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COMSOL CONFERENCE 2016 MUNICH

3D Modeling of a Planar Discharge in a CO_2 Laser Using a Multilevel Approach

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The ROFIN Group

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LASER MACRO

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… is one of the leading manufacturers of laser sources and laser-based solutions for industrial materials processing.

Macro

The Power of Light

- Hamburg/Germany
- High-powered industrial material processing

Micro

Focus on Fine Solutions

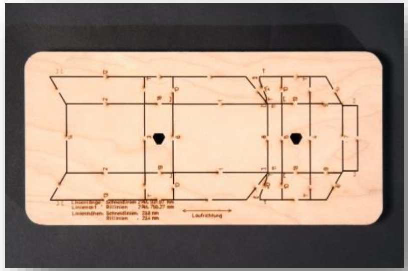
- Starnberg/Germany
- Laser sources and systems for processing materials down to the micro range

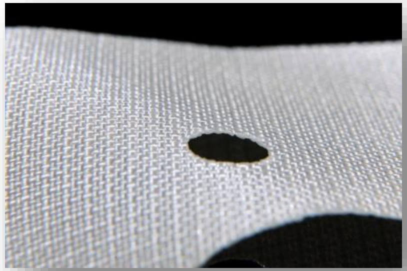
Marking

The Mark of Excellence

- Bergkirchen/Germany
- Marking solutions that consistently fulfill customer requirements in regards to precision, individuality and economic efficiency

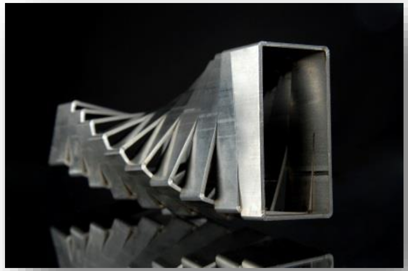
Application Examples
Cutting (Metal & Non-Metal)

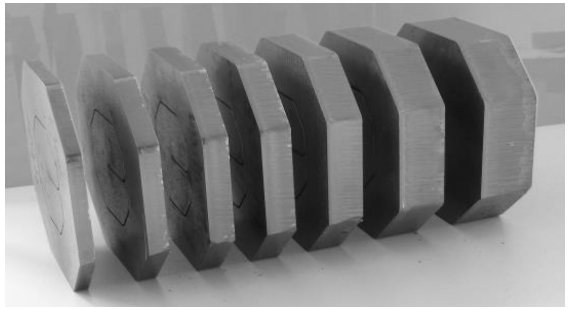

Dieboards


Airbag fabrics


Tableware


Acrylic





ROFIN Product Portfolio
Macro – The Power of Light

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Fiber Lasers

Fiber laser
compact version
up to 6,000 W

Fiber laser
up to 8,000 W

CO_2 Lasers

Diffusion-cooled CO_2 laser
1,000 – 8,000 W

Diode Lasers

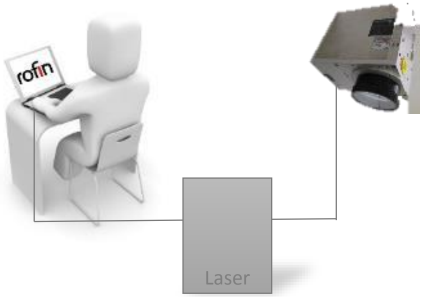
Diode laser
up to 6,000 W

Solid-State Lasers

Q-switched laser
500 – 1,000 W

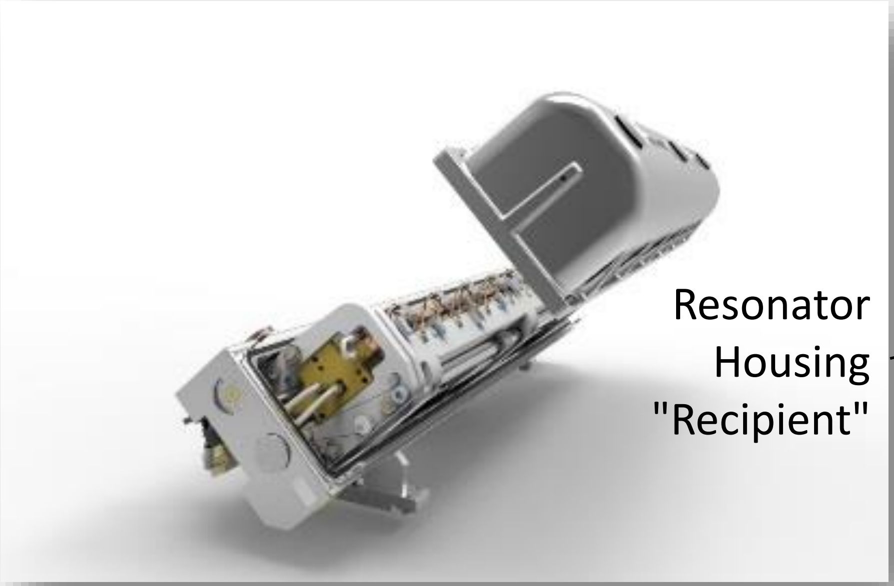
Laser Systems

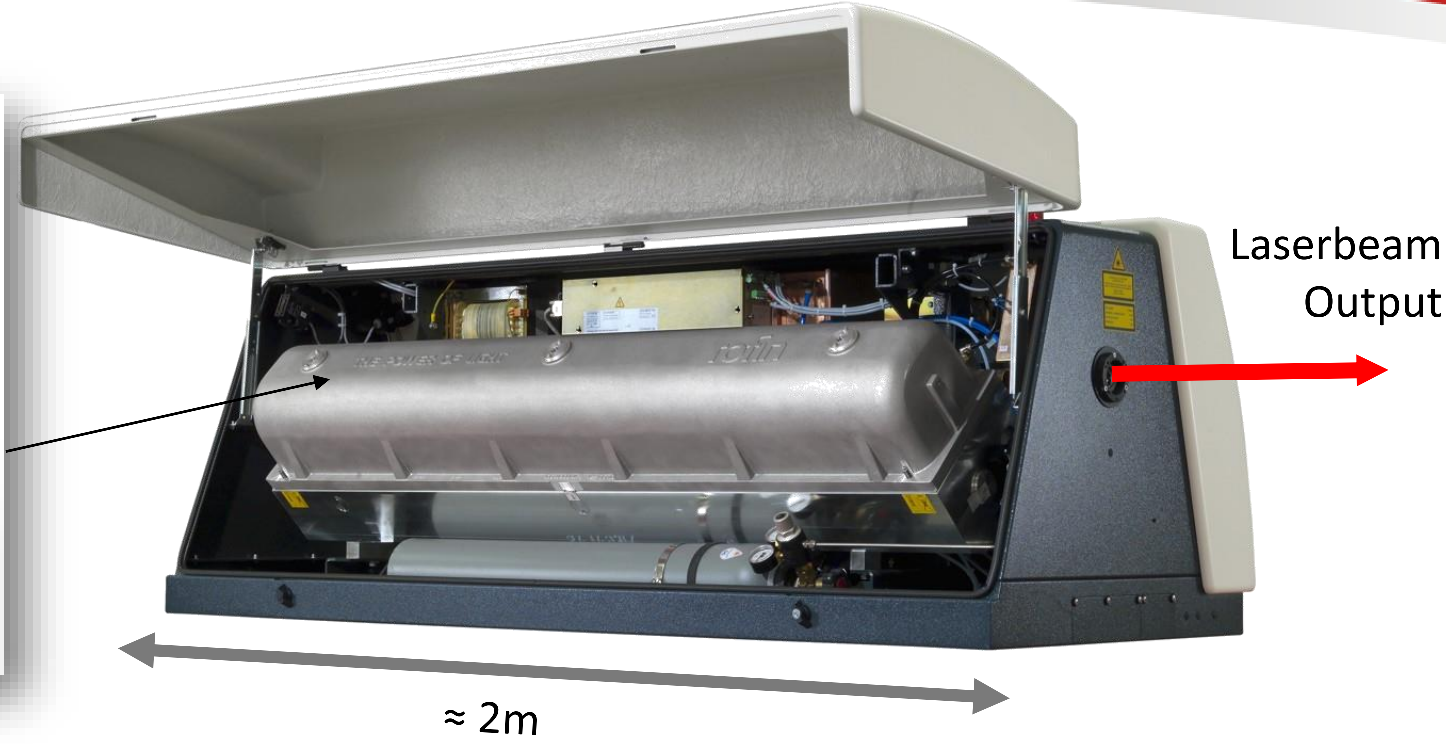
Profile Welding System (PWS)
for CO_2 and fiber laser



