DS2 Structure Autopsy†

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Abstract
Cells of the NLCTA DS2 structure were removed from the tunnel and sectioned for microscopical examination. The purpose was to relate surface condition to observed surface electric field limitations. Significant electrical breakdown damage was found, most prominently on the furthest upstream cells.

1 Introduction
Observed limitations to the surface field gradient in the DS2 structure were speculated as being due to breakdown damage, leading to copper (mass) loss. This mass-loss then leads to an incorrect phase advance. To test this theory, a section of the structure was removed for microscopic analysis by secondary electron microscopy (SEM) and energy-dispersive x-ray spectrometry (EDX).

2 Experimental Details
After removal from the accelerator housing, the structure cells were segmented by clean dry hack-sawing. Excess metal chips were shaken loose and the cells individually wrapped in lint-free paper.

A description of the SEM and EDX analytical techniques may be found in the Appendix. Images and x-ray spectra were collected at 15 keV primary beam energy. Images for each cell are presented for 100X and 1000X magnifications, to facilitate direct comparison between cells. Images that contain EDX spectra consist of low and high mag views with a spectrum below.

Figure 1 shows the cell cross section as well as the SEM electron beam orientation for perpendicular beam incidence imaging. The cells are manufactured from OFE copper with the iris disk having been diamond-turned.

Cell 8 is discussed in detail because it is the lowest upstream cell and shows the most breakdown damage. Cell are referred to as “upstream” and “downstream”, relative to the accelerator beam direction.

3. Results
Cell 8, Upstream:
Figure 2 A, B and C are a series of SEM perpendicular beam incidence images for Cell 8.

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The general breakdown damage observed is typical for all examined DS2 cells but the damage is most severe for low number (upstream) cells. An in-situ measurement of the damage shows that the majority of “hits” are occurring within about two mm of the inside edge of the iris aperture (specifically, 2.36 ±0.37 mm for cell 8).

The topographic appearance of breakdown sites ranges from single “hits” to more extensive multiple strikes at the same site, of the type exhibited in Figure 2C. The sites are typical of those observed on other high surface field electrodes, namely

1) Sites cluster in high field areas; in this case, within 2mm of the iris ID;
2) Sites are randomly distributed within the high field area for well-degassed material;
3) Sites rarely contain foreign material (by EDX examination) that could be the breakdown initiator.

A few strikes were found at grain boundaries, Figure 3 for example, but those are infrequent. Quite the opposite has been observed on non-degassed electrodes in the past where gas leaving the grain boundary participates in a plasma-sustained breakdown. Interesting sites were routinely measured with EDX for the presence of foreign material but mostly showed only copper. Some carbon and oxygen at sites are usually detected but at levels that are equal or lower than those on the surrounding undamaged cell surface.

To get a more direct look at the iris ID, Cell 8 was tilted up 40°. The resulting image, Figure 4, of the iris ID shows, again, a randomly distributed pattern of sites. There does not appear to be a clustering of sites at the equator of the iris. Some debris is evident, as it was on all cell surfaces. Typical debris was composed principally of carbonaceous fragments, with some copper shards (probably from the sawing process) and concrete and alumina particles.
Small particulate debris is mostly carbanaceous in nature.

Cell 8, Downstream:

All remaining images in this document are taken at perpendicular electron beam incidence. Figure 5 A, B and C show the downstream side of Cell 8.

The site density is somewhat lower than the upstream side of Cell 8. The site imaged in Figure 5C was particularly interesting because of voids formed by the material pileup action of multiple breakdowns. This cell also showed the presence of carbon spots, not located on any of the other cells documented in this paper. The spotted area begins about 0.5 mm in from the iris ID and extends out about halfway on the iris radius. EDX examination of the spots in Figure 6 show them to carbon-rich compared to the unmarked areas nearby. The source of these carbon spots is unknown.
Figure 6. Image and EDX spectra of carbon–spotted area on Cell 8, downstream. The spectrum was collected from the spot marked by the white box in the right-hand image. The carbon signal was much lower in the light-colored copper areas nearby.

Also found on Cell 8, downstream, was the presence of saliva residue, potassium chloride. A series of increasing magnification pictures of the residue is presented in Figure 7. The residue is on top of breakdown sites and, therefore, appeared after cell removal for sectioning.

Figure 7. Residue of saliva at increasing magnification. Iris ID is located at left in “A”. The spectrum in “C” was collected from the area marked by the white box in the right-hand image.

*Other Cells:*

The remaining cells that were examined are mostly shown without extensive comment, as most of their features are similar to Cell 8. Exceptions are noted in the figure captions.
Cell 20, Upstream. Detail of iris ID is shown in next image.

Cell 20, Upstream. This site is very near, if not on, the iris equator. The site material is wholly copper.

Cell 20, Upstream. The interesting feature near the iris ID, on the right is magnified below.

Cell 20, upstream. The black residue appears to be melted into the site. EDX identified its remains as carbon.
Cell 20, Downstream. The site density is lower than earlier cells, but the damage on the iris equator is just as interesting.

