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Solid target boronization of the MST reversed-field pinch during pulsed discharge cleaning

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Abstract

A solid rod of hot-pressed boron carbide is currently being used as the source of boron during boronization of MST. In previous work we have demonstrated that boronization can be effectively accomplished by insertion of a low apparent density B_4C rod into the edge hydrogen plasma of normal high-power RFP discharges. We have now extended that technique and can boronize MST by inserting a negatively biased B_4C rod into pulsed discharge cleaning (PDC) helium plasmas. The same positive results of reduced impurity contamination and particle reflux are achieved with this new boronization method. The bias for the target is provided by the ohmic heating transformer which is pulsed to produce the PDC discharges. Current flow through the B_4C rod is limited by an inductor. The amount of hydrogen in the amorphous boron carbide films is minimal because the only hydrogen in the PDC plasma is that left over from RFP discharges.

1. Introduction

We have demonstrated on the MST reversed-field pinch (RFP) that solid target boronization can be done by inserting a negatively biased boron carbide rod into pulsed discharge cleaning (PDC) helium plasmas. In previous work we have boronized MST by inserting a low apparent density B_4C rod into the edge hydrogen plasmas of normal high-power RFP discharges (Den Hartog [1]). Solid target boronization (Hirooka [2]) has the same positive effects (primarily lower plasma impurity content) as plasma assisted chemical vapor deposition (gas boronization) [3–7], but is safer, lower cost, and can be performed such that no hydrogen is trapped in the wall coating during formation.

The MST RFP is a high temperature (electron and ion temperatures ≤ 500 eV), high plasma current ($I_p \leq 700$ kA), moderate pulse length (60 ms), large ($R = 1.5$ m, $a = 0.52$ m) plasma confinement device [8,9]. The primary plasma facing surface is aluminum; a small amount of this surface (about 10%) has been covered with a combination of graphite and ceramic tiles and limiters that protrude out from the wall less than 2.5% of the minor radius. The plasma must be allowed to closely approach the 50 mm thick aluminum conducting wall of the vacuum confinement vessel (VCV) in order to insure MHD stability (Ho [10,11], Alper [12]). Helium and/or hydrogen pulsed discharge cleaning (rapid repetition of short, low energy plasma discharges—a variation of the technique known as "Taylor discharge cleaning" [13]) is used to remove impurities from the wall after the vacuum vessel has been opened to the atmosphere. However, even lengthy pulsed discharge cleaning failed to lower oxygen contamination of RFP plasmas below a few percent [14]. Our initial work on solid target boronization of MST consisted of inserting a hot-pressed B_4C (78% boron by weight) rod into the edge plasma of RFP hydrogen discharges [1]. Auger analysis revealed that the a-B/C:H coating formed compared favorably with those made by gaseous boronization. Impurity contamination (most notably oxygen) of the plasma was reduced and wall-refueling of the discharge was dramatically lowered. During these experiments we noted that ablation of boron did not begin until the rod had absorbed a heat flux of about 10 W/mm^2 integrated over 25 ms.

Once MST has been boronized, it is possible to maintain the coating by retracting the B_4C rod into edge scrape-off region and allowing a small amount of boron carbide to be ablated into the plasma during

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every RFP discharge. This type of coating maintenance is almost automatic since it requires no monitoring by the MST operator and does not perturb the plasma. However, actual formation of the a-B/C:H film during high-power RFP discharges does require monitoring of the target insertion depth and plasma parameters to prevent excessive ablation of the rod during a single shot. The next step, then, was to develop an automatic method of building up the a-B/C:H film. Since MST is regularly pulsed discharge cleaned, these plasmas were an obvious venue in which to perform boronization.

Our initial attempt to boronize during pulsed discharge cleaning was simply to place a B_4C target in the 3 msec, 100 kA pulsed discharge cleaning (PDC) plasmas (Fig. 1) that are run every night on MST on a five second cycle time. Positive results such as lowered impurity content and less wall fueling were achieved in subsequent RFP discharges, but the effects were not dramatic. Auger analysis of aluminum surface samples placed flush with the wall failed to reveal any coating of boron. We concluded that PDC discharges alone are not robust enough to provide the integrated power flux necessary to produce substantial ablation of the boron carbide target. Thus, we developed a method to deposit power in the target by drawing current to it from the plasma.

2. Solid target boronization in PDC

In order to increase the power to the boron carbide target during a PDC discharge, it is biased negatively with respect to the conducting wall boundary of the

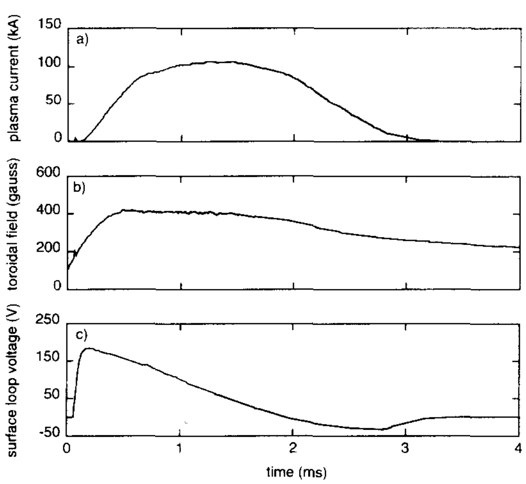

Fig. 1. A typical PDC discharge on MST: (a) the plasma current, (b) the average toroidal magnetic field, and (c) the toroidal surface loop voltage.

