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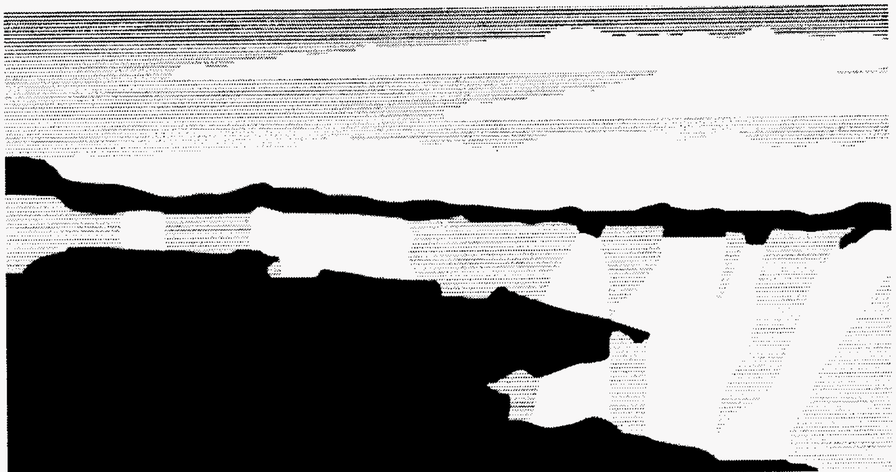

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Industrial Process Driven System Requirements for PSII Applications

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Introduction

Plasma Source Ion Implantation (PSII) is a room temperature, plasma-based surface enhancement technology which is being commercialized through the efforts of a group of companies including General Motors, Asea Brown Boveri, Litton Electron Devices, Nano Instruments, Diversified Technologies, Ionex, PVI, Empire Hard Chrome, A.O. Smith, Harley-Davidson, Kwikset, Boeing, DuPont, and NorthStar Research, as well as Los Alamos National Laboratory and the University of Wisconsin, Madison. PSII makes use of the characteristics of ionized gas (a plasma - typically generated from N_2, NH_3, or carbon containing gases such as CH_4 or C_2H_2) surrounding a target or target assembly and high negative voltage, high current pulses, to accelerate ions into the target surface from essentially all directions, creating beneficial modifications (hardening, reduced coefficient of friction, enhanced resistance to corrosion, etc.) in the target surface. /1,2,3,4,5, 6,7,8,9,10/ Beneficial surface modifications achieved can include increases in surface hardness and consequent wear life, improved corrosion resistance, and decreases in the surface coefficient of friction, and are similar to those obtained through conventional ion beam implantation /11,12/. The process, however, differs from conventional ion beam implantation in several important aspects (see Figure 1). Since the ions are being accelerated into the target by mechanisms within the plasma, which surrounds the target, the process is not "line-of-sight" - i.e. requiring an unobstructed path from a single ion source to the surface being treated. This allows the relatively easy treatment of multiple surfaces of a single target or simultaneous treatment of multiple targets, without the need for in-vacuum manipulation of the target assembly as would be required with conventional ion beam implantation. In addition, the average ion current to the target surface can be much larger (by an order of magnitude or more) that that typically utilized in conventional ion beam implantation (typically much less than one amp) /13,14,15/, significantly reducing the required treatment time for large, complex target assemblies. This is possible because all target surfaces (up to many square meters area) are being treated simultaneously with a high pulsed-current source, which also minimizes local surface heating effects.

A number of issues are critical to the successful design and operation of a commercial PSII system. These include overall vacuum system design, plasma source requirements and plasma-target interaction considerations, pulsed, high voltage sub-system (typically referred to as modulator) requirements, and target requirements and limitations. Critical system components are outlined in Figure 2, and overall system design issues will be briefly covered in the following sections of this paper.

