Role of the Diffusion Current in Nonequilibrium Modelling of Welding Arcs

Margarita Baeva

Leibniz Institute for Plasma Science and Technology, Greifswald, Germany

COMSOL

COMSOL CONFERENCE 2014 CAMBRIDGE

INP Greifswald

Leibniz-Gemeinschaft

FROM IDEA TO PROTOTYPE

Introduction

Aim of research

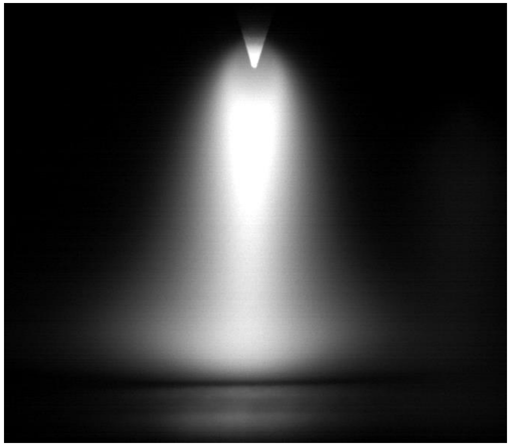
- Unified non-equilibrium model of the arc plasma and electrodes
- Arc-electrode interaction

Outline

1. Subject: free-burning arc
2. Basic features of the model
3. Diffusion current and generalized Ohm’s law
4. Realization in COMSOL
5. Results
6. Concluding remarks

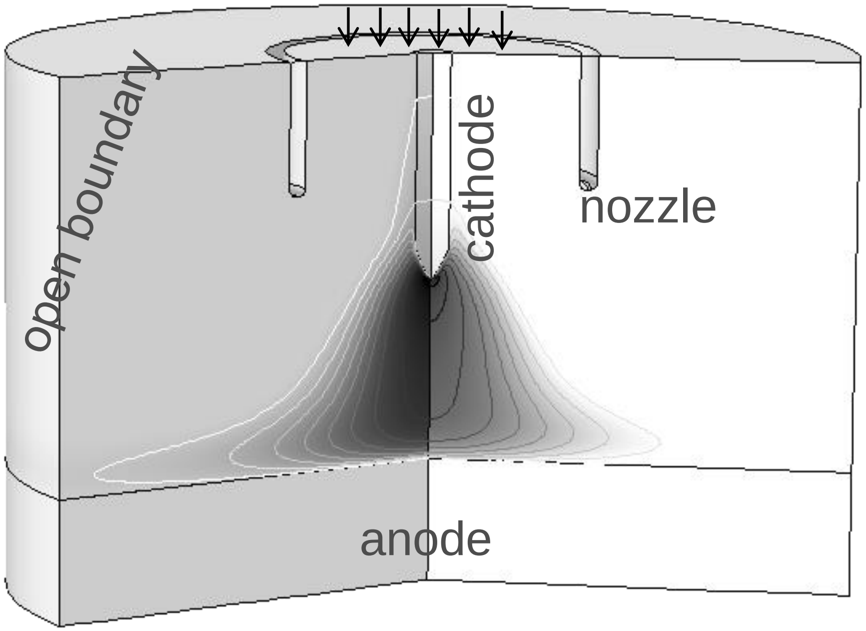
1. Subject: free-burning arc

- **Free-burning arc** – an idealized representative of DC arcs encountered in tungsten-inert gas welding, transferred arc furnaces, DC plasma torches for cutting and spraying, switching devices …
- **Electrodes** – important constituents of plasma devices determining the discharge properties
- **Near-electrode regions** – enable the current transfer, control the energy balance and heating of electrodes
- **Modelling** allows us to study the plasma-electrode interaction, to describe the arc from electrode to electrode



1. Subject: free-burning arc

General schematic of the model



Cathode: W, La-W rod, r=1-2 mm, hemispherical/conical tip

Gas: Ar, 1 atm (12-15 slpm), arc length 5-10 mm

Anode: Cu, steel (water cooled)

