

Hadron-tracking calorimeter in a medical application

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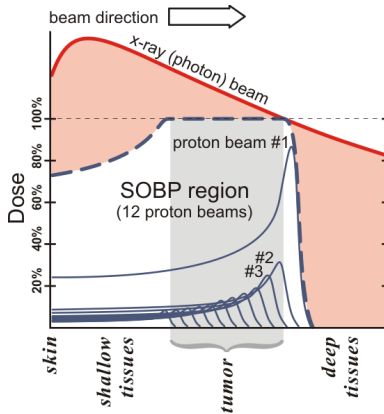
4. December 2019.



Motivation – Treatment of cancer

- It causes 9.6 million death
- Surgery
- Radiotherapy
 - External beam radiation therapy
 - Widespread solution: X-ray photon therapy
 - More advantageous: **hadron treatment** (mainly with protons)
 - Brachytherapy
 - Radioisotope treatment
- Chemotherapy
- Hormone therapy

Advantage of **hadron treatment**:
More concentrated energy loss

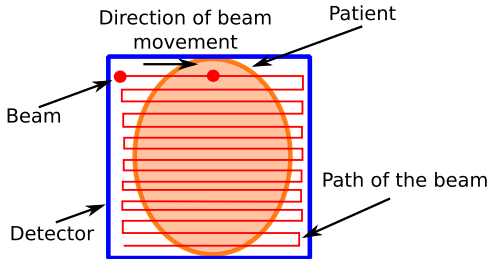


Spread out Bragg peak (SOBP)

Hadron therapy – Advantages and gates in spread out

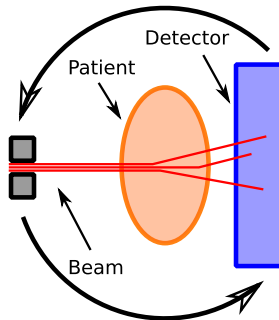
- Well focused energy deposit
⇒ lower dose in healthy tissues
Results:
 - It cause less side effect
 - It is better applicable in the near of critical organs
 - Higher daily dose → **more effective treatment**
- Applicability:
There is not available a accurate imaging tool
 - Today:
X-ray CT → it measures the nucleon density
Calculation of the electron density based on the nucleon density → **1.7-11 % error**
 - More accurate:
Proton CT → it measures the electron density → **0.5 % error**
Not available today → it is worth to develop!

Proton computertomograph (CT) – How does it works?



Scanning

Direction of rotation
of the detector and the beam

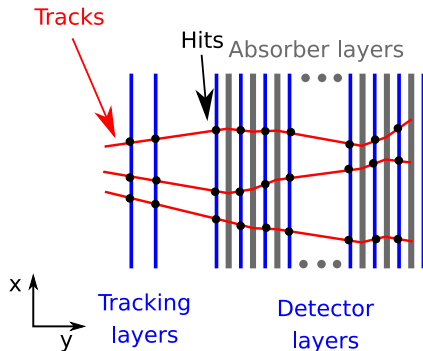


Rotating

Developing a hadron-tracking calorimeter

Motivation: proton CT for treatment of cancer

- From alternating ALPIDE and aluminum absorber layers
- 41 layer, 108 ALPIDE per layer
- 4428 ALPIDE \rightarrow 18% of ITS of ALICE
- 1% energy resolution
- $10^7 - 10^9 \frac{\text{particle}}{\text{sec}}$ in about 1cm^2
- 486cm^2 detector area
- about $200 \frac{\text{MeV}}{u}$ protons

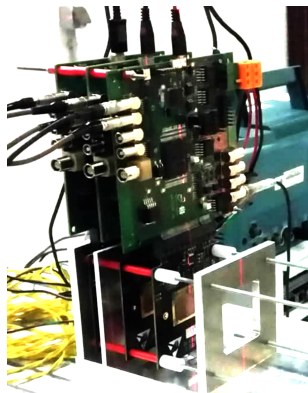
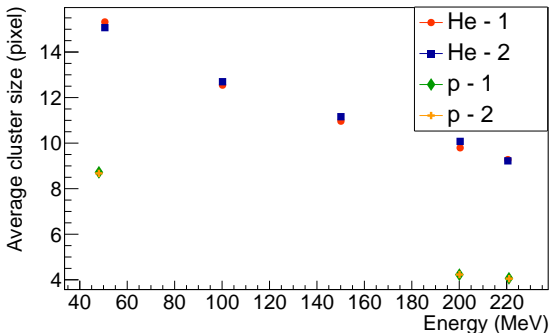


- It is an application of the latest development in ALICE
- Later it can be used in fundamental research

