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論文内容の要旨

The effective ion charge, Z_{eff}, has been measured from visible bremsstrahlung continuum. The Z_{eff} diagnostic system using a visible spectrometer has been newly designed and constructed instead of an old interference filter system to eliminate line emissions from the signal and to measure the Z_{eff} value in low-density plasmas. An astigmatism-corrected Czerny-Turner-type visible spectrometer coupled with a charge-coupled device (CCD) has been installed in LHD to measure the visible bremsstrahlung continuum at 5300Å. The system utilizes 44 optical fibers vertical array for radial profile measurement. The spectrometer is equipped with an additional toroidal mirror for further reduction of the astigmatism in addition to a flat and two spherical mirrors and three gratings (120, 300, and 1200 grooves/mm) with 30cm focal length. The circular images from all the 44 optical fibers with the core diameter of 100μm can be detected without astigmatism in the wavelength range of 2000Å-9000Å. Combination of the optical fiber with a lens (focal length: 30mm) provides spatial resolution of 30mm at the plasma center. A performance test clearly indicates an excellent focus image of the fiber suggesting the absence of the cross-talk between adjacent fiber images. The diagnostic system has been absolutely calibrated using a standard tungsten lamp and an integrated sphere to analyze the visible bremsstrahlung continuum quantitatively.

A full vertical profile has been observed from the elliptical plasmas of LHD at horizontally elongated plasma cross section through the 44-fiber parallel array with vertical observation length of ~1m. The line emissions can be entirely eliminated by use of the visible spectrometer instead of the interference filter. However, a nonuniform bremsstrahlung emission profile, which is originated in the thick ergodic layer surrounding the main plasma, has been unfortunately observed for normal discharges ($n_e \leq 10^{14}cm^{-3}$) using H_2 gas puffing in all the magnetic configurations of LHD. After analyzing the detailed structure of the nonuniform bremsstrahlung, the lower half of the vertical bremsstrahlung emission profile is found to be free of the strong edge nonuniform bremsstrahlung emission in inwardly shifted magnetic axis configurations ($R_{ax} \leq 3.60m$). Then, the visible bremsstrahlung intensity is checked at the lower half profile against the density. It is found that the Z_{eff} measurement is possible at low densities of $2\times10^{13}cm^{-3}$, whereas the density threshold was $3\text{-}4\times10^{13}cm^{-3}$ when the interference filter was used for the measurement. On the other hand, the nonuniform bremsstrahlung emission is vanished in extremely high-density discharges ($n_e \geq 10^{14}cm^{-3}$) maintained with solid H_2 multi-pellet injection because the plasma edge boundary at the outside of the ergodic layer is shrunk and the large poloidal nonuniformity in the edge density and/or temperature is removed from the ergodic layer. As a result, the profile analysis of the visible bremsstrahlung continuum becomes possible for all the configurations in such high-density discharges with H_2 pellets.

When the chord-integrated signal is converted into the local emissivity using Abel inversion technique, the solution is very sensitive to the distortion of the magnetic surface structure. The influence of the magnetic surface distortion based on the finite β effect is examined as the error estimation in addition to the unclear edge plasma boundary due to the presence of the ergodic layer. The analytical result indicates that the determination of the normalized minor radius for each observation chord gives a larger influence on the Abel inversion rather than the determination of the chord length. When the observed chord-integrated bremsstrahlung intensity profile is flat, the resultant uncertainty seen in the bremsstrahlung emissivity profile becomes large, in particular, at the plasma center. Therefore, the Z_{eff} profile has to be checked by analyzing with density and temperature profiles, which are measured from Thomson scattering diagnostics, in order to verify the diagnostic reliability. The performance test of the present diagnostic system is quantitatively done using neutral-beam-heated discharges with H_2 and C pellet injections, where the Z_{eff} values should be principally close to 1 and 6, respectively. The result is Z_{eff}=1.2 for the H_2 pellet injection and Z_{eff}=7 for the carbon pellet injection. Taking into account helium and intrinsic impurity ions existing in the plasmas, which are originated in the pressurized gas used for the pellet acceleration and the plasma facing components, respectively, the values evidently proves the validity of the present Z_{eff} diagnostics.

