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Plasma shield for in-air beam processes[a)]

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A novel concept/apparatus, the Plasma Shield, is introduced in this paper. The purpose of the Plasma Shield is designed to shield a target object chemically and thermally by engulfing an area subjected to beam treatment with inert plasma. The shield consists of a vortex-stabilized arc that is employed to shield beams and workpiece area of interaction from an atmospheric or liquid environment. A vortex-stabilized arc is established between a beam generating device (laser, ion or electron gun) and a target object. The arc, which is composed of a pure noble gas, engulfs the interaction region and shields it from any surrounding liquids like water or reactive gases. The vortex is composed of a sacrificial gas or liquid that swirls around and stabilizes the arc. The successful Plasma Shield was experimentally established and very high-quality electron beam welding with partial plasma shielding was performed. The principle of the operation and experimental results are discussed in the paper. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2837052]

I. INTRODUCTION

In current art, many industrial processes like ion material modification by ion implantation, dry etching, and microfabrication, as well as electron beam processing, like electron beam machining and electron beam melting is performed exclusively in vacuum, since electron guns, ion guns, their extractors, and accelerators must be kept at a reasonably high vacuum, since chemical interactions with atmospheric gases adversely affect numerous processes. Various processes involving electron, ion, and laser beams can, with the Plasma Shield, be performed in practically any environment. For example, electron beam and laser welding can be performed under water, as well as *in situ* repair of ship and nuclear reactor components. The Plasma Shield should result in both thermal (since the plasma is hotter than the environment) and chemical shielding. The latter feature brings about in-vacuum process purity out of vacuum, and the thermal shielding aspect should result in higher production rates.

As the name suggests, the Plasma Shield is designed to chemically and thermally shield a target object by engulfing an area subjected to beam treatment with inert plasma. The shield consists of a vortex-stabilized arc that is employed to shield beams and workpiece area of interaction from an atmospheric or liquid environment. A vortex-stabilized arc is established between a beam generating device (laser, ion or electron gun) and the target object. The arc, which is composed of a chemically inert gas (like a pure noble gas), engulfs the interaction region. This arc then shields the interaction region from any surrounding liquids like water or reactive gases. The vortex is composed of a sacrificial gas or liquid that swirls around and stabilizes the arc, which displaces the environmental fluid.

The Plasma Shield had its origin as an extension of the Plasma Window.[1,2] The latter has shown to be a rather effective interface between vacuum and atmosphere that facilitated unprecedented effective transmission of ion, electron, and x-ray beams from vacuum to atmosphere. However, once the beams exited to atmosphere and struck a target object, the process performed was subjected to adverse environmental effects. Electron beam welding performed (with a Plasma Window) in the atmosphere resulted in welds with visible oxidation, even though welds were performed at an unprecedented stand-off (and low power) with excellent penetration. To rectify this shortcoming, the Plasma Shield was developed. Recently partial plasma shielded electron beam welding experiments were performed resulting in the expected high quality in-air electron beam welding. The principle of operation and experimental results are described and discussed in this paper.

II. INITIAL CONSIDERATIONS AND OPERATION PRINCIPLES

It is relatively easy to surround an object with plasma by either injecting plasma from a plasma source to engulf the object, by biasing the object, and creating a discharge to its surrounding, or with an rf discharge. However, in order to generate an effective shield, the plasma must be dense and stable. The plasma must displace all the environmental fluid, requiring high pressure and density. Thus, arc discharges are needed for most foreseen applications, since they have the required density and pressure. The objective is to develop an arc that can be extended onto a target object and cover an area to be treated, while displacing the environmental fluid. Another crucial requirement is that the arc-generating device must have hollow geometry in order to facilitate unimpeded beam propagation.

Stabilizing arc plasmas can be accomplished by a variety of techniques:[3] wall stabilization,[4] transpiration cooling,[5] vortex stabilization,[6,7] electrode stabilization,[8] and magnetic stabilization. The first three stabilization techniques are based on cooling the outer boundary of a plasma column.

[a)]Paper TI2 3, Bull. Am. Phys. Soc. **52**, 275 (2007).
[b)]Invited speaker.

