From “Whiskers” to “Dust” – the Critical Role of Dedicated Diagnostic Techniques in Promoting Paradigm Shift

R V Latham

Emeritus Professor of Applied Physics

Aston University, Birmingham, UK

***Abstract*- The development of theoretical models to explain complex physical processes is an essential part of the scientific method. However, such models must always be the subject of on-going scrutiny and experimental evaluation, and it is in this context that purpose-designed diagnostic techniques play a critical role. This paper presents an historical account of how this process has been crucial in the evolution of our understanding of the underlying physical mechanisms that control the behaviour of the high voltage vacuum gap.**

I. INTRODUCTION

The subject of High Voltage Vacuum Insulation (HVVI) only achieved a life of its own with the launching in 1964 of the regular two-yearly ISDEIV meetings. Prior to this, the subject had been treated as a side issue by the engineers and scientists who were working on high voltage (HV) devices at that time, and who generally resorted to using a range of essentially “black art” approaches to suppress the occurrence of spark discharges. However, as the demands for improved technological performance grew, it became increasingly evident that a greater effort was needed to understand the physical mechanisms that were responsible for spark discharges. It was against this background that industry turned to the scientific community to come up with an explanation, or model, that would explain why vacuum did not behave as the perfect insulator that it had previously been assumed to be.

The only evidence available to these early scientists was the fact that, prior to breakdown, a small, unstable electric current flowed between the electrodes, which subsequently came to be known as the pre-breakdown current (PB). It was therefore quite naturally assumed that this “cold” PB current was certainly implicated, if not responsible, for the ultimate breakdown phenomenon. So, it is quite understandable that that these scientists assumed that the PB electron emission had to be somehow related to the only other “cold” electron emission process known at that time, namely the Field Electron Emission (FEE) mechanism previously studied by Fowler and Nordheim in the 1920’s. The problem was, however, that the FEE mechanism required surface fields in excess of 10+9 V/m, whereas the fields between planar electrodes at which PB currents occur are typically two to three orders of magnitude lower than this. The challenge facing those early modellers was therefore to think of a way in which the gap field between a pair of parallel electrodes could be “enhanced” by several orders of magnitude. Their solution was to recognise that a mechanically polished electrode surface is far from smooth on the microscopic scale, and would be very likely to have isolated “micro-spikes” where the field would be geometrically enhanced to the required values to promote FEE. According to this model, breakdown would occur when the current drawn from a whisker was sufficient to vaporise it and thereby create a plasma that provided a conducting medium for the consequent flash-over of the HV gap.

Thus was born the very plausible “Whisker” model of vacuum breakdown. In fact, it was the best in town at the time, and was the current paradigm when the participants gathered for that first ISDEIV meeting in the US back in 1964. The full story of the subsequent adoption of this model of the vacuum breakdown mechanism as the prevailing paradigm can be found in the author’s two books on the subject [1], [2], with more details being found at www.rodlatham.co.uk. These same two books also describes how, over a thirty-year period, involving the development of a range of sophisticated diagnostic techniques, the “Whisker” paradigm was eventually replaced by the currently prevailing “Dust” paradigm: a process that constitutes a perfect example of the famous mechanism of “paradigm shift” described by Thomas Kuhn in his well-known book “The Structure of Scientific Revolutions” [4].

Note: The following discussion------------etc—as per original manuscript

II. DIAGIAN STUDIES OF THE PREBREAKDOWN ELECTRON EMISSION MECHANISM

A. Dynamic Imaging of the Spatial Distribution of Prebreakdown Emission Sites

The discrete nature of the PB emission process, as implied by the Whisker model, was verified by Millikin and co-workers in the early 60's by employing a phosphor-coated glass planar anode in the simple experimental set-up illustrated in Fig. 1 (pp 62-63). Subsequently, this technique was developed by the author's group by replacing the phosphor anode with a transparent glass anode that had the advantages of giving a higher spatial resolution without the risk of cross-contamination, and the opportunity to use high-speed photography to study the temporal evolution of the breakdown process (pp 63-65). An example of the type of image recorded from this system is shown in Fig. 2 (p 2). From measurements of the PB current-voltage characteristic, a Fowler-Nordheim plot can be constructed whose slope can be used to calculate the effective field enhancement factor, or beta-factor, for the HV gap (pp 26-28), which typically have values in the range 250-500.

