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IMPLEMENTATION OF A FREQUENCY-AGILE, HIGH POWER BACKWARD WAVE OSCILLATOR

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Abstract--Recent work at the University of New Mexico (UNM)[1] has demonstrated how finite length effects in a high power vacuum backward wave oscillator (BWO) can be exploited to achieve frequency agility for constant beam and magnetic field parameters. This enhanced bandwidth is obtained through the axial displacement of the slow wave structure with respect to the cutoff neck "inlet" to the electrodynamic system. This paper describes progress on the implementation of this automatic displacement to facilitate the incorporation of a robust controller, as proposed by Abdallah, *et al.*[2] The purpose of this controller is to demonstrate a "smart tube" where a variety of objectives, such as i) maximizing the frequency bandwidth for a given constant power output, ii) maximizing the radiated peak power at a given frequency, or iii) maximizing the beam-to-microwave power conversion efficiency, can be achieved automatically.

I. Introduction

High-power relativistic backward wave oscillators are considered narrowband sources of radiation in the millimeter wave regime (see, for example, Benford and Swegle[3]). For many applications, it is advantageous to determine the response of a system to high power microwave radiation over some extended bandwidth around the center frequency. Previously it was determined that the only way in which to achieve some measure of frequency tunability or *agility* was to adjust the electron beam-generation cathode potential, or adjust the magnitude of the guide magnetic field. However, since in typical high power BWOs the anode-cathode (*A-K*) gap spacing determines the diode impedance, and thereby the emitted beam current for a given cathode potential, adjusting the diode voltage does not offer much tunability. Our earlier work (Moreland, *et al.*[1]) demonstrated how finite length effects in high-power backward wave oscillators could be exploited in a controlled manner to achieve enhanced frequency agility. The control of the finite length effects was demonstrated to yield a bandwidth of about 500 MHz centered around 9.5 GHz at hundreds of MW power levels for constant beam, slow wave structure, and magnetic field parameters. The incorporation of a feedback controller will automate this procedure and allow for the ability to achieve a variety of control objectives (such as maximized bandwidth for a given constant power level) for the same hardware configuration. It is this goal that we term a “smart tube.”

Section II of this paper reviews our earlier work in which the enhanced frequency agility was demonstrated experimentally and through particle-in-cell simulations. Section III presents recent results from a *learning control algorithm* to achieve a set of control objectives relevant to this experimental work. Section IV presents our initial engineering design to implement the enhanced frequency agility. This work and plans for the future are summarized in Section V.

II. Demonstration of a Frequency-Agile BWO

In the simple classical description of a BWO an electron beam interacts with a backward propagating wave in an infinite uniform slow wave structure (SWS). In an actual finite length device there are end reflections resulting in both forward and backward propagating harmonics. Since high-power BWOs typically radiate the energy in the forward direction by reflecting the backward propagating harmonics from a “cutoff neck” at the entrance to the SWS, these forward propagating harmonics must be included for a complete description of this relativistic device. The experiments that demonstrated enhanced frequency agility in a high power BWO were performed on the UNM Sinus-6 short pulse, repetitively pulsed electron beam accelerator. The experimental setup is shown in Fig. 1. In this experiment the SWS was uniform in ripple amplitude

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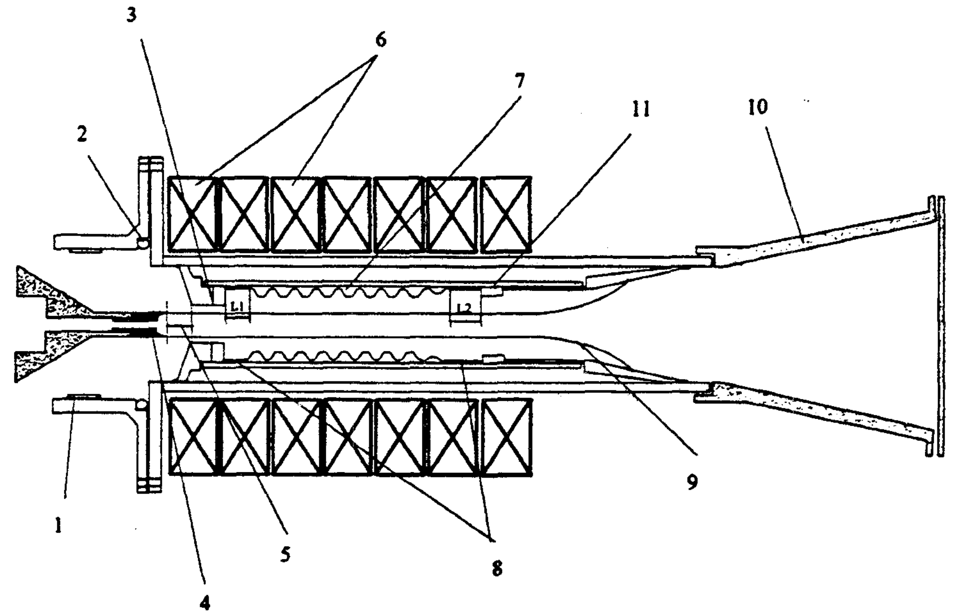

