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学位論文題目 Development of 3D radiation measurement using IR imaging  
video bolometers for the study of radiation collapse in LHD

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論文内容の要旨

Summary of thesis contents

High density operation is preferred for a future fusion reactor since the fusion output is proportional to the density squared. Especially in magnetically confined plasmas, the energy confinement time increases with density. High density operation is also beneficial for the heat load reduction on plasma facing components called the divertor. At high density, the radiation loss is increased and the divertor heat load decreases. The maximum achievable density in a magnetically confined plasma is, however, limited by a density limit that has been expressed by semi empirical scaling, e.g. the Greenwald density limit for tokamaks and the Sudo limit for helical plasmas. The density limit of the tokamak is often accompanied by a current disruption which can inflict much damage on the reactor and should be avoided. On the other hand, in helical plasmas, where large plasma current is not needed since the plasma is confined by the magnetic fields generated by external magnet coils, the radiation loss rapidly increases when the edge plasma density approaches the Sudo limit and finally, plasma collapses in a relatively benign manner due to the large radiation loss. Therefore, for the steady state operation of a fusion reactor, understanding of the physics mechanism of the density limit and the radiation collapse is quite important. In this study, the temporal evolution of the radiation collapse in helical plasmas of the Large Helical Device (LHD) is studied by using infrared (IR) imaging Video Bolometers (IRVB). Since the helical plasmas are characterized by a three dimensionally (3D) complicated shape, simple assumptions, such as e.g. axial symmetry, are not applicable and therefore a 3D approach is necessary. This thesis is composed of three parts, i.e., the development of the IRVB, the development of the 3D measurement and the investigation of the radiation collapse.

The IRVB has been developed for the measurement of 2D radiation profile patterns. The IRVB provides a distribution of the incident radiation on an IRVB foil. The IRVB has the advantage of having a large number of channels in a 2D array. This advantage is also beneficial for the 3D measurement. For the 3D measurement, in this study, three improvements have been applied to the IRVB. The first improvement is the selection of the material for the IRVB foil. The performance of the IRVB depends on the foil material. In this study the thermal characteristics of foil materials have been evaluated systematically. As the candidates of the foil material, Au, Pt, Ta, W were examined. These were illuminated by a He-Ne laser and their thermal characteristics were evaluated. Among these candidates Pt shows the best characteristics in the simultaneous achievement of high sensitivity and fast time response. According to the test results Pt has been selected. The second improvement is the foil calibration. The IRVB measurement as an absolute measurement requires a knowledge of the distribution on the foil of 3 foil parameters. However because two of the three parameters, foil thickness and emissivity, had not been evaluated, the IRVB measurement mainly served as a qualitative measurement. To evaluate the distribution of these two parameters, a new calibration technique has been developed. The calibration technique evaluates the effective thickness and effective emissivity

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distribution on the foil with a comparison between the 2D temperature which is measured from the laser illuminated foil, and the calculated 2D temperature using a Finite Element Method (FEM). The evaluated distribution of the effective foil thickness and the effective emissivity made possible for the first time a quantitative measurement using an IRVB. The third improvement is the calculation of a projection matrix and the design of the fields of view of the IRVBs. The 3D measurement requires a 3D knowledge of the relation between each IRVB channel's signal and 3D space. To obtain the relation, a calculation is made of the contribution of the radiation from each plasma volume element to the field of view of each IRVB channel. The fields of view of the IRVBs are designed to complete the coverage of the plasma using the calculated fields of view.

In this study two methods have been developed for the 3D radiation profile measurement. The first one is an algebraic reconstruction of the radiated power density from the IRVB images. For the algebraic reconstruction, Tikhonov regularization with the criterion of minimum Generalized Cross Validation (GCV) is employed as the reconstruction technique. The reconstruction has been numerically and experimentally examined. The simulated radiation profile using the EMC3-EIRENE code has been used as a numerical phantom in a numerical test of the reconstruction and has been reproduced with the reconstruction process. In reconstruction tests with experimental data which are taken before and after the plasma collapse, reconstruction results have responded to changes in the plasma condition. The first application to plasma measurements of a challenging 3D reconstruction has been performed. The reconstruction provides 3D radiation profiles as a quantitative 3D measurement. The time resolution of the 3D measurement is 20ms and the spatial resolution is roughly 5cm. Although a quantitative understanding of the reconstructed profile can be obtained by this algebraic reconstruction, a quantitative discussion of the reconstructed profiles relative to the changes in the plasma is still difficult.

