ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM126

COOLING AND THERMOMECHANICAL STUDIES FOR THE IMPACT TATTOOS BEAM DUMP DESIGN

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Abstract

The Isotope and Muon Production using Advanced Cyclotron and Target technology (IMPACT) project at the Paul Scherrer Institut aims to produce and fully exploit unprecedented quantities of muons and radionuclides for further progress in particle physics, material science and life science. The proposed Targeted Alpha Tumor Therapy and Other Oncological Solutions (TATTOOS) facility will provide, for research purposes, medically relevant radionuclides, via proton-induced spallation. This new 100 µA / 590 MeV proton beamline will deliver up to 45 kW to the beam dump.

To design the beam dump, a hybrid analytical / numerical cooling model was developed to reduce the total amount of CFD simulations. This model consists of analytical surface temperatures applied as boundary conditions to an ANSYS thermal model. It was validated using CFD simulations and then used in the design process of the beam dump. A temperature dependent multilinear isotropic hardening model was used to simulate the behaviour of annealed copper. Irradiation induced hardening was also taken into account.

INTRODUCTION

The initial studies reported in the IMPACT Conceptual Design Report (CDR) [1] gave a first estimation on the temperatures reached for nominal operating conditions in the beam dump. The design consisted in an Oxygen-Free Copper (OFE) full cylinder of 150 mm radius and 250 mm depth cooled via stainless steel pipes windings brazed around the dump. The design principle is based on the existing beam dumps at PSI as shown Fig. 1.

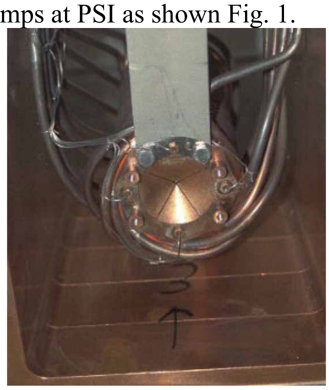

Figure 1: Beam Dump BHE3 - HIPA facility PSI [1].

The goal of the studies reported here is to deliver a detailed design of the "active" part of the beam dump including expansion slits during a worst-case scenario (WCS).

FRAMEWORK & REQUIREMENTS

TATTOOS Beamline

The TATTOOS beamline will be located at the 2.4 mA High Intensity Proton Accelerator (HIPA) at the Paul Scherrer Institut (PSI) [2], and will operate at a beam intensity of 100 µA, split from the main beam via an electrostatic splitter [3]. The beam will be directed towards the target station thanks to a set of bending and steering magnets [4]. Just upstream of the target station, a set of two fast dipole magnets (called Wobblers) will flatten the beam distribution on the target [5]. Located at the end of the beam line, the beam dump will absorb the protons and the secondary particles coming from the spallation target [6].

Power Deposition

The power deposited depends on several factors. The shape and material of the target influence the power profile and the total power on the dump. The radius of the rotating beam from the Wobbler also plays a role in the beam dilution and finally the beam optics too but to a lesser extent.

Scenarios such as commissioning and accidental situations were evaluated and the WCS occurs when the 100 µA beam impinges the dump directly without target and without beam flattening. This corresponds to a scenario when the wobblers stop working and as consequence the pencil beam had molten already the target. The power distribution along the beam axis in the WCS is presented Fig. 2. The total power is 45 kW for the geometry studied in the CDR.

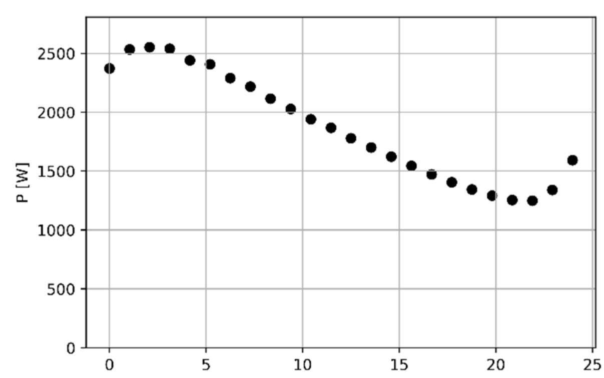

Figure 2: Power deposited per slice of about 1 cm along the beam dump for the WCS.

Requirements

The thermal and structural requirements are reported in Table 1.

