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INITIAL BORONIZATION OF THE DIII-D TOKAMAK

by

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Initial Boronization of the DIII–D Tokamak

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Abstract

A system has been installed to deposit a thin film of elemental boron on the walls of the DIII–D tokamak, in order to reduce the influx of impurities during plasma discharges. Subsequently new regimes of substantially improved tokamak energy confinement were obtained. The deposition of the boron layer is achieved during a glow-discharge session using a helium-diborane gas mixture and a film of $\approx$100 nm is deposited.

The boronization system includes special storage and handling precautions for the diborane, a delivery and metering system for the glow-discharge, modifications to the tokamak's residual gas analyzer system, and a dedicated system for handling and neutralizing the exhaust gas from the tokamak.

Tokamak discharges with similar parameters before and after boronization are used to characterize the effects of the boron film. Nickel has been reduced by a factor of 30, while impurities such as oxygen and carbon are reduced fivefold. A system of pulsing the glow discharge has been developed in order to improve the uniformity of the film applied.

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I. INTRODUCTION

Impurity control in plasmas is an important issue in the development of fusion power since impurities both dilute the hot plasma and cool it through radiation, lowering the fusion power yield. Recently a thin boron film has been applied to the plasma facing surfaces of DIII–D to reduce impurity influx. This process, called boronization, uses a glow discharge in diborane gas to apply the film and was first developed at Textor at KFA Jülich in 1988.[1] It has advantages over carbonization, where a layer of carbon is applied with a methane glow discharge,[2] because oxygen levels are reduced to extremely low levels with a simultaneous reduction in the levels of high-z metals such as nickel. These reductions remain for more than one hundred plasma discharges without a re-application of the film. The application of this technique to DIII–D has resulted in the identification of new operating regimes in DIII–D with energy confinement increased by a factor of 1.8 over previous results.

II. THE BORONIZATION SYSTEM

In order to carry out this process, the toxic gas diborane (B_2D_6) must be introduced into the tokamak vacuum vessel in a laboratory setting. Considerable attention was paid to safety, as diborane is immediately dangerous to life and health at 40 ppm and explosive in concentrations from 0.8 to 0.98%.

The boronization delivery system consists of a commercial toxic gas cabinet to house the diborane bottle and flow controllers, located some 100 feet from the DIII–D tokamak (Fig. 1). Two independent coaxial transfer lines, with the outer volume under vacuum, carry the gas mixture to injection ports at 135° and 300° toroidally. Absolute control is provided by gate valves at the DIII–D tokamak. The injection system can not only control the diborane flow to the DIII–D vessel but in

addition has the capability of providing a methane gas mixture using independent flow controllers so that a boron and carbon film can be applied. The gas is normally diluted to 10 percent in helium.

During boronization the tokamak exhaust system consists of one of the standard DIII–D turbo-molecular pumps (5000 l/s) backed by a Roots blower. The special diborane system foreline has a thermal decomposer operating at 700°C, followed by a water scrubber. The exhaust is then expelled from the building roof through a two inch vent, assisted by a small 20 CF/M fan. Oil used in the mechanical pump and Roots blower is a special PFPE (perfluoropolyether) type to avoid absorbtion of the diborane into the pump oil.

In order to evaluate the vacuum quality during boronization the residual gas analyzer (RGA) remains in service. Exhaust from the tokamak's RGA is sent through a water scrubber and vented to the roof. DIII–D's RGA has been modified to provide a low conductance path (0.05 inch orifice) to the tokamak, minimizing the RGA's throughput of diborane gas. This was done for two reasons, one to allow just a water scrubber to be used and secondly because hot filaments, as in an RGA, are pyrolytically coated by boron in the presence of diborane.