Vacuum System Requirements

Neutral gas working pressures for the PSII process are typically in the 0.2 to 1.0 milli-Torr range, with plasma densities in the mid 10^8 to mid 10^9 /cm^3 range, so that system pumping requirements driven directly by the implantation process are relatively minor. The basic pumping requirements are determined by the need to keep the overall plasma and neutral impurity concentrations relatively low (no more than a few percent of impurities in both the neutral gas and plasma ion concentrations). Impurities in the system can be generated by vacuum system leaks, outgassing from the chamber walls or from the implantation target, by sputtering of surface contaminants from the implantation target, or by impurities in the working gas introduced into the system. For reasonably clean targets with minimal target outgassing, even a relatively large target chamber (8-10 m^3) can be served by <1000 l/s pumping speed at the 0.2 to 1.0 milli-Torr pressure level. (Which can be provided by a single turbo-molecular or diffusion pump and roughing system.) The much more demanding system pumping requirements are driven by the need to keep initial pump down times relatively short, so that overall process cycle times will be as short as practical. One potential method of minimizing cycle time for batch processing in vacuum systems is to utilize multiple load-locks, in which targets are loaded through isolated chambers which are attached to the main vacuum chamber by a gate valve, or other isolation device. A target is placed in one load-lock, which is pumped to a pressure approaching the system base pressure before it is opened to the main chamber and the target transferred. While this first target is being processed, a second target is loaded into the second load-lock and pumped down. When processing of the first target has been completed, it is removed through its load-lock, and the second target is then inserted. (The system could also be configured for unidirectional motion, in which one load-lock is consistently used to load targets, while the second is used to unload processed targets.) This procedure works well for relatively small targets, but can become difficult and expensive to implement for large, heavy targets - which would require large isolation valves, and substantial in-vacuum manipulation capabilities for target transfer. Independent of the use of a load-lock, initial pump-down pumping speed requirements are determined by the target chamber size, effective outgassing rate of the chamber and target, and the desired total time to reach a given base pressure. In the absence of significant outgassing, the required pump-down time may be simply estimated as: $t \approx (Vol/s1)\ln(P_{initial}/P_{rough}) + (Vol/s2)\ln(P_{rough}/P_{final})$, where t is the pumping time required, Vol is the system volume, s1 is the high-pressure, or roughing system pumping speed, s2 is the high vacuum system pumping speed, and $P_{initial}$, P_{rough}, and P_{final} are the initial, intermediate roughing, and final desired system pressures. Since typical roughing pressures (at which the system can be switched to a high vacuum pump such as a turbomolecular or diffusion pump) are usually in the milli-Torr range, the total pump down time is often dominated by the size of the roughing pump system. (Outgassing of the system, or targets inserted into the system, can dramatically increase the required pumping time.) Shorter total pump down times may be achieved by the use of mechanical booster pumps of various designs. These are relatively high speed pumps which operate in an intermediate pressure range (from 10 Torr or more down to the milli-Torr range). Typically, a system is pumped to a pressure well below the desired working pressure before the process gas is introduced, in order to minimize impurities.

An additional consideration for the vacuum system is the requirement for shielding the x-rays produced by secondary electrons impacting the chamber wall. For multi-cubic-meter systems running at no more than ~70 kV, the chamber walls will in general be thick enough (1/2 inch or so) to sufficiently shield the x-rays. Additional shielding may be required around ports and other thinner portions of the system, or if voltages above the 70 kV level are required for a particular application.

Plasma Sheath Issues and Plasma Source Requirements

The PSII process relies intrinsically on the characteristics of the plasma which surrounds the target, and the transient plasma sheath which is established during the process. The application of a negative high voltage pulse creates the transient plasma sheath around the target, and accelerates ions into the target surface. The transient plasma sheath has been described in great detail in numerous papers (/16,17,18,19/), and the general sequence of sheath evolution is described as follows, and illustrated in Figure 3.

