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Thermal study of an integrated target to an electromagnetic horn

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OUTLINE

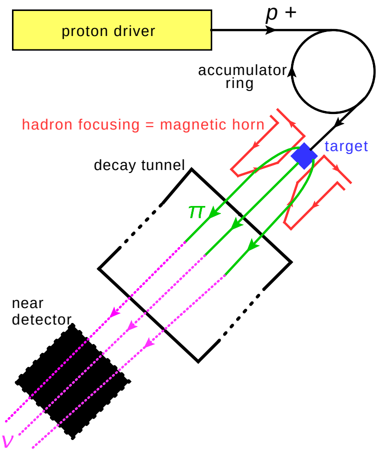
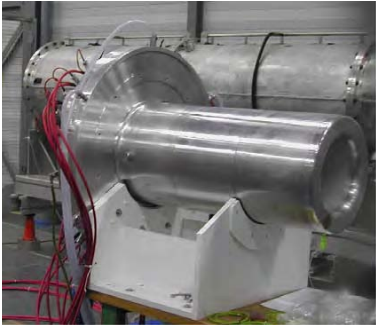


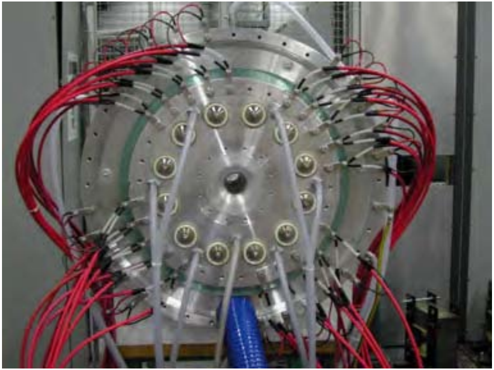
FIGURE: Euronν project: Neutrino factory schematic

- Neutrino factory project
- Electromagnetic horn with integrated target: working principle
- Goal: determine the cooling requirement to maintain the max temperature below a limit
- Model: equations, heat sources, boundary conditions, assumptions
- Results
- Summary/conclusion

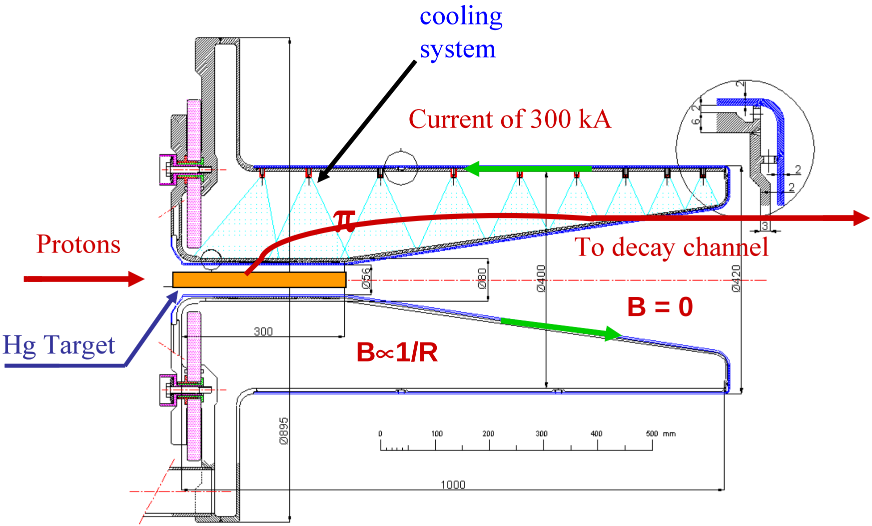
ELECTROMAGNETIC HORN



a) CERN Horn prototype

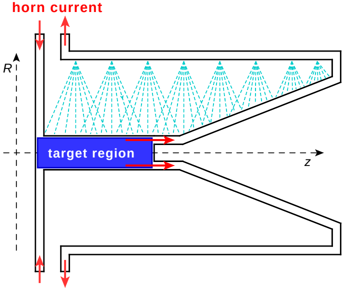


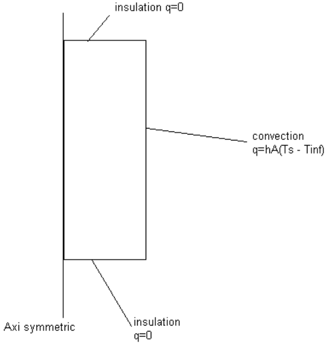
b) electrical connections and water inlet/outlet


