Report on the Status of the C-Mod Lower Hybrid Couplers 5/23/2005

A new lower hybrid launcher built in collaboration with PPPL was installed on Alcator C-Mod in January of 2005. The grill for this launcher consists of four coupler modules, each with 24 waveguides and windows (Figure 1). The launcher, installed in-vessel along with the lower hybrid limiters, is shown in Figure 2. The couplers were fabricated out of 6242 titanium alloy which was picked primarily for its approximate thermal expansion match to the alumina material used for the vacuum windows. Since plasma operation resumed in February, over 200 kW of lower hybrid power has been coupled to the plasma. Scans of relative waveguide phase ($N_{||}$) indicated excellent agreement with the predicted coupler performance. However, video images of the launcher couplers often showed injections of material (dust) from the couplers (Figure 3). These effects appeared to improve with operation of the lower hybrid system and were considered part of the coupler conditioning process. On May 1st C-Mod was brought up to 500 Torr D_2 so that an edge Thomson scattering calibration could be performed. This calibration was unsuccessful because the scattering signal from dust in the vessel dominated the calibration signal. Two previous calibration backfills also indicated large amounts of dust in the machine, but the source of the dust could not be tracked down. Inspections of windows that could be isolated from the vessel with gatevalves showed small amounts of Ti and Mo, but the Mo levels were very low compared to previous campaigns. On May 2nd, the third boronization of the run campaign was performed. This boronization concentrated on the antennas and limiters (and therefore the launcher) to a greater extent than previous boronizations.

When plasma operation resumed on May 3rd plasma performance had greatly degraded and, at first, only short plasma discharges could be produced. This problem was quickly traced to large amounts of dust being injected into the plasma. Spectroscopic measurements indicated the importance of titanium in the plasma. A large fueling source, presumably gas liberated from the dust, prevented density control of the discharge. Video images of the launcher raised the possibility that a large amount of dust had been liberated from the coupler surfaces, and that the dust was partially filling the bottom sections of the waveguides (Figure 4). As the run week proceeded, plasma performance improved and fewer injections of dust from the launcher were observed. Deleterious effects on plasma operation had been noted on the first run day following the second Thomson scattering calibration backfill on March 5. In retrospect, the behavior, including observation of dust and in-vessel fueling, was quite similar to, though much less severe than, the observations on May 3-6. These *March* observations were made prior to any boronizations or operation of the LH antenna.

On the evening of May 6th, several hours after the last run day of the week, a significant vacuum leak opened up through the lower hybrid launcher. This leak necessitated removal of the launcher. To minimize the intrusion of water vapor, which would have prolonged the plasma cleanup process, the vessel was brought up to argon, the port and launcher were covered by an argon purged bag, and the launcher was removed. While still purging the vessel with argon, as much dust as possible was vacuumed from the machine, and the machine was then pumped down.

Using SEM/EDS analysis techniques, essentially all dust removed from the launcher and from the vessel has been shown to be the titanium alloy used for the couplers. Only trace amounts of other elements have been found (e.g., boron and molybdenum). Approximately 15 grams of titanium dust was vacuumed from the vessel, and larger amounts are expected to be removed from the launcher as the analysis of the coupler components proceeds. The EDS analysis technique does not allow for the detection of deuterium, so it is possible that much of the material recovered is in fact TiD_2 . Other analysis techniques are currently being used to quantify the amount of deuterium in the dust samples.

As can be seen in Figures 5 and 6, serious erosion of the coupler surfaces has been found. Erosion of the channels extended deep into the waveguide and, in some cases, dust was found piled up against the alumina vacuum windows (approximately 10 cm from the coupler face). Many grams of titanium have been eroded from the surfaces. The septa which separate the waveguide channels have been badly eroded, and in several locations, removed several millimeters back into the guide.

It is not clear what the relative contributions from the D_2 backfills, boronizations, routine ECDC, or plasma operation were to the damage observed. Titanium is known to form hydrides when the oxide layers protecting the surface are removed, and the titanium is exposed to hydrogen at elevated temperature. We have done tests of the titanium alloy used in the couplers in which the sample was etched to remove the oxide, placed in vacuum, baked, and then exposed to a 500 Torr D_2 backfill for 24 hours at 60^o C. This sample showed no deleterious effects from the deuterium. However, the components in-vessel could have gone to higher temperatures in a deuterium background during plasma operation or during the boronization process. Both standard ECDC (in deuterium), which is typically run each evening following a run, and normal plasma operation could have removed the oxide layer from the titanium and made it more susceptible to the background deuterium during the Thomson scattering calibration backfills. A possible scenario is that the deuterium reacted with the titanium to form TiD_2 which is less dense than the titanium base alloy and would cause spalling at the grain boundaries. The dust removed from the vessel was typically less than 15 μm in size, which is consistent with the grain size expected in the titanium.