Scanner Processing Solution (SPS)
for CO_2 and fiber laser

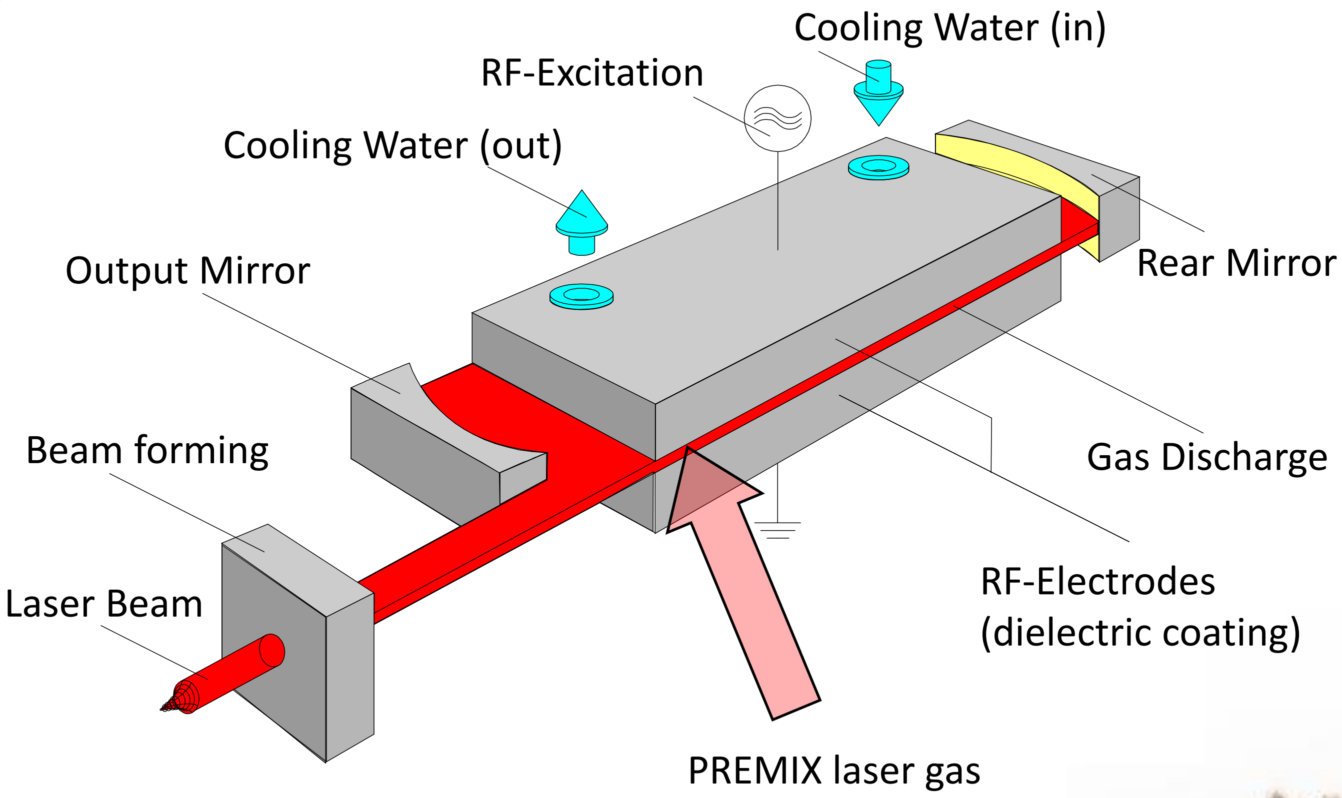
Slab laser principle
Laser head (resonator side)





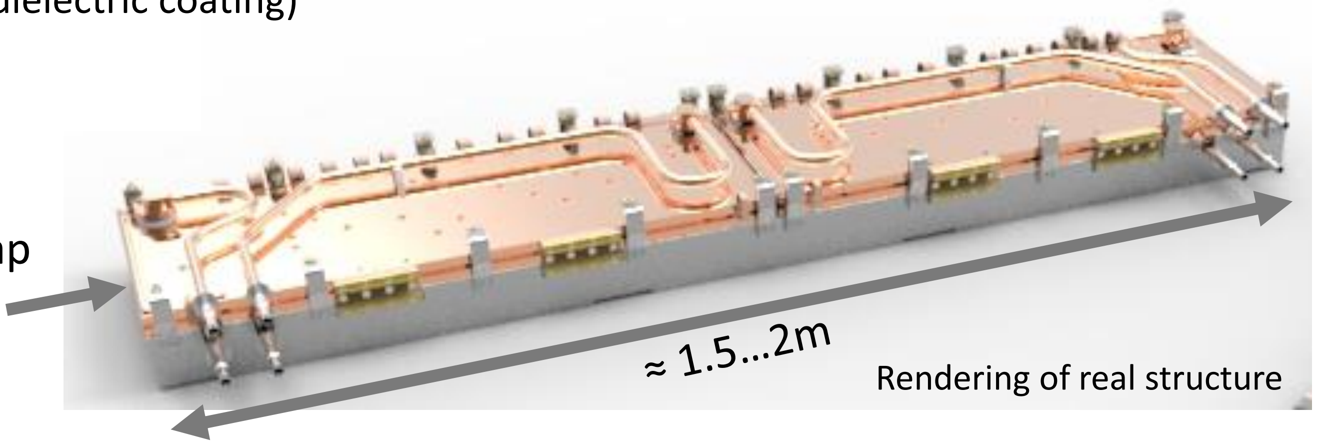
Slab laser principle

Resonator



- Real laser: complex 3D geometry
  only few symmetries
- Simplified geometry is not applicable for RF simulation
- **Advantage:**
  Plasma discharge region is almost perfectly „1D“

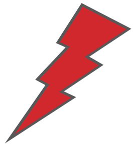
Electrode gap
≈ 1…2mm



Rendering of real structure

Modeling approach

- Task: simulate homogeneity of discharge
- Direct 3D simulation of plasma ⇔ RF:
  - Huge span of time and length scales
  - Too many degrees of freedom



µm ⟷ m

ns ⟷ s…h

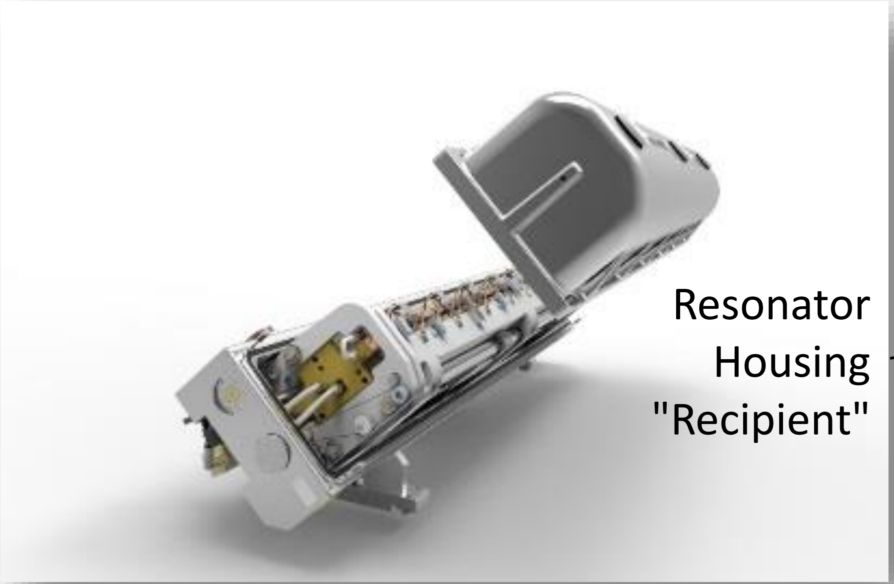
- Solution: separation of scales (+ dimensions)

