45 MW, 22.8 GHz Second-Harmonic Multiplier for High-Gradient Tests*

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Motivation:

- In order to investigate the frequency scaling of breakdown, high power tests are necessary at frequencies from X-band upwards.

- Key elements for these tests are high power (10’s to 100’s of MW), 0.5-1 $\mu$sec pulsed RF sources.

- A “quick-and-cheap” high-power RF source, an Harmonic Multiplier, is proposed for this application and described in this talk.
Second-harmonic 22.8 GHz harmonic multiplier:

● **Simple two-cavity structure, with room-temperature solenoid**

● **Uses the gun built for the SLAC XL-4 klystron, and a**

● **50 MW SLAC X-band klystron as the RF driver. Needs two modulators or maybe one two-pack.**

*driver: 11.4 GHz + Δf into TE111 mode,*

*output: 22.8 GHz + 2Δf out in TE211 mode.*

Note that phase stability is comparable to that of the 11.4 GHz klystron driver, and that technology (gun, modulator) is already proven.
20 GHz, 7th harmonic multiplier

[J.L. Hirshfield, et al, 2000]:

20 GHz seventh harmonic co-generator
Sketch of the proposed two-cavity 2\textsuperscript{nd} harmonic frequency multiplier, not to scale:

- The gun from XL-4 klystron is used.
- Two WR-90 input waveguides are connected to output waveguides of a SLAC 50 MW klystron, and are oriented on the drive cavity at 90° with respect to one another and excited with 90° phase difference to drive the input cavity in a rotating TE\textsubscript{111} mode.
Beam energy $U_{\text{max}}$ after acceleration in the first cavity vs. input beam power, and corresponding gun voltage $U_{\text{min}}$. Prf = 50 MW, $K = 1.2 \times 10^{-6} \text{ A} \cdot \text{V}^{-3/2}$.

Maximum magnetic field $B_{\text{max}}$, and field $B_{\text{min}}$ at the entrance to the 1st cavity vs. the input beam power. Prf = 50 MW, $K = 1.2 \times 10^{-6} \text{ A} \cdot \text{V}^{-3/2}$.

- Reasonable choice of the beam power (optimized conversion efficiency). is ~50 MW (280 kV, 170 A). Magnetic field is 5.7 kG at entrance where Brillouin radius is 0.8 mm.
- Beam area compression is 1390:1.
The total geometrical emittance is found to be 0.9 mrad·cm. It is still lower than the thermal emittance of about 1.4 mrad·cm, and gives the possibility to provide the required beam transverse compression of 1400:1.
### Parameters for 22.8 GHz, 2\textsuperscript{nd} harmonic multiplier.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>input beam power</td>
<td>50 MW</td>
</tr>
<tr>
<td>maximal magnetic field</td>
<td>7.8 kG</td>
</tr>
<tr>
<td>beam area compression</td>
<td>1390:1</td>
</tr>
<tr>
<td>RF drive power</td>
<td>50 MW</td>
</tr>
<tr>
<td>RF drive frequency</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>operating mode in the drive cavity</td>
<td>rotating TE\textsubscript{111}</td>
</tr>
<tr>
<td>peak electric field in the drive cavity</td>
<td>140 kV/cm</td>
</tr>
<tr>
<td>loaded Q of the drive cavity</td>
<td>12</td>
</tr>
<tr>
<td>output frequency</td>
<td>22.848 GHz</td>
</tr>
<tr>
<td>operating mode in the output cavity</td>
<td>rotating TE\textsubscript{211}</td>
</tr>
<tr>
<td>output power</td>
<td>47.5 MW</td>
</tr>
<tr>
<td>conversion efficiency, overall efficiency</td>
<td>95%, 48.7%</td>
</tr>
<tr>
<td>peak electric field in the output cavity</td>
<td>416 kV/cm</td>
</tr>
<tr>
<td>loaded Q of the output cavity</td>
<td>50</td>
</tr>
</tbody>
</table>
Magnetic circuit configuration, with 3 coils and 4 iron pole pieces. Plot at top shows the magnetic field profile generated by this circuit. Drawing at bottom shows drive cavity (left) and output cavity (right).

Beam particle energies (blue) and radial excursions (red) with the $\text{TE}_{211}$ mode output cavity tuned to 22.848 GHz. Cavity outlines are also shown.
Schematic of output power extraction into the $TE_{01}$ mode in a circular waveguide. Chokes and ceramic rings that are necessary to insulate the collector body away from ground are not shown; pumping ports are also not shown.
a) Output cavity layout (dimensions in mm). b) RF electric and magnetic field profiles on the output cavity surface between points A and B in Fig. 14 for a stored energy of 1 mJ.
Computed trajectories in the beam collector, including three generations of secondary electrons, for conditions of full power operation.

Particle trajectories in the beam collector for condition of zero drive power in the input cavity, including three generations of secondary electrons.
Collector layout with dimensions in mm (upper figure), and field pattern (lower figure). The output cavity rotating $\text{TE}_{211}$ mode is coupled through a circular waveguide that is connected to the beam collector, wherein five modes propagate. All these modes are combined into a single rotating $\text{TE}_{21}$ mode after the output collector taper. Uses trapped modes, doesn’t avoid them.
(a) $\text{TE}_{21}$ to $\text{TE}_{01}$ mode converter layout (one quarter is shown) and optimal dimensions in mm, (b) field pattern in input converter cross section, and (c) in the output cross section.
a) Zigzag in TE_{22} mode square waveguide; (b) optimal dimensions in mm. Scattering losses into other modes in the zigzag do not exceed 0.5%.

Transition between square TE_{22} waveguide of the zigzag and circular TE_{01} waveguide.
It is possible to scale the 100-MW X-band, two-mode window used in the 75-MW KEK klystron [S.Yu. Kazakov] to operate at 22.848 GHz. This window has a maximum electric field in the ceramic of 37 kV/cm. From this, it can be estimated that the scaled 22.8 GHz window at an output power of 47.5 MW will have a field of 52 kV/cm, a level that is still acceptable.

$\text{TE}_{01}-\text{TE}_{02}$ TW window (100 MW, 11.424 GHz). (a) Layout and dimensions (ceramic is shown in red) and (b) high-power model. 22.8 GHz version will have dimensions roughly half of these.
Conclusions

● Through use of 50 MW X-band drive power from SLAC SL-4 klystron and the beam from SLAC XL-4 gun, preliminary simulation results indicate that a simple two-cavity harmonic multiplier can be designed and built to furnish ~47 MW of phase-stable RF power at 22.85 GHz for use in high gradient accelerator R&D.

● Fourth harmonic multiplier fed by 3 GHz klystron may be designed for CLIC test facility at 12 GHz.