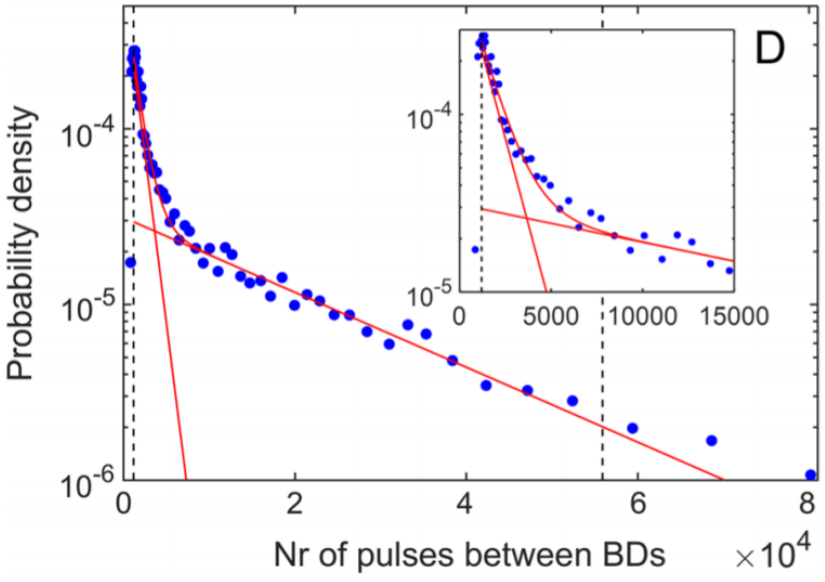
Overview of Recent Developments in Breakdown Theory

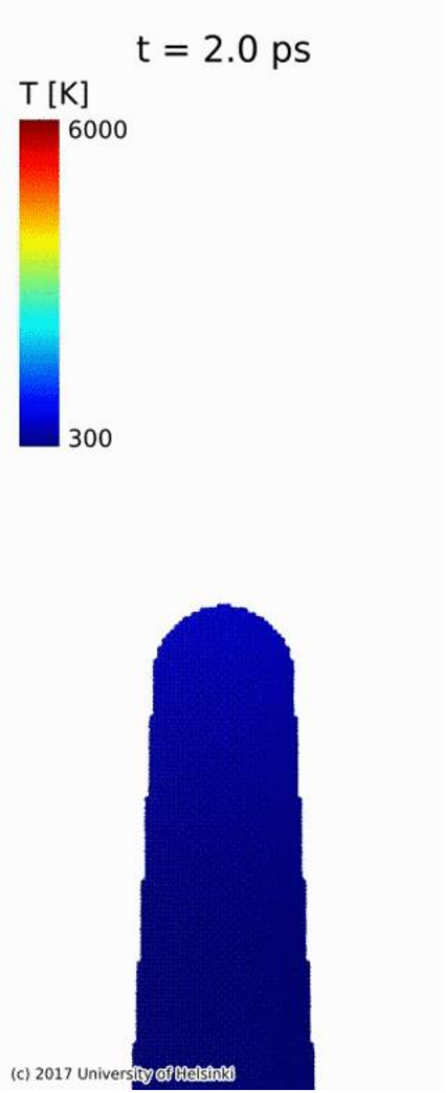
Jan Paszkiewicz on behalf of the CLIC collaboration

Breakdown Nucleation

Evolution of a Breakdown

- Vacuum breakdown: runaway process involving heating of a field-emission site resulting in a breakdown plasma.
  - Large current density causes heating, heating causes more electron emission.
- Breakdowns are sporadic and occur randomly: evidence of some nucleation process (small initial perturbation to start the runaway).