Multi-level approach *(model hierarchy)*

„0D“	• Steady-state behaviour of plasma *gas chemistry / electron statistics / mobility / rates*
1D	• Discharge properties in electrode gap *U/I-curve, depending on frequency, gap width,…*
3D	• Use response curves for large scale simulations

Slab laser principle

Laser head (resonator side)



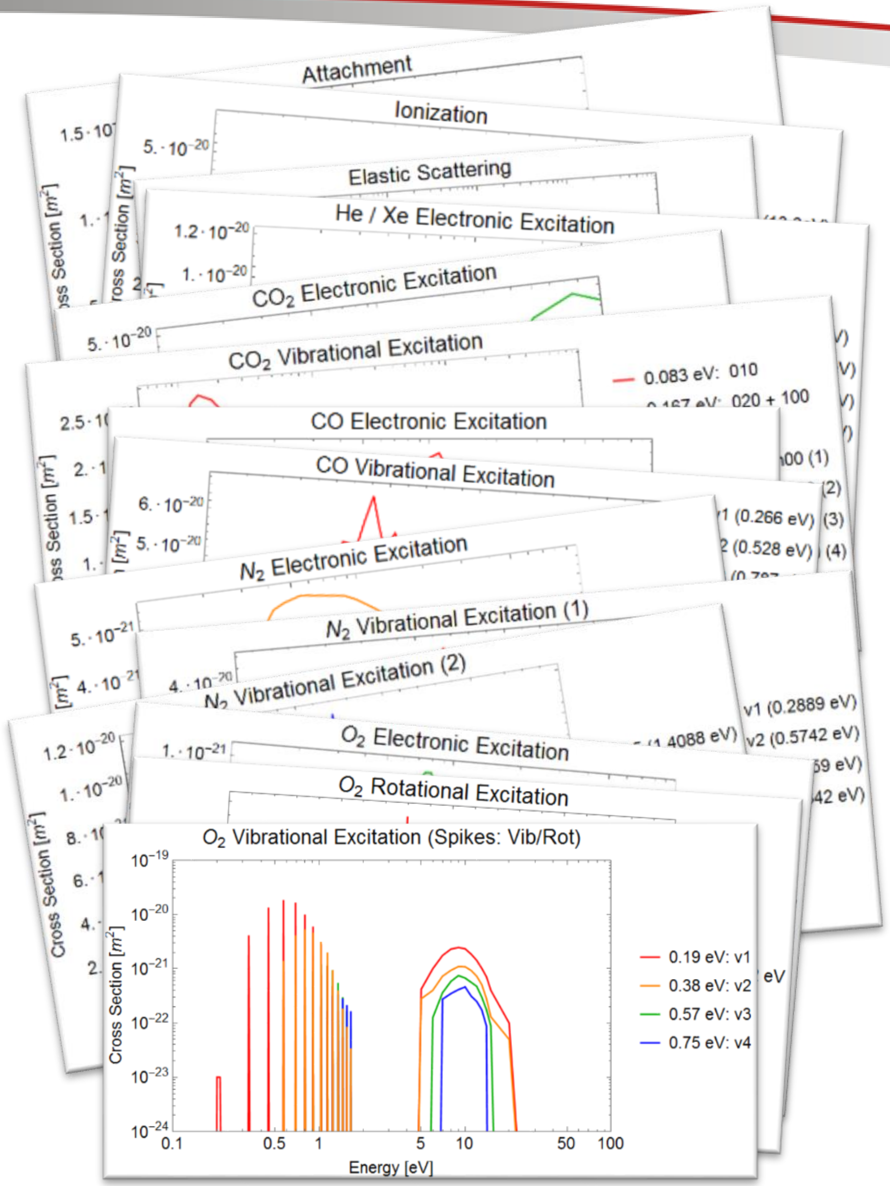
Recipient bounds modeling domain
(no need for PML/TBC)

Lasermix® 690:
65% He, 19% N_2, 4% CO_2, 6% CO, 3% O_2, 3% Xe

Gas Chemistry

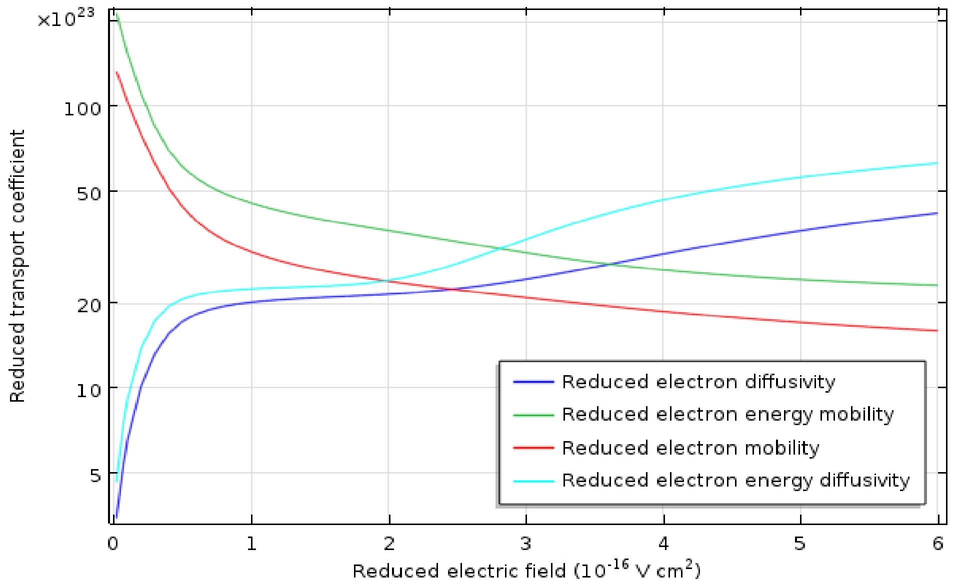
Lasermix® 690:

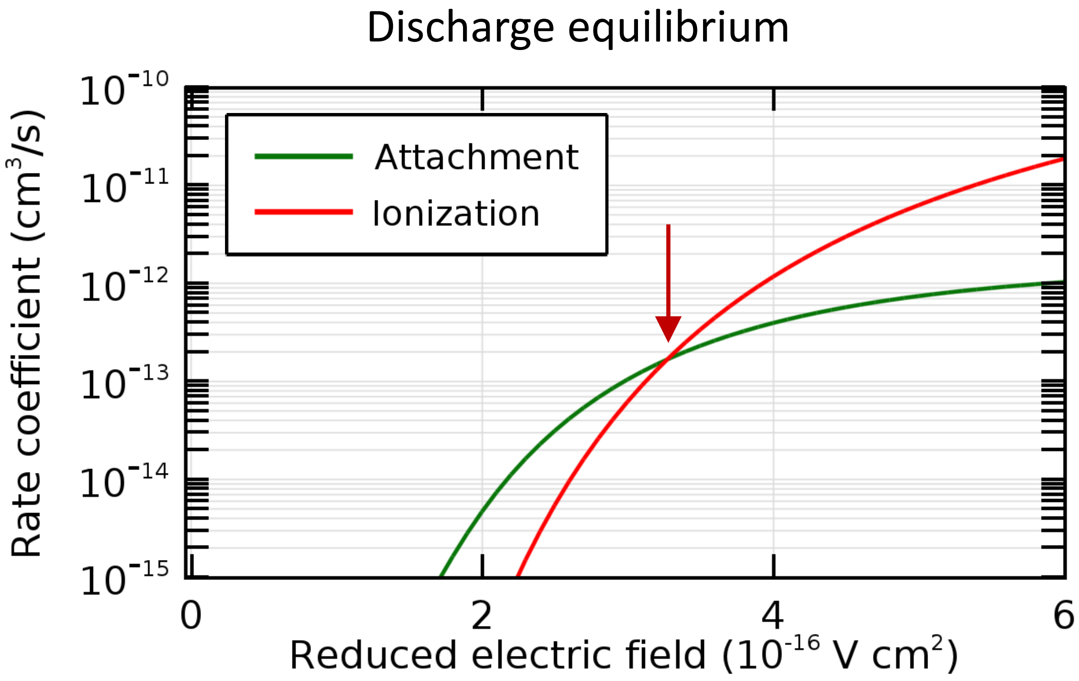
- 6 gas mixture components
  (65% He, 19% N_2, 4% CO_2, 6% CO, 3% O_2, 3% Xe)
- 21 (relevant) molecule species
  (plus vibrational levels)
- 59 relevant electron collision processes
- For each reaction:
  effective collision cross sections …



