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学位論文題目	核融合中性子プロファイル高速計測のための 中性子計数システムの開発
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論文内容要旨

Development of nuclear fusion reactor gained great progress and nuclear fusion was recognized as a clean and safe energy source after the accomplishment of confining a high temperature plasma with the electron temperature of 1 keV for several ms in the T-3 tokamak device in old Soviet Union in the beginning of 1960. In the 1990s, the critical condition is attained at three biggest tokamak fusion devices, JT-60U(Japan), JET(EU) and TFTR(U.S.). Now, the experimental fusion device, ITER (International Thermonuclear Experimental Reactor) is under construction under the frame work of international collaboration. ITER aims as the prototype of a nuclear fusion reactor, at steady-state operation by maintaining the plasma current by a continuous heating with three objectives in the following:

- Produce more power than it consumes. This is expressed by the value of Q, which represents the amount of thermal energy that is generated by the fusion reactions, divided by the amount of input power. The Q value smaller than one means that more power is needed to heat the plasma than is generated by fusion. ITER is expected to reach to Q=10, or Q larger then five together with the pulse width of fusion extending towards a steady-state. This is done in the so called "burning plasma", and most of the power for plasma heating is provided by the fusion reactions themselves.

- Implement and test the key technologies and processes needed for future fusion power plants including technologies for superconducting magnets, development of components which withstand high heat loads and remote handling techniques.
- Test and develop concepts for breeding tritium from lithium-containing materials inside thermally efficient high temperature blankets surrounding the plasma.

On the other hand, it has been a long standing subject how manages unstable plasma to burn steadily for a long time to reach self-ignition plasma. In order to confine the plasma in a tokamak for a long time, self-heating of the plasma by an α particle is indispensable, in other words, it is necessary to fulfill nuclear fusion combustion conditions to heat by an α particle. For example, in order to fulfill self-ignition conditions, in addition to the Joule heat generated by the plasma, heating from the outside is necessary. Although steady-state operation with continuous heating is one of the objectives in ITER, many MHD instabilities are observed in the heating condition before reaching steady-state condition and elucidation of the MHD instability is serious issue for the realization of steady-state operation in ITER. Especially, it becomes clear that clarification of Alfvén Eigen mode (AE mode) is necessary from the recent burning plasma experiments. This high frequency phenomenon is of great interest and one of the key-issue in plasma physics in recent years. This instability occurs in Alfén frequency band by α particles from fusion reactions. By this phenomenon, the performance of confinement of α particles deteriorates causing influences, such as decline in heating efficiency and a loss α particle giving damage to the vacuum vessel. Now, many experiments for AE mode are carried out with RF heating and neutral particle beam injection. In such experiments, many of neutrons are produced by fusion reactions between energetic ions and bulk ions, therefore the neutron production rate provides the information about performance of confinement of energetic ions. Moreover, neutron spatial distribution provides the information where the energetic ion losses occurred or whether energetic ion losses extend to whole plasma or not. Consequently, the neutron emission profile measurement is one of the most important diagnostics in order to clarify the influence of energetic ion loss in AE mode.

In JT-60U, the instrument for neutron emission profile measurement consists of a stilbene neutron detector and a six channel collimator array viewing a poloidal cross section thorough the plasma. The stilbene detector is a kind of an organic scintillator and has sensitivity to neutrons and γ-rays. Therefore, the counting of only neutron events was carried out by using of built-in pulse-shape discrimination circuit at intervals of 1 ms. By this measurement, before and after the AE mode, it was observed that the spatial distribution of energetic ions changed significantly. However, the maximum counting rate of this detector is limited to about 1.3×10^5 n/s due to the dead time in n-γ discrimination circuit. In order to clarify a high-frequency phenomenon like AE mode changing in hundreds of kHz, it is necessary to observe a fluctuation within a short period. To overcome this limitation, it is necessary to develop a method of discrimination of neutrons from γ-ray during a short period in the order of ten's of nano-second, and also even under the condition that two or more pulses overlap each other (pile-up). Moreover, in the experiment at large tokamak experimental devices with scintillation detector, the rate of neutron incidence changes between $10^4 \sim 10^6$ (n/s), and it will cause serious gain change of photomultiplier tubes. According to such backgrounds, the author developed the system in order to observe high-frequency phenomena such as AE mode with the statistical error of less than several percent and has a function for spectrometer with time resolution better than 10 ms.

