[2]B. H. Ripin *et al.*, Phys. Rev. Lett. 34, 1313 (1975).
[3]R. A. Haas *et al.*, Phys. Fluids 20, 322 (1977).
[4]J. A. Stamper and D. A. Tidman, Phys. Fluids 16, 2024 (1973); J. A. Stamper, Phys. Fluids 19, 758 (1976).
[5]J. J. Thomson *et al.*, Phys. Rev. Lett. 35, 663 (1975).
[6]B. Bezzerides *et al.*, Phys. Rev. Lett. 38, 495 (1977).
[7]Wee Woo and J. S. DeGroot, Phys. Fluids 21, 124 (1978).
[8]H. Kuroda, in *Proceedings of the Conference on Laser Engineering and Applications, Washington, D. C., 1977* (IEEE, New York, 1977).
[9]V. V. Aleksandrov, private communication.
[10]D. T. Attwood, in *Proceedings of the Twelfth International Congress on High Speed Photography, Toronto, 1976* (Society of Photo-Optical Instrumentation Engineers, Redondo Beach, Calif., 1976), Vol. 97, p. 413. Later studies (private communication) at 100 psec and 10^{15} W/cm^2 for $\lambda = 2660$ Å showed no fields larger than 100 kG.
[11]D. V. Giovanielli, private communication.
[12]J. A. Stamper *et al.*, in Naval Research Laboratory (NRL) Memorandum Report No. 3591, 1977 (unpublished), p. 63.
[13]E. A. McLean *et al.*, Appl. Phys. Lett. 31, 825 (1977).
[14]R. H. Lehmberg and J. A. Stamper, NRL Memorandum Report No. 3703, 1978 (to be published).
[15]J. M. McMahon *et al.*, in NRL Memorandum Report No. 3591, 1977 (unpublished), p. 3.
[16]J. A. Stamper *et al.*, Phys. Rev. Lett. 26, 1012 (1971).
[17]D. G. Colombant and N. K. Winsor, Phys. Rev. Lett. 38, 697 (1977).
[18]B. H. Ripin, NRL Memorandum Report No. 3684, 1977 (unpublished).
[19]B. H. Ripin *et al.*, Phys. Rev. Lett. 39, 611 (1977).
[20]E. A. McLean *et al.*, to be published.

Laser-Induced Desorption of Impurities from the Macrotor Tokamak Walls

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Flash heating by a laser pulse has been used to desorb loosely bound species from a spot on the tokamak wall. Spectral analysis of the suddenly increased impurity radiation from the plasma in front of the laser-heated spot gives information on the species and the amount of impurity atoms present on the surface at a specific point in time of the tokamak discharge. Loosely bound chromium has been found on the stainless-steel surface.

Since adequate plasma confinement and heating seem possible, impurity evolution and control are recognized now as being critical remaining obstacles on the way to magnetic fusion energy. Too high impurity concentrations adversely influence almost every aspect of plasma behavior in tokamaks. Usually a large fraction of the Ohmic power input is lost from the plasma by impurity radiation.[1] Oxygen and carbon are the main low-Z impurities in present-day tokamaks. Contamination of the plasma by these loosely bound species can be reduced by proper methods of discharge cleaning.[2] High-Z impurities like chromium, iron, nickel, etc., are also of great concern, particularly since they are present in the plasma at much higher density than expected from theory. No *in situ* surface preparation techniques exist today for their reduction.

In situ surface analysis of the impurities on the walls just before and during the tokamak discharge is most important for a better understanding of processes related to plasma-wall interactions, discharge cleaning, recycling, and impurity transport. Laser-induced desorption of loosely bound species[3] combined with time-resolved spectral analysis of impurity radiation were used in this experiment to demonstrate a new powerful method for *in situ* surface analysis under realistic conditions, i.e., at any time during the discharge.

An unfocused "low-power" laser pulse of 2.5–3 J, ~25 ns full width at half-maximum, from a K-1500 Korad ruby laser was directed through a window towards the inner wall of the Macrotor vacuum chamber, Fig. 1. A surface spot of about 10 cm^2 is flash heated by the absorbed laser radi-

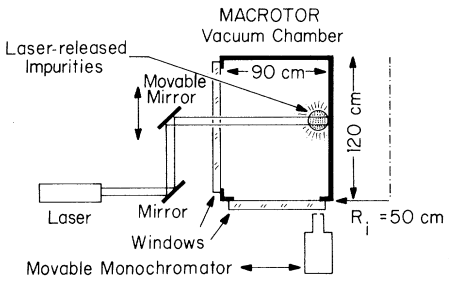

FIG. 1. Schematic of the experimental arrangement.

