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Temperature and Stresses in the LE Target with 6.4 mm Wide Segments

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Introduction

The advanced conceptual design of the LE target (the target intended to be used in the NuMI low energy neutrino beam) is described in [1], while [2] gives results of calculations of dynamic stresses induced in the target material by the 8.6 μs single turn extracted primary beam, as well as results of LE target prototyping, which were fabricated to test the general construction technics and that alignment tolerances can be met.

Following a new conception of the baffle protection colimators, which keeps the focusing system and all decay region from entering of the missteered primary proton beam, the width of graphite target segments was increased from 3.2 mm up to 6.4 mm at the same proton beam spot size. In response to these changes in a target design this Report presents results of temperature and stress calculations showing ~20% increase of the safety factor. Approximately 10% loss of neutrino events with $3.5 < E_\nu < 6.0$ GeV due to extra absorption of secondaries in a target material was considered as acceptable taking into account a few percents increase of neutrino events with $E_\nu < 3.5$ GeV.

Cross-section of the LE target with 6.4 mm wide segments is shown in Figure 2.1. The target core is a row of 47 graphite segments, each 18 mm high and 20 mm long. The segments are soldered by means of a soft solder to two steel cooling pipes with external diameter 6.0 mm and wall thickness 0.3 mm. The target core is inserted into a 0.4 mm thick 30 mm diameter aluminum casing and centered by five 5 mm thick aluminum spacers.

Energy Deposition in the Target

Calculations of energy deposition were made using the MARS14(2000) code [3] for the primary proton beam with Gaussian distributions in both transverse directions $\sigma_x \times \sigma_y = 0.7 \times 1.4$ mm^2.

The energy deposition density at the beam axis reaches the maximal value of ~0.095 GeV/cm^3/proton in 4÷6 segments and then decreases continuously to ~0.025 GeV/cm^3/proton at the downstream end of the target. Distributions of average power deposited in the target (Figure 2.3) are given for the primary beam with intensity of 4×10^{13} protons per 1.9 s. The power deposited in target segments is equal to 2.96 kW. With addition of 0.42 kW deposited in steel pipes and in cooling water, the total load to the water cooling system is about 3.4 kW (Table 2.1).

Elements of the LE target	Width of a target segment:	
	3.2 mm	6.4 mm
Graphite segments	2.065	2.959
Cooling pipes	0.077	0.212
Cooling water	0.048	0.203
Aluminum casing	0.118	0.148
Total	2.308	3.523

Table 2.1: Energy deposition (kW) in different elements of the LE target.

Cooling of Target Segments

Calculated values of a heat transfer coefficient, a pressure drop, a flow rate and a temperature rise of a cooling water as functions of a water flow velocity in the target cooling system are given in Table 2.2. Calculations were made for cooling pipes with internal diameter of 5.4 mm and roughness of 0.02 mm. Taking into account that the input temperature of a cooling water is equal to 37°C, a relatively wide range of water flow velocities from 2 up to 4 m/s is acceptable for cooling of target segments.

Velocity of a cooling water, m/s	2	3	4
Heat transfer coefficient, kW/m^2/K	10	14	18
Pressure drop, atm	0.32	0.68	1.2
Water flow rate, l/min	2.7	4.1	5.5
Water temperature rise, °C	18	12	8.8

Table 2.2: Main parameters of the LE target cooling system.

Temperature and Stresses in Target Segments

Calculations of target temperature, as well as stresses induced in a target material by the single turn extracted primary beam with $\tau = 8.6$ μs were made by the ANSYS (Figure 2.2) under the following boundary conditions:

- the thermo-resistance between target segments and cooling pipes is equal to zero. The input temperature of cooling water is equal to 37°C;
- a heat transfer coefficient to the ambient atmosphere is equal to zero, i.e. the target is in vacuum;

- for thermal radiation, target segments have an emissivity of 1.0 and the ambient temperature is 20°C.

No prestress of the material was included in stress calculations. Despite of the some difference in thermal expansion coefficients of the graphite and cooling pipe steel [1], the high plasticity soft solder, used for soldering of target segments to cooling pipes, prevents arising of stresses in graphite during cooling of the soldered assembly from ~300°C to the room temperature.

Results of calculations of temperature and stresses in a target segment with the highest energy deposition density are given in Figure 2.4–2.8 and in Table 2.3. Comparison of these results with those obtained without thermal radiation shows its relatively small influence on the steady-state temperature of a target.

