

Thermal Simulations of a Proton CT Calorimeter Detector

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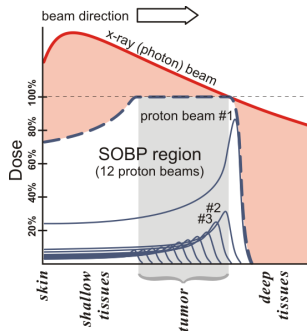
on behalf of Bergen proton CT collaboration
([full collaboration list](#))

Ref: [Front. in Phys. Med. Phys. Im. ID: 568243](#), [Phys. in Med. & Bio. ID: 110623.R3](#), [NIM A 860 \(2017\) 51–6152](#), [Phys. Med. 63 \(2019\) 87–97](#)

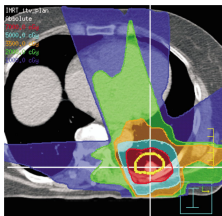
Forum on Tracking Detector Mechanics 2021, 19 May 2021

Motivation: improve proton therapy

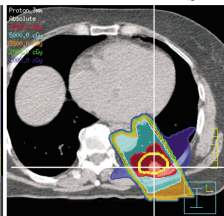
- Original idea by Wilson in 1946
- Widespread in the last 20 years
- More advantageous dose distribution due to Bragg-peak
⇒ less side effect



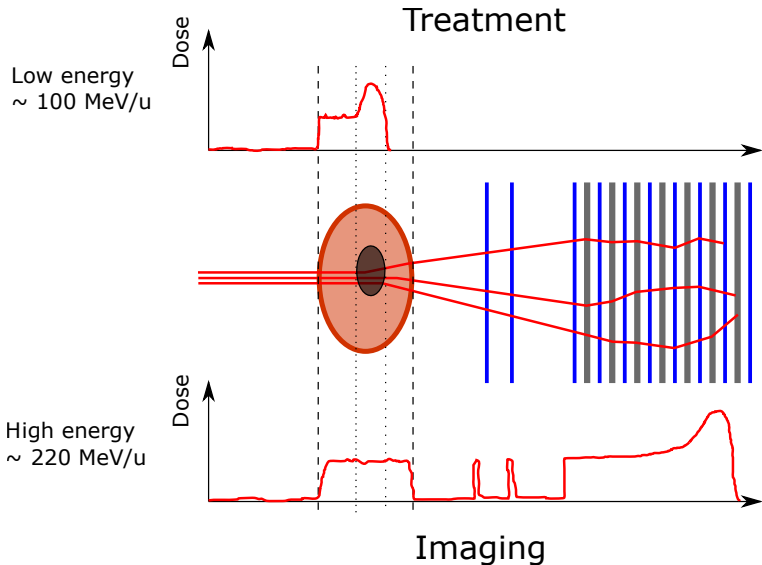
X-ray



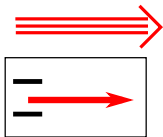
Proton



Proton therapy and proton imaging



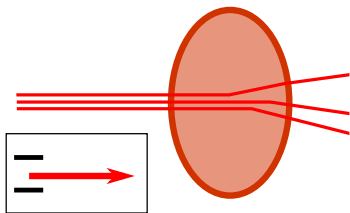
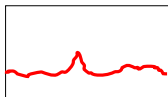
Introduction: how Bergen pCT calorimeter works?



Incoming vector
and energy

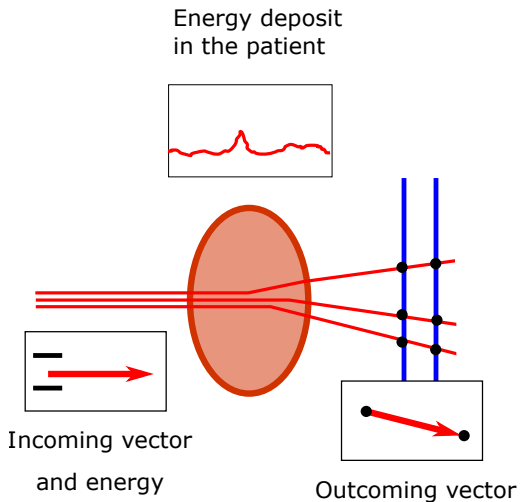
Introduction: how Bergen pCT calorimeter works?

