Electron emission behavior at small gaps in vacuum interrupters

Sig Nelson, Tushar Damle, Rami Jaber, Abdelrahman Haridy, Erik Taylor

Presented by

Erik Taylor

5 June 2025

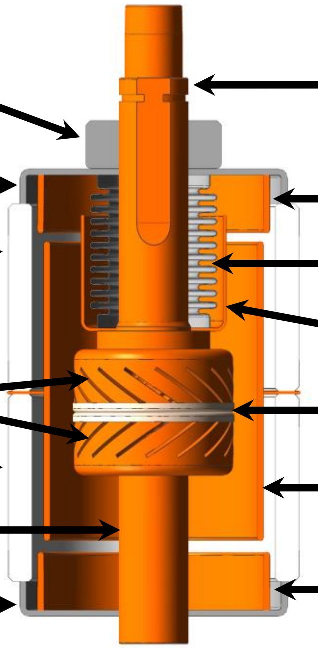
Overview

- Electron emission experiments at small contact gaps on vacuum interrupters.

  - Background.
  - Experimental setup.
  - FEA modeling of the electric field magnitude.
  - Repeatability of the measurements.
  - Effect of additional conditioning.
  - Effect of contact gap.
  - Comparison to other electron emission data.
  - Effect of different conditioning on breakdown voltage.
  - Summary.

Background

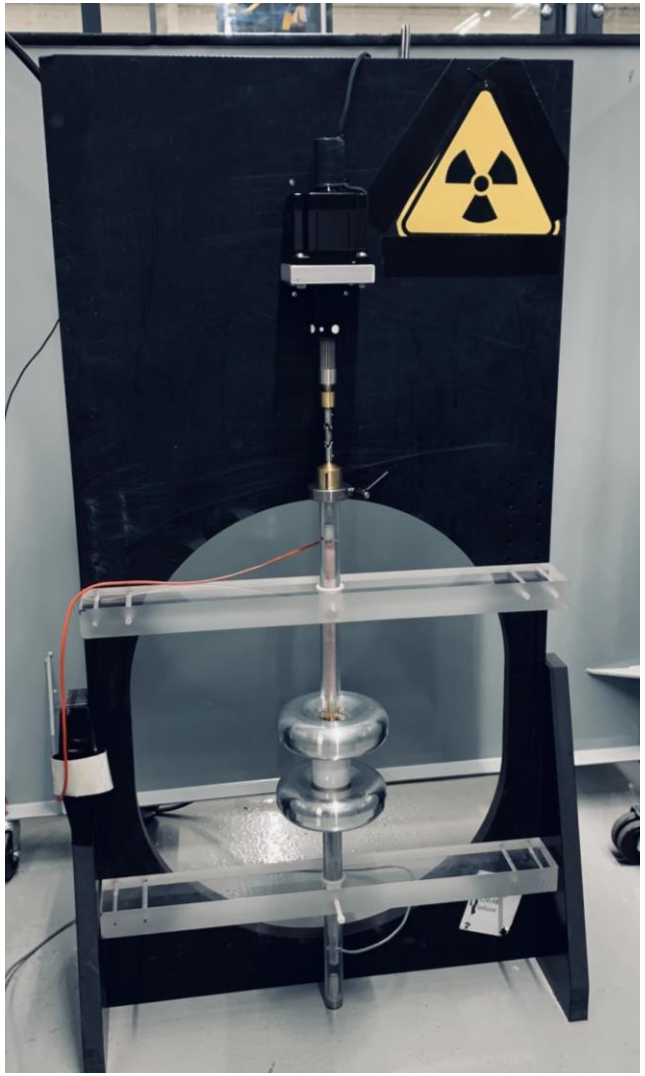
- Vacuum interrupters



- Used in medium voltage (1-38 kV) and high voltage (≥72 kV) electrical power systems.
- Need to perform several duties well.
  - Pass current when closed.
  - Open and interrupt (short-circuit) currents.
  - Close onto (short-circuit) currents.
  - Hold off voltage when open.
- Critical voltage is lightning impulse withstand voltage.
  - At the high end of MV and HV, requires contact gaps 16-60 mm.
  - At the low end of MV, contact gaps ≤ 8 mm.