Width of a target segment, mm	3.2	6.4
Temperature before beam spill, °C	94.8	58.2
Temperature rise, °C	256	272
Temperature after beam spill, °C	351	330
Max. equivalent stress at the center of segment (all-axis compression), MPa	27.9	27.4
Max. equivalent stress at the rounded corner of segment (all-axis stretch), MPa	29.1	23.5
Safety factor	1.8	2.2

Table 2.3: Temperatures and maximal thermal stresses in target segments with the highest energy deposition density.

Since the graphite has different compressive and tensile strength limits, which are equal to 210 MPa and 95 MPa respectively for used ZXF–5Q grade with density of 1.81 g/cm^3 [4], the crucial point for a target material integrity is at the rounded corner of segment where graphite is subjected to all-axis stretch. Taking into account that the high cycle fatigue endurance limit of graphite is in the range of 0.5–0.6 [5], the safety factor (the ratio of the fatigue endurance limit to the maximal equivalent stress occurring in target segments) is about 2.2.

[1]Thermal expansion coefficients of the ZXF-5Q graphite and steel used for production of cooling pipes are equal to 8.1×10^{-6} and 10.2×10^{-6} 1/K at 20°C, and almost equally increase with a temperature.

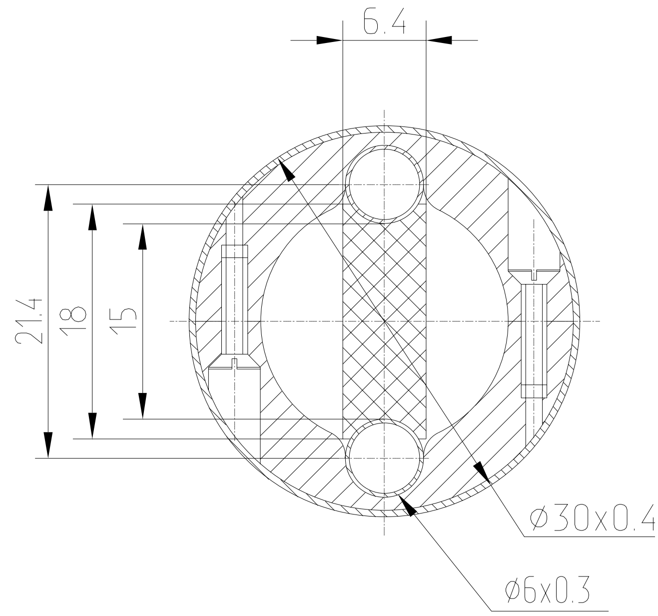

Figure 2.1: Cross-section of the LE target.

