J Fusion Energ (2013) 32:547–551
DOI 10.1007/s10894-013-9613-1

ORIGINAL RESEARCH

# Water Flow Calorimetry System of EAST Neutral Beam Injector

**Ling Yu · Chundong Hu · Sheng Liu · Yongjian Xu**

**Abstract** Neutral beam injection (NBI) is recognized as one of the most effective means of plasma heating. The EAST NBI water flow calorimetry system (WFCS) based on PCI extensions for instrumentation (PXI) was established, it can measure temperature rise and flow rate of cooling water of the heat load components, and achieve beam power distribution and neutralization efficiency. Experimental data obtained from WFCS are feedback of the ion source operation state and direct the operation parameter optimization of the ion source. Experimental results show that the WFCS is stable, reliable, and meet the experimental requirements fully.

**Keywords** Neutral beam · Temperature rise · Calorimetry · Neutralization efficiency

## Introduction

Achievement of the ignition of fusion plasmas is one of the important subjects of plasma heating. It is well known widely that NBI is the most effective method for effective plasma heating and has been also verified to be applicable for current drive. Neutral beam injection (NBI) has been recognized as one of the most effective means for plasma heating by the international fusion community and experiments have shown that NBI can achieve not only to heat plasma but also to drive current effectively [1–3]. As the first full superconducting non-circular cross section Tokomak in the world, EAST's scientific goal is to explore the forefront physics and engineering issues on the construction of Tokomak fusion reactor. The target values of NBI are beam energy 50–80 keV, injection beam total power 2–4 MW, beam pulse width 10–100 s [4, 5]. The beam power will deposit on the beam collimator due to the beam divergence and it will cause heat damage to heat-load components, or even destroy the entire NBI system. In order to decrease the risk and measure the distribution of beam power deposition, a WFCS based on the PXI technology is established on EAST NBI [6–8]. This paper represents the structure and measurement results of WFCS.

## Structure and Composition

Main components of the NBI system are two high-current ion sources, beam diagnosis system, vacuum system, gas supply system, cooling water system and so on as shown in Fig. 1. The accelerator of EAST-NBI consists of four grids electrostatic exaction accelerated systems, which are a plasma grid (PG), a gradient grid (GG), a suppressor grid (SG), and an exit grid (EG).

The main function of the WFCS: (1) monitor the operation state of flow switches and pressure switches of cooling water which flow in the heat-loading component, (2) measure the cooling water temperature rise of the accelerating grids, (3) calculate the neutralization efficiency and distribution of beam power deposited on the heat-loading components of beam line.

Water flow calorimetry system has great significance for the operation of EAST-NBI. It can not only provide the distribution parameter of beam power deposition, but also provide a security guarantee for the operation of EAST-NBI.

The WFCS consists of the differential temperature transducer (DTT), flow meters, flow switches, pressure switches,

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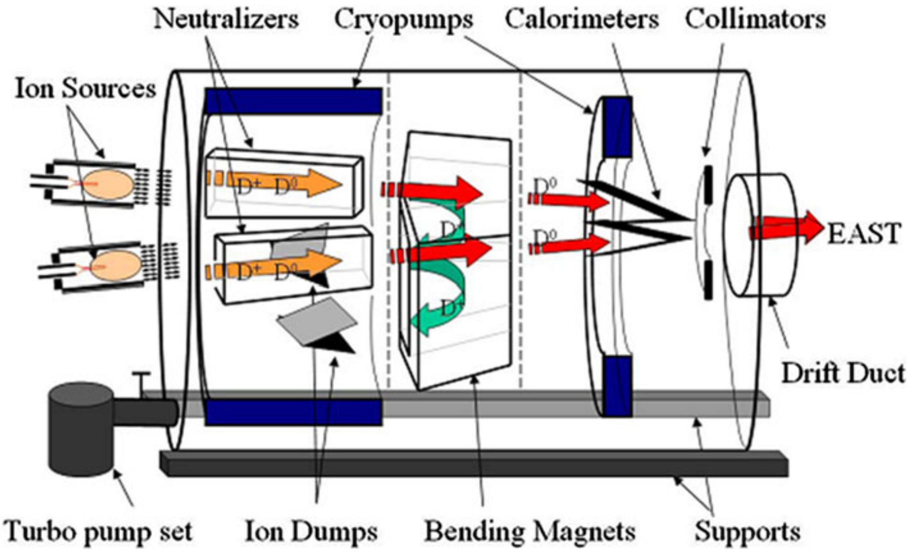

**Fig. 1** Schematic view of EAST-NBI

PXI series capture card and other components. Figure 2 is the WFCS hardware architecture.

