Focused Cross Flow LBE Target for ESS

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Jörg Wolters, Michael Butzek

Contents

- **2003 reference design for a mercury target**
  - concept
  - boundary conditions
  - new findings (attained after 2003; e.g. during FP7 in 2009)

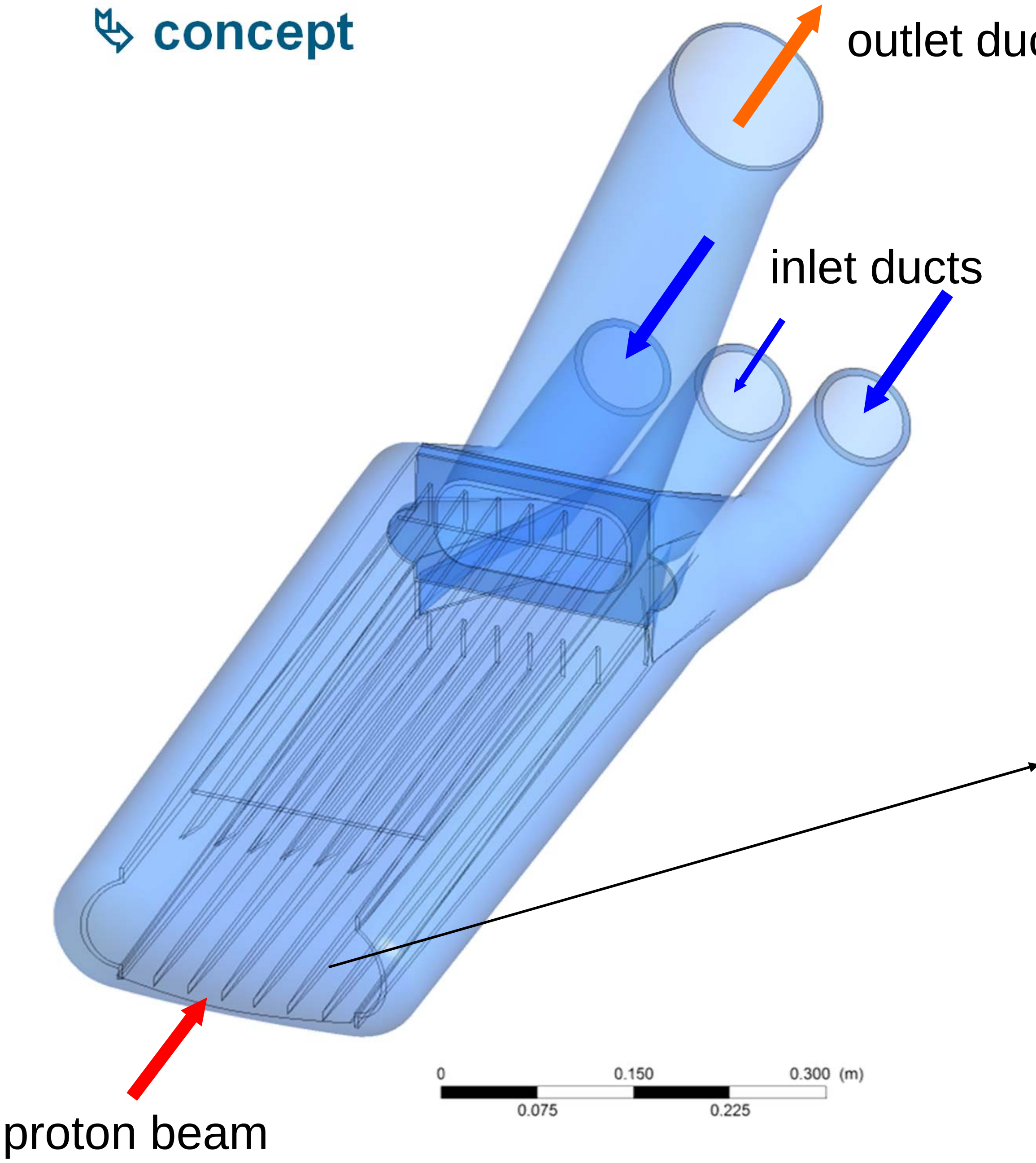
- **Changes to boundary conditions and their effect on the target design**
  - LBE (lead-bismuth eutectic) as preferred liquid metal
  - proton energy and beam profile
  - pulse frequency
  - short pulse ⇒ long pulse

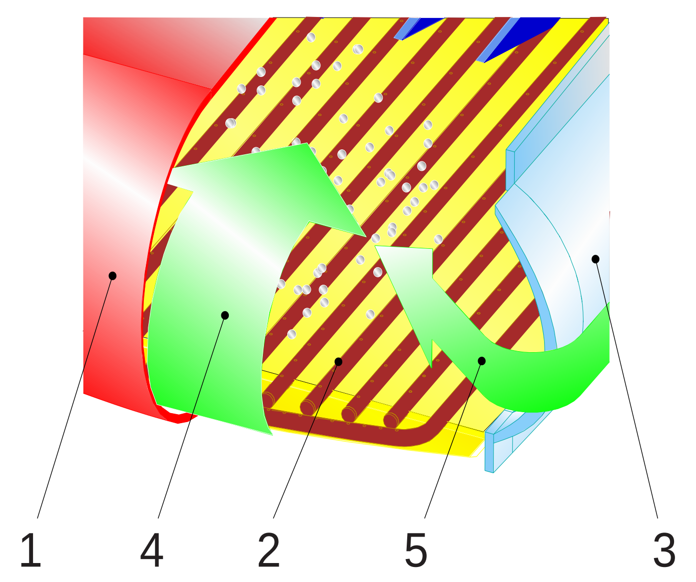
- **Focused Cross Flow Target**
  - concept
  - updated boundary conditions
  - pros and cons

- **Conclusions and outlook**

2003 reference design for a mercury target

↳ concept



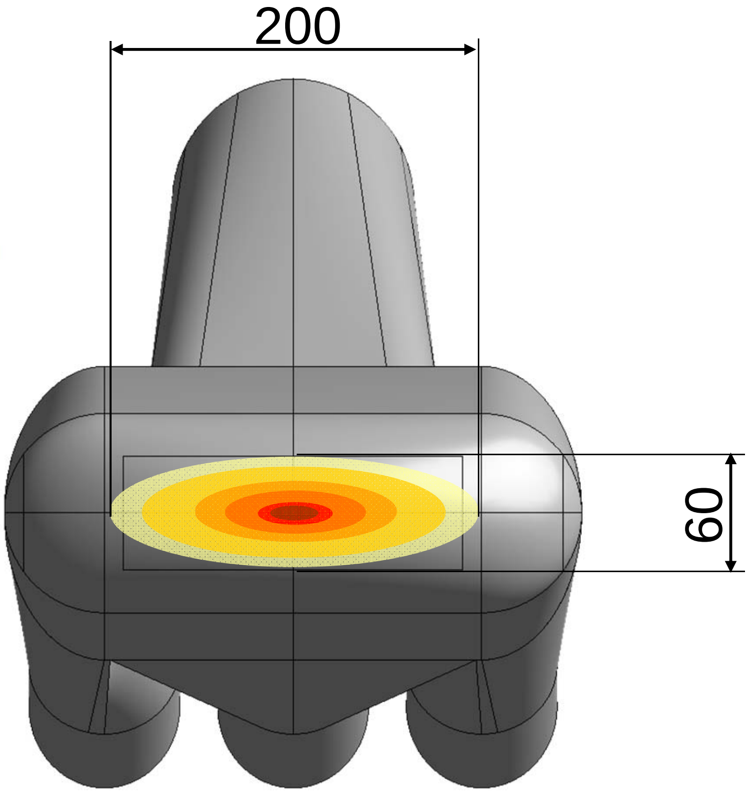


1: proton beam entry window;
2: bottom flow separator plate with potentially needed gas injector system;
3: lateral flow separator plate;
4: indicated mercury center flow;
5: indicated mercury lateral flow.

2003 reference design for a mercury target

↳ boundary conditions

- 5 MW beam power / ~2.9 MW heat deposition (incl. 20% safety margin)
- 50 Hz pulse frequency
- 1.4 µs pulse length
- 1.334 GeV proton energy
- elliptical beam footprint (200mm x 60mm)
- parabolic beam profile
- 175 kg/s mercury flow
  (best operating conditions for
  15% of total mass flow rate through
  bottom inlet duct)
- 100 °C inlet temperature
- ~220 °C mean outlet temperature
  - $\Delta T_{window} \cong 7$ K / pulse
  - $\Delta T_{Hg} \cong 37$ K / pulse

