COMSOL CONFERENCE 2014 CAMBRIDGE

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Electrical Scale-up of Metallurgical Process

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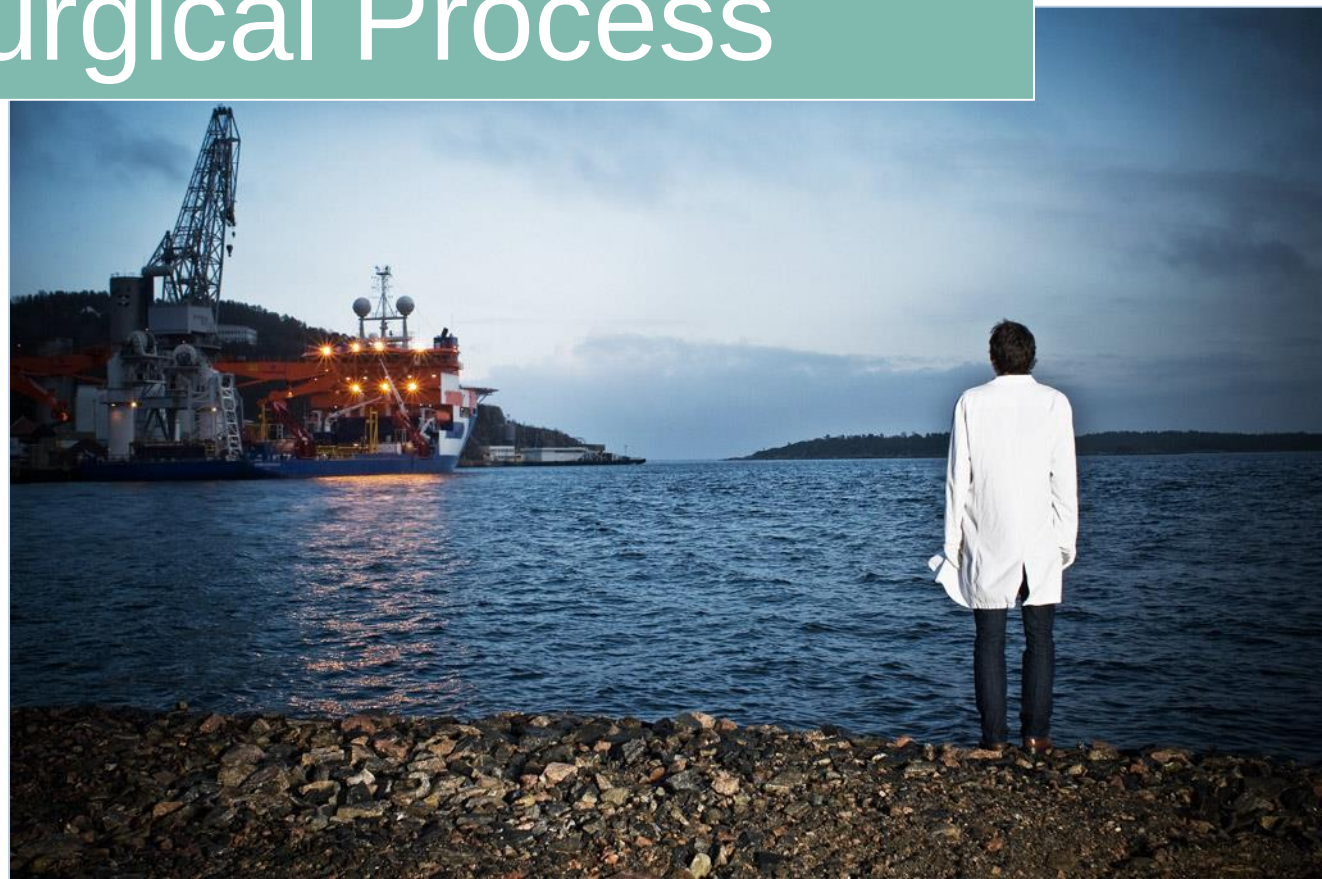
COMSOL Conference
18th of September 2014
Cambridge, UK



Outline

- Problem formulation
- Theory
- Model setup
- Simulation results
- Conclusions

Problem formulation

- Case: Study scale-up of generic metallurgical process for primary metal production
  - How is current distribution affected by changing the size of the geometry?
  - Change electrode system from 1 phase to 3 phase.

Theory

- Current distribution governed by Maxwell's equations.