Advantage of PXI technology: (1) high scalability, performance and compatibility, it can work with both PXI and compact PCI modules, (2) the entire graphical system design platform with intuitional, convenient and easy to maintain, (3) fast and flexible data storage options.

DTT of WFCS is provided by delta-t Company. The DTT has been used to measure the cooling water temperature rise of heat-loading component. The response time of DTT is less than 0.25 s, the accuracy is ±0.04 °C, the sensitivity of DTT is 0.401 mV per degree Celsius differential in normal.

The equipments of WFCS are provided by the ADlink Technology and National Instruments (NI). It include the eight-slot chassis PXIS2630, CPU PXI3950, 64 channel acquisition card DAQ2206 with acquisition rate 250 kHz, 16 channel acquisition card PXI6251 with sampling rate 1.25 MHz, 64 channel DIO acquisition card 7433 and 7434 with sampling rate 10 kHz, 32 channel thermocouple connector configuration available of TC2095, TC2095 includes cold-junction compensation circuitry, 32 channel thermocouple amplifier SCXI1102, SCXI1349 is used adapter to connect SCXI systems to PXI acquisition devices, and mounting bracket for secure connection to the SCXI chassis.

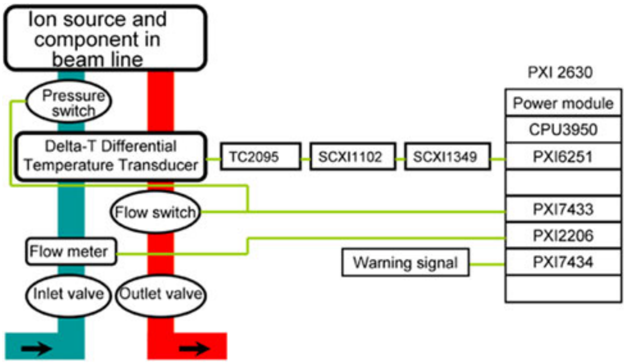

**Fig. 2** The WFCS hardware architecture

32 channel thermocouple/voltage input module SCXI-1102 maximum sampling rate of up to 333 kS/s, over voltage protection to ±42 V, the sampling rate is adjustable from 10 Hz to 10 kHz. During experiment operation, DDT will record the cooling water temperature rise of the accelerating grids and head-loading components of beam line and the data will be transmitted, saved and analyzed. The cooling water tubes of total NBIS are listed in Table 1.

Water flow calorimetry system program was written using the LabView software of NI company. The function of program are lists below: (1) plotting the curves of the cooling water temperature rise of each heat-loading component in real time, (2) calculating the distribution of power deposited on accelerating electrodes and heat-loading

**Table 1** The cooling water tube of NBIS

| | |
|---|---|
| Ion sources | Arc chamber |
| | PG |
| | GG |
| | SG |
| | EG |
| Beam line | Source collimator |
| | Baffle collimator |
| | Neutralizer |
| | Ion return collimator |
| | Ion dump |
| | Magnet collimators |
| | Magnet pole shields |
| | Calorimeter |

