High Power Microwave Devices: Development Since 1880

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***Abstract*— High power microwave systems have emerged as a promising new technology that has many applications, which include high power radar, directed energy weapons, laboratory sources for susceptibility and vulnerability testing of electronic systems. These systems are built, applied, and studied in many developed countries such as in United States of America and China. In the recent years, other countries such as Russia, Western Europe, Japan, Taiwan, India, South Korea, and Singapore have also entered the research spheres. In this paper an introduction to the emergence of HPM and the sequential evolution of the technology, that plays an important role in several applications, are discussed. The discussion extends to types of HPM sources, and their effects of electromagnetic interference on electronic systems.**

Keywords—High power microwaves; HPM; Electromagnetic Pulse; EMP; Electromagnetic interference; EMI

I. INTRODUCTION

Transforming the energy of electron beams into microwaves is the key process in HPM systems. Microwaves are distinguished by the electromagnetic energy at small wavelengths, i.e. in the centimeter or millimeter scales. Recently, considerable attention has been paid on the development of HPM sources, due to various background developments. If the electric and the magnetic fields occur concurrently, the electron movement depends on the direction of both fields. When the two fields are in equal orientations or in opposite, then magnetic field does not exert any force on the electron, and the movement of the electron only will depends on the electric field [1]. O-type devices (linear beam tubes) use a magnetic field for holding the electron beam together in the path of the tube during its travel. Electrons acquire significant amount of potential energy from the electric field but not from the magnetic field. Therefore, when the magnetic flux density $\vec{\mathbf{B}}$ and the electric field intensity $\vec{\mathbf{E}}$ are at a correct angle to each other, the electron beam can be affected by the magnetic force. This kind of field is called a crossed field (M-type device). Electrons that are emitted from the cathode will be accelerated by the electric field; and the magnetic field causes more bending in their path whenever their velocity increases. Lorentz Force $\vec{\boldsymbol{F}}$ on a free particle of an electron charge q and mass m in the presence of both the electric field intensity $\vec{\mathbf{E}}$ and the magnetic flux density $\vec{\mathbf{B}}$, and is given by (1), with $\boldsymbol{v}$ is the velocity of a positive (+) charge in m/s.

$$\vec{\boldsymbol{F}} = -q\left(\vec{\boldsymbol{E}} + \boldsymbol{v} \times \vec{\boldsymbol{B}}\right) = m\frac{dv}{dt} \qquad (1)$$

A practical HPM tube needs several technologies, incorporating a power supply at high voltage, high power RF circuit, high power electron gun, an electron-beam collector, and a suitable RF vacuum window. Also, there will be circulators, loads, waveguides, and antennas. However, description of any HPM device starts with the production of electron beam, the driving of power supply that is used, and some kind of electron gun. HPM sources are widely used for various civilian and defense applications, which include material processing, counter electronic development, and radar systems [2]. Electromagnetic energy of microwaves is used at modest levels of power for RF communications or radar. For instance, microwaves at X-band with wavelengths around 3 cm long, or C-band with 5.7 cm long, or L-band with 20 cm long, are used often for communications or radar. HPM is a powerful component in high power radar, directed energy weapons (DEW), sources for susceptibility testing and vulnerability of the electronic systems in RF laboratories [3].

HPM applications require microwave radiation with either high peak power or high average power, which contain 1) acceleration of RF in high energy collider, i.e. high power narrowband amplifiers at frequencies 10GHz – 100GHz, 2) the heating and driving current plasma in tokamak, i.e. a device that uses a powerful magnetic field to detain plasma in the shape of a torus, high average power oscillators at frequencies over 100GHz, 3) nonlethal crowd control at active denial technology, for high average power at 94 GHz, and 4) communication and radar systems, at moderate of average power, broad bandwidth amplifiers at frequency range of 10 GHz [1]. High power narrowband sources that have been developed primarily by the Department of Defense (DoD), United States of America (USA) for developing non-lethal DEW for electronic attack was known as e-bomb [8]. At peak output power in the range of 1GW, with 1GHz frequencies, 100 ns order of pulse duration is desirable for that device. Although the capability of pulse repetition is desired, at long pulse durations and high powers such capacity becomes quite difficult.