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon}$$

$$\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$$

$$\vec{\nabla} \times \vec{B} - \frac{1}{c^2} \frac{\partial \vec{E}}{\partial t} = \mu \vec{J}$$

Theory

- Assumptions:
  - Harmonic electric field
  - Propagating in x-direction into an infinite half-plane of conducting media
- Non-dimensionalization: $x = L\tilde{x}, \qquad E = E_0\tilde{E}$

$$\frac{\partial^2 \tilde{E}}{\partial \tilde{x}^2} - 2i\left(\frac{L}{\delta}\right)^2 \tilde{E} + \left(2\pi\frac{L}{\lambda}\right)^2 \tilde{E} = 0 \qquad (1)$$

Skin depth: $\delta = \sqrt{\dfrac{2}{\omega\sigma\mu}}$

Theory

- Different regimes for the electric field depending on the terms $(L/\delta)^2$ and $(2\pi L/\lambda)^2$:
  - Electromagnetic waves, $\lambda \ll L$
  - Alternating current (AC), $\lambda \gg L$
    - High frequency, $\delta < L$
    - Low frequency, $\delta \gtrsim L$
  - Direct current (DC), $\delta \gg L$ (approximation $L \lesssim \delta/5$)
- Approximation of (1) for alternating current

$$\nabla^2 \vec{E} = \frac{2i}{\delta^2} \vec{E}$$

Theory

- Cylindrical coordinates, $r \in [0, R]$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) - \frac{2i}{\delta^2}E = 0$$

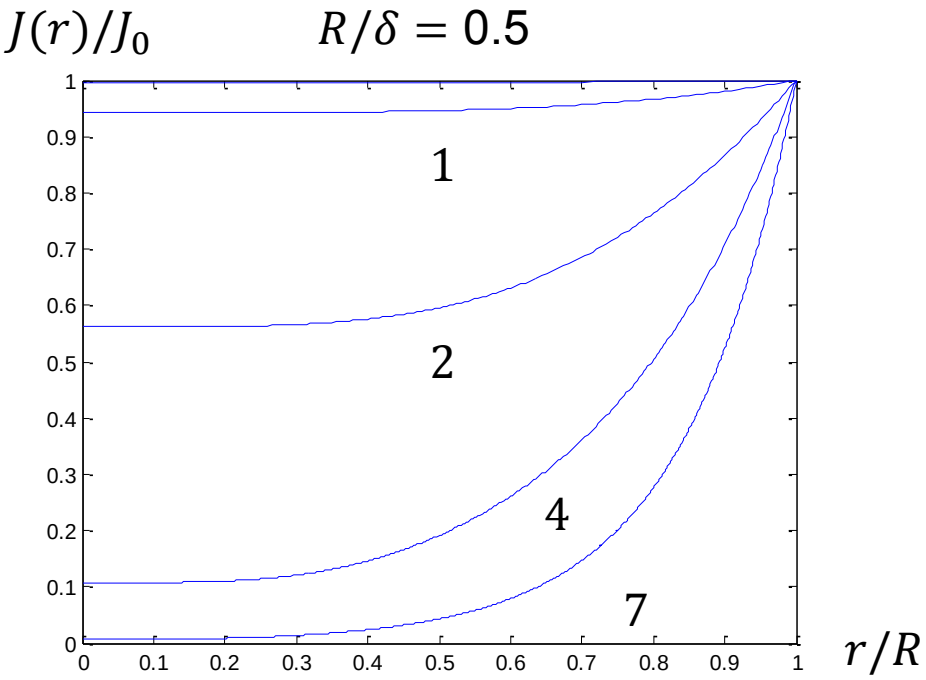
- Current density:

$$J(r) = J_0 \left| \frac{\mathrm{J}_0\left((1-i)\frac{r}{\delta}\right)}{\mathrm{J}_0\left((1-i)\frac{R}{\delta}\right)} \right|$$

