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Electrode modelling for metal halide lamps

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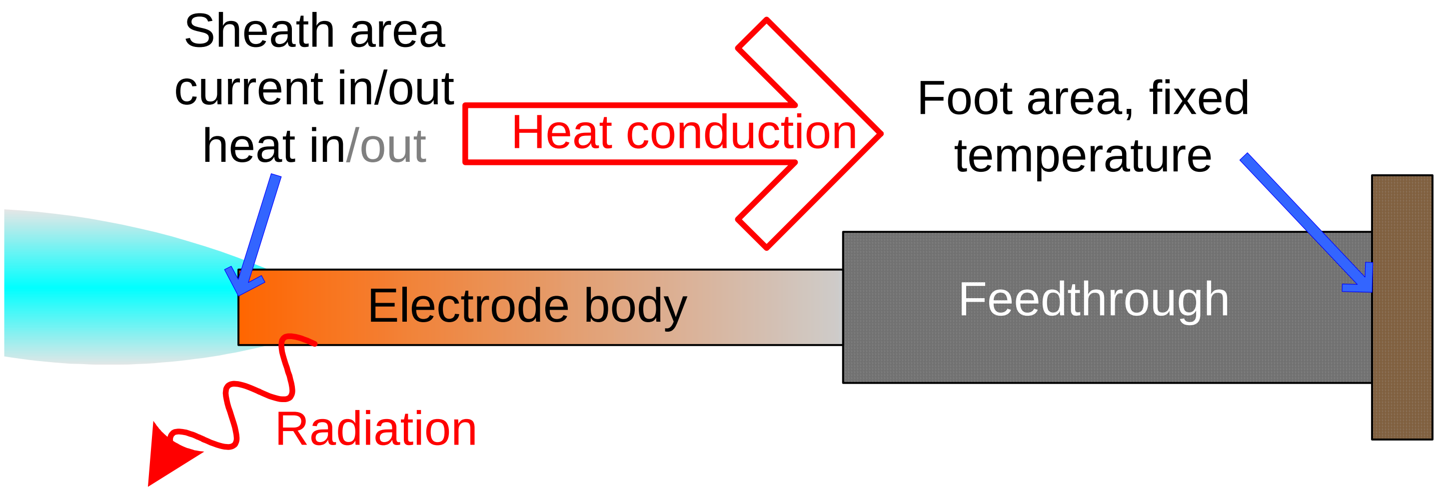
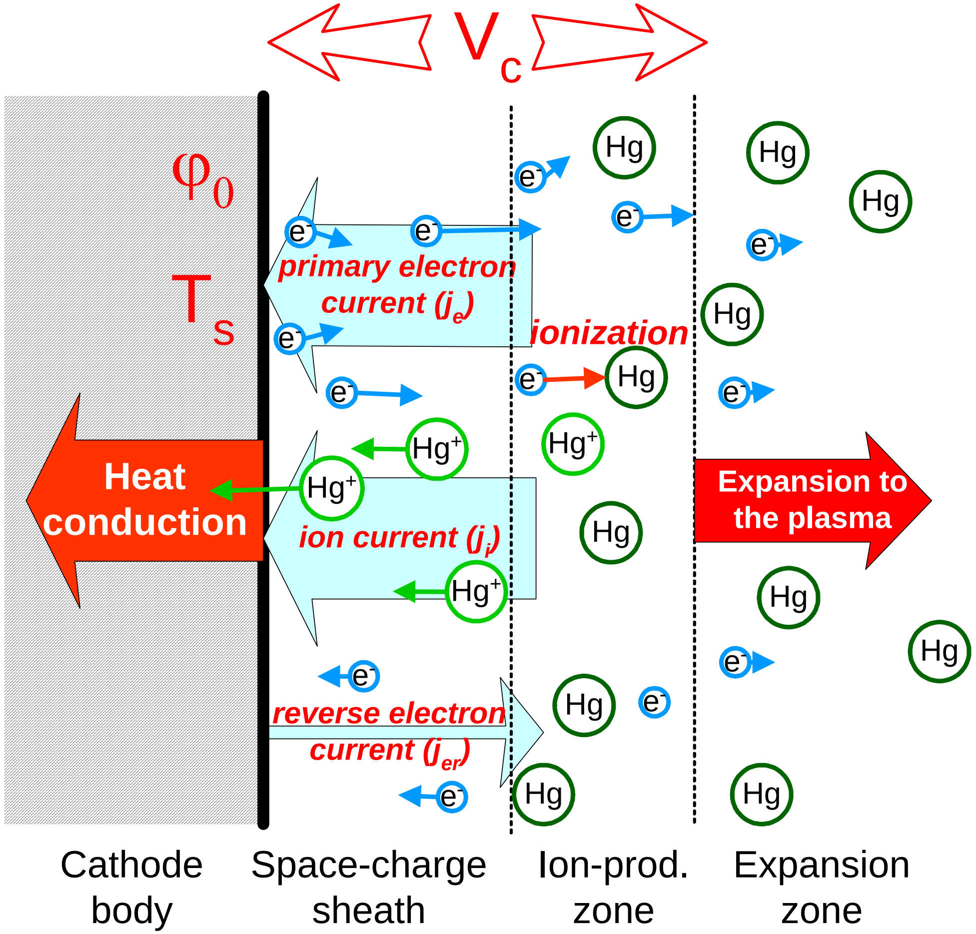
Model basics

- Current flows from/to discharge via a transition zone, the so-called sheath-area, producing heat in this area.
- Energy is lost by radiation.
- Heat flows through electrode body and feedthrough towards lamp wall material (and influences coldest spot temperature).



