High-Efficiency Inductive Output Tubes Using a Third Harmonic Drive on the Grid

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Abstract—In this article, we discuss the use of a third harmonic component to the drive voltage on the grid of an inductive output tube (IOT). High-efficiency IOTs are typically characterized by efficiencies up to 70%–75%. However, the achievement of efficiencies greater than 80% would substantially reduce the operating costs of next-generation accelerators. In order to achieve this goal, we consider the addition of a third harmonic component to the drive signal on the grid of an IOT. The use of a third harmonic drive component in IOT guns has been considered in order to apply such a gun as the injector of radio frequency linear accelerators (RF linacs). Here, we consider that the IOT will be used to provide the rf power to drive RF linacs and apply the third harmonic with the intention of increasing the efficiency of the IOT. We consider a model IOT with a 700-MHz resonant cavity and using an annular beam with a voltage of 30 kV, an average current of 6.67 A, yielding a perveance of about 1.3 μP. We simulate this IOT using the NEMESIS simulation code which has been successfully validated by comparison with the K51H90W-2 IOT developed by Communications and Power Industries. It is found that the effect of the third harmonic on the efficiency is greatest when the phase of the third harmonic is shifted by π radians with respect to the fundamental drive signal and with third harmonic powers greater than about 50% that of the fundamental drive power. For the present example, we show that efficiencies approaching 86% are possible by this means.

Index Terms—Harmonic grid drive, high-efficiency, inductive output tube (IOT).

I. INTRODUCTION

HIGH-EFFICIENCY inductive output tubes (IOTs) are typically characterized by efficiencies up to 70%–75%. However, the achievement of efficiencies greater than 80% would substantially reduce the operating costs of next-generation accelerators. In order to achieve this goal, we consider the addition of a third harmonic component to the drive signal on the grid of an IOT [1]. The use of a third harmonic drive component in IOT guns has been considered in order to apply such a gun as the injector of radio frequency linear accelerators (RF linacs). Here, we consider that the IOT will be used to provide the drive power for RF linacs and apply the third harmonic with the intention of increasing the efficiency of the RF output of the IOT.

IOTs are sometimes referred to as klystrodes [3] and are used for high power applications such as the drivers for radio frequency accelerators [4]–[7]. A schematic illustration of an IOT is shown in Fig. 1 [8]. In an IOT, a prebunched beam is generated by applying a radio frequency signal to the grid of an electron gun, and is then accelerated to higher energies by a dc potential before injection into a resonant cavity. The modulated beam is preconditioned to excite the resonant mode of the cavity, after which the spent beam is directed into a collector.

Recent development of a high-power multibeam IOT [9] intended for the production of RF power for the accelerator underlying the European Spallation Neutron Source [10] achieved an efficiency of 65% with a peak power of 1.2 MW at a frequency of 705 MHz. The cost of RF power for such facilities is an important driver for accelerator operations, and the production of an IOT with still higher efficiencies could provide significant cost reductions. A 5% increase in the efficiency reduces the power required for a 200-kW device by 10 kW. This is a significant operational cost savings for systems running continuously or at high duty. This is the prime motivation for studying the application of the third harmonic component to the drive on the IOT gun(s).

Consider a model IOT with a 700-MHz resonant cavity and using an annular beam with a voltage of 30 kV, an average current of 6.67 A, yielding a perveance of about 1.3 μP.
This IOT is simulated using the NEMESIS simulation code [8] which has been successfully validated by comparison with the K5H90W-2 IOT developed by Communications and Power Industries (CPIs). It is found that the effect of the third harmonic on the efficiency is greatest when the phase of the third harmonic is shifted by $\pi$ radians with respect to the fundamental drive signal, and with third harmonic powers greater than about 50% that of the fundamental drive power. For the present example, we show that efficiencies approaching 86% are possible by this means.

The organization of the article is as follows. The numerical model incorporated in the NEMESIS simulation code is described in Section II. The simulation results for the 700-MHz IOT both with and without the third harmonic drive are described in Section III, and a summary and conclusion is given in Section IV.

