

Surface Ionization with Cesium Converters for Space Applications

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Neutral particle imaging can be used for remote sensing of magnetospheric plasmas. Due to the low fluxes of neutral particles and the very transient nature of many phenomena in such environments, a highly sensitive detection method is required. Neutral particles in the energy range between 10eV and 1keV have not previously been accessible to a mass, energy and angle analysis. Surface ionization, a well-established laboratory technique, can efficiently convert neutral particles in this energy range into negative ions to be analyzed with mass spectrographs. This article describes surface ionization with low work function surfaces as a method and discusses its applicability in spaceborne instrumentation.

1. INTRODUCTION

One of the main objectives of space physics is to understand the Earth's magnetosphere, its interaction with the ionosphere, and the energy input by solar radiation (photon and particle flux). After decades of in situ plasma measurements, which provided point measurements, new techniques are needed to provide maps of plasma distributions by remote sensing. In addition to the imaging capability, high temporal resolution, and thus high sensitivity, is necessary, since many magnetospheric processes are transient.

Although neutral atom imaging is a relatively new technique [McEntire and Mitchell, 1989] a few applications have been reported [Hsieh et al., 1992]. For energies larger

than 10keV, adaptations of standard instruments for measuring energetic ions can be used. Hsieh and Curtis [1997] give a review of the status of this instrumentation. However, the energy range below 1keV has been inaccessible to direct measurements so far. For standard mass spectrometry, neutral particles have to be ionized before being analyzed and detected. Surface ionization has been identified as the only ionization technique which has the potential for sufficient ionization yield in the energy range of 10eV to 1keV within the constraints for space instrumentation [Ghielmetti et al., 1994; Wurz et al., 1995].

In the past 15 years new surface ionization techniques have been developed for application in fusion plasma research. With these techniques ionization efficiencies up to 67% in the energy range from several eV to about 1keV [Van Wunnik et al., 1983, Geerlings et al., 1985] have been achieved. Surface ionization makes use of low work function (WF) surfaces for converting neutral particles to negative ions by resonant charge exchange after reflection from a converter surface. This technique introduces new demands on the design of instruments and requires the development of new analyzer elements with matched ion optical properties. An instrument satisfying these demands has been described by Ghielmetti et al. [1994] and by Wurz et al. [1995]. Alternate concepts that combine surface ionization techniques with a spectrometer have been described by Herrero and Smith [1992] and by Gruntman [1991].

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2. SURFACE IONIZATION

An extensive review of charge exchange in atom-surface collisions is given by *Los and Geerlings [1990]*. To describe the concept of charge exchange, a one-dimensional model is used. As the neutral particle moves towards a metal surface, its affinity level is energetically lowered by an image-charge potential resulting from the interaction between the atom and the solid. Affinity states lying below the Fermi level of the metal can be populated by resonant electron tunneling from the metal, but the electrons can also tunnel back to the metal if empty states are available. The finite lifetime of an electron in the affinity state leads to an energy broadening via the Heisenberg uncertainty principle. The lowering and broadening of the affinity level is illustrated schematically by *Van Amersfoort et al. [1985]* in their Figure 1. Close to the surface an equilibrium of bi-directional tunneling electrons is established. Thus the charge state of the incoming particles does not matter. Incoming positive ions are neutralized by resonant and Auger type electron transfer [*Hagstrum, 1954*]. If an equilibrium situation is considered, the charge state of a particle at a certain distance from the surface is given by the overlap of the broadened and lowered affinity state and the metal's conduction band. A simple model [*Overbosch et al., 1980*] describes the charge exchange efficiency in a non-equilibrium situation with the assumption that the charge state is frozen at the so-called freezing point due to the decreasing resonance width. Several parameters are important for the charge exchange efficiency. These are the electron affinity of the incoming particle, the WF of the surface, the electron density of the surface, and the velocity and angle of the impinging particles.

The difference between the WF and the electron affinity is the crucial parameter determining the efficiency, since it is a measure for the overlap between the affinity state and the conduction band. For this reason, surface ionization works well for atoms with high electron affinities, e.g., H, C, and O atoms (0.75, 1.27, and 1.46eV). Measurements of O^- and C^- have been reported by *Van Pinxteren et al. [1989]*. The production of singly charged negative ions has also been observed for species with low negative electron affinities such as He [*Verbeek et al., 1984*], which forms a metastable negative ion.