The cathode: General sheath model

- Transition zone divided in 4 areas.
- Electrons are emitted from surface.
- Electrons are accelerated towards ion-production zone and create ions.
- Ions are accelerated towards surface and recombine there.



Electron emission

- Starting point: Richardson equation

$$j_e = A_R T_S^2 e^{\left(-\frac{e\varphi}{k_b T_s}\right)}$$

- Workfunction (φ) can be influenced by electric field at electrode surface. This field is generated by the space charge in the 'space-charge sheath'. Schottky effect

$$\varphi = \varphi_0 - \sqrt{\frac{eE_s}{4\pi\varepsilon_0}}$$

- Other methods are available, but are more complex and give similar results.
- Approximation for the field at the electrode surface is the McKeown equation.

$$E_s^2 \cong 4\frac{j_i}{\varepsilon_0}\sqrt{\frac{m_i V_c}{2e}}$$

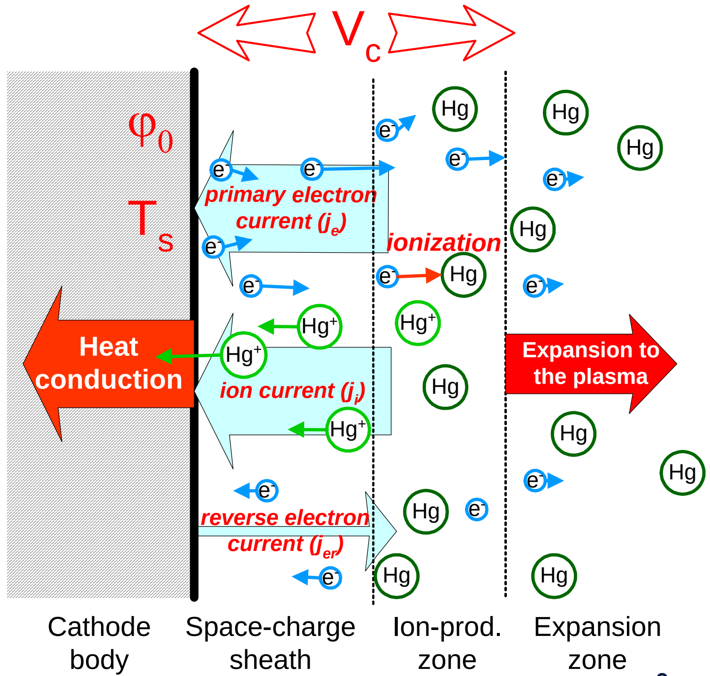
Workfunction

- Monolayer emitters decrease workfunction:
  - –Metals like Na, Dy and Sc can cover the electrode surface and change its workfunction.
- Our model:
  - –Monolayer is partly covering surface.
  - –Coverage (theta) is calculated by balancing the adsorption and desorption of the metals.
- Possible improvement:
  - –Include ion current/electric field in adsorption term.

Ion current

$$j_e * V_c = j_i * V_i$$

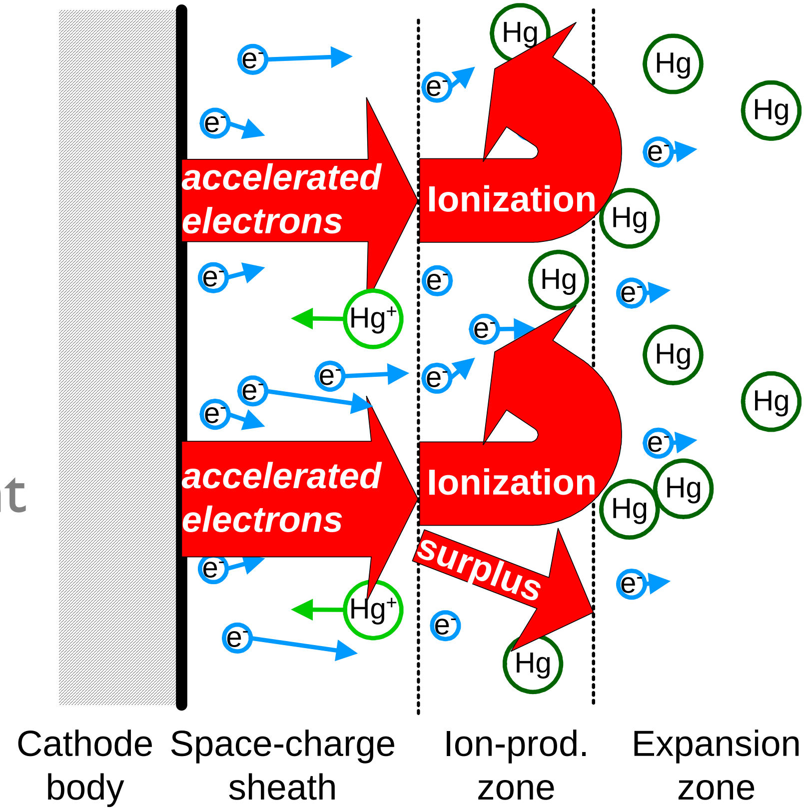
- Bade & Yos: All energy from electrons (j_e*V_c) is used to ionize atoms.
- Problem for high current densities: not enough atoms present to deliver ion current.
- Solution: Introduce maximum ion current with Saha equation and Dalton's law.



