Presented at the COMSOL Conference 2008 Hannover

PHILIPS

sense and simplicity

The Multiphysics Approach: The Electrochemical Machining Process

R. van Tijum, T. Pajak
Advanced Technology Center

November, 2008

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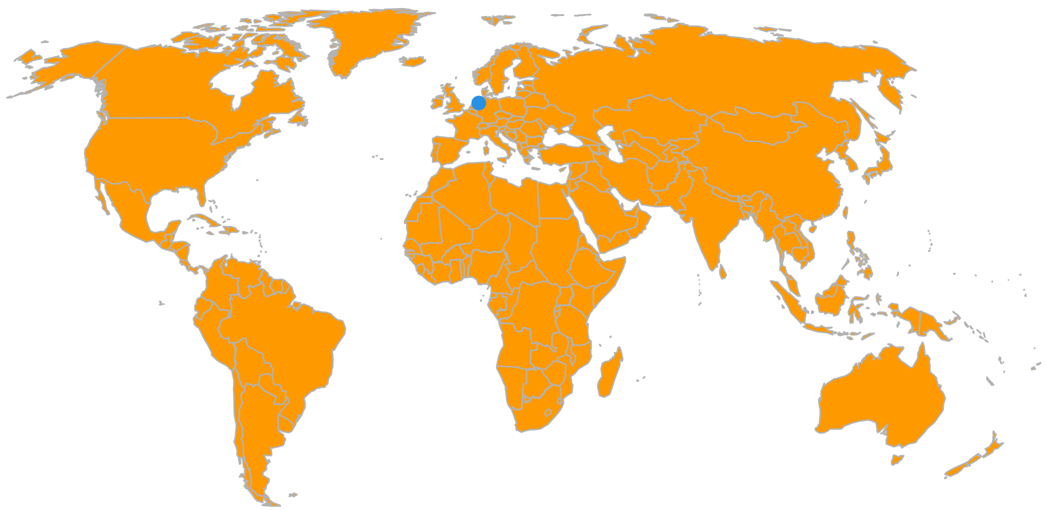
Outline

- Introduction
- ECM Process description
- Validation
- Application
- Conclusion

Royal Philips Electronics

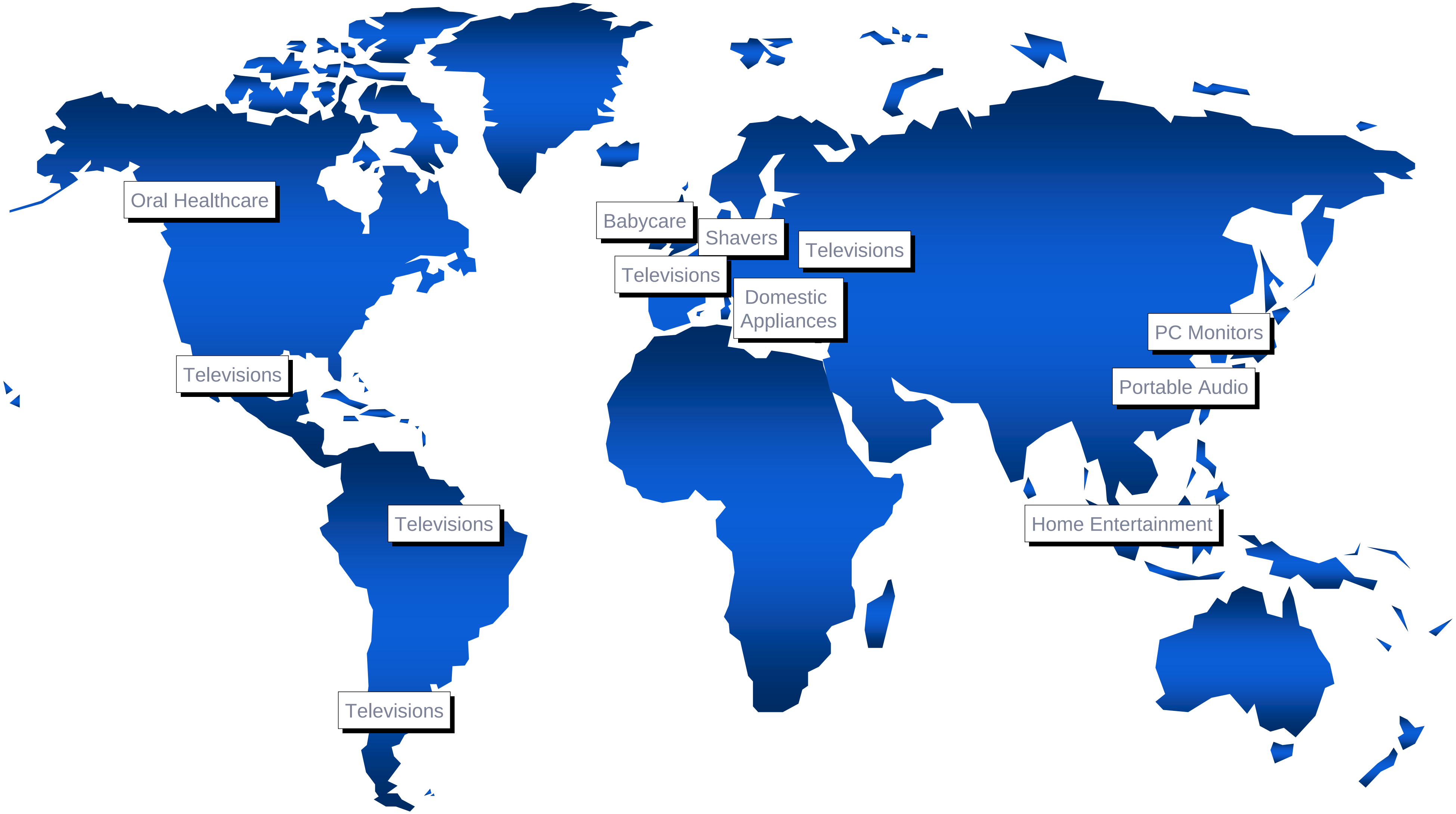
- Founded in 1891
- Headquarters: Amsterdam, The Netherlands
- One of the largest global diversified industrial company with sales in 2007 of EUR 26,793 million
- A multinational workforce of 133,000 employees (April 2008)
- An R&D force with expenditures of EUR 1,629 million (2007)

Globally present with manufacturing sites in 28 countries and sales outlets in 150 countries



A global presence

Design, development and assembly centers throughout the world



2007 results: Consumer Lifestyle*

- Focused on innovative lifestyle solutions for personal wellbeing
- Many leading market positions
- Contributing to the Philips brand
- Strong marketing and sales capabilities
- Consumer-driven insights and dedicated business models driving innovation and differentiation
- Entering strategic new value spaces
- Driving sustainable, profitable growth

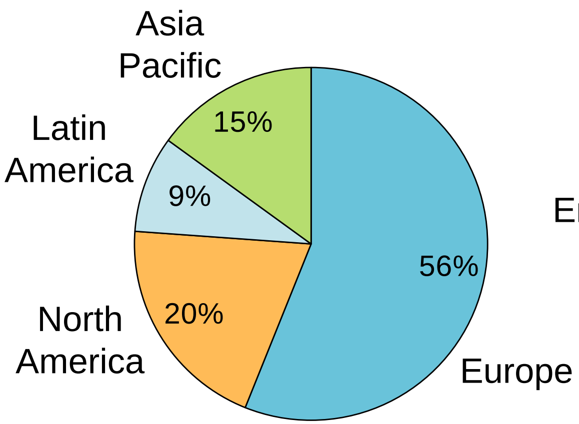
Active Crystals

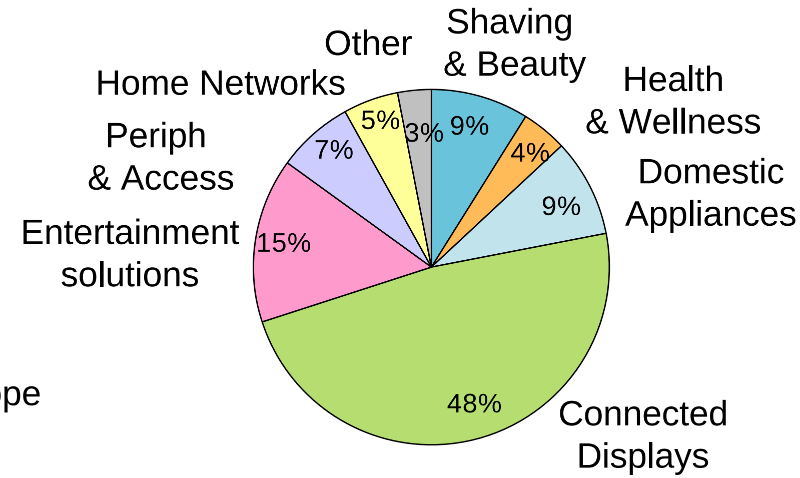
Portable Media devices

Arcitec

Flexcare

Sales FY2007





*Results given are based on 2007 results reported by the Consumer Electronics and DAP divisions prior to their merger into the Consumer Lifestyle sector on January 1, 2008