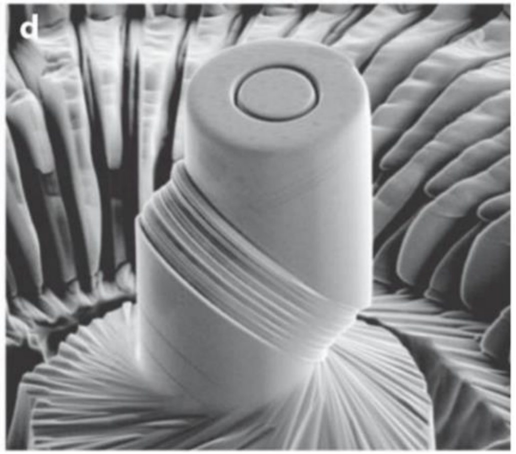




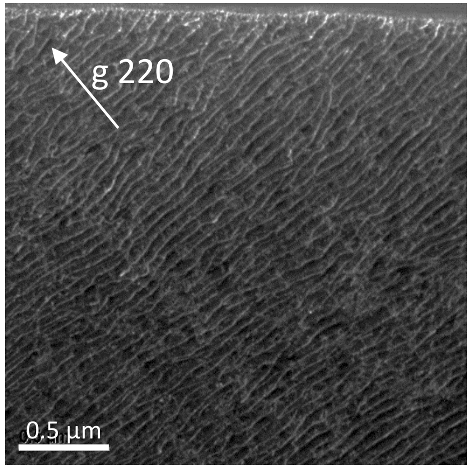
Nucleation in CLIC Structures

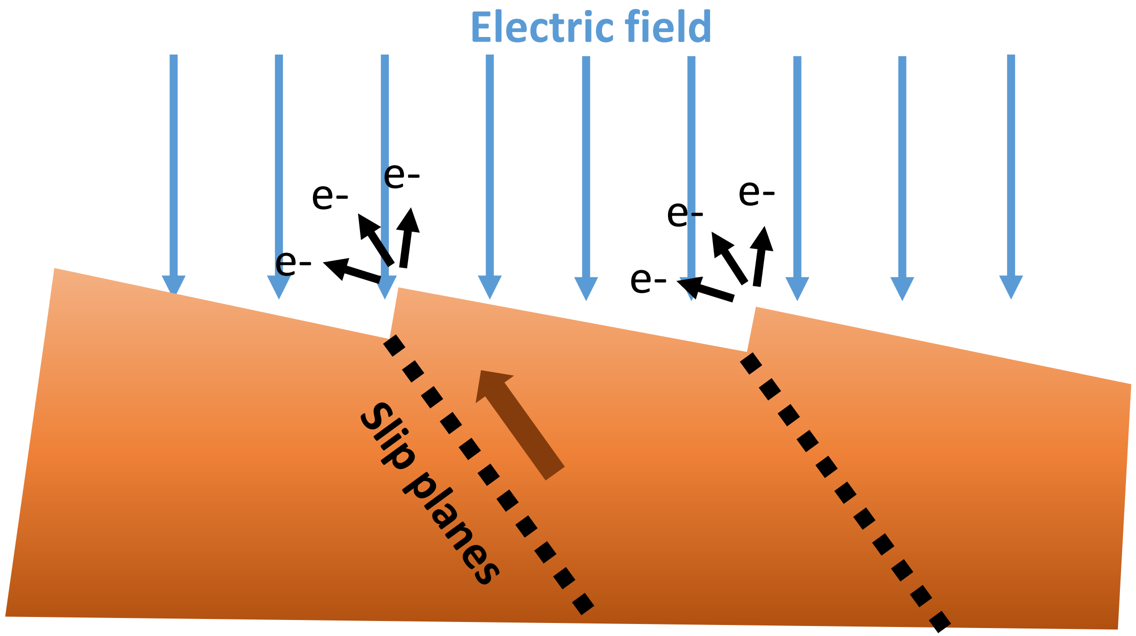
- The electric field inside CLIC RF structures applies a very strong attractive force to the copper surface (> 160 MPa assuming β=30), enough to cause plastic deformation.
- This deformation occurs along slip planes, and a sharp, field-enhancing feature can suddenly appear on the surface.
- Some of these features can result in thermal runaway and breakdown.
- Dislocation motion on small scales is stochastic: explains stochastic behaviour of breakdowns.