The dimensions of the sheath are determined primarily by the initial plasma density, the voltage applied to the target, and the duration of the voltage pulse. The initial configuration (Figure 3a) has a nearly uniform plasma surrounding the target. Due to the great difference in mass between the electrons and ions in the plasma, the electrons move rapidly away from the target during the early portion of the voltage pulse, exposing plasma ions (Fig. 3b). This initial "matrix sheath" dimension $D_{initial}$ is given by $D_{initial} = (2\varepsilon_0 V/en)^{1/2}$ for planar geometry, where ε_0 is the permittivity of free space ($= 8.9 \times 10^{-12}$ farad/meter), V is the negative voltage applied to the target, e is the ion charge ($= 1.6 \times 10^{-19}$ coulomb for singly charged ions), and n is the plasma density per cubic meter. The electric field now present in the sheath region accelerates ions into the target, as depicted in Fig. 3c. As ions are implanted into the target and lost from the sheath, the sheath edge recedes from the target, as shown in Fig. 3d. The sheath thickness increases during this time as $D(t) = D_{initial}\left((2/3)\omega_{pi} t + 1\right)^{1/3}$, where ω_{pi} is the ion plasma frequency ($\omega_{pi} = (ne^2/\varepsilon_0 M)^{1/2}$), n, e, and ε_0 are as defined above, and M is the ion mass in kg. Eventually, the sheath edge will extend to the vacuum chamber wall, or arcing will occur, limiting the useful pulse duration for implantation. Typical pulse widths range from several microseconds to almost 100 microseconds. Useful discussions of plasma sheath behavior for various conditions and geometries are provided in the previous references /16,17,18,19/. From the fundamental equations describing the sheath evolution, it is clear that higher initial plasma densities result in smaller sheaths. Sheath dimensions which are small compared to the scale size of important target features result in more uniform implantation of the critical target surfaces.

A number of possible mechanisms exist for generation of the initial plasma for the PSII process. These include both capacitive and inductive RF sources, electron emissive sources, microwave sources, electron cyclotron resonance (ECR) sources, magnetron sources, vacuum arc sources, etc. /20,21,22/. The optimal source for PSII applications would be capable of generating a uniform, low to moderate density plasma ($\sim 10^{14}$- 10^{17} /m^3) around the target, simple to implement and operate, and robust and reliable. Inductively coupled RF sources (both steady-state and pulsed) are capable of generating high densities near the source (10^{17}/m^3 range, and above - details of source behavior can be found in a paper by Tuszewski /23/), but generally do not produce this density level uniformly throughout a large chamber, as is required for PSII. Vacuum arc sources are capable of producing plasmas from metallic species which would otherwise be difficult to obtain from gaseous sources (organo-metallic compounds with high vapor pressures), but would require multiple sources to provide a reasonable level of plasma uniformity around a single target. Production of a uniform plasma throughout a complex target assembly is unlikely for a source of this type. ECR, magnetron, and other sources require ancillary magnetic fields for their operation, and are therefore more complicated to implement. For operation with gaseous implantation species (primarily nitrogen and carbon - from hydrocarbon gases such as methane) in relatively large systems (many cubic meters volume), one of the most useful sources is a capacatively coupled RF plasma source. For this type of source operating at the ~1000 Watt level, a single, simple antenna is capable of generating a relatively uniform plasma in the 10^{14}-10^{15}/m^3 range around targets in moderate volume systems (~5-10 m^3) from a neutral gas fill pressure of below 1 milli-Torr.

Modulator Requirements

The key component in a successful PSII system is the high voltage, high current switching sub-system - the "modulator". This system must be able to repetitively switch large currents (hundreds to several thousand Amperes), with switching times of a few microseconds, in order to allow implantation of large surface area targets with good quality and uniformity over the target surface. During the quasi-steady state portion of the plasma sheath evolution, the total current drawn by the target can be estimated from $I_t = A(\gamma+1)(4\varepsilon_0/9)(2e/M)^{1/2}V^{3/2}/D^2(t)$, where V is the voltage applied to the target, A is the target surface area, and γ is the surface secondary electron emission coefficient (which can be as large as 10 to 20 for some materials), and M, e, and D(t) are as defined above. The modulator must supply at least this current in order to maintain the desired implantation voltage on the target (typically from 20 to 70 kV, or more). In order to keep the initial voltage rise period relatively short (no more than a few microseconds), the modulator must also be capable of transiently supplying an even larger current, since the target initially appears as a predominantly capacitive load during the time in which the ion matrix sheath is being established. The high voltage and high current levels required for large targets result in instantaneous switched power requirements which are in the megawatt range, and average power requirements from tens to hundreds of kilowatts - depending on the pulse width and pulse repetition rate of the system. Pulse widths of 5-30 microseconds are common in experimental systems, with repetition rates of up to several thousand pulses per second, and implantation times of several hours. Since it is desirable to keep the total implantation time as short as possible, there is a very strong incentive to utilize high plasma densities (which result in high current demands on the modulator), and high repetition rates (which increase the average power requirements). Primary constraints on these parameters are the total power available for the modulator, and the thermal dissipation characteristics of the target and support assembly. The modulator must also be well controlled and protected in order to minimize the impact of arcing. Arcs can present a significantly lower impedance to the modulator than the normal target, and can lead to severe target surface damage if uncontrolled. Fast arc detection circuitry must be an integral part of the modulator, as well as controls which temporarily blank the modulator output in order to quench any arcs which do occur. Successful modulator designs have been based on high voltage, high current vacuum tube circuits of various types, solid state devices (Insulated Gate Bipolar Transistor packages), and pulse forming networks (PFNs).

