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ELECTRICAL BREAKDOWN IN VACUUM
WORKING GROUP REPORT

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Co-Chairmen:

Robert Anderson
Sandia National Laboratories*
Albuquerque, NM

Lynn Hatfield
Dept. of Physics
Texas Tech University
Lubbock, TX

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MEMBERS

Garry Allen (LANL)
Malcolm Buttram (SNL)
George Erickson (LANL)
Rod Latham (Aston U.)
George Vogtlin (LLNL)
John Bayless (PSI)
Lon Enloe (AFGL)
Art Guenther (LANL)
Charles Mansfield (LANL)

INTRODUCTION

The working group on electrical breakdown in vacuum was charged with considering all possible mechanisms by which electrical breakdown might occur either through the vacuum or along insulator bushings in large area electron beam emitter assemblies. It was understood that present systems need to be scaled up, by an order of magnitude or more in both beam area and total energy, to meet demands for higher power and larger size machines, and that increases in the e-beam current density and transport efficiency are also sought. A consideration of the consequences of such a scale-up was pertinent to many of the topics listed in the working-group agenda. Our group attempted to address each of

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these topics and this summary of the group deliberations is organized accordingly.

Bulk breakdown in vacuum and flashover across insulator bushings are quite different phenomena. Therefore, there really are two different topics to consider. On the other hand, in practical devices, breakdown of either type may be due to similar problems. For example, small particles such as dust or pieces of a velvet cathode can initiate breakdown by acting as emission sites and the breakdown can be through the vacuum or along an insulator surface[1, 2]. Present knowledge of the behavior of vacuum gaps is discussed in references 1 through 4, and recent developments in understanding surface flashover of insulators in vacuum are reviewed in references 5 through 7 and in the paper presented by R. Anderson at this workshop.

In a workshop tutorial, M. McGeoch reported that breakdown occurs at diode gap fields given by

$$E = 70(t_p)^{-1/2} \qquad (1)$$

where E is in kV/cm and t_p is the pulse length in μs. It was understood that breakdown occurs through the vacuum near the edge of the electron beam, and is not thought to involve the insulator. As might have been expected, the electric stress is calculated to be at a maximum in the region of the breakdown. In diodes of the LANL type (large magnetic field parallel to the beam) the current density is non-uniform and larger at the beam edge, which might also be contributing to the breakdown.

The above vacuum breakdown field can be compared with the empirical expression for insulator flashover given by J.C. Martin [8]:

$$E = 175(t_{eff})^{-1/6} (A)^{-1/10} \qquad (2)$$

where units are the same as in Eq. (1) and A is the insulator lateral area in cm^2. The time t_{eff} is the time for which the voltage exceeds 89% of the pulse maximum value. Inserting values of 1 μs and 1 m^2 into this formula and also into Eq. (1) results in roughly the same breakdown field (70 kV/cm) for both vacuum breakdown and insulator flashover. In present machines, insulator bushing flashover does not seem to be the limiting factor; there is ample space to permit a large insulator with fields severalfold lower than at the diode gap, and inductance (which is increased with a larger insulator) has not become a major determinant of the pulse shape. If a segmented-cathode design is adopted, however, severe constraints may be placed on the space available for insulators. Furthermore, a scaled-up machine may subject the insulator bushing to increased stray magnetic fields, greater contamination, or a more hostile radiation environment, so that Eq. (2) no longer applies. For these reasons, the possibility of insulator flashover cannot be dismissed.

WORKING GROUP DISCUSSION

Diode Size. Increased diode size means larger area for the emitter and anode foil as well as surrounding structures. The so-called "area effect", a ubiquitous phenomenon of apparently statistical origin, would be expected to cause vacuum breakdown at a lower voltage than for a structure of smaller size, assuming the same diode gap. If larger insulator bushings are required with larger-area diodes, the area-effect term in Eq. (2) also predicts an increased probability of breakdown. As discussed above, breakdown appears to originate at the edge of the beam, or near the edge of the emitting velvet on the cathode. There is a tendency for poor electrical contact between the emitting fabric and metal electrode to force arcing at the circumferential edge, which would be exacerbated with larger cathodes. This arcing may be triggering breakdown. Improvements in the electrical connection to the velvet at the edge or a better geometry at the edge may be required with larger area diodes.