Experiment showing deformation along slip planes



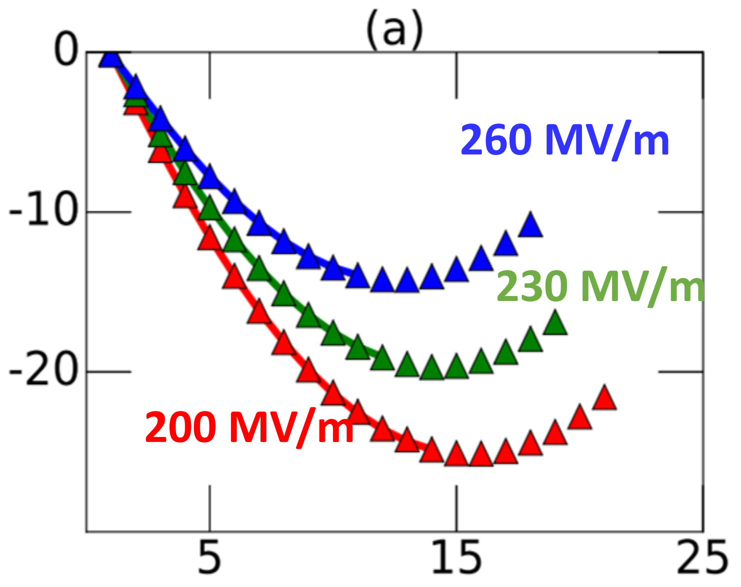
Sample from the CLIC Crab Cavity



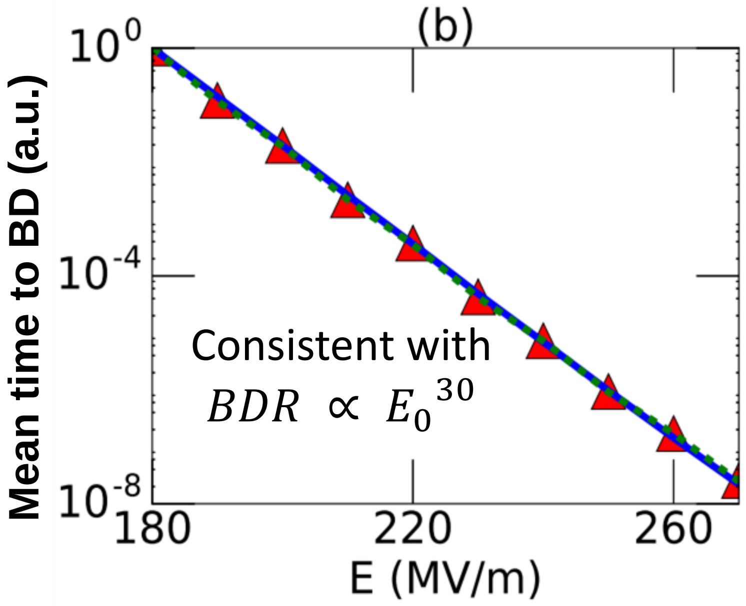


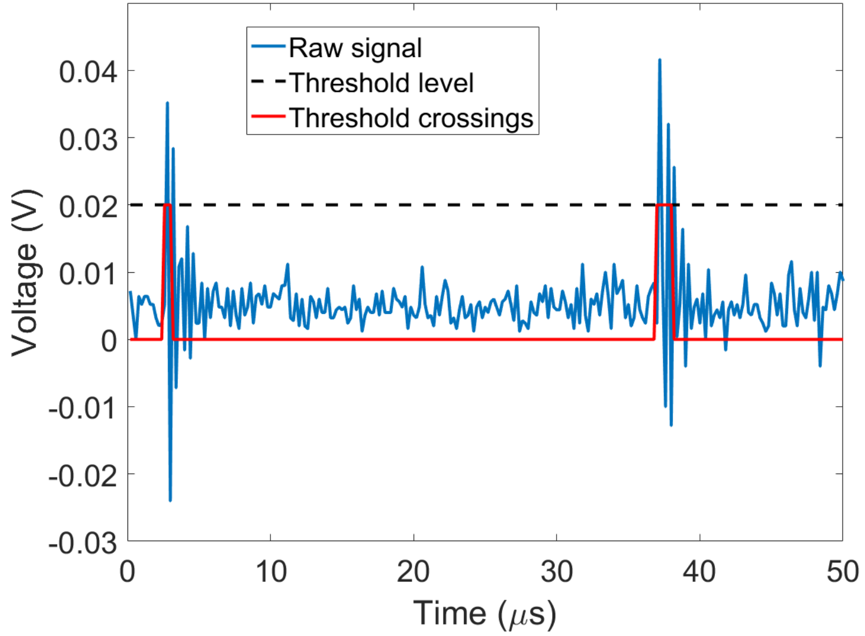
Quantitative Results

- Theoretical work from Jerusalem shows this explanation is consistent with the $BDR \propto E^{30}$ dependence seen in high-gradient experiments.
- Dark-current spikes caused by subcritical nucleation events have been measured in DC experiments at CERN.



Number of mobile dislocations per slip plane

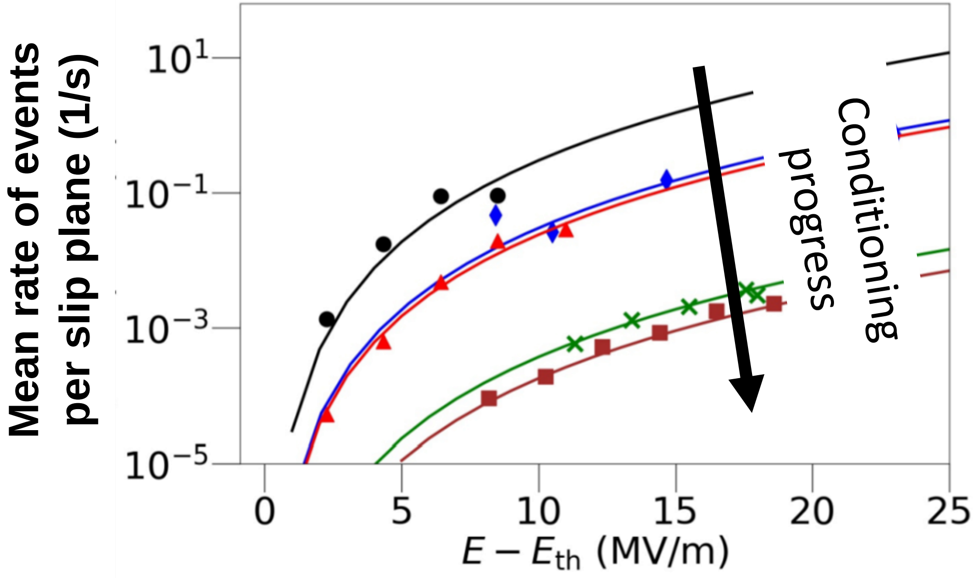




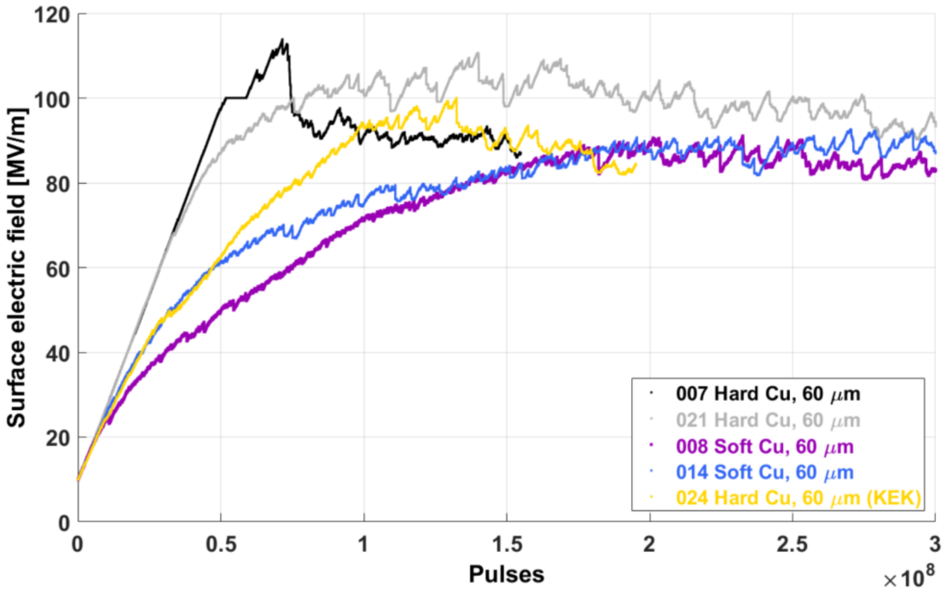
Implications of Nucleation: Conditioning

- If breakdowns need nucleation events to occur, then preventing nucleation should prevent breakdowns.
- Dislocation mobility is related to the ductility of a material.
- Conditioning is thought to occur via hardening due to repeated pulsed stress: rate of nucleation events was observed to decrease at the DC electrodes conditioned.
- Hard Cu DC electrodes condition much faster, a test of a hard Cu RF structure is planned.

