THERMAL AND MAGNETIC STRESS IN THE HORN: STATIC CASE

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OUTLINE

- Model: electrical/resistive heating, Magnetic field/magnetic pressure, Temperature field/ thermal stress
- Material properties: electrical and thermal conductivity function of temperature
- Magnetic stress
- Thermal stress
- Total stress
- Fatigue limit
- Total stress with increased cooling or thickness.
- Conclusion

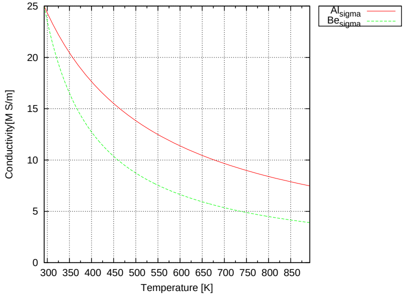
Coupled physics models

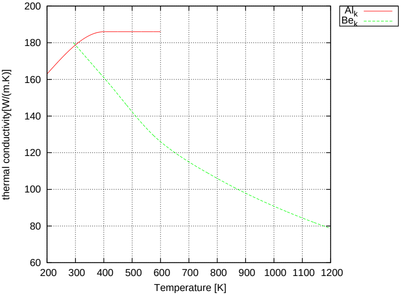
Model	Equation	Input	BC	Output
AC/DC	$j\omega\mu\mathbf{H} + \frac{1}{\sigma+j\omega\epsilon}\nabla\times[\nabla\times\mathbf{H}] = 0$ $\sigma = \sigma(T)$	$H_{0\phi} = \frac{I_{rms}}{2\pi r}$	$\mathbf{n}\times\mathbf{E} = 0 \Leftrightarrow H_n = 0$	$\mathbf{J}, \mathbf{B}$ Qav_{emqh}
Thermal	$\nabla\cdot[k\,\nabla T] + q = 0$ $k = k(T)$	$q = Q_{beam} + Qav_{emqh}$	$q'' = \bar{h}[T - T_\infty]$	T
Mechanical linear elast	$\frac{\partial\sigma_r}{\partial r} + \frac{\partial\tau_{rz}}{\partial z} + \frac{\sigma_r-\sigma_\theta}{r} + F_r = 0$ $\frac{\partial\tau_{rz}}{\partial r} + \frac{\partial\sigma_z}{\partial z} + \frac{\tau_{rz}}{r} + F_z = 0$ $\vec{\sigma} = \mathbf{E}\vec{\epsilon}$	$dF_r = -Re(B_\phi)\times Re(J_z)$ $dF_z = Re(J_r)\times Re(B_\phi)$ $\Leftrightarrow p(r) = \frac{\mu {I_0}^2}{8\pi^2 r^2}$	$u_r(z=0) = 0$ $u_z(r=0) = 0$	$\mathbf{u}$ $\mathbf{s}$
Mechanical & thermal	idem $\vec{\epsilon} = \vec{\epsilon_{el}} + \vec{\epsilon_{th}}$ $\vec{\epsilon_{th}} = \mathbf{I}\alpha(T - T_{ref})$	idem α, T	idem $T_{ini} = T_{ref}$	$\mathbf{u}_{tot}$ $\mathbf{s}_{tot}$

- $I_0 = 350kA$, $I_{rms} = 8750A$. To model total stress, assume a magnetic pressure corresponding to peak current I_0.
- $Q_{beam} = 55kA$ deposited in the Beryllium target of length $L = 0.78$m and radius $R = 15$ mm.(obtain with Fluka).
- Cooling: $\{h_{target}, h_{horn}\} = \{10-20, 1-2\}\ kW/(m^2K)$
- non linear because both electrical and thermal conductivity are temperature dependant.
- axisymmetric model: all variables are function of r and z.

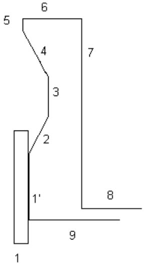
MATERIAL PROPERTIES

- Model 1: constant electrical and thermal conductivity for Al and Be
- Model 2: Temperature dependant electrical and thermal conductivity for Al and Be





Resistive losses



Q[kW]	tot	1+1”	2	3	4	5 + 6	7	8	9
$\sigma = \sigma_0$	27	14	2.5	1.0	2.6	4.1	1.3	0.23	1.4
$\sigma = \sigma(T)$	37	20.8	2.7	1.0	2.9	6.5	1.3	0.23	1.5

- Total electrical loss are 37% higher than the one calculated with constant electrical conductivity
- Most electrical losses came from the inner conductor, conical sections and top end of the horn.
- $q_{elec} = \frac{\rho}{2} J^2$, the resistivity increased with temperature, $\Rightarrow$ essential to maintain the inner conductor at low temperature.