Making a difference

The Consumer Lifestyle businesses

Television

Shaving & Beauty

Domestic Appliances

Audio Video & Multimedia

Peripherals & Accessories

Health & Wellness

ATC, Advanced Technology Center

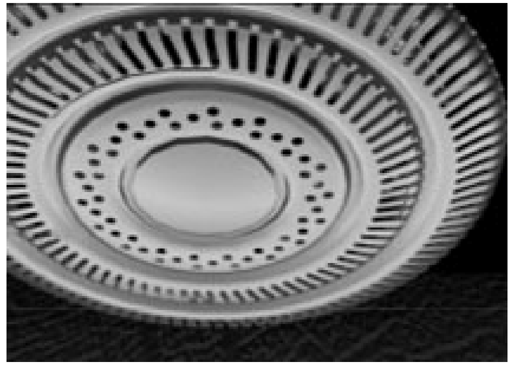
- ATC is CL’ technology center serving all Lines of Business
- 110 employees (90% PhD, MSc and BSc)
- Our key success factor is our in-depth understanding of CL applications focussing on domestic appliances

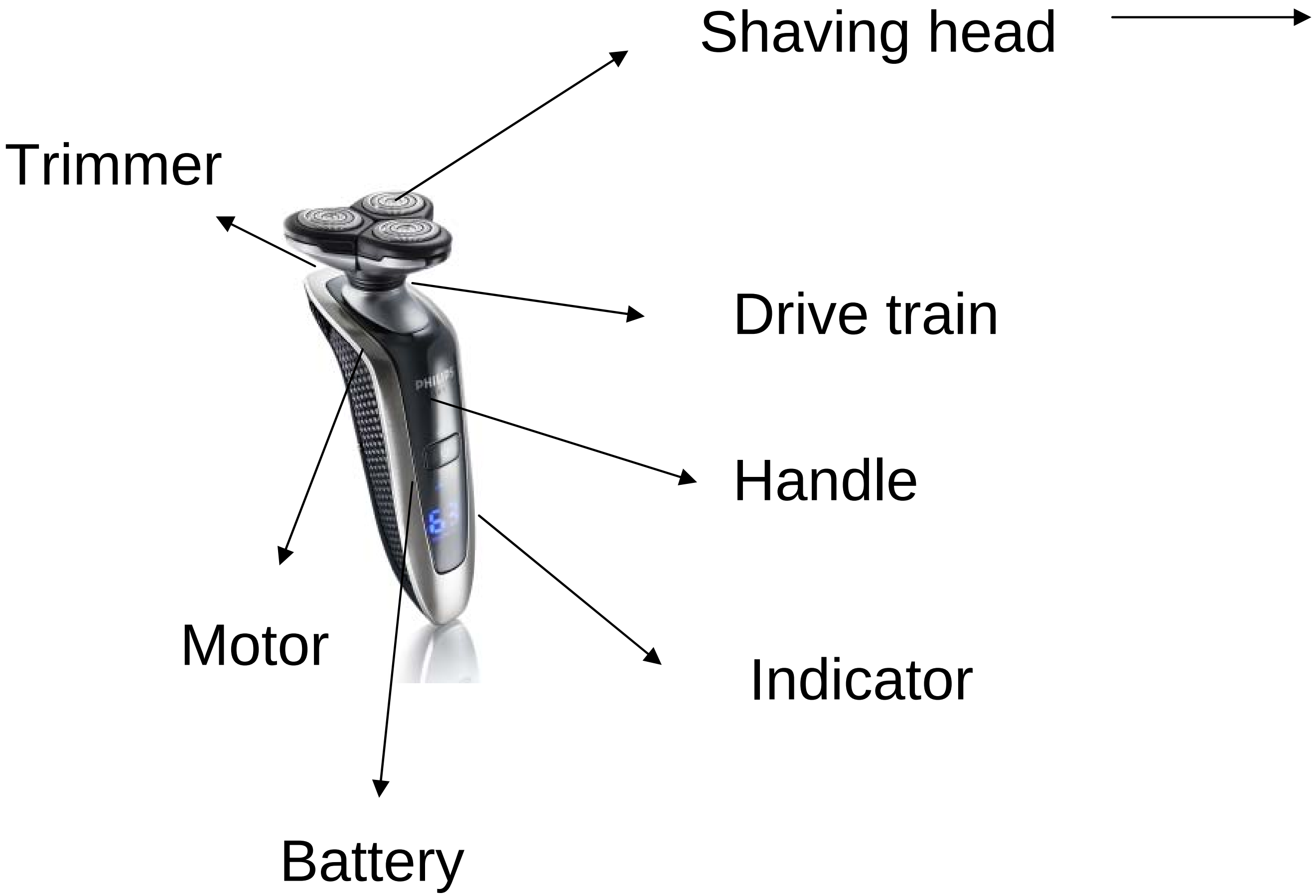
Shaving & Beauty

Domestic Appliances

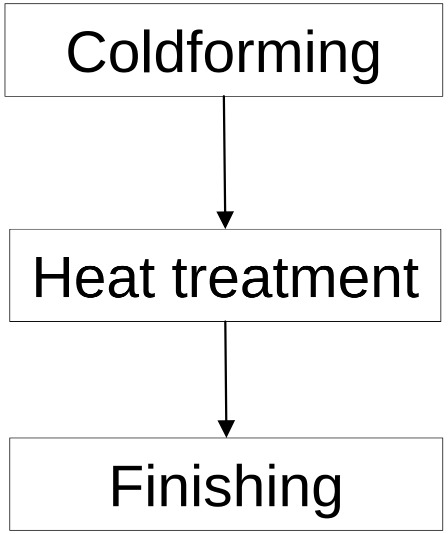
Health & Wellness

Cap

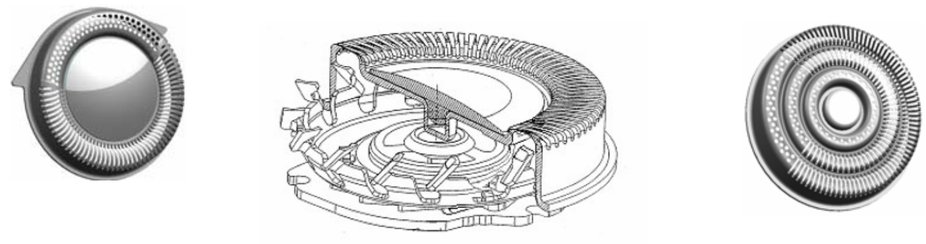



Shaving head
Trimmer
Drive train
Handle
Motor
Indicator
Battery

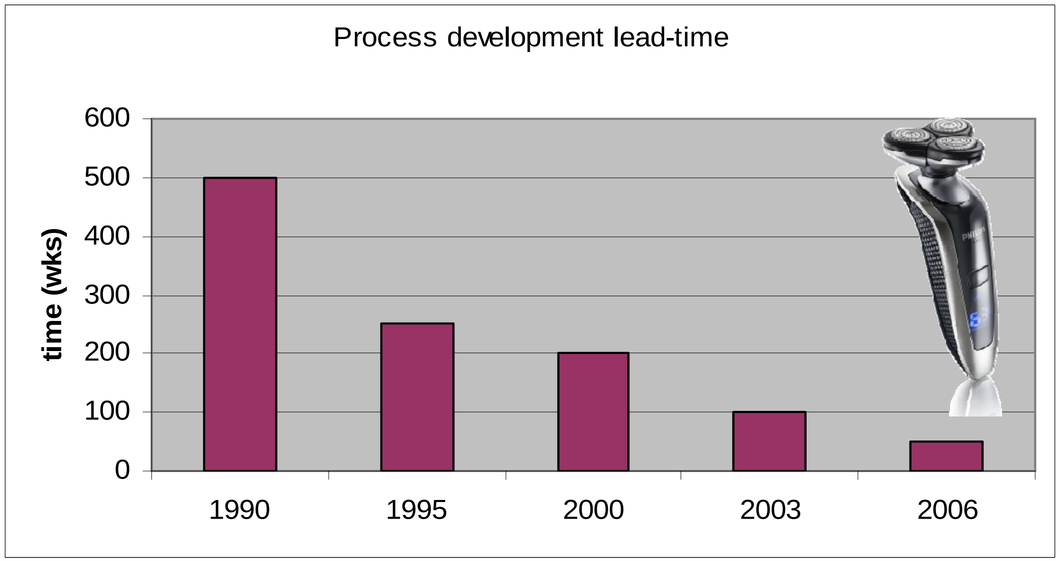
Shaving cap production process



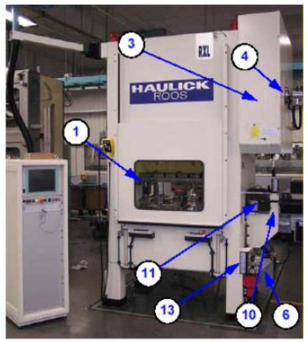
More complex shape