Therefore, another method of 3D model fitting has been developed to quantitatively investigate the physics mechanisms of the radiation collapse. Nine parameters have been selected to characterize the radiation profile, i.e. semi major and minor radius of radiation region, the center of radiation region, the width of radiation region, radiation intensity, the asymmetric factor for inboard-outboard asymmetry, the asymmetric factor for toroidal asymmetry, the local peaking factor and the specific size of the local peak. Using these nine parameters, the radiation is fitted to the model to minimize the mean square error between an experimental IRVB image and a synthetic IRVB image which is calculated from the model. The model fitting quantifies the temporal evolution of the radiation profile as the changes in the nine parameters. The time resolution of the model fitting is 40ms.

The developed 3D measurements have been applied to the study of the radiation collapse. Results of the model fitting show significant changes in the evolution of the radiation structure as model parameters change, during radiation collapse over a time period of 300 ms. The radiation region is minor radially localized before radiation collapse as the first step of the

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structure changes and the radiation region shrinks and radiation from the inboard side is significantly enhanced during radiation collapse. With changes in the radiation structure which are obtained by model fitting, it is possible to define the initiation of the radiation collapse, which has been difficult to define until now by using only the total radiation from the resistive bolometer.

To clarify the detail of the observed structure changes by the model fitting, algebraic reconstruction with Tikhonov regularization is also applied to the radiation measurement for the same plasma discharge. A result of the algebraic reconstruction shows that the inboard enhancement initiates at the vertically elongated cross section and then it is extended to the other poloidal cross sections along the Last Closed Flux Surface (LCFS). The inboard side of the vertically elongated cross section is at the nearest point to the wall.

The radiation structure of carbon II (426.7nm) and III (464.7nm) emission at the timing of the shrinking and the inboard enhancement has also been investigated using a visible imaging spectrometer. The measurement result of the imaging spectrometer shows the carbon emission peak moves inward from the x-point and ergodic region towards the LCFS at that timing. It indicates that the shrinking and the inboard enhancement is related to the electron temperature. To clarify the relation, the electron temperature profile and the radiation profile which is obtained from the model fitting have been compared before and during the radiation collapse.

The comparison has provided a scenario of how the radiation structure changes during the radiation collapse as follows: When the electron temperature reduces, the radiation region starts to concentrate as the first step. As a second step, enhancement of the radiation from the inboard side and shrinking of the radiation region occur simultaneously.

As a third step, the radiation region crosses the LCFS and the radiation power reaches a peak. Finally, the radiation region is concentrated at the center of the plasma. In this scenario, asymmetry in the radiation structure plays an important role. When the parallel transport is large enough, this kind of asymmetry cannot appear. To discuss the asymmetry, the mean free path at the plasma edge is investigated. At first, the mean free path decreases linearly with the electron density. This relation is changed before the initiation of the asymmetry. In this phase, the mean free path suddenly drops nonlinearly with increasing electron density. This behavior indicates that the asymmetry during radiation collapse is related to the reduction in parallel transport.

In this thesis, the IRVB measurement has become a quantitative measurement and is related to the 3D plasma space using a projection matrix calculation, through three improvements. Two methods for quantifying the 3D radiation structure have been developed with the improved IRVB measurement. In addition to a 3 dimensional tomography method, a nine parameter model quantifies the characteristics of the changes in the radiation structure during radiation collapse and algebraic reconstruction shows radiation collapse is initiated at the inboard side of the vertical cross section. Several events during the radiation collapse evolution have been observed for the first time from the model parameters and algebraic reconstructed profiles. By relating these events, a scenario for the radiation collapse has been obtained. That is the main result of

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this thesis. The developed IRVB improvement and 3D measurement techniques will also be applicable in the future to enhancing the understanding of radiation collapse and other radiation phenomena.

Summary of the results of the doctoral thesis screening

磁場閉じ込め核融合プラズマでは、輻射損失が急激に増大し、プラズマを消滅させる輻射崩壊現象によって、運転できる粒子密度の上限（密度限界）が決定される。核融合反応による出力は密度の二乗に比例するため、この密度の上限を決める輻射崩壊現象の物理を明らかにすることは核融合炉を安定に運転できる条件を求めるために極めて重要である。本論文は、世界で初めてとなる三次元輻射分布計測手法を確立し、この輻射崩壊現象時の輻射分布構造の変化を観測して、これまでにない知見を得たものである。

