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Real-time impedance matching system for ICRF heating in LHD

K. Saito [a,*], C. Takahashi [a], M. Yokota [a], G. Nomura [a], F. Shimpo [a], T. Seki [a], H. Kasahara [a], R. Kumazawa [a], J.S. Yoon [b], J.G. Kwak [b], Y. Zhao [c], T. Mutoh [a], A. Komori [a], The LHD Experimental Group

[a] National Institute for Fusion Science, Toki, Gifu 509-5292, Japan
[b] Korea Atomic Energy Research Institute, P.O. Box 105, Yuseong, Daejeon 305-600, Republic of Korea
[c] Institute of Plasma Physics, Chinese Academy of Science, Hefei, Anhui 230031, People's Republic of China

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Abstract

In the Large Helical Device (LHD), long-pulse plasma experiments have been conducted using an ion cyclotron range of frequencies (ICRFs) heating system. Real-time impedance matching is necessary to keep injecting ICRF heating power into the plasma against the variation of the antenna impedance that changes gradually during a long-pulse plasma discharge. A feedback control system for the real-time impedance matching was constructed and utilized for long-pulse plasma discharges. As a component of the impedance matching device, liquid stub tuners were used. The reflected power ratio was reduced and kept sufficiently low by controlling the liquid heights during long-pulse plasma discharges, and the problem of the gradual increase in the reflected power was solved.

Keywords: ICRF heating; LHD; Liquid stub tuner; Steady-state operation; Feedback control

1. Introduction

Steady-state operation is one of the most important factors for a fusion reactor. The Large Helical Device (LHD) [1] is suitable for steady-state operation, because plasma current is not necessary to sustain a plasma discharge. The ion cyclotron range of frequencies (ICRFs) heating system was developed for high-power steady-state operation in the LHD [2], and it plays an important role in the operation. The impedance matching device is an important component of the ICRF heating system. It reduces the power reflected from the ICRF antenna to the final power amplifier (FPA), resulting in efficient power transmission and protection of a tetrode tube from the reflected power. The impedance matching device consists of two or three liquid stub tuners [3,4].

For long-pulse plasma discharge with ICRF heating, a real-time impedance matching system is necessary to maintain the injection of ICRF power into the plasma, because the antenna impedance changes gradually during the discharge [5]. For this purpose, a high-speed matching realized by a ferrite tuner system [6,7] or frequency control system [8] is not necessary. As a first step for impedance matching during long-pulse plasma discharge, we attempted manual frequency adjustment in the LHD [9]. This worked in the early phase of a discharge, but the shift of frequency was limited within the allowable bandwidth of the amplifiers, with the result that the reflected power ratio eventually rose to the interlock level.

We next attempted automatic feedback control of the liquid stub tuners using a trial-and-error method [9]. Two liquid heights of stub tuners were alternately controlled. If the reflected power fraction increased, a different shift direction of liquid height was chosen in the next trial. Therefore, this method has the risk of increasing the reflected power ratio by incorrectly changing the liquid height. Moreover, the convergence time to the matching point is long, because the liquid stub tuners have to be controlled one by one. Since both of these methods were insufficient, a new real-time impedance matching system had to be developed.

In the case of short-pulse plasma discharges, impedance matching is routinely obtained by manually adjusting the liquid heights in the stub tuners during intervals between discharges [5]. The optimum liquid heights for the next discharge are calculated using the complex reflection coefficients measured with a directional coupler on the outlet of the FPA and the liquid

* Corresponding author at: National Institute for Fusion Science, Department of Large Helical Device Project, 322-6 Oroshi-cho, Toki-shi, Gifu 509-5292, Japan. Tel.: +81 572 58 2202; fax: +81 572 58 2622.
E-mail address: saito@nifs.ac.jp (K. Saito).