Step 1: Plasma Properties (0D)

- Electron energy distribution function (EEDF) not known a priori
- Calculation of EEDF, mobilities and rates (Boltzmann Equation, Two-Term Approximation)
- Interpolated functions for subsequent simulations





Step 1: EEDF + Rates (Results)

- Calculated rates agree with known roles of mixture components in the discharge:

He	cooling	Highest elastic contribution
Xe	ionization	Highest ionization rate
O_2	attachment	Highest attachment rate in equilibrium
N_2	energy transfer	High electron impact cross section (vibration)
CO_2	laser transistion	Resonant coupling to N_2 vibration
CO	Long term stability	Dissociation equilibrium CO / CO_2 / O_2

Pumping scheme of a CO_2 laser

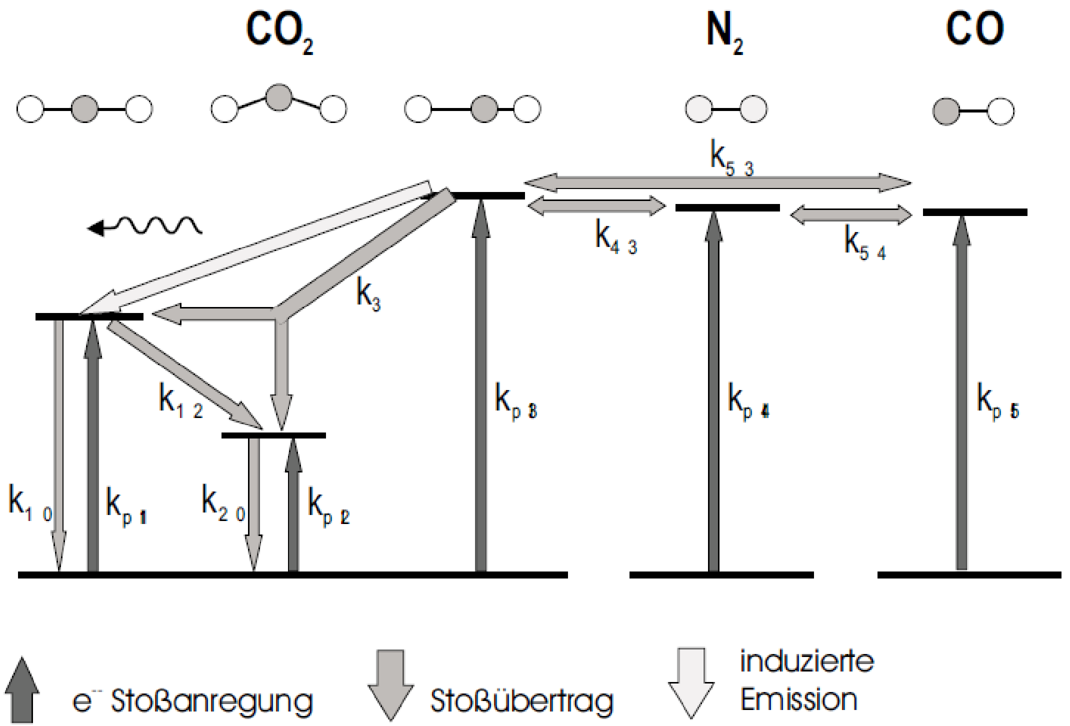
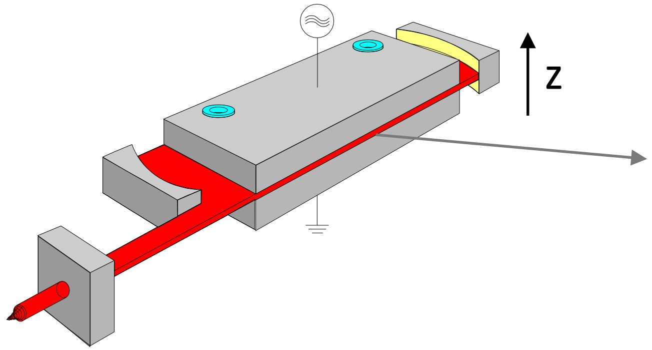
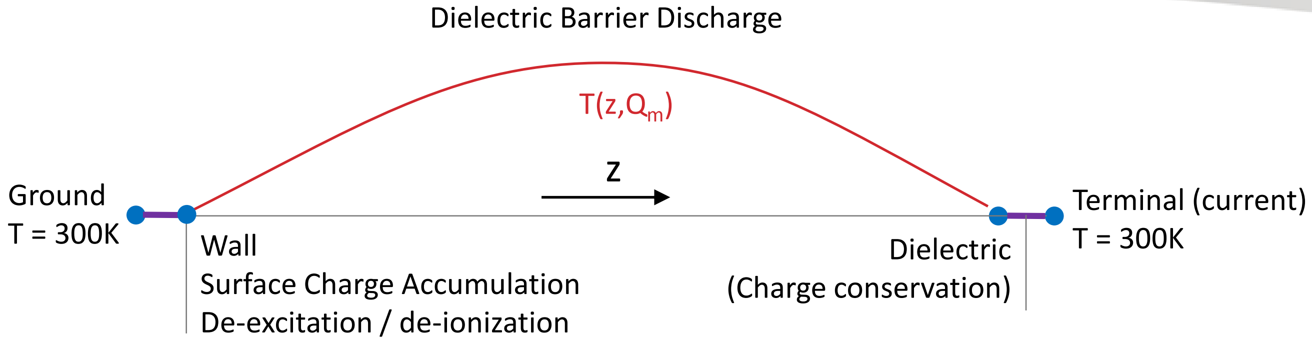


Image source: J. Schulz, Diffusionsgekühlte, koaxiale CO2-Laser mit hoher Strahlqualität, Dissertation, RWTH Aachen (2001)

Step 2: 1D Discharge - Setup





- For stability analysis, plasma temperature has to be self-consistent
  - Parabolic temperature profile $T(z,Q_m)$
  - only dependent on *average* heat source Q_m
  - no need for solving the heat equation
- Self-consistent calculation via Global ODE*:

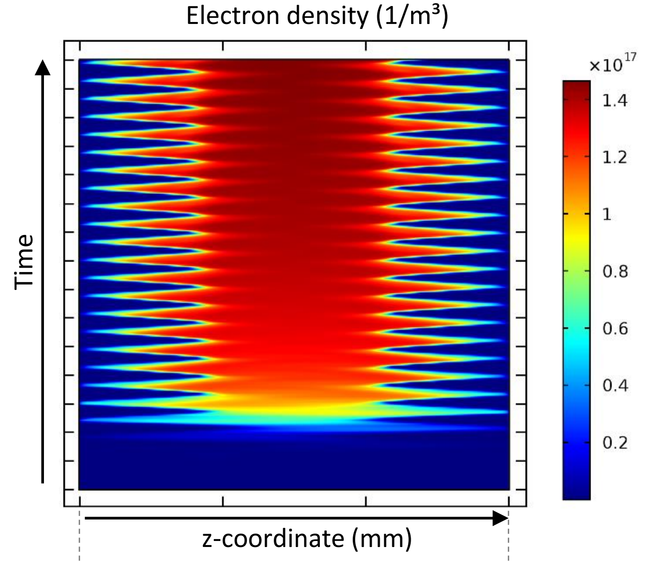
$$\frac{\partial Q_m}{\partial t} = (Q_{int} - Q_m)/\tau_P$$

