# THERMAL STUDY OF TARGET

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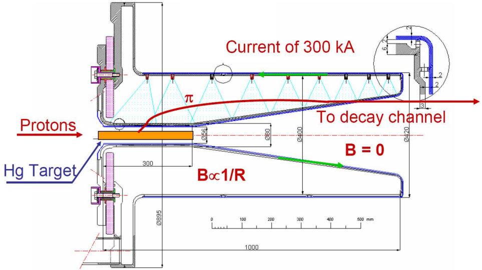
# OUTLINE

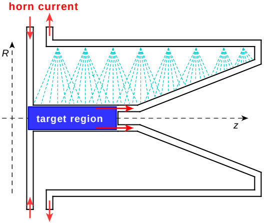
- Goal
  obtain max temperature inside the target, select materials, power feasibility, cooling requirements
- Model
  geometry, equations; boundary conditions
- Results
  power distribution; temperature distribution

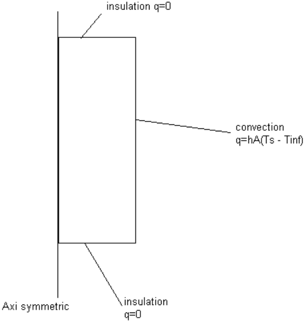
# HORN PROTOTYPE, CERN



- Integrated target, cooling, electrical parameters: CERN-NUFACT Note 80 (2001), Note 129 (2003)
- Horn simulation; power distribution: CERN-NUFACT Note 134 (2003); NUFACT Note 42 (2000)
- Horn profile: CERN-NUFACT Note 138 (2004)
- 4 capture scheme: CERN-NUFACT Note 77 (2001)
- Horn vibration measurements: CERN-NUFACT Note 126 (2003)

# GEOMETRY





- electromagnetic horn to focus the pions
- integrated target
- 2 heat sources: beam + joule losses
- cooling circuit, impinging jets

- axi symmetric model, radius $R = 1.5$ cm, length $L = 78$ cm.
- boundary conditions: insulation + convection
- $\bar{h} = \{5, 10, 15, 20\}$ kW/($m^2$K)

# JOULE LOSSES, ANALYTIC

- Current flows between the surface and the skin depth
- Joule losses increase with smaller radius.

$$\begin{aligned}
\text{crosssection}: &\quad S = \pi\delta\left(2r_e - \delta\right) \\
\text{skin depth}: &\quad \delta = \sqrt{\frac{2\rho}{\omega\mu}} \\
\text{resistance} &\quad \frac{R}{l} = \frac{\rho}{S} \\
\text{Power} &\quad \frac{P}{l} = R\, i_{rms}^2 = [108,\ 77.5,\ 64]\, kW/m
\end{aligned}$$

for $r = [1.1,\ 1.5,\ 1.8]\, cm$, $\rho = 4.8 \times 10^{-8} \Omega m$ at $20\,^\circ\mathrm{C}$,
$i_{rms} = 15$ kA, $\omega = 2\pi f = 2\pi \times 5000$ Hz

# JOULE LOSSES, COMSOL MODEL

- Maxwell's equation + electric and magnetic potential
- Solve equation 1 to obtain the magnetic potential

$$\begin{aligned} \nabla \times \mathbf{H} &= \sigma \mathbf{E} + \frac{\partial \mathbf{D}}{\partial t} \\ \mathbf{B} &= \mu \mathbf{H} = \nabla \times \mathbf{A} \\ \mathbf{E} &= -\nabla V - \frac{\partial \mathbf{A}}{\partial t} \end{aligned}$$

Time harmonic currents, equation reduced to:

$$\nabla \times \left( \frac{1}{\mu} \nabla \times \mathbf{A} \right) + (j\sigma\omega - \omega^2 \epsilon)\mathbf{A} = 0 \qquad (1)$$

average volume energy density:

$$q_{elec} = \frac{1}{2}\rho \mathbf{J} \cdot \mathbf{J}^* = \frac{1}{2}\sigma \mathbf{E} \cdot \mathbf{E}^* = \frac{1}{2}\sigma\omega^2 \mathbf{A} \cdot \mathbf{A}^*$$

# HEAT EQUATION, STEADY STATE

$$\begin{aligned}\nabla \cdot [k\, \nabla T(r,z)] + q(r,z) &= 0\\ q(r,z) &= q_{beam}(r,z) + q_{elec}(r,z)\end{aligned}$$

$k$ is the thermal conductivity.

