STEADY STATE HEATING TECHNOLOGY DEVELOPMENT FOR THE LHD

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ABSTRACT

Construction of the LHD has been completed and it went into the experimental phase in early April 1998. The first plasma was obtained with ECH with a power level of 300 kW. Three heating schemes, ECH, ICRF, and NBI, are adopted and join the heating experiment in the second experimental campaign.

Since the LHD has superconducting coils, one of the missions of plasma heating in the LHD is demonstration of a steady state plasma. Intensive technology development for steady state plasma heating has been carried out at NIFS since 1992. The paper summarizes the achievements of these developmental activities in the past several years. The knowledge obtained may be applicable to ITER, where steady state plasma heating is essential.

I. ICRF STEADY STATE TECHNOLOGY DEVELOPMENT

R&D experiments have been conducted using a test assembly which consists of a transmitter, a dummy load, transmission lines, a coaxial switch, a DC-break, an impedance matching circuit, a pre-matching stub tuner, a ceramic feedthrough and a test loop antenna installed in a vacuum chamber.

The transmitter was newly designed and constructed. A unique double coaxial output cavity was employed to facilitate wide band frequency tunability from 25 to 100 MHz. An Eimac tetrode 4CM2500KG was used. With forced air cooling of the cavity, an RF power of 1.6 MW was obtained for 5000 sec, a long pulse record for this range of frequency and power[1].

New standardized designs for water cooled coaxial lines and junctions were developed and tested; the diameters of outer and inner coaxes are 240 mm and 104 mm. The original idea of a liquid stub tuner has been employed in the impedance matching circuit. It utilizes the difference of the RF wave length between the gas and liquid in order to eliminate the sliding contactors used in conventional stub tuners. The latter had been causing difficulties in making reliable stub tuners for high power long pulse ICRF systems. Another key component where the R&D work is extended is the vacuum feedthrough; the inner and outer conductors are water cooled and the ceramics are gas cooled. Various shapes of the ceramics were tested and Si_3N_4 was examined as a new feed through material[2].

To summarize the steady state component development, all the components listed above finally cleared the stand off voltage of 40 kV for 30 min as tabulated in table-1. It should be noted that the stand off voltage is higher by about 20 % for pulses shorter than 10 sec. The liquid stub tuner was demonstrated to be a reliable component by standing off 50 kV[1]. Tunability was also demonstrated by varying the liquid surface height with 46 kV of RF voltage. Here, 40 kV of operating voltage corresponds to 1.6 MW injection to the plasma in the LHD, assuming a plasma loading resistance of 5 W.

For LHD ICRF experiments, two kinds of antennas have been designed and fabricated. One is a conventional loop antenna (Fig. 1) for fast wave heating[3] and the other is a folded wave guide antenna (Fig.2) for ion Bernstein wave heating[4]. The steady state technology obtained in the R&D was fully incorporated in the design of these antennas.

high power amplifier	1.6 MW, 5000 sec (steady state)
feedthrough	40 kV 30 min
liquid stub tuner	50 kV 30 min
coaxial line	50 kV 30 min
water cooled antenna	40 kV 30 minu

Table-1. The stand off voltages of ICRF components as tested with a pulse of 30 min.

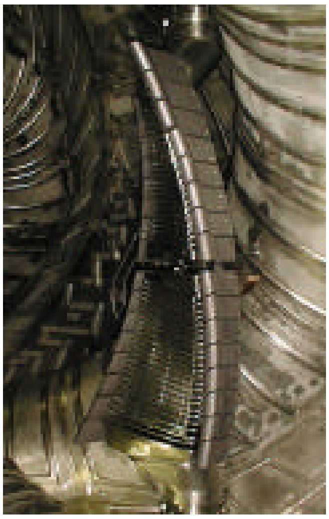

Fig.1. Water cooled antenna installed in the LHD.

