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(Form 3)

Summary of Doctoral Thesis

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Title: Study of hydrogen pellet ablation cloud via spatially resolved spectral measurement

Spatially resolved measurements of the ground state neutral density (n_a^1), the electron density (n_e) and temperature (T_e) in an hydrogen pellet ablation cloud have been conducted in the Large Helical Device (LHD). Spatial-resolution is achieved thanks to the narrow band-shaped field-of-view of the optics of the observation system. Some of the photons emitted by the ablation cloud are collected by the optics and send to a visible spectrometer. Each obtained spectrum can be associated to a slice of the recorded ablation cloud of a certain volume (V_s). It is possible to derive the profiles of the plasma parameters n_a^1, n_e and T_e along the ablation cloud by analyzing the experimental spectra with a spectral model. Results obtained from least-squares fitting the data behave accordingly to the consensus, to the exception of T_e which is lower than what is usually expected from an ablation cloud. The present study provides a new approach based on passive spectroscopy to study and understand the internal structure of pellet ablation clouds.

Nowadays, Magnetic Confinement Fusion (MCF) is considered as a solution to produce clean energy. The MCF approach roughly consists of enclaving a plasma into a magnetic trap, and heating it to very high temperatures so that nuclear fusion processes occur between the particles composing it. However, in order for such method to reach a level of efficiency high enough for energy production purposes, it has been deemed necessary to inject fuel pellets into the core plasmas of MCF devices to sustain them and to ensure that nuclear fusion processes occur as optimally as possible.

When an injected pellet interacts with the background plasma of a fusion device, it tends to diffuse its matter content in the region directly surrounding it. This phenomenon referred to as the pellet ablation process can be measured and quantified into what is called the deposition profile. Under optimal conditions, most of the deposited particles should reach the core of the fusion plasma because this is where the nuclear fusion process is supposed to happen. However, most of the current estimations of pellets deposition profiles do not predict an optimal delivery to the plasma core of big sized reactor projects such as the International Thermonuclear Experimental Reactor (ITER).

Therefore, in order to improve the potency of the pellet ablation process, it is necessary to understand its functioning more accurately. While it is already possible to get a rough picture of how pellets behave once injected into an MCF device, theoretical models and experimental observations have yet to be fully reconciled when the focus is put on how pellets behave at a local scale. A conflicting point that exists between theory and reality is related to the characteristics of the layers of plasma surrounding an ablating pellet. These layers are commonly called ablation cloud or plasmoids. Studying an ablation cloud is easier than studying a pellet because, contrarily to the latter, the former is actually a plasma that can be observed by the intense light it emits. Up until a few years ago, technological advancements only allowed to observe plasmoid through their region which radiate the most. However, improvements of recording methods that have been achieved in terms of higher resolutions and faster acquisition rates made it possible for researchers to have access to the inner structure of ablation clouds and offered the opportunity to challenge some of the commonly accepted theoretical models.

The plasma fusion research has been going through what could be referred to as a "Local Thermodynamic Equilibrium" plasma crisis and the study of fuel pellet ablation clouds is not exempt from it. Local Thermodynamic Equilibrium (LTE) is a condition which is often considered in plasmas. The LTE condition contains a set of approximations which allow plasmas to be characterized more easily than if they had to be treated by a more complete approach. Some criteria need to be fulfilled in order for the LTE condition to be applied. It is also possible to apply the LTE condition only partially depending on how many of these criteria are valid. It has been shown in a study that it is possible to consider plasmoids as being into what is referred to as a "Complete LTE" state (CLTE). This is an interesting state to consider, especially when seen from the point-of-view of the ground state atomic population density. When valid, the CLTE condition allows for the atom density to be derived everywhere in an ablation cloud at any recorded time and, ultimately, reconstruct the deposition profile of a plasmoid from the moment it is formed to the moment it is fully ablated. However, another study based on the premise that plasmoids are in CLTE led to an unexpected T_e profile. In concept, ablating fuel pellets are cold blocks of particles that are dissolved by interacting with a much hotter surrounding environment making it normal to think that the temperature in a plasmoid should be lower at its core than at its edges. Nonetheless, opposite results have actually been obtained from the second study. The CLTE condition supposed in the spectral model developed in this study has been highlighted as being at the source of this difference. Whereas CLTE has been proposed to be applicable in ablation clouds, it has only been verified by observing their global temporal behavior. Moreover, observation of ablation clouds have only be conducted on plasmoids that never went deep into the background plasma. Meaning that when considering the spatio-temporal observation of plasmoids, the CLTE condition may not apply at every point in time and space.