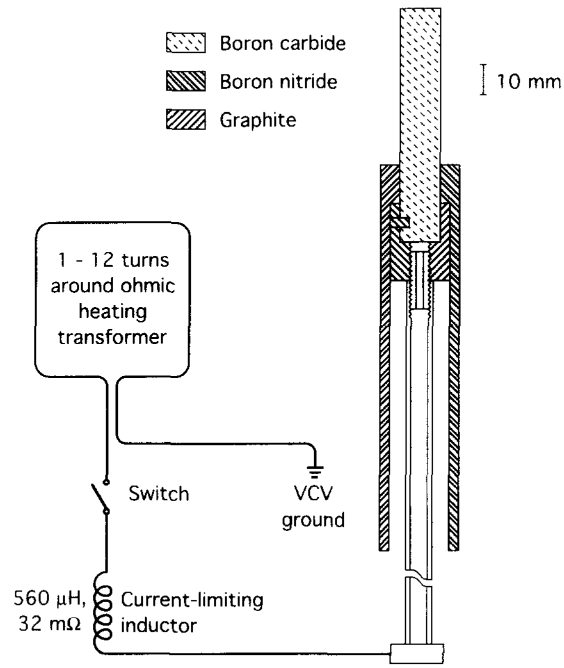

Fig. 2. The B_4C rod holder and bias circuit as configured for PDC boronization.

MST plasma. A bias of several hundred volts enhances the heat flux to the target and results in effective ablation.

The obvious source of power to bias the target was the ohmic heating transformer which is pulsed to produce the PDC discharges. The biasing system we have constructed consists of several secondary windings around the ohmic transformer core and a small inductor to limit current flow through the B_4C rod (Fig. 2). The number of secondary windings can be adjusted in order to maximize ablation without causing catastophic damage (cracking) to the target. Note the long boron nitride shield which begins at the base of the B_4C rod and continues down well below the B_4C holder. This shield prevents current being drawn from the PDC plasma or the VCV to the holder.

Solid target boronization in PDC is typically done overnight in MST. This was easy to implement as the PDC system is automated and produces approximately 10^4 discharges over a typical night of operation. The B_4C rod is inserted deeply into the plasma, about 10 cm beyond the limiter. The negative bias voltage resulting from five secondary turns around the ohmic transformer core results in a satisfactory ablation rate of the target. Bias voltage and target current waveforms are shown in Fig. 3 for the PDC discharge illustrated in Fig. 1; peak current is 440 A with a corresponding voltage of 230 V. Note that the waveform of the target current nicely matches the PDC plasma current wave-

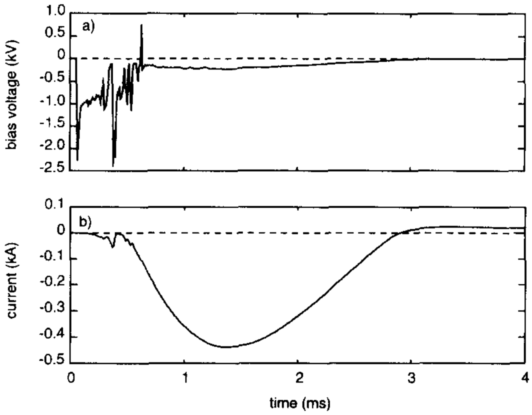

Fig. 3. (a) Bias voltage and (b) current to the B_4C target during the PDC discharge illustrated in Fig. 1.

form, with no current flowing to the target until the PDC plasma is established.

Biasing the target positively with respect to the VCV ground does not produce satisfactory ablation. Positive bias appears to draw a diffuse electron current over the surface of the rod. On the other hand, negative bias often results in visible (and often spectacular) ablation, probably due to the mechanical impact of the helium ions on a localized area of the rod (Fig. 4). Visual inspection of the rod after a boronization session reveals the presence of many small (500 μm wide by 100 μm deep) "craters" on the surface of the rod (Fig. 5). There is no evidence of major damage and only a small fraction of the rod is ablated away during a PDC session.

As can be seen from Fig. 3, during the peak of the PDC discharge, over 100 kW of electrical power is flowing to the rod, usually concentrated in the small area craters mentioned above. Integrated over the PDC pulse, this means that typically 100 J are deposited in the rod. Even if only a small fraction of this energy goes to heating the surface of the rod, it is certainly large enough to reach the ablation threshold of ~ 250 mJ/mm^2 of surface heating noted during our solid target boronization experiments in RFP plasmas.