For safety a stationary air monitoring system samples four points in the building. It is sensitive to diborane concentrations of as low as 10 ppb. In addition, portable detectors sensitive to a range of toxic gases including diborane are carried during hazardous operations. Valve positions, pressures, and glow parameters are monitored and interlocked by the DIII–D vacuum system progammable logic controller (PLC).[3]

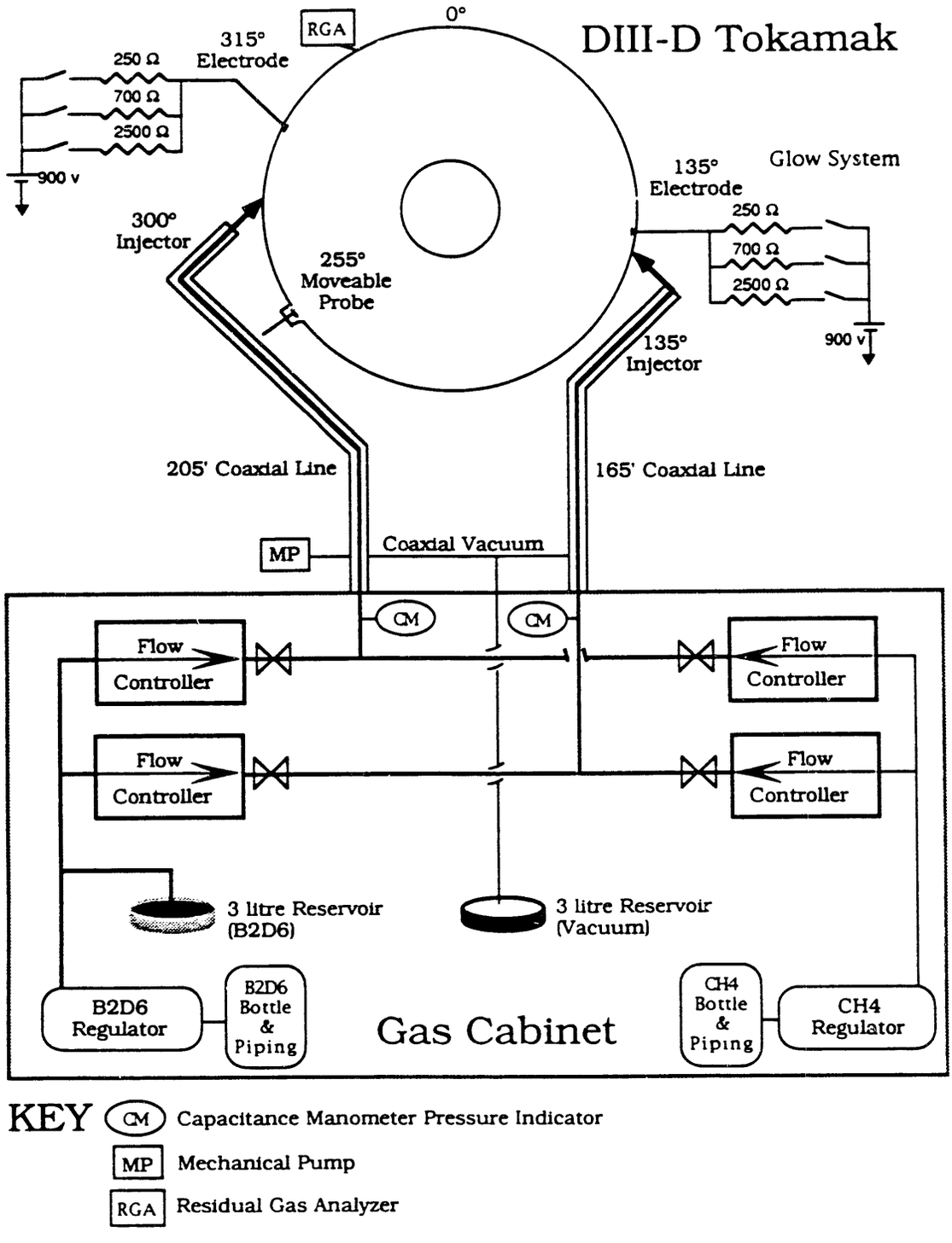

Fig. 1. A schematic view of DIII–D's boronization system showing the delivery system, and the glow electrodes, and sample probe locations.

III. THE PROCESS

In order to carry out the boronization, a glow is initiated in deuterium, and diborane gas, with He as the carrier, is injected into the DIII–D tokamak. The injected gas molecules are ionized and driven to the wall at the sheath potential, coating it with boron. The byproducts, mainly deuterium and helium, are pumped away by the special diborane pumping system. By injecting a combination of diborane and methane gas a film of boron and carbon may be deposited. To improve the film deposition the vessel walls are heated to 300°C.[4] A typical session consists of 3 to 4 hours of glow discharge, consuming some 30 to 40 grams of diborane.