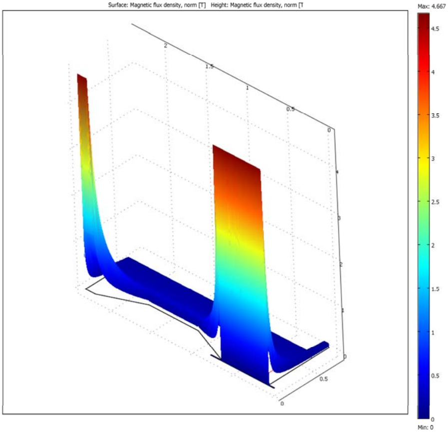


FIGURE: Magnetic flux distribution

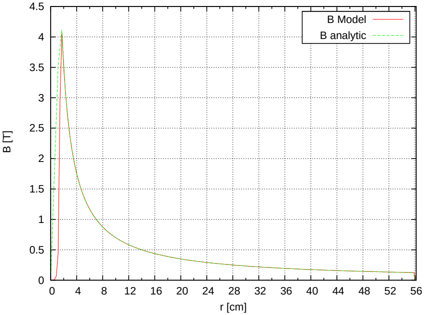
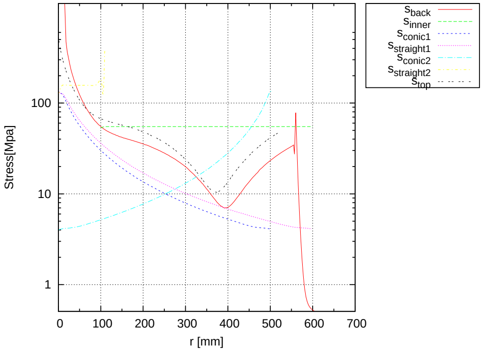


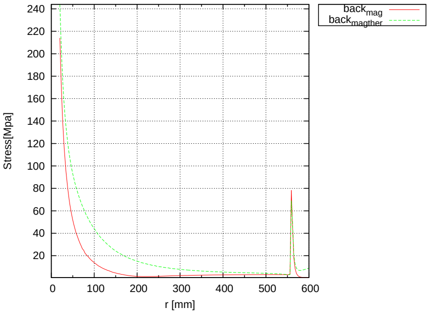
FIGURE: Radial magnetic flux distribution, analytic and model

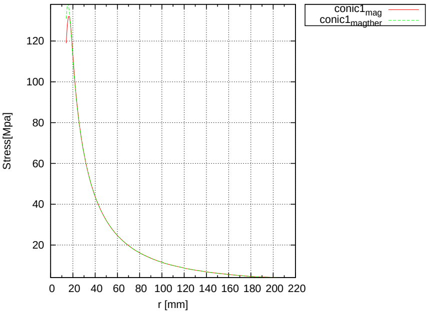
STRESS FROM MAGNETIC PRESSURE IN THE HORN



- Stress in the conductor around 100 Mpa
- Stress increase with smaller radius

MAGNETIC STRESS IN THE BACK AND CONICAL CONDUCTOR





- magnetic stress is dominant, peak stress corresponding to $I_0 = 350$ kA, frequency: 12.5 Hz.
- thermal stress important for domain with high temperature
- can increase thickness to lower the total stress

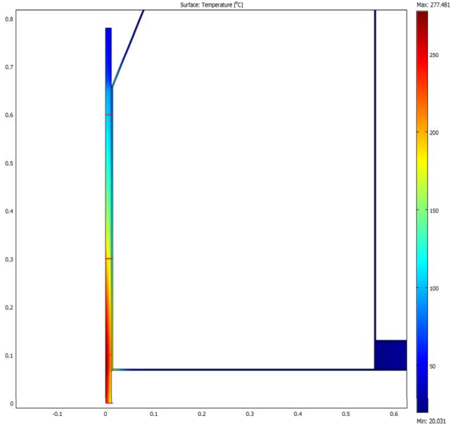


FIGURE: Target and horn, T_{max} above 270 °C, $h_{target} = 10kW/m^2K$, $h_{horn} = 1kW/m^2K$

