MULTI-MEGAWATT HARMONIC MULTIPLIER FOR TESTING HIGH-GRADIENT ACCELERATOR STRUCTURES*

V.P. Yakovlev[1], and J.L. Hirshfield[1,2]
[1]Omega-P, Inc., New Haven, CT 06511, USA
[2]Physics Department, Yale University, New Haven, CT 06520, USA

Abstract

Basic studies for determining the RF electric and magnetic field limits on surfaces of materials suitable for accelerator structures for a future multi-TeV collider, and for the testing of the accelerator structures and components themselves, require stand-alone high-power RF sources at frequencies between 10 and 45 GHz. Relatively simple and inexpensive two-cavity harmonic multipliers at 22.8, 34.3, or 45.7 GHz are suggested as the stand-alone multi-MW RF power sources for this application. Their design is based on the use of an existing SLAC electron gun, such as the XP3 gun, plus a beam collector as used on the XP3 klystron. RF drive power would be supplied from an 11.4 GHz, 50 MW SLAC- or KEK–type klystron and modulator, and a second modulator would be used to power the gun in the multiplier. Preliminary computations show that 41, 36, and 30 MW, respectively, can be realized in 2nd, 3rd, and 4th harmonic multipliers at 22.8, 34.3, and 45.7 GHz using 50 MW of X-band drive power.

GENERAL

In order to develop RF technology in the low-cm and mm wavelength domains for a future multi-TeV electron-positron linear collider, it is necessary to test in realistic regimes accelerating structures, RF pulse compressors, RF components, and to determine limits of RF breakdown and metal fatigue. A key element of a test facility required for such experiments is a high-power (tens of MW), 0.5-1 μsec pulsed microwave amplifier in the frequency range from 11 up to 45 GHz [1]. A relatively simple and inexpensive two-cavity harmonic multiplier [2] at 22.8, 34.3, or 45.7 GHz is suggested to be the stand-alone multi-MW RF power source for this application. A sketch depicting such a high power harmonic multiplier is shown in Figure 1, not drawn to scale. In one possible incarnation, a 340 kV, 150 A linear pencil beam from the electron gun at bottom is directed through the iron pole piece; thence to the TE_{111} input drive cavity tuned to 11.424 GHz; thence to the TE_{n11} output cavity, with $n = 2$, 3, or 4; thence to the beam collector. Two WR-90 input waveguides are connected to SLAC- or KEK-type X-band klystron output waveguides [3], 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. This coupling scheme has been used successfully in the Omega-P/Yale S-band accelerator *CARA* [4] and in gyro-harmonic traveling-wave harmonic converters [5]. For $n = 2$ it is possible, for example, to use two output waveguides as in the second-harmonic 7- and 11-GHz magnicons [6,7], while for $n = 3$ it is possible to use four output waveguides as in the 34-GHz magnicon [8] in order to extract power from degenerate independent TE_{n11} modes of the output cavity at the n-th harmonic of the input frequency, i.e., at 22.848, 34.272 respectively. Use of two or four output waveguides and windows is preferred if their power-handling capacity is sufficient; otherwise a converter to a higher-order output mode will be used. The electron gun for the harmonic converter beam could be powered using one unit from, for example, a SLAC "two-pack" modulator operating at somewhat reduced voltage (400 kV and 340 kV for the examples presented below). The two-pack modulator could thus drive one fundamental 11.424 GHz klystron, plus one at a time of the three harmonic converters, to provide, in one laboratory setting, high-power pulsed RF test stands at four frequencies that would span perhaps the entire range of frequencies of interest for high gradient investigations. No other approach for generation of high-power RF for high gradient R&D appears at hand that can be implemented at several frequencies, using largely available technology, at modest cost, and in a relatively short time. Preliminary parameters for these harmonic multipliers using a 50-MW SLAC XP3 klystron [3] as a driver are given in Tables 1 and 2. As can be seen from Table 1, the electron gun, RF drive cavity, beam collector, and magnetic circuit would be identical for harmonic multipliers at all three output frequencies. Thus, the three

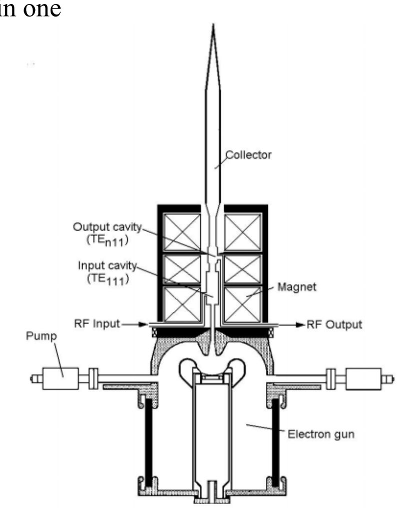

Figure 1. Sketch for conceptual design of harmonic multiplier, not drawn to scale.

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

units could be built for a cost smaller than three times the cost for one.

