HIGH POWER 20 GHz RF SOURCE BASED ON SEVENTH HARMONIC CO-GENERATION*

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Abstract

The TE_{72} mode in cylindrical waveguide has its group velocity nearly equal to that of the TE_{11} mode when the operating frequency of the former is seven times of that of the latter. Thus the two modes have almost the same resonant magnetic field, and coherent radiation can be generated at the 7th harmonic when the fundamental energizes a gyrating electron beam by the cyclotron autoresonance interaction. It is shown analytically that the electron's gyration radius, normalized to waveguide radius, must be less than 0.5431 in the cyclotron autoresonance interaction. This analytical prediction is well confirmed by computer simulations. For a 300 kV, 30 A warm beam driven by 20 MW rf power at 2.856 GHz, simulations indicate that 7th harmonic power of up to 16 MW at 20 GHz can be obtained.

1   INTRODUCTION

Gyroharmonic conversion as a process for efficient production of high-power radiation has been investigated and analyzed in a number of prior publications [1-4]. Gyroharmonic conversion is a frequency-multipler concept, for which two approaches have been proposed. In the first [1,2], low frequency rf drive power is used to accelerate an electron beam using the TE_{11} mode by CARA (cyclotron autoresonance acceleration) [5-8], and the beam is then allowed to selectively emit coherent radiation at a harmonic of the drive frequency in a converter section. To cause the accelerated beam from CARA to fulfill both synchronous and grazing conditions in the converter, a drift region is inserted [6], and the harmonic index is specified by proper choice of converter circuit parameters. The second approach to gyroharmonic conversion is co-generation [4], where the lowest mode with almost the same required resonant magnetic field as that of TE_{11} at the drive frequency is the TE_{72} at the 7th harmonic, and transfer of drive power and generation of harmonic power occur in the self-same structure. The harmonic index is selected by the interaction mechanism, instead of only by circuit parameters. Because no drift region is needed in co-generation, strong rf trapping is always present and preserves good gyrophase coherence among the beam particles, resulting in better beam quality and higher interaction efficiency.

2   PRINCIPLES OF CO-GENERATION AND MAXIMUM GYRATION RADIUS

Co-generation can be understood by examining the cyclotron autoresonance condition that maintains electron synchronism with rf electric fields. The resonance condition for TE_{sl} mode at the sth harmonic is

$$s\omega = s\Omega_0/\gamma + ck_{z,sl}\beta_z \quad \text{or} \quad \Omega_0 = \omega\gamma(1 - n_{sl}\beta_z), \quad (1)$$

where ω is the drive frequency, c is the light speed in free space, γ and β_z are the electron's relativistic energy factor and normalized axial velocity, the refractive index or normalized group velocity for TE_{sl} mode is $n_{sl} = k_{z,sl}c/\omega$ with $k_{z,sl}$ the axial wave number, and the rest gyration frequency is $\Omega_0 = eB_0/m_0$ with e the electron's charge, m_0 the electron's rest mass, and B_0 the axial magnetic field. For a waveguide radius of 3.3 cm and fundamental operation at 2.856 GHz, the refractive index n_{11} is 0.3605 and n_{72} is 0.3521, these differ by only 2.3%. From Eq. (1) we find the resonance magnetic fields for TE_{11} and TE_{72} modes are nearly identical, with difference of less than 1.3% for $\beta_z = 0.99$, 0.5% for $\beta_z = 0.5$, and 0.3% for $\beta_z = 0.3$. Calculations indicates that $TE_{13,3}$, $TE_{24,5}$, and $TE_{30,6}$ are also of near-degenerate [4].

When an electron beam is pumped by drive power in the TE_{11} mode, all electrons rapidly get phase-trapped and accelerated synchronously. At the same time, the beam begins to emit coherent radiation preferably into TE_{72} mode, although $TE_{13,3}$, $TE_{24,5}$, and $TE_{30,6}$ modes also have nearly equal resonant magnetic fields. This is because the larger the azimuthal mode index, the more the electric field distribution is concentrated in the region close to the waveguide wall. Radiation into higher modes decreases with increase in mode index. Moreover, higher harmonics are more sensitive to beam phase spread.