Figure 1. Experimental setup for BWO experiments demonstrating enhanced frequency agility. Shown in the diagram are (1) capacitive voltage divider, (2) Rogowski coil, (3) cutoff neck, (4) cathode, (5) *A-K* gap, (6) magnetic field coils, (7) slow wave structure, (8) smooth circular waveguide with shifting lengths L_1 and L_2, (9) electron beam, (10) output horn antenna, and (11) reflection ring.

(except for the final period which had a smaller ripple amplitude for impedance matching considerations), period, and total length. (Note that this is in contrast to our earlier study where a nonuniform amplitude SWS was used - see Moreland, *et al.*[4]) As is indicated in Fig. 1, sections of smooth-walled waveguide were inserted to accomplish "forward shifting," *i.e.*, the introduction of a cavity between the SWS and the cutoff neck. The effect of this cavity was to change the phase difference between the forward and backward propagating waves at the inlet to the SWS. This resulted in a dramatic change in the beam-to-microwave power conversion efficiency, as is plotted in Fig. 2 (left). Note that in the figure the efficiency is normalized to the "unshifted" case. Also plotted in Fig. 2 (left) is the result of TWOQUICK fully electromagnetic, 2.5 D particle-in-cell simulations.

Forward shifting had an additional effect, namely a change in the frequency of the microwave radiation, as is indicated in Fig. 2 (right). This frequency change is attributed to the change in volume of stored electromagnetic energy, the so-called cavity perturbation effect (see Slater[5]). It is this combination of the effect of a change in the cavity volume between the cutoff neck and the initial cavity of the SWS on both microwave generation efficiency and frequency that we are exploiting in a controlled manner to achieve the frequency-agile BWO. The experiments performed on the Sinus-6 accelerator yielded a bandwidth of about 500 MHz around a center frequency of 9.5 GHz at a consistent radiated peak power level of several hundred MWs. (Details on both the experimental and simulation results can be found in Moreland, *et al.*[1])

III. "Learning Control"

The initial work reported in Abdallah, *et al.*[2] was a neural network model used to fit the input/output characteristics of the Sinus-6 driven BWO. This model simply provides a mathematical relationship between the beam parameters that can be adjusted (such as cathode voltage and beam current for a given *A-K* gap spacing, magnetic field strength, and SWS configuration) and the output that can be measured (peak radiated power and radiation frequency). In this sense, the system (entire Sinus-6 accelerator and BWO) is treated as a "black box" and the model is devoid of the details of the physics. Nevertheless, this model does provide an accurate set of output parameters for a given set of input parameters. The work reported by Abdallah *et al.*[2] is being extended to take into account the effects of forward shifting. A block diagram of this system is shown in Fig. 3.

