Development of a Calorimetric Target for the Second Neutral Beam Injection Beamline on HL-3

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Abstract

In neutral beam injectors, the calorimetric target constitutes one of the critical water-cooled components, responsible for receiving and measuring beam power. Furthermore, through the implementation of a built-in thermocouple array, the temperature rise at various positions on the target plate can be monitored in real time, thereby enabling the determination of the power density distribution of the extracted ion beam or neutral beam. On the second neutral beam injection beamline of the HL-3 device, the calorimetric target design employs a linear pushrod mechanism for vertical positioning and a "W" -shaped target plate structure for neutral beam energy absorption. Additionally, the fluid calculation module of Ansys Workbench was utilized to simulate the temperature distribution of the calorimetric target under full-power operating conditions, with results demonstrating that the design satisfies the operational requirements of the second neutral beam injection beamline.

Full Text

Preamble

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Abstract

Background: In neutral beam injectors, the calorimetric target is a critical water-cooled component responsible for receiving and measuring beam power. By incorporating a built-in thermocouple array, real-time monitoring of temperature rise at different target positions enables determination of the power density distribution of extracted ion or neutral beams.

Purpose: To develop a calorimetric target for the HL-3 device neutral beam injector that satisfies requirements for target plate positioning and thermal load absorption.

Methods: The calorimetric target design employs a linear push-rod mechanism for vertical positioning and a "W" -shaped target plate structure for neutral beam energy absorption. The fluid calculation module of Ansys Workbench was utilized to simulate temperature distribution under full-power operating conditions.

Results: Under full-power operation with the deflecting magnet activated, the maximum temperature rise of the calorimetric target reaches 526.4°C, cooling to room temperature within 30 seconds, thereby meeting the operational requirements of the beam line.

Conclusions: A calorimetric target satisfying all usage requirements has been successfully developed.

Keywords: Neutral beam injectors, Calorimetric target, Finite element calculation

Introduction

The calorimetric target is a crucial component in neutral beam injectors. When high-energy beam particles strike the calorimeter, they transfer their substantial energy to the target plate, causing its temperature to rise. Through heat conduction and convective heat transfer, the energy deposited within the target plate is gradually removed by cooling water, achieving the purpose of absorbing and dissipating beam energy. By measuring the temperature difference between outlet and inlet water along with water flow rate, the total received beam energy can be calculated through integration. Additionally, the calorimetric target can measure temperature rise signals at different positions in real time via a built-in thermocouple array, thereby determining beam distribution, beam divergence angle, and beam alignment status [1].

In the second neutral beam injection line of the HL-3 (China' s Fusion Engineering Test Reactor) device, the calorimetric target is installed between the deflecting magnet and the scraper, as shown in Figure 1 [Figure 1: see original paper]. The dashed box in the figure indicates the calorimetric target, whose end face is positioned 3,100 mm from the ion beam extraction surface. The HL-3 7MW neutral beam injector ion source discharge parameters are designed as: 120 kV × 40 A, with a pulse width of 5 s, yielding an extraction power of 4.8 MW per ion source. Each neutral beam injector is equipped with four ion sources, resulting in a combined maximum extraction power of 19.2 MW.

1. Structural Design of the Calorimetric Target

For neutral beam injection heating lines, the calorimetric target is primarily utilized during commissioning and calibration experiments. When neutral beams are injected into the plasma, the target plate must be retracted to clear the beam transmission path. The HL-3 7MW neutral beam heating line injector employs a vertically lifting W-shaped calorimetric target. During NBI commissioning experiments, the target is lowered to the beam alignment position; during NBI heating experiments, it is raised to allow beam transmission.

The overall structure of the calorimetric target is shown in Figure 2 [Figure 2: see original paper], consisting of four main components: a bottom support frame, a "W" -shaped copper target body, a water cooling circuit, and a lifting mechanism.

The bottom support frame is a welded structure made of 304 stainless steel, featuring solid steel plates at the top and bottom with "X"-shaped reinforcing ribs welded between four vertical columns. During installation, the bottom support is positioned and welded to the vacuum chamber floor. Four height-adjustable support legs are mounted above the base, which bear the entire weight of the target plate when it is in the lowered position during experimental commissioning (when neutral beams are not injected into the device). Additionally, two tapered positioning pins on the support correspond to positioning holes beneath the target body, ensuring the copper target aligns with the beam center after lowering.

