Chapter 14

Application of Pulsed Power Technology

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At Atomic Weapons Research Establishment (AWRE), United Kingdom, J. C. "Charlie" Martin and his group began work on pulsed power in 1960 mainly for flash X-radiography of explosive events and also to simulate radiation from nuclear weapons [1]. In some of the literature it is stated that work on pulsed power technology started in Sandia National Laboratories, US as early as 1950's with the intent to utilize it in defense applications [2]. In the beginning the development related to pulsed power technology experiences an explosive growth in US, England, and USSR from 1960s, as it was related to the development of atomic bomb, but information was restricted. In BARC, pulse power program was started at in 1970s with Fusion research as the main application. Worldwide, several big systems were developed starting from few hundreds of kV to few tens of MV in voltage and several hundreds of kA to MA in peak current. These big systems were typically single shot in nature and main application was neutron generation, and Flash X-rays generation for Hydrodynamic studies and Fusion research. However, slowly application of pulse power technology started appearing in other activities also, such as, Particle Accelerators, Free Electron Lasers, High Power Microwaves (HPM), Magnetic Pulse Welding (MPW) and several other Industrial in nature. This chapter presents a glimpse of application of pulse power technology at APPD, BARC showing its spread in a large variety of strategic and industrial domain.

14.1. Applications of Pulse Power Systems at APPD, BARC

The applications of the pulse power systems include the Flash X-ray (FXR), High Power Microwave (HPM) and Pulsed Neutron Generation. Typically these applications require a large peak voltage of the order of few hundreds of kV to few MV and a peak current of few tens of kA and few tens of nanoseconds pulse duration. However, neutron generators require a high peak current (few hundreds of kA) but relatively low peak voltage (few tens of kV) pulse power generators of microsecond duration.

14.1.1. Flash X-ray Generation

Flash X-rays (FXR) are intense, short duration X-rays produced from pulsed electron beams for dynamic radiography. These pulsed electron beams or intense relativistic electron beams (IREB) are generated by the process of explosive electron emission (EEE). Accelerator & Pulse Power Division (APPD), Bhabha Atomic Research Centre (BARC) has developed several pulse power systems that have been utilized in generating FXR sources in various diode geometries with operating voltage ranging from 200 kV to 1 MV [3].

A. FXR Generation at KALI Systems

APPD, BARC has developed 5 GW, 60 ns REB source for IREB generation and its application. FXR spot size for this radiography system was optimized. A method was adopted for spot size measurements based on resolution of different spatial frequencies. Spot size was optimized to 2 mm for maximum dose of 2 R at 150 mm distance. An active radioactive source was also radio graphed [4].

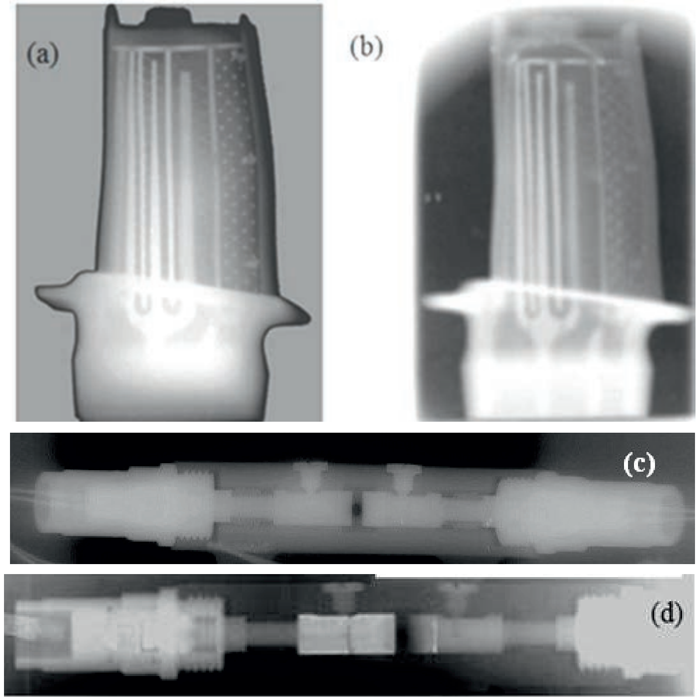

Figure 14.1. (a) Radiograph of Aero engine turbine blade with Flash X-rays from KALI-30 GW (650 kV, 10.5 kA, 80 ns), Imaging plate BAS-SR2025 (b) Neutron radiograph of aero engine turbine blade using CIRUS reactor facility with neutron flux 3.6×10^8 n/cm^2.sec and Neutron Image plate BAS ND-2025. (c) X-ray Radiograph of INSAT cable cutter with KALI-30 GW and (d) Neutron radiograph of INSAT cable cutter with CIRUS facility.