This thesis consists of six chapters. In the first chapter, recent progress of nuclear fusion reactor development and problems to be solved are summarized. The importance of neutron emission profile measurement and the purpose of this study are described.

In the second chapter, the author described the neutron measurement technique in nuclear fusion experimental facility, and investigated the technique for high-speed neutron spectroscopy. The technique of neutron spectroscopy employing a heavy neutron collimator array and neutron detectors is generally used for neutron emission profile measurement. As a neutron detector, an organic scintillator is mainly used. A trans-stilbene crystal scintillator is used in JT-60U. This scintillator has excellent n-γ discrimination property and very high energy resolution as well as high efficiency similar to an NE213 liquid scintillator widely used for neutron measurement. Moreover, neutron and γ-ray discrimination is possible by a build-in analog circuit. Various techniques are developed for n-γ discrimination using analog circuits on the basis of the different decay time of scintillation fluorescence to neutrons and γ-rays. Most techniques use "amplifier" which performs integration processing of a signal, and require several μs for shaping the waveform. In the measurement under high counting rate, it is required to measure signals properly even under the "pile-up" condition where two or more signals overlap each other. The currently available "pile-up rejector" only rejects the "pile-up" event and dose not contribute to improve the count rate of the circuitry. For this reason, it is efficient to acquire the train of signals waveform from a detector as a one signal and to perform waveform processing in off-line analysis. To perform such measurement, in the case of traditional type of ADC (analog-to-digital conversion circuit), Wilkinson type and a successive approximation register (SAR) type, used in the radiation measurement are not appropriate in a conversion speed (several μs ~ hundreds of μs). Considering that a waveform changes every moment in a nano-second step, it is impossible to save the output waveform from a photo-multiplier tube. In stead, in recent years, a technique to acquire the analog waveform into PC as digital data, called "Digital Signal Processing (DSP)" technique is used in the field of elementary particle physics or high-energy physics as a versatile technique. Flash-ADC used in DSP satisfies the above-mentioned requirement. In the present study, DC282 manufactured by Acqiris Co. Ltd. was adopted as a high speed Flash-ADC appropriate for the present purpose.

In addition, as mentioned above, in the measurement using a photomultiplier tube under high counting rate environment, gain fluctuation of a photomultiplier is worried. This phenomenon depends on the increase of anodal current of the photomultiplier tube due to intense radiation. To overcome the problem, the following measures will be effective:

(1) increase the current through the voltage divider of the photomultiplier, and

(2) change of the potential distribution between the dynode to reduce the space charge effect.

These will help to reduce the effect but complete elimination is not possible for a photomultiplier. Therefore, in addition to two measured above mentioned, the author adopted the way of

(3) installing a LED for each photomultiplier and measure the light signal during the experiment to monitor the gain of the photomultiplier and correct the change off line after the experiment.

In the third chapter, the author describes the data acquisition systems developed to correspond MHz region, optimization of the data acquisition method and the analysis of a "pile-up" phenomenon by use of a Flash-ADC. It became possible by introducing a Flash-ADC to acquire the signal of a detector as a series of signals. Data acquisition time is fixed by a sampling period and the memory capacity of a Flash-ADC. When considering a "pile-up" phenomenon, it is necessary to perform n-γ discrimination in a shorter duration. In this chapter, the author evaluated the effect of the sampling period on the performance of the n- γ discrimination, and the optimum values of the sampling period from the view point of speeding up the system. Moreover, the method of n- γ discrimination method under the "pile-up" condition was examined.

In forth chapter, the neutron detector was newly designed to suppress the fluctuation of the photomultiplier tube in the measurement using the photomultiplier tube under a high counting rate radiation field. The photomultiplier tube of the neutron detector currently used at JT-60U has small current in the voltage divider circuit, and it will cause the gain fluctuation even with a little counting rate change. The newly designed neutron detector adopts a tapered dividers circuit with higher divider current to make it less sensitive to count rate change and to space charge effect. Further, to monitor the gain fluctuation quantitatively and enable the correction off line, a LED-optical fiber system for introducing the light of LED into a photomultiplier tube was equipped. The gain correction is done by using the pulse-height data of LED acquired by DSP as calibration value.