Rate of nucleation events vs. E field and conditioning:



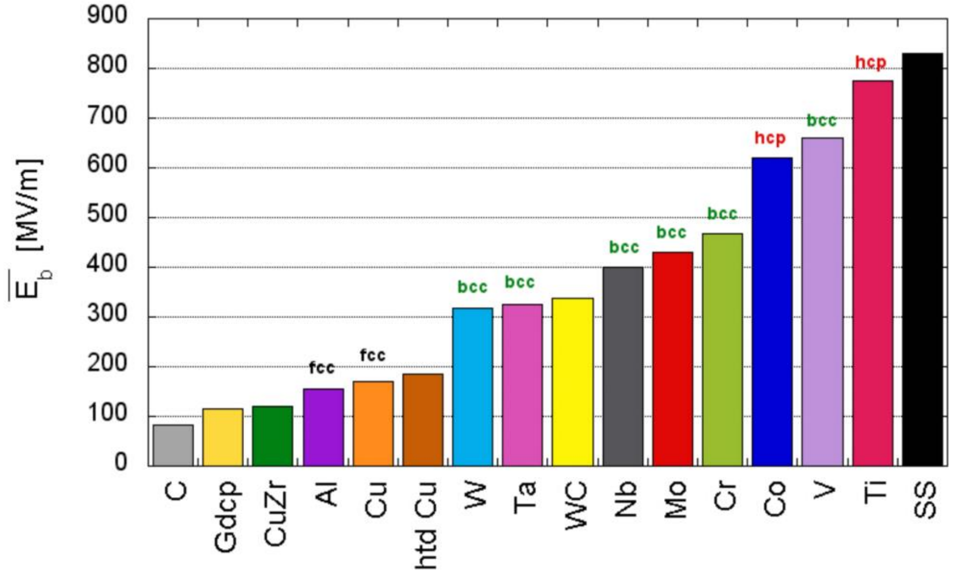
Conditioning of hard vs. soft Cu DC electrodes:



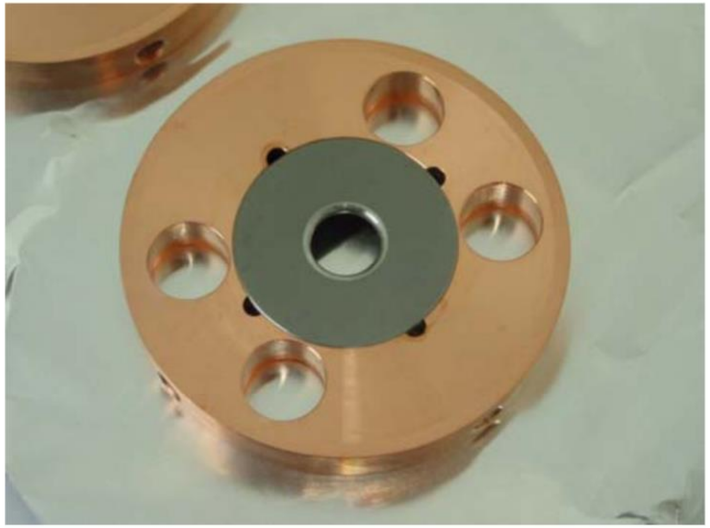
Implications of Nucleation: Materials

- If breakdowns need nucleation events to occur, then preventing nucleation should prevent breakdowns.
- Dislocation mobility is related to the ductility of a material.
- Other materials than copper have superior breakdown performance, but there are often complications.

Maximum E field reached by DC samples:



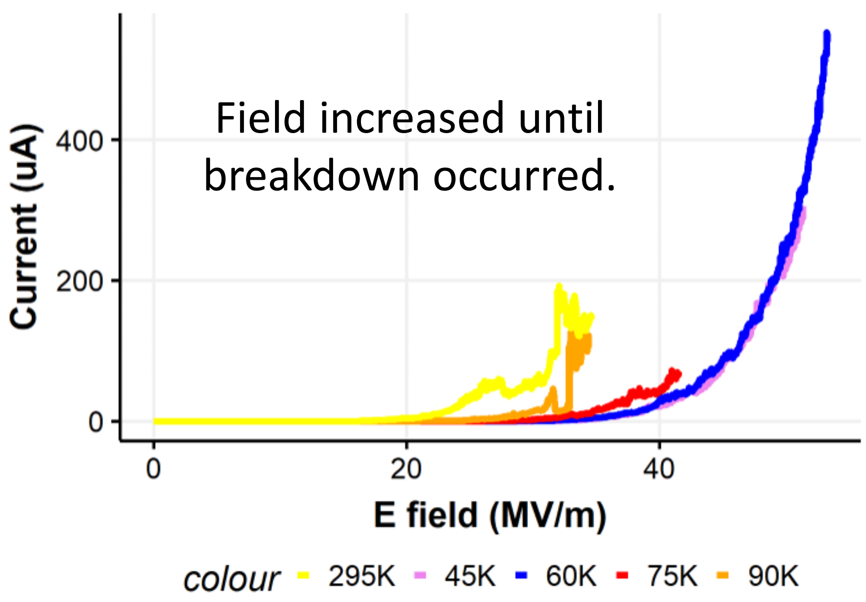
CLIC structure disc with tungsten iris:



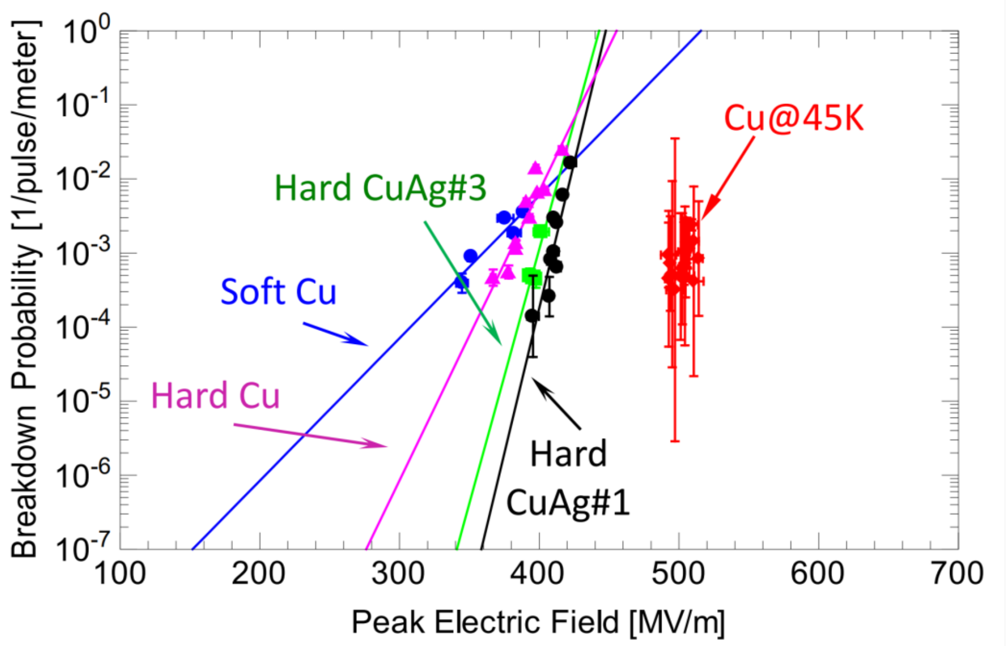
Implications of Nucleation: Temperature

- If breakdowns need nucleation events to occur, then preventing nucleation should prevent breakdowns.
- Dislocation motion is known to depend strongly on temperature.
- Cryogenic breakdown experiments show significant improvement in maximum E-field.

