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論文内容の要旨
Summary of thesis contents

The objective of this thesis is to study the dynamics of the 3D radiative structures in the Large Helical Device (LHD) during the resonant magnetic perturbation (RMP) assisted plasma detachment experiments. Plasma detachment is foreseen as an important operational regime for future fusion devices. This inevitability is due to the ability of detached plasmas to keep the overall heat loads on the plasma facing components within the engineering design limits, eventually prolonging the lifespan of those expensive components. Plasma detachment is a phenomenon with a rich mix of diverse physical processes. The RMP assisted plasma detachment experiment carried out on LHD has shown a modification in the edge radiative structures, once the discharge enters in to the detachment phase. The dynamics of the radiative structures in LHD are studied in two dimensions (2D) using an Infrared imaging Video Bolometer (IRVB). The plasma edge of LHD is modelled using the EMC3-EIRENE code which, qualitatively, shows trends similar to the experimental observations. Quantitatively, there is a disagreement between the experimental and the modeling results which will be addressed as a part of this research project.

This thesis has two broad themes. Firstly, the IRVB diagnostic has been improved in terms of its sensitivity and signal to noise ratio, calibrated thoroughly to quantify the measurements and several validations and noise estimations are carried out to gain confidence in the analyzed data. The quantitative results, the first of their kind, are presented and compared with the modeling results from EMC3-EIRENE. Secondly, the dynamics of the plasma radiation are experimentally studied and a quantitative comparison with the modeling is attempted. Such a quantitative comparison is a first step towards establishing and validating a set of free parameters used in the EMC3-EIRENE transport code and will improve the assumptions made in the transport model. The IRVB installed at the top diagnostic port of LHD was chosen to be upgraded since it offers a unique view of the toroidal and radial extent of the plasma. An infrared periscope was designed and built to increase the sensitivity and the signal to noise ratio (SNR) of the diagnostic. Addition of the periscope to the IRVB led to a theoretical improvement of the sensitivity by 1.4 times and the SNR by 4.5 times. The effective SNR has actually increased by a factor > 4 after this upgrade which matches closely with the theoretical estimate.

Along with the improvement in SNR and sensitivity of the diagnostic, the calibration of the IRVB platinum foil is also necessary to accurately estimate the spatial variation of the thermophysical properties of the foil. A calibration method previously used for estimating the thermal diffusivity of the thick plates, was adopted and applied to a thin bolometer foil for the first time. The heat diffusivity estimated for the Pt foil using this method was found to be 2-2.5 times lower than the literature value. This was attributed to the effect of the graphite coating applied to improve the

emissivity of the foil. The decrease in the thermal diffusivity also explains the higher sensitivity of the platinum foil versus the gold foil. This method is independent of any assumptions and fast enough to calibrate the entire foil and analyze the data in < 6 hours.

The improved and calibrated IRVB was used during the 17th experimental campaign to study the RMP assisted detachment. The merits of the diagnostic upgrade are evident from the qualitative comparison of the experimental results with the modeling results. Modeling predicted a flip in the radiation from the RMP X-point to the O-point during detachment, at higher densities. This fact was confirmed, for the first time, experimentally by using the improved IRVB diagnostic. The IRVB was for the first time brought to a stage by all the improvements and calibration that it can confidently quantify the radiation emitted by the plasma. These quantified experimental results serve as a guideline for choosing the correct impurity diffusion and sputtering coefficient which can improve the match between the radiation estimated by the EMC3-EIRENE model and the experimental observations. In an attempt to establish a better match between the experiment and the modeling, firstly, the impurity diffusion coefficient was changed from $D_{\perp}=1\ \mathrm{m^2/s}$ to $D_{\perp}=2\ \mathrm{m^2/s}$ which spreads out the radiation distribution to better match the experiments. The quantitative comparison is attempted using the normalized integrated power from the experiment and the modeling. The comparison signifies that the model still predicts more power than the experiment, especially after the detachment, which is indicative of a reduction in the sputtering coefficient after the plasma detaches. The sputtering coefficient is therefore reduced from 1% to 0.5% after the discharge goes into the detachment to establish a better match between the experiments and the modeling. This significantly reduces the amount of radiation estimated by the code and the resulting modeling results are in better agreement with the experiments. Such a comparison is an ongoing process and would result in a set of parameters for which the model and experiments would converge. Hence the improved and calibrated IRVB serves as a guideline for fine-tuning the model assumptions. The thesis is organized as follows.

Chapter 1 provided a brief overview about the divertor and its operational regimes.

Chapter 2 reviews the process of detachment in further detail, gives a brief introduction about LHD and various diagnostic systems and describes the detachment experiments on LHD with relevant observations.

Chapter 3 gives a brief introduction to the IRVB diagnostic used to study the radiation during the detachment experiments on LHD and elaborates on its figure of merits and the necessity for improvement in its sensitivity.