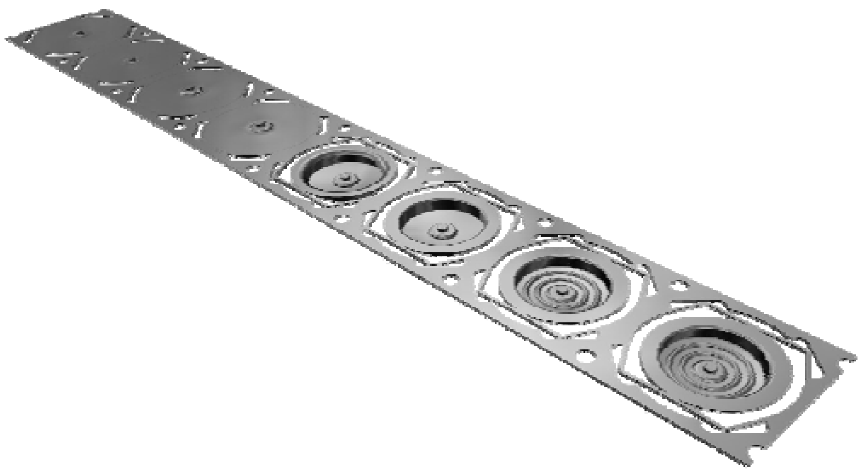


Shorter time to market

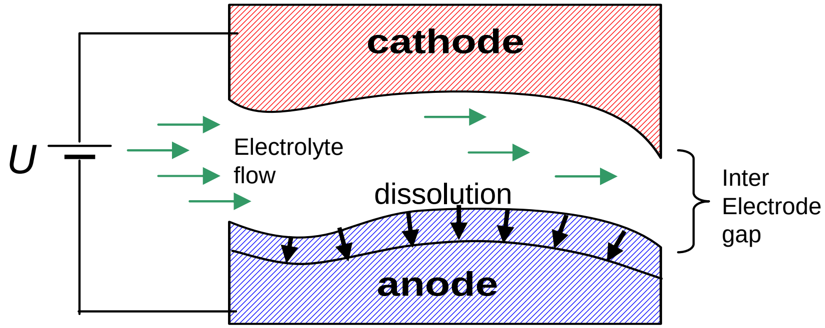


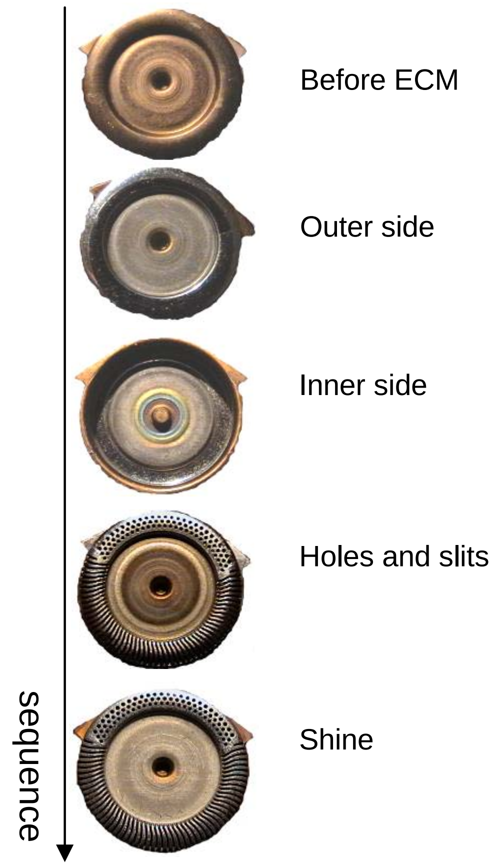
Cold forming





Finishing (ECM)





Business objectives

We are constantly seeking opportunities to:

- Enhance shaving performance
- Increase profitability
- Improve process robustness & predictability

Product accuracy

Investments and process cost

Cost of Non Quality

Approach

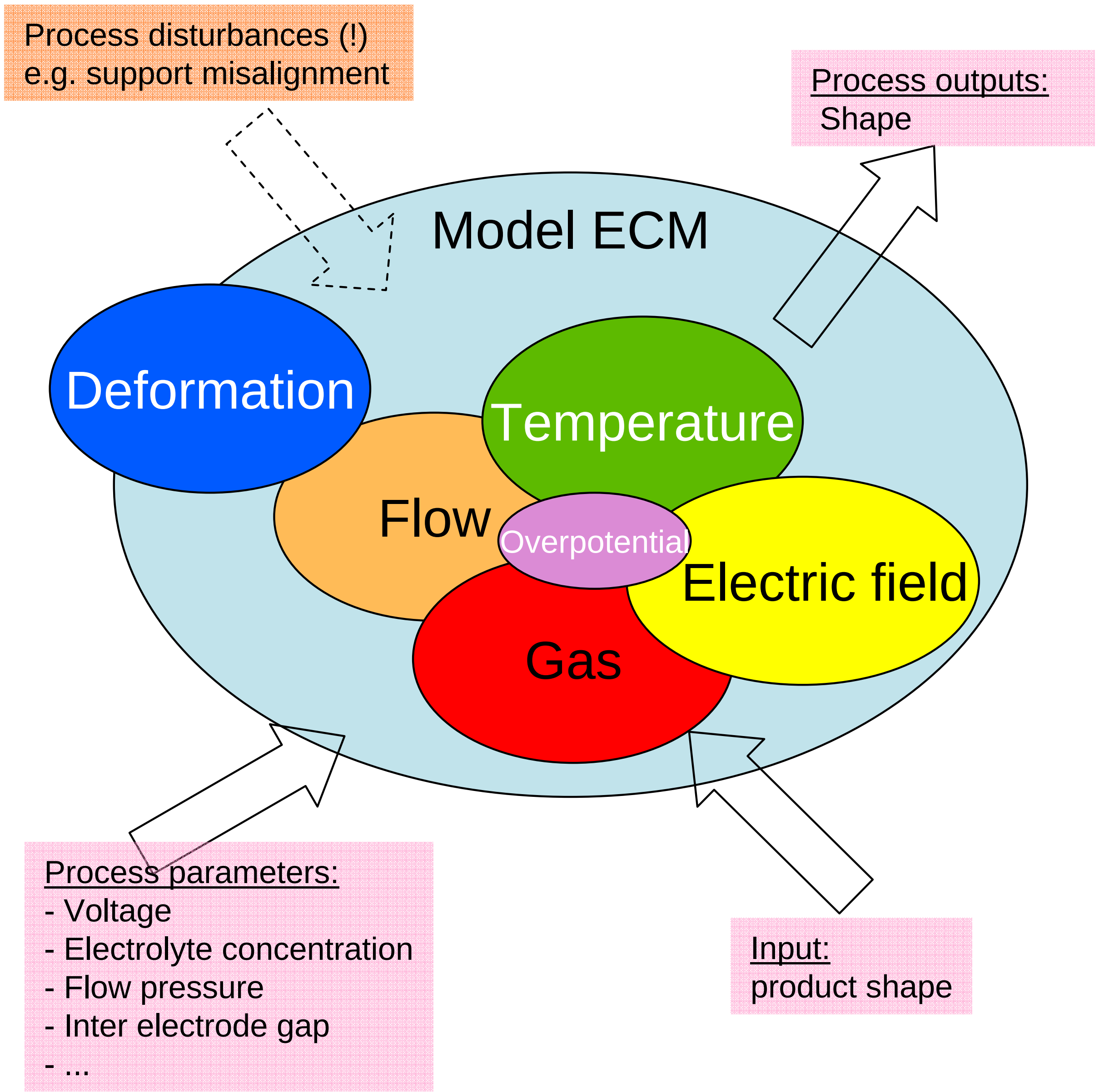
- To simulate the ECM process

    - *ECM is not a black box process !*
    - *Process simulation to be used upfront experiment to get process settings much closer to these optimal for given result.*
    - *Simulation results depends on the model used; it can greatly support and minimize experimental effort but cannot eliminate real-time experiments.*

