C2Po1D-02: Thermomechanical optimization of actively cooled thermal shield in PIP II Cryogenic Distribution System

T Banaszkiewicz[1], M Chorowski[1], P Duda[1], R C Dhuley[2], A Martinez[2], J Poliński[1], W M Soyars[2], M Stanclik[1]

[1] Wrocław University of Science and Technology, Poland,

[2] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510 USA

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1. Introduction

The thermal shields are used wherever it is necessary or economically viable to limit the flow of heat due to radiation between two surfaces with different temperatures. Equation (1.1) describes the relationship between the temperatures of bodies exchanging heat and the surface heat flux transferred between the bodies as a result of radiation.

$$q_r = \sigma\varepsilon'(T_1^4 - T_2^4) \qquad (1)$$

Where:

q_r- heat flux transferred by radiation W/m²,

σ – black body radiation constant

($\sigma = 5.67 \cdot 10^{-8}$ W/m²K⁴),

ε' – equivalent emissivity of the analyzed system, depending on the bodies' material and surface condition

To prevent from direct outer jacket thermal radiation, the cold surfaces at around 5 K are tightly surrounded by shields and baffles cooled by a gaseous helium.

In order to proper functioning of the thermal shield its surface's temperature field should be as much as possible uniform and close to the temperature of the process pipe that cools the screen. Therefore, thermal shield and elements for their thermalization with cooling pipe are made of materials characterized by a high thermal conductivity coefficient, as copper or aluminum.

Due to the cooling pipe for the thermal shield is usually made of stainless steel, there is a difference in the thermal expansion coefficient of this two elements. This necessitates the design of elements for thermalization must also be characterized with adequate mechanical flexibility.

Both the temperature of the thermal shield and the method of its thermalization are very important aspects responsible for its proper function. The optimal value of the screen temperature can be determined on the basis of the entropy minimization method. The method of thermalization of the thermal screen used in the cryogenic distribution system of the PIPII accelerator was developed on the basis of the Wroclaw University of Science and Technology experience gained from other projects realized for leading international research centers.

2. Determining the optimal temperature of the thermal shield

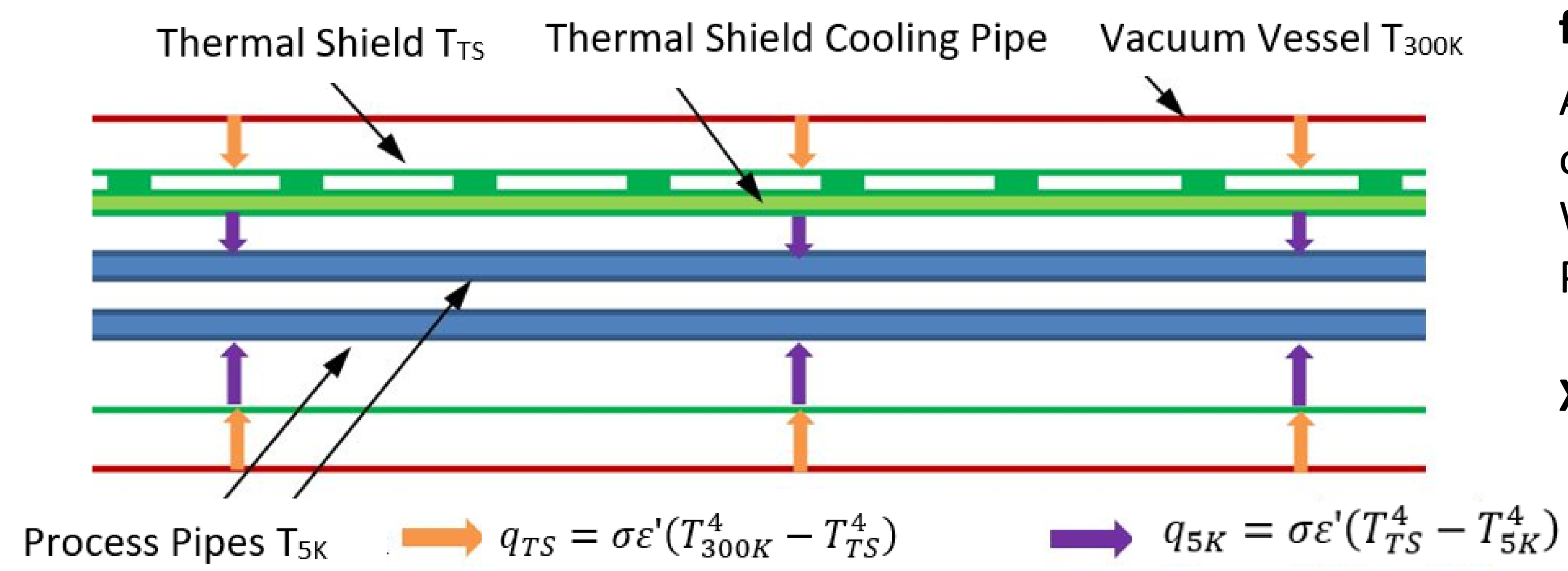


Fig. 1. The simplified example of the operation of an actively cooled thermal shield