Experimental setup

- How to analyze the voltage withstand behavior.

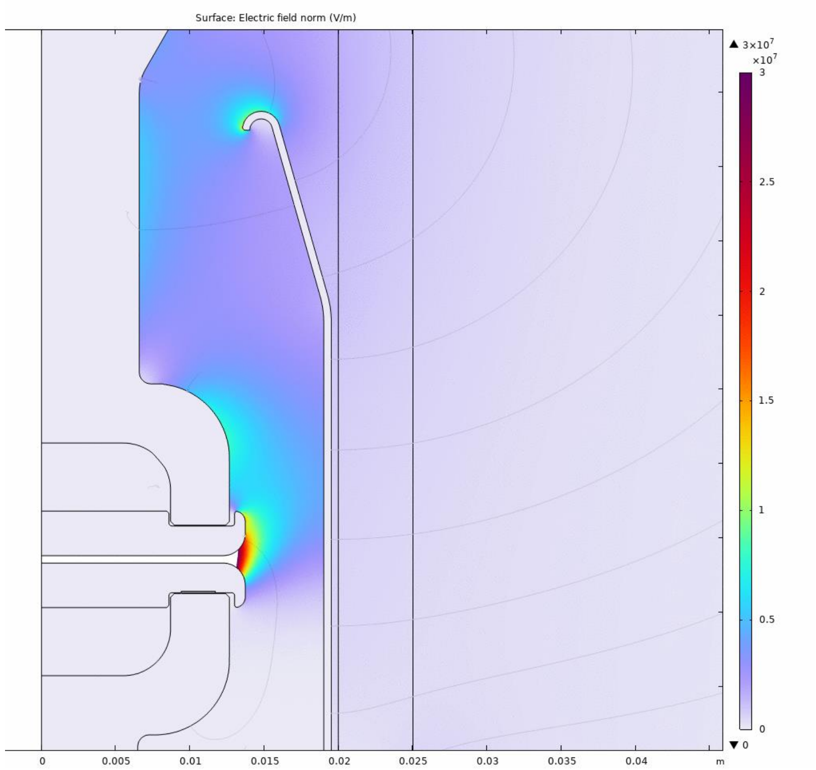


- Obvious option is performing the voltage tests.
  - Specialized equipment, limited access.
  - Slow to charge for test, slow to switch polarities.
  - Conditioning / de-conditioning effects.
- Measuring emission current with DC voltage.
  - At modest contact gaps, possible with reasonable power supplies and manageable x-ray emission.
  - Integrated with computer control of both the voltage and contact gap (and maximum current).
  - Tests up to ~ 40kV in air.
  - Rapid testing and rapid sample change.

Thanks to Mark Muir for the initial experimental development.