- $q_{beam}$: power distribution inside the target, obtained with Fluka simulation. $P^{beam} = \{1, 4\}$ MW, proton kinetic energy 4.5 GeV, beam width $\sigma^{bm} = \{4, 6\}$ mm.
- $q_{elec}$: resistive loss with $i_{rms} = 15$ kA
-

| material | conductivity [W/mK] | $\sigma^{bm}$ [mm] | $Q_{beam}$ [kW] | $Q_{elec}$ [kW] |
|---|---|---|---|---|
| Al | 170 | 4 | 278 | 60 |
| | | 6 | 256 | 60 |
| Be | 80…200 | 4 | 165 | 56.3 |
| | | 6 | 153 | 56.3 |

# BOUNDARY CONDITIONS

## Thermal

- Thermal insulation $q = 0$ everywhere except on the surface $r = 1.5$ cm
- Convection cooling on the cylinder surface with $\bar{h} = \{5, 10, 15, 20\}$kW/(m$^2$K)

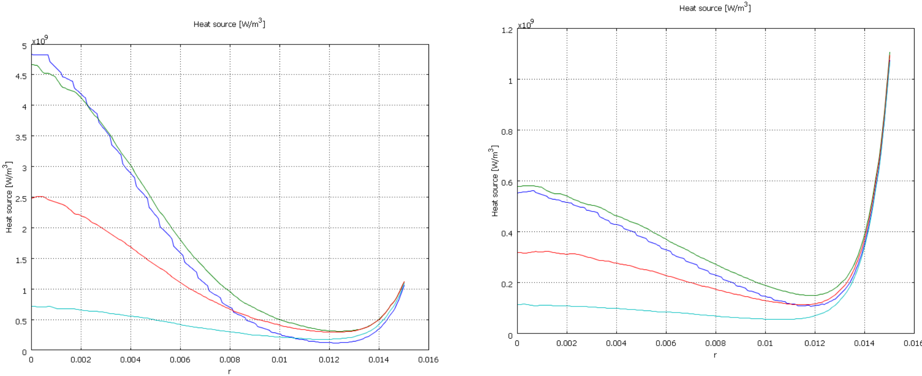
$$q = 2\pi R\, L\, \bar{h}\, (T_s - T_\infty)$$

$T_s$ and $T_\infty$ the surface and fluid temperature, $q$ heat flux

## Electrical

- $z = \{0,\ 0.78\}$ m, $r = 0$ m: $\nabla \times \mathbf{A} = 0$ ( $A_\perp = 0$ and $B_n = 0$)
- $r = R$; surface current: $J_s = \frac{I_0}{2\pi R} = \frac{\sqrt{2} \times 15kA}{2\pi R}$

# POWER DISTRIBUTION, ALUMINIUM

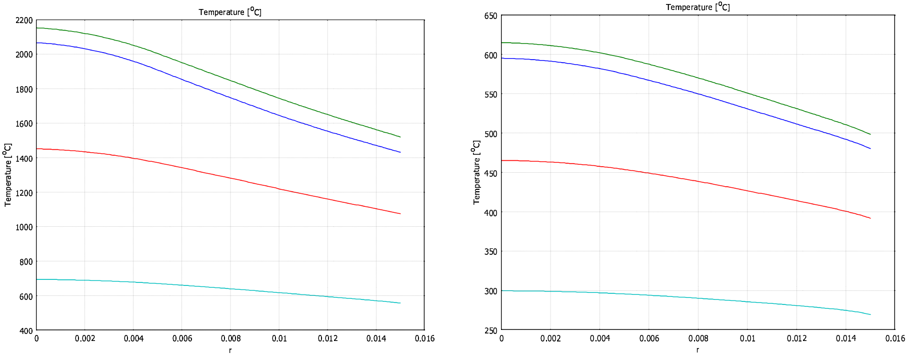


a) Al, 4 MW, $\sigma = 4$ mm

b) Al,1 MW, $\sigma = 6$ mm

FIGURE: Power density distribution in [W/m$^3$] for $P^{beam} = \{1, 4\}$ MW and beam profile $\sigma = \{4, 6\}$ mm in Al target. Electrical current $i_{rms} = 15$ kA at 5000 Hz, for $z = \{0, 10, 30, 60\}$ cm (blue, green, red, light blue)

