High-Efficiency, High Average Power, Multiple Beam Inductive Output Tubes

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Abstract: The development of high efficiency, Multiple Beam Inductive Output Tubes (IOTs) with efficiencies greater than 80% would substantially reduce the operating costs of next-generation particle accelerators. We discuss the development of a multiple-beam IOT that employs a third harmonic drive component on the grid to achieve efficiencies greater than 80%. We discuss a novel input coupler, grid design, and simulation of the output cavity. This presents a path forward to the design and production of such high efficiency IOTs.

Keywords—*Inductive Output Tube, Multiple-Beam, Harmonic Drive*

INTRODUCTION

The U.S. Department of Energy (DOE) is funding research to develop MW-level RF sources capable of high average power operation. Specifically, the DOE is funding research on source with average power exceeding 100 kW. To achieve these power levels, Calabazas Creek Research (CCR), in collaboration with Georgia Tech Research Institute (GTRI), is developing multiple beam Inductive Output Tubes (MBIOTs). High-efficiency inductive output tubes 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. To achieve this goal, we consider the addition of a third harmonic component to the drive signal on the grid to increase efficiency. 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 [1]. 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 [2] which has been successfully validated by comparison with the K5H90W-2 IOT developed by Communications & Power Industries, Inc. The effect of the third harmonic on the efficiency is greatest when the phase is shifted by π radians with respect to the fundamental drive signal and with third harmonic powers greater than about 50% of the fundamental drive power. For the present example, we show that efficiencies approaching 86% are possible.

The program is also investigating two approaches to reduce cost and increase reliability. IOTs traditionally use pyrolytic graphite (PG) grids to generate the modulated electron beam. PG grids can operate at significantly higher temperatures than metal grids; however, they are difficult to fabricate, expensive, and exhibit low yields. There are also few vendors capable of this fabrication, placing great risk on the supply chain. CCR is investigating IOT guns using metal grids. Metal grids are machinable with conventional methods, and thousands are routinely fabricated each year for traveling wave tubes.

Another issue with multiple beam IOTs is uniformly driving the grids of the individual electron guns. GTRI designed an efficient, compact, low-cost, input coupler that drives each electron gun in phase. The configuration would significantly reduce the complexity and cost of multiple beam IOTs.

THE INPUT COUPLER AND GRID

Input Coupler

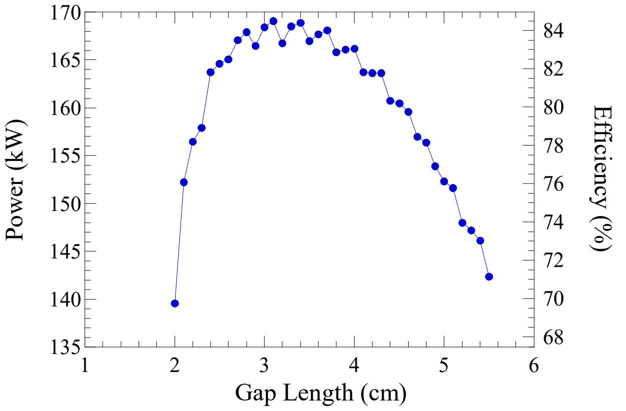

Fig. 1: Optimization of the gap length.

Efficient operation of a multiple beam IOT requires that the RF signal applied to the grid of each electron gun be uniform in electric field and at the same RF phase. In a previous program, GTRI designed and simulated an input coupler consisting of a single coaxial input followed by a radially symmetric drive to the individual electron guns. The approach allows one to balance the RF drive to each electron gun, minimize path loss, match phase, and uniformly drive each gun grid. Tuning along each individual gun path is also possible, which may provide optimal RF coupling to each cathode-grid gap. Additional information will be provided.

A. Grids

Since their initial development, IOTs incorporated PG grids in the electron gun. The motivation was to manage the anticipated heating from cathode radiation and electron beam impact. PG grids can handle significantly higher temperatures than metal grids with reduced thermal expansion. PG grids, however, are difficult to fabricate and machine. It requires complex equipment to generate the PG spherical structures and machine the grid patterns. Consequently, the cost is high and the yields can be quite low. In contrast, metal grids are simply fabricated using traditional machinery at relatively low cost with high yields. Thousands are fabricated each year for TWTs and other gridded devices.