Cell 20, Downstream. This cell exhibited significant mechanical wiping damage. It had both mechanical scratches and carbon residue, on top of breakdown sites. The black areas are carbanaceous, possibly from lint-free or tissue paper.

Cell 20, Downstream. Again, the site material is copper.

Cell 78, Upstream. Similar site density to Cell 20, without the mechanical damage.
Cell 78, Upstream. Again, there is site material above the original surface elevation, at the iris equator in this image.

Cell 78, Downstream. Many fewer breakdown sites on this side of the cell.

Cell 78, Upstream. This feature has copper splatter in the upper left corner, from a nearby (not in view) breakdown site. The dark oval feature is composed of multiple elements: the white below-center particle is silicon oxide with trace chlorides, black splotches are carbonaceous, gray area is copper with trace of carbon and chloride.

Cell 78, Downstream. A string of sites following a grain boundary, suggesting there is still sufficient gas within this grain to sustain a plasma.

Cells 86 and 87 were sectioned at a later time than the rest of the cells discussed in this document. They were cut dry with a power hack-saw. Cell 86, downstream, was exposed to room ambient while in storage and, consequently, collected debris. Most of these debris consisted of aluminum oxide, carbonaceous particles and paint chips. Cell 86, upstream, was exposed to the saw blade and, as a consequence, has a smattering of rust.
particles from the blade on that side. More details are in the image captions.

Cell 86, upstream. Smaller, more numerous sites than the downstream side.

Cell 86, upstream. Typical aluminum oxide particle.

Cell 86, upstream. Rust flake from saw blade.

Cell 86, upstream. Calcium sulphate (gypsum) particle. The dark ring appears to be a moisture stain emanating from the particle.
Cell 86, upstream. Classic carbonaceous particle. Source could be pollen grain, skin flake, paper, etc. Sharp edges have high secondary electron yield, hence the white border. This one appears to have been a breakdown site.

Cell 86, downstream. The particle at the upper left appears embedded. Possibly, because it is in good electrical contact (evidenced by its dark appearance), it avoided breakdown.

Cell 86, downstream. Grain structure and circumferential machining grooves are evident. Low site density.

Cell 86, downstream. A carbonaceous particle (beneath the small white box on right image) located on the surface. Time of infection (before installation or after removal from accelerator) unknown.
Cell 87, upstream. This cell also had rust flakes (not shown here) on it, from the sawing process.

Cell 87, upstream. The fine white lines, running from lower left to upper right, are steps/terraces in the crystal structure of the grain.

Cell 87, upstream. The crater bottom in the right image has traces of concrete residue (C, O, Si, Cl, Mg, Al, Ca) in it.

Cell 87, downstream. This image and the following one show surface mechanical damage.
Cell 87, downstream. In addition to scratches, there are deeper indentations, such as the short straight groove at the image top.

Cell 87, downstream. The large central particle is probably concrete. Typical elements for concrete include Mg, O, C, Al, Si, Cl, K, Ca and Fe. The smaller fragments are sometimes richer in Cl.

Cell 87, downstream. One of the C-Cl particles. Calcium chloride is added to concrete as a curing accelerator (Cl source). Fly ash is added to reduce excessive expansion at cure and to reduce cost (C source).

The image presentation now returns to hand-sawn cells.

Cell 151, Upstream. This surface has a few small sites.
Cell 151, Upstream. The bright “horizon” at the iris ID is due to enhanced secondary electron emission at the very smooth glancing incidence surface, i.e., essentially no surface damage at the iris.

Cell 151, Downstream. This iris equator damage could be a machining tearout and not a breakdown site. There is no evidence of melting.

Cell 151, Downstream. Again, very few sites.

Cell 151, Downstream. This cell side had a number of round and worm-like indents on it, possibly from being touched by a measuring tool. The previous image may also be such “touching” damage.
Cell 151, Downstream. EDX of this defect (from white box on right image) shows it to be silica. It appears to have been a partially-exposed sub-surface inclusion that was revealed by breakdown activity.

4. Discussion

Breakdown sites were most numerous on the upstream side of cells, with lowest numbered cells having the highest site density plus a high proportion of multiple “hits” at a single location.

In most cases, no obvious source for a breakdown was located. There was considerable debris available for breakdown initiation but it was difficult to determine at what stage the debris was added. Several cells also showed evidence of mechanical damage, although such damage did not appear connected with sites, therefore the damage probably occurred after cell operation.

Debris consisted mostly of carbonaceous particles and flakes, concrete fragments, and rust. One spectacular inclusion, on cell 151 downstream, was located and was involved in a breakdown. But finding the breakdown initiator in this case was possible only because of its unusual appearance and the relatively small amount of site damage.

5. Conclusion

In an effort to locate breakdown initiators, an appropriate cell will be searched in non-damaged areas, using Auger spectroscopy. The damage at breakdown sites of the cells examined is generally so severe that locating the remnants of initiators in them, after breakdown, is unfruitful.

5. Appendix

Scanning Electron Microscopy (SEM)

Energy-Dispersive X-Ray Analysis (EDX)