A larger gyration radius is preferred for interaction with high harmonics, since high-order mode field distributions are closer to the waveguide wall. However, the gyration radius is constrained by the synchronous condition Eq. (1), resulting in

$$\frac{r_L}{R_w} \le \frac{\beta}{j'_{11}}\left[\frac{1 - n_{11}^2}{1 - (n_{11}\beta)^2}\right]^{1/2} < 0.5431, \quad (2)$$

where r_L is the gyration radius, R_w is the waveguide radius, $j'_{11} = 1.841184$ is the first root of the derivative of Bessel function $J_1(\chi)$, and $\beta = (1 - 1/\gamma^2)^{-1/2}$ is the

normalized total electron's velocity. Eq. (2), which is in good agreement with computer simulation, states that the normalized gyration radius must be less than 0.5431 regardless of the beam's energy and waveguide radius in CARA.

3 RESULTS OF SIMULATION

Simulation results are presented here for co-generation with parameters given in Table I. For all examples, a single-energy injected electron beam with a guiding center spread of 10% and an rms axial velocity spread of 0.02% is assumed. This velocity spread value is scaled from that for the Litton $K = 1 \times 10^{-6}\,A - V^{-3/2}$ 100 kV gun now in operation in the Yale/Omega-P 4th harmonic converter experiment. 512 computational particles are taken, with 8 values of velocity spread, 8 values of phase spread, and 8 values of guiding center spread.

TABLE I: Parameters in simulation of co-generation.

Injection gun voltage	300 kV
Injector gun perveance	$0.18 \times 10^{-6}\,A - V^{-3/2}$
Beam current	30 A
rms axial velocity spread	0.02%
Beam guiding center spread	10%
Waveguide radius	3.3 cm
Refractive index (TE_{11} mode)	0.3605
Refractive index (TE_{72} mode)	0.3522
rf drive frequency	2.856 GHz
rf drive power	20 MW
Output frequency	19.992 GHz
Guide magnetic field	< 2.4 kG

To measure performance of co-generation, one can define a direct efficiency, given by

$$\eta_{\text{direct}} = \frac{P_{72}(\text{out})}{P_{11}(\text{in}) + P_{72}(\text{in}) + P_{\text{beam}}(\text{in})}, \qquad (3)$$

where $P_{sl}(\text{in})$ is the TE_{sl} mode input power, $P_{\text{beam}}(\text{in})$ is the input beam power, and $P_{72}(\text{out})$ is the TE_{72} output power. Fig. 1 shows the results for a co-generator with an optimized detuning of $\Delta = -0.02$. Detuning, defined as $\Delta \equiv \Omega_0/\left(\omega < \gamma >< \beta_z >\right) + n_{11} - 1/< \beta_z >$, measures how much the magnetic field profile deviates from exact resonanance; introduction of detuning reduces impairment of beam quality caused by initial velocity spread. In this case, at $z = 83.8$ cm, output power at the 7th harmonic is seen to be 5.52 MW, at the fundamental to be 10.45 MW, and at the 13th harmonic to be 0.04 MW. Possible competing modes $TE_{13,3}$, TE_{62} and TE_{82} are seen to have only a minuscule influence on 7th harmonic co-generation. The direct efficiency is 5.52/(20+9) = 19.03%. The failure of normalized average gyration radius $< r_L/R_w >$ to fall below 0.3 indicates that particles have lost good phase synchronism with the TE_{11} mode, and thus can not give up more than a limited amount of transverse momentum.
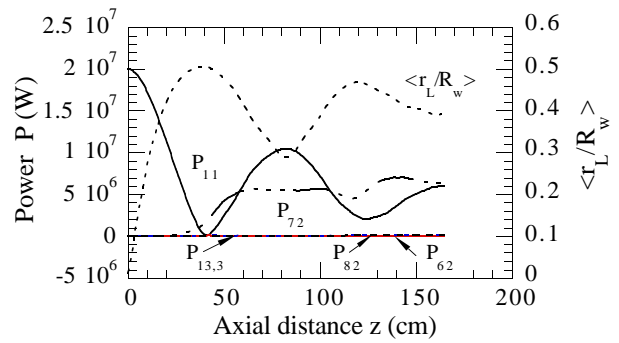

Figure 1: Dependence of rf power P and normalized gyration radius $< r_L/R_w >$ on axial distance z. TE_{11} and TE_{72} modes always coexist and a detuned resonant magnetic field profile is used. Peak value of 7th harmonic power at 20 GHz is 5.52 MW at $z = 83.8$ cm.