Though understanding the nature of the coupler damage is of interest, our primary effort is now concentrated on working with PPPL to replace the four couplers. No titanium will be allowed in the new design, and only materials that have been successfully used in C-Mod over the lifetime of the machine are being seriously considered (e.g., inconel, stainless steel). Low temperature brazes and ways to restrain the materials during brazing to limit the CTE effects are being modeled, and prototypes are being prepared. After the launcher is fitted with new couplers, it will be reinstalled into the torus.

Tokamak operations resumed on May 19, 2005. On the second day of operations (May 20), routine full length 1 MA discharges with ICRF H-modes were being produced, titanium levels in the plasmas were significantly reduced, and there was little evidence of the effects of dust on the discharges.

Figure 1. Four titanium couplers arranged as they would be installed

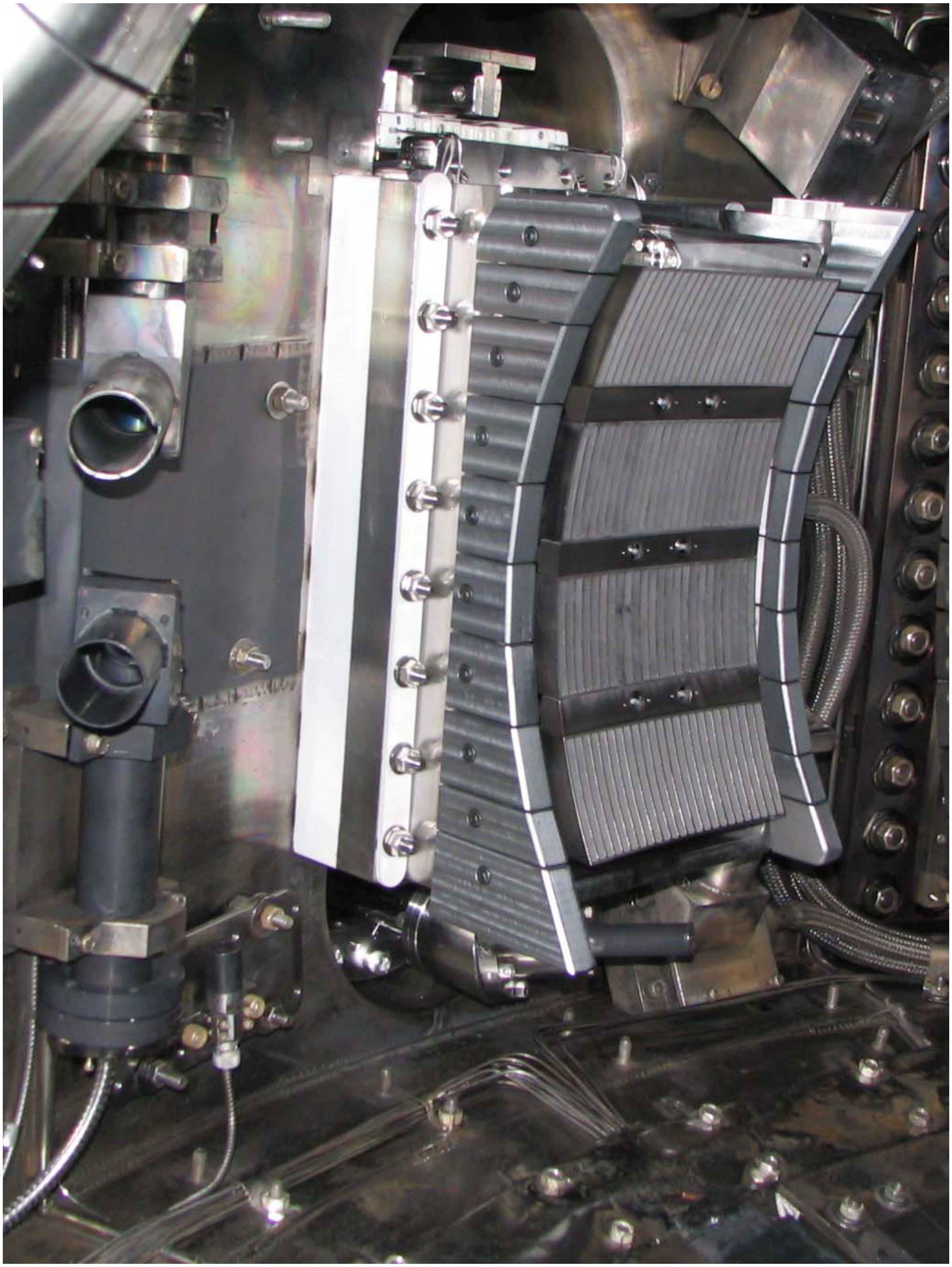

Figure 2. Grill and lower hybrid limiters after January installation

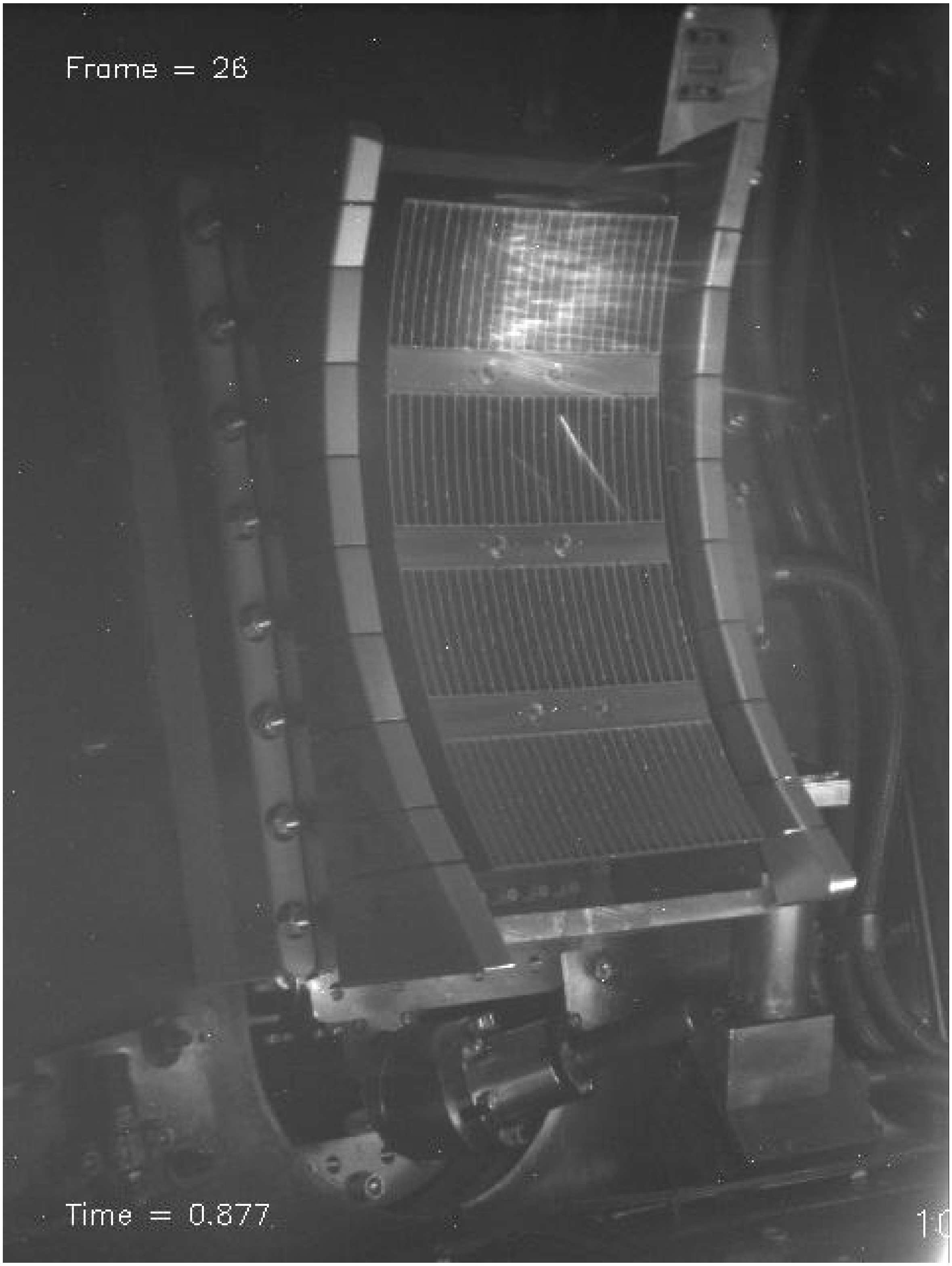

Figure 3. Injections of dust or sputtered Ti during lower hybrid conditioning

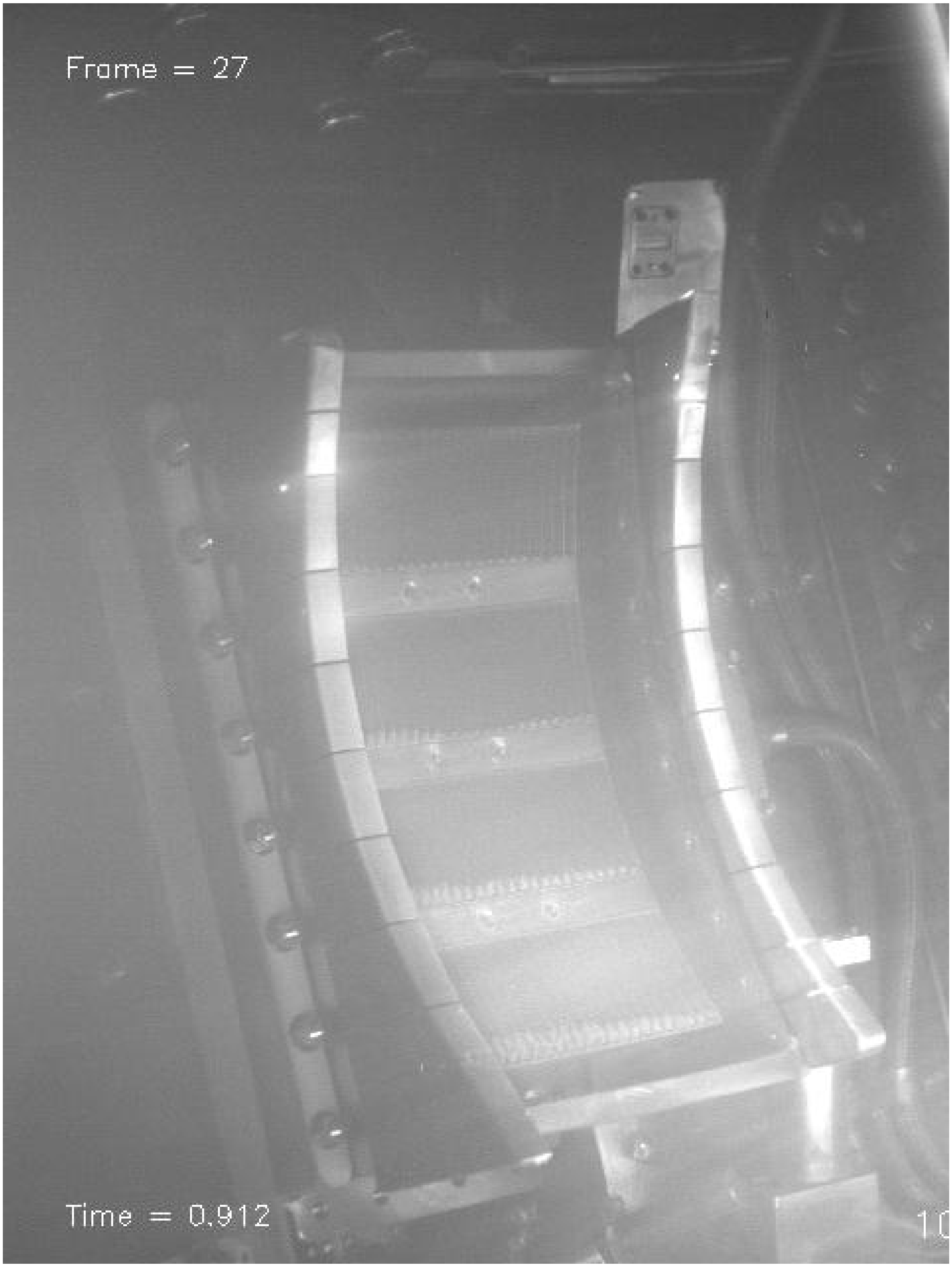

Figure 4. Debris (dust) can be seen at the bottom of the waveguide channels following the third backfill and boronization. Contrast this view to figure 3.