FEA modeling

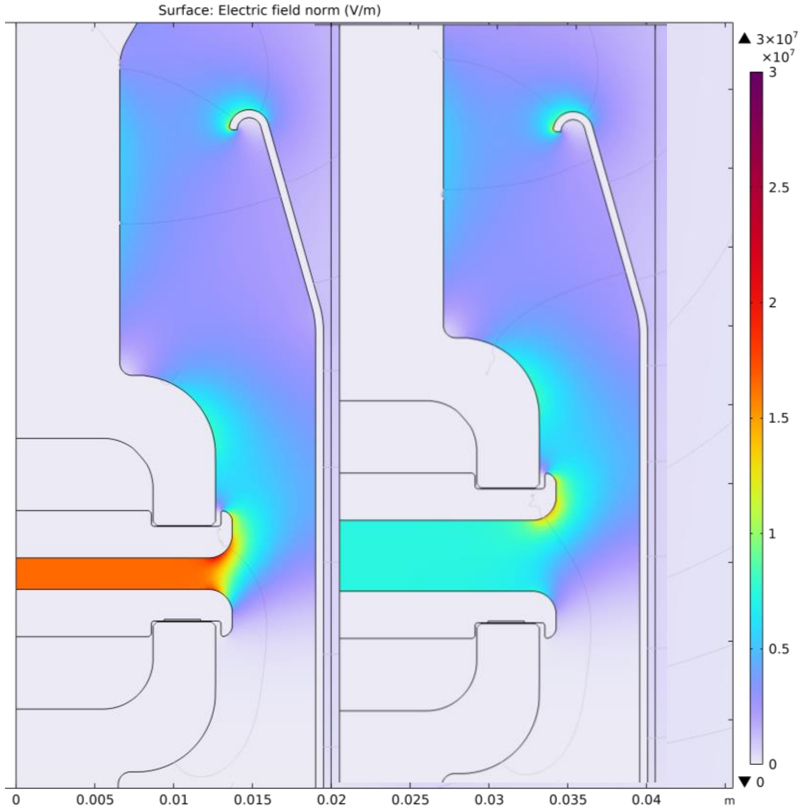
- Electric field stress on contacts as a function of the gap



- Two contacts, with metal wall connected to lower contact.
- Gaps ≤ 2 mm, relatively even stress over contact surface.
- At higher gaps, distinct peak electric field stress on edge of moving contact.
- Stress on end of metal wall plays more of a role at larger gaps.
- See if these behaviors appears in emission current measurements.

FEA modeling (backup slide in case movie does not work)

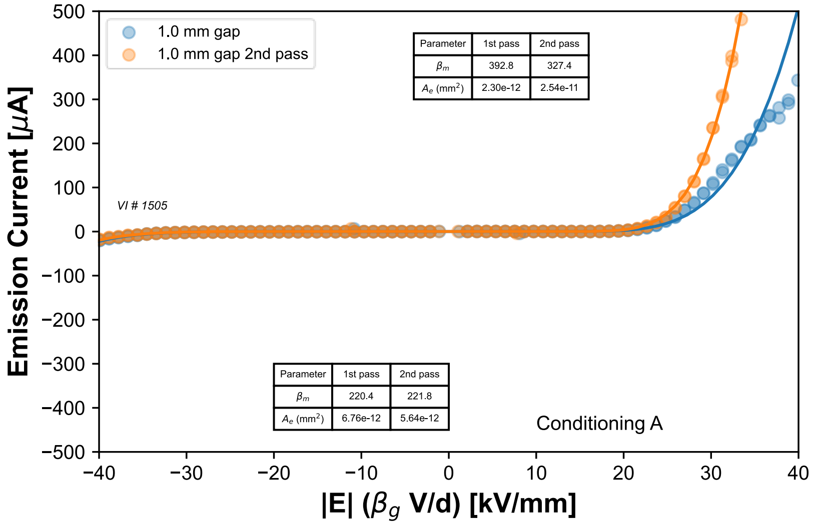
- Electric field stress on contacts as a function of the gap