5 Desired states

- Process development time is decreased
- Development cost is minimized
- Experiments run mainly virtually (are simulated)
- Real experiment goes ‘first time right’ after simulation
- Simulated process is robust and accuracy fulfills specification requirements

Inventory of process governing principles

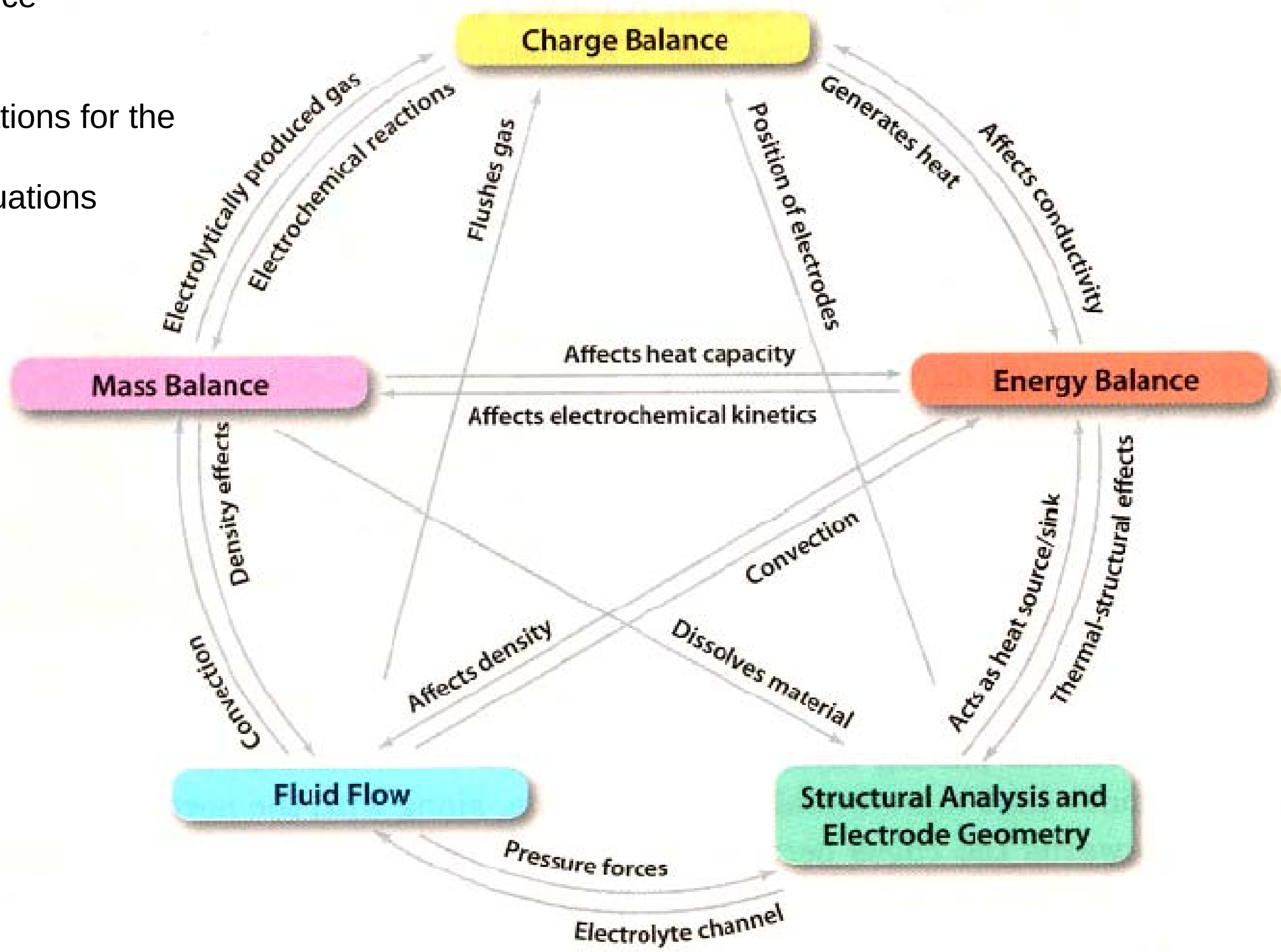


- **Faraday's law** driven dissolution
- **Navier-Stokes** description of electrolyte flow conditions (also for compressible non-Newtonian liquid) in laminar & turbulent domain
- **Ohm's Law** and distribution of electric field
- **Joule-Lentz** heat generated during dissolution increasing electrolyte conductivity
- Oxygen & hydrogen **gas evolution** altering flow conditions and decreasing conductivity
- **Overpotential** of cathode & anode
- **Current efficiency** dependency
- Possible elastic **deformation** of the typically fragile (thin wall) product due to electrolyte pressure

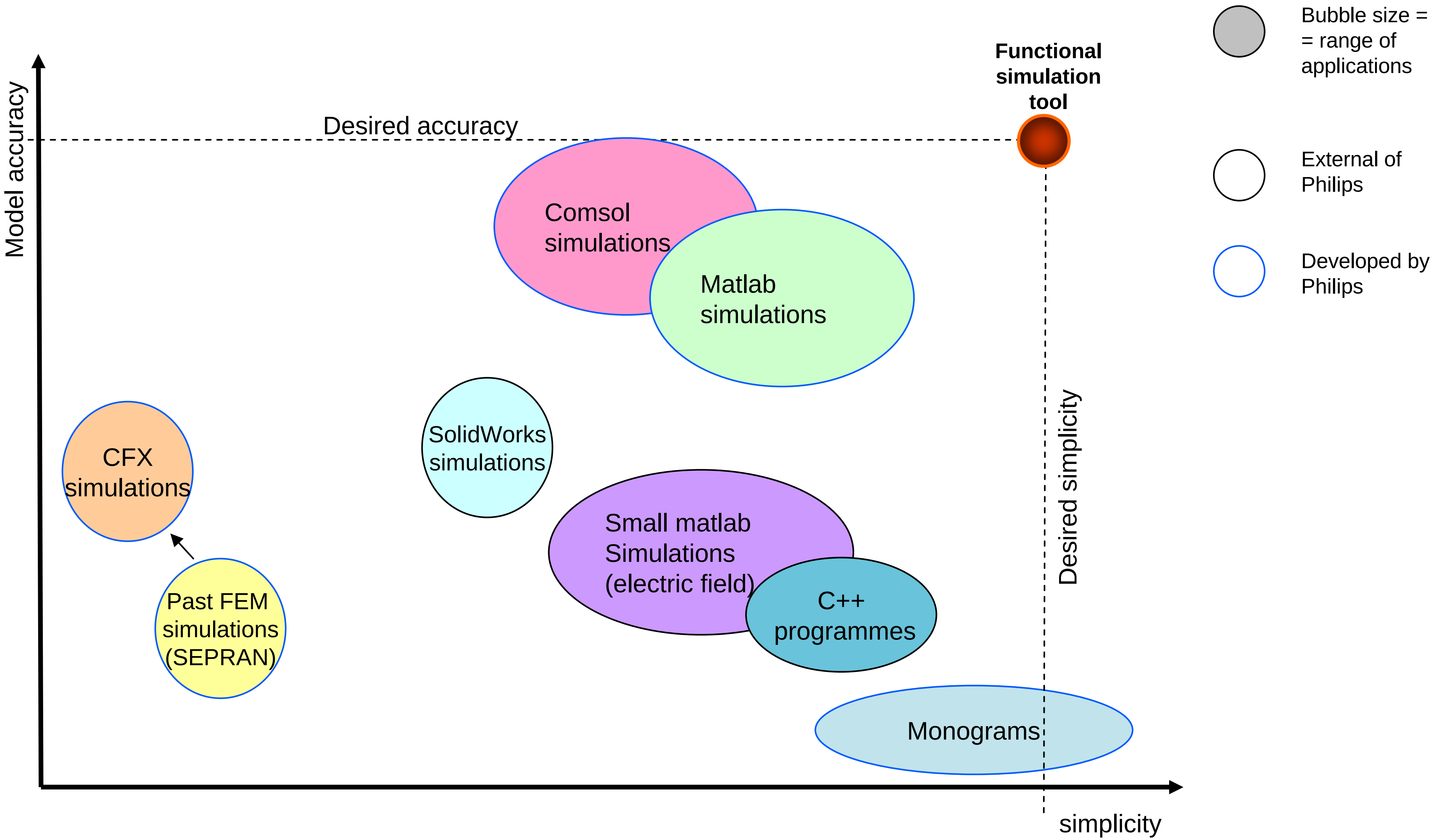
Multiphysics high level problem description