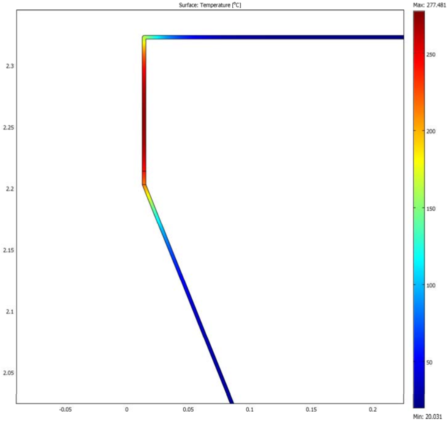


FIGURE: Top end of the horn, T_{max} above 270 °C, $h_{target} = 10kW/m^2K$, $h_{horn} = 1kW/m^2K$

Temperature field, $\sigma(T)$, $k(T)$

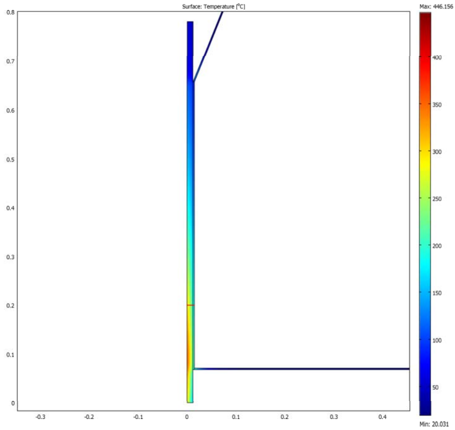


FIGURE: Target and horn, T_{max} around 350 °C, $h_{target} = 10kW/m^2K$, $h_{horn} = 1kW/m^2K$

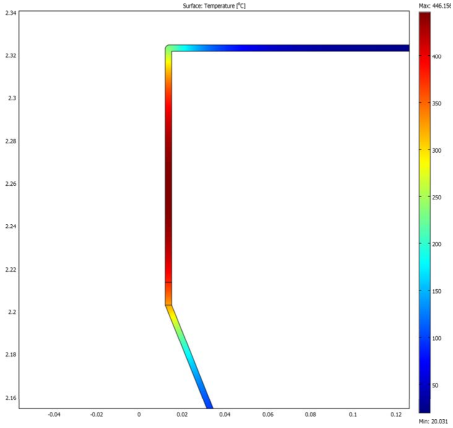


FIGURE: Top end of the horn, T_{max} above 440 °C, $h_{target} = 10kW/m^2K$, $h_{horn} = 1kW/m^2K$

TEMPERATURE FIELD, $\sigma(T), k(T)$

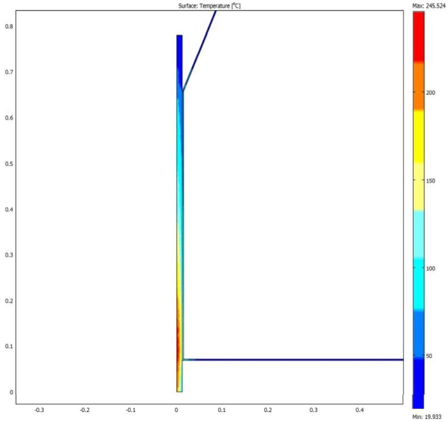


FIGURE: Target and horn, T_{max} around 245 °C, $h_{target} = 20kW/m^2K$, $h_{horn} = 2kW/m^2K$

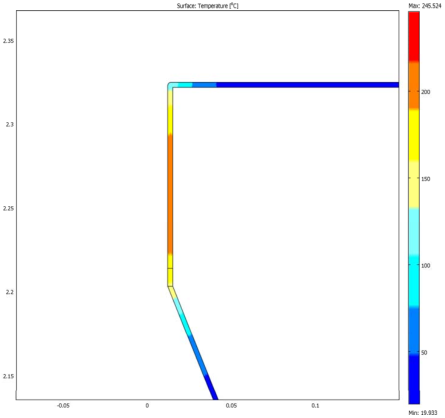


FIGURE: Top end of the horn, T_{max} above 200 °C, $h_{target} = 20kW/m^2K$, $h_{horn} = 2kW/m^2K$

