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Investigation of cathode spot behavior of atmospheric argon arcs by mathematical modeling

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http://www.ifs.ing.tu-bs.de/doc/1997/gd_xii_jw

1. Introduction:

Overall target:
Modeling of high pressure arcs for industrial applications, i.e. quantitative computation of practical relevant arc data in new parameter ranges (*ab initio* modeling).

Applications:
Atmospheric and higher pressure arcs for materials processing (e.g. welding) and lighting purposes.

Objectives:

A) evaluation of arc column modeling:

- can arc column models (2-D) provide any insight in processes near the electrodes?
- can we get cathode spot data from comparison with arc temperature measurements?
- is there an extrapolation capability of arc column models to new arc configurations?

B) pre-evaluation of integrated arc modeling:

- what can we await from integrated (column, electrode sheaths & bodies) modeling?
- accuracy targets for experimental data needed to evaluate integrated models?

ifs

ITP

2. Arc measurements used:

Experimental method: emission spectroscopy

I / I_{arc}	5mm	10mm	20mm
100A	[8, 12, 13]	[7]	[7]
200A	[8, 12]	[7]	[7]
300A	[12]	[7]	[7]

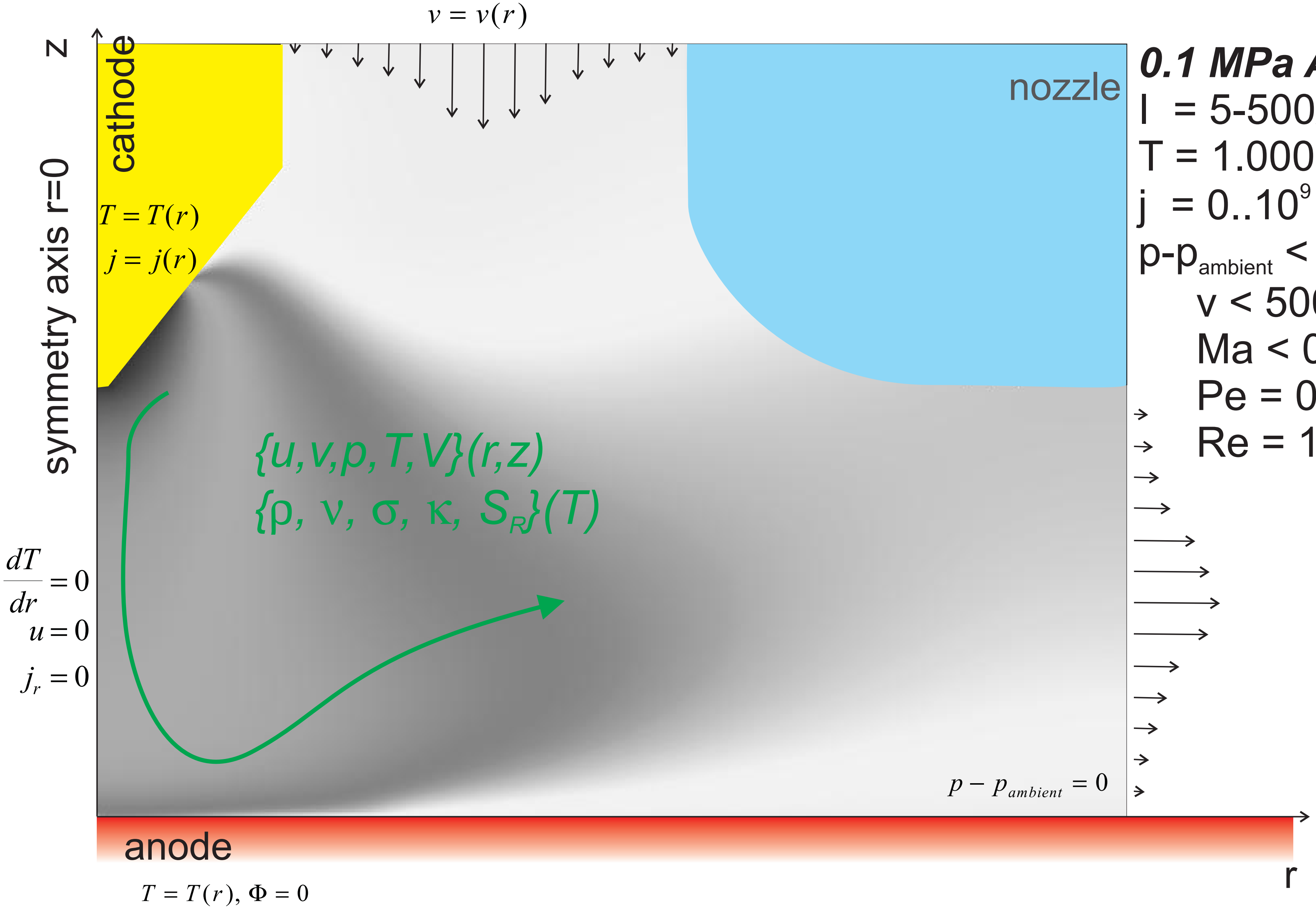
Experimental error: ~5%

Comparison: $2*(T_{exp}-T_{mod})/(T_{exp}+T_{mod})$ [%] as a function of (r,z)

Restriction: Experimental data is available only for the arc column
(distance >0.1 mm from the cathode tip)

[7] K. C. Hsu, K. Etemadi and E. Pfender, *J. Appl. Phys.* **54**, 1293 (1983)
[8] G. N. Haddad and A. J. D. Farmer, *J. Phys. D: Appl. Phys.* **17**, 1189 (1984)
[12] J. Haidar, *J. Phys. D: Appl. Phys.* **28**, 2494 (1995)
[13] M. F. Thornton, *J. Phys. D: Appl. Phys.* **26**, 1432 (1993)

