White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***July 29, 2015***

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	
• Turbulence and transport	S
• 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	
Either Oral or Poster	X
Will not attend	

Title:	*Cathode Research Areas for Beam, HPM, and other High Power Applications*
Corresponding Author:	Martin Gundersen
• Institution:	University of Southern California
• email:	mag@usc.edu
Co-Authors:	Andras Kuthi, and Rehan Kapadia

**(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.*)**

- ***Describe the research frontier* and importance of the scientific challenge.**

Cathodes–Enabling Very High, Robust Electron Emission and Electron Beam Production: Here are summarized several areas where further research has strong potential for productive device development and dramatic improvement in cathode performance will be enabling for new technologies in energy, research and defense. The areas for cathode improvement described here include controllable field emitter arrays and plasma-based concepts.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Controllable Field Emitter Arrays: Controllable field emission electron emitting arrays hold promise for use in high current density electron beam devices as replacement for power consuming thermionic emitters. Large field-emitter arrays, however, are limited in total current due to non-uniformity and resulting instability problems. As a solution to these problems current-limiting devices, such as a vertical junction field effect transistor (VJFET) for each Carbon Nanotube (CNT) emitter site have shown the

feasibility of this approach, including the demonstration of significant total currents from uncontrolled emitters, and development of a fabrication scheme extendable to arrays of 1 cm^2 area for an expected total controlled current of 1 A. It would be particularly of interest to renew these efforts and expand current densities to in excess of $1A/cm^2$. Although substantial initial studies have been conducted, in the spirit of a white paper most details are suppressed. Process development for this final p-type VJFET array structure is illustrated in Figure 1. An array of vertically aligned CNTs is shown in Figure 2.

Plasma-Based Sources: Hollow Cathode-Based Beam sources, currently under investigation by Prof. Phelps at Strathclyde, have been found to produce high current, high brightness, low emittance beams, up to current densities of the order of $\approx 1kA/cm^2$. It is of considerable potential usefulness to both investigate extraction of these high brightness beams from their sources, and to investigate their usefulness in space-cahrge compensated plasma environments.

An optically-gated version of such a device is shown in **Figure 3** in a simple but effective form. The high voltage is applied across the two Mo electrodes. Higher voltage versions of these devices have been fabricated at USC and in Europe at the U. Erlangen with multiple electrodes. A partial list of related publications is also included. These sources have been developed and have been produced commercially both as beam and as high power thyratron-type switches (pseudosparks and Back-Lighted Thyratrons (BLT)), developed under AFOSR and DOE support.

One source of beam electrons is indicated in a simulation due to Pitchford et.al., shown in **Figure 4**. Shown is the formation of plasma as the device is switched. In the lower part of the figure it is clear that in the cathode region (lower left of figure) a high electric field occurs during the transient plasma formation. This field is sufficiently high to extract electrons from the back surface of the cathode, resulting in a beam of electrons for a period of some nanoseconds. The current drawn has been seen in some devices in excess of $100A/cm^2$, and up to $\approx 1kA/cm^2$ with very good emittance properties.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

Successful development of high current cathodes, such as field emission arrays or plasma-based cathodes, will have many applications for instant-on high power microwave tubes, accelerators for varying applications, medical imaging systems, x-ray sources and ionization and neutralization beam sources for spacecraft propulsion.

We believe that there are ample possibilities for a range of different investigating teams to carry this work through and produce a real breakout in high current emission cathodes for applications such as HPM, accelerators and beam devices. The white paper is meant to indicate that there is ample work for many researchers at different institutions, and that success will lead to enabling technology. The main points are that 1) Cathodes (and related beams) are poised as an enabling technology for devices ranging from HPM to accelerators based on plasma concepts, and that 2) good research directions exist, including addressable, and hence uniform cathode emission, as well as very high current cathodes, and these will have significant impact.

References (Maximum 1 page)

These references are to work primarily at USC, and do not include, in the spirit of a white paper, considerable work at other institutions and by other researchers. The list is meant to provide supporting information for the preparation leading to these proposed ideas, which envision work by multiple researchers.

1. H. R. Bauer and M. A. Gundersen, "Penetration and equilibration of injected electrons into a high-current hydrogen pseudospark-type plasma," J. Appl. Phys. **68** (2), 512 (1990).
2. T-Y. Hsu and M. A. Gundersen, "A high-power electron beam source based on the superemissive cathode," Appl. Phys. Lett. **61** (21), 2515 (1992).
3. R-L. Liou, T-Y. Hsu, and M. A. Gundersen, "Long pulse electron beam generation from the back-lighted thyratron," Appl. Phys. Lett. **61** (22), 2647 (1992).
4. R. Liou, H. Figueroa, A. H. McCurdy, G. Kirkman-Amemiya, R. J. Temkin, H. Fetterman and M. A. Gundersen, "Emission of microwave and millimeter wavelength radiation during hollow cathode discharge operation of the back lighted thyratron," Appl. Phys. Lett. **61** (23), 2779 (1992).
5. A. Anders, S. Anders and M. A. Gundersen, "Model for explosive electron emission in a pseudospark "superdense glow", Phys. Rev. Lett. **71** (3), 364 (1993).
6. L. C. Pitchford, N. Ouadoudi, J. P. Boeuf, M. Legentil, V. Puech, C. Thomaz, and M. A. Gundersen, "Triggered breakdown in low pressure hollow cathode (pseudospark) discharges), J. Appl. Phys. **78** (1), 77 (1995).
7. K. Frank, J. Christiansen, T. Redel, R. Stark, M. Setter and M. A. Gundersen, "Acceleration of electrons to > 0.5 MeV during space-charge neutralization of a 20 keV transient electron beam," Appl. Phys. Lett. **68** (10), 1424 (1996).
8. C. Jiang, A. Kuthi, and M.A. Gundersen, "Toward ultracompact pseudospark switches," Applied Physics Letters 86, pp. 024105:1-3, 2005.
9. C. Jiang, W. Hartmann, A. Kuthi, and M.A. Gundersen "Pseudospark Electron Beam as an Excitation Source for EUV Generation," Appl. Phys. Lett., Vol. 87, pp. 131501:1-3, 2005.