The film is deposited using a glow discharge achieved with two electrodes spaced 180° toroidally shown in Fig. 1. Typical glow discharge parameters are 300 to 400 volts, with 3 amps of current drawn by each electrode, maintaining a pressure of 5–8 mTorr.[5]

In order to monitor the deposition of the film, samples are inserted to the plane of the outer wall, by means of an attachment to an existing DIII–D diagnostic probe. Depth profiles of the film samples have been made by Ar-ion sputtering and Auger Electron Spectroscopy.

Diborane is very easily ionized and thus has a short mean free path relative to the dimensions of the vacuum vessel. Initially only one gas injection point was used and it was noted after the first boronization that the deposition profile in the DIII–D tokamak was not toroidally uniform. During subsequent boronizations, the toroidal uniformity of the film has been improved by adding a second injector port and operating in a pulsed glow discharge mode. The second injector port was installed 165° toroidally from the first injector corresponding to a circumferential distance of 7 meters. Pulsed glow discharges have been achieved by cycling the glow current

from 6 to 0.6 A. This is done by controlling the resistance between the power supply and the glow anode. The purpose of the pulsed glow is to allow the neutral diborane pressure to increase nearly uniformly around the machine at a low glow current. Ideally this would be done with no glow discharge. However, glow discharge initiation is difficult without pressure, so the glow current is reduced instead. Once a more uniform diborane concentration is established, the glow current is increased to create enough ions to deposit the boron on the walls. An example of the diborane partial pressure during a pulsed glow is shown in Fig. 2 where the glow current is switched from 6 A for 20 s to 0.6 A for 20 s. Typical times are much shorter (5 s off and 2.5 s on but a longer time is chosen in Fig. 2 to illustrate the decay constant). Note that the time for the partial pressure of diborane to increase is 5.05 s, which is shorter than the characteristic pumpout time of the vessel with the diborane pumping system (approximately 20 s). This indicates that even at the low glow current, there is still some film deposition. Attempts to further reduce the low glow current by increasing the resistance have not been successful. When high current is initiated, the temporal behavior can be described by two characteristic decay times shown in Fig. 2, of 2.1 seconds and 17.9 seconds. Since the fast decay time probably corresponds to the depletion of the uniform neutral diborane density in the vessel, the high current glow time is chosen to be of the same order as the fast decay time (2.1 s) during normal operations.

With the improvements discussed above, the toroidal uniformity of the film has been increased. Auger depth profile analysis of samples inserted during the first and third boronizations are shown in Figs. 3(a) and 3(b) respectively. For the third boronization, a diborane-methane mixture was initially applied, producing a boron-carbon film, because its properties, partaiculary adhension to metal surfaces, are well characterized.[4] During the boronization process the methane flow was stopped,