Military platform is one of the most vulnerable entities that require the most stringent protection against electromagnetic interference. In the past, especially during the Cold War era, there was a high interest in research programs on HPM weapons in the USA and USSR camps. Now in Europe, practically in France, United Kingdom, Germany, and Sweden there are considerable activities on HPM which are the most outstanding. Also in Asia, there are on series weapons programs in India and China which including HPM. For China, researches are done on Gyrotrons, FEL at laboratories, which the HPM technologies were purchased from Russia. Plasma heating by Gyrotrons, accelerators by Klystrons, and Free Electron Laser (FEL) are among the programs that have intensively developed in Japan [1].

II. HISTORY OF HIGH POWER MICROWAVE DEVICES DEVELOPMENT

HPM is defined as devices that exceed 100 MW in peak power with frequencies between 1 and 300 GHz at centimeter and millimeter wave ranges. However, for a klystron, it may exceed 100 MW and reach to power levels over 15GW, which had represented a

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convergence of many historical trends, as shown in Fig. 1. HPM can be created as an electromagnetic pulse (EMP) at an instantaneous time, for example, by using great batteries and capacitors. Using a specially shaped of antenna, HPM energy can be concentrated to generate effects equal to High Altitude Electromagnetic pulse (HEMP) at a limited distance, or a restricted area. Contrasting HEMP, nevertheless, the HPM radiation at higher frequencies uses shorter waveforms which make it more difficult to focus against devices and highly effective against electronic equipment. A simple mechanical device, e.g. a suitcase sized device with a special focusing antenna would be able to produce an instantaneous HPM shock wave that can damage and disrupt several computers within a range of 1 mile. Also, at high power levels of MW with longer time interval, HPM energy could cause physical harm to persons close to the source emitter or on the path of energy beam [4, 5].

In 1880s, microwaves were first generated by Hertz. With advent of gridded tubes in the early twentieth century, radio came at lower frequencies.

In the 1930s, by connecting resonant cavities to electrical circuits, many investigators recognized that higher frequencies can be acquired, and Klystron was produced in 1937 as the first cavity device. After that, during World War II, a continuous activity followed by the invention of the Backward Wave Oscillator (BWO), Magnetron, and Traveling Wave Tube (TWT) [1].

In 1950s, due to the efforts to control thermonuclear fusion, understanding of the interaction between particles and waves was emerged. Ultimately, developments for a new tube using Gyrotrons at frequencies over 100 GHz and higher average power were required.

In 1960s, the beginning of pulsed power led to extension of the electrical technology, as well to the creation of charged particle beams at voltages of 1MV and currents of 10 kA. Intense beams and wave particle interaction gained in the study of plasma physics were used in generation of microwaves. Also, in 1960s, Cross-Field Amplifiers (CFA) were developed [1].

Thereafter, i.e. in the 1970s, there was a strong emergence for solid state of microwave sources at lower power levels, but extremely compact [1]. As a result of this lineage, HPM community lies closer to pulsed power communities and the plasma physics than the conventional microwave tubes as in Fig. 2. Due to this, HPM technology was at first slow to resolve pulse shortening challenge that limits HPM to shorter pulses at hundreds of nanoseconds [1].

During the period of 1970s and 1980s, conventional microwave sources such as the Magnetron, TWT, and BWO were the first HPM sources which used higher currents and stronger beam couplings within the interaction region, and this led to an increase power. Also, production of relativistic electron beams at high voltages and electron energies that were greater than 511 kev energy rest of electron had been a big significant milestone for HPM devices development. The production of new devices, such as Virtual Cathode Oscillator (Viractor) and Relativistic Klystron was the most important that depended basically on very high currents accompanied to the high voltages. Finally, it is a strong emergence of devices that depend on energy tuning of the output frequencies such as FEL and Cyclotron Auto Resonant Maser (CARM) [1].

