White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	S
• Turbulence and transport	
• Interactions of plasmas and waves	P
• Plasma self-organization	
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
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Will not attend	

Title:	High Power Microwave Science
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)

Enhanced civilian and military infrastructure requires expanded capability to project increased microwave power from ~0.1 to 1,000 GHz. Examples include electronic attack defenses, accelerator sources, fusion plasma heating, advanced materials research, future space exploration, advanced radar, remote stand-off threat detection, and the rapid transmission of massive volumes of data over long distances [1-5]. Meanwhile, advances in HPM science address many of the same fundamental challenges that ubiquitously confront high-energy-density plasma and advanced accelerator research [1]. For example, producing and managing a high-energy-density system (beams, radiation power) requires addressing the same issues of intense beam generation, dense charged-particle fluid confinement, extreme-environment-compatible materials, and intense radiation and particle diagnostic sensor development, development of compact pulsed power, and gas phase chemistry and kinetics that confront high-energy plasma researchers everywhere. HPM science, like high energy density plasma science, is a rich scientific field encounters extreme energy densities and vast orders-of-magnitudes dynamic ranges in scale-lengths, timescales, field intensities and charged particle energies. Therefore, substantial and meaningful advances will require the synergistic combination of advances in predictive theory, computation, experimental measurement, and novel integration of advanced electronics (sensors, system control, pulsed power generation) and advanced signal processing. The field of HPM science belongs in the realms of "Beams and Coherent Radiation" and "Interactions of plasmas and waves" but also overlaps with "Plasma Atomic Physics and the interface with chemistry and materials science". The challenges are big but the potential scientific and societal impact substantial, and pursuit of advances involves a frontier of opportunities that will occupy decades of future effort. As shown in Fig. 1, compact, "sealed tube" sources encounter a ~ $1/f^2$ power-versus-frequency-limit frontier [1]. This has been exceeded, up to a certain extent, at THz-regime frequencies (0.1 – 10 THz) - by *unbounded* (highly-overmoded, quasi-optical) systems employing large, high energy electron accelerators, as shown in Fig. 2 [5]. Nevertheless, opportunities for impactful societal benefits as well as basic science research needs drive an imperative for even further advances in HPM science. Some of the challenges occupying the research frontier are described below.

<u>HPM Sources</u>

The research frontier is to extend the power limits of HPM sources in ways that also realize compactness, high efficiency, long life and multi-use potential (e.g., multi-frequency or wideband gain). One of the grand challenges of HPM oscillator science is to scale the amazing abilities of ubiquitous oven magnetrons to GW, kJ levels. In spite of demonstrations of 4 GW/4 kJ pulses [4] and predictions of 70% efficiency [6], many issues remain concerning beam-plasma interaction, pulse shortening, mode competition, and scalability. Opportunities to try new approaches include coherently combining multiple (N) oscillators [7] to achieve N-squared scaling or using non-cylindrical configurations such as the relativistic recirculating planar magnetron [8] that have potential to push fundamental heat, current, or power density limits. Another grand challenge is to realize multi-frequency HPM sources. Stable multifrequency HPM oscillators are physically complex systems promising rich basic physics insights as well as practical value. Meanwhile, the science of multifrequency or arbitrary waveform amplification has been extensively studied in conventional, medium-power TWTs [9, 10] and klystrons [11] but a bold new frontier is to understand the scaling of these phenomena to relativistic HPM amplifiers. Realizing compact HPM amplifiers through direct emission gating [12] is a challenge worthy of investigation. A third research opportunity resides in the investigation of *time-domain* sources, where HPM radiation is emitted from single-shot (ultrawideband pulses) or periodic-pulse-trains of plasmas generated by ultra-short-pulsed lasers (femtosecs) rather than beam-excited, resonant electromagnetic (EM) circuits. [13, 14] Major questions include optimizing HPM output and the dynamics of these plasmas. Finally, there is both a need and an opportunity for research of higher power, compact (portable) sources of mm-wave and THz-regime radiation [1,5].

Pulsed Power

Recent advances in compact pulsed power include linear transformer drivers [15], folded Bluemleins [17], explosive drivers [18], and helical flux compression [19] have dramatically increased capabilities in peak and average power and portability. Future research opportunities should push boundaries of new materials or architectures that increase resistance to electrical stress fatigue or breakdown (in the lines or storage capacitors) and/or incorporate nonlinear components for direct DC to HPM conversion [16].

Cathodes

For electron-beam-driven HPM sources, the quality of the beam directly determines the quality of the interaction efficiency and the quality of the radiation output (spectrum, mode purity, etc). Consequently, advances in cathodes directly translate into improved HPM sources. Frontiers in cathode physics include understanding how interfaces, cathode morphology, bipolar flows and space charge effects determine emittance, brightness, and cathode lifetime, especially in cold (field emission) cathodes. A rich new field for HPM science is the study of nanoscale charge transport [20]. Meanwhile, an entirely new frontier of *materials by design* has emerged for cathode physics, in which *ab initio* and *high-throughput* computing techniques allow discovery of new materials with low work function, chemical stability or other optimized properties. [21]. These topics are still in their infancy.