Maximum Current Density. Increasing the current density may lead to several problems. Foremost among these is the production of anode plasma which depends on anode heating and thus depends on the beam-current density. Therefore, a higher current density may lead to early diode closure by anode plasma.

Increased current density almost inescapably implies higher self-magnetic fields as well as the need for higher guide fields. This could adversely affect beam uniformity and increase the rate of plasma closure, and may degrade the performance of the insulator bushing if stray components of the guide field are not controlled.

The vacuum gap may be required to withstand higher fields if the current density is increased. In the approximation of planar space-charge-limited (Child Langmuir) flow, the current density (A/cm^2) is

$$J = (0.073) V^{3/2} d^{-2} = (0.073) E^2 V^{-1/2} \qquad (3)$$

where V is the applied voltage in kV, d is the gap spacing in cm, and E is expressed in kV/cm. Evaluating this expression at a field of 70 kV/cm and a voltage of 10^6 volts, for example, results in a current density of 11 A/cm^2. At a given voltage, an increased current density can only be accomplished by increasing the electric field.

A further issue which needs to be resolved is the apparently chaotic behavior of large-area electron beams demonstrated in the numerical simulations reported by M. Jones in his workshop presentation. We were not certain whether this phenomenon was an artifact of the numerical method or an actual physical effect which might become catastrophic at higher current densities.

Maximum Pulse Length. Plasma expansion into the vacuum and melting of the anode foil are the major effects which limit pulse length. As pointed out above, anode heating can give rise to anode plasma. To a first approximation, the temperature rise is proportional to the product of the pulse length and the current density, $t_p J$. Sustained operation of the beam will eventually cause foil melting or breakdown in the vacuum. If the electron beam uniformity deteriorates during the pulse, thermal damage will occur even sooner. Furthermore, as pointed out by M. Buttram, plasma from isolated hot spots tends to expand much more rapidly than from a spatially uniform source. Plasma is also developed at the cathode. Although this plasma continues to flow into the gap during the pulse, it may be possible to halt closure from the cathode plasma by proper operation of the diode (as discussed in R. Klinkowstein's workshop presentation).

In any case, in large e-beam machines there will be some pulse length for which the inevitable "late time emission" of electrons and plasma from various structures throughout the diode will eventually cause breakdown. It would be worthwhile to find out how the presence of a magnetic field affects this situation.

Experience has not shown that surface flashover of the insulator bushing imposes a pulse-length limit. For pulse lengths exceeding a few microseconds, the electric field that elicits flashover becomes effectively independent of the pulse length. A possible exception may occur if intense ultraviolet is present [9].

Transmission Efficiency. Obviously, an anode foil with a high transmission efficiency is desirable in order to maximize the beam delivered to the target. High transmission efficiency also has the potentially beneficial effect of minimizing x ray production. At first thought, it would seem that very thin foils, or foils made of low-density material, would provide an additional benefit of minimal heating from beam absorption. However, both the deposition of energy in a foil and the thermal capacity of a foil tend, simply, to be proportional to the mass of material in the foil. Thus, the temperature rise is not strongly dependent on either thickness or composition. G. Erickson pointed out that a

Mg foil works well in an e-beam pumped KrF laser because the MgF that forms when the foil is heated creates a stable, protective layer.

At present it is not known if x rays are contributing to breakdown problems, nor does the x-ray intensity at various locations in diodes appear to be well characterized. The possibility of adverse, x-ray induced effects nevertheless exists. Sission in polymers and promotion of structural damage at microcracks are examples of x-ray initiated aging processes. X rays may also produce photoelectrons from insulators in regions where the electric field is not high enough to produce field emission.

If it becomes established that x rays are causing problems, low-atomic-number elements could be used in the anode foil and the supporting Hibachi structure to limit x ray production. A Hibachi of Be would produce fewer x rays than Ti and the photons would have lower energy. Carbon-carbon composites have the same desirable features and should be pursued.

<u>State-of-the-Art</u>. The documented benefits of several materials, designs, and procedures suggest the path that further development should follow. Present insulator bushings use stacked 45° angle polymer or epoxy (DEA 828) dielectrics. Standoff voltages correspond to 40 kV/cm. G. Vogtlin estimated that this gives, perhaps, a safety factor of 3. Conducting structures are made of Al, stainless steel, Mo, and Ti. Aluminum should not be used unless it is anodized. A special hard anodizing process stops field emission from Al up to 1 μs at 150 kV/cm [10].

