Effect of R and C on vacuum breakdown
studied by PIC/MCC simulations

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Motivation

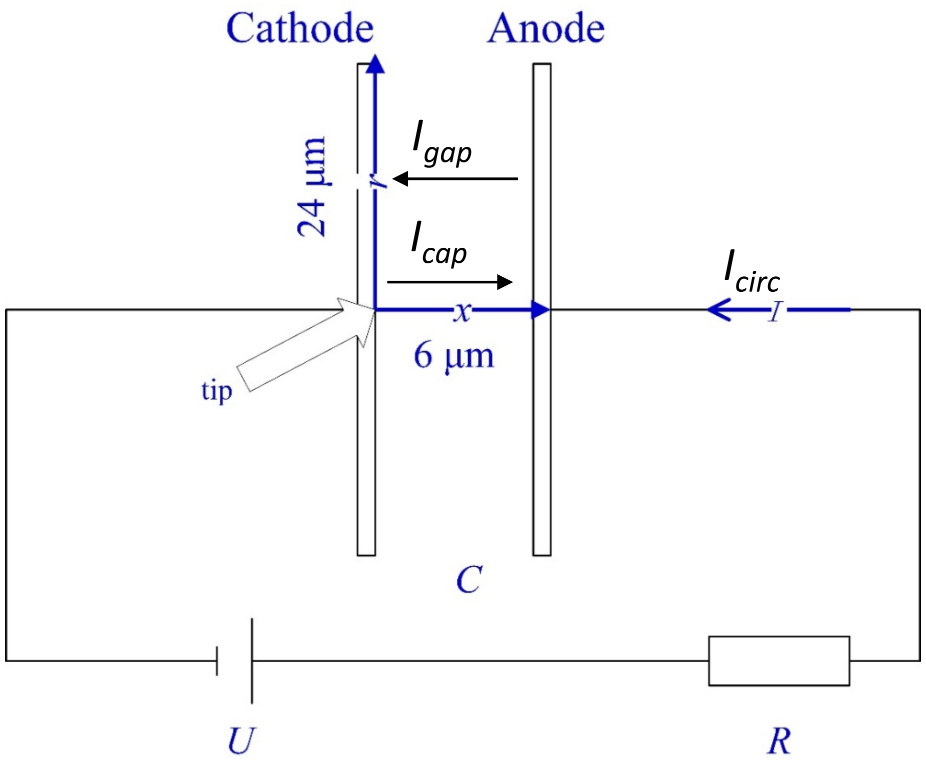
- Lower the breakdown rate in accelerating structures
- Lower the pre- breakdown rate in vacuum circuit breakers in power system

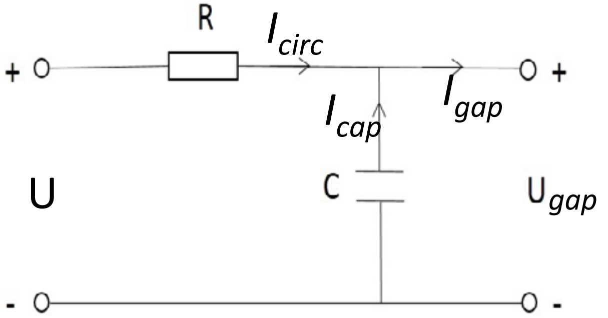
  Pre-breakdown: before the electrodes switch on, breakdown happens in the vacuum gap, bridging the gap in advance, leading to over voltage in power system

Outlines

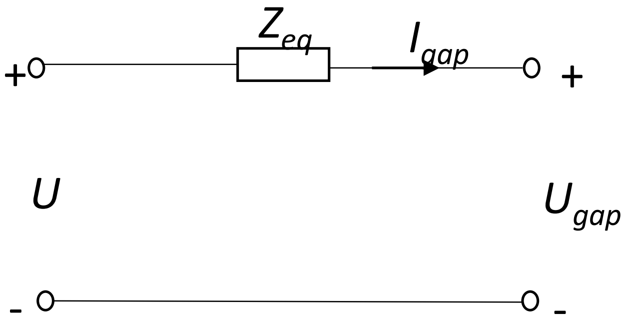
- PIC/MCC modeling of the vacuum breakdown onset
- The minimum gap voltage V_0 and current I_0 needed for the breakdown
- Effect of R and C on the vacuum breakdown

