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学位（専攻分野）	博士(学術)
学位記番号	総研大甲第350号
学位授与の日付	平成１０年9月３０日
学位授与の要件	数物科学研究科　核融合科学専攻 学位規則第４条第１項該当
学位論文題目	Development of a Pulsed Radar Reflectometer for Compact Helical System Plasmas
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論文内容の要旨

Density is one of the main parameters to characterize a plasma. Microwave reflectometry has been used for the electron density profile and fluctuation measurements in many plasma devices. The advantages of the reflectometry are:

1. obtaining information about local plasma electron density (not line averaged value like in the case of interferometry);
2 .requiring only a small port for access to the plasma ;

In this thesis a very young type of microwave reflectometry is treated: pulsed radar reflectometer. We have developed the pulsed radar reflectometer for Compact Helical System (CHS). Major emphasis will be placed on technical aspects. It must be also stressed that this work is the first trial for helical systems.

In the conventional reflectometry a wave of the specific frequency is launched towards the plasma to be reflected from the layer in the immediate vicinity of the critical density. The phase difference of the launched wave and reflected wave contains the information on the position of the reflecting layer. In the case of pulsed radar reflectometry, short (~1ns) microwave pulses are launched into the plasma. The pulse is reflected from a corresponding critical density layer and received by the time of flight measurement system. The measured quantities for those types of reflectometers are phase or time delay. The advantages of the pulsed radar are as follows in comparison with the conventional reflectometry:

1. temporary losses of the reflected signal are not so serious, each pulse carries all information about the position of the critical density layer;
2. false reflection from window, horn lens or waveguides could be easily filtered, because they all occur outside of interested time window;
3. due to the very short time for the microwave propagation, plasma fluctuations seem to be "frozen" and they will not affect the measurements significantly;
4. effect of mode coupling becomes less critical because reflected ordinary and extraordinary mode pulses arrive at the different time; simultaneous measurements of O- and X-mode reflection are in principle possible yielding the total magnetic field;

Numerical simulation has been done to study the propagation and detection processes of the microwave pulses. Due to the dispersion in plasmas, the pulse shape of the microwaves is deformed. This deformation causes timing error in the Constant Fraction Discriminator (CFD), which yields a logic pulse. This discriminator is inevitable for our system to do amplitude insensitive measurements. The pulse deformation is more serious for shorter pulse width, and leads to a larger error in the timing. We have found that the errors decrease with the increase of the pulse width and errors are negligible (less than 1%) for pulse width longer than about 1 ns.

A 1-channel (with changeable frequency 51, 54, 57 GHz) pulsed radar system has been designed for CHS. It is similar to that developed by RTP tokamak group, where pulsed radars were introduced for the first time. The difference is that our system uses bandpass filters at the IF stage, and can be upgraded to a multichannel system more easily. The system consists of:

1. microwave pulse production part;
2. microwave transmission, vacuum window and antenna, bandstop filter;
3. mixer and IF pulse electronics;
4. time of flight measurement electronics

To produce a suitable microwave pulse (short, large amplitude and well shaped) we tested special nonstandard fast switches (Millitech fast PIN switch and IRE varactor-diode fast modulator). The minimum pulse widths are 1.9 ns and 0.28 ns, respectively with heterodyne type detection, and the output power is around 50 mW at the peak of amplitude. Since a serious pulse broadening occurs in the long fundamental waveguide (WG), its length has been minimized. Although two independent launching and receiving antennas are used for most reflectometers, we use only one antenna for launching and receiving. This causes the problem that a small reflection (~2%) at the vacuum window makes a false pulse. In principle, the problem does not affect the measurements, because the false reflection occurs at a time window different from that for the true reflection (from plasma). This is the advantage of pulsed radar reflectometry. By using another PIN switch in front of the mixer we have succeeded for the first time in reducing the effect of false reflection to a practically acceptable level. Since the frequencies of ECH and reflectometer are rather close each other, we use a bandstop filter to reject strong ECH microwaves. Instead of an RF detectors, we use a mixer and IF electronics, so that the system has a good signal to noise ratio (SNR), and the potential for the multichannel system. A CFD yields the peak timing of the reflected pulse, and the timing is independent of the amplitude. This is very useful for the measurements, because large amplitude change occurs often. A Time-to-Amplitude Converter (TAC) is used to measure the time delay of the reflected pulse. The output of the TAC is sampled by an Analog-to-Digital Converter (ADC).

Free space time measurements have been done to calibrate the timing electronics. Instead of the plasma cut-off layer, a metallic mirror is used and moved by 50-90 cm in front of the antenna. A spatial resolution of 0.3 cm has been reached, that comes from the accuracy of TAC output reading.