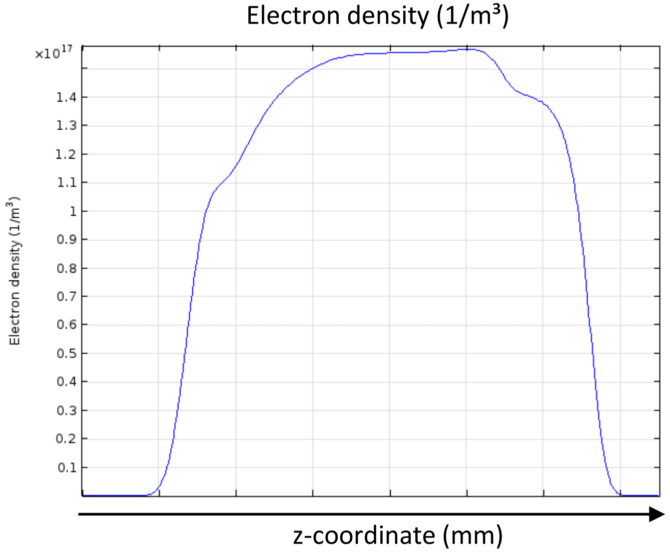
Q_m = average heat source
Q_{int} = integrated capacitive losses
τ_p = averaging time constant (3…5 RF cycles)

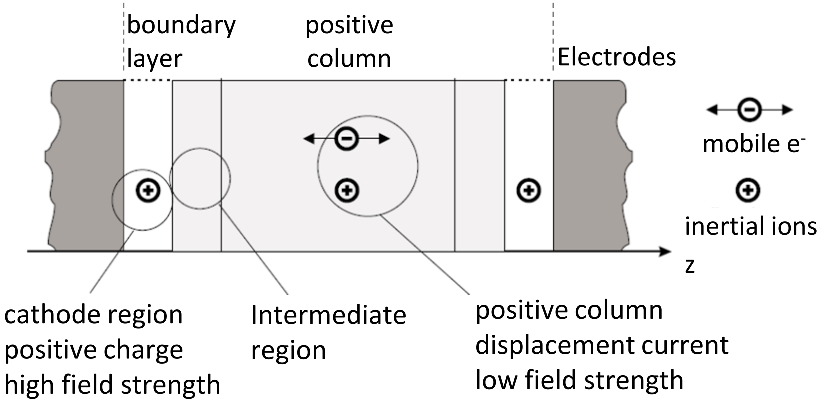
- „Temporal“ evolution does not reflect actual thermal time scale!
- Artificial time scale τ_p ensures fast convergence to quasi-steady state

* Calculation of Q_{int} and global ODE is decoupled from plasma physics using the nojac operator and a segregated solver for better convergence

Step 2: 1D Discharge - Results







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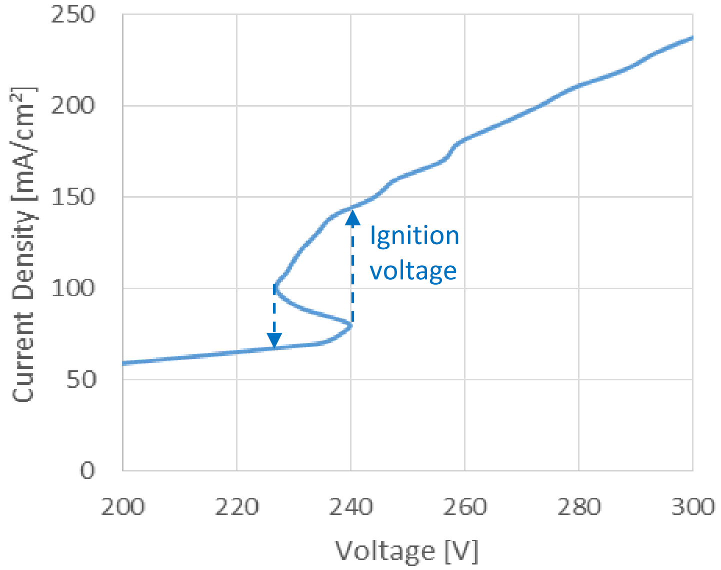
Result parameters for 3D:

- Impedance
- Temperature (cooling)
- Collision rates (laser pumping)
- Boundary layer thickness
- …



Step 3: 3D simulation – Material impedance

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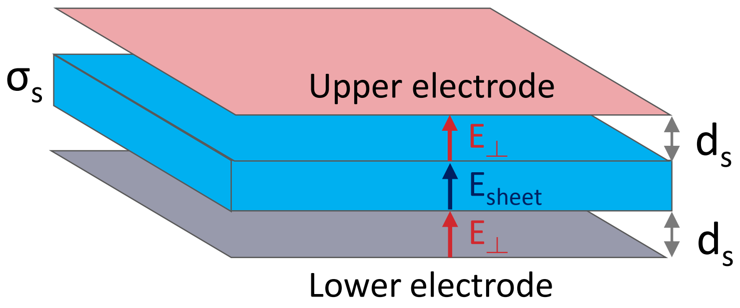
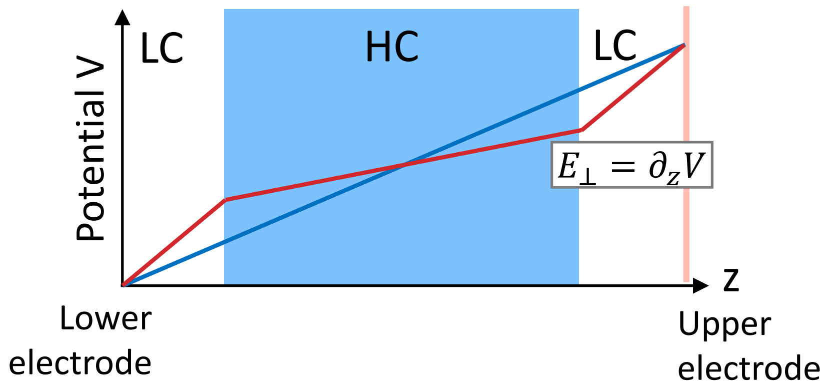
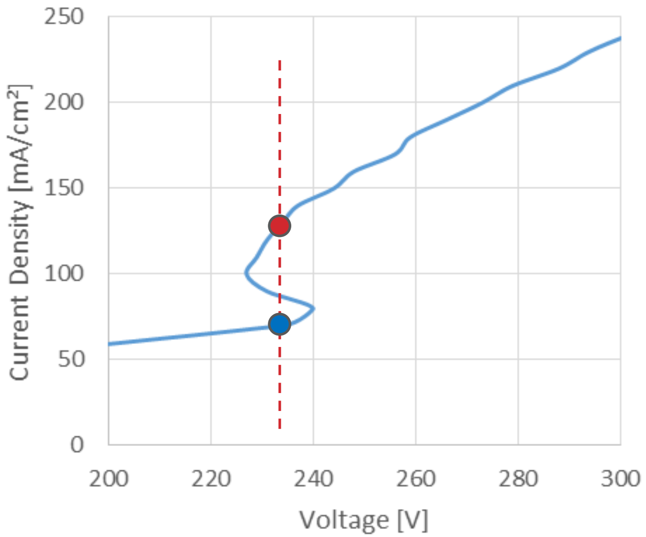
- Task: find a „solid“ surrogate material which resembles the same UI-curve
- Replacement of plasma discharge (steady-state properties) by „plate capacitor“ with conductive sheet (as part of a complex 3D structure)



- Evaluate normal electric field at boundary instead of terminal voltage:
  - ambiguous solutions exist for identical voltage drop
  - unique solution regarding normal field at boundary
  - Accessibility of variable