Simulation model





$U=I_{gap}\,Z_{eq} + U_{gap}$
$Z_{eq}=R/(1+\omega RCj)$

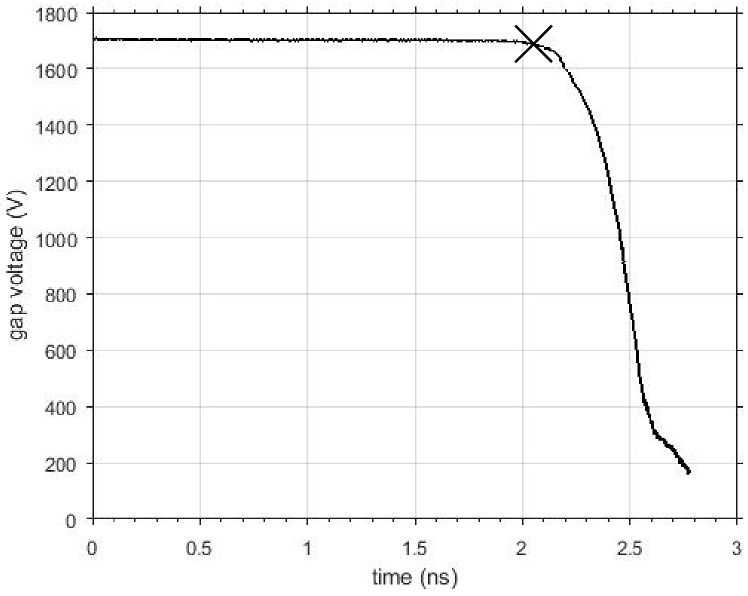


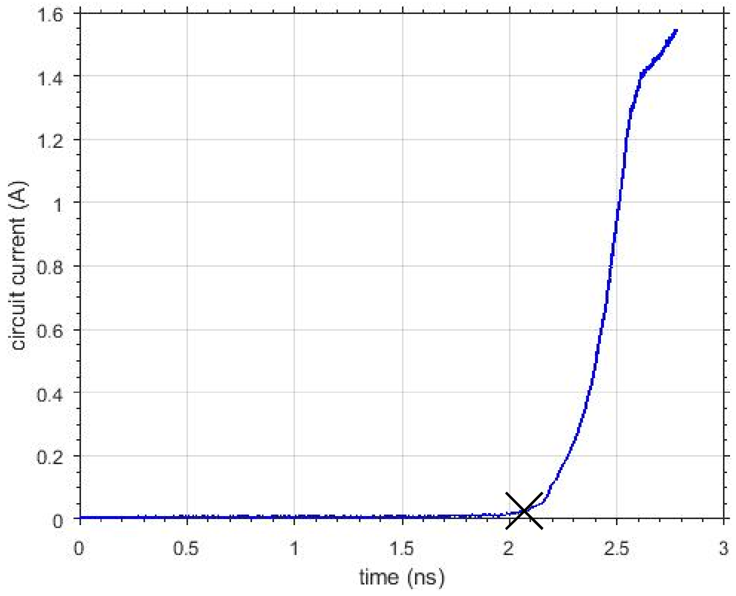
- field enhancement factor β = 35
- ratio between evaporated Cu neutrals and field-emitted electrons $r_{Cu/e}$ = 0.015
- External voltage U is DC voltage
- ArcPIC code

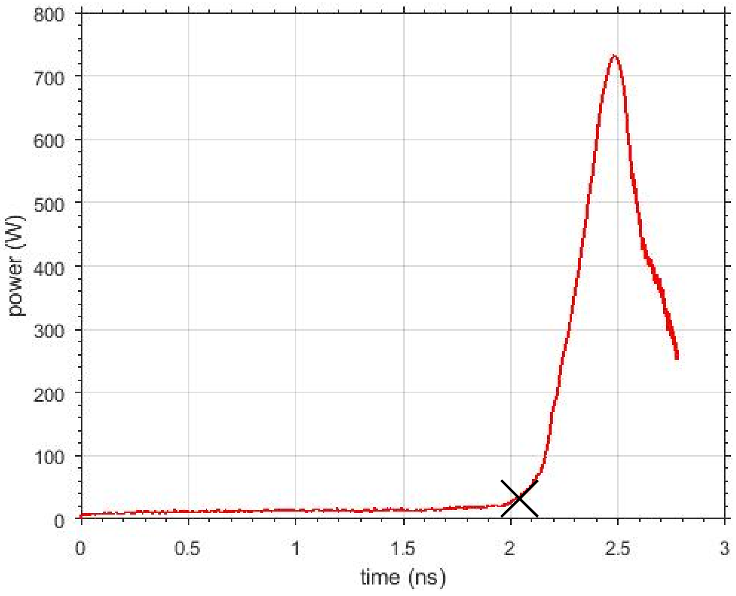
  Helga Timko, *et al*. From Field Emission to Vacuum Arc Ignition: a New Tool for Simulating Copper Vacuum Arcs.

Modeling breakdown onset

Time evolution of **gap voltage**, **current** and **power** (C=0 pF, R=1000 Ω, U=1711 V)







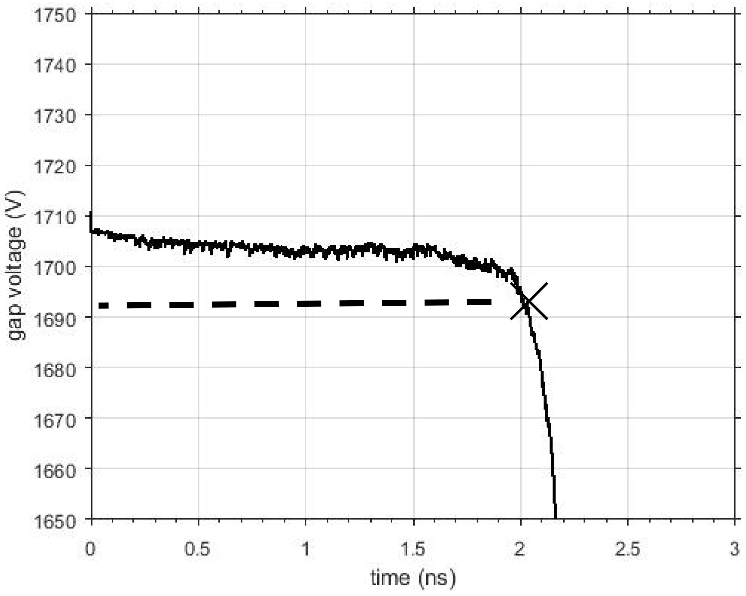
The “breakdown” occurs when the voltage on the discharge gap begins to dive. $\frac{\Delta U_{gap}}{U_{gap}\Delta t} > 5e^7/s$

