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Discharge mechanisms in liquid nitrogen – breakdown field strength of gaseous nitrogen

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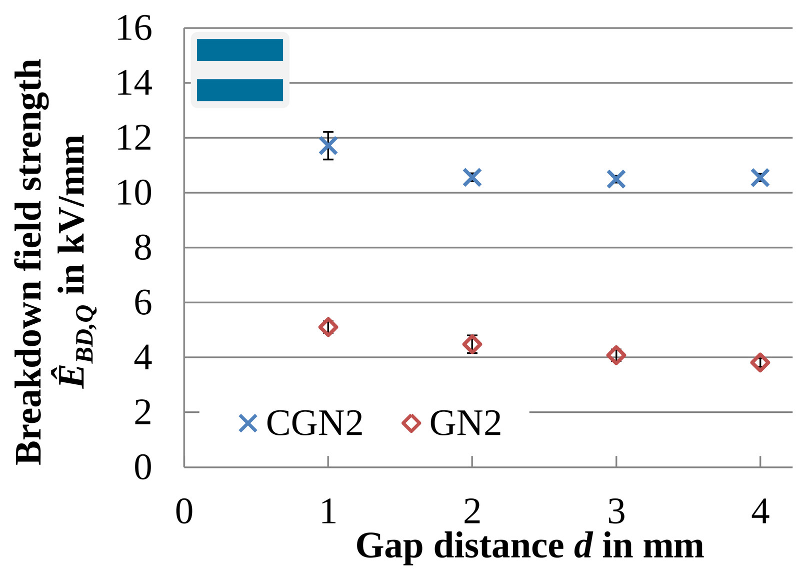
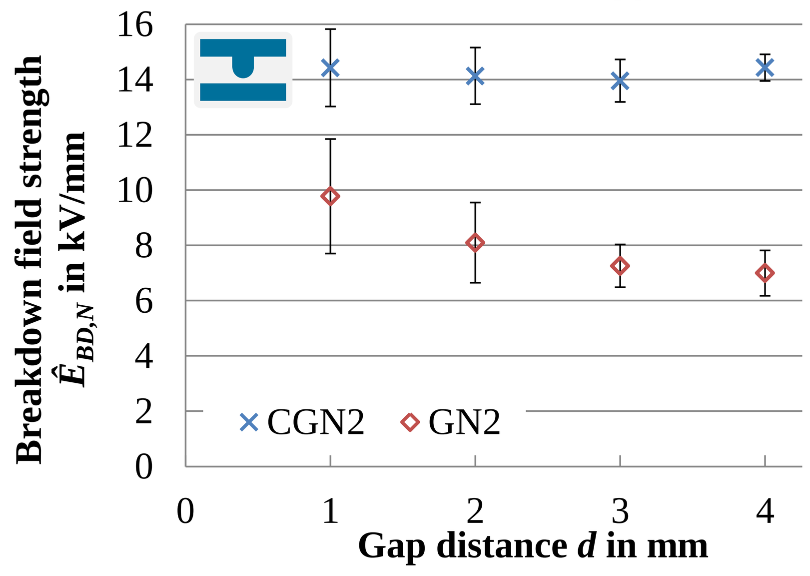
Introduction

- Breakdown mechanism of liquid nitrogen (LN_2) not yet completely determined but necessary for design of HTSL-systems
- Vapor bubbles already identified as major influence on breakdown voltage and possible breakdown initiation
- Disguised gas breakdown as potential breakdown process
- Further discussions require knowledge of electric field strength in cryogenic gaseous nitrogen
- More accurate calculative prediction of breakdown voltage of HTSL-system with knowledge if breakdown occurs according to Streamer or Townsend mechanism

