

Achievements in LHD Project and Development to Post-LHD Project

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1. Introduction

The Large Helical Device (LHD) [1,2] at the National Institute for Fusion Science (NIFS, Toki, Japan) conducted plasma experiments from 31 March 1998 to 25 December 2025, celebrating its Grand Finale after nearly 28 years of operation. As the world's largest superconducting helical confinement device, LHD was envisioned in the early 1980s, at a time when major tokamaks were expected to achieve breakthrough results. In that context, NIFS addressed two foundational questions: (i) what research objectives would enable world-leading, cutting-edge scientific studies; and (ii) how should such objectives be pursued experimentally? The answers crystallized into three complementary missions: (1) to select the heliotron concept as the next-generation large-scale helical confinement device; (2) to comprehensively investigate issues in toroidal confinement systems, including those shared with tokamaks; and (3) to explore the potential for a steady-state fusion reactor based on the engineering advantages of helical systems. A productive scientific tension existed between the pursuit of universality (mission 2) and the demonstration of an alternative steady-state concept (mission 3). This paper summarizes principal scientific achievements and introduces the post-LHD research platform, the MCPoP project.

2. Performance Extension

LHD advanced the performance frontier of helical plasmas. Among abundant achievements, topics of high β , long-pulse steady-state operation and high ion temperature are highlighted.

In the high-beta direction, stable plasma confinement at $\beta = 5\%$ was sustained for more than $100 \tau_E$ [3], surpassing typical tokamak beta values and opening an entirely unexplored parameter regime (Fig. 1). In the steady-state direction, a 2 keV plasma was maintained for 48 minutes using only 1.2 MW of RF heating

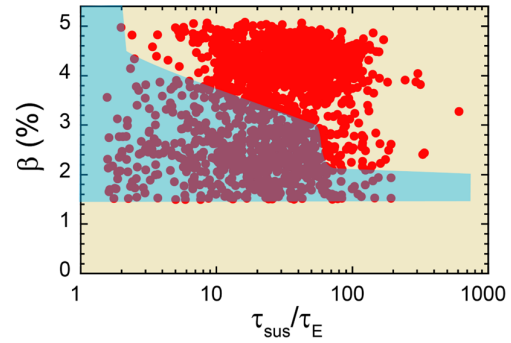


Fig.1 $\beta = 5\%$ sustained for $>100\tau_E$

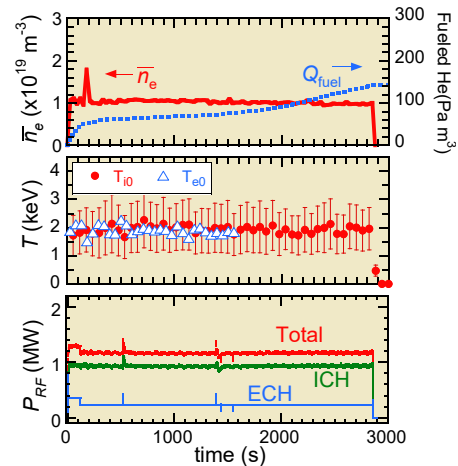


Fig.2 48-minute steady-state plasma at 2 keV, 1.2 MW RF heating. Reprinted from [4].

(Fig.2), directly demonstrating the current-drive-free steady-state capability inherent to helical systems [4]. High-temperature operation was extended in deuterium [5,6]: $T_i > 10$ keV at 19.2 MW(see Fig.3), and simultaneous $T_i = T_e \approx 8.7$ keV (~ 100 million $^\circ\text{C}$) at 26.9 MW.

3. Novel Phenomena

Conjunction with these achievements in performance extension, a lot of findings of novel phenomena to develop new horizon in plasma physics.

3.1 Benign interchange instability

The widely accepted 'minimum-B' guideline prescribes that a magnetic hill is unstable against the interchange mode.

LHD operates in a magnetic-hill configuration yet achieves $\beta = 5\%$ without pressure collapse. MHD simulation including kinetic effect of trapped particles revealed that stability is secured under high beta [7].

3.2 Zonal flow and neoclassical optimization

Experiment clearly shows that the inward shift of the magnetic axis with reduced effective helical ripple ε_{eff} improves confinement. It should be noted that this improvement exists even in collisional regime where neoclassical transport does not play an essential role [8]. Theory predicts that ε_{eff} enhances residual zonal flow amplitude, suppressing turbulent transport. GKV gyrokinetic simulations confirmed this confinement improvement [9]. This mechanism provides a theoretical foundation connecting neoclassical optimization to turbulent-transport reduction.

3.3 Non-local transport

Non-locality and coupling of transport has been identified in a variety of experiment. Under particle control by divertor pumping, core heat transport is improved despite of no evident change in the edge [10]. Precise diagnostics for propagation of turbulence and heat revealed coexisting local and non-local turbulence [11]. Low-Z impurity powder injection via a powder dropper [12] improved energy confinement and accelerated heavy-impurity transport.

