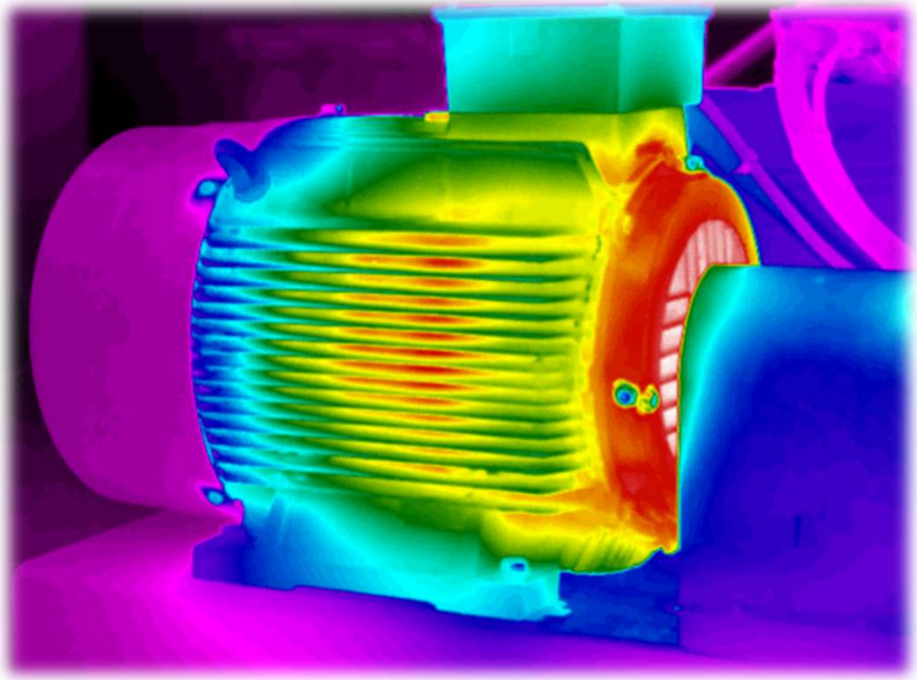
Cooling



Performance limits

- Electrical
  - *At too high voltage, the electric insulation will break down*
- Mechancial
  - *At too high speed, the rotor will be unbalanced or desintegrate*
- Thermal
  - *At too high temperature, the electric insulation will break down*

Thermal balance

- When the heat generated, and the heat dissipated are in balance

Thermal vs Electrical

$$\Delta T = \begin{cases} R_{th} \cdot Q_R \\ \dfrac{1}{C_{th}} \displaystyle\int Q_C \cdot dt \end{cases}$$

Termal resistivity

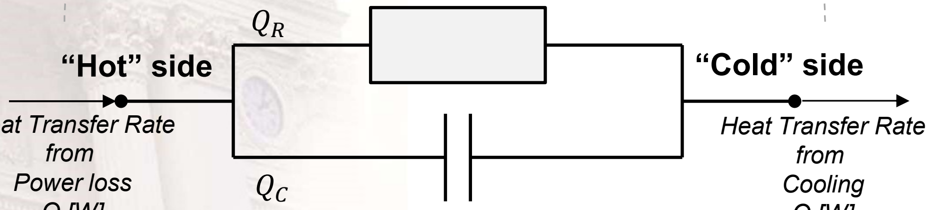
$$\left[\frac{K \cdot m}{W}\right]$$

Termal conductivity

$$\left[\frac{W}{K \cdot m}\right]$$

$$\left[\frac{K}{W}\right] \quad R_{th} = \rho_{th} \cdot \frac{l}{A} = \frac{1}{\lambda} \cdot \frac{l}{A}$$

Thermal resistance



"Hot" side

Heat Transfer Rate from Power loss Q [W]

"Cold" side

Heat Transfer Rate from Cooling Q [W]