Target and Mounting Considerations

The success of the PSII process depends not only on the characteristics of the system used in the process, but also on the details of the target(s) and the mounting structure utilized within the process chamber. The target surface material, geometry, and application failure mechanisms must be suitable for significant improvement through the PSII process. Surface materials which have been successfully improved through the PSII process include chromium and high chromium alloy steels (with nitrogen implantation), tungsten and aluminum alloys (with carbon implantation), titanium alloys (with nitrogen implantation), more common iron alloys (with nitrogen implantation), and others. Given a suitable target surface material, the target failure mechanism and location must be evaluated. Mild abrasive wear failure is a prime candidate for PSII enhancement, if the surface material and failure location are appropriate. Failure areas must be accessible to the plasma ions, with accessibility determined by the location of the failure area and the relative scale size of the target surface and the plasma sheath. Areas of the target which are shielded from the implanting ions either by portions of that target, or by shielding from adjacent targets in a target assembly, will not be suitably enhanced. Portions of a target surface which are good (and poor) candidates for PSII enhancement are illustrated in Figure 4. Another target consideration involves thermal management. Since the PSII process deposits energy into the target surface, targets usually must be cooled if they are to be maintained at essentially room temperature. High aspect ratio targets (e.g. long and thin) are therefore poor candidates for treatment unless they can be cooled through a central channel. Some targets with a relatively small surface to volume ratio (large industrial stamping dies, for example) may require no active cooling, as the thermal mass of the target is sufficient to keep the temperature excursion relatively small during the PSII processing.

Summary

PSII processing has been proven effective in enhancing the characteristics and service life of a number of industrial components. Based on these results and cost estimates for commercial scale processing of components, the PSII process is being commercialized through the efforts of a group of companies including General Motors, Asea Brown Boveri, Litton Electron Devices, Nano Instruments, Diversified Technologies, Ionex, PVI, Empire Hard Chrome, A.O. Smith, Harley-Davidson, Kwikset, Boeing, DuPont, and NorthStar Research, as well as Los Alamos National Laboratory and the University of Wisconsin, Madison. Commercialization has been achieved on a small scale through a facility being operated at Empire Hard Chrome, in Chicago Il., and additional small and large scale facilities are being planned. Successful implementation of the PSII techniques requires careful consideration of the basic plasma parameters, target characteristics and target support, modulator, and the interactions of the plasma-target-modulator system.

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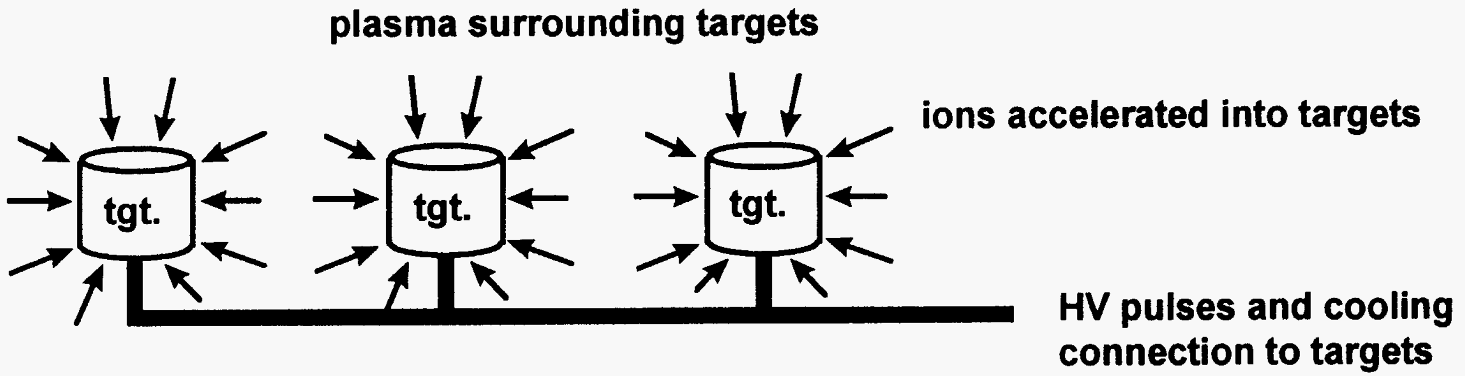
Figure Captions

