Ka-BAND HIGH POWER HARMONIC AMPLIFIER FOR BUNCH PHASE-SPACE LINEARIZATION*

X. Chang[†,1], Y. Jiang[1], S. V. Shchelkunov[1], J. L. Hirshfield[1,2]
[1]Yale University, New Haven, CT, USA; [2]Omega-P R&D, Inc., New Haven, CT, USA

Abstract

A future European light source CompactLight is being proposed to extend FEL operation further into the x-ray region than other light sources by using a linac operating at X-band (12 GHz) with a short Ka-band (36 GHz) section for linearizing bunch phase space. The Ka-band system requires a high-power RF amplifier, synchronized with the main X-band source. We report here on design of a third-harmonic klystron amplifier for this application. Our design employs a four-cavity system with a multi-cell extended interaction output cavity. Initial simulation results indicate that more than 10 MW of 36-GHz power can be obtained with an efficiency exceeding 20%, and with 12-GHz drive power of 30 W. A preliminary design for a proof-of-principal experimental test of this concept is described.

INTRODUCTION

European scientists are proposing an advanced light source CompactLight [1] which aims to extend FEL operation into the hard X-ray region and thus beyond present state-of-the-art. CompactLight is to employ advanced concepts for bright electron photo injectors, high-gradient X-band structures at 12 GHz, and innovative compact short-period undulators. The proposed facility will enjoy lower electrical power demand and a smaller footprint than would a comparable C- or S-band system.

To correct the longitudinal phase space non-linearity as arises in the X-band (12 GHz) linac, a Ka-band, third-harmonic (36 GHz) short linac is proposed, which requires a high RF power source, of the order of 10 MW [2]. Such a power level is generally achieved using a klystron, but is difficult to realize at Ka-band. A main reason is that a large diameter beam pipe is required to transport a high current beam, so spurious modes could easily be excited in the beam pipe. Furthermore, the radius of TM010 mode Ka-band cavities (4.7 mm) is comparable to the beam pipe radius; this lowers beam transit time factors significantly due to field leakage from the cavities into the beam pipe.

The Yale University Beam Physics Lab operates a pulsed electron gun and associated DTI Marx-band modulator, with a peak voltage and current of 500 kV and 218 A, as pictured in Fig.1. We present here a preliminary design for a klystron amplifier that employs this gun and embodies an X-band bunching system and a third-harmonic Ka-band output cavity to supply a total output power of more than 10 MW for initial tests of the CompactLight Ka-band linac.

Fig. 1. 500 kV, 218 A electron gun tank (at left) connected to the 500 kV, 250 A Marx modulator (at right) in the Beam Physics Lab at Yale University.

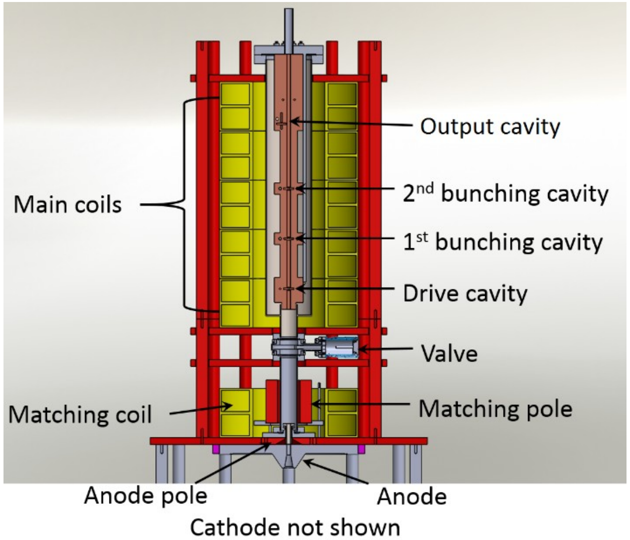
3[RD] HARMONIC KLYSTRON DESIGN AND SIMULATION

A design of the test stand for a related experiment (beam driven bimodal cavity [3] for raising acceleration gradient) has been realized, as shown in Fig. 2. The design for the 3[rd] harmonic klystron we are proposing is similar to that: it embodies a beam matching system, X-band bunching cavities, output cavity, and magnetic field system. The main differences are that the main magnetic field is taken to be 3.0 kG instead of 2.3 kG; and the frequencies of the drive and bunching cavities are 12 and 36 GHz instead of 11.424 and 34.272 GHz.

