T24_vg1.8_disk
11WNSDVG1.8
CLIC_G un-damped @ 11.424 GHz
measurements versus simulations

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CERN
1.07.2009
Acknowledgements

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SLAC:
Z. Li
First cell

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$a$ [mm]</td>
<td>3.307</td>
</tr>
<tr>
<td>$d$ [mm]</td>
<td>1.753</td>
</tr>
<tr>
<td>$e$</td>
<td>1.16</td>
</tr>
<tr>
<td>$f$ [GHz]</td>
<td>11.433</td>
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<tr>
<td>$Q$(Cu)</td>
<td>6814</td>
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<tr>
<td>$v_g/c$ [%]</td>
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<tr>
<td>$r'/Q$ [LinacΩ/m]</td>
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<tr>
<td>$E_s/E_a$</td>
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<td>$H_s/E_a$ [mA/V]</td>
<td>2.6</td>
</tr>
<tr>
<td>$S_c/E_a^2$ [mA/V]</td>
<td>0.37</td>
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### Last cell

<table>
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<th>Value</th>
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<td>a [mm]</td>
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<td>d [mm]</td>
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<td>e</td>
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<tr>
<td>f [GHz]</td>
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<td>Q(Cu)</td>
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<td>vg/c [%]</td>
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<td>r'/Q [LinacΩ/m]</td>
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<td>Es/Ea</td>
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<td>Hs/Ea [mA/V]</td>
<td>2.3</td>
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<tr>
<td>Sc/Ea² [mA/V]</td>
<td>0.28</td>
</tr>
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</table>
Gradient in 24 regular cells

Average unloaded of 100 MV/m

Average loaded of 100 MV/m

\[
\frac{dP}{dz} = -\frac{\omega}{Qv_g} P - \sqrt{\frac{\omega R'}{v_g Q}} I P^2
\]

| Number of regular cells: \( N_c \) | 24 |
| Bunch population: \( N \) | \( 3.72 \times 10^9 \) |
| Number of bunches: \( N_{b} \) | 312 |
| Bunch separation: \( N_{cycl} \) | 6 rf cycles |
Simulation setup 1 & 2

**HFSS-quad**

HFSS simulation of ¼ of the structure:
Surface conductivity (Cu): $58 \times 10^6$ S/m
Surface approximation: $ds=6 \ \mu m$
Total number of tetrahedra: $N_{tetra} = 1170348$
Mesh density: $\sim 40000$ tetr / ¼ cell

**S3P-quad**

S3P simulation of ¼ of the structure made by Zenghai Li at SLAC-ACD
Surface conductivity (Cu): $57 \times 10^6$ S/m different
Simulation setup 3

HFSS-cells + couplers

HFSS simulation of ¼ of input coupler + segment of 5 deg. of the cells + ¼ of output coupler:
Surface conductivity (Cu): 58e6 S/m
Surface approximation: ds=1 μm,
Total number of tetrahedra for cells: Ntetr = 506075
Mesh density: ~ 350000 tetr / ¼ cell
(10 times higher than in HFSS-quad setup)
Measurement setup 1 (reflections)

Reflection = S11+S12

Frequency correction due to air ($\varepsilon = 1.00059$)
Frequency in vacuum: $f' = f \sqrt{1.00059} \approx f + 3.5$ MHz @ X-band
Reflection: comparison

There is very small (~1MHz) or no difference in frequency between simulations and the air corrected measurements.
Measurement setup 2 (transmission)

Transmission = S13+S23
Transmission: comparison

- There is small difference between HFSS and S3P simulation results due to different conductivity used in the simulations.
- Both simulation results show higher transmission than air corrected measurements by about 0.2 dB.
Some useful equations

\[ P_{out} = P_{in} e^{-2\tau} \text{ where } \tau = \ln|S_{12}| \text{ attenuation} \]

On the other hand

\[ P_{out} = P_{in} e^{-\frac{\omega t_f}{Q}} \text{ where } Q = \frac{\omega W}{P_{loss}} \text{ - average quality factor} \]

\[ t_f = \frac{W_0}{P_{in}} \equiv \frac{d (\phi = \arg S_{12})}{d \omega} \text{ - filling time } \equiv \text{ group delay} \]

\[ W \text{ - stored energy in lossy structure} \]

\[ W_0 \text{ - stored energy in lossfree structure} \]