Measurement: Cluster size – energy

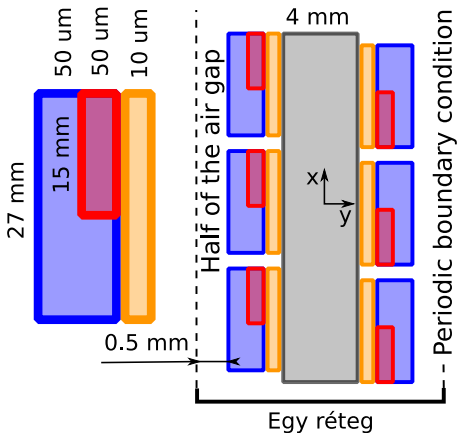
Motivation: use the cluster size in the energy measurement

- Measurement: **cluster size** \Leftrightarrow **energy**
- Cluster size also depends on the temperature
- p and He⁺⁺, 50 – 220 $\frac{\text{MeV}}{u}$, about $4 \cdot 10^3 \frac{\text{particle}}{\text{second}}$



Layer structure and thermal loads of the calorimeter

Cross section of one layer



Colors:

- Red: tracking detector
- Gray: Absorber layer
- Blue: Chip-cable
- Orange: Glue

Volumetric heat generation:

- Electronics:
700 W in the detector
- Particle beam:
35 mW in the detector
 \Rightarrow neglectable

Symetry \Rightarrow no perpendicular heat transfer in the middle of the air between layers

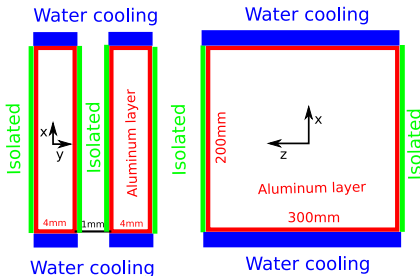
Requirements

- Maximum allowed temperature: 40 °C
- Energy measurement based on the temperature of the detector \Rightarrow correction
- Temperature difference \Rightarrow inaccurate energy measurement \Rightarrow Maximum allowed temperature difference: 5 °C
- Roomtemperature: 25 °C
- Absorber: aluminum \Leftarrow good absorption scattering ratio
- No extra material between the layers \Leftarrow scattering
- Not toxic materials \Leftarrow medical use

Cooling system concepts

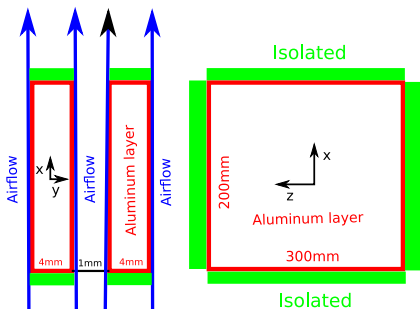
Water cooling

- Fix temperature in the top and the bottom of the detector
- No heat transfer in the other surfaces of the detector



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



Temperature distribution

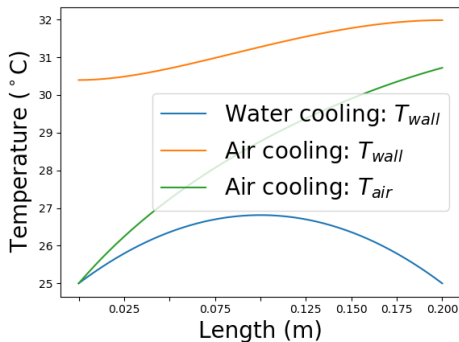
Water cooling

Wall model:

- Fix temperature in the sides
- Volumetric heat generation

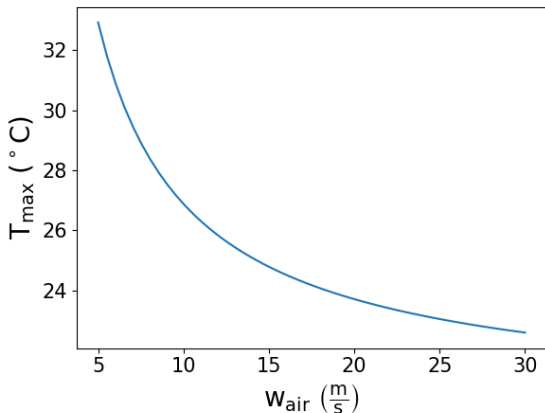
Air cooling

- Heat transfer coefficient based on Tachibana and Fukui
- Numerical solution for the temperature distribution