II. NEMESIS SIMULATION CODE

The numerical formulation implemented in the NEMESIS code [8] contains elements similar to what is employed in particle-in-cell simulation codes. Integration of the dynamical equations is performed in time, so the code can treat implicitly particles that might turn around. This can be important in high-efficiency designs where particles lose a great deal of energy.

NEMESIS contains an equivalent (LRC) circuit model for the cavity voltage with a model for the circuit fields taken from Kosmahl and Branch [11] which is scaled using the cavity voltage. The integration of particle trajectories makes use of the circuit fields obtained in this fashion, as well as an analytic model for the focusing fields and a 2-D Poisson solver for the space charge fields.

The numerical procedure is illustrated in Fig. 2. The procedure in stepping from $t \rightarrow t + \Delta t$ begins with a fourth-order Runge–Kutta integration of the equivalent circuit equations. We typically take 100 steps per wave period to ensure accuracy in this calculation. Once the circuit equations have been stepped, electrons are injected into the cavity if the time coincides with the bunch phase. We inject $N$ charge rings of charge. The charge associated with $i$th ring is $(2i-1) I_b(t) \Delta t/N^2$. After injection, the trajectories are integrated using a Boris push [12], which is a second-order accurate, two-step process in which the particle momenta are integrated first followed by the particle positions. At this point, the source current is calculated by averaging the current obtained using $(x_i, v_{i+\Delta t/2})$ and $(x_{i+\Delta t}, v_{i+\Delta t/2})$. This ensures second-order accuracy for the overall procedure. Finally, we test whether any particles have left the system (from either end of the cavity or by striking the wall), and, if necessary, eject them from the simulation. This is repeated as many times as necessary to simulate any given pulse time.

The inclusion of the third harmonic is done via the following model for the drive current, where $I_p$ is the peak current, $\varepsilon$ denotes the ratio of the third harmonic to the fundamental, and $\phi$ is the phase shift of the third harmonic relative to the fundamental

$$I(t) = I_p \left[ \sin \left( \pi \frac{t}{\tau_{\text{width}}} \right) + \varepsilon \sin \left( 3 \pi \frac{t}{\tau_{\text{width}}} + \phi \right) \right]^2$$  \hspace{1cm} (1)

for $t < \tau_{\text{width}} < 1/f$ and zero otherwise, where $f$ is the wave frequency and $\tau_{\text{width}}$ denotes the portion of the wave period over which electrons are drawn off the grid. The ratio of the average to peak current using this model for the drive current is

$$\frac{I_{\text{avg}}}{I_p} = \frac{1 + \varepsilon^2}{2} \frac{\tau_{\text{width}}}{\tau_{\text{period}}}.$$  \hspace{1cm} (2)

The schematic illustration of an IOT as shown in Fig. 1 employs a solid beam. In contrast, here we consider an annular beam. An IOT is composed of three elements: the gridded gun, the output cavity, and the collector. Here, we simulate the output cavity for a given injected electron beam both with and without the third harmonic drive, where our primary purpose is to investigate the effect of the third harmonic.

As mentioned above, the NEMESIS formulation has been validated by comparison with the K5H90W-2 IOT developed by CPIs [7]. This tube was designed to use a 37-kV beam with a current of several amperes. The tube is tunable over the range of 650–805 MHz. The cavity $Q$ is in the range of 100–200 and $R/Q$ is about 100 $\Omega$. A comparison of the measured performance of the tube with the predictions of NEMESIS is shown in Fig. 3 over a range of currents from 1.5 to 3.3 A, $Q = 200$, and with the ratio of the average to peak current of 0.15. It is evident that good agreement between the measurements and the simulations is found.
The configuration under study consists in a cavity tuned to a resonant frequency of 700 MHz with $R/Q = 100 \, \Omega$ and a loaded $Q = 84.6$ with a radius of 9.009 cm, a length of 9.144 cm, and where the center of the gap is located 4.571 cm downstream from the entrance to the cavity. The optimal gap length and the optimal position of the gap center were found through a multiple-parameter series of simulations. The optimal gap length, over a range of gap centers, was found to be about 3.1 cm in the absence of the third harmonic. The electron beam voltage and current are 30 kV and 6.67 A, respectively, and is injected as an annulus centered about the axis of symmetry with an inner radius of 5.128 cm and an outer radius of 8.079 cm. A solenoidal focusing field is used with an amplitude of 126 G which is close to the Brillouin field which is given when the electron cyclotron frequency $\omega_c = \sqrt{2} \omega_{pe}$, where $\omega_{pe}$ is the electron plasma frequency [13]. The ratio of the average to peak current is 0.15. In the absence of any third harmonic drive, this implies that the ratio of the width of the pulse to the resonant period ($=1/f$, where $f = 700 \, \text{GHz}$) is 0.30. Note that from (2) the ratio of the average to peak current depends upon the resonant period, the bunch width, and the relative strength of the third harmonic. In this work, we held $I_{\text{avg}}/I_{\text{peak}}$ and the resonant period fixed so that the bunch width varied with the relative strength of the third harmonic.