1990s was the golden age of HPM, in which huge trends were made in the creation of higher power levels at higher frequencies. Researchers in Russia developed new devices, i.e. Relativistic Diffraction Generator (RDG), Multiwave Cerenkov Generators (MWCGs), and Multiwave Diffraction Generators (MWDGs), which were based on large interaction regions at microwave wavelengths in diameter. Also, Ultra Wideband (UWB) devices were launched, which typically generate high power in the range of ~ 1GW with a very short duration of 1ns. UWB used direct excitation of an antenna to generate pulses instead of extracting energy from the electron beam [1].

After 1990s, Nonlinear Transmission Lines (NLTLs) have emerged to generate narrowband radiation by taking an input rectangular voltage pulse and converting it to oscillations. These sources exploit nonlinearities in dielectric or magnetic materials and require neither electron beams nor a vacuum [1].

In the USA, FEL generated high powers at higher frequencies, while Klystrons and Relativistic Magnetrons generated them at lower frequencies. Measure of the success for these efforts can be achieved by the product of the peak power microwave and square of frequency Pf^2 as in Fig. 3. Conventional microwave sources made three orders of magnitude progress between 1940 and 1970. HPM progressed at $Pf^2 \sim 1\text{GW.GHz}^2$ rising an additional three orders of level in the following of 20 years. FEL has the highest magnitude produced to date, with an output power of 2 GW at 140 GHz, and Pf^2 is $4\text{x}10^4$ GW.GHz^2. The early golden age of HPM ended with a sobering recognition which device development was stalling at around 10 GW and 1 KJ of pulse energy. These parameters were accomplished through enormous effort and without taking whole advantage of advanced three dimensional computational modeling tools that become more widely available [1].

III. HPM RESEARCH PROGRESS IN USA

Studies in [6-24] are related on HPM and done at Plasma, Pulsed Power, and Microwave Laboratory (PPML), University of Michigan, USA which involved simulations and designs of a new model of Magnetron. The device is named Recirculated Planar Magnetron (RPM), and claimed to be able to enhance a power and current, reduce thermal load, as well to relieve the geometric limits in scale of high frequencies compare to the conventional Magnetrons [10]. This RPM contains 12 cavities, with 6 on each planar side. HFSS simulations, two dimensional MAGIC PIC simulations shown steady pi-mode act in less than 15 ns with microwave power getting 200 MW per cavity, with an operating voltage of - 300 kV [6-19].

Franzi et al. [6-14] discussed some possible advantages of this device for airborne applications, where two important factors are cost and weight of the magnetic field coils, which could be lower in RPM compared to the conventional Magnetron.

Jordan et al. [15-19] started their research with development 3D printed plastic anodes structures for use in a RPM-12 which electroplated and thermal sprayed with copper named as RPM-12b and RPM-12c, these structures were compared to a solid aluminum anode named a RPM-12a. The 3D printed anodes produced microwave powers of 150 MW with efficiency of 27%. An L-band RPM operated at 1GHz using -300 kV pulsed voltage 0.3 to 0.5 µs, and 0.2 T axial magnetic field. An RPM with 12 cavities was simulated to yield power output in the range of 400-500 MW at 1.9 GHz with efficiency of 60% for over 0.5 µs.

Greening et al. [20-23] developed Multi-Frequency RPM (MF-RPM) which contain a slow wave structure (SWS) with 6 cavities at 1 GHz and 8 cavities at 2 GHz MF-RPM. Experiments were claimed to have effectively extracted dual frequency oscillations, i.e. 1 GHz with 20 MW and 2 GHz with 7 MW. MF-RPM 6 and MF-RPM 8 driven by Michigan Electron Long Beam Accelerator that uses a Ceramic insulator (MELBA-C) with a -300 kV, 0.3-0.5 µs pulse duration. In [20-23] it is mentioned that using a series of waveguide tapers, directional couplers, and bandpass filters power of each harmonic could be measured. The taper of WR-650 to deliver 1GHz as TE_{10}, the WR-340 with bandpass filters to deliver 1GHz component and the WR-187 for 4-GHz component that exists exclusively as TE_{10}, with the other frequencies being cut off.

