3.9 GHz components design

Speaker: Nikolay Solyak (from behalf of LCLS-II design team)

3.9GHz Review, FNAL, May. 26, 2016
Outline

• 3.9 GHz system functionality
• Requirements
• Cavity design modification
• HOM design
• Coupler design
• Heating issues
• Frequency Tuner
• BPM; Gate-valve; HOM absorber.
• Conclusion
FLASH and XFEL - ACC39 performance

- ACC39 routinely operates at 18.9 to 19.7 MV/m
  - Capable of operation at 22 MV/m
    - Limitation set by thermal interlocks – concern about compromising HOM’s on cavities 3 & 5 (trimmed 2-post style)
- Amplitude stability ≤ 2x10^{-5} pulse-to-pulse
- Phase stability ≤ 0.003° pulse-to-pulse
Commissioning of the European XFEL Injector

Third harmonic module AH1 (INFN, Milano)

- 18 December 2015: First rough calibration
  - Nominal pulse structure Fill Time: 750 µs
  - Flat Top: 650 µs
  - Gradient well above nominal 30 MV of VS voltage
  - First quench > 45 MV

- 10 February 2016:
  - QL aligned well within the 10% requirement
  - Phases within 15°

- 16 February 2016: Back on beam
  - Moved to -180° (wrt on-crest), calibration with beam energy

For details on SC modules see D. Reschke’s talk on Thursday THYB01 on Performance of Superconducting Cavities for the European XFEL.
LCLS-II reqs. (PRD and FRD)

SCRF 3.9 GHz Cryomodule  LCLSII-4.1-PR-0097-R2

Table 1. Main 3.9 GHz Cryomodule and Cavity Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of CMs</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of Cavities per CM</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of Active Cavities</td>
<td>14</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>2 °K</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cavity Average $Q_0$ and Min Value</td>
<td>$2.0 \times 10^9$</td>
<td>$1.5 \times 10^9$</td>
<td>-</td>
</tr>
<tr>
<td>Average Operating Gradient with 14 Cavities</td>
<td>13.4 MV/m</td>
<td>-</td>
<td>14.9 MV/m</td>
</tr>
<tr>
<td>On-Crest, 14 Cavity Voltage</td>
<td>64.7 MV</td>
<td>-</td>
<td>72.0 MV</td>
</tr>
<tr>
<td>Nominal Beam to RF Phase</td>
<td>-150°</td>
<td>-90°</td>
<td>-180°</td>
</tr>
<tr>
<td>Active Cavity Length (L)</td>
<td>0.346 m</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cavity $R/Q$</td>
<td>750 Ω</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fundamental Mode Coupler $Q_{ref}$ (Fixed)</td>
<td>$2.7 \times 10^7$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Alignment Tolerances for the 3.9 GHz Cryomodules

<table>
<thead>
<tr>
<th>Misalignment</th>
<th>RMS error</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity X,Y misalignments w.r.t. CM</td>
<td>0.5</td>
<td>mm</td>
</tr>
<tr>
<td>Cryomodule X,Y misalignments w.r.t. Linac</td>
<td>0.3</td>
<td>mm</td>
</tr>
<tr>
<td>Cavity Z misalignments w.r.t. CM</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Cryomodule Z misalignments w.r.t. Linac</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Cavity tilt misalignments</td>
<td>0.5</td>
<td>mrad</td>
</tr>
<tr>
<td>Cryomodule tilt misalignments</td>
<td>0.1</td>
<td>mrad</td>
</tr>
<tr>
<td>Cavity roll misalignments</td>
<td>10</td>
<td>mrad</td>
</tr>
<tr>
<td>Cryomodule roll</td>
<td>2</td>
<td>mrad</td>
</tr>
</tbody>
</table>

Table 3. Tuning/stability requirements

- Two CMs; 8 cavity / each
- 9 Cu plated bellows
- Coupler orientation as per XFEL
- ~150 W heat load/cryomodule (2K)
- BPM at downstream end (1.3GHz type)
- No magnet
Cavity gradient and Q0 requirements
(recent data from XFEL cavity production)