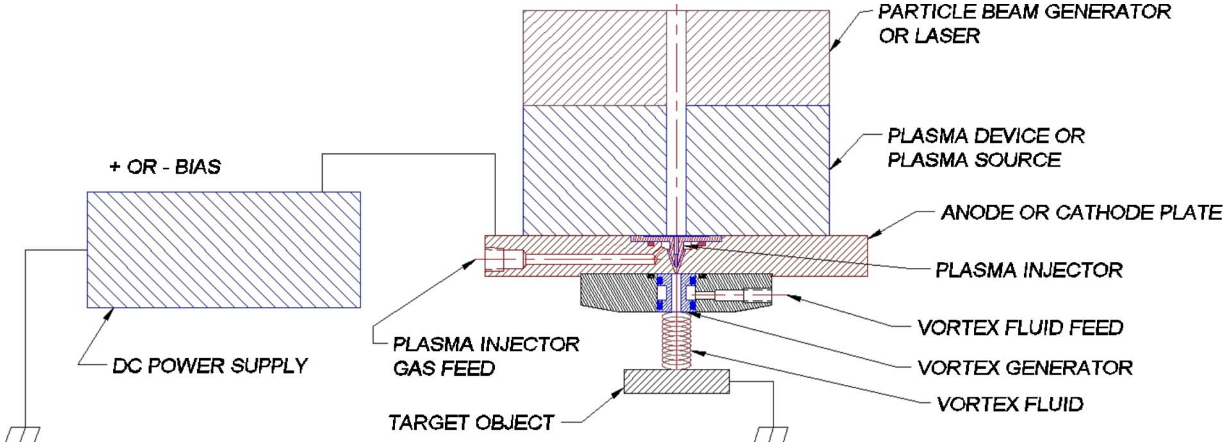


FIG. 1. (Color online) Schematic of the plasma shield concept.

Wall stabilized arc is an arc enclosed in a tube consisting of a stack insulated water-cooled conducting disk (usually made of copper). In transpiration-cooled arcs, the cooled wall is replaced by a transpiration-cooled constrictor. And in a vortex-stabilized arc, a whirling cold fluid cools the arc boundary. Any accidental outward excursion of an arc column results in an increase in radial heat loss. Consequently, the plasma temperature is reduced, and hence, the plasma conductivity in that location. Since electricity flows in the path of least resistance, the arc is forced to return to its equilibrium axial position.

Electrode stabilization and magnetic stabilization are not practical, since the first is restricted to extremely short (no longer than 1 mm) arcs, while the latter requires very large magnetic fields; magnetizing atmospheric pressure plasma involves magnetic fields that are in the order of 20 Tesla. For completeness sake it should be mentioned that free burning, self-stabilized arcs are also impractical due to their high intensity (will damage the workpiece). Wall and transpiration cooling stabilized arcs are also not good plasma shield candidates, because the arcs must be surrounded by a solid object (wall or constrictor). Thus, the best candidate seems to be a vortex-stabilized arc.

Literature search of vortex-stabilized arcs revealed that previously vortex-stabilized arcs were confined in a solid chamber. In all these arcs, the vortex generating fluid is injected tangentially to generate a vortex, whose centrifugal force drives the cold fluid against the chamber wall. An axially stable arc can then be established. These arcs operated with water[6,7,9] or gas[10] vortices.

However, as our Plasma Shield concept is illustrated in Fig. 1, none of these arcs satisfy the requisite free-standing plasma (without surrounding walls). Thus, a crucial objective of this work is to develop free-standing (not enclosed in a chamber or surrounded by any walls) stable arcs in atmosphere or in water between a beam generator and a target object (to be treated by the beam). Once a stable vortex is established, an arc can then be struck to target abject. Additionally, the length of the free-standing arc should be maximized for cases where beam treatment must be performed in crevices. Thus, it is important to maximize vortex length. Literature search and consulting with one of the pioneers in the field of vortex stabilized arcs,[11] failed to reveal any previous research and/or scaling that could help in fluid injector design that could have helped in vortex generator design.

In the absence of either prior experimental or theoretical data, the adapted approach to generating a free-standing vortex stabilized arc was by trial and error. Hence, the first experiments were performed with configurations described in the patent application[12] for this technology (since then, the patent was granted). Though very recent and subsequent to experimental results presented in the next section, a very crude simulation[13] (using Fluent software) of a water swirl (generated in a 4 cm long, 1 cm radius cylindrical tube with a 150 l/min water flow at an angular velocity of 30 rad/s) showed that a 4 cm long free-standing water vortex could be generated.

