Snowmass should review high field gradient limits and vacuum arcs

J. Norem[1,2], Z. Insepov[3,4], A. Hassanein[4]

[1] Argonne National Laboratory (retired)
[2] Nano Synergy Inc.
[3] National Research Nuclear University (MEPhI), Moscow
[4] Purdue University

The problem of modeling vacuum arcs and NC linac gradient limits should be reviewed at Snowmass. While future HEP projects are designed to solve problems of cosmic importance, on a more basic level, they are funded generously because they are also expected to provide "spin off" that can improve technology in more mundane fields. Arc physics is fundamental, involving the limiting electric and magnetic fields in contact with surfaces and current densities in bulk conductors, however there is no common model that people apply to this problem, and a general theory of gradient limits for linacs does not yet exist.

Although vacuum arcs have been studied for 120 years, the general feeling in the field is that arc physics is "unsettled". B. Juttner wrote this in 2001[1], a European paper admitted it in 2017[2], and people say it all the time. The reason for this seems to be that while arcs are easily accessible, they are hard to study, mostly because there are more variables than measurable parameters in individual experiments. Their physics also involves short timescales, high power densities, large parameter ranges and multidisciplinary modeling. For over a century, the field has coped with these problems by seeking work-arounds, rather than understanding. For most applications this is an adequate answer, since the range of useful materials and operational ranges are fairly small and component reliability is the primary goal. For linacs the best example is the Kilpatrick limit, proposed in the 'fifties, and still in use. It should be possible, however, to understand the problem, rather than just cope with it.

Over the years a huge amount of data has been produced, both immediately relevant and from further afield, which can and should be applied to this problem. However, the dominant general model, Explosive Electron Emission, evidently based on the physics of exploding wires, seems to require surface asperities shaped like fenceposts (or unicorn horns), but does not predict any mechanism that would produce these asperities so it cannot produce a self-consistent picture of breakdown.

The goal should be a model that would explain how high fields and current densities can damage solid surfaces, what the thresholds are, how plasmas are produced, how these plasmas evolve, how the plasmas damage surfaces, what this damage consists of, how damage sites can be vulnerable to further failures and most importantly, how to predict and improve their performance. This model would help to confidently design better power switching and thin film sputtercoating components, the most direct uses of this technology, as well as minimizing power losses from high voltage transmission lines, instabilities and component failures in large tokamaks like ITER, and failures of electronic components.

We believe useful models, incorporating data and mechanisms from many fields, do exist. We have published a paper in 2013 describing ours, and just submitted another paper describing some of the phenomena it explains and predicts[3]. Combining data and mechanisms from the widest class of experiments, including failure mode analysis from solid state electronics and Atom Probe Tomography theory, we can explain and derive the spectrum of field enhancements, the field emission current from a single conditioned emitter, the electron temperature of the plasma spot, the source of shorting currents, the local threshold field for breakdown and the damage seen in SEM images showing how they can produce the field enhancements required at breakdown.

Because the problem of limiting field gradients and current densities has so many applications, there is a wide range of applicable data from other fields that should be considered in any analysis of linac gradient limits. Atom Probe Tomography, for example has systematically studied almost all solid conductors to determine their limiting surface electric field, both to field induced evaporation and catastrophic failure. Likewise, books have been written about electromigration damage at high current densities in solids. Using this wide range of data should produce a model of wide applicability improving our picture of vacuum arcs.

We believe our model, which divides the arc behavior into four stages and can consider all the mechanisms that need to be involved, and using data from other fields as needed can, in principle, explain the arcing simply, completely and usefully, but this has not been checked for a wide range of arcs, or used as a guide to future experiments and literature studies, which should be able to further constrain modeling.

Some useful references:
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2. W. Wuensch, A. Degiovanni, S. Calatroni, A. Korsback, F. Djurabekova, R. Rajamaki, J. Giner-Navarro, Phys. Rev. STAB **20** 011007 (2017)
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