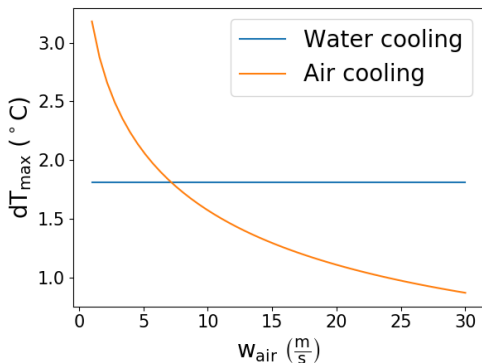
T_{\max} comparison – Water and Air cooling

- **Water cooling:** T_{\max} is changeable with the T of the coolant
- **Air cooling:** T_{\max} changeable with airspeed, $w := 10 \frac{\text{m}}{\text{s}}$
- Requirement: $T_{\max} < 40 \text{ }^\circ\text{C}$, both concept meets with this



ΔT comparison – Water and air cooling

- **Water cooling:** $\Delta T = 1.8 \text{ }^\circ\text{C}$ for benchmark
- **Air cooling:**
 - airspeed $\uparrow \rightarrow \Delta T \downarrow$
 - $w = 10 \frac{\text{m}}{\text{s}}$ and $\alpha = 62 \frac{\text{W}}{\text{m}^2 \cdot \text{K}} \rightarrow \Delta T = 1.6 \text{ }^\circ\text{C}$
- Requirement: $\Delta T < 5 \text{ }^\circ\text{C}$, both concept meets this



Summary

- Energy measurement: path length in absorber and cluster size
- Silicon detector \Rightarrow temperature dependency
- Cooling concepts:
 - **Water cooling** in the top and bottom
 - **Air cooling** between the layers
- Both can meet the requirements \Rightarrow other aspect in decision
- This calorimeter can measure huge particle rate
 \Rightarrow it can be useful in other applications also

Thanks for the attention!

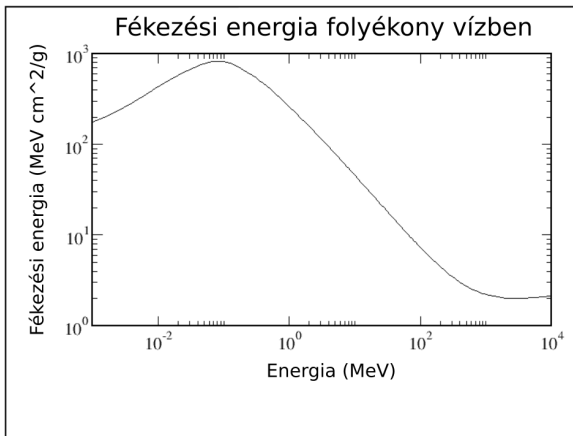
This work would not be possible without the support of NKFIH/OTKA K 120660, Hungarian Scientific Research Fund – OTKA.

Tartalék diák

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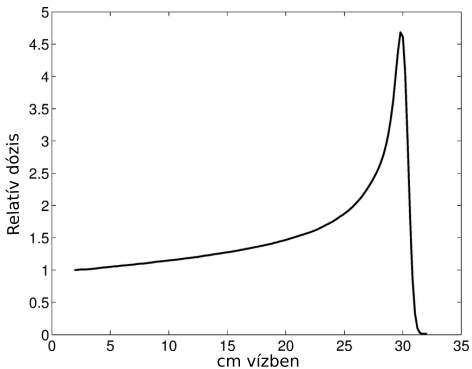
Stopping power (Fékezési energia)

Stopping Power = $\frac{E}{L \cdot \rho} \left[\frac{\text{MeV} \cdot \text{cm}^2}{\text{g}} \right]$ ahol: E a leadott energia, L a megtett hossz és ρ az anyag tömegsűrűsége



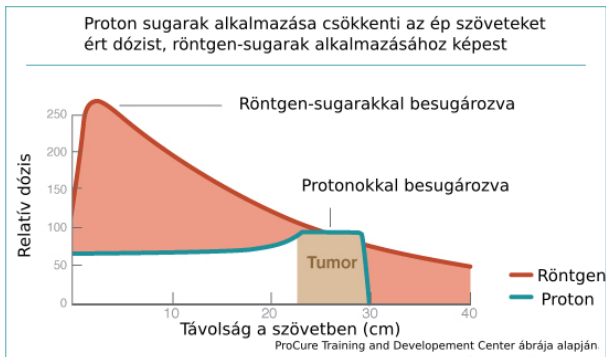
Bragg-csúcs

- Víz ekvivalens hossz: az a hossz, ami alatt a részecske azonos energiát adna le vízben
 - Relatív dózis: vizsgált pontban és a belépési pontban egységnyi út alatt leadott energia hányadosa
- Besugárzás tervezéskor használják