Values of the Z_{eff} quickly vary with densities in a range of $1 \leq Z_{eff} \leq 4$. In particular the Z_{eff} becomes large at lower density range of $n_e \leq 5\times10^{13}cm^{-3}$ and at inwardly shifted magnetic axis positions of $R_{ax} \leq 3.60m$. In LHD the effect of impurity screening is remarkably enhanced when the density increases or the magnetic axis is shifted outwardly. This seems to be the reason for the observed Z_{eff} behavior. The Z_{eff} profiles are also analyzed for peaked, flat and hollow density profiles. A flat Z_{eff} profile is generally obtained for all different density profiles. The present experimental result indicates that the impurity partial pressure is radially constant to the electron or ion pressure.

Visible bremsstrahlung emission profiles have been studied over a wide range of electron densities in H_2 gas-puff and solid H_2 pellet fueled discharges. Peaked profiles are observed in high-density discharges ($n_e \geq 10^{14}cm^{-3}$) with the pellet injection, whereas hollow profiles are observed in the normal discharges ($n_e \leq 10^{14}cm^{-3}$) with gas puffing. The total bremsstrahlung radiation is analyzed from the visible bremsstrahlung profile by integrating the energy and plasma volume. It is found that the total bremsstrahlung radiation quickly increases with the density in the pellet discharges, of which the increment is scaled by the square of density, while it is roughly constant against the density in the gas-puff discharges. The total bremsstrahlung radiation becomes equal to the total radiation loss in the pellet discharges. The ratio of the total bremsstrahlung radiation to the total input power only ranges in 3-10% for the gas-puff discharge. In contrast, the ratio increases with the density and reaches 30-40% for the pellet discharge. Flat Z_{eff} profiles are observed not only in the gas-puff discharges as mentioned above but also in the pellet discharges. It indicates that any impurity accumulation is not occurred in the high-density operation using the H_2 pellet injection.

On the other hand, the radial profile measurement of Z_{eff} using visible bremsstrahlung in LHD has often encountered difficulties, because the intensity profile is largely deformed by the nonuniform visible bremsstrahlung emissions from the edge ergodic layer surrounding the core plasma as mentioned above. For that purpose a space-resolved flat-field extreme ultraviolet (EUV) spectrometer has been newly adopted to measure the Z_{eff} profile using the EUV bremsstrahlung continuum in the wavelength range of 70-75 Å. The EUV bremsstrahlung intensity profiles have been measured and checked for all the configurations in LHD. As a result, it is found that the nonuniform bremsstrahlung emission from the thick ergodic layer is entirely eliminated by use of the EUV emission because the EUV bremsstrahlung with such relatively high photon energy of 170eV can not be emitted in the low-temperature region such as the outside of the ergodic layer. The Z_{eff} profile can be successfully measured for most of discharges regardless of magnetic field structures of the ergodic layer. The Z_{eff} profiles measured in the EUV range show a fairly good agreement with those measured in the visible range. The present result clearly reveals that the use of the EUV bremsstrahlung continuum is an alternative way to the Z_{eff} measurement in toroidal plasmas with nonuniform bremsstrahlung emissions at the edge. Typical results from the EUV bremsstrahlung measurement also shows a totally flat Z_{eff} profile with error bars of ±14%. The intensity of the EUV bremsstrahlung is four orders of magnitude stronger than that of the visible bremsstrahlung. Therefore, it is expected that the Z_{eff} measurement based on the present alternative method becomes possible at further low-density ranges such as $1\text{-}2\times10^{13}cm^{-3}$.