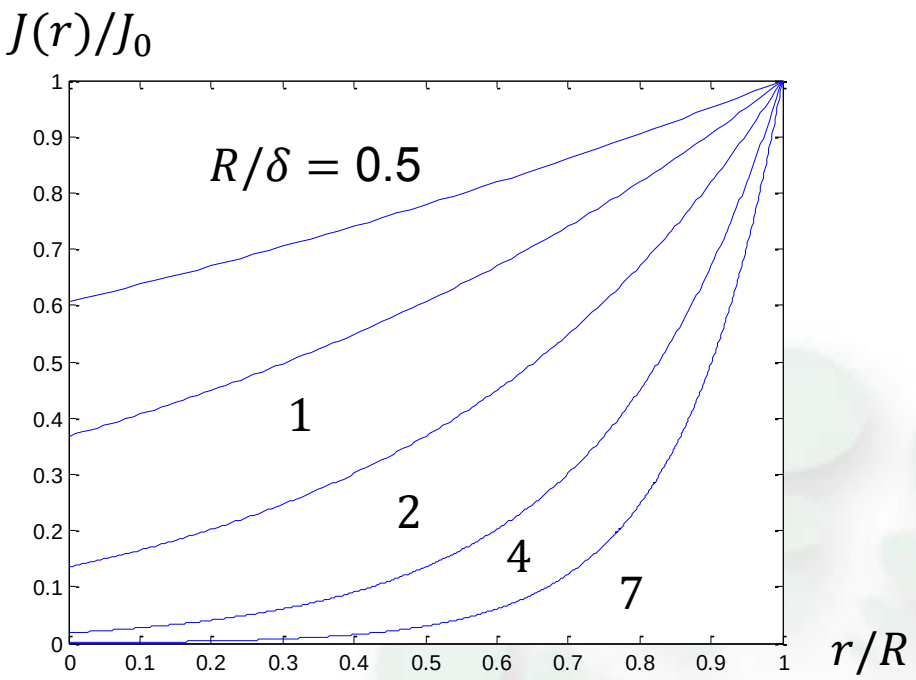
- $J_0(x)$ is zero order Bessel function of first kind
- Approximation yields: $J(r) \approx J_0 e^{-(R-r)/\delta}$

