Back to the Future: How a plasma mode might change the electric power grid

White Paper for *Frontiers of Plasma Science Panel*

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

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	
Will not attend	X

Title:	Back to the Future: How a plasma mode might change the electric power grid
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The research frontier and importance of the scientific challenge

We have observed an unusual operating mode of a magnetized, cold-cathode electric discharge plasma. At the macroscopic level, the voltage between the electrodes in this mode is very low by the standards of cold-cathode plasmas, and sputtering is below the detection limit of our emission spectroscopy diagnostic method [Smi]. At the microscopic level we find that the plasma visually organizes itself into a small bright spot on the cathode surface that moves in a circular motion at high speed along a path that is defined by magnets that are embedded in the cathode.

We do not yet have a defensible picture of the mode, but there have been several persistent themes in the attempt to develop one, that give some indication of the scientific challenge. One theme is that the plasma in the bright spot is close to full ionization, with thermal equilibrium between the electrons, ions, and residual gas atoms. Another theme is that there is a dynamic balance of neutral gas atoms between the spot and it surrounding plasma, which is thought to be a more conventional, weakly ionized plasma. We try to not invoke new or exotic mechanisms, so we continue to assume that the dominant ionization process is electron-impact ionization of the helium fill-gas atoms, that the resulting ions are singly-charged, and that the plasma is sustained by the traditional secondary emission mechanism, where

electrons are released from the cathode in response to incident ions. However, the conditions are sufficiently extreme that field emission may contribute, and any of these assumptions could easily be shown to be completely wrong, in the end.

The approach to advancing the frontier, and new research tools or capabilities that are required

The small size, detailed structure, and rapid movement of the plasma in this operating mode are severe challenges for any experimental, theoretical, or computational investigation. We expect that a simple semi-quantitative physical picture will emerge at some point, but that it should be supported with measurements and models that can quantify key species densities and temperatures in a system that is in a dynamic steady-state (if not fully time-dependent) and at least 2.5-dimensional.

It is difficult to determine at this time whether this operating mode has been reported previously. Operating modes with low voltage, sometimes in combination with low sputtering, have been reported [Moz,Kou]. However, we have found that there are a number of low-voltage operating modes that are not easily distinguished by voltage alone, and that it can be challenging to categorize them in the absence of high-speed movies, which are not reported in the prior art. Beyond these references there is a vast literature on cold cathode plasmas and on plasma devices to control electric power, which may shed light on the mode (eg, [Hull]).

Impact of this research on plasma science and related disciplines, and potential for societal benefit

The plasma properties described here were found as part of a Project to develop high-voltage, high-power plasma switches for use in high-voltage direct-current (HVDC) power conversion terminals on the electric power grid [ARPA-e]. Present HVDC terminals are based on thyristors and related power semiconductor devices; they work well but are expensive in part because of the complexity of using strings of relatively low-voltage switches to control power at high voltage.

The hypothesis of the Project is that a power conversion terminal based on fewer, high-voltage plasma switches can be much simpler and less expensive, and more detailed system analysis has borne out this early estimate. The cost of grid-scale power conversion directly impacts the economics of long-distance transfer of power from distant renewable resources (solar, hydro), installations where power is transmitted through cables (offshore wind), and places where power must flow between unsynchronized alternating-current grids. Looking forward, plasma switches might be an enabling technology for a true DC grid, and improve grid resilience because they are robust to certain system upsets and support black-restart capability after widespread power outages.

There is some relation between this work and efforts to develop a new generation of material deposition technology known as high-power impulse magnetron sputtering (HiPIMS) systems [Gud]. The arrangement of the cathode and magnetic fields is similar in the two systems, but the operating conditions are quite different, because our goal is to minimize sputtering, while the goal of HiPIMS is to maximize sputtering and material deposition rate. Both our system and HiPIMS show plasma rotation.

Finally, a key technical challenge for high-power plasma switches is the intense heat load (10^2–10^3 W/cm^2) on the cathode in any practical device, even in this beneficial low-voltage mode. So there is another key project hypothesis, that the cathode can be operated in the liquid state, such that it can self-heal from certain kinds of damage, and can be actively pumped and regenerated [Som]. There is accordingly a strong overlap between the implementation of a liquid cathode, the use of low-volatility liquid metal bearings in the sealed vacuum environment of a medical x-ray tube [Sch], and the development of liquid metal divertors in tokamaks [Jaw].

Acknowledgements

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References

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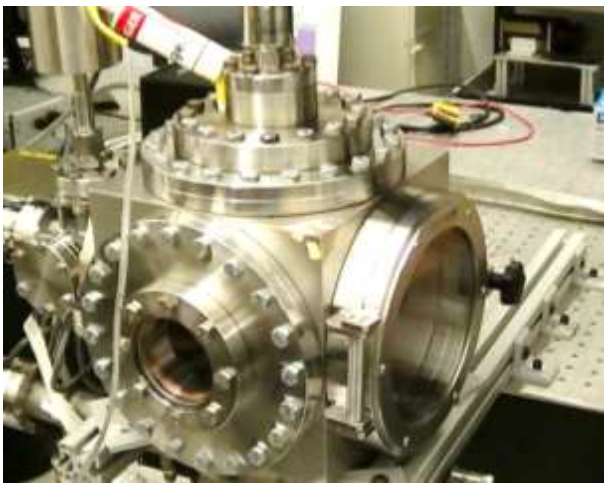
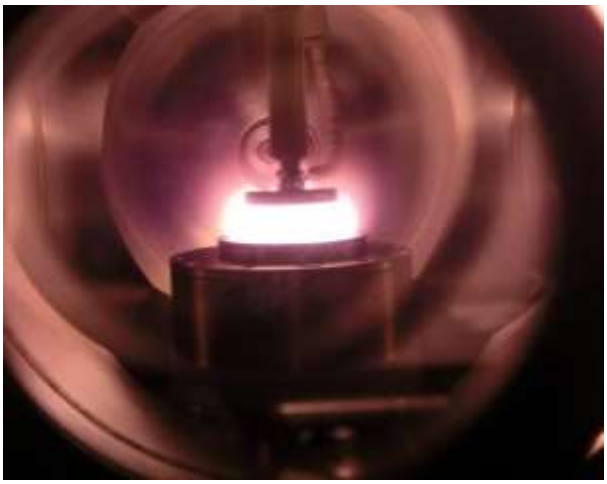
Figures



Benchtop cathode development system



Open-shutter photograph of the plasma in the Benchtop cathode development system

High-voltage Switch and Control Electronics

High-voltage Switch testing
The Switch is shown in the white circle