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Measurement of beam power and profile for DNB on HT-7 tokamak

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Abstract

In normal experimental operation, a diagnostic neutral beam (DNB) can produce 6 A of extracted beam current in hydrogen at an energy of 49 keV with a pulse length of 100 ms. Hydrogen and deuterium beams can be produced as well. The diagnostic neutral beam has been added to the diagnostic set so that charge-exchange recombination spectroscopy (CXRS) can be used to acquire ion temperature and rotation. The beam power and beam profile distribution of the DNB injection can be obtained with a thermocouple probe measurement system on the HT-7 superconducting tokamak. The thermocouple probe measurement system with 13 thermocouples crossly distributed on the probe plate was used to measure the temperature rise of each coppery target, so the profile distribution of the ion/neutral beam was obtained by calculation. In this paper, the structure of the probe plate on the DNB for HT-7 tokamak and some measurement results are presented.

Keywords: Diagnostic neutral beam; Target calorimeter system; Beams power; Beams profile distribution

1. Introduction

Diagnostic neutral beam (DNB) project has been in progress for HT-7 superconducting tokamak device. The DNB combined with charge-exchange recombination spectroscopy (CXRS) has been widely used to measure many important plasma parameters [1]. To study the role of the ion thermal transport, the radial electric field, and turbulence in the high performance HT-7 plasma, a modulated diagnostic neutral beam project has been in progress at ASIPP. The main DNB system [2] is same as one produce 6 A of extracted beam current in hydrogen at an energy of 49 keV. At the plasma, the density of the components will be typically in the ratio of [E:E/2:E/3:E/18] = [12:34:37:17]. The DNB system can produce deuterium and helium beams as well. It can be operated to produce a beam as often as once every 3 min the beam produced can be a single pulse with duration of 100 ms.

The DNB provides the neutral particle beam, which is sent to the tokamak and can collide with the ion and electron in the plasma and sends out the

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charge-exchange recombination spectroscopy. This method generally is used in the measurement of the space and time distribution of the power density of three kinds of impurity particles (e.g. carbon, neon, argon ion) and the observation of the new classical effect that the fusion core of the impurity particle strengthens along with the increase of the number of the nucleus electric charge, and the running status and the electric discharge process control of the tokamak can be checked by this method, furthermore, the produced plasma can be enabled to achieve best. The Fusion Research Center in the University of Texas, U.S. once for a long time studied and used the DNB project [3] in its fusion equipment. In the DNB aligning period, after the measurement of the energy and the distribution of neutral beam and use of the alignment system on the equipment, the optimum condition of the quality of the injected beam needed for diagnostic interpretation can be achieved, then the gate valve that separates the beam line and the tokamak is opened to carries on the experiment of the DNB injection for the tokamak.

The DNB system for HT-7 tokamak is 150 kW (NB)/50 keV. As shown in Fig. 1, the ion source of the DNB system is a barrel ion source with 15 cm diameter extraction area, and the four electrode grids of the ion source are long-curvature sphere, thus the beam will be focused, and the distance between the focus of the beam and the last grid is 2.56 m, and the diameter of neutral beam at focus is 5 cm. From the ion source, the neutralization chamber with 1.0 m long and the bending magnet is set in order. The DNB line incorporates two thermocouple probes, one is located downstream from the bending magnet, the other setting in the drift tube is called alignment probe. Because both of the two thermocouple can measure the profile power distribution of the beam, such structure can allow us to check the alignment of the injected beam, to measure the total power and power density profile, and to optimize the beam without injecting into the tokamak, and the gate valve separating the beam line from the tokamak is protected by the alignment probe too. In the experiments of the DNB system, the aim of optimization is to obtain the best neutral beam that has high energy, high total power and high full energy component. This information can then be used to optimize the perveance and the beam neutralization, to determine some parameters of the injected beam needed for diagnostic interpretation, and to provide the observation