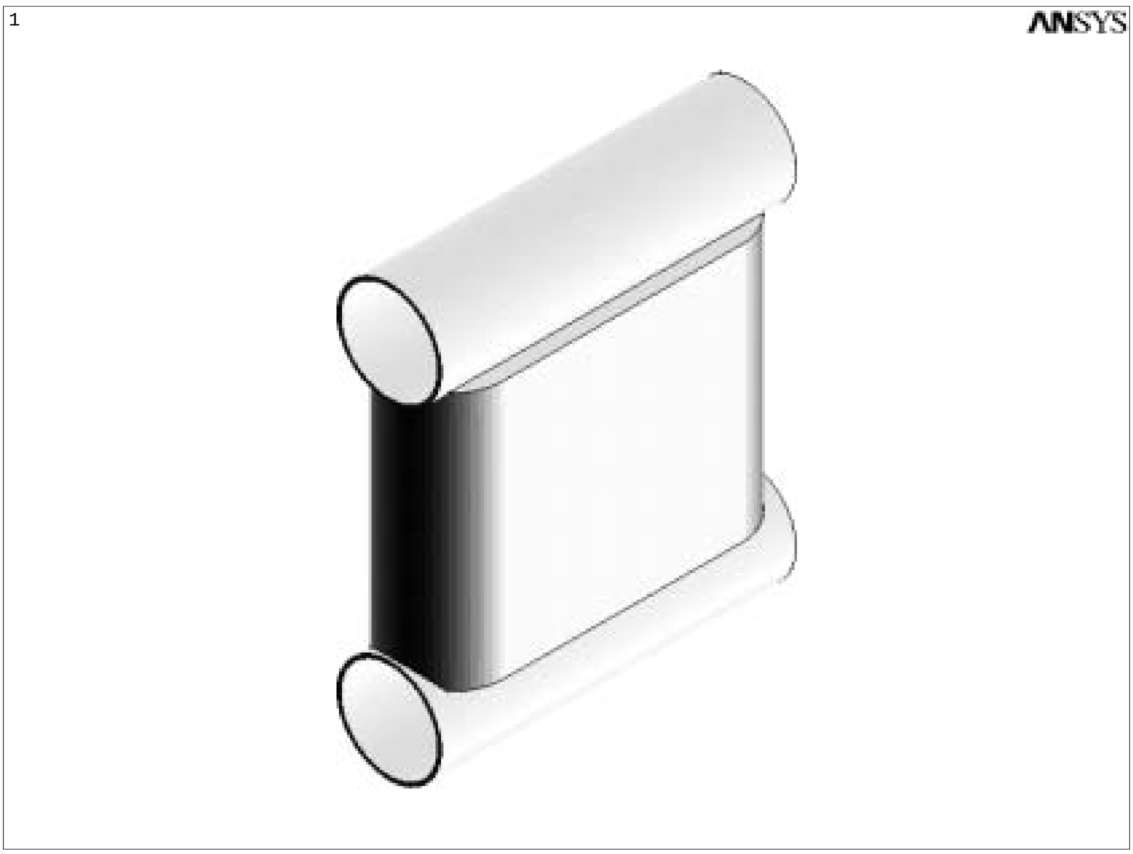

Figure 2.2: The ANSYS model of a target segment.