Table 1. Preliminary parameters for beam and drive cavity of harmonic multipliers.

beam voltage, kV*	340
beam current, A*	150
beam perveance × 10^6, A-$V^{-3/2}$*	0.75
beam power, MW*	51
magnetic field at entrance of drive cavity, kG	6.1
magnetic field at exit of drive cavity, kG	8.8
Brilliouin radius of beam at entrance of drive cavity, mm	0.65
Beam radius at entrance of drive cavity in simulations,mm	0.80
cathode diameter, mm*	66.7
beam area compression (120:1 electrostatic,* 14.5:1 magnetic)	1700:1
RF drive power, MW	50
RF drive frequency, GHz	11.424
operating mode in drive cavity	TE_{111}
peak electric field in drive cavity, kV/cm	181

*Parameters correspond to those for the electron gun in the XP3 SLAC klystron, operated at reduced voltage.

In Figure 2a, an idealized magnetic circuit configuration and the resulting magnetic field profile are shown for the preliminary simulation studies that are described here. A more realistic magnetic circuit design for a W-band 8^{th}-harmonic converter that is similar to the proposed converters [2] is shown in Fig. 2b. The total power required for this magnet at full field is 32.3 kW. This level of magnet power might be unacceptable for an RF source to power an operating linac. But for a test source, where operating efficiency need not be high, but where initial capital cost should be as low as possible, the use of externally-powered coils such as those shown here can be justified.

Figure 3 shows an example of 3-D simulation studies for n = 3 that led to the results summarized in Table II. The plot show the energy of beam electrons (in blue) and the magnitude of radial excursions for the electrons (in red), as well as the outlines of the two-cavity configuration and the final pole piece. One sees that the beam is accelerated from 340 keV to about 675 keV in the drive cavity, and then decelerated to about 400 keV in the output cavity.

It is also instructive to describe the variations in harmonic output power with variations in input drive

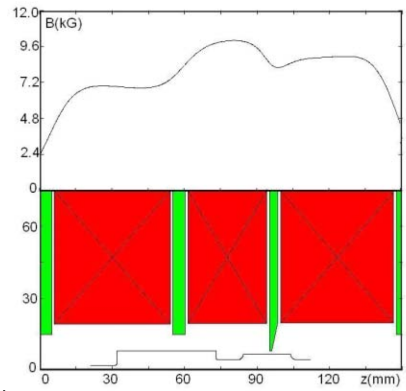

Figure 2a. Magnetic circuit configuration, showing three coils and four iron pole pieces. The plot at top shows the magnetic field profile. The outline drawing at bottom shows the drive cavity (left) and the output cavity (right).

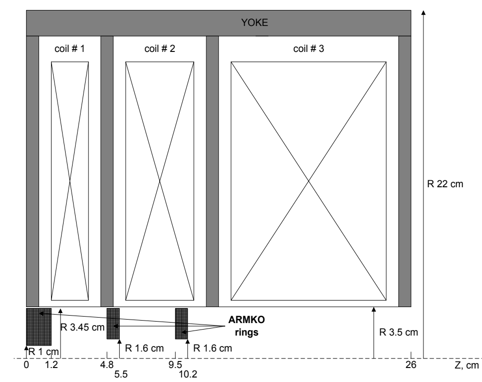

Figure 2b. Schematic design of the room-temperature magnet system. Shown are the dimensions of the three coils, and of the split, removable Armco rings and iron yoke structure. This structure, mounted vertically, is designed to allow removal from the tube without breaking vacuum. The clear bore diameter of 7 cm should be large enough to allow the beam collector to pass through.

power at 11.424 GHz, since this illustrates the inherent flexible and robust qualities of this RF source. In particular, a computed drive curve for the 3^{rd} harmonic converter described above is shown in Figure 4. For this curve, only the RF drive power is altered, with all other parameters (beam, magnetic profile, cavity geometries) held constant.

Table 2. Preliminary RF output parameters for 2^{nd}, 3^{rd}, and 4^{th} harmonic multipliers.

harmonic number n	output frequency (GHz)	operating mode in output cavity	output power (MW)	conversion efficiency (%)	maximum electric field in output cavity (kV/cm)
2	22.848	TE_{211}	41	82	397
3	34.272	TE_{311}	36	72	489
4	45.696	TE_{411}	30	60	563

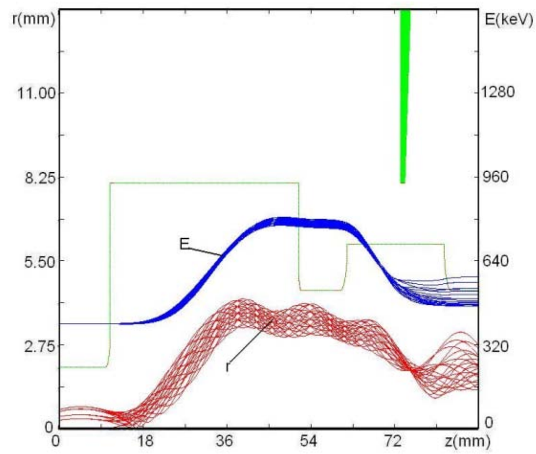

Figure 3. Beam particle energies (blue) and radial excursions (red) for $n = 3$ (frequency tripler), with the TE_{311} mode output cavity tuned to 34.272 GHz. Cavity outlines are also shown. Simulations were made using magnicon codes [9].

