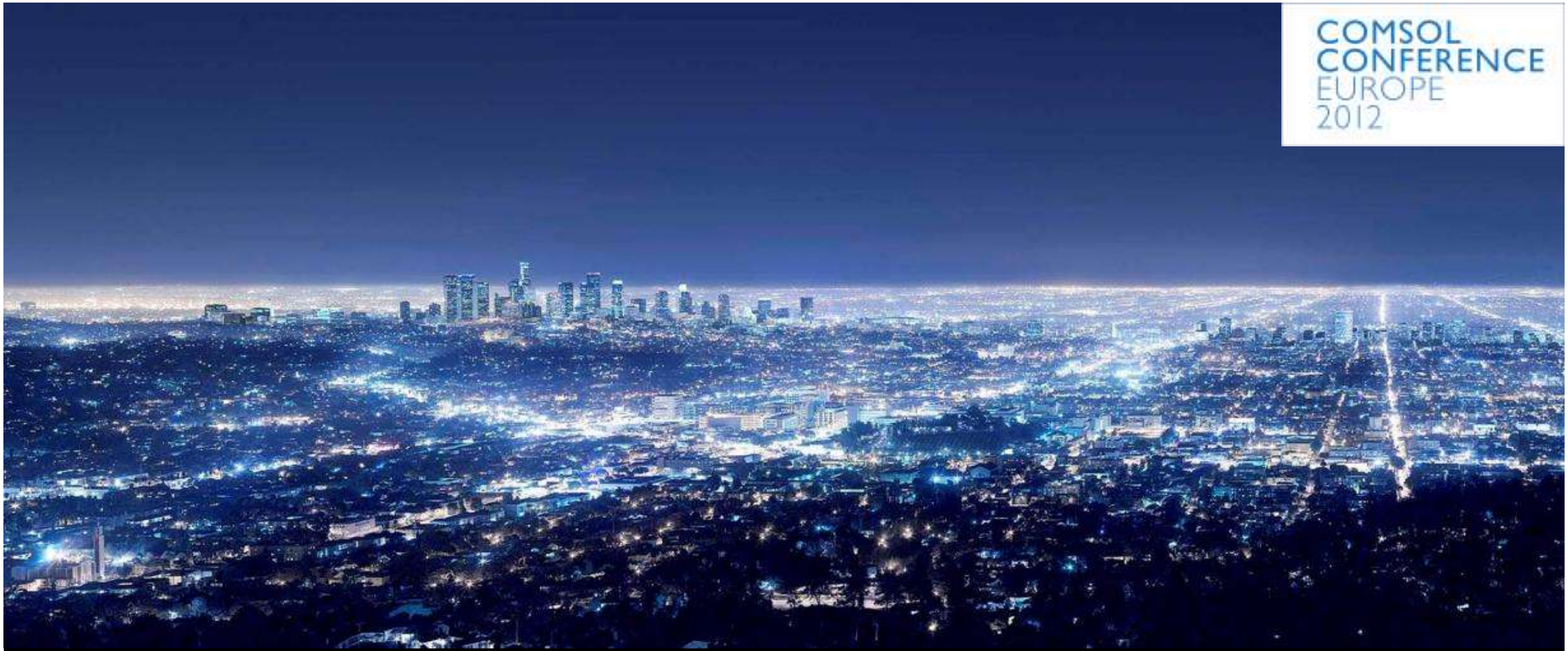

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Thomas Christen, ABB Corporate Research, ABB Switzerland Ltd

Nonstandard High-Voltage Electric Insulation Models

Power and productivity for a better world™

Simulation for Insulation Design

- ❑ Standard procedure (usually AC)
  1. Calculate electric field (test conditions, …)

$$\boxed{\nabla\cdot\left(\varepsilon_r\varepsilon_0\nabla\phi\right)=0}$$

  2. Check for dielectric withstand
     - Electric breakdown (E < breakdown field)
     - Thermal runaway (electro-thermal simulation)
- ❑ Nonstandard procedure for
  - ○ Direct Current (DC) simulations

$$\boxed{\begin{aligned}-\nabla\cdot\left(\varepsilon_r\varepsilon_0\nabla\phi\right)&=\rho\\ \partial_t\rho+\nabla\cdot j&=0\end{aligned}}$$

  - ○ E-Field simulation including electric breakdown

equation for charge carrier avalanche → sparks etc.

