Thermal analysis of EPOS components

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Abstract. We present a simulation study of the thermal behaviour of the moderator and the electrostatic lens of the positron source EPOS at the Research Center Dresden-Rossendorf. The positron moderator and the upper part of the electrostatic extraction einzellens are directly exposed to the primary electron beam with an energy of 40 MeV and a current of 1 mA. Thus, it was necessary to investigate whether the construction can stand the high temperatures. As a result we found that thin moderator foils with a thickness less than 40 \( \mu \)m will not reach too high temperatures. The thickness can be varied up to 0.2 mm, so we adjust the temperature in order to anneal lattice defects. These defects are caused by radiation. The wall of the extraction lens which is made from a stainless steel tube must be distinctly thinned to 0.05 mm to avoid damage temperatures. The time-dependent simulation shows, that the final temperatures are reached after less than a minute.

1. Introduction
The positron beam technique is a unique tool to study crystal lattice defects and open-volume cavities of nanometer scale [1]. The Forschungszentrum Dresden-Rossendorf provides an intense pulsed 40 MeV electron beam with high brilliance and low emittance (ELBE). It gives the unique possibility to construct an intense, pulsed positron beam for materials research. The EPOS System (ELBE Positron Source) generates an intense pulsed beam of mono-energetic positrons by pair production on a tungsten converter and a moderator with a repetition time of 77 ns and a bunch length of 5 ps. A detailed description to realize the EPOS project has already been published [2]. After the positrons are generated in the converter, the positrons will be moderated and an electrostatic lens focuses the positrons on a point of 1.5 mm diameter to transport the positrons by means of a magnetic guidance field into the positron laboratory. Because the moderator and a part of the lens will be hit by the intense primary electron beam, it is necessary to investigate the temperature behaviour of both parts in the electron beam. The results can be used for an efficient choice of construction material and the geometry of the moderator and the electrostatic lens [3].

2. Evaluation of the heat generation rates
The heat generation rates in the moderator and the upper part of the lens were calculated with the Monte Carlo code MCNP-5, release 1.40 [4]. MCNP is a Monte Carlo N-Particle code that can be used for stochastically simulating neutron, photon or electron transports. The code...
Figure 1. Part of the EPOS configuration. The ELBE electron beam hits the electron-gamma converter and is broadened from 5mm diameter to an angle so that the whole beam dump is exposed. The positron moderator is placed in front of the converter and parallel to the entrance plane of the upper tube of the positron focusing lens (see figure 2).

is able to treat an arbitrary three-dimensional configuration of materials. For neutrons and photons energy point wise cross-section data given in Evaluated Nuclear Data Libraries (such as ENDF/B-VI) are used to account for the various interactions with the materials. In case of electrons they are treated by means of a continuous-slowing-down model. The code allows the estimation of a broad range of integrals of the space-, energy- and direction-dependent particle fields together with their statistical errors. For the study presented in this report the mean values of the heat generation by photons and electrons averaged over user-defined volumes were calculated in a coupled electron/photon/neutron transport simulation. Figure 2 shows the arrangement and the definition of the estimation volumes (cells). The moderator foil was chosen to have a homogeneous thickness of 20 \( \mu \text{m} \) (cell 202). The electrostatic lens consists of 3 tubes. Only the upper lens tube is hit by the electron beam. Thus, only this tube is taken into the consideration and is shown in figures 1 and 2. The lens tube having a wall thickness of 1 mm (cell 241) is in the upper part, which is exposed to the high-energetic electron beam electrochemically thinned to a wall thickness of 50 \( \mu \text{m} \) (cell 210, 220 and 230 to 236). On top of this tube an electrostatic extraction grid of stainless steel is welded (cell 243). The results of the calculation for the different cells are listed in table 1. The energy input values are given as integral values in the volumes \( V_i \) for one electron with an energy of 40 MeV. The volumetric heat generation is obtained by:

\[
Q_{i}^{\text{vol}} = \frac{E_i I}{V_i e}
\]

where I is the current of the electron beam and \( I/e \) equals the number of electrons per seconds.
Figure 2. Arrangement of the upper part of the electrostatic lens and the moderator. The definition of the MCNP cells is indicated.

