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A tetrode based fast pulsed microwave source for electron cyclotron resonance breakdown experiments

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To study electron cylotron resonance (ECR) breakdown and afterglow plasma in an experimental linear plasma system, a pulsed microwave source with rapid rise and fall of microwave power is desired. A pulsed microwave source with fast rise and fall capability for ECR breakdown experiments has been designed and tested for performance in the system. A tetrode, controlled by a modulator card, is used as a fast switch to initiate microwave power from a conventional magnetron operating at 2.45 GHz. The typical rise time of microwave power is $\sim 3\ \mu$s and a fall time of $\sim 10\ \mu$s. Using this scheme in a realistic pulsed microwave source at 800 W power, ECR breakdown of neutral gas is achieved and the plasma delay and fall time are observed from the plasma density measurements using a Langmuir probe. The design details of the fast rise pulsed microwave source are presented in this article with initial experimental results. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2671793]

I. INTRODUCTION

Electron cyclotron resonance (ECR) discharge is a well-established technique of plasma formation in basic plasma experiments,[1] in tokamaks,[2–5] and in material processing.[6] In tokamaks, the operating magnetic field ranges from 1 to 5 T. Fundamental and second harmonic experiments using gyrotrons as a microwave source are carried out at these magnetic fields. Basic experiments[1] operating at toroidal magnetic field ranging from a few 100 G to 0.1 T employ rf tubes or magnetrons as microwave sources. A 2.45 GHz magnetron is generally used for various material processing applications.

In a linear experimental system, plasma is formed by the ECR technique using a conventional 2.45 GHz magnetron. In order to systematically study the formation and decay of plasma, a pulsed microwave source with fast rise and fall time is required. The rise time should be a few orders lower than the typical initiation time of the breakdown of the neutral gas under consideration. The fall time of the pulsed microwave source should be lower than the particle confinement time in the system. Hence, a pulsed microwave source centered around a tetrode is designed and realized.

II. EXPERIMENTAL SETUP

The experimental setup is a cylindrical stainless steel (SS304) vacuum vessel with 6.41 cm radial and 10 cm axial length. It has four circular and one rectangular radial ports and two circular axial ports. The vacuum vessel is pumped by diffusion and rotary pumps which give a base pressure of 6×10^{-6} mbar. A time invariant magnetic field of 875 G at the center of the vacuum vessel is produced by two identical coils placed axially on flowing 5.3 A direct current. A schematic of the microwave system coupled to experimental chamber is shown in Fig. 1. The microwave system consists of an 800 W, 2.45 GHz magnetron, three port circulator with a water cooled dummy load, WR340 directional coupler to measure the forward and reflected microwave power, 10 mm thick toughen glass blank as the waveguide window, and Schottky diode detectors to measure the microwave power. Electron plasma density is measured with a Langmuir probe[7] having a 5 mm long, 0.5 mm thick tungsten probe tip. The signals from Langmuir probe are acquired on a Tektronix TDS224 oscilloscope (with a bandwidth of 200 MHz) and transferred to a PC using RS232 cable and the WAVESTAR software package.

III. MICROWAVE SOURCE WITH FAST SWITCH

The microwave source is a National Electronics magnetron, model 2M107A-8250. The power supply circuitry for

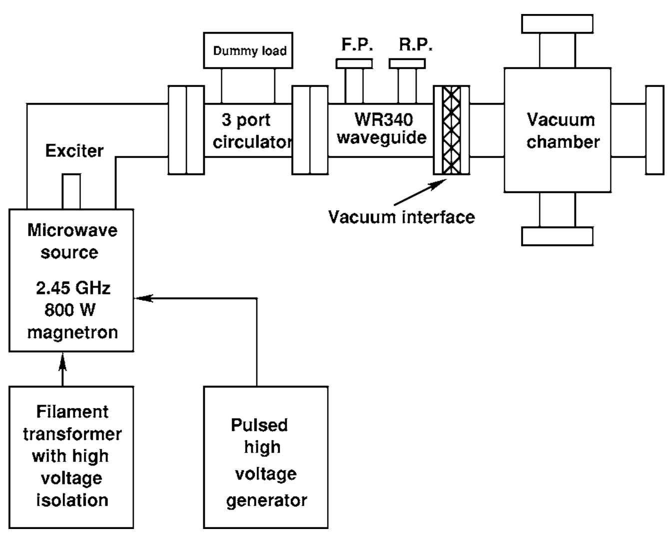

FIG. 1. Schematic of experimental setup.