3. The arc (column) model:



0.1 MPa Argon:

$I = 5\text{-}500\,A$

$T = 1.000\text{-}25.000\ K$

$j = 0..10^9\ A/m^2$

$p - p_{ambient} < 2000\ Pa$

$v < 500 m/s$

$Ma < 0.3$

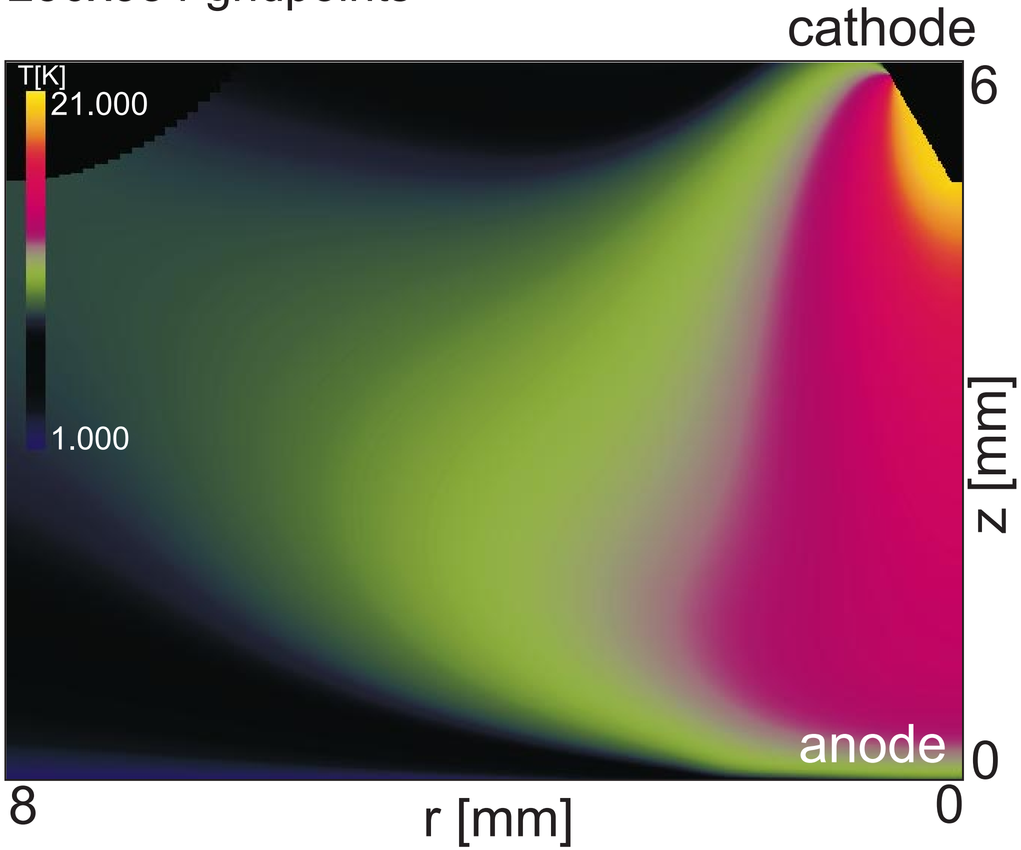
$Pe = 0..10$

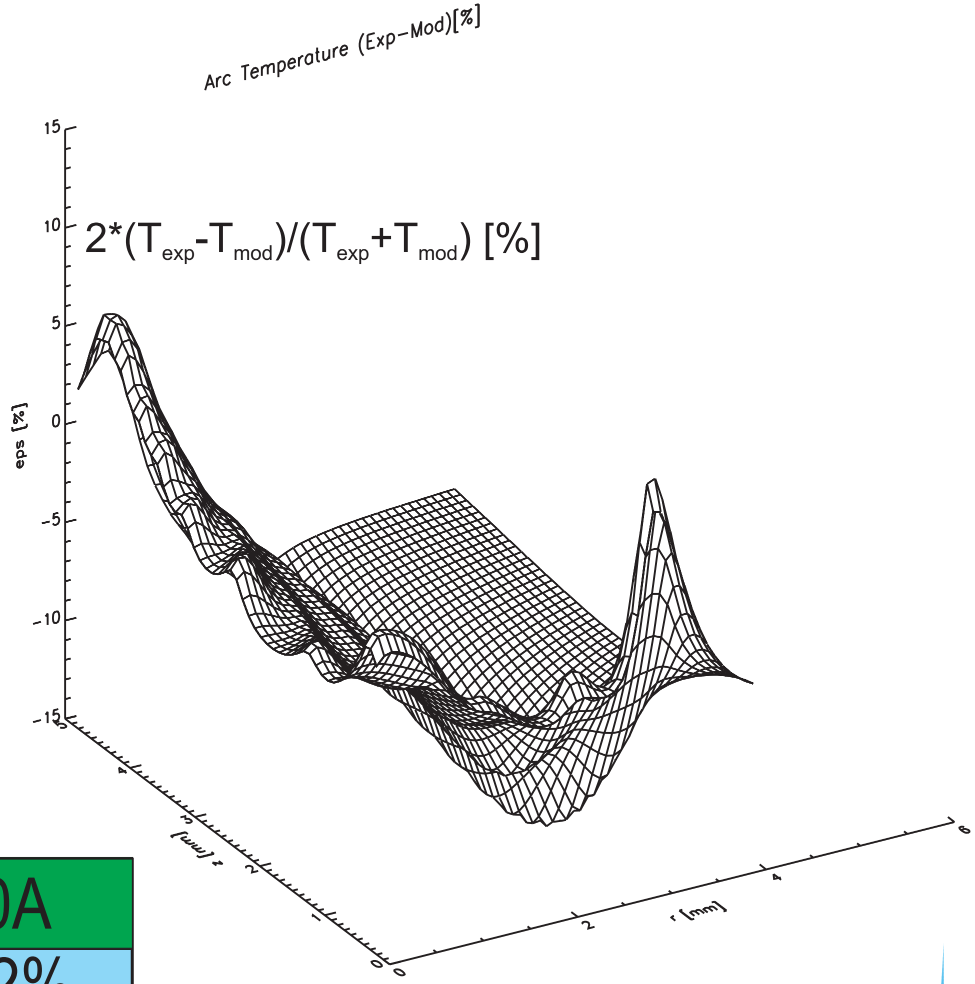
$Re = 1..1000$

4. Quantitative comparison of experimental and modeling data:

Model: 5mm argon-arc (0.1MPa),
I=100A, $j_0=10^8$ A/m^2, 60° Tip
256x384 gridpoints

Experiment:
arc parameters see model
emission-spectroscopy [Hsu'82]





Model \ Exp.	100A	200A
100A	-5,8%	+5,2%
200A	-18,3%	-7,2%

5. Cathode spot data derived from the comparison:

I / I_{arc}	5mm	10mm	20mm
100A	1.0±0.3	1.3±0.2	1.1±0.4
200A	1.0±0.4	1.2±0.2	1.1±0.3
300A	1.0±0.4	0.8±0.3	1.0±0.4

Cathodic peak current density [$10^8 A/m^2$] "determined" from the comparison of spectroscopical arc temperature data with modeling results.

