45 MW, K-BAND SECOND-HARMONIC MULTIPLIER FOR TESTING HIGH-GRADIENT ACCELERATOR STRUCTURES*

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Abstract

A relatively simple and inexpensive two-cavity 45 MW, 22.8 GHz second-harmonic multiplier to be used as an RF source for high-gradient experiments is described. The design is based on use of an existing SLAC electron gun, such as the XL-4 gun. RF drive power would be supplied from a 50 MW SLAC klystron and modulator, and a second modulator would be used to power the gun in the multiplier. An important feature of the harmonic multiplier is use of a TE_{01} circular waveguide for output RF power extraction fed through the beam collector.

GENERAL

A key element of the test facility required for high-gradient (HG) experiments is a high-power (tens of MW), 0.5-1 μsec pulsed microwave amplifier in the frequency range from 11 up to 30 GHz [1], to be used for investigations of frequency scaling of the RF breakdown limit. A relatively simple and inexpensive two-cavity harmonic multiplier [2] at 22.8, 34.3, or 45.7 GHz was suggested to be the stand-alone multi-MW RF power source for this application.

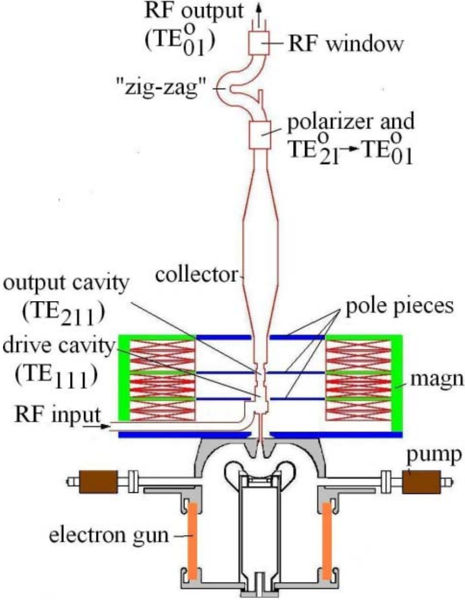

Figure 1: Sketch of 2nd harmonic frequency multiplier, not to scale.

The 22.8 GHz version described here, utilizing as it does an existing SLAC electron gun XL-4 and modulator, and based on a relatively-simple two-cavity structure, is probably the least costly candidate for a new RF source. A sketch depicting such a high power harmonic multiplier is shown in Figure 1, not drawn to scale. In the frequency multiplier configuration proposed here, a linear pencil beam from the electron gun at bottom is directed through an iron pole piece; thence to the TE_{111} input drive cavity tuned to 11.424 GHz; thence to the TE_{n11} output cavity, with $n = 2$; thence to the beam collector and output waveguide. Two WR-90 input waveguides are connected to output waveguides of a SLAC SL-4 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_{111} mode.

The electron gun of the SLAC XL-4 50-MW solenoid-focused X-band klystron provides a beam having a perveance of 1.2×10^{-6} A-$V^{-3/2}$ and a maximum pulsed power of 130 MW [3]. The rated pulse length is 1.6 μsec, and the pulse repetition rate is up to 120 Hz, for a duty factor of up to about 2×10^{-4}. The beam from the gun is directed through the iron pole piece, than accelerated in the drive cavity where its orbit radius is increased. For initial beam powers of [20, 35, 50] MW, the maximum orbit radius is computed to be [4.7, 4.3, 3.8] mm: for higher initial beam power the current is higher and, thus, the final energy after the acceleration is smaller for fixed power, and the orbit is smaller. Taking into account that the radius of the second cavity is 6.7 mm (that is limited by cut-off for the TE_{211} mode), one concludes that the beam power should be not less than ~50 MW. Results of 2nd harmonic multiplier optimizations are listed in Table 1. Beam dynamics were calculated for realistic RF and DC magnetic fields, taking into account transverse space charge effects. Figure 2 shows an idealized magnetic circuit configuration and the resulting magnetic field profile for the preliminary simulation studies that are described here. Figure 3 show results of 3-D simulation studies. The plots show the energy of beam electrons and the magnitude of radial excursions for the electrons, as well as the outlines of the two-cavity configurations and the final pole piece. One sees that the beam is accelerated from 280.5 keV to about 560 keV in the drive cavity, and then decelerated to about 300 keV in the output cavity.