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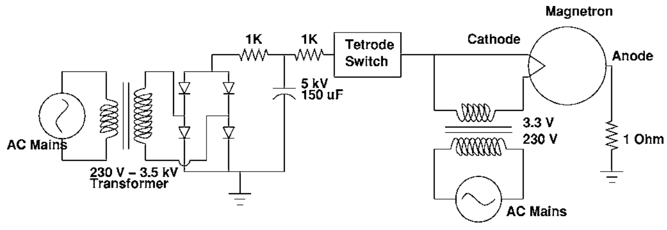

FIG. 2. Magnetron power supply circuit.

this magnetron is shown in Fig. 2. It consists of a low voltage 3.3 V/12 A ac power supply to heat the filament of magnetron by flowing current through it and a separate high voltage −4.1 kV/1 A dc power supply provides bias to the cathode. To operate the magnetron, the filament is heated continuously and a pulse voltage of −3.6 to −4.1 kV is applied on the cathode. In this scheme the anode which forms the magnetron casing, is grounded. A series tetrode switch is used to generate a negative voltage pulse (~4 kV) which is applied to the cathode of magnetron.

The schematic of the tetrode switch is shown in Fig. 3. The control grid of the series tetrode is held at cutoff by applying a −100 V to it. When microwave power is required, the control grid is driven +10 V with respect to the cathode. The pulses to the control grid are obtained from a floating modulator card. The choice of BEL-1000A (Ref. 8) as a series switch, lies in its capacity to withstand 5 kV dc without arcing inside the tube and its low interelectrode capacitance leading to fast switching speed.

The optical isolation consists of a transmitter and receiver connected through a fiber optic cable. The circuit diagram of the transmitter which transmits the trigger pulse provided either by a push-button switch or by a remote transistor-transistor logic (TTL) signal is shown in Fig. 4. The monoshot used here is LS74121 with a positive edge trigger. It gives two complementary output pulses of width which is variable in the range 1–20 ms. The monoshot output drives a transistor used as driver. A single channel simplex 100/140 μm glass fiber cable of HFBRAWAS010 HP provides a high voltage isolation of 50 kV/m at leakage current of 50 nA and carries the optical radiation from the transmitter up to the receiver. The receiver circuit is shown in Fig. 5.

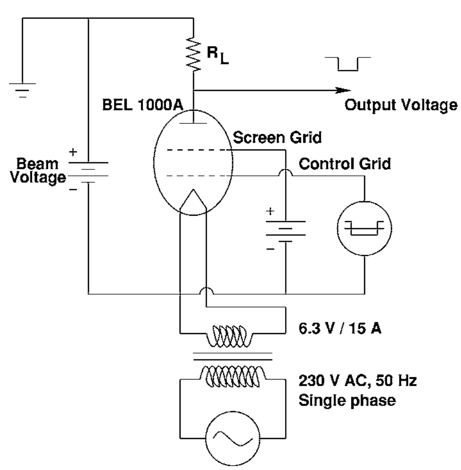

FIG. 3. Series tetrode as a switch.