Simulation requirements for fundamental R&D

- Quick & Computational resource friendly
  - Parameter studies
  - Various different (test) scenarios

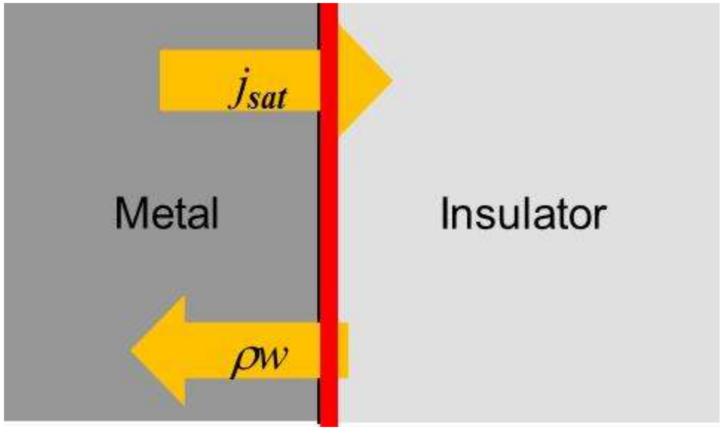
- Flexible with respect to physics /modeling
  - Bulk (PDEs, ODEs, …)
  - Insulator interfaces / surfaces
  - Boundary conditions (electric contacts, …)
  - Multi-physics

Example: Space Charge Injection in Insulators

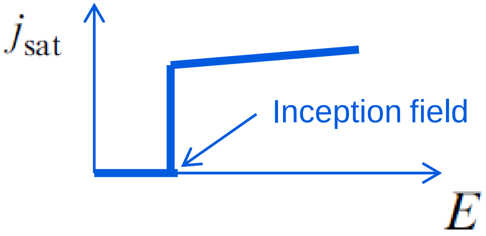
- Insulator bulk equations (no intrinsic carriers)
  - Poisson $-\nabla\cdot\left(\varepsilon_r\varepsilon_0\nabla\phi\right)=\rho$
  - Continuity $\partial_t\rho+\nabla\cdot\boldsymbol{j}=0$
  - Current density $j=\left|\rho\right|\mu(E)\boldsymbol{E}-D\nabla\rho$

