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T. Watari, T. Shimozuma, Y. Takeiri, R. Kumazawa, T. Mutoh, M. Sato,
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STEADY STATE HEATING TECHNOLOGY DEVELOPMENT FOR LHD

T.WATARI, T.SHIMOZUMA, Y.TAKEIRI, R. KUMAZAWA, T.MUTOH, M.SATO,
O.KANEKO, K.OHKUBO, S.KUBO, H.IDEI, Y.OKA, M.OSAKABE, T. SEKI,
K.TSUMORI, Y.YOSHIMURA, R.AKIYAMA, T.KAWAMOTO, S.KOBAYASHI,
F. SHIMPO, Y.TAKITA, E.ASANO, S.ITOH, G. NOMURA, T.IDO, M.HAMABE,
M.FUJIWARA, A.IIYOSHI

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, 509-5292 Japan

S.MORIMOTO*, T.BIGELOW**, Y.P. ZHAO***

*Kanazawa Institute of Technology, 7-1, Oogigaoka, Nonoichi, Ishikawa, 921, Japan
**Oak Ridge Natiomnal Laboratory, TN37831, USA.
***Institute of Plasma Physic, Academia Sinica, 230031, Hefei, Anhui, China

ABSTRACT

The LHD has finished construction and went into Experimental phase in early April 1998. The first plasma was obtained with ECH with the power level of 300kW. Three heating schemes, ECH, ICRF, and NBI are adopted and join the heating experiment in the second experimental campaign.
Since the LHD has super-conducting coils, one of the missions of plasma heating in LHD is demonstration of steady state plasma. Intensive technology development for steady state plasma heating has been carried out at NIFS since 1992. This paper summarizes the achievement 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 co-axial switch, a DC-break, an impedance matching circuit, a pre-matching stub tuner, a ceramic feed through 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 of this range of frequency and power[1].

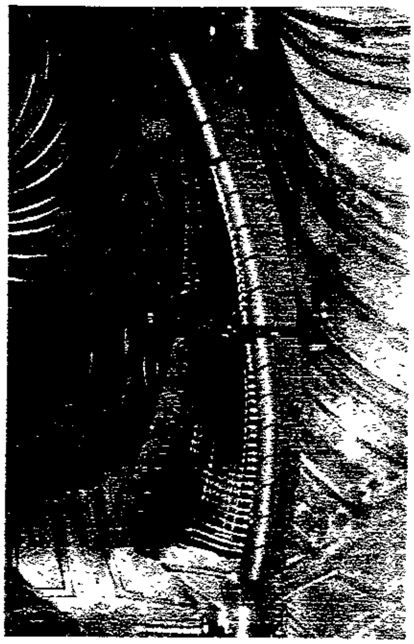
New standardized design for water cooled coaxial lines and junctions were developed and tested; the diameters of outer and inner coaxes are 240 mm and 104 mm. The original idea of a liquid stub tuner has been employed in impedance matching circuit. It utilizes the difference of the RF wave length between 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 system. Another key component where the R&D work is extended is a vacuum feed through; the inner and outer conductors are water cooled and the ceramics are gas cooled. Various shapes of the ceramics were tested and Si3N4 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 shorter pulses than 10 seconds. 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 LHD, assuming a plasma loading resistance of 5 Ω.

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	1.6MW 5000 sec (steady state)
feed through	40kV 30 minutes
liquid stub tuner	50kV 30 minutes
coaxial line	50kV 30 minutes
water cooled antenna	40kV 30 minutes

Table-1 The standoff voltages of ICRF components as tested with 30 minutes long pulse.



