NuMI Low Energy Target

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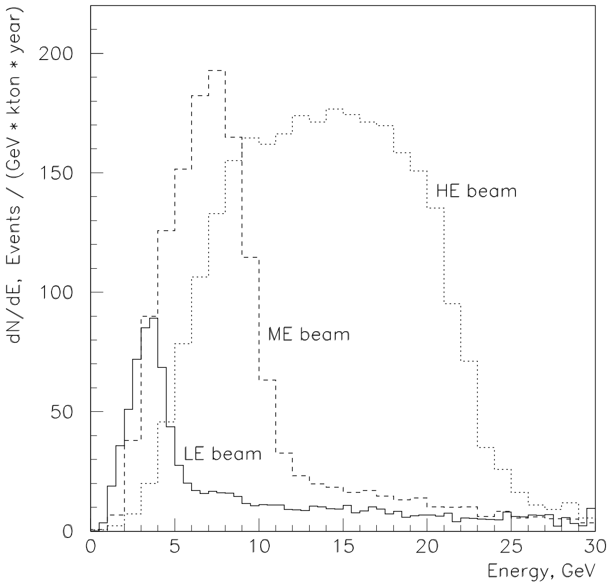
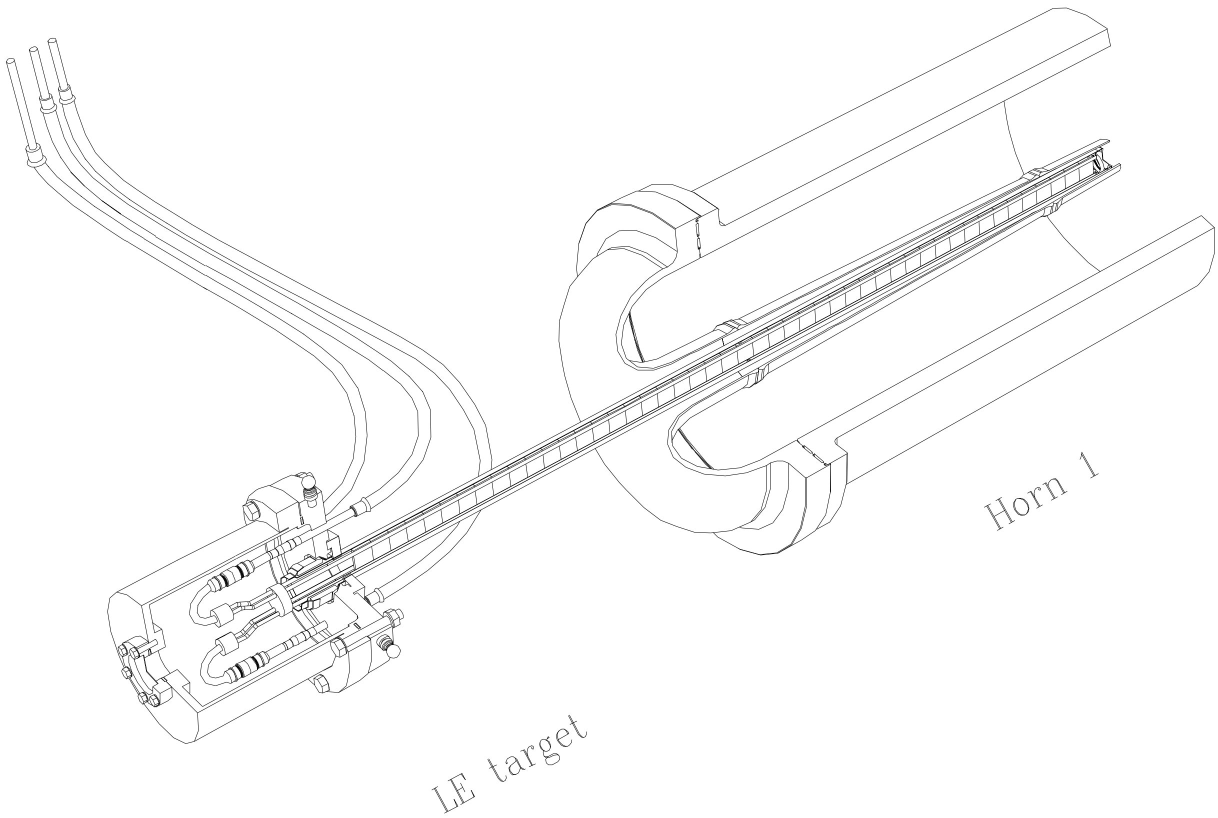
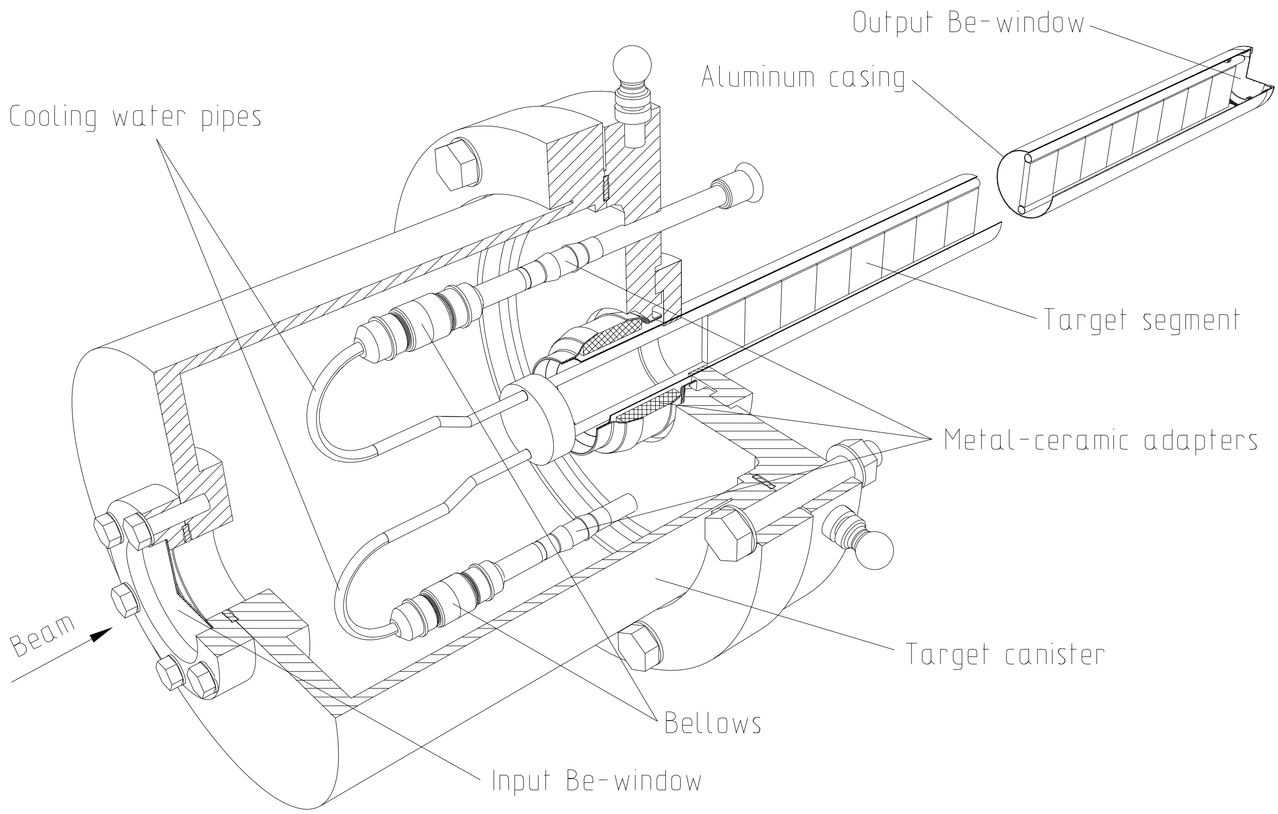