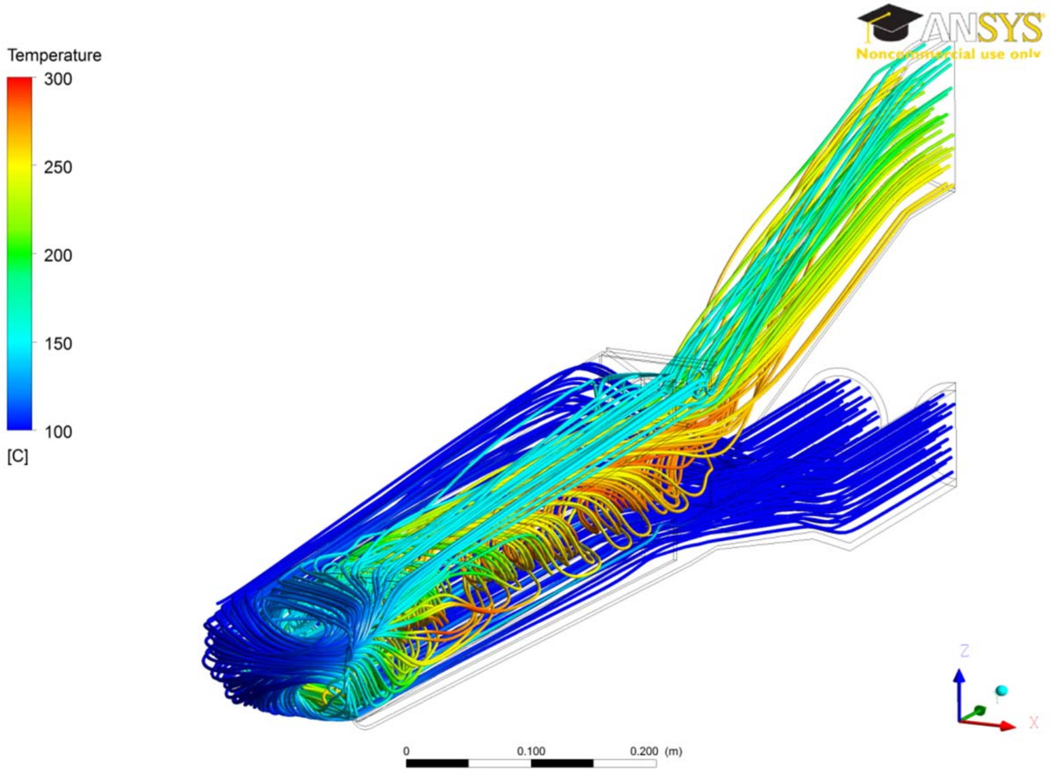


elliptical beam footprint

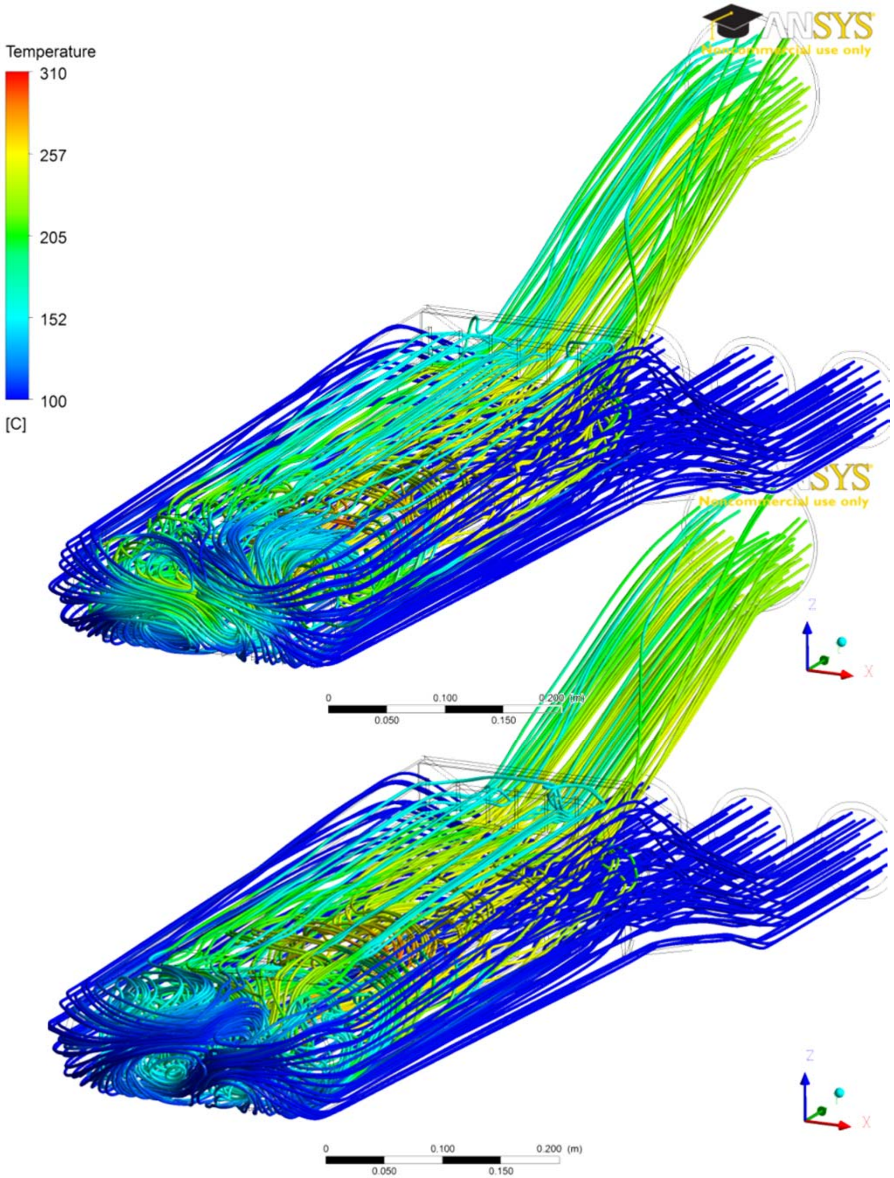
2003 reference design for a mercury target

↳ new findings

- flow instabilities (transient effects and effects due to slightly unsymmetric inlet conditions) can lead to zones of high temperatures in the bulk outlet region of the target, alternately touching the walls



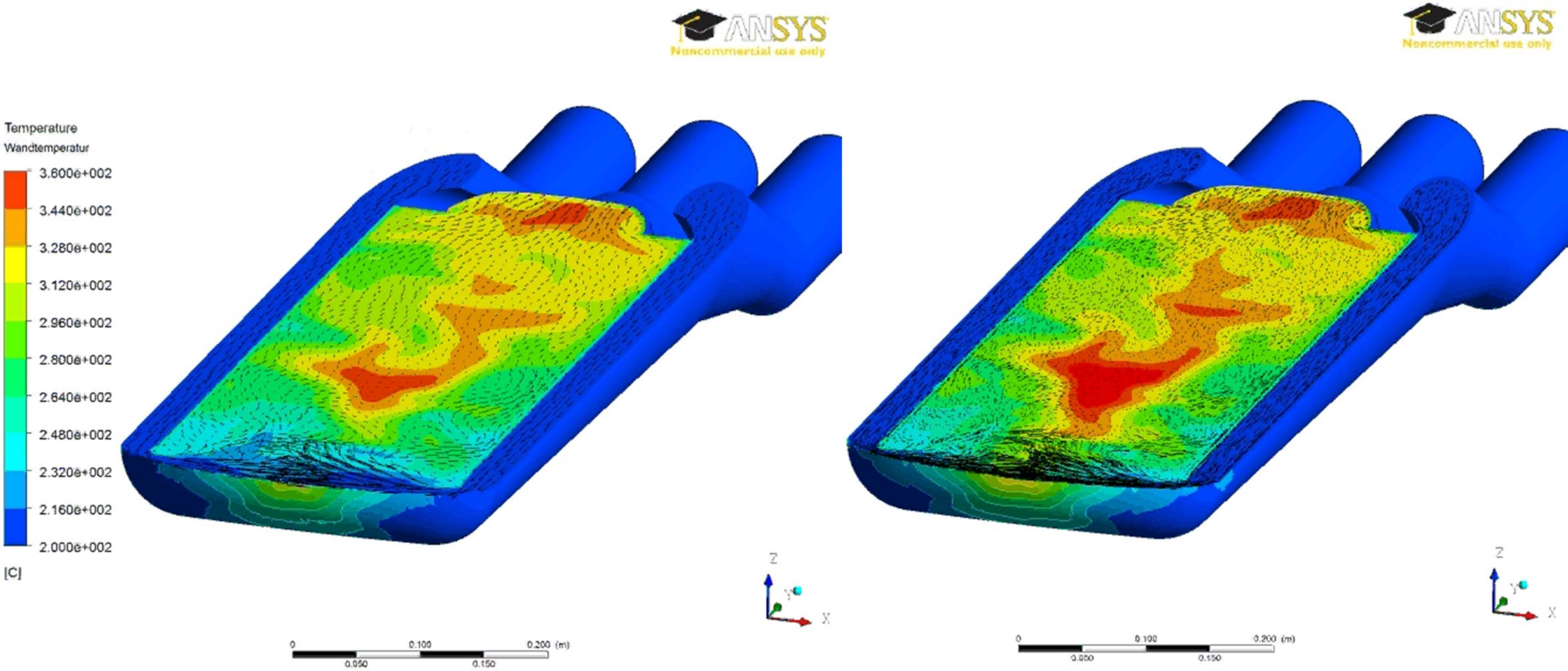
left: stationary calculation performed for a half-model showing stable vortices in the front part



right: transient calculation performed for a full-model showing strong fluctuations

2003 reference design for a mercury target

↳ new findings



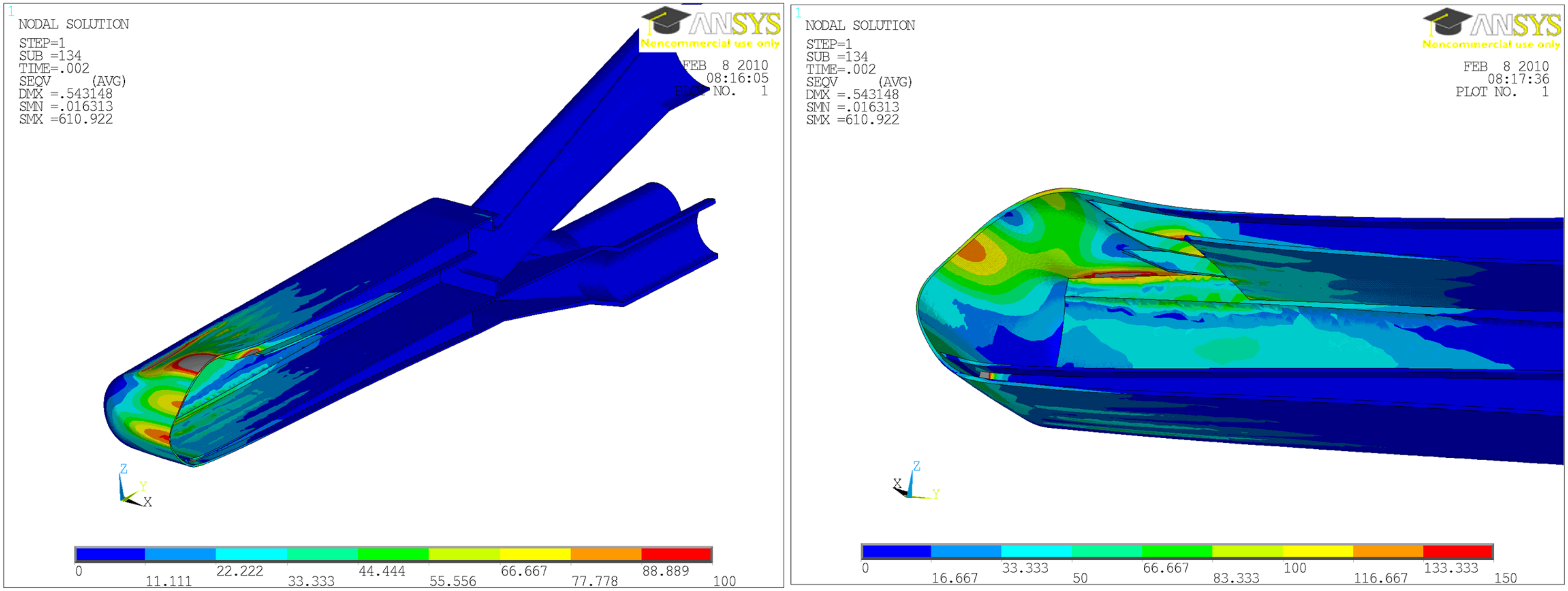
left: transient calculation for perfectly symmetric inlet conditions

right: transient calculation for unsymmetric inlet conditions (mass flow rate suddenly increased by 2% for right and decreased by 2% for the left side duct)