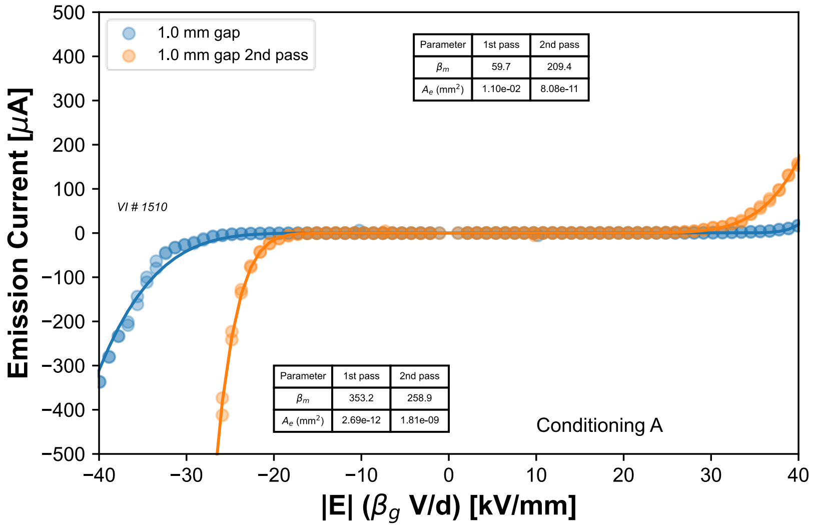


- Two contacts, with metal wall connected to lower contact.
- Gaps ≤ 2 mm, relatively even stress over contact surface.
- At higher gaps, distinct peak electric field stress on edge of moving contact.
- Stress on end of metal wall plays more of a role at larger gaps.
- See if these behaviors appears in emission current measurements.

Repeatability on new samples

- Standard voltage conditioning (version A)

