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ASSESSMENT OF BEAM-INTERCEPTING DEVICE ROBUSTNESS FOR INTENSITY INCREASE IN CERN'S NORTH AREA

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Abstract

CERN's North Area comprises several target and experimental systems and is a zone of interest for future development. Provision of beam to this area relies upon several beam-intercepting devices located in various branched transfer lines from the Super Proton Synchrotron. In several lines, these include a primary production target system of beryllium plates followed by a combined collimation, attenuation and dump device made from a set of aluminum, copper and iron blocks and known as a 'TAX' (Target Attenuator [for] eXperimental areas). These may operate in a range of configurations depending on experimental needs. Future operational regimes with higher beam intensities (increased from a current specification of 1.5×10^{13} to 4.0×10^{13} p^+/pulse), shorter pulse times (4.8 s reduced to 1.2 s), greater repetition rates (14.4 s cycle time reduced to 7.2 s) and ten times the annual intensity place more stringent thermo-structural demands on these existing devices, beyond their original specification. This contribution outlines the engineering analysis, including beam-matter interaction studies and thermo-structural simulations, carried out to assess their robustness under such conditions.

INTRODUCTION

CERN's North Area is the focus of ongoing interest for future experimental facilities, particularly in the context of 'Physics Beyond Colliders' [1]. These installations require higher-intensity proton beams and shorter repetition cycles than are currently available, and necessitate the assessment and consolidation of existing beamline infrastructure to cope with such conditions [2]. This assessment includes several important beam-intercepting devices, particularly a beryllium target system and a multi-purpose dump-collimator device known as a 'TAX' (Target Attenuator [for] eXperimental areas), which together form the focus of this contribution. The pre-existing design is outlined; new engineering studies on device limitations are presented; and conclusions for high intensity operation discussed, with some additional consideration of possible avenues for consolidation in future.

SYSTEM OVERVIEW

The North Area (NA) beamlines deliver a 400 GeV/c primary proton beam in a slow extraction from the Super Proton Synchrotron (SPS) to various target systems, producing secondary beams for downstream users. Several branched beamlines operate in shared mode, serving multiple experimental areas during the same extraction. One branch of particular interest is the TT24 transfer line which delivers beams to the ECN3 experimental cavern (the focus for new installations and high-intensity proposals [3–5]) and the EHN1 experimental hall. It includes the T4 target along with upstream and downstream bending ('wobbler') magnets as well as the TAX. This system enables production of secondary beams using the target and selection by charge/momentum using the pre/post-target bending of the wobbler magnets and angled apertures of the TAX. The TAX also provides capability for collimation (varying aperture size), attenuation (using apertures with beryllium inserts) and dumping (directly on the block) by selecting different vertical positions of each of four independent modules.

HIGH INTENSITY SCENARIOS

Proposed operational scenarios in Table 1 set the general requirements for beam delivery, although conditions vary depending on cycle combinations, shared or dedicated routing in the North Area as well as the experimental proposal considered, with the T4 in fact bypassed in some cases. This study considers two simplified cycles—a 1.2 s pulse every 7.2 s; and a 4.8 s pulse every 14.4 s—to assess the robustness of the T4 and TAX at higher intensity, establish limitations and the extent of possible consolidation required, with conclusions also extendable to other target systems.

Table 1: High Intensity Scenarios

Parameter	Current	Proposed
Intensity [p^+/pulse]	1.5×10^{13}	1.5×10^{13}–4.0×10^{13}
Pulse length [s]	4.8	1.2–4.8
Repetition period [s]	14.4	7.2–14.4

T4 TARGET SYSTEM

Design and Materials

The T4 target system consists of five layers with beryllium plates of 40–500 mm in length, clamped at the sides by aluminium alloy supports which rest within a surrounding aluminium alloy chassis (Fig. 1). Energy deposited in the plate is primarily dissipated by conduction towards the supports and then to convective cooling fins subjected to a vertical forced airflow. Beryllium (grade S-200-F [6]) provides a

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low-Z target material with good physics performance for secondary beam production and thermo-mechanical properties, having a density of 1850 kg/m^3, specific heat of 1900 J/kgK, thermal conductivity of 180 W/mK, coefficient of thermal expansion of 12 µε/K, Young's modulus of 300 GPa and yield strength of 240 MPa, all reported at room temperature.

