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Improving measurement accuracy by optimum data acquisition for Nd:YAG Thomson scattering system[a)]

T. Minami,[1,b)] Y. Itoh,[2] I. Yamada,[2] R. Yasuhara,[2] H. Funaba,[2] H. Nakanishi,[2] and T. Hatae[3]
[1]*Institute of Advanced Energy, Kyoto University, Gokasho,Uji, Kyoto 611-011, Japan*
[2]*National Institute for Fusion Science, Oroshi, Toki-shi, Gifu 509-5292, Japan*
[3]*Japan Atomic Energy Agency, 311-0193, Mukoyama, Naka, Ibaraki 801-1, Japan*

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A new high speed Nd:YAG Thomson scattering AD Convertor (HYADC) that can directly convert the detected scattered light signal into a digital signal is under development. The HYADC is expected to improve a signal to noise ratio of the Nd:YAG Thomson scattering measurement. The data storage of the HYADC which is required for the direct conversion of whole plasma discharge is drastically reduced by a ring buffer memory and a stop trigger system. Data transfer of the HYADC is performed by the SiTCP. The HYADC is easily expandable to a multi-channel system by the distributed data processing, and is very compact and easy to implement as a built-in system of the polychromators. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4891416]

I. INTRODUCTION

Because of the high repetition rate applied by Nd:YAG laser, Nd:YAG Thomson scattering (YTS) method is advantageous for time evolution measurement of plasma profiles.[1,2] However, the YTS system requires a high speed data processing, because a short laser pulse width (∼10 ns) is required to improve the signal-to-noise ratio (SNR). Till date, a charge to digital convertor (CDC), which integrates the detected signal and converts it to digital data, was commonly used as the data acquisition system of the YTS measurement. However, a CDC is not necessarily optimal for the YTS, as it is not easily expandable to a multi-channel system. Moreover, implementing the CDC in a polychromator of the YTS is difficult because it is not a compact system and the functions of the commercial CDC are not suitable for the YTS. Therefore, we are developing a new ADC dedicated to the YTS method, called high speed YAG Thomson scattering ADC (HYADC).

The HYADC is being designed to directly convert the scattered light signal into the digital data. The direct conversion has three advantages: (1) An increased amount of sampled data compared to the CDC improves the SNR. (2) A precise background light reduction can be performed using the digitized data detected just before the laser injection. (3) The HYADC can analyze the short pulse interval laser injection of the multi-pulse Nd:YAG Thomson scattering measurement. Even when the signal is overlapped, the HYADC can separate both signals.

Previous direct AD converters adopt a time-interleaving technique,[3] making it a complicated structure and expensive.[2] Moreover, because the time-interleaving technique requires several AD converter chips, accuracy of the conversion is degraded because of the dispersed characteristics of chips. Recently, a high speed pipe-line type AD converter with 12 bits resolution and a 500 MHz sample rate (ADS5463, Texas Instruments Inc.)[4] was introduced into the market. We designed the HYADC on the basis of this chip. As the scattered signal is converted by a single chip, the HYADC is a simple and compact structure; additionally, it has the improved conversion accuracy and is affordable compared to the previous direct converters.

In this paper, we discuss an improvement in the SNR by the HYADC, and describe the HYADC structure. This paper also describes the reduction in the data volume produced by the HYADC for long plasma discharge and data transfer by SiTCP.[5]

II. ESTIMATION OF IMPROVED SNR BY THE HYADC USING A SIGNAL PROCESSING MODEL

Improvement of the SNR is estimated by a signal processing model, which is developed by the DIII-D tokamak.[6] The model simulates the relation between the gate width of a CDC integrator in the YTS data processing system and the noise caused by the presence of the background light. The model estimates the SNR for the pulsed light detected by an avalanche photo diode (APD) as follows:

$$\frac{S}{\sigma_s} = \sqrt{\frac{Qp}{F\left[\left\{\frac{2(t_G-D)}{D^2} - e^{-t_S}\right\} R_{Q_b} + 1\right] + \left(\frac{\delta S_0}{S}\right)^2 Q_p}}, \quad (1)$$

$$t_G = \frac{\tau_G}{\tau_F}, \quad t_S = \frac{\tau_S}{\tau_F}, \quad D = 1 - e^{-t_G}, \quad (2)$$

where τ_F is the decay time of the APD, which is determined by the resistance of the current to voltage conversion for the APD and the stray capacitance of the APD and the amplifier circuit. τ_G is the gate width of the integrator, τ_S is the time separation of the two gates. Q_p is the photoelectrons count which is produced by the laser pulse, F is the excessive noise factor of the multiplication of the APD. R_{Q_b} is the ratio of