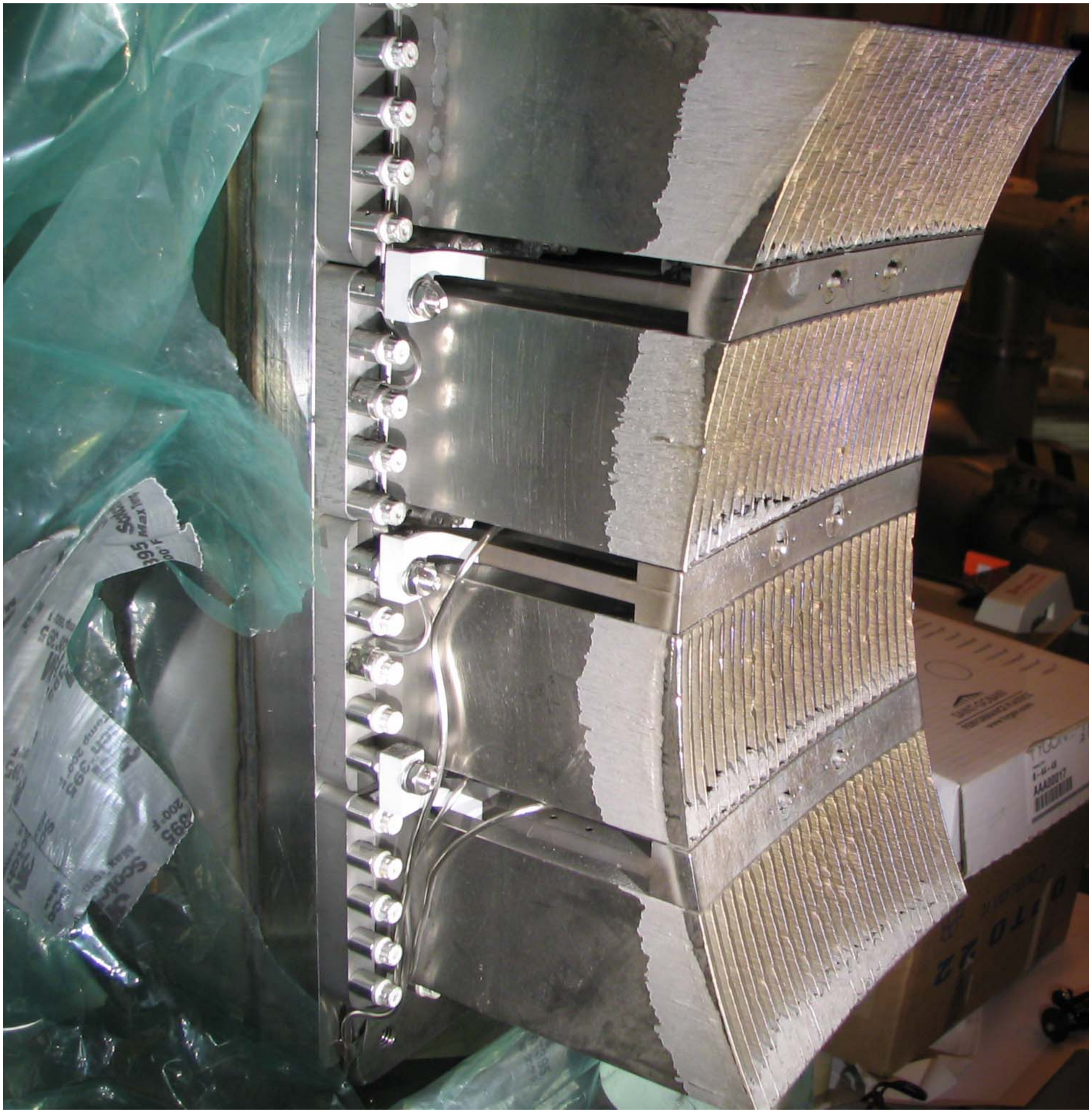

Figure 5. Side view showing affected area extended well behind face of grill. Debris in waveguides can also be seen.

Figure 6. Front view shows debris extending well into guides. Erosion of the septum between guides clearly shown.