Finally

\[ Q = \frac{\omega t_f}{2\tau} \]
Transmission: comparing group delay

There is no difference between both HFSS and S3P simulations and the air corrected measurements.
Transmission: comparing Q-factor

- There is no difference in Q-factor (~7000) between HFSS and S3P simulations.
- The measured Q-factor of about 6600 is lower than the simulated value by about 6%.
Measurement setup 3 (bead pull)

VNA port1

VNA port2

E^2 \sim S11-S11

Perfect load

Perfect load
Bead pull in complex plane

**Measurements: S11-<S11>**

- $f=11.415$ GHz
- $f=11.416$ GHz
- $f=11.417$ GHz
- $f=11.418$ GHz
- $f=11.419$ GHz
- $f=11.42$ GHz
- $f=11.421$ GHz
- $f=11.422$ GHz
- $f=11.423$ GHz
- $f=11.424$ GHz
- $f=11.425$ GHz
- $f=11.426$ GHz
- $f=11.427$ GHz
- $f=11.428$ GHz

**HFSS-cells: E**

- $f=11.42$ GHz
- $f=11.421$ GHz
- $f=11.422$ GHz
- $f=11.423$ GHz
- $f=11.424$ GHz
- $f=11.425$ GHz
- $f=11.426$ GHz
- $f=11.427$ GHz
- $f=11.428$ GHz

**ReS11**

- $f=11.415$ GHz
- $f=11.416$ GHz
- $f=11.417$ GHz
- $f=11.418$ GHz
- $f=11.419$ GHz
- $f=11.42$ GHz
- $f=11.421$ GHz
- $f=11.422$ GHz
- $f=11.423$ GHz
- $f=11.424$ GHz
- $f=11.425$ GHz
- $f=11.426$ GHz
- $f=11.427$ GHz
- $f=11.428$ GHz

**ImS11**

- $f=11.415$ GHz
- $f=11.416$ GHz
- $f=11.417$ GHz
- $f=11.418$ GHz
- $f=11.419$ GHz
- $f=11.42$ GHz
- $f=11.421$ GHz
- $f=11.422$ GHz
- $f=11.423$ GHz
- $f=11.424$ GHz
- $f=11.425$ GHz
- $f=11.426$ GHz
- $f=11.427$ GHz
- $f=11.428$ GHz

**ReEz**

- $f=11.415$ GHz
- $f=11.416$ GHz
- $f=11.417$ GHz
- $f=11.418$ GHz
- $f=11.419$ GHz
- $f=11.42$ GHz
- $f=11.421$ GHz
- $f=11.422$ GHz
- $f=11.423$ GHz
- $f=11.424$ GHz
- $f=11.425$ GHz
- $f=11.426$ GHz
- $f=11.427$ GHz
- $f=11.428$ GHz

**ImEz**

- $f=11.415$ GHz
- $f=11.416$ GHz
- $f=11.417$ GHz
- $f=11.418$ GHz
- $f=11.419$ GHz
- $f=11.42$ GHz
- $f=11.421$ GHz
- $f=11.422$ GHz
- $f=11.423$ GHz
- $f=11.424$ GHz
- $f=11.425$ GHz
- $f=11.426$ GHz
- $f=11.427$ GHz
- $f=11.428$ GHz
Bead pull: field magnitude

Measurements: $|\text{sqrt}(S_{11} - <S_{11}>)|$

HFSS-cells: $|E|$
Field distribution at different frequencies

120° rf phase advance per cell frequency 11.424 GHz

Best match frequency 11.420 GHz
RF phase advance per cell at different frequencies