Thermal capacitance

$$C_{th} = c \cdot M$$

$$\left[\frac{Ws}{K}\right]$$

$$\left[\frac{Ws}{K \cdot kg}\right]$$

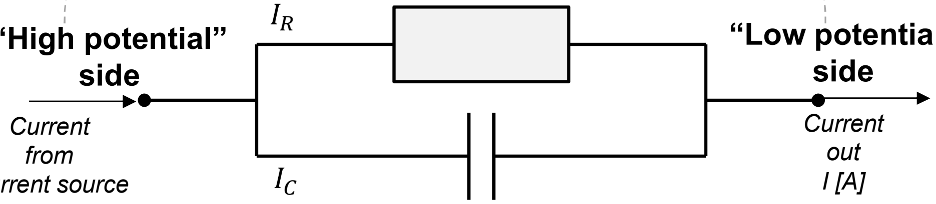
Heat capacity

$$\Delta u = \begin{cases} R_{el} \cdot I_R \\ \dfrac{1}{C_{el}} \displaystyle\int I_C \cdot dt \end{cases}$$

$$\left[\frac{\Omega \cdot m^2}{m}\right] = \left[\frac{V \cdot m}{A}\right]$$

$$\left[\frac{V}{A}\right] \quad R_{el} = \rho_{el} \cdot \frac{l}{A}$$

Electrical resistance



"High potential" side

Current from Current source I [A]

"Low potential" side

Current out I [A]