Surplus of electron energy

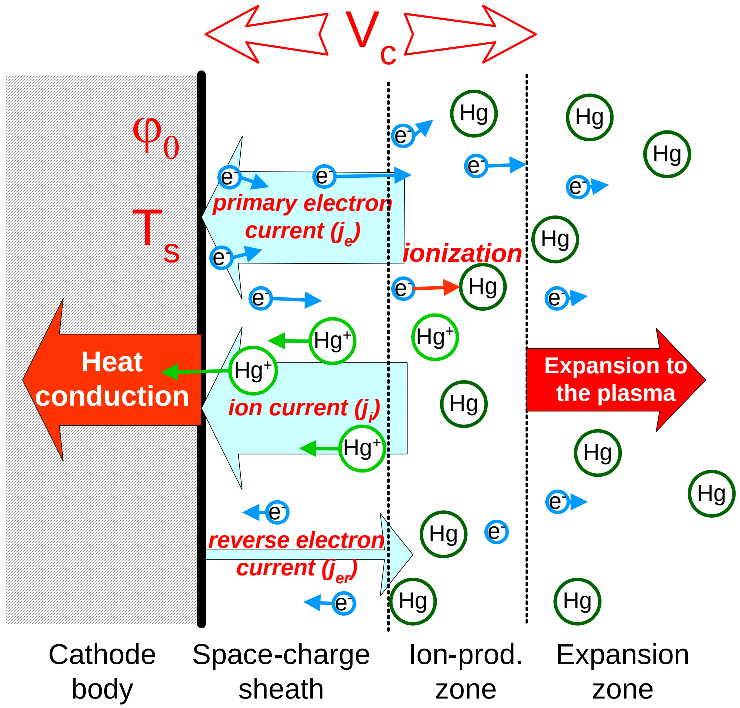
- If not all energy is used for ionization, where does it go?
  - Bötticher: energy is lost in radiation and conduction to plasma, but is not calculated.
  - Geijtenbeek: energy is lost via expansion to plasma. A significant part of the electron energy is already removed before the maximum theoretical current density is reached.

$$j_e * V_c = j_i * V_i$$



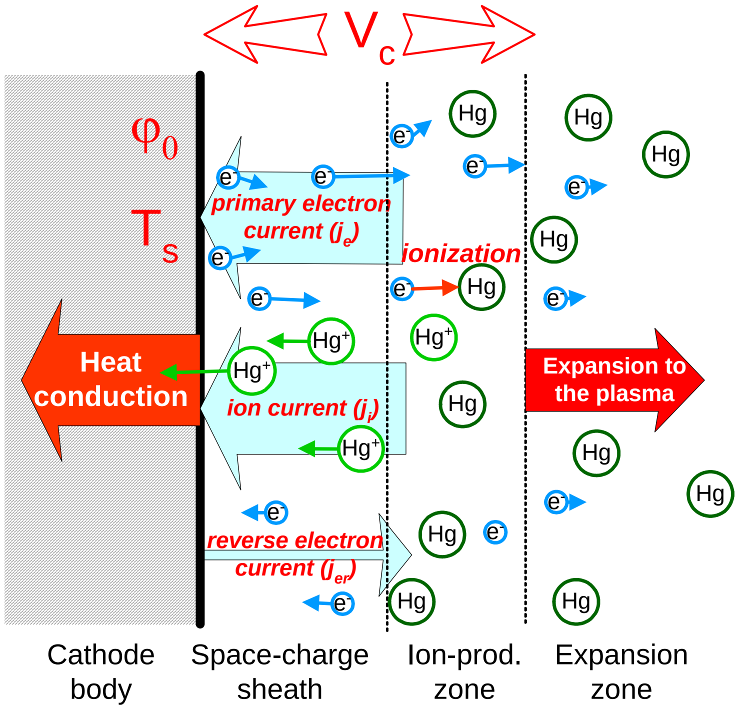
Other current carriers

- Reverse electron current: electrons from ion production zone which are fast enough to fight the cathode fall.
- Multiply ionized atoms.
- Auger electrons: electrons emitted by the impact of another particle on the electrode surface.



