Effects of the series impedance on vacuum arc plasma onset

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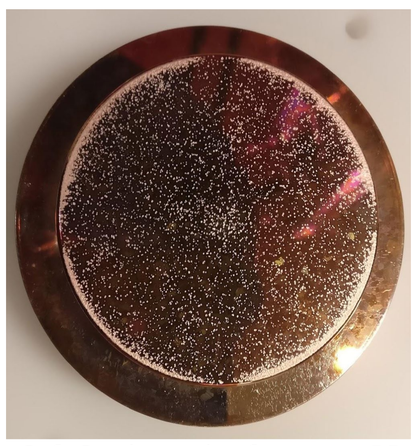
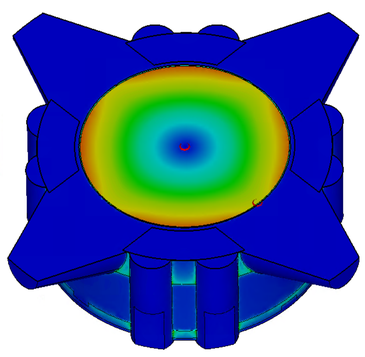
Abstract

The surface electric field has been regarded as the only parameter that determines the occurrence of a vacuum breakdown (VBD) for a given surface condition. However, recent studies have accumulated an increasing amount of evidence indicating that the ultimate limit depends strongly also on the electromagnetic power that is available to be delivered at the VBD site. Here we study this dependence both experimentally using a pulsed DC system and by numerical plasma simulations using the particle-in-cell (PIC) model ArcPIC [Timko et. al. Contrib. Plasma Phys. 55, 299(2015)]. By varying the series impedance, we controllably limit the power coupling from the source to the vacuum discharge gap. The experimental results show that the breakdown voltage increases with increasing impedance, i.e., with increasing circuit resistance and decreasing capacitance. The ArcPIC results showed that a minimum current is required to ignite the plasma, and the breakdown voltage is defined by the circuit impedance and the critical power loaded to the gap just before the breakdown.

Introduction



Soft Cu electrode after many BDs



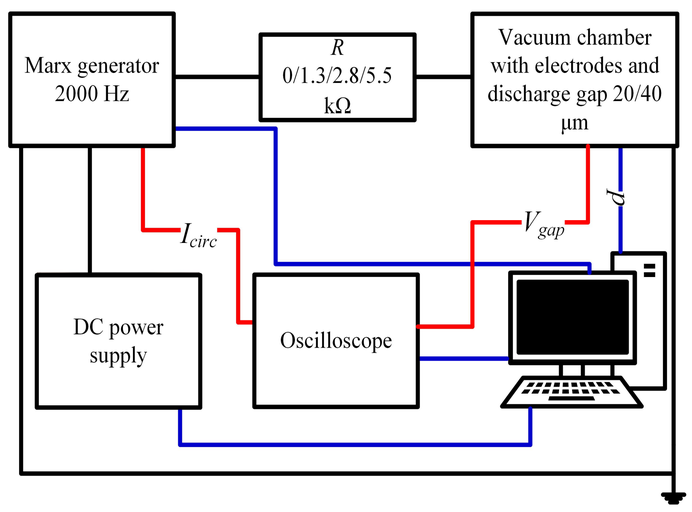
Calculated S_c (Jan Paszkiewicz)

Evidence for EM power availability dependence

- Breakdowns in DC systems accumulate on the edges, although the field is uniform
- BDs in accelerators accumulate in regions of high power flow
- BDs in accelerators accumulate at early cells