The velocity of the particle is important for the charge exchange efficiency because it determines the interaction time of the particle with the surface. In the limit of very high velocities the resonant charge transfer is too slow to populate the affinity level and thus the charge exchange efficiency goes to zero. At very low energies few negative ions are observed since the electron in the affinity level has sufficient time to tunnel to an empty state in the metal on the outgoing

trajectory. For H atoms reflected off a Cs/W(110) converter the conversion efficiency shows a broad maximum around an energy of 100eV normal to the surface [*Van Os et al., 1988*]. When increasing the normal velocity component to achieve a higher charge exchange efficiency by choosing a smaller impact angle one has to account for inferior reflection properties as the angular broadening of the reflected beam increases.

Low WF surfaces are typically generated by coating a metal surface with a thin layer of an electropositive metal. This causes an additional surface dipole layer which reduces the WF markedly [*Lang, 1971*]. An extensively studied combination is Cs/W(110), used either with 0.6 monolayer or a full monolayer of Cs [*Van Wunnik et al., 1983; Geerlings et al., 1985; Amersfoort et al., 1985*]. The WF shows a minimum of 1.45eV for the submonolayer coverage and equals the value of bulk Cs (2.15eV) for the full monolayer, which is far below the WF of the bare W substrate of 5.25eV.

3. EXPERIMENTAL SETUP

We built an experiment using an ion beam to test various conversion surfaces for their suitability for application on a space platform. The aim of this experiment was to show that surface ionization works under moderately good vacuum conditions and thus to qualify this technique for application in an outgassing environment in space.

The experiment consists of an ion source, a beam guiding system, a sample chamber with surface reconditioning units and a detection unit. These parts are in a vacuum chamber pumped by a turbomolecular pump. After bake-out, a pressure of 5×10^{-8} mbar is achieved. A schematic of the experimental setup is shown in Figure 1. The ion beam is formed in an electron impact ion source. From a similar ion source we know for H_2 that H^+ and H_3^+ are present only at a percent level relative to H_2^+ in the ion beam [*Ghielmetti et al., 1983*]. After acceleration the ions are deflected with a cylindrical energy analyzer (resolution of 1% FWHM) on the entrance aperture of the sample chamber. Two collimators limit the beam divergence at the sample surface to 1° . By rotating the conversion surface, the impact angle α of the ion beam relative to the surface normal ranges between 90° and 0° . The reflected beam is analyzed with a 2D position-sensitive MCP detector. A retarding potential analyzer (RPA) with three grids is mounted in front of the detector, which floats on an adjustable high voltage. The detector unit, including the RPA, is shielded electrostatically. It can be rotated independently of the converter surface around the same axis. The outer grids of the RPA are grounded to shield the inner grid, which has a permanent bias to suppress positive ions. Their fraction in the reflected beam is