ation. Only a thin surface layer is heated since the skin depth for the high-frequency laser radiation is very small, of the order of 100 Å. After the laser pulse, heat conduction into the metal due to the initial steep temperature gradient reduces the surface temperature rapidly with a time constant of about 50 nsec. The surface temperature change of stainless steel as function of time has been calculated[4] for a 25-nsec rectangular laser pulse and an irradiance of 10 MW/cm². For a surface with a reflectance of 50%, the temperature increases during the laser pulse by approximately $\Delta T \approx 600$°K. No phase change and vaporization of the metal occurs for a 25-nsec laser pulse as long as the absorbed power density remains $\lesssim 80$ MW/cm². The flash heating leads to instantaneous thermal desorption of loosely bound species from the laser-illuminated spot. Atoms penetrating into the tokamak plasma are excited and ionized. The locally increased impurity radiation is easily detectable as the following discussion shows.

Typical impurity concentrations in tokamaks[5-7] are of the order of $\gtrsim 10^{11}$ oxygen atoms/cm³. Be proper discharge cleaning of Microtor and Macrotor, the amount of oxygen in the plasma of these tokamaks has been reduced to about 10^{10} atoms/cm³. By admitting controlled amounts of oxygen it was found that the surface density of oxygen corresponds then to about a fraction of 1/100 of a monolayer. A "typical" monolayer is assumed to have a surface density of 2×10^{15} atoms/cm². The impurity densities in the plasma and on the surface are linearly correlated as long as the surface density is less than a monolayer. For the surface conditions of Microtor and Macrotor as given by wall temperature, roughness, plasma temperature, hydrogen recycling, etc., only about 1% of the loosely bound oxygen available on the surface is found in the plasma. Potentially all the loosely bound oxygen, i.e., 2×10^{13} oxygen atoms/cm², can be released from the surface of a tokamak into the plasma. Thus, when a cloud of $N = 2\times10^{14}$ atoms suddenly released from the 10-cm² laser-illuminated spot has expanded to a volume of 1 liter, its density of $n_L = 2\times10^{11}$ oxygen atoms/cm³ is well above the background density of $n_b = 10^{10}$ oxygen atoms/cm³. The impurity radiation from this cloud should give a signal greater by a factor of $(\int_0^{10\,\mathrm{cm}} n_L dl)/(\int_0^{40\,\mathrm{cm}} n_b dl) \approx 5$ than the background radiation to the monochromator placed 5 cm from the wall, where the line of sight through the circular-cross-section Macrotor plasma of 45-cm radius is $l \simeq 40$ cm long. Such a fivefold increase of the signal coincident with the laser pulse is easily detectable with a monochromator which is scanning the volume in front of the laser-illuminated spot.

The desorbed atoms and molecules from the laser-cleaned spot will be adsorbed on other surfaces of the tokamak or pumped out of the machine. Recontamination of the cleaned spot between consecutive discharges seems to be negligible for the pressure and surface conditions of Macrotor.

A monochromator monitored the laser-induced intensity changes of the oxygen O II 4415-Å line, the carbon C III 4647-Å line, and the chromium Cr I 4275-Å line. The monochromator could be moved away from the inner surface of Macrotor in radial direction to study the impurity penetration into the plasma. The laser pulse could be fired at any time during the 30-msec tokamak discharge. Most measurements were done during a relatively quiescent period about 18 msec after onset of the discharge when the current reached its maximum value. A second monochromator measured as a reference the impurity radiation from the plasma emitted through the next port spaced 45° around the machine from the laser entrance port.

Most noticeable was the "cleaning effect" of the first laser shot on a new spot on the surface. Figure 2 shows the result of three consecutive shots onto the same surface spot. After a large outburst of oxygen, no detectable signal is recorded during the next shot. For the last shot the charging voltage of the laser amplifier capacitor was increased from 7.5 to 8.0 kV. This increase of the laser energy produces a small signal, see Fig. 2(c). The entrance slit of the monochromator was located 3 cm in the radial direction from the inner wall. A large-amplitude, short-duration signal is obtained in this position close to the wall, Fig. 2(a) [see also Fig. 4(a)].

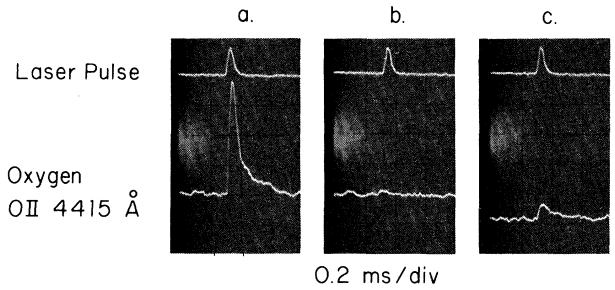

FIG. 2. Oxygen-impurity radiation from the tokamak plasma for three consecutive laser shots (a), (b), (c) onto the same surface spot. The laser energy was increased for shot (c). The monochromator viewed the plasma 3 cm away from the inner wall. The vertical position of the onset of the oxygen trace in (c) is arbitrarily shifted downwards in comparison to (a) and (b).