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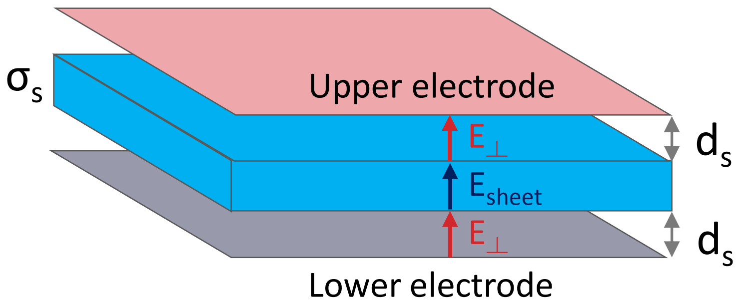
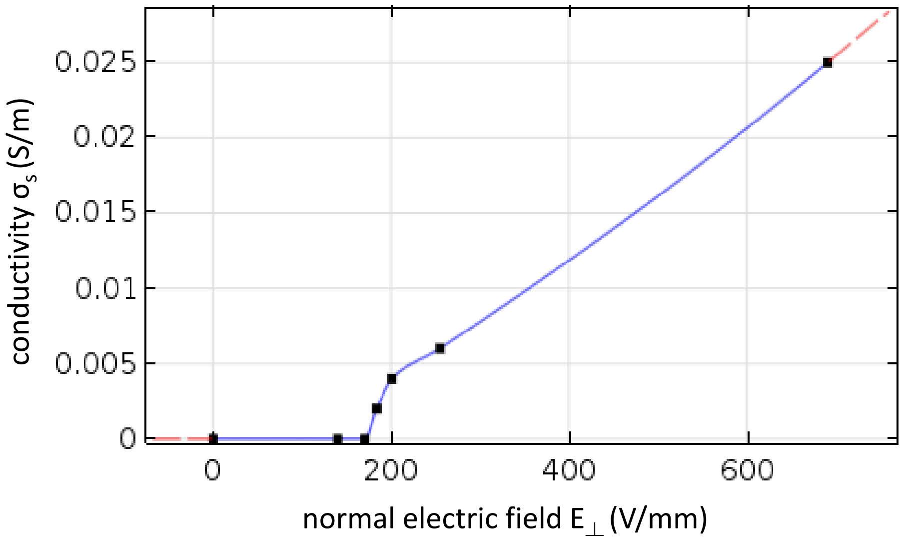
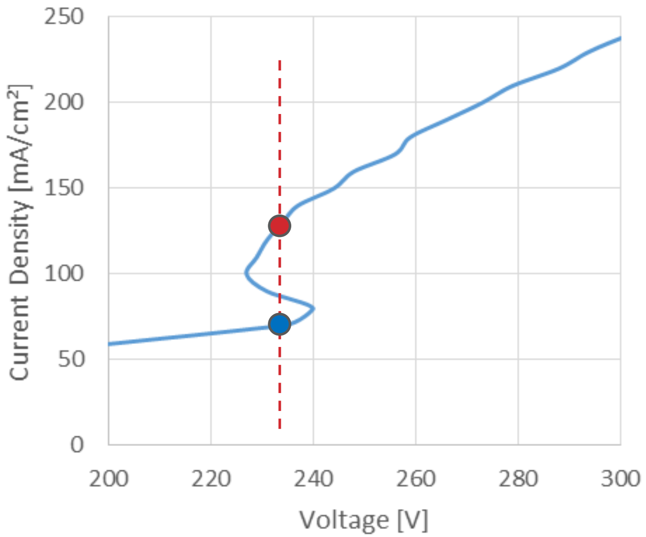


- Interpolation function:
  unique, continuous, smooth

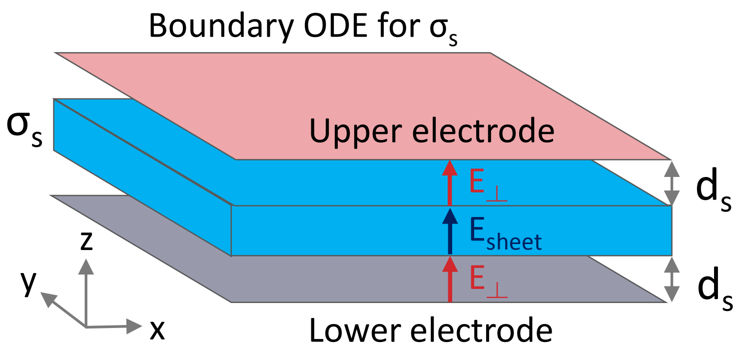




Step 3: 3D simulation – COMSOL implementation

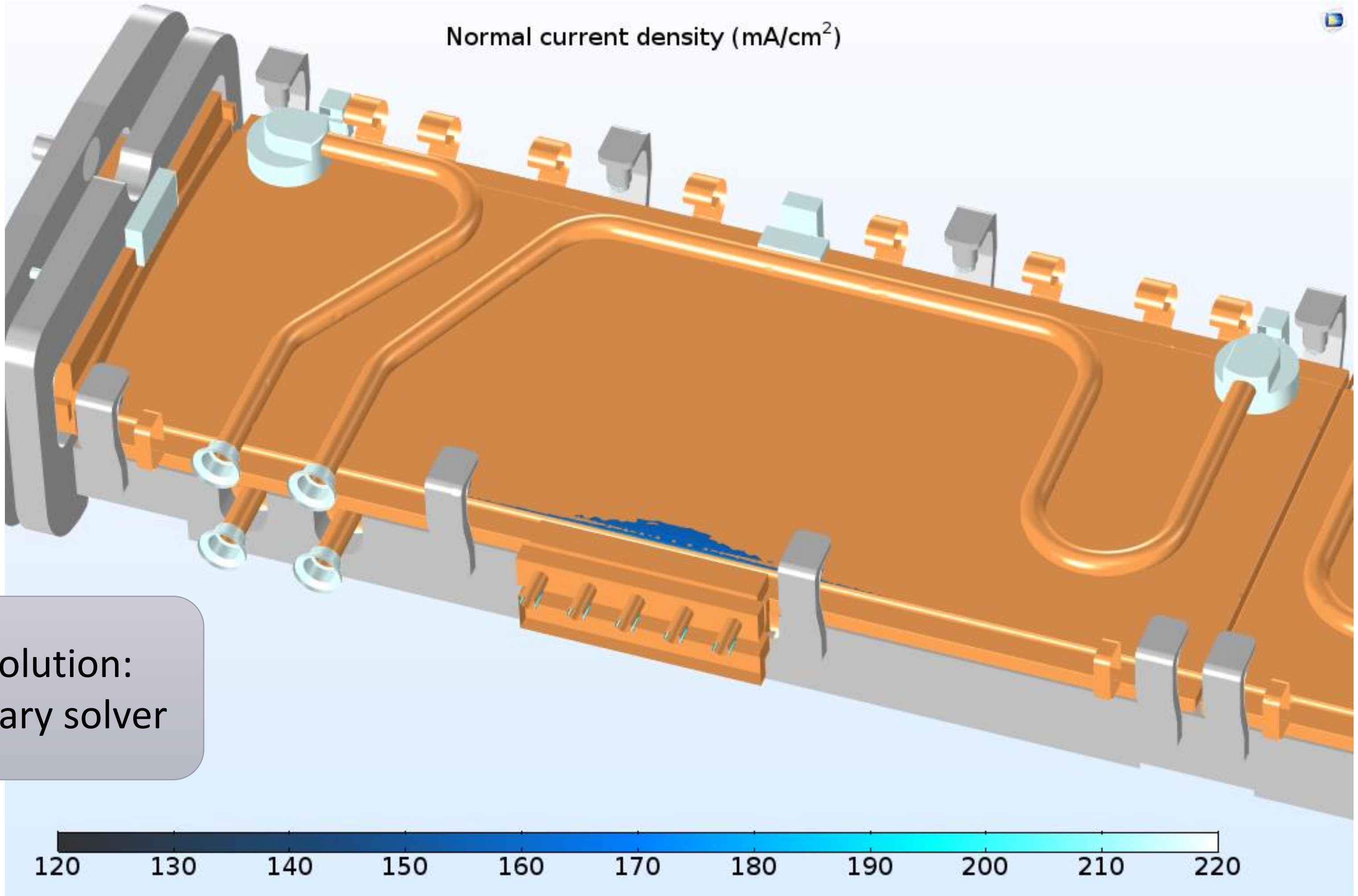
- 3D RF simulations (emw – frequency domain)

- Upper electrode surface: „reference boundary“
  - interpolation function $\sigma_s(|E_\perp|)$
  - Boundary ODE: $\sigma_s - \sigma_m = 0$ (to avoid stiff matrix)
  - Model coupling (projection) from boundary to sheet volume