Figure 1. Schematic comparison of PSII and conventional ion beam implantation. PSII utilizes the plasma sheath to accelerate ions into the target (or multiple targets) from all directions. Conventional, accelerator based ion implantation is a line-of-sight process, which requires in-vacuum manipulation of a target to implant complex surfaces.

Figure 2. Block diagram of a typical PSII system. Major system components include the vacuum chamber, pumping system, high voltage DC power supply, high voltage pulser or modulator, cooling system, target support assembly, plasma generation system, and working gas input system.

Figure 3. Plasma sheath temporal behavior for a planar target. 3(a) shows the initial configuration with nearly uniform plasma surrounding the target. 3(b) indicates the formation of the ion matrix after electrons have been excluded from the region close to the target. 3(c) indicates ions accelerating through the sheath region into the target surface. 3(d) shows the expanded sheath late in the voltage pulse. 3(e) indicates the relative times of a-d during the voltage pulse.

Figure 4. Schematic representation of portions of a complex target which are good (or poor) candidates for PSII enhancement with a given plasma sheath position.


plasma surrounding targets
ions accelerated into targets
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HV pulses and cooling
connection to targets


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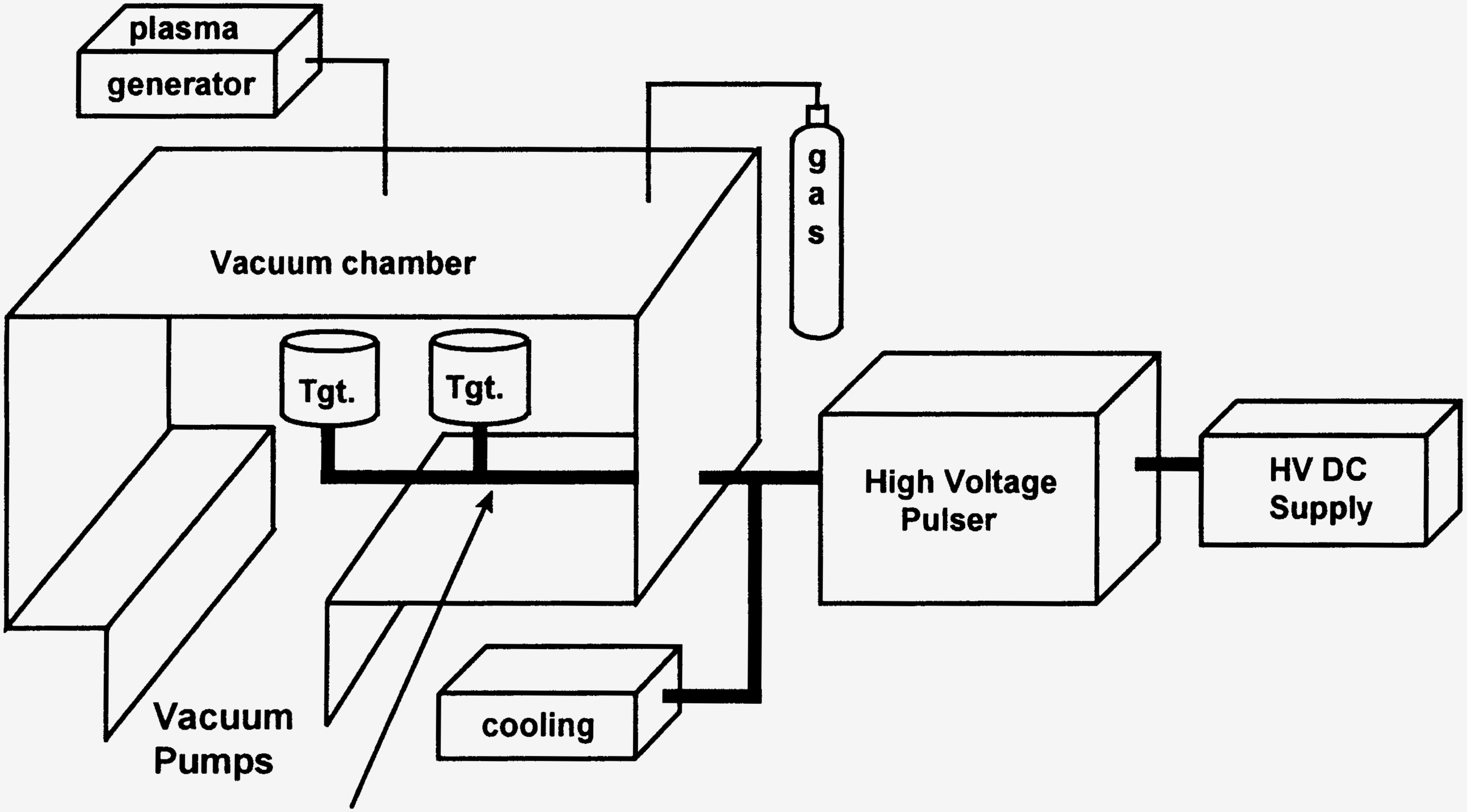
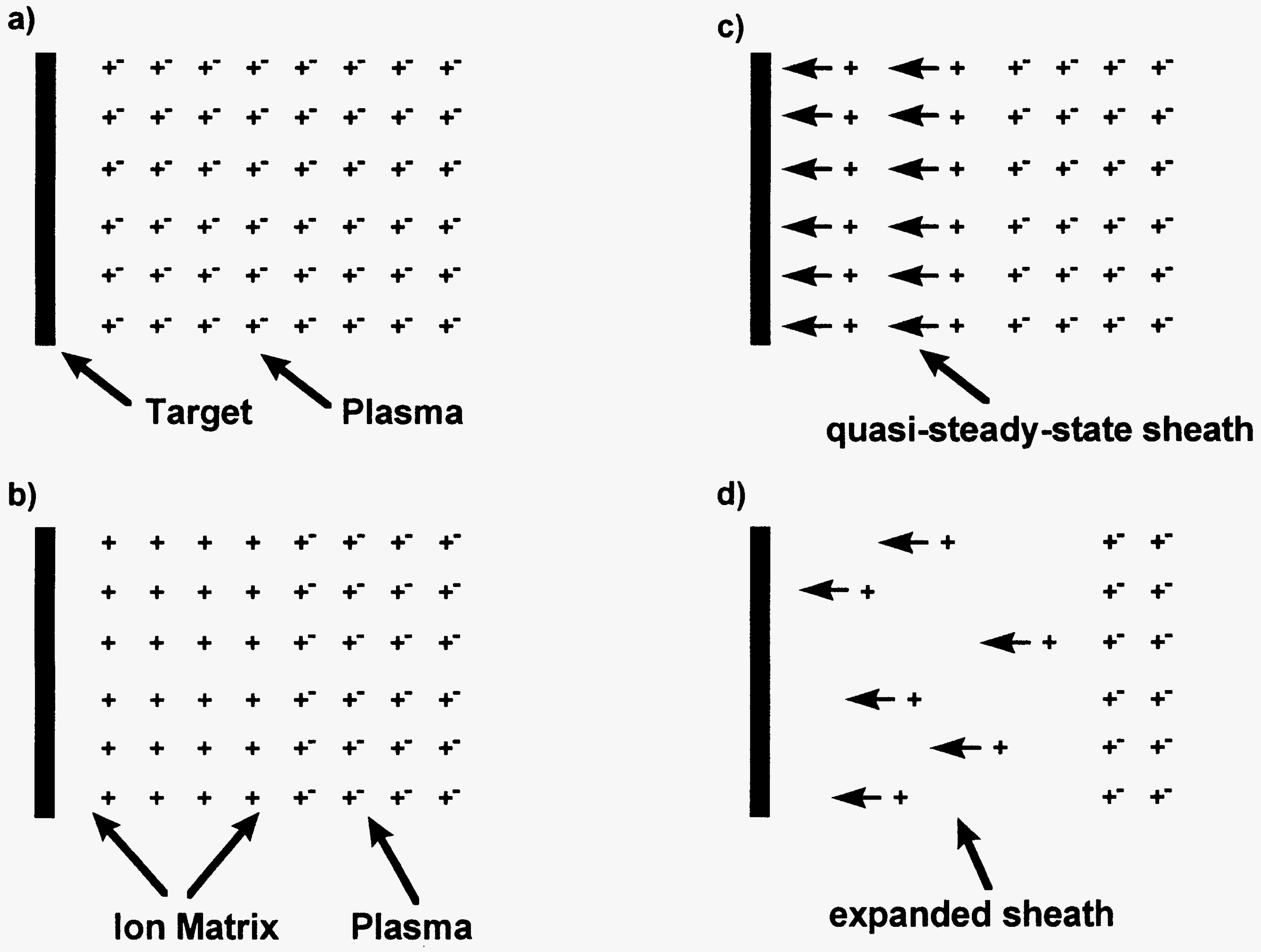
ion beam from accelerator
in-vacuum manipulator