ECM model "by balance"

- Mass balance equations for the process gap
- Energy balance equations



ECM modelling map – internal / external Philips



Material dissolution

- Reactions (selection):

$$Me \leftrightarrow Me^{n+} + n \cdot e^{-}$$

$$2 \cdot e^{-} + 2 \cdot H_2O \leftrightarrow H_2 + 2(OH^{-})$$

$$2H_2O \rightarrow O_2 + 4H^{+} + 4e$$

- Material dissolution:

$$v_n = K \cdot \eta(J) \cdot J \text{ [m/s]}$$

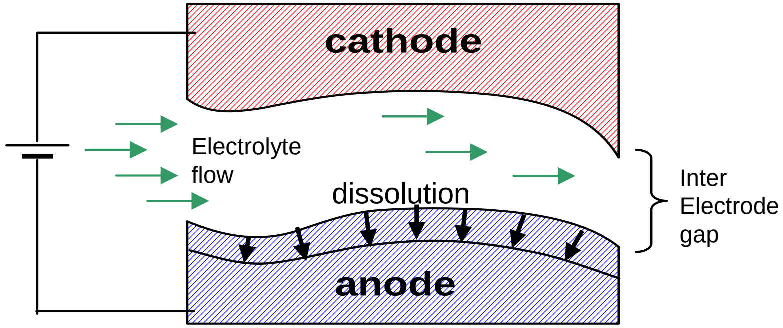
- Efficiency $\eta(J)$:

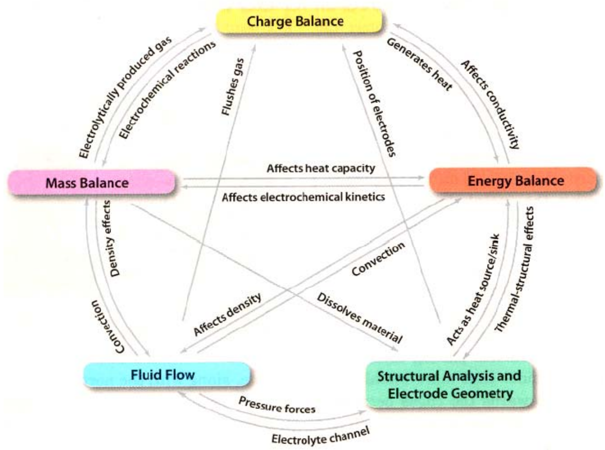
$$\Delta m_{\text{theory}} = \frac{M \cdot I}{z \cdot F} \cdot \Delta t$$

$$\eta(J) = \frac{\Delta m_{\text{experimental}}}{\Delta m_{\text{theory}}} = c_1 + \frac{2}{\pi}(c_2 - c_1) \cdot \text{atan}(c_3(J - c_4)) \text{ [\%]}$$

where:

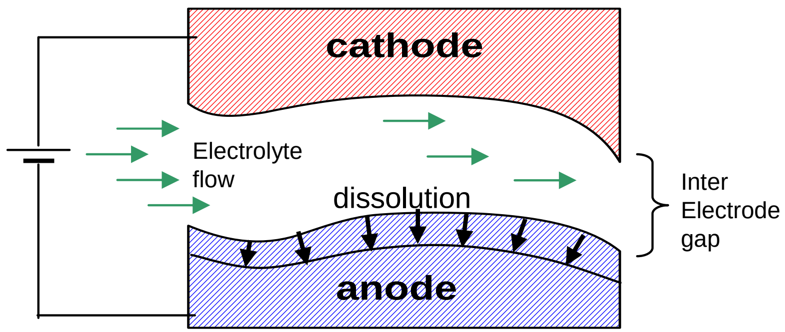
J	current density
K	electrochemical constant
c_1, c_2, c_3, c_4	process constants

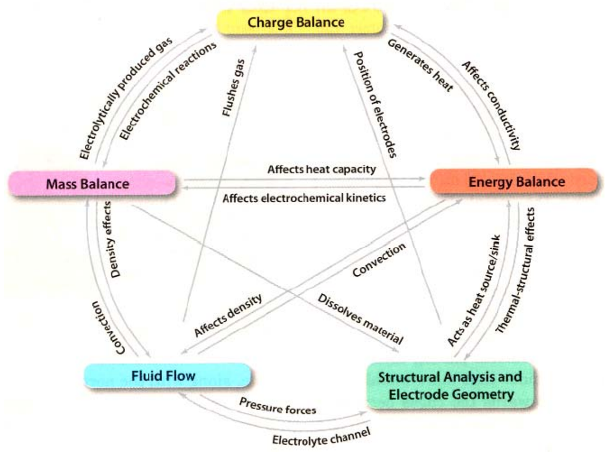




Conductivity

- Temperature (T)
  - Joule's heating
  - Conduction
  - Convection
- Gas concentration (C)
  - Flux at the surface
  - Diffusion
  - Convection





Conductivity:

$$\frac{1}{\sigma} = \rho_0 (1 + volfrac)^{bp} \cdot (1 + \alpha (T - T_0)) \, [\mathrm{m/S}]$$

Where the gas volume fraction is:

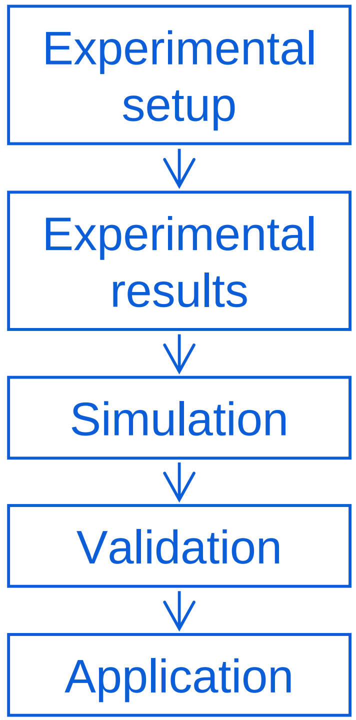
$$volfrac = \frac{C}{C + M_{el}} \, [\text{-}]$$

Multiphysics model validation case

- Variables:
  - Inlet temperature (10, 25 and 40 ^{o}C)
  - Solution concentration (50, 130 and 230 g/l)

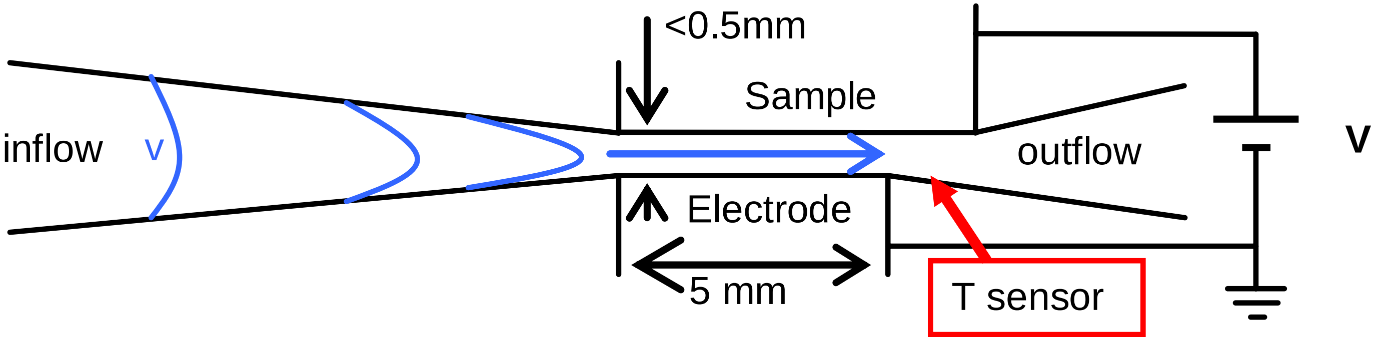
- Outcome:
  - Material removal efficiency to determine:

$$\eta(J) = c_1 + \frac{2}{\pi}(c_2 - c_1)\cdot \text{atan}(c_3(J - c_4))\,[\%]$$