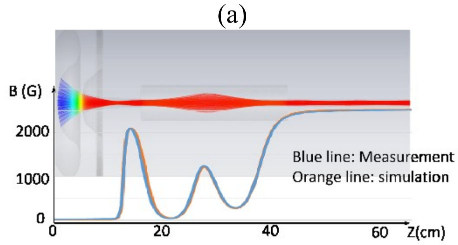
Beam tracking simulations indicate that a 500 keV, 218 A beam can be confined within a 6 mm diameter pipe with a solenoid magnetic field of 2.3 kG or higher, as shown in Fig. 2(b). We designed our klystron with a conservative beam voltage of 350 kV, with a corresponding current of our 0.62 μperv gun of 128 A. With a 3.0 kG magnetic field, the beam can be compressed to propagate within a 5.5 mm diameter beam pipe.

The bunching cavities and output cavity are designed to be in two split copper pieces for suppressing excitation of spurious modes, simplified machining, avoiding brazing, and tuning, as shown in Fig. 3. For the 5.5 mm diameter beam pipe, the cutoff frequency for the TM010 mode is 41.7 GHz, so a 36 GHz TM010 mode cannot propagate in the pipe. The distances between the drive cavity and first bunching cavity, and between the two bunching cavities, are 10 cm; while the distance between the 2nd bunching cavity and the output cavity is 7 cm.

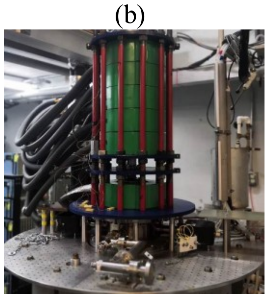
* Supported by USA National Science Foundation, Award #1632588
† xychang6666@gmail.com



(a)



(b)



(c)

Fig. 2. (a) Layout of the 500 kV beam test stand for experimental studies of the 10-MW Ka-band 3rd harmonic klystron. (b) Start-to-end tracking simulation of a 350 kV, 128 A beam and the magnetic field distribution along the axis. (c) Assembly of the experimental setup.

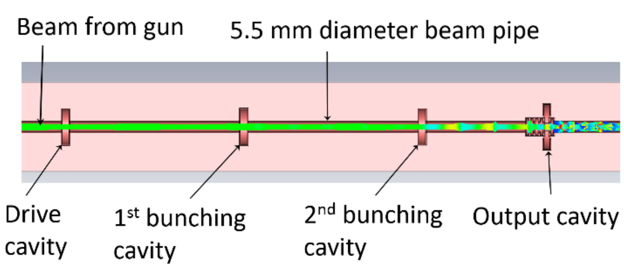
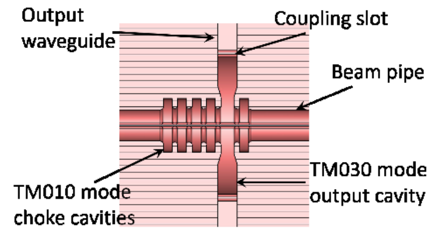


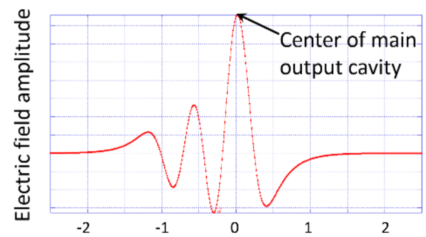
Fig. 3. Top view of the half split of the four-cavity amplifier structure.