Table 1. Results of the energy calculation. The energy input values are given as integral values in the volume $V_i$ for one electron with an energy of 40 MeV.

| Cell | Volume $V_i$ [cm$^3$] | Energy input [MeV] | Comment |
|------|------------------------|--------------------|---------|
| 202  | 1.414e-2               | 1.18e-2            | W-moderator |
| 210  | 3.000e-2               | 5.77e-5            | additional cells to account for the gradient in beam direction |
| 220  | 3.000e-2               | 2.42e-4            | gradient in beam direction |
| 230  | 3.919e-2               | 9.10e-3            | ring1, height 1 cm |
| 331  | 3.919e-2               | 4.26e-3            | ring2, height 1 cm |
| 332  | 3.919e-2               | 2.28e-3            | ring3, height 1 cm |
| 233  | 3.919e-2               | 1.37e-3            | ring4, height 1 cm |
| 234  | 3.919e-2               | 8.84e-4            | ring5, height 1 cm |
| 235  | 3.919e-2               | 6.09e-4            | ring6, height 1 cm |
| 236  | 3.919e-2               | 4.28e-4            | ring7, height 1 cm |
| 241  | 7.389e+0               | 1.88e-2            | lower part of the lens |
| 243  | 1.461e-3               | 5.32e-4            | grid at the top of the lens |

3. Thermal calculations

3.1. Model
Based on the code ANSYS a finite element model is used to calculate the transient temperature distribution in the moderator, the grid and in the positron lens. Heat conduction within the materials and radiation heat transfer at the surfaces are considered. The heat generation density is obtained from table 1. An axisymmetric model was chosen assuming that the temperature gradient in beam direction is negligible.

3.2. Material properties
For the positron moderator two material options are considered: Pt and W. The lens and the grid are made of stainless steel. The extraction grid has an open area of 90%. To take this fact into account in the model reduced (or effective) material constants are used. The material properties from table 2 were used [5].
Table 2. Material properties for the thermal analysis.

| Material       | Tungsten | Platinum | Steel | Steel (grid) |
|----------------|----------|----------|-------|--------------|
| Density [kg/m³] | 19259    | 21450    | 7800  | 780          |
| Heat conduction coef. [W/m/k] | 174 | 71.6 | 15 | 1.5 |
| Specific heat [J/kg/k] | 130 | 133 | 510 | 51 |
| Emission coef. $\epsilon(T)$ | $\epsilon(T)$ | 0.24 | 0.24 |

3.3. Load and boundary conditions
The volumetric heat generation density is obtained by converting the value of table 1 using equation 1 assuming a current of $I = 1$ mA, thus a total electron power of 40 kW. One obtains the values given in table 3. The volumetric heat sources are “switched on” at $t = 0$ and remain constant afterwards. The heat generation rates in table 3 are valid for the full power mode. During the diagnostic mode 1% of these values are used. The initial temperature of the whole structure at $t = 0$ is $T_0 = 308$ K, the ambient temperature is assumed to be constant $T_a = 353$ K. For the volumetric heat generation rates in Pt we assumed the same values as in W.

Table 3. Heat generation rates.

| Cell | Heat generation rate [W/m³] | Comment                                      |
|------|-----------------------------|----------------------------------------------|
| 202  | 8.345e+8                    | moderator                                    |
| 220  | 8.067e+8                    | additional range for gradient (added to 230) |
| 230  | 2.322e+8                    |                                              |
| 231  | 1.087e+8                    |                                              |
| 232  | 5.818e+7                    |                                              |
| 233  | 3.496e+7                    | upper part of lens (thickness 0.05 mm)       |
| 234  | 2.256e+7                    |                                              |
| 235  | 1.554e+7                    |                                              |
| 236  | 1.092e+7                    |                                              |
| 241  | 2.554e+6                    | lower part of lens (thickness 1 mm)          |
| 243  | 3.641e+6                    | grid                                         |

3.4. Results
Transient calculations were performed for different scenarios. The following parameters were varied:

- the power of the beam (1% - diagnostic mode and 100% - full power mode)
- the moderator material (W or Pt)
- the thickness of the moderator
- the heat generation in the grid (100% - upper bound; 10% - realistic case)

The calculations were calculated as a function of time after switching on the electron beam. They were stopped when a steady state temperature field was reached.
Temperature in the Moderator  The heat-up of the moderator was calculated for Pt and W with a nominal thickness of 0.04 mm at 100% beam power. Figure 3 shows the maximum temperatures vs. time for W and Pt respectively.