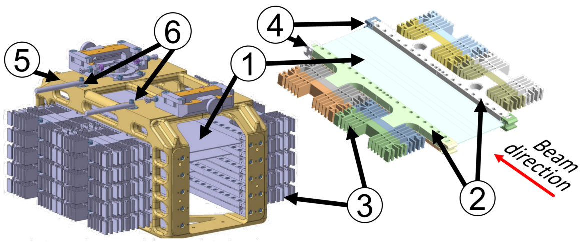

Figure 1: T4 full target assembly (left), one layer (right): 1. Be plates, 2. Al supports, 3. Al cooling fins, 4. end pieces, 5. chassis, 6. guide pins.

Beam-Matter Interaction

Beam-matter interaction studies used the FLUKA Monte-Carlo code [7, 8] to compute a profile of energy deposited per unit volume. In the 500 mm plate (considered the worst case), the maximum is 1.2 kJ/cm^3 at 1.5×10^{13} p^+/pulse and 3.1 kJ/cm^3 at 4.0×10^{13} p^+/pulse, with total energy deposited in the plate of 1.0 kJ and 2.7 kJ respectively. For the 1.2 s / 7.2 s cycle, this gives a deposited power of 840–2300 W during the pulse and 140–380 W averaged over time. Meanwhile the 4.8 s / 14.4 s cycle gives 210–570 W deposited during the pulse and 70–190 W over time.

Thermo-Structural Studies

Finite Element Modelling Finite element analysis (FEA) was completed in ANSYS® Workbench™ [9] for the 500 mm target layer (Fig. 1) and a beam position corresponding to the typical wobbler magnet configuration. Using a temperature-dependent material model, transient thermal and quasi-static structural simulations were made for the development of steady-state conditions, followed by one pulse from that initial steady state, and also for one pulse from room temperature. The model consisted of around 1.7M quadratic elements with a hexahedral mesh of 6 divisions through thickness in the target plate. The contact between the plate and supports was assumed frictional ($\mu = 1.2$) with a conservative thermal contact conductance of 1000 W/m^{2}K.

Boundary Conditions and Loads Convection conditions were applied, particularly to the cooling fins with a heat-transfer coefficient (HTC) of 25 W/m^{2}K (calculated by Nusselt correlations [10] with a 1.7 m/s airflow and supported by preliminary CFD), and also to the target plate and supports with HTCs of 4–8 W/m^{2}K and an air temperature of 30 °C in all cases. Radiation (to ambient) conditions were also applied where appropriate.

Structurally, the model is constrained by vertical zero-displacement constraints on the horizontal edges of the end pieces, as if resting on the support rails of the chassis, combined with horizontal zero-displacement conditions on one point of each guide pin hole. This, in conjunction with contact conditions between parts, accounts for all rigid body degrees of freedom. Conservatively high bolt forces of 10 kN per bolt were applied to pre-stress the frictional contact.

Thermal simulation temperature results were transferred to the structural model, generating the stresses of interest.

Results Results (Table 2) suggested, for the 4.8 s / 14.4 s cycle, that the full proposed intensity of 4.0×10^{13} p^+/pulse could be supported in sustained operation whilst keeping beam-intercepting region stresses below the 240 MPa yield strength (σ_y). Yielding around bolt holes in the clamped region was considered acceptable given sufficient margin from the 2 % elongation at break. For the more demanding 1.2 s / 7.2 s cycle, the limit was indicated at 3.0×10^{13} p^+/pulse (Fig. 2). However, these are reported with no inherent conservatism or safety margin and do not account for possible radiation damage or fatigue effects over time. Hence, more cautious operational limits should be enforced in practice.