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[b)]Author to whom correspondence should be addressed. Electronic mail: minami@iae.kyoto-u.ac.jp

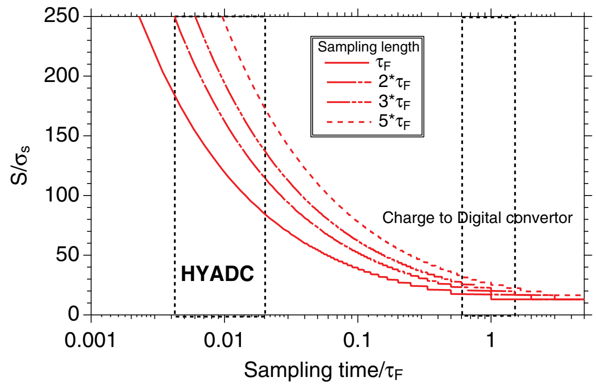

FIG. 1. SNR estimation as a function of sampling time, normalized by τ_F for HYADC and CDC. The estimation was performed for different sampling lengths.

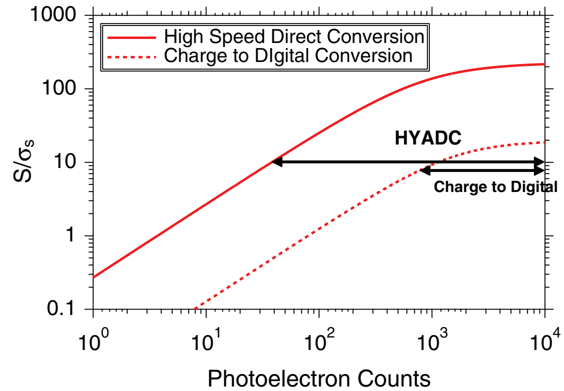

FIG. 2. SNR as a function of the photoelectron counts, which is detected by the APD.

the background signal to scattered light signal, and $\delta S_0/S$ is the background noise normalized by the signal. This model shows that the short gate width compared to the APD decay time improves the SNR.

The improvement of the SNR is estimated by the following equation:

$$\left(\frac{\sigma_S}{S}\right)^2 = \frac{1}{N^2}\sum_i\left[\left(\frac{\sigma_{S_i}}{S_i}\right)^2 + \left(\frac{\delta t}{\tau_F}\right)^2\right], \qquad (3)$$

where N is the sampling number, $\frac{\sigma_{S_i}}{S_i}$ is the SNR of the single sample, and $\frac{\delta t}{\tau_F}$ is jitter of the integration time (2% is assumed). The result is shown in Figure 1.

The short sampling time reduced the measurement error, including quantization error of the digital conversion, in small signal, which improved the measurement accuracy. Notably, estimation was carried out for different sampling lengths, referring to the time between the start and end of sampling. The normalized sampling time of the HYADC is designed to be $0.005-0.02s$, while that of the CDC is typically $0.5-1.5s$. Accordingly, because of the reduction of the sampling time, the SNR of the HYADC was several orders of magnitude larger than that of the CDC. The long sampling length increases the SNR of the HYADC, while the increase for CDC is small. The SNR as a function of the photoelectron count detected by the APD is estimated in Figure 2.

Assuming that the minimum detectable SNR of the scattered light is ten, the detectable photoelectron count is reduced ten-folds compared to the CDC. Therefore, the measurable plasma density, which is proportional to the scattered light, is expected to be ten times lower than that of the CDC.

III. REDUCTION OF DATA VOLUME FOR LONG PLASMA DISCHARGE

A high sampling rate ADC increases the data volume recorded in the memory, thus increasing the storage cost for a long plasma discharge. To resolve the storage problem, the limited scattered light signal from immediately prior to just after the pulsed signal was recorded by a hardware procedure because the pulse width of the scattered light signal is very short (∼200ns) compared to the plasma discharge time. The hardware procedure records solely the signal corresponding to the period of scattered light produced, with the data in which the scattered light is not produced deleted.