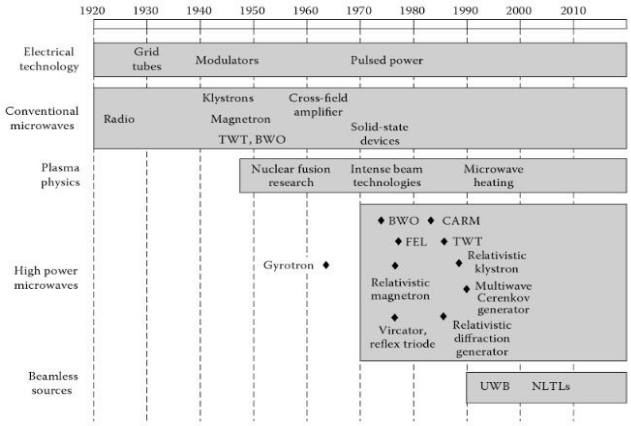

Fig.1. Emergence of HPM and its Historical Origins [1]

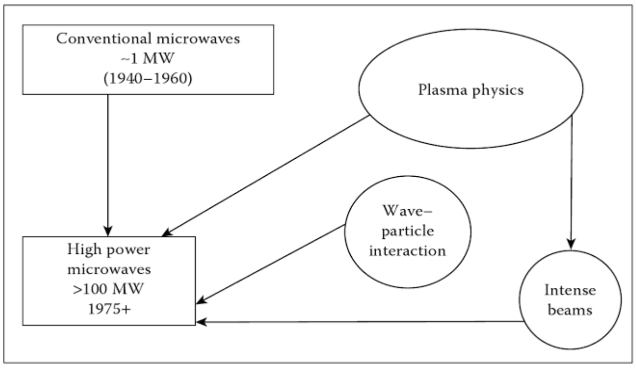

Fig.2. The linkage between developments of HPM sources with plasma physics and wave particle interaction [1]

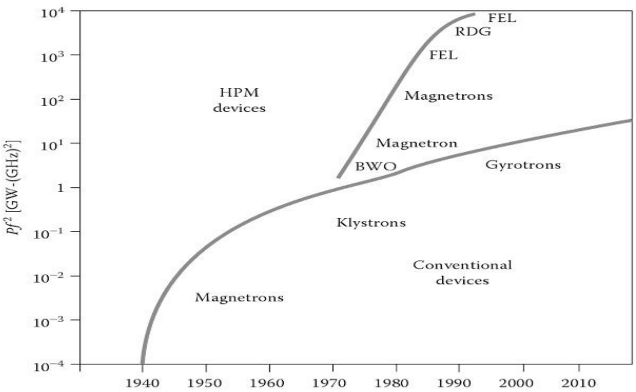

Fig.3. Growth of microwave devices in terms of the figure of merit Pf^2, with identify the year when the plotted value of Pf^2 was first achieved [1]

IV. HPM Research Progress in China

In China, several HPM devices were developed by Northwest Institute of Nuclear Technology (NINT), National University of Defense Technology (NUDT), and China Academy of Engineering physics (CAEP), which are located at Shaanxi, Changsha, and Beijing, respectively. The research progresses of HPM are continual and efforts to overcome the pulse shortening phenomenon, increase pulse duration, increase the power efficiency. Considerable attention has been paid to the development of HPM sources in NUDT, which concentrated on the following aspects, 1) suppress the pulse shortening phenomenon in O-type Cerenkov HPM devices, 2) develop compact Relativistic BWOs at low band in S, C, and X bands, 3) increase the power efficiency in M-Type magnetically insulated transmission line oscillator (MILO), i.e. HPM tubes without guiding magnetic field, 4) increase power capacities and power efficiencies at higher frequencies for the Ttriaxial Klystron Amplifier (TKA) and relativistic Transit Time Oscillator (TTO) [25-32]. Cerenkov HPM sources could be used to generate short Gaussian microwave that are attractive for many application, such as short pulse radar, plasma diagnostics, and sounding systems. The importance of the Gaussian microwave beam is the concentration of maximum energy density along its axis.