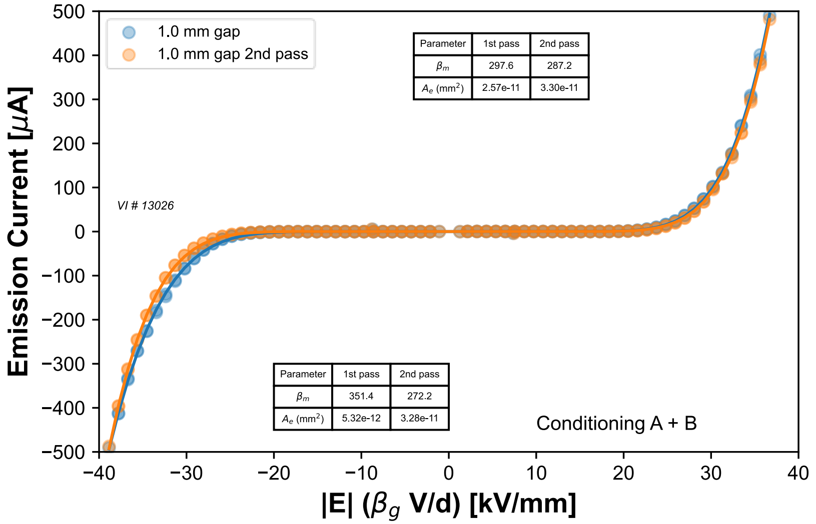


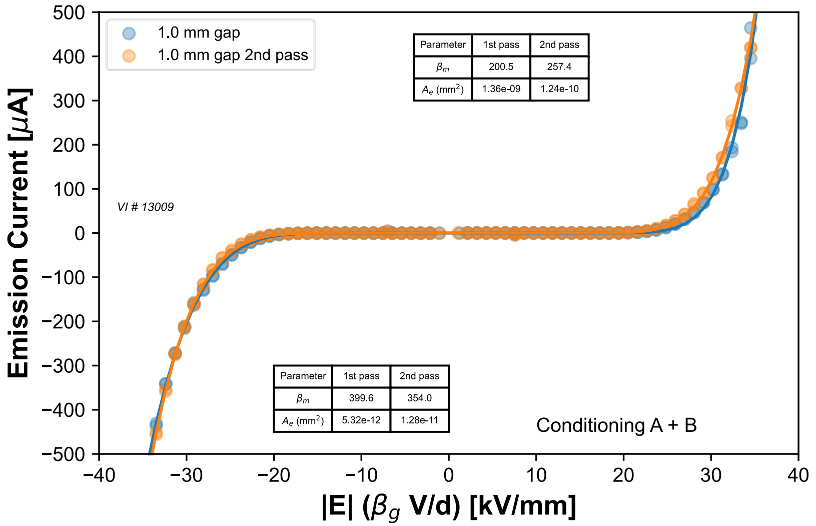


- Voltage scan at different contact gaps.
  - Start at largest gap, scan the voltage.
  - Polarity is relative to the moving contact.
  - Reduce the contact gap in 0.5 mm steps and repeat.
  - Range of 1-3 mm and -40 to 40 kV for these experiments.
  - Second run is a simple repeat of the scan.
  - Convert to electric field stress, including peak β_g.
  - Sign of electric field is relative to moving contact.
- Data for two VI's at 1.0 mm contact gap with standard voltage conditioning.
  - Differences between samples.
  - Differences between first and second scan.
  - (Comparatively) high electric field to get emission current.

Effect of additional conditioning

- Standard voltage conditioning (A) plus additional conditioning step (B)

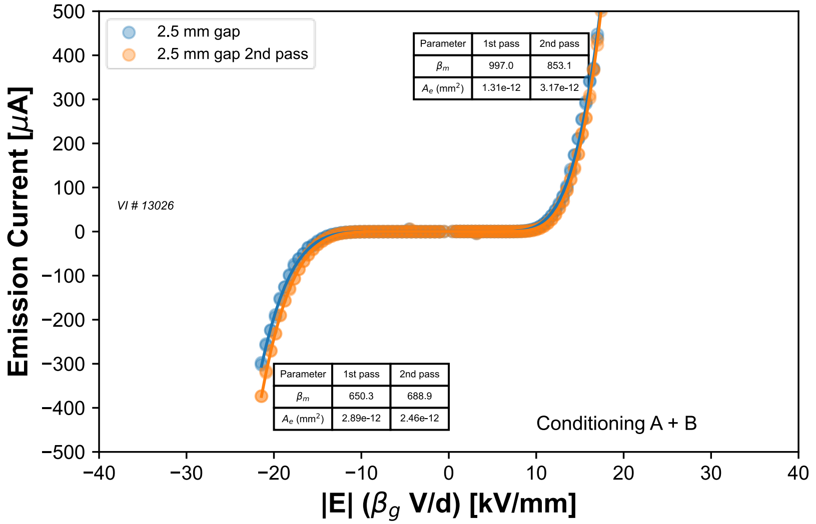


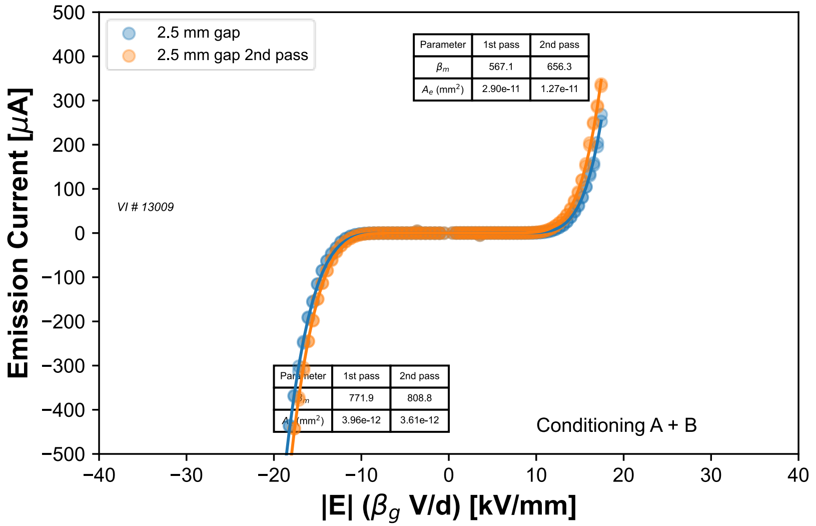


- Two VI’s also at 1.0 mm contact gap.
- Additional conditioning step.
- Very good repeatability between first and second scan.
- Similar behavior between the samples.
  - Similar fit parameters to emission current equation.
  - Contrast with conditioning A.
- Minimal difference between polarities.
  - Reasonable at small contact gap.