Output coupling from a high-power RF source can be an irksome issue, because of the high RF electric and magnetic fields in the output cavity. The "conventional" means of output coupling, which typically uses two output waveguides side-coupled to the output cavity, suffers the following disadvantages. *(i)* With two output waveguides

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*Work supported by the U.S. Department of Energy

and two coupling slots in a TE_{211} cavity, it is necessary to make six additional compensating protrusions [4] in order to preserve quadruple symmetry of the RF fields in the cavity. This makes the cavity unduly complicated for tuning and fabrication, considering it's small size. For the TM_{311} output cavity in the Yale/Omega-P 34 GHz magnicon the situation was more tractable because the output cavity had a significantly larger diameter. *(ii)* In order to achieve the required loaded output cavity *Q* factor, one should use wide coupling slots that may lead to significant electric and magnetic field enhancements, that in turn can lead to breakdown and metal fatigue on the edges of the coupling slots [5,6]. *(iii)* There is insufficient space for long slots, because of the presence of a pole piece in the middle of the cavity (see Fig. 2). *(iv)* The two output waveguide are not the most convenient arrangement for practical use of the RF source, since an external power combiner and mode converters would be required for transmission of the total power to a load in a single waveguide.

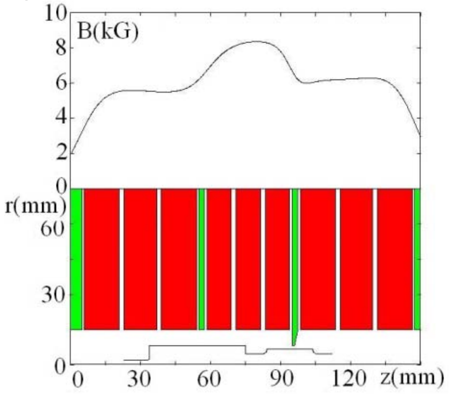


Figure 2: Magnetic circuit configuration, with 3 coils and 4 iron pole pieces. Plot at top shows the magnetic field profile generated by this circuit. Drawing at bottom shows drive cavity (left) and output cavity (right).

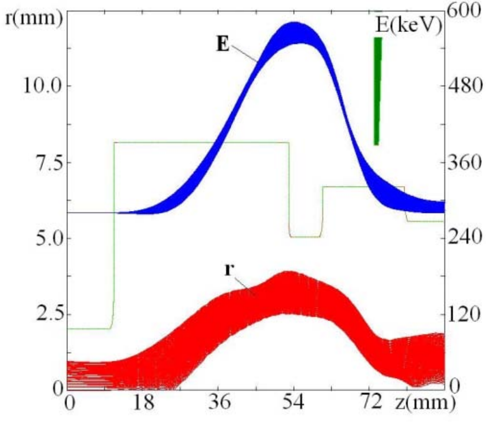


Figure 3: Beam particle energies *E* and radial excursions *r* with the TE_{211} mode output cavity tuned to 22.848 GHz. Cavity outlines are also shown.

In view of these disadvantages of side-coupled output cavity waveguides, it is appealing to extract power through a straight-ahead cavity output aperture as used in some gyrotrons. A possible output schematic is shown in Fig. 4, that ends up with a TE_{01} circular waveguide that is very convenient for low loss power transmission to a load. For this scheme, the rotating TE_{211} mode output cavity 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 TE_{21} mode after the output collector taper. The TE_{21} mode with circular polarization is converted to TE_{21} mode with linear polarization, and thence to the TE_{01} mode in circular waveguide. A TE_{01}-TE_{02} TW RF window is installed after a "zigzag," that protects the window from primary and secondary beam electrons. The zigzag has a circular channel whose axis coincides with the tube axis (see Fig. 4). An on-axis molybdenum rod is inserted along the beam axis to prevent waveguide wall damage from ion focusing. The rod channel diameter is ~2 mm, small enough to not effect RF reflection in the zigzag waveguide.

Table 1: Parameters for 22.8 GHz, 2^{nd} harmonic multiplier

beam voltage	280.5 kV
beam current	170 A
beam power	50 MW
magnetic field at entrance of drive cavity	5.7 kG
magnetic field at exit of drive cavity	7.8 kG
Brilliouin radius of beam at entrance of drive cavity	0.78 mm
beam radius at entrance of drive cavity in simulations	1.0 mm
cathode diameter	71.4 mm
beam area compression	1390:1
electrostatic beam compression	72:1
magnetic beam compression	19:1
RF drive power	50 MW
RF drive frequency	11.424 GHz
operating mode in the drive cavity	rotating TE_{111}
peak electric field in the drive cavity	140 kV/cm
loaded Q of the drive cavity	12
output frequency	22.848 GHz
operating mode in the output cavity	rotating TE_{211}
output power	47.5 MW
conversion efficiency	95%
peak electric field in the output cavity	416 kV/cm
loaded Q of the output cavity	50

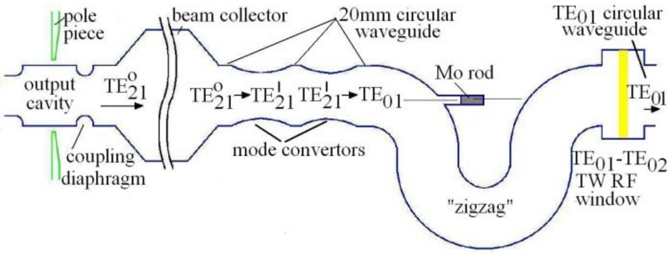


Figure 4: Schematic of output power extraction into the TE_{01} mode in a circular waveguide. Chokes and ceramic rings that are necessary to insulate the collector body away from ground are not shown; pumping ports are also not shown.