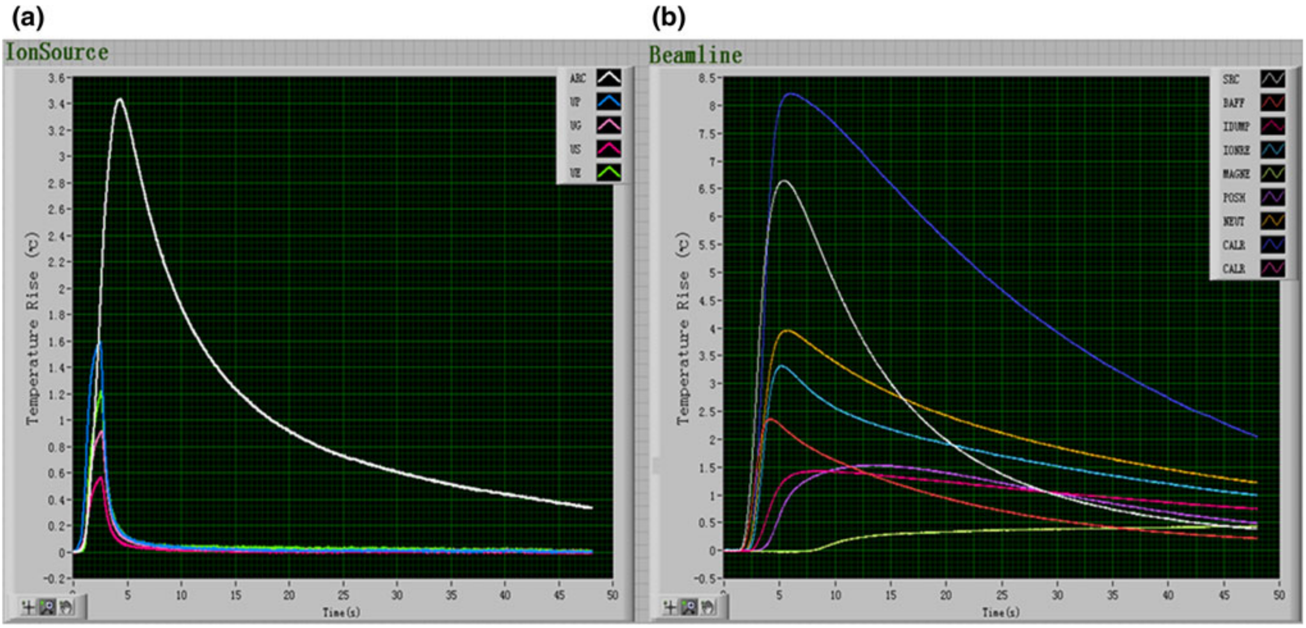

**Fig. 3** The WFCS acquisition interface (**a** ion source, **b** beam line)

components of beam line, (3) calculating the neutralization efficiency, (4) monitoring the flow rate and the press status of cooling water, (5) providing data query of experimental results.

The interface of WFCS is shown in Fig. 3. Figure 3 (left) is the curve of cooling water temperature rise of the accelerating electrodes, and Fig. 3 (right) is the curve of the cooling water temperature rise of heat-loading components of beam line. The neutralization efficiency and power deposited on the each accelerating electrode and heat-loading components can be calculated according to the data (flow rate and temperature rise) obtained by WFCS.

The pressure and flow state of the cooling water were obtained by the pressure switch and the flow switch mounted in the cooling water pipe. In order to meet the requirement of the beam extraction operation, the water pressure can be adjusted respectively. According to the flow rate and the temperature rise obtained by flow meter and DTT, the power deposition of each heat-loading component can be calculated.

$$P = c_p m' \int_0^\infty T(t)dt \tag{1}$$

here, $c_p$ is the specific heat of water, $m'$ is the cooling water mass flow rate of heat-loading component, T(t) is temperature rise of cooling water.

Considering the acquisition time $t_f$ in each shot, the Eq. 1 can be written

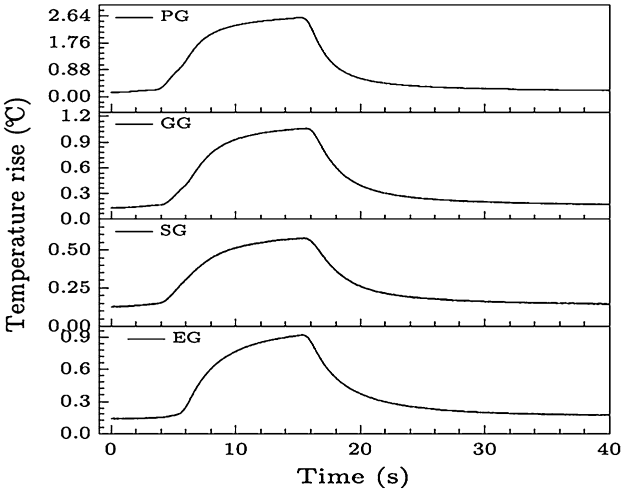

**Fig. 4** The cooling water temperature rise of each accelerating electrode (52 kV, 22 A, 10 s)

**Table 2** The value and the percentage of the power deposited on the accelerating electrodes (52 kV, 22 A, 10 s)

| Accelerating | PG | GG | SG | EG |
|---|---|---|---|---|
| P(W) | 8,908 | 4,327 | 3,049 | 4,016 |
| Percentage | 0.78 | 0.38 | 0.26 | 0.35 |