III. EXPERIMENTAL RESULTS

To proceed experimentally, one of the embodiments described in the patent[12] covering this technology, as shown in Fig. 1 was fabricated and experimented. Components were designed and fabricated to generate a free-standing arc stabilized by a gas vortex. Figure 2 shows the top view of the vortex generator. Though a Plasma Window is not necessary to generate a Plasma Shield, a Plasma Window was used as a plasma source. Basically, a vortex generator was mounted on

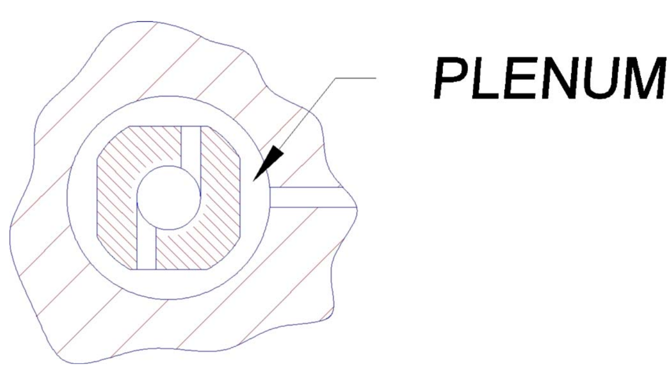
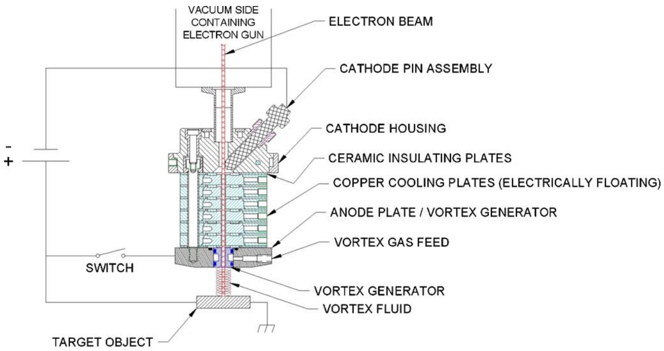
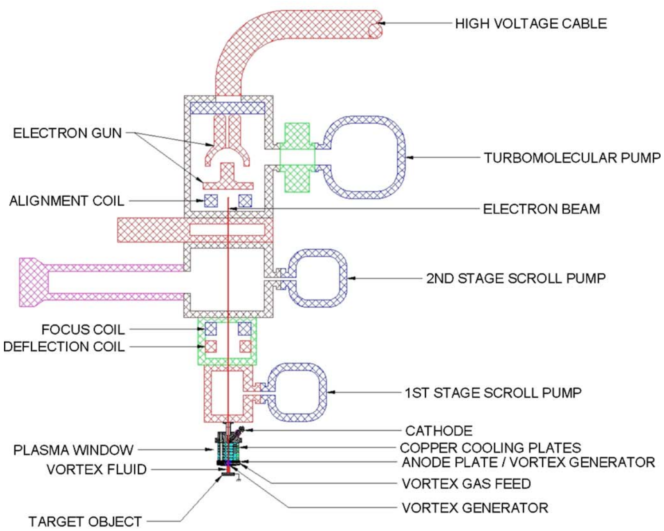


FIG. 2. (Color online) Top view of the vortex generator sketch.



(a)



(b)

FIG. 3. (Color online) Diagrams of the experimental setup (not to scale). (a) Cascade arc that serves as a Plasma Window is the plasma source. Switch is used to electrically float the vortex generator. (b) Electron beam welder with the Plasma Window and vortex generator as used during welding experiments.

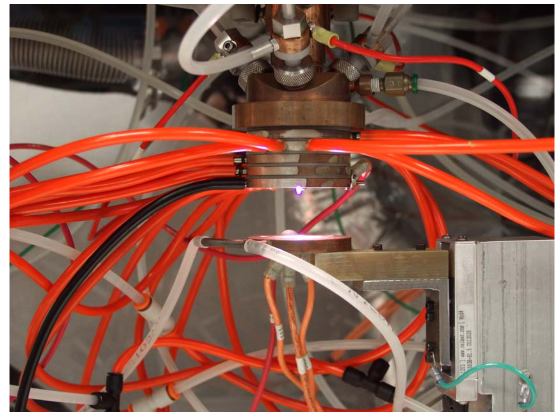


FIG. 4. (Color online) Photo of the Plasma Window and vortex generator (inside the bottom plate) forming a Plasma Shield generator with a plasma plume protruding out (courtesy of Acceleron Inc.).

a Plasma Window, which was to be mounted on an electron beam welding column. The Plasma Window (whose description can be found in Refs. 1 and 2) function was to separate the electron gun vacuum from the atmosphere where the target object is located as well to be a plasma source. As it can be seen in Fig. 1, the plasma generator was followed by a venturi-shaped plasma injector, whose purpose was to "suck" plasma from the plasma generator through the vortex generator and onto a target object.