Room temperature initial conditions (rather than steady-state) are less demanding. Even for the 1.2 s / 7.2 s cycle, a pulse at full proposed intensity could be accepted. However, given the short steady state evolution time (of the order of 10 minutes), this may not be sustained beyond a single pulse.

Table 2: T4 FEA Results – Limiting Cases for Sustained Operation – Stress for Beam-intercepting Region Only

Cycle	Intensity limit [p^+/pulse]	Von-Mises stress [MPa]	Max. temp. [°C]	Vert. plate displacement [µm]
1.2 s / 7.2 s	3.0×10^{13}	206 ($0.86\sigma_y$)	204	156
4.8 s / 14.4 s	4.0×10^{13}	107 ($0.45\sigma_y$)	144	115

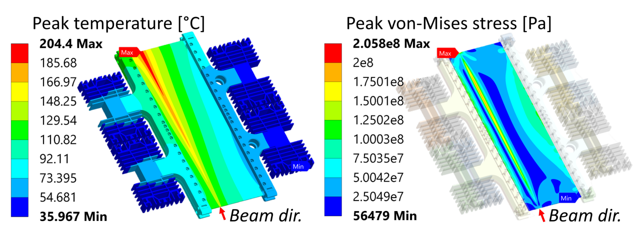

Figure 2: T4 FEA results – 1.2 s / 7.2 s cycle, sustained operation at 3.0×10^{13} p^+/pulse.

TAX DUMP-COLLIMATOR

Design and Materials

The T4 TAX (Fig. 3) comprises four modules, each of them containing 4 blocks of various materials: one of Al-6082, two of Cu-C10300 and one of pearlitic grey cast iron in the upstream modules; and two of Cu-C10300 followed by two of cast iron in the downstream modules. Contained within a thick (80 cm) iron shielding, the four independently-movable modules each rest upon their own water-cooling table with stainless-steel pipes cast directly into a copper alloy platform. This active water cooling system, in combination with natural convection of air around the blocks, is crucial to reduce temperatures and thermal stresses.

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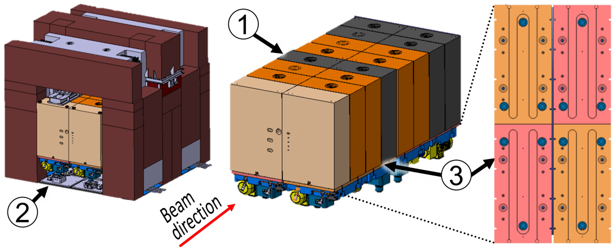

Figure 3: 1. TAX absorbing blocks: Al (beige), Cu (orange), Fe (grey); 2. TAX with shielding; 3. Cooling tables.

Beam-Matter Interaction

Beam-matter interaction studies again used FLUKA to calculate a deposited energy distribution in the most critical module for the most demanding case (full beam dump with target out of beam). Peak deposited energy per unit volume may reach 0.72 kJ/cm^3 at 1.5×10^{13} p^+/pulse and 1.92 kJ/cm^3 at 4.0×10^{13} p^+/pulse, with total deposited energy around 816 kJ and 2175 kJ respectively. This gives 56–114 kW average deposited power for the 4.8 s / 14.4 s cycle, and 151–302 kW for 1.2 s / 7.2 s.

Thermo-Structural Studies

Finite Element Modelling Each TAX module is thermally and mechanically independent, meaning that finite element analysis may focus only on the most critical module where the primary beam is dumped. Like the T4, modelling is completed in ANSYS® Workbench™ with thermo-structural simulations for the evolution to the steady state, followed by transient simulations of one pulse from that initial steady state, and also for one pulse from room temperature. The model consists of around 2.2M linear elements, mostly hexadedral (absorbing blocks) with some tetrahedral (cooling table). The blocks rest on the cooling table with only their weight providing the interface pressure for thermal contact conductance (a strong influence on temperatures).