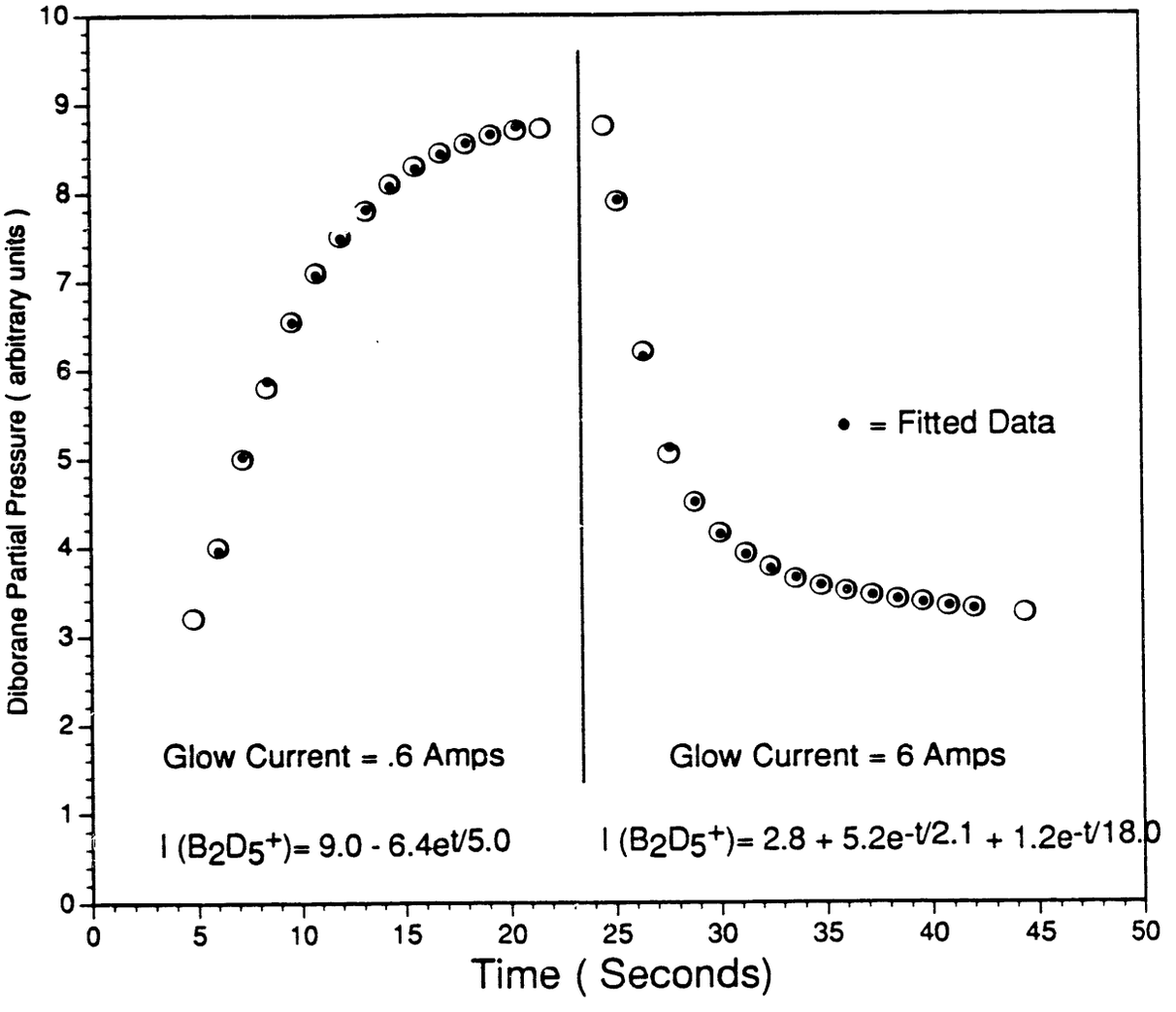

Fig. 2. The partial pressure of diborane in the DIII–D tokamak during a pulsed glow, as measured by the residual gas analyzer. The partial pressure rises during the low current phase of the glow, and then decays rapidly during the high current phase. Fitted data are overlayed on the experimental data showing good agreement.

producing a relatively pure boron film near the surface as shown in Fig. 3(b). A pure boron film exposed to plasma discharges can produce lower radiated power and lower Z_{eff} tokamak discharges than a B/C film.[6]

Since the thickness of the films is roughly proportional to the sputtering time, the film thickness at the probe location, has increased by a factor of 3.5 over the first boronization. Although the third boronization consisted of a boron/carbon film while the first boronization was only a boron film, the percentage of boron (purity of the film) deposited at the plasma facing surface of the sample was significantly higher after the third boronization, this is probably because the use of two gas injection points and pulsed glow, a more uniform film.

A cross-sectional electron micro-photograph of the film is shown in Fig. 4. There are three regions which can be readily observed: the silicon substrate, the boron carbon region, and the pure boron region. This is consistent with the Auger analysis shown in Figs. 3(a) and 3(b). It should be noted that the the thickness of the film, 347 nm, is not representative of the surrounding plasma facing surfaces because the surface probe was inserted in a large port. Since the probe was at the wall potential, it tended to concentrate electric field lines from the glow sheath potential, producing a higher particle flux to the probe than to the surrounding walls.[7] For similar glow discharge parameters this flux enhancement should be approximately constant, allowing the comparison between the first and third boronizations discussed above.

Following the boronization session an eight hour bake (T av = 350°C) was used to help desorb the deuterium from the deposited film. However after the fourth and fifth boronization this post-boronization bake was eliminated. It has been found that a 30 minute session of helium glow is sufficient to allow tokamak discharges with low wall recycling.

