1.20 Development of software PHA for measurements of 
soft-X-ray spectral distribution in HL-2A tokamak

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The conventional Pulse Height Analyzer (PHA) or so-called Multi-Channel Analyzer (MCA) had been used to measure the soft or hard X-rays energy spectra radiated by tokamak plasma for tens years. Though conventional MCA has been improved continuously along with the advancement of electronics and computer, but the complicated electronic circuits and the expensive cost remain unchangeable. Especially the dividing time PHA that is normally used to measure the time evolution of soft and hard X-rays energy spectra radiated by the tokamak (or other fusion devices) discharge for measuring every short time interval (example during 10 ms, 50 ms, or 100 ms) is inconvenient for data processing and exchange. For example, one must set up the operation parameters such as integral time for counting, channel numbers for every spectrum, noise level and so on, before the starting measurement using conventional dividing time PHA.

The traditional PHA relies on special analog to digital converter (ADC), electronic circuits and system software to obtain the energy spectrum. It is well known that there are three types of special ADC for conventional PHA; they are Wilkinson, successive-approximation, and flash ADCs. The advantage of Wilkinson ADC is low differential non-linearity (typically ≈ 0.5%) and uniformity channel widths, and the disadvantage is long conversion times (from 20 to 165 μs for 8192 channels), which is dependent on the amplitude of input signal pulse. The conversion times of successive approximation ADC are independent of pulse amplitude of input signal, but they are larger than 0.875 to 20 μs. The conversion times of flash ADC are in the nanosecond range, the disadvantage is larger differential non-linearity (non-uniformity channel widths), herewith, thereby, flash ADC is not applicable for high-resolution pulse height spectroscopy.

The SPHA described in this paper is neither similar to the traditional PHA, nor to be the same with DSP MCA. It relies upon universal waveform ADC and software to analyze the pulse height and to obtain the energy spectrum. A commercial ADLINK PCI-9820 is used as analog-to-digital converter in the SPHA, this device uses a pair of 65 MS (Mega Samples)/s, 14-bit pipeline ADCs to digitize input signals with high accuracy (0.61 mV). It provides an internal 60 MHz time base for data acquisition. It is ideal for high-speed waveform capturing and supports SDRAM (Synchronous Dynamic Random Access Memory) memory ranging from 64 MB to 512 MB. The digitized data is stored on-board SDRAM before being transferred to host memory. Though the ADC digitize the signals that come from spectrum amplifier at the end of the signal processing chain, but the full process of pulse height analyses and the formation of energy spectra are thoroughly completed by software. Because of this SPHA operates in off-line status, therefore there are no the dead time and the signal loss.

The characteristics of SPHA has been tested by using a scanning pulse generator, the results show that the integral non-linearity ≤ 0.5% and differential non-linearity are very low (typically ≈1%) for analyzing 0 – 5 V pulse height, and there are uniformity channel widths if the sampling frequency of ADC is 60 MHz. Even if the sampling frequency of ADC is 30 MHz, for small pulse signals (pulse height ≤ 3 V), the integral non-linearity ≤1%, and differential non-linearity is less than 2% respectively. The software and conventional MCA have been calibrated using a group of radiation reference sources for measurement of thermal and superthermal electron temperature. The typical energy spectra of reference radiation sources Cu kα,β measured by using SPHA and conventional PHA respectively, and their channel numbers are the same as 256, because it is enough for the measurements of thermal and superthermal electron temperature. The energy resolutions are 139 eV (for SPHA) and 142 eV (for conventional PHA) respectively for Cu kα (8.04 keV), if the sampling frequency is 30 MHz. The calibrations of energies versus channel numbers for SPHA and traditional PHA are shown in Fig. 1, respectively. This figure shows that the linearity of energies versus channels is very well for SPHA, and it is the similar to the conventional PHA.

Time evolution of soft x-ray spectra is measured by SDD system, the thermal and superthermal electron temperatures are derived from the energy spectra. Because the ratio of peak counts to background counts is very high in the energy spectrum for a mono-energy source such as Mn kα (5.894 keV), the p/b ≥ 400 – 3000, these spectra can also be regarded as the electron velocity distributions roughly. We see that the core of

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plasma ($z = 0$) is heated by ECW, the configuration of electron velocity distribution changes obviously during ECRH comparing with the Ohmic heating phase. The increase of superthermal electron can be found in velocity distribution; and the intensity of soft X-ray radiation is enhanced an order of magnitude during ECRH. Above mentioned phenomena are stronger at $z = 0$ than that at $z = -16.4$ cm chord. These experiment results demonstrate that the energy of ECW is deposited in the core of plasma by on axis ECRH ($B_z \approx 2.41$ T), in this case, the electron velocity distribution is changed by ECRH. On the other hand, sometimes the heating effect is more pronounced at $z = -16.4$ cm, than that at $z = 0$. This difference may come from the different electron density in the Ohmic heating phase before ECRH, and can be explained by the avalanche phenomenon of superthermal electron and the accessibility of ECW for different electron densities. This mechanism is roughly same as runaway avalanche, which assumes that some trace amount of superthermal electrons with higher energy exist in the plasma, these electrons can knock out the thermal electrons from the plasma through a close or a large angle Coulomb collision with background thermal electrons.

As mentioned above, it is obvious that the software MCA has more advantages that the conventional MCA, especially the time interval SPHA that is used to measure the time evolution of soft or hard X-rays energy spectra radiated by tokamak (or other fusion devices) plasma is very convenient and easy for data processing, transferring, communication and exchange. The characteristics of SPHA such as the differential and integral non-linearity, the uniformity of channel width, the energy resolution and the counts per channel are better than the conventional PHA, or at the least to be same as the latter.

There are a few of signals loss between this spectrum and next one for traditional dividing time MCA, but in this scenario no signal loss for SPHA. The other important characteristics of SPHA include that there is no dead time in the operation, the better time resolution, the stronger ability for pile-up rejection, the simpler electronic circuits, and the cheaper cost than the traditional dividing time MCA and the DSP-MCA. The software MCA are also limited by ADC, it is necessary to improve the sampling frequency and accuracy for obtaining the high resolution (high channel numbers such as 8192 - 16384 channels), the SDRAM needs a huge memory space. Therefore, the software MCA is suitable for 256 to 1024 channels resolution.