Electrical capacitance

$$C_{el} = \varepsilon \cdot \frac{A}{d}$$

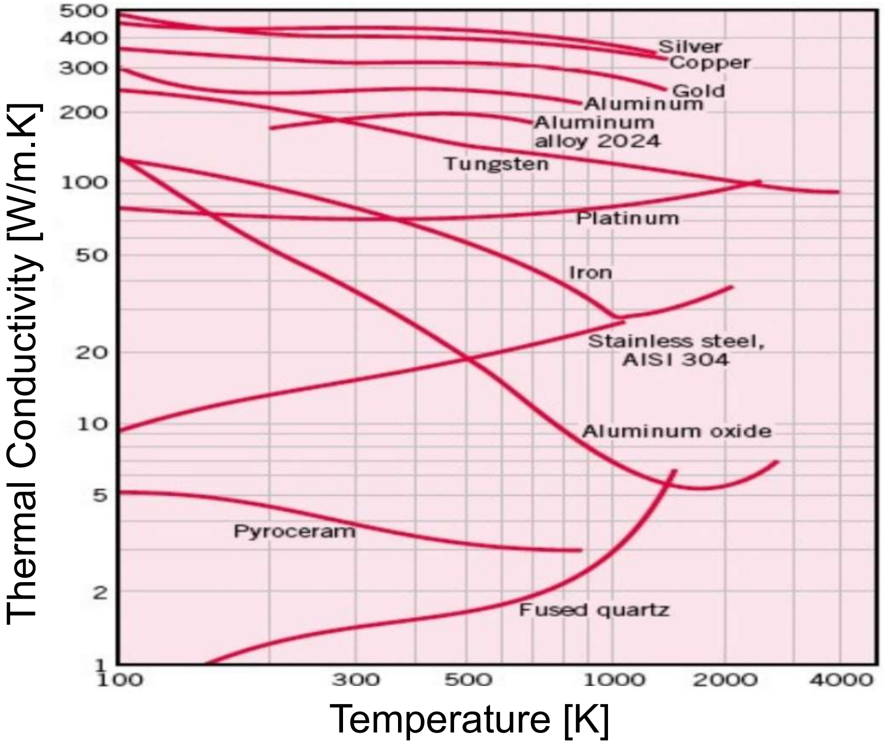
$$\left[\frac{As}{V}\right]$$

$$\left[\frac{F \cdot m}{m^2}\right]$$

Permittivity

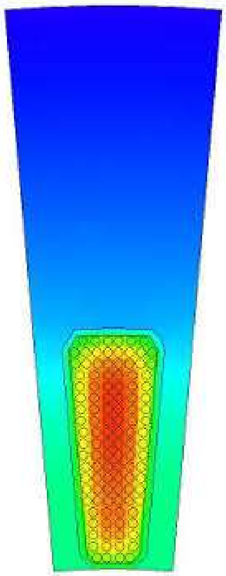
Thermal Conductivity of Solids

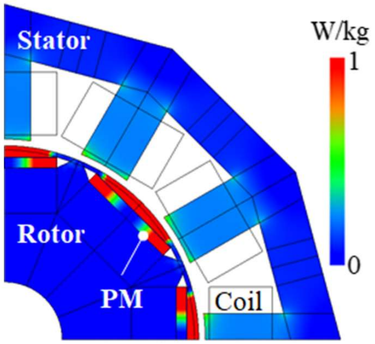
- Aluminum most used thermal conductor
  - *2 … 3 times better than Iron*



Heat loss sources in electrical machines

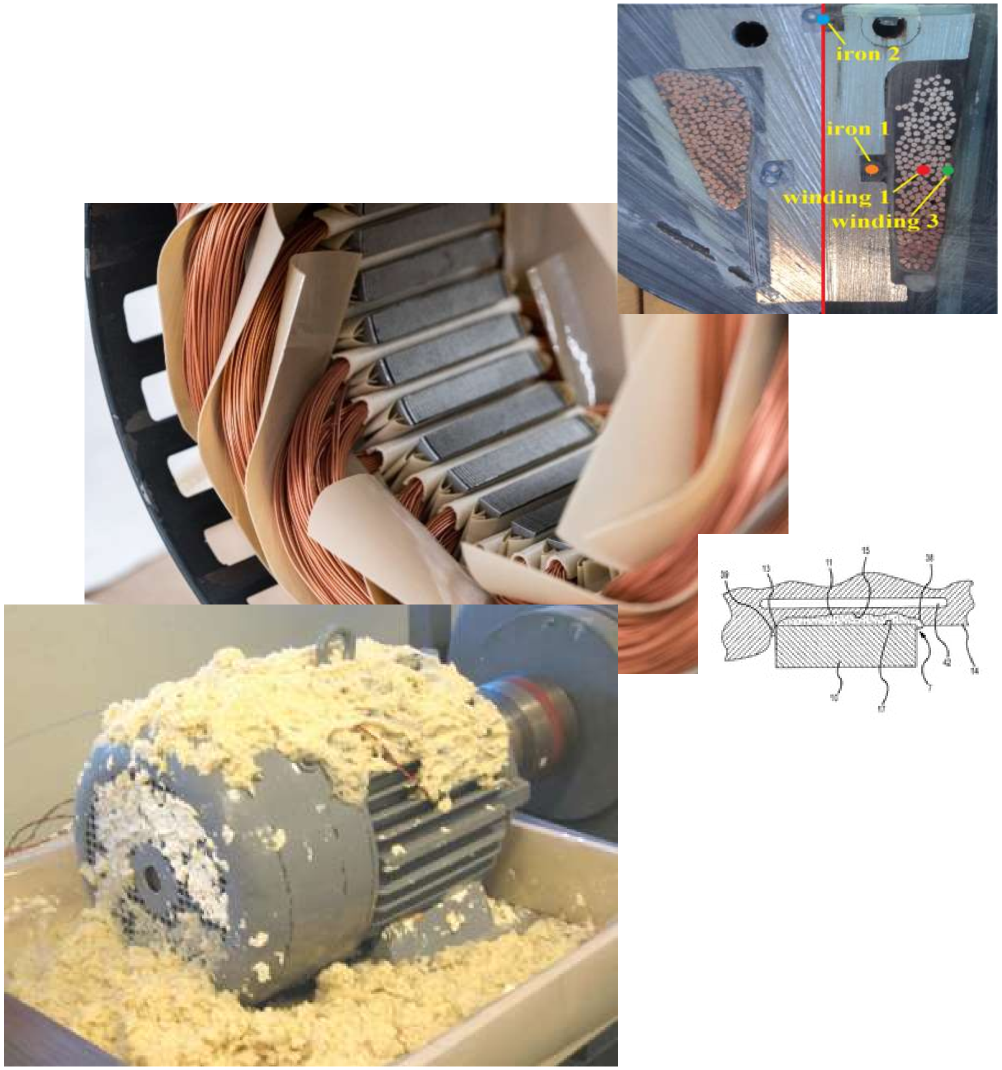
- Windings: DC and AC losses
- Core: hysteresis and eddy current losses
- Magnets: eddy current losses