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14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM126

Table 1: Requirements for the Beam Dump Design

Requirements	Comment
$\max(T_{Cu}) < T_H(Cu)$	Avoid creep.
$\max(T_w) < T_{Boiling}(w)$	Avoid loss of cooling efficiency.
$v_w < 9\ \mathrm{m.s^{-1}}$	Avoid erosion of the pipes.
$\max(\varepsilon_{pl,virgin}) < 2\ \%$	Allow small amount of strain hardening in un-irradiated copper.
$\max(\sigma_{eq,irr}) < \sigma_{y,irr}$	Avoid plasticity at high displacement per atom (dpa).
$\Delta l < {d_{slits}}/{2}$	Avoid closing of slits.

With $\max(T_{Cu})$ the maximum temperature in the copper, $T_H(Cu)$ the homologous temperature of copper, $\max(T_w)$ the maximum water temperature, $T_{Boiling}(w)$ the boiling temperature at the operating pressure, v_w the water velocity, $\max(\varepsilon_{pl,virgin})$ the maximum of plastic strain in un-irradiated copper, $\max(\sigma_{eq,irr})$ the maximum Von Mises stress in irradiated copper, Δl the deformation in the normal direction of a slit, d_{slits} the width of a slit.

ANALYTICAL COOLING MODEL

Definition

The analytical model consists of the discretization of the beam dump in disks of about 1 cm thickness along the proton beam axis. For each slice "*i*", the total power P_i from the MCNP6.2 [7] simulation is computed and then divided by the number of pipes n_{pipes} and the ratio between the pitch h_{helix} and the slice thickness Δz_i, to obtain the power per pipe per slice $P_{i,pipe}$:

$$P_{i,pipe} = \frac{P_i}{n_{pipes}\,\frac{h_{helix}}{\Delta z_i}}$$

Using temperature-dependent water properties [8] to calculate the Reynolds *Re* and Prandtl *Pr* number, the Nusselt number is calculated using the correlation from [9] for the inner surface of a helical pipe. *D* corresponds to the coil diameter and *d* the pipe diameter:

$$\boldsymbol{Nu_i = 0.012\left(\frac{D}{d}\right)^{0.088} Re_i^{\,0.8} Pr_i^{\,0.4}}$$

The bulk temperature $T_{B,i}$ and the surface temperature $T_{S,i}$ are calculated respectively using the energy balance for a steady-flow system and Newton's law of cooling. For the bulk temperature, the inlet temperature is taken as the outlet temperature of the previous slice $T_{B,i-1}$.

Validation of Analytical Flow Temperatures

The validation of the analytical model is performed on the CDR geometry with ANSYS Fluent [10]. A non-conformal polyhedral mesh of 26 million cells was used with mapped and coupled interfaces. The turbulence models k-ω SST and Reynolds Stress Model for a flow rate of 0.8 kg/s were compared to the hybrid model similar results were obtained.

The flow in a helical pipe undergoes centrifugal forces leading to a secondary effect pushing the cold flow outwards, inducing non-uniform surface temperature. To account for this phenomenon in the assessment of the analytical model, the averaged circumferential CFD surface temperatures are computed and plotted on Fig. 2 along with the analytical surface temperature.

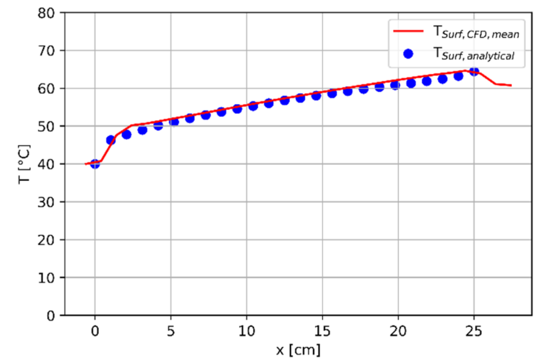

Figure 3: Surface temperatures along the Beam Dump obtained via CFD and the analytical model.

Figure 3 shows good agreement between the analytical surface temperatures and the CFD averaged surface temperatures.

HYBRID MODEL

To account for conduction through the pipes, the temperature on the external surface of the pipe is calculated as in [11] and the obtained temperature, $T_{BC,i}$, is applied as boundary condition in a thermal simulation.

$$T_{BC,i} = T_{S,i} + \frac{q_i.\ln\left({r_o}/{r_i}\right)}{2.\pi.\lambda_{steel}.\Delta z}$$

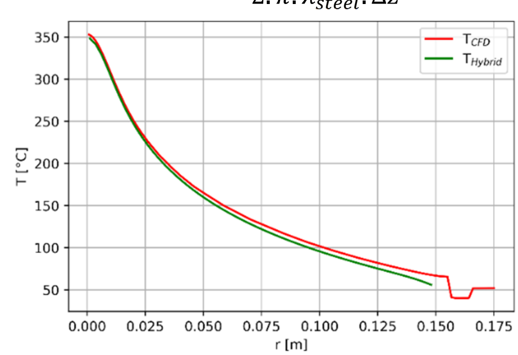

Figure 4: Radial temperature profile at the front-end obtained via CFD and the hybrid model.