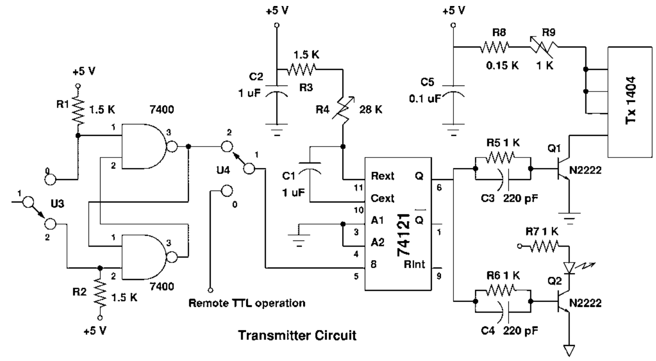

FIG. 4. Transmitter circuit.

The comparator circuit compares the output of CA3140 with reference voltage. LM311 is an open collector output type, a pull-up resistor of 1 kΩ is used at output. To drive the control electronics section (modulator card), two transistors are operated such that two complementary pulses are obtained. The minimum current required to drive the modulator card is 10 mA which is achieved by using a current limiting resistor

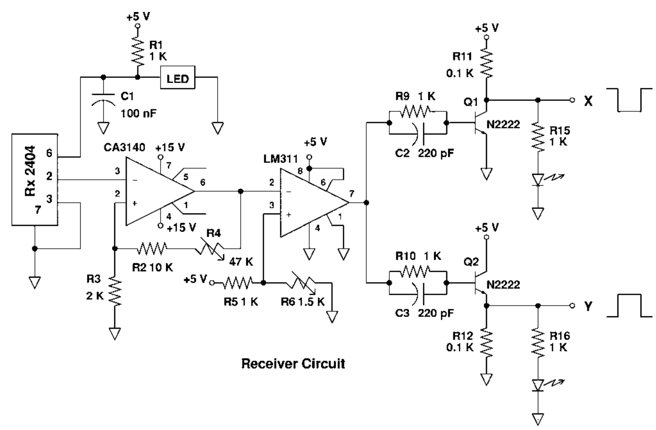

FIG. 5. Receiver circuit.

of 100 Ω.

The modulator card gives a controlled pulse voltage of +10 to −100 V to the tetrode. The schematic of the modulator card is given in Fig. 6. It consists of an output pair of metal-oxide-semiconductor field-effect transistors (MOSFETs) configured in the totem pole. The gates of the output

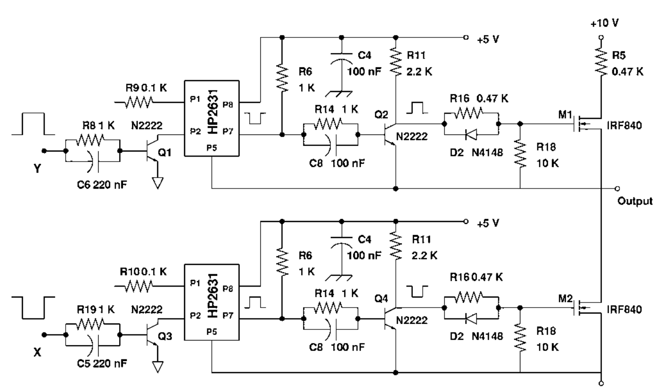

FIG. 6. Modulator circuit.

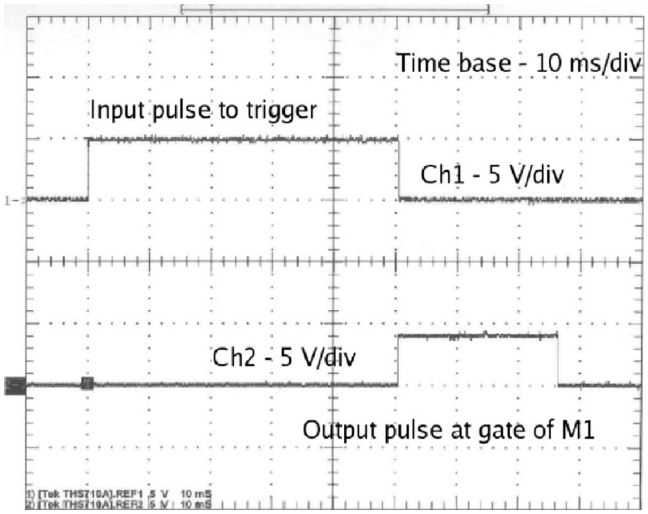

FIG. 7. Upper gate output.

