Thermal Simulations of a Proton CT Calorimeter Detector

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on behalf of Bergen proton CT collaboration
(full collaboration list)

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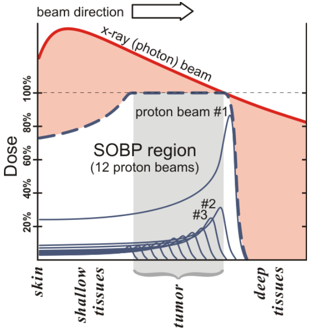
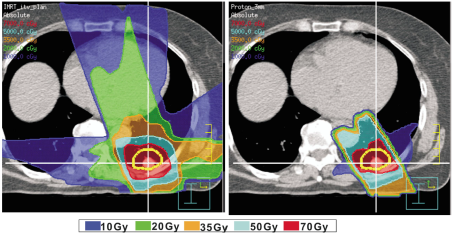
Motivation: improve proton therapy

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

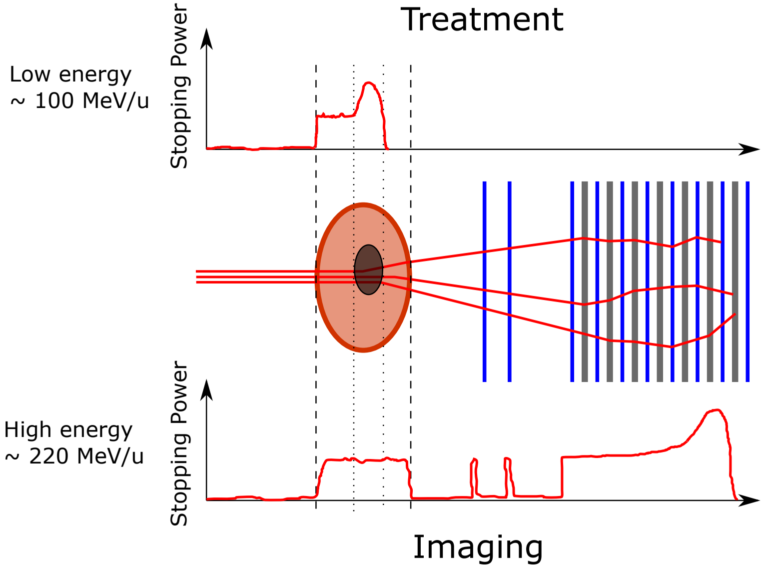


X-ray

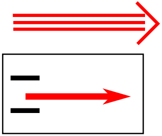


Proton

Proton therapy and proton imaging



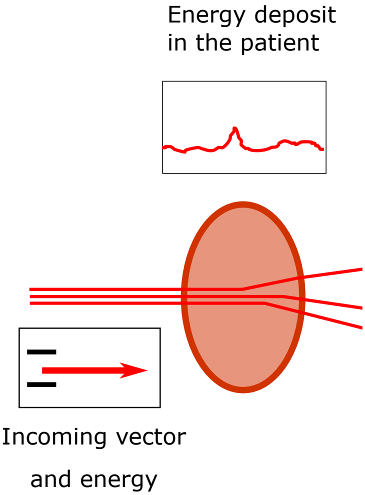
Introduction: how Bergen pCT calorimeter works?



Incoming vector

and energy

Introduction: how Bergen pCT calorimeter works?



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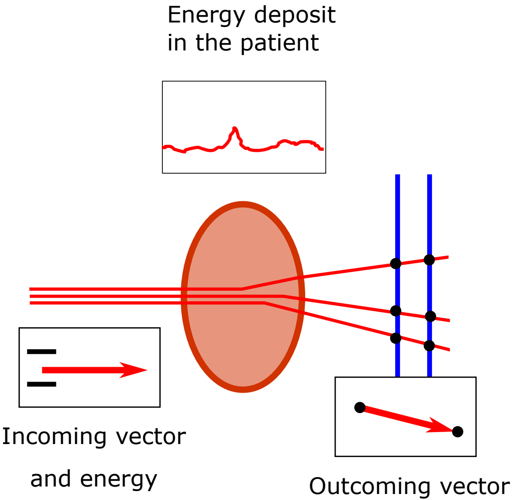