![Figure 3. Temperature [K] vs. time [s] in the Pt and W moderator 100 % beam power.](image)

It can be seen that the steady state temperature is reached at about \( t = 8 \) s in both cases. The final temperature in W is 1144 K and in Pt 1158 K. The somewhat smaller value in W correlates to the slightly larger emission coefficient at 1000 K (Pt: 0.12, W: 0.14). In the following we investigate the influence of the moderator thickness on the maximum temperature. It is obvious that the maximum temperature will increase with increasing thickness, since the volume to surface ratio is given by:

\[
\frac{V}{A_{surf}} = \frac{s}{2 + 4s/D}
\]

where \( s \) and \( D \) are thickness and diameter respectively \((s \ll D)\). The thickness should be chosen in such a way that:

- the maximum temperature is sufficiently far from the melting temperature of the material (W: 3683 K; Pt: 2045 K) and
- the maximum temperature is high enough to enable the healing of the microstructural point defects caused by the irradiation.

![Figure 4. Maximum moderator temperature in dependence on thickness.](image)

The thickness of the moderator was varied from 0.01 mm to 0.7 mm for W and from 0.01 mm to 0.48 mm for Pt. The dependence of \( T_{\text{max}} \) on the thickness is shown in figure 4. The total heat input, which is proportional to the thickness, is indicated in the upper horizontal axis. The temperature gradient in the moderator is rather small (5 K) and can be neglected.
Temperatures in the lens  The temperature distributions in the lens (grid and tube) are discussed for the case of 100% heat generation. For the upper border case the influence of the emission coefficient of steel is investigated in the range $0.03 \leq \epsilon \leq 1$. The emission coefficient of steel strongly depends on the surface finishing; therefore the “nominal” value given in table 2 might be inaccurate. Figure 5 shows the temperature vs. time for 100% beam power at different locations. The steady state is reached approximately after 60 s. Figure 6 shows the steady state temperature distribution in the extraction tube.

The influence of the emission coefficient on the maximum (steady state) temperature is shown in figure 7 and figure 8. It can be seen that the hottest point is the end part where the grid is connected to the tube (“grid periph”). Here, the electron beam has the highest intensity. In the lower part of the tube (cell 241) the temperatures are significantly lower than in the upper part. It can be concluded that for $\epsilon \geq 0.05$ the maximum temperature in the tube is clearly lower than the melting temperature of steel ($\approx 1760$ K).
4. Conclusions
We performed a time-dependent thermal analysis of metallic parts (positron moderator and electrostatic extraction lens) of the positron source EPOS being directly exposed to the high-energetic, high-flux electron beam of the radiation source ELBE at the Research Center Dresden-Rossendorf. The temperature of the moderator can be adjusted by varying the thickness of the foil. It is possible to obtain high enough temperatures to ensure defect annealing under operation conditions. This will lead to a larger positron diffusion length, and thus to a higher efficiency of the electron-positron conversion. The ideal thickness of the moderator foil by the electron beam energy of 40 MeV is in the range of 0.5 to 2 mm, but in this region the temperature is too high. Because the annealing temperature of platinum is lower than tungsten, the moderator should be made of platinum with a thickness of 0.2 mm. In this case, the temperature on the moderator is 1550 K and the point defects can anneal.

The extraction lens tube is made of stainless steel. The upper part which is hit by the high-intense electron beam must be thinned electrochemically in order to reduce the heat load. A version having a wall thickness of only 50 µm has been realized and will be tested soon. We expect a temperature not higher than 1150 K. This is far from the melting temperature of stainless steel (1760 K). The mesh grid on top of the extraction tube which is also made from stainless steel will have a temperature of about 1100 K at full beam power. All this parts will be at a stable operation temperature after less than 60 s.

References
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