The extended interaction output cavity is shown in detail in Fig. 4(a). The main output cavity operates at the TM030 mode at 36 GHz, which makes its radius much bigger than that of TM010 mode cavities at this frequency. This not only improves the beam-cavity interaction, but also reduces the effects of the output coupling slots on the field distribution. There are two symmetric WR-28 output waveguides.

Two TM010 choke cavities on either side of the main cavity are used to improve the transit time factor, while three more TM010 cavities ahead of the main cavity support an extended interaction. Distances between the cavities have been optimized such that the period of the spatial field distribution along axis synchronizes (i.e. in π-mode) with the electron beam at 36 GHz. The transit time factor for this design is 0.55 at a beam energy of 350 keV.



(a)



(b)

Fig. 4. (a) Output cavity, with two WR-28 output waveguides. (b) SUPERFISH result for the electric field along the axis.

Beam dynamics simulations were performed with CST PIC particle studio on Yale's High Performance Cluster. The drive cavity is driven with 30 W of 12 GHz power, the input beam energy is 350 keV and its current is 128 A. Fig.5 shows the output signal in a unit such that its square is power in watts from one of the two output waveguides, after parameter optimization. The signal reaches steady state after 30 ns. The output power from each waveguide at steady state is 5.31 MW, for a total power of 10.6 MW. The total input beam power is 44.8 MW, so the gain is 55 dB and the efficiency is 23.7%.

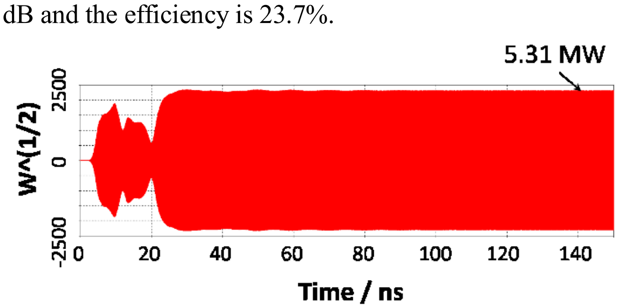


Fig.5. One of the two output signals, in a unit such that its square is the power in watts.

The 23.7% efficiency for our Ka-band frequency-tripling klystron amplifier would likely disqualify it as one of many such RF sources as would be needed for a high energy Ka-band linac. But for the short Ka-band linac section proposed for bunch linearization in the much larger X-band linac planned for CompactLight, low Ka-band source efficiency may not be a disqualifying deficiency.

CONCLUSION

A Ka-band 36 GHz, 3rd harmonic klystron has been designed based on the 500 kV pulsed gun operating at Yale University. Simulations indicates that by choosing a TM030 mode output cavity combined with the TM010 mode choke cavities and three extended interaction cavities, a transit time factor of 0.55 for the output cavity and a 350 keV, 128 A beam can be achieved. The total output power in our design reaches 10.6 MW with an effective gain of 55 dB and 23.7% efficiency.. It is not inconceivable that higher output power can be achieved with higher beam voltage and current. The design in this example provides a promising way to obtain at least 10 MW of 36 GHz power for testing the linac design for linearizing beam phase space in the accelerator for CompactLight.

ACKNOWLEDGEMENT

The authors acknowledge important discussions that clarified technical issues for CompactLight with Dr. Bruno Spataro, Dr. Luigi Faillace, and Dr. Mostafa Behtouei of LNF/INFN Frascati, Italy.

REFERENCES

[1] http://www.compactlight.eu/Main/HomePage

[2] M. Behtouei, B. Spataro, L. Faillace, M. Migliorati, L. Palumbo, "New Analytical Derivation of Group Velocity in TW Accelerating Structures", 19-24 May 2019, IPAC2019, Melbourne, Australia, MOPGW030.

[3] X. Chang, Y. Jiang, S. V. Shchelkunov, J. L. Hirshfield, "Beam Driven Bimodal Cavity Structure for High Gradient Acceleration", proceedings of this conference, 1-6 Sept. 2019, NAPAC2019, Lansing, MI, USA, WEPLM50.