2003 reference design for a mercury target

↳ new findings

- time scale of the long-pulse (2 ms) is still small compared to inertia effects of the target material in the rear end of the target
- thermal expansion of the target material is compensated by local compression of the material itself and a local expansion of the target container in the front part
- expansion of target container may lead to significant stresses in the window region



stressing of the target window for a mercury long-pulse target at 16 $^2/_3$ Hz

Changes to boundary conditions

↳ LBE as preferred liquid metal

- ➢ LBE as preferred target material for a liquid metal target

⇒ same pressure drop can be expected for a mass flow rate of:

$$\dot{m}_{LBE} = \dot{m}_{Hg}\sqrt{\frac{\rho_{LBE}}{\rho_{Hg}}} = 155\,\frac{kg}{s}$$

⇒ heat removal capability is comparable:

$$\frac{\dot{m}_{LBE}\cdot c_{p_{LBE}}}{\dot{m}_{Hg}\cdot c_{p_{Hg}}} = 0.95$$

⇒ heat transfer coefficients are comparable:
(e.g. formulas for turbulent pipe flow, d ≅ 100mm):

$$\frac{\alpha_{LBE}}{\alpha_{Hg}} = 1.084$$

↳ thermal-hydraulic design is similar for mercury and LBE

but

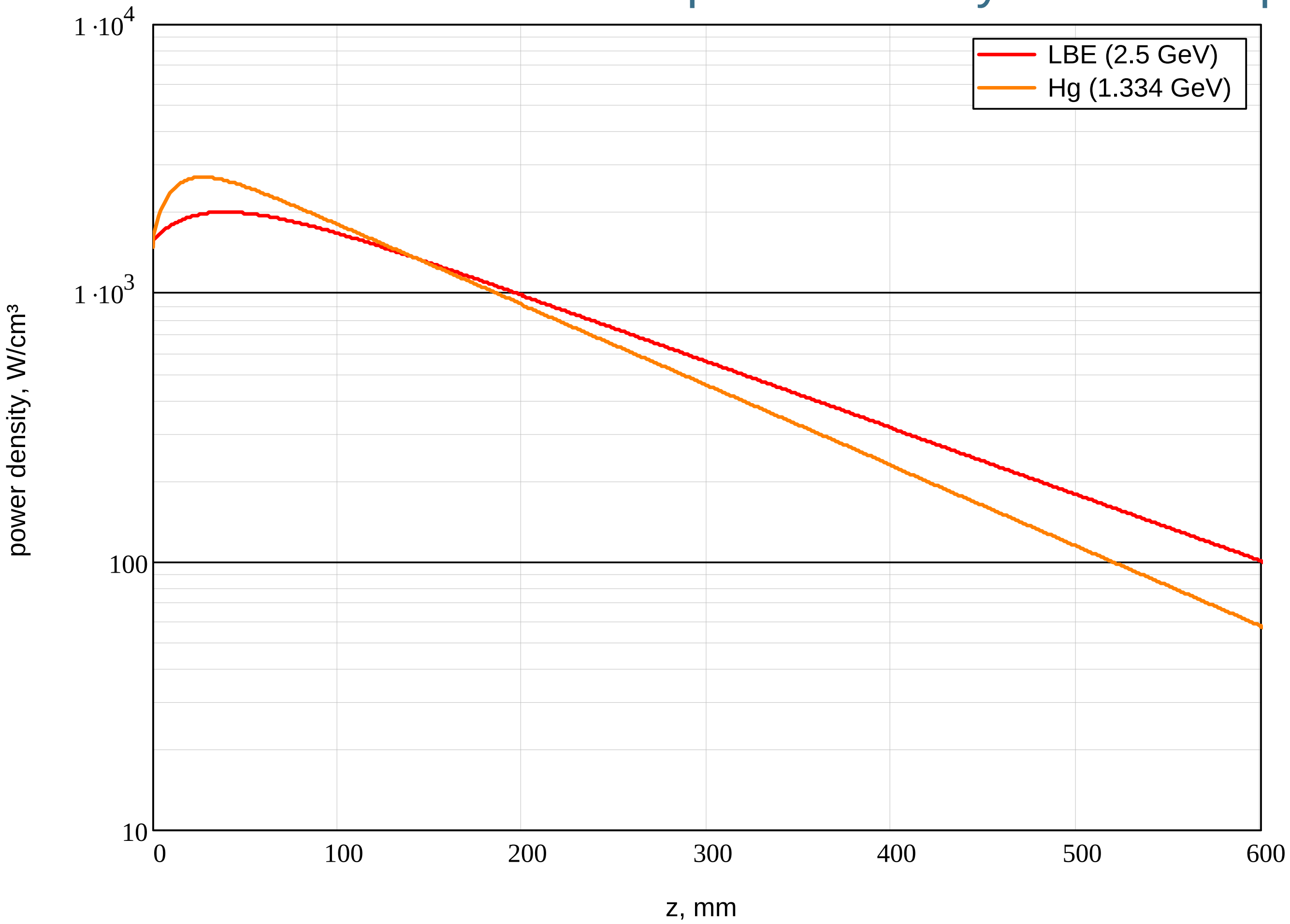
- ➢ to avoid solidification of LBE, the inlet temperature must be significantly higher: 175 – 200°C (> 125°C) for LBE instead of 100°C for mercury
- ➢ no risk of evaporation (evaporation temperature is 1670°C for LBE instead of 357°C for mercury)

Changes to boundary conditions

↳ <u>proton energy</u> and beam profile

↳higher proton energy ⇒ reduced power density in the front part

⇒ increased power density in the rear part



Power density along the beam axis for Hg with 1.334 GeV protons and LBE with 2.5 GeV protons, both for 2.3 MW heat deposition