Diagrams of the vortex generator are displayed in Fig. 2, which was made of two sections: a plate, i.e., the main body surrounding a tube for gas feed, a plenum, and an insert containing two tangential injection slits. The inner (beam) channel diameter is 2.49 mm, and plenum length (along the beam direction) is 4.6 mm, which is also the maximum slit size. Slots with downward tilt seem ideal for vortex-generating tangential injectors. However, due to a manufacturing limitation, two rows of 4 holes of 0.8 mm diameter each were used for tangential injection instead of slots.

Numerous attempts were made to initiate arc discharge in the plasma generator (plasma window) of the Fig. 3(a) configuration, extend the arc through the plasma injector and the vortex generator onto a target object in atmosphere. All attempts failed; the arc could not be extended beyond the plasma injector. Therefore, the plasma injector was eliminated.

In this modified configuration after firing the plasma window arc and optimizing gas pressure input for the vortex generator, a plasma plume extended into the atmosphere as it can be seen in Fig. 4. The working gas was argon; arc current was 45 A, arc voltage was 85 V. The white bright portion of the plume was 6 mm long. This mode of operation was accompanied by a strong ozone smell. Attempts to extend the discharge onto a target object located at a distance of 1 cm failed. This mode, with a plasma plume, shall be referred to as a partial shield.

After some trial and error a technique was developed for discharge extension onto a target object. After a discharge is established as shown in Fig. 4, a water-cooled target object, with bias identical to the vortex generator, is brought within 1–2 mm of the vortex generator. Like the previously described plasma window operation, arc current and voltage were 45 A and 85 V, respectively. A switch is opened to electrically float the vortex generator, which in this case served as an anode. Now the target object becomes the anode with a free-standing discharge. It is important to note that in the case of a stationary target, the target must be cooled to prevent its melting and/or uncontrolled arcing. Next the target is pulled away to extend the free-standing discharge as shown in Fig. 5, which was taken through very dark welding glass, since the free-standing arc was extremely bright. A maximum length of 2.5 cm was obtained for the free-standing extended arc. Arc current was maintained at a constant 45 A; the arc voltage increased roughly linearly with length of the free-standing discharge up to 195 V at the maximum length. The resultant discharge is a cathode-to-target-arc, where the cathode to vortex generator portion is a 3.9 cm long wall stabilized cascade arc, and the vortex generator to target portion is a 2.5 cm long free-standing vortex stabilized arc. From the voltage characteristics (85 V across 3.9 cm vs 110 V across 2.5 cm), it is obvious that the two portions of the arc have different characteristics, suggesting the atmospheric portion to be denser and/or cooler and/or

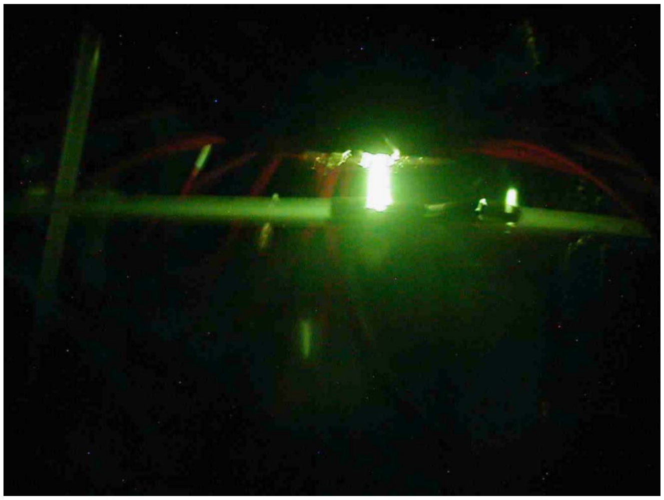


FIG. 5. (Color online) Photo of a free-standing arc between the Plasma Shield generator and a water-cooled copper plate. Photo taken through a welding mask (courtesy of Acceleron Inc.).