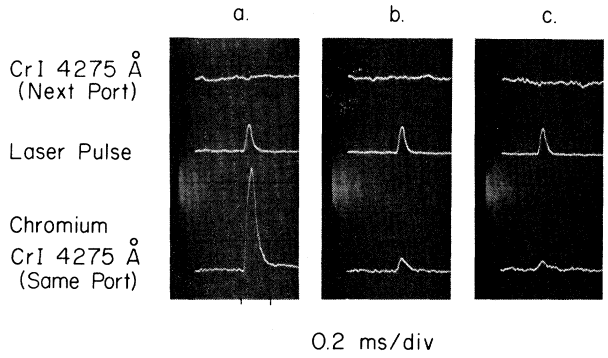

FIG. 4. (a) Large release of loosely bound chromium during the first laser shot onto a new surface spot. Depletion of chromium is indicated by the smaller signals of the two consecutive shots (b) and (c) onto the same spot.

Figure 3 shows a similar shot-to-shot depletion of carbon from a laser-heated spot. The first laser shot onto a new surface spot produces a large signal. The signal from the third consecutive shot onto the same spot, Fig. 3(b), is barely distinguishable from the background. In this case, the monochromator was placed 15 cm from the wall. A broadening in the signal can be seen with increasing distance from the wall as expected for an expanding cloud. The laser-induced C III 4647-Å line signal decreased rather abruptly in amplitude over the radial distance of 16–20 cm from the wall due to burnout of this line in the hotter regions of the plasma.

For chromium, Fig. 4 implies that it exists in loosely bound form on the stainless-steel surface of the vacuum chamber of the Macrotor tokamak. Again, the first laser shot onto a new surface spot causes a large chromium influx into the plasma. The much smaller signals of the second and third shot indicate that depletion of loosely bound chromium atoms occurs. We suspect that many of the sputtered chromium atoms, when returning from the plasma to the wall, are not located on lattice sites where they are tightly bound to the crystal structure. The total coverage of the surface with hydrogen and partial monolayers of oxygen, carbon, water, and methane probably contributes to the formation of a kind of amorphous form of chromium on the surface which is loosely bound. Since the chromium cannot be discharge cleaned and pumped from the tokamak like water and methane, the existence of such loosely bound high-Z impurities on tokamak walls increases the impurity problem considerably. The behavior of iron and nickel will be investigated in the near future.

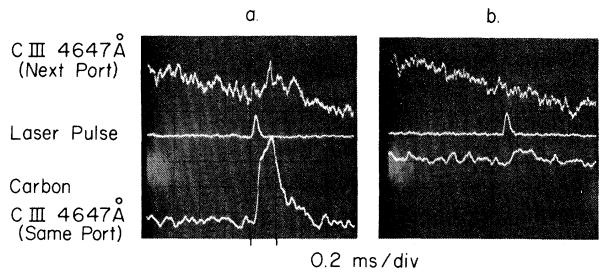

FIG. 3. Carbon-impurity radiation: (a) for the first laser shot on a new spot, (b) for the third shot onto the same spot. The lower trace records the C III emission from the plasma 15 cm in front of the laser-heated spot. As a reference the upper trace shows the C III impurity radiation at the neighboring next port of Macrotor.

In summary, we have reached the following conclusions: (1) We have demonstrated that laser-induced desorption combined with coincident spectroscopic measurements of changes of the impurity radiation represents an easily applicable method for *in situ* analysis of impurities present on tokamak walls during the discharge. (2) Even after hours of discharge cleaning, flash heating by a laser pulse seems to be very effective in desorbing loosely bound impurities from a surface spot. (3) The experiments confirm for the plasma and surface conditions of the Macrotor tokamak that only small fractions of the impurities available on the walls are present in the plasma. Consequently, the impurity problem may become worse with increased plasma and wall temperatures in future machines as the laser desorption experiment indicates. (4) A disturbing result of

this experiment is the observation that high-Z chromium impurities are present on the tokamak surface in a loosely bound form.

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[1]A. Gibson, Nucl. Fusion 16, 546 (1976).

[2]Lena Oren and R. J. Taylor, Center for Plasma Physics and Fusion Engineering, University of California at Los Angeles Report No. PPG-294, 1977 (to be published).