To increase efficiency, one can kill the TE_{11} mode after drive power is depleted, using a selective absorber. It is found that use of a segmented straight-line magnetic profile beyond the power-depleted point can also increase 7th harmonic power. As shown in Fig. 2, 7th harmonic output is seen to rise to 10.20 MW at $z = 99$ cm, and the direct efficiency is increased to 35.17%. Comparing Fig. 2 with Fig. 1, we find that mode suppression and adjustment of magnetic profile has considerably improved direct efficiency, but the circuit becomes longer and somewhat more complicated.
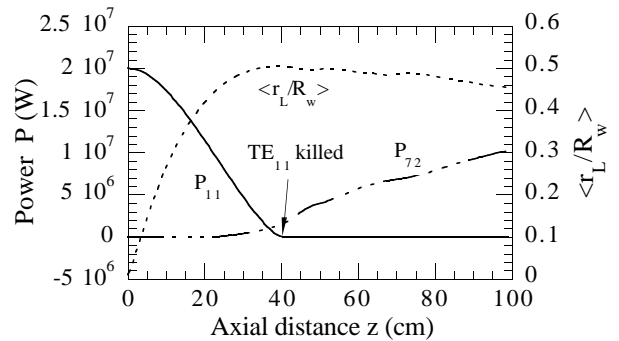

Figure 2: Dependence of rf power P and normalized gyration radius $< r_L/R_w >$ on axial distance z. TE_{11} mode is killed and segmented straight-line magnetic field profile is employed after TE_{11} mode is depleted. 7th harmonic 20 GHz power is 10.20 MW at $z = 99$ cm.

It is found by simulations that injection of a portion of 7th harmonic power with proper phase can effectively reduce gyrophase spread. Fig. 3 shows results with a 7th harmonic injection power of 2.0 MW, but with other parameters the same as in Fig. 1. Now it is seen that the 7th harmonic output at $z = 86.5$ cm is 12.11 MW, indicating a net gain of 10.11 MW, as compared with 5.52 MW output without injection. Fundamental power at $z = 86.5$ cm is 9.27 MW. The significant increase in 7th harmonic output results from much better particle trapping when injection is employed. Now the direct efficiency is 12.11/(9+2+20) = 39.06%.
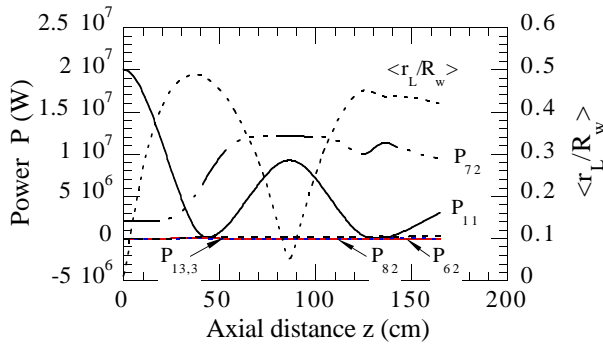
Figure 3: Dependence of rf power P and normalized gyration radius $< r_L/R_w >$ on axial distance z. An injection power of 2.0 MW at 20 GHz is used, with other parameters the same as in Fig. 1. 7th harmonic power at 20 GHz is 12.11 MW at $z = 86.5$ cm.

Figure 4: Dependence of rf power P and normalized gyration radius $< r_L/R_w >$ on axial distance z. An injection power of 2.0 MW at 20 GHz is used, with other parameters the same as in Fig. 2. 7th harmonic power at 20 GHz is 15.96 MW at $z = 87.5$ cm.
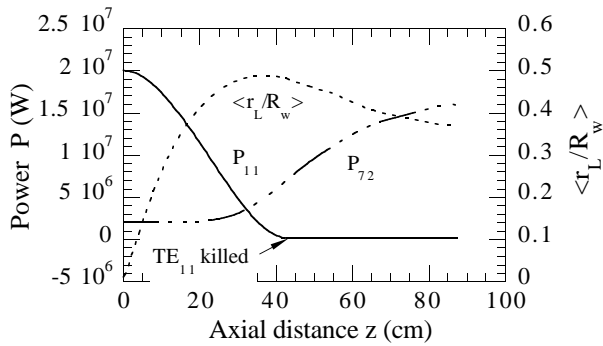
Harmonic injection also benefits co-generation for the Fig. 2 case where TE_{11} mode is killed beyond its power-depleted point. Fig. 4 shows results with a 7th harmonic injection power of 2.0 MW, but with other parameters the same as in Fig. 2. It is seen that 7th harmonic power grows to 15.96 MW at $z = 87.5$ cm, corresponding to a direct efficiency of 51.48%.