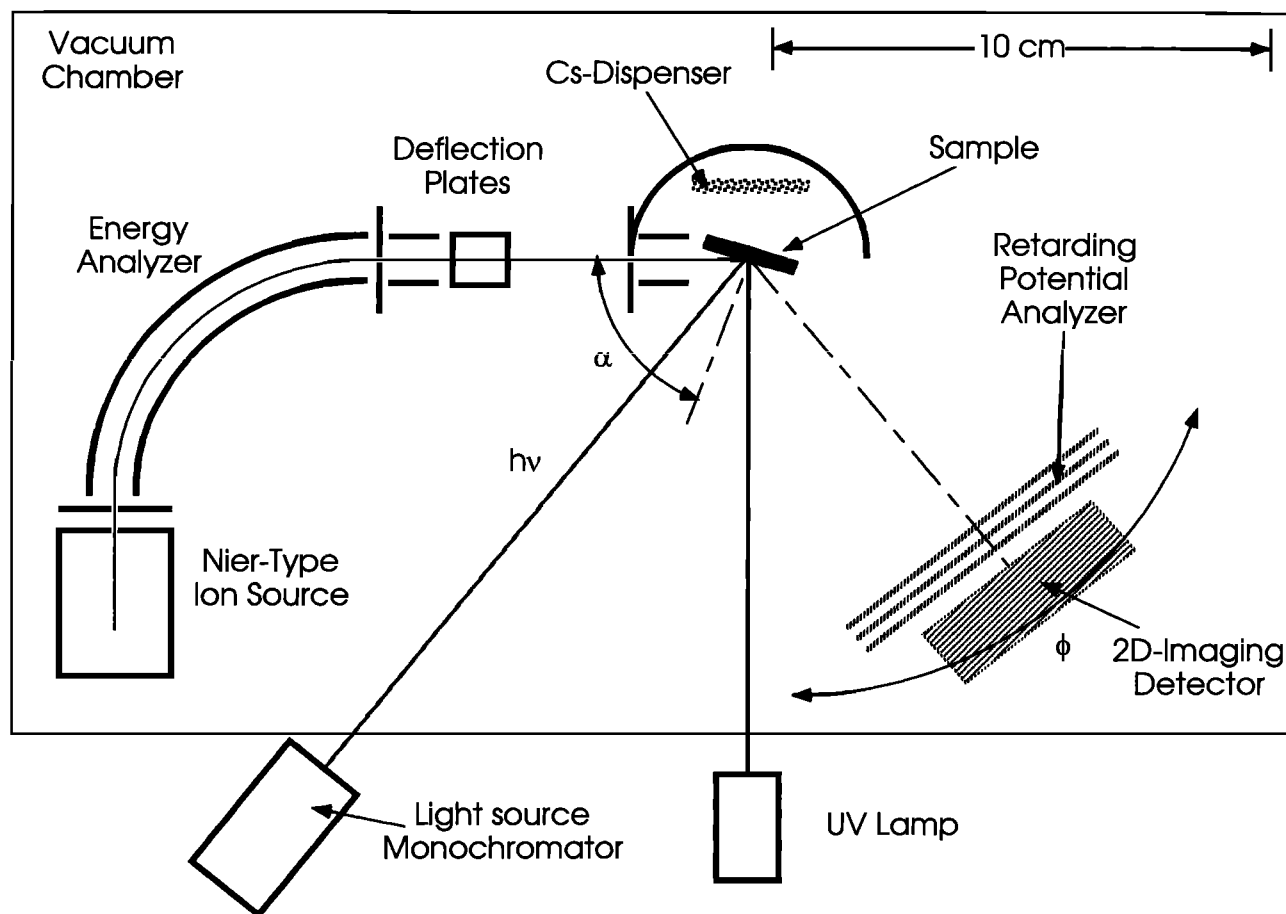


Figure 1. Schematics of the experimental setup. The primary ion beam impinges on the sample surface at an adjustable angle α relative to the surface normal. The reflected beam is detected with a 2D MCP detector that has a retarding potential analyzer mounted on its front. The work function is measured photoelectrically with monochromatic light of adjustable wavelength coupled into the chamber with fiber optics.

negligible at these energies, however, parts of the primary beam could hit the detector at impact angles α close to 90° . To sweep out negatively charged particles from the reflected beam, a negative bias is applied to the detector. By measuring the intensity of the entire reflected beam, and its neutral component (by sweeping out the negatively charged ions), the ionization efficiency η of the surface can be calculated from

$$\eta = 1 - \frac{N_0}{N_{tot}} \quad (1)$$

where N_0 denotes the counts of the neutral beam within a given detector area and time interval, and N_{tot} the counts of the total beam within the same area and time interval. To this simple equation corrections are applied accounting for the energy dependence of the detection probability, for the different detection efficiencies for neutral particles and for negative ions, and for the effects of contaminants in the ion

beam resulting from ionized background gas [Schletti, 1996]. From the 2D-images, the conversion efficiency can be measured at different reflection angles. In addition to the conversion efficiency, angular scattering is measured.

The conversion unit consists of a W(110) single crystal serving as substrate on which an accurately controlled amount of Cs is deposited from a dispenser by evaporation. It takes 45s to deposit one monolayer of Cs based on manufacturer's specifications and our own measurements. To clean the surface, it is heated resistively up to 1600K for a few seconds.

With a fiber-optical system mounted on the vacuum chamber the surface is illuminated with monochromatic light of adjustable wavelength. By measuring the photoelectric current the WF of the converter surface is determined.

To test the UV response of the surface, it can be exposed to very intense ultraviolet radiation in the wavelength range from 145 to 185nm produced by a QUANTATEC Xe lamp.