Energy deposit
in the patient

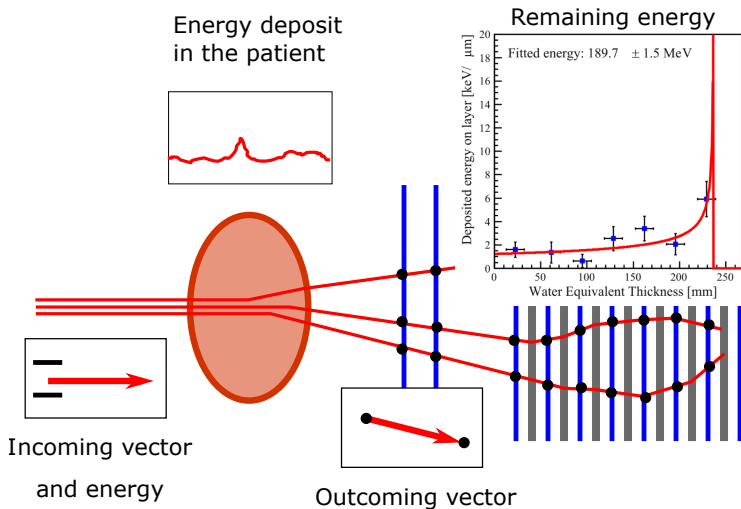


Incoming vector
and energy

Introduction: how Bergen pCT calorimeter works?

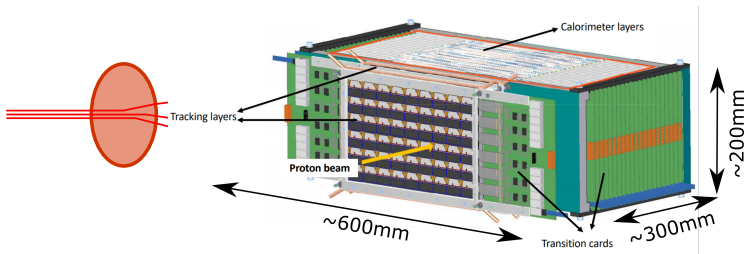


Introduction: how Bergen pCT calorimeter works?



How much heat is generated in the sensitive area?

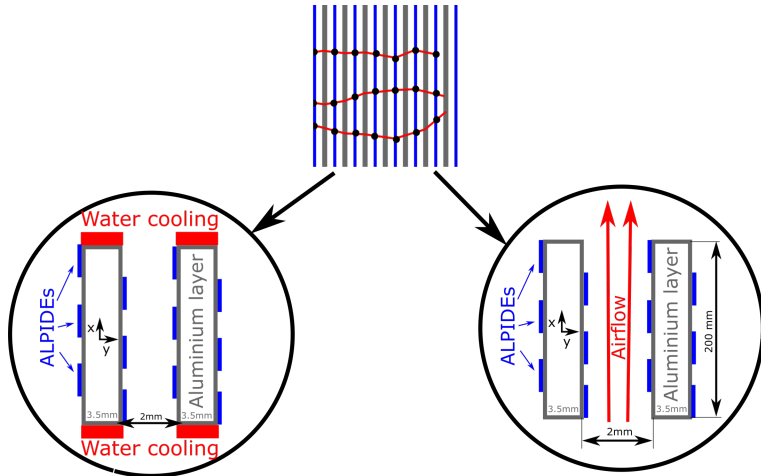
- Bergen pCT detector: 2 tracker + 41 calorimeter layers
- $\sim 300 \times 300 \times 200 \text{ mm}^3$ sensitive volume
- $4644 \text{ ALPIDEs} \times 300 \frac{\text{mW}}{\text{ALPIDE}} \approx 1.4 \text{ kW}$ heat generation
- Allowed temperature: $T_{\text{Max}} = 30^\circ\text{C}$
- Allowed inhomogeneity in calorimeter part: $\Delta T = 5^\circ\text{C}$



How to transfer heat away? $\Rightarrow$ Two cooling concepts

Water cooling

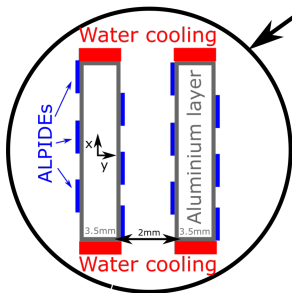
Air cooling



How to transfer heat away? $\Rightarrow$ Two cooling concepts

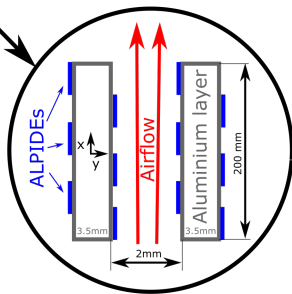
Water cooling

- Cooling out of sensitive area
- Carrier transfers heat out
 $\Rightarrow$ Fix temperature gradient



Air cooling

- Airflow through sensitive area
 $\Rightarrow$ Control: airspeed
- Is it effective enough?