Target parameters and event rates per kton-year for NuMI beams:

Beam	LE	ME	HE
L, m	0.94	1.20	1.60
Z, m	–0.34	–1.40	–4.00
$\langle\rho\rangle$, g/cm^3	1.74	1.54	1.16
ν_μ CC	496	1424	2936





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

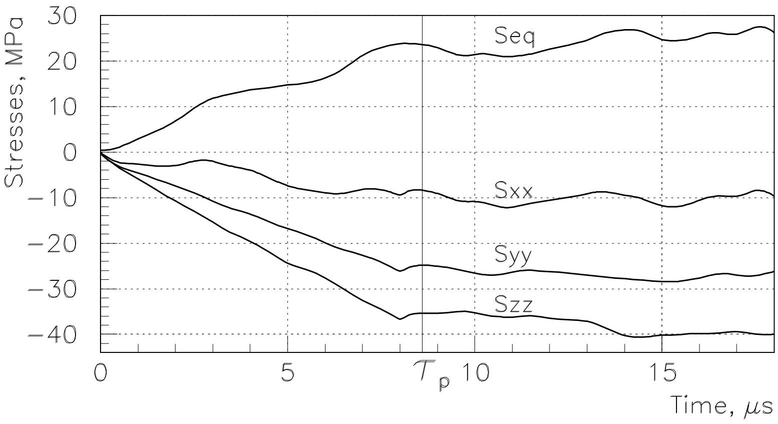
Graphite segments	2.959
Cooling pipes and water	0.415
Aluminum casing	0.148
Total	3.523

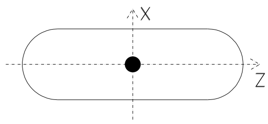
Main parameters of the LE target cooling system:

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

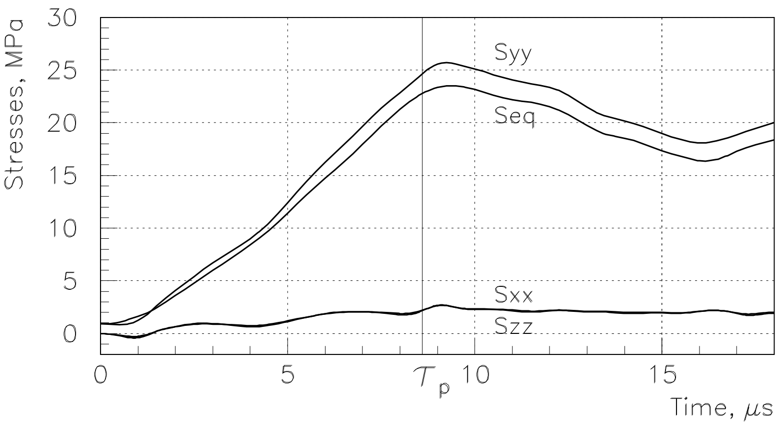
For the target segments with the highest energy deposition density (~0.095 GeV/cm^3/p):

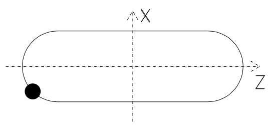
Temperature before beam spill	58.2°C
Temperature rise	272°C
Temperature after beam spill	330°C





$(S_{eq})_{max} = 27.4$ MPa

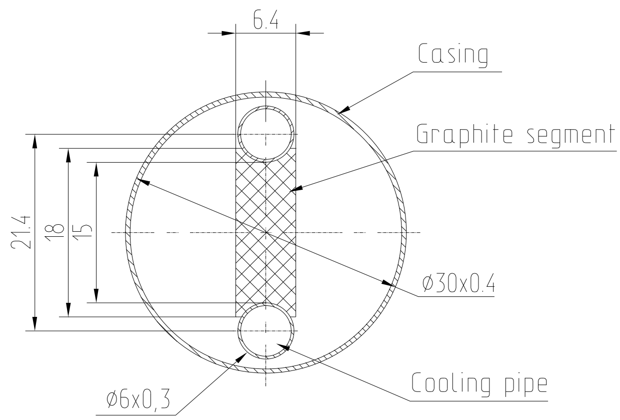




$(S_{eq})_{max} = 23.5$ MPa

ZXF-5Q (1.81 g/cm^3):	Compressive Strength	210 MPa
	Tensile Strength	95 MPa

The high cycle fatigue endurance limit of graphite is 0.5–0.6
The safety factor is $\frac{(0.5-0.6)\times 95}{23.5} \sim 2.2$