DC electrode results, Uppsala:



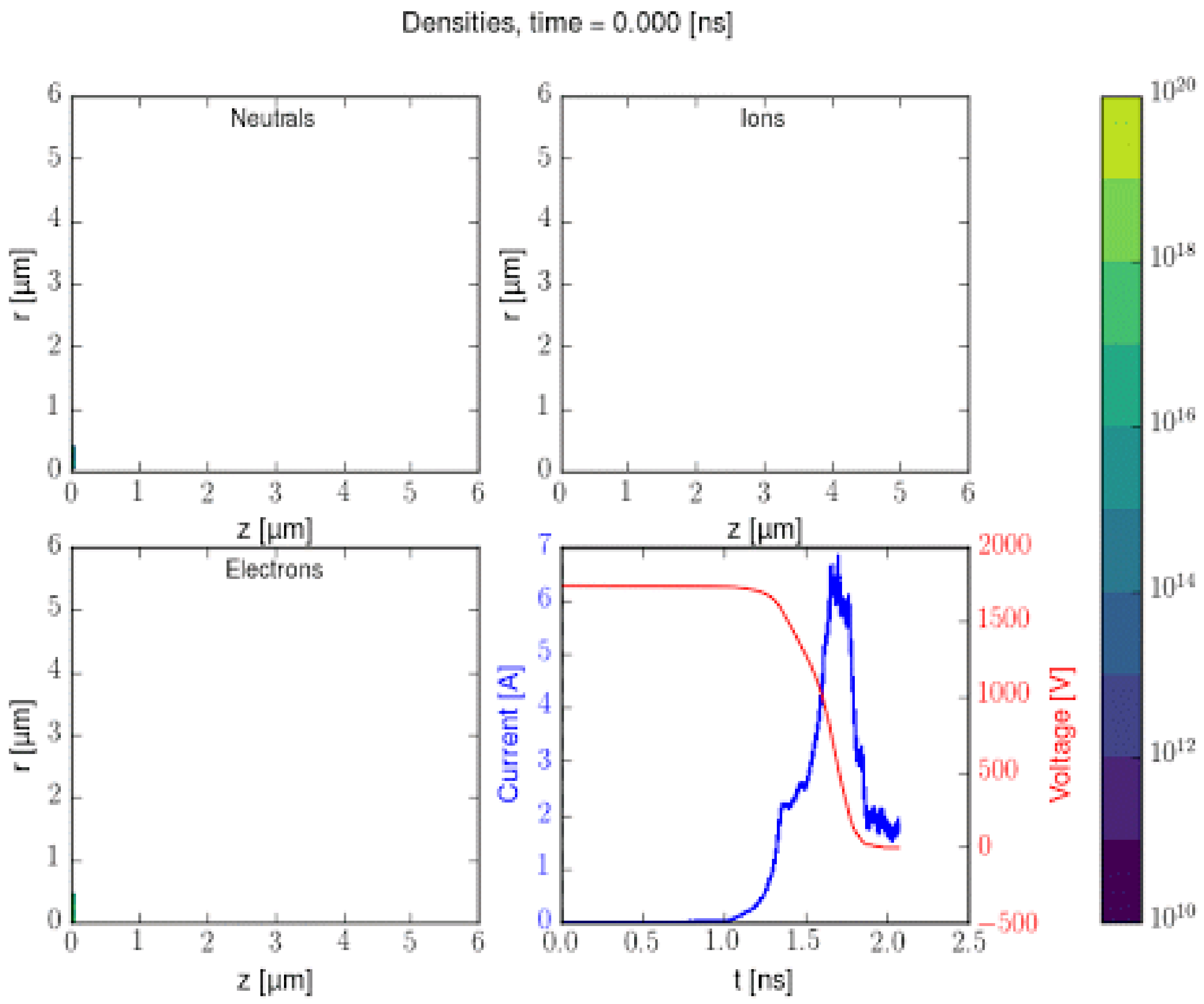
X-band RF cavity results, SLAC:



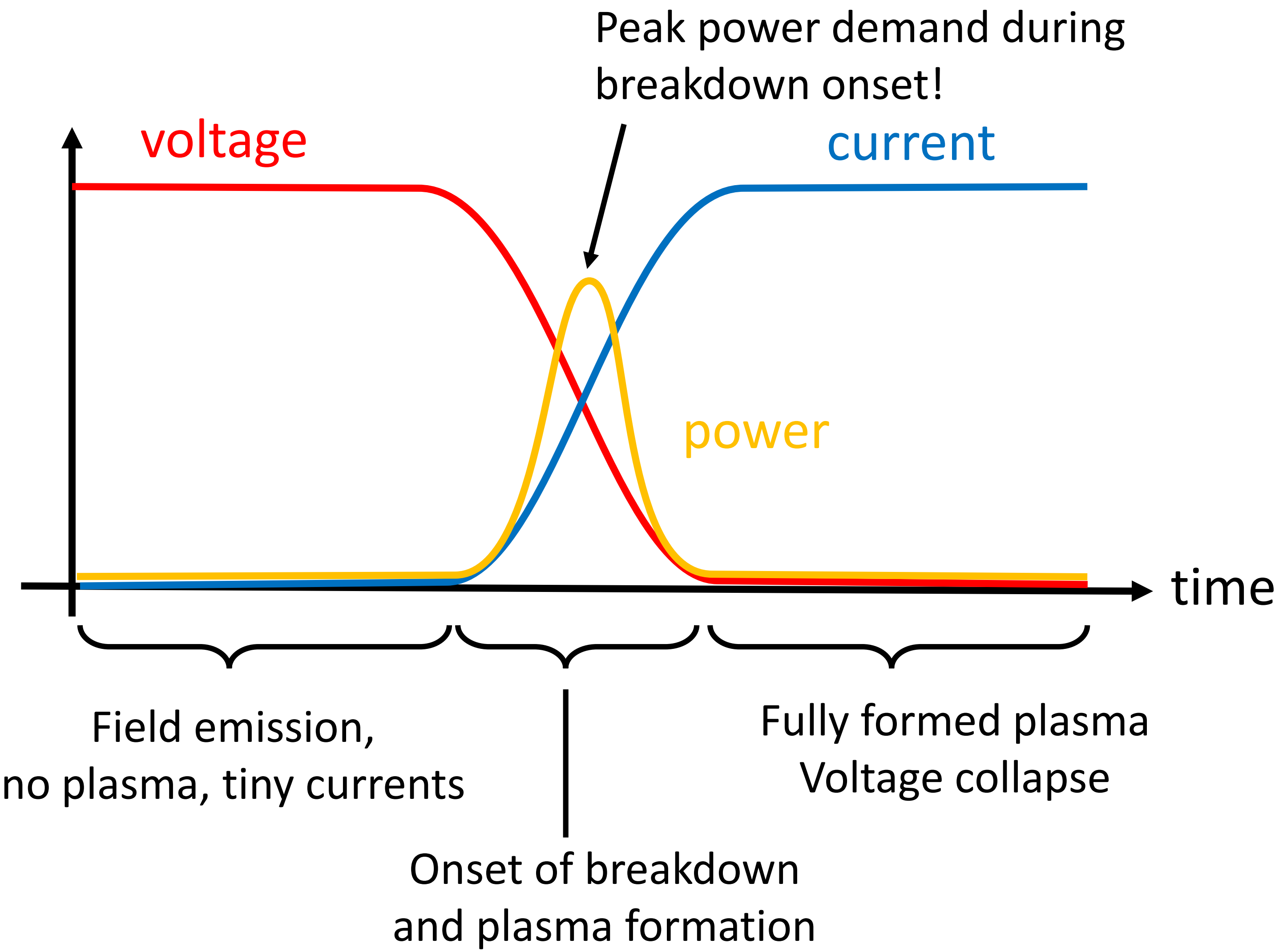
Breakdown Onset

Evolution of a Breakdown, Again

- After nucleation, thermal runaway and plasma formation occur.
- The breakdown takes a short but finite time to develop (c. 200 ps).
- Many charged particles produced in the process – accelerating these particles requires a large influx of power.
- If power flow is insufficient, the field will decrease and the breakdown can be extinguished.