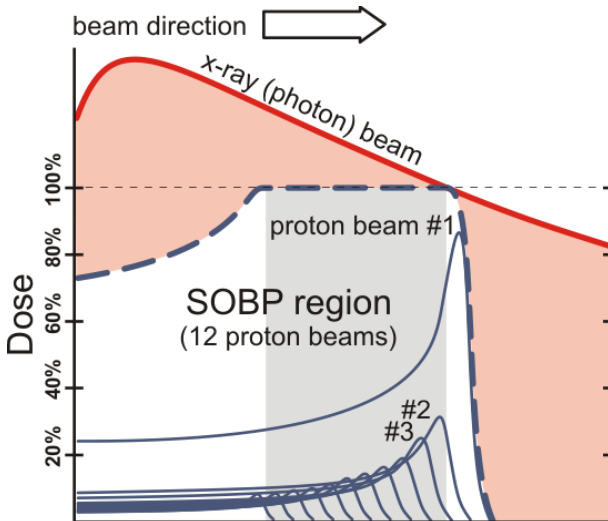
Relatív dózis – Röntgen-foton és proton

- Kék vonal: proton terápia által okozott relatív dózis
- Piros vonal: röntgen-fotonokkal végzett sugárterápia relatív dózis
- : Piros terület: protonok alkalmazásával elkerülhető dózis
- Barna: dózis a tumorban



Elosztott Bragg-csúcs – Röntgen-foton és proton

Spread out Bragg peak (SOBP): elosztott Bragg-csúcs.



Numerikus megoldás – "B" koncepció

Következő hőmérséklet:

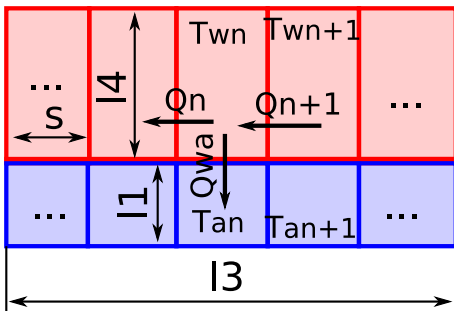
- $Q_{w,a} = \alpha \cdot 2 \cdot s \cdot l_2 \cdot (T_{wn} - T_{an})$
- $Q_{n+1} = Q_n + Q_{w,a} - Q_V$
- $T_{wn+1} = T_{wn} + \frac{Q_{n+1} \cdot s}{\lambda \cdot l_2 \cdot l_4}$
- $T_{an+1} = T_{an} + \frac{Q_{w,a}}{c \cdot \rho \cdot l_1 \cdot l_2 \cdot v}$

Cellák:

- "w": detektor réteg cella
- "A": levegő cella

Paraméterek:

- $v = 10 \frac{m}{s}$ levegő sebessége
- $T_0 = 25 \text{ } ^\circ\text{C}$ szoba hőmérséklete
- $\rho = 1.19 \frac{kg}{m^3}$ levegő sűrűsége
- $c = 1013 \frac{J}{kg \cdot K}$ levegő fajhője
- $\lambda = 237 \frac{W}{m \cdot K}$ az abszorber hővezetési tényező
- $Q_V = 10 \text{ mW}$ cellában keletkező hő
- $l_2 = 0.3 \text{ m}$ a detektor szélessége
- $s = 0.1 \text{ mm}$ a cellák magassága
- $l_1 = 1 \text{ mm}$ légréteg vastagsága
- $l_3 = 0.2 \text{ m}$ réteg magassága
- $l_4 = 4 \text{ mm}$ réteg vastagsága

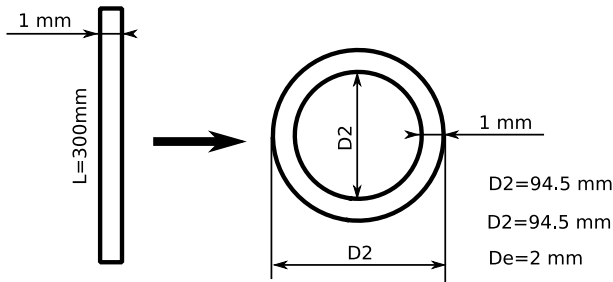


Ekvivalens geometria – "B" koncepció

Hőátadási tényező (Tachibana és Fukui):

$$\alpha = \frac{\lambda}{D_e} 0.017 \left(1 + 2.3 \frac{D_e}{L} \right) \left(\frac{D_2}{D_1} \right)^{0.45} Re^{0.8} Pr^{1/3}.$$