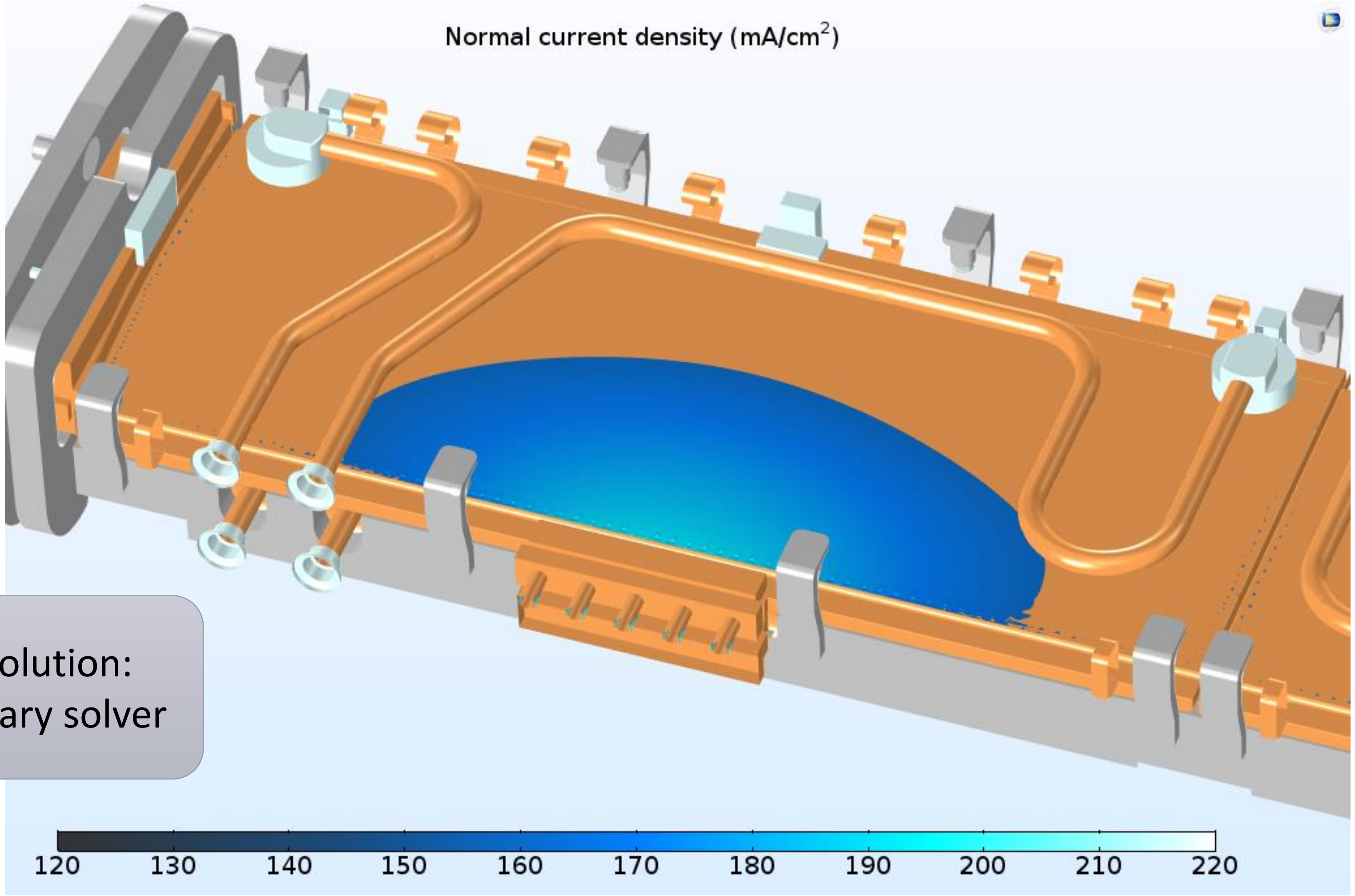
- Geometric multigrid solver (segregated RF / boundary ODE)
  - Number of DoFs: 6.737.446
  - Solution Time: 2 hours (8 Core CPU, 256GB RAM)

Step 3: 3D simulation – Results



No actual time evolution:
Iterations of stationary solver

Step 3: 3D simulation – Results



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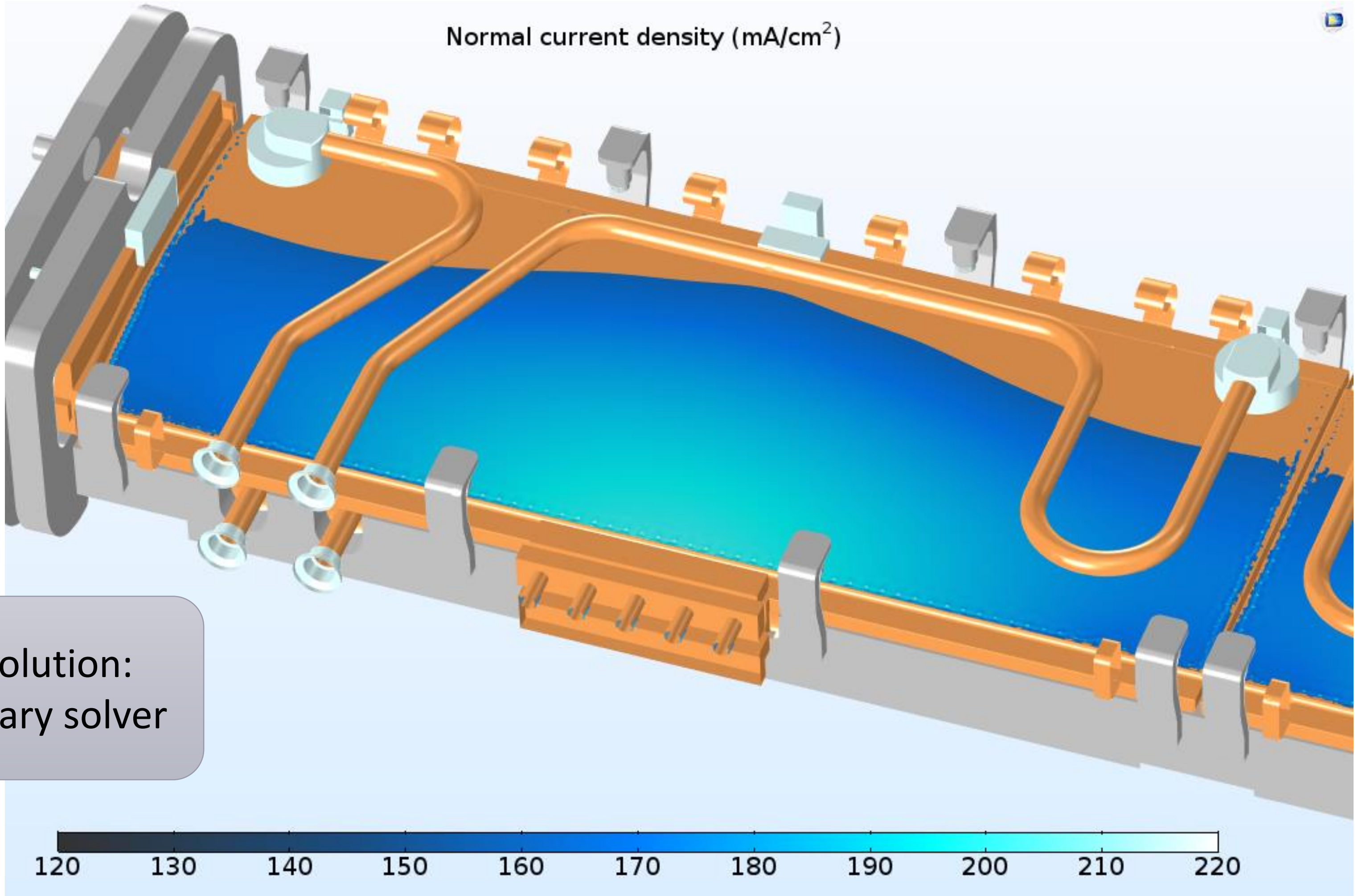

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Step 3: 3D simulation – Results