ELECTRICAL CONDUCTIVITY

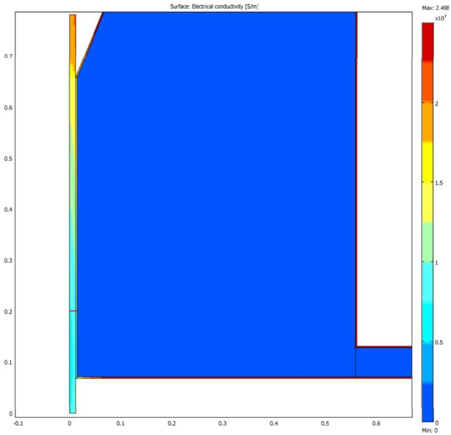


FIGURE: Target and horn, $\sigma_{max} = 2.5E7[S/m]$

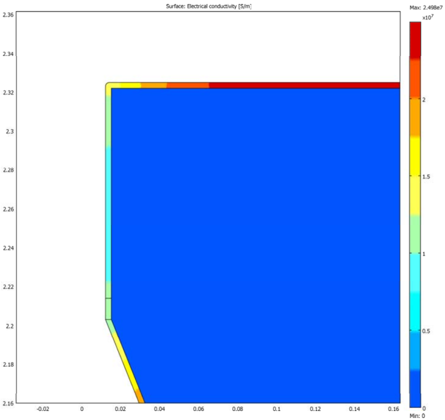
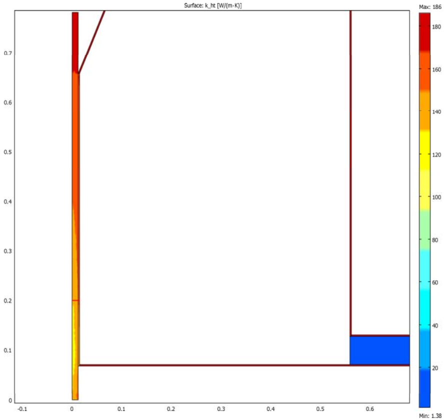


FIGURE: Top end of the horn, $\sigma_{max} = 2.5E7[S/m]$



- thermal conductivity of Al do not vary significantly for Al
- thermal conductivity of Be strongly with temperature $\Rightarrow$ maintain low temperature

TARGET STRESS, $\sigma, k = cste$

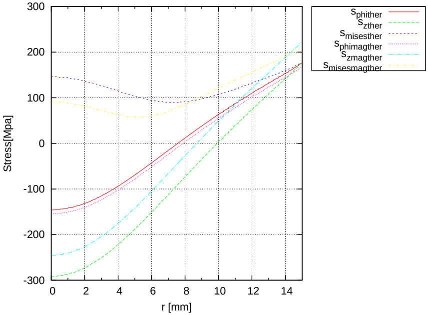


FIGURE: Stress components in the target $z = 2$cm, thermal and mag+thermal stress

- cooling target $h = 10\ kW/(m^2K)$
- $S_\phi = S_r = p(R) = -8.66$ MPa. Model correct checked with analytic expression
- $|S_{\phi mag}| \ll |S_{\phi ther}|$
- $S_{zmag+ther} = S_{zther} + 46$ Mpa
- cylinder in compression in the z direction for $r \epsilon [0, 1]$ cm
- cylinder in traction in z direction for $r \epsilon [1, 1.5]$ cm
- Von mises stress level: $\sim 100 - 200$ Mpa
- Fatigue strength of Beryllium ~ 100 Mpa

STRESS IN THE CONDUCTORS, $\sigma, k = cste$

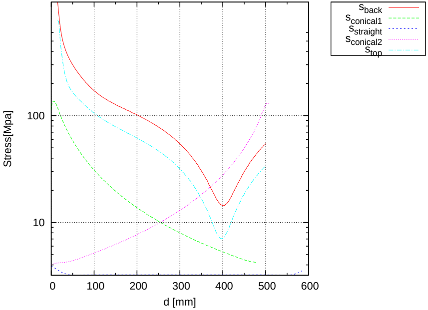


FIGURE: Von mises stress distribution for each conductor segment

- Stress gets very high for low radius
- high stress level in perpendicular junction, stress concentrations; singularities.
- Important stress level $>>$ 100 Mpa in back; top and conical sections; especially at low radius.