Felts or velvets attached to the cathode body, the state-of-the-art cold emitter, have serious drawbacks; these surfaces provide electron beams which are only coarsely uniform and generate large amounts of particulates as they age. There is also the problem of poor electrical contact leading to edge arcing, mentioned earlier.

The group consensus was that clean room procedures, ideally, should be used for assembly in an attempt to get rid of particles down to and including a size of 1 μm. This may not be practical if major internal sources of contamination, the fabric on the cathode in particular, are not improved.

Limiting Factors. Our group identified several limiting factors which supplement those implicit in the foregoing discussions. As the diode is scaled up in physical and electrical size the time to prepare the machine between shots increases, the time required for maintenance increases, and the probability of an imperfection increases. Therefore, the Mean Time Between Failures (MTBF) becomes a limiting factor.

Even if clean room procedures are followed in assembly, large amounts of particulates are liberated from the cathode on every shot. In fact, the emitting fabric eventually goes bald. A cleaner, more durable cathode is required to obtain a higher MTBF.

A single point failure becomes more serious as the diode energy increases. The entire machine could be destroyed if sufficient energy is available to be deposited at the site of a failure. This argues for a cathode built from multiple, electrically isolated e-beam modules. The tradeoff is between the expense of fabrication and the expense of repair.

Experience indicates that insulator flashover and vacuum breakdown exhibit large statistical scatter. There are always a very few, low voltage breakdowns. A safety factor of 2 for the insulation might not be too conservative.

High Payoff Research Areas. A number of general areas of research were agreed on. High on this list is the development of an improved cathode emitter. Coatings which inhibit insulator flashover and coatings which reduce field emission from conductors should also be pursued. New materials may hold some promise; a specific example might be to use optical quality PMMA for insulators. This material is largely free of particulate inclusions. Another example is to find a cleaner cathode material which would not produce excessive particulates in use.

The effects of UV radiation, x rays, stray magnetic fields, outgassing, etc. on the flashover voltage or vacuum breakdown are the primary material dependent concerns. The question arose as to whether or not there is a critical time-integrated fluence of x rays required to have an effect on insulators. C.L. Enloe has shown that such seems to be the case for UV radiation [9]; his work also suggests that reversing the angle of the insulator segments (installing them upside down) might lead to better performance in an environment of high-intensity UV radiation. Clearly, the optimal insulator geometry in larger machines may not be identical to conventional +45° designs.

Processing of materials is the determining factor in their actual "in use" surface properties. The effects of processing could be pursued more actively. Attention should be paid to reliability and maintainability as a function of materials, processing, geometry, and operation. This could significantly increase the MTBF. However, data useful for an evaluation of reliability and maintainability can only be obtained by detailed, expert design of the experiments [11]. The group consensus was that targeted research funds are required and that the above recommendations cannot be accomplished as part of a hardware development effort.

Novel Ideas. Several novel ideas were proposed by our group with respect to particulate removal and the use of coatings to inhibit field emission and insulator flashover. Debris in the diode might be removed or collected using a process that resembles electrostatic precipitation. This is a possibility for both conducting and insulating particles. A separate electrode might be required if appropriate d.c. or long pulse bias cannot be applied across the diode. Ultrasonic agitation of various diode parts might assist in dislodging particles from surfaces.

A d.c. bias on the diode with or without gas present might produce desirable conditioning. This may result in insulator charging which is beneficial with the proper polarity of applied bias [12]. Furthermore, the geometry of the diode is suitable for using an r.f. glow discharge in low pressure gas to clean internal surfaces. An oxygen/helium discharge would burn away organics, but the emitting fabric would require protection from the plasma.

Coatings have been used to inhibit surface flashover on insulators [13, 14], but these studies are still in their infancy. Anodizing Al to reduce field emission has already been mentioned. M. Buttram used red Glyptol on conductor surfaces in the TROLL machine and observed no field emission for 2 μs at 120 kV/cm [15]. Electrolytically deposited polysulfone was also suggested [16]. Multiple-layer coatings might actually grade the fields on conductor surfaces. An example of suitable materials for grading is boron nitride on boron carbide. The nitride has a high resistivity while the carbide resistivity is much lower. For protection of insulator surfaces, CVD diamond is a worthwhile candidate. With any coating scheme, however, the usefulness of the coating is questionable if areas which eventually suffer damage become emission sites that are difficult to repair.