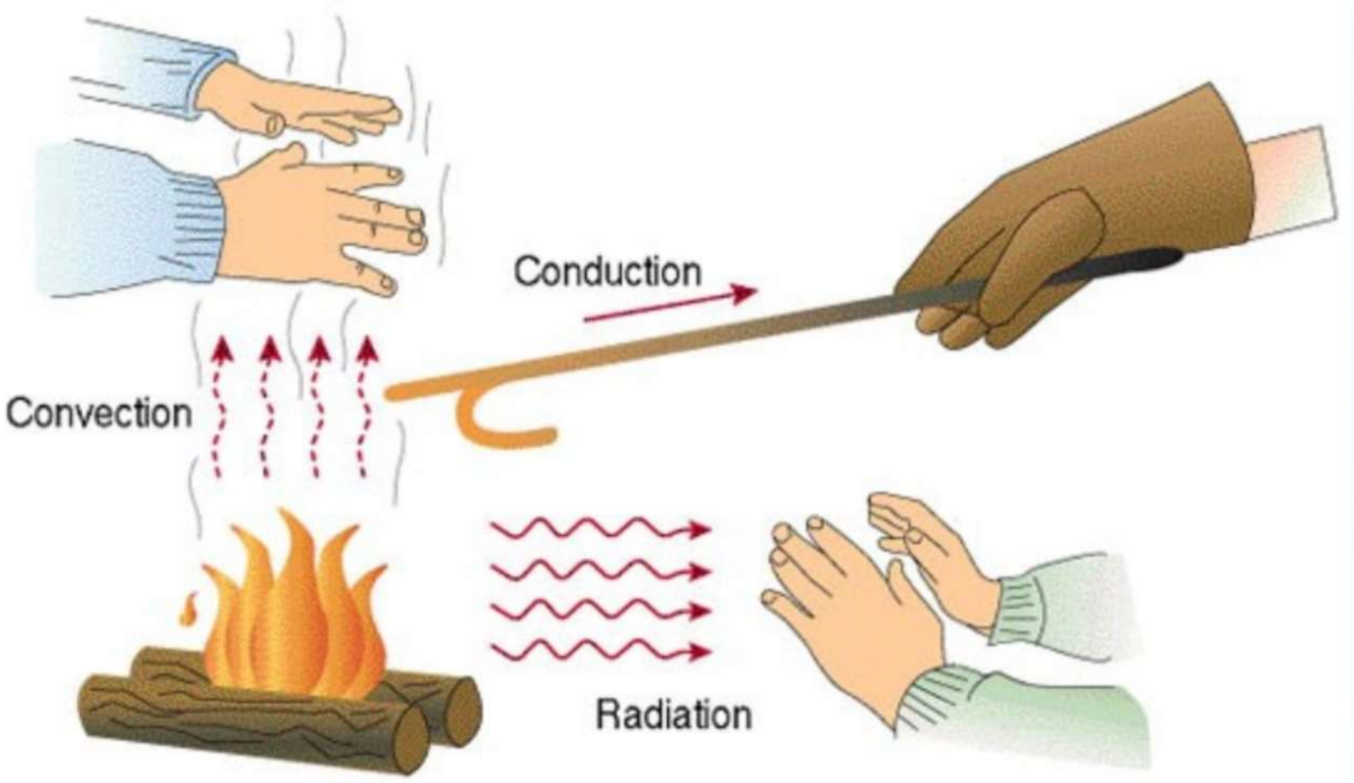


Thermal barriers

- Incomplete slot fill
- Slot liner
- Pressure fits
- Poor convection conditions...