The goal of the present thesis is to try to verify if the CLTE condition can be used to derive the profile of the plasma parameters in ablation clouds that are located in the plasma core region of LHD. It will be shown that it tends not to be the case, and that it is required to use another method. Consequently, an alternative spectral model is presented. In order for this study to be conducted, the introduction of a new experimental device is also required. This is why a thorough explanation of a new diagnostics system based on spatial measurement spectroscopy is introduced as well. That apparatus is developed to collect spectroscopic data related to the spatial profile of any targeted plasmoid. Data obtained via this experimental device can be used to derive the distribution profile of different plasma parameters of plasmoids along one of their direction of elongation. This observation device is a sort of conceptual bridge between the two previously mentioned experiments. Unless the first experiment which introduced the concept of CLTE, this device has the ability to analyze the light emitted from the plasmoids at a local scale. Furthermore, unless the second experiment that tried to derive plasma parameters using a spectral model that required the CLTE condition to work, this new device can be used with spectral models that are not restricted by the CLTE condition. Finally, in contrast with both previous experiments, this one focuses on plasmoids that are not in the plasma edge region but in the plasma core region of LHD.

Pellet injections experiments presented in this study have been conducted during the 19th experiment campaign in LHD. The LHD is a heliotron type fusion experimental device located in Toki, Japan. It is especially recognized for the stability of its steady-state operating mode and the quality of its plasma confinement. It is equipped with a pellet injection system that already had the opportunity to prove itself in the past. All of these advantages make the LHD an ideal platform to test out whether the CLTE condition can be applied in plasmoids or not. Another relevant detail to point out is that results obtained by the two previously mentioned experiments have also been done in LHD. During this 19th experiment campaign, numerous configurations of pellet(s) injections have been conducted and, for the first time in LHD, deuterium and deuterium/hydrogen plasmas experiments have been carried out in addition to the usual hydrogen plasma experiments. Of course, both deuterium and hydrogen pellets have been injected as well.

The observation device developed for this study consists of a visible spectrometer that is sent light that has been collected by an observation system which is composed of a cylindrical lens and an optical fiber. This observation system takes advantage of the beam-shaping properties of cylindrical lenses by creating a narrow band-shaped field-of-view that is about 14 mm wide. The spectrometer is a two components system. The first component is a toroidal grating for flat-field polychromators while the second one is a dual line camera. Although the spectrometer has been designed so that it does not need to be adjusted, it is possible to fine-tune it by slightly translating and rotating the grating. There is no other moving part in this spectrometer. A fast acquisition rate is required to conduct spatially-resolved measurements of plasmoids because their life-expectancy into a plasma is just about a few hundred microseconds. This is why using a line camera is advantageous. Its quick data processing rate allows the spectrometer to output one spectrum every 14 μs. No entrance slit, intermediary mirror and additional lenses are used in order to ensure the highest brightness possible. Simultaneous recordings with a fast camera is also done to confirm that spatially-resolved measurements are actually achieved. The wavelength range of interest of the recorded spectra is located around the Balmer series emission lines of a hydrogen plasma. Plasma parameters such as n_a^1, n_e and T_e are also derived from these spectra by fitting them with a spectral modeling code. The spectral model in question is based on the suppositions that photons emitted from plasmoids are mainly originating from the Balmer series and a continuum that has for main contributions the radiative recombination and radiative attachment processes. The line-shapes of the emission lines are dominated by the Stark-broadening. Calculations of the line-intensities are done from calculations of the Saha-Boltzmann-equation (LTE condition) or the collisional-radiative model (CRM) whether the chosen approach uses the usual CLTE condition or the newly proposed model (non-CLTE). The main difference between the CLTE and non-CLTE approaches is that n_a^1 is an independent variable in the second approach. Data obtained from the plasmoid of the sixth pellet of discharge #135454 have been analyzed. By comparing the spectral data of the spectrometer with the imaging data of the fast camera, it is possible to attribute an approximate slice of plasmoid to each spectrum. Results show that spatial-resolution measurements can effectively be obtained from this spectral data. Least square fittings of the spectral data with the new spectral model indicates that it is possible to derive the plasma parameters of plasmoids with enough accuracy to observe their internal structure. The new spectral model is used, because results show that it is not possible to fit accurately the experimental spectra with a spectral model in which the CLTE condition is supposed. Qualitatively, the derived n_a^1 and n_e profiles are bell shaped with a slight dip visible near the center of the plasmoid. The T_e profile is the lowest at the center of the plasmoid and slightly increases towards the edges. Quantitatively, results obtained are mostly in agreement with what can be found in other simulations and similar experiments. The derived n_e profile ranges from $1x10^{23}$ m^{-3} to almost $2x10^{23}$ m^{-3} while n_a^1 swings from $1x10^{26}$ m^{-3} to $4x10^{23}$ m^{-3}. As for T_e, its profile announces almost 0.4 eV near the bottom part (where the densities are at their highest) and slightly increases when headed toward the edges. However, the complexity of the spectral model makes it difficult to assess the margin of error involved in these results.