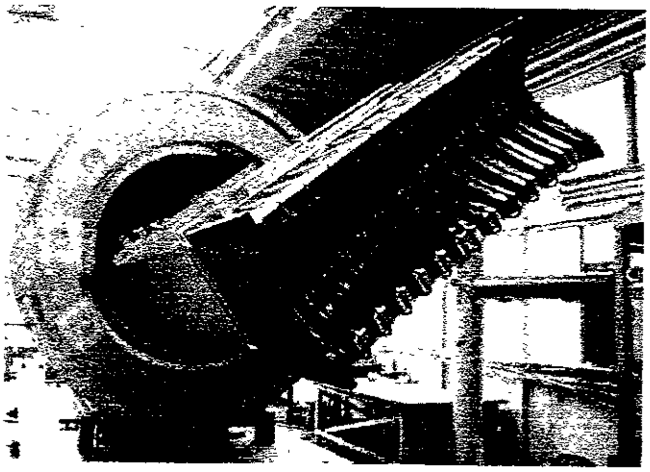


Fig.1 The water cooled antenna installed in LHD

Fig.2 Folded wave guide antenna

II. ECH STEADY STATE TECHNOLOGY DEVELOPMENT

The most important issue of steady-state ECH is development of CW (Continuous Wave) gyrotrons. ECH for LHD requires two frequency 84 GHz and 168 GHz corresponding to fundamental and second harmonic Heating. CPI and Toshiba companies have been the partner in the development of 84GHz and 168 GHz high power CW gyrotrons, respectively.

By means of strong water cooling of the tube, the 84GHz gyrotron achieved 500kW for 2sec., 400kW for 10.5sec., 200kW for 30sec. and 100kW for 30min.[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 (500kW) was limited within 2 sec. by the temperature rise of the output sapphire double-disk window, which can be replaced by better material currently avairable. The records with lower power (<400kW) and longer pulse are limited by the degradation of vacuum condition; an important understanding gained in these experiments. A new 84GHz 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 CW gyrotron. The basic CPD performances of the gyrotron was confirmed for following short pulses : 250kW / 0.2sec. and 150kW / 0.5 sec. pulses, and 130kW 0.1 sec. / 10% duty . The operational conditions are: collector voltage 65kV , a body voltage 80kV, and anode voltage 25kV. The other merit of CPD gyrotron is that rigourous stability of collector is not required. Aging of the tube is procceding for 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 gas-cooling 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 88.9mm demonstrated transmission of 130kW 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 shorter thermal time constant leading to a much less window temperature rise.

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

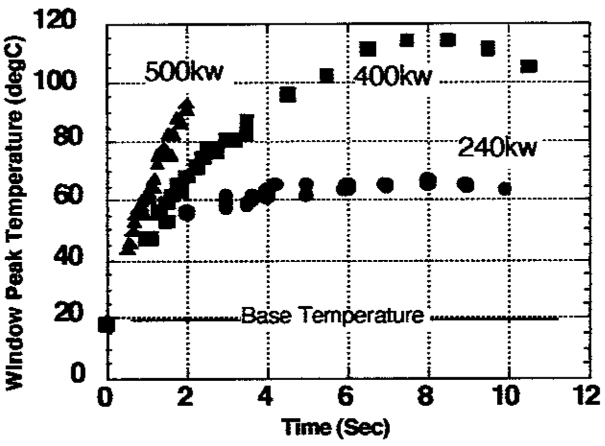


Fig. 3 Variation of peak window temperature during RF pulse of various out put power. The maximum rating of of the saphire window is 120 degee .

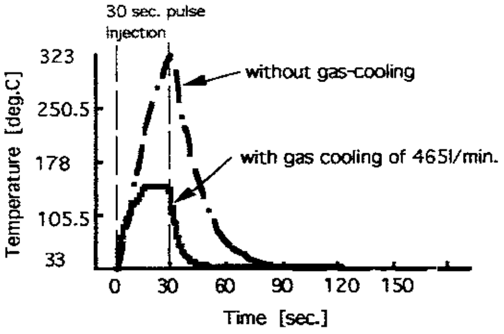


Fig. 4 Time evolution of the peak temperature on the disk during 130kW, 30sec. injection without gas-cooling and with gas-cooling of 465l/min.

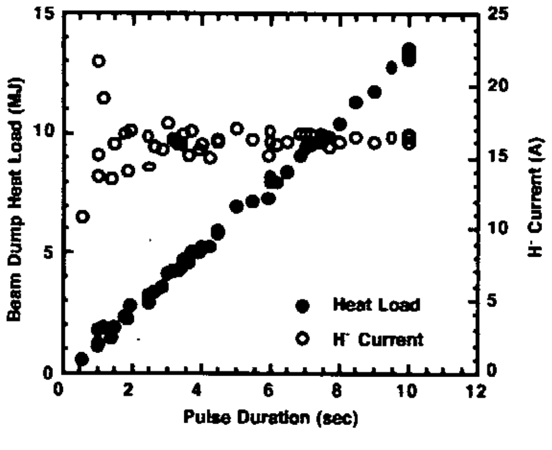
III. NBI STEADY STATE TECHNOLOGY DEVELOPMENT

The NBI system of LHD is designed for high energy (180keV), high power (15MW) and pulsed operation (10sec), 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 been almost reached.