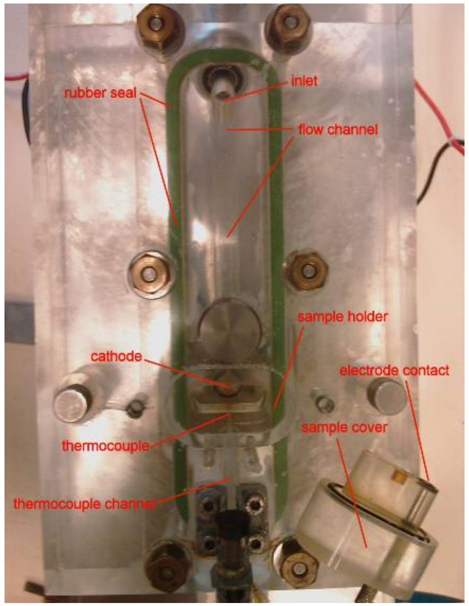


Experimental setup

Schematic of the lab scale process:



Experimental setup (top view):



Experimental results

Material dissolution speed:

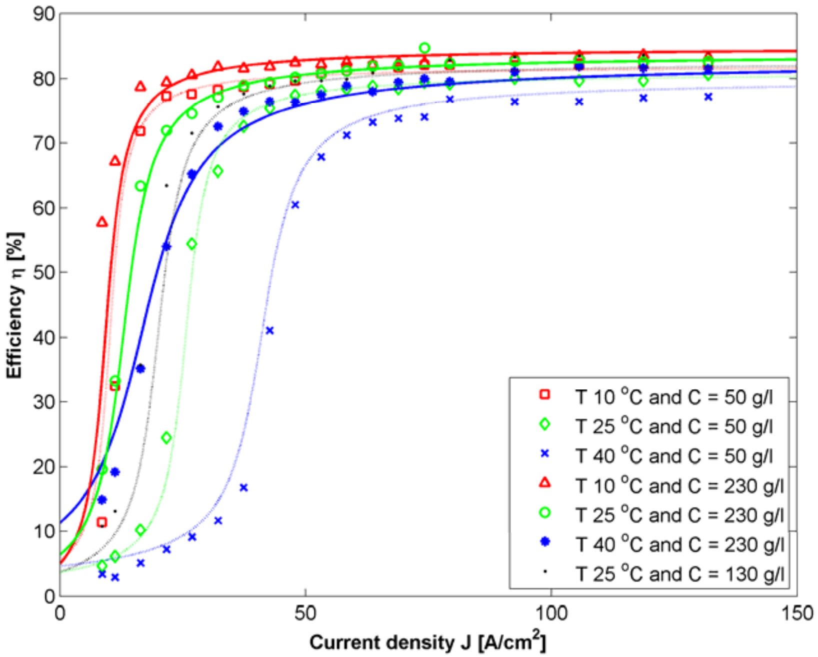
$$v_n = K \cdot \eta(J) \cdot J \text{ [m/s]}$$

Efficiency:

$$\eta(J) = \frac{\Delta m_{\text{experimental}}}{\Delta m_{\text{theory}}} = c_1 + \frac{2}{\pi}(c_2 - c_1) \cdot \text{atan}(c_3(J - c_4)) \text{ [\%]}$$

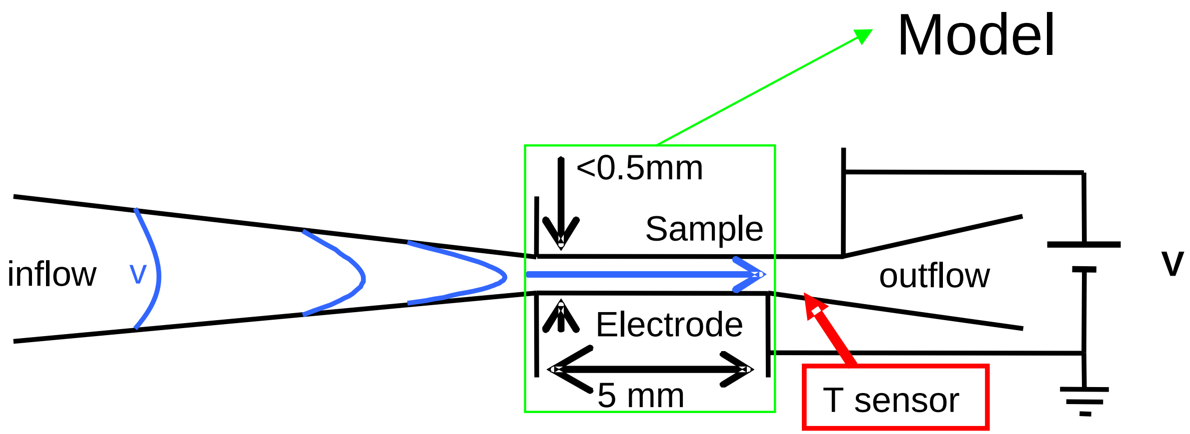
Best fit:

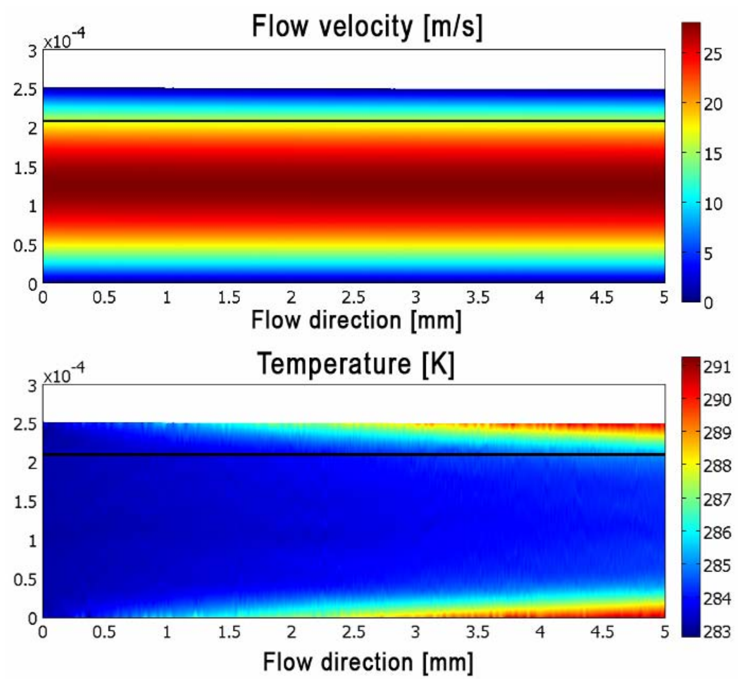
$$c_1 = 40.7$$
$$c_2 = 75.4 - 0.0676 \cdot T + 1.86 \cdot \ln(C)$$
$$c_3 = 0.684 - 0.00772 \cdot T - 0.0475 \cdot \ln(C)$$
$$c_4 = -2.05 + 1.25 \cdot T + 0.0387 \cdot C - 0.00437 \cdot C \cdot T$$



Experimental setup
↓
Experimental results
↓
Simulation
↓
Validation
↓
Application