Results of the doctoral thesis screening

博士論文審査結果

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Title
論文題目　Study of hydrogen pellet ablation cloud via spatially resolved spectral measurement

固体水素ペレット入射は磁場閉じ込め核融合プラズマへの燃料供給手法として有望であり，さまざまな実験装置において研究が行われている。既存のプラズマ装置におけるペレット入射実験と核融合プラズマにおける粒子供給のギャップを埋めて，核融合プラズマへの粒子供給特性を予測するためには，シミュレーションによる外挿が有効な手段である。ペレット粒子供給過程は，(1) ペレット溶発による高密度溶発雲の生成と，(2) 高密度溶発雲が背景プラズマへ均質化する 2 つの素過程からなるが，シミュレーションの検証のためには，溶発雲の電子温度および電子密度分布などを明らかにすることが必要である。これまでに，溶発雲全体からの発光スペクトル解析により，溶発雲内の代表的な電子温度および電子密度の導出が行われた例はあるが，イメージング分光計測を用いたパラメータ分布計測の試みにおいては，本来ならば中心部にある極低温の粒子源から高温の背景プラズマに向かって電子温度が上昇するところが，中心部で電子温度が最も高く，背景プラズマに向かって温度が低くなる「上に凸」の電子温度分布形状となるため，解析手法に問題があることが示唆されており，これらパラメータの空間分布計測手法は確立していない。

イメージング分光計測では，いくつかの干渉フィルターにより異なる波長域の発光強度を求め，それらからスペクトル全体を再構成することで電子温度および電子密度を導出したが，そのためには，一般に溶発雲プラズマ内で成立しているとされる完全局所熱平衡の仮定が必要であった。出願者は，電子密度が比較的低い溶発雲周辺部での完全局所熱平衡の成立性に疑問をもち，その前提に依拠しない計測および解析手法の確立を目指すとともに，溶発雲内の各局所位置での完全局所熱平衡成立性の検証を行うことを研究の目的とした。

観測視線の角度と光学系の工夫により，ペレットの移動方向に直交するスリット状の視野を用意し，視野を横切って移動する溶発雲に対し高速の分光計測を行うことで，溶発雲が伸長する磁力線方向約 20cm の領域に対して 10 点程度の空間分解計測を行うことに成功した。最初に，計測されたスペクトルに含まれる水素原子バルマーβ線のシュタルク広がりの解析から，各計測位置における電子密度を求め，中心に窪みを持つ山型の分布を得た。空間分解された完全スペクトル計測の例は無く，成果を論文誌 ATOMS に発表した。

発光線と連続光を含む観測波長域全体のスペクトルを解析するため，原子モデルに基づくスペクトル生成プログラムを構築した。完全局所熱平衡に基づくモデル（CLTE モデル）と，完全局所熱平衡を仮定しないモデル（non-CLTE モデル）を用意した。両者の最も大きな違いは，原子の基底状態密度の取り扱いにある。CLTE モデルでは，水素原子の基底状態を含むすべてのエネルギー準位のポピュレーション密度はサハ・ボルツマンの式で得られるが，non-CLTE モデルでは原子の基底状態密度を独立のパラメータとし，励起準位密度は衝突輻射モデルにより求められる。スペクトル構築に必要な輻射付着過程に伴う連続スペクトルの強度は原子の基底状態密度に比例するため，フィッティングにおいて重要な役割を果たす。

解析の対象としたペレットでは，得られたすべての計測スペクトルについて CLTE モデルでは満足できるフィッティング結果を得ることができなかった。連続光スペクトルは 0.4 eV 程度の電子温度を示唆するが，その電子温度の CLTE モデルでは，連続光と発光線の強度比が実験結果と大きく乖離することがその原因であった。一方，non-CLTE モデルでは，基底状態密度を通して連続光強度を調整し計測スペクトルに一致させることができるため，フィッティングにより計測結果を良く再現するスペクトルを得ることができた。non-CLTE モデルによるフィッティングで得られた電子温度分布は，中心部が低温で周辺部に向かって温度が上昇する「下に凸」の分布形状となり，従来のイメージング計測で得られていた「上に凸」の分布形状とは異なる結果となった。また，観測される温度分布が比較的平坦であることから，発光が観測できる溶発雲の高密度領域では低温状態が維持されており，急激な温度変化はないことが明らかとなった。

今回の実験事実は，ペレット溶発の解析において従来から仮定されてきた完全局所熱平衡状態が普遍的に成立する条件ではないということを示しており，今後のシミュレーション研究にも大きな影響を与えるものである。また，完全局所熱平衡状態が成立しない条件下においても電子温度および電子密度空間分布の測定方法を開拓したことは重要な成果であり，総合的判断により，本論文の内容は博士（理学）の授与に値すると結論した。