Water cooling: calculations

1D steady state Fourier equation:

$$0 = \lambda \frac{\partial^2 T(x)}{\partial x^2} + q_v ,$$

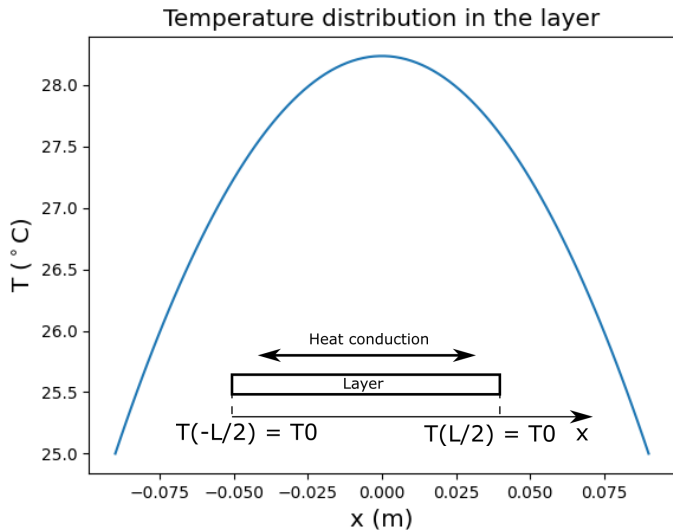
where $T(x)$: temperature , x : coordinate, L : length,
 q_v : volumetric heat generation and λ : thermal conductivity
Boundary conditions, temperatures are T_0 :

$$T(0) = T_0 \quad \text{and} \quad T(L) = T_0 .$$

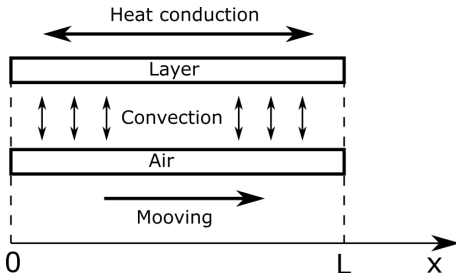
Integrable differential equation $\Rightarrow$ Solution:

$$T(x) = -\frac{q_v}{2\lambda}x^2 + \frac{q_v}{2\lambda} \left(\frac{L}{2}\right)^2 + T_0 .$$

Water cooling: temperature distribution



Air cooling: calculations



The heat conduction in layer:

$$0 = \lambda \frac{\partial^2 T_c(x)}{\partial x^2} - \frac{Q_c(x)}{V_c} + q_0 .$$

The temperature change of airflow:

$$\rho c v \frac{\partial T_a(x)}{\partial x} = \frac{Q_c(x)}{V_a} .$$

The convection between them:

$$Q_c(x) = \alpha A [T_c(x) - T_a(x)] .$$

T_c : layer temp. , T_a : air temp. , Q_c : heat transfer from layer to air, q_0 : volumetric heat generation, V_c : layer volume, V_a : air volume, A : contact area, λ : layer thermal conductivity, ρ : air density, c : specific heat capacity of air, v : airspeed, α : heat transfer coefficient between layer and air.

Air cooling: calculations

Layer temperature: $T_c(x) = C_1 e^{r_1 x} + C_2 e^{r_2 x} + C_3 x + C_4$.

Air temperature: $T_a(x) = \frac{\lambda}{\rho c v} \frac{\partial T_c}{\partial x} + \frac{1}{\rho c v} q_0 x + \frac{1}{\rho c v} \hat{c}$.

C_1 , C_2 , r_1 , r_2 , C_3 , C_4 and $\hat{c}$ are constants based on: α , A , L , ρ , c , v , λ , V_c and V_a .