Recent XFEL production cavities (INFN-Zenon);
• At 2K the all cavities have Qo in range $\sim(2-3) \cdot 10^9$ (except 2)
• No field slope up-to $\sim17$ MV/m; Quench at 20-23 MV/m, VTS
• No Q degradation after welding to HV

Risk: LCLS-II cavity (cw) requirements more stringent than XFEL (pulse) !!!
⇒ Require Prototyping and Testing
Effect of large field asymmetry and cavity orientation

3.9 GHz Cryomodule Options

1.3GHz like Cryomodule Layout:
yrot=180 deg of cavities

FLASH-like Cryomodule Layout:
zrot=180 deg of cavities

XFEL/LCLS2 Cryomodule Layout

<table>
<thead>
<tr>
<th>1.3GHz-like</th>
<th>XFEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \varepsilon_x$ (%)</td>
<td>6.0</td>
</tr>
<tr>
<td>$\Delta \varepsilon_y$ (%)</td>
<td>24.4</td>
</tr>
</tbody>
</table>

Emittance growth in 3.9 GHz system

$\Delta \varepsilon_x$ (%) $\sim$ 6.0%
$\Delta \varepsilon_y$ (%) $\sim$ 24.0%
Cavity/coupler design issues and proposed modifications for LCLS-II CW operation

- Cavity, bellows and Helium vessel
- HOM coupler
- Power Coupler
- Blade-Tuner with piezo

### Table 1 Parameters of operating mode of the 3.9 GHz cavity

<table>
<thead>
<tr>
<th>Operating Mode Parameters</th>
<th>XFEL</th>
<th>LCLS-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, [GHz]</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Stored Energy, [J]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>R/Q, [Ω]</td>
<td>746</td>
<td>751</td>
</tr>
<tr>
<td>Effective Length, [m]</td>
<td>0.346</td>
<td>0.346</td>
</tr>
<tr>
<td>Maximum Electric Field on Axis, [MV/m]</td>
<td>25.4</td>
<td>25.3</td>
</tr>
<tr>
<td>Accelerating Gradient, [MV/m]</td>
<td>12.36</td>
<td>12.40</td>
</tr>
<tr>
<td>Normalized Surface Electric Field</td>
<td>2.25</td>
<td>2.24</td>
</tr>
<tr>
<td>Normalized Surface Magnetic Field, [mT/MV/m]</td>
<td>4.90</td>
<td>4.88</td>
</tr>
</tbody>
</table>
Cavity drawings: FLASH $\rightarrow$ XFEL $\rightarrow$ LCLS-II

FNAL/FLASH design

INFN/Zenon modification

(starting point for LCLS2)

LCLS-II:

Additional modifications to meet requirements.
LCLS-II 3.9 GHz cavity design

- INFN = modified FNAL design of the cavity for XFEL project. Modifications are done to simplify/improve production (Zenon) and tuning. Drawings and 3D models are available (thanks INFN team)
- CW operation in LCLS-II is more severe regime for the cavity. Some minor modifications are needed to reduce risks and eliminate tuning and heating problems.

Proposed modifications in cavity RF design.

- **Issue #1**: Frequency of lowest dipole mode trapped in coupler end of the cavity is too close to operating mode frequency, 3.9 GHz. As a result the tuning of notch frequency is difficult and 3.9 GHz frequency power leak is significant.
  
  Solution: Move away frequency of this mode
  
  Modification: Reduce beam pipe and bellow diameter from 40 to 38mm.

- **Issue #2**: Overheating of the HOM antenna (quench ~20MV/m at cw/VTS)
  
  Modification: Increase length of bump

- **Issue**: Heating of bellow between cavities
  
  Modification: reduce bellow ID from 42 to 38mm
Reduce beam pipe diameter from 40mm to 38mm.

- No modification of cavity cells.
- Add small conical transition between beam pipe and end cell.

