State-of-the-art high-fidelity DBD plasma simulations

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What are the goals / applications?

Connect fundamental studies and applications

What should be optimized? Thrust? Maximum velocity? Heating? Spatial and temporal distribution?

Applications

Flow Modeling

Large Scale Experiments

Plasma Modeling

“Fundamental” Experiments
# Overview of DBD modeling approaches

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<th>Plasma modeling</th>
<th>Flow modeling</th>
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<td>Physical models</td>
<td>• Drift-diffusion approximation continuity for charge densities</td>
<td>• 2D/3D Navier-Stokes</td>
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<td></td>
<td>• 2-moment model: continuity for charge densities + energy equation for $T_e$</td>
<td>• Complex geometry profiles</td>
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<td>• 5-moment model: continuity for charge densities + continuity for momentums +</td>
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<td>• Kinetic approach (PIC, DSMC)</td>
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<td>• Hybrid model</td>
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<td>Numerical</td>
<td>• Adaptive / non-uniform / unstructured meshes</td>
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<td>approaches</td>
<td>• Adaptive time steps</td>
<td>• Highly-parallel</td>
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Plasma model requirements

• Solve for charged species motion coupled with Poisson Solver
• Include all necessary plasma processes, including electron impact ionization, recombination, attachment, detachment, photoionization
• Resolve from micron scales in sheath region to cm plasma/flow interaction scales
• Resolve from picosecond time scales for ionization to millisecond time scales for plasma/flow interaction
• Use appropriate physical model for plasma description in particular conditions
## Plasma models

### Model Complexity

<table>
<thead>
<tr>
<th>Drift-diffusion approximation</th>
<th>2-moment model</th>
<th>5-moment model</th>
<th>Kinetic approach – Particle in Cell</th>
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<tbody>
<tr>
<td>“Easy” to implement</td>
<td>Drift-diffusion + electron energy equation</td>
<td>Momentum and energy equations</td>
<td>Detailed plasma description</td>
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<tr>
<td>Best for relatively low E/n</td>
<td>Low to moderate E/n</td>
<td>Low to moderate E/n</td>
<td>Non-local effects</td>
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<tr>
<td>High pressures</td>
<td>High pressures</td>
<td>Low to high pressures</td>
<td>Low to high E/n</td>
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### Code Performance
Numerical optimization

Geometrical scales
(from microns to cm) –
4 orders of magnitude
• Non-uniform grids
• Unstructured grids
• Adaptive grids

Time scales
(from ps to ms) –
9 orders of magnitude
• Adaptive time-steps (short for breakdown, long for plasma decay)
• Large time steps in implicit scheme – correct or not?

Algorithm optimization
• Move from SOR and Jacobi to Multigrid for Poisson Solver
• From integral to differential equations for radiation transfer
• Use implicit schemes with large time scales?

Code performance
• Highly Parallel simulations
• Resolution of 3D structures
### Reduced Order Models:

- **Ignore negative ions:**
  - Failed in description of force direction
- **Short simulation time:**
  - Failed in description of slow processes such as surface charge accumulation

#### Need Experimentally Validated First Principle Model First!
Tolerance, accuracy

**Qualitative results**
- Suitable to guide experiments
- Sacrifice some accuracy and tolerance
- May predict incorrect scaling and performance

**Quantitative results**
- Accurate DBD description
- Should be tested for both numerical and physical accuracy
- Will predict correct scaling and performance

Suitable to guide experiments
Sacrifice some accuracy and tolerance
May predict incorrect scaling and performance

Accurate DBD description
Should be tested for both numerical and physical accuracy
Will predict correct scaling and performance
Examples

2D fluid parallel code with photoionization and adaptive time steps (Princeton)

3D PIC parallel code VORPAL (Tech-X)

2D fluid code with adaptive grids (Boeuf)

Adaptive time step:
5 hours to simulate first 100 ns (electron and ion plasma),
0.5 hours to simulate 10 us (ion only plasma)

Parallel simulations:
~4 times faster on 4 processors
## Challenges for “Ideal” Plasma Model

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- **Hybrid**: 
  - Adaptive grids
  - Adaptive time steps
  - Parallel
  - 3 dimensional
  - Easy to couple with CFD
  - Experimentally validated
  - Accurate
  - Wide range of gas discharge problems