Effect of contact gap

- Increasing gap from 1.0 mm to 2.5 mm (conditioning A+B)



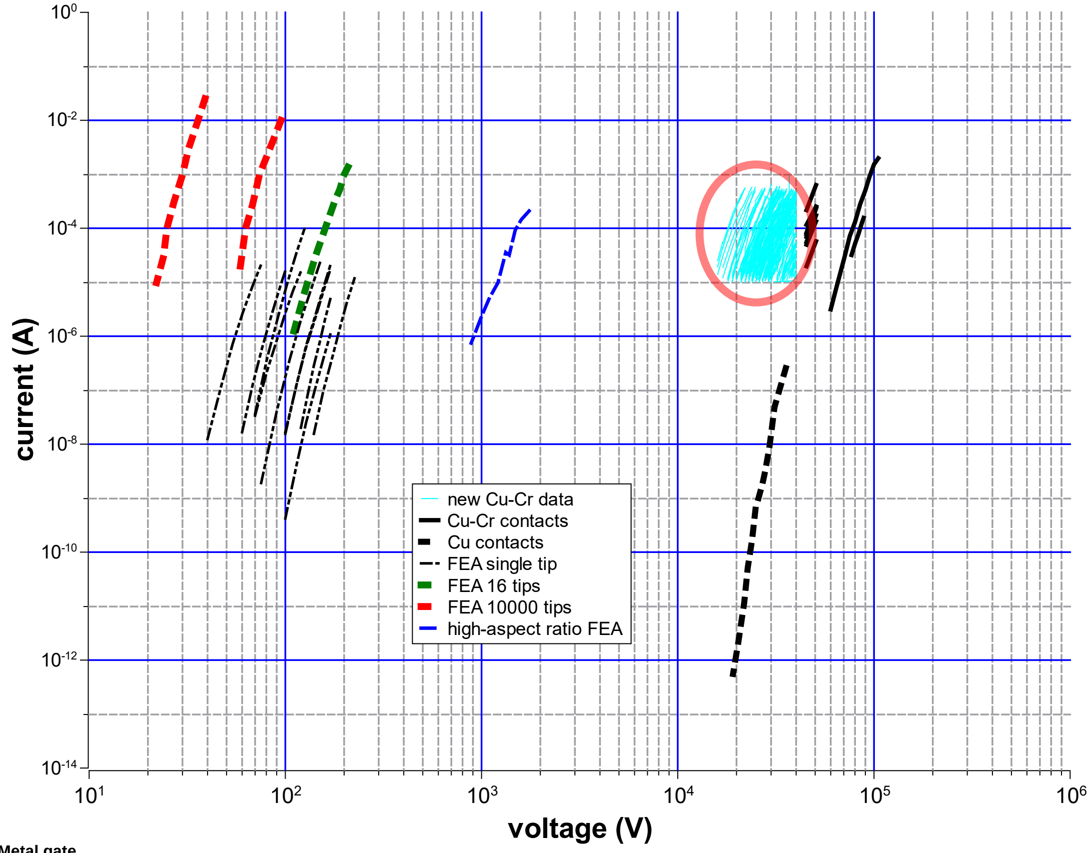


- Data for same two VI's at 2.5 mm gap.
- Again, very good repeatability between first and second scan.
- Also, similar behavior between the samples.
- Emission starts at lower electric field.
  - Even when including the macroscopic geometry effects.
- Minimal difference between polarities.
  - Effect of β_g already included.
  - Suggests emission current controlled by peak electric field.
  - Less influence from the area under electrical stress.