Fig 1 A Transparent Anode Imaging system with a high-speed recording of a breakdown event.

B. Electron Optical Imaging of Electrode Surface Profiles

The earliest direct experimental evidence for the existence whiskers, or micro-protrusions, as they came to be more scientifically called, was reported by Little & Smith, and by Jedynak, both in 1965 (p 67). Their findings were based on electron optical studies of the profiles of electrodes that had been used in a HV gap and then transferred to a transmission electron microscope for observation. To eliminate the possibility that the reported whiskers were the result of an HV discharge, rather than its initiator, the author's group subsequently adapted an electron microscope to facilitate an in situ study of the profile of a cylindrical HV electrode as the gap field was progressively increased to breakdown. Shown in Fig. 3 are a pair of micrographs published in 1968 of the "before" and "after profiles of the cathode surface (pp 67-69), which

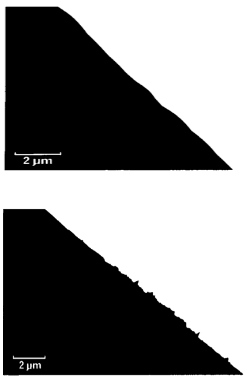


Fig. 2 "Before" and "after" electron optical profile images of an HV electrode surface

clearly show that whiskers are a *consequence*, rather than the cause of breakdown. It can also be concluded from this result that the whiskers were not sharp enough to produce the degree of geometrical field enhancement required for promoting the FEE assumed to be responsible for PB currents and subsequent breakdown; neither do they correspond to the high beta-values calculated from the corresponding F-N plot of the gap. It was also significant that all early attempts to improve electrode performance by electrode polishing techniques failed to produce any consistent improvement (pp 49-51). In fact, shortly after recording the profile image of Fig. 2, the scanning electron microscope became an available tool, which revealed that the whisker structures were in fact the frozen tongues of metal that formed the rims of splash craters resulting from discharge events between the electrodes.

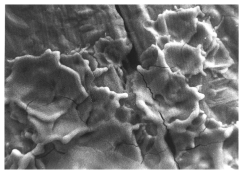


Fig. 3 A SEM image of the electrode surface imaged in profile in Fig. 2 above, and showing that the "whiskers" are the tongues of frozen metal that form the rims of discharge craters.

Faced with this evidence, it was clear to the author that an alternative emission mechanism must be responsible for the "electron pin-holes" that give rise to PB currents, and that it was therefore necessary to develop a further range of diagnostic techniques to investigate the true origin of these currents.

C. Electron Spectroscopy Studies of Emission Sites

Having regard to the optical analogue, where spectroscopy provides a powerful tool for analysing the underlying emission mechanism of an optical source, it was decided, to employ electron spectroscopy to similarly analyse the physical nature of the PB emission mechanism. The instrument that was developed by the Aston Group involved interfacing a scanning anode probe hole system, as previously used by Cox (pp 71-74) for locating emission sites in a scanning electron microscope, with a hemispherical deflection electron analyser (pp 89-96). The essential finding of this complex investigation is illustrated in Fig. 4, which compares the emission spectra obtained from a reference metal whisker, or micro-point emitter, with that obtained from a typical emission site on a broad-area HV electrode. This finding therefore further called into question the validity of the "Whisker" model of PB emission and, very importantly, indicated that some sort of "non-metallic" process was involved in the emission mechanism. Subsequently, this conclusion was confirmed by Hurley from optical spectroscopy studies of the light emitted from cathode spots (pp 100-103).