4. THE APPLICABILITY OF SURFACE IONIZATION IN SPACE INSTRUMENTATION

To assess the applicability of surface ionization with cesiated surfaces to space instrumentation, four important issues have to be investigated:

- I) The degradation of the converter due to residual gas.
- II) The degradation of the converter due to intense UV radiation.
- III) Cs migration in the instrument.
- IV) Particle reflection properties of the converter surface.

4.1. Converter Degradation due to Residual Gas

We did not perform this study under stringent UHV conditions because our explicit aim is to show the applicability of surface ionization under less favourable circumstances as experienced in space instrumentation. Our apparatus has no device to assess the atomical cleanliness of the W substrate and the Cs layer, thus lacking precise information about surface contamination. This is similar to the situation where an instrument would be in space and surface contamination could not be assessed either.

Figure 2 shows the measured negative ion fraction in the reflected beam for H_2^+ primary ions with an energy of 225eV impinging on the surface under an angle of $\alpha=82^\circ$. The W(110) substrate was covered with a full monolayer of Cs. High ionization yields are obtained with this configuration. On the inbound path the incoming positive molecular ions are efficiently neutralized and dissociated [Van Toledo *et al.*, 1992]. Thus the charge state before reflection has no influence on the final charge state in this energy range.

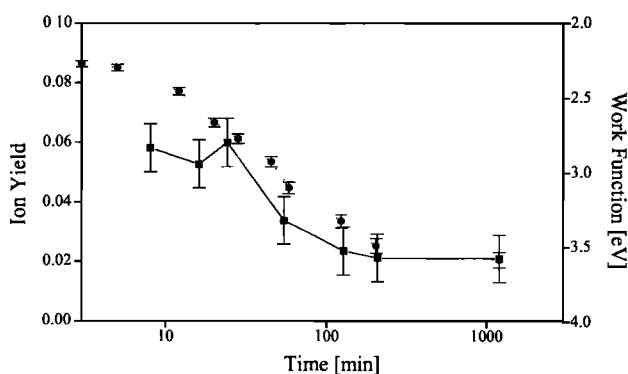


Figure 2. Measured negative ion fraction in the reflected beam (solid line) for H_2^+ impinging under 82° at an energy of 225eV on a W(110) surface covered with a full monolayer of Cs. The molecular ions are efficiently neutralized and dissociated on the inbound path. The decrease in ionization efficiency is caused by the increasing WF (dashed line) due to the adsorption of residual gas (background pressure 10^{-7} mbar).

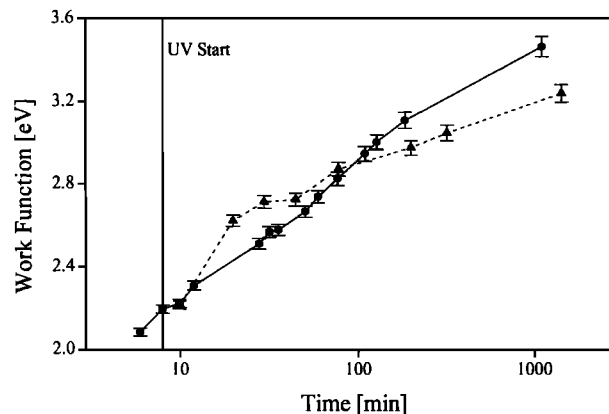


Figure 3. Time dependence of the WF with (triangles) and without (circles) UV exposure. Shortly after surface preparation the UV exposure increases the WF slightly, but on long term the UV exposed surface shows lower WF. The Cs overlayer is basically unaffected by the very intense UV.

Schneider *et al.* [1982] have observed no difference in the final charge state for D and D^+ as primary particles.

A few minutes after surface preparation, we measured an ionization efficiency of 6%. The efficiency decreases with time due to the adsorption of background gas on the converter surface, which increases the WF. It is very important that even 24 hours after the surface preparation the conversion efficiency, while significantly decreased, was still observable in spite of the relatively high pressure of 10^{-7} mbar. Another test run was performed to confirm that the residual gas affects the converter surface: Leaking O_2 into the chamber to deliberately increase the pressure increases the WF while lowering the ionization efficiency. The adsorption of electronegative constituents will cause an increase of the WF, whereas hydrogen will lead primarily to a decrease of the resonance width [Amersfoort *et al.*, 1986]. Both mechanisms reduce the conversion efficiency of the surface. If the ambient pressure is reduced by one order of magnitude the characteristic time of operation would increase by the same factor. Such an improvement is possible for a space instrument so that a regeneration of the converter surface would not be necessary more frequently than every ten days.