In addition to Fig. 4, comparisons were also performed along the beam axis at several radial positions. Validations of the hybrid model on other components of the IMPACT project were also carried [12].

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THERMO-MECHANICAL DESIGN

Material Properties

As the copper disks are foreseen to be brazed together at 830°C, the material properties of annealed copper were used. Moreover, the beam dump will undergo lattice changes through irradiation, so both stress-strain curve of OFHC copper as un-irradiated material and neutron irradiated at 0.3 dpa [13-15] were implemented via a Multilinear Isotropic Hardening Rule to assess the structural behaviour in ANSYS Mechanical.

Design Process

All the simulations were performed in steady-state. Any important modification of the geometry of the Beam Dump requires a new MNCP6.2 simulation to evaluate the power deposited.

The first step of the design process was to add expansion slits to the CDR design. In the beam direction, the beam dump is divided into 6 disks separated by 1.5 mm slits. On each disk, 4 radial slits of 1.5 mm width slanted by 15° to prevent any "see-through" angle for the beam were designed. These slits separate each disk into four quarters facing the beam unevenly, thereby increasing the maximum temperature to about 450°C in the simulations. In order to mitigate this effect, the thickness of the first two disks was reduced to decrease the amount of power deposited and to lower the temperature. To compensate this loss of thickness and still ensure the full stopping power, the length of the dump was increased to 300 mm.

Figure 5 shows the temperature distribution on the final design with a maximum temperature of 362°C (the beam travels from left to right).

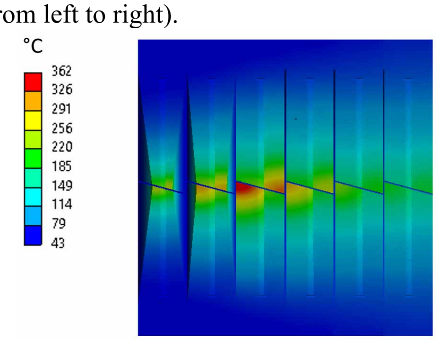

Figure 5: Temperature distribution in °C for the WCS on the longitudinal cross section of the Beam Dump.

When the temperature met the criteria of $T_{max} < T_H$, FEM simulations were performed to assess the structural integrity of the beam dump. The simulations were performed on the third disk which undergoes the highest temperature increase as can be seen in Fig. 5.

The main point of interest was the stress concentration at the tip of the slits in the irradiated case. At other PSI-used beam stops a ϕ = 2 mm hole is common, but to fulfil the requirement of no plastic deformation under irradiated condition the hole was enlarged to allow a better stress distribution. Initially, with the 2 mm hole, the maximum equivalent stress was 272 MPa, slightly over the 270 MPa yield strength of the material. As shown on Fig. 6, after enlarging the hole to ϕ = 8 mm, the maximum stress was reduced to 195 MPa resulting in a 28% safety margin.

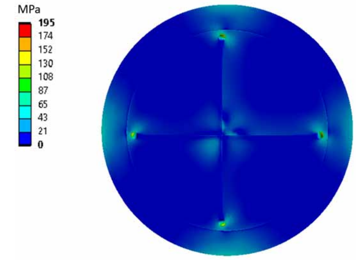

Figure 6: Stress distribution in MPa at the front-end of the 3rd disk with irradiated data.

Finally, taking in account the latest studies on the target and the rotating beam radius, the diameter of the beam dump could be reduced to 135 mm and thus, the cost of copper purchase was lowered significantly. The final simplified design is shown on Fig. 7.

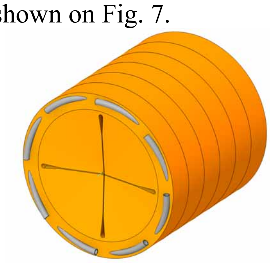

Figure 7: TATTOOS Beam Dump final design from simulation studies (pipes in grey, copper in orange).