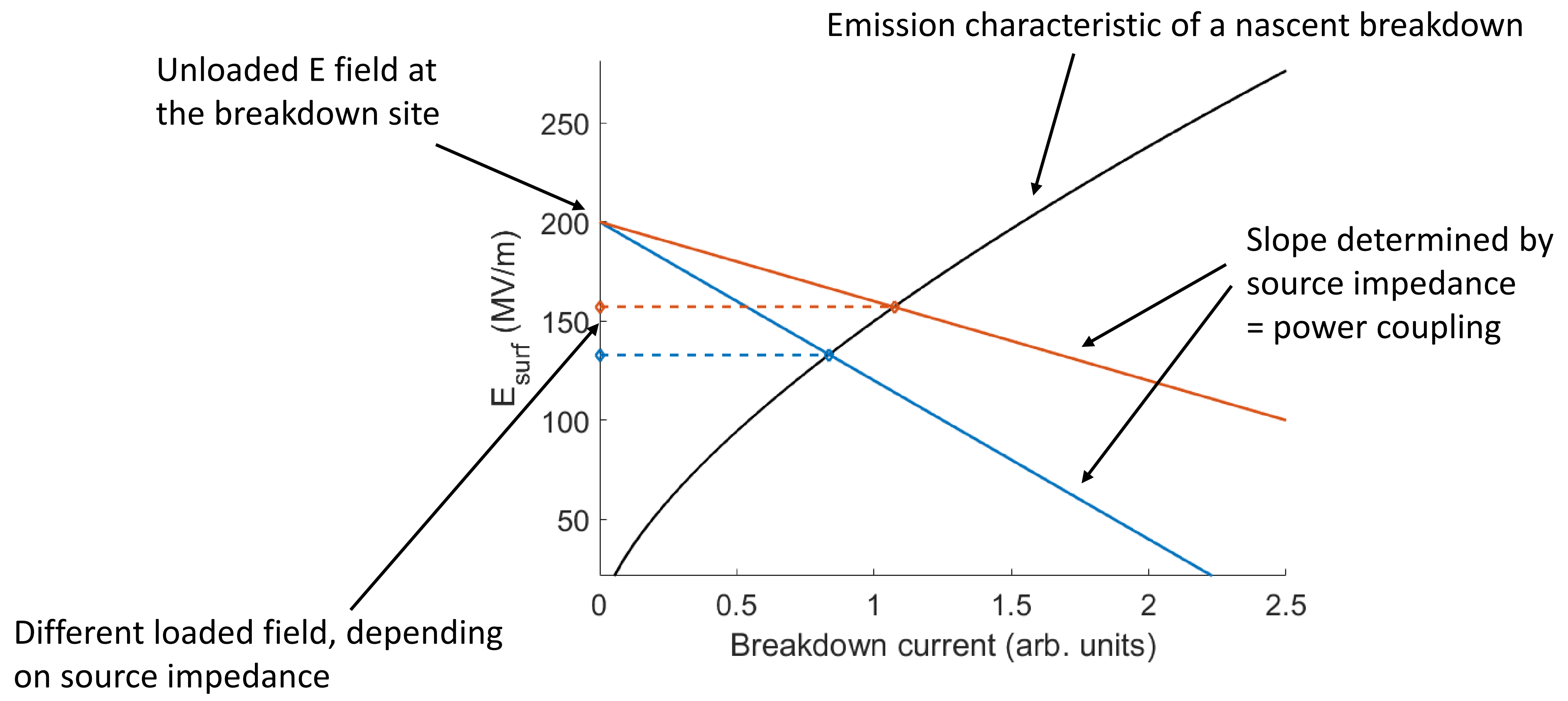
Power Absorbed by a Nascent Breakdown



Breakdown-Loaded Electric Field

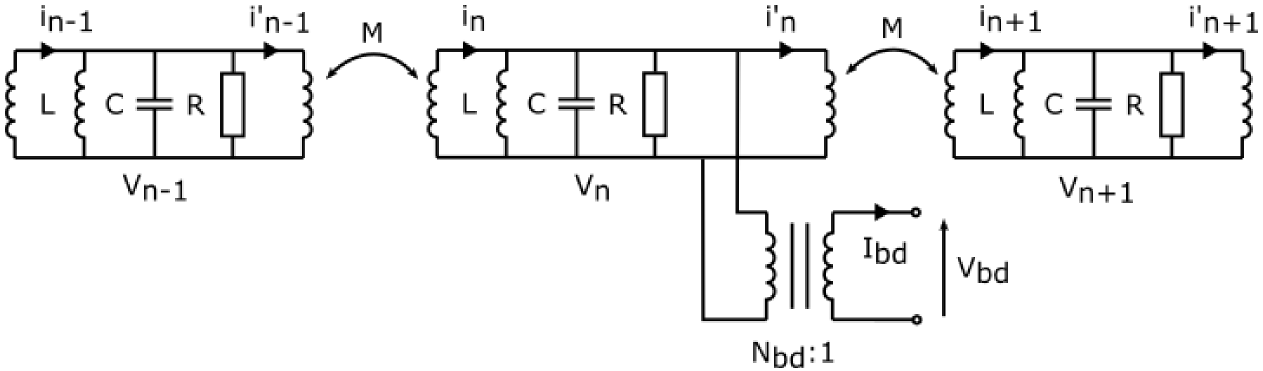
- The ultimate achievable gradient is a function of available power, like with S_c.
  - $S_c = Re\{E \times H\} + \frac{1}{6} Im\{E \times H\}$
  - Consider power during BD onset, not before!
- The current emitted by a nascent breakdown is a function of the surface E field.
- But the local surface E field decreases under BD loading, caused by the emitted current.
- Higher sustained E field under loading = higher BDR.
- Maximum gradient depends on both the unloaded E field, and how well power can be supplied to sustain the field.

Dependence on properties



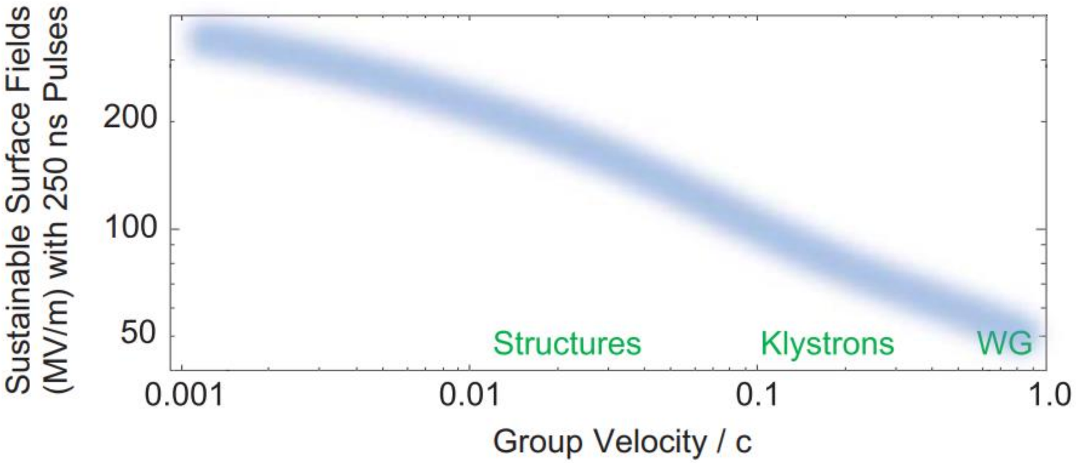
Calculation of Breakdown Impedance

- Breakdown impedance can be calculated with an analytical circuit model of a coupled-cell RF structure.
- Impedance is closely related to group velocity.
- Correlation between group velocity and breakdown performance has been noted by others.
- Can be calculated numerically via the coupling impedance to a small antenna representing the breakdown.



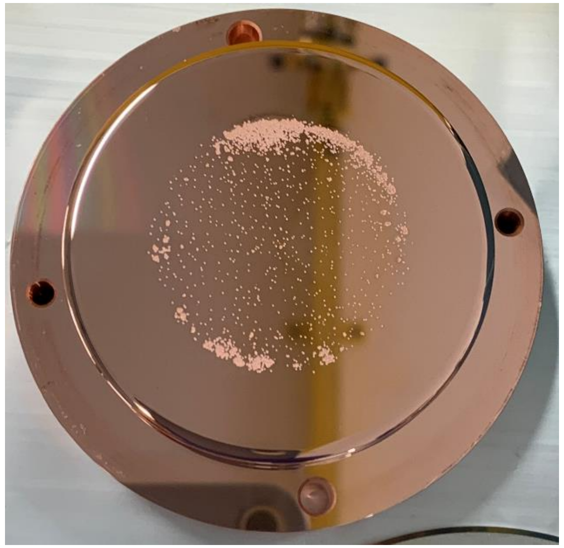
$$R_{bd}(\omega) = \frac{R}{Q}\frac{4\omega\omega_r}{\omega_\pi^2-\omega_0^2}\left(1-2\frac{\omega_r^2-\omega^2}{\omega_\pi^2-\omega_0^2}\right)^{\frac{1}{2}}\left(\frac{l_{ant}}{a}\right)^2\left(\frac{E_0}{E_{acc}}\right)^2$$