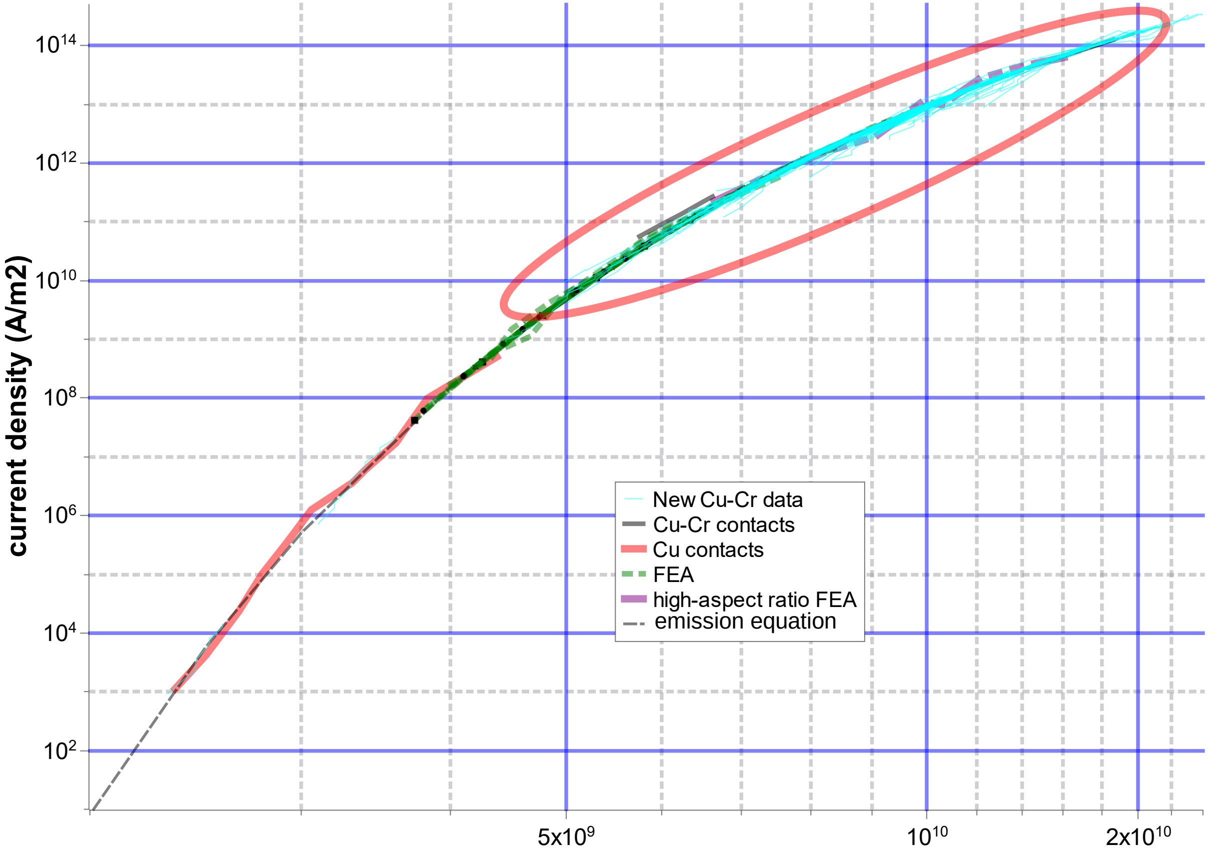
Comparison to other electron emission data

- New data includes tests from 1-3 mm gap and three different conditioning cases.