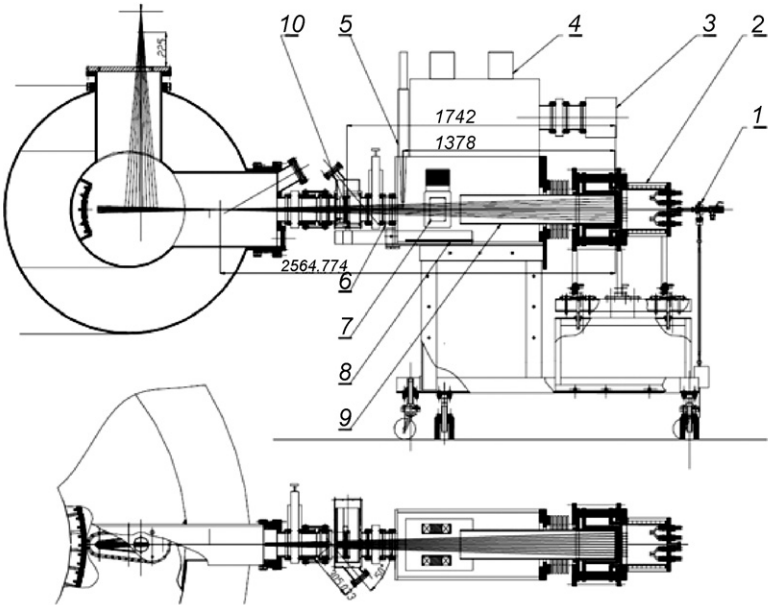

Fig. 1. Sketch of the structure of DNB system of HT-7 tokamak. (1) The gas supply valve; (2) the ion source; (3) the molecule pump; (4) cryopumps; (5) thermocouple probe; (6) drift tube; (7) bending magnet; (8) ion dump; (9) neutrallizer; (10) alignment probe.

and the analysis convenience to improve the plasma restraint. The main functions of this system are checking the alignment of the injected beam, measuring the total power and power density profile; enable conditioning of the beam without injecting into the tokamak, and protecting the gate valve separating the beam line from the tokamak. Therefore, the method of heat section board with calorimeter is one effective way to measure the high-energy beam profile distribution [4].

2. Structure of the thermocouple probe and measurement theory

The basic structure of the thermocouple probe located downstream from the bending magnet is shown in Fig. 2. The designed probe plate is a copper board with water-cooling and can be moved out or into the beam path by a pneumatically operated linear actuator to intercept whole of the beam. It is 150 mm × 180 mm square and 6 mm thick, and thirteen 2 mm diameter holes crossly distributed on the center of the probe plate allow samples of the beam to penetrate the probe plate, and the distance between each two neighboring holes on a same range is 13.5 mm. Each hole corresponds to a thermally isolated and electrically copper disk mounted on the back of the probe plate behind the hole, and the sample of the beam through a hole is stopped by the copper disk, and the mass of each of the coppery target is 0.52 g.

In the calculation of the data, the beam density distribution is calculated by measuring the temperature rise of each copper disk along the radial direction of the beam spot as the following equation:

$$P = mC_{\mathrm{p}} \frac{\int \Delta T \, \mathrm{d}t}{t_{\mathrm{B}}} \qquad (1)$$

where ΔT is temperature rise of each coppery target, m the mass of the coppery target, C_{p} the specific heat of the coppery target, and t_{B} is the beam pulse time. According to Eq. (1), defined the area of the heat leak hole on the heat section board is S, the power density of the beam at the position of the hole on the plate is $\rho = P/S$. Therefore, the maximum value of injected power on the heat section board is $P_{\max} = \rho_{\max} S$. In this formula, $\rho_{\max}$ is the largest power density value of all of the discs and S is the area of the heat section board [5]. Obviously, this predicted value is the maximum one of the actual injected beam power.

The structure of the alignment probe is similar with the front one, but only 10 holes crossly ranged on the plate but not symmetrical, as shown on the right in Fig. 2, and such design is helpful for the fitting of the data. Its copper disks are same with the front probe, and the calculation of the measurement data is same with that too.

