IMPROVING THE RESOLUTION OF THOMSON SCATTERING LIDARS BY APPLICATION OF NOVEL DECONVOLUTION-BASED ALGORITHMS

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1. Investigatory goals

Effective observation and control of the fusion process is only possible when based on effective plasma diagnostics involving the determination with high accuracy and (spatio-temporal) resolution of the electron temperature T_e and concentration n_e and of the pressure P in the torus. Thomson scattering (TS) methods are routinely used for measuring plasma temperature and density in fusion devices, but the only tokamak to have a LIDAR variant of this diagnostic (see figure1) is the Joint European Torus (JET), Culham, UK [1]. The TS lidar approach is based on the remote sensing of the plasma with an intense laser pulse and on the detection of the backscattered light from the plasma electrons. It allows one to obtain simultaneously the T_e and n_e profiles along a lidar line of sight (LOS) through the torus core. This diagnostic has been successfully used for reliable measurement of T_e and n_e profiles at JET [2-4] and is intended to be used in ITER [5]. The investigations performed are of great importance for the ITER LIDAR development as JET is the only place in the world where this measurement technique can be tested.

The determination of T_e and n_e profiles by using TS lidar diagnostic is based on the analysis of the information provided by the TS lidar profiles (the time-to-range resolved profiles of the received back-scattered light power) [6,7]. For this purpose, the single-scattering lidar equation which describes the relation between the measured lidar profile, the parameters of the lidar system, and the characteristics of the investigated high-temperature plasma along the LOS should be solved. There are different effective approaches for TS data processing developed previously [8-10] and recently [11-13], each one having some advantages.

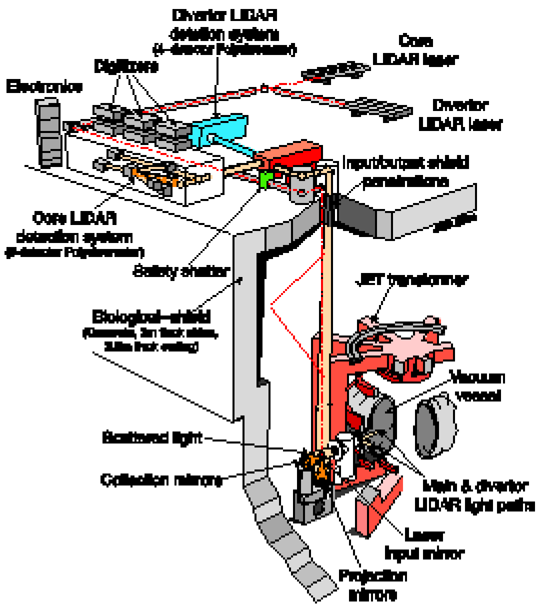

Figure 1. JET Thomson scattering Lidar system.

It is usually accepted that the range resolution of the lidars is of the order of the spatial size of the effective lidar pulse response, which is a convolution of the sensing laser pulse shape and the pulse response function of the receiving electronics. So, in order to achieve a better resolution, shorter sensing pulses and faster registration electronics should be used. The short-pulse lidar equation holds true when the effective pulse response shape of the lidar is shorter than the least longitudinal variation scale of the fusion plasma characteristics. In the opposite case, the lidar equation describing the lidar return has the form of the convolution of the short-pulse lidar profile with the system response shape. Then, different deconvolution techniques may be used for improving the sensing resolution [13,14]. Such techniques concerning the TS lidar sensing of electron temperature and density profiles have already been investigated by us analytically and by computer statistical modeling [15,16].

The research on this topic is carried out under Task 2.2.2 *Improving the resolution of Thomson scattering lidars by application of novel deconvolution-based algorithms* of the Contract of Association between the European Atomic Energy Community (EURATOM) and INRNE in the frame of 7th Framework Programme of the European Atomic Energy Community (Euratom) No. FU07-CT-2007-00059 by a Bulgarian team from the Institute of Electronics and the Institute of Nuclear Research and Nuclear Energy at the Bulgarian Academy of Sciences in a collaboration with the JET Thomson Scattering team, JET Electron Kinetics Group at the Culham Centre for Fusion Energy, UK.

The statistical modeling of the deconvolution procedures confirmed their capability in improving the resolution and accuracy of recovering T_e profiles in thermonuclear plasmas. The possibility was confirmed as well of achieving considerably higher recovery accuracy and resolution in the new generation fusion reactors (ITER, DEMO) intended to ensure considerably higher sensing signal-to-noise ratio due to higher electron concentration, sensing-pulse energy and quantum efficiency of the photon detectors, and to faster signal-receiving electronics compared to the corresponding characteristics of JET. As an important new result, the simulations showed that the theoretical estimates of the statistical error in the determination of the electron temperature from deconvolved lidar profiles practically coincided with those derived from the computer statistical modeling. In this way, a simulation-aided explicit theoretical formulation was obtained of the temperature measurement error and the corresponding error bars.

In 2012 we continued our investigations in this field. We endeavored to reveal the influence of the system response shape on the distortions of the recovered electron temperature and density profiles. Also, we investigated the performance of the developed by us deconvolution algorithms and proved their efficiency by real data processing.