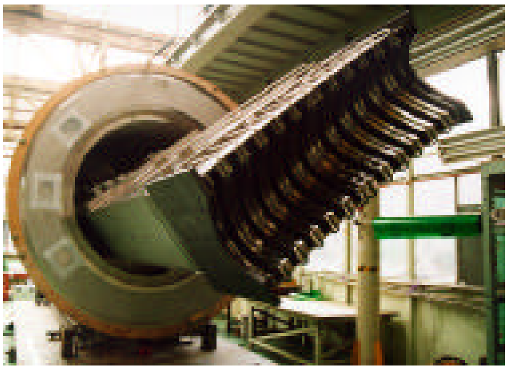

Fig.2. Folded wave guide antenna.

II. ECH STEADY STATE TECHNOLOGY DEVELOPMENT

The most important issue of steadystate ECH is development of CW (continuous wave) gyrotrons. ECH for the LHD requires two frequencies ,84 GHz and 168 GHz, corresponding to fundamental and second harmonic heating. CPI and Toshiba companies have been the partners in the development of 84 GHz and 168 GHz high power CW gyrotrons, respectively.

By means of strong water cooling of the tube, the 84 GHz gyrotron achieved 500 kW for 2 sec, 400 kW for 10.5 sec, 200 kW for 30 sec and 100 kW for 30 min[5-6]. Figure 3 shows the time evolution of the peak temperature of the gyrotron output window disk. Long pulse operation at high power levels (500 kW) was limited within 2 sec by the temperature rise of the output sapphire double-disk window, which can be replaced by better material currently available. The records with lower power (<400 kW) and longer pulse are limited by the degradation of the vacuum condition, an important understanding gained in these experiments. A new 84 GHz gyrotron was fabricated with improved pumping. The idea of Collector Potential Depression (CPD) is adopted to reduce thermal load, which allows compact design of a collector in a CW gyrotron. The basic CPD performance of the gyrotron was confirmed for the following short pulses: 250 kW/ 0.2 sec and 150 kW/ 0.5 sec pulses, and 130 kW 0.1 sec /10% duty. The operational conditions are: collector voltage 65 kV, body voltage 80 kV, and anode voltage 25 kV. The other merit of a CPD gyrotron is that rigorous stability of the collector voltage is not required. Aging of the tube is being conducted in order to achieve longer pulse and CW operation .

High power CW vacuum barrier windows are another important issue. We propose a low loss silicon nitride composite disk(Si3N4) [7] with surface gascooling as a new type of window. This material has low tangent and excellent mechanical strength and enables uses at high temperature. Tests of a gas-cooled window with a diameter of 88.9 mm demonstrated transmission of 130 kW CW power in HE_{11} mode with a small rise of the peak temperature of the disk. The power flux density exceeded 8 kW/cm^2 on the center of the window. It is demonstrated in Fig. 4 that the window with gas cooling has a shorter thermal time constant leading to a much smaller window temperature rise.

The Toshiba 168 GHz gyrotrons are loaded with the proposed gas-cooled silicon nitride window. The pulse length achieved so far is 500 kW/1sec output. The maximum temperature increment of the window reached only 160 ˚C at the end of a 1 sec pulse. The pulse length is rather limited by the tube itself. The gas cooled windows of the same idea are also adopted for the LHD device CW window.

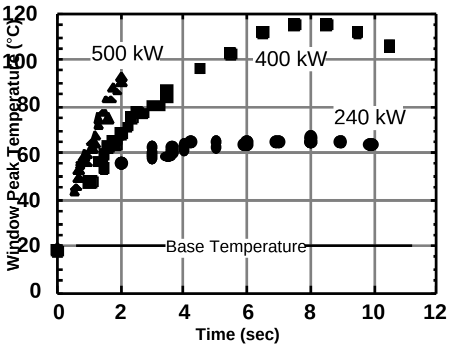

Fig. 3. Variation of peak window temperature during RF pulses of various output power. The maximum rating of the sapahire window is 120 ˚C .

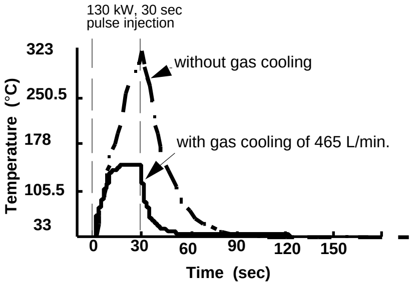

Fig. 4. Time evolution of the peak temperature on the disk during 130 kW, 30sec injection without gascooling and with gascooling of 465L/min.