**FLASH: Lowest Dipole HOMs. Beam Pipe Ø 40 mm and Bellows Ø 42 mm.**

- $F = 3.992 \text{ GHz}, Q_E = 3.6e4$
- $F = 4.047 \text{ GHz}, Q_E = 8.0e4$

**LCLS2: Lowest Dipole HOMs. Beam Pipe Ø 38 mm and Bellows Ø 38 mm.**

- $F = 4.092 \text{ GHz}, Q_E = 2.7e4$
- $F = 4.188 \text{ GHz}, Q_E = 7.4e3$

In current design lowest mode is closer (min ~10-20 MHz vs. 100MHz in simul.) to operat. mode. Lowest dipole mode frequency shifted by **100 MHz** up away from operating mode frequency.
Modification of HOM coupler

- Reduce penetration of antenna inside HOM to reduce heating → F-part modification

- Increase wall thickness on the top of HOM can to prevent cracks and vacuum leak

- To modify length of HOM feedthrough
  (choice of feedthrough design: Fermilab vs. XFEL)
HOM F-part modification to reduce antenna heating

Reduce penetration to beam pipe. Increase length of bump in F-part

Current design

 Modified design

- Current design HOM antenna quenches at ~20 MV/m in VTS. Expected that quench limit will even lower in CW regime at HTS and CM.
- RF power dissipation on HOM antenna reduced by factor of 5.4 after modification
HOMs Resonant Losses in the 3.9GHz LCLS-II cavity (run #1)

Frequency, [GHz]
4 5 6 7 8 9 10

$P_{\text{max}}$, [W]

1e-8
1e-7
1e-6
1e-5
1e-4
1e-3
1e-2
1e-1
1e+0
1e+1

Ø 40 mm
Ø 38 mm

Nov. 20, 2015
N. Solyak
HOM can thickness increase from 1.0 mm to 1.3 mm.

Thickness of hat is a concern:
- Was broken when h=1mm (FLASH).
- XFEL design has thickness of 1.15 mm → one prototype cavity has a leak.
- Proposal to have 1.3mm.

Conclusion: 1.3mm is acceptable thickness of can wall
Notch filter tuning requirements

Passband of the 3.9 GHz notch filter (left) and corresponding power radiated through HOM coupler at nominal accelerating gradient (right).

Tuning accuracy $\pm 2$MHz $\Rightarrow P < 0.1$ W

For 1.3 GHz HOM accuracy for notch filter frequency $\sim 0.5$MHz
HOM and pick-up feedthrough:

**XFEL design (used for 1.3GHz and 3.9 GHz)**

Field probe for 3.9 GHz (modified 1.3GHz design)

Antennas are modified for 3.9 GHz

All feedthroughs are ordered in Kyocera for 24 cavities

\[ Q_{ext} = 7.5 \times 10^{10} \]

<table>
<thead>
<tr>
<th>Pullout radius, (Rp)</th>
<th>1 mm</th>
<th>3 mm</th>
<th>6 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ant. Offset, (H)</td>
<td>21.9</td>
<td>22.4</td>
<td>23.4</td>
</tr>
</tbody>
</table>
3.9 GHz: Power removed by HOM coupler

- Median $P < 3\ W$ ($Q=2e5$)
- Prob. $10^{-2}$ (in 1/100 cavities) to have $P > 10\ W$ ($Q=1e7$)

Simulation model includes copper plated bellows between cavities
HOM frequencies have random distribution ~ 1MHz rms
Max values of R/Q for each mode is used (vs. cavity to cavity distance) – overest.
$Q_{\text{HOM}} < 10^6$ for most dangerous modes ($P_{\text{max}} < 7W$, prob. $10^{-2}$ per 2 HOMs)

A. Sukhanov

R/Q of monopole modes in cavity chain

N.Solyak
HOM antenna heating issues

• Maximum power flux to HOM coupler up to 4W:
  ✓ < 0.5 W – leakage from operating mode
  ✓ Max power flux to 2K is 0.1W (from power dissipated in cable)

• Part of this will be dissipated in cable (0.6dB/m) and will heat HOM antenna.
• Heat removal from feedthrough (2K) and from the cable intercepts (5K and 50K) is essential part of design.