Boundary conditions:

$$\left. \begin{array}{l} T_a(x)|_{x=0} = T_0 \\ \frac{\partial T_c(x)}{\partial x}|_{x=0} = 0 \\ \frac{\partial T_c(x)}{\partial x}|_{x=L} = 0 \end{array} \right\} \Rightarrow \hat{c} \text{ and } C_1 \text{ and } C_2$$

Air cooling: calculations

Heat transfer coefficient (α) based on Tachibana and Fukui^[1]:

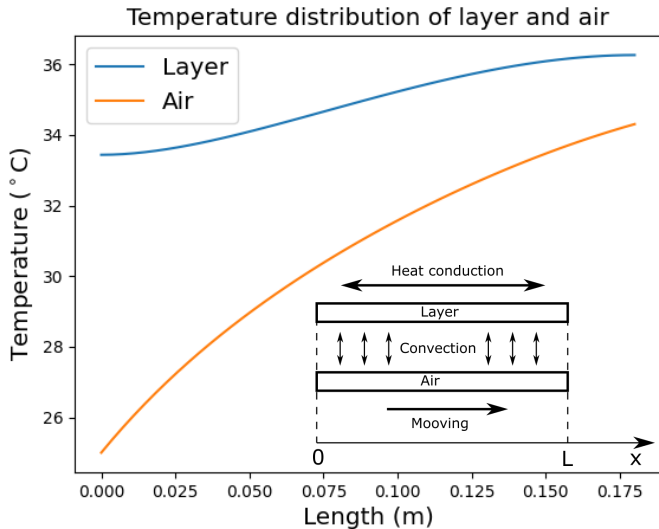
$$\alpha \approx \frac{\lambda}{D_e} 0.017 \left(1 + 2.3 \frac{D_e}{L} \right) \left(1 - \frac{\pi D_e}{K} \right)^{0.45} \text{Re}^{0.8} \text{Pr}^{0.33},$$

where λ : thermal conductivity, K : width of the gap, L : length of the gap, d : thick of the gap, $D_e = \frac{4K \times d}{2K + 2d} \approx 2d$: equivalent diameter, Re : Reynolds number, Pr : Prandtl number.

Warning! Strong extrapolation: α was measured for turbulent flows and we use them for laminar $\rightarrow$ upper estimates of α

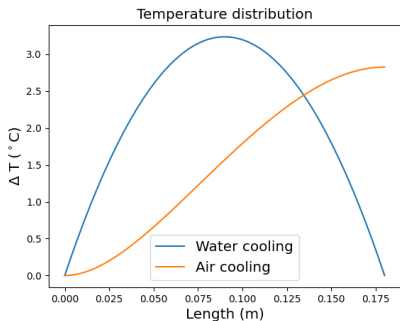
[1]: Fujio Tachibana and Sukeo Fukui, Convective Heat Transfer of the Rotational and Axial Flow between Two Concentric Cylinders, Bulletin of JSME, 7(26):385-391, 1964.

Air cooling: temperature distribution

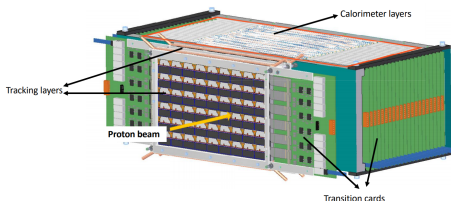


Comparison of the two cooling strategy

- **Water cooling:** $T_{\max} = 23.2\text{ }^{\circ}\text{C}$ and $\Delta T = 3.2\text{ }^{\circ}\text{C}$
- **Air cooling:** $w = 10\text{ }\frac{\text{m}}{\text{s}}$ and $\alpha = 73\text{ }\frac{\text{W}}{\text{m}^2 \times \text{K}} \rightarrow$
 $T_{\max} = 36.3\text{ }^{\circ}\text{C}$ and $\Delta T = 2.8\text{ }^{\circ}\text{C}$
- Requirement 1: $T_{\max} < 30\text{ }^{\circ}\text{C}$, only water cooling meets
- Requirement 2: $\Delta T < 5\text{ }^{\circ}\text{C}$, both concept meet



- Bergen pCT Collaboration is developing a proton CT
- Data taking time: main limitation of available prototypes
⇒ Goal: overcome this limitation
- First test results expected within two years
- We investigated two cooling system concepts
- Water cooling met all requirements ⇒ under construction now



Thank you for your attention!

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This work would not be possible without the support of the Research Council of Norway (Norges forskningsråd), grant number 859 250858; the Trond Mohn Foundation, grant number BFS2017TMT07; NKFIH/OTKA K135515, Hungarian Scientific Research Fund – OTKA.