For determining the optimal temperature of the thermal shield, it is necessary to calculate the entropy streams generated as a result of the heat inleaks to the pipe cooling the thermal shield and to the 5K process pipes. Equation (2) was used to determine the entropy streams generated in the considered system.

$$S''_{\Delta T} = \frac{q''}{T} - \frac{q''}{T+\Delta T} = \frac{q''(T+\Delta T - T)}{T^2\left(1+\frac{\Delta T}{T}\right)} = \frac{q''}{T_C^2\left(1+\frac{\Delta T}{T_C}\right)} \qquad (2)$$

Where:

$\Delta T = T - T_c$, T– ambient temperature, T_c - temperature of the cryogenic medium, q''– the heat flow to the cryogenic medium W/m², $S''_{\Delta T}$ –the entropy stream generated per unit area W/m²K.

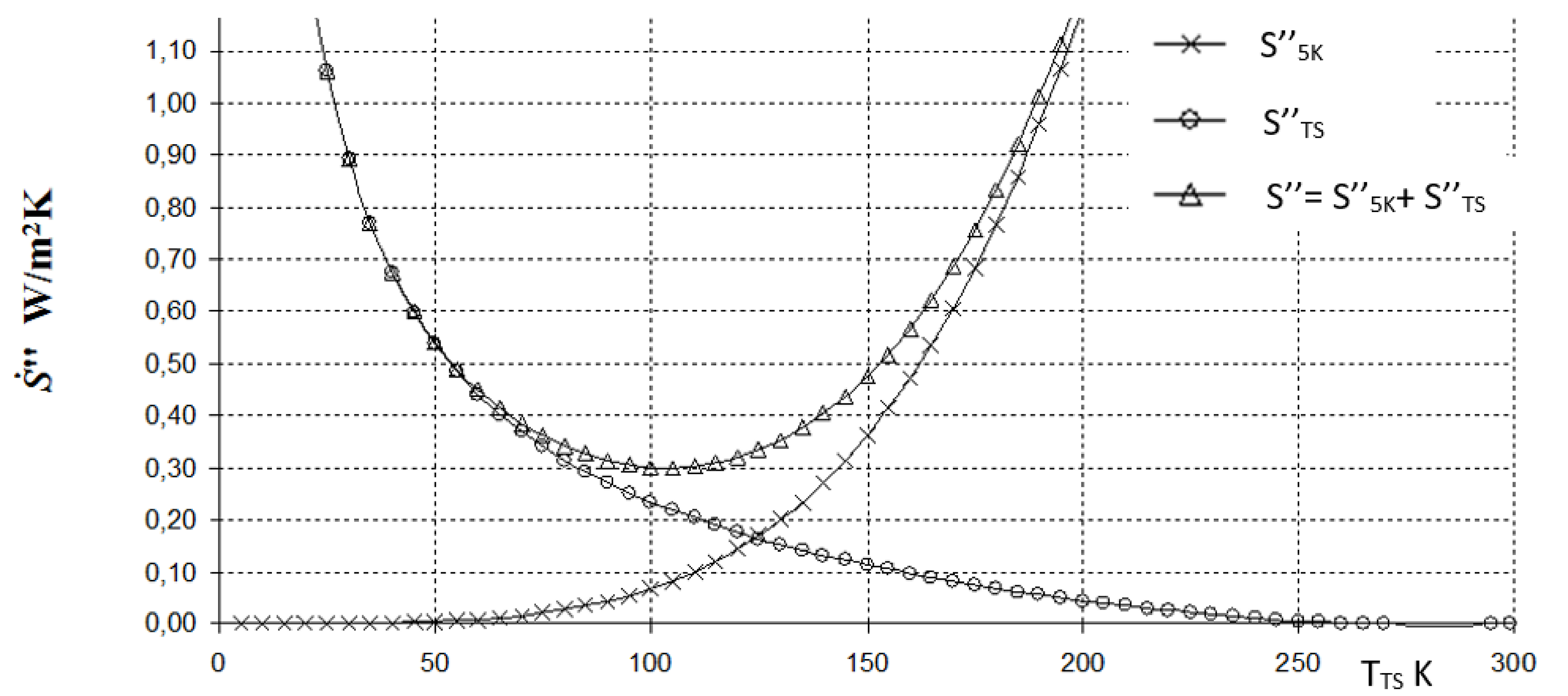
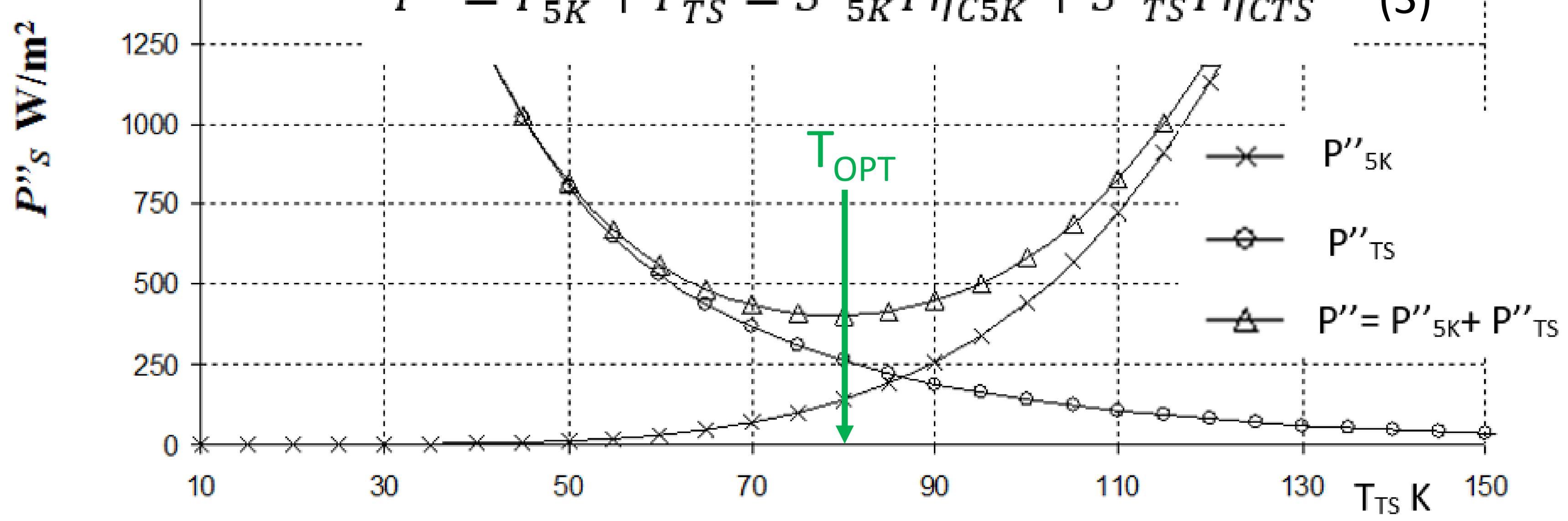