120° rf phase advance per cell frequency: 11.424 GHz

Best match frequency: 11.420 GHz
<table>
<thead>
<tr>
<th>Measuremnts (Vac)</th>
<th>S12</th>
<th>Pout/ Pin</th>
<th>τ=0.5ln (Pout/ Pin)</th>
<th>tf=dф/ dω [ns]</th>
<th>tf=W0 /Pin [ns]</th>
<th>Q=ωtf/2τ</th>
<th>Q=ωW/(Pin-Pout)</th>
<th>Q=ωW/Ploss</th>
<th>Pin100 24 cells [MW]</th>
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</thead>
<tbody>
<tr>
<td>0.715</td>
<td>0.511</td>
<td>0.336</td>
<td>60.9</td>
<td>-</td>
<td>6600</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>HFSS ¼</td>
<td>0.732</td>
<td>0.536</td>
<td>0.312</td>
<td>-</td>
<td>58.4</td>
<td>6720</td>
<td>7010</td>
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<tr>
<td>HFSS InCoup OutCoup Cells 24+2</td>
<td>0.731</td>
<td>0.534</td>
<td>0.313</td>
<td>60.7</td>
<td>59.8</td>
<td>6960</td>
<td>6940</td>
<td>6640</td>
<td>42.2</td>
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<td>0.99875</td>
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<td>0.311</td>
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<td>59.0</td>
<td>6910</td>
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<td>S3P (SLAC)</td>
<td>0.730</td>
<td>0.533</td>
<td>0.315</td>
<td>60.8</td>
<td>6974</td>
<td>6980</td>
<td>41.1</td>
<td>42.4</td>
<td></td>
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</tbody>
</table>
Summary on comparison

• Simulation results of HFSS and S3P show very good agreement

• Q-factor
  • All 3 different ways of calculating Q-factor: S3P, HFSS-S-parameter solver and HFSS-eigenmode solver give very close values of about 7000
  • The measurements of the T24_vg1.8_disk structure made at CERN show 6% lower Q-factor of 6600

• RF phase advance
  • Both HFSS and S3P simulations and air corrected measurements simulations show 120° rf phase advance frequency of 11.424 GHz which is the design frequency
  • Good agreement (± 0.5 MHz) between simulations and measurements demonstrates extremely high (sub-micron) precision of machining. For example, it is equivalent to ± 0.6 µm tolerance on the outer wall radius RF phase advance

• Structure matching
  • There is a design error in structure matching of about 4 MHz. The match frequency is 11.420 GHz. To some extent this is also in agreement with the measurements
HFSS S-par solver: v10.1 versus v11.1
Simulation setup 4

HFSS-cells + couplers

HFSS simulation of ¼ of input coupler
+ segment of the cells made in HFSS by 5 deg. Sweep (3D geometry created in HFSS)
+ ¼ of output coupler:
Surface conductivity (Cu): 58e6 S/m
Surface approximation: ds=1 μm,
Reflection

**Input**

<table>
<thead>
<tr>
<th>f [GHz]</th>
<th>Reflection [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.4</td>
<td>HFSS10</td>
</tr>
<tr>
<td>11.405</td>
<td>HFSS11</td>
</tr>
<tr>
<td>11.41</td>
<td>S3P</td>
</tr>
</tbody>
</table>

**Output**

<table>
<thead>
<tr>
<th>f [GHz]</th>
<th>Reflection [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.4</td>
<td>HFSS10</td>
</tr>
<tr>
<td>11.405</td>
<td>HFSS11</td>
</tr>
<tr>
<td>11.41</td>
<td>S3P</td>
</tr>
</tbody>
</table>

4 MHz
Transmission

4 MHz

Transmission [dB]

f [GHz]
Group delay and Q-factor

![Graph showing group delay and Q-factor](image)
RF phase advance per cell

HFSS v10.1

f = 11.42 GHz
f = 11.421 GHz
f = 11.422 GHz
f = 11.423 GHz
f = 11.424 GHz
f = 11.425 GHz
f = 11.426 GHz
f = 11.427 GHz
f = 11.428 GHz

HFSS v11.1

f = 11.429 GHz
f = 11.43 GHz
f = 11.431 GHz

ReEz [kV/m]  ImEz [kV/m]  ReEz [kV/m]  ImEz [kV/m]  ReEz [kV/m]  ImEz [kV/m]
Summary on HFSS

• It seems that there is a bug in HFSS v11.
• The results of the simulations using HFSS v11 are shifted up in frequency by 4 MHz with respect to the results of the simulations using HFSS v10 or S3P
• Use HFSS-S-parameter solver VERSION 10 or S3P