DISPLACEMENT FIELD, $\sigma(T), k(T)$

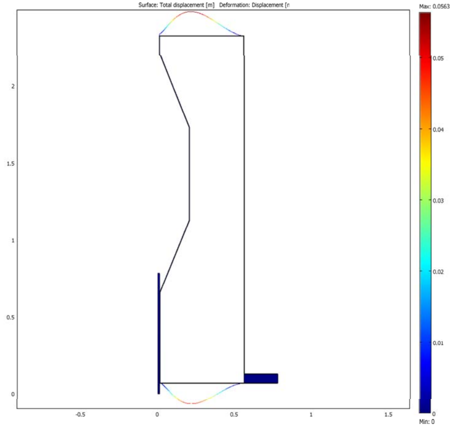


FIGURE: Total displacement due to magnetic and thermal stress, $U_{max} = 5$ cm

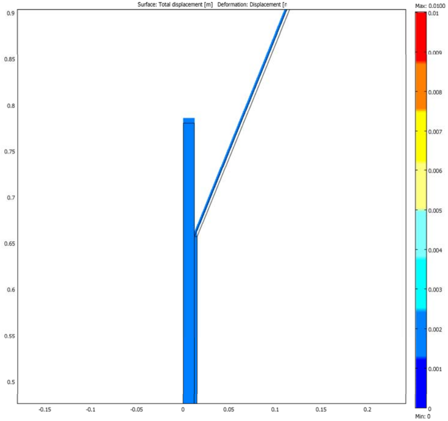


FIGURE: Total displacement in the target/conductor region, $U_{max} \sim 2,3$ mm

TARGET STRESS, $\sigma(T), k(T)$

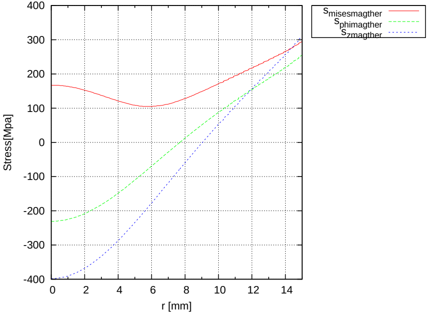
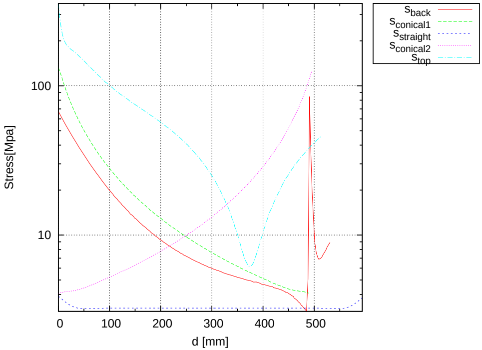


FIGURE: Stress in the radial direction at $z = 2$ cm

- cylinder in traction in z direction for $r \epsilon [0.8, 1.5]$ cm
- stress level higher than fatigue strength (2 times higher than fatigue strength of Be)
- would be (maybe ?) ok if the target was not a structural element of the horn
- for an integrated target: level of stress too high:$\Rightarrow$ increased cooling to decreased thermal stress.

Horn stress, $\sigma(T), k(T)$



- Stress increase with lower radius
- too high stress level in conical section
- stress level higher than fatigue strength
- difference only in the beryllium part (target) because thermal conductivity of Be changes with temperature, $\Rightarrow$ thermal stress

FATIGUE

- $N = 8E8$: total number of pulses
- 4 horns: $\frac{N}{4}$ pulses per horn at frequency 12.5 Hz.
- $\tau = \frac{N}{f} = 16 \times 10^6$s , $\sim$ 6 months continuously
- Al: no fatigue limit, properties degrading as N increased
- max stress for AL as low as possible, maybe below 50 Mpa
- fatigue limit of Be: $\sim$ 100 Mpa.
- different story for weld junctions
- Need study on irradiation effect on materials and lifetime.
- Effect of water on lifetime ?

Conclusion/solutions

- increased thickness and/or increased cooling to decreased thermal stress.
- model with increased thickness
- need to have low stress to have acceptable lifetime.
- others: fatigue joints, welding.
- effect or irradiation; structural damage
- effect of water