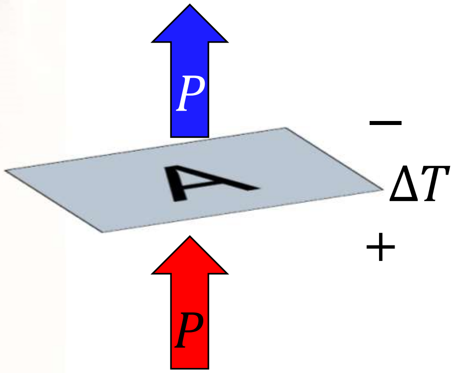
Heat transfer

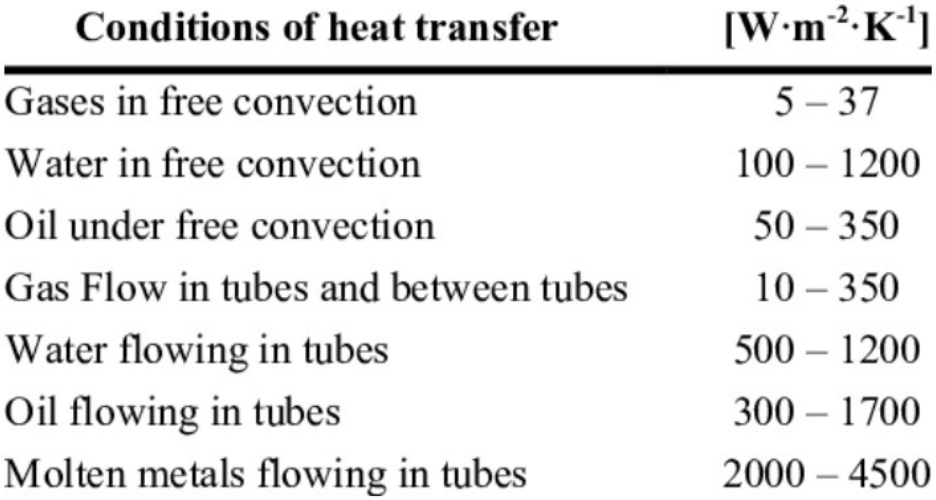


Heat transfer II - Convection

- Normally the case with water or oil cooled machines
- Heat transfer coefficient, h
  - *Depends on fluid, speed , surface properties, channel size …*

$$h = \frac{P}{A \cdot \Delta T}$$





Conditions of heat transfer	$[\mathrm{W \cdot m^{-2} \cdot K^{-1}}]$
Gases in free convection	5 – 37
Water in free convection	100 – 1200
Oil under free convection	50 – 350
Gas Flow in tubes and between tubes	10 – 350
Water flowing in tubes	500 – 1200
Oil flowing in tubes	300 – 1700
Molten metals flowing in tubes	2000 – 4500

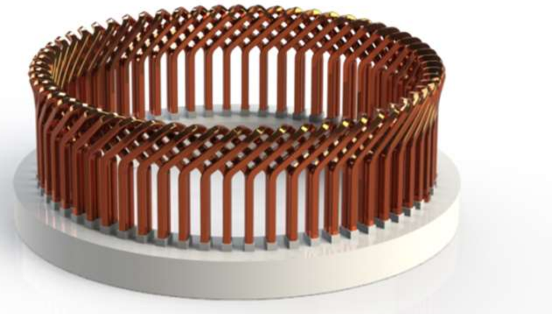
Increased Cooling ...?