The Kilo Ampere Linear Injector (KALI) 30 GW system (erstwhile KALI-5000) is a Marx generator and Blumlein Pulse forming line (PFL) based pulse power generator having operating voltage up to 1 MV, current of 30 kA and pulse width of 80 ns (FWHM). The on axis FXR dose generated in planar geometry using KALI-5000 system is proportional to $V^{2.8}$ [3]. The typical beam parameters were 365 kV and 18 kA peak voltage and current respectively and the maximum dose measured was 46 mR at 1 m. In cylindrical diode configuration, A. Sharma *et al.* have reported FXR generation and source characterization at higher voltage levels of 600 – 800 kV [5]. Figure 14.1 displays few radiographs of the Aero-engine turbine blade and INSAT cable cutter using the KALI-30 GW system and its comparison with the Neutron radiograph using CIRUS reactor facility.

B. Folded Pulse Forming Line Based FXR Generator (225 kV, 6 kA, 150 ns)

The Folded Pulse Forming Line type Marx Generator based FXR system has been designed and developed indigenously at the APPD, BARC using PFN based capacitors [6]. It is capable of producing a Max Dose of 5 mR @ 1m, at 225 kV and 6 kA peak voltage and current respectively, having pulse width (FWHM) 150 ns. This system has been used extensively for the Dosimeter material development, evaluating the response time and saturation level and also for the Radiography of different metallic samples. Figure 2 displays the Folded Pulse forming line based FXR generator and radiograph of a condenser.

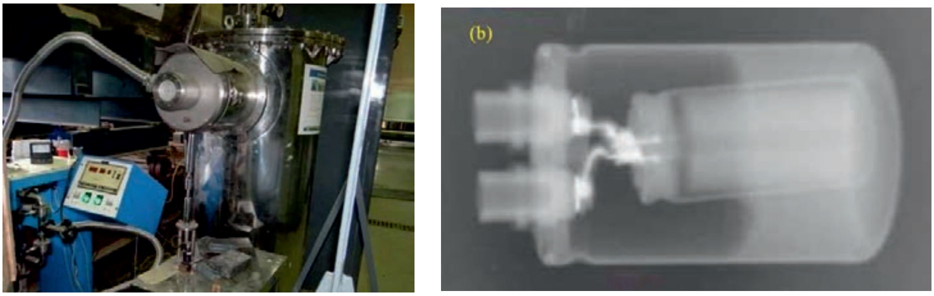

Figure 14.2. Photograph of the Folded Pulse Forming Line Marx Generator based Flash X-ray system and (b) radiograph of a large size condenser.

C. Marx Generator Based Compact Cable Fed FXR System (450 kV, 5 kA, 75 ns)

The 450 kV Marx based FXR system was developed for meeting the requirement of imaging where the FXR tube head is compact and portable. The high voltage is fed through a cable feed through arrangement from the pulsar to the diode. This system can be operated within a voltage range of 125 – 450 kV and produces X-ray pulses of time duration 50 – 75 ns. The maximum dose generated by this system is 11 mR @ 1 m and the angular dose has been estimated [7]. The FXR system can be operated remotely from a control console. The actual photograph of the system and radiography of an aluminum manifolds displayed in Figure 14.3.

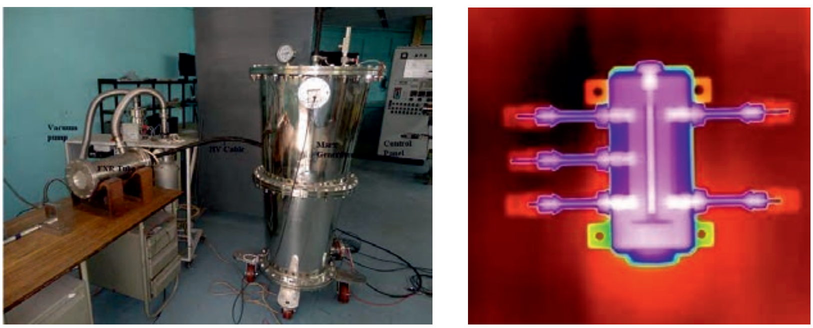

Figure 14.3. FXR system photograph and radiography obtained from system.