CONCLUSION

In the framework of the TATTOOS project, a new beam dump was designed via thermo-mechanical simulations to withstand 45 kW from a 100 μA beam. This corresponds to the WCS where the wobbler fails and the target is molten. However, a failure of the beam wobbler would be detected by the machine protection system which, in turns, would trigger a beam interlock and avoid therefore the occurrence of the WCS. According to Table 2, temperatures for water and copper are acceptable. The structural analysis shows low risks of slits closing and a low risk of fracture. A hybrid analytical/numerical model was developed to avoid costly CFD simulations and was successfully validated.

Table 2: Summary of the Simulation Results

Requirements	Simulation results
$\max(T_{Cu}) < T_H(Cu)$	362°C < 405°C
$\max(T_w) < T_{Boiling}(w)$	65°C < 100°C
$v_w < 9\ m.s^{-1}$	$1{,}5\ \mathrm{m.s^{-1}} < 9\ \mathrm{m.s^{-1}}$
$\max(\varepsilon_{pl,virgin}) < 2\%$	0,89% < 2%
$\max(\sigma_{eq,irr}) < \sigma_{y,irr}$	195 MPa < 270 MPa
$\Delta l < {d_{slits}}/{2}$	0,28 mm < 0,75 mm

The next steps envisaged for the beam dump development include the detailed design of the complete beam dump insert, the cooling loops and the integration of monitoring devices (thermocouples, beam halo monitors, etc.).

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REFERENCES

[1] R. Eichler *et al.,* "IMPACT conceptual design report", Paul Scherrer Institute, Villigen PSI, Switzerland, PSI Rep.No.22-01, Jan. 2022.

[2] D. Kiselev *et al.*, "Status and future projects of the PSI High Intensity Proton Accelerator", in *JPS. Conf. Proc.*, Tsukuba, Japan, p. 01104, Sep. 2019. `doi:10.7566/jpscp.33.011004`

[3] M. Olivo, U. Rohrer, E. Steiner, "An electrostatic beam splitter for the SIN 590 MeV proton beam line", *IEEE. Trans. Nucl. Sci.*, vol. 28, pp. 3094-3096, Jun. 1981. `doi:10.1109/TNS.1981.4332020`

[4] M. Hartmann., *et al.* "Design of the 590 MeV proton beamline for the proposed TATTOOS isotope production target at PSI", *Journal of Physics: Conference Series*. Vol. 2420. No. 1. IOP Publishing, 2023. doi:10.1088/1742-6596/2420/1/012105

[5] D. Reggiani *et al.*, "Simulation of a beam rotation system for the SINQ spallation source at PSI", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper THPWO pp. 3954-3956.

[6] S. Jollet *et al.*, "Development of the TATTOOS Target", presented at IPAC'23, Venice, Italy, May 2023, paper TUPM127, this conference.

[7] C. J. Werner, *et al*., *"MCNP6.2 Release Notes",* Los Alamos National Laboratory, report LA-UR-18-20808, 2018.

[8] P. Stephan and V. H. Atlas, "D3.1 - Properties of Pure Fluid Substances," in *Fundamentals of Heat Transfer*, VDI, pp. 301-393, 2010.

[9] B. Hardik, P. K. Baburajan, and S. V. Prabhu, "Local heat transfer coefficient in helical coils with single phase flow", *Int. J. Heat Mass Transfer*, no. 89, pp. 522-538, 2015.

[10] "ANSYS." ANSYS, Inc.: `https://www.ansys.com/`

[11] Y. A. Cengel, *"Heat Transfer, a practical approach 2nd edition"*, 2003.

[12] R. Sobbia *et al.*, "Cooling and thermomechanical studies for the IMPACT HIMB collimator system", presented at IPAC'23, Venice, Italy, May 2023, paper TUPM121, this conference.

[13] B. N. Singh, A. Horsewell, P. Toft, and D. J. Edwards, "Temperature and dose dependencies of microstructure and hardness of neutron irradiated OFHC copper.", *Journal of Nuclear Materials,* vol. 224, no. 2, pp. p. 131-140, 1995.

[14] B. N. Singh, D. J. Edwards, and P. Toft, "Microstructure and mechanical properties of neutron irradiated OFHC-copper before and after post-irradiation annealing", Risoe National Lab. Materials Research Dept, Roskilde, Denmark, Rep. RISO-R-1213(EN), Feb. 2001.

[15] M. Li and S. J. Zinkle, "4.20 - Physical and mechanical properties of copper and copper alloys," in *Comprehensive nuclear materials*, Elsevier Ltd., 2012, pp. 667-690.