



Development of hard X-ray spectrometer with high time resolution on the J-TEXT tokamak



T.K. Ma, Z.Y. Chen*, D.W. Huang, R.H. Tong, W. Yan, S.Y. Wang, A.J. Dai, X.L. Wang, J-TEXT Team

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China

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ABSTRACT

A hard X-ray (HXR) spectrometer has been developed to study the runaway electrons during the sawtooth activities and during the runaway current plateau phase on the J-TEXT tokamak. The spectrometer system contains four NaI scintillator detectors and a multi-channel analyzer (MCA) with 0.5 ms time resolution. The dedicated peak detection circuit embedded in the MCA provides a pulse height analysis at count rate up to 1.2 million counts per second (Mcps), which is the key to reach the high time resolution. The accuracy and reliability of the system have been verified by comparing with the hardware integrator of HXR flux. The temporal evolution of HXR flux in different energy ranges can be obtained with high time resolution by this dedicated HXR spectrometer. The response of runaway electron transport with different energy during the sawtooth activities can be studied. The energy evolution of runaway electrons during the plateau phase of runaway current can be obtained.

1. Introduction

Disruption is a severe event during tokamak operation, which leads to the rapid loss of the plasma thermal and magnetic energy [1,2]. This instability causes the plasma current quench (CQ) in the time scale of ten milliseconds. Various damages can be caused including heat loading to the plasma facing components (PFCs) during thermal quench (TQ), $J \times B$ forces from poloidal halo current during CQ phase and the conversion of plasma current into energetic runaway electrons (REs) that are eventually stopped by the PFCs [3,4]. These REs can easily gain energy with about 10–100 MeV range from the magnetic energy, which could reduce the lifetimes of PFCs significantly and cause a severe damage in future reactor [5,6]. The conversion of up to more than half of the pre-disruption plasma current into runaway current has been observed in several tokamaks [7]. The formation of REs is a serious concern because of the large RE amplification (knock-on avalanche), which could result in ~10 MA runaway current in ITER [7–11]. Due to the small strike area and peak energy deposition, the runaway electron beam could melt or ablate the wall materials [8]. Thus, the study of the generation, evolution, confinement and suppression of REs is the key requirement for the integrity of ITER [7,8].

For the study of REs, several methods can be used such as the measurement of hard X-ray (HXR) radiation resulted from thick target

bremsstrahlung when REs are lost to the chamber wall and thin target bremsstrahlung when REs interact with impurity ions in plasmas [12], the measurement of photoneutron generated by the photonuclear reaction [13,14] and the measurement of synchrotron radiation originated from the energetic REs [15]. Both the photoneutron and the synchrotron radiation measure the energetic REs. The spectrometer of HXR is a powerful tool to study the detailed energy evolution of REs from the order of 100 keV to tens MeV [7,16,17]. Multi-channel analyzer (MCA) is one of the important and conventional tools to process signals from detectors of X-ray, γ -ray and neutrons [18], which can be used to study time evolution and interaction of high-energy particles with plasmas. In this paper, a HXR spectrometer with high count rate (1.2 Mcps) which enables high time resolution up to 0.5 ms has been developed on the J-TEXT tokamak. The key unit of the HXR spectrometer is a dedicated MCA which can be operated with high time resolution. The real-time data processing and transmission algorithm is applied for the system to realize both on-line and off-line analysis of spectra, this provides the possibility for the real-time monitor of REs on J-TEXT tokamak [19]. In the last decades, great efforts have been addressed in the development of instruments for X-ray and γ -ray spectroscopy [20]. The requirements for higher energy and time resolution, faster throughput rate and lower cost have pushed the development in signal process, control logic, software algorithm and

* Corresponding author.

E-mail address: zychen@hust.edu.cn (Z.Y. Chen).

data acquisition system for MCA [21].

The layout of this paper is as follows: the design and construction of the HXR spectrometer are described in Section 2. The performance and experimental results on the J-TEXT tokamak are given in Section 3. Section 4 is the summary.

2. Design of the hard X-Ray spectrometer

2.1. Experimental set-up

J-TEXT is a conventional tokamak with an iron core [22]. It has a major radius of $R=105$ cm. The minor radius can be modified in the range of 25–29 cm by a movable graphite limiter. The maximum toroidal magnetic field is $B_t=2.3$ T at present. The maximum plasma current is $I_p=220$ kA with 600 ms pulse length. The line averaged electron density is in the range of $n_e=(0.5-6) \times 10^{19} \text{ m}^{-3}$.

Considering the energy range and the detection efficiency, four NaI scintillator detectors have been used to measure the HXR radiation in energy range of 0.5–10 MeV resulted from the thick target bremsstrahlung when REs are lost from the plasmas and impinge on the vessel walls [12,16,23]. All of the detectors are installed on the stainless steel stand at the mid-plane of the device. Three NaI detectors are arranged at port 6 and another one is located at port 14 faced to the limiter, as shown in Fig. 1. The detector D1 (crystal $\Phi 40 \times 40$ mm) is faced to the electron approach direction with the lead collimation. The collimator is 600 mm in length with $\Phi 30$ mm aperture. The detector D2 (crystal $\Phi 75 \times 75$ mm) is faced to the electron radial direction. The aperture of lead collimator is $\Phi 30$ mm and the length is 1000 mm. The detector D3 (crystal $\Phi 75 \times 75$ mm) is faced to the backward electron direction. The aperture of lead collimator is $\Phi 30$ mm and the length is 800 mm. All detectors mainly measure the radiation of REs interacting with the first wall at port 6. The detector D4 (crystal $\Phi 40 \times 40$ mm) is directed to the limiter. The collimator is 600 mm in length with $\Phi 30$ mm aperture. Additional lead shielding is used for detectors D3 and D4 to decrease the HXR flux and scattered radiation, these two detectors are mainly used for the study of REs' behavior during the runaway current plateau phase. The electrode biasing system (EBS) was installed at port 8 to study the improvement of confinement. The Nuclear Instrument Module (NIM) standard amplifiers with baseline restorer are used for amplifying the signals from the detectors. Then an eight-channel MCA with digital pile-up rejection module is coupled to the amplifiers to collect pulse signals for energy spectrum analysis.