COMSOL multiphysics model





Experimental setup
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Experimental results
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Simulation
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Validation
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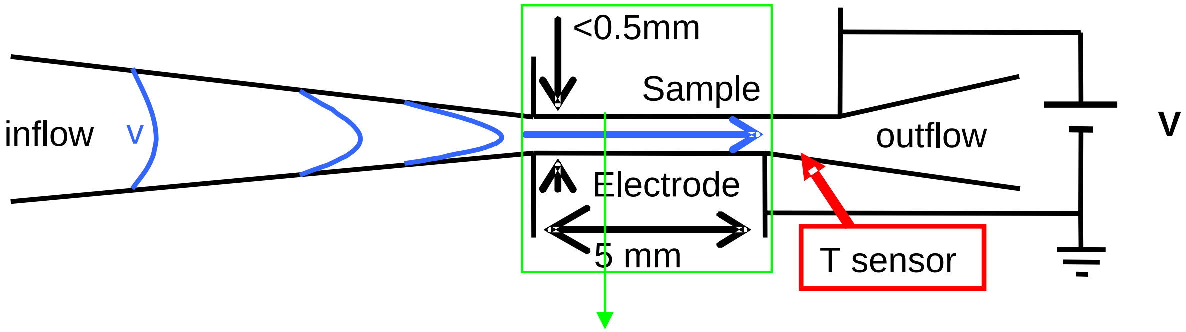
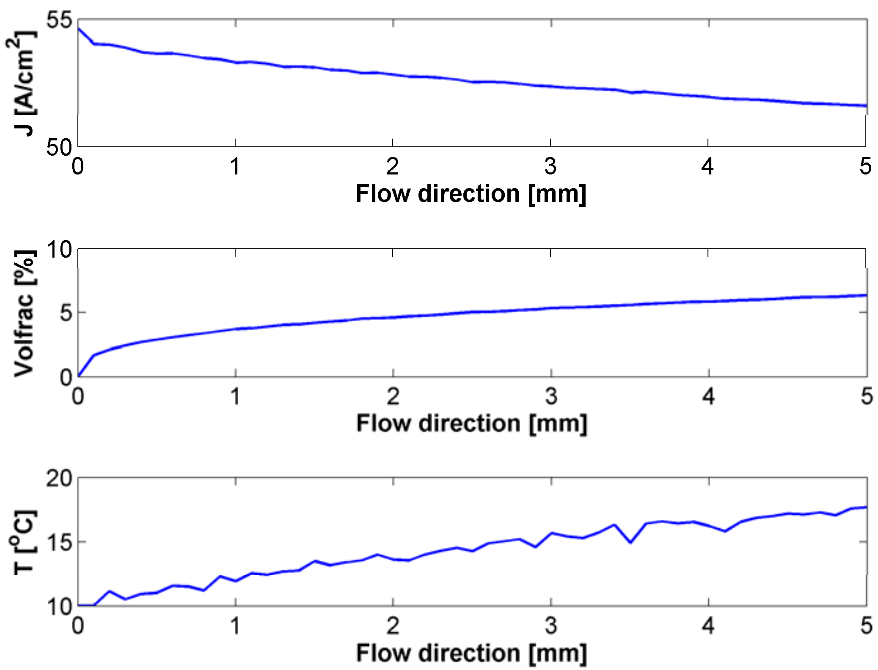
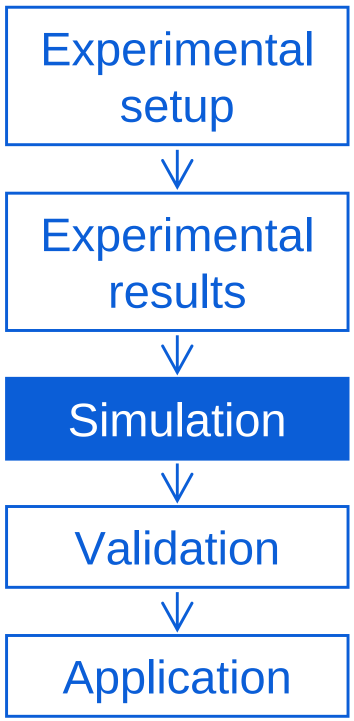
Application

Comsol multiphysics model: process variables

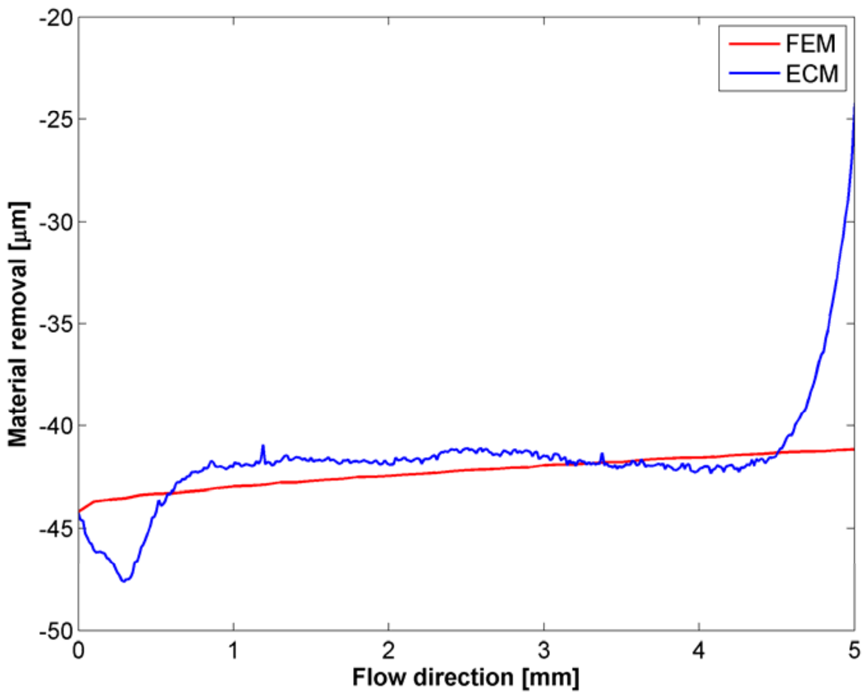






Validation of material removal

- Comparison of profile measurements and simulations



Experimental setup
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Experimental results
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Simulation
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Validation
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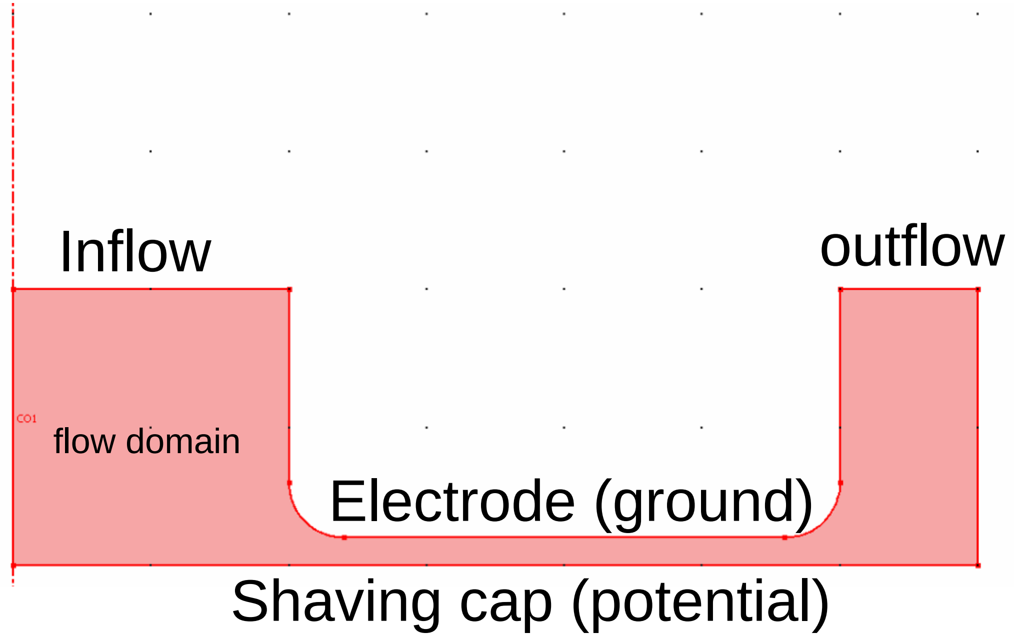
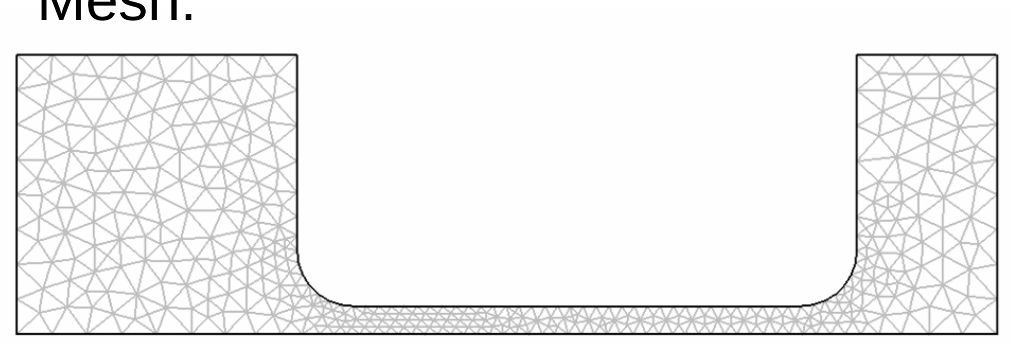
Application

Example: creating a cavity in a shaving cap



Mesh:



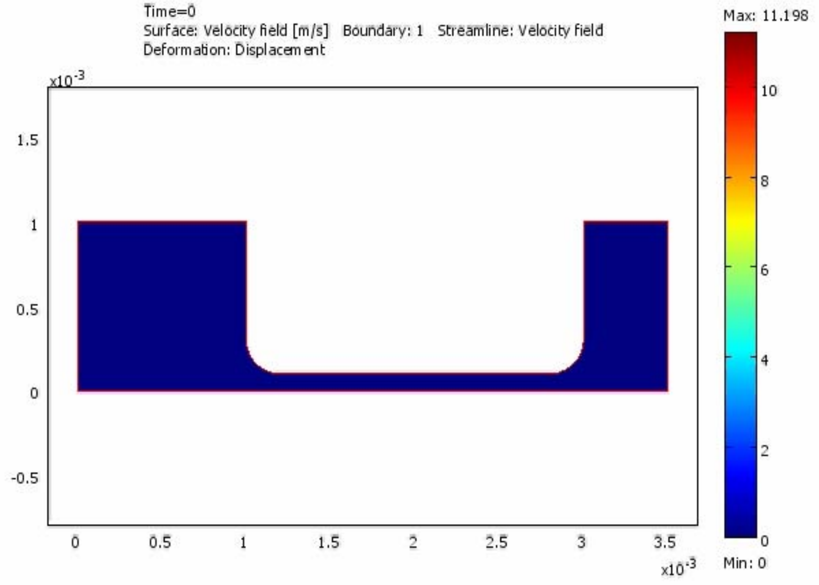
Simulation:

- Coupled physics (axial symmetric):
  - Navier-stokes (u,v)
  - Potential (V)
  - Convection/diffusion (C)
  - Convection/conduction (T)
  - Moving mesh (r,z)

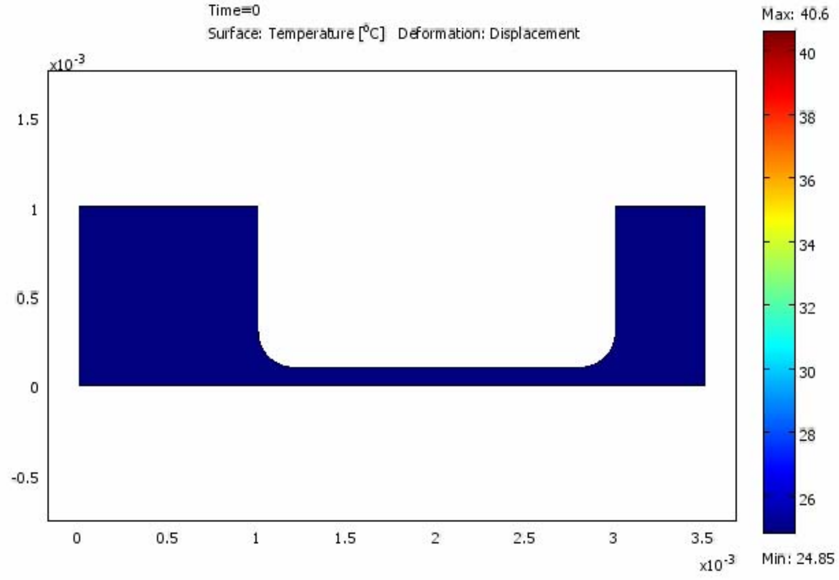
-Time: 0 to 10 seconds

- Feed rate: 25 um/s

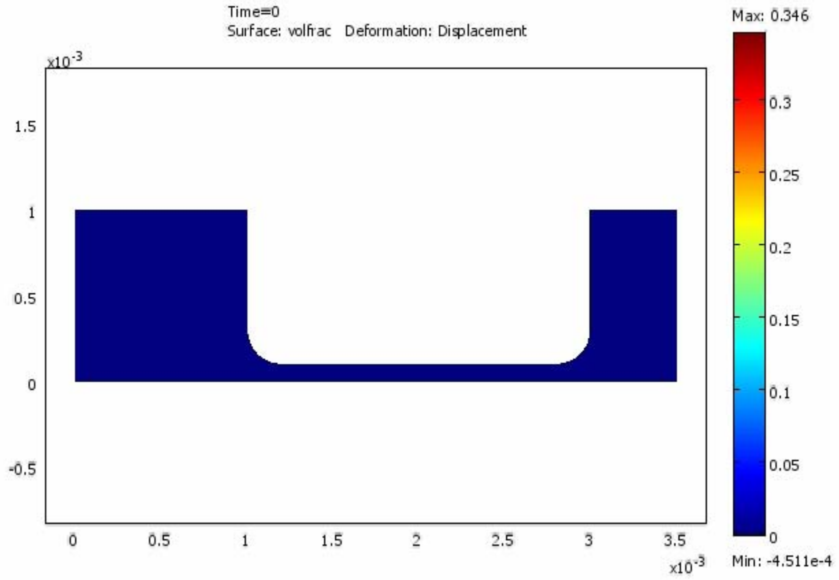
Flow velocity [m/s]



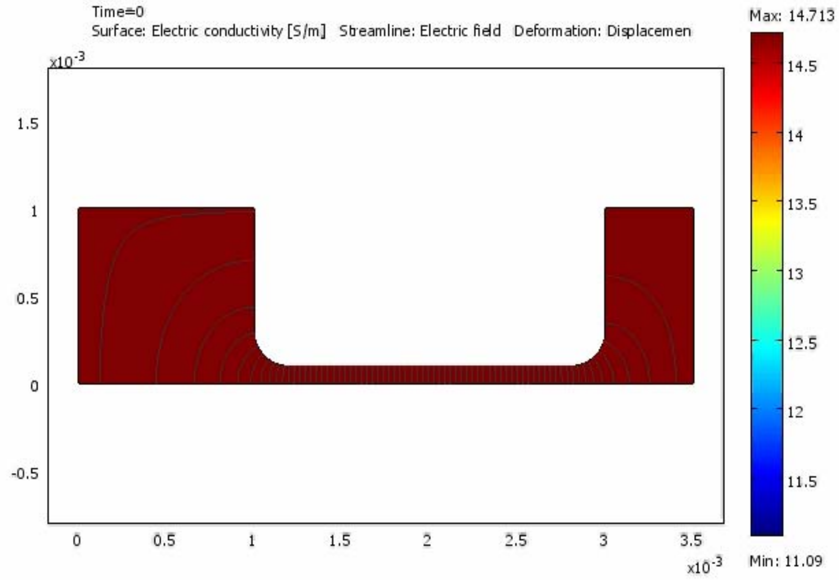
Temperature [K]



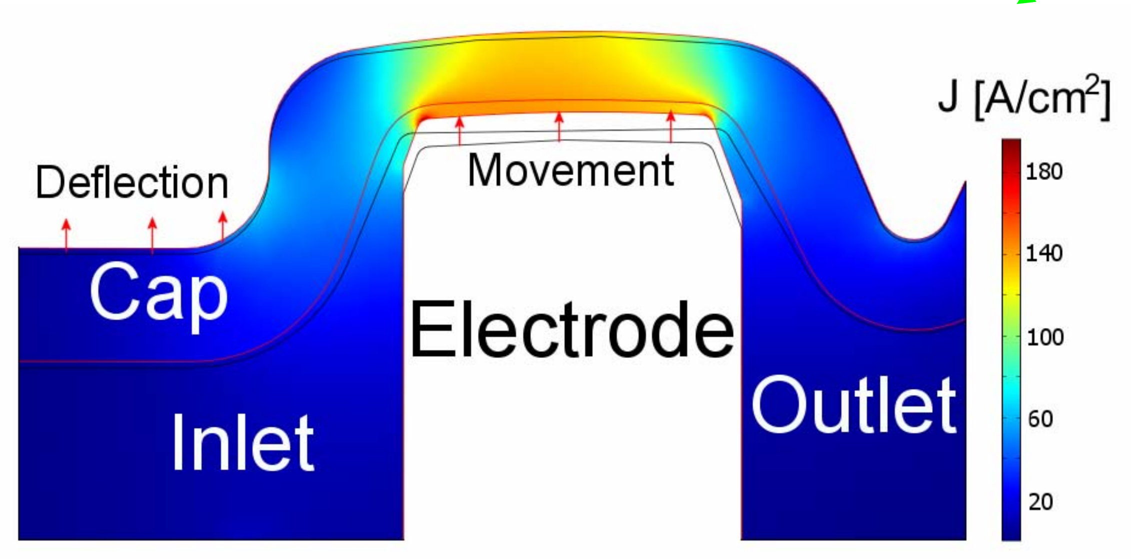
Reaction gas fraction [-]

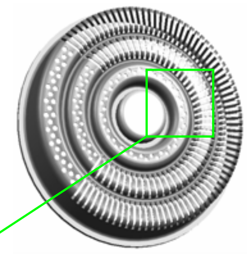


Conductivity [m/s]



Simulation of material dissolution in practice





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Conclusions

Progress so far:

- Development cost is minimized ☺
- Process development time is decreased ☺
- Experiments run mainly virtually (are simulated) ☺
- Real experiment goes 'first time right' after simulation ☺
- Simulated process is robust and accuracy fulfills specification requirements ☺

Acknowledgement

We would like to thank:

- Dr. W. Hoogsteen for his contribution in the experimental research and consultancy
- P.J. Huizenga MSc for his research work on this subject during his traineeship

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