Coeff. of Thermal Expansion:

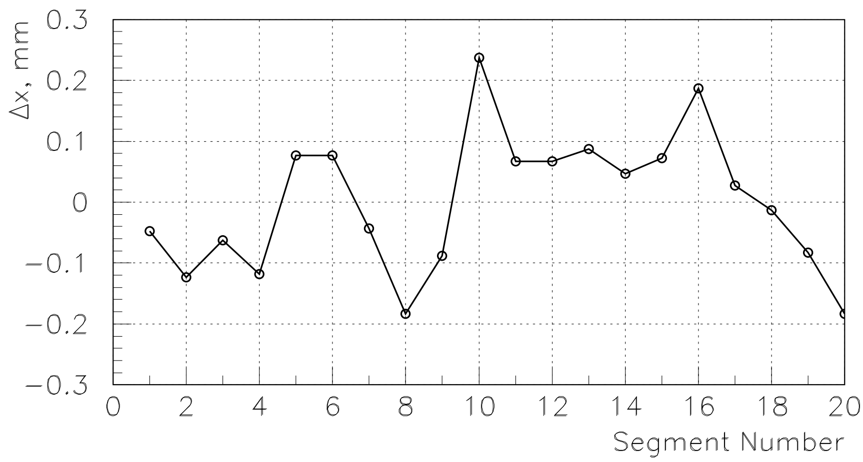
ZXF-5Q graphite: 8.1×10^{-6}, 1/K

CT852 steel: 10.2×10^{-6}, 1/K

Soldering of graphite segments and steel cooling pipes:

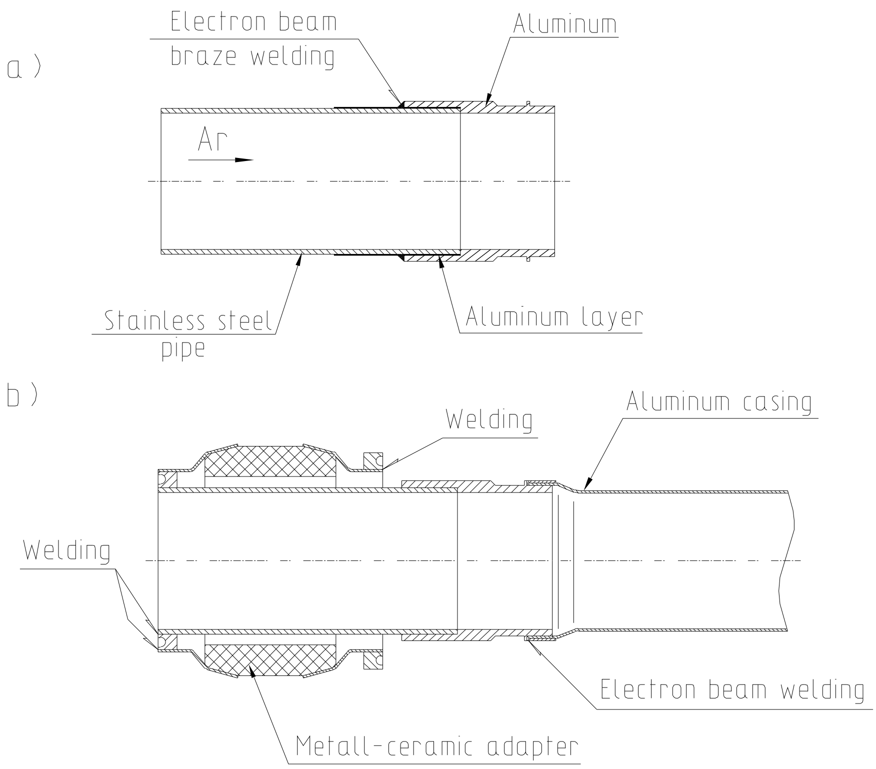
- soldering surfaces of graphite segments are coated with the 3–4 μm layer of nickel;
- a nickel layer, as well as cooling pipes are coated with ~0.1 mm layer of a soft solder with the melting temperature of 300°C (85%Sn+Zn+Ag);
- graphite segments are forced against the cooling pipes and heated to the temperature above 300°C.