D. Marx Generator Based Portable Short Duration FXR System (200-550 kV, 10 kA, 45 ns)

Many dynamic radiography applications require the FXR pulse width <50 ns. The MARX based portable FXR source was designed and developed for similar type of radiographic purpose. Photograph of the portable sealed FXR diode with ion pump is shown in Figure 14.4.

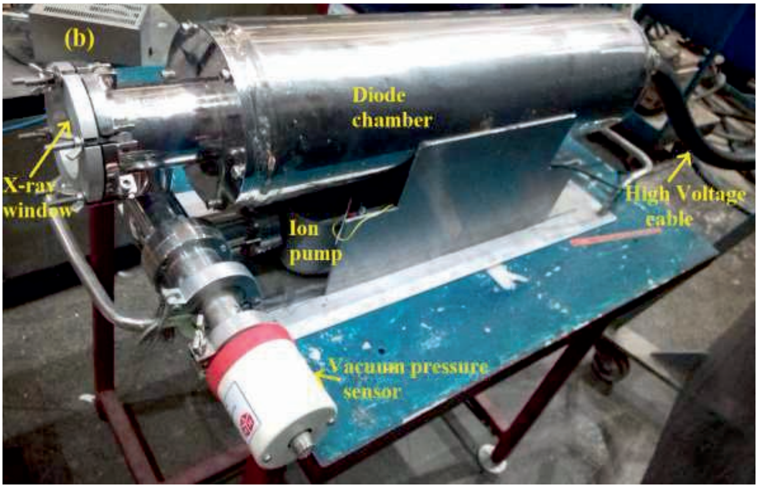

Figure 14.4. Portable FXR tube head of the short duration FXR System system.

The high voltage is connected to the FXR diode from the Marx Generator using cable feed through arrangement. The FXR diode is cylindrical and can generate X-ray pulses of duration ≤ 40 ns. The portable FXR tube is maintained at a pressure level of 1×10^{-6} mbar by a diode sputter ion pump [8]. The FXR source size, FXR spectrum, pulse width and penetration capability of the system have been characterized. Maximum dose recorded for this system was 62 mR @ 1 meter distance from source.

14.1.2. High Power Microwave Generation

A. Space-Charge Devices

One of the important applications of pulsed power system is the High Power Microwave (HPM) generation, simplest device is an Axial Virtual Cathode Oscillator [9]. In this device a very high negative voltage is applied to the cathode and IREB is generated via explosive electron emission mechanism [9]. This electron beam is made to pass through a mesh anode, where an electron beam space charge cloud is formed. This electron beam cloud oscillates and generates high power microwave. This device comes into three variants: (1) Axial Vircator, (2) Reflex triode & (3) Coaxial Vircator. A brief comparison of various HPM systems and generated peak power is given in Figure 14.5.

In the axial vircator [10] shown in Figure 14.6(a), negative high voltage is applied at the graphite cathode and electron beam is generated which propagate towards the mesh anode.

Electrons after passing through the mesh experience no accelerating field. In this region the space charge limited current of the geometry is deliberately kept much below than the electron beam current. Thus electron beam can't propagate in the region after anode mesh. Due to accumulation of charges in the region after anode mesh charge cloud is formed. This charge cloud keeps oscillating to generate microwave radiation. Generated radiation is extracted from a radiation antenna.

In the coaxial vircator [9] geometry shown in Figure 14.6(b), electrons are emitted in coaxial manner from cathode. Electron beam crosses the anode mesh and intense electron beam cloud is formed inside the mesh structure. Due to oscillation of electron beam cloud inside the mesh microwaves are generated, which are extracted from the radiating antenna. The efficiency of this device is much higher than the axial Vircators.

In the reflex triode geometry [11] shown in Figure 14.6(c) a positive high voltage is applied to the anode terminal. The IREB is generated from cathode and gets accelerated towards anode mesh. After anode mesh the electric field distribution decelerates the electron beam and electron beam cannot propagate in this region. Electron beam forms cloud below the anode mesh and this cloud oscillates to generate microwaves. Generated microwaves are extracted from Perspex window.

Vircator is an extremely simple device and usually doesn't require any magnetic field, but its electron beam to microwave conversion efficiency is very low (~1-2%). Its efficiency may be further improved using magnetic field and resonant cavity [12]. But this improvement is still not comparable to other existing devices, whose efficiency ranges from ~10-60%.