$$P = c_p \int_0^{t_f} m'T(t)dt + c_p \int_{t_f}^{\infty} m'T(t)dt \tag{2}$$

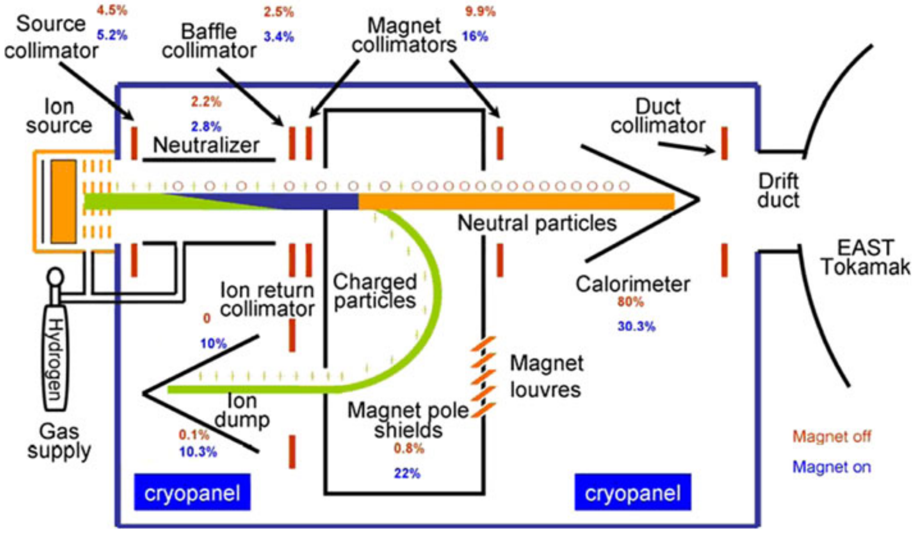

**Fig. 5** Beam power deposition distribution on the heat load components (*Orange* magnet off, *Blue* magnet on, Vacc = 80 kV) (Color figure online)

Due to the limit of acquisition time, acquisition time $t_f$ is less than 5 min in general. The cooling water temperature can not return to the initial temperature (see Fig. 3). The curve of temperature drop with an exponential decay can be observed in the Fig. 3, so the Eq. 2 can be written

$$P = c_p \int_{0}^{t_f} m' T(t) dt + c_p \int_{t_f}^{\infty} m' a \exp(-bt) dt \tag{3}$$

Here, a, b is the coefficient of exponential function and a, b can be obtained by data fitting.

## Results and Discussions

According to different requirements of the cooling water quality for ion source and the beam line components, the WFCS is divided into two independent water supply systems, the ion source and the beam line, respectively.

The temperature of the accelerating electrodes cooling water will rise during beam extraction, WFCS can take away the heat deposited on the accelerating electrode actively. Figure 4 shows the cooling water temperature rise curve of acceleration electrode (52 kV, 22 A, 10 s). We can find that all electrodes almost reach thermal equilibrium state. In this state (52 kV, 22 A), the energy taken away by the cooling water at each electrode is equal to the energy deposited on the electrodes. It shows that the current accelerating electrodes can meet the requirements of long pulse beam extraction.

Take one shot (52 kV, 22 A, 10 s), for example, according to the curve of the temperature rise (see Fig. 4), combined with flow rate of cooling water in the electrodes and pulse width, we can obtain the value and the percentage of the power deposited on the accelerating electrodes (see Table 2).

The heat-loading components of NBI beam line include the collimators, ion dump, pole shield and calorimeter. The heat deposited on the heat-loading components can be taken away by WFCS during beam extraction.

According to the curve of the temperature rise, combined with flow rate of cooling water in the heat-load components and pulse length, we can obtain the value and the percentage of the power deposited on them. Figure 5 shows beam power deposition distribution on the heat load components. In addition, the neutralization efficiency can be calculated based the data on Fig. 5.

## Conclusion

Water flow calorimetry system has high compatibility, flexible expansibility and anti-electromagnetic interference. Experimental results show that the WFCS is stable, reliable, and meet the experimental requirements fully.

**Acknowledgments** This work has been supported by the National Natural Science Foundation of China (Grant No. 11075183).

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