Discriminating Acquisition of 15-MeV Protons from D-^{3}He Fusion Reaction in LHD

Tsuguhiro WATANABE, Junichi MIYAZAWA, Hiroshi YAMADA, Sadayoshi MURAKAMI[1)], Suguru MASUZAKI, Masaki OSAKABE, Mitsutaka ISOBE, Masayuki TOKITANI and Osamu MOTOJIMA

National Institute for Fusion Science, Oroshi, Toki 509-5292, Japan
[1)]*Kyoto University, Department of Nuclear Engineering, Kyoto 606-8501, Japan*

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Discriminating acquisition of 15-MeV protons is possible in LHD D-^{3}He experiments (D^+ beam to ^{3}He plasma), due to the nonaxisymmetric structure of the magnetic field and the ultra-high energy of the fusion products. The collisionless orbits of D-^{3}He fusion products are studied numerically in the standard magnetic field configuration of LHD. Three sets of fusion product acquisition systems are installed in LHD and numerical computations show the possibility of discriminating between fusion products and plasma particles. The acquisition rate of 15-MeV protons is expected to be in the range of 12 ~ 28 %.

Keywords: LHD, D-^{3}He, 15-MeV proton, nuclear fusion energy

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In LHD, the problem of instability of plasma confinement is essentially overcome, and the confinement performance is greatly improved (high T, high n, high β, steady state operation) [1,2]. Based on LHD experimental results, a next generation DEMO Reactor, called Force Free Helical Reactor has been designed [3].

Demonstration of extraction of net electric power from a fusion device is important to prove that nuclear fusion energy can solve the earth's energy and environmental issues.

It is necessary to inject high power into a plasma for its production and sustainment. Fusion products must be discriminated from plasma particles to clearly demonstrate net fusion power extraction. Effective acquisition performance is necessary to obtain sufficient power for operating home electric appliances.

The LHD magnetic field has a high magnetic shear configuration in the peripheral region. The lines of force outsides the last closed flux surface (LCFS) show a fractal structure and create a chaotic field line layer [4]. The plasma in the chaotic field line layer is clearly detected by CCD-cameras in LHD experiments [5,6]. The conducting end plate effect [7] of diverter legs which are slipped out from the chaotic field line layer, can also stabilize the ballooning mode and the vertical displacement events of the plasma column.

Here, we computationally show the possibility of discriminating the acquisition of 15-MeV protons from the D-^{3}He reaction in LHD.

$$D + {}^3He \rightarrow {}^4He\,(3.67\,MeV) + p\,(15\,MeV). \qquad (1)$$

author's e-mail: watanabe.tsuguhiro@toki-fs.jp

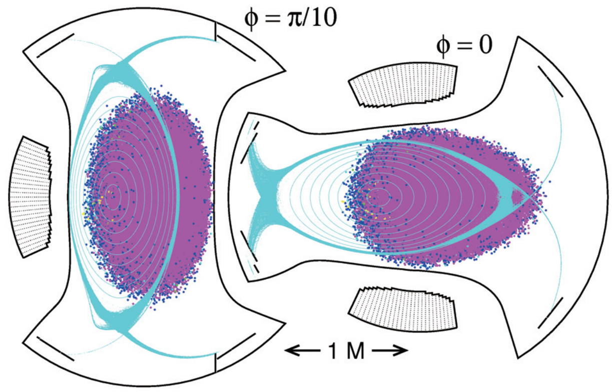

Fig. 1 Confinement of high energetic particles outside the chaotic field line region. Poincaré plots of particles injected from NBI#2 (co-NBI, 180-keV) at $B_{ax} = 0.3$ T are shown, which are equivalent to $E = 15$ MeV protons at $B_{ax} = 2.75$ T. The vast majority of the co-NBI particles are confined as shown by magenta dots (direct loss rate of the co-NBI particles ≃ 1.28 %). The small sky blue dots represent magnetic field lines.

In the LHD magnetic field configuration, $\boldsymbol{B} \times \nabla B$ drift motion enhances the adiabaticity of passing particles with $v_{\parallel} > 0$. Passing particles with $v_{\parallel} > 0$ can be confined over the LCFS [5]. The displacement of particle orbits from the magnetic surface, Δ, can be estimated as a poloidal Larmor radius:

$$\Delta \simeq \sqrt{\frac{E}{M_p}}\frac{M_p}{qB_p} \simeq \begin{cases} 0.043 \quad \text{m} \quad \text{for } 180\,\text{keV} \\ 0.40 \quad \text{m} \quad \text{for } 15\,\text{MeV}, \end{cases} \qquad (2)$$

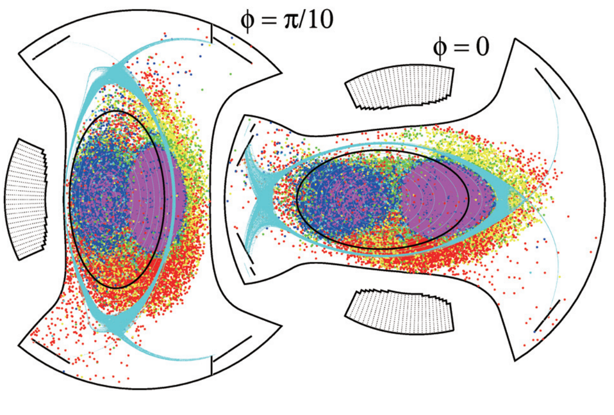

Fig. 2 Poincaré plots of the fusion products, 15-MeV protons. The solid black lines represent the magnetic surface of the outer boundary for birth points of the fusion product. The dot colors correspond to the lifetime $\times \sqrt{E/M_p}/(2\pi \times 3.9)$ of each proton.