Current: 100 – 200 A

Axially symmetric 2D

2. Basic features of the model

- **Non-equilibrium description in the whole arc domain**
  - no assumption of thermal and chemical equilibrium but quasineutrality
- **Navier-Stokes equations for conservation of**
  - mass
  - momentum
  - energy of electrons and heavy species
  - species (atoms, singly charged ions)
- **Current continuity, Ohm’s and Ampère’s law**
- **Electric and heat conduction in the electrodes**

$$\nabla \cdot \rho \vec{u} = 0$$

$$\rho(\vec{u} \cdot \nabla)\vec{u} = \nabla \cdot \left(-p\hat{I} + \hat{\tau}\right) + \vec{j} \times \vec{B}$$

$$\nabla \cdot \vec{J}_\varepsilon = -e\vec{j}_e \cdot \vec{E} + S_\varepsilon,$$

$$\nabla \cdot \vec{J}_h = e\vec{j}_i \cdot \vec{E} - \rho C_p \vec{u} \cdot \nabla T + S_h,$$

$$\nabla \cdot \vec{J}_i = S_i - \rho\vec{u} \cdot \nabla y_i,$$

$$\nabla \cdot \vec{j} = 0,$$

$$\frac{\vec{j}}{e} = \vec{j}_i - \vec{j}_e,$$

$$\nabla \times \left(\mu_0^{-1}\vec{B}\right) = \vec{j},$$

$$-\nabla \cdot \left(\lambda \nabla T\right) = \sigma E^2$$

$$\nabla \cdot (\sigma \nabla \Phi) = 0$$

INP Greifswald

Diffusive mass fluxes of the individual components

$$\vec{J}_i = \rho y_i \left(\vec{w}_i - \vec{u}\right) \qquad \sum_i \vec{J}_i = 0 \qquad \rho\vec{u} = \sum_i \rho_i \vec{w}_i$$

Stefan-Maxwell equations

$$\sum_{j \neq i} \frac{n_i n_j k_B T_{ij} C_{ij}}{n D_{ij}} \left(\vec{w}_i - \vec{w}_j\right) = -\nabla p_i + y_i \nabla p - R_i^T + Z_i n_i e \vec{E}$$

$$\sum_{j \neq i} \frac{z_i z_j}{\hat{D}_{ij}} \left(\vec{w}_i - \vec{w}_j\right) = \vec{G}_i = \vec{H}_i + \frac{Z_i e}{m_i} \rho_i \frac{\vec{E}}{p}$$

$$\vec{J}_i = \frac{y_i}{z_i} \rho D_i \vec{G}_i - y_i \sum_j \frac{y_j}{z_j} \rho D_j \vec{G}_j$$

Generalized Ohm's law

$$\vec{j} = \sum_i q_i \vec{J}_i = \frac{e}{m_A} \vec{J}_I - \frac{e}{m_e} \vec{J}_e$$

$$\vec{J}_I = f_I \vec{H}_I + f_e \vec{H}_e + c_E \vec{E}$$

$$\vec{J}_e = g_I \vec{H}_I + g_e \vec{H}_e + d_E \vec{E}$$

$$\vec{j} = \left(\frac{e}{m_A} f_I - \frac{e}{m_e} g_I\right) \vec{H}_I + \left(\frac{e}{m_A} f_e - \frac{e}{m_e} g_e\right) \vec{H}_e + \left(\frac{e}{m_A} c_E - \frac{e}{m_e} d_E\right) \vec{E}$$

$$\vec{j} = \sigma \vec{E} + \Delta \vec{j}_{diff}$$

3. Diffusion current and generalized Ohm's law

INP Greifswald

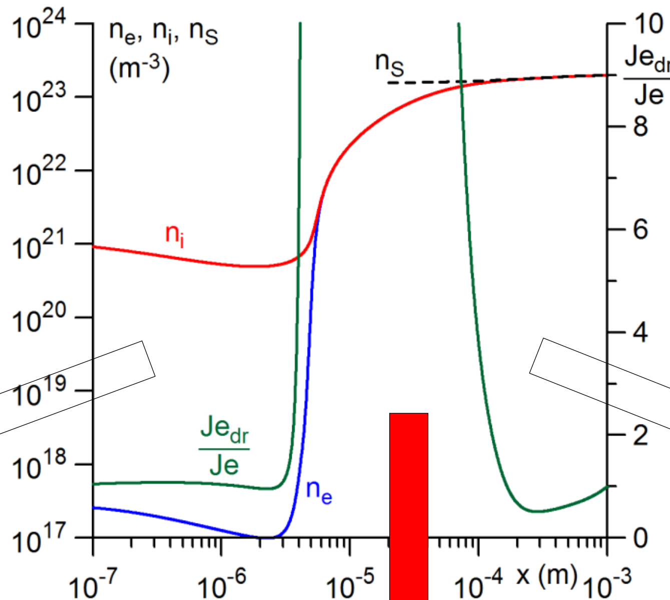
$$\vec{j} = \sigma\vec{E} + \Delta\vec{j}_{diff}$$