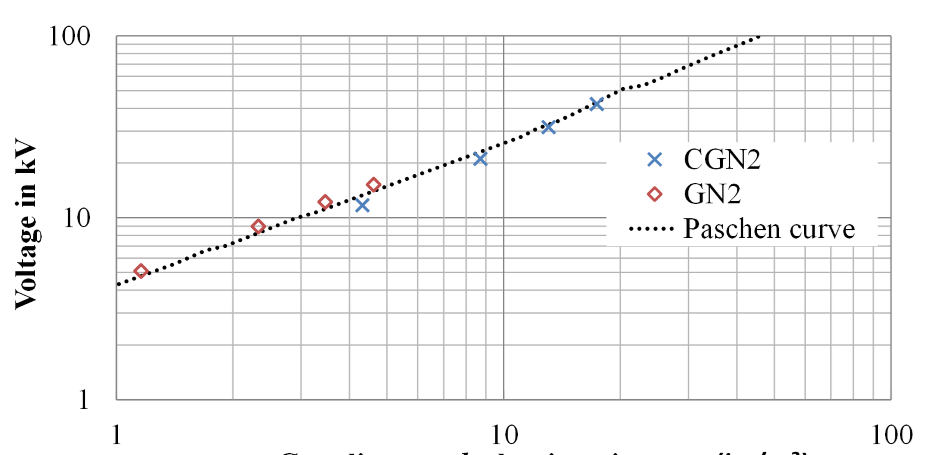
Measurement results

- Breakdown field strengths (determined by simulation with $\hat{U}_{BD}$):

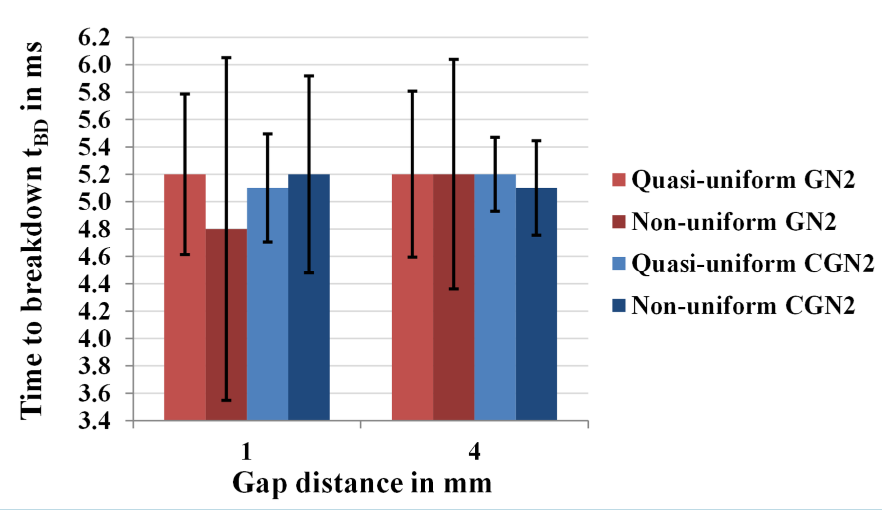




- Voltages for quasi-uniform field are in agreement with Paschen's law



- Higher standard deviation at non-uniform field due to volume effect (availability of starting electrons) visible at time to breakdown t_{BD}
- Highest deviation expected and observed at 1 mm and non-uniform field in GN2

