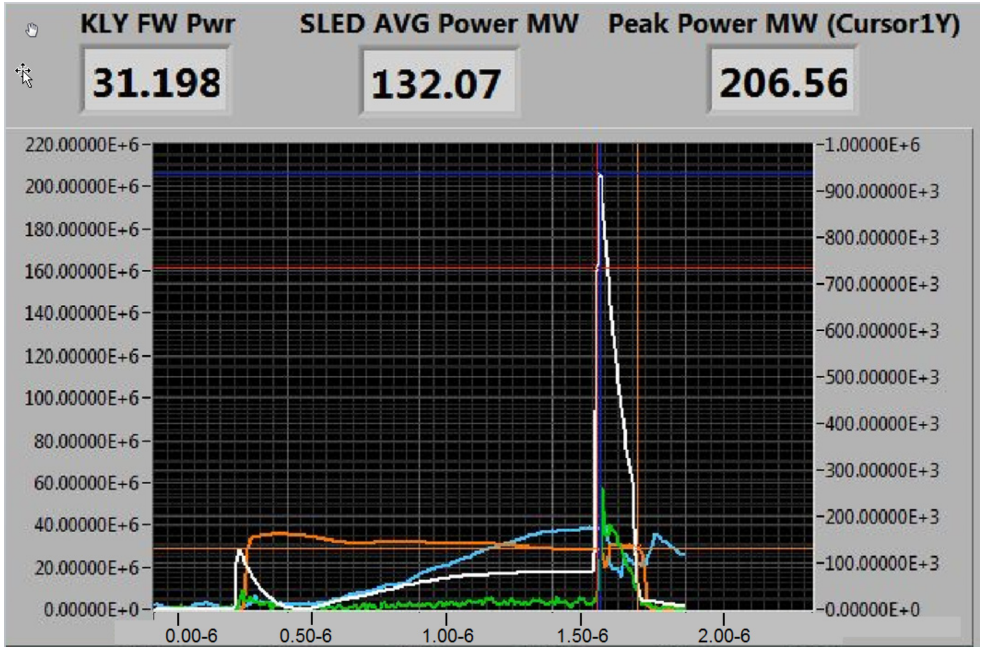
High Power Operation of SLED System



Theoretical Calculation

$$\frac{\int_{1.335}^{1.5} P(t)\,dt}{0.165} = 3.925$$

$$P(1.335) = 7.578$$



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

SLAC

- 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.