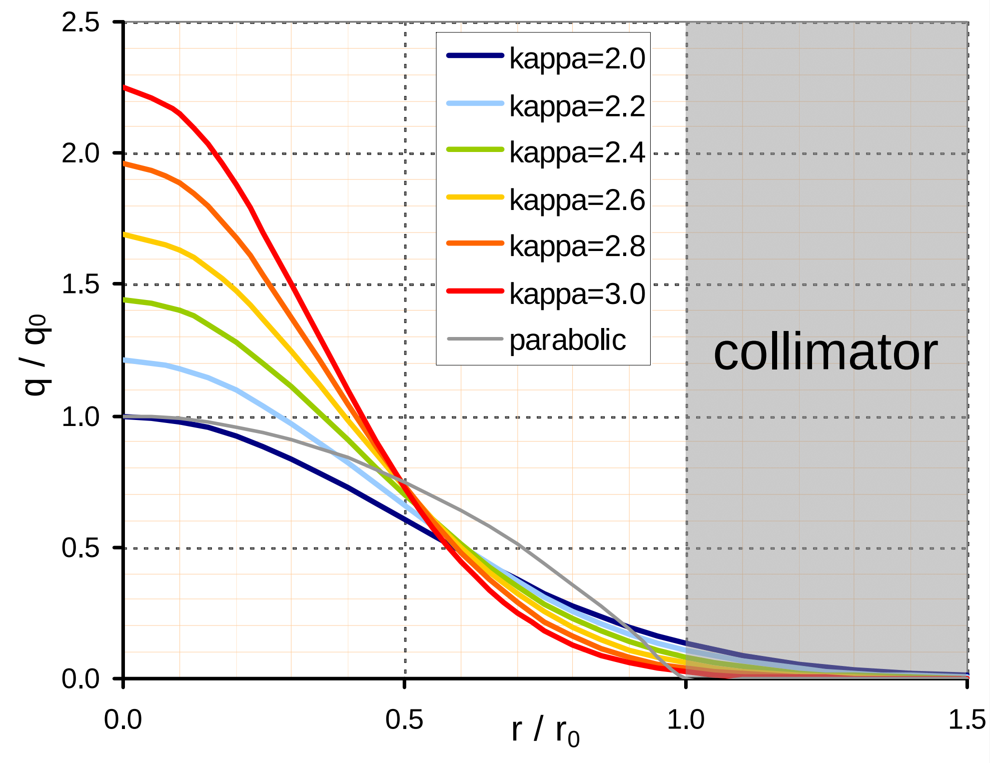
Changes to boundary conditions

↳ proton energy and beam profile

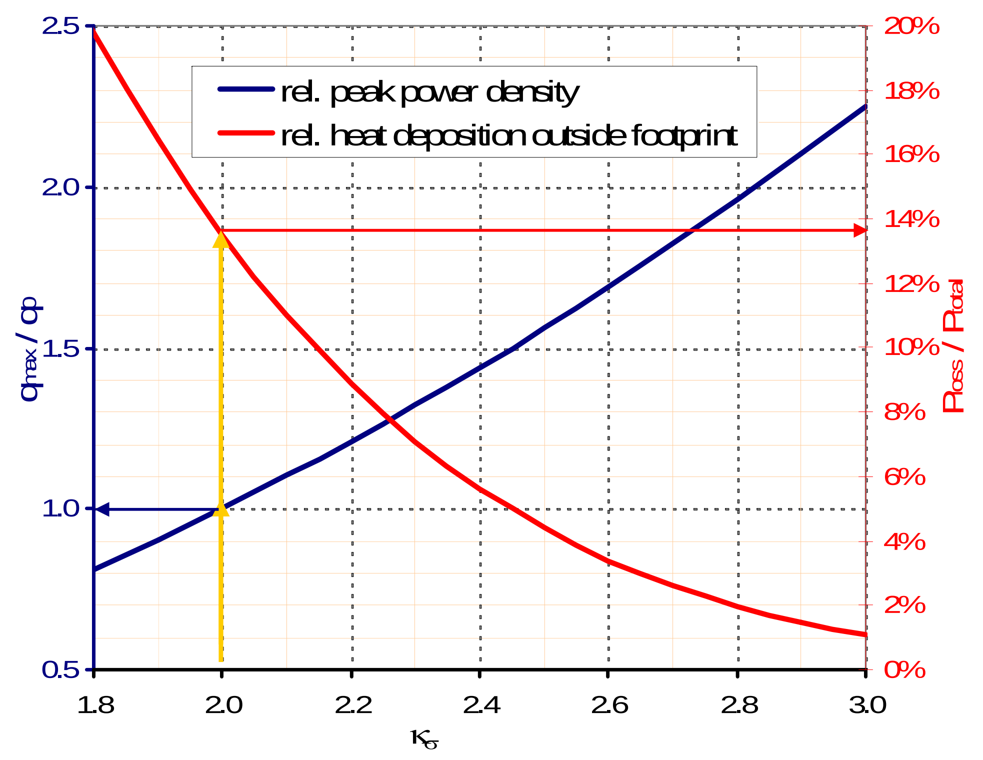
↳Gaussian beam profile with ± $\kappa_\sigma \cdot \sigma$ within the beam footprint

⇒ peak power density will be increased by $\kappa_\sigma^2/4$

⇒ energy outside of elliptical beam footprint: $e^{-0.5\cdot\kappa_\sigma^2}$ of total thermal energy (has to be removed by collimator)



left: radial distribution of rel. power density for different Gaussian profiles



right: rel. peak power density and heat loss for different Gaussian Profiles

Changes to boundary conditions

↳ pulse frequency

- decreased pulse frequency will increase the energy per pulse and therefore the temperature increment per pulse in the structure and fluid
- maximum values for a Gaussian beam profile and $\kappa_\sigma=2$

$\Delta T_{\text{window,50 Hz}} \cong 6$ K / pulse

⇩

$\Delta T_{\text{window,16 2/3 Hz}} \cong 18$ K / pulse

$\Delta T_{\text{LBE,50 Hz}} \cong 26$ K / pulse

⇩

$\Delta T_{\text{LBE,16 2/3 Hz}} \cong 79$ K / pulse

Changes to boundary conditions

↳ short pulse (1.4 μs) ⇒ long pulse (2 ms)

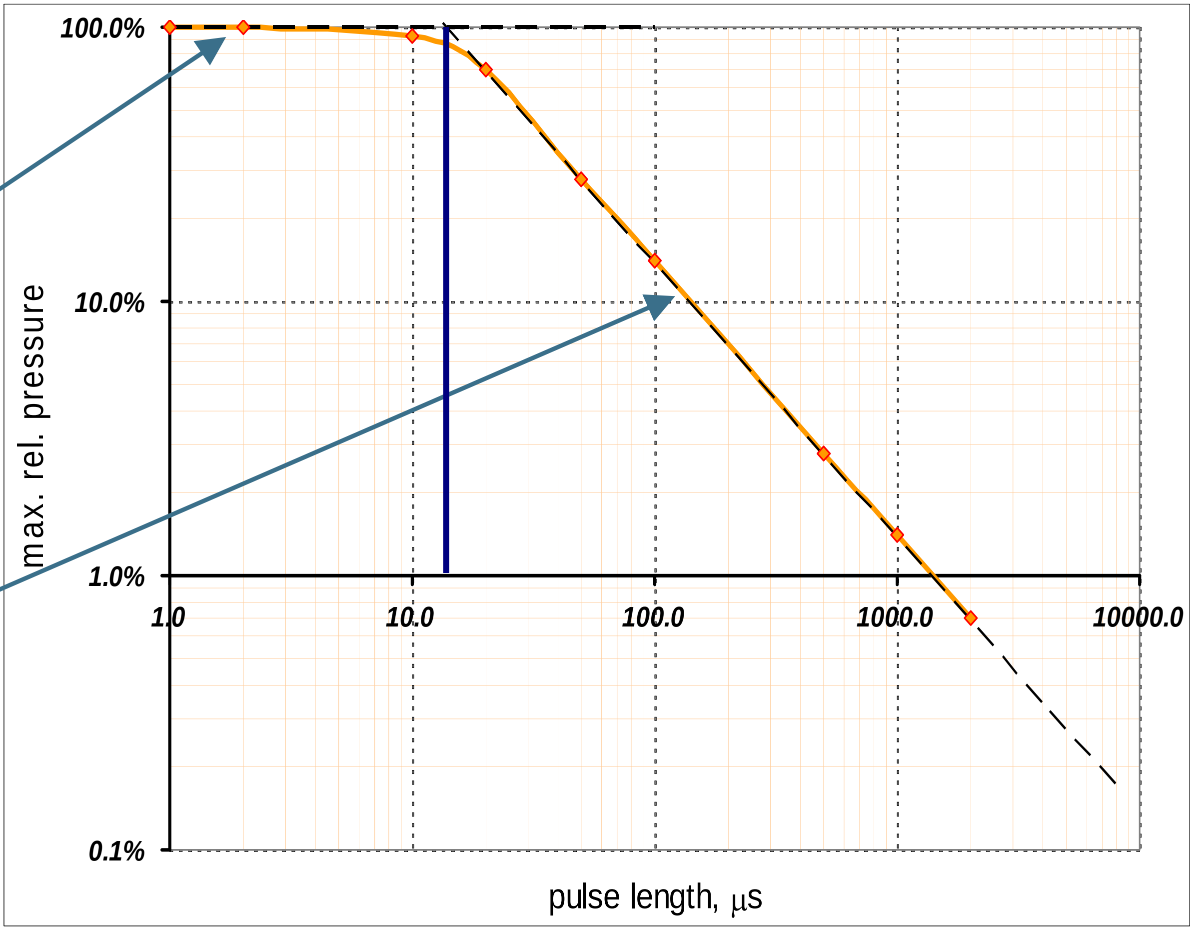
↳for the long pulse target the risk of cavitation damage is significantly reduced compared to the short pulse target

completely compressed thermal expansion of fluid

↳pressure pulse only depends on total energy per pulse and not on the pulse length

sudden change in heating rate will cause a pressure pulse at the beginning (positive) and the end (negative) of each proton pulse

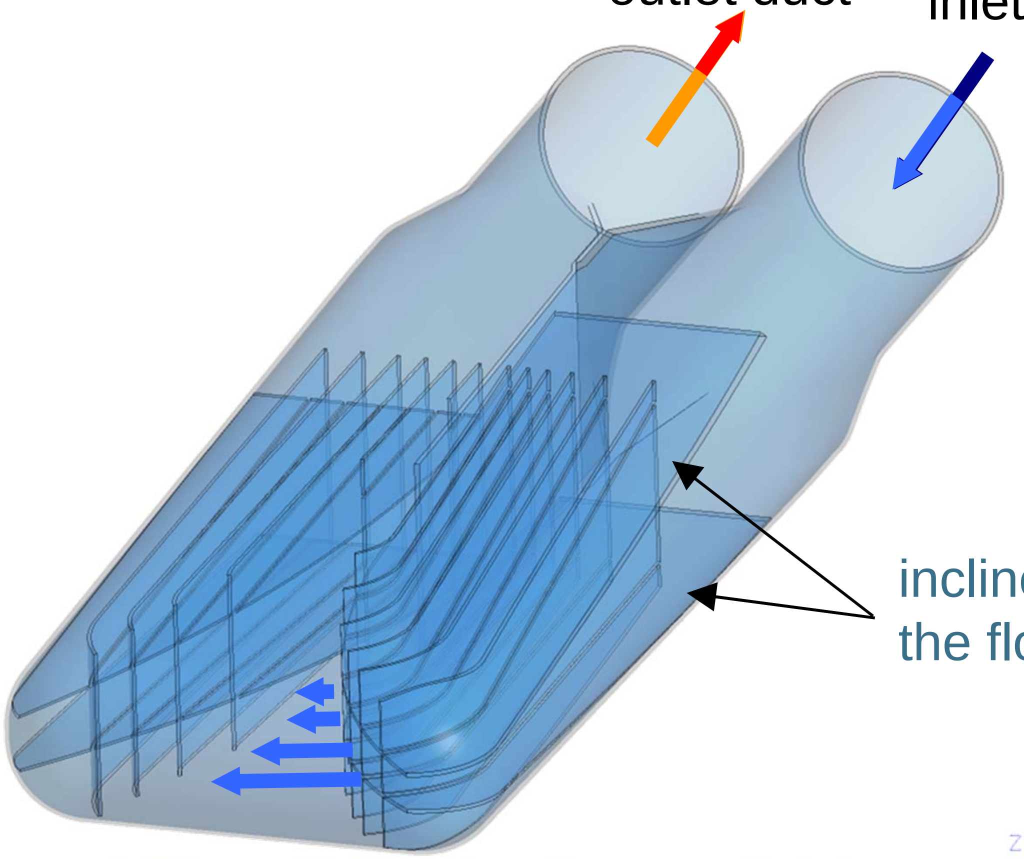
↳ pressure pulse strongly depends on pulse length