3. Discussion

High-power RFP discharges following PDC solid target boronization exhibit reduced impurity contami-

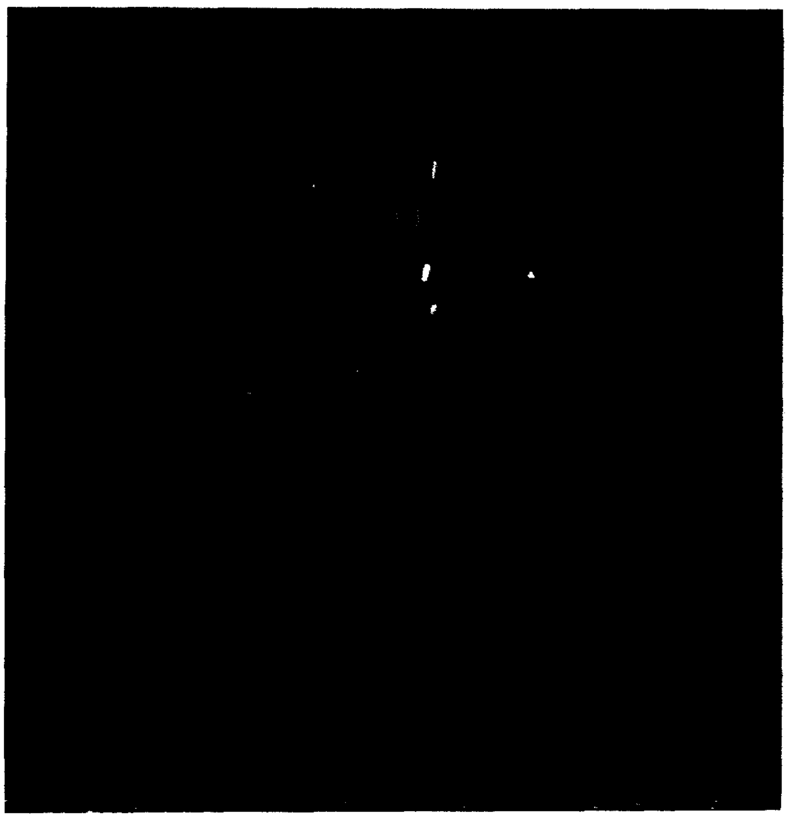

Fig. 4. Ablation of the B_4C target during a PDC discharge.

nation and particle reflux. The magnitude of the improvement is similar to that achieved previously from boronization done during RFP discharges [1]. Since that work was done we have noticed a new phenomena associated with boronization of MST. It appears that sawtooth events in RFP discharges are suppressed when MST is well-boronized [9,15]. A discharge exhibiting a long sawtooth-free period is shown in Fig. 6. Both radiated power and ohmic input power fall to about 30% of levels typically observed on MST during a normal sawtoothing discharge. Study of this phenomena continues since the mechanism responsible for sawtooth suppression is not yet known.

Fig. 5. The surface of the B_4C target after many PDC discharges. Note the craters caused by ablation events such as those shown in Fig. 4.

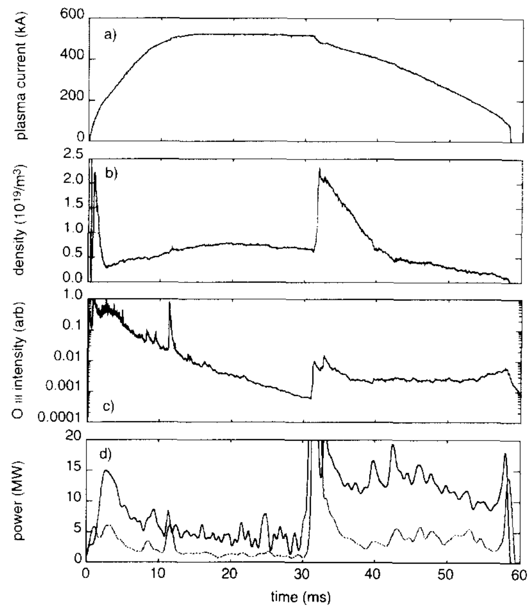

Fig. 6. An RFP discharge in MST with a long sawtooth-free period (12 to 30 ms), obtained after an extensive session of PDC boronization: (a) the plasma current, (b) the line-averaged electron density, (c) the OIII (375.99 nm) intensity, and (d) ohmic input power (solid) and radiated power (dashed). Note the large sawtooth event at 30 ms that terminates the sawtooth-free period.

In the immediate future for the MST solid target boronization system is installation of additional biased solid target holders. This system will be fully automated and will allow simple and quick PDC boronization of MST. We also hope to examine the possibility of graphite fiber meshes as a matrix to hold elemental boron for release into the plasma [16]. Such targets may have higher thermal shock resistance and better electrical conductivity than the hot-pressed B_4C rod we currently use.

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