Dependence of peak E field on group velocity

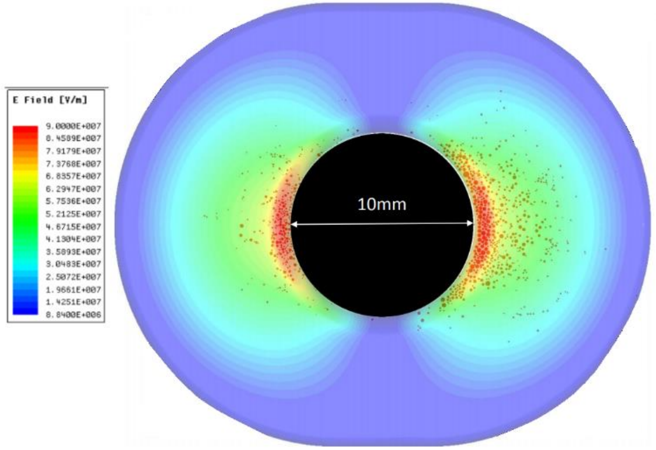


Breakdown-Loading Model Results

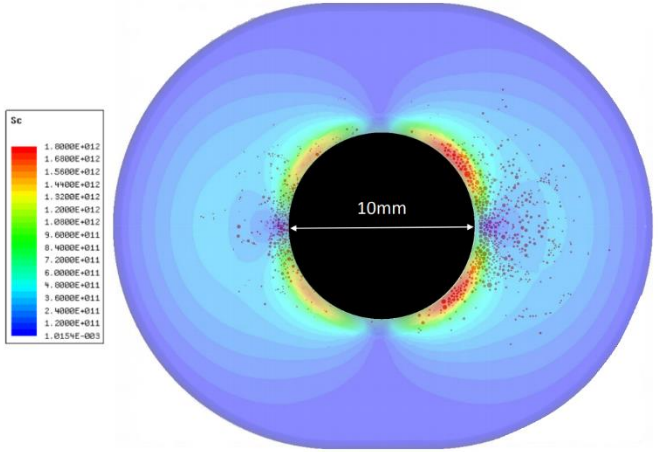
- The model has successfully reproduced many behaviours seen in experiment, including:
    - Tendency of breakdowns to cluster close the to input of TW structures despite tapering.
    - Breakdown locations in the CLIC Crab Cavity following the E field pattern but not the Sc pattern (below).
    - Correct dependence on group velocity in TW structures.
    - Breakdowns on edges of DC electrodes despite uniform E field (right).
    - Gap size dependence in DC experiments.
- The key insight is that power coupling is crucial.

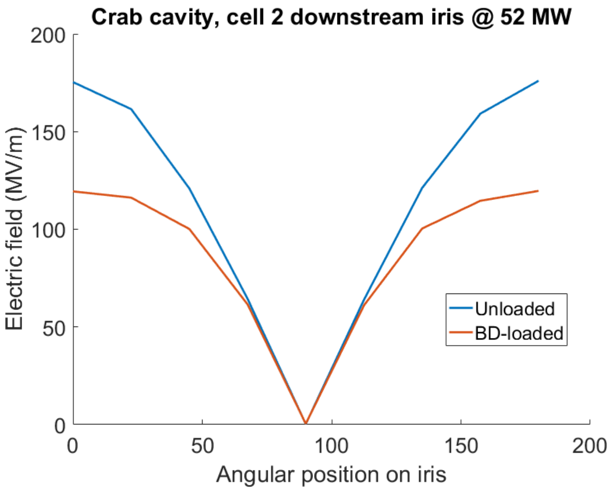


Breakdown locations vs. E field



Breakdown locations vs. Sc





Thank You

References

- W. Wuensch, et . al., “Statistics of vacuum breakdown in the high-gradient and low-rate regime,” Phys. Rev. Accel. Beams, vol. 20, p. 011 007, 1 Jan. 2017
- A. Kyritsakis et. al., J. Phys. D: Appl. Phys. 51, 225203 (2018)
- D. Dimiduk, M. Uchic, and T. Parthasarathy, “Size-affected single-slip behavior of pure nickel microcrystals,” Acta Materialia, vol. 53, no. 15, pp. 4065–4077, 2005
- E. Z. Engelberg, et. al., “Stochastic Model of Breakdown Nucleation under Intense Electric Fields,” Physical Review Letters, vol. 120, no. 12, p. 124 801, Mar. 2018.
- I. Profatilova et. al., “Behaviour of copper during initial conditioning in the pulsed DC system”, CERN-ACC-2019-0058
- A. Descoudres, et. al., “DC breakdown experiments with cobalt electrodes”, CERN-OPEN-2011-029
- C. Adolphsen, et. al., “High-Gradient Test of a Tungsten-Iris X-Band Accelerator Structure at NLCTA,” CERN, Geneva, Tech. Rep. CERN-OPEN-2006-072
- M. Jacewicz, et. al., “Preliminary results from the cryogenic pulsed DC system,” MevArc 2019, Padova.
- A. D. Cahill, J. B. Rosenzweig, V. A. Dolgashev, S. G. Tantawi, and S. Weathersby, High gradient experiments with X-band cryogenic copper accelerating cavities, Phys. Rev. Accel. Beams 21, 102002
- H. Timko et. al., Contrib. Plasma. Phys. 4, 229 (2015).
- S. Dobert, et. al., “High gradient performance of NLC/GLC X-band accelerating structures,” in Proceedings of the 2005 Particle Accelerator Conference, 2005, pp. 372–374
- E. R. Castro, “Microscopy at CERN,” in Mini MeVArc meeting, Tartu, Estonia, 2017