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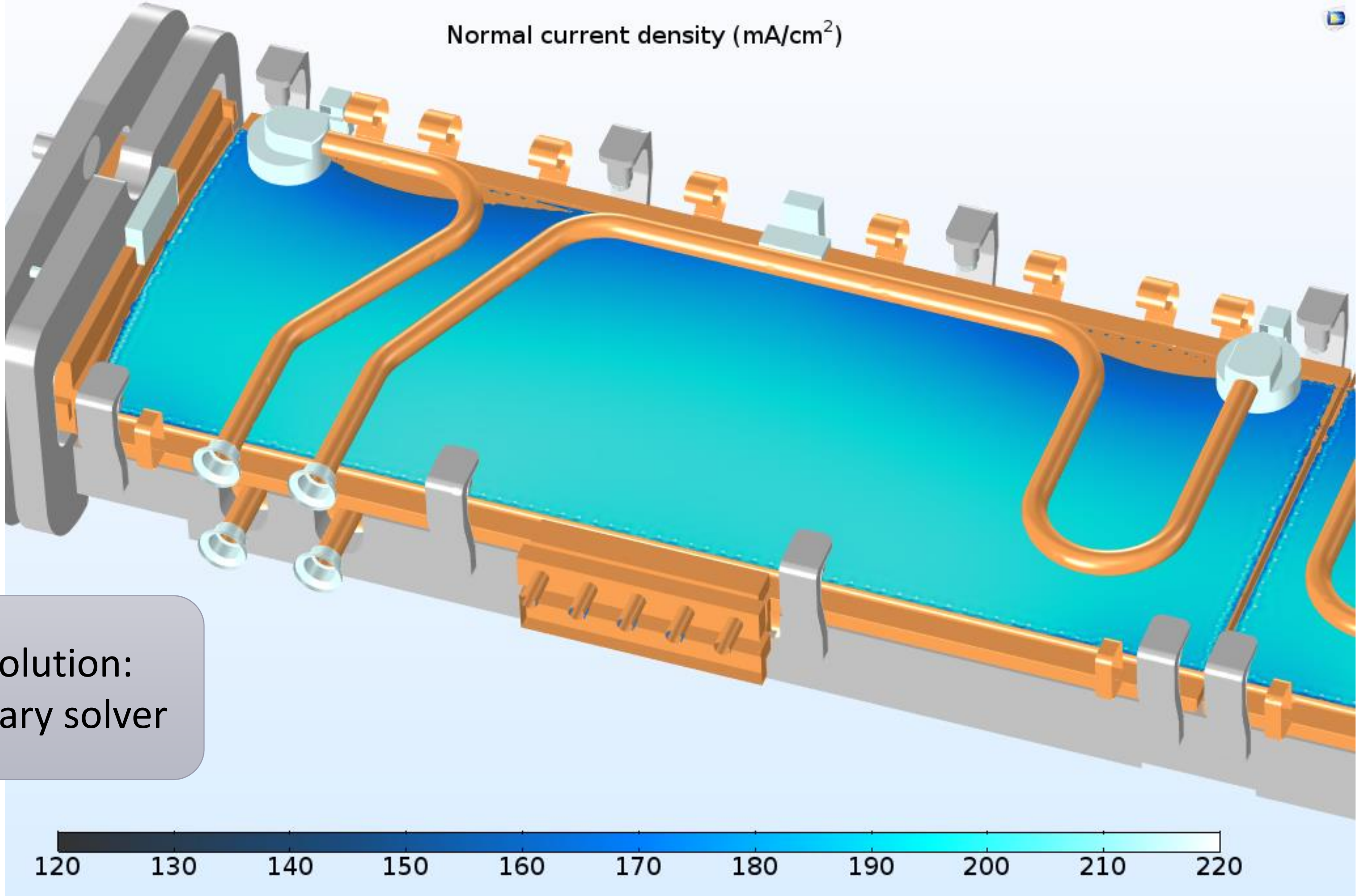

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Step 3: 3D simulation – Results

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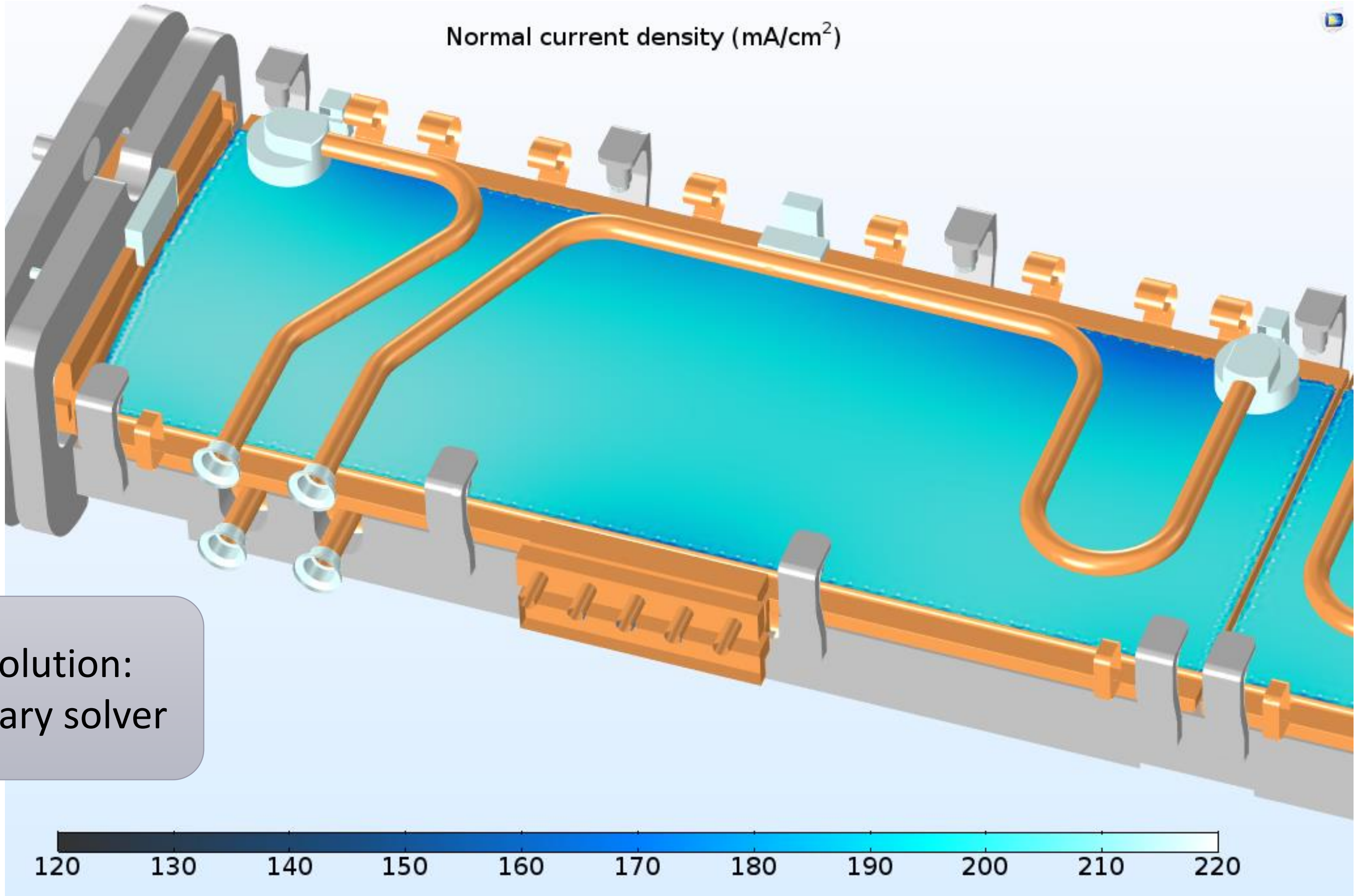

No actual time evolution:
Iterations of stationary solver

Conclusion & Outlook

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- Multilevel approach enables 3D simulation of a planar gas discharge in a laser
- Mutual coupling of RF field and plasma physics is maintained
- Characteristics of the discharge can be evaluated at any point in a complex 3D geometry
- Model has been successfully applied
  - Design of RF feeding / matching architecture
  - Prediction of working point for alternative gas compositions
  - Good agreement with experimental results

- Perspectives:
  - Temporal evolution of the ignition phase
  - Pressure variations during switch-on or pulsed operation
  - Further development and optimization of current and future products

Thank you for your attention.

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