The measurement system of the target calorimeter on the DNB line is shown in Fig. 3. To each target, a pair of Chromel/Alumel wires is spot welded to form a Type K thermocouple. The weak voltage sig-

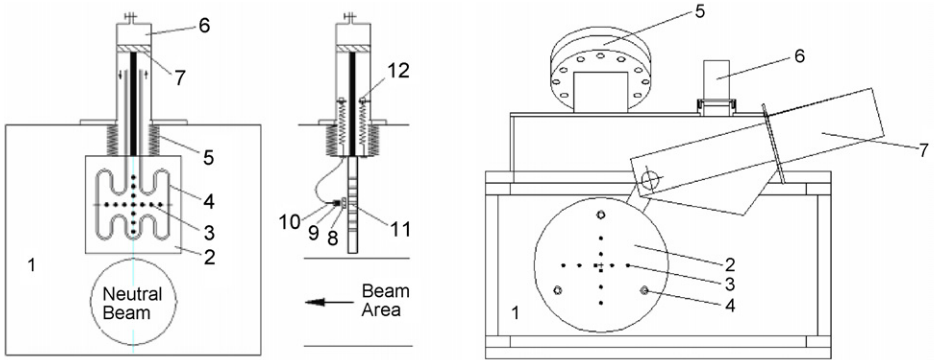

Fig. 2. Structure of the two thermocouple probes, and the thermocouple probe and the alignment probe are shown in the left and the right image, respectively. In the left image: (1) vacuum tank; (2) heat section board; (3) thermocouple; (4) cooling water duct; (5) ripple duct; (6) cylinder; (7) moving piston; (8) insulation piece; (9) sample copper; (10) thermocouple; (11) heat-leaking hole; (12) signal derivation interface. In the right image: (1) vacuum tank; (2) heat section board; (3) thermocouple; (4) fixed bolt; (5) observation window; (6) signal derivation interface; (7) cylinder.

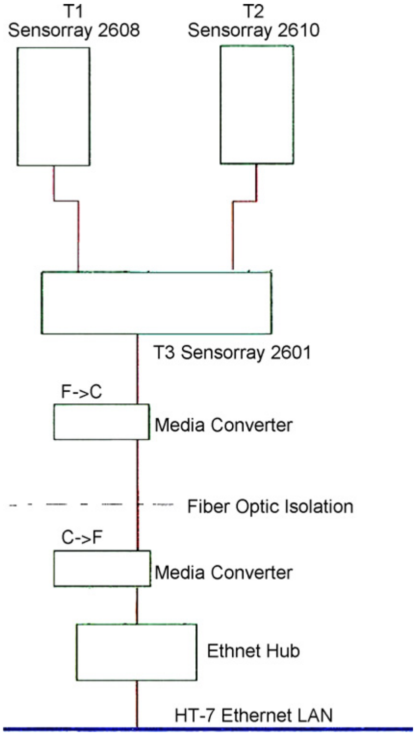

Fig. 3. Block diagram of target calorimeter measure system.

nal outputted from thermocouple is modulated and is transmitted by the Sensoray's model 2600 real-time industrial I/O network system. This star cluster system inherently solved the formidable problems of ground loops and platform obsolescence. Component costs were greatly reduced. Power monitors and multiple RS-232/RS-422 ports are built into the gateway module, so satellite modules were not needed for those functions. Built-in support for interlock circuits and power distribution minimized the need for external terminal blocks. The modules connected together easily with standard Category-5 patch cables. The module system connects to an Ethernet client by means of a low cost, 10BaseT/100BaseTX Ethernet interface. In addition to providing a platform-independent interface, the transformer-isolated Ethernet circuitry provides excellent noise immunity by eliminating client–server ground loops.