The functional dependence of the conversion efficiency on the WF is also displayed in Figure 2. The close correlation between the WF and the ionization efficiency can be used for a reliable in-flight diagnostics of the instrument. By means of the WF measurement and a thorough pre-flight calibration determining both ionization and reflection probabilities, the absolute neutral particle flux can be determined in space accurately at any time. In a spaceborne sensor the WF will be measured by illuminating the con-

verter surface with light emitting diodes. The measured photocurrent depends strongly on the WF of the surface [Schletti, 1996], and thus the WF can be retrieved accurately.

4.2. Ultraviolet Response of the Cs/W(110) Surface

To test the UV response of the Cs/W(110) surface, it was illuminated with a UV lamp for extended periods and the WF, as a measure of the conversion efficiency, was monitored. Our lamp produces a continuous spectrum of UV photons with lower energy than the La photons which dominate geocoronal UV light. Since the photon energy of our lamp by far exceeds the relevant binding energies of Cs on the substrate and of contaminants, our conclusions are qualitatively applicable. The results of one run with UV exposure and one without UV illumination are shown in Figure 3. For short times the WF is slightly higher when the surface is exposed to UV light. This is due to photodesorption of background gas from the walls of the vacuum chamber, which considerably increases the pressure in the chamber. On longer timescales, the UV irradiated surface has lower WF. This means that contaminating adsorbates on the converter surface are removed by photodesorption. However, the Cs overlayer is not affected by UV light as one can conclude from the fact that the WF evolves qualitatively the same way with and without UV exposure. The converter surface in the test stand is irradiated with $2 \times 10^{13} \text{ ph s}^{-1} \text{ cm}^{-2}$ (manufacturer spec.). In space, a La photon flux from the geocorona on the converter surface of $2 \times 10^7 \text{ ph s}^{-1} \text{ cm}^{-2}$ is expected [Meier and Mange, 1973], assuming a field of view of the instrument of $8^\circ \times 90^\circ$. We conclude that the conversion surface is only slightly affected by UV exposure and that photodesorption of the Cs overlayer can be neglected.

4.3. Thermal Desorption of Cesium

It is well-known that Cs with its low melting point of 302K is a reactive and volatile element. This, however, is not a problem in our application because we are using only one monolayer at a time. One monolayer Cs on W(110) corresponds to a surface density of $5.5 \times 10^{14} \text{ atoms cm}^{-2}$. For thin layers the heat of desorption is a strong function of the Cs coverage [Ehlers and Leugn, 1984]. For the Cs/W(110) surface the heat of desorption increases from 0.82eV per atom, which is the value for bulk Cs, to more than 3eV for almost zero coverage. If there is more than one monolayer of Cs on the substrate, the excess Cs will quickly evaporate (evaporation of one monolayer of bulk Cs takes of the order of seconds at room temperature) and as soon as one monolayer is reached the evaporation rate decreases expo-

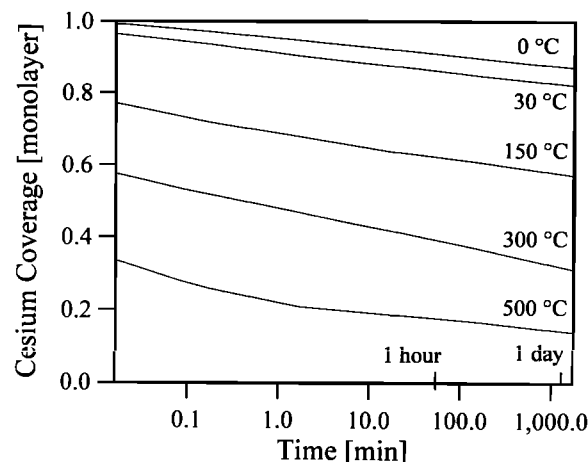


Figure 4. Calculated thermal desorption of a Cs overlayer on W(110) for different temperatures when starting with a full monolayer at $t=0$. Because the heat of desorption increases strongly with decreasing Cs coverage, evaporation is very slow compared with bulk Cs. Desorption heat data of Ehlers and Leugn [1984] have been used for this calculation.