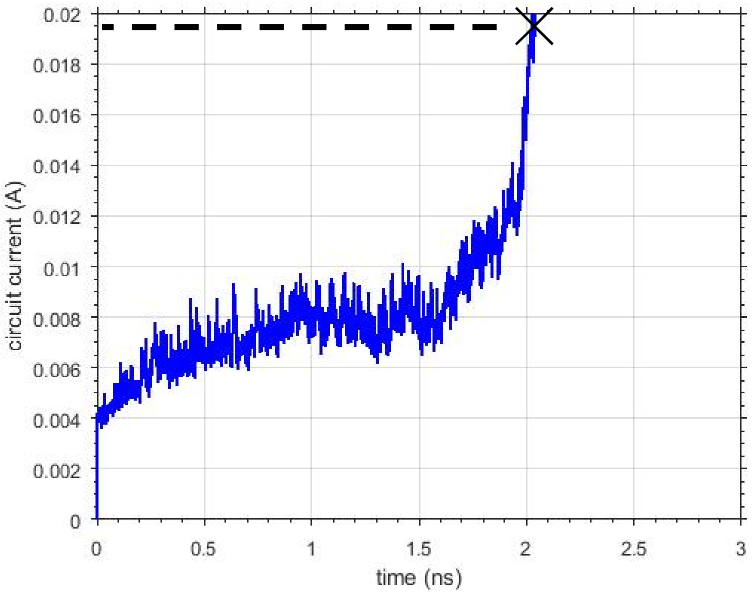
C=0 pF, R=1000 Ω, U=1711 V, t =2.03 ns

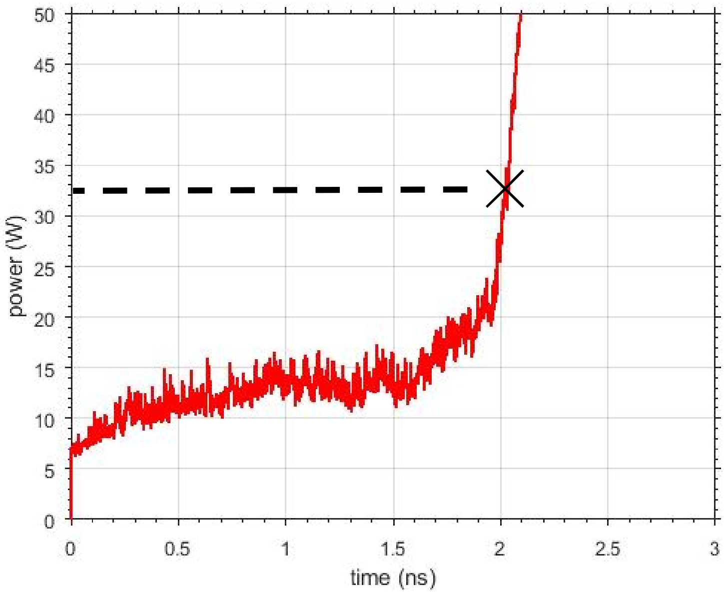
×: the breakdown

Modeling breakdown onset

Zoom on the breakdown onset





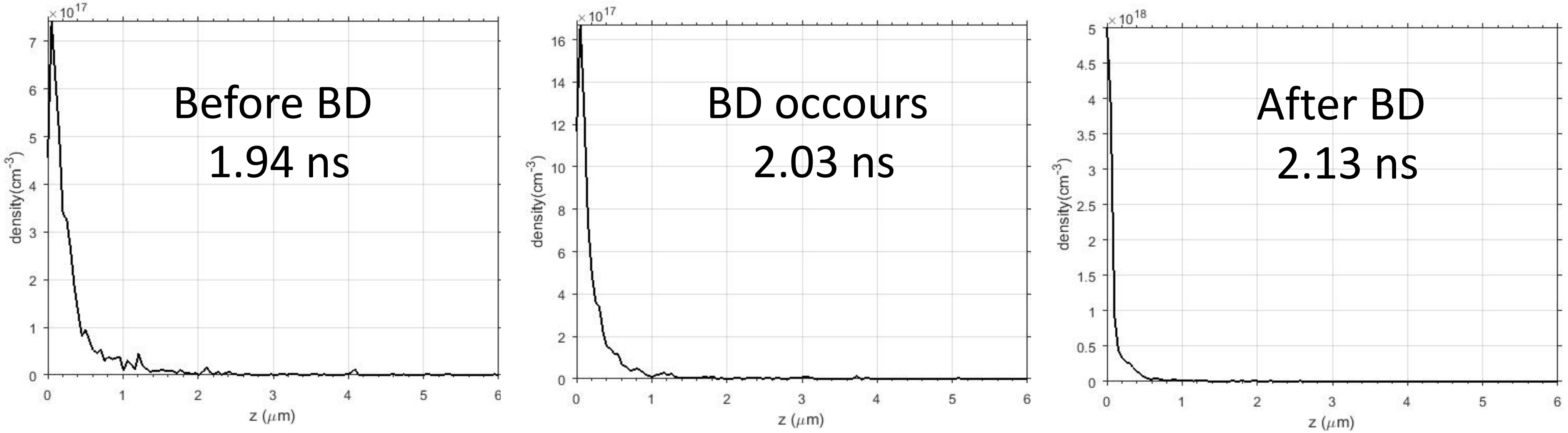


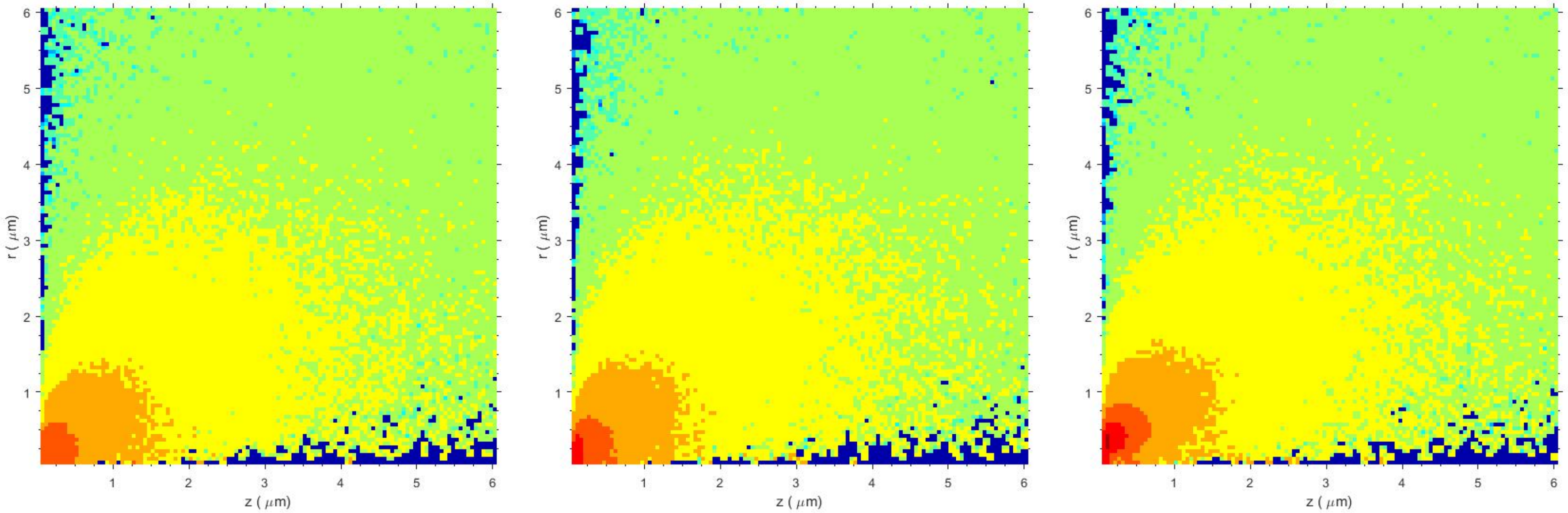
BD-loaded voltage 1690.8V

BD-loaded current 20mA

BD-loaded power 33.8W

Modeling breakdown onset ---- atom density



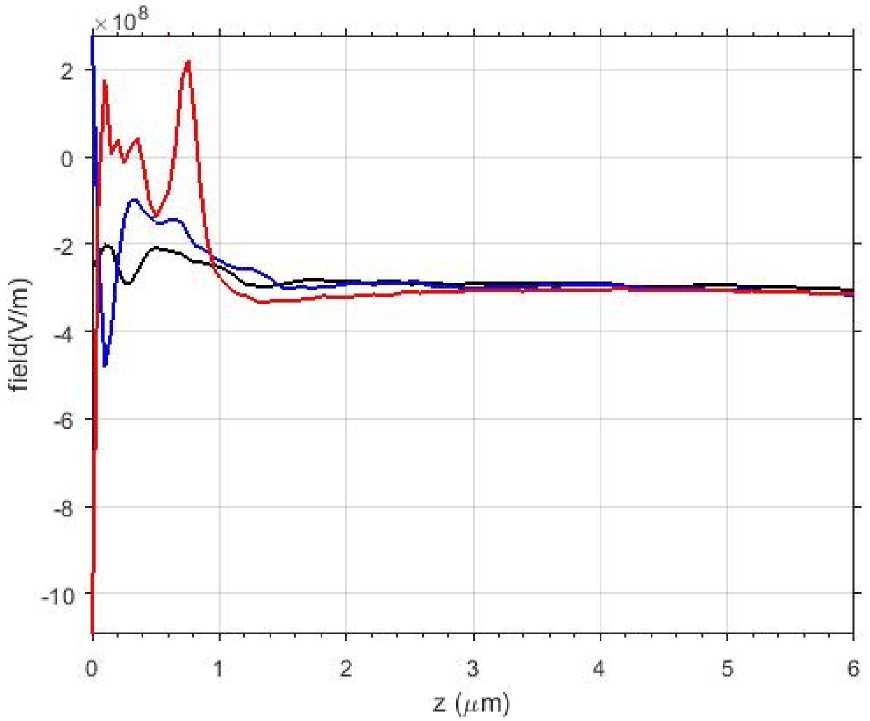