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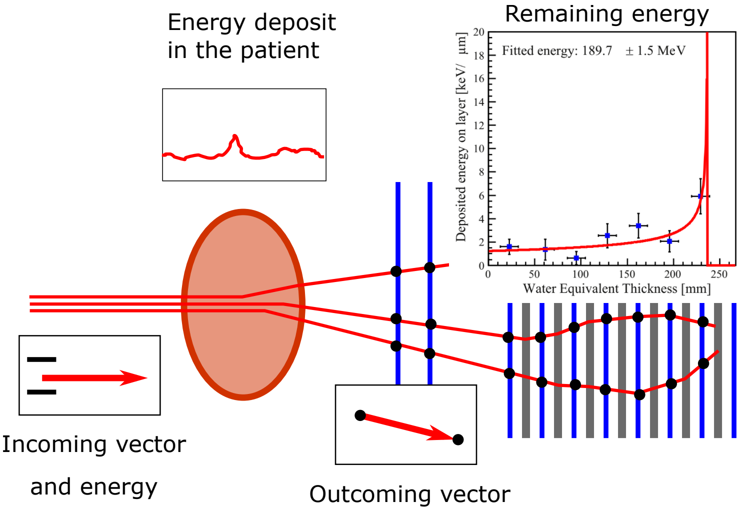
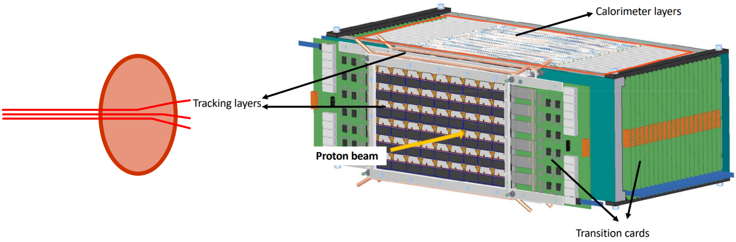


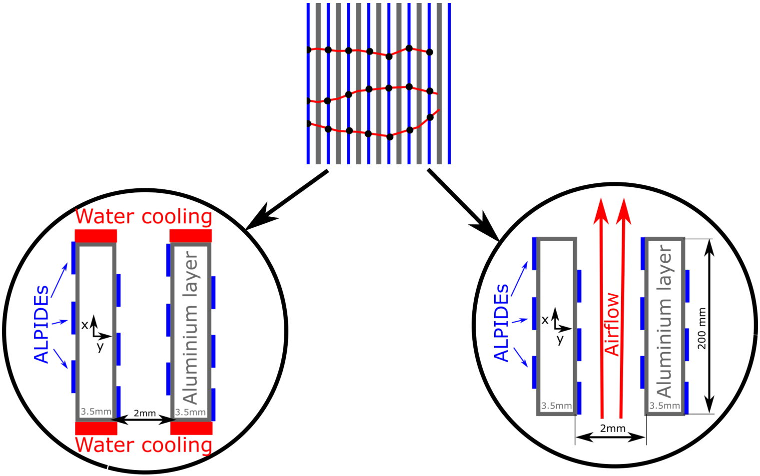
How much heat is generated in the sensitive area?

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



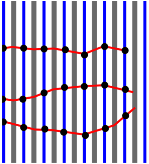
How to transfer heat away? ⇒ Two cooling concepts

Water cooling | **Air cooling**



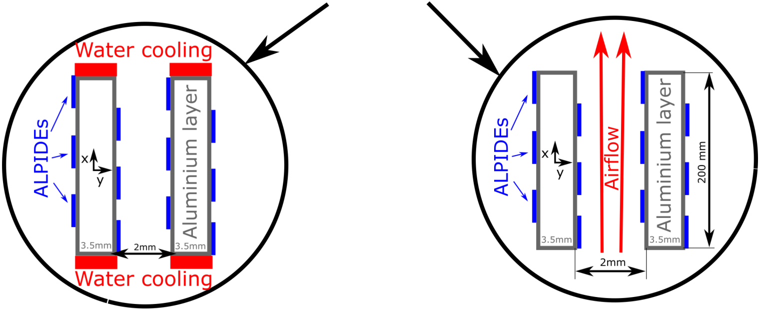
Water cooling

- Intensive water cooling ⇒ temperature at edge remains constant ⇒ All heat is transferred away through edge



Air cooling

- Third type of boundary condition in surfaces, which contact with the air flow
- No heat transfer in the other surfaces of the detector



1D steady state Fourier equation:

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

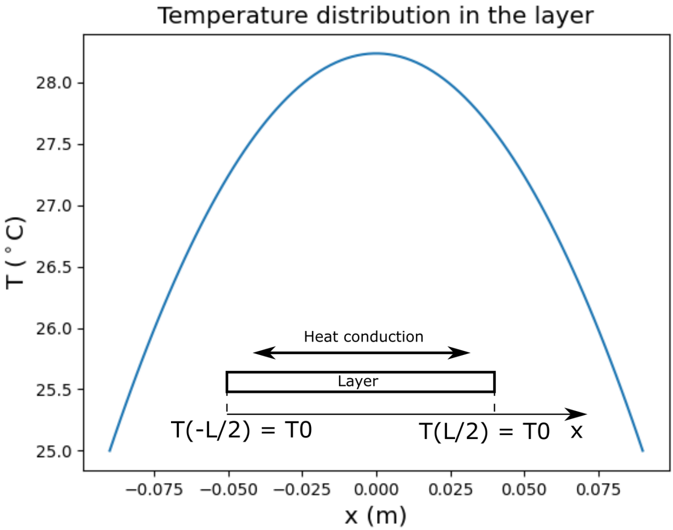
where $T(x)$: temperature , x: coordinate, L: length,
q_v: volumetric heat generation and λ: thermal conductivity
Boundary conditions, temperatures are T_0:

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

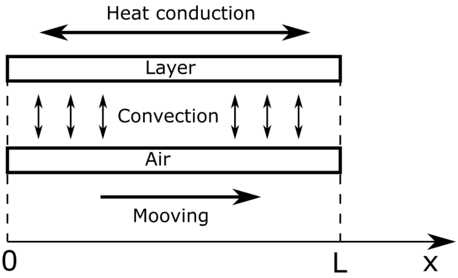
Integrable differential equation $\Rightarrow$ Solution:

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

Temperature distribution of water cooling



Calculations of air cooling



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.

Calculations of air cooling

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:

$$T_a(x)|_{x=0} = T_0 \quad \Rightarrow \hat{c}$$

$$\left.\begin{aligned} \frac{\partial T_c(x)}{\partial x}\Big|_{x=0} &= 0 \\ \frac{\partial T_c(x)}{\partial x}\Big|_{x=L} &= 0 \end{aligned}\right\} \quad \Rightarrow C_1 \text{ and } C_2$$

Calculations of air cooling

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

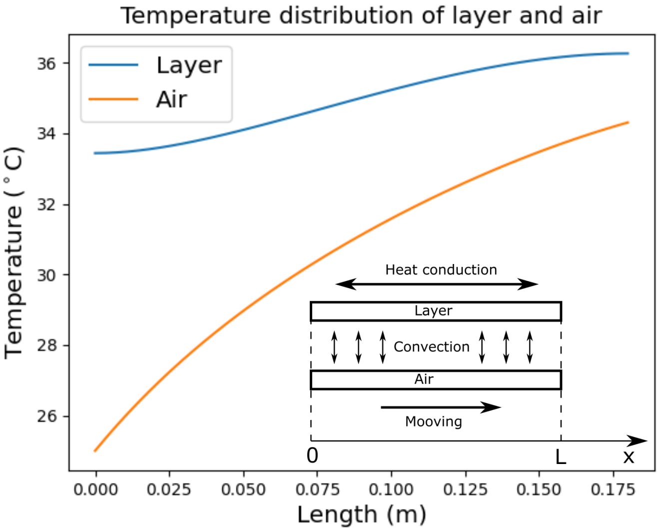
$$\alpha \approx \frac{\lambda}{D_e} 0.017 \left(1 + 2.3\frac{D_e}{L}\right)\left(1 - \frac{\pi D_e}{K}\right)^{0.45} Re^{0.8} Pr^{0.33},$$

where λ: thermal conductivity, K: width of the gap, L: length of the gap, d: thick of the gap, $D_e = 4\frac{K \times d}{2K + 2d} \approx 2d$: 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 α

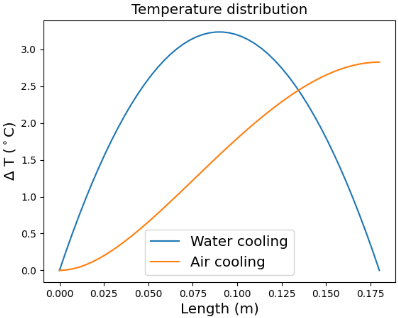
[1]: Fujio Tachibana and Sukeo Fukui, Convective Heat Transfer of the Rotational and Axial Flow between Two Concentric Cylinders, Bulletin of JSME, 7(26):385-391, 1964.

Temperature distribution of air cooling



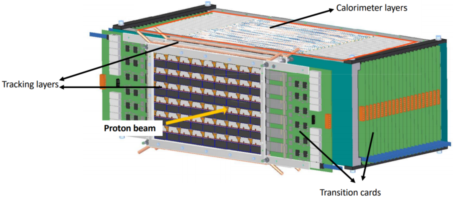
Comparison of the two cooling strategy

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



Summary

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



Thank you for your attention!

Members of the Bergen pCT collaboration: University of Bergen, Norway; Helse Bergen, Norway; Western Norway University of Applied Science, Bergen, Norway; Wigner Research Center for Physics, Budapest, Hungary; DKFZ Heidelberg, Germany; Heidelberg Ion-Beam Therapy Center (HIT), Germany; Utrecht University, The Netherlands; RPE LTU, Kharkiv, Ukraine; Suranaree University of Technology, Nakhon Ratchasima, Thailand; China Three Gorges University, Yichang, China; University of Applied Sciences Worms, Germany; University of Oslo, Norway; Eötvös Loránd University, Budapest, Hungary

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