Measured linear displacements of target segments in the horizontal plane for the 20 segments LE target prototype (with 3.2 mm wide segments!):

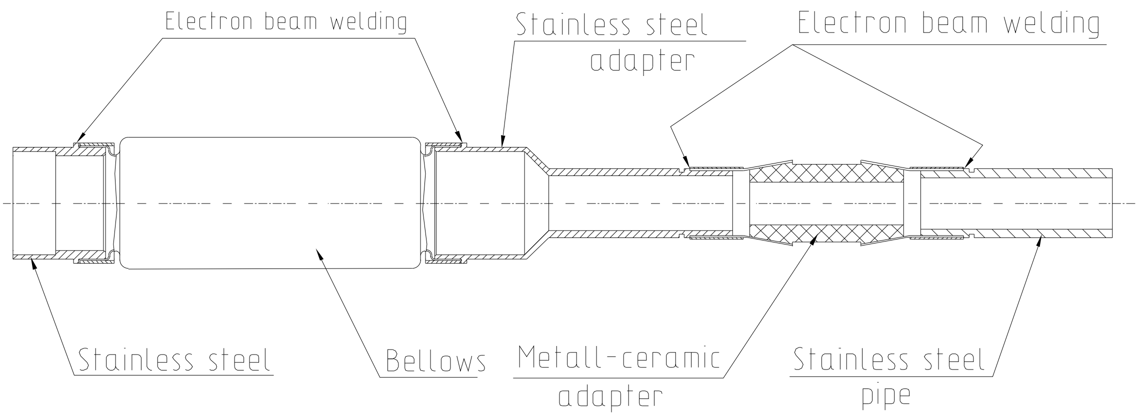


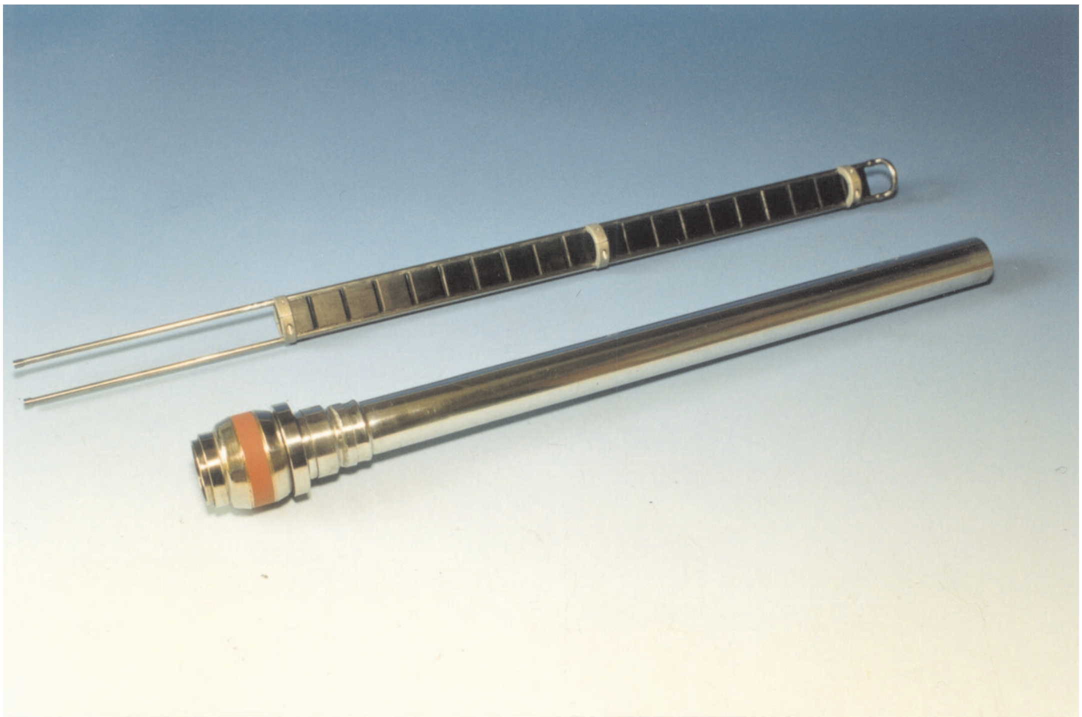
Joining of different materials in some parts of the LE target design:

1) Bimetallic transition from the aluminum to the stainless steel (a) and welding of the metal-ceramic adapter to the target casing (b).