HPM-breakdown and HPM-plasma interactions

Understanding and controlling interactions between localized, dense plasmas and strong EM fields is important for plasma heating, plasma chemistry, materials processing, advanced active radar systems, atmospheric and ionospheric modification, highly-charged ion sources, DNP-NMR spectroscopy, and remote detection of concealed radioactive materials [22-26]. Multipactor avalanche breakdown of conducting and dielectric surfaces by HPM fields [27-30] is important for many devices, and the problem is yet to be fully solved. Localized multipactor heating of surfaces can lead to gas desorption, leading to a transition to a localized plasma discharge [31]. Aspects needing further research include detailed, energy-dependent electron-neutral collision kinetics, gas chemistry, non-flat surfaces and magnetic fields. Another promising research topic is localized volumetric breakdown by intense, focused mm-wave and THz-regime beams [32-35]. Understanding and controlling surface breakdown of both distributed and spatially-periodic discharges would enable longer HPM pulses [3], HPM electronic attack counter-measures and novel active reflect-array and radiation optics. Meanwhile, traditional studies of HPM interactions with gases and surfaces have largely overlooked the physics of vacuum ultraviolet (VUV) radiation in the breakdown plasma formation [36]. New predictive models, validated by new experiments and able to explain recent experiments [37] are needed.

Advanced materials

As with any extreme-environment science, including fusion, high energy physics, and high energy density plasma science, new materials are both *the* critical enabler and an exciting research frontier for advances in HPM science. The opportunities here are greater than ever, due to advances in predictive computational algorithms, hardware, and physical models. Examples include new electromagnetic materials (especially plasmonic and metamaterials), new extreme-energy-tolerant refractory materials (for low-outgassing anodes) and, as discussed above, new cathode materials (thermionic, photo- and field emission).

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Figures (maximum 1 page)

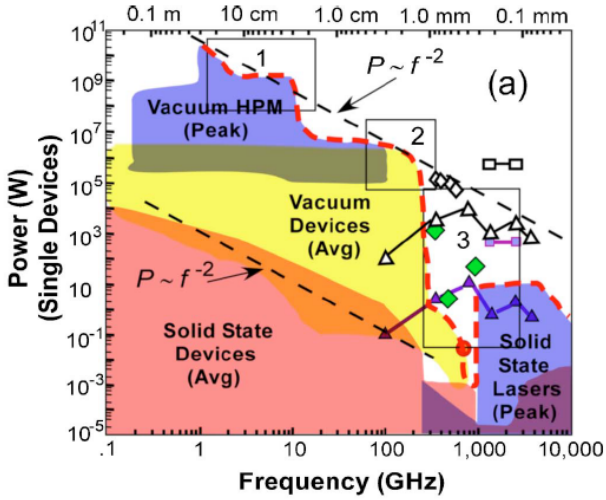

Fig. 1. Power vs frequency of solid state and vacuum electronic devices. The dashed red thick line is the maximum power research frontier. The filled diamond data points represent THz regime average power gyrotron oscillator operation, the filled square data points represent the Novosibirsk FEL average power achievements, the filled triangle data points represent the Jefferson Lab FEL average power results, and the filled circle data point represents a regenerative traveling wave tube oscillator. The open diamond data points represent THz regime gyrotron peak powers, the open square data points are peak powers from the Novosibirsk FEL, and the open triangles are peak powers from the Jefferson Lab FEL. From Ref. [1].

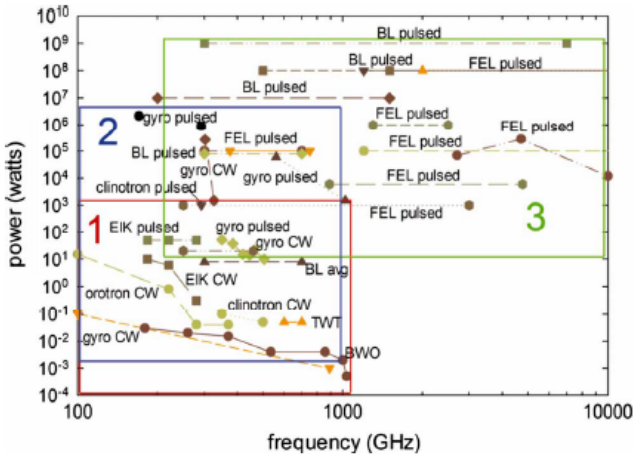

Fig. 2. Achievements in power versus frequency for THz and near-THz vacuum electronic sources. The sources include three cateogories: (1) compact sources with high mobility; (2) compact gyrotrons with moderate mobility; and (3) stationary accelerator-based sources. Specific source types include: BWOs, clinotrons, orotrons, TWTs, EIKs, gyrotrons (gyro), FELs, and BL sources using coherent transition or synchrotron radiation. From Ref. [5].