The "W"-shaped copper target body is the most critical component, responsible for absorbing neutral beam power and measuring beam distribution. Based on beam line design parameters—an ion source acceleration voltage of 120 keV and extraction current of 40 A per source—the combined power density distribution of neutral and ion beams at the target' s incident face (without considering neutralization) is shown in Figure 3 [Figure 3: see original paper], with peak power density reaching 12.8 kW/cm^2 at the beam center. Typically, copper target plates can only withstand a maximum power density of 2 kW/cm^2; direct perpendicular impact of beam energy would cause oxygen-free copper targets to soften before heat exchange occurs, rendering them unsafe. Therefore, the copper target plate adopts a "W" shape. Thermal loading is highest at the beam center and decreases toward the target edges. Considering overall target length, the body is designed as a gradually expanding trumpet shape. Each trumpet section comprises 20 oxygen-free copper target strips, each measuring 80 mm wide, 1,020 mm tall, and 25 mm thick. Two deep holes (12 mm diameter) are machined inside each strip for cooling water inlet and outlet. The central two strips have the smallest angle of 12°, while the outermost strips have the largest angle of 46°.

As a measurement component, the calorimetric target must monitor temperature rise signals at different positions in real time via a built-in thermocouple array to determine beam distribution, divergence angle, and alignment. Accordingly, 10 thermocouples are installed on each central strip along the beam convergence direction, while two thermocouples (upper and lower) are installed on each outer strip. The target opening angles and thermocouple positions are shown in Figure 4 [Figure 4: see original paper].

Among all water-cooled components, the calorimetric target bears the heaviest thermal load. Compared to other components, it withstands approximately 80% of the neutral beam extraction power when the deflecting magnet is off (non-injection condition), and still endures 50% of total extraction power when the magnet is on. To maximize cooling efficiency, two "W"-shaped water distribution manifolds are designed above the target body, connecting each target strip' s inlet and outlet in parallel. An 80 mm diameter stainless steel pipe extends from each manifold. At a water flow rate of 150 m^3/h, the water velocity inside each strip reaches 9.3 m/s.

The lifting mechanism consists of four support columns, a drive motor, linear push rods, laminated bellows, and connecting plates. Per neutral beam injector design requirements, the target must completely clear the beam channel during plasma injection, necessitating a lifting height of 1,100 mm. The lifted load includes the oxygen-free copper target body, water circuit, and connecting plates, totaling approximately 1.5 tons. The first neutral beam line previously used a winch mechanism with a motor-driven gear reducer pulling steel cables. However, the gear reducer was structurally complex, heavy, and difficult to dismantle after installation atop the calorimetric target, creating significant installation challenges. Therefore, a commercially available electric push-rod mechanism was selected, offering simpler structure, lower weight, and the ability to install the lifting mechanism after target body installation, reducing costs. The electric push-rod specifications are: 32 mm screw diameter, 30 kN thrust, and 1:7.25 worm gear reduction ratio. During lifting, the four columns simultaneously serve as guide rails, with pulleys installed on the lifting connection plate to ensure vertical movement. Limit switches installed at corresponding positions on the columns output position signals to the control system when the target reaches designated positions, enabling monitoring of target status.

2. Thermal Analysis Calculations

Heat conduction is the primary energy transfer mechanism in the calorimetric target. Using Ansys to simulate the heat transfer process enables calculation of maximum temperature rise under any neutral beam power, thereby determining safe operating ranges for neutral beam power and pulse width during inertial calorimeter operation. For computational convenience, a half-model was simulated with the following assumptions: (1) energy loss due to thermal radiation is negligible; (2) water property variations due to temperature rise are negligible; (3) initial temperature distribution is uniform at 20°C. Analysis was performed for two operating conditions:

Case I: Full-power operation, water flow 120 m^3/h, pulse width 5 s, neutralization efficiency 50%, deflecting magnet ON. This represents the stable full-power operating condition for the second neutral beam line. Results shown in Figure 5 [Figure 5: see original paper] indicate that after 5 seconds of full-power neutral beam operation, the target plate' s maximum temperature reaches 526.5°C, well below copper' s melting point of 1,084°C, confirming the target can withstand full-power beams. After discharge cessation, the plate temperature begins to decrease, dropping to 22.6°C by 30 seconds (Figure 6 [Figure 6: see original paper]), demonstrating the design meets requirements.

Case II: Full-power operation, water flow 150 m^3/h, pulse width 5 s, deflecting magnet OFF. This extreme condition occurs when the deflecting magnet is deactivated, causing both neutral and ion beam energy to strike the target. Results shown in Figure 7 [Figure 7: see original paper] reveal target temperature rise reaching 987°C, approaching the melting point of oxygen-free copper. Therefore, the deflecting magnet must remain ON during full-power operation to divert the ion beam to the beam dump and protect the calorimetric target.

3. Development Progress

Following engineering finalization, all components of the calorimetric target have been manufactured and are currently undergoing installation and commissioning, as shown in Figure 8 [Figure 8: see original paper]. Upon completion, the target will be installed on the injector for full-load testing.