A novel idea from optical practice was suggested by A. Guenther. Just before assembly, collodion sprayed on surfaces, allowed to dry, and then peeled off will remove materials of all sizes from the surfaces, including fingerprints.

<u>Unique Facilities/Capabilities</u>. The group identified a number of facilities that could be used to address some of the problems outlined in this section.

R.V. Latham (Aston University, UK) has developed an "Integrated Analysis Facility" which can be used to study emission sites on conductors, emission from triple points, UV radiation enhanced emission, etc. These studies can be done at elevated temperatures, with various processing with gas or other treatments.

G. Vogtlin (Lawrence Livermore National Laboratory, CA) has access to a pulser capable of a 3 ns, 400 kV pulse with a 72 Ω output impedance, suitable for testing emitters or bushings in vacuum. In addition, he has a 1.2 MV Marx generator with a 50 ns risetime which can also be applied to samples in vacuum.

Garry Allen (Los Alamos National Laboratory) has a vacuum bushing tester employing a Marx rated at 1 MV, with a pulse length variable between 200 ns and 5 μs. An electron beam facility for testing the effects of electron beams on materials is also available.

C.L. Enloe (AFGL) and R. Gilgenback (U. of Michigan) have developed a technique for measuring the effects of UV radiation on insulator flashover.

W. Moeny (Tetra Corp., Albuquerque, NM) has a 600 kV Marx equipped with a crowbar switch and attached to a dielectric test cell.

Cooperative Opportunities. Since many of the problems encountered in the electron beam diodes have to do with surfaces, particles, and imperfections leading to breakdown and surface damage, A. Guenther suggested that the techniques learned in studying laser damage on optical materials might be applicable. For example, processing is extremely important for optical materials. A great deal about the effects of processing and the cause of damage was learned through the use of sophisticated surface analysis techniques. These techniques could be applied to learn what properties of coatings are required for use on dielectrics and conductors in H.V. machines. In addition, an interdisciplinary approach should be adopted to incorporate people from other areas, such as polymer chemists, metallurgists, ceramists, etc. In other words, we need to do materials engineering.

Diagnostics. Some new techniques should be applied to diagnose diode operation. Optical probes, perhaps using fiber optics as the sensing elements, could be applied to measure electric fields (particularly at the cathode) and currents [17, 18]. To measure the plasma distribution during the pulse, fast emission spectroscopy could be used.

Acoustic probes might be able to listen for microdischarges at voltages below breakdown and perhaps locate the discharge sites. Mass spectroscopy would be useful in two ways: A fast mass spectrometer (low mass resolution) could analyze the gas generated in the diode during a pulse, and a slow, high-mass-resolution spectrometer combined with a laser which evaporates material from the cathode (laser microprobe) would allow in-situ analysis of the cathode surface after operation.

A novel way to measure the cathode voltage was suggested by R. Anderson. The cathode structure is large enough to contain a tiny electron gun which shoots through a hole in the cathode. This beam could be energy analyzed at ground (anode) potential to obtain the cathode voltage as a function of time. Alternatively, a portion of the emitted beam could be directed into an energy analyzer for the same purpose.

SUMMARY OF RECOMMENDATIONS

From a review of the many recommendations offered by the group members, we have compiled the following list of action items, arranged in order of priority:

a) Solve the beam-edge breakdown problem, or at least elucidate its causes. Tailoring of the e-beam to taper off at its edge, or at at least not have an edge concentration, might help.

b) Redesign the cathode emitter to give a uniform beam, low particulate release, and control over edge arcing. Exotic-composite or microstructure technology may be applicable (e.g., an aligned array of microscopic carbon fibers protruding from a metal matrix).

c) Study the effects of debris, UV, x rays, and stray magnetic fields on insulator flashover. It is crucial that these studies employ radiation levels, magnetic field components, etc. that correspond approximately in magnitude to the environment expected in the scaled-up machines. Magnetic field effects with fields at odd angles, where there is a significant component parallel to the electric field (as might be the case from stray guide fields), have received little attention to date.

d) Study the benefits/drawbacks of cathode coatings to control stray electron emission. This may be particularly important if a segmented-cathode design is adopted, because of local high-field anomalies.

e) Consider cleanup procedures and the possible need for clean room assembly.

f) Resolve questions regarding the apparently chaotic behavior of large e-beams found with numerical simulations.

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