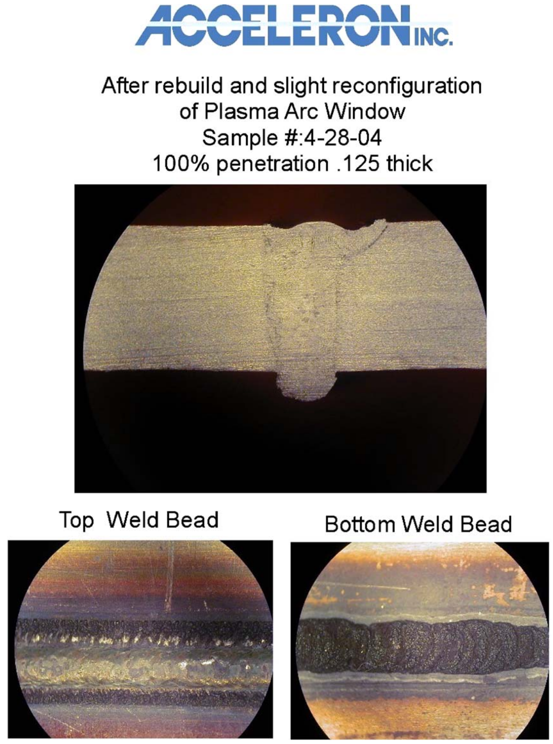


FIG. 6. (Color online) Pictures of an unshielded nonvacuum electron beam weld. Dark colors on the beads (lower photos) indicate oxidation. Top photo shows the weld cross section.

having a lower ionization fraction. This mode, with an arc extended to the target, shall be referred to as Plasma Shield.

With an extended free-standing arc, the ozone smell was practically gone. Measurements with an ozone meter were performed for the two operating modes partial shield and Plasma Shield. All measurements indicated that the ozone level is deceased in the case of Plasma Shield operation. Since the experiments were carried out in a large industrial setting with varying ventilation, measurements were not reproducible on a daily basis; hence no quantitative numbers will be presented. Ozone generation is due to exposure of atmospheric oxygen to electrical discharge. Decrease in ozone level implies that the plasma discharge is shielded from atmospheric oxygen. Therefore, the observed qualitative decrease in ozone level strongly suggests that a swirl of unionized argon surrounds the free-standing arc in the case Plasma Shield operation; a fact consistent with the free-standing arc stability.

Finally, the Fig. 3(a) apparatus, with the anode containing the built in vortex generator, was mounted on an electron beam (EB) welder [Fig. 3(b)]. Since no provisions were made to allow the welding table to function as the experimental target object, only partial shielding was utilized during welding. For clarification (again), partial shielding is provided by plasma that extends beyond the anode into air due to the low pressure generated by the vortex (the plasma plume partially displaces atmospheric gases). Full shielding occurs when vortex stabilized plasma is projected (driven by voltage) from the plasma window anode to target object. With this setup, welding experiments with partial shielding were performed, and compared to previous nonvacuum electron beam welding with a Plasma Window. Figure 6 shows the previously obtained welding result.[14,15] The dark color of the weld beads indicates oxidation. In Fig. 7, a weld with partial shield is shown. Welding electron beam energy and current were 150 keV and 20 mA, respectively. Though the Fig. 6 nonvacuum welds are considered of good quality[16] (except for the oxidation), the Fig. 7 results are indicative of cleaner welds. Quantitatively, this observation is confirmed by weld analysis.[17]

Additional significant results were obtained in this setup compared to pure plasma window operation:

(1) Welding with pure argon operation was achieved, i.e., welding at even lower plasma window power is possible.
(2) Superior electron beam propagation was observed: propagation in atmosphere, for about 7.5 cm, was ob-

FIG. 7. (Color online) Photo of a partially shielded nonvacuum electron beam weld, which indicates plasma shielding effectiveness (courtesy of Acceleron Inc.).

served with the arc operating in pure argon (compared to 1.5 cm with plasma window only and some helium).

(3) Upstream pressure was lower by a significant factor (of about 2). It means that addition of the plasma shield to the plasma window greatly improved vacuum separation.