Aside from this original thought of pulsed high power injection, there is another interesting path of steady-state operation (~30 min.) with lower power (1-3MW) [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 process 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 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. 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, 1.3MW for 10 sec injection 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 injector, the residual ion beam dumps are made of swirl tube with fin, which can remove more than 2 kW/cm2 of heat load continuously. Cryo-sorption pump with a pumping speed of 1360 m3/s works continuously for 30 min.

NBI heating experiment in LHD has started since September 1998 with 80keV-1MW injection. The injection power is gradually increasing as the aging proceeds. A long-pulse NBI experiment in LHD is planned in parallel to the high-power short-pulse injection, prior to the steady-state neutral beam injection into LHD. The injection energy and power are 80 keV and 500 kW, respectively, and the pulse length will be prolonged to 1min. Real steady state operation, 1MW - 30min injection into LHD, will be done after the enforcement of the NBI power supplies.



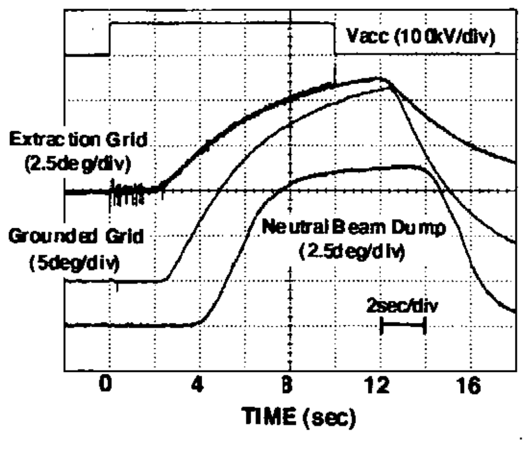


Fig.5 The heat load measured at the dummy load on 10 second long pulse NBI injection.
Fig.6 Temprature rise of cooling water outlet of various grids of negative ion source

REFERENCES :

[1] R.Kumazawa, T.Mutoh, T.Watari, T.Seki, F.Shimbo, et.al.,
in Proceedings of 19h symposium on Fusion Technology,Vol.1, 617 (1997)

[2] T. Mutoh, R. Kumazawa, T. Seki, F. Simpo, G. Nomura, et.al.,
in Proceedings of 17th symposium on Fusion Engineerign,Vol.1, 465 (1998)

[3] T. Mutoh, R. Kumazawa, T. Seki, F. Simpo, G. Nomura, et.al.,
Journal of Plasma and Fusion Research.SERIES, Vol.1, 334(1998)

[4] R.Kumazawa, T.Mutoh, T.Seki, F.Shimbo, G.Nomura, et.al.,
Journal of Plasma and Fusion Research.SERIES, Vol.1, 330(1998)

[5] T. Shimozuma, M. Sato, Y. Takita, S. Kubo, H. Idei, et al,
19th Symposium on Fusion Technology, (16-20 September 1996, Lisbon Portugal),
PB-8, Elsevier, Amsterdam (1996) pp553-556.

[6] M. Sato, T. Shimozuma, Y. Takita, S. Kubo, H. Idei, et al.,
Conference Digest of the 20th International Conference on Infrared and Millimeter Waves,
(11-14 December 1995 ,Orlando, Florida) T4.3, pp195-196.

[7] T. Shimozuma, S. Morimoto, M. Sato, Y. Takita, S. Itoh, International Journal of Infrared
and Millimeter Waves Vol.18, No.8, p1479(1997).

[8] O. Kaneko, Y. Takeiri, K. Tsumori, Y. Oka, M. Osakabe,
in Proceedings of the 16th International Conference on Fusion Energy, (Montreal, 1996),
International Atomic Energy Agency, Vienna (1997), Vol. 3 pp. 539-545.

[9] Y. Takeiri, O. Kaneko, Y. Oka, K. Tsumori, M. Osakabe,
Journal of Plasma and Fusion Research SERIES, Vol. 1 (1998) pp. 405-408.

[10] Y. Takeiri, Y. Oka, M. Osakabe, K. Tsumori, O. Kaneko,
Review of Scientific Instruments, Vol. 68, No. 5 (1997) pp. 2003-2011.

[11] Y. Takeiri, M. Osakabe, Y. Oka, K. Tsumori, O. Kaneko,
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