cooling
system
Current of 300 kA
π
Protons
To decay channel
Hg Target
B = 0
B∝1/R
300
1000
Ø56
Ø80
Ø400
Ø420
Ø895
0
100
200
300
400
500 mm

PHYSICS

- High pulsed currents: peak currents 300kA, pulse duration 100μs $\Rightarrow$ AC currents, skin depth; joule losses, magnetic field, magnetic pressure/force, vibrations, fatigue.
- Interaction target/proton beam: High power density deposit: $3kW/cm^3$. Pulse length: $5\mu s$ $\Rightarrow$ thermal stress wave, fatigue, irradiation.
- Cooling circuit $\Rightarrow$ convection heat transfer; fluid dynamics (turbulent), heat transfer
- Life time of the system $\Rightarrow$ fatigue analysis.





- 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)

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

$$\text{crosssection}: \quad S = \pi\delta\,(2r_e - \delta)$$

$$\text{skin depth}: \quad \delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

$$\text{resistance} \quad \frac{R}{l} = \frac{\rho}{S}$$

$$\text{Power} \quad \frac{P}{l} = R\, i_{rms}^2 = [108,\ 77.5,\ 64]\ kW/m$$

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

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

Time harmonic currents, equation reduced to:

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

average volume energy density:

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

For time harmonic fields, the time average of the product of two vectors is:

$$\overline{\vec{A}(\mathbf{r}, t) \cdot \vec{B}(\mathbf{r}, t)} = \frac{1}{2} Re(\mathbf{A} \cdot \mathbf{B}^*) \tag{2}$$

$$\vec{A}(\mathbf{r}, t) = Re(\mathbf{A} e^{j\omega t}) \tag{3}$$

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

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]	σ^{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

Model-Boundary conditions

Thermal: Heat conduction, 2d axisymmetric

- 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)

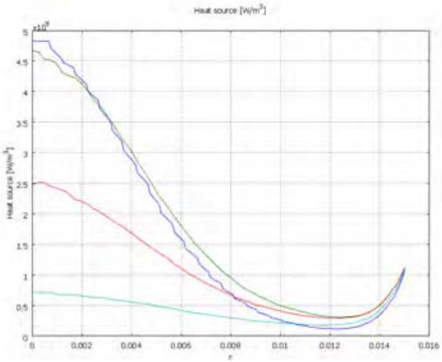
$$q = 2\pi R\, L\, \bar{h}\, (T_s - T_\infty)$$

T_s and T_∞ the surface and fluid temperature, q heat flux

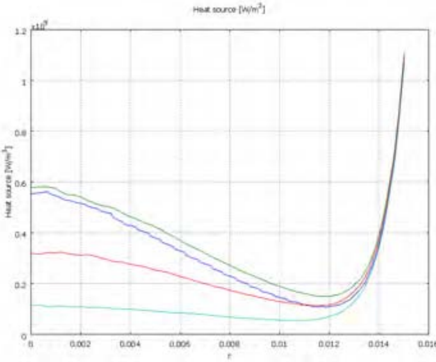
Electrical: Meridional induction current, vector potential, 2d axisymmetric