Atom density leading to BD $1*10^{18}cm^{-3}$ explained by the mean free path for collisions.

There should be a minimum voltage V_0 resulting this critical neutral density.

Modeling breakdown onset ---- cathode sheath

Gap center field



Before BD 1.94 ns

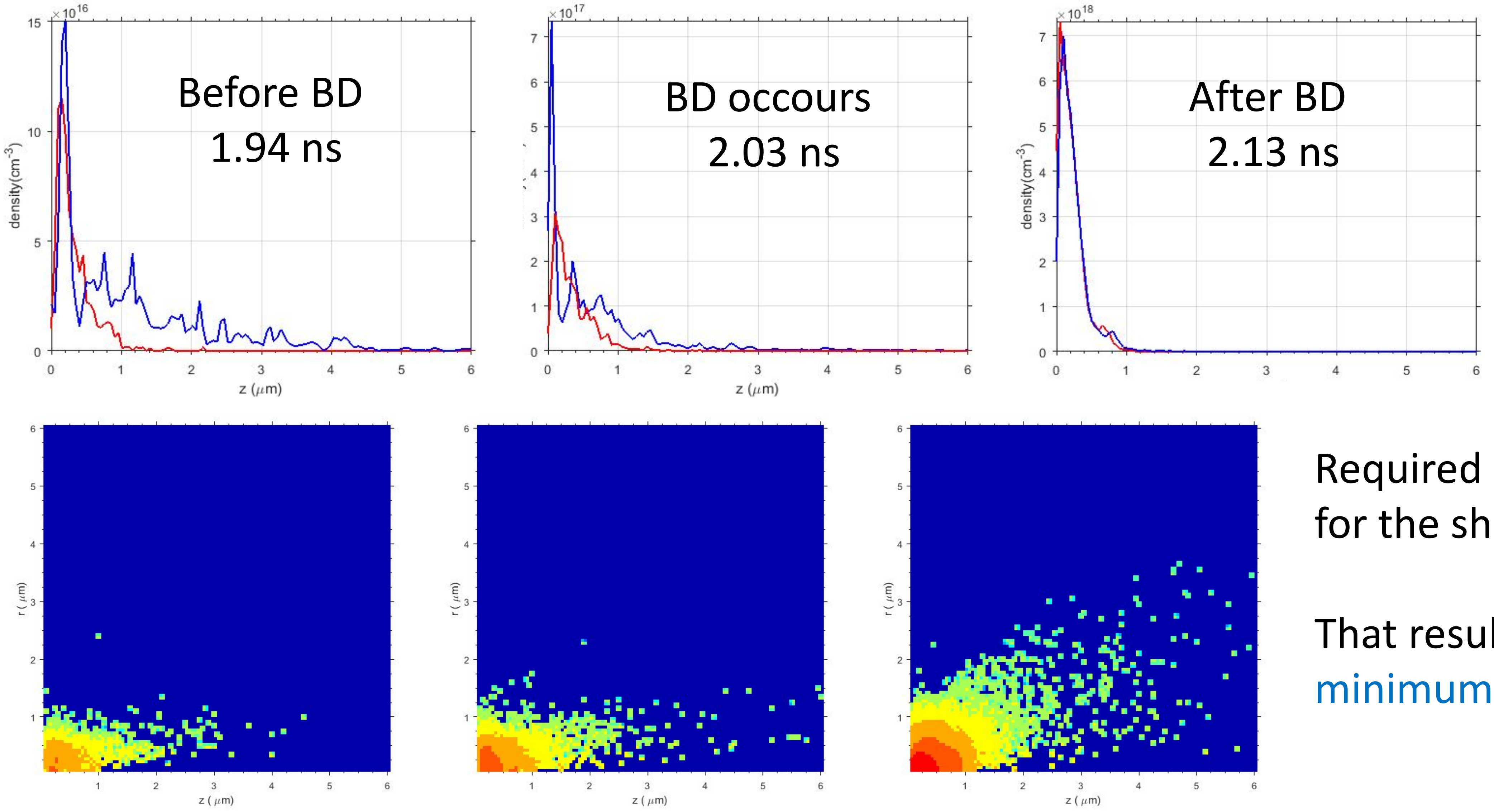
BD occours 2.03 ns

After BD 2.13 ns

cathode sheath formation: the space charge enhanced field is comparable to the external field