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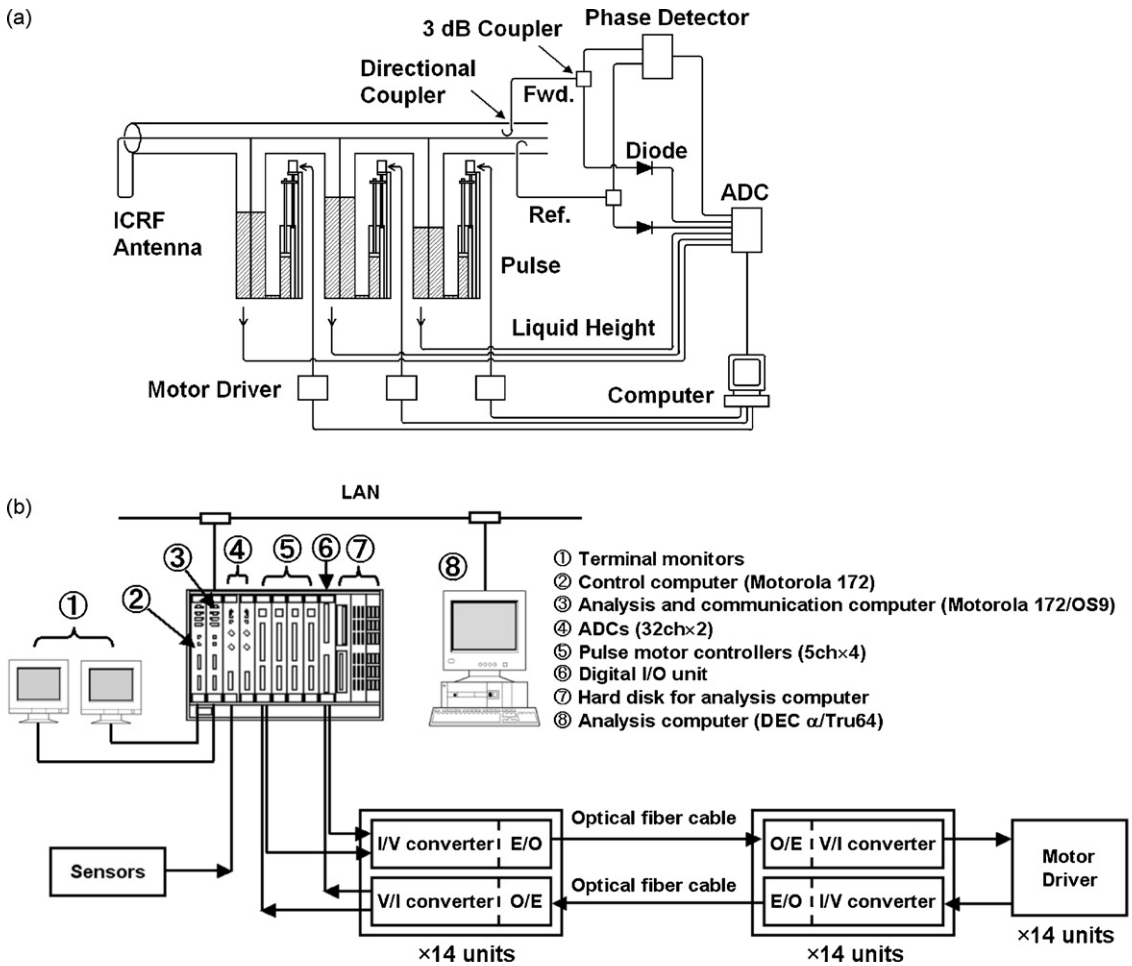

Fig. 1. (a) Schematic view of real-time impedance matching system and (b) control system.

heights, assuming that the antenna impedance at the next plasma discharge is the same as that at the former plasma discharge. It takes a long time to calculate the optimum liquid heights and to change the liquid heights manually, so, the operation is performed between discharges, but real-time control would be possible if the pulse length was long and the operation was performed automatically. Therefore, we constructed a feedback control system and a real-time impedance matching test was conducted [9]. The reflected power ratio was kept sufficiently low by the control of liquid heights in stub tuners against the variation of resistance in the resistor attached to the outlet of the impedance matching device, thus verifying that the system was useful.

2. Real-time impedance matching system

Fig. 1(a) shows a schematic view of the real-time impedance matching system from Ref. [9]. The main components are liquid stub tuners, a directional coupler, 3 dB couplers, a phase detector, diodes, a control system including analog–digital converters (ADCs) and computers, motor drivers, and cylinders driven by pulse motors. The signals of the forward and reflected waves (V_f and V_r) detected with the directional coupler are divided at the 3 dB couplers and sent to the phase detector and diodes. The signal of phase difference, $\phi = \phi_r - \phi_f$ measured with the phase detector, and the signals rectified at the diodes are transmitted to the ADCs and converted to digital signals. The ADCs also digitize the signals of the liquid heights detected using differential pressure gauges. There are two limit switches to detect the top and bottom ends of a cylinder for the purpose of an interlock. The limit switches are also used for the calibration of pulse counts. After manually moving the cylinders until they stop at the switches, the pulse counts are set to 0. Fig. 1(b) shows a detail of the control system. It consists of computers, ADCs, pulse motor controllers, a digital I/O unit, and related parts.

Fig. 2 shows a simplified flowchart of the feedback control. The computer calculates the antenna impedance using V_f, V_r, ϕ, and the liquid heights. The optimum liquid heights are calculated assuming the antenna impedance does not change. The pulse motors then adjust the liquid heights toward the optimum liquid heights at the same time. The speed of impedance matching is not as high as that of ferrite tuners or a frequency controller because the liquid height must be changed (typically 2 cm/s). The liquid heights are obtained between discharges with differential pressure gauges attached at the bottom of stub tuners. During the radio frequency (RF) power injection, liquid heights are calculated from the total pulse counts sent to the motors, since the