For the parameters of interest in the present study, we first consider the performance in the absence of the third harmonic drive. A plot showing the output power as a function of time is shown in Fig. 4 for the above-mentioned parameters. As shown in the figure, the power increases to a steady-state after about 50–60 ns. The plot shows the instantaneous power, which is the product of the voltage and current across the load. Since both the voltage and current vary as $\cos(\omega t)$, the product has a bulk (or average) component as well as a harmonic oscillation that varies as $\cos(2\omega t)$. It is this rapid oscillation that gives the figure the appearance of a solid rising bar. However, the average power is half that of the maximum and reaches a steady-state of about 170 kW. Note that this already corresponds to an efficiency of about 84–85%.

The linewidth, $\Delta f/f$, of this configuration is 3.1%, as shown in Fig. 5. Since this study is aimed primarily at IOTs used for accelerator applications, a broad linewidth is not important and the tube can be designed to operate over a narrow range of frequencies.

The results shown in Figs. 4 and 5 were obtained using the optimal cavity/beam parameters. In order to illustrate the sensitivity of the design to cavity/beam parameters, we now consider the effect of various parameters on the performance.

We first consider the sensitivity of the performance to the gap. The multiple-parameter study of performance versus the gap length and gap center shows that the performance is relatively insensitive to the position of the gap center, but is more sensitive to the gap length. For the gap located in the center of the cavity, the variation in performance with gap length is shown in Fig. 6. It is clear from the figure that the optimal gap length is about 3.1 cm.

The effect of the third harmonic on the performance of the IOT depends on the phase relationship of the harmonic with respect to the fundamental. This is evident in Fig. 7 where we plot the output power (left axis) and the efficiency (right axis) versus the phase of the third harmonic (blue) as well as the performance in the absence of the third harmonic (red). As shown in the figure, the effect of the third harmonic is maximized for a phase shift of about $\pi$ radians. At that point, the efficiency reaches a peak of approximately 86.3%. This compares with an efficiency of about 84.5% in the absence of the third harmonic.
The third harmonic results shown in Fig. 7 were obtained using $\varepsilon = 1$. The variation in the effect of the third harmonic with harmonic power is an important consideration in the design of the IOT, and we show the variation in performance with $\varepsilon$ in Fig. 8 for the optimal $\pi$ phase shift. It is clear from the figure that the optimal effect of the third harmonic is found for $\varepsilon$ greater than about 0.5 but is relatively insensitive to increases beyond that value (86.3%).

IV. SUMMARY AND CONCLUSION

In this article, we have described a model for the inclusion of a third harmonic component on the drive of a high-efficiency IOT. The numerical formulation is an extension of that incorporated into the NEMESIS simulation code which has previously been validated by comparison with the K5H90W-2 IOT developed at CPIs [8].

It is found that the effect of the third harmonic on the efficiency is greatest when the phase of the third harmonic is shifted by $\pi$ radians with respect to the fundamental drive signal and with the third harmonic powers greater than about 50% of the fundamental drive power. For the present example, we show that efficiencies approaching 86% are possible by this means. Results in progress for a multibeam configuration show that improvements in the performance due to the third harmonic can reach 5%–10%, and this will be reported in a future article.

An extension of this work relating to the development and testing of a prototype multibeam IOT which includes innovative designs for the input coupler and the grids is under study. Preliminary work on this project indicates that electronic efficiencies exceeding 85% are possible. This will be presented in a future work which is in preparation.

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