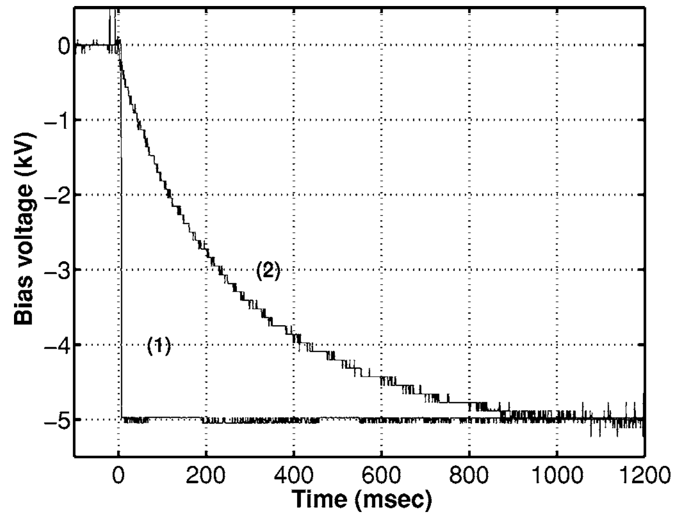

FIG. 9. Fast (1) and slow (2) rise of negative high voltage bias.

totem pole are driven by optocoupled pulses which are inverted with respect to each other. A "no-race" condition is satisfied by adequately dampening the input drive to the gate of MOSFETs. This operation is illustrated in Figs. 7 and 8, respectively. In both oscillograms, the upper trace is input trigger while the lower trace is the output pulse at the gate of the MOSFET.

The rise of negative high voltage bias on the cathode of magnetron is compared before and after the inclusion of the tetrode series switch in the circuit. In Fig. 9, curve (2) shows the slow rise in $\sim$1 s, which increases the power output from magnetron slowly while with the inclusion of the tetrode switch, the bias voltage rises within 3–4 μs as shown in curve (1). This voltage is applied to the cathode as a negative bias to the magnetron to generate output power.

IV. RESULTS

During the experiment, ECR breakdown with hydrogen is observed for a fill pressure of 1×10^{-3} mbar for 800 W fixed input microwave power on the central axis of the experimental system where the fundamental cyclotron resonance resides. Prior to the microwave pulse, the magnetic field is switched on. During the flat-top of the magnetic field, the microwave power is pulsed for $\sim$30 ms using the series tetrode. The electron plasma density is measured by a Langmuir probe along with the microwave power as measured from the directional coupler. The microwave power output from the magnetron is observed to have a rise time of $\sim$3 μs as highlighted in Fig. 10. In this oscillogram, the top trace is the microwave power from the forward port of the directional coupler and the bottom trace is the plasma density as measured by the negatively biased Langmuir probe. Plasma formation delay time can be measured using the above information. Using this experimental setup, the plasma formation delay time has been measured ranging from 60 μs to 27 ms depending on the parameters during the experiment.

The microwave power falls down to zero from the maximum value within $\sim$10 μs, which is fast enough to measure the plasma fall time that is the time taken by plasma density to fall below $1/e$-th of its value as shown in Fig. 11. In this oscillogram, the top trace is forward microwave power as

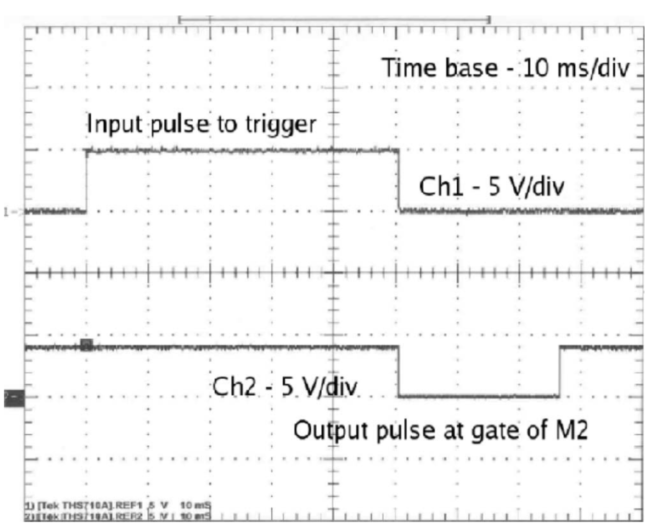

FIG. 8. Lower gate output.

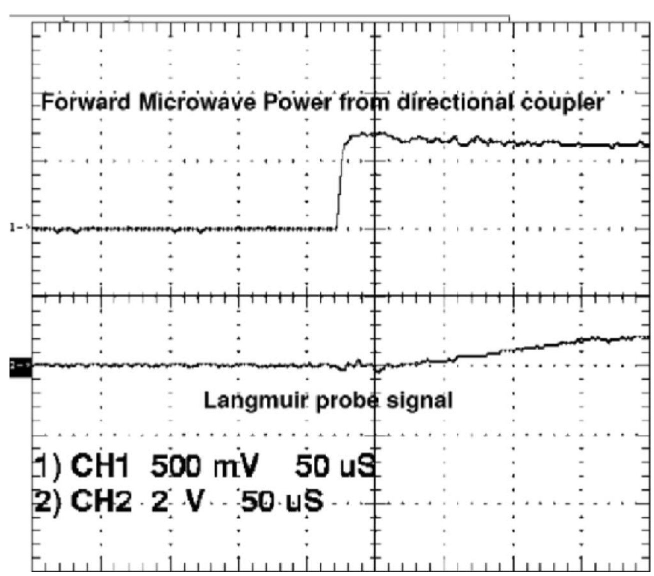

FIG. 10. Oscillogram trace for plasma delay time.

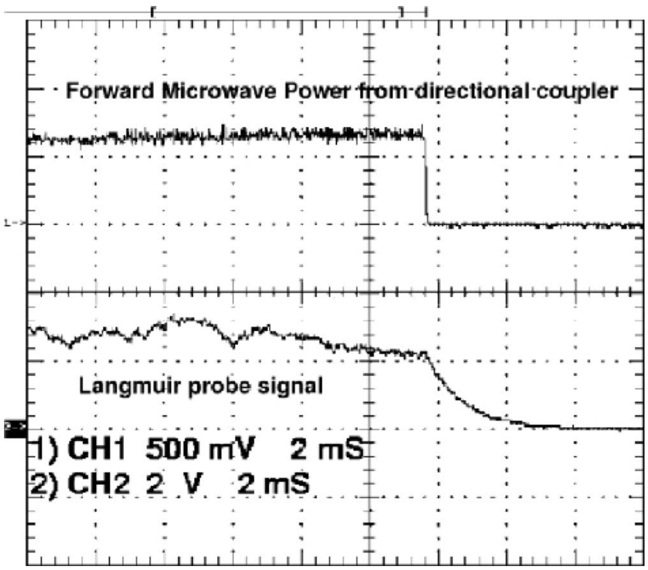

FIG. 11. Oscillogram trace for plasma fall time.

measured by the directional coupler and the bottom trace is the plasma density measured with a Langmuir probe. The measured after-glow time is found to range from 1 to 1.5 ms depending on experimental conditions.

V. DISCUSSION

To study the transient phenomena of ECR breakdown, a fast rise and fall pulsed microwave source is conceived, designed, and realized. The pulsed microwave source, centered around a series tetrode switch, has been successfully tested and used in experiments. Microwave power rise time of $\sim 3\ \mu s$ and fall time of $\sim 10\ \mu s$ is experimentally observed with this source. ECR breakdown parameters such as plasma delay and fall time are measured from density measurements using a Langmuir probe.

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