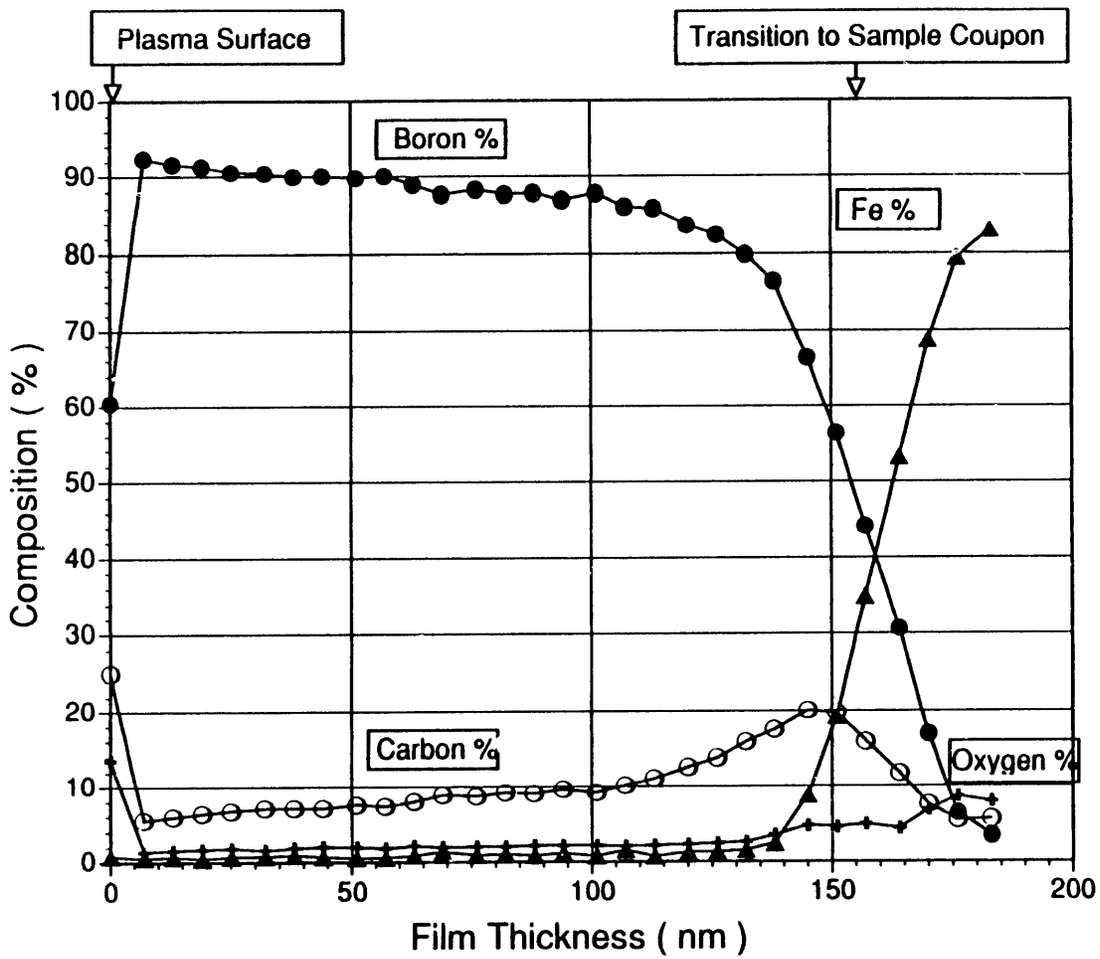

Fig. 3(a). The film composition as measured by Ar-Ion Sputtering techniques examining a sample coupon inserted to the plasma facing wall during the first boronization of DIII-D. The film is over 90% Boron near the surface and remains relatively pure the sample coupon material (Fe) is identified beneath the coating. The film thickness is approximately 100 nm.