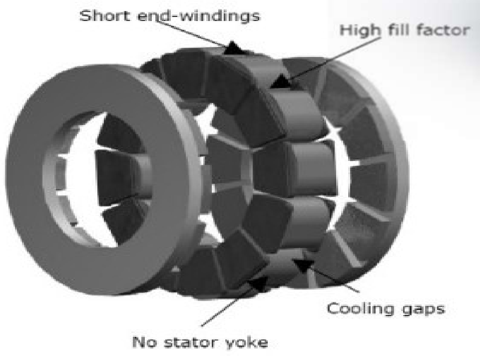
- Air cooling outside
- Water sleeve cooling
- Oil cooling, also on end winding and maybe inside rotor

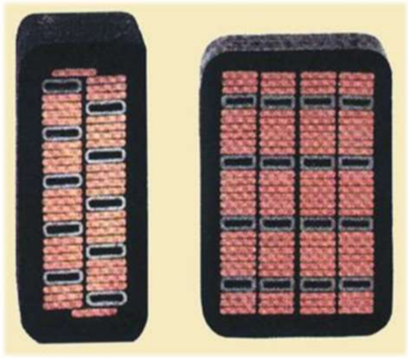
Peak Power determined by thermal capacitance

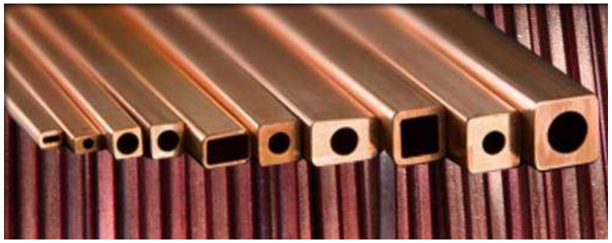
- Oil cooling directly on the windings
- Cooling inside the stator windings
- Cooling inside the stator conductors