The processed signal is transmitted to the long-distance computer through the network optical fiber link in order to calculate the energy and distribution of the DNB beam. The transient voltage suppressor (TVS) is located upstream to the A/D switching circuit. When the instantaneous high-energy impact is put on the beginnings and ends of the TVS, it can make its impedance reduces with extremely high speed (highly achieve 10^{-12} s magnitude) and absorb big current at the same time. So the voltage between beginnings and ends of the TVS can be clamped in a preconcerted value to prevent unneutralized high power particle from damaging the digitizers.

An Ethernet I/O system (IOS) can be located far from the remote host computers. The IOS can actually be distributed so that its I/O interfaces reside at their optimal locations: close to the field wiring. Although not as fast as host-resident I/O, 100BaseTX Ethernet runs circles around RS-232, RS-422 and RS-485. Also, Ethernet's network (IP) and transport (TCP/UDP) protocol layers are widely used standards [6]; these layers are not standardized on other popular serial interfaces. Additional computers can be connected to an Ethernet in seconds with standard patch cables. This enables a second host – possibly serving as a diagnostics access point or as a backup host in a fault-tolerant system – to monitor and control the IOS. Perhaps most importantly, Ethernet offers protection from platform obsolescence. Ethernet is available for virtually every hardware platform in existence, and will continue to be available for the foreseeable future.

The maximum temperature rises on the probe plate were measured with and without bending magnet as a function of extracted current. This information can then be used to optimize the perveance, to optimize the beam neutralization, and to determine some parameters of the injected beam needed for diagnostic interpretation.

3. Experimental results and analysis

In the experiments of the DNB system, the probe measures in each un-injected beam shot. If the beam need inject to tokamak, the thermocouple probe will be raised out of the beam path, and the alignment probe will be moved to leave the beam path too. The thermocouple probe measurement data of one of the typical neutral beam shots with the energy 42 keV and the current of high voltage loop 4.5 A is shown in Fig. 4. The maximum temperature rise on the copper disks on probe plate is 5.7 °C, which corresponding power density of 2.8 MW/m^2. It is also known by Fig. 4 that

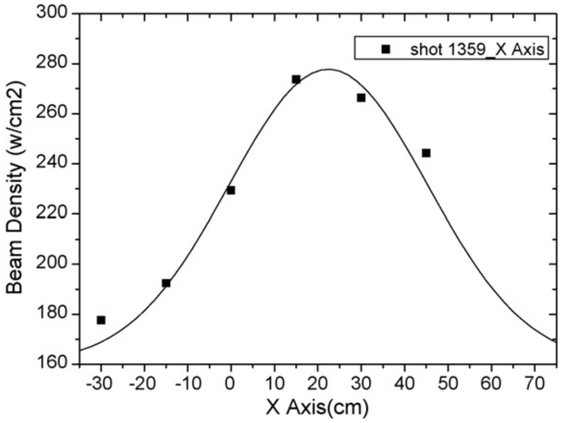

Fig. 4. Gaussian fit of the beam density rise on the copper disks at *X*-axis of the probe plate measured on target calorimeter when DNB is working at 42 keV/4.5 A, neutral beam.

the profile distribution of beam has a little dispersion to the right-up direction.

The neutralization efficiency of the DNB can be measured by these thermocouple probes. As shown in Fig. 5, the profile power distributions of two typical shots are measured by the alignment probe. The two shots are measured with and without bending magnet, respectively, and the working parameters of both of the two shots are 47.7 keV energy and 7 A the current of high voltage loop. Obviously, the beam has dispersion to the center. From the comparison of the power distributions of the two shots, the neutralization efficiency can be obtained roughly that is about 57%. Because the thermocouples only measure the power of many points on the plate, the power distribution of all the other points of the plate must be obtained by the fitting of the data. The fitting program of the two probes has many bugs now, and this work will be done in the next experiment of the DNB system.