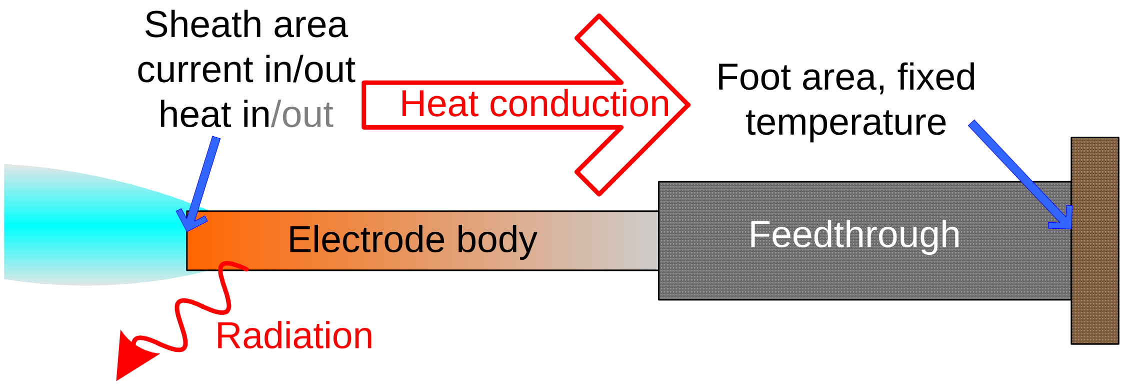
Other energy flows

- Heat transport by neutrals.
  - –Diffusion.
  - –Convection.
- Initial energy of all particles traversing the space-charge sheath.
- Vaporization of cathode material.



Electrode body

- Most important: heat conduction through electrode body.
- Surface radiates according to Plancks law.
- Heat conduction coefficient is temperature dependent
  (~ 130 W/m/K @ 1500K vs ~ 100 W/m/K @ 3000K)
- Electrode melting behaviour.
- Current through electrode causes Joule heating.



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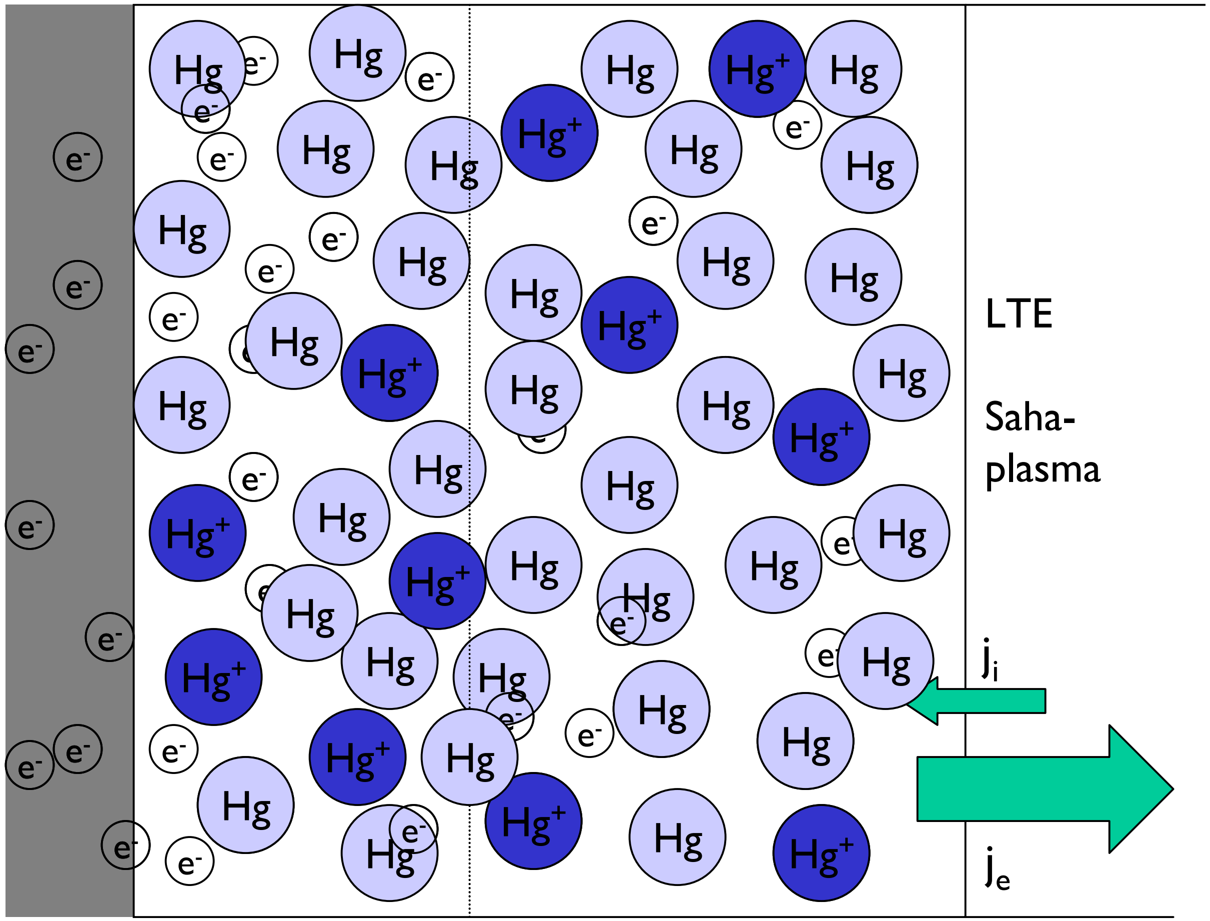
How valid is the current sheath approach?