• Choice of cable and specs is part of current activity. Use the same cables as in 1.3GHz CM, but ~1m shorter.
Beamline components heating: wakes

Bunch length (sigma) | 1mm
---|---
8x (Cavities + bellow) | 135.5 V/pC
CM (8cav/9bellow/gaps) | 151.64 V/pC

Wake power (300µA; σ=1mm) is **13.65 W** per CM, and only **9.5 W** above beam pipe cut-off frequency

| Components in 2 CM’s | Power Deposition, [W] |
|---|---|---|
| A (baseline) | B |
| No HOM, PC | HOM PC | HOM PC |
| BLA (1 or 2) | 16.2 | 13.5 | 10.5 |
| SS tube 2.5m | 1.65 | 1.4 | 2.2 |
| Bellows (17) | 0.36 | 0.3 | 0.4 |
| Gate Valve (4) | 0.6 | 0.45 | 0.7 |
| Spool (2) | 0.02 | 0.02 | 0.03 |
| HOMC (32) | 0 | 0.5 | 0.75 |
| FPC (16) | 0 | 2.7 | 4.1 |

Total power in 2 CMs ~19 W
Heating of bellows from operating mode RF

Table 2 Operating mode RF losses in the End Group at 14.9 MV/m gradient

<table>
<thead>
<tr>
<th>End Group Component</th>
<th>G-Factor</th>
<th>RF Loss, [mW]</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Copper (RRR=15)</td>
<td>Stainless Steel (316LN)</td>
<td></td>
</tr>
<tr>
<td>Bellows Body (Upstream)</td>
<td>$2.1 \times 10^{11}$</td>
<td>0.9</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Bellows Body (Downstream)</td>
<td>$1.4 \times 10^{11}$</td>
<td>1.4</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Bellows Flange (Upstream)</td>
<td>$9.2 \times 10^{11}$</td>
<td>0.2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Bellows Flange (Downstream)</td>
<td>$5.6 \times 10^{11}$</td>
<td>0.3</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>HOM antenna (XFEL)</td>
<td>$3.2 \times 10^{8}$</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>HOM antenna (LCLS-II)</td>
<td>$1.7 \times 10^{9}$</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
Chimney Power Limit

\[ P = \frac{(E_{\text{acc}} \cdot L)^2}{(R/Q) \cdot Q_0} \]

- Cryoloading at 2K

<table>
<thead>
<tr>
<th></th>
<th>Nominal parameters</th>
<th>Max in CM</th>
<th>Max power (VTS/HTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{acc}} ) (MV/m)</td>
<td>13.4</td>
<td>14.9</td>
<td>16.4 (+10%)</td>
</tr>
<tr>
<td>Q0</td>
<td>2.9e9</td>
<td>2.9e9</td>
<td>1.5e9</td>
</tr>
<tr>
<td>( P/\text{cav} ) (W)</td>
<td>14.3</td>
<td>17.7</td>
<td>28.6</td>
</tr>
</tbody>
</table>

Chimney the heat load limit is at least 30 W (ID = 60.2 mm (short) \( \rightarrow \) 73 mm (long part))

N.Solyak
Cavity Mechanical Resonances
(Stiffness of the Tuner = 40 kN/mm)

Longitudinal modes

- L#1: 506.2 Hz, k=0.75 Hz/µm
- L#2: 785.1 Hz, k=4.75 Hz/µm
- L#3: 1076.4 Hz, k=0.75 Hz/µm

Transverse modes

- T#1: 218.9 Hz
- T#2: 231.7 Hz
- T#3: 370.8 Hz
- T#4: 526.1 Hz
- T#5: 719.7 Hz
- T#6: 865.7 Hz

Frequencies (Hz) of Longitudinal modes L#1-L#3 vs. Stiffness of the Tuner (kN/mm)

I. Gonin
Dressed Cavity LFD and $dF/dP$

- **Graph 1:** LFD vs. Tuner Stiffness
  - Legend:
    - Orange dots: Updated Design 2.8 mm
    - Gray dots: Updated Design 2.5 mm
  - X-axis: $kN/mm$
  - Y-axis: $Hz/(MV/m)^2$

- **Graph 2:** $dF/dP$ vs. Tuner Stiffness
  - Legend:
    - Orange dots: Updated Design 2.8 mm
    - Gray dots: Updated Design 2.5 mm
  - X-axis: $kN/mm$
  - Y-axis: $Hz/mbar$
Coupler was designed for pulse operation ($P=50\text{kW}$, $\text{DF}=2\%$).