  → strongly nonlinear

- Physics strongly determined by boundary condition

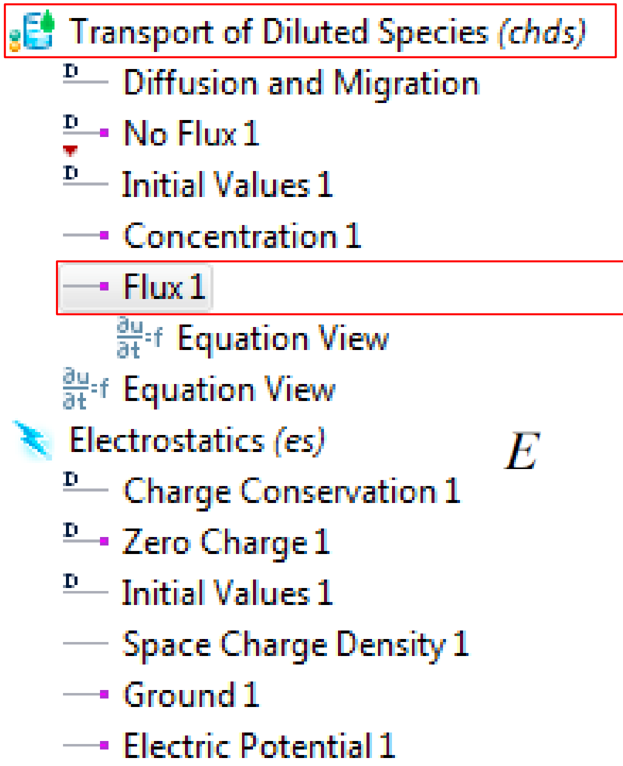


$$\boxed{j_n = j_{sat} - w\rho}$$



Example: Space Charge Injection

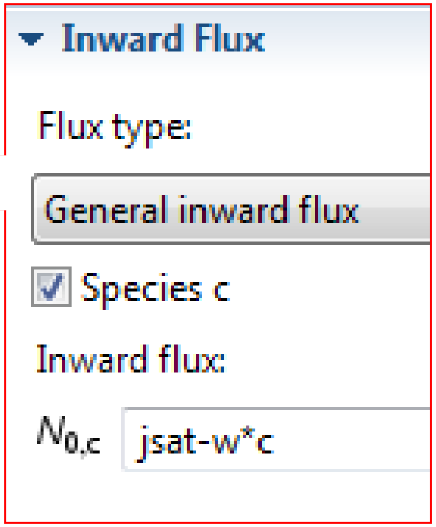
- Comsol Model



- Transport of Diluted Species *(chds)*
  - Diffusion and Migration
  - No Flux 1
  - Initial Values 1
  - Concentration 1
  - Flux 1
    - Equation View
  - Equation View
- Electrostatics *(es)*
  - Charge Conservation 1
  - Zero Charge 1
  - Initial Values 1
  - Space Charge Density 1
  - Ground 1
  - Electric Potential 1

E

Injection Boundary condition



Inward Flux

Flux type:

General inward flux

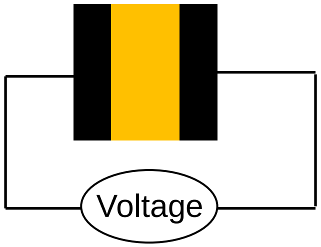
☑ Species c

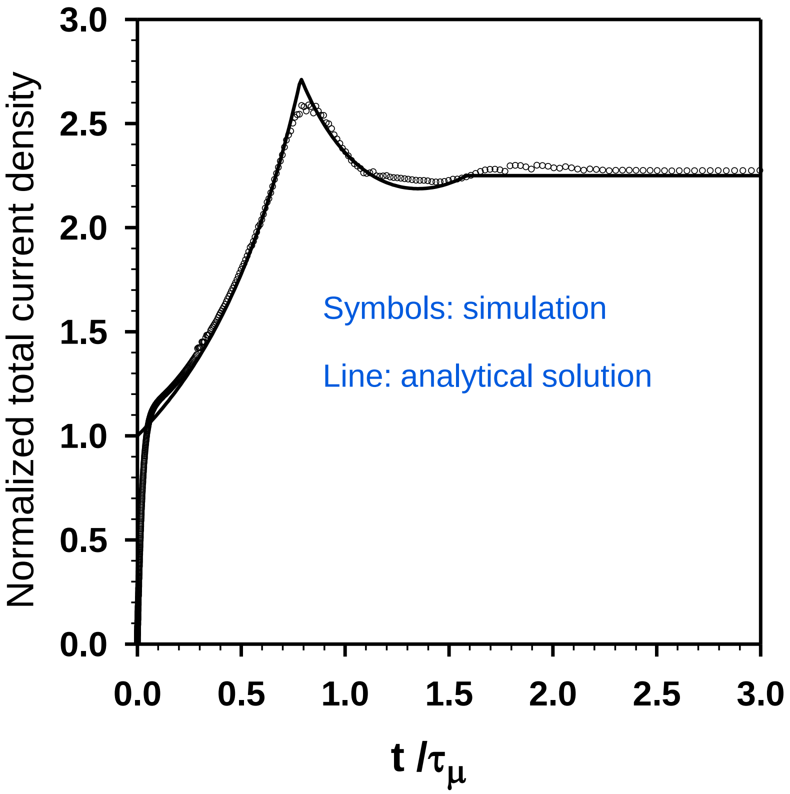
Inward flux:

$N_{0,c}$ jsat-w*c

Example: Space Charge Injection

- ❑ Plate-plate geometry
- ❑ Current-time transient after switching on a DC voltage