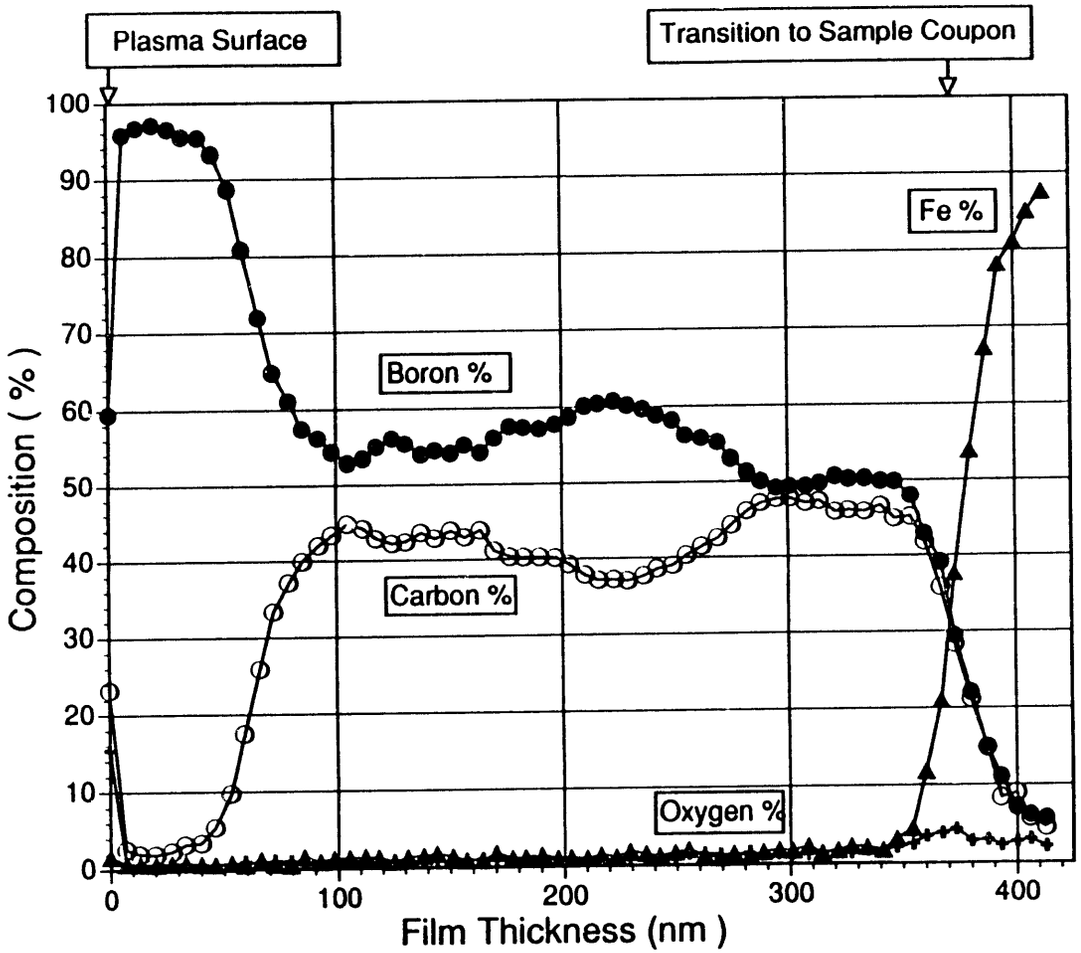

Fig. 3(b). After the third boronization the composition of the film shows even higher purity (96% Boron) near the surface, changing to a boron/carbon mixture during the diborane/methane gas mixture phase of the boronization session, and finally a transition to the material (Fe) of the sample coupon. Film thickness is approximately 347 nm.