The structure of the HYADC is shown in Figure 3. The data conversion procedure of the HYADC were designed as follows. (1) Writing of the digitized scattered light signal data to the ring buffer memory begins with the start trigger of the plasma discharge. (2) The ring buffer memory, with enough capacity to record the data corresponding to 4 μs (2000 samples), is prepared. This capacity is enough to record all scattered light waveforms produced by one laser pulse or multiple laser pulses. (3) The ring buffer memory records the new AD converted data by overwriting the old data. (4) When the HYADC receives the trigger of a laser injection, recording of the ring buffer memory is stopped. Time points determining the beginning and ending of the scattered light signal are calculated. (5) The recorded data in the ring buffer memory corresponding to the time between the start and end time points of the scattered light are transferred to a main memory.

Consequently, the data volume that is stored in data storage is estimated to be reduced to below 0.01% compared to the volume which is required when the whole data are recorded in the storage. The memory capacity that is required for the data acquisition of the whole plasma discharge is drastically reduced, then even if the period of the plasma discharge is longer than 20 min, the data acquisition is possible without the memory full in spite of the high sampling time.

IV. DATA TRANSFER OF HYADC BY SITCP

HYADC data transfer to the analysis system is executed by SiTCP, developed by KEK.[1] SiTCP can transfer the data recorded in the HYADC on the TCP/IP protocol performed by a logic circuit without CPU. The transfer rate of the SiTCP was verified as 95% of the theoretical maximum rate of the Ethernet,[5] with the rate increased by future development of the Ethernet technique. Therefore, the transfer rate was sufficient to apply the YTS measurement to a real time feedback system for the plasma control.

As the SiTCP is based on a TCP/IP protocol, it is easy to construct a distributed data processing system of

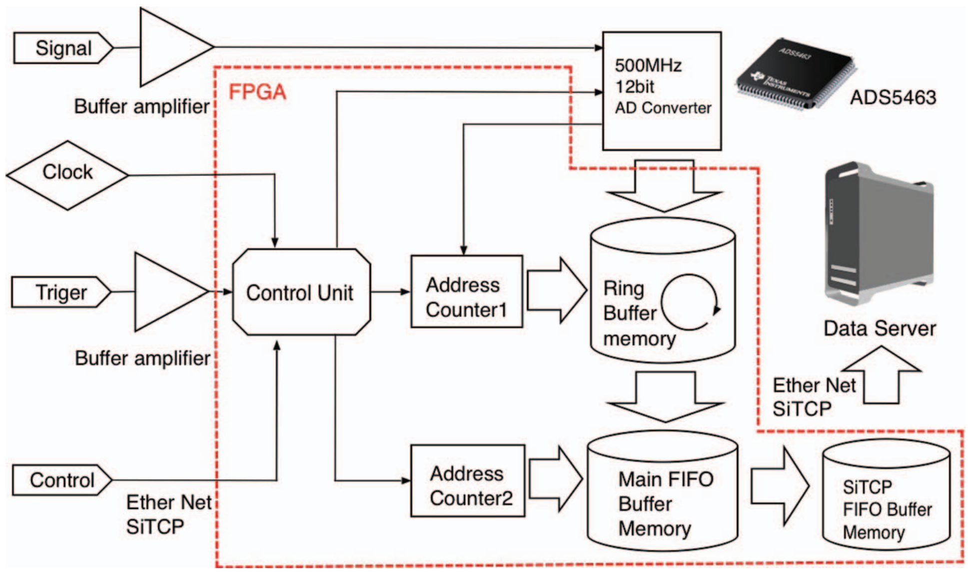

FIG. 3. Schematic diagram of HYADC structure.

multichannel polychromators using switching hubs. Similarly, developing data transfer software using the socket procedure is easy, is supported by most computers, and can be controlled by EPICS,[7] which is required in the ITER project. Because the SiTCP consists of a few chips, embedding it in the polychromators is easy.

V. SUMMARY

The HYADC is designed to directly convert scattered light signals into digital data using the high speed and resolution pipeline type ADC. The HYADC is expected to improve the SNR of Nd:YAG Thomson scattering measurement by ten-folds. The HYADC is designed to record the digitized data of the scattered signal in the ring buffer memory. The memory capacity that is required to measure the scattered light of the whole plasma discharge is drastically reduced. The data transfer from the HYADC was performed by SiTCP, which has a sufficient transfer rate to apply the YTS measurement to real time feedback control of the plasma discharge. HYADC is easily expandable to a multichannel system by distributed data processing and moreover, is very compact and easily implemented as a built-in system of polychromators.

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