Focused Cross Flow Target

↳ concept

➢Main concept of the ‘focused cross flow design’:
- cross flow design for same container geometry than 2003 reference target
- inclined horizontal plates accelerate the flow in the horizontal midplane
- flow pattern in the critical zones is adjusted by curvature and variable spacing of baffles (in order to generate a certain pressure drop for each ‘channel’)


outlet duct

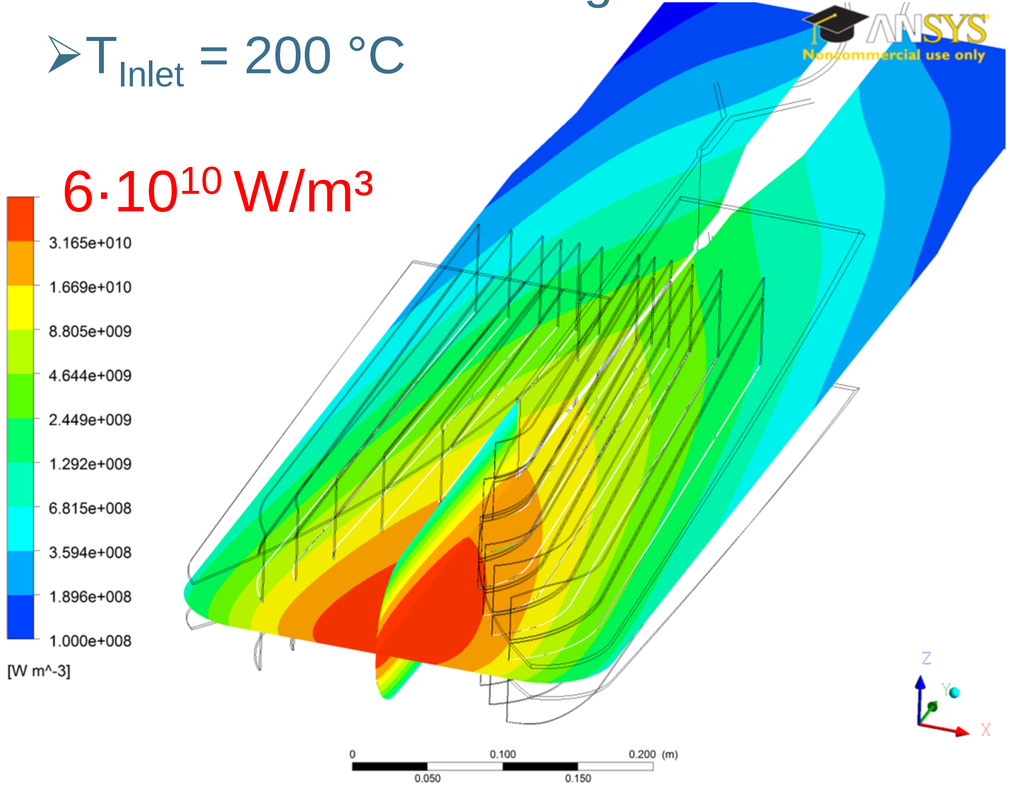
inlet duct

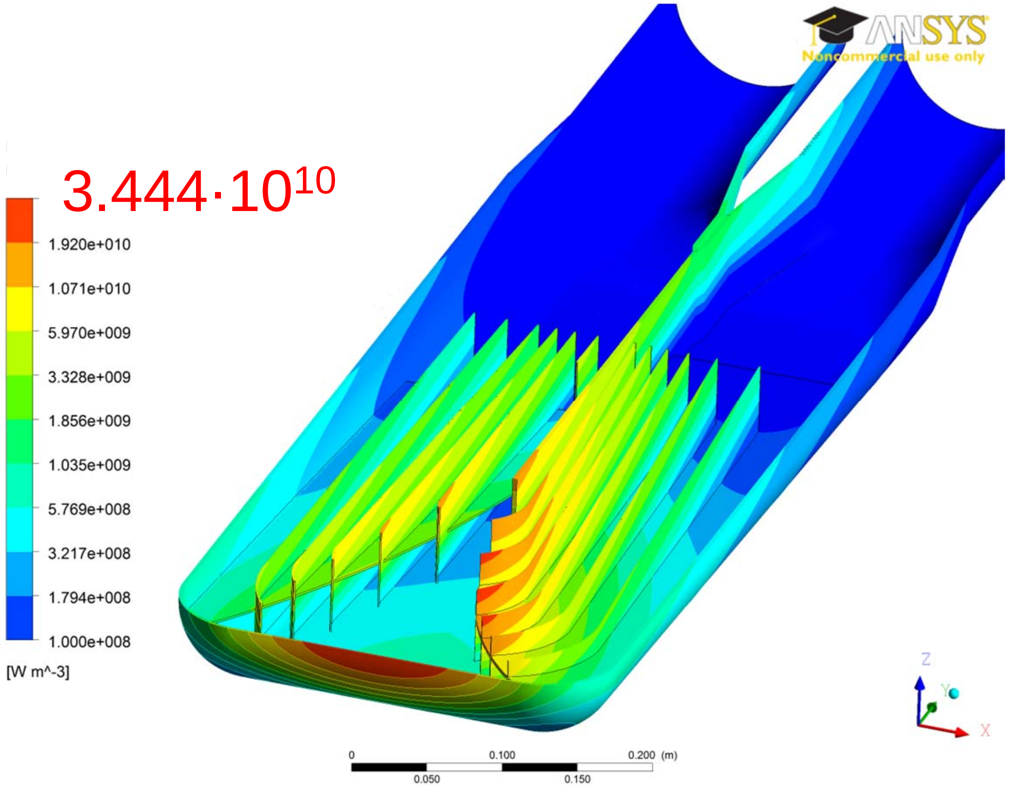
inclined plates to focus the flow to the mid-plane

Focused Cross Flow Target

↳ updated boundary conditions

- ➢total thermal power: 2.3 MW (FLUKA calculation by E. Noah)
- ➢pulse length: 2 ms
- ➢pulse frequency: 16 $^{2}/_{3}$ Hz
- ➢mass flow rate: 155 kg/s
- ➢T_{Inlet} = 200 °C





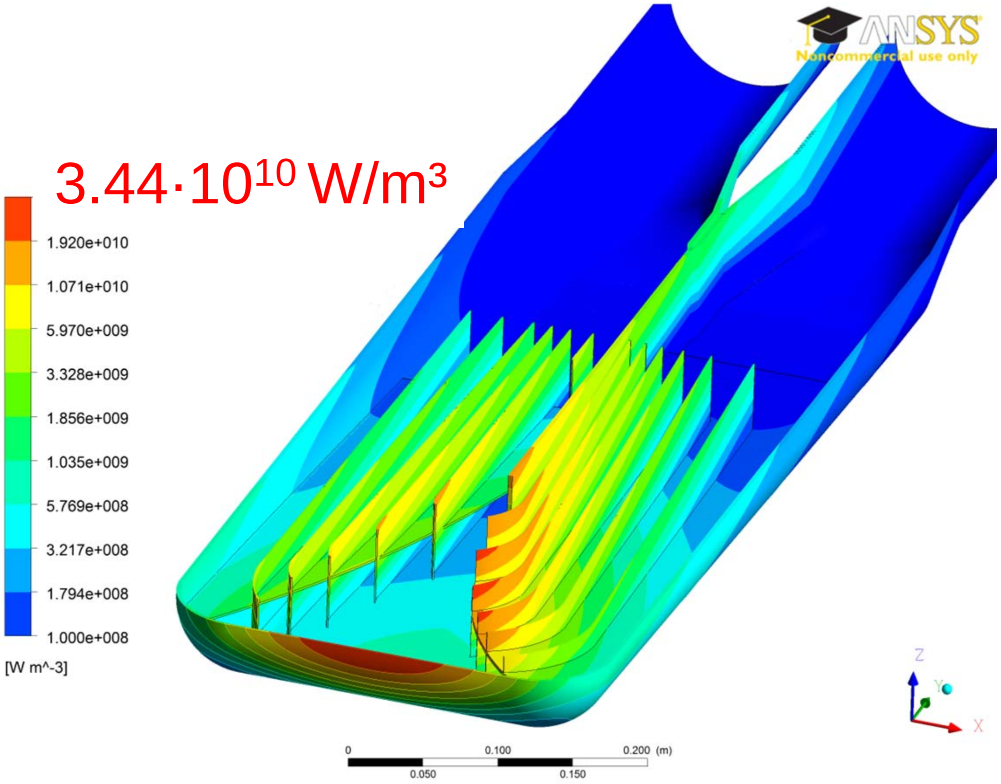
left: power density for LBE during pulse in W/m³

right: assumed power density for steel during pulse in W/m³ (scaled by density)