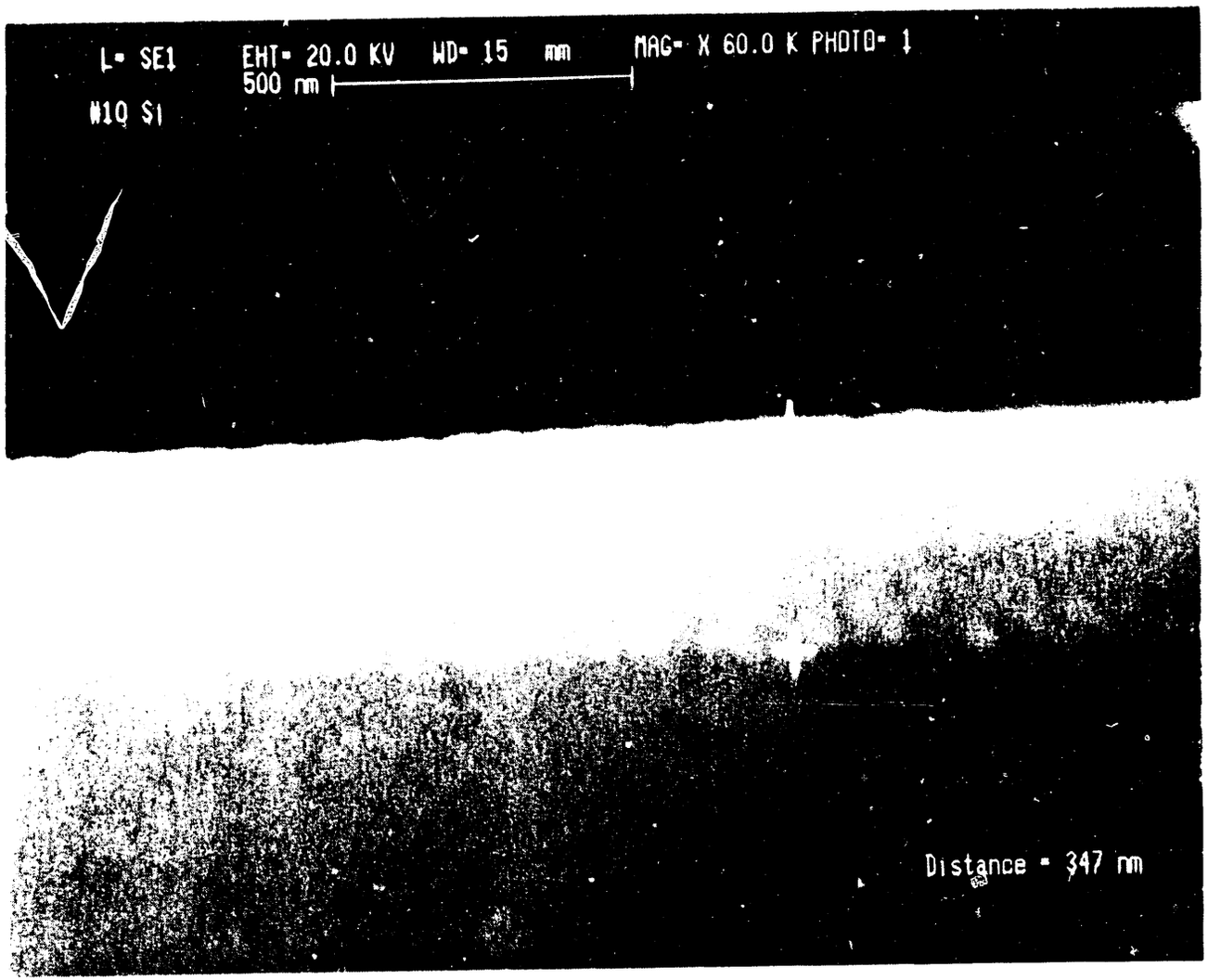

Fig. 4. A photograph taken by scanning electron microscope (SEM) showing the sample film thickness after the third boronization to be 347 nm.

IV. RESULTS

After boronization the impurities in the tokamak discharges were reduced. This is inferred from impurity line UV radiation. An example of the impurity reduction in shown in Fig. 5 for similar beam heated tokamak discharges ($B_T = 2.1$ T, lower single null divertor, $D^\circ \rightarrow D^+$). It can be seen that carbon is reduced by a factor of ~2–5, oxygen by ~10 and nickel by ~10–30. This reduction in impurities is observed to last for over 100 discharges, although a modest increase in nickel impurity radiation is observed during post boronization discharges. The source of this nickel contamination is presently being investigated.[8]

After the boronization a new regime of very high confinement (VH–mode) was observed with energy confinement times a factor of 1.8 above the previous DIII–D H–mode scaling relation.[9] VH–mode had not been observed during the previous 5 years of DIII–D operation before boronization. VH–mode discharges are also characterized by reduced impurity radiation, neutral pressure, and Z_{eff} when compared to similar discharges before boronization. Boronization has also produced reliable operation at lower densities than were previously possible.

Reduction of impurities related to the antenna is also very important for our ICRF experiments. The second diborane gas inlet was located near the antenna to assure good coating of the antenna and near by protective tile surfaces. Subsequent experiments indicated a reduction of impurity influx during ICRF experiments. The indicated reduction in the minimum plasma density is also important to these experiments.