- What if densities become so high that we can no longer talk about a collisionless sheath?
- For high densities free path lengths are smaller than Debye-length.



How valid is the current sheath approach?

- There is no collision-free zone for lamps with realistic mercury pressures.
- Therefore the McKeown equation is not valid.

$$E_s^2 \cong 4\frac{j_i}{\varepsilon_0}\sqrt{\frac{m_i V_c}{2e}}$$

- However, the models using this approach seem to give reasonably correct predictions:
  (Bade&Yos / Tielemans&Oostvogels, Eldes 1, Geijtenbeek “Cathode model”, Bötticher)

How does an HID anode operate?

- Mechanism seems simple but is just as complicated as the cathode sheath.

Simple view:

- Hot electrons fly into the cold anode and recombine.
- This causes heating of the anode by:
  - Thermal energy of the electrons $I*(5kT_e/2)$.
  - Absorption at the surface $I*\varphi$.

Question: how does arc attachment play a role in this?

Solving the equations.

Approach:

Use a simple method to make a model fit for two purposes:

- Create understanding of electrode behaviour for lamp developers.
- Get more insight in electrode physics for electrode experts.

Solving the equations.

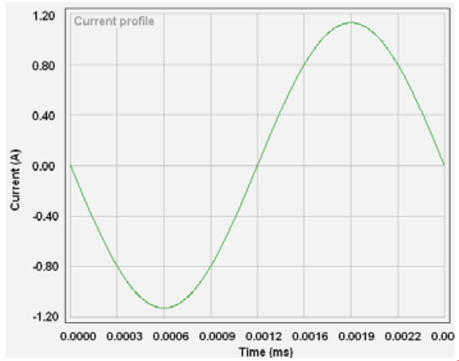
Model:

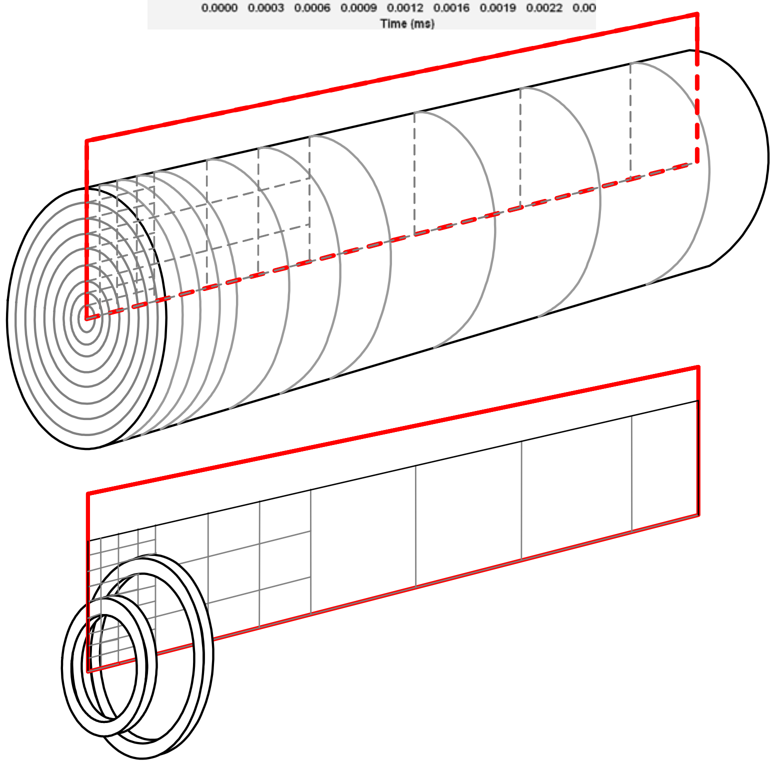
Completely in-house developed Delphi-program containing:

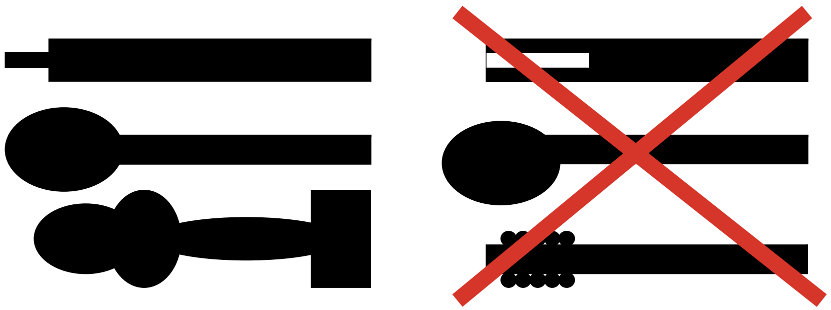
- 2D rotational symmetric heat conduction model solved explicitly (phase resolved).
- Easy to-use and flexible user-interface.
- Sheath model solved using j and q tables.
- Basic anode approach.

Heat conduction model

- 2D, rotational symmetric.
- Phase-resolved: every iteration is one current period.
- Possibility to use various sheath models.
- Possibility for spot-attachment in the centre of the cathode.