A 51GHz 1-channel pulsed radar reflectometer has been installed in CHS. As a wave polarization, ordinary and extraordinary modes are launched. We probed the plasma with microwave pulses of 1.9 ns. The plasmas were initiated by IBW

(Ion Bernstein Wave) or ECH and heated by NBI and ECH. These measurements were done for discharges with the magnetic field of 0.85 T and the maximum electron density of about 6×10^{19} m^{-3}. At the first stage, we used an oscilloscope instead of CFD-TAC time of flight measurement electronics. Due to the function of oscilloscopes, we could get only one waveform for each discharge. The result showed that the reflected waveform was distorted but not significantly, and that in most cases the amplitude of the reflected pulses is rather small. When we read the peak timing by eyes, the relation between the time delay and the line averaged density agreed with the calculated curve both for O-/X-modes launching experiments.

As the next step, we used the CFD-TAC electronics by which we could get the time behavior for each discharge. The repetition rate of the pulse launching and measurement is 200 kHz. The launching polarity is adjusted to X-mode to measure relatively low density plasma. When the discharge starts, the density gradually increases. Below the critical density, the pulse passes through the plasma and is reflected at the back wall of the vacuum vessel. The reflected pulse passes through the plasma again and detected by the receiving system. This situation is called as delayometry. When the density increases, the cut off appears and moves towards the antenna. The time behavior of the time delay agrees with the calculation of this scenario by assuming the parabolic density profile. Instead of assuming the whole profile, we assume a linear profile between the plasma edge and the cut-off layer. Then the estimated position of the cut off layer coincides well with Thomson scattering measurements. The spatial accuracy of the determination of the position of the reflected layer during plasma measurements was about 5-8 mm.

While the reflectometer can follow the fast and large changes in density, the HCN interferometer fails, which is partly shown in the ice pellet injection experiment. The fast movement of the cutt-off density layer during the density collapse was successfully measured with the pulsed radar reflectometry. This fact demonstrates the reflectometer has a high temporal resolution.

The first pulsed radar measurements in a helical system have been done. We have succeeded in measuring the density with one antenna system, that means reflectometry requires only a small port. The density fluctuations could also be measured because of its high spatial and temporal resolution of pulsed radars.

論文の審査結果の要旨

本学位論文は、短パルスマイクロ波をプラズマ中にO, Xモードで入射し、カットオフ層で反射されて帰ってくるパルスの飛行時間を測定することによってプラズマの密度分布、揺動を測定するパルスレーダー反射計に関するものである。CHSにおいては、幅1-2ns, 周波数51-55GHzの短パルスを200-400kHzの高繰り返しでプラズマ中に入射している。この測定法は、既にトカマク(RTP, START, TEXTOR等)で試みられ、ミラー装置Γ-10でも開発中であるが、将来の核融合炉（例えば、ITER）における密度測定の有望な方法として注目されている新しい方法であり、非常に高い時間分解能をもち、密度揺動の影響を受けないで密度分布を測定することができるという特徴を有している。ヘリカルプラズマに対しては世界で初めての試みである。入射と反射計測の両方の機能を合わせ持ち、測定ポートが少なくて済む等、近接性に優れた1アンテナ系を採用している。この方式に伴う困難、即ち真空窓での反射の混入やヘリカル装置での複雑なプラズマ形状に起因する反射波の強い減衰などの問題などを、本研究では電子回路系と入射ホーンでのレンズ採用などの工夫により解決した。

これによって、

1) プラズマの電子密度がカットオフ密度よりも低密度の場合には干渉計として働き、高密度の場合には反射計として働くことを、O, Xモードについて確認し、詳細な結果を得ることができた。また、
2) アイスペレット入射に伴う速い密度変化を測定し、プラズマのコラプスに伴う密度分布の変化、特に磁気軸に向かうプラズマの移動などについて詳細な知見が得られた。
3) 中性粒子入射加熱による低ベータプラズマに見られるバースト状MHD揺動に伴う密度揺動が測定され、低周波数（数kHz）では磁気揺動と同様のスペクトルをもつことが示された。このMHD揺動の同定について新しい知見を提供している。

本論文では、世界で初めてヘリカルプラズマに適用し種々の課題を解決するとともに、パルスレーダーの特徴を生かし、密度分布と密度揺動の同時測定を1アンテナ系で可能にした。これは、LHDを含む将来の核融合実験装置での密度分布・揺動測定に新たな展望を開くものであり、本論文は学位論文としてふさわしい学術内容を持っていると認められる。

パヴリチェンコ君の学位論文に関して、専門分野、基礎分野について口述により学力を確認した。プラズマと電磁波との相互作用、測定回路技術、ヘリカル磁場構造、CHSプラズマの諸特性などについて広範囲の質問に的確に答えた。これにより、学位を与える上で十分な知識を有するものと判断できた。また、英文論文(top author)を1編発表している。本論文は英語で書かれており、英語についての学力も十分であると認められた。