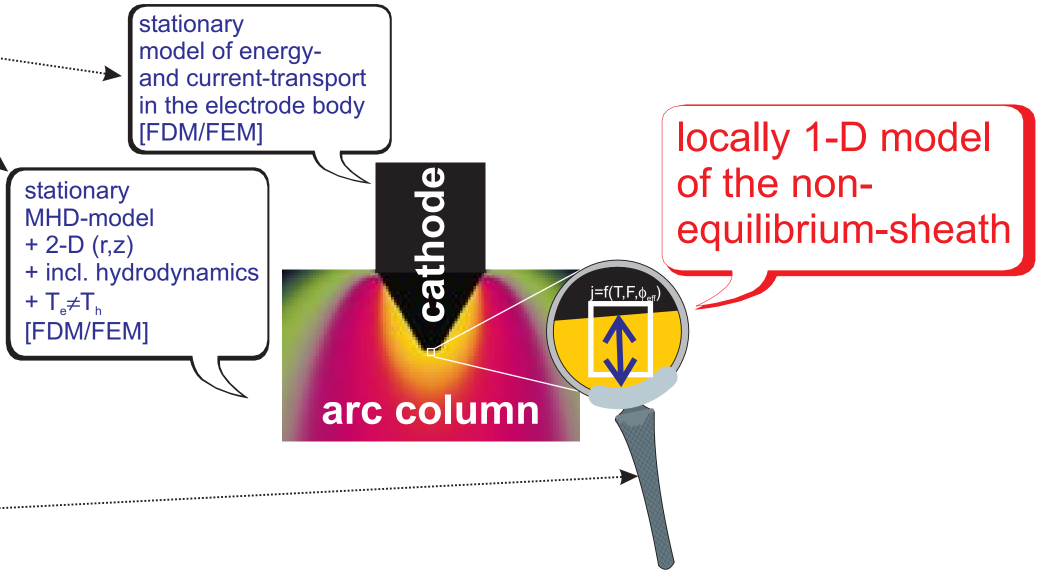
I / I_{arc}	5mm	10mm	20mm
100A	20.5±1.0	21.0±1.0	20.5±1.0
200A	20.5±1.0	21.0±1.0	21.0±1.0
300A	21.5±1.0	21.0±1.0	21.0±1.0

Cathode peak temperature [kK] "determined" from the comparison of spectroscopical arc temperature data with modeling results.

Conclusion:

- The LTE model of the arc column (CFD/MHD) is accurate with respect to arc temperature measurements of about 5% experimental error.
- The inverse problem (determination cathodic boundary conditions) can not be solved with sufficient accuracy.
- Regarding the (numerical) sensitivity analysis of anodic current and pressure distribution with respect to the cathode boundary conditions, these are found to be indeterminate by pure arc column models.

6. Integrated arc models shortly discussed: *state-of-the-art*



stationary
model of energy-
and current-transport
in the electrode body
[FDM/FEM]

stationary
MHD-model
+ 2-D (r,z)
+ incl. hydrodynamics
+ $T_e \neq T_h$
[FDM/FEM]

locally 1-D model
of the non-
equilibrium-sheath

Arc column models (>50 papers):
- LTE, convection, ...
- electrode effects indeterminate
- boundary conditions = fitting parameters!?

Cathode-sheath models (>50 papers):
- 1-D, spatial or global balances
- “zoo” of physical effects and simplifications
- boundary conditions = fitting parameters!?

Integrated models (<10 papers):
- local 1-D subgrid [Delalondre et.al. 1990,Lowke et.al. 1992 ff.]
- extended 2-D-model (diffusion-enhanced *non-LTE* conductivity) [Fischer, Neiger, ...]

Current objectives:
- quantitative evaluation / proof of extrapolation capability
- implementation into practical useable software / visualization
- application (computation of discharge behavior **in advance**)

Conclusion: a conceptional framework for the implementation of **all** individual physical models provided in open literature is needed!?

6. Integrated arc models: *the transfer-function-concept*:

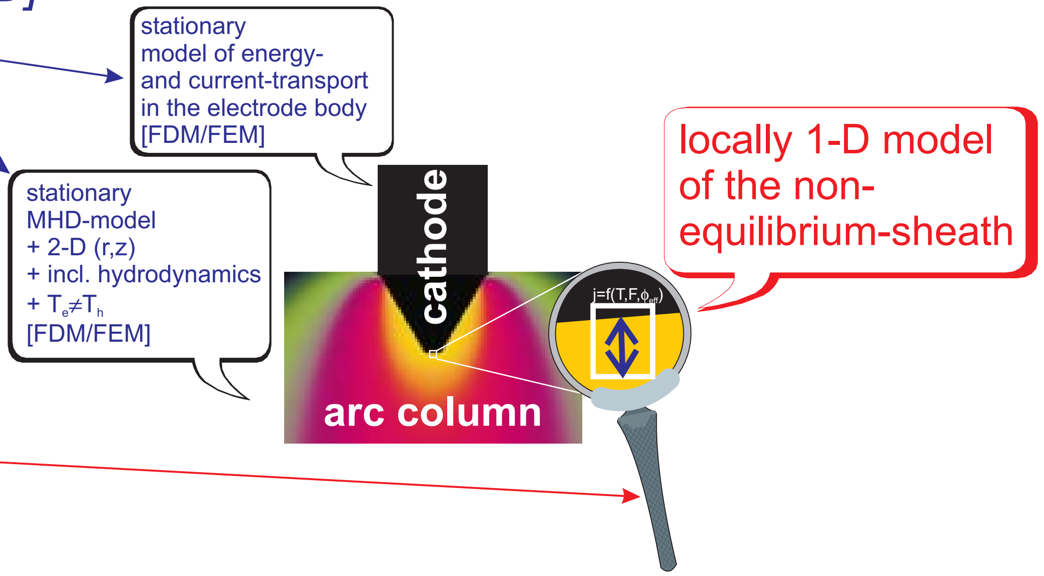
Basic idea:

separation of physical descriptions *and* numerical implementations:

- 2-D-regions (plasma, electrodes) ⇒ *[CFD/MHD]*

and

- local 1-D boundary layers
  in front of the electrodes
  (processes, with larger scales had to be included into the multi-dimensional description of the plasma
  e.g. $T_e \neq T_h$ i.e. PLTE)
  ⇒*[special numerical methods,
  e.g. ODE-BVP-Solver, Δx≠const.]*



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Advantages:

- boundary layer thickness is computed rather than prescribed.
- strong non-linear phenomena become treatable
  (e.g. cathode-sheath models incl. space charges & Bohm criteria)
- limitation of the overall numerical effort
  by computing the transfer-function independent of a special geometry of the electrode-plasma-transition:
  - that can be used for different discharge geometries!
  - that may be simplified for some applications!?

6. Integrated arc models: *examples for cathode transfer functions*

[Lowke et.al., *J.Phys.D* 30 ('97) 2033]

- local spatial dependence:
  $n_e(x)$ from the ambipolar diffusion equation
- assumed to be constant:
  $T_e = T_h = T_{plasma}(r,z)$
- thermionic electron emission: $j \leq j_{Richardson}$
- local energy source term for the cathode surface:
  $q_C = -\varepsilon\, a\, T^4 - |\, j_e|\, \phi_{eff} + j_{ion}\, V_{ion}$ - "$\lambda\, \nabla\, T$"
- no space charge zone (Schottky-model)

$\Rightarrow$ well defined problem with the transfer-function $\{T_P, E_P, T_C\} \Rightarrow \{\sigma_{eff}, \kappa_{eff}, q_C\}$

Results:

- better than trivial model (fig. 4), reducing numerical effects at the cathode
- numerically practical (1-D sub-model with small logical depth)
- anodic current density still depends on numerical parameters!?

$\Rightarrow$ the trivial model with optimal grid choice may be also sufficient:

$j = \sigma_{plasma}\, E_P \;=\; j_{ion} + j_{Richardson} \;\Rightarrow\; j_{ion} \;\Rightarrow\; q_c = -\varepsilon\, a\, T^4 - |\, j_e|\, \phi_{eff} + j_{ion}\, V_{ion}$ - "$\lambda\, \nabla\, T$"

$\sigma_{eff} = (1/\sigma_P + 1/\sigma_C)^{-1}$, $\kappa_{eff} = (1/\kappa_P + 1/\kappa_C)^{-1}$

trivial transfer-function: $\{T_P, E_P, T_C\} \Rightarrow \{\sigma_{eff}, \kappa_{eff}, q_C\}$

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6. Summary and conclusions:

- even a combination of column modeling and spectroscopy in the arc column provide only minor insight into cathode spot behavior.
- the quantitative and spatial dependent comparison of LTE arc column models with spectroscopic temperature data emphasize the validity of the LTE/CFD-model (for arcs in local thermal equilibrium).
- integration of locally one-dimensional boundary layer models seems to be an excellent approach to provide insight in cathode spot behavior, but
  - ♦ there is no widely accepted 1-D-cathode-layer model.
  - ♦ implementation into the column model should be generalized in order to allow for different 1-D-models.
  - ♦ a generalization (transfer-function approach) should allow for 1-D-models with no prescribed boundary layer thickness.

First results from current efforts [0.1 MPa argon, thoriated tungsten cathode]:
within the overall range of possible parameters (T_C,T_P,V_P) of our transfer function:

- ♦ results in a boundary layer thickness of 50-75µm.
- ♦ results in a cathode voltage drop of 4-7 V mainly occurring in the space charge sheath.