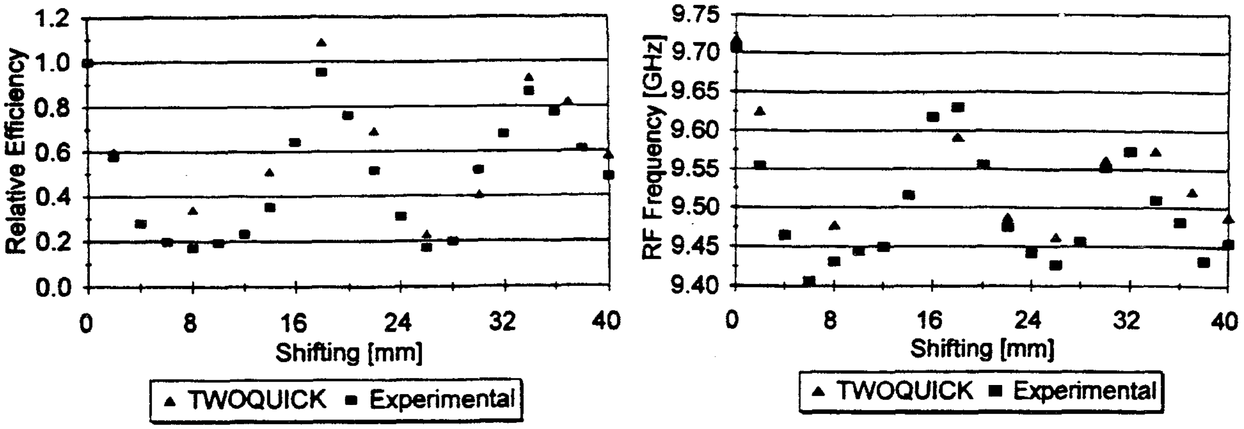

Figure 2. Relative efficiency as a function of forward shifting as observed in the experiment and TWOQUICK simulations (left); RF frequency as a function of forward shifting as observed in the experiment and TWOQUICK simulations (right).

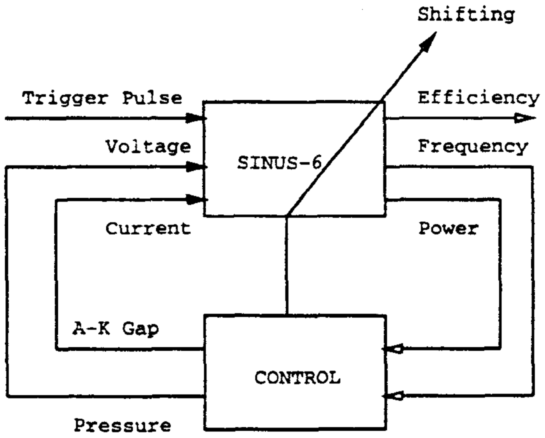

Figure 3. A block diagram of the Sinus-6 BWO and its control system incorporating forward shifting.

The ideas of "learning control" have been applied to the Sinus-6 BWO, as presented by Abdallah, *et al.*[6] The ideas of learning control have been successfully employed in the control of robot manipulators involved in repetitive maneuvers where it is usually difficult to model the effects of friction. The learning control then tries to modify the control law based on the error signal which is due to unmodeled friction dynamics. At each time the robot repeats the same task, the learning control algorithm improves its performance based on the new error signal generated. This learning control scheme is described in Fig. 4.

The mathematical development of learning control as applied to the Sinus-6 BWO was developed by Abdallah, *et al.*[6] and will not be discussed in this paper. The learning control algorithm was applied to the neural network modeled data set (described in Abdallah, *et al.*[2]) In an initial attempt at using this method we desired to control the microwave radiation frequency and the peak radiated power to a set of preselected values. The results are plotted in Fig. 4. In this figure we observe the number of calculation "steps" (iterations) required to control the frequency and power to one set of preselected values. Note that at each iteration the learning algorithm adjusts to decrease the deviation from the desired preselected values. In the two cases presented in Fig. 4 it took only a few steps to achieve the desired control values. The corresponding computational time is practically instantaneous, and thus leaves sufficient time for the mechanical system