The upgrade of the JET Core LIDAR with more sensitive photon detectors resulted in a substantial increase of the signal-to-noise ratio in the output lidar profiles [17], which gave rise to an interest in the possibility of extracting information about the plasma evolution (pedestal & core) from the lidar data. The attractiveness of such an analysis is of great importance for the plasma diagnostic by the future ITER Core Lidar [5]. The first results on testing the sensitivity of improved Core Lidar data to the ELM processes on the torus edge were obtained.

The rms errors were investigated, analytically and by computer simulations, in the determination by Thomson scattering lidar of the electron temperature T_e and concentration n_e and the pressure in fusion plasmas, using fitting approach [18].

2. Research activities and results obtained in 2012

2.1. Deconvolution-based higher-resolution processing of real TS Core LIDAR data

The performance was investigated of the deconvolution algorithms developed by us (and preliminarily proved analytically and by computer statistical modeling) when processing real lidar data. The research was focused on the analysis and implementation of different methods for deconvolution of registered signals in each spectral channel of the JET Thomson scattering LIDAR diagnostics in order to improve the range resolution of the profiles measured of the electron temperature T_e and concentration n_e. The total JET LIDAR system response time was estimated to be ~ 800 ps, which corresponds to a spatial resolution interval of ~ 12 cm that is practically insufficient for accurate registration of the narrow plasma pedestal area. The deconvolution of the lidar signals is important not only for registration of the T_e and n_e profiles with higher resolution, but also as a first necessary step in investigating the pedestal evolution on the basis of the TS lidar data. Using lidar data, the problem was solved of the correct determination of the real system response function. Both methods under investigation, the Fourier-deconvolution method [13,16] and the stabilized matrix method [19], showed good performance, which will lead to better recovering of the electron temperature and concentration profiles. The expected shift was also observed of the seeming edges of the profiles from the torus walls to the internal torus zone. After deconvolution, the electron concentration pedestal was observed to be steeper compared to the initially registered one. As a whole, the deconvolved T_e and n_e profiles are close to those obtained by other diagnostics, namely, high-resolution Thomson scattering.

A program for acquisition, calibration, and processing of JET TS lidar data was adopted in view of performing deconvolution of the lidar profiles registered and further determination with higher resolution of the electron temperature and density profiles.

2.2. Influence of the system response shape on the convolution-due distortions of the electron temperature and density profiles recovered by TS lidar

The influence was analyzed of the system response shape on the convolution-due distortions of the electron temperature and density profiles as recovered by a TS lidar. It was shown that in the case of symmetric (Gaussian) laser pulses, far from the pedestal area, the convolution does not distort the information about the electron temperature and density. Such distortions exist in the pedestal areas, concerning mainly the n_e profiles and depending on both the temperature and the density profiles. These distortions could be minimal only at sufficiently slant temperature profiles. In the case of asymmetric (e.g., exponentially-shaped) laser pulses, distortions of the information about n_e exist along the whole line of sight within the plasma torus. These distortions depend again on the n_e and T_e profiles and could be minimal at sufficiently slant T_e profiles. The above conclusions are valid when using the fitting approach to measuring n_e and T_e. When using center-of-mass wavelength (CMW) approach, the temperature information is also distorted in the case of asymmetric sensing pulses, depending on the n_e profiles and the steepness of the T_e profiles.

2.3. Analysis of sensitivity of JET Core LIDAR data to the ELM evolution

The sensitivity was demonstrated for the first time of JET Core LIDAR data from the upgraded system (during JET experimental campaigns C28, C29 and

C30) to the ELM processes on the plasma edge. To this purpose, the mean evolution curves were created for the pedestal electron density and temperature amplitudes and the pressure amplitude. Also, the mean evolution rates of restoration of the pedestal density, temperature and pressure were calculated.

A comparison was performed between the mean electron temperature evolution curves, created by the JET Core lidar data, and the ECE radiometer electron temperature data, sampled in the same lidar slice instants. A relatively good agreement was demonstrated between the two evolution curves.

The approach developed provides an opportunity for a simultaneous analysis of the sensitivity of a large set of JET plasma parameters to the ELM evolution within the entire plasma torus.

This approach is deemed as very promising for the analysis of the ITER performance and the dynamics of the ITER core plasma on the torus edge.

2.4. Errors in the determination of the electron temperature and density and the pressure using a fitting approach for TS data processing

The rms errors were investigated, analytically and by computer simulations, in the determination by a Thomson scattering lidar of the electron temperature T_e and concentration n_e and the pressure P in fusion plasmas, using a fitting approach. Unlike previous such studies, we accounted for the correlation between the fluctuations of the statistical estimates of the electron temperature and concentration. Analytical expressions of the errors as functions of the electron temperature were derived for the cases of log-linear and non-linear fitting procedures at a high measurement signal-to-noise ratio. Computer simulations were also performed of the nonlinear fitting procedure, which confirmed the analytical results. It was shown that in the log-linear fitting procedure, the correlation between the estimates of the electron temperature and concentration leads to an increase in the rms errors in determining the concentration and the pressure, compared to the case of no correlation. In the non-linear fitting procedure, the same correlation increases the n_e-measurement error while influencing only slightly the error in the determination of the pressure.

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