In a configuration requiring a large number of sources, such as a high energy electron-positron collider, one could interconnect neighboring sources in tandem, so that any 2.856 GHz output of one source would partially feed the next source; in that case the "makeup" power required for each source (except for the first one) would be reduced. In this case, one can define the output efficiency of a single co-generator in the tandem sequence as

$$\eta_{\text{output}} = \frac{P_{72}(\text{out})}{P_{11}(\text{makeup}) + P_{72}(\text{in}) + P_{\text{beam}}(\text{in})}. \quad (4)$$

A higher efficiency can be achieved through recovery of spent beam energy if a depressed collector is employed [9]. Inclusion of beam energy recovery leads to a definition of an enhanced efficiency, defined as

$$\eta_{\text{enhanced}} = \frac{P_{72}(\text{out}) + \eta_{\text{rec}} P_{\text{beam}}(\text{out})}{P_{11}(\text{makeup}) + P_{72}(\text{in}) + P_{\text{beam}}(\text{in})}, \quad (5)$$

where η_{rec} is the efficiency for recovery of spent beam power, and $P_{\text{beam}}(\text{out})$ is the beam power at the end of the co-generator. For an ideal collector, the recovery efficiency is given by $\eta_{\text{rec}} = (\gamma_{\min} - 1)/(< \gamma > -1)$, where $\gamma_{\min}$ is the minimum relativistic energy factor in the spent beam. Table II shows comparison for the four configurations of co-generation discussed above. Effects of power injection on co-generation can be found by comparing the Fig. 1 and Fig. 2 cases with the Fig. 3 and Fig. 4 cases respectively; effects of beam energy recovery on co-generation can be found by comparing the output efficiency η_{output} with the enhanced efficiency η_{enhanced}.

TABLE II: Comparison for four configurations of 7th harmonic co-generation at 20 GHz.

	P_{72}-out (MW)	η_{direct} (%)	η_{output} (%)	η_{rec} (%)	η_{enhanced} (%)
Fig. 1	5.52	19.03	29.75	69.1	77.6
Fig. 2	10.20	35.17	35.17	78.6	85.4
Fig. 3	12.11	39.06	55.73	94.4	96.5
Fig. 4	15.96	51.48	51.48	90.2	94.4

4   CONCLUSIONS

Co-generation is a novel means for efficient gyro-harmonic conversion. By injection of harmonic power to improve particle trapping and recovery of spent beam energy to enhance efficiency, simulations have shown that an overall 7th harmonic efficiency of over 90% can be achieved for a 16 MW 20 GHz co-generators with a 300 kV, 30 A electron beam pumped by 20 MW power at 2.856 GHz.

5   REFERENCES

[1] A. K. Ganguly and J. L. Hirshfield, Phys. Rev. E **47**, 4364 (1993).

[2] J. L. Hirshfield, A. K. Ganguly, and C. Wang, in *Pulsed RF Sources for Linear Colliders*, edited by R. C. Fernow, AIP Conf. Proc. No. 337, (AIP, New York, 1995), p. 200.

[3] J. L. Hirshfield, C. Wang, and A. K. Ganguly, IEEE Trans. Plasma Sci. **24**, 825 (1996).

[4] C. Wang and J. L. Hirshfield, and A. K. Ganguly, Phys. Rev. Lett. **77**, 3819.

[5] B. Hafizi, P. Sprangle, and J. L. Hirshfield, Phys. Rev. E **50**, 3077 (1994).

[6] C. Wang and J. L. Hirshfield, Phys. Rev. E **51**, 2456 (1995).

[7] M. A. LaPointe, R. B. Yoder, C. Wang, A. K. Ganguly, and J. L. Hirshfield, Phys. Rev. Lett. **76**, 2718 (1996).

[8] Hirshfield, M. A. LaPointe, A. K. Ganguly, R. B. Yoder, and C. Wang, Phys. Plasmas **3**, 2163 (1996).

[9] K. Sakamoto, M. Tsuneoka, A. Kasugai, T. Imai, T. Kariya, K. Hayashi, and Y. Mitsunaka, Phys. Rev. Lett. **73**, 3532 (1994).