# TEMPERATURE DISTRIBUTION, ALUMINIUM

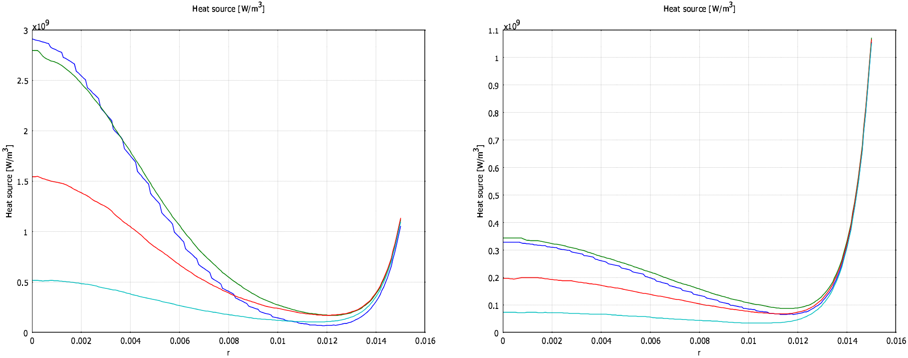


a) Al, 4 MW, $\sigma = 4$ mm, $\bar{h} = 5$ kW/(m$^2$K)

b) Al,1 MW, $\sigma = 6$ mm, $\bar{h} = 5$ kW/(m$^2$K)

FIGURE: Temperature distribution for $P^{beam} = \{1, 4\}$ MW and beam profile $\sigma = \{4, 6\}$ mm in Al target. Electrical current $i_{rms} = 15$ kA at 5000 Hz, for $z = \{0, 10, 30, 60\}$ cm (blue, green, red, light blue)

# POWER DISTRIBUTION, BERYLLIUM



a) Be, 4 MW, $\sigma = 4$ mm

b) Be,1 MW, $\sigma = 6$ mm

FIGURE: Power density distribution in [W/m$^3$] for $P^{beam} = \{1, 4\}$ MW and beam profile $\sigma = \{4, 6\}$ mm in Be target. Electrical current $i_{rms} = 15$ kA at 5000 Hz, for $z = \{0, 10, 30, 60\}$ cm (blue, green, red, light blue)

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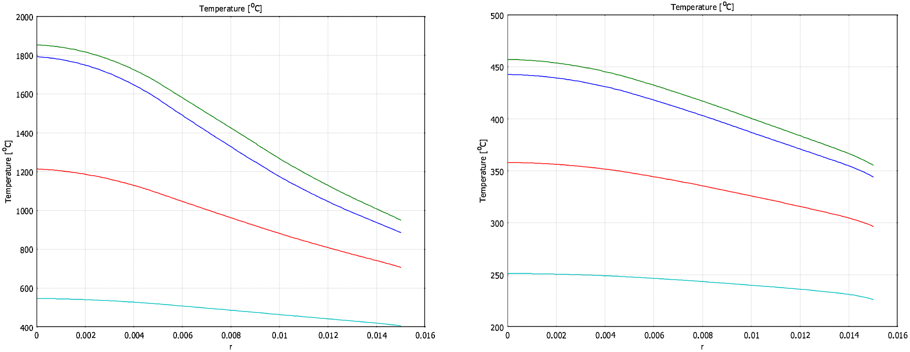


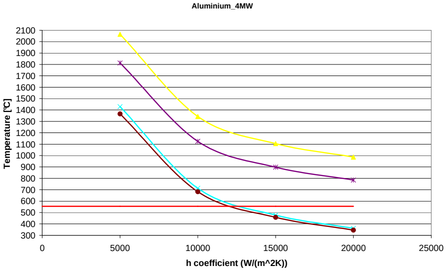
a) Be, 4 MW, $\sigma = 4$ mm, $\bar{h} = 5$ kW/(m$^2$K)

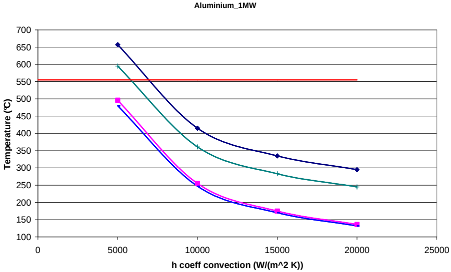
b) Be,1 MW, $\sigma = 6$ mm, $\bar{h} = 5$ kW/(m$^2$K)