LCLS-II requirements: $P_{\text{max}}=2\text{kW cw}$; quasi – TW regime:
- W/o modification inner conductor of warm part will be overheated up to 1000 K.

Proposed modifications:
- Shorter antenna ($QL\sim2.7\times10^7$ vs. $1.5\times10^6$)
- Increase thickness of copper plating on inner conductor from 30 $\mu$m to 120 $\mu$m
- Reduce length of 2 inner bellows in inner conductor from 20 to 15 convolutions.
- Increase thickness of ceramics in cold window to move parasitic mode away.
For solving the inner conductor overheating problem we propose to reduce the length of two inner bellows from 20 to 15 convolutions and to increase the thickness of a copper plating on the inner conductor from 30 to 120 microns.

### COUPLER THERMAL ANALYSIS

<table>
<thead>
<tr>
<th>SS Inner Conductor</th>
<th>$T_{max}$ K</th>
<th>Losses @50K</th>
<th>Losses @5K</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 µm plating</td>
<td>1000</td>
<td>9.2</td>
<td>0.8</td>
</tr>
<tr>
<td>100 µm plating</td>
<td>507</td>
<td>9.3</td>
<td>0.8</td>
</tr>
<tr>
<td>150 µm plating</td>
<td>427</td>
<td>9.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Assumptions**
- $Pin=2kW$ TW,
- 10µm on outer,
- $RRR=50$; ASE,
- 10% roughness
- $ε=9.8$, $tan=3e^{-4}$,
Main coupler antenna configuration

Nominal power coupler antenna positions in the 3.9 GHz cavity for XFEL (left) and LCLS-II (right); QL=2.5e7
Trapped modes in cold ceramic window

Trapped mode resonances measured in the 3\textsuperscript{rd} harmonic power coupler (shift -20MHz). Transmission losses more than 3 dB, bandwidth ~ 0.5 MHz.

Two nearest trapped modes in the coupler ceramic window (simulations)

The inner and outer diameters of ceramic changed symmetrically by 0.25 mm each, which shifts down by 33 MHz the frequency of nearest parasitic mode and, thus, secures of \(~50\) MHz isolation from the operating mode. (sensitivity of parasitic mode frequencies vs. ceramic radius is \(\pm65.6\) MHz/mm)

Trapped modes in cold ceramic window

Set-up for ceramic measurement. \(\varepsilon=9.71; \tan\delta=3.6\times10^{-4}\) (averaged over 5 modes)
COMSOL solid model and mechanical boundary conditions.

Von Misses stresses for 0.5 mm longitudinal deformations of each bellows.

Solid model of 15 convolutions stainless steel bellows with 120 μm copper plating.

<table>
<thead>
<tr>
<th>Stresses Description</th>
<th>MPa/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner conductor, transverse,</td>
<td>38</td>
</tr>
<tr>
<td>Outer conductor, transverse,</td>
<td>45</td>
</tr>
<tr>
<td>Inner conductor, longitudinal</td>
<td>253</td>
</tr>
<tr>
<td>Outer conductor, longitudinal</td>
<td>98</td>
</tr>
</tbody>
</table>

Summary of stresses in 15 convolutions bellows

Typically copper bellow endurance limit for infinite cycles is from 83 to 166 MPa or **300 MPa** for a low cycle fatigue strength CPI feedback)
Tuner SUMMARY/STATUS

• Use XFEL 3.9GHz slim blade tuner (INFN) with minor modifications to meet LCLS-II requirements.
• Modification introduced:
  ❖ #1 -adding fine/fast piezo tuner
  ❖ #2 replacement of the Sanyo/HD actuator on Phytron electromechanical actuator.

Note: Piezo-capsule and Phytron actuator selected for 1.3GHz tuner. Both active components passed several lifetime and rad. hardness tests
INFN slim blade tuner modifications – adding Fine/Fast (piezo) tuner

Moved second ring, welded to He Vessel. to accommodate 66mm piezo-stacks

Two PI piezo-capsules (4 piezo-stacks). Will deliver more than 10kHz. Even one piezo can deliver required fine tuning stroke >1kHz.
Concept: Use 1.3GHz beam line components (ID=78mm) in transition between cavity string:
- BPM,
- Gate-valve,
- Beamline HOM absorber (~10 W)
Conclusion

- Design is completed and Technology of all components exist (based on FNAL/XFEL/INFN).