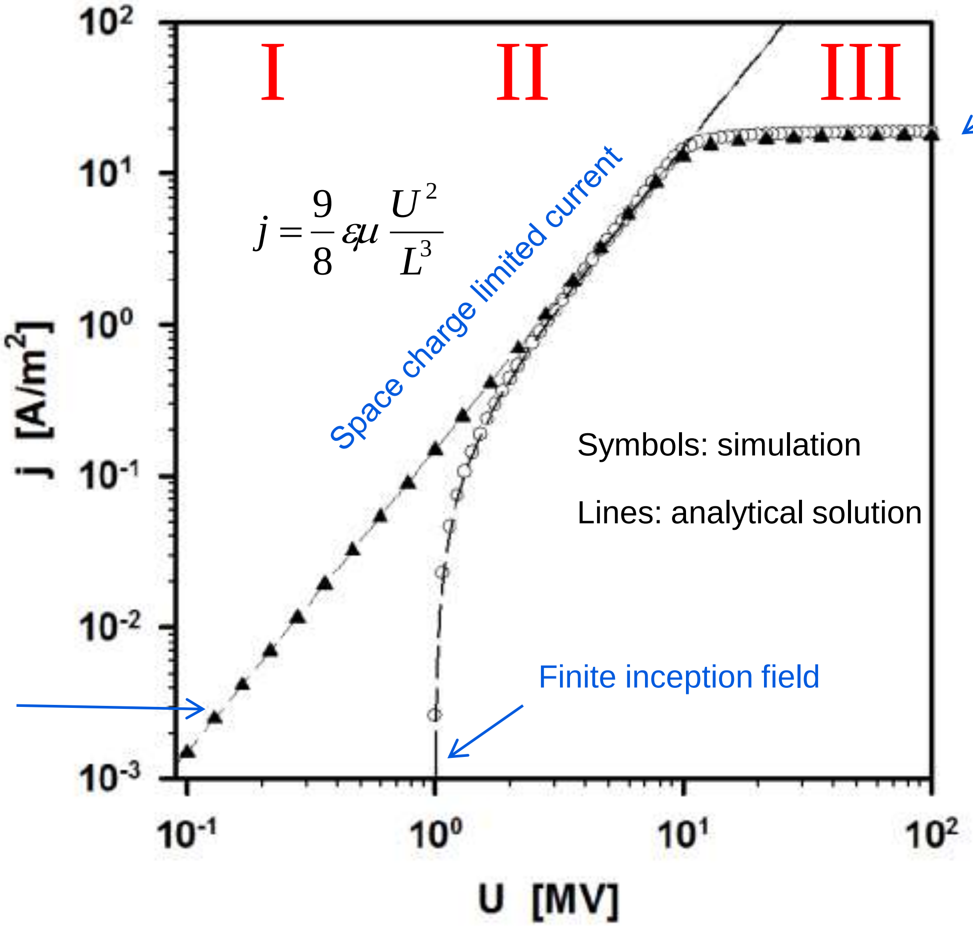




Example: Space Charge Injection

- ❑ Plate-plate geometry
- ❑ Steady-state current-voltage characteristics: three regions

