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Innovative Thermal Plasma Generation and Its System for Materials Processing

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Thermal plasmas, with their inherently high energy density and chemical reactivity, have long been recognized as powerful tools in materials science. Their capability to generate temperatures exceeding several thousand kelvin enables not only physical transformations (melting, evaporation, dissociation) but also a wide range of chemical reactions that are difficult to realize in conventional thermal systems. This makes thermal plasmas promising platforms for nanoparticle synthesis, functional coating, waste decomposition, and porous material generation.

Despite these advantages, practical deployment of thermal plasma processes often faces challenges related to arc instability, nonuniformity, and limited control over the reaction environment. To address these issues, our research group has developed a novel thermal plasma system based on an alternating current (AC) multi-electrode arc configuration. The system incorporates diode rectification to selectively control current directionality and arc attachment, thus enhancing the discharge stability and expanding the controllable parameter space.

This system allows for a wide range of gas atmospheres (Ar, N_2, air, or mixtures) and feedstock materials (metal powders, precursors, organics), enabling diverse process applications. One of the key advantages of this design is its suitability for continuous, large-volume operation with dynamic plasma structure modulation.

To gain detailed insight into the arc behavior and energy distribution, we have integrated high-speed imaging and two-color pyrometry into the system. This enables the real-time acquisition of spatially and temporally resolved temperature fields at sub-millisecond scales. Beyond simple temperature profiling, we apply statistical analysis to these temperature maps, calculating local mean, variance, skewness, and kurtosis—so-called "meta-distribution" descriptors. These allow us to characterize the nature of arc fluctuations, thermal gradients, and localized energy spikes that may influence reaction kinetics.

We demonstrate that modulation of arc behavior—either via current waveform shaping or gas flow perturbation—can directly influence the nucleation and growth of nanoparticles synthesized downstream. For example, in-flight treatment of metal powders under different arc fluctuation modes results in significant variation in particle size distribution and morphology, as confirmed by SEM and TEM analyses.

A comprehensive schematic of the system architecture, diagnostic methods, and representative product morphologies is shown in Figure 1. This figure also illustrates how spatial diagnostics are linked to process control and final material properties. The integration of innovative arc control, quantitative diagnostics, and statistical interpretation represents a powerful strategy for advancing thermal plasma technologies toward scalable and controllable materials processing.

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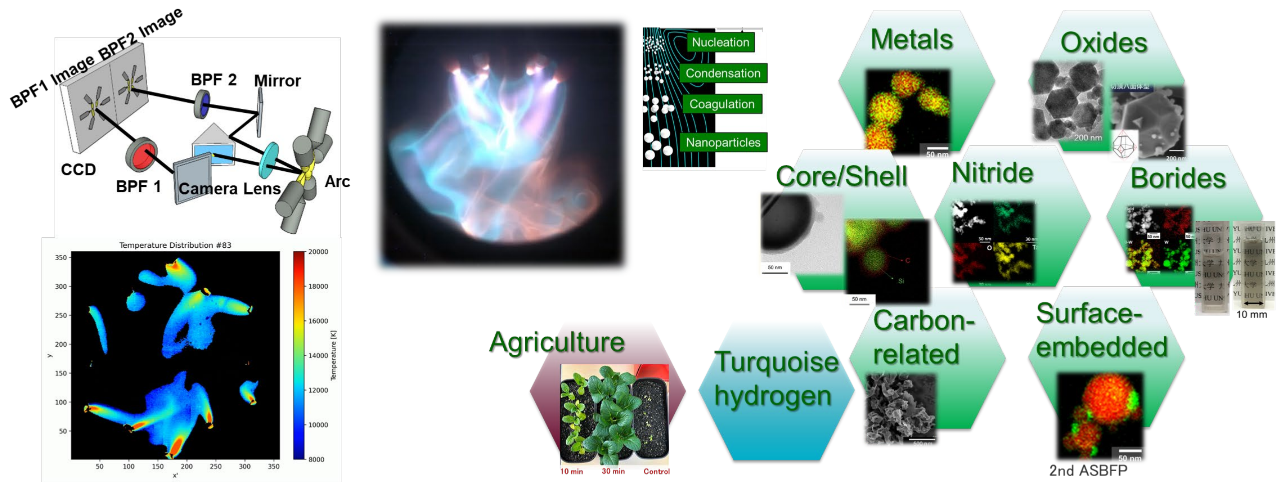

Figure 1 Schematic of innovative thermal plasma system, diagnostics, and nanomaterial products