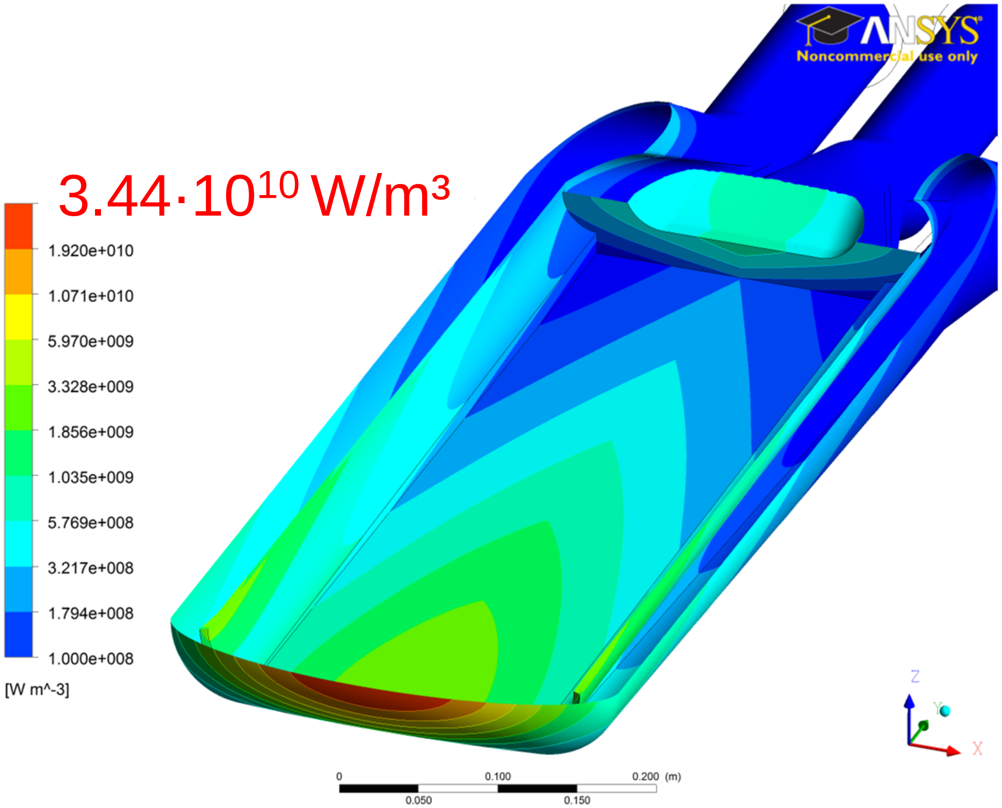
Focused Cross Flow Target

↳ pros and cons

- ➢ additional structural material within the zone of high heat deposition



left: power density in structural material for the focused cross flow target

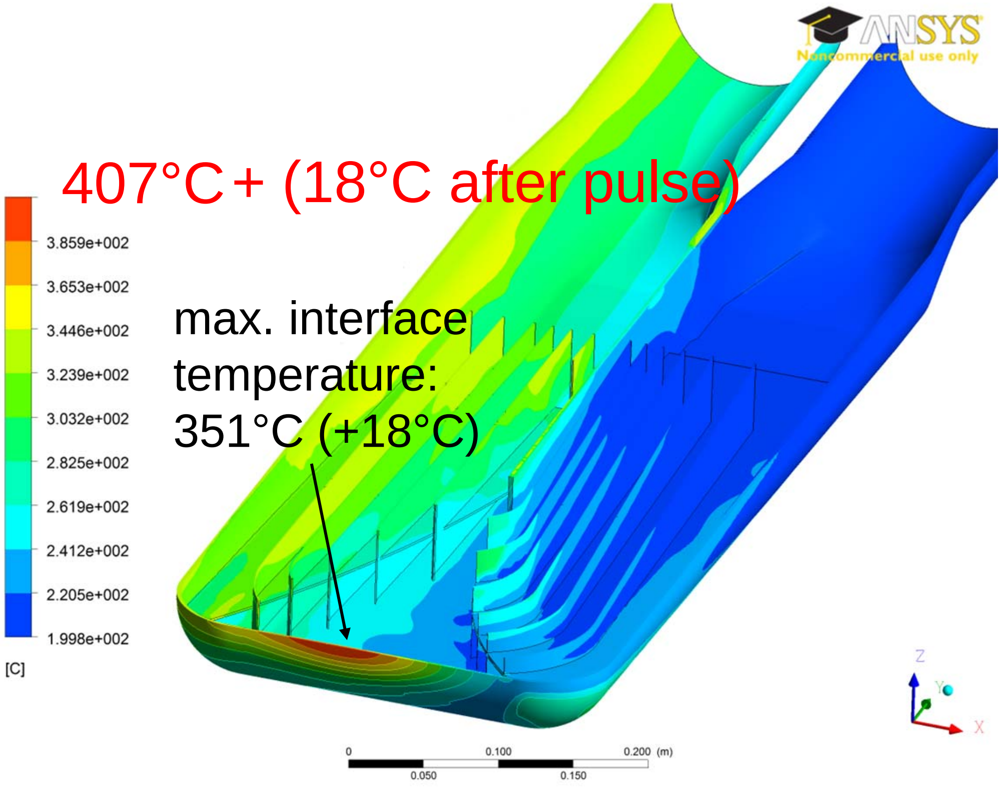


right: power density in structural material for the 2003 target design

Focused Cross Flow Target

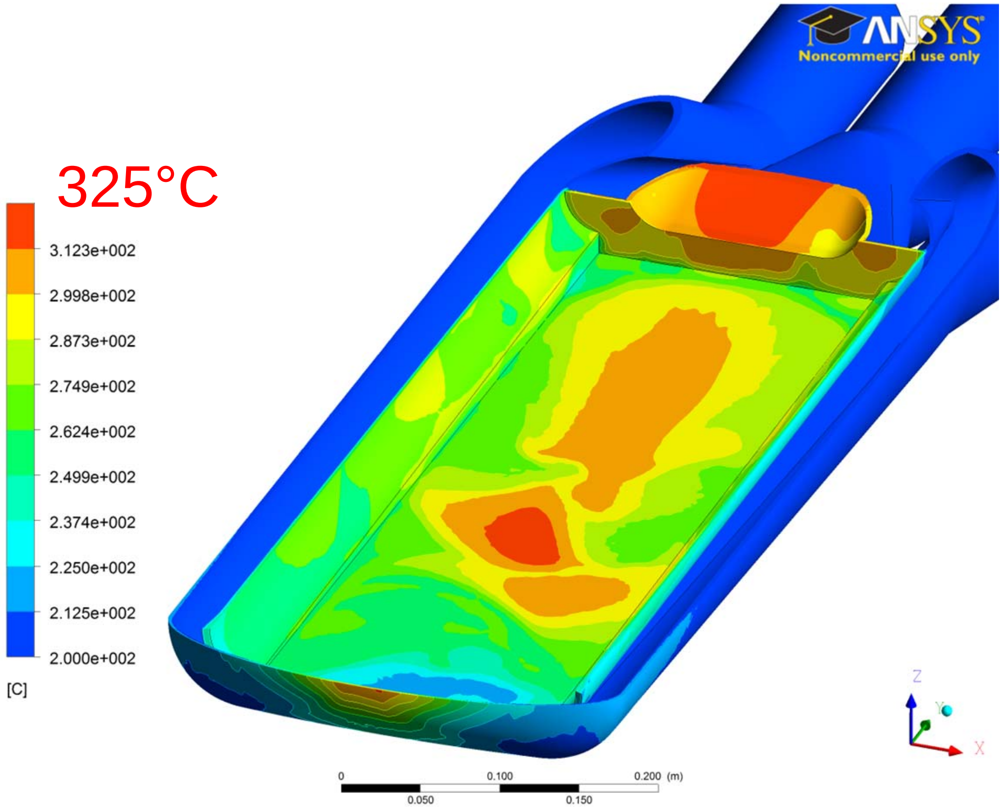
↳ pros and cons

- window cooling inferior to 2003 reference design



407°C + (18°C after pulse)

max. interface temperature: 351°C (+18°C)



325°C

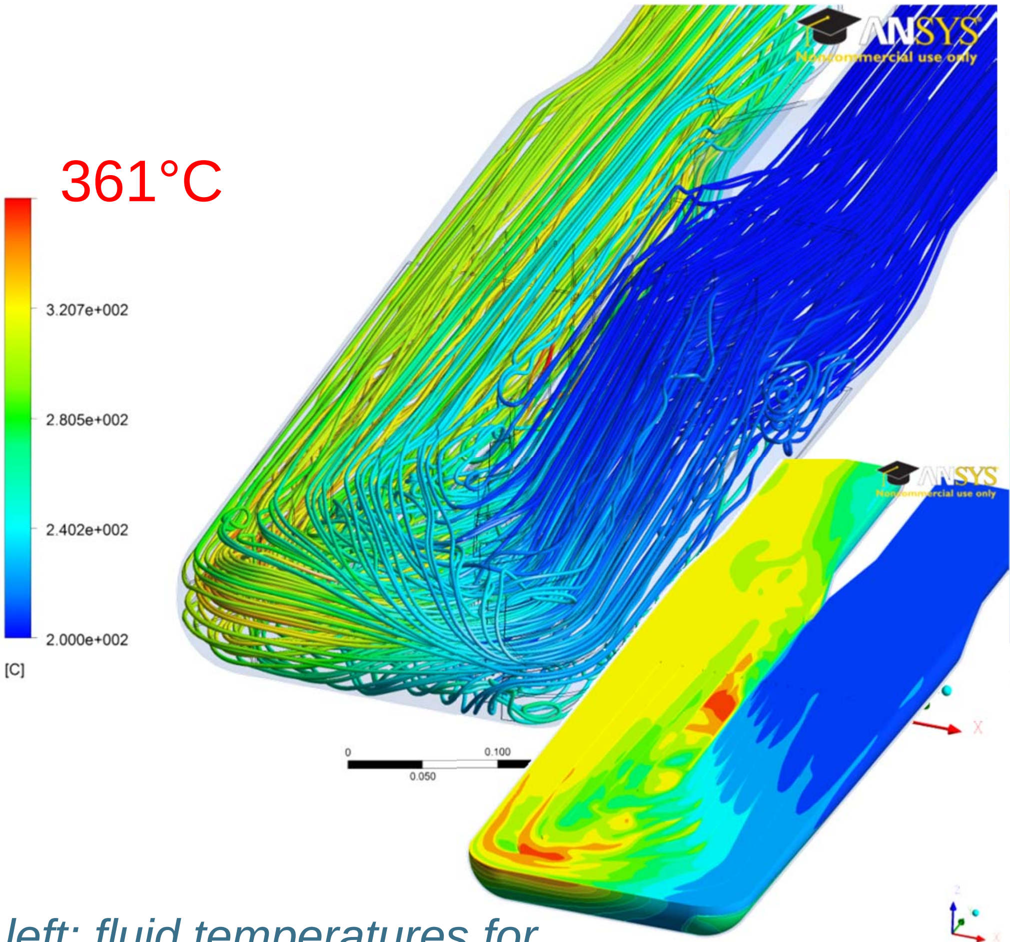
left: structural temperatures for focused cross flow target