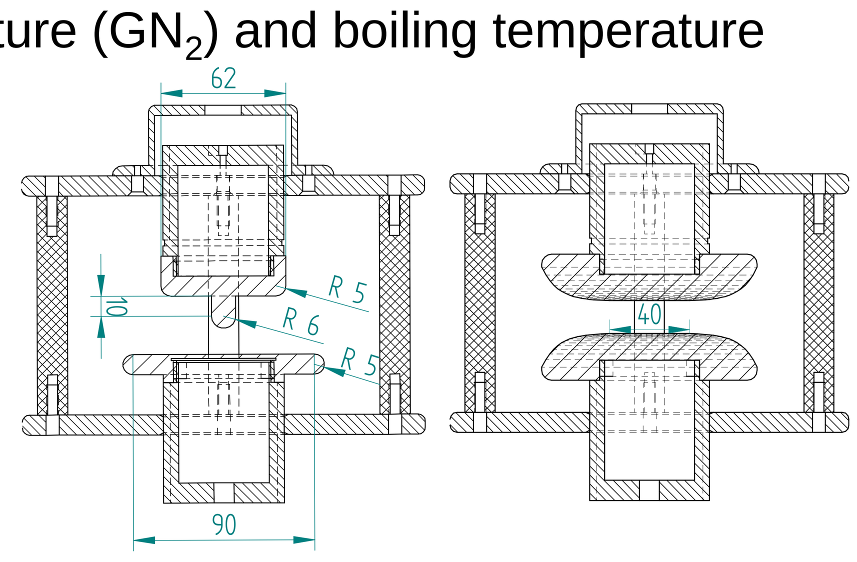


Conclusion

- Breakdown voltages for quasi-uniform field in GN_2 and CGN_2 follow Paschen's law
- Breakdown field strengths for quasi-uniform field are in agreement with literature, thus values for non-uniform field are assumed as utilizable
- In GN_2: Streamer and Townsend mechanism are possible
- In CGN_2: Townsend seems to be the primary breakdown process

Measurement setup and procedure

- AC breakdown tests are done for:
  - Quasi-uniform and non-uniform field
  - Nitrogen gas at room temperature (GN_2) and boiling temperature of LN_2 (CGN_2)
  - At ambient pressure
  - Electrode gap 1 - 4 mm
- In a closable open bath cryostat
- Above LN_2 volume



- Gas-temperature measured prior to AC tests in dependence of LN_2-level
- Measurements start when LN_2-level reaches a defined distance to the surface of the bottom electrode
- Constant voltage ramp with 200 V/s (GN_2) and 500 V/s (CGN_2) till breakdown, at least 22 breakdowns for each parameter set
- Breakdown voltage $\hat{U}_{BD}$ = Peak voltage of half cycle before breakdown

Simulation results

- With measured $\hat{U}_{BD}$ simulations (electrostatic, 2D rotationally symmetric) of electric field strength distribution $E(r, z)$ are done
- Maximum electric field strength = breakdown field strength $\hat{E}_{BD,max}$
- Gas constants A and B (e.g. Paschen's law) are adapted for cryogenic nitrogen (= C & D) by relating them to gas density ρ instead of pressure p
- With $E(r, z)$ and gas constants, the primary ionization coefficient α along electric field lines is calculated:

$$\alpha(E) = A \cdot p \cdot \exp(-B \cdot p / E) \Rightarrow \alpha(E) = A' \cdot \rho \cdot \exp(-B' \cdot \rho / E)$$

- Integration of α along electric field line yields factor k:

$$k = \int \alpha dx \Rightarrow 2.5 < k_{Townsend} < 14 < k_{Streamer} < 18$$

Field	Gap in mm	Density in kg/m³	$\hat{U}_{BD}$ in kV	$\hat{E}_{BD,max}$ in kV/mm	α_{max} in 1/mm	***k***
Quasi-uniform	1	4.320	11.7	11.7	4.1	**3.5**
	2	4.352	21.1	10.6	2.1	**3.4**
	3	4.353	31.5	10.5	2.1	**4.8**
	4	4.353	42.2	10.6	2.2	**6.7**
	1	1.157	5.1	5.3	11.7	**10.6**
	2	1.163	9.0	4.5	7.1	**12.2**
	3	1.154	12.2	4.1	4.9	**12.2**
	4	1.154	15.2	3.8	3.6	**11.6**
Non-uniform	1	4.609	13.0	14.4	8.6	**4.8**
	2	4.663	22.9	14.1	7.3	**4.6**
	3	4.764	30.9	14.0	6.2	**3.6**
	4	4.662	39.1	14.4	8.3	**4.8**
	1	1.162	8.8	9.8	30.1	**35.6**
	2	1.172	13.1	8.1	43.8	**49.9**
	3	1.170	16.1	7.3	33.0	**39.5**
	4	1.170	18.9	7.0	29.8	**35.0**

- k for CGN2 between 3.4 – 6.7 → Townsend mechanism
- k for non-uniform field and GN2 very high; but with lowest measured breakdown voltage k = 13.6 – 17.8
- k for GN2 between 10.6 – 17.8 → Transition from Townsend to Streamer and Streamer mechanism