In conclusion, the astigmatism-corrected Czerny-Turner-type visible spectrometer has work well for the bremsstrahlung continuum measurement showing good spatial resolution and high sensitivity. The Z_{eff} profiles are analyzed in neutral-beam heated plasmas for different density profiles and different density ranges after absolute calibration of the spectrometer. The flat Z_{eff} profile is observed for all different density profiles and different density ranges. It indicates that the impurity partial pressure is radially constant. The total bremsstrahlung radiation becomes equal to the total radiation loss in high-density operation with H_2 multi-pellets. The Z_{eff} measurement based on the EUV bremsstrahlung continuum is newly demonstrated as the alternative approach to eliminate the nonuniform bremsstrahlung emission from the ergodic layer.

博士論文の審査結果の要旨

核融合プラズマに於いて不純物量を定量化することは燃料水素の純度を知る上で非常に重要な研究課題となっている．その純度を表す最も的確な指標として実効電荷数（Zeff）が定義されているが，Zeffについて詳細な空間分布を測定した例はこれまで報告されていない．出願者は制動放射連続スペクトルから大型ヘリカル装置（LHD）におけるZeffを時間的・空間的に詳細に評価することを目的として研究を開始した．

LHDでは従来から光ファイバー，干渉フィルター及び光電子増倍管を組み合わせることにより可視域制動放射分布を計測していたが，線スペクトル信号の混入，ファイバー間の信号強度の混在，高い計測密度下限（4x1013cm-3）等，多くの計測上の問題が指摘されていた．そこで出願者は線スペクトルの混入を回避するため干渉フィルターに替え可視分光器を用いることを発案した．分光器の焦点距離を30cmという短焦点にすることで光学系を明るくし，トロイダル凹面鏡を採用することで収差を大幅に減らすことに成功した．また，受光系に冷却型CCD検出器を直接使用することで信号強度のS/N比を大幅に改善した．以上の結果，CCD検出器上に44チャンネル光ファイバー像を忠実に再現でき，ファイバー間の信号強度混在が無く高い空間分解能と明るい光学系を同時に有する計測器の開発に成功した．5300Å付近の制動放射を利用して詳細な空間分布を得ると共に，計測密度領域を低密度側（2x1013cm-3）へ拡張した．

視線積分量である可視制動放射強度分布からアーベル変換の手法に基づき局所放射強度分布を求めるために，ベータ効果による楕円プラズマの磁気面変形を考慮し視線積分長や視線半径位置を最適化できる磁気面形状を詳細に検討した結果，信頼性の高い局所放射強度分布を得た．この局所放射強度分布と同時計測された電子温度・密度分布を使用して最終的に高精度なZeff空間分布を得ることに初めて成功した．その結果，一般的なLHD放電では密度領域，密度分布形状及び燃料供給法（ガスパフ，ペレット）の違いによらずZeff分布が空間的に一定値を取ることを発見し，不純物の分圧が空間的に一様に保持されることを初めて示した．

この成功を基に出願者は更に，一部の磁場配位ではプラズマ周辺部からの可視制動放射が空間分布評価の障害になっている現状を克服するため極端真空紫外域での Zeff 分布計測に世界で初めて挑戦し，170eV（73Å）という比較的高いエネルギーの制動放射を利用することで温度の低いプラズマ周辺からの制動放射の寄与を排除し，全ての LHD 磁場配位でZeff分布計測を可能にした．高温プラズマでは制動放射強度はエネルギーの増大と共に飛躍的に大きくなるので，ここで得られた成果に基づき今後分光系と観測波長領域を最適化すれば可視分光法に比べ更なるZeff計測密度領域の下限拡張が可能となる．

以上のように出願者は新しい発想に基づく Zeff 計測法の開発を行い，世界最高精度のZeff分布計測に成功すると共に，不純物分圧が空間的に一定に保持されるというヘリカルプラズマ特有の新たな性質を初めて明らかにした．これらの成果は核融合プラズマにおける不純物輸送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．