Finite saturation current



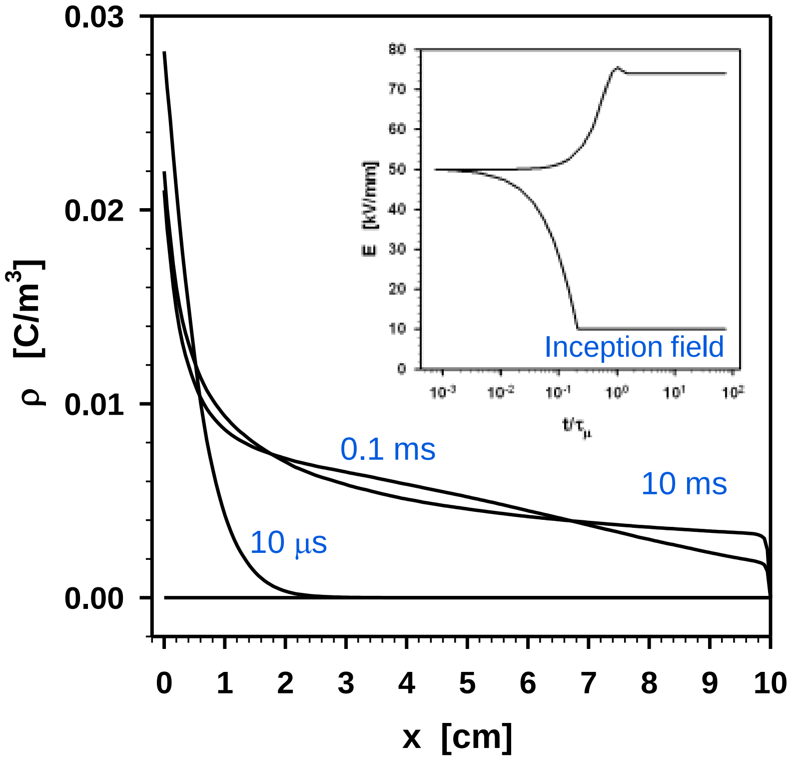
$$j = \frac{9}{8}\varepsilon\mu\frac{U^2}{L^3}$$