The probe plate is a heat metering equipment based on inertial system. Regarding the heat flux behind the beam, the section board needs large area and mass to absorb the pulse energy. It connects with a cooling system at the same time. The thermo-diffusion process that the heat transmits from the volume of the board to the cooling medium needs a time delay, thus the total power of the injected beam can be obtained by the measurement of the temperature rise of the cooling water of the probe plate, and in the real measurement, because most of the energy of the beam is carried out by cooling water, this temperature rise can be measured from the difference of the temperature of the cooling water in the inlet and outlet of the cooling tube of the probe plate, and then the total power of the beam can be obtained by a time-cumulative calculus of the water cooling:

$$P = \int_{t_0}^{t_1} cv(T_{\mathrm{t}} - T_0)\,\mathrm{d}t \tag{2}$$

where P is the total power of the beam, c the thermal capacity of water, v the flux of water, t_0 and t_1 are the time of beam extraction and temperature of cooling water at outlet full back to the inlet temperature, respec-

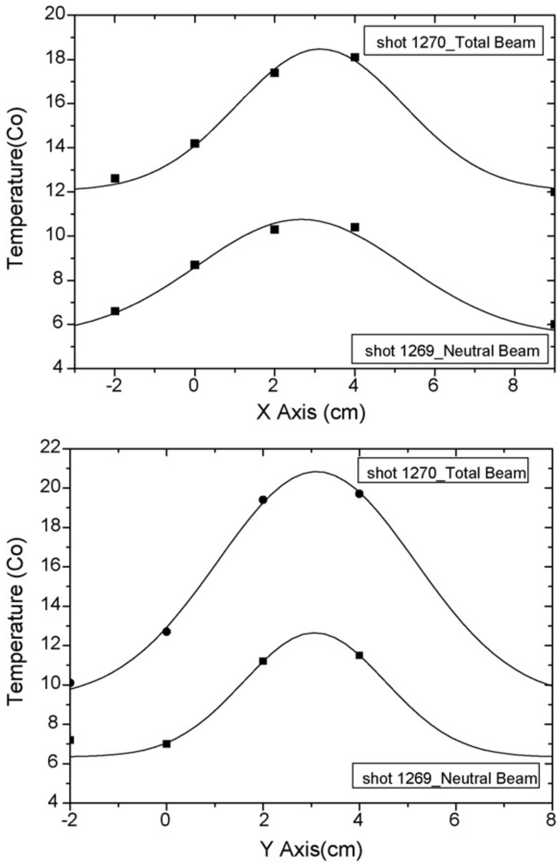

Fig. 5. Gaussian fit of the temperature rise on the copper disks of the probe plate measured on target calorimeter, where the above and the below are corresponding to the case without and with bending magnet and experimented at 47.7 keV/7 A, respectively, and left and right are corresponding to the measurements of the copper disks at *X*- and *Y*-axis, respectively.

tively, and T_t and T_0 are the temperature of cooling water at outlet and inlet.

Such cooling-water temperature power measurement system has been installed at the DNB system but not consummate. In the next experiment, this measurement system can be used, and the data of the total power of the beam obtained by thermocouples will be compared with the data obtained this system.

4. Summary

The total power that DNB needs is basically equal to the power that the acceleration electrode supplies [7]. The power distribution of entire beam may broadly divide into three parts: the power that various electrodes of the ion source consume, deflection ion power that ion dumps absorb, and the injected power that enters to the HT-7 tokamak plasma. Looked from the experimental result that it needs massive experimental data to carry on the value computation and theoretical analysis [8]. The importance, that enlarging the gas target in the neutralization chamber and obtaining best target's thickness to enhance the neutralization efficiency, and that the arc ionization in the ion source needs large atom and ion share, is fully proved.

However, the heat that disappears through heat radiation on the probe plate and the heat that transmits by the periphery strut beside the probe plate are not considered. Therefore, by using this method, the calculated total power of the injected beam on the probe plate will be relatively smaller. When carrying on experimental analysis, the water cooling-water temperature power measurement system will be consummated, and the calculated values obtained by the two power measurement systems could be synthesized to be the actual total power value of the injected beam on the probe plate. In further experimental study, the measured data of the charge-exchange recombination spectroscopy (CXRS) diagnosis can be used to precisely verify the beam power and the accuracy of the beam profile distribution.

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