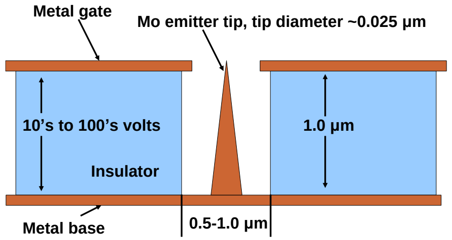
Actual measured data



Good fit to emission current equation for wide range of experiments



Using A_e to convert to J and β to convert to |E| **electric field (V/m)**

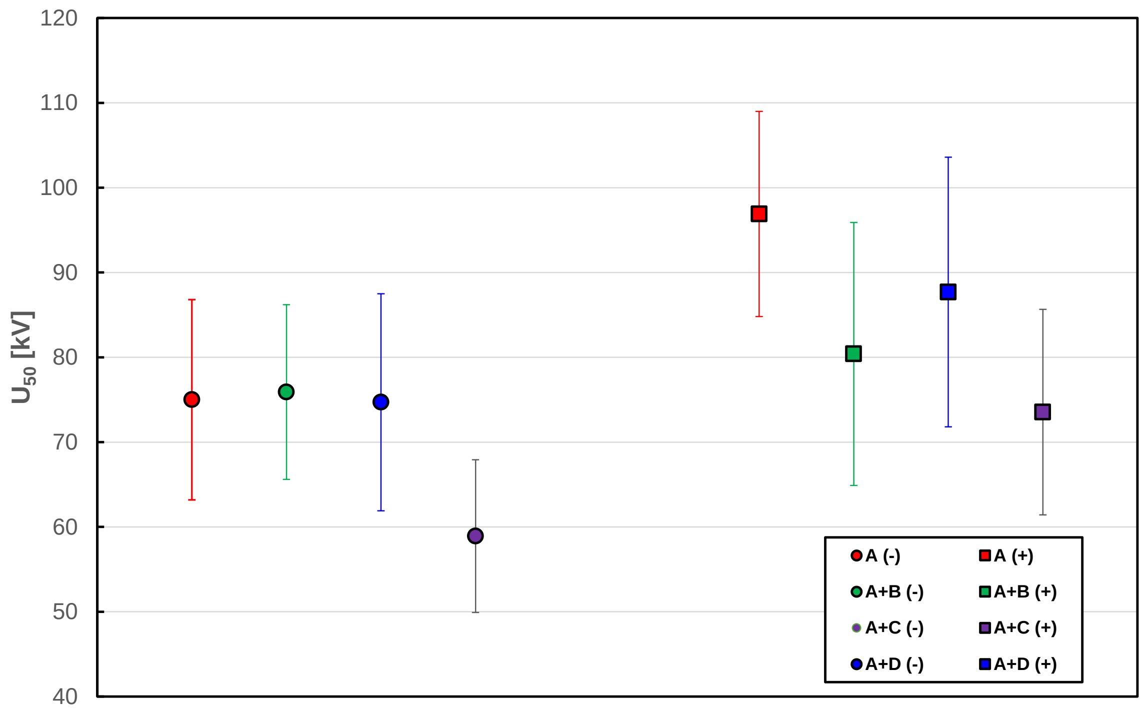


Example of a FEA (field emitter array)
Source of data < 2000 volts

Erik D. Taylor, "Environmentally friendly high-voltage AC switching technology: vacuum circuit breakers," in Green HV Switching Technologies for Modern Power Networks, Kaveh Niayesh, Ed. United Kingdom: Institution of Engineering and Technology, 2023, chp. 3.

Effect of conditioning on breakdown voltage

- 50% breakdown voltage for lightning impulse withstand voltage (U_{50})



- Tests at a single contact gap.
- Distribution of breakdown voltages after accounting for conditioning.
- Four different conditioning procedures.
- Results.
  - Observed difference between A and A+B/A+C in emission current tests.
  - No simple correlation in breakdown behavior.
- Unfortunately, do not have emission current measurements for these samples.
  - Repeat with the measurements before and after and attempt to correlate in detail.

Summary

- Much work remains but now have a useful tool.

- Vacuum interrupters at the lower end of medium voltage can be studied using emission current.
  - Higher voltage VI’s use larger contact gaps, which complicate the experimental setup.
- Straightforward setup allows for rapid scans of the voltage and contact gap.
- Effects of different gaps and conditioning on the emission current.
- Good general agreement to a range of other emission current data.
- Initial comparison to breakdown data.
- Straightforward to acquire more data, and work is very much in progress.