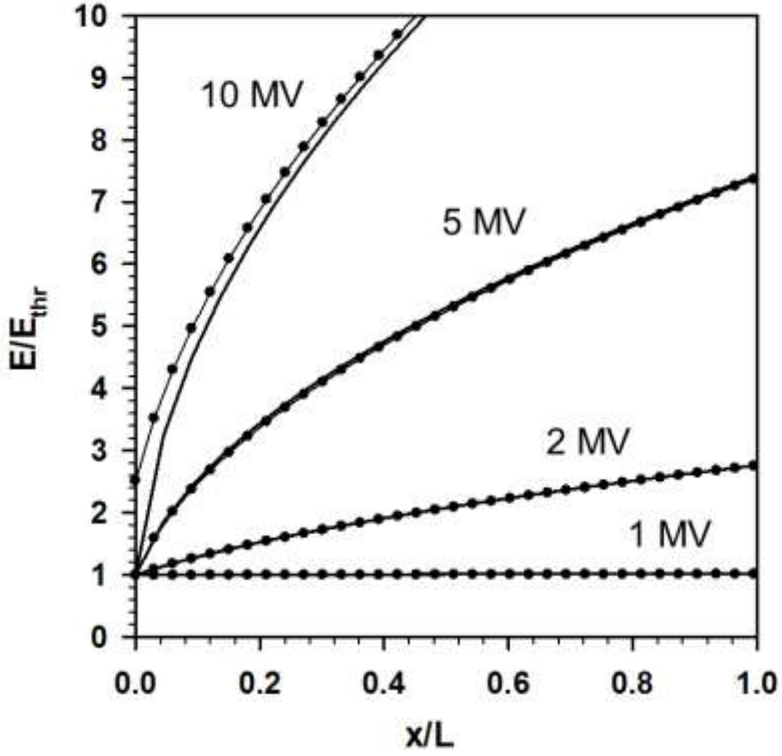
Zero inception field

Finite inception field

Example: Space Charge Injection

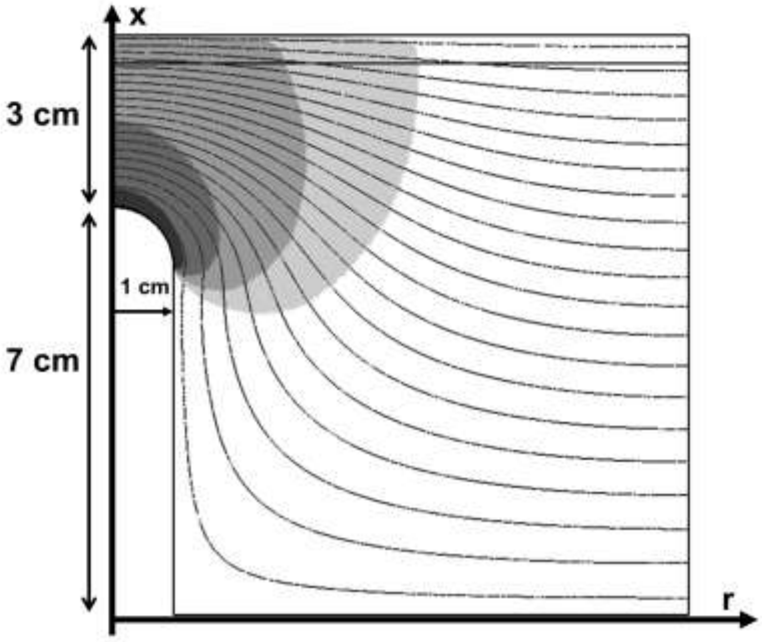
- Non-uniform space charge and electric field distributions