Xiao et al. [25] from NINT, investigated on RBWO using the Cerenkov mechanism due to its high power efficiency, high output power, and high repetition operations. This device combines the advantages of transition radiation with Cerenkov radiation with the characteristics of high power capacity, high efficiency, and stable frequency. Simulation results showed that the frequency of 4.3 GHz, output power of 10 GW, and conversion efficiency is 48% when the beam current is 17.3 kA and diode voltage 1.2 MV. Xiao et al. in [26] also discussed on mechanism of phase control in a Klystron-like RBWO by an input signal. In simulation, with 4.21 GHz frequency, an input signal 100 kW power, the output microwave power is 5 GW when the beam current is 9.8 kA, diode voltage is 750 kV, and corresponding to a power ratio of output microwave to input signal of 47 dB.

MILO is M-type device, with more attention was done in NUDT compared to NINT and CAEP. MILO covers frequencies from S-band, L-band, X-band, and C-band to Ku-band with advantages of stable operation, high power output, compact configuration, and self-magnetic insulation. However, drawbacks that it has lower efficiencies and lack of tunability. Major development directions for the MILO are increasing output power, power conversion efficiency, pulse duration, and repetitive frequency [27-29].

Wang et al. [29] from CAEP, studied L-band double ladder cathode MILO, with the experiment results in at frequency of 1.23 GHz, 46 ns of duration pulse, the output power is 3.57 GW, and efficiency of 8%, where generated under the voltage of 740 kV and current of 61 kA.

Zhenbang Liu et al. [30] also from CAEP, searched for the TKA where it is put forward to realize RKA operating in high frequency bands. To perform long pulse HPM generation, an experimental study on a long pulse X-band coaxial multi-beam was presented with 16 electron beams and propagation tubes are divided into small regions to suppress self-oscillation and leakage of TEM and TE modes. Experimental results reported in [30] are 0.82 GW output HPM at X-band frequency of 9.384 GHz, with pulse width of 40 ns, the diode voltage and beam current are 720 kV and 2.8 kA, and the injection microwave power is 30 kW with gain of about 44 dB.

Zhang et al. [31] introduced an enhanced suppression method of the TEM mode leakage with two reflectors in the TKA which is an effective method at high frequencies to amplify microwave with lower power injection and achieve a 1 GW level output. Results in [31] illustrated that the radiation microwave is ~240MW at frequency range from 9.355 to 9.395 GHz, X-band, 100 ns of pulse duration, beam current and diode voltage are 6.3kA and 570kV, the guiding magnetic fields about 1 T, the input microwave power and frequency are 90 kW and 9.37 GHz, respectively with gain about 34dB. It was claimed that there is no asymmetric mode competition resulting in the pulse shortening. Therefore, the asymmetric mode competition is effectively suppressed in the TKA with an asymmetric input cavity.

Also, attention has been paid to the development of HPM sources from the TTO in NUDT due to its virtues such as high power, high stability, monochromatic output RF signal, and compact structure. Asymmetric competition mode in relativistic Ku-band coaxial TTO is investigated by Ling et al. [32]. A novel Ku-band coaxial TTO to enhancement of the power capacity and efficiency at high frequencies is proposed with low guiding magnetic field. Simulation results at

TM_{01} operation mode of device are 1 GW output power at Ku-band microwave frequency is of 14.25 GHz, the pulse duration of 95 ns, 420 kV of diode voltage, 8.3 kA of beam current, and guiding magnetic fields of 0.7 T. Experimental results reported in [32] with diode voltage and beam current are 500 kV and 10 kA, with 0.7 T of magnetic fields, 1 GW of output power, 14.2 GHz frequency, and 20% conversion efficiency.

V. CONCLUSIONS

The sequential development of technology and the emergence of HPM devices have become a major part of many applications, which include high power radar and vulnerability testing of electronic systems. In this paper, the introduction to the emergence of these devices has been discussed. What has been accomplished is demonstrated in some developed countries such as PPML Lab in USA, and NINT, NUDT, and CAEP Labs in China which initiated, implemented and studied these systems.

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