FIGURE: Temperature distribution for $P^{beam} = \{1, 4\}$ MW and beam profile $\sigma = \{4, 6\}$ mm in Be target. Electrical current $i_{rms} = 15$ kA at 5000 Hz, for $z = \{0, 10, 30, 60\}$ cm (blue, green, red, light blue)

continue with $\bar{h} = \{5, 10, 15, 20\}$ kW/(m$^2$K)

# TEMPERATURE VERSUS CONVECTION COEFF H, AL

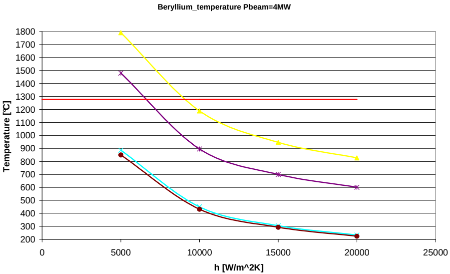


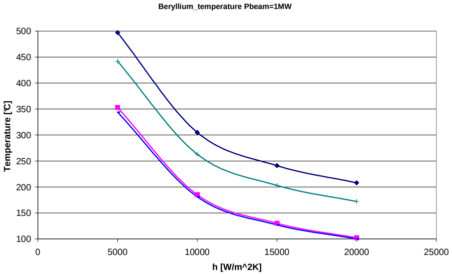


- $T_{core}$, $T_s$: core and surface temperature for $\sigma^{bm} = \{4,6\}$ mm and $P^{beam} = 4$ MW
- $T_{core}^{4mm}$, $T_{core}^{6mm}$, $T_s^{4mm}$, $T_s^{6mm}$ (yellow, purple, blue, brown)
- Temperature exceeds melting point of Al (555 °C)at 4 MW
- not feasible with Aluminium at 4 MW for this h cooling range

- $T_{core}^{4mm}$, $T_{core}^{6mm}$, $T_s^{4mm}$, $T_s^{6mm}$ (dark blue, green, pink, blue) for $\sigma^{bm} = \{4,6\}$ and $P^{beam} = 1$ MW
- $T_{core} \lesssim 300\,^{\circ}\mathrm{C} \rightarrow \bar{h} \gtrsim 13,20kW/m^2K$ $(\sigma = 6,4mm)$
- large core temperature difference between $\sigma = 6,4mm$ beam, not for surface temperature

# TEMPERATURE VERSUS CONVECTION COEFF H, BE





- $T_{core}^{4mm}$, $T_{core}^{6mm}$, $T_s^{4mm}$, $T_s^{6mm}$ (yellow, purple, blue, brown) for $\sigma^{bm} = \{4,6\}$ and $P^{beam} = 4$ MW
- $T_{core} - T_s \backsimeq 900, 600\,^{\circ}\mathrm{C}$, $\sigma = 4, 6$ mm
- $T_{core\;\sigma=4} - T_{core\;\sigma=6} \backsimeq 220 - 290\,^{\circ}\mathrm{C}$
- high temperature
- Max temperature lower with $\sigma = 6$ mm

- $T_{core}^{4mm}$, $T_{core}^{6mm}$, $T_s^{4mm}$, $T_s^{6mm}$ (dark blue, green, pink, blue) for $\sigma^{bm} = \{4,6\}$ and $P^{beam} = 1$ MW
- $T_{core} - T_s \backsimeq 144, 98\,^{\circ}\mathrm{C}$, $\sigma = 4, 6$ mm
- $T_{core\;\sigma=4} - T_{core\;\sigma=6} \backsimeq 55\,^{\circ}\mathrm{C}$
- $T_{core} \lesssim 300\,^{\circ}\mathrm{C} \rightarrow \bar{h} \gtrsim 8, 10 kW/m^2K$ $(\sigma = 6, 4mm)$

# CONCLUSION – NEXT STEPS

- Study of target cooling for $\{1, 4\}$ MW - beam and Joule effect
- Aluminium material cannot be used at 4 MW
- Possible for Beryllium (and also AlBeMet, Carbon)
- Seem difficult to use a solid target at 4 MW; need very efficient cooling $\bar{h} \gtrsim 20kW/(m^2K)$
- Ok at 1 MW with high cooling rate $\bar{h} \sim 10kW/(m^2K)$
- Next steps
  cooling - find explicit realisations: flow rates, pressures, nozzle dimensions
  design complexity versus physics performance degradation
- Other: mechanical stress