Non-selfsustained discharge →selfsustained discharge: BD

Modeling breakdown onset ---- plasma density



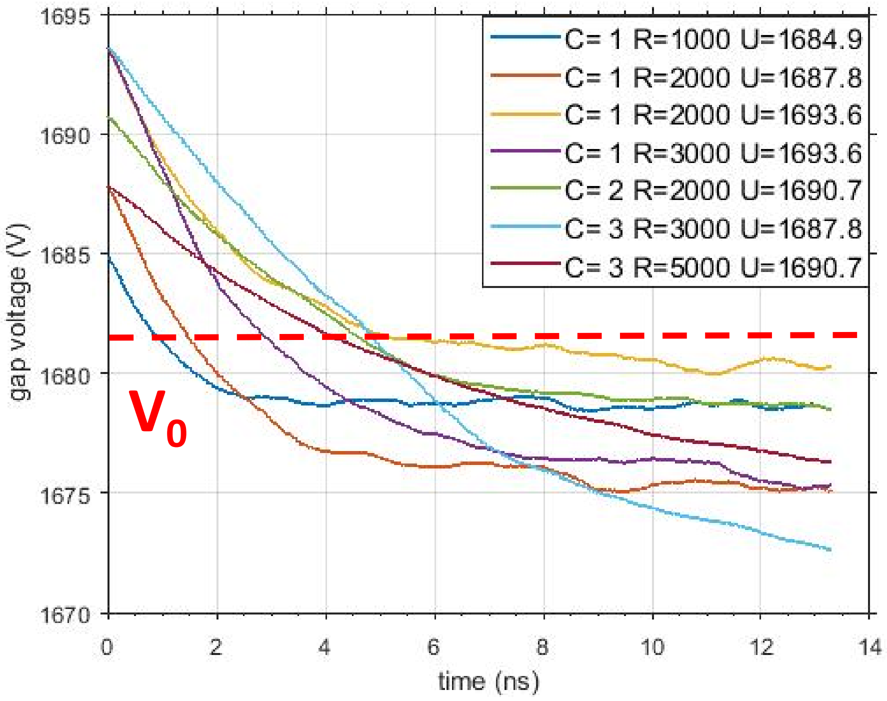
Required charge density for the sheath is $10^{18}cm^{-3}$

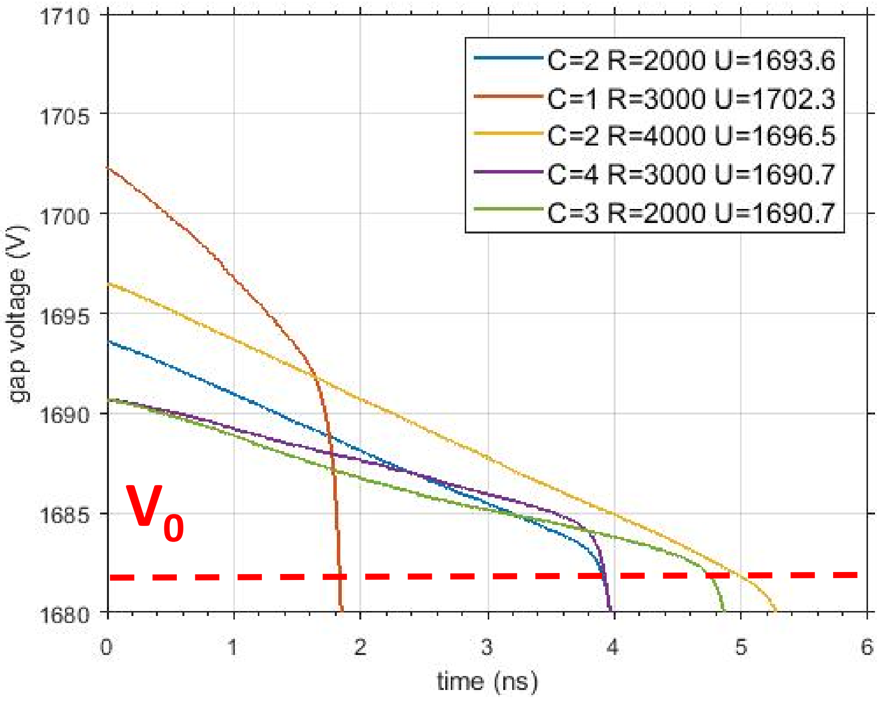
That results in a minimum current I_0

- Find the minimum gap voltage V_0 and gap current I_0 required for BD
- Find the minimum external DC voltage V_{bd} required for BD

  For each couple of R (varying in 1000~5000Ω) and C (varying in 0~4pF), the external DC voltage applied on the circuit increases from 1600V to 1800V. The minimum resulting BD is the breakdown voltage V_{bd}