nentially. The combination of these two facts lets us conclude that we know the Cs layer thickness with sufficient precision to be one monolayer, which is confirmed by our WF measurements. The cesium coverage shown in Figure 4 has been calculated using experimental data of the heat of desorption for a Cs/W(110) [Ehlers and Leugn, 1984] surface without any contamination by assuming a first order desorption process. We conclude from Figure 4 that thermal desorption is not a problem at room temperature. The surface is regenerated by thermally desorbing the Cs and the adsorbed contaminants and then coating the substrate with Cs again. The Cs within the dispenser is bound in a metal salt and starts to evaporate at around 250°C, so no contamination of the instrument will take place during normal operation from either the Cs dispenser or from the converter surface. Contamination of internal surfaces of an instrument due to Cs evaporation during reconditioning, which would be performed an estimated 10 to 100 times during a mission, would be below one monolayer of Cs. With the low vapor pressure for submonolayers, migration of Cs within the instrument is minimal. In our test stand, the sensitive MCP detector is about 12cm away from the Cs dispenser, and after one and a half year of operation, no decrease in performance was observed.

4.4. Reflection Properties

The use of converter surfaces in mass- and energy-analyzing instruments requires sophisticated ion optics, because the ions start from the converter surface with considerable

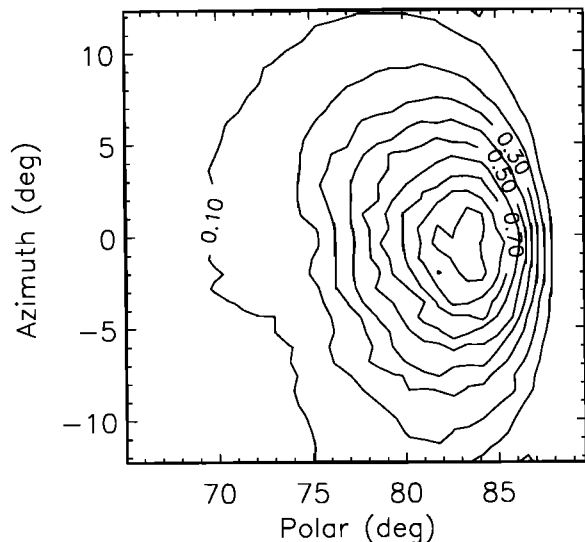


Figure 5. Angular scattering of a 400eV H_2^+ beam impinging at 80° on a W(110) surface coated with one monolayer of Cs. The beam profile is normalized to its maximum intensity.

angular and energy spread. Thus the reflection properties of the surface are relevant to the resolution of the instrument. Simulations with the MARLOWE code [Robinson, 1989] showed that atomically flat surfaces produce less angular scattering than atomically rough surfaces [Aellig, 1995]. This can be observed when comparing a cesiated W(110) substrate coated with either a full or a half monolayer of Cs. Since the latter does not form a closed surface, it exhibits stronger angular scattering. Together with the more complicated preparation this makes the submonolayer system less preferable. The particle reflection coefficient is also an important parameter, because it is proportional to the sensitivity of the instrument. In this respect also the fully Cs covered surface is more preferable than the half-covered. However, even for the half-covered surface a particle reflection coefficient of 0.92 was simulated for 300eV atomic hydrogen impinging at 75° relative to the surface normal. Figure 5 displays the measured angular scattering in polar and azimuthal direction for a H_2^+ beam impinging on a Cs coated W(110) surface at an angle of 80° with an energy of 400eV. The angular scattering (FWHM of 11° in azimuthal direction and 8° in polar direction) is consistent with the results obtained with the MARLOWE simulations [Aellig, 1995].

5. CONCLUSIONS

We discussed the crucial aspects of the Cs/W(110) conversion system for a space application in detail and demonstrated its feasibility for space instrumentation. We showed

that surface conversion into negative ions can be performed despite contamination due to residual background gas and that the converter surface does not degrade upon intense UV irradiation. Other candidate surfaces for conversion systems are currently under investigation. Future goals are not only higher efficiency, but also a longer standing time of the surface between reconditioning and the search for converter systems which do not need the application of a surface coating, and therefore considerably increase the ease of use.

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