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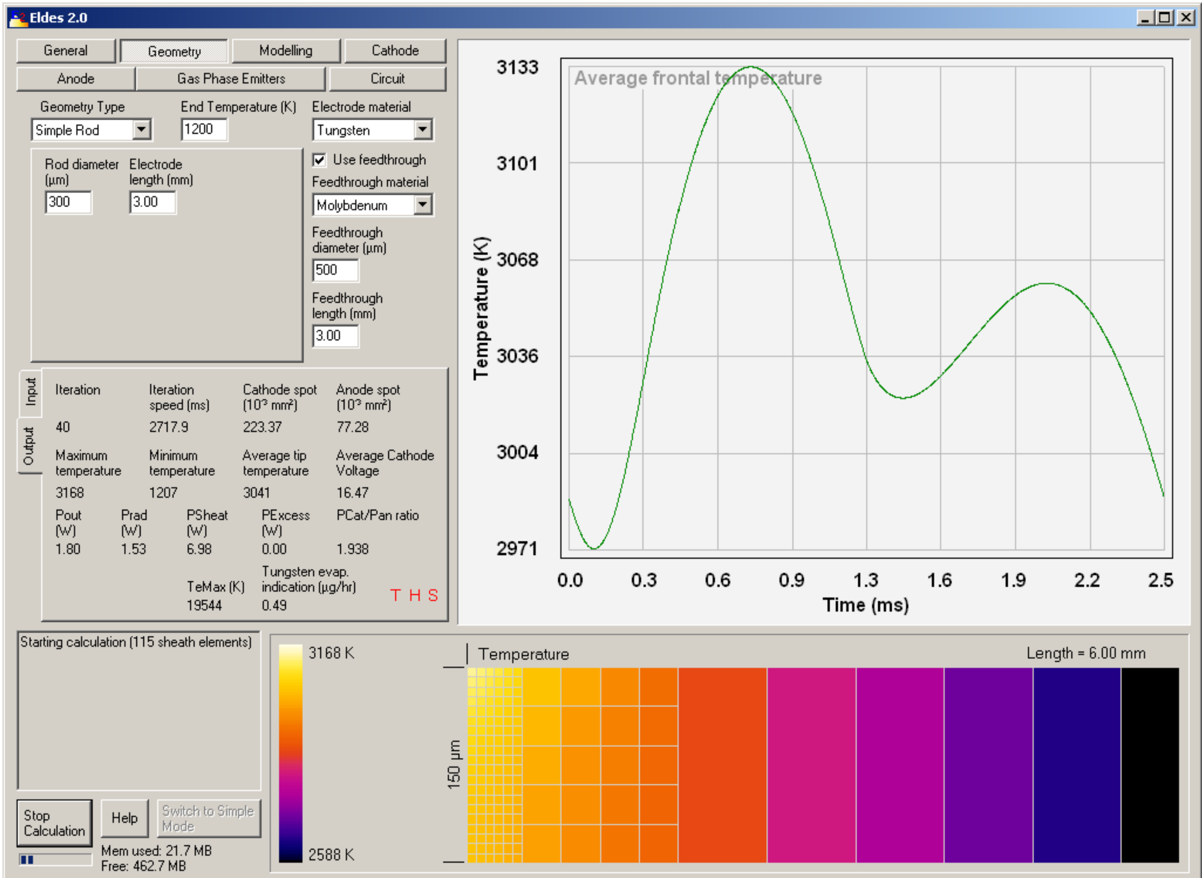
User interface

- Many options for geometry, materials and wave shapes.
- Large variety of retrievable data.
- ‘Simple mode’ for straightforward use.



Cathode sheath calculation

$j(T_e,V_c)$ and $q(T_e,V_c)$ tables are generated at the start of a calculation.

Equations are solved by finding the V_c for which

$$I(t) = \iint j(T_e, V_c)\, dA$$

gives the correct (time-dependent) current for that particular temperature distribution.
($j(T_e,V_c)$ is a monotonous rising function of V_c)

$q(T_e,V_c)$ now gives the heat flux for the next step.

Cathode sheath calculation

With result for V_c, j and q and the temperature distribution other properties like T_{ipz}, j_i and j_e are calculated.

Problems encountered:

- For spot attachment, calculation area should be limited to avoid ‘ring-attachment’.
- When reverse electron current is taken into account $j(T_e,V_c)$ is no longer a monotonous rising function of V_c.

Monolayer emitters

Two options:

1. Use a different work function of the surface (e.g. 3eV instead of 4.55eV)
2. Use an adsorption-desorption model.
   - Monolayer emitter coverage is calculated as function of surface temperature.
   - Work function is calculated linearly between pure tungsten and emitter workfunction.