minimum gap voltage V_0



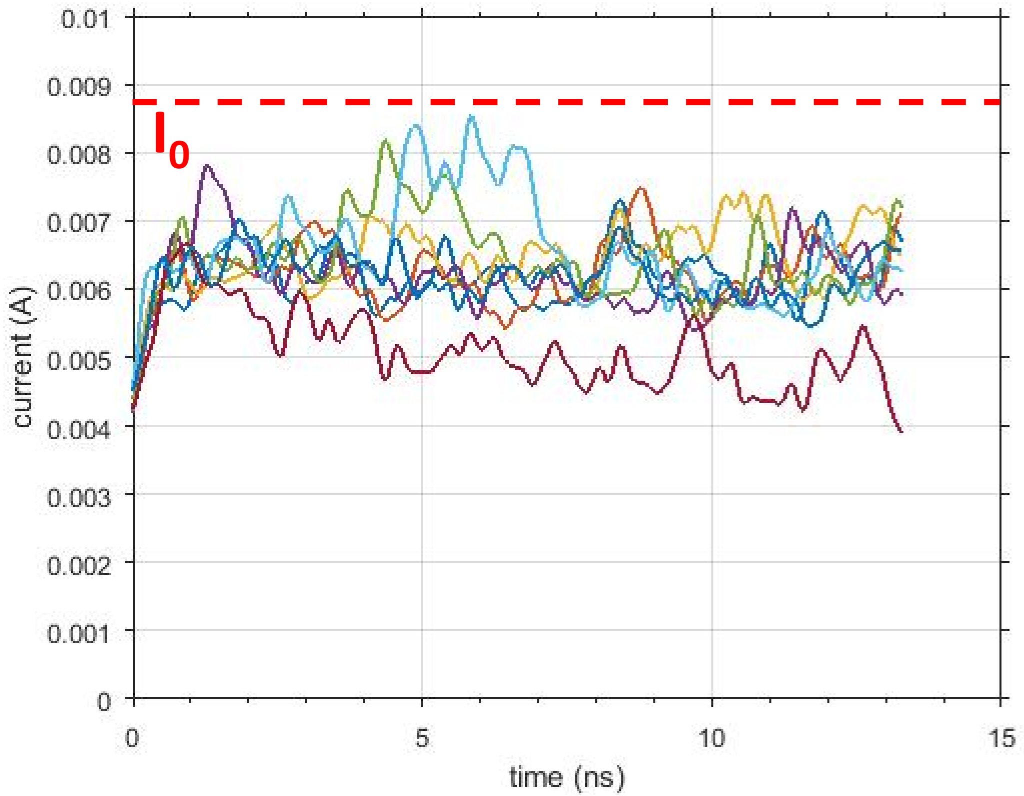


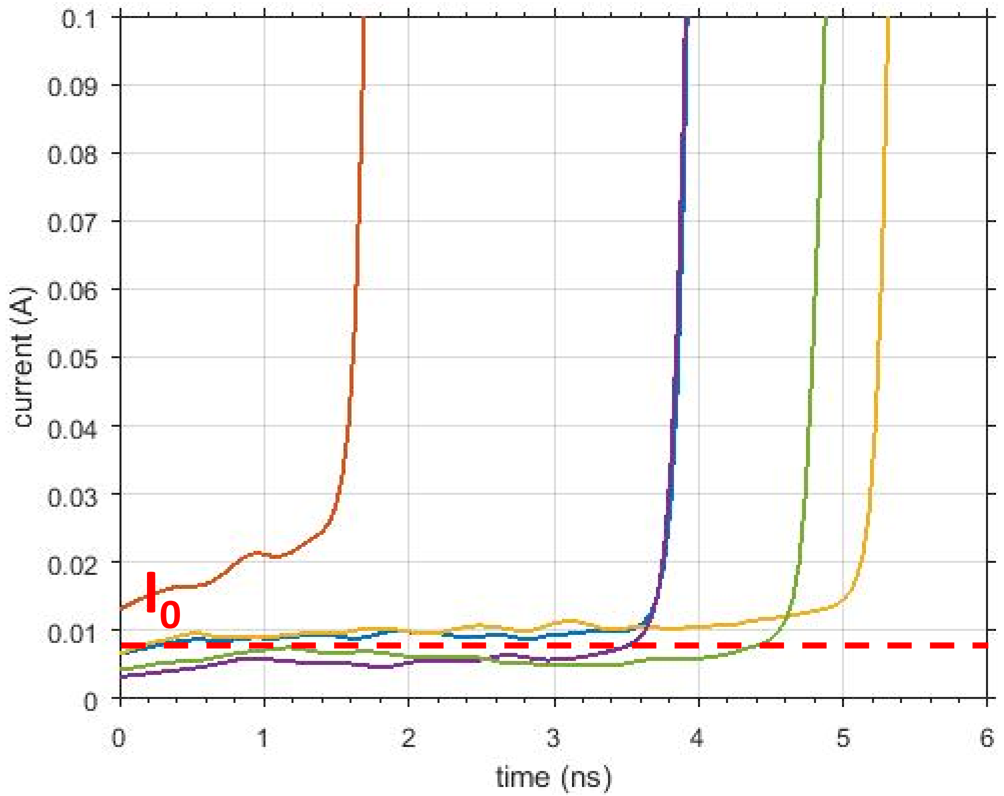
No-BD case: gap voltage falls below V_0 before BD