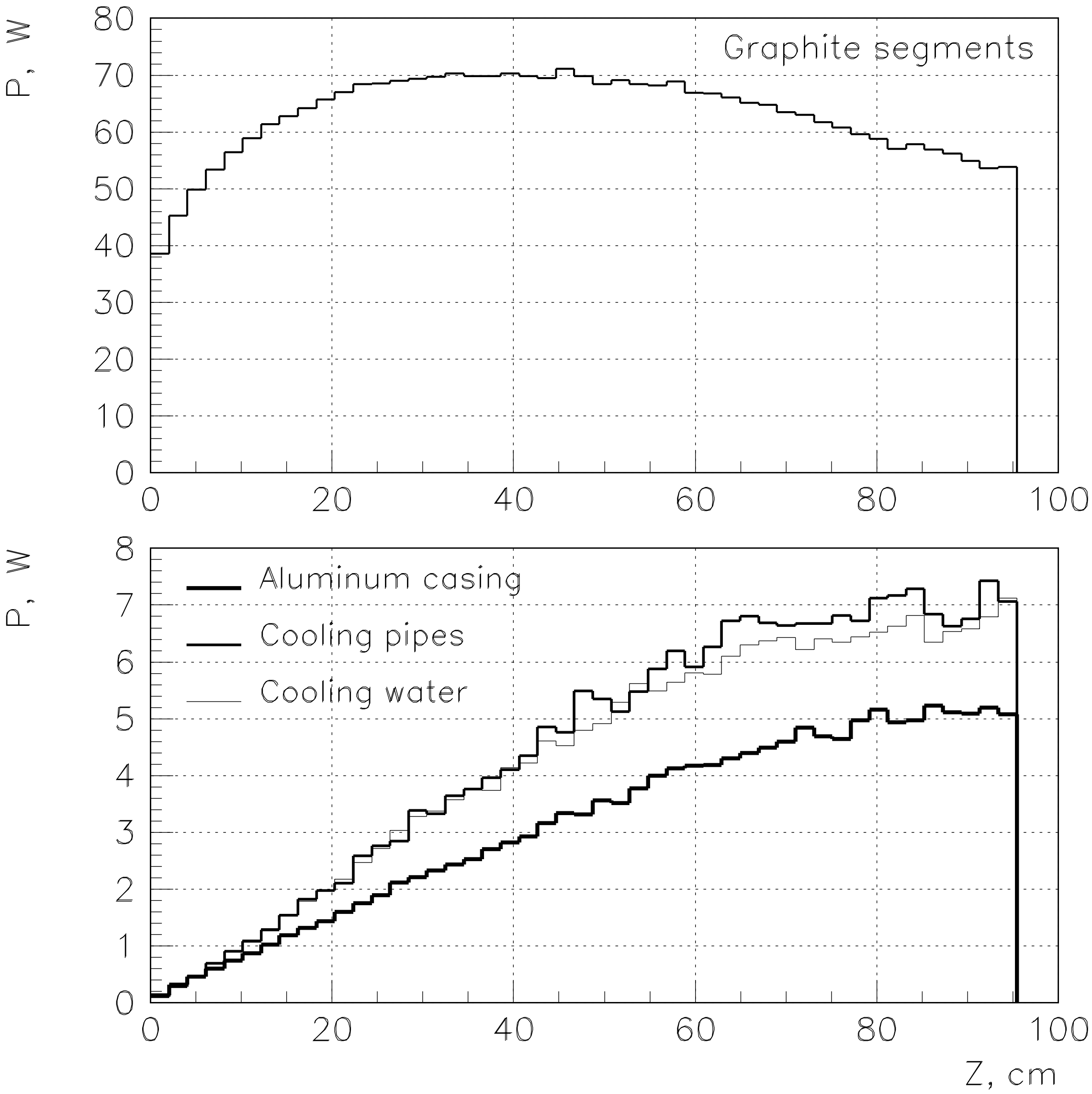

Figure 2.3: The average power deposited in different elements of the LE target design.