3.4 Isotope effect

Deuterium experiment with fine profile measurements, not only n_e , T_e and T_i profiles but also impurity profiles

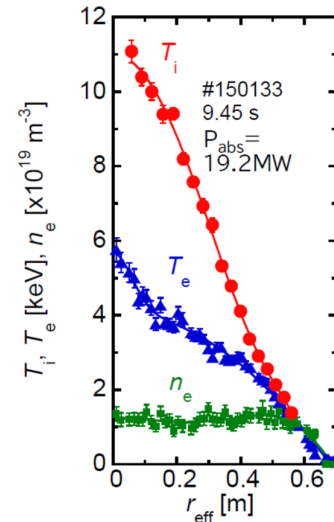


Fig.3 High ion temperature with T_i exceeding 10 keV.

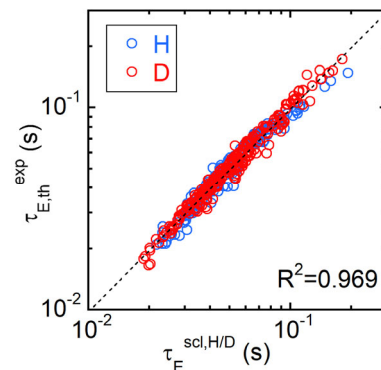


Fig.4 Regression analysis of τ_E .

had made very precise $\tau_{E,th}^{scl,HD-NBI} \propto A_{eff}^{0.01} Z_{eff}^{-0.11} B^{0.87} \bar{n}_e^{0.71} P_{abs}^{-0.85}$ documentation available. Regression analysis clear of energy confinement time shows that isotope effect on confinement is not evident in engineering expression (see Fig.4), which seems to be contradict gyro-Bohm nature [13]. Comparison of dimensionally identical H and D plasmas (same ρ^* , v^* , β ; different mass A) suggested that co-existence of improvement due to the mass and gyro-Bohm nature.

3.5 Impurity hole

Extremely hollow impurity density profiles were observed in high- T_i plasmas [14]. Global neoclassical simulation suggested outward impurity convection due to ∇T_i even with negative E_r [15]. A dramatic density decrease during internal transport barrier formation, remain unexplained — possibly involving energetic-particle effects in phase space.

3.6 Phase-space dynamics

Velocity distribution measurements showed ion energy increase at MHD burst onset via Landau damping [16] with velocity-space anisotropy relaxing within the ion-ion collision time (see Fig.5). The $\nabla T-q$ relationship was also found non-unique, suggesting additional thermodynamic forces beyond conventional transport theory [17]. The nature of sub-critical instability was characterized by the identification of heat flux and turbulence even in the stable regime against the drift mode [18].

4. Post-LHD Project: MCPoP

The MCPoP (Micro Collective Phenomena of ultra-high temperature Plasma) project inherits the LHD legacy and its unresolved mysteries. Its two central questions are: (1) what causes confinement and transport degradation, and what is the recipe to improve it? and (2) what causes abrupt phenomena, and how can they be predicted, avoided, or mitigated?

MCPoP's approach exploits phase-space exploration beyond conventional physical space, enabled by: (a) innovative diagnostics with high spatio-temporal resolution; (b) versatile plasma manipulators; and (c) advanced data science and first-principles simulation. The ultimate scientific aim is to achieve complete agreement between high-precision experiments and first-principles simulations, elevating fusion plasma physics to a 'precise predictive science'.

The experimental platform of MCPoP comprises the Compact Helical Device (CHD), reusing the former CHS hardware, and the upgraded CHD-U. Unlike LHD, where continuous helical winding constrains the magnetic field distribution on the magnetic surface, CHD-U

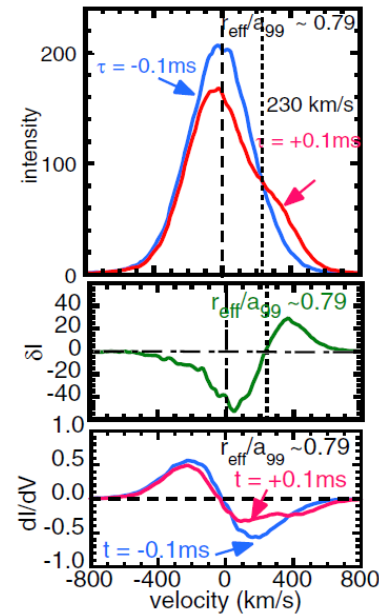


Fig.5 Identification of distortion of velocity distribution function after the MHD burst by fast CXRS. Reprinted from [16].

provides large flexibility through modular coil design, enabling access to quasi-isodynamic (QI) and quasi-axisymmetric (QA) configurations within a single device.

5. Summary and Outlook

The LHD project achieved and exceeded its original missions over nearly 28 years. Remarkable extension of plasma performance was seen in high β (5%), long pulse (48min.) and high ion temperature (10keV). Conjunction with these parametric progresses, a variety of novel phenomena have been identified and characterized. These findings have stimulated elaboration of theory and simulation, in particular, 3-D gyro-kinetic [19,20] and MHD with kinetic effect [7]. These results collectively constitute a major advance in the science of toroidal plasma confinement, and they provide directly relevant insights for the design of future helical fusion reactors and for the broader understanding of toroidal plasmas.

The transition from LHD to MCPoP is not an ending but a purposeful transformation. The unresolved mysteries left by LHD define a rich agenda for MCPoP. Through compact yet highly capable experiments with world-leading diagnostics, flexible magnetic geometries, and integrated data science and first-principles simulation, MCPoP aims to establish fusion plasma physics as a ‘precise predictive science’ and to lay the scientific foundation for the next generation of fusion energy research.

Acknowledgments

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