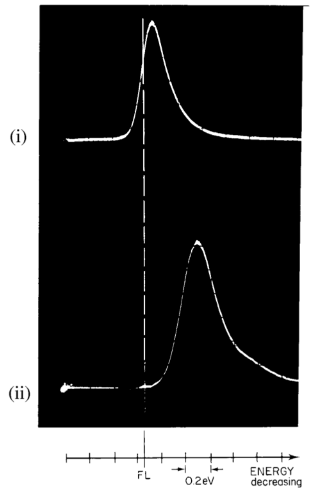


Fig. 4 Contrasting the electron spectra obtained from (i) a metallic micro-tip such as used in point-plane diode simulation studies (pp 205-229), and (ii) a prebreakdown emission site on a planar electrode surface (pp 89-96).

D. Morphological Studies of Emission Sites using a Scanning Microprobe Anode

To finally solve the puzzle of what exactly it was on an HV electrode surface that gave rise to the "electron pin-holes" that allowed electrons to escape of electrons at anomalously low fields, it was decided to develop a technique for dynamically locating emission sites in situ a scanning electron microscope (SEM) incorporating an X-ray analysis facility, so that their morphological structure and chemical composition could be unambiguously identified. The system pioneered by the Aston Group employed a mechanically scanned micro-point anode to "search' a planar cathode surface in order to locate an emission site on the axis of the SEM, which could subsequently be imaged by the SEM (pp 74-77). The essential finding of this investigation is illustrated in Fig. 5, which shows that PB emission sites, or

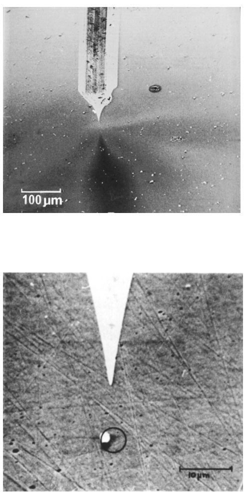


Fig. 5 Low- and high-resolution images of the scanning micro-point anode technique which conclusively showed that prebreakdown emission sites, or "electron pin-holes", are associated with particulate contamination (pp 74-77).

"electron pin-holes" are associated with contaminant particulates, often carbon, that inevitably decorate an as-produced electrode surface. Subsequently, Fischer and his group in Geneva added an Auger analysis facility to the basic system (pp78-81), and used this to study the material composition of the emission sites on the niobium material used for the superconducting cavities that were being developed for the LEP accelerator at CERN. It is also of interest to note that this same scanning micro-point anode system was used as the basis of the scanning tunnelling microscope (STEM) of Binning and Rohrer that was also being developed in Switzerland at that time (pp79-81), and who went on to win a Nobel prize.

E. Photoemission Microscopy of Emission Sites

Having established that a PB emission site is associated with the presence of a contaminant micro-particle, the questions remained as to a) by what mechanism does a particle emit electrons, and b) what physical characteristics predispose a particle to emit. To address these questions, the Aston group designed the sophisticated photo-field emission microscope shown in Fig. 6, that provided high-resolution dynamic images of an emitting particle (pp 81-84). An example of the type of image obtained with this system is also presented in Fig. 6, and clearly shows that the total emission from an isolated carbon particle is composed of contributions from both "edge" and "bulk" sub-sites. It had been hoped to exploit this technique for on-going studies but, in the event, the programme had to be abandoned due to lack of funding.

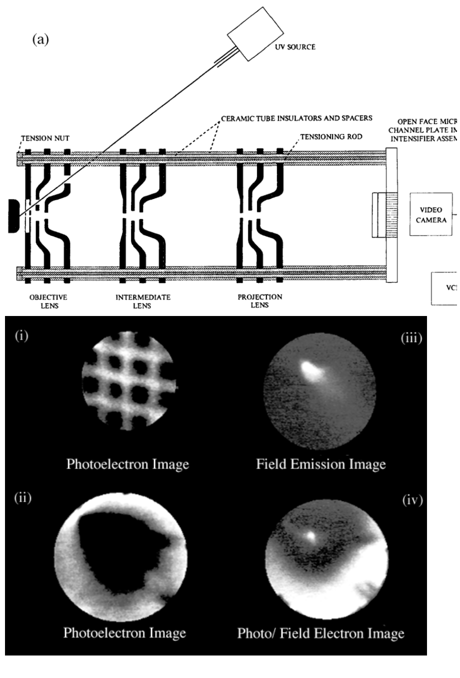


Fig. 6 The photoemission microscope system that was developed for in situ studies of the emission process from individual particles, typical images obtained from (a) a reference grid, (b) a zero-field image of a particle, (c) and (d) photo+field emission images of an emitting particle (pp 81-84).