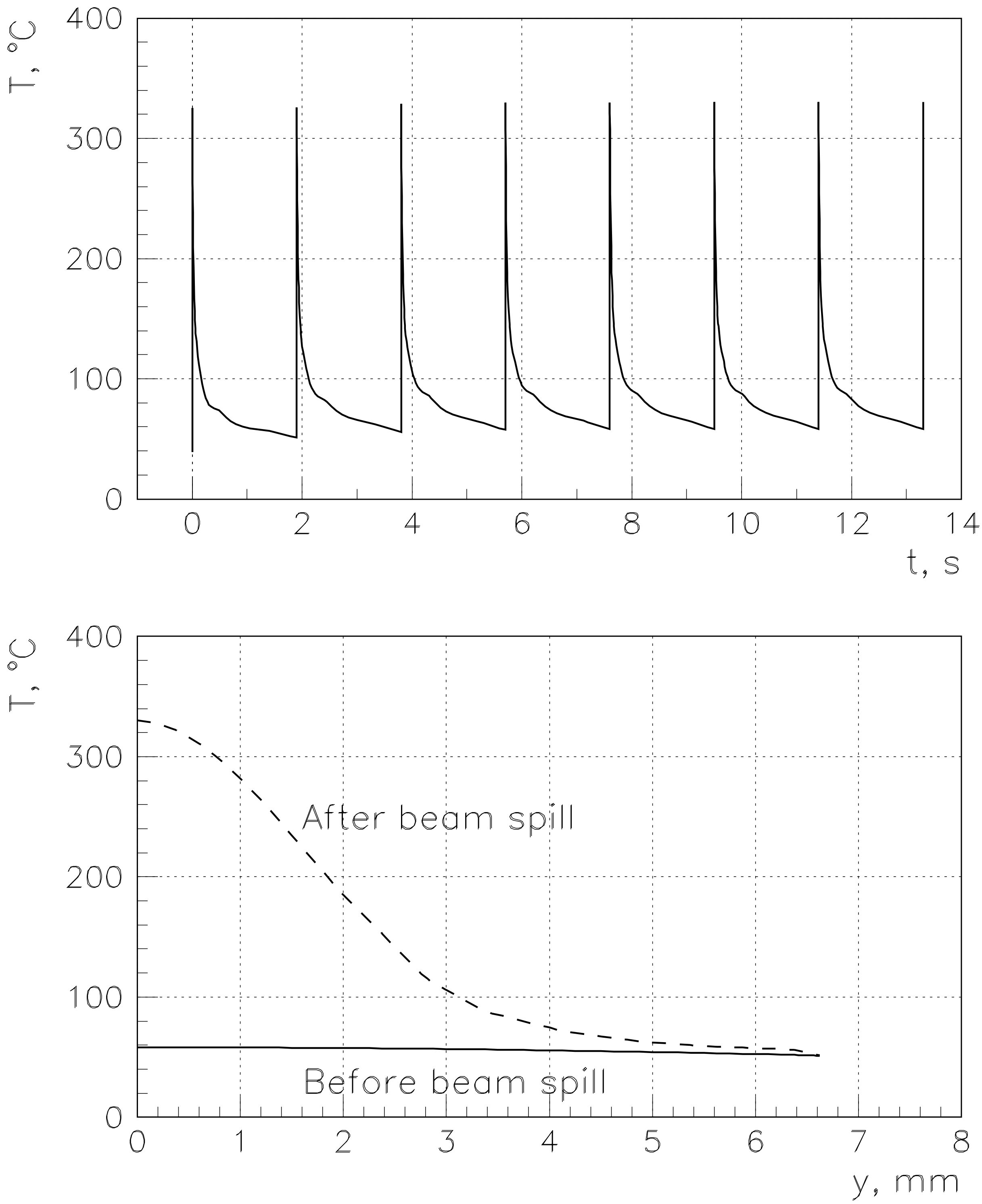

Figure 2.4: Time evolution of temperature at the center (top) and temperature distribution along the vertical axis (bottom) in a target segment with the highest energy deposition density.

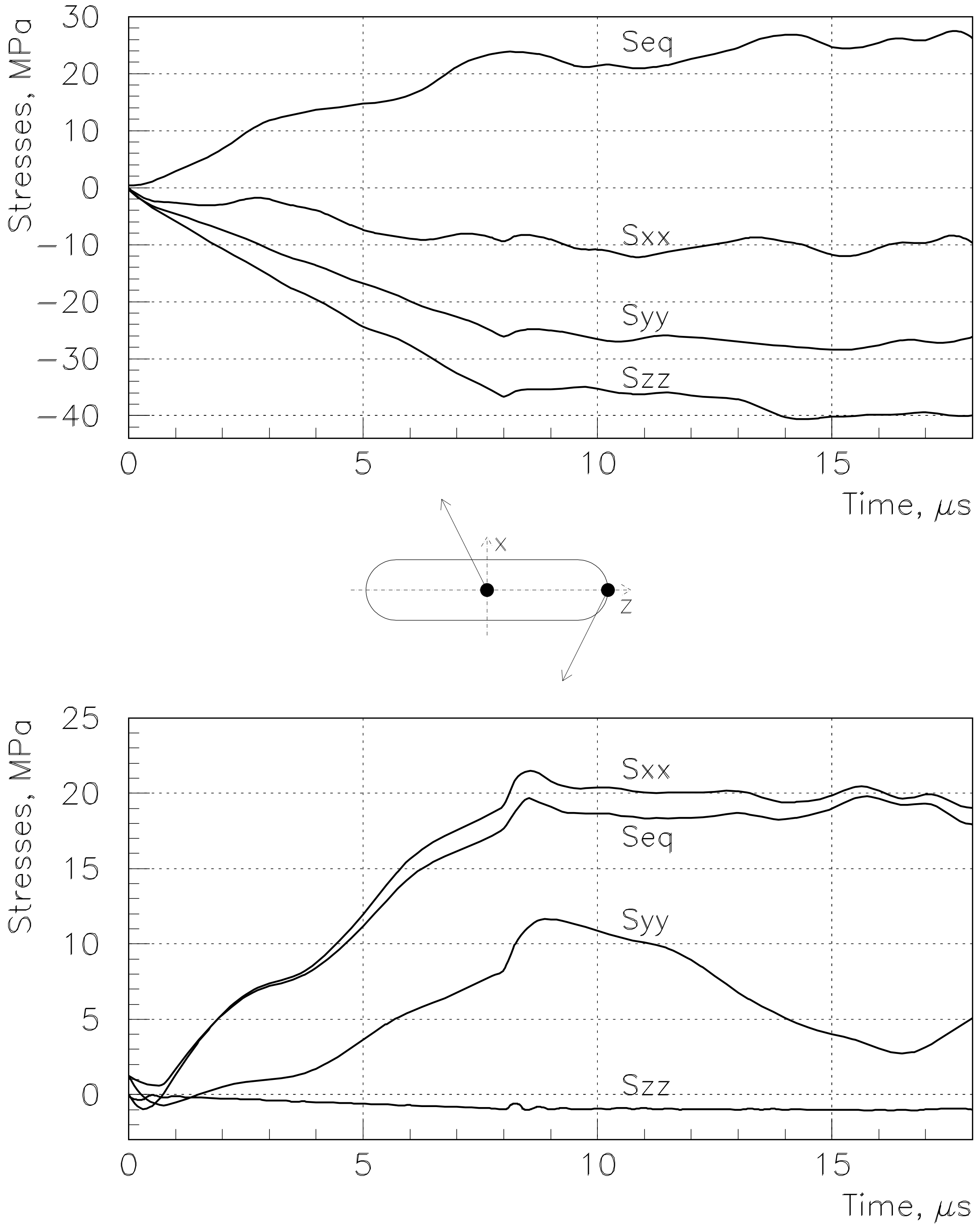

Figure 2.5: Time evolution of stresses at two points of the beam axis plane in a target segment with the highest energy deposition density.