- $z = \{0,\ 0.78\}$ 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



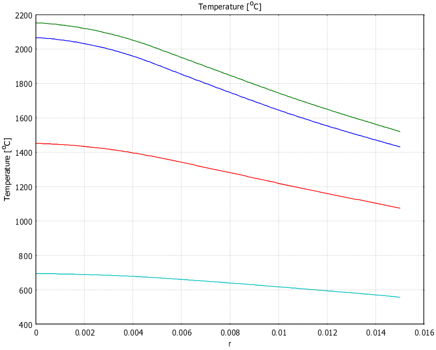
a) Al, 4 MW, $\sigma = 4$ mm



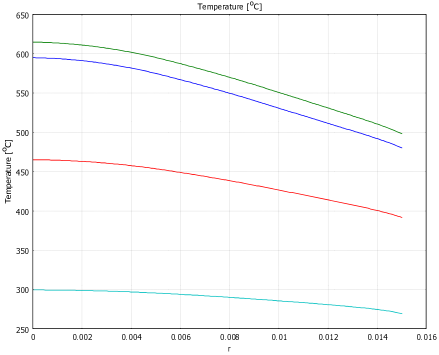
b) Al,1 MW, $\sigma = 6$ mm

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



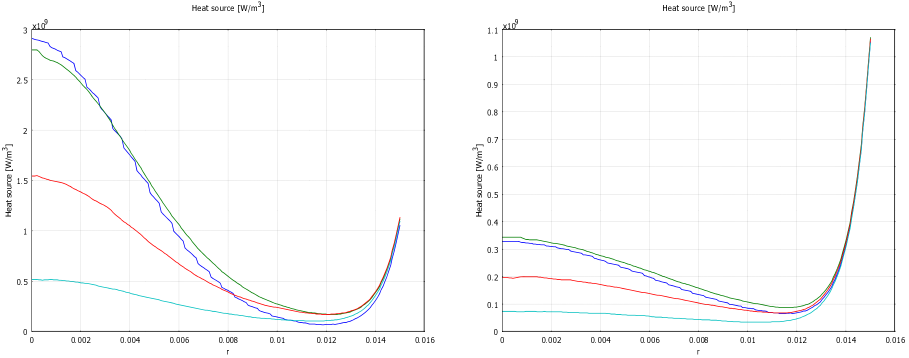
a) Al, 4 MW, $\sigma = 4$ mm, $\bar{h} = 5$ kW/(m^{2}K)



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

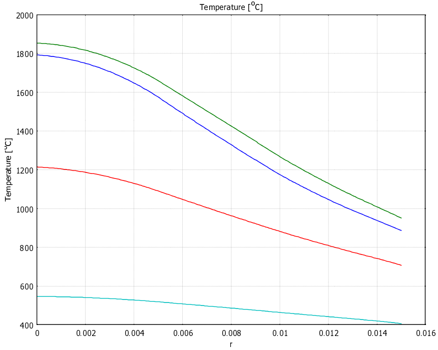


a) Be, 4 MW, $\sigma = 4$ mm

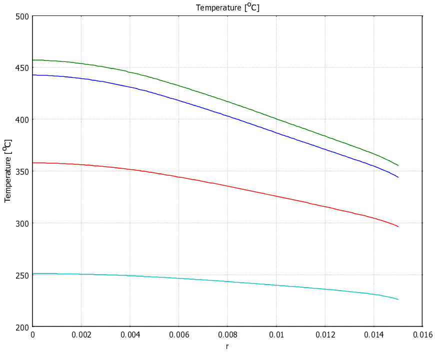
b) Be,1 MW, $\sigma = 6$ mm

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)

TEMPERATURE DISTRIBUTION, BERYLLIUM



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

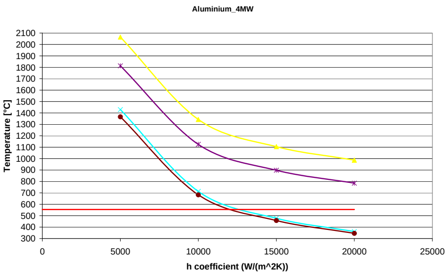


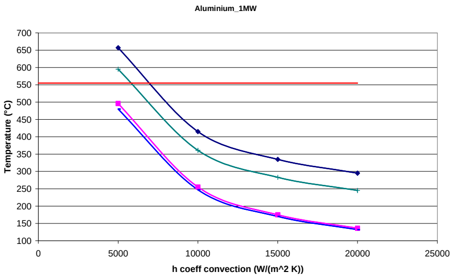
b) Be,1 MW, $\sigma = 6$ mm, $\bar{h} = 5$ kW/(m^{2}K)