[3]F. Schwirzke, H. Brinkschulte, and M. Hashmi, J. Appl. Phys. 46, 4891 (1975).

[4]J. S. Polk, M.S. thesis, Naval Postgraduate School, June 1977 (unpublished).

[5]TFR Group, Phys. Rev. Lett. 36, 1306 (1976).

[6]E. B. Meservey *et al.*, Nucl. Fusion 16, 593 (1976).

[7]P. E. Stott, C. C. Daughney, and R. A. Ellis, Nucl. Fusion 15, 431 (1975).

Mercury Extrusion from Linear-Chain Mercury Compounds

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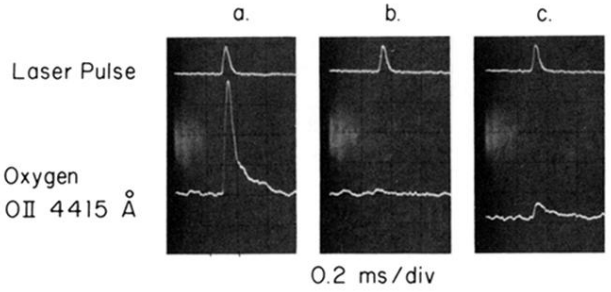
Evidence is presented from differential thermal analysis to show that mercury is extruded from the linear-chain mercury compounds $Hg_{2.86}AsF_6$ and $Hg_{2.91}SbF_6$ when cooled below 200 K. The anisotropic superconductivity observed recently in $Hg_{2.86}AsF_6$ is shown to result from extruded mercury.

A series of recent observations in the linear-chain mercury compound $Hg_{2.86}AsF_6$ have been interpreted as evidence of anisotropic superconductivity.[1,2] Although the critical temperature and critical magnetic field are very similar to those of pure mercury, it was considered improbable that metallic mercury is the source of such an extremely anisotropic and temperature-dependent effect. We report in this Letter the results of differential thermal analysis (DTA) of the linear-chain mercury compounds $Hg_{2.86}AsF_6$ and $Hg_{2.91}SbF_6$ which demonstrate the presence of metallic mercury at low temperatures. This mercury is extruded from the compounds when they are cooled below 200 K and is reincorporated into the compounds upon warming. The observed superconductivity in $Hg_{2.86}AsF_6$ is due to the extruded mercury and the observed anisotropy and temperature dependence follow naturally from our model of mercury extrusion.

The room-temperature crystal structure of both linear-chain mercury compounds consists of linear, nonintersecting mercury chains in a tetragonal array of AsF_6^- or SbF_6^- octahedra.[3] The mercury chains are situated in nonintersecting channels parallel to the a and b axes and are incommensurate with the three-dimensional host lattice. Short-range ordering along the mercury chains appears below 200 K.[4] Other measurements indicate that there is a change near 200 K in the coefficient of thermal expansion,[5] electrical resistivity,[6] thermoelectric power,[7] magnetic susceptibility,[8] and nuclear-magnetic-resonance relaxation time[9] and suggest the possibility of changes in the mercury chains or host lattice with temperature. The present work was undertaken to study these changes with the help of differential thermal analysis.

In DTA experiments, the difference in temperature between a sample and reference is measured as the temperature of their environment is varied at a continuous rate. The temperature of the sample depends upon the amount of energy absorbed or released by it. If, for example, upon warming the sample undergoes a phase transition at which latent heat is absorbed, the temper-



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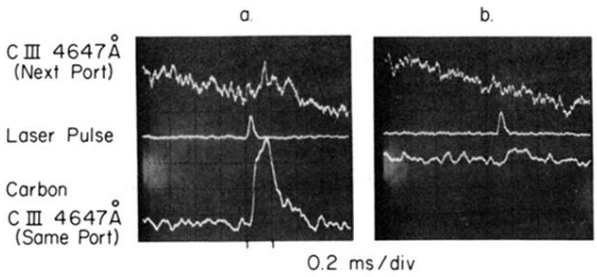

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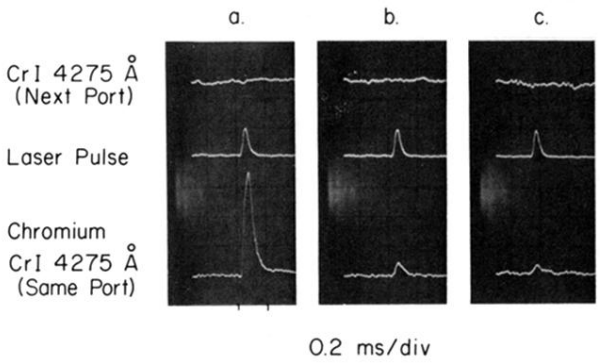

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