2) Welding of different parts in a water cooling system.



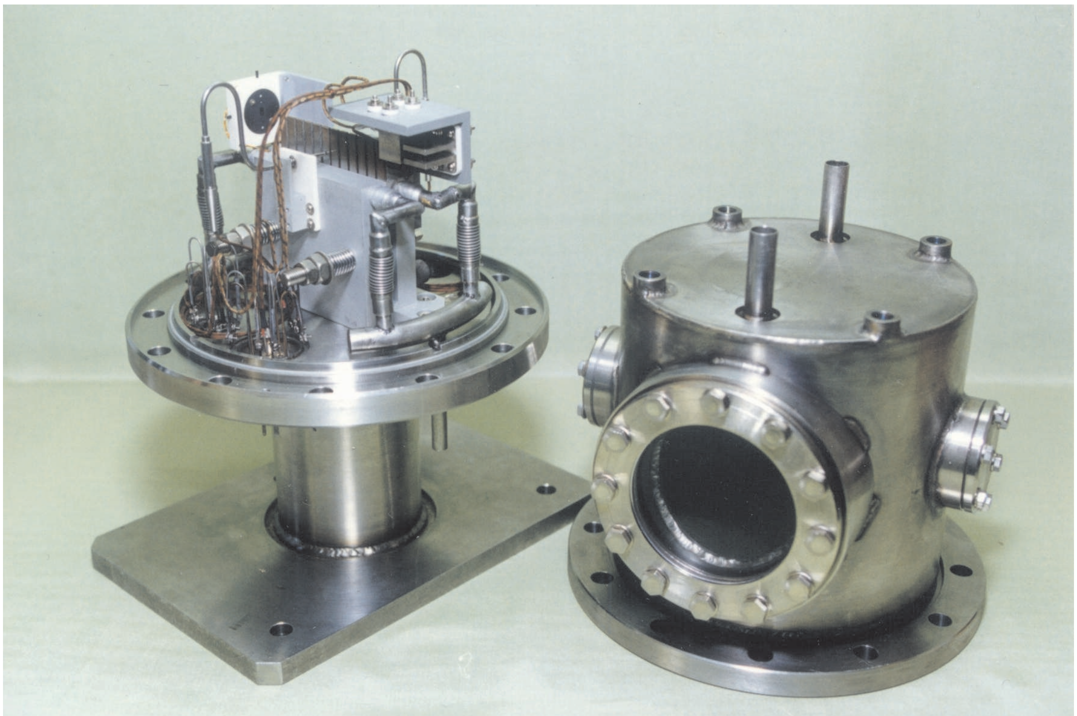


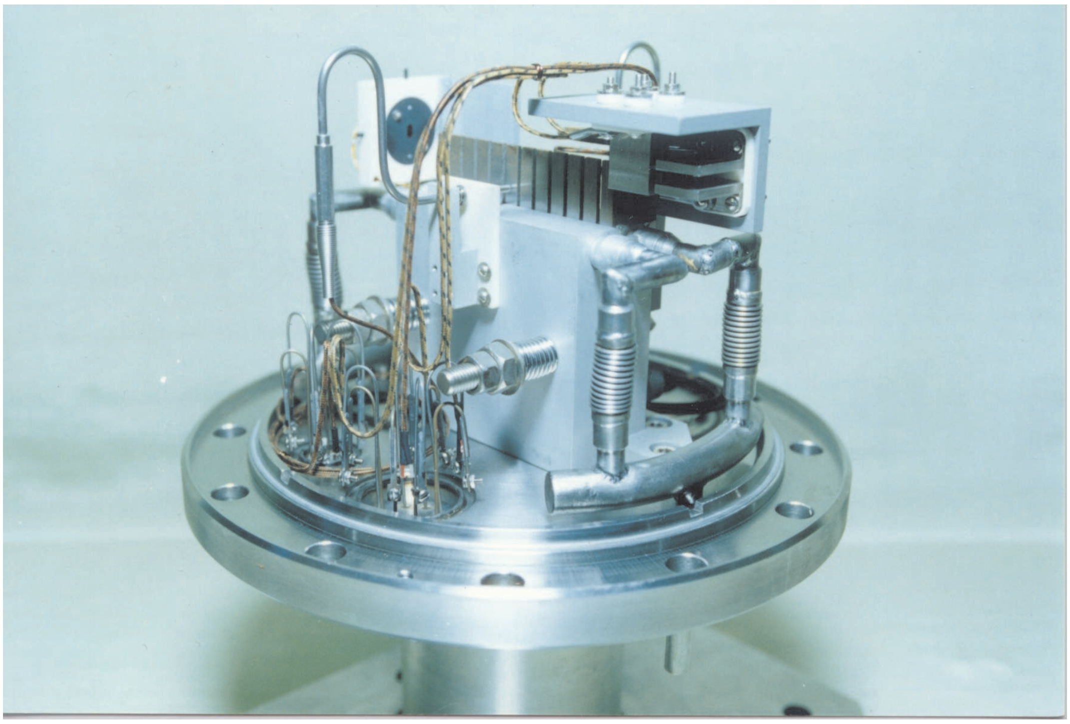
The prototype of the ME target with all main features of the full-size design was constructed in IHEP and tested at the 120 GeV Main Injector beam in 1999. The goals of prototype test included:

- to check if accumulated radiation dose will cause some changes in material properties, and as a result, early failures of target segments;
- find out if the target material withstand the stress induced by the high intensity beam and test that off-axis beam does not destroy the target;
- test charge-read-out (Budal) monitoring of the target in vacuum and in helium atmosphere for insulation coated and uncoated target segments.

Scaling from the full-size ME target to prototype:

ME Target	Full-size	Prototype
Beam energy, GeV	120	120
Number of protons per spill	$4{\cdot}10^{13}$	$5{\cdot}10^{12}$
Beam size $\sigma_x \times \sigma_y$, mm^2	0.7×1.4	0.3×0.3
Segment width, mm	3.2	1.78
Segment length, mm	20	8.0
Maximum energy deposition density, kJ/cm^3	0.70	0.86
Temperature at the beam axis, °C:		
T_{max}	508	467
ΔT	280	394
T_{min}	228	73
S_{eq} at the center of segment, MPa	25	27





1. Radiation damage of graphite

The expected dose for the central region of NuMI target is 5×10^{25} p/m^2 ($\sim$2 dpa)