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CCR is proposing to use metal grids in the multiple beam IOT being developed on this program. The current design incorporates six electron guns to provide beam power to generate 100 kW of average RF power. By dividing the beam power among multiple guns, the average beam loading on each gun can be reduced to manageable levels. Current thermal calculations indicate that molybdenum grids would reach a peak temperature less than 600°C. Mechanical design will be required to address the increased thermal expansion associated with metal grids.

THE OUTPUT CAVITY

The output cavity is simulated using the NEMESIS simulation code [2]. NEMESIS was originally developed to simulate helix and coupled cavity TWTS, IOTs, and klystrons. It is PIC-like in the sense that an ensemble of particles injected into the output cavity is integrated in time using the full Lorentz force equations subject to the cavity fields, magnetostatic focusing fields, and the space-charge fields. The numerical procedure is as follows. At each time step the cavity fields are updated using representative circuit equations for the voltage and current followed by an analytic model for the cavity fields. At the same time, the charge density is found by mapping the particles to a grid after which a Poisson solver provides the space-charge fields on the grid. The cavity fields, the space-charge fields, and the magnetostatic focusing fields are then used to integrate the particle trajectories. This is repeated for each time step. At the present time, the space-charge fields are found using a two-dimensional Poisson solver. A fully three-dimensional Poisson solver is under development. In the meantime, we model the output cavity using a simplified annular beam model.

The IOT under consideration uses a 30 kV/6.67 A annular electron beam with a thickness of about 3 cm, yielding a perveance of about 1.3 μP. Brillouin flow requires a solenoidal magnetic field of about 126 G. The output cavity is resonant at 700 MHz with $R/Q = 100\ \Omega$, and a loaded Q of 84.6. The radius of the cavity is about 9 cm as is the cavity length. The optimal gap length was found to be about 3.1 cm, as shown in Fig. 1. Note that no 3rd harmonic was assumed. The optimized efficiency is in excess of 80% even in the absence of the 3rd harmonic drive. The cavity bandwidth is found to be about 3.1%.

The inclusion of the 3rd harmonic is done via the following model for the drive current, where ε denotes the ratio of the 3rd harmonic to the fundamental and φ is the phase shift of the 3rd harmonic relative to the fundamental.

$$I(t) = I_p \left[\sin\left(\pi \frac{t}{t_{width}}\right) + \varepsilon \sin\left(3\pi \frac{t}{t_{width}} + \varphi\right)\right]^2,$$

for $t < \tau_{width} < 2\pi/f$ and zero otherwise, where τ_{width} denotes the portion of the wave period over which electrons are drawn off the grid.

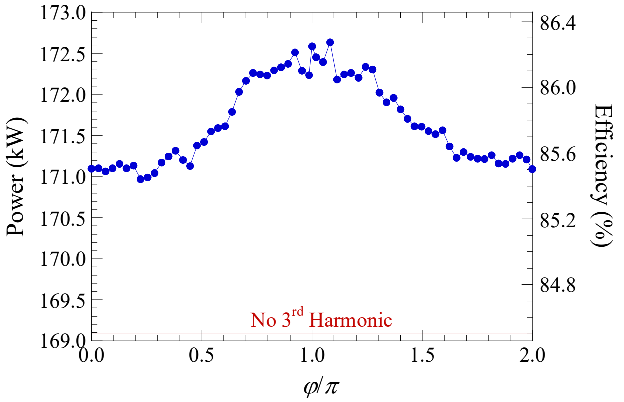

Fig. 2: Performance with the 3rd harmonic.

The effect of the 3rd harmonic current modulation on the performance of the IOT relative to that without the 3rd harmonic is shown in Fig. 2 for $\varepsilon = 1$. We find that (1) the 3rd harmonic performance is optimized for a phase shift of about j = p, and (2) that the 3rd harmonic yields about a 2% improvement in the output power.

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