IV. DISCUSSION

Results presented in the experimental section of this paper do suggest that plasma shielding may accomplish the expectations set forth in the Introduction. Stable free-standing arcs between a Plasma Window and a target object were established. Nonvacuum electron beam welding, performed with partial plasma shielding (with argon plasma plume) covering welded workpieces, produced much cleaner welds. Unlike previous attempts[14] to displace atmospherics gases by using a venturi with a Plasma Window, which failed due to blowing-off the molten pool, vortex flow had no adverse affect on the welding process. The most likely reason is the fact that the vortex generated a lower pressure region, which is filled by plasma from the cascade arc without causing violent flow.

Comparison of nonvacuum welds, without any shielding (Fig. 6, where oxidation is obvious) and nonvacuum welds with partial shielding (Fig. 7, that shows a rather clean weld), are indicative that considerable shielding was accomplished. Although a water vortex simulation predicts that a stable few cm long vortex can be established is encouraging, it should be regarded as very preliminary work. Superior electron beam propagation in atmosphere and greatly improved Plasma Window vacuum separation with partial plasma shielding, is, at least in part, most likely due to heating and rarifying of the atmosphere. With full shielding electron beam propagation in atmosphere (through the free-standing arc) should be as good as through the plasma window due to the strong focusing effect of the arc current.[1,2,14] In these papers, it was shown that plasma current generates an azimuthal magnetic field which exerts a radial inward Lorentz force on beam electrons, which overcompensates for scattering by gas atoms and ions.

Future plans are to perform electron beam welding with full plasma shielding in-air and underwater.

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[1] A. Hershcovitch, J. Appl. Phys. **78**, 5283 (1995).
[2] A. Hershcovitch, Phys. Plasmas **5**, 2130 (1998).
[3] E. Pfender, *Gaseous Electronics*, edited by M. N. Hirsh and H. J. Oskam (Academic, New York, 1978), Vol. 1, Chap. 5.
[4] H. Maecker, Z. Naturforsch. A **11a**, 457 (1956).
[5] E. Pfender, G. Gruber, and E. Eckert, "Experimental investigation of transpiration-cooled constricted arc," in *Proceedings of the International Symposium on High Temperature Technology I.U.P.A.C.* (Butterworth, Washington, D.C., 1969), p. 3.
[6] O. Schoenherr, Z. Elektrochem. Angew. Phys. Chem. **30**, 365 (1909).
[7] H. Gerdien and A. Lotz, Wiss Veröff. Siemens-Konz **2**, 489 (1922).
[8] G. Ecker, Ergeb. Exakten Naturwiss. **33**, 1 (1961); S. I. Braginskii, *Reviews of Plasma Physics* (Consultants Bureau, New York, 1965), Vol. 1, pp. 205–311.
[9] E. Pfender, "Generation of an almost fully ionized, spectrally clean, high density hydrogen plasma," in *Proceedings of the International Conference on Ionization of Phenomenological Gases*, 6th ed., Paris, France (North-Holland, Amsterdam, 1964), Vol. 34, p. 369.
[10] R. Krichel, S. Druxes, and G. Schmitz, Z. Phys. **217**, 336 (1968).
[11] E. Pfender, private communication (2004).
[12] A. Hershcovitch and R. Montano, "Shielded beam delivery apparatus and method," U.S. Patent No. 7,075,030 issued on 11 July 2006.
[13] E. Foroozmehr and A. Dimitrovska, "Modeling of vortex column used in shielding of plasma beam" final project in Computational Fluid Dynamics course, taught by B. Anthohe in the Department of Mechanical Engineering, Southern Methodist University, 2007 (unpublished); R. Kovacevic, private communication (2007).
[14] A. Hershcovitch and the Acceleron Team, Phys. Plasmas **12**, 057102 (2005).
[15] A. Hershcovitch, Nucl. Instrum. Methods Phys. Res. B **241**, 854 (2005).
[16] http://www.acceleron-enbeam.com/plasmawindow/plasmawindow.htm#; where results of independent evaluation are posted by Acceleron Inc., 21 Lordship Rd., E. Granby, CT 06026.
[17] Report No. 06-15743 of Quali-Tech, Inc. to Acceleron Inc., 28 February 2006 in NICE[3] Acceleron final project report (unpublished); archived at the Brookhaven National Lab Office of Intellectual Property, M. Fury, private communication (2007).