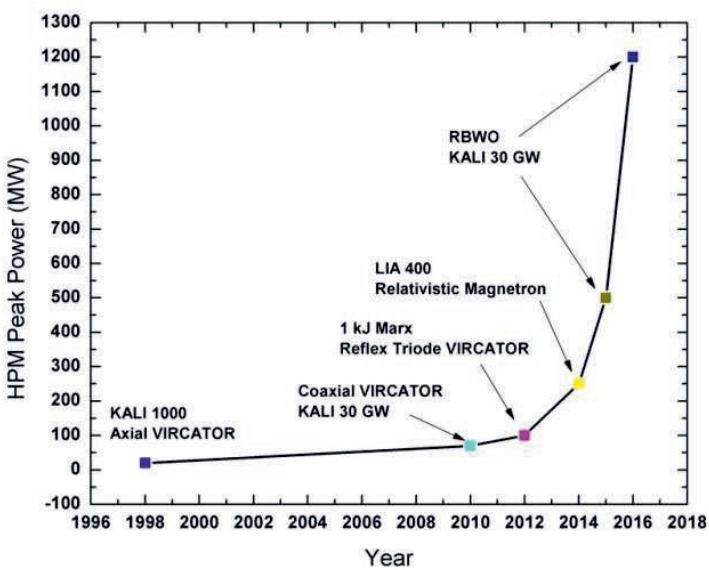

Figure 14.5. The journey of experimentally measured HPM power using various pulsed power systems at APPD, BARC.

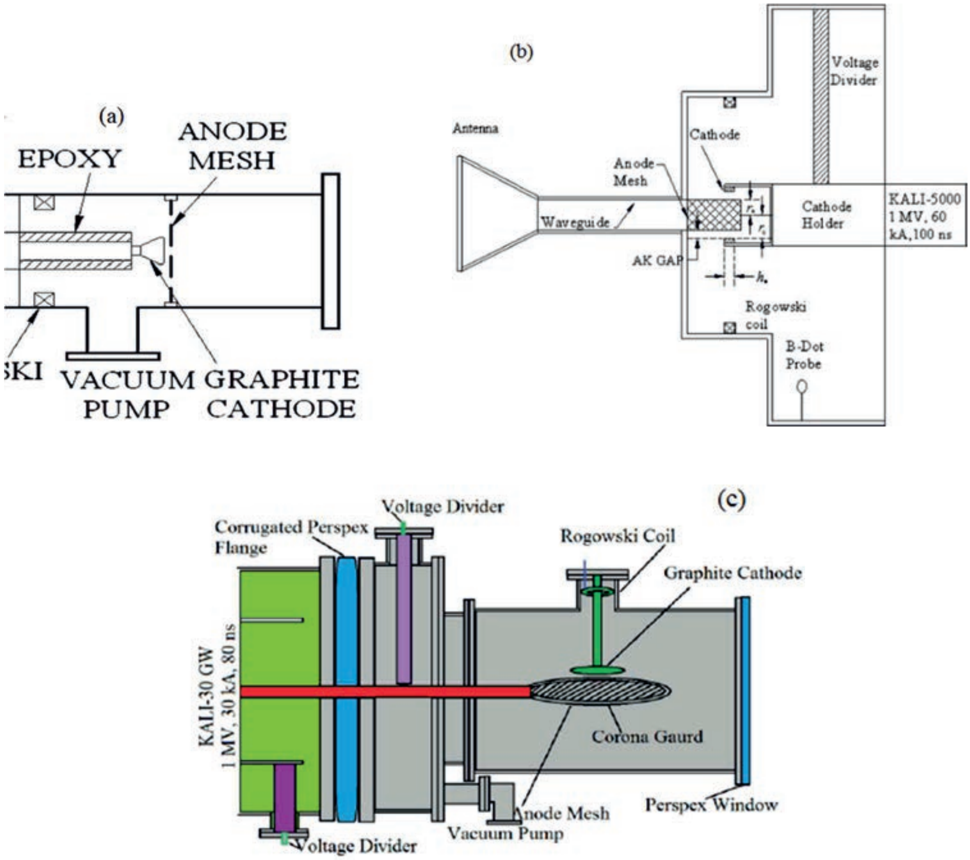

Figure 14.6. Schematic of (a) Axial Vircator, (b) Coaxial Vircator and (c) Reflex Triode.