Boundary Conditions and Loads Contact conductances were calculated conservatively (100–1000 W/m^{2}K, depending on materials) based on the Mikic-Yovanovich equation [11]. Meanwhile, Colburn's Formula [12] gave the convective HTC in the cooling pipes for a minimum flow rate of 20 l/min as 9134 W/m^{2}K. Radiation cooling was also included given its relevance at high temperatures. For simplicity, blocks are structurally connected by bonded contact to the cooling table, which is constrained in the vertical direction. Weak springs are applied for stability.

Results Simulations indicated that proposed intensities are unacceptable since sustained dumping, even at 1.5×10^{13} p^+/pulse, gives temperatures of 1205 °C for the 4.8 s / 14.4 s cycle and 2507 °C for 1.2 s / 7.2 s, implying local melting in the first copper block (Fig. 4). Limiting intensities (Table 3) were much lower at 8.0×10^{12} p^+/pulse and 3.0×10^{12} p^+/pulse respectively. This prevents melting (at 1080 °C) and keeps stresses in an acceptable range relative to the yield strength of the copper (100 MPa at 20 °C, assuming annealed conditions due to uncertainty). Some plastic deformation is tolerated; however, beyond these intensities, potentially significant ratcheting of plastic strains may cause substantial degradation of the material.

From room temperature (rather than the steady state), results for the 4.8 s / 14.4 s cycle suggest that the TAX could withstand the order of 10 pulses at 1.5×10^{13} p^+/pulse. Nevertheless, this demands caution due to the non-negligible risk of material damage by accumulating plastic strains. Furthermore, whilst stresses are localised to the beam-intercepting region when dumping at room temperature, stresses at the apertures become more significant as temperatures increase.

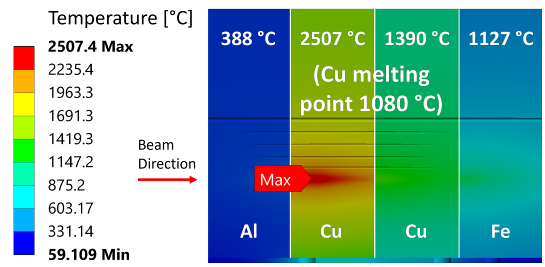

Figure 4: TAX steady-state temperature distribution, dumping at 1.5×10^{13} p^+/pulse for the 1.2 s / 7.2 s cycle.

Table 3: TAX FEA Results for the First Copper C10300 Block – Limiting Cases for Sustained Operation

Cycle	Intensity limit [p^+/pulse]	Von-Mises stress [MPa]	Max. temp. [°C]	Yielding
1.2 s / 7.2 s	3.0×10^{12}	86	274	Moderate
4.8 s / 14.4 s	8.0×10^{12}	95	362	Moderate

CONCLUSIONS

Analysis presented indicates that, for the simplified cycles considered, the T4 target can support higher intensities up to the limits specified. Due to the nature of operational scenarios, improvements to the target are not immediately necessary provided that suitably defined limits are enforced.

For the TAX, analysis indicates that higher intensities are unacceptable due to high Cu and Al temperatures and possible damage in the dumping region and apertures. Intensity limits for sustained operation are much lower. Whilst the TAX has operated beyond these limits (up to 1.5×10^{13} p^+/pulse) without apparent problem, further increases cannot be supported and improvements are required for the future scenarios proposed.

POSSIBLE FUTURE UPGRADES

Although not crucial for current proposals, future consolidation of the T4 target may include cooling system upgrades, a modified clamping mechanism to reduce stresses, a multi-part target plate or material changes.

More critically, for the TAX, modifications to the block design and water-cooling system, and potential optimisation of the material and energy deposition profile are the focus to guarantee survival under the operational scenarios proposed.

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