III. NBI STEADY STATE TECHNOLOGY DEVELOPMENT

The NBI system of the LHD is designed for high energy (180 keV), high power (15 MW) and pulsed operation (10 sec), using hydrogen [8]. The decision to use negative ion sources has provided a substantial challenge. The developmental work in the past several years has concentrated on extracting 30A~40A of negative ion beam and that goal has almost been reached.

Aside from this original thought of pulsed high power injection, there is another interesting path of steadystate operation (~30 min) with lower power (1-3 MW) [9]. Here, development of a long-pulse negative ion source is important. The key is in the suppression of the accelerated electrons, which causes heat load on the downstream grids. Recently, the shape of the extraction grid hole was optimized so that the generated secondary electrons would not leak into the acceleration gap [10], and the operational gas pressure was lowered in order to eliminate the neutralization of the negative ions during the acceleration, one of the processes which produces electrons. As a result, the heat load of the grounded grid was reduced and production of a long pulse high-power negative ion beam was achieved (330 kW for 10 sec by use of 1/5 of the grid area of the LHD-NBI source [11]).

Based on this result, a prototype negative ion source has been designed and fabricated which has a three-grid single-stage accelerator with grid area of 25 cm x 125 cm. A negative ion current of 25A has been obtained with an acceleration energy of 104 keV for 1.0 sec. In a long pulse test, as shown in Fig. 5, injection of 1.3 MW for 10 sec was achieved as confirmed on the beam dump located 13 m downstream. The cooling water temperatures of extraction and grounded grids rise to saturated levels suggesting that it is steady state in effect, as shown in Fig. 6. As for the components of the injector, the residual ion beam dumps are made of swirl tube with fins, which can remove more than 2 kW/cm^2 of heat load continuously. A cryosorption pump with a pumping speed of 1360 m^3/s works continuously for 30 min.

An experiment on NBI heating in the LHD began in September 1998 with 80 keV-1 MW injection. The injection power gradually increased as the aging proceeds. A long-pulse NBI experiment in the LHD is planned in parallel with the high-power short-pulse injection, prior to the steadystate neutral beam injection into the LHD. The injection energy and power are 80 keV and 500 kW, respectively, and the pulse length will be prolonged to 1 min. True steady state operation, 1 MW - 30 min injection into the LHD, will be done after upgrading the NBI power supplies.

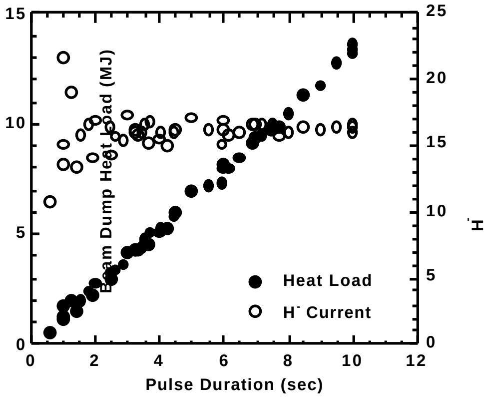

Fig. 5. Heat load measured at the dummy load for 10 sec long pulse NBI injection.

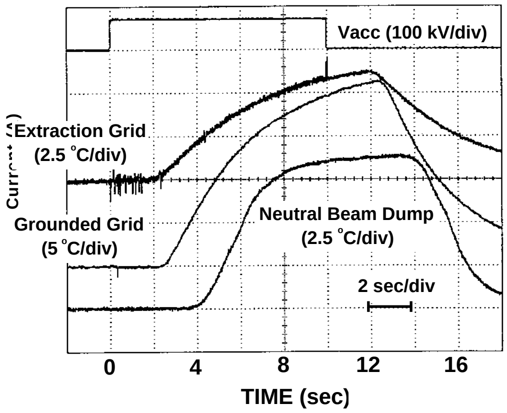

Fig. 6. Temperature rise of cooling water outlet of various grids of the negative ion source.

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