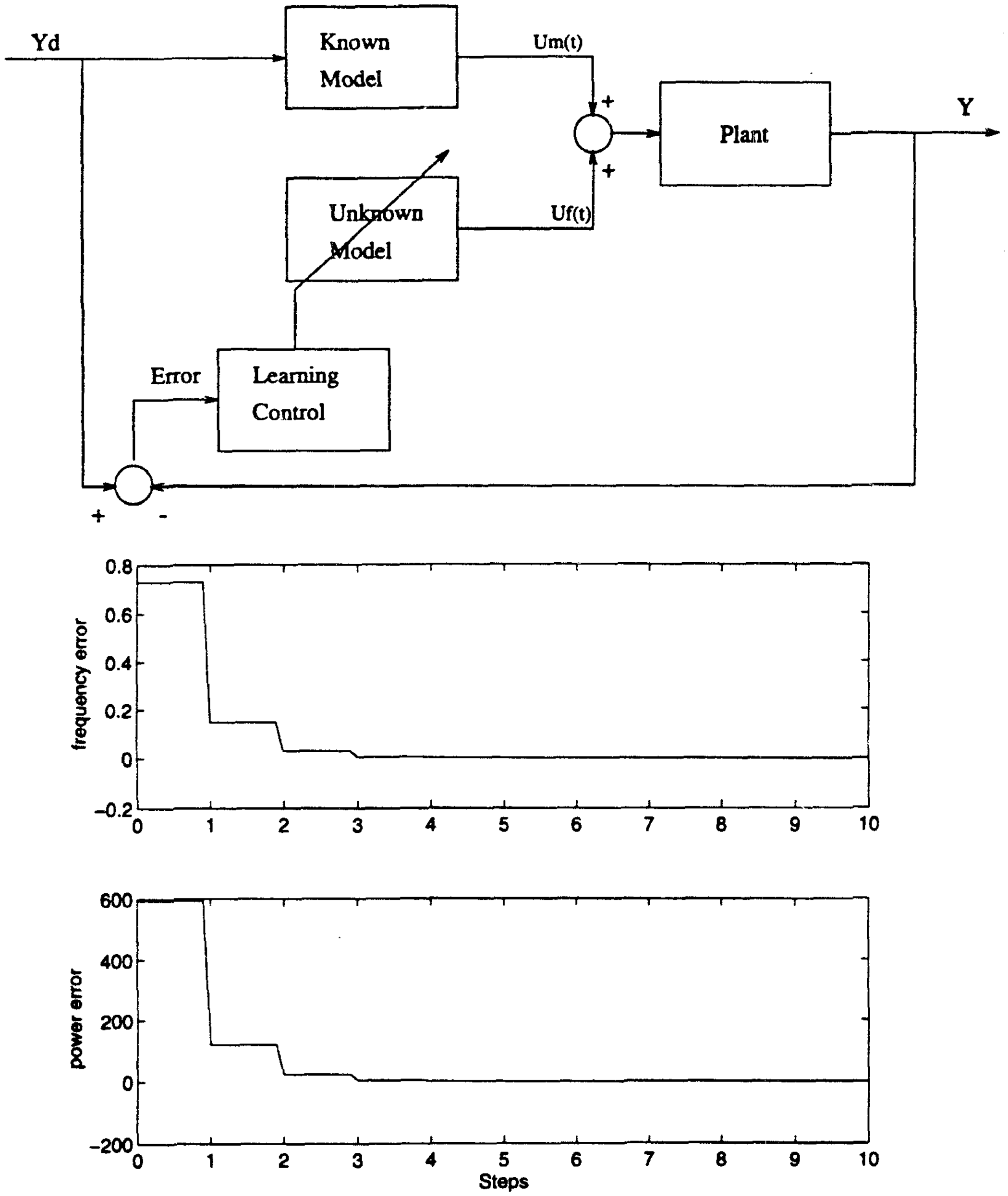

Figure 4. Block diagram illustrating the learning control algorithm (top). Also shown are plots of frequency error and power error as a function of the number of steps (iterations) required to achieve the control objective (bottom).

(proposed in the next section) to perform the required adjustments in between the nominal 10 seconds available between shots of the Sinus-6 accelerator and magnetic field producing circuitry.

IV. Initial Engineering Design

The hardware implementation of the frequency-agile high power BWO is planned as follows. The initial control scheme will utilize the following input parameters. The cathode potential will be adjusted through a change in the pressure of the spark gap switch (for details on the Sinus-6 hardware see Moreland, *et al.*[4]). The *A-K* spacing will remain fixed. The slow wave structure identical to that described in Moreland, *et al.*[1] will be used, except that it will be a rigid fixture, as opposed to being a set of individual rings supported in a metallic tube. A mechanism is proposed to perform the forward shifting as follows. The output section leading to the conical horn antenna presently used on the BWO system will be modified to rotate about the symmetry axis of the BWO system while maintaining vacuum integrity. A rotary feedthrough incorporating a worm drive will enable a flange, upon rotating, to axially displace the SWS system. Since the Sinus-6 accelerator is already setup to be fired using TTL output from a computer, the actual control hardware and software will be readily integrated.

V. Summary of Results and Future Investigations

The implementation of the frequency-agile BWO is proceeding according to plans. The scientific basis of providing bandwidth to a nominally narrowband source for constant beam, magnetic field, and SWS parameters has been demonstrated. Neural network models have been obtained to relate the output characteristics of the Sinus-6 BWO to its input parameters. A learning control algorithm was successfully used to simulate various control objectives in an efficient manner. Finally, the actual hardware implementation of the forward shifting is presently being designed and is expected to be constructed and tested by the end of the summer 1997.

Plans for the future include adding a remotely controlled mechanism for adjusting the *A-K* gap spacing to further increase the parameter space accessible using the various control strategies under considerations.

Progress on this, as well as related projects at the University of New Mexico and its consortium partners can be found in Ref. 7.

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7. *http://www.eece.unm.edu/faculty/chaouki/MURI_CD/Frame1.htm*