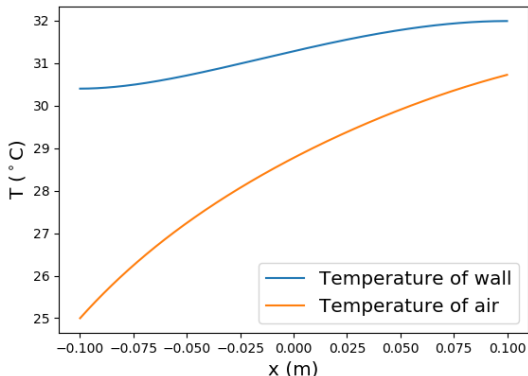
- λ az abszorber hővezetési tényezője
- Re a Reynolds-szám, Pr a Prandtl-szám
- L a detektor magassága
- D_1 , D_2 és D_e az ekvivalens geometria paraméterei



Hőmérséklet eloszlás – "B" koncepció 1

Hőmérsékleteloszlás a "B" koncepció esetén, az áramvonal mentén.

Paraméterek: $T_{\text{szoba}} = 25 \text{ }^{\circ}\text{C}$ és $w_{\text{lev}} = 10 \frac{\text{m}}{\text{s}}$

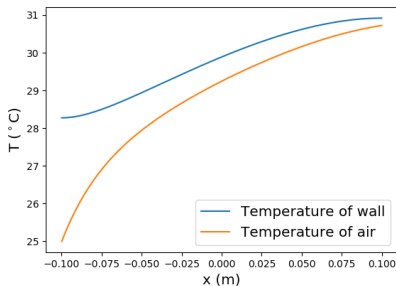
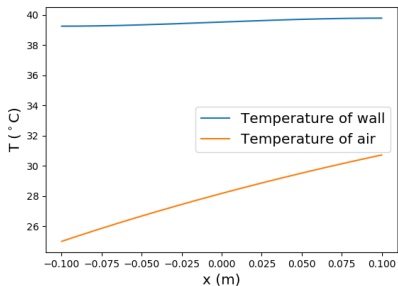


Hőmérséklet eloszlás – "B" koncepció 2

Hőmérsékleteloszlás a "B" koncepció esetén, az áramvonal mentén.

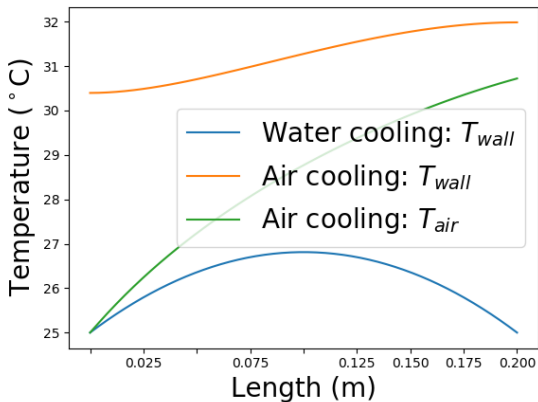
Paraméterek: $T_{\text{szoba}} = 25 \text{ } ^\circ\text{C}$ és $w_{\text{lev}} = 10 \frac{\text{m}}{\text{s}}$

Irreális hőátadási tényezők: $\alpha_1 = 15 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$ és $\alpha_2 = 200 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$

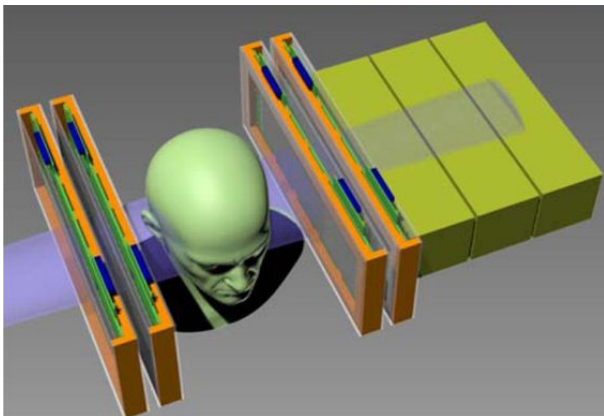


Hőmérséklet-eloszlások – "A" és "B" koncepció

- Paraméterek: $T_{szoba} = 25 \text{ } ^\circ\text{C}$ és $w_{lev} = 10 \frac{\text{m}}{\text{s}}$
- L: levegő belépési pontjától számított távolság



Proton Komputertomográf



Proton terápia kezelő szoba



Monolitikus aktív pixel szenzor

Monolithic Active Pixel Sensor (MAPS): Monolitikus Aktív Pixel Szenzor