- To meet LCLS-II requirements cavity, coupler, HV and tuner designs are modified to reduce risks and improve performance at cw operation.

- Simulations and studies for the dressed cavity and beamline components are done to prove proposed modifications and predict performance in LCLS-II cryostat.

- Prototypes of Cavity and Auxiliaries (Tuner, main coupler, magnetic shielding, feedthroughs,…) will be tested in HTS (DV) before major procurement starts.
Thanks:

Back-up slides
LCLS-II 3.9GHz Cryomodule, (F10014857 in Team Center)

- 8 - 3.9GHz cavities
- Power couplers from both sides
- 2-coldmass supports
- Interconnection sliding bellow
- 38” OD vacuum vessel pipe
- One thermo shields:50K
- 5K intercept

XFEL cavity orientation (z-rotation:180 deg)
LCLS-II. 3.9GHz Cavity String (F10014812)

- Gate Valve
- Spool piece
- 3.9 cavity Style-A
- 3.9 cavity Style-B
- Blade tuner
- Spool piece and BPM
Comparison

3.9 GHz vs. 1.3 GHz:

Iris Aperture: 30mm vs. 70mm (ratio 2.34)

\[ \frac{E_{p}}{E_{acc}} \quad ; \quad 2.26 \quad \text{vs.} \quad 2.0 \] (13% higher)

\[ \frac{H_{p}}{E_{acc}} (\text{mT}/\text{MV/m}) \quad 4.86 \quad \text{vs.} \quad 4.26 \] (14% higher)

\[ \frac{R}{Q} \quad (\text{Ohm}) \quad 750 \quad \text{vs.} \quad 1000 \]

BCS resistance ratio \( \left( f^2 \right) \) (9 times higher)
<table>
<thead>
<tr>
<th>Vendor</th>
<th>Times Microwave</th>
<th>Huber+Suhner</th>
<th>Gore Type 42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Type</td>
<td>TFlex-401</td>
<td>TFlex-401t</td>
<td>SFT-304</td>
</tr>
<tr>
<td>Inner Cond OD [in]</td>
<td>0.0641</td>
<td>0.062</td>
<td>0.062</td>
</tr>
<tr>
<td>Outer Cond ID [in]</td>
<td>0.208</td>
<td>0.185</td>
<td>0.185</td>
</tr>
<tr>
<td>Outer Cond OD [in]</td>
<td>0.249</td>
<td>0.227</td>
<td>0.227</td>
</tr>
<tr>
<td>Cable OD [in]</td>
<td>0.27</td>
<td>0.250</td>
<td>0.250</td>
</tr>
<tr>
<td>Material of Conductor</td>
<td>CuAg</td>
<td>CuAg</td>
<td>CuAg</td>
</tr>
<tr>
<td>Dielectric</td>
<td>PTFE (ε_r=2.04)</td>
<td>ePTFE</td>
<td>ePTFE</td>
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<tr>
<td>Velocity %</td>
<td>69.5</td>
<td>69.5</td>
<td>76</td>
</tr>
<tr>
<td>Attenuation [dB/m] at 1 GHz</td>
<td>0.26</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>Outer Braid</td>
<td>CuAg</td>
<td>CuAg</td>
<td>CuAg+Polymide/Al+CuAg</td>
</tr>
<tr>
<td>Jacket Material</td>
<td>FEP</td>
<td>TEFZEL 750</td>
<td>FEP</td>
</tr>
<tr>
<td>Temperature Rating [C]</td>
<td>-65 to +125</td>
<td>-55 to +200</td>
<td>-55 to +200</td>
</tr>
<tr>
<td>Shielding</td>
<td>&gt;100 dB</td>
<td>&gt;100 dB</td>
<td>&gt;110 dB</td>
</tr>
<tr>
<td>Radiation Resistance [Rad]</td>
<td>1e5</td>
<td>3e7</td>
<td>1e5</td>
</tr>
<tr>
<td>Material of Connectors</td>
<td>Brass</td>
<td>Brass</td>
<td>Brass</td>
</tr>
<tr>
<td>Price of 3m long assemblies(min is 250)</td>
<td>$147</td>
<td>$175</td>
<td>$157</td>
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</table>
## Lead Intercepted Power (3.9 GHz)