Peak Power determined by Direct winding cooling capability



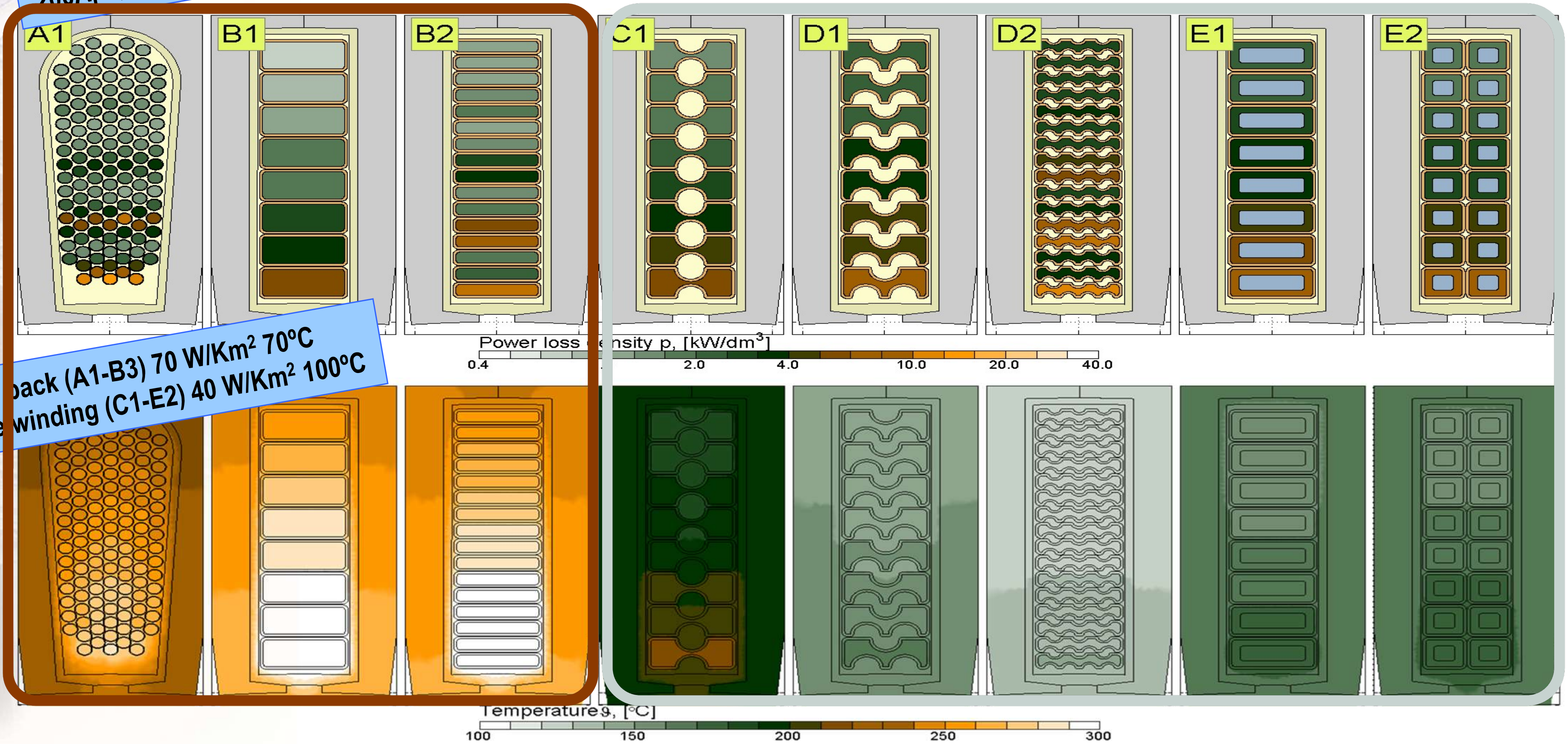






Alternative designs

Nominal
200Apk, 300Hz



Stator pack (A1-B3) 70 W/Km² 70ºC
Inside winding (C1-E2) 40 W/Km² 100ºC

A simple example

- Assume.
  - For the winding
    - *10 A/mm^2 in winding*
    - *60 C water temp*
    - *Copper resistivity: 1.7e-8 Ohm*m*
    - *Fill factor 50 %*
  - *Cooling:*
    - *Heat transfer Coefficient h=1000*
- Thermal conductivity (λ):
  - *Winding (Copper): 400*
  - *Slot insulation: 1*
  - *Stator core (Iron): 80*
  - *Air: 0.024*
- Estimate
  - *Conductor temperature*

Assume:

- *All copper losses in one point in the middle of the winding*
- *The slot liner is 1 mm thick*
- *The iron path starts at half the tooth height and has tooth width (15+10)mm*
- *The shrink fit of the core leads to a 0.05 mm airgap between the housing and the core*

$$P_{loss} = \rho_{el.cu} \cdot \frac{0.1}{0.01 \cdot 0.03 \cdot k_{fill}} \cdot \left(10e6 \cdot 0.01 \cdot 0.03 \cdot k_{fill}\right)^2 = 26\ W$$

$$R_{cu} = \frac{1}{\lambda_{winding}} \cdot \frac{0.005}{0.030 \cdot 0.1} = 0.042\ [K/W]$$