Approximately 60-70 additional papers and presentations at conferences exist as well.

Figures (maximum 1 page)

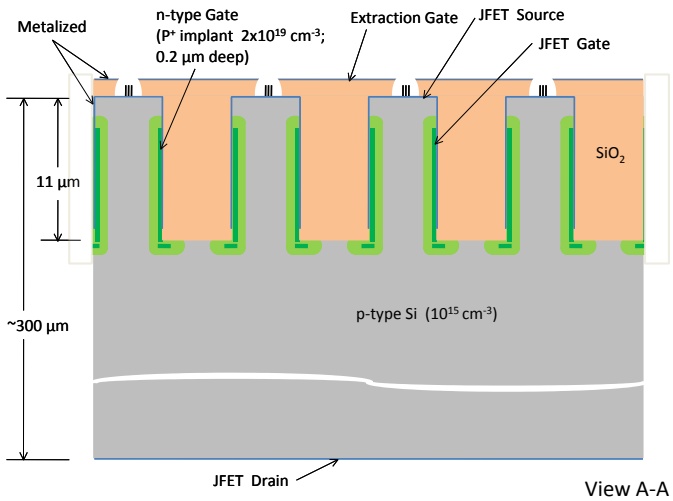

Figure 1: Cross section of SI-based JFET for control of CNT emission.

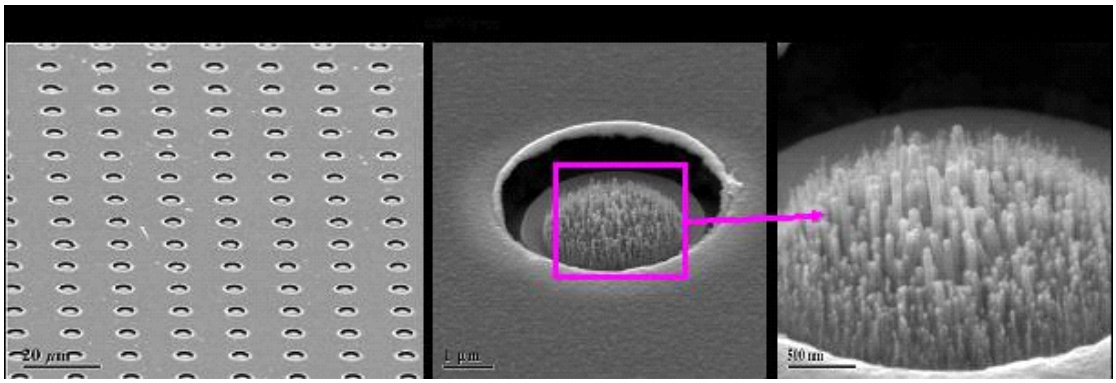

Figure 2: Array of vertical CNTs grown at USC for distributed, controllable cathode emission studies.

Figure 3: Glow discharge device for producing electron beams, example. Optically gated, beam current in excess of 100A/cm^2 in neutral density ≈10^{16}/cm^3, plasma density approx. 10^{14}/cm^3.

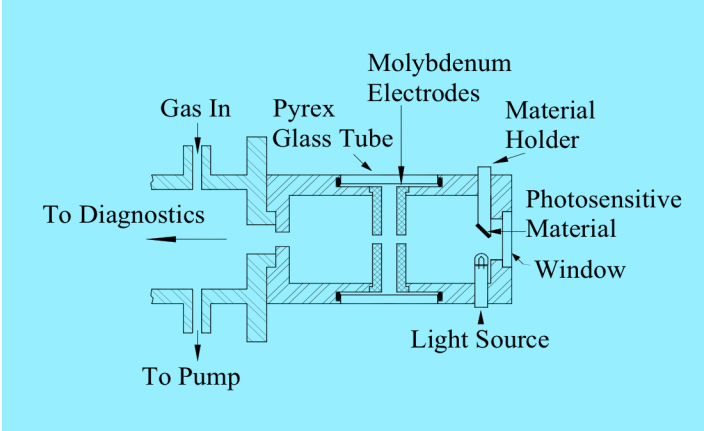
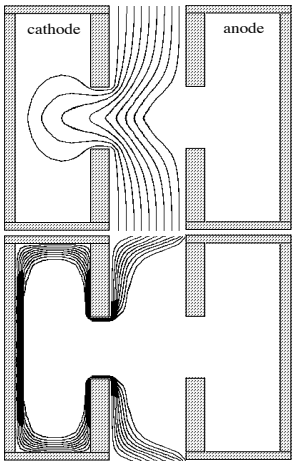
Figure 4: Formative phase of hollow cathode plasma.