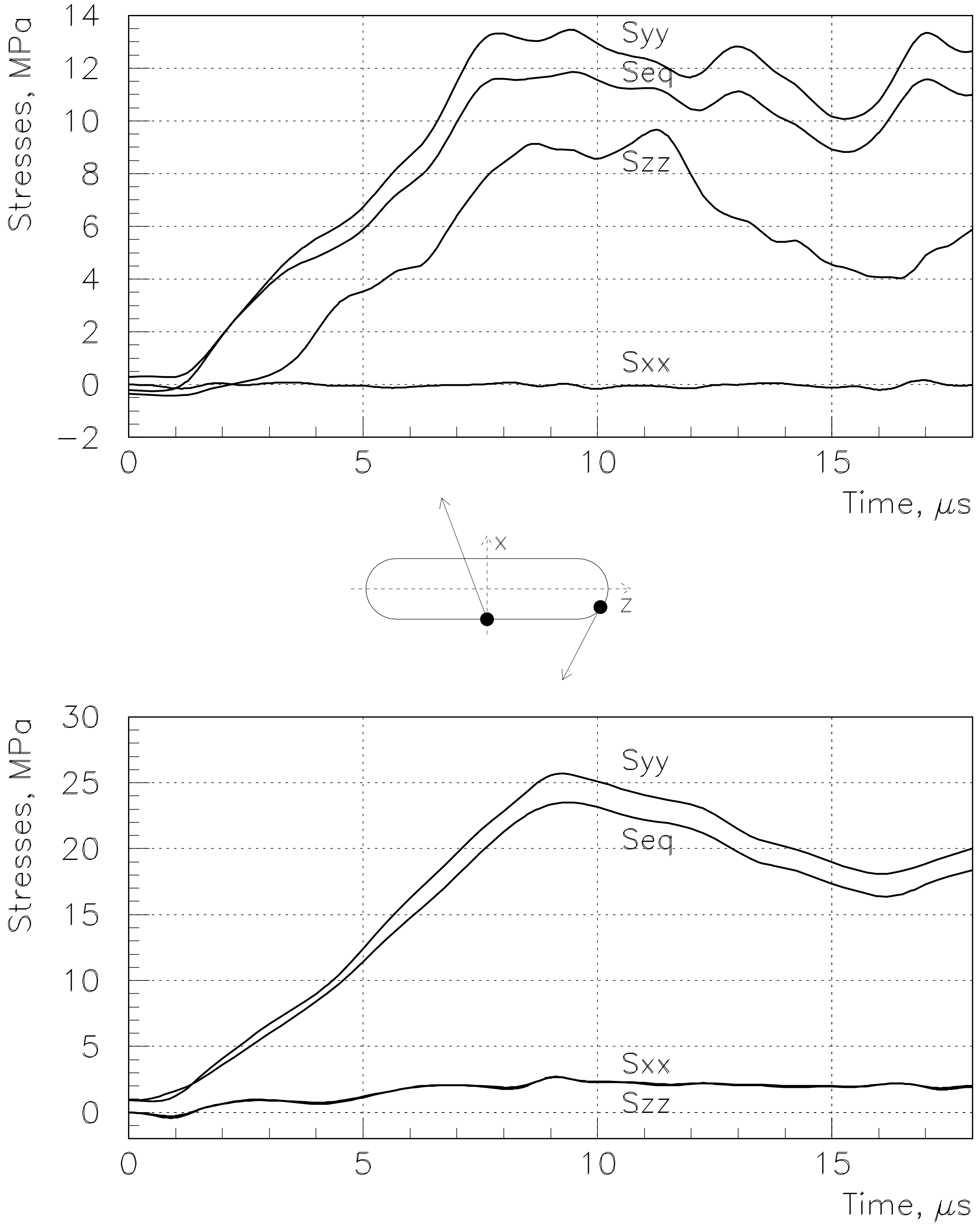

Figure 2.6: Time evolution of stresses at two points of the beam axis plane in a target segment with the highest energy deposition density.