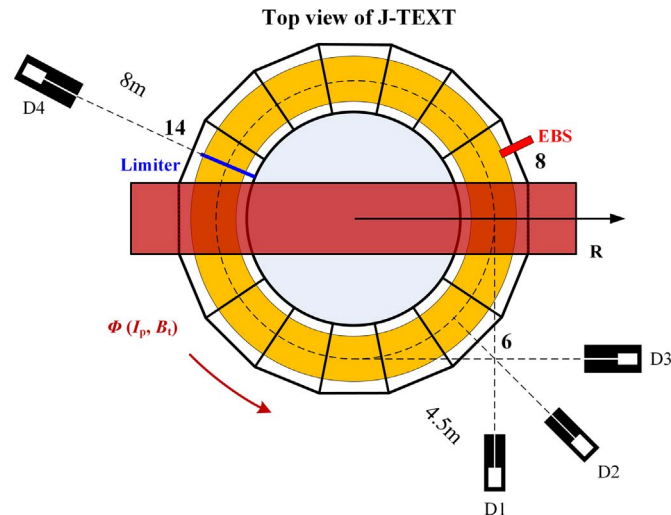


Fig. 1. Layout of the hard X-ray spectrometer on J-TEXT. The distances from the detectors D1, D2 and D3 to the chamber wall are 4.5 m, and the distance from the detector D4 to the limiter is 8 m. The direction of plasma current is shown by the red arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Experimenters can directly control the MCA by Ethernet and graphic user interface without complex and extra equipment in the remote control room.

2.2. Design of multi-channel analyzer

The multi-channel analyzer on J-TEXT is designed for the study of REs during the sawtooth activities and during the runaway current plateau phase. The equipment contains eight input channels, every channel is associated with an independent module based on embedded system controlled by digital signal processor (DSP). All channels can work up to time resolution of 0.5 ms with 2048 ADC gain at the same time for real-time operation. The MCA system mainly consists of three parts: analog circuit module, digital signal processing module and control software on PC. Fig. 2 shows the structure chart of the multi-channel analyzer. The working principle of the MCA is as follows: The signal from the X-ray detector is processed by the built-in pre-amplifier firstly, then output signal from pre-amplifier is amplified by an amplifier with baseline restorer. The output of the amplifier is coupled to a novel pulse peak detection circuit based on phase compensation. The peak detection circuit generates peak signal to launch A/D conversion and transmits pulse losslessly to ADC. The DSP reads the data from the first in first out (FIFO) register intermittently and transmits the data to PC by the network cable.

The analog circuit module of the system mainly contains the input buffer and dedicated peak detection circuit. The circuit is specially designed for high frequency pulse, which keeps the high accuracy in a wide input range of amplitude and frequency. In the signal processing module, a 4 K bit FIFO is used, which frees up the resource of micro controller unit (MCU) and makes it possible to achieve complicated calculation and higher time resolution. The bottom hardware of every channel is associated with a four layer printed circuit board in order to compact the wiring space and provide an entire power plane for inhibition of electromagnetic interference. The components of the boards are all surface mount devices to reduce the parasitic parameter. The bottom hardware of the system communicates with upper-layer applications by the 100 Mbit/s fast Ethernet using TCP/IP protocol which can provide stable and long-distance connection. The graphical user interface of the system is developed by C# language. Control parameters such as acquisition time, ADC gain and time resolution can be easily changed for every channel on the interface. The interface benefits many advantages such as high compatibility on Windows platform, easier maintainability and faster development cycles from .NET Framework. Some particular optimization is implemented in the program of MCU in order to achieve higher time resolution for the HXR spectrometer. Several changes are made in boot and initialization code trying to avoid useless operation. Another optimization is that the MCU doesn't need to process data for complex TCP/IP protocol because the embedded single chip can sort the origin data to standard TCP/IP format. Furthermore, the specific data transmission algorithm (zero exclusion) is used in Ethernet data package to lighten the network load for the real-time processing on the designing of MCA.

3. Experimental results

Because of the limit of maximum operating counting rate for detectors, the sine wave from signal generator has been used to test the system's accuracy and ideal max output rate without pile-up effect. Fig. 3 shows the measured output rate with the input count rate in the time resolution of 0.5 ms. Actually, the accuracy of the system is not relative to the time resolution, and the output throughput will increase with the decrease of time resolution because of the internal algorithm of data processing. We chose a fixed circuit parameter to fit the quasi-Gaussian input pulse with the shaping time of 0.4 μs , it was found the accuracy of the system is decreasing with the increase of input count rate. Fig. 4 is the result of calibration for the HXR spectrometer using

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