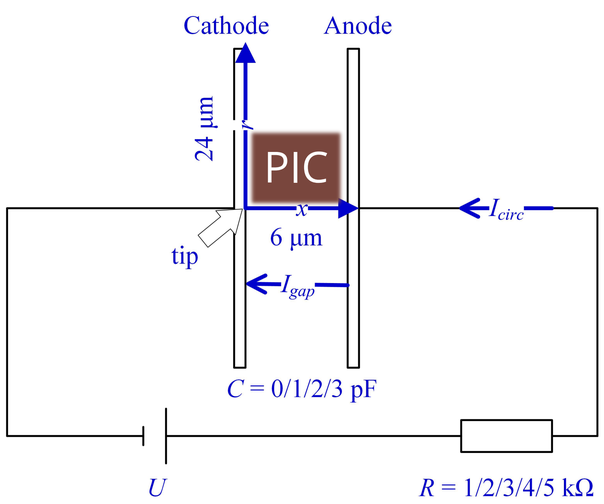
Methods

Experiment



- Classical Large Electrode system
- Varying series resistor & gap capacitance

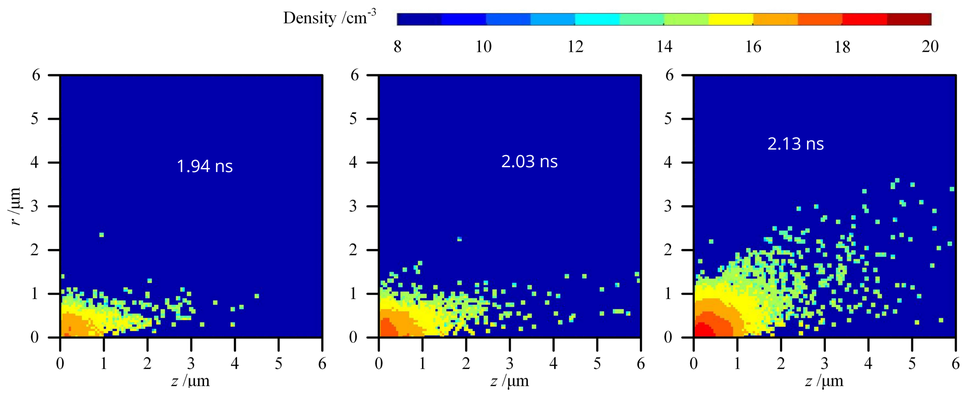
Simulation

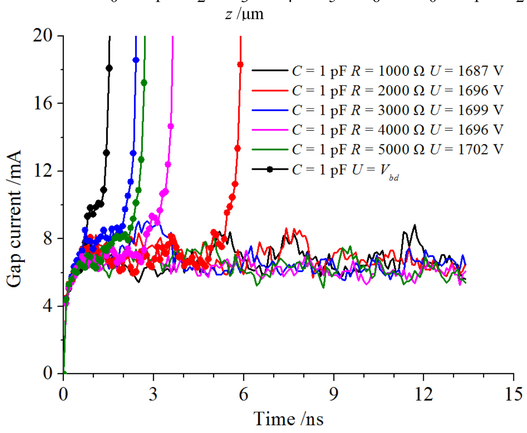


- Classical ArcPIC [Timko, et. al.]
- Varying series resistor & capacitor

Results

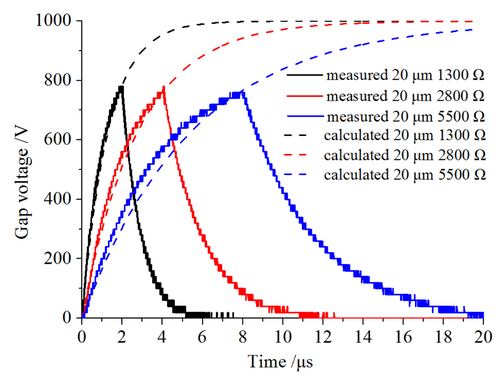
PIC density evolution during a BD:

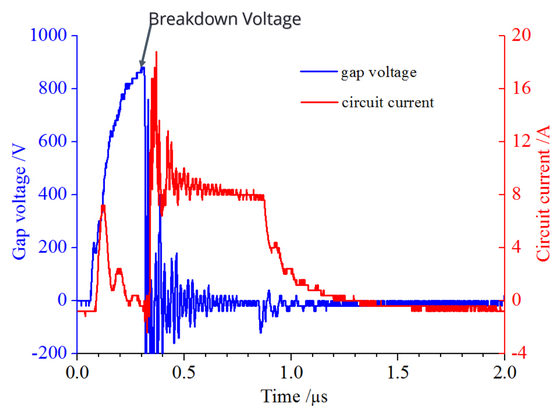


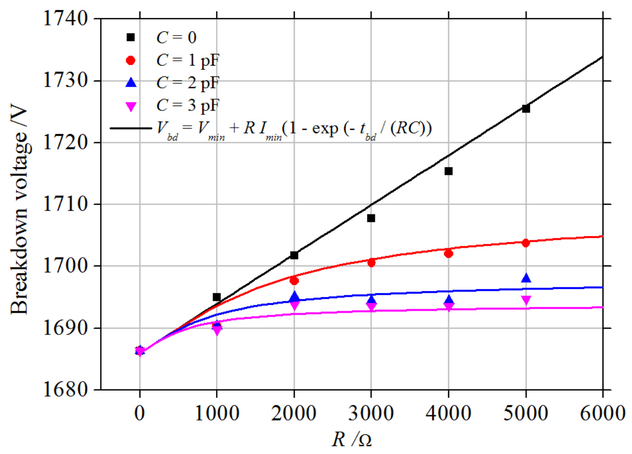


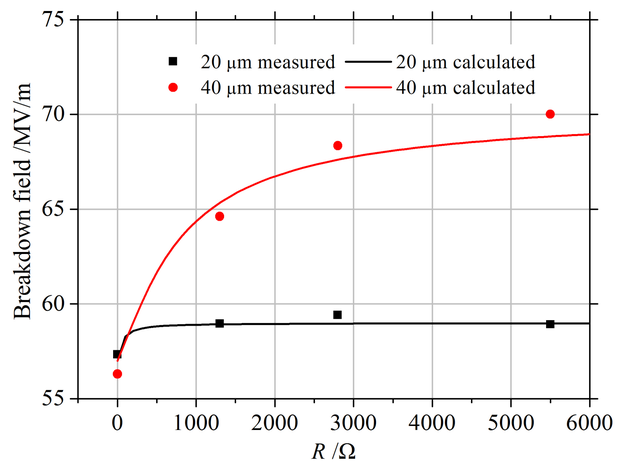
- PIC runs with BD go to runaway. Without they have stable current
- Find V_{bd}: Scan Voltage until BD occurs in a simulation
- Criterion for no BD: current stable up to 13 ns

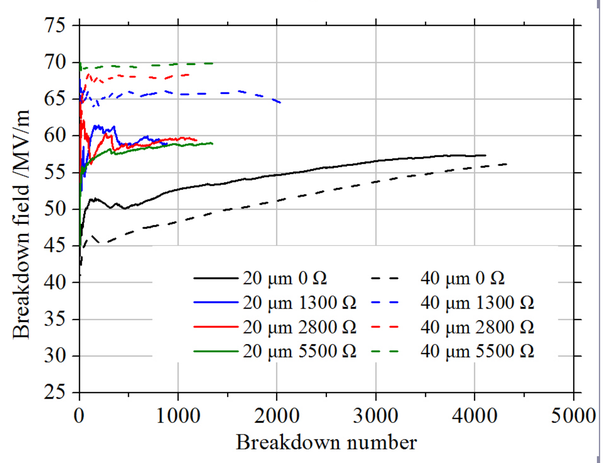
Pulse evolution with and without BD











- V_{bd} depends on R, C as: $V_{bd} = V_m + RI_m\left(1 - \exp\left(-\frac{t_{bd}}{RC}\right)\right)$
- PIC fitted parameters: $V_m = 1.686$ kV, $I_m = 8$ mA, $t_{bd} = 3$ ns
- Experimental fitted $V_m = 1.140, 2280$ kV, $I_m = 0.4$ A, $t_{bd} = 0.1, 0.8\ \mu s$ (qualitative agreement with PIC)

Conditioning curves show:

- Higher R, higher BD field
- Higher capacitance, lower BD field
- Together: **BD field increases with the coupling impedance**

Conclusions & Outlook

- We give a tentative explanation of the BD dependence on the coupling of electromagnetic power
- PIC: ionization avalanche is limited by the suppression of the voltage by the loading current
- Our results support the hypothesis that the minimum-current-loaded field, i.e., $E_L = E_0 - I_m Z_{bd}$ determines whether breakdown will occur, with E_0 being the field without current, I_m the minimum current required for BD, and Z_{bd} the coupling impedance
- More elaborate models, including the complex surface evolution, are necessary to quantify this precisely