drift — diffusion

Plasma properties in the near-cathode region

$T_e \neq T_I$

$n_e \neq n_I$



$T_e \neq T_I$

$n_e = n_I = n_S$

$T_e \neq T_I \;\; ; \;\; n_e = n_I \neq n_S$

$J_{e,dr} \approx J_{e,diff} >> J_e$

N. A. Almeida, M. S. Benilov, G. V. Naidis, J. Phys. D: Appl. Phys. 41:245201 (2008))

4. Realization in Comsol

Modules used

- **Laminar flow** **p, u**
- **Electric currents** **j, V**
- **Magnetic fields** **A -> B**
- **Weak form PDE** **T, T_e, y_i**

Computation details

- **2D axisymmetric**
- **stationary**
- **fully coupled,**

direct (PARDISO)

Mesh

triangular elements 18.6k

number of elements 19.4k

smallest element size

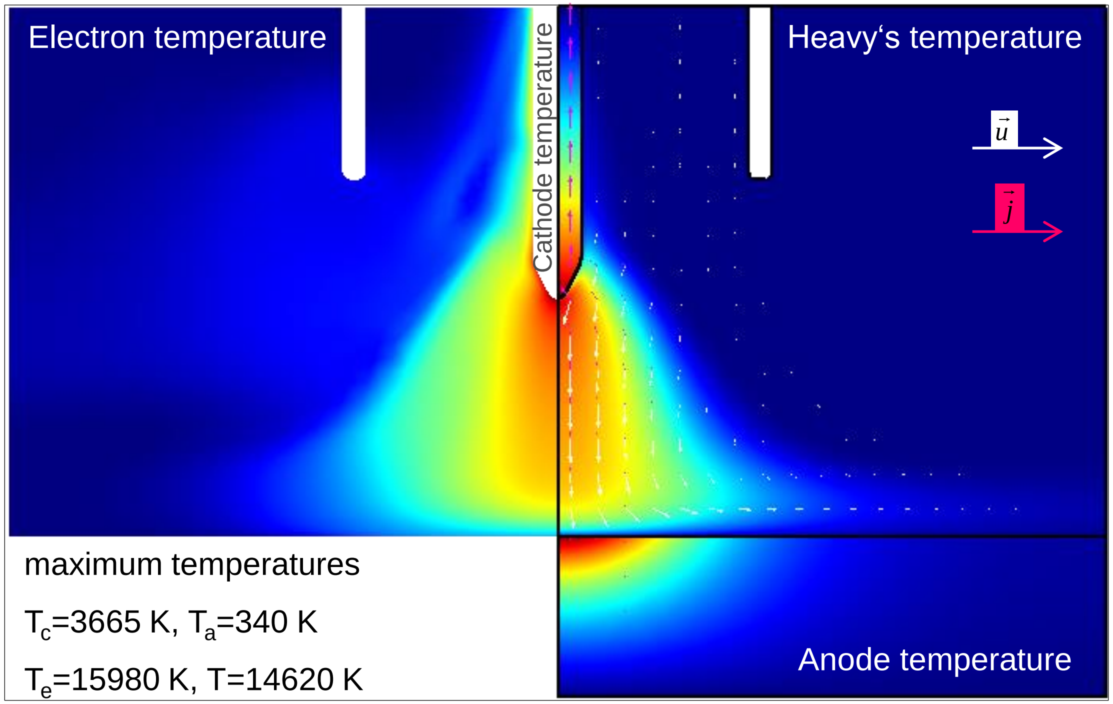
on the cathode tip ~(10-20) µm

maximum element size 1 mm

Discretization

quadratic

Temperature distribution

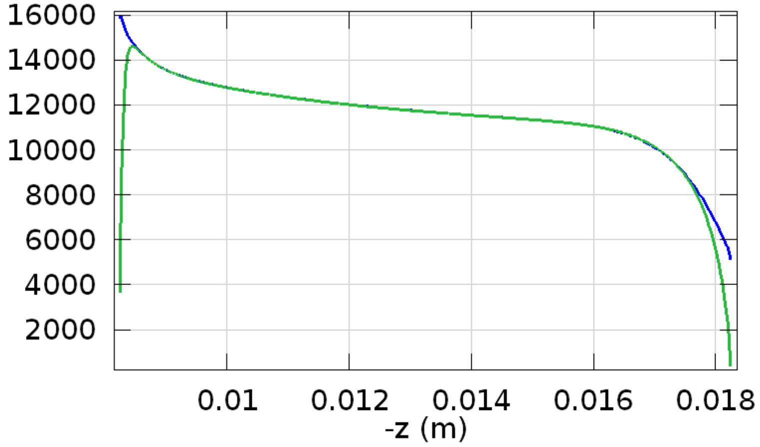


Thermal equilibrium in the core plasma

Nonequilibrium – near-electrode regions and arc fringes

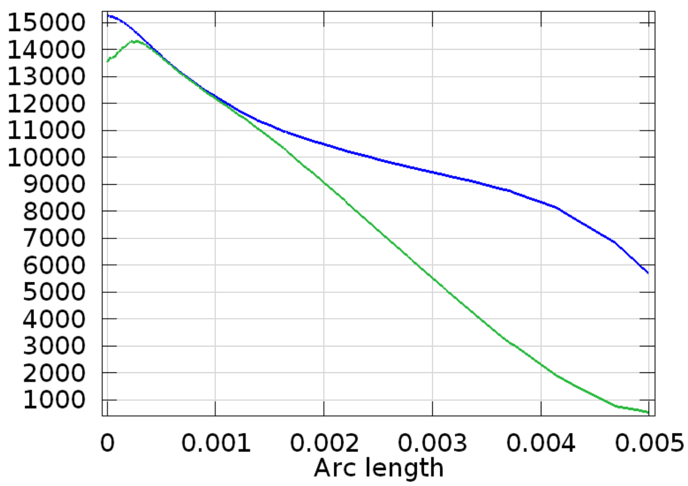
Temperature distribution

along the arc axis

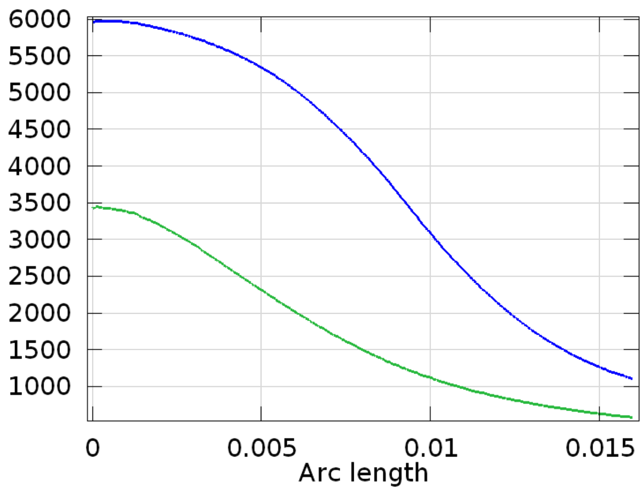


cut line perpendicular to the arc axis

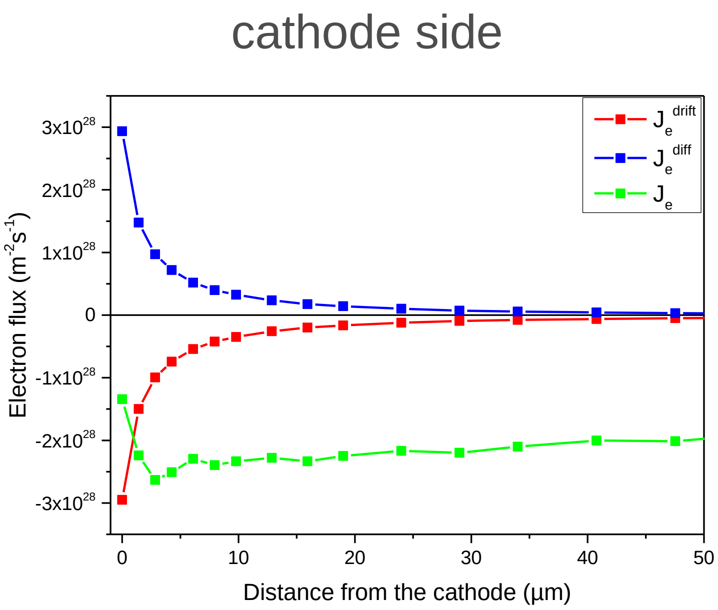
0.1 mm away from the cathode tip

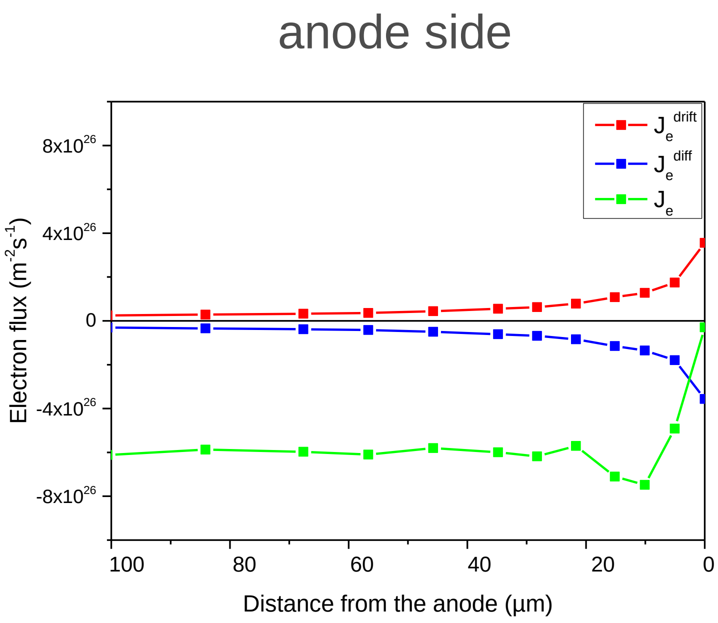