Devices other than Vircators utilize magnetic field for electron beam guiding or focusing. This magnetic field may be applied externally or may be generated by self-magnetic field of the beam itself. Depending on the *B*-field direction with the electron beam, all the microwave devices may be classified into two categories, M-type device and O-type device.

B. M-type Devices

In an *M-type* device, electron beam propagate in a direction which is perpendicular to magnetic field line. The discussion here will be restricted to devices which are generally used for HPM generation using highly intense electron beam. The principal device falling under *M*-type device category is relativistic magnetron [13]. A schematic of relativistic magnetron with electron beam spoke formation is shown in Figure 14.7. In this device a cylindrical graphite cathode emits explosive electrons, which is having negative high voltage. These electrons interact with the cavities to generate microwaves. Applied axial magnetic field prevents electron beam to hit the anode. It is a cylindrical device having 6, 8 or 12 no's of cavity vanes depending upon the design.

A 300 MW 8 cavity magnetron is operational with LIA-400 system for IEMI radiation. This magnetron operates at 300 kV, 3.0 kA beam current and magnetic field induction of 0.3-0.4 T is used. Two point extraction is used from this structure as shown in Figure 14.7.

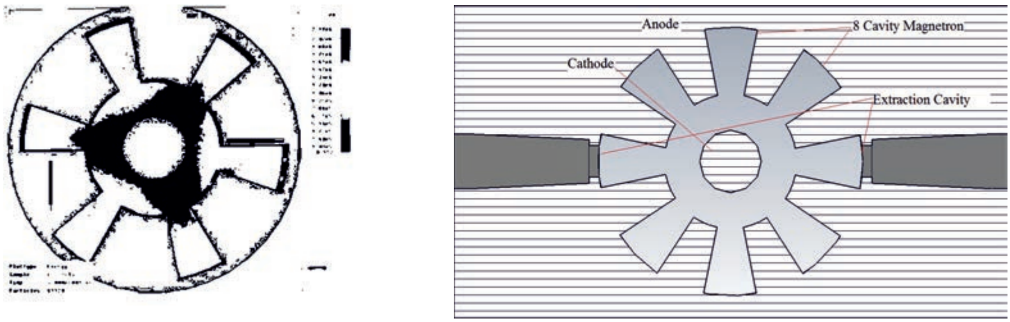

Figure 14.7. Schematic of relativistic magnetron having six vane cavities and eight vane cavities.

The extraction slots are tapered to match the dimensions of the WR284 waveguide, which is 34×72 mm. The output microwave from both the extraction port has a phase difference of 180°. Hence the one waveguide is $\lambda/2$ length longer than the other one. Gain of the radiating antenna is 16 dB. Peak electric field of 55 kV/m is measured using double ridged waveguide horn antenna at 10 m distance from the source window.

C. O-type Devices

O-type devices are those in which electron beam propagation and magnetic field is in the same direction. Relativistic klystrons [14], travelling wave tubes (TWT) [15] and relativistic backward wave oscillators (RBWO) [16] come in this category. In such devices magnetic field is just used as the guiding field to electron beam propagation. Relativistic klystrons (RK) and TWTs are basically amplifiers and RBWO is an oscillator. The BWO device has been used for HPM generation in S-band and X-band frequencies. A CST Simulation model of the BWO system is displayed in Figure 14.8.

BWO device works on the principle of resonance between phase velocity of microwave and electron beam velocity. Since the intensity of microwave is low thus net power transfer takes place from electron beam in to microwave. The SWS is used for slowing down the phase velocity of the microwave and make it equal to the electron beam velocity. Generated microwave have negative group velocity and propagate in the direction towards cathode. A reflector known as resonant reflector is placed to reflect incoming backward microwaves in the forward direction. After reflection from resonant reflector microwaves are extracted from a suitable radiating antenna. In APPD, BARC, S-band frequency BWO has generated peak power levels of 1.1 GW and in X-band frequency 1.0 GW of peak power has been generated. The S-band and X-band BWO devices developed by APPD, BARC are shown in Figure 14.9 [17]. The S-band BWO has five cell SWS and X-band BWO has seven cell SWS. The microwave conversion efficiency of these devices is 24% to 28%.