III. TECHNOLOGICAL IMPLICATIONS

The most important outcome of the 30-year programme of diagnostic studies described above has been a paradigm shift in technological approach to improving the insulating performance of HV electrodes. Thus, instead of chasing the false goal of an ideally "smooth" electrode surface, the emphasis is now on cleanliness. So, in practical terms, surface polishing techniques have been largely replaced by clean room technology for the manufacture and assembly of HV devices. This new approach was first pioneered by the superconducting RF cavity community, most notably at CERN in Geneva, and Cornell in the US (pp 432-457). In fact, the operating performance of the type of cavity illustrated in Fig 7 was doubled over a five-year period by applying a range new processing techniques that grew out of the new understanding of the mechanism responsible for PB emission.

(i)

(ii)

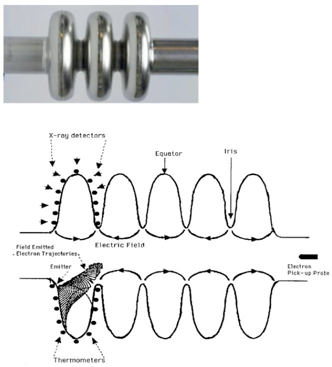


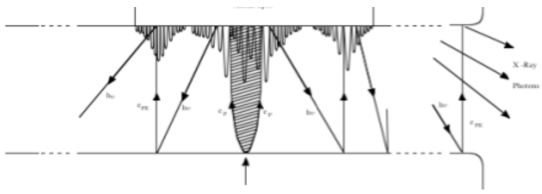
Fig. 7 (i) An example of the type of multi-cell superconducting RF cavities whose performance has benefitted from the use of clean-room and associated technologies, and (ii) a schematic image of this type of cavity showing a) the typical location of PB emission sites, b) the resulting electron trajectories, and c) the associated diagnostic facilities (pp 432-457).

In fact, the superconducting cavities that are currently being used in the LHC collider in CERN, would not have been available had not the necessary clean-room assembly procedures been developed on an experimental basis with isolated units in the earlier LEP accelerator.

IV. FUTURE DIRECTIONS

Whilst the elimination of particulate contamination from HV electrode surfaces has led to a dramatic improvement in performance, the problem of PB electron emission, and subsequent breakdown, has not gone away; its onset has merely moved to higher field levels. This implies that there must be another emission mechanism operating on the nano-, rather than micro-, scale, and that in order to suppress it, one must first understand its physical origin. So, in the view of this author, there is no alternative but to attack the problem with a battery of purpose-designed diagnostic techniques. It is possible that some of the above techniques could be employed in a modified form, but more than likely new approaches will prove to be the key to success.

EXTENDED ANODE SPOT



PRIMARY ELECTRON SOURCE

Fig. 8 An illustration of how a Secondary Electron Cascade model can account for a) an extended anode spot, b) an enhanced PB current, and c) the emission of X-ray photons from the edge of an HV gap [3].

As a final observation, it could well be that the anode plays a more active role than hitherto assumed, particularly in relation to the initiation of discharge, or breakdown, events. For example, it could be profitable to investigate whether the type of secondary electron initiated discharge event discussed by the author in his recent monograph [3], and illustrated schematically in Fig. 8, might play a significant role.

ACKNOWLEDGMENT

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I would also like to take this opportunity of acknowledging the invaluable contributions made by all of my past research students. Without their highly skilled experimental measurements, it would not have been possible for our group at Aston University to make an important contribution to the subject. It was also a great personal pleasure for me to work with all of these young people. Finally, I should to thank Professor Sir Frederick Crawford for the support and encouragement that he gave me during his time as Vice Chancellor of Aston University.

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E-mail of author: lathamrv@aston.ac.uk