Fig. 2. The entropy streams generated in the considered system

Basis of the determined streams of entropy S''_{Tc} (Gouy-Stodola theorem) and Carnot efficiency η_{CTc} for a cryogenic refrigerator operating at T_c temperature level (3), it is possible to determine the loss of useful power resulting from heat inleaks.

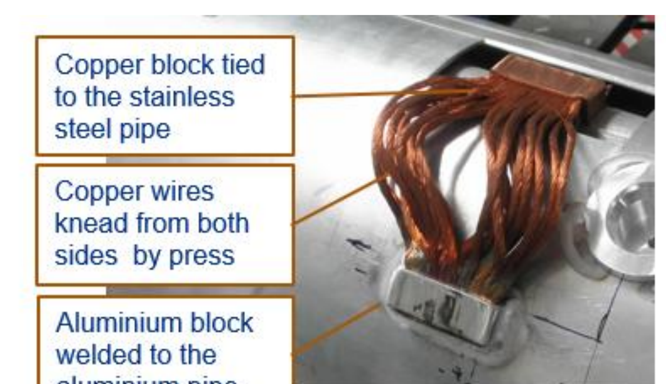
$$P'' = P''_{5K} + P''_{TS} = S''_{5K} T \eta_{C5K} + S''_{TS} T \eta_{CTS} \qquad (3)$$



3. Determining the best way of thermalization of the thermal shield based on experience from other projects

A very important parameter affecting the proper operation of the thermal shield is the method of its thermalization, i.e. making a thermal connection between the shield and the cooling pipe. When selecting the screen thermalization method for the cryogenic distribution system of the PIPII accelerator, the experience gained on the basis of previously completed projects was used.