right: structural temperatures for the 2003 target design

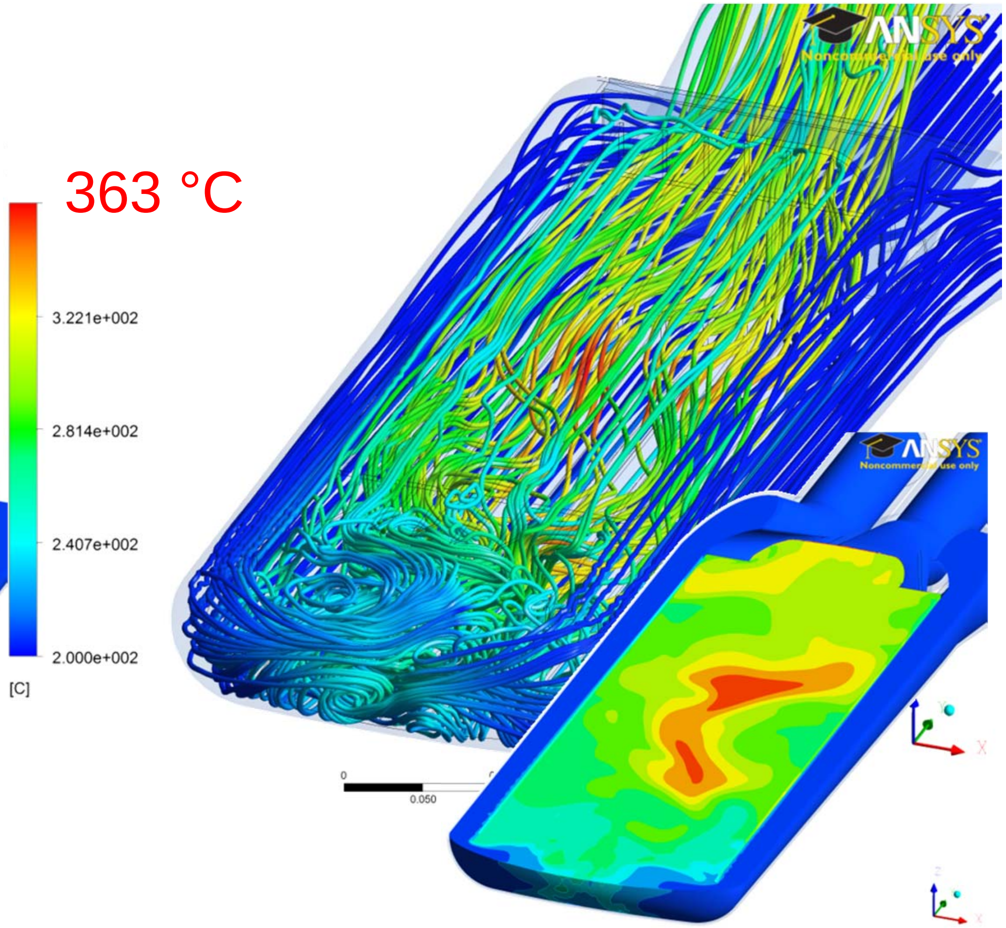
Focused Cross Flow Target

↳ pros and cons

- more reliable flow pattern and consequently more reliable heat removal
- less temperature fluctuations close to the container walls



left: fluid temperatures for
focused cross flow target

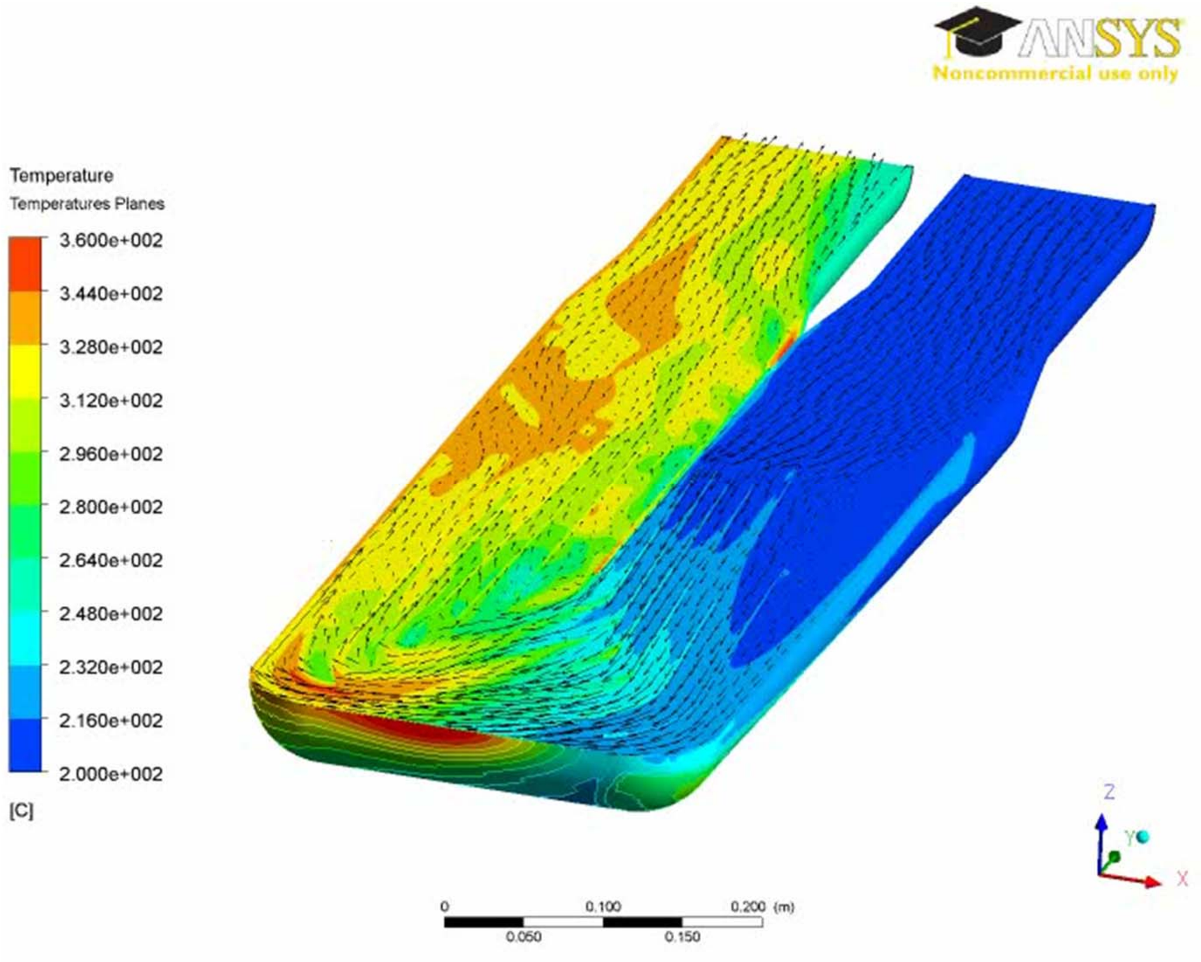


right: fluid temperatures
for the 2003 target design

Focused Cross Flow Target

↳ pros and cons

- more reliable flow pattern and consequently more reliable heat removal
- less temperature fluctuations close to the walls

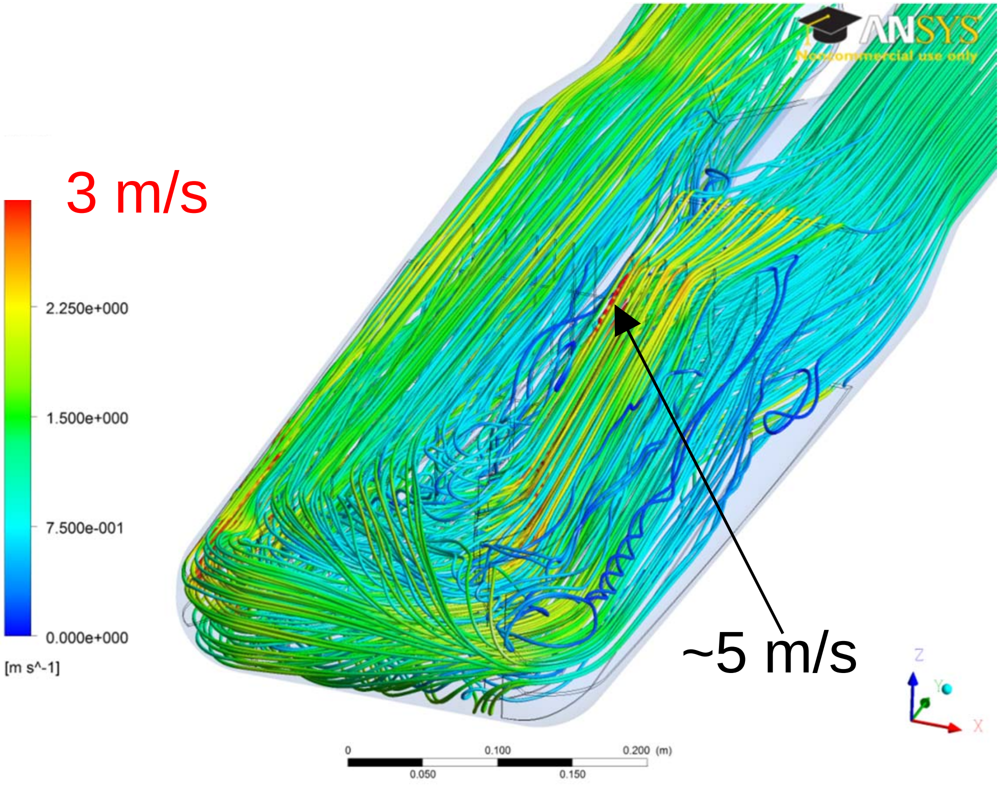


fluid temperatures for focused cross flow target

Focused Cross Flow Target

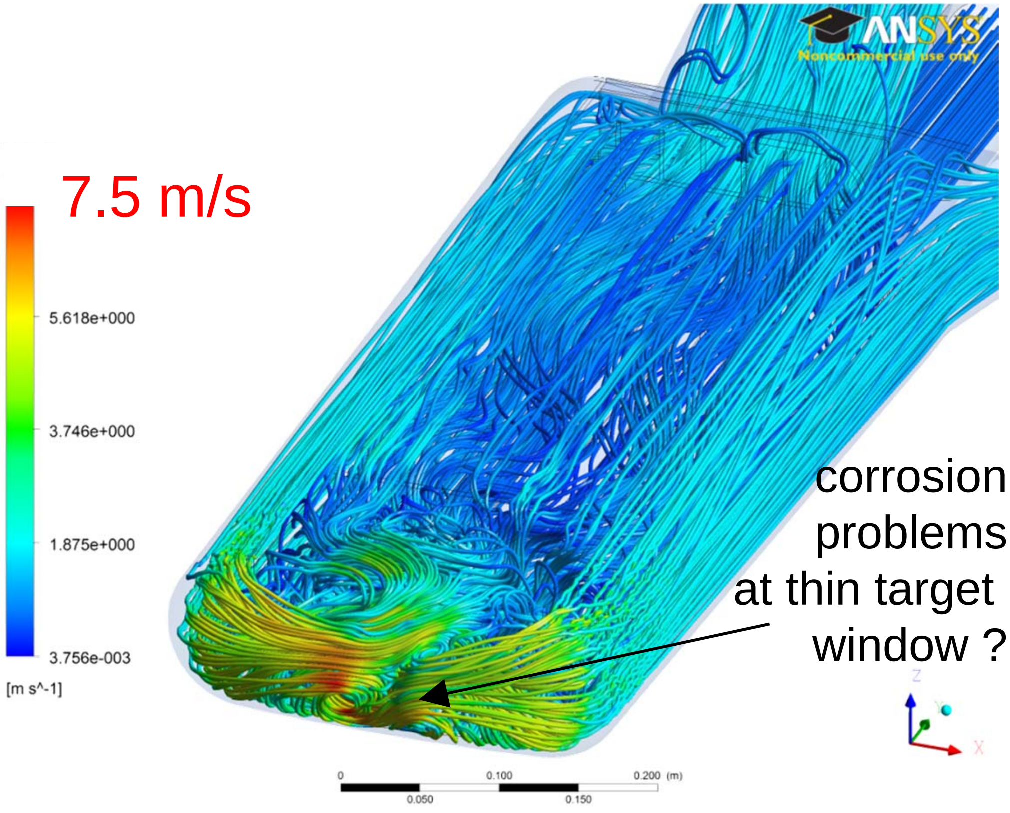
↳ pros and cons

- ➢ reduced velocities at target window
  - ↳ less erosion problems



3 m/s

~5 m/s



7.5 m/s

corrosion problems at thin target window ?