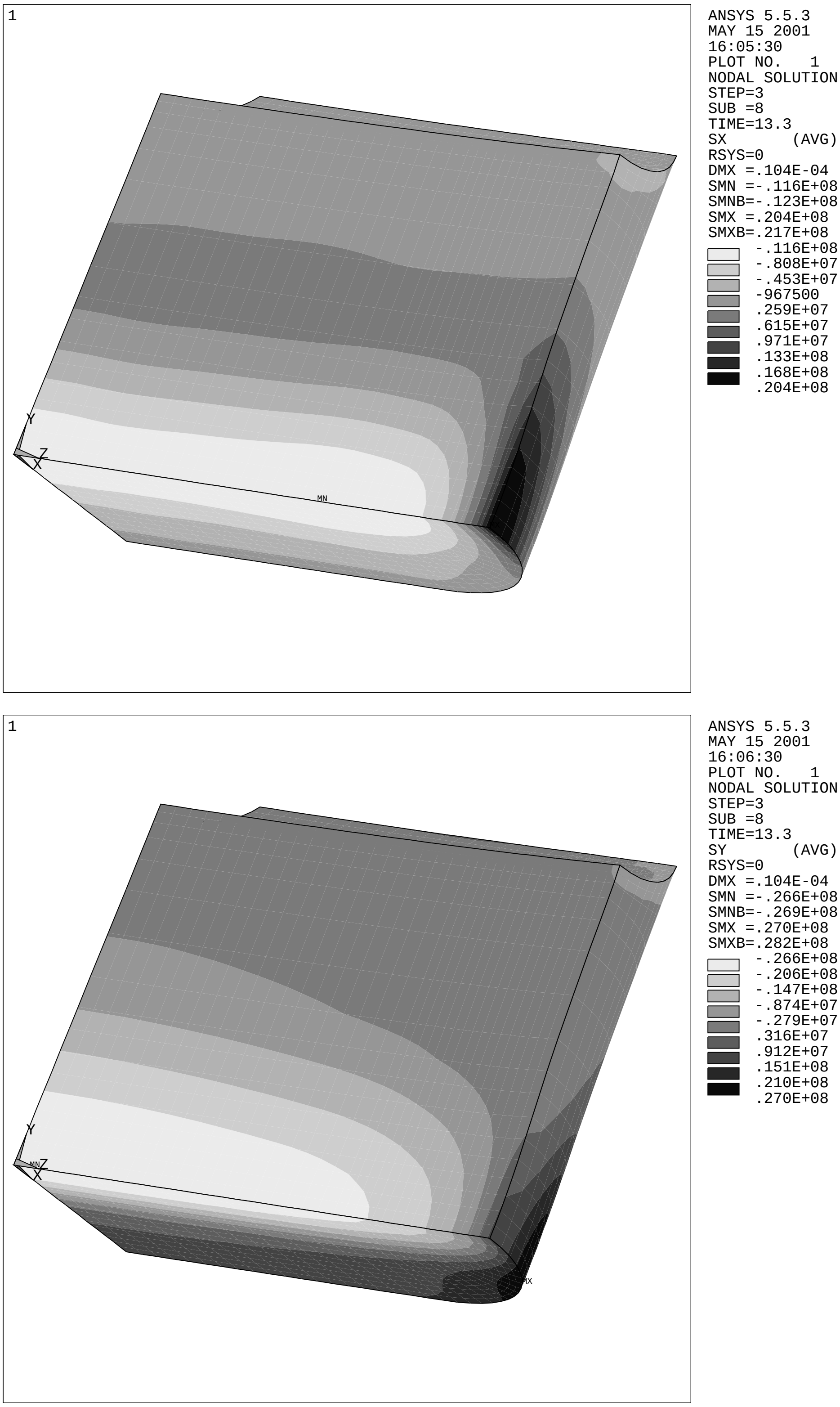

Figure 2.7: Stress distributions after the beam spill ($t = 9\mu s$) in a target segment with the highest energy deposition density.