XATL1 - transfer line for XFEL project (DESY, Hamburg)



Advantages:

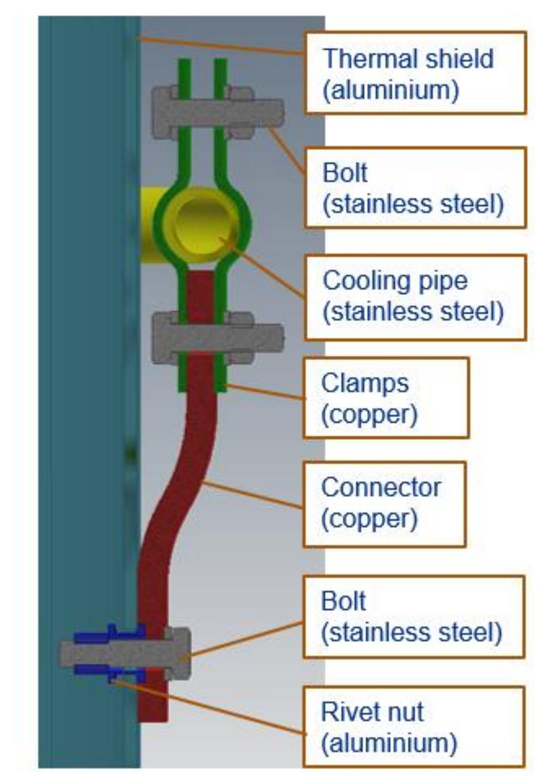
- good thermal conduction on weld connection side,
- flexibility and wide range of connected elements movement,
- possibility to install in narrow places,

Disadvantages:

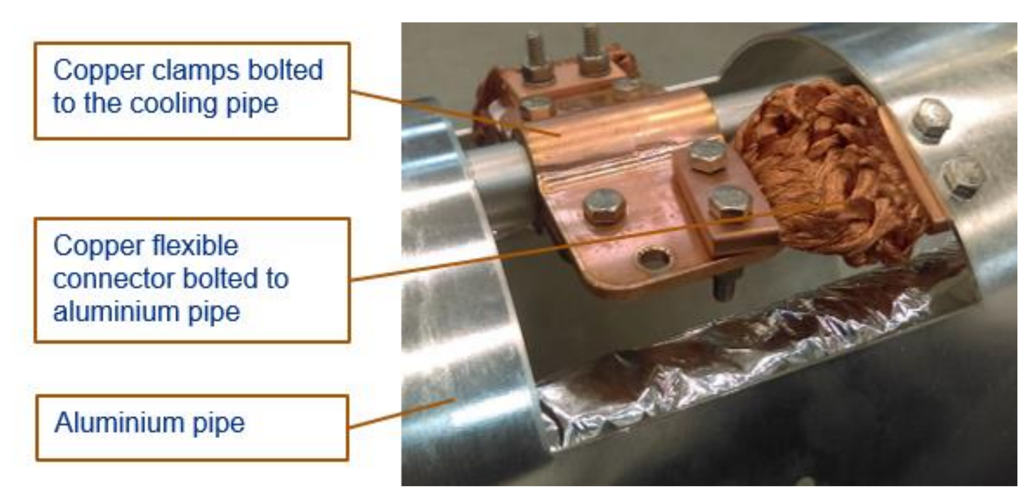
- many details made from the raw materials: copper and aluminum blocks, stainless steel binding wires,
- many different processes as water jet, milling, squeezing on the press, welding aluminum blocks,
- possibility to loose clamping because of many cool down-warm up cycles

VTS2 – helium cryostat (HZB, Berlin)

- **Advantages:**
- copper straps available on market,
- flexibility and wide range of connected elements movement,
- good thermal contact between copper clamps and cooling pipe,
- possibility to install in narrow places



ESS – Cryogenic Distribution System (Lund, Sweden)



- **Advantages:**
- copper straps available on market,
- flexibility and wide range of connected elements movement ,
- good thermal contact between copper clamps and cooling pipe, more screws per one joint,
- possibility to install in narrow places,

4. Conclusions

Based on experience from previous projects, it can be concluded that the best method to connect the copper braid and the screen cooling pipe is to use copper clamps, which are tightened with a screw connection. However, the best solution at the connection of the copper braid with the aluminum shield is to weld the aluminum end to the thermal shield. Such a design solution has been applied in the design of the Cryogenic Distribution System of the PIPII Accelerator.