Theory

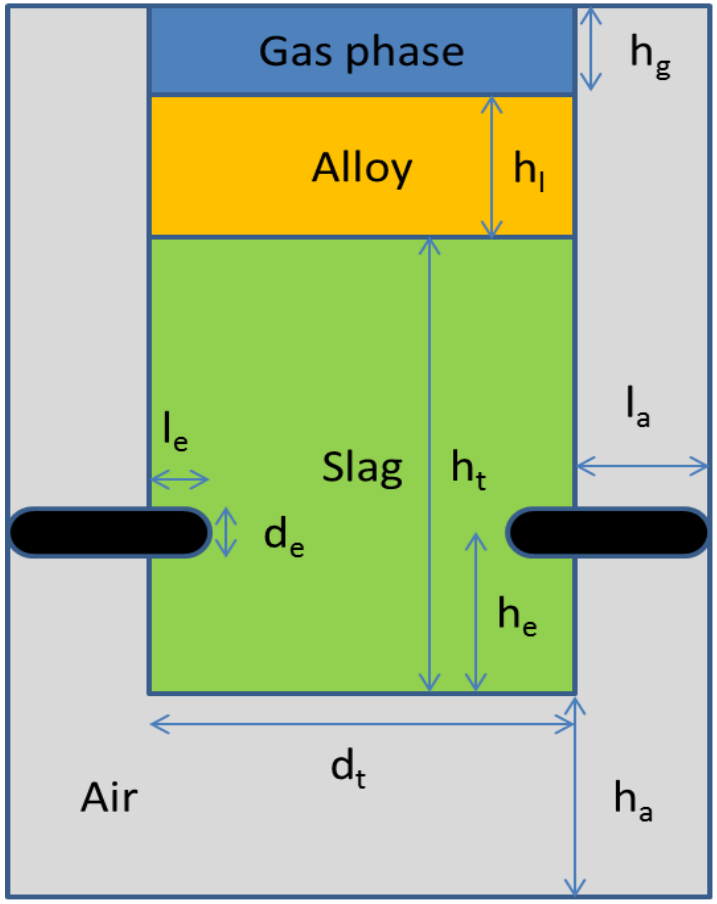
Exact solution

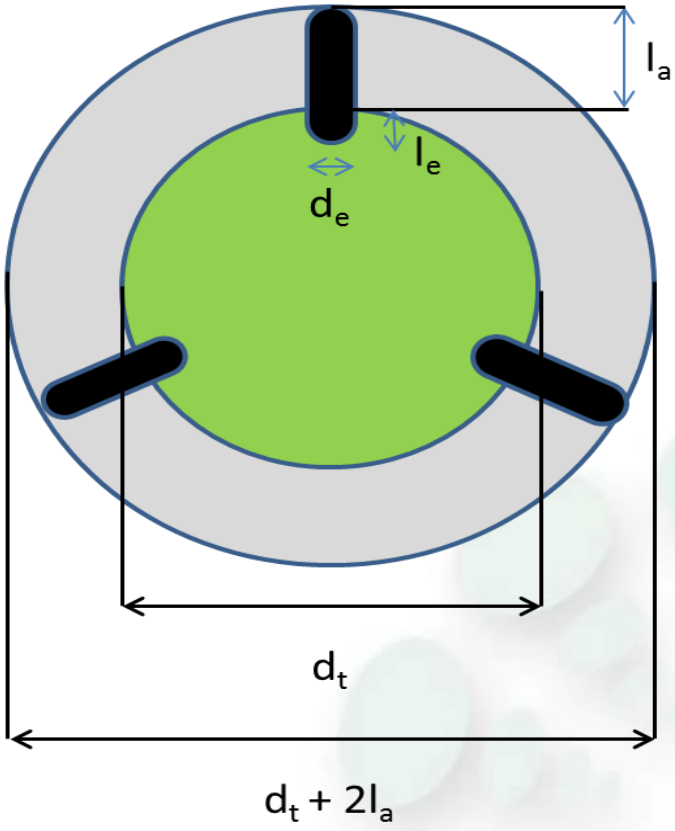


Approximate solution



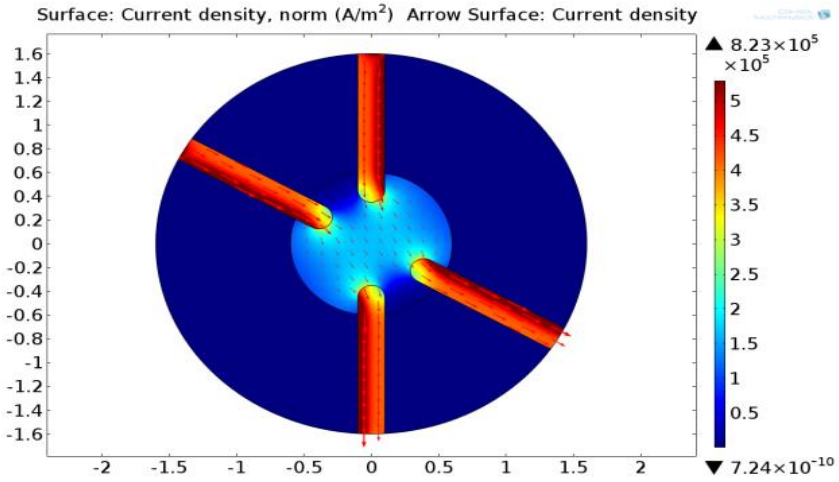
Geometry

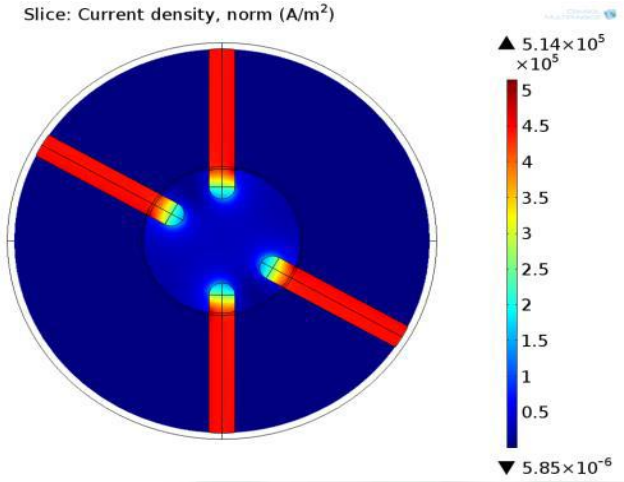

Gas phase
Alloy
Slag
Air
h_g
h_l
h_t
h_e
h_a
l_e
l_a
d_e
d_t


l_a
l_e
d_e
d_t
$d_t + 2l_a$