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

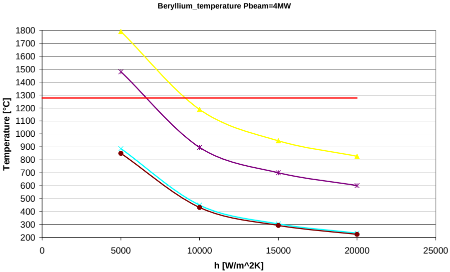


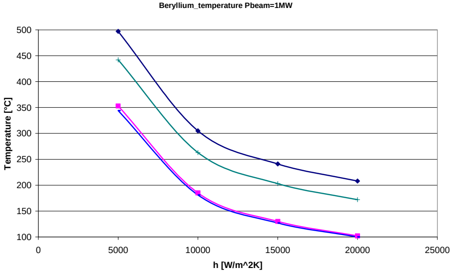


- T_{core}, T_s: core and surface temperature for $\sigma^{bm} = \{4, 6\}$ mm and $P^{beam} = 4$ MW
- T_{core}^{4mm}, T_{core}^{6mm}, T_s^{4mm}, T_s^{6mm} (yellow, purple, blue, brown)
- Temperature exceeds melting point of Al (555 °C)at 4 MW
- not feasible with Aluminium at 4 MW for this h cooling range

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

Temperature versus convection coeff h, Be

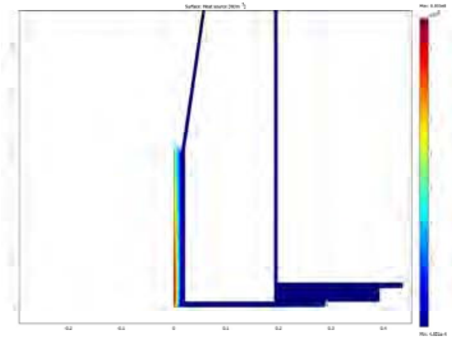


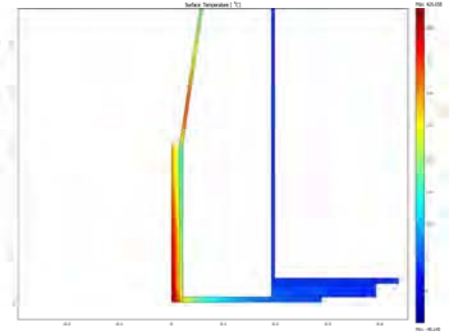


- T_{core}^{4mm}, T_{core}^{6mm}, T_s^{4mm}, T_s^{6mm} (yellow, purple, blue, brown) for $\sigma^{bm} = \{4, 6\}$ and $P^{beam} = 4$ MW
- $T_{core} - T_s \simeq 900, 600\,^\circ\mathrm{C}$, $\sigma = 4, 6$ mm
- $T_{core\,\sigma=4} - T_{core\,\sigma=6} \simeq 220 - 290\,^\circ\mathrm{C}$
- high temperature
- 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
- $T_{core} - T_s \simeq 144, 98\,^\circ\mathrm{C}$, $\sigma = 4, 6$ mm
- $T_{core\,\sigma=4} - T_{core\,\sigma=6} \simeq 55\,^\circ\mathrm{C}$
- $T_{core} \lesssim 300\,^\circ\mathrm{C} \rightarrow \bar{h} \gtrsim 8, 10 kW/m^2K$ $(\sigma = 6, 4mm)$

TARGET AND HORN, POWER DENSITY AND TEMPERATURE DISTRIBUTION





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 $\bar{h} \sim 10kW/(m^2K)$