The output cavity (depicted in Fig. 4) has a coupling iris 11 mm in diameter, that couples it to the TE_{21} single-mode, 20 mm diameter waveguide. The coupling iris provides the required loaded *Q* of 50. The fields on the coupling iris are still smaller than in the center of cylindrical part of the cavity, where the electric field reaches a maximum value of 416 kV/cm for an output power of 47.5 MW, while the magnetic field reaches 173 kA/m that corresponds to a temperature rise during the pulse of less than 30°C, well below the "safe" temperature rise of 80-100°C. The single mode waveguide is opened to the beam collector. The beam collector has two tapers (input and output) with lengths of 80 mm, and a cylindrical part 53 mm in diameter and 130 mm in length. For maximum output power of 47.5 MW the maximum areal average heat deposition on the collector surface is 60 W/cm^2; in the absence of the RF input signal it is equal to 58 W/cm^2. These values are within acceptable limits.

Five modes propagate in the collector, but the sizes of the tapers and the cylindrical part have been optimized so that all the modes are combined back into one TE_{21} mode in the 20 mm diameter waveguide right after the output taper. The field pattern in the collector is also shown in Fig. 5. There is no interaction of these modes with the beam because the magnetic field is small in this region, and there is no resonance condition for the rotating field excitation. Fig. 6 shows the idea underlying the TE_{21} to TE_{01} mode converter

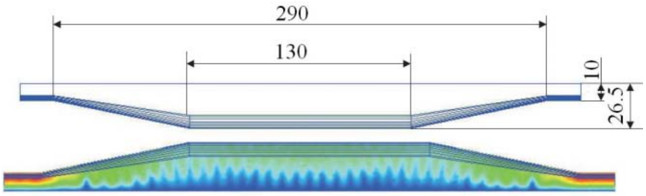
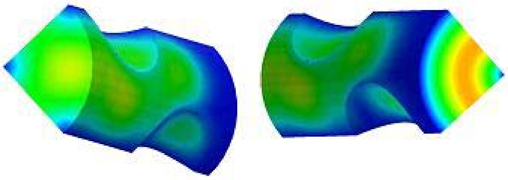


Figure 5: Collector layout with dimensions in mm (upper figure), and field pattern (lower figure).



a) b)

Figure 6: TE_{21} to TE_{01} mode converter idea. (a) field pattern in input converter cross section, and (b) in the output cross section.

In order to protect the output ceramic window from stray primary and secondary electrons that survive transmission through the collector, a special "zigzag" is planned that will be installed before the window. This novel element has a square transverse cross section and operates in the TE_{22} mode. The zigzag is depicted in Fig. 7. Two converters from circular-to-square waveguide and back are also used, as depicted in Fig. 8. To clear the zigzag structure and mode converters, the internal diameter of the solenoid bore should be at least 200 mm, so the pole pieces shown in Fig. 2 must be integrated onto the RF system. It is possible to scale the 100-MW X-band, two-mode window used in the 75-MW KEK klystron [7] 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.

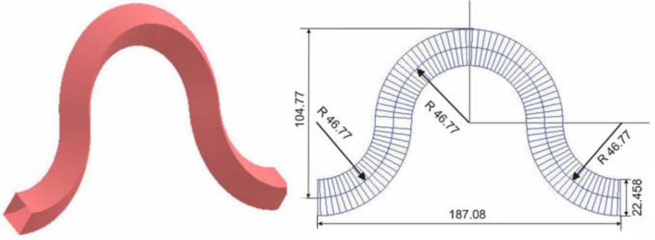


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Figure 7: (a) Zigzag in TE_{22} mode square waveguide; (b) optimal dimensions in mm. Scattering losses into other modes in the zigzag do not exceed 0.5%.

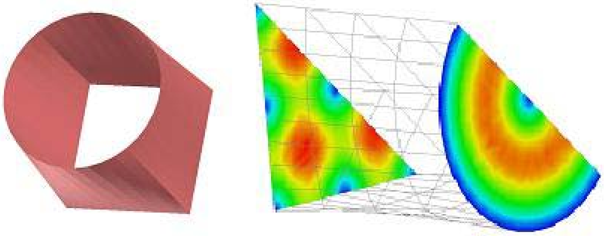

Figure 8: Transition between square TE_{22} waveguide of the zigzag and circular TE_{01} waveguide.

CONCLUSIONS

Through use of 50 MW X-band drive power from a SLAC SL-4 klystron and the beam from a 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.

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