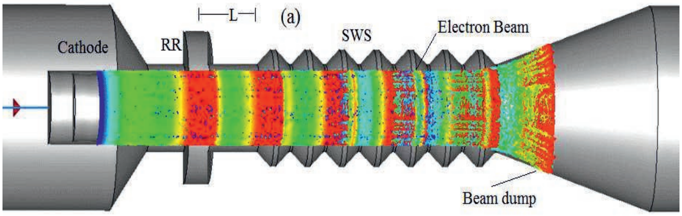

Figure 14.8. A CST Simulation model of the X-band BWO with electron beam Trajectory.

Figure 14.9. The S-band BWO and X-band BWO developed in APPD, BARC.

Thus in conclusion space charge devices like Vircators are easy to implement but have lower microwave conversion efficiency and peak power is limited up to 100 MW. Relativistic magnetron in S-band frequency could achieve 300 MW with 30% efficiency. BWO devices have achieved 1 GW output power with 24% to 28% conversion efficiency.

14.1.3. Ultra-Wide Band (UWB) Generators

For ultra-wide band (UWB) applications very fast rise time and small pulse duration pulse power systems are required [18]. Three pulse power systems have been developed for UWB applications. In the UWB application the radiating antenna is directly fed by the very fast rising but short pulse duration high voltage pulse.

A. UWB with Half TEM Horn Antenna

A 300 kV, 2 kA high voltage UWB system is developed at APPD, BARC Mumbai. This UWB system comprises Marx generator of 20 stages along with peaking circuit and Half TEM horn antenna. The Marx generator is charged at 30 kV DC using variable dc power supply (30 kV, 200 mA) and produces 300 kV, 140 ns, 2 kA pulse into Half TEM horn antenna. The Half TEM horn antenna radiates fast rising pulse produced at the Marx Generator output. Trigger operation of the Marx generator is performed using IGBT based trigger circuit and fiber optics. The system radiates 5 kV/m electric field at 10 m distance from source [19].

Figure 14.10 displays the UWB system with Half TEM horn antenna. This UWB system has height of 2.5 meters with overall diameter of 1.5 meters. It has a weight of 470 kg. In the radiated field frequency components up to 100 MHz are present. System is compact and can be truck mounted for mobile usage. This type of UWB system can be used for vulnerability and susceptibility testing of electronic circuits and also used in shielding effectiveness testing. This system is based on Marx generator topology without any pulse forming line (PFL). In the future systems PFL is added to reduce the pulse duration and improve the rise time of the high voltage pulse.

Figure 14.10. Photographs of the UWB system with half TEM horn antenna.

B. Compact High Voltage Balanced TEM UWB System

A high power 120 kV, 66 Ω UWB radiator system is developed at BARC, Mumbai to generate intense electromagnetic fields. The UWB system consists of a Marx Generator and a pulse forming line to generate a 120 kV peak voltage, 5 ns pulse with a rise time of ~300 picoseconds [20].

A balanced TEM horn type antenna radiates 10 kV/m electric field at 10 m distance from the system. The photograph of the UWB system is displayed in Figure 14.10. This system can be used for vulnerability and susceptibility testing of electronic circuits and systems, shielding effectiveness testing, buried target detection, electrical characterization of materials, space debris detection etc.

C. UWB System with Half Impulse Radiating Antenna (HIRA)

A high voltage UWB system with Half Impulse Radiating Antenna (HIRA) [21] is developed at APPD, BARC Mumbai as shown in Figure 14.10. A 20 stage Marx Generator charges a solid dielectric PFL of 100 Ω characteristic impedance using an inductor. Solid dielectric PFL consists of a low inductance spark gap switch acting as a peaking switch. Output of the PFL is fed to HIRA with 100 Ω impedance. The HIRA antenna designed and developed at APPD, BARC is highly directive with 3 dB beam-width better than 6 degrees. This system generates 20 kV/m *E*-field at 10 m distance from HIRA antenna and has a foot print of 2.1 m × 1.5 m. It has a weight of 400 kg. In the radiated field frequency components up to 1 GHz are present. System is very compact and it can be truck mounted for mobile applications. The radiating antenna has 6 degrees of 3 dB beam width in H-plane of radiation.

This system also can be used for similar applications as discussed for the previous UWB systems. It has higher range and higher frequency constitution than the previous system.