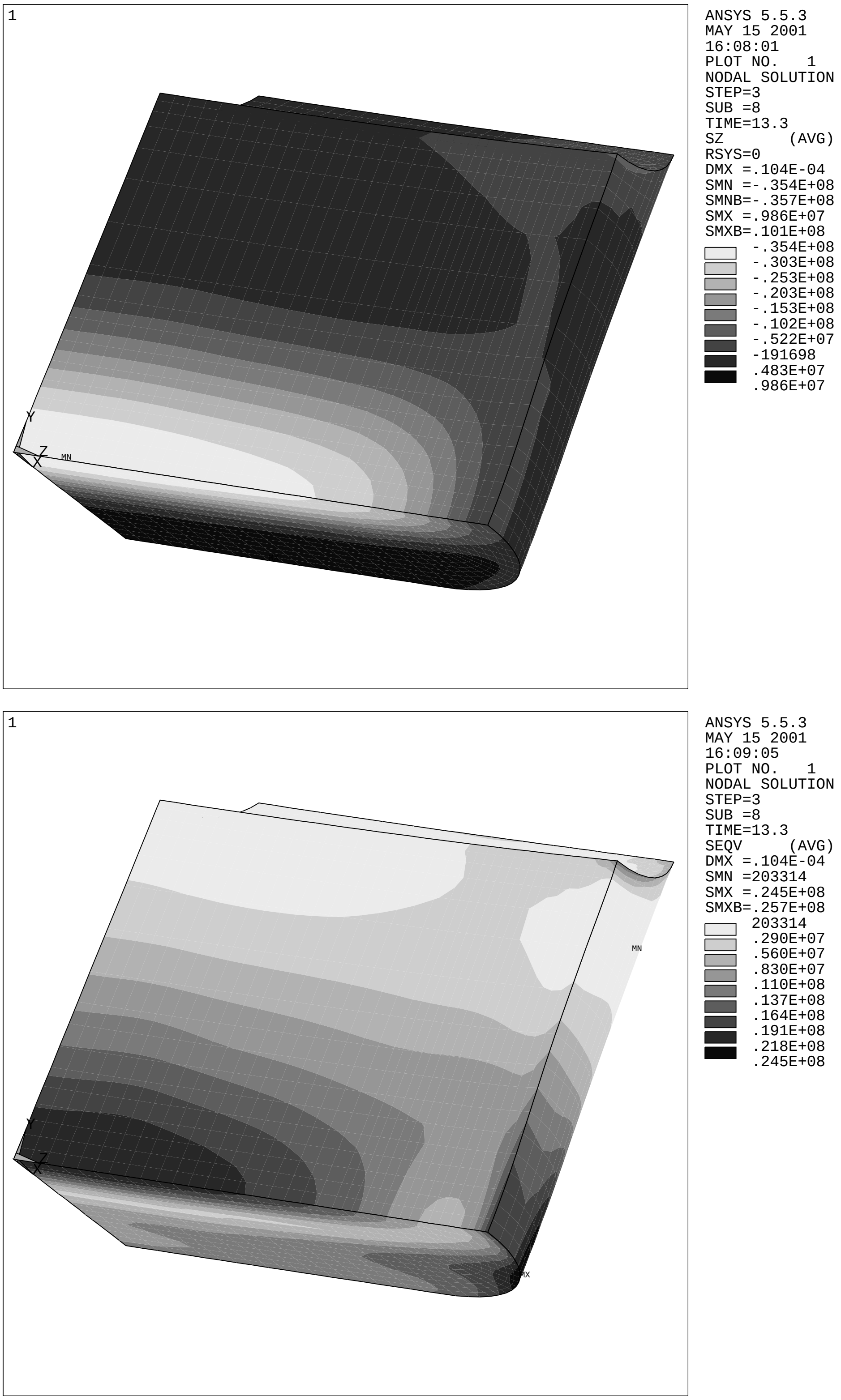

Figure 2.8: Stress distributions after the beam spill ($t = 9\mu s$) in a target segment with the highest energy deposition density.

References

[1] Advanced Conceptual Design of the LE Target and the Beam Plug, Protvino, 1999, NuMI-B-543.

[2] Dynamic Stress Calculations for ME and LE Targets and Results of Prototyping for the LE Target, Protvino, 2000, NuMI-B-675.

[3] N.V. Mokhov, "The MARS Code System User's Guide", Fermilab-FN-628 (1995); N.V. Mokhov et al., "MARS Code Developments", Fermilab-Conf-98/379 (1998); N.V. Mokhov and O.E. Krivosheev, "MARS Code Status", Fermilab-Conf-00/181 (2000); http://www-ap.fnal.gov/MARS/.

[4] Poco Graphite Inc., A Unocal Company, 1601 South State Street, Decatur, Texas 76234.

[5] B.S.Wilkins, J. of Materials, 7(2), 251 (1972). B.S.Wilkins and A.K.Reich, AECL-4216 (1972).