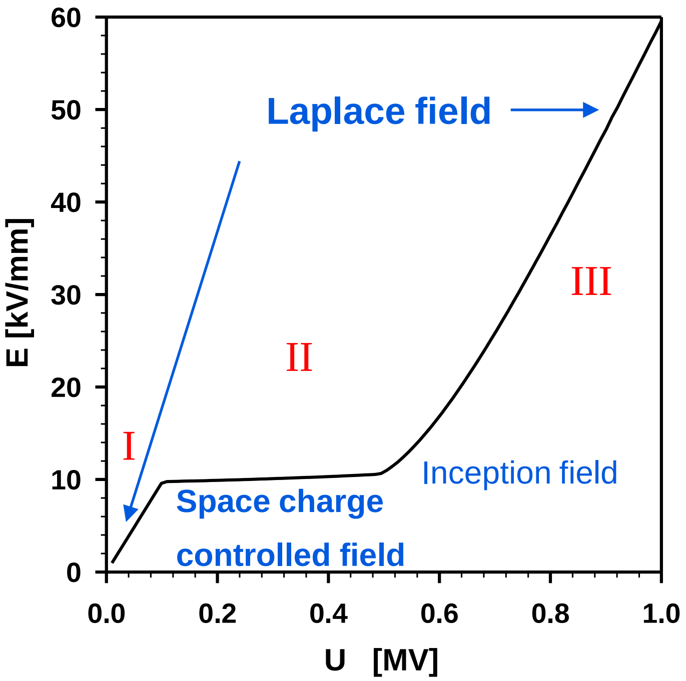




Example: Space Charge Injection

- ❑ Rod-plate geometry
- ❑ Field limitation of spatial field enhancements





Example: Space Charge Injection

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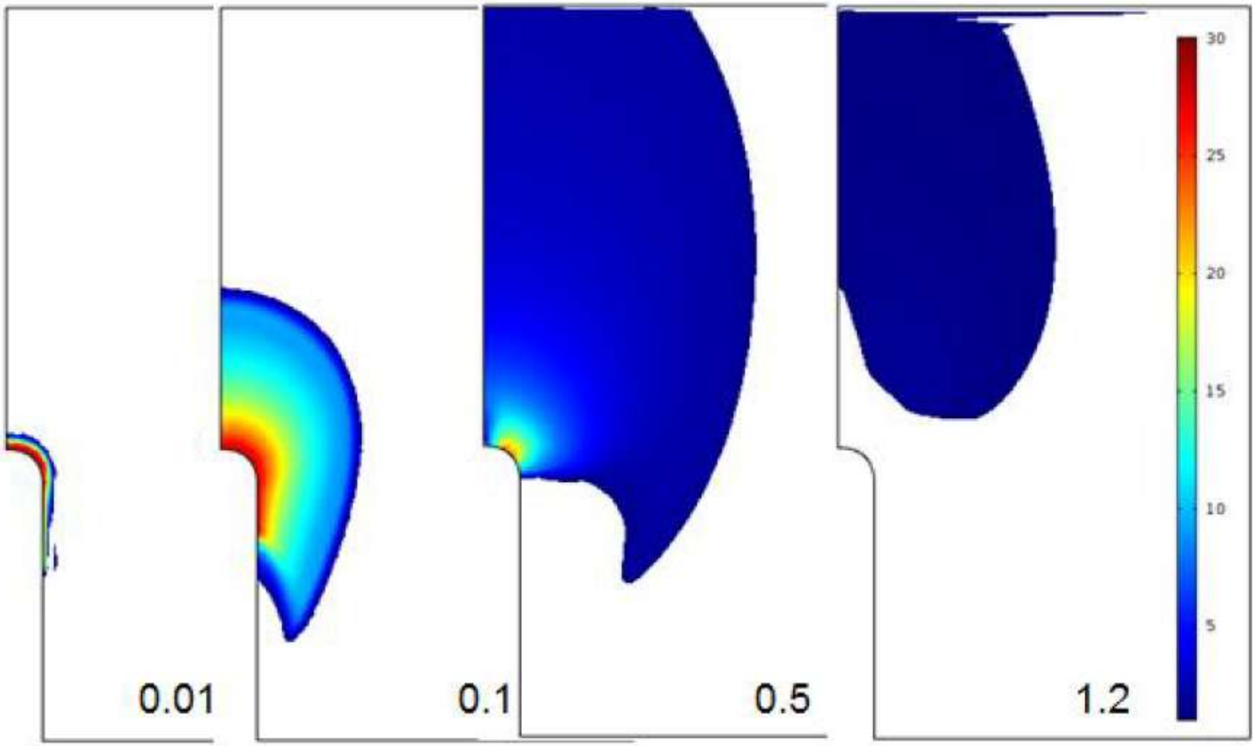
- ❑ Voltage pulse
- ❑ Injected space charge clouds at different times (in units of “time of

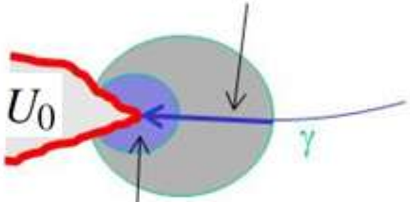


Example: Streamer Inception

- Inception
  - Electron impact ionization avalanche growth if effective ionization coefficient $\alpha(E) > 0$
  - Streamer inception criterion $\int_\gamma \alpha(\mathbf{E})\, ds \geq C_{\text{inc}}$
  - Model: 1st order PDE for scalar field ϕ $\frac{d\phi}{ds} = \alpha > 0$

$$\boxed{-\mathbf{v}\cdot\nabla\phi = \alpha(E)\underset{\text{(Heaviside)}}{\Theta(\alpha)}}$$

$$\mathbf{v}(\mathbf{x}) = \frac{\mathbf{E}}{E}$$



$$\boxed{\phi(\mathbf{x}) \geq C_{\text{inc}}}$$

- FEM simulation: Approximation with 2nd order PDE

$$D\Delta\phi - \mathbf{v}\cdot\nabla\phi = \alpha(E)\Theta(\alpha)$$

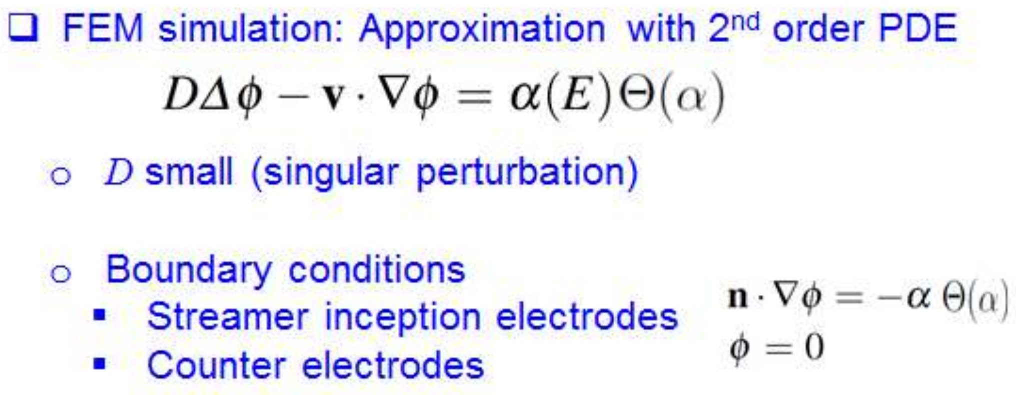
  - D small (singular perturbation)
  - Boundary conditions
    - Streamer inception electrodes $\mathbf{n}\cdot\nabla\phi = -\alpha\,\Theta(\alpha)$
    - Counter electrodes $\phi = 0$