### Narrow Leads

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>0</td>
<td>6.30</td>
<td>189.88</td>
<td>287.86</td>
<td>-484.04</td>
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<td>1</td>
<td>18.06</td>
<td>217.86</td>
<td>358.44</td>
<td>-394.68</td>
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<td>2</td>
<td>29.84</td>
<td>246.19</td>
<td>435.51</td>
<td>-298.46</td>
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<td>3</td>
<td>41.63</td>
<td>274.95</td>
<td>520.27</td>
<td>-194.23</td>
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<tr>
<td>4</td>
<td>53.49</td>
<td>304.20</td>
<td>614.21</td>
<td>-80.58</td>
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<tr>
<td>5</td>
<td>65.44</td>
<td>334.01</td>
<td>719.21</td>
<td>44.26</td>
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<tr>
<td>6</td>
<td>77.43</td>
<td>364.58</td>
<td>837.66</td>
<td>182.56</td>
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<td>7</td>
<td>89.46</td>
<td>396.08</td>
<td>972.68</td>
<td>337.22</td>
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<td>8</td>
<td>101.50</td>
<td>428.79</td>
<td>1128.35</td>
<td>512.10</td>
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<tr>
<td>9</td>
<td>113.61</td>
<td>462.98</td>
<td>1310.21</td>
<td>712.38</td>
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<td>10</td>
<td>125.80</td>
<td>499.07</td>
<td>1525.91</td>
<td>945.19</td>
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</table>

### Wide Leads

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<tr>
<th>Power Flow [W]</th>
<th>2K [mW]</th>
<th>5K [mW]</th>
<th>50K [mW]</th>
<th>300K [mW]</th>
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<tbody>
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<td>0</td>
<td>9.27</td>
<td>164.76</td>
<td>242.83</td>
<td>-416.87</td>
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<tr>
<td>1</td>
<td>21.91</td>
<td>193.01</td>
<td>313.60</td>
<td>-326.02</td>
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<tr>
<td>2</td>
<td>34.61</td>
<td>221.87</td>
<td>393.03</td>
<td>-226.41</td>
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<tr>
<td>3</td>
<td>47.43</td>
<td>251.44</td>
<td>483.14</td>
<td>-116.22</td>
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<tr>
<td>4</td>
<td>60.39</td>
<td>281.94</td>
<td>586.51</td>
<td>6.86</td>
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<tr>
<td>5</td>
<td>73.47</td>
<td>313.74</td>
<td>706.51</td>
<td>145.86</td>
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<td>6</td>
<td>86.67</td>
<td>347.22</td>
<td>847.86</td>
<td>304.90</td>
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<tr>
<td>7</td>
<td>100.05</td>
<td>383.02</td>
<td>1017.10</td>
<td>489.75</td>
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<tr>
<td>8</td>
<td>113.67</td>
<td>422.00</td>
<td>1223.63</td>
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<td>9</td>
<td>127.78</td>
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<td>1481.52</td>
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<td>10</td>
<td>142.70</td>
<td>517.64</td>
<td>1812.94</td>
<td>1301.92</td>
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</tbody>
</table>
**Thermal simulation for HOM cable (TFlex401)**

\[ P_{\text{antenna}} = 9 \text{uW} \text{ (140mT with modified design, 63 mT with original design)} \]

Cable is OK up to 9 W input power flow (80°C cable limit).

M. Hasan/T. Khabiboulline

Nov. 20, 2015

N. Solyak
Modification: FEP → Tefzel for outer conductor

**Conclusion**

- New antenna design has better thermal performance
- Preliminary analysis shows that the TFlex-401t/Huber-SF329 cable used for the 1.3GHz cryo-module will work for up to 8W power flow out of the HOM ports for the 3.9GHz cryo-module
- Wide Leads are critically needed