The total dose accumulated in prototype test was 0.23×10^{25} p/m^2 ($\sim$0.08 dpa)

Low dose effects:

- an increase of elastic modulus E by substantial factor depending upon the material (30–40% at the 0.1 dpa for the H-451 graphite);
- an increase of tensile strength accordingly to $\sigma \geq \sigma_0\sqrt{E/E_0}$.

2. Stresses in the prototype

The expected number of proton pulses for NuMI target is 10^7 per year

Estimated number of proton pulses in prototype test was $\leq 3 \times 10^5$

High intensity (10^{13} ppp) beam scans (0.1 mm steps horizontally):

$\sigma_x \times \sigma_y$, mm^2	0.31×0.35	0.27×0.23	0.16×0.21
dE/dV, kJ/cm^3	1.44	2.42	4.27
ΔT at the beam axis, °C	593	896	1420

For the smallest beam spot size at $x \simeq 0.6$ mm:
$(S_{eq})_{max} = 160$ MPa at the lateral side of target segment (all-axis extension) is noticeable larger than the tensile strength of ZXF-5Q graphite (95 Mpa).

No visible changes in the target segments integrity!?

- an increase with a temperature of the tensile strength of graphite (125 MPa at 600°C vs 95 MPa at 20°C);
- an inadequate accuracy of energy deposition and stress calculations giving results which exceed the actual values;
- a visual inspection was not enough to detect invisible failures or micro-cracks in target segments.

3. Charge-read-out monitoring of a primary beam in the target