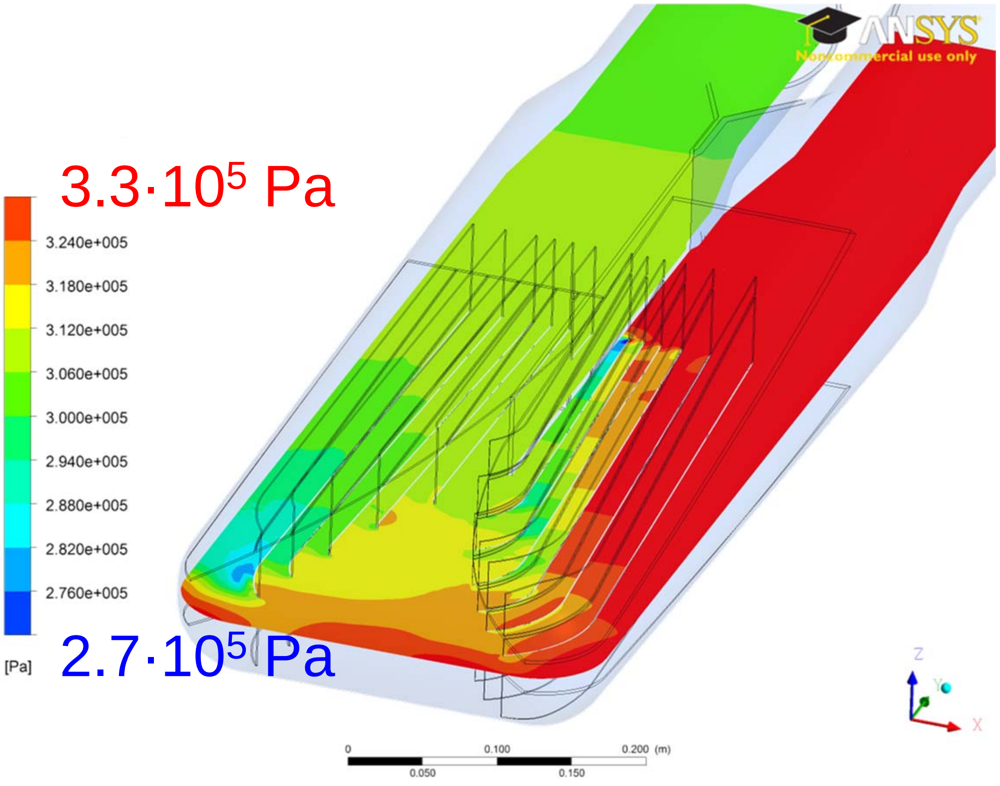
left: fluid velocity for focused cross flow target

right: fluid velocity for the 2003 target design

Focused Cross Flow Target

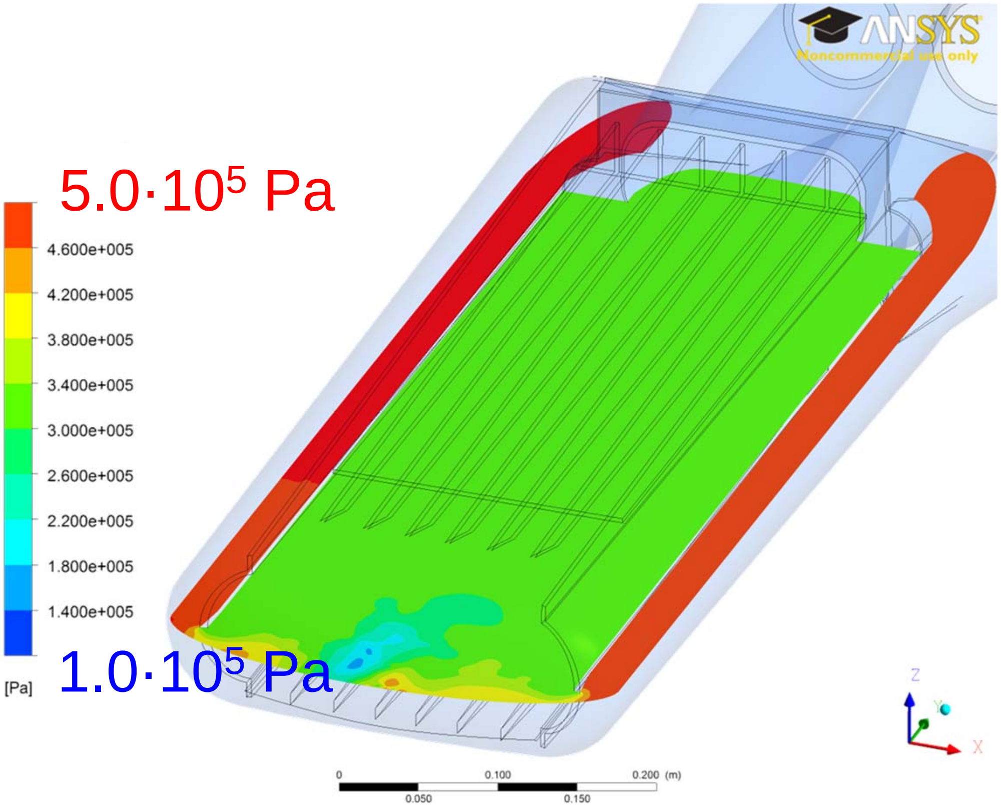
↳ pros and cons

- significantly reduced pressure drop
  - ↳ permitting higher flow rates



$3.3 \cdot 10^5$ Pa

$2.7 \cdot 10^5$ Pa



$5.0 \cdot 10^5$ Pa

$1.0 \cdot 10^5$ Pa

left: absolute pressure;
pressure drop: $\Delta p \simeq 0.3$ bar

right: absolute pressure;
pressure drop: $\Delta p \simeq 1.9$ bar

Preliminary Conclusions & Outlook

- The focused cross flow target has still some potential for optimization with respect to window cooling and heat removal capability (e.g. baffle arrangement, increased mass flow rate)
- Window cooling and heat removal in the zone of maximum power density seems to be already sufficient for a 5MW proton beam

Outlook

- Temperature and velocity limits have to be defined for the target
- Further optimization of flow field
- Evaluation of thermal and mechanical stresses in the target (e.g. stresses due to pulsed operation, possible thermal striping, …)
- Producibility aspects have to be clarified

Changes to boundary conditions

↳ LBE as preferred liquid metal

➢ LBE as preferred target material for a liquid metal target

⇒ same pressure drop can be expected for a mass flow rate of

$$\dot{m}_{LBE} = \dot{m}_{Hg}\sqrt{\frac{\rho_{LBE}}{\rho_{Hg}}} = 155\frac{kg}{s}$$

(effect of viscosity neglected)

⇒ heat removal capability is comparable:

$$\frac{\dot{m}_{LBE}\cdot c_{p_{LBE}}}{\dot{m}_{Hg}\cdot c_{p_{Hg}}} = \frac{155\frac{kg}{s}\cdot 146\frac{J}{kg\cdot K}}{175\frac{kg}{s}\cdot 136\frac{J}{kg\cdot K}} = 0.95$$

Changes to boundary conditions

↳ LBE as preferred liquid metal

⇒ heat transfer coefficients are comparable:
(e.g. formulas for turbulent pipe flow, d ≅ 100mm)

$$\frac{\alpha_{LBE}}{\alpha_{Hg}}=\frac{\dfrac{\dfrac{\left(1.8\cdot\log\left(\mathrm{Re}_{LBE}\right)-1.5\right)^{-2}}{8}\cdot\mathrm{Re}_{LBE}\cdot\mathrm{Pr}_{LBE}}{1+12.7\cdot\sqrt{\dfrac{\left(1.8\cdot\log\left(\mathrm{Re}_{LBE}\right)-1.5\right)^{-2}}{8}}\cdot\left(\mathrm{Pr}_{LBE}^{\frac{2}{3}}-1\right)}\cdot\dfrac{\lambda_{LBE}}{d}}{\dfrac{\dfrac{\left(1.8\cdot\log\left(\mathrm{Re}_{Hg}\right)-1.5\right)^{-2}}{8}\cdot\mathrm{Re}_{Hg}\cdot\mathrm{Pr}_{Hg}}{1+12.7\cdot\sqrt{\dfrac{\left(1.8\cdot\log\left(\mathrm{Re}_{Hg}\right)-1.5\right)^{-2}}{8}}\cdot\left(\mathrm{Pr}_{Hg}^{\frac{2}{3}}-1\right)}\cdot\dfrac{\lambda_{Hg}}{d}}=1.084$$

↳thermal-hydraulic design is similar for mercury and LBE

but

↳to avoid solidification of LBE, the inlet temperature must be significantly higher: 175 – 200 °C (> 125°C) for LBE instead of 100°C for mercury

↳no risk of evaporation (evaporation temperature of 1670 °C for LBE instead of 357 °C for mercury)