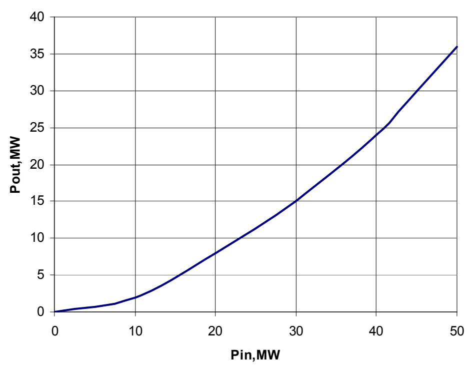

Figure 4. Drive curve, showing output power at 34.272 GHz vs. input power at 11.424 GHz for fixed magnetic field and fixed beam parameters.

The smooth drive characteristic shows that harmonic multipliers should be ideal RF sources for high gradient experiments, where a wide range of smoothly-adjustable output power and pulse width at a given frequency is likely to be desirable.

One should note that the frequency multiplier gives the unique possibility to conduct experiments with pulse compression systems like SLED-II [10], because the multiplier has very wide bandwidth, and the time of a 180° phase flip is determined only by the driving klystron. In addition, the phase change of the input signal for a harmonic multiplier should not be 180°, but 180°/n (where n is the harmonic number). For example, in a frequency doubler the 11.424 GHz klystron driver should provide only a 90° phase flip, that reduces it's phase switching time compared to a 180° phase flip. In Fig. 5 one can see simulation results for a 180° phase flip in the frequency doubler. The total intrinsic switching time does not exceed 2.7 nsec.

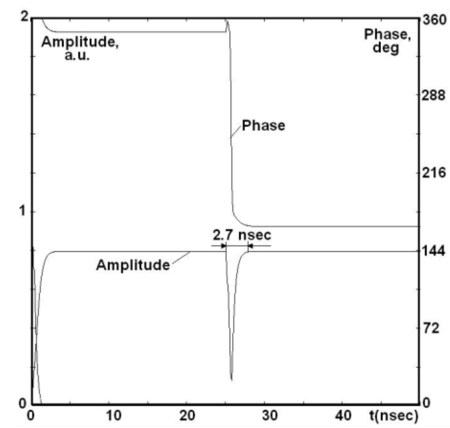

Figure 5. Simulation results for a 180° phase flip in the frequency doubler ($n=2$). Input power is 50 MW. The amplitude and phase of the output signal are shown *vs.* time. The phase of the multiplier drive signal is assumed to change instantaneously by 90° at $t = 25$ nsec.

CONCLUSIONS

Through use of 50 MW X-band drive power and a 340 kV 150 A beam, preliminary simulation results indicate that a simple two-cavity harmonic multiplier can be designed and built to furnish ~40 MW of phase-stable RF power at 22.85 GHz for use in high gradient accelerator R&D.. Similar devices using the same RF drive system and magnet can be built (with somewhat lower powers) for use at 34.3 and 45.7 GHz. These devices would operate using available SLAC klystrons, klystron modulators, XP3 electron guns, and klystron collectors. The harmonic multipliers could thus be built without undue delay, and without excessive new financial investment, for high-gradient accelerator R&D.

REFERENCES

[1] US Workshop On High-Gradient Researches For Multi-TeV Linear Collider, SLAC, July, 2005 http://www.slac.stanford.edu/grp/ara/HGWorkshop/HGWorkshop.htm

[2] J.L. Hirshfield, *et al.*, AIP Conference Proc. 569, Woodbury, N.Y., 2001, p. 765.

[3] D. Sprehn, "SLAC RF Source Research at X-Band," SLAC-PUB-10159, September 2003.

[4] M. A. LaPointe, *et al., Phys. Rev. Lett.* 76, p. 2718 (1996)

[5] J.L. Hirshfield, *et al., Phys. Plasmas* 3, p. 2163 (1996)

[6] E.V. Kozyrev, et. al., RF98 Workshop, AIP **474**, p.187.

[7] O.A. Nezhevenko, *et al.,* PAC2001, Chicago 2001, p.1023.

[8] O.A. Nezhevenko, *et al.*, *IEEE Trans. Plasma Sci.*, vol. 32, No 3, June 2004, p. 994.

[9] V. P. Yakovlev, *et al.*, AIP Conference Proc. 647, Woodbury, N.Y., 2002, p. 421.

[10] S.G. Tantawi, "New Development in RF Pulse Compression," SLAC-PUB-8582, Aug. 2000.