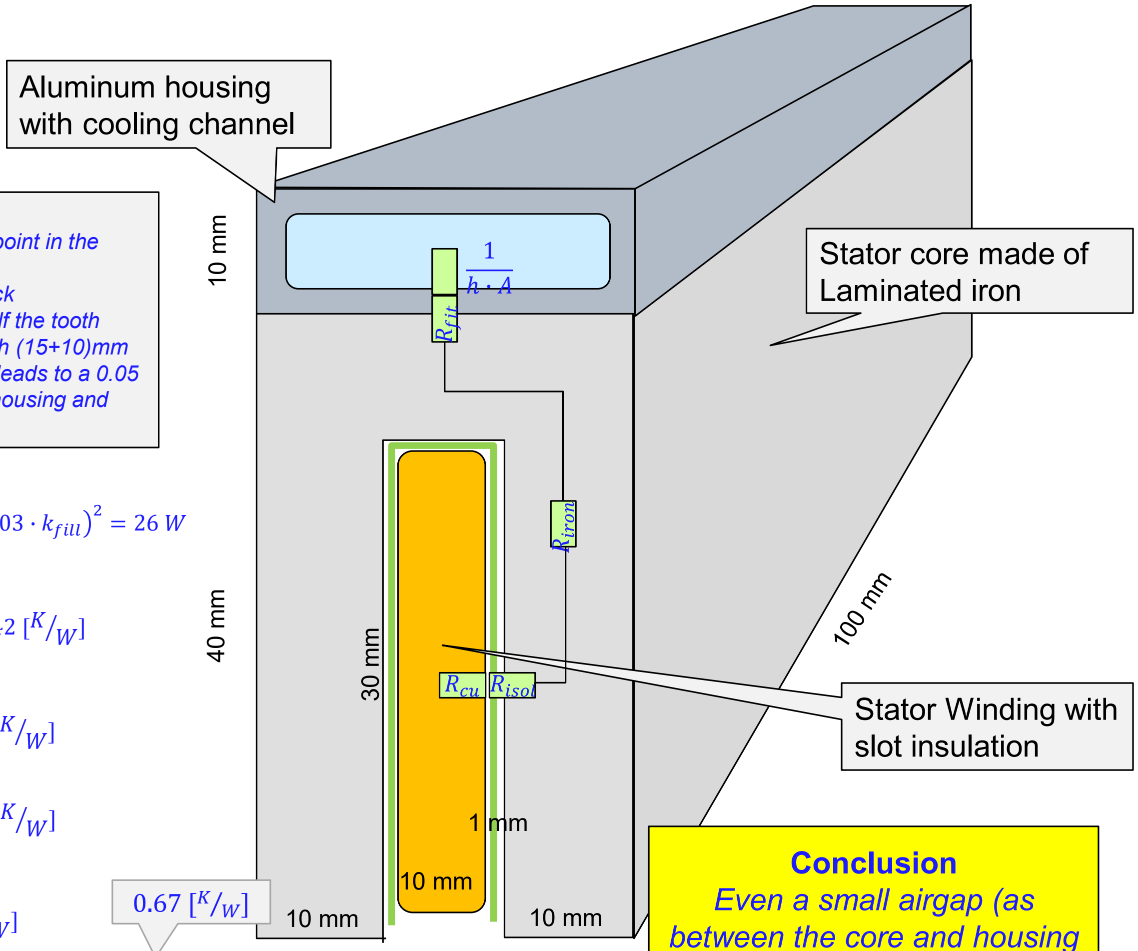
$$R_{isol} = \frac{1}{\lambda_{liner}} \cdot \frac{0.001}{0.030 \cdot 0.1} = 0.33\ [K/W]$$

$$R_{iron} = \frac{1}{\lambda_{core}} \cdot \frac{0.025}{0.010 \cdot 0.1} = 0.31\ [K/W]$$

$$R_{fit} = \frac{1}{\lambda_{air}} \cdot \frac{0.00005}{0.015 \cdot 0.1} = 1.4\ [K/W]$$

$0.67\ [K/W]$

$$T_{wind} = T_{coolant} + P_{loss} \cdot \left(R_{cu} + R_{isol} + R_{iron} + R_{fit} + \frac{1}{h \cdot A}\right) =$$
$$= 60+25.5*(0.042+0.33+0.31+1.4+1/1000/0.015/0.1) = 130\ C$$



Conclusion

Even a small airgap (as between the core and housing (0.05 mm assumed), can contribute a lot to the winding temperature!

That’s all folks...