Target support and cooling assembly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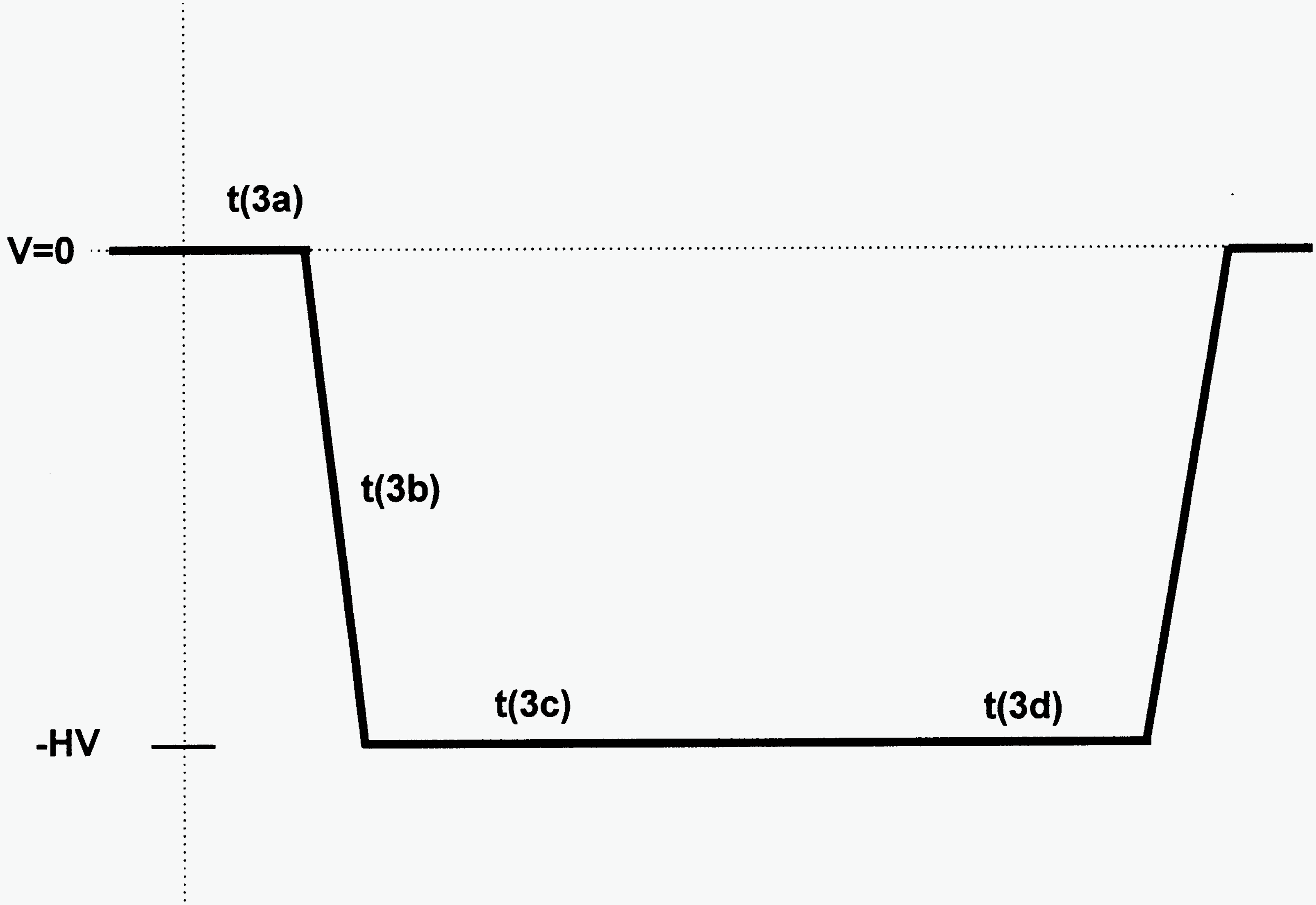
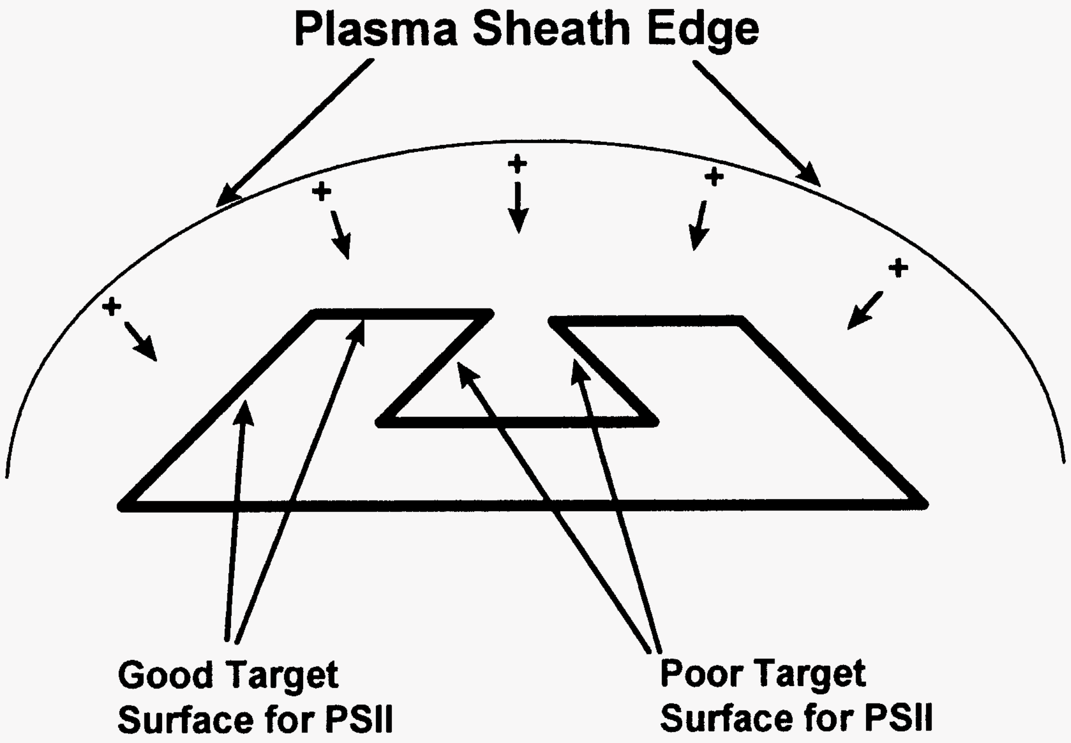
Target
Plasma
b)
Ion Matrix
Plasma
c)
quasi-steady-state sheath
d)
expanded sheath

e)




Plasma Sheath Edge
+
+
+
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Good Target
Surface for PSII
Poor Target
Surface for PSII

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