Chapter 4 gives a brief description about the infrared periscope along with the radiometric considerations and evaluation of the optical performance of the periscope. This chapter also compares the experimental data with and without the periscope and justifies the improvement in the signal to noise ratio and the sensitivity improvement with the addition of the periscope.

Various calibration techniques, used for determining the thermophysical and optical properties of the IRVB foil material, are reviewed in Chapter 5 and in light of their drawbacks, a new photo thermal technique is introduced for determining the thermal diffusivity of the IRVB foil. The merits of this technique are also discussed along with other interesting observations that affect the sensitivity of the IRVB.

After improvising the diagnostic sufficiently and having calibrated the IRVB foil, the data analysis procedure is reviewed and validated for confidently quantifying the measured radiation from the plasma using the IRVB in Chapter 6. The noise estimates are also reconsidered in Chapter 6.

The quantified results from the IRVB diagnostic are then compared with the results from the EMC3-EIRINE code in chapter 7 and an attempt is made to improve the correlation between the experiment and modeling by varying the free modeling parameters in the EMC3-EIRINE code.

Chapter 8 concludes the thesis with an outlook on the future prospects of this study.

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博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

Quantitative study of 3D radiation dynamics during resonant magnetic perturbation assisted detached plasmas in the Large Helical Device

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本論文は、LHDからの放射の３次元構造の動的変化を研究する為の、イメージングボロメーターシステムの改良と実験結果について述べている。論文の前半はシステムの改良をどのように行ったかについて述べられており、後半はデタッチメント実験における観測結果とEMC3-EIRENEコードの計算結果との比較について述べられている。

イメージングボロメーターシステムの改良については、１）ペリスコープの開発、２）感度較正法の開発、３）イメージ再構成コードの開発を行った。イメージングボロメーターシステムとはピンホールを使って放射強度分布のイメージを薄膜に投影し、その温度分布を遠赤外線カメラで計測するものである。広い視野を確保しつつ十分な空間分解と感度を得る為にペリスコープを開発し、空間分解能として11cm、時間分解能としては100msで、信号ノイズ比は210となり、以前に比べ4.5倍向上した。遠赤外線カメラで計測した温度上昇から放射分布を求めるためにはLEDを使って放射強度と温度上昇との関係を測定し白金の薄膜の拡散係数等のパラメータを決定する必要がある。正確な感度較正法の開発を行い、白金の薄膜に炭素コーティングしたために熱拡散係数が下がる事を確かめた。イメージングボロメーターシステムで観測される放射分布は、プラズマの放射強度を各ピクセルが見込む視野にそって体積積分したものである。一方シミュレーションでは３次元の各点の放射強度が計算されているので、計算と実験を比較するには、実験データを逆変換して放射強度を求めるか、計算データを積分して放射イメージを算出するかのどちらかが必要となる。本論文では後者の手法が採用され、計算された放射強度を各ピクセルが見込む視野にそって体積積分して薄膜上でのイメージを求めるイメージ再構成コードの開発が述べられている。

この改良されたイメージングボロメーターシステムを使って、デタッチメント実験での放射強度の計測を行った。その結果、デタッチメント遷移に伴い、放射強度のピークがヘリカルX− ポイントから磁気島Xポイントに、さらにO− ポイントに移動する現象を観測した。放射強度のピークが磁気島XポイントからO− ポイントに移動する現象は、EMC3-EIRENEコードでは予想されていたが、いままでのシステムでは観測されていなかった。今回のペリスコープの改良によって初めて観測された。また今回可能となった定量的比較によって、以下の事が明らかになった。
エルゴディック領域の実効的な拡散は、磁力線に垂直な拡散と磁力線に平行な運動の径方向への投影の重ね合わせで決定される。シミュレーションでは磁力線に垂直な不純物拡散を背景プラズマ（閉じた磁気面）と同じとして計算している。本研究によるコード計算により再構成された放射強度像よりもはるかに広がった放射強度の空間分布が観測された。その実験結果は磁力線に垂直な拡散は従来仮定していた値（背景プラズマ（閉じた磁気面）での値である$1m^2/s$）よりも明らかに大きな値（$4m^2/s$）が必要である事を示唆している。またデタッチメント遷移前後の放射強度について、観測結果とシミュレーション結果を比較した結果、シミュレーションではデタッチメント遷移後に放射強度が急激に増加するのに対し、観測結果ではゆるやかに増加するという違いが明らかになった。これはデタッチメント遷移後にシミュレーションでは不変としているスパッタリング係数が実効的に1%から0.5%に半減している事に対応している。

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このように、イメージングボロメーターシステムの改良とその観測結果とシミュレーション結果との比較によって、意義深い研究成果が得られている。これらの成果は核融合プラズマにおける不純物およびデタッチメント制御に関する研究の進展に大きく貢献するものである。よって本論文の内容は学位（理学）の授与に十分値すると判断した。