Chapter 1
Introduction

X-ray detection systems using semiconductor detector arrays are developed as position sensitive X-ray imaging systems for the purpose of analyzing temporally and spatially varying plasma behaviour [1-5]. In the GAMMA10 tandem mirror [4,5], open ended magnetic fields produced for magnetically confined plasma formation are still strong even in the outside regions of the coil locations. Plasma diagnostic systems including X-ray detectors are placed in such high-field and limited narrow-spacing areas.

Useful characteristics of semiconductor detectors for plasma diagnostics are listed as follows: These detectors satisfy the above-described requirements of (i) compactness for narrow detector space, (ii) low-level outgas for the use in high-vacuum conditions under 10^{-8} Torr, as well as (iii) high degree of immunity to ambient magnetic fields of the order of a Tesla. These provide remarkable merits compared to the use of detectors including photomultipliers and microchannel plates (MCPs) [6], which utilize avalanche electrons for signal outputs.

From the above several advantages, we install semiconductor detector arrays to carry out the first simultaneous measurements of X rays emitted from both circularly shaped central-cell and elliptically shaped anchor-region plasmas. Minimum-B field configuration in the anchor region is produced by baseball-shaped coils for maintaining magnetohydrodynamic (MHD) plasma stability [5].

Recently, progress in theoretical studies of the quantum efficiency of semiconductor X-ray detectors is made; novel findings including the invalidity of the conventional standard theory on the X-ray energy response utilized over this quarter of the century [7], as well as the experimental verification of our proposed theory on the energy response [8,9] are made.

In spite of the above-described usefulness and the recent steady progress in the understandings of the semiconductor detector physics, it is still difficult for semiconductor X-ray detectors to determine electron temperatures T_e ranging below 100 eV because of the X-ray absorption due to the existence of a dead layer covering over the detector surface. Furthermore, the conventional "X-ray absorption method" requires many plasma discharges with good reproducibility because of the necessity of shot-to-shot changes of X-ray absorption filters.

In this thesis, the first report of simultaneous observations of T_e in both central cell and anchor region is made by the use of a single plasma discharge alone on the basis of the combination of the above-described theoretical development of X-ray analyses and our newly proposed "matrix-type" semiconductor detector. These temporally and spatially resolved X-ray analyses cover the T_e range from a few tens eV up to several tens keV. The characteristic features and its first applications to plasma X-ray diagnostics are detailed in the following sections.

The GAMMA 10 tandem mirror is originally designed in the shape with minimum-B inboard anchors for finding optimum magnetohydrodynamic (MHD) stabilizer configurations [4,5,10-28], as compared with the other configurations including those with outboard anchors located inside potential plugging regions [12], or compact end anchors having an additional role in potential plugging of end loss ions [13]. Considerable efforts have, therefore, been devoted for constructing the scaling law of the requirement of the anchor plasma beta against the central cell beta values so as to find the interchange stability conditions in standard tandem mirror operations under the inboard minimum-B configuration on GAMMA 10 [14,23,24].

As an easily attainable experimental indicator, the ratio of the anchor to the central cell diamagnetisms is intensively studied and plotted for finding the MHD stability boundary [14,23,24]. This important scaling of the diamagnetism relation, however, provides only information on practical outline for the MHD stability, and no direct presentations of the internal structural behaviour of spatially resolved bulk plasma motions are reported even at this time.

In this thesis, the detailed data on the internal core plasma structural behaviour during the MHD destabilization are presented by the use of the developed X-ray diagnostics in comparison to the previous reports with probe measurements and H_α diagnostics dominated over the peripheral plasma region [24,25], as well as the mode identification with microwave scattering and reflectometer diagnostics [23,26], since the requirement of the direct observations of interior plasma structural behaviour including the plasma temperature profiles during the MHD instability have still remained as an unsolved issue in order to construct the overall view of the MHD phenomena.

This thesis is thus prepared to clarify this unsolved remainder issue; that is, how the interior core plasmas behave temporally and spatially during the MHD destabilization in a tandem mirror. In this thesis, a finding of the bulk plasma rotation without a change in its shape and structure is reported. The onset of the rotation is studied, and identified to be closely related to a scaling of the MHD stability boundary (i.e. the anchor beta requirements for stabilizing central cell hot ion plasmas). The first simultaneously obtained data on electron and ion behaviour analysed from the X-ray signals in the central cell and the anchor region as well as consistently behaved end loss ion signals with X-rays have clarified an overall view of a rotation of the GAMMA 10 plasma column in detail. These data confirm the previously expected start up scenario of pressure driven interchange instability in tandem mirror plasmas.

The next issue is to clarify the predominant factor in determining T_e. This has been one of the unresolved problems in tandem mirrors. The conventional "X-ray absorption method" requires many plasma discharges with good plasma reproducibility because of the necessity of shot-to-shot changes of X-ray absorption filters. Thus, it is also difficult for the conventional X-ray systems to study the scalings of T_e with various plasma parameters, for instance, an important scaling of T_e with central-cell electron confining potentials ϕ_b. In order to find out generalized physics interpretations covering over the experimental results, theoretical analyses are carried out by the use of a widely applicable energy-balance equation. In this article, the first report of observations of T_e profiles for the electron cyclotron heated plasmas and its physical interpretations is made by the use of a single plasma discharge alone on the basis of our newly proposed "matrix-type" semiconductor detector.

This thesis is organized as follows: in chapter 2, the overview of the GAMMA 10 tandem mirror, along with two typical plasma production modes, as well as plasma diagnostic devices and methods are described; in chapter 3, X-ray analysis methods using semiconductor detectors are described; in chapter 4, the new generalized theory on the X-ray energy response of semiconductor detectors is summarized along with its theoretical formula. Furthermore, the mechanism of potential formation from Cohen's strong ECH theory and Pastukhov's theory for the effects of thermal-barrier potentials on electron confinement are described; in chapter 5, the development and characterization of a novel matrix-type semiconductor detector and its experimental data are described; in chapter 6, as an example of the applications of a novel matrix-type semiconductor detector, X-ray analyses of irreproducible MHD phenomena and a scaling law of T_e with central-cell electron confining potentials ϕ_b for the electron cyclotron heated plasmas are described. Finally, the present investigations are summarized in chapter 7.