1	2	5	10	100
red	yellow	green	sky blue	blue

Magenta dots are puncture plots of confined particles.

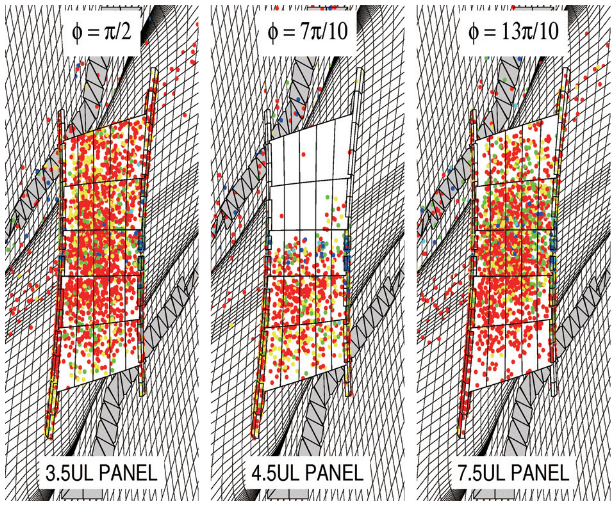

Fig. 3 Hit point patterns of 15-MeV proton on the acquisition systems, vacuum vessel wall, and diverter tiles. The 3.5UL panel produces a shadow region on the 4.5UL panel because $B_\phi > 0$.

Table 1 Summary of the numerical computation for the extraction of 15-MeV protons from the D-^{3}He Experiment.

total particle number	42,161	100 %
confined particles	1,901	4.51 %
hit points on vacuum vessel wall	22,520	53.41 %
hit points on diverter tiles	6.064	14.38 %
hit points on 3.5UL panel	5,134	12.18 %
hit points on 4.5UL panel	2,053	4.87 %
hit points on 7.5UL panel	4,489	10.65 %

where B_p is the poloidal magnetic field (estimated as 1 T) and E, M_p, and q are the energy, mass, and charge of a proton, respectively. In LHD, therefore, the fusion products, 15-MeV protons, can be confined over the chaotic field line region with a large margin, as shown in Fig. 1, although the co-NBI orbits (E = 180 keV) do not exceed the chaotic field line region, whose width is on the order of 0.1 m.

To semi-quantitatively evaluate the extraction rate of fusion energy from D-^{3}He experiment in LHD, we have numerically studied the collisionless orbits of the fusion products, 15-MeV protons, under the following assumptions. The magnetic field is standard (R_{ax} = 3.6 m, B_{ax} = 2.75 T, γ = 1.254). Birth points of the fusion products are assumed to be uniform inside a magnetic surface designated by a normalized minor radius $\rho \simeq 0.8$, as shown by the black oval in Fig. 2. The initial pitch angles are isotropically distributed. Three sets of acquisition systems (3.5, 4.5 and 7.5UL panels) for fusion products are assumed to have the geometry of ICRF antennas (3.5, 4.5 and 7.5UL antenna) [8]: these are maximally drawn to the vacuum vessel wall (d = 0.07 m). We confirmed that NBI and plasma particles do not hit these acquisition systems. The maximum computational time step is set to 0.065 ms which is the same as the 100 toroidal turns of thermal velocity of the 15-MeV proton. Particles with lifetimes longer than the maximum time step are treated as confined particles. The collision effects of neutral particles outside the LCFS are negligible, because of the ultra-high energy of 15-MeV protons.

Poincaré plots of the fusion products, 15-MeV protons, in the poloidal cross-sections specified by toroidal angle ϕ = 0 and $\phi = \pi/10$ are shown in Fig. 2. The influence of the acquisition systems is small, because they are placed downstream of the magnetic field.

The acquisition rate of the 4.5UL panel placed downstream of the 3.5UL panel, is relatively small, as shown in Table 1. This is reasonable because the main target particles for acquisition are particles with $v_\parallel > 0$: these can be confined outside the chaotic field line region. The hit point pattern of 15-MeV protons on the acquisition systems support this view as shown in Fig. 3.

Present computation shows that if an appropriate acquisition system is installed outside the chaotic field line region, the acquisition rate $R_{15\,\mathrm{MeV}}$ for 15-MeV protons in LHD D-^{3}He experiment can be estimated roughly as

$$0.12 \lesssim R_{15\,\mathrm{MeV}} \equiv \frac{\text{collected protons}}{\text{total generated protons}} \lesssim 0.28. \quad (3)$$

The collected 15-MeV proton energy can be transformed into net electric power using thermoelectric elements or some new direct converter systems.

Fusion power is estimated using the GNET code [9] under the condition of the tangential D$^+$ beam (180 keV, 15 MW) to ^{3}He plasma ($n_{^3\mathrm{He}} \simeq 2 \times 10^{19}\,\mathrm{m}^{-3}$). The reaction rate is estimated as 2.7×10^{16}/s. Then the beam target fusion reaction will generate 63 kW kinetic energy from the 15-MeV protons in LHD D-^{3}He experiment.

A project for direct power generation from D-^{3}He experiment in LHD is under way.

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