BD case: BD-loaded voltage is higher than V_0

V_0 is about 1682V

minimum gap current I_0



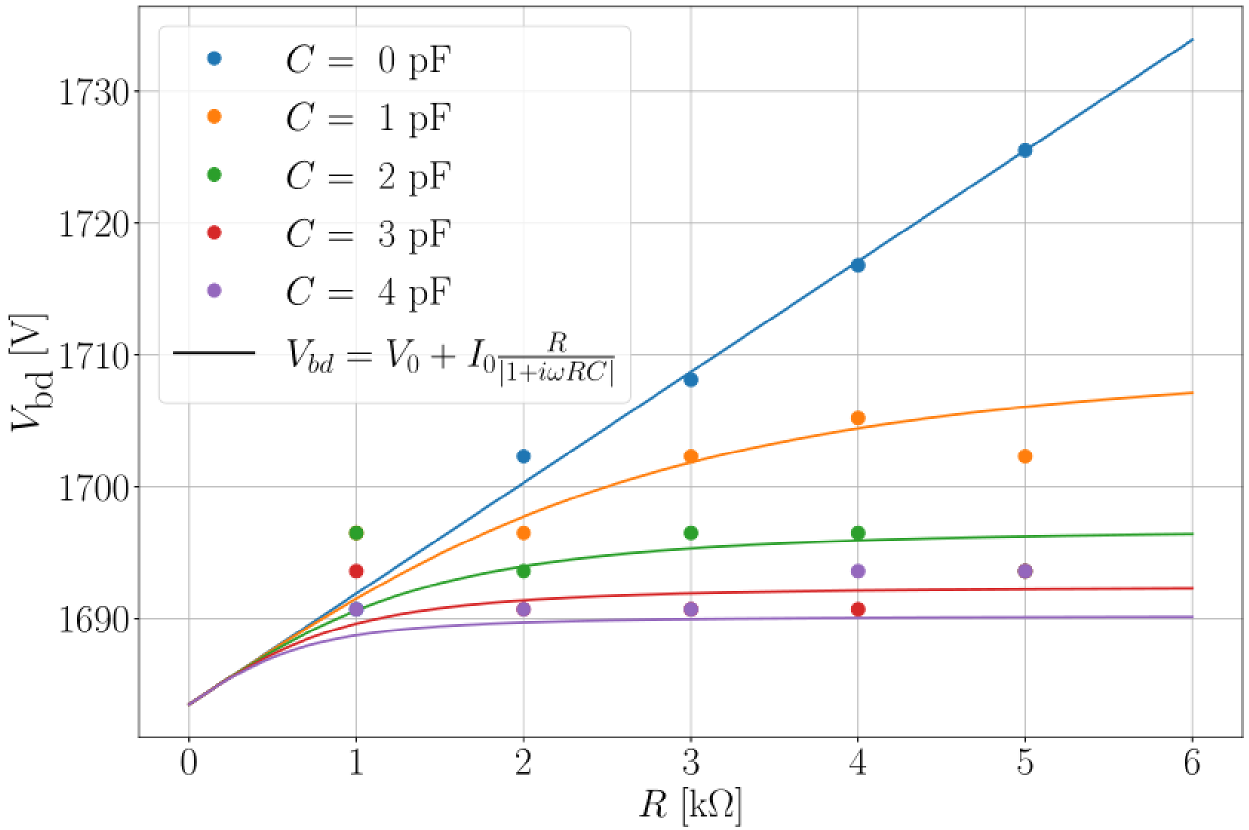


No-BD case: gap current cannot reach the barrier I_0

BD case: BD is unavoidable when the gap current reaches I_0

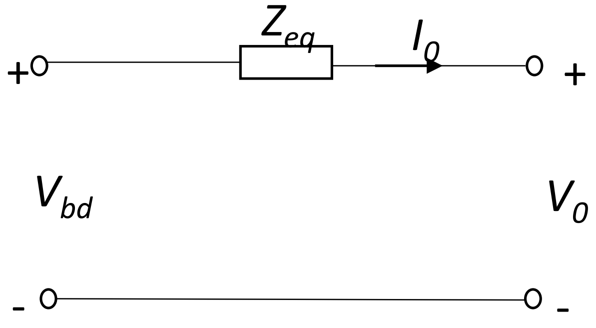
I_0 is about 9mA

Breakdown voltage V_{bd}



Dot: obtained by PIC/MCC simulations

Line: calculated according to equivalent circuit using V_0=1683.5V, I_0=8.4mA and an approximated frequency 50MHz.