Example: Streamer Inception

- ❑ Inception

Main Idea

Reduce the integral along field-lines of a vector field to a first order PDE



- ❑ FEM simulation: Approximation with 2nd order PDE

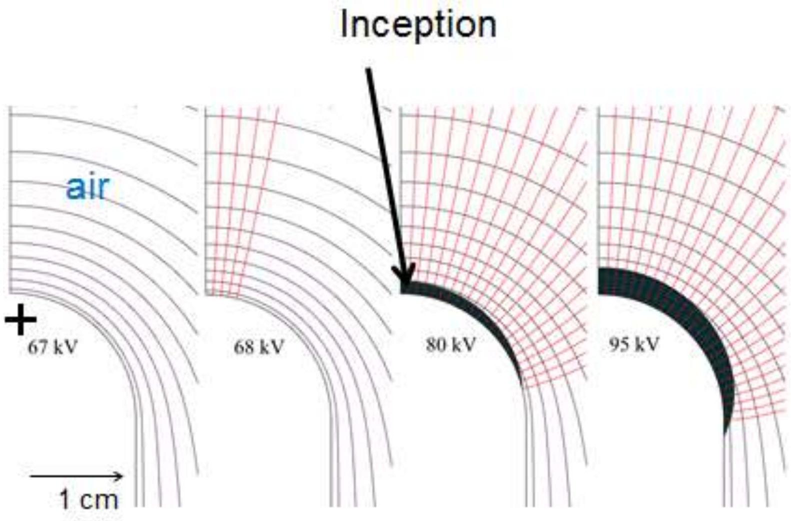
$$D\Delta\phi - \mathbf{v}\cdot\nabla\phi = \alpha(E)\Theta(\alpha)$$

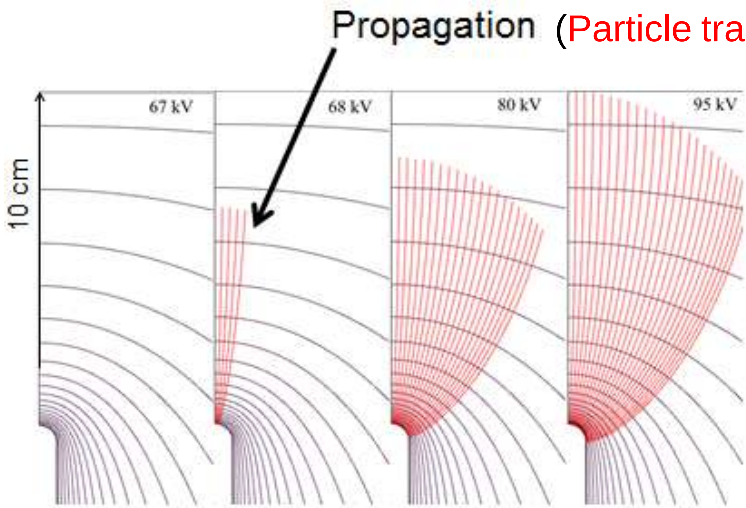
  - ○ D small (singular perturbation)
  - ○ Boundary conditions
    - ▪ Streamer inception electrodes $\quad \mathbf{n}\cdot\nabla\phi = -\alpha\,\Theta(\alpha)$
    - ▪ Counter electrodes $\quad \phi = 0$

Example: Streamer Inception and Propagation

- ❑ Plug-plate
- ❑ Simulation Procedure:

1. E-Field
2. ϕ – Field
3. Particle Tracing





(Particle tracing)

Conclusion

Modeling flexibility of a simulation tool is crucial for basic R&D

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