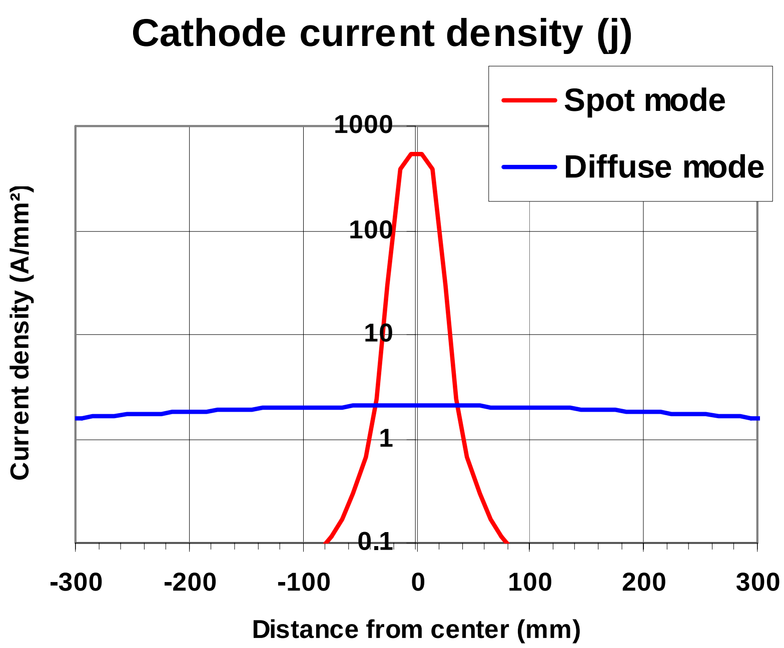
Anode calculation

- Current is distributed evenly over given area.
- Heat input is simply given by $q=j*(V_a + \varphi)$, with both V_a and φ as input parameters.

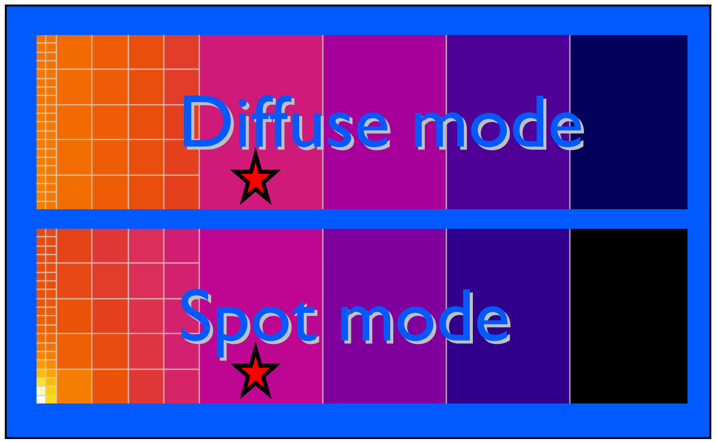
- This clearly needs improvements.

Model results: spot-diffuse.

- For certain (heavy) electrodes, the solution is dependent on starting conditions:
  - –High initial temperatures result in diffuse attachment.
  - –Low initial temperatures result in spot attachment.



Mode:	Spot	Diffuse
Spot diameter	42 μm	350 μm*
Cathode fall	41 V	40 V
Sheath power	10.0 W	14.0 W
Maximum temperature	3783 K	2905 K
Temperature ☆	2357 K	2726 K

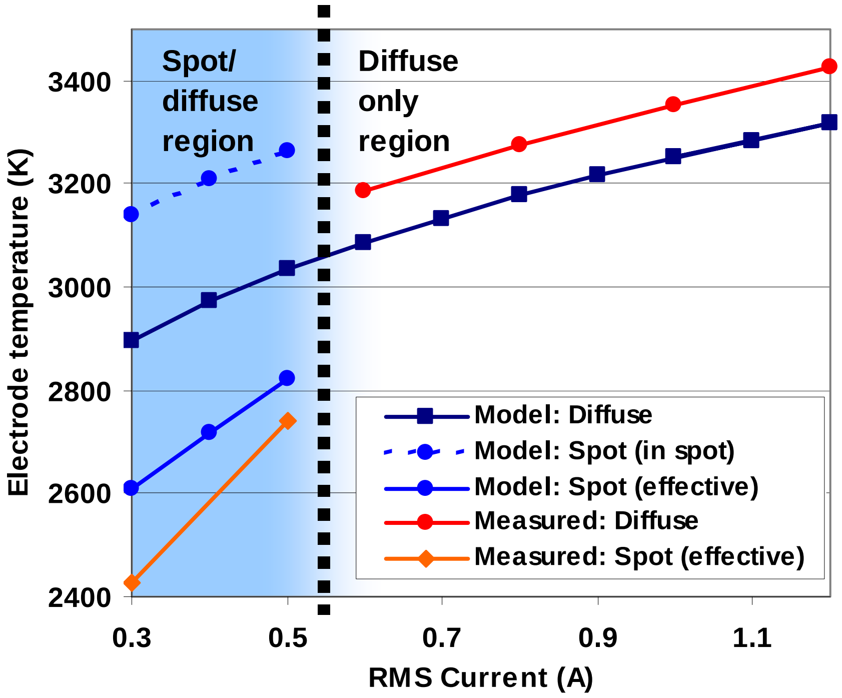


* enforced spot size

Model results: spot-diffuse.

Results very similar to measured results.

For low currents in model two solutions, in measurements only one (spot).