大型ヘリカル装置（Large Helical Device、以下LHDと記す）に代表されるヘリカル型磁場閉じ込め装置で発生されるプラズマは本質的に三次元構造を有していること、及び輻射崩壊時には輻射分布が磁気面上で非一様となる構造を持つことがこれまでの観測から示唆されていることから、輻射崩壊現象の物理過程を詳細に明らかにするには、三次元の輻射分布計測手法を確立することが必要とされていた。この問題に取り組んだ本論文は、ハードウェアの研究開発、解析手法の研究開発、及びLHDにおける実験観測データの解析とその物理解釈の3つの内容で構成されている。

ハードウェアとしては、LHDに赤外線ビデオボロメータ（Infra Red Video Bolometer、以下IRVB）4台からなるシステムを整備した。この計測に最適な高い感度と時間分解能を併せ持つ金属薄膜を自らの試験を通じて評価、選定するとともに、薄膜上に投影される輻射分布の較正手法を新たに研究開発し、これまで定性的だった三次元輻射分布計測を定量的なものとした。本研究で最も困難な点は、約3千個のIRVBピクセルデータから、プラズマ内に設定された約100万個の体積要素（voxel）で記述される三次元輻射分布を推定することであった。IRVBによる計測は視線積分であり、ヘリカルプラズマの三次元性のために軸対称性を仮定できないこと、観測対象が大きいためにピンホールカメラからの深度距離によって視体積が変化すること、更には輻射計測の視野が観測窓の制限を受けることが解析を困難にする。出願者は、ヘリカル対称性を用いるなどして有効voxel数を合理的に約1万6千個に絞り込み、Tikhonovの正則化手法を用いた三次元トモグラフィと、輻射分布の特徴を表すパラメータを用いた独自のモデルへのフィッティングという二つの手法を研究し、両者を相補的に用いることでこの問題を解決した。これらを用いて実験観測データを解析し、輻射崩壊の発生過程を明らかにした。密度限界よりも密度が十分低く、定常にプラズマが維持される場合には、磁気面に沿ってプラズマパラメータが均一化されることにより、輻射分布は磁気面関数となる。これに対して輻射崩壊時には、(1) プラズマ周辺部密度の密度限界付近への増加に伴い、最初にトーラス型真空容器の内筒側で、かつ壁とプラズマとの距離が近くなる場所において、最外殻磁気面の外で局所的に輻射損失が増大する、(2) 更に密度が増加すると、この局所的な輻射損失増大領域がトロイダル方向に伝播し、電子温度の急激な減少をもたらすトーラス内筒側全体が輻射領域となる、(3) 輻射領域が最外殻磁気面を横切ってプラズマ閉じ込め領域に侵入する、(4) 全輻射損失が最大となり、輻射領域が中心領域に収束していく、ことを示した。出願者は更に、この観測に基づいて輻射崩壊の物理過程を電子の平均自由行程の密度依存性から説明した。すなわち、密度限界付近では、電子の平均自由行程が有する負の密度依存性が強くなり始め、密度増加に伴って平均自由行程は急激に数m程度以下まで減少する。この急激な変化が磁気面上

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で局在した非一様な輻射分布の発生をもたらすことを異なった磁場配位にわたって検証した。これは、輻射崩壊の機構を解明するために、極めて重要な知見である。

以上のように、出願者は世界で初めてとなる三次元輻射分布計測手法を確立し、それを用いてヘリカルプラズマにおける輻射崩壊の物理シナリオを明らかにすることで、密度限界の物理解釈に大きな進展をもたらす貢献をした。よって、本論文は学位（工学）の授与に十分値すると判断した。

1月13日に開催された博士論文本審査では、出願者による1時間程度の論文内容発表の後、論文全般に関わる事項についての質疑応答を1時間30分程度行った。審査委員からは、三次元輻射分布の再構成に用いた数式の意味、コレスキー分解を適用することの是非、再構成においてvoxel毎に重み付けを行うことについての可能性、薄膜材料選定に用いた評価関数の意味、平均自由行程とエネルギー閉じ込めの相関を調べた物理的背景、輻射損失における可視光成分の寄与についてなど、広範な質問がなされた。出願者はそれぞれの質問に対する的確に回答し、審査委員との議論を通して研究内容について十分な知識と理解を有していることを示した。

1月27日に行われた公開発表会においても、出願者は内容を要領良くまとめて指定時間内に口頭発表を終了し、再構成手法に関する質問等に対する的確に答えた。

主任指導教官は英語を母国語としており、研究指導は英語を用いて行われてきた。博士論文は英語で記述されており、本審査における質疑応答の一部も英語で行われた。出願者が第一著者となっている査読付き英文論文が4編出版されており、国際学会でも5件の発表を行っている。これらのことから審査委員会は出願者の英語能力は十分であると判断した。以上の結果、審査委員全員一致で試験を合格とした。