This paper presents the overall structural design of the calorimetric target based on design parameters for the HL-3 device' s second neutral beam injection line. The heat-bearing target section employs a "W" -shaped configuration assembled from oxygen-free copper strips to increase heat dissipation area. The lifting mechanism utilizes a proven electric push-rod design, reducing costs and simplifying installation compared to the first beam line. Thermal calculations demonstrate that under full-power operation with the deflecting magnet ON, the maximum temperature rise is 526.4°C, cooling to room temperature within 30 seconds, satisfying beam line requirements. However, if the deflecting magnet is deactivated, temperature rise can reach 987°C, posing a melting risk.

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Author Contributions

ZHOU Bowen: Conceptual design, mechanical design and modeling, data analysis, data visualization, original draft preparation.
TANG Peiqin: Simulation calculations.
WAN Yinxiang: Data compilation.
YU Peixuan: Data visualization.
LUO Huaiyu: Mechanical design.
WEI Huiling: Manuscript review and revision.
GENG Shaofei: Funding acquisition, project management, supervision.

References

1. Liu He, Cao Jianyong, Yang Xianfu. Heat Transfer Simulation and Experimental Study of Inertial Calorimeters for Neutral Beam Devices[C]//Chinese Nuclear Society. Progress Report on China Nuclear Science and Technology (Volume 2) —Proceedings of the 2011 Annual Conference of the Chinese Nuclear Society, Volume 7 (Nuclear Electronics and Nuclear Detection Technology Section, Pulse Power Technology and Its Applications Section, Nuclear Fusion and Plasma Physics Section). Southwestern Institute of Physics, 2011: 10.

2. Qin Yunwen (compiled). Physical Basis of Tokamak Experiments. Atomic Energy Press. ISBN 978-7-5022-5218-2, P587.

3. Strachan J D, Adler H, Alling P, et al. Fusion energy production from TFTR plasmas fueled with deuterium and tritium. *Phys. Rev. Lett.* Vol.72 (1994), 3526.

4. Solder F X, Baranov Yu F, et al. Approach to steady state high performance in DD and DT plasmas with optimized shear in JET. *Nucl. Fusion*, Vol.39 (1999), 407. DOI: 10.1088/0029-5515/39/11Y/329.

5. Fujita and the JT-60 team. High-performance experiments towards steady-state operation in JT-60U. *Plasma Phys. Control. Fusion* 39 (1997), B75. DOI: 10.1088/0741-3335/39/12B/006.

6. Yuan Baoshan, Jiang Shaofeng, Lu Zhihong (compiled). Engineering Fundamentals of Tokamak Devices, Chapter 11. Beijing, Atomic Energy Press, 2011.

7. YU Liming, CHEN Wei, JI Xiaoquan, et al. Observation of Multiple Broadband Alfvénic Chirping Modes in HL-2A NBI Plasmas[J]. *Chinese Physics Letters*, 2021, 38(05): 47-51. DOI: 10.1088/0256-307X/38/5/055202.

8. K.TSUMORI, Y.TAKEIRI, K.NAGAOKA, et al. High Power Neutral Beam Injection in LHD[J]. *Plasma Science and Technology*, 2006, 8(01): 24-27. DOI: 10.1088/1009-0630/8/1/6.

9. Zhou Hongxia, Cao Jianyong, Yu Peixuan, et al. Engineering Design of the Water Cooling System for the HL-2M Device Neutral Beam Heating System[C]//Chinese Nuclear Society. Progress Report on China Nuclear Science and Technology (Volume 6) —Proceedings of the 2019 Annual Conference of the Chinese Nuclear Society, Volume 7 (Computational Physics Section, Nuclear Physics Section, Particle Accelerator Section, Nuclear Fusion and Plasma Physics Section, Pulse Power Technology and Its Applications Section, Radiation Physics Section, Nuclear Engineering Mechanics Section, Nuclear Testing and Analysis Section). China Atomic Energy Press, 2019: 6. DOI: 10.26914/c.cnkihy.2019.056442.

10. Wei Huiling, Cao Jianyong, Yu Peixuan, et al. Development of the Ion Source Discharge Chamber for the 5 MW Neutral Beam Heating Beam Line of the HL-2M Device[J]. *High Power Laser and Particle Beams*, 2020, 32(04): 127-131. DOI: 10.11884/HPLPB202032.190275.

11. He Liu, Jianyong Cao, Huiling Wei, et al. The latest progress of the 1st NBI beamline on HL-2M Tokamak. *Fusion Engineering and Design*, Volume 123, 2017, Pages 448-452, ISSN 0920-3796, DOI: 10.1016/j.fusengdes.2017.02.109.

12. X T DING, W CHEN. Review of the experiments for energetic particle physics on HL-2A[J]. *Plasma Science and Technology*, 2018, 20(09): 97-109. DOI: 10.1088/2058-6272/aad27a.

Note: Figure translations are in progress. See original paper for figures.