5 mm x 500 µm W rod electrode inside a Hg-lamp operated on 120Hz AC square wave current

Introduction: Gaseous emitter

Idea:

- In hot arc core metal halides decompose into atoms and ions:

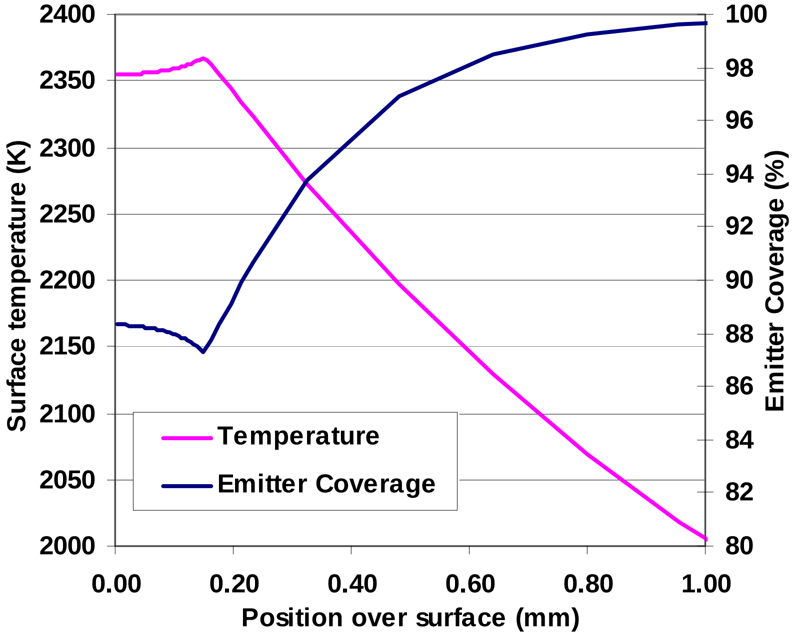
  $DyI_3 \Rightarrow Dy + 3\ I$

  $Dy \Leftrightarrow Dy^+ + e^-$

- Atoms adsorb on electrode surface, stay there for some time.
- This coverage with "emitter" atoms lowers the work function.

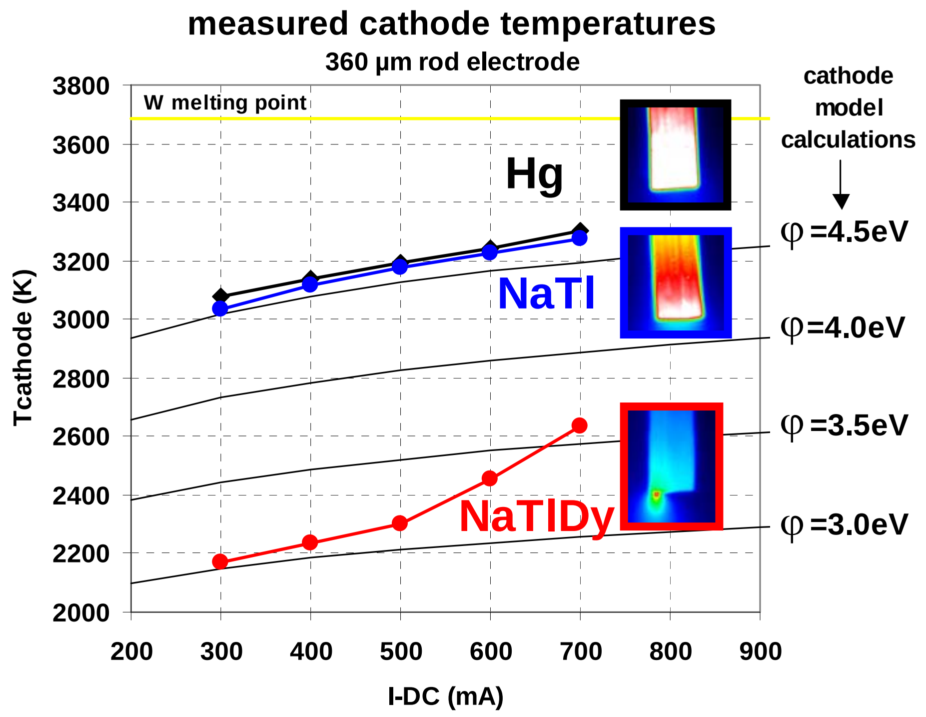
However

With adsorption-desorption model lowest coverage on hottest locations (=in spot):



Problem

- Lamps containing gas-phase emitters (Dy, Sc, Th…) almost always show spot-attachment.
- Model calculations always show diffuse attachment for these lamps with realistic currents.



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Conclusions

We developped a useful program for understanding electrode behavior and predicting electrode effects.

Benefits:

- Gives visual 2D phase resolved info.
- Calculated electrode temperatures usually match measured values reasonably close.
- Electrode behavior as function of current wave shape can be predicted quite accurately.
- Allows to extract effective workfunctions and anode heating voltages from T-profile measurements.
- User-interface is easy to use and program is very flexible.

Conclusions

Shortcomings:

- Electrodes with monolayer emitters almost always show spot attachment, while our model predicts diffuse attachment.
- Cathode sheath physics needs improvements to be more theoretically correct.
- No good physical model for the anode.
- Not possible to easily calculate perfect electrode for a specific lamp design (lamp-developers dream).