14.2. Conclusion & Future Research

APPD, BARC has developed several pulsed power systems with output electrical power ranging from 1 GW to 30 GW mainly for the application of Flash X-rays and High Power Microwave generation. The output pulse duration of these system ranges from 300 ns to 50 ns depending on the application. In the FXR generation application a maximum 1.2 R radiation dose is achieved at 1 m distance from anode target at KALI-30 GW system. An X-ray dose of 62 mR is measured at 1 m distance from source at coaxial Marx generator with less than 40 ns X-ray pulse width. The X-rays from this system penetrates, 32 mm steel plate placed at 2.5 distance from source.

The high power microwave generation was started from space charge devices like Vircators. These devices could generate narrow band microwaves having peak power up to 100 MW. The conversion efficiency of these devices was limited up to 2%.Thus for more microwave power attention was shifted towards resonant devices like relativistic magnetrons and backward wave oscillators.

Relativistic Magnetron has generated 300 MW peak microwave power on LIA-400 system at 3 GHz frequency. Electrical parameters were 300 kV, 3 kA with pulse duration of 125 ns. Microwave power on excess of 1 GW has been demonstrated in S-band and X-band frequencies with BWO devices. The microwave pulse duration is 60 ns in S-band frequency at KALI 30 GW system and 30 ns in X-band frequency at coaxial Marx generator.

The pulse duration of the pulse power system for HPM generation depends on the output microwave frequency. Typically 300 T pulse flat top is required in the electrical pulse for microwave generation with microwave pulse having time period of T. For flash X-ray generation minimum 30 ns electrical pulse duration from pulse power system is required. The pulse power systems for HPM generation are summarized in Table 14.1.

Table 14.1. The pulse power systems for HPM generation at APPD, BARC.

Pulsed Power System	System Ratings (Voltage, Current, Energy)	High Voltage Generation System	Pulse Forming Line	Pulse Width	Repetition Rate	HPM Source with Efficiency	Antenna with Gain	Measured HPM Power, Frequency	E-Field Measured at a Distance from The Window
KALI-200	200 kV, 20 kA, 200 J	Radial Tesla Transformer	Oil PFL	50 ns	Single Shot System	Axial Vircator <1 %	Open Ended Wave Guide (6 dB)	S-Band	
KALI-1000	300 kV, 20 kA, 1000 J	Radial Tesla Transformer	Water PFL	100 ns	Single Shot System	Axial Vircator <1 %	Open Ended Wave Guide (8 dB)	87 MW,4-6.6 GHz	5.1 kV/m @ 10 m
1 kJ Marx Based Respective System	300 kV, 12 kA 1000 J	Marx Generator	NIL	300 ns	10 Hz	Reflex Triode Vircator 2 %	Open Ended Wave Guide (8 dB)	100 MW, 2.2-4 GHz	5.3 kV/m @ 10 m
KALI-5000	1000 kV, 50 kA, 5000 J	Marx Generator	Blumlein PFL (Castor Oil)	100 ns	Single Shot System	Coaxial Vircator < 1 %	Conical Horn Antenna (10 dB)	26 MW, 2.8 GHz	2.8 kV/m @ 10 m
						Reflex Triode Vircator < 1%	Open Ended Wave Guide (8 dB)	43 MW, 6.5 GHz	3.6 kV/m @ 10 m
LIA-400	400 kV, 4 kA, 160 J	Transformer	Stripline	100 ns	8 Hz, 300 Hz at 160 kV output voltage	Relativistic Magnetron, 25 %	Pyramidal Horn Antenna (18 dB)	280 MW, 3.0 GHz	130 kV/m @ 4 m
KALI-30 GW	1000 kV, 33 kA, 2500 J	Marx Generator	Blumlein PFL (Transformer Oil)	80 ns	Single Shot System	Relativistic BWO 22 %	Conical Horn Antenna (10 dB)	1.2 GW, 3.28 GHz	600 kV /m @ 1 m
Compact Marx	500 kV, 5 kA, 250 J	Marx Generator	NIL	100 ns	Single Shot System	Relativistic BWO 22 %	Conical Horn Antenna With COBRA Lens (16 dB)	450 MW, 3.25 GHz	160 kV/m @ 4 m
Coaxial Marx	700 kV, 7 kA	Marx Generator	NIL	21 ns	Single Shot System	Relativistic BWO 21%	Conical Horn Antenna (21 dB)	1000 MW, 9.2 GHZ	200 kV/m @ 10 m

APPD, BARC has also developed several high power ultra wideband (UWB) repetitive systems for various applications, the measured field various from 10 kV/m to 20 kV/m at 10 m from the Antenna.

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