In the fifth chapter, neutron measurement was done by applying the developed neutron high speed counting system to the detector of JT-60U. The detector viewing the central section of the plasma in a vertical collimator array was used for measurement. This system could measure the neutron without saturation in count rate up to about 10^6 cps even in the discharge which produced a large amount of neutrons and saturated the old neutron counting system. Moreover, when gain fluctuation arose, it became possible to perform feedback processing and to obtain the pulse height distribution in every 10 milliseconds. In addition, the memory capacity of Flash-ADC was extended to enable the sequential measurement for 5 seconds without dead time.

By applying this system to all the channels for neutron emission profile measurement, a powerful diagnostic system for the elucidation of the phenomenon changed by hundreds of kHz like AE mode will be realized enabling rapid advance in plasma physics towards realization of the steady-state operation in the future fusion device like ITER. Furthermore, the application of the system to the measurement of 14 MeV neutron by triton burn-up and to other diagnostic system, such as a diamond detector currently used for measurement of neutral particles, is also expected. In addition, this system is expected to become more powerful, faster and highly precise, with the development of Flash-ADC and the DSP technology.

論文審査結果の要旨

核融合炉の開発研究は自己点火条件の達成に向けて進められているが，近年，外部からの加熱に伴って生じるアルベン固有モードなど数 100 kHz 領域における高速不安定性とそれに伴うα粒子の閉じこめ劣化，の解明が重要な課題となってきた。そのために，この高速現象を的確に把握できる MHz 以上の高計数率特性を有する計測手法が不可欠である。本論文は、高速不安定現象を中性子を用いて観測可能とするための MHz 領域の中性子スペクトロメータシステムの開発とその応用手法に関するもので，全 6 章からなる。

第 1 章は緒言であり、研究の背景を述べている。

第 2 章では，中性子計測システムに要求される特性を整理し，それを満たすための要件を明らかにしている。高速性に加えて高感度，スペクトル測定の可能性，を考慮してスチルベン検出器を選択し，高速化に不可欠なパイルアップ信号の処理も可能とするために，デジタル信号処理手法(DSP)を導入すること，高速動作で問題となる光電子増倍管の利得変動への対処の必要性，その手法を示している。

第 3 章では、高速データシステムの開発の詳細を述べている。スチルベン検出器の陽極信号を高速のフラッシュ ADC に入力してデジタル波形データを収集するものであるが，信号を一連の波形データとして取り扱うことによってパイルアップデータの処理も可能とする新しい概念を提示している。さらに，限られた記憶容量のもとで，収集可能な事象数を最大とするために，スチルベン検出器について，エネルギー情報と波形情報を取得するに必要なサンプリング周波数と積分時間の下限を実験的に明らかにしている。これによって，10 MHz 近い高速のデータ収集を可能とした。これは、本論文の根幹をなす重要な成果である。

第 4 章では，こうした高計数率において起こりえる光電子増倍管の利得変化に対処するために，変化に強い電圧分圧回路に改良するとともに，発生した場合にデータの補正を可能とするよう LED の基準信号を光電子増倍管に導入し，放射線とは波形の異なるデータとして収集して DSP によって補正を行う新しい手法を開拓した。実際の計測に適用し，その有効性を実証している。これは汎用性のある有用な知見である。

第 5 章では，このシステムと手法を日本原子力機構の核融合実験装置 JT-60U に適用した結果を示している。開発したシステムによって，ほぼ MHz までの中性子スペクトルデータの収集が可能となり，高速不安定性の観測についての有用性が実証されるとともに，LED を用いたデータ補正法の有効性も実証された。これは現在世界のベストレコードに位置づけられるもので，他機関においてもこの手法の導入が検討され始めた。

第 6 章は総括であり結論を述べている。

以上、要するに、本論文は核融合炉開発において不可欠となった MHz 以上の高速な中性子スペクトル計測をスチルベン検出器にデジタル信号処理手法を適用することを可能としたもので，他の研究分野への応用可能性も含め，量子エネルギー工学の進展に寄与するところ少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。