2D Simulation Results

- 2D modeling a challenge due to infinite electrode plates

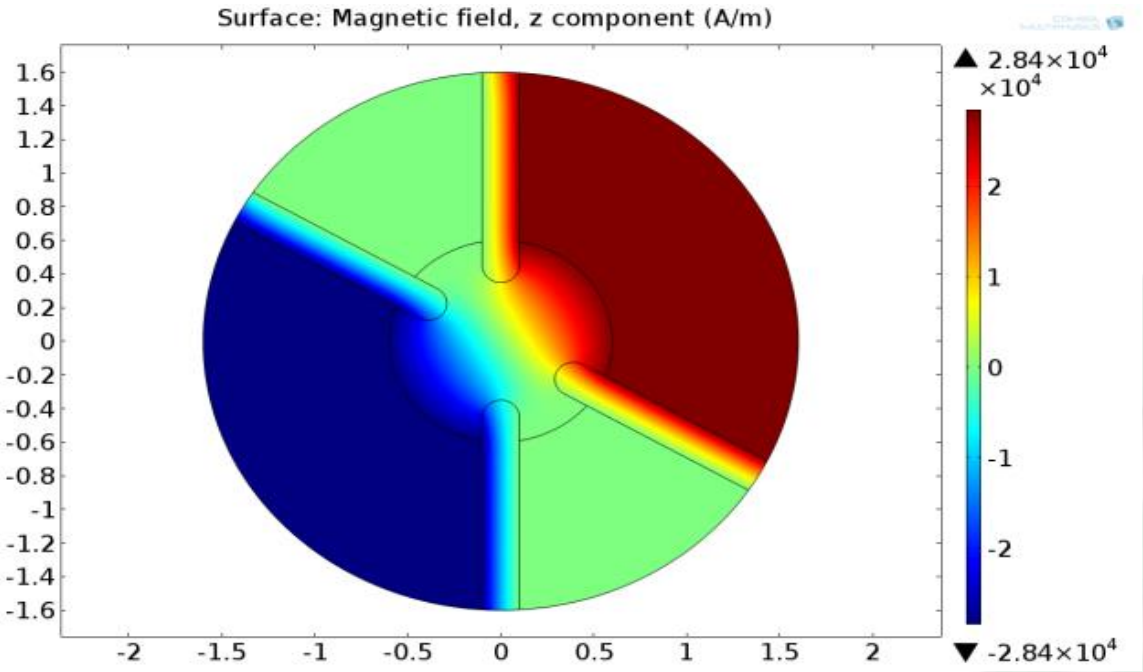




- Effect vanishes for 3D model

2D Simulation Results

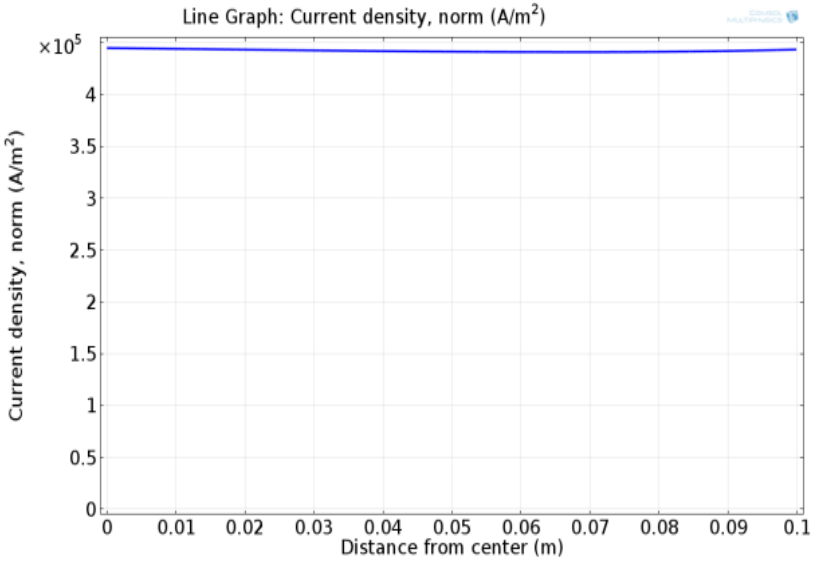
- Due to Ampère's law magnetic field is proportional to the current and independent on distance