0.1 mm away from the anode



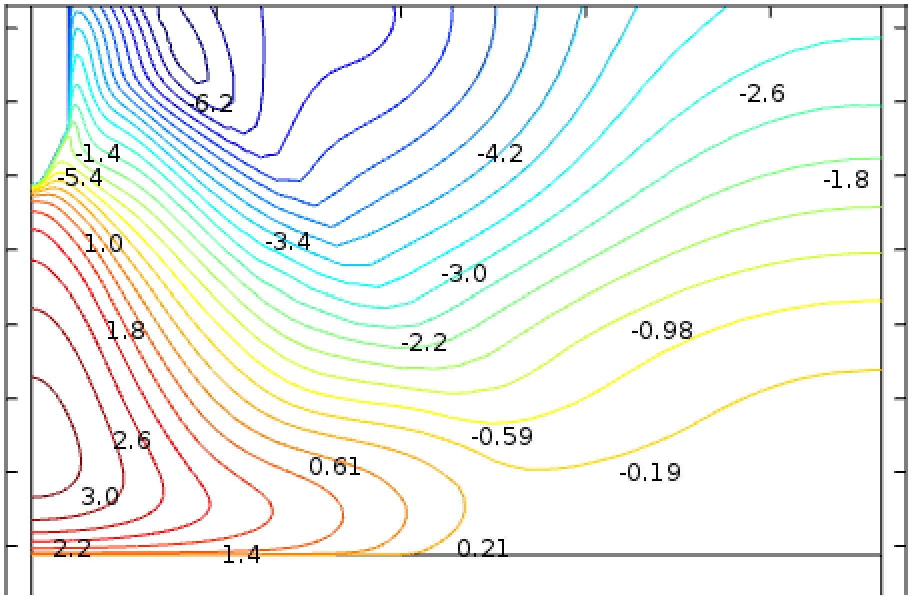
5. Results



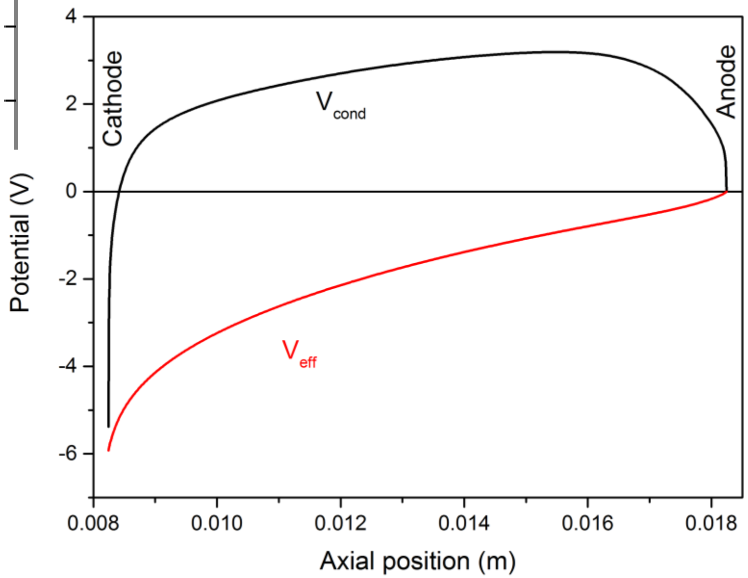


The drift transport of electrons to the electrode is virtually compensated by the diffusion transport.

Electric potential



effect of the diffusion current



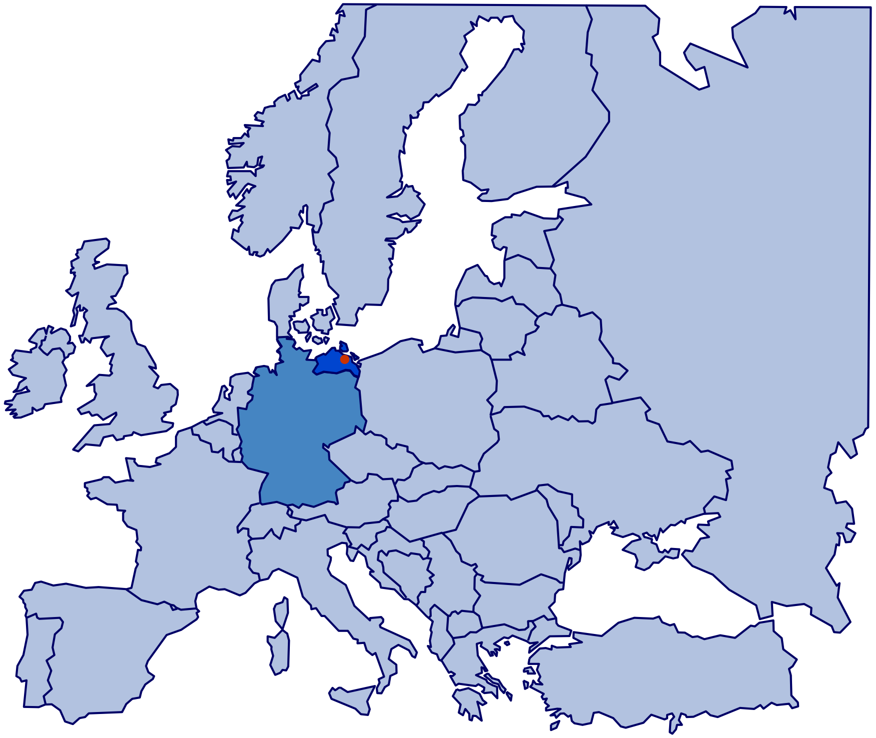
negative anode fall needed to supress a part of the electron flux to the anode

Concluding remarks

- COMSOL Multiphysics was used to solve a set of fully coupled physics equations describing welding arc in the frame of a nonequilibrium model.
- The generalized Ohm's law including a diffusion current component was implemented in order to describe the processes on the plasma edge in a physically justified manner.
- "Wish" list

  1. implementation of finite volume approach for Electric currents (to obtain correct current densities on internal boundaries)
  2. implementation of limiters (to preserve physically reasonable results)

Contact



Leibniz Institute for Plasma Science and Technology

Address: Felix-Hausdorff-Str. 2, 17489 Greifswald

Phone: +49 - 3834 - 554 300, Fax: +49 - 3834 - 554 301

E-Mail: welcome@inp-greifswald.de, Web: www.inp-greifswald.de