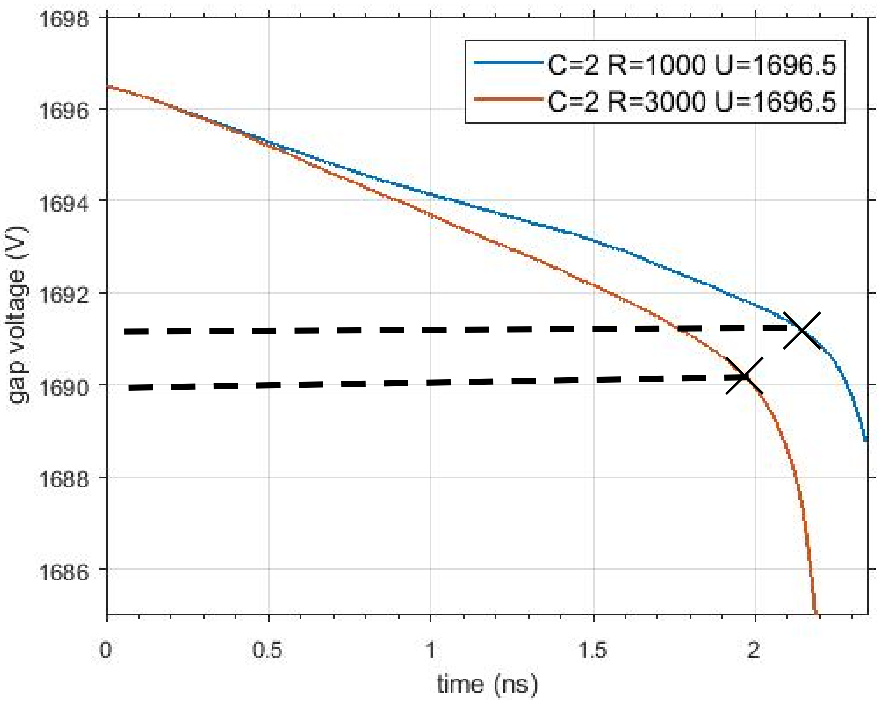


agree well

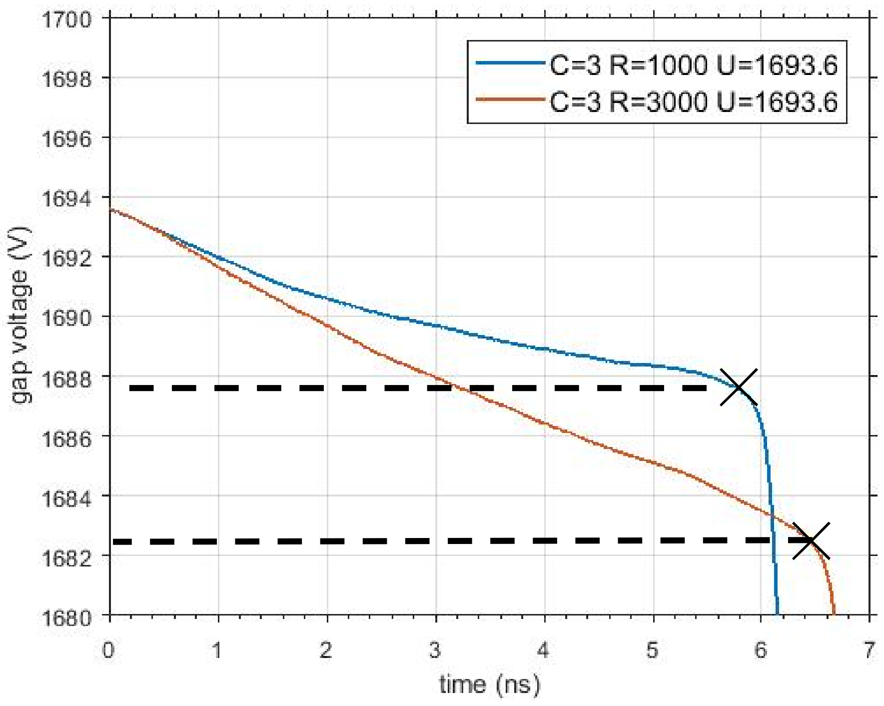
R↑ C↓ Z_{eq}↑ V_{bd}↑

Effect of R and C on BD

Example 1

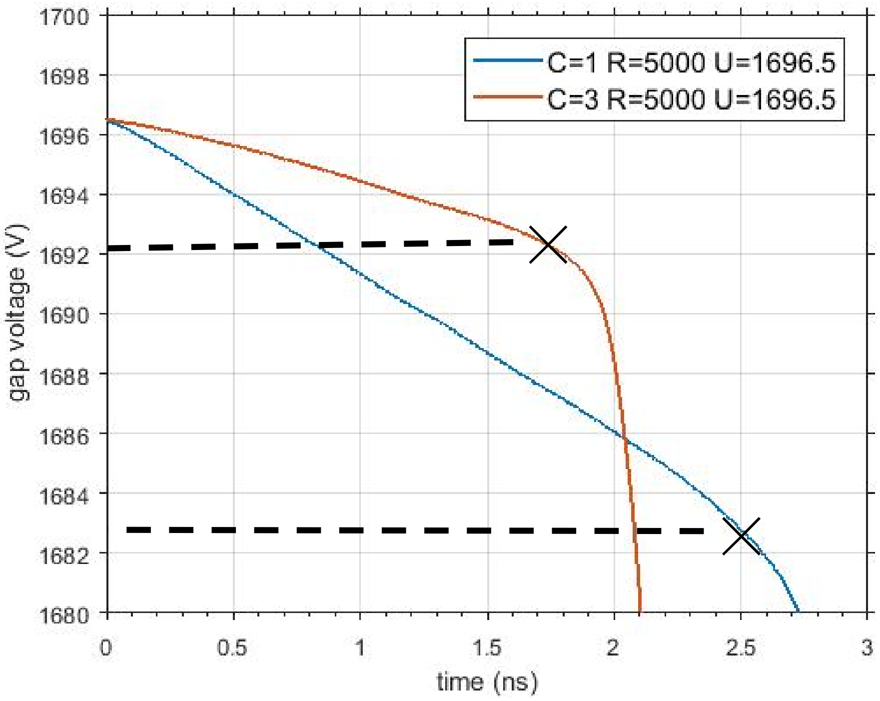


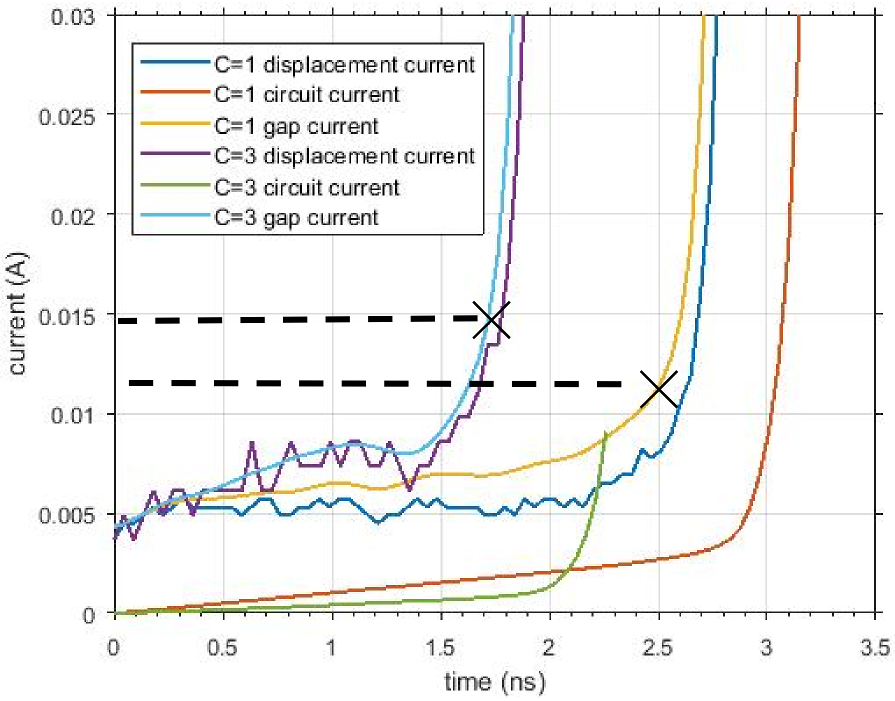
Example 2



Given the same external voltage, R ↑ V_{bd}↑ BD-loaded voltage ↓

Effect of R and C on BD





Given the same external voltage, C ↑ V_{bd}↓ BD-loaded voltage ↑ BD-loaded current ↑

$I_{gap}=I_{circ}+I_{cap}$, higher C contributes to higer displacement current I_{cap}

Conclusions

- From PIC/MCC simulation, BD corresponds to the neutral density of $10^{18}cm^{-3}$, sheath formation and the charge density of about $10^{18}cm^{-3}$, which indicates there should be a minimum gap voltage V_0 and gap current I_0, in other word, a critical power, needed for BD.
- From simulation results, V_0 is about 1682V and I_0 is about 9mA.
- V_{bd} obtained by PIC/MCC simulations agree with those calculated by equivalent impedance using V_0 and I_0.
- When R decreases or C increases, V_{BD} decreases, applied the same voltage, BD-loaded voltage and BD-loaded current increases, in other words, the power coupled to the gap increases, which agrees with Jan Paszkiewicz's theory using local power coupling as a predictor of BD.

Jan Paszkiewicz, *et al*. Local power coupling as a predictor of high-gradient breakdown performance. High Gradient Workshop,2021.

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Thank you!