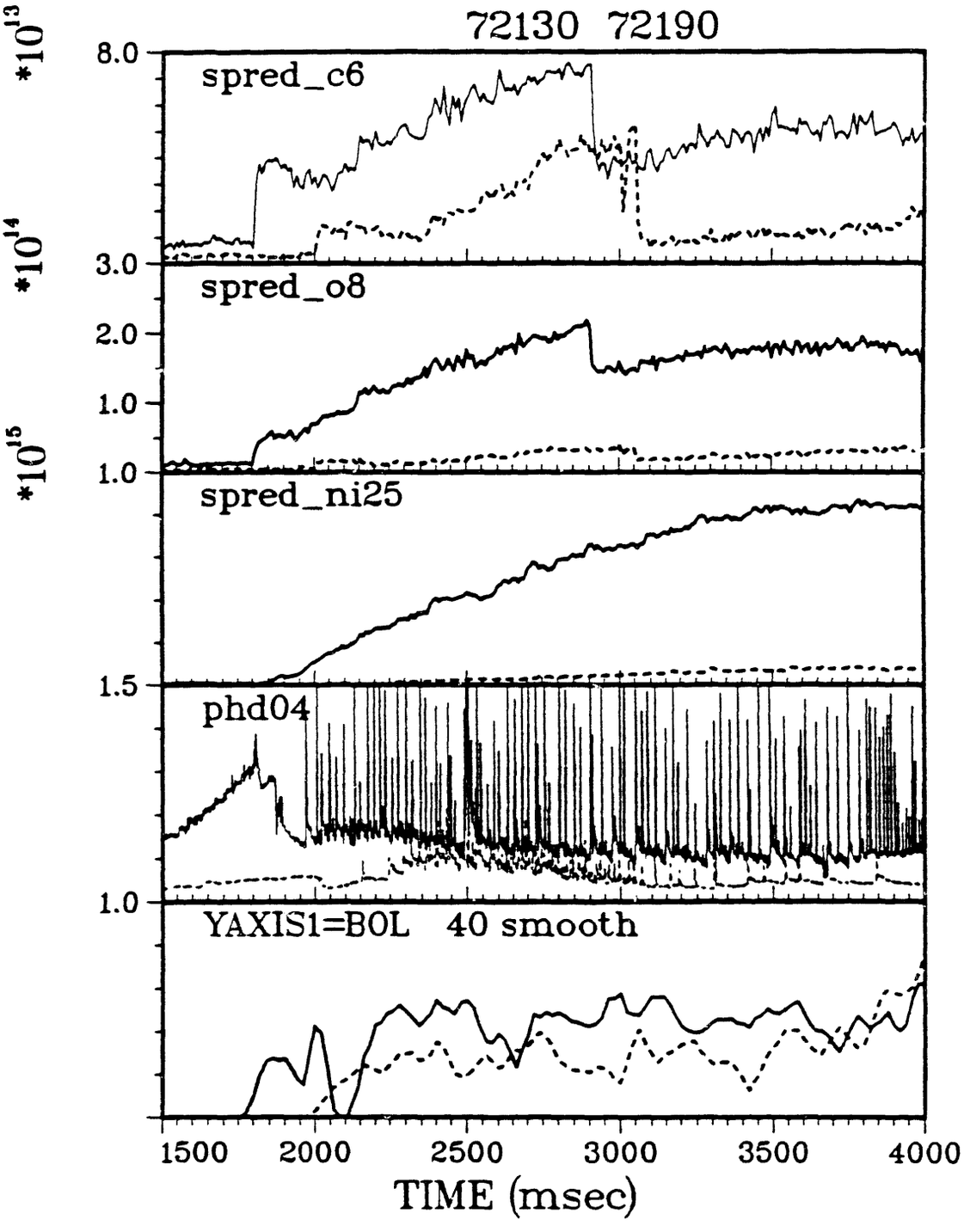

Fig. 5. Nickel, Carbon, and Oxygen are significantly reduced for tokamak discharges after boronization, compared to pre-boronization discharges with similar parameters. In addition D_α line radiation measured by a photodiode array is reduced, indicating reduced recycling from the plasma facing components. Radiated power is also reduced.

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