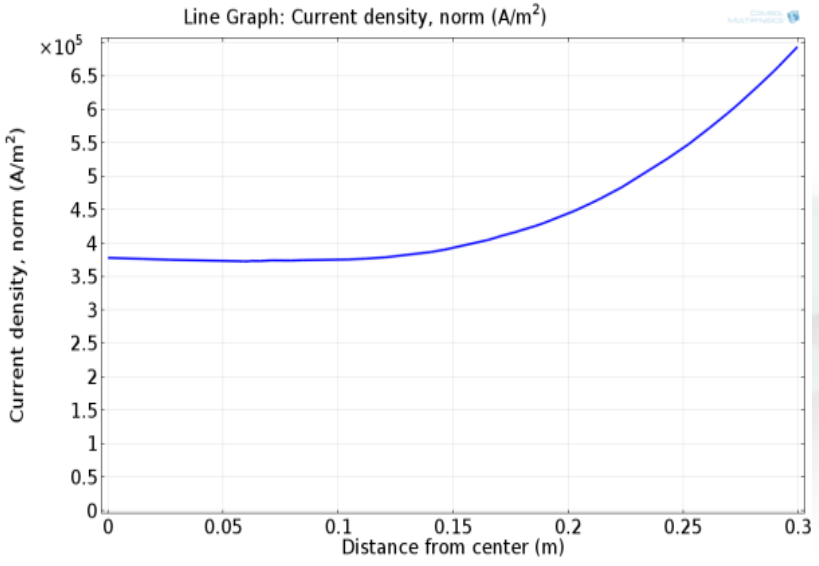
3D Simulation Results

- Current density along electrode radius

$(R/\delta)^2 \approx 0.5$

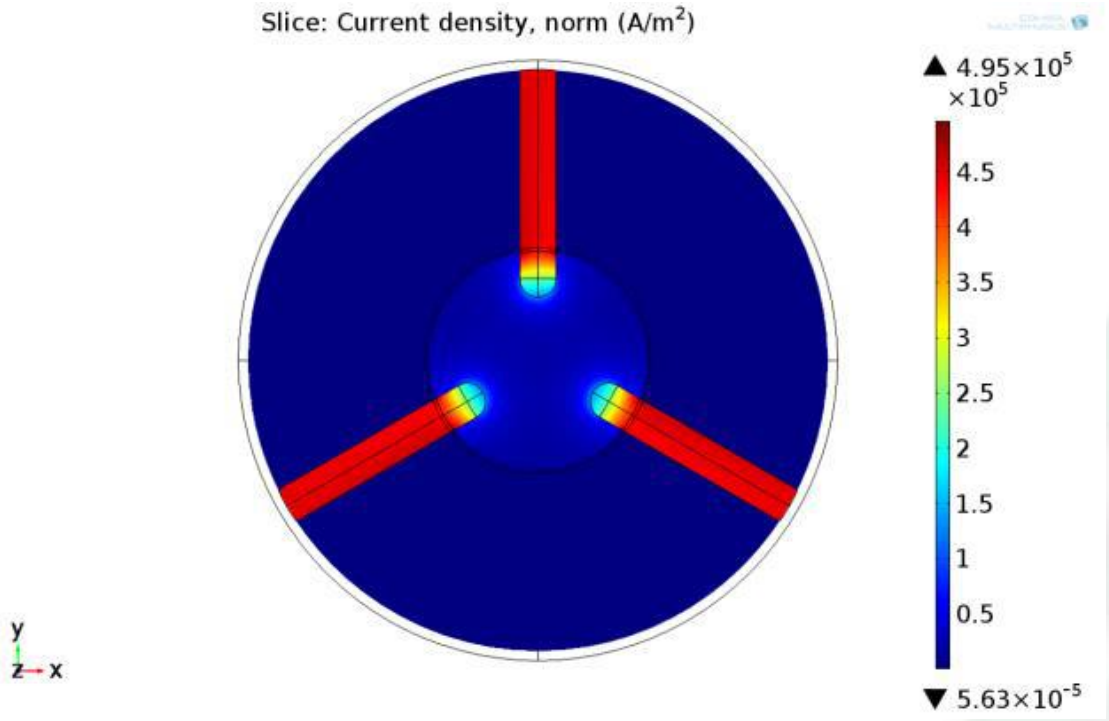


$(R/\delta)^2 \approx 4$



3D Simulation Results

- Resistive loss (current density) in slag is almost half compared to two 1 phase electrode pairs



Conclusions

- Shown three different regimes
  - Electromagnetic waves
  - Alternating current
  - Direct current
- Identified the parameter $(L/\delta)^2$ for electrical scale-up
  - DC approximation is reasonable for $L \lesssim \delta/5$
- 2D AC simulation show unreasonable strong proximity effects