PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 74, No. 1
January 2010
pp. 123–133

Measurement of high-power microwave pulse under intense electromagnetic noise

AMITAVA ROY[1,*], S K SINGH[1], R MENON[1], D SENTHIL KUMAR[2], R VENKATESWARAN[2], M R KULKARNI[1], P C SAROJ[1], K V NAGESH[1], K C MITTAL[1] and D P CHAKRAVARTHY[1]

[1]Accelerator and Pulse Power Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085, India

[2]Microwave Tube Research & Development Centre (MTRDC), Defence Research Development Organization (DRDO), BE Complex, Jalahalli P.O., Bangalore 560 013, India

*Corresponding author. E-mail: aroy@barc.gov.in

MS received 22 May 2009; revised 5 August 2009; accepted 1 September 2009

Abstract. KALI-1000 pulse power system has been used to generate single pulse nanosecond duration high-power microwaves (HPM) from a virtual cathode oscillator (VIRCATOR) device. HPM power measurements were carried out using a transmitting–receiving system in the presence of intense high frequency (a few MHz) electromagnetic noise. Initially, the diode detector output signal could not be recorded due to the high noise level persisting in the ambiance. It was found that the HPM pulse can be successfully detected using wide band antenna, RF cable and diode detector set-up in the presence of significant electromagnetic noise. Estimated microwave peak power was ∼59.8 dBm (∼1 kW) at 7 m distance from the VIRCATOR window. Peak amplitude of the HPM signal varies on shot-to-shot basis. Duration of the HPM pulse (FWHM) also varies from 52 ns to 94 ns for different shots.

Keywords. Microwave generation; microwave measurements; electromagnetic interference; electron beams; noise measurements; microwave devices; microwave tubes.

PACS Nos 84.40.Fe; 84.40.Az; 85.10.Ka; 52.70.Gw

1. Introduction

Single-shot nanosecond duration high power microwave (HPM) pulses have been generated and characterized for various applications [1,2]. HPM sources are being developed for applications in plasma heating, particle acceleration, high-power radar, and many other industrial and military fields [2]. One of the crucial part of the HPM system development is diagnosing intense single microwave pulses with powers greater than 100 MW and pulse widths between 5 and 100 ns [3]. Gigawatt power HPM pulses have been generated by various devices [2]. One among several

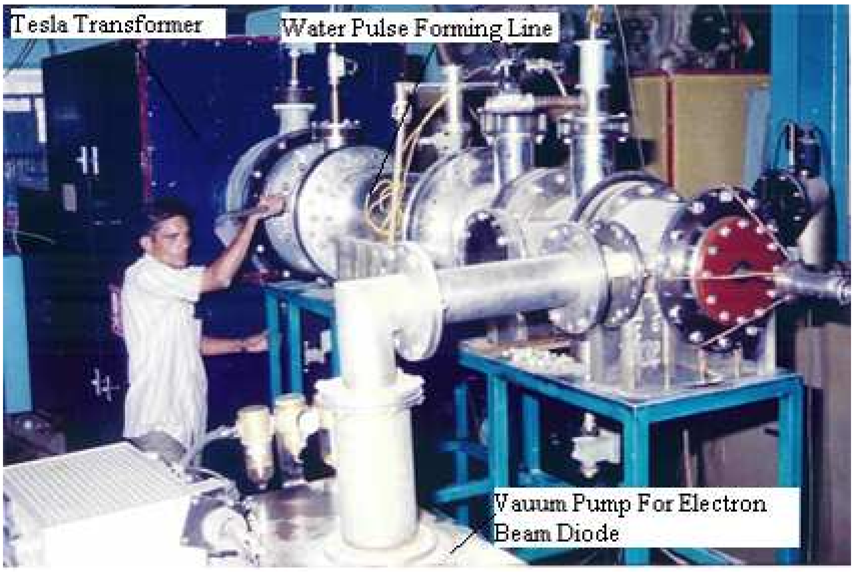

Figure 1. A photograph of the KALI-1000 pulse power system.

types of pulsed high-power microwave generators is the virtual cathode oscillator (VIRCATOR). The VIRCATOR is considered to be very attractive due to its high-power capability, frequency tunability and device simplicity [2,4,5]. In a VIRCATOR, an electron beam is emitted from a cathode and accelerated through a semitransparent anode. If the current exceeds the space charge limited current, a space charge (virtual cathode) forms behind the anode. The virtual cathode is unstable, and its oscillations can generate microwaves.

Different experimenters have tried various techniques to measure ns pulse duration HPM power and frequency [3]. Typically, the HPM power measurement is accurate within 20% (±1 dB), the pulse energy to within 20%, and the frequency to within 1% [3]. These diagnostic techniques are not limited to use on any one type of HPM sources, but can be applied to a variety of HPM sources [6].

For HPM power measurement the most widely used apparatus is the transmitting–receiving system [3]. Transmitting–receiving systems are useful at high-power levels because all the HPM energy is broadcast into an anechoic chamber where a receiver picks up a known small fraction of the transmitted power. In this case, the amount of external attenuation required can be minimized. These measurements rely on the Friis transmission equation

$$P_{\mathrm{T}} = P_{\mathrm{R}}(4\pi r/\lambda)^2/G_{\mathrm{R}}G_{\mathrm{T}}, \tag{1}$$

where the subscript T refers to the transmitter, the subscript R refers to the receiver, P is the power, G is the antenna gain, r is the transmitter to receiver separation distance and λ is the free space wavelength. The $(r/\lambda)^2$ characteristics allows large attenuations.

Experiments were performed using the pulsed power generator KALI-1000 (kilo ampere linear injector: maximum output voltage 300 kV, output impedance 15 Ω,

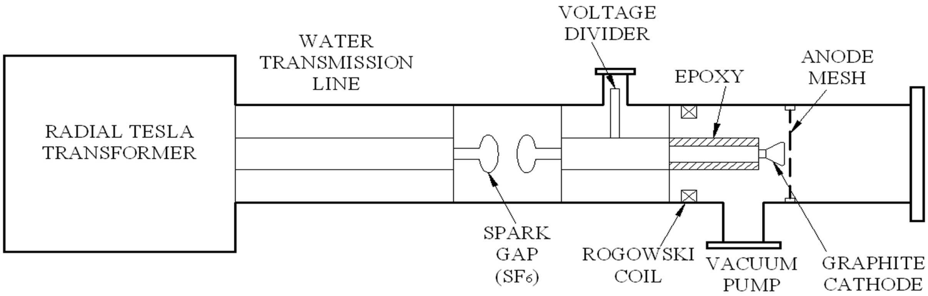

Figure 2. Schematic of the experimental set-up.

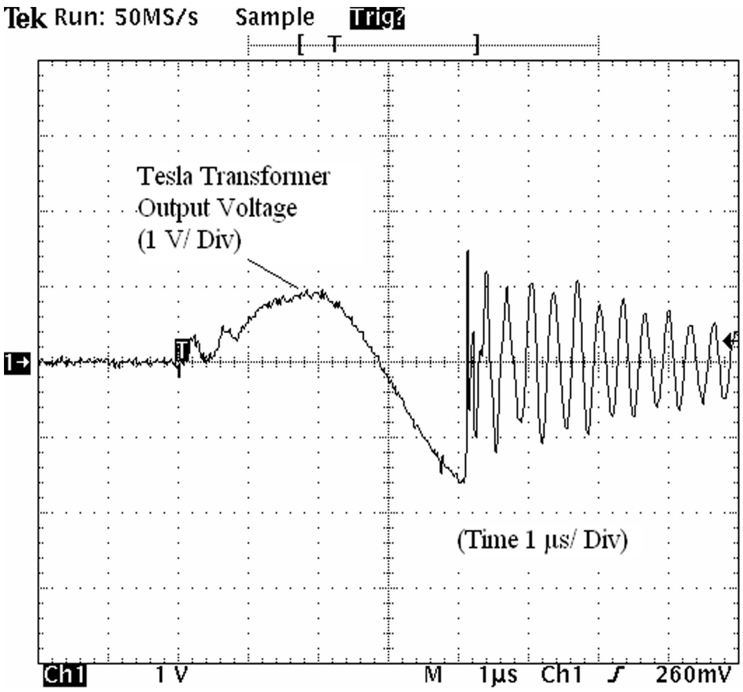

Figure 3. Tesla transformer output signal.

and pulse duration 100 ns) to generate and measure HPM signal from a VIRCATOR device. KALI-1000 consists of a radial tesla transformer, a water transmission line and electron beam diode with voltage and current diagnostics. During the experiment it was observed that along with HPM the KALI-1000 system radiates intense electromagnetic noise (of a few MHz frequencies). This article describes HPM power measurements by transmitting–receiving systems and various experimental techniques used to override the noise signal to improve the microwave signal amplitude from the diode detector.

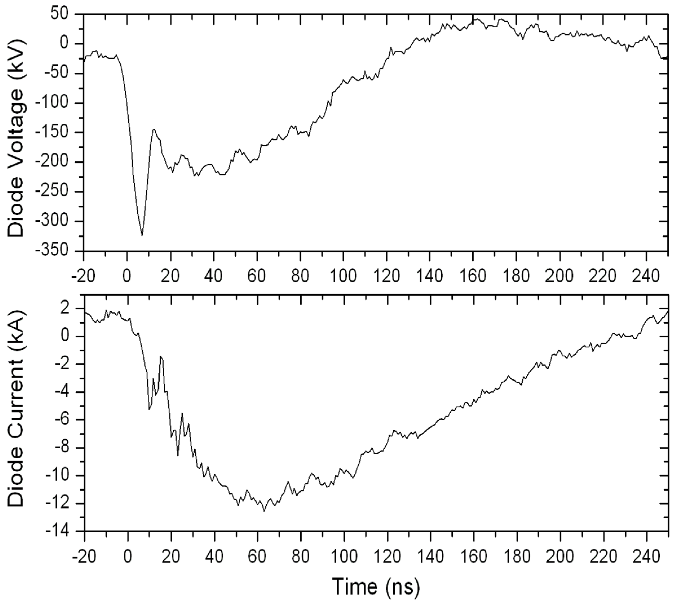

Figure 4. Electron beam diode voltage and current waveform for 6 mm A–K gap with 70 mm diameter graphite cathode.

2. KALI-1000 pulse power system and high-power microwave generation from virtual cathode oscillator

Figure 1 shows a picture of the KALI-1000 pulse power system. Figure 2 displays the schematic of the KALI-1000 system along with the VIRCATOR. The KALI-1000 pulse power system developed at APPD, BARC, has a Tesla transformer, water pulse forming transmission line (PFL) and a gas spark gap to generate high voltage pulse. The Tesla transformer has a turn ratio of 1 : 60. The PFL is 1.3 m long and uses demineralized water as dielectric and the capacitance is 4 nF. The spark gap contains two electrodes of Rogowski profile separated by 2 cm and uses SF_6 gas pressure. A vacuum field emission diode was used to generate intense relativistic electron beams (IREB). The high voltage pulse generated from the pulse power system is applied to the field emission diode. The diode consists of a planar graphite cathode (70 mm diameter) and copper anode mesh (240 mm diameter) at various anode–cathode (A–K) gaps and various voltage levels. A resistive $CuSO_4$ voltage divider and a self-integrating Rogowski coil were used to measure the diode voltage and current pulses respectively. The Tesla transformer output voltage signal has been measured by a capacitive voltage divider. Figure 3 shows a typical Tesla transformer output signal. The outer body of the Tesla transformer has been made of FRP sheet. Tesla transformer acts as a source of intense electromagnetic noise during the operation of the KALI-1000 pulse power system.

After the copper mesh anode flange, there is an axial virtual cathode oscillator chamber (length 25 cm, diameter 25 cm) for microwave generation. The IREB is injected to the VIRCATOR chamber for HPM generation. In the VIRCATOR

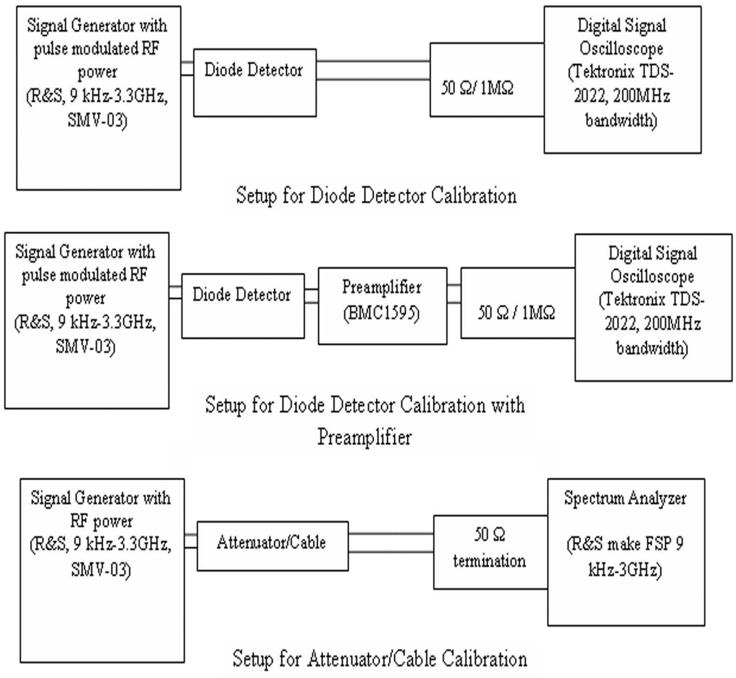

Figure 5. Calibration set-up of HPM diagnostic components.

chamber, the beam front forms a virtual cathode at a distance equal to the A–K gap if the injected current is greater than the space charge limiting current by four times. It is given by [4]

$$I_{\mathrm{l}} = \frac{4\pi\varepsilon_0 m_0 c^3 (\gamma^{2/3} - 1)^{3/2}}{e[1 + 2\ln(R/r_{\mathrm{b}})]}, \tag{2}$$

where r_{b} is the beam radius, R is the drift column radius, γ is the relativistic factor and e and m_0 are the electron charge and rest mass respectively. The estimated limiting current from (2) for the KALI-1000 VIRCATOR chamber is ~0.8 kA.

The virtual cathode reflects the electrons that follow the beam front. The electrons thus oscillate between the cathode and virtual cathode causing microwave emission. The reflection frequency is given by [2]

$$f_{\mathrm{r}} = \frac{v}{4d}, \tag{3}$$

where v is the velocity of electrons and d is the A–K gap.

The virtual cathode oscillation frequency in GHz is given by [2]

$$f_{\mathrm{vc}} = 10.0 \left(\frac{J}{\beta\gamma}\right)^{1/2}, \tag{4}$$

where J is the current density in kA/cm^2.

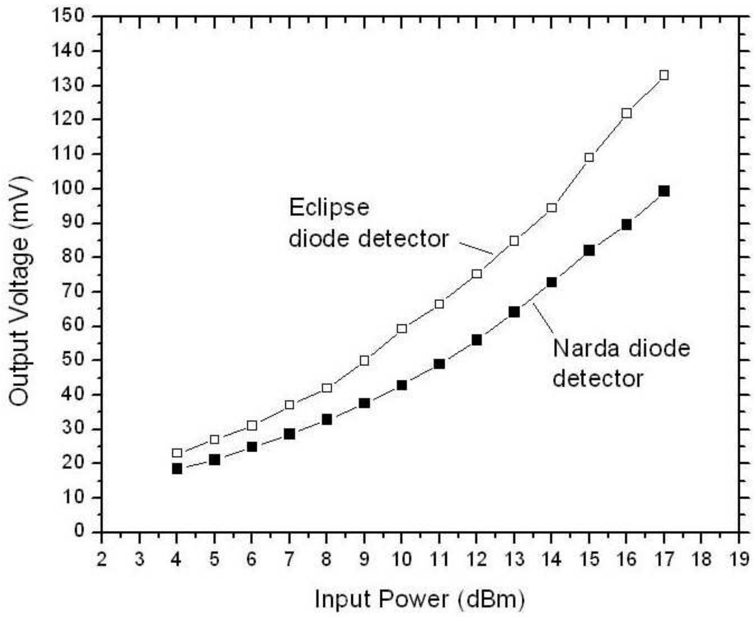

Figure 6. Calibration curve of the Eclipse and Narda make diode detectors using standard modulated RF source at 2 GHz.

The frequency at which maximum power is emitted will be between $f_{\rm r}$ and $f_{\rm vc}$ and the emission is broadband [2]. The estimated HPM frequency from (3) and (4) for the experimentally obtained electron beam diode parameters in the KALI-1000 system is around 6 GHz.

A vacuum level of the order of $<5 \times 10^{-5}$ mbar was maintained in the diode chamber as well as the VIRCATOR chamber by a diffusion pump backed by a rotary pump. The typical electron beam parameters were 200 kV, 14 kA, 100 ns. High-power microwave has been detected by neon lamp discharge by HPM illumination when placed a few metre distance from the VIRCATOR window. Microwave power has been optimized by changing the A–K gap. It was found that the peak power occurs around 6 mm A–K gap. The electron beam diode voltage and current waveforms for 6 mm A–K gap is shown in figure 4.

3. HPM measurements

HPM power measurements are carried out by the standard transmitting–receiving systems. HPM measurements were done using zero bias Schottky diode detectors along with a horn antenna and sufficient attenuation so as to reduce the power level below the power rating of the diode detector. HPM signal has been captured by the double-ridged horn antenna placed a few metre distance from the VIRCATOR window. A shield room [7] is situated around 20 m away from the KALI-1000 system. All the oscilloscope measurements are carried out inside the shield room.

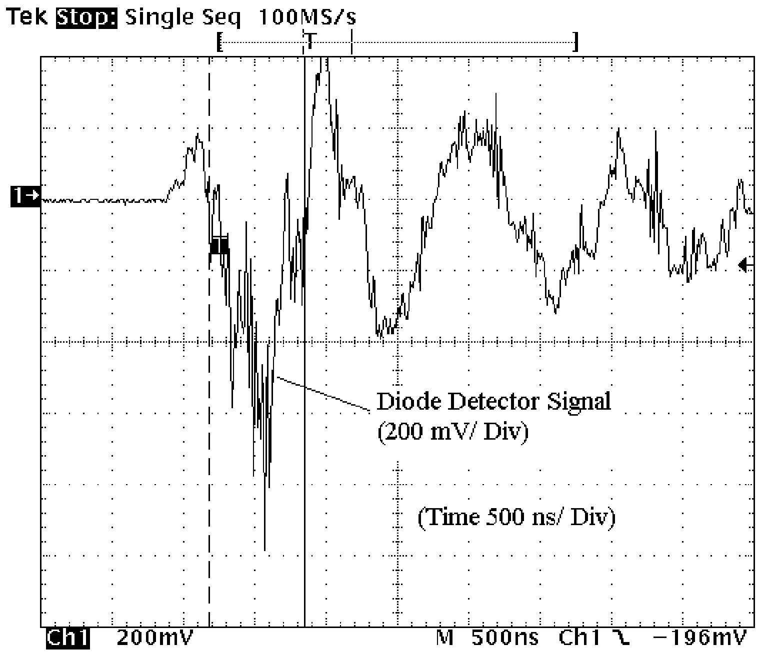

Figure 7. HPM signal after detection when carried to the scope by a BNC cable.

3.1 *With BNC cable*

Initially the diode detector has been kept near the KALI-1000 system and the detector signal has been taken to the shield room by a BNC cable. For each shot, the beam parameters were recorded using Lecroy model WS 454 (500 MHz, 2 GS/s) scope. Microwave detector output was recorded using Tektronics make oscilloscope TDS 520D (500 MHz, 1 GS/s).

Various components used in the diagnostics were calibrated using standard modulated (a few ms to ns) RF source. The calibration set-up for various components has been shown in figure 5. It was found that the output of the detector signal is nothing but noise. This is because of the fact that the noise signal amplitude was more than the detector output signal (a few mV).

Figure 6 displays the calibration curve of the Eclipse and Narda make diode detectors using standard modulated RF source at 2 GHz. The microwave signal after detection was carried to the scope by a BNC cable. Figure 7 shows a diode detector signal. One can see from figure 7 that the signal amplitude is quite high (~1 V) and the duration is ~700 ns. A few shots were taken only with the BNC cable with and without 50 Ω terminations (antenna, attenuators and the diode detector have been removed). It was found that the recorded signal is the same as that of figure 7. So this signal is nothing but noise picked up by the BNC cable. Also the noise signal varies on shot-to-shot basis. To reduce the noise level, different techniques were tried such as putting the BNC cable inside a metal

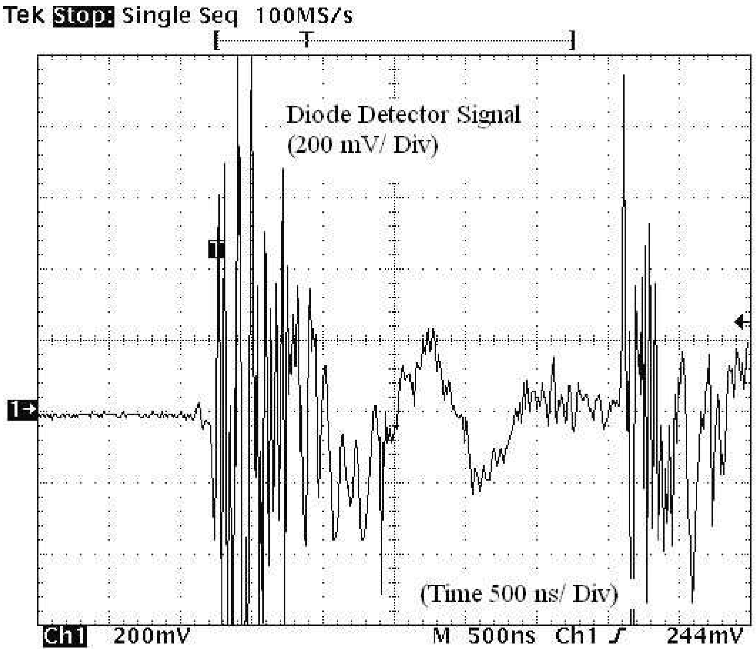

Figure 8. Diode detector signal when the BNC cable is kept inside a metal conduit.

conduit, grounding the conduit to the signal cable ground, to the inner wall of the shield room etc. Figure 8 shows a diode detector signal when the BNC cable is kept inside a metal conduit. Isolating the scope supply from the AC mains was also tried during the recording, but in vain. It was observed that ∼300 mV noise persisted throughout. A few shots were also taken by shielding the Tesla transformer with a 1.5 mm thick aluminum sheet. This helped reducing the noise level to ≤200 mV. But the diode detector output signal is (figure 6) <150 mV. So shielding the Tesla transformer could not help as we were unable to cover the Tesla transformer completely with the aluminum sheet due to some other problems.

3.2 *With a preamplifier*

To override the noise signal and to improve the microwave signal amplitude from the diode detector, a preamplifier (BMC 1595) was used at the output of the microwave detector. This preamplifier has a gain of 10 and 50 Ω impedance. This also could not help in detecting the microwave signal as the noise level too got amplified. Figure 9 displays a typical signal after a preamplifier is used.

It was observed that noise was picked up by the BNC cable when the BNC cable along with the conduit was kept inside the shield chamber, though the amplitude was low. So the use of BNC cable was stopped.

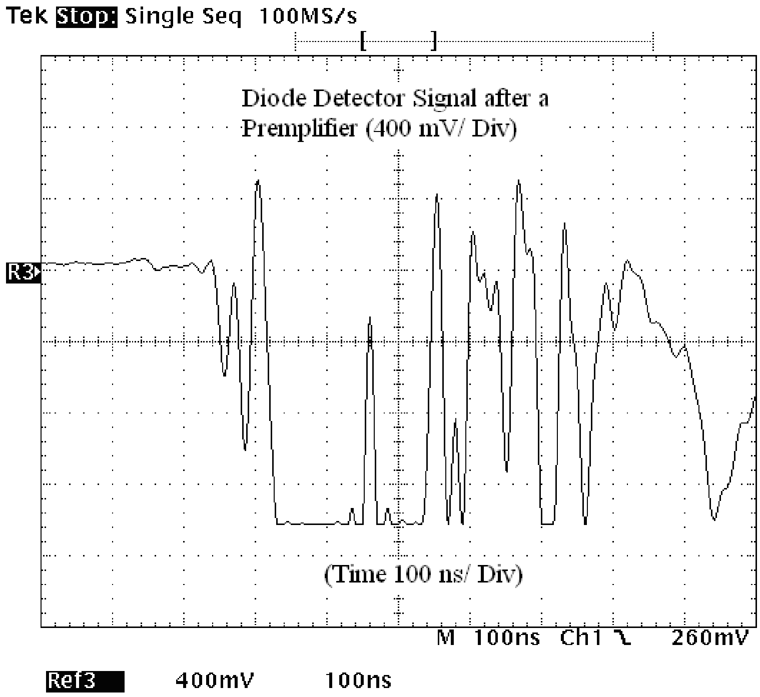

Figure 9. Diode detector signal after a preamplifier is used when the BNC cable is kept inside a metal conduit.

3.3 *With an RF cable*

Microwave signal was recorded successfully when RF cable was used to carry the signal from the receiving antenna and the diode detector was at the scope end inside the shield chamber. A few shots were taken replacing the receiving antenna with a 50 Ω termination. No signal was recorded with a 50 Ω termination. This confirms that the noise picked up by the detector with RF cable is zero. Figure 10 shows a diode detector (Narda make) signal with the antenna at 7 m distance from the VIRCATOR window after 30 dB attenuation. Estimated microwave peak power is ∼59.8 dBm (∼1 kW) at 7 m distance from the VIRCATOR window. The corresponding beam peak voltage and current was 256 kV and 9 kA. It was observed that there was a shot-to-shot variation in the microwave peak power. Duration of the HPM pulse (FWHM) also varies from 52 to 94 ns for different shots. Figure 11 shows the HPM diagnostics set-up by which HPM signal has been measured successfully in the presence of significant electrical high frequency noise. A few attempts were also made to measure the frequency of radiation using YIG base tunable band pass filter. As the pass band frequency of the filter is only ∼100 MHz we are unable to detect any signal using the filter. Detailed frequency analysis will be carried out in our future experiments.

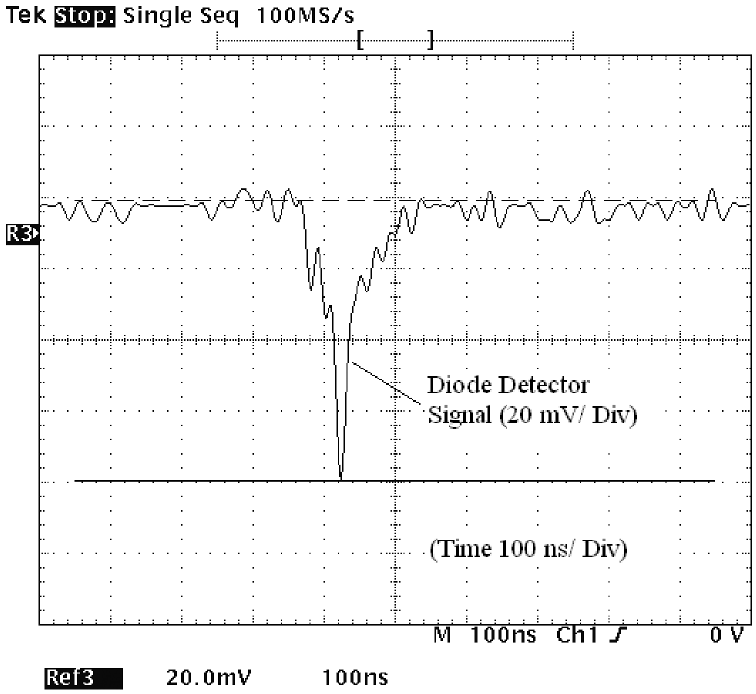

Figure 10. HPM signal from the diode detector when measured with an RF cable.

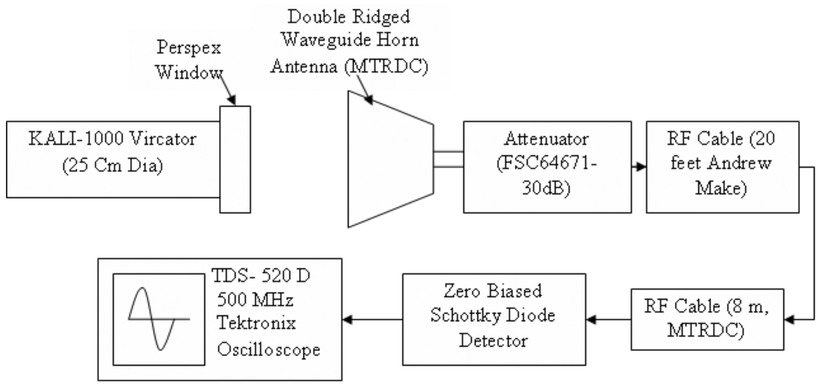

Figure 11. HPM diagnostics set-up by which HPM signal has been measured successfully in the presence of significant electrical high frequency noise.

4. Conclusions

High-power microwave has been generated from the KALI-1000 pulse power system using a virtual cathode oscillator device. The typical electron beam parameters were 200 kV, 12 kA, 100 ns, with a few hundreds of A/cm^2 current density. HPM power measurements were carried out with a transmitting–receiving system. During the initial measurements, BNC cable enclosed by a metal conduit was used to detect microwave signal from the diode detector. It was observed that noise was overriding the actual microwave pulse. Several attempts were made to minimize the noise level. Finally, HPM pulse has been successfully detected using wide band antenna, RF cable and diode detector set-up. Signal-to-noise ratio improved due to inherent shielding present in the RF cable. Also diode detectors are very sensitive to electromagnetic noise and X-rays. Placing them in close proximity to pulsed power and e-beam diode that emits X-rays will produce much noise. In the improved set-up we have placed the diode detector inside the shield room far away from the pulse power source. At 7 m distance from the VIRCATOR window the estimated microwave peak power was $\sim$59.8 dBm ($\sim$1 kW). The corresponding beam peak voltage and current was 256 kV and 9 kA. It was observed that there was a shot-to-shot variation in the microwave peak power.

Acknowledgemets

The authors are very much thankful to Dr L M Gantayet, Associate Director, BTD Group, BARC and Dr A K Ray, Ramanna Fellow, BARC for providing useful guidance, facilities and efficient manpower. They are also grateful to Dr Lalit Kumar, Director MTRDC for providing the microwave diagnostic set-up and technical support. The authors would like to place on record their sincere thanks to Dr K S Bhat, Additional Director, MTRDC, Dr S K Datta, Scientist F, MTRDC and Mr Venugopala Rao, SO(G), BARC for their continuous encouragement and support. The authors are thankful to Mr Sailesh Khole, Electronics Division, BARC for providing the preamplifier. They are also thankful to Mrs C I Sujo and Mr Gopal Joshi of Electronics Division, BARC for providing the calibration facility.

References

[1] James Benford, *IEEE Trans. Plasma Sci.* **36(3)**, 569 (2008)
[2] J Benford, J Swegle and E Schamiloglu, *High power microwaves*, 2nd ed. (Taylor & Francis, Boca Raton, FL, 2007)
[3] L M Earley, W P Ballard, L D Roose and C B Wharton, *Rev. Sci. Instrum.* **57(9)**, 2283 (1986)
[4] D J Sullivan, J E Walsh and E A Coutsias, Virtual cathode oscillator (VIRCATOR) theory, in: *High power microwave sources* edited by V Granastein and I Alexeff (Artech House, Norwood, MA, 1987) p. 441
[5] L E Thode, Virtual cathode microwave device research: Experiment and simulation, in: *High power microwave sources* edited by V Granastein and I Alexeff (Artech House, Norwood, MA, 1987) p. 508
[6] Y J Chen, A A Neuber, J Mankowski, J C Dickens, M Kristiansen and R Gale, *